

Hadron production and polarisation of gluons in the nucleon in the μ -N interactions in the COMPASS experiment at CERN

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For Alicja Kownacka and Roman Kownacki, my Grandparents

Dla Alicji i Romana Kownackich, moich Babci i Dziadka

Abstract

This thesis presents a determination of the gluon polarisation $\Delta G/G$ in the nucleon. The result was obtained studying the Photon–Gluon Fusion process with the open charm mesons production. The data come from the COMPASS experiment at CERN using a polarised ${}^6\text{LiD}$ target and a 160 GeV polarised muon beam. The analysis is based on the data taken in 2002–2004. The result is $\Delta\mathbf{G}/\mathbf{G} = -\mathbf{0.62} \pm \mathbf{0.44}(\text{stat.}) \pm \mathbf{0.18}(\text{syst.})$ at the QCD scale $\mu^2 = 13 \text{ GeV}^2$ and the average x_g equal to 0.15 with RMS of 0.08. This result translates into $\Delta G(x_g = 0.15, \mu^2 = 13\text{GeV}^2) = -8.0 \pm 6.3$ for the GRV98 gluon distribution. The presented value is the first experimental determination of the gluon polarisation done with the open charm mesons method and also a primary objective of COMPASS. It is in agreement with other lepton scattering results, obtained with the high- p_T method (COMPASS, SMC and HERMES) and with results from proton-proton interactions (STAR and PHENIX). All of the measurements point towards a small gluon polarisation in the nucleon. As the analysis requires charm particles reconstruction, a special attention was given to the studies of the hadron mass spectroscopy with the COMPASS spectrometer. These studies are also summarised in the thesis.

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Introduction

“...It is a mysterious beast, and yet its practical effect prevails over the whole of science. The existence of spin, and the statistics associated with it, is the most subtle and ingenious design of Nature – without it the whole Universe would collapse...” **Tomonaga**

In the early 1925 Pauli proposed the idea that electrons are described with an extra “classically undescribable two-valuedness” quantum number. The concept was motivated by an observation of the atomic energy levels impossible to be explained by the naïve quantum theory existing at the time. With an additional quantum number, Pauli was able to formulate the famous exclusion principle, according to which two electrons cannot be in the same quantum state. Later that year Uhlenbeck and Goudsmit suggested that this quantum number is related to the electron intrinsic angular momentum, called spin. Soon it was realised that the Stern and Gerlach experiment, conducted as early as 1921 but misinterpreted then, had provided with an evidence of the subsistence of intrinsic angular momentum of electron and proved it is quantized. The idea of electron being spin $\frac{1}{2}$ particle and having two possible projections of spin at a given axis: $s_z = +\frac{1}{2}$ and $s_z = -\frac{1}{2}$ was accepted¹. The proton spin determination was performed by the end of the twenties. Later also the neutron spin was measured. They are the same as that of electron.

The structure of nucleon can be probed scattering a beam of high energy leptons on a nuclear target. Such measurements performed at SLAC in the late sixties provided evidence for a quark substructure of the nucleon. The image developed since then perceives nucleons as composed of two kinds of objects – quarks and gluons. Quarks are spin $\frac{1}{2}$ particles and apart from the fractional electric charge, carry also colour charge. There exist six kinds of quarks, called flavours: up (u), down (d), strange (s), charm (c), bottom (b) and top (t); but only three of them (u, d, s) share masses smaller than the nucleon mass and thus can contribute significantly to its internal structure. The quarks can interact with each other through exchange of gluons being also endowed with the colour charge. Gluons are spin 1 particles and are electrically neutral. Both, quarks and gluons, can contribute to the total spin of the nucleon. The analysis presented in this thesis aims at the direct measurement of the gluons contribution.

If $\Delta\Sigma$ denotes the number of quarks with spins parallel to the nucleon spin minus the number of quarks with anti-parallel spins, the quark spin contribution is equal to $\frac{1}{2}\Delta\Sigma$. Similarly, the contribution from the gluons is equal to the number of gluons with spins parallel minus the number of gluons with spins anti-parallel to the nucleon spin and is denoted by ΔG . Contributions from the angular momenta of quarks and gluons

¹Throughout this thesis $\hbar = c = 1$ is assumed.

are called J . Thus the nucleon spin (s_z) can be written as:

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + J \quad (1)$$

The $\Delta\Sigma$ can be further decomposed into the contributions from quarks and anti-quarks of different flavours:

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s + \Delta\bar{u} + \Delta\bar{d} + \Delta\bar{s} \quad (2)$$

With the three independent quantities, $\Delta\Sigma$, ΔG and J , various scenarios fulfilling the sum rule (1) are possible. The simplest scenario based on the non-relativistic QPM assumes that two valence quarks have their spins parallel to the spin of the nucleon and one has its spin anti-parallel. This corresponds to the $\Delta\Sigma=1$, $\Delta G=J=0$. Including relativistic effects results in $\Delta\Sigma \approx 0.6$ [1].

The first experiment to measure the polarisation effects in the inelastic lepton-nucleon scattering, E80 [2], was conducted in the mid-seventies at SLAC in USA. In the eighties the kinematical range for the measurements was considerably extended by the European Muon Collaboration (EMC) [3] at CERN due to the much higher beam energy. The result for $\Delta\Sigma$ was $0.12 \pm 0.09 \pm 0.14$; considerably smaller than 0.6. The EMC result triggered a number of experiments in Europe – SMC at CERN [4], HERMES at DESY [5], and in USA – E142, E143 and E155 at SLAC [6–8]. They all confirmed the EMC observation. Presently COMPASS at CERN [9] aims at a direct measurement of the ΔG . Two different approaches based on tagging the Photon–Gluon Fusion (PGF) process are used here. The tagging is via the detection of the open charm mesons or the high- p_T hadron pairs. This thesis is dedicated to the first method. That approach has never been used for polarisation effects studies before. The other method, employed also previously by SMC and HERMES experiments, depends strongly on Monte Carlo simulations.

Studies of the open charm mesons require very efficient hadron identification and reconstruction. Therefore this thesis consists of two parts: the first one dedicated to the hadron spectroscopy and the second – focused directly on the ΔG measurement. The structure is the following. Chapter 1 describes the theoretical motivation and methods used for the determination of the gluon polarisation in the nucleon. In the second chapter the COMPASS spectrometer and the software tools used for the events reconstruction and analysis are presented. The chapter is concluded with a section dedicated to a new detector that was constructed in Warsaw. Chapter 3 describes the studies of the reconstruction of neutral hadrons decaying into charged particles in the detector and outlines the search for rare hadronic states. The next chapter presents cuts leading to the most efficient selection of the open charm mesons while chapter 5 introduces mathematical techniques aiming at the estimation of ΔG . Chapter 6 presents the final result on the gluon polarisation determined in the open charm production channel. Chapter 7 deals with a detailed discussion of systematic effects. A summary of the analysis and an outlook on the future improvements of the gluon polarisation measurement are presented in chapter 8.

A measurement of the gluon polarisation with the open charm method is the main goal of COMPASS. The author has performed one of the two parallel analyses of the data which included: selection of the open charm events, optimisation of the cuts, simulations of the analysing power and studies of the systematic error. The author was also involved

in the studies of the low momenta tracks poorly reconstructed in the spectrometer and in the tests that led to the optimisation of the features of a new detector added to the COMPASS experimental setup in 2006. The part dedicated to the hadron spectroscopy is the author's own contribution as well.

Results described in this thesis were presented by the author at the following conferences:

- Cracow Epiphany Conference on Hadron Spectroscopy, Cracow, 2005 [10];
- Cascade Physics - A New Window on Baryon Spectroscopy, Jefferson Laboratory, USA, 2005;
- SPIN-PRAHA-2006, Prague, 2006 [11];
- 42nd Rencontre de Moriond, QCD and High Energy Hadronic Interactions, La Thuile, 2007 [12].

A part of the thesis dedicated to the hadron spectroscopy is described in [13]. A paper with results on the gluon polarisation studied with the open charm mesons will soon be submitted for publication in the Physical Review Letters.

Chapter 1

Theoretical and Experimental Introduction to the ΔG Measurement

In this chapter a short introduction to the polarised lepton-nucleon inelastic scattering is presented. A discussion of the spin independent and spin dependent structure of the nucleon is included. It is focused on the measurements of the gluon polarisation inside the nucleon. The chapter is composed of three parts: dedicated to relevant theoretical ideas, to the experimental methods, and presenting a short overview of the present and past experiments measuring the polarised gluon distribution.

1.1 Inelastic Scattering

Knowledge of the internal structure of the nucleon is obtained mainly from the inelastic scattering measurements. Here we call inelastic scattering a process of high energy lepton scattering on constituents of a nucleon. The scattering is via a virtual boson exchange and leads to a destruction of the initial nucleon. In what follows the scattering is considered for the fixed target experiments as all the information on the polarised nucleon structure obtained up to now comes practically from such measurements.

The scattering measurements can be restricted only to two independent variables, that is to the energy of the scattered lepton (E') and its deflection angle (θ) with respect to the direction of flight of the incoming lepton. Such measurements are called inclusive. Often also specific interaction products are measured. Such analyses are referred to as semi-inclusive or exclusive (when the whole final state is reconstructed). The analysis presented in this thesis is based on the reconstruction of the open charm mesons. Therefore it is of the semi-inclusive kind.

In the case of COMPASS the interacting lepton is a muon and the mediating boson (muon-nucleon centre-of-mass energy about 17 GeV) is a photon. Since the electromagnetic constant α is small it is well justified to assume that during the interaction only one photon is exchanged¹.

The inelastic scattering interaction diagram is presented in Fig. 1.1. If the laboratory system coordinates are fixed with the Z axis pointing in the direction of the incoming

¹This assumption is valid for the targets composed of light elements ($Z \ll 1/\alpha$), *e.g.* for the COMPASS target.

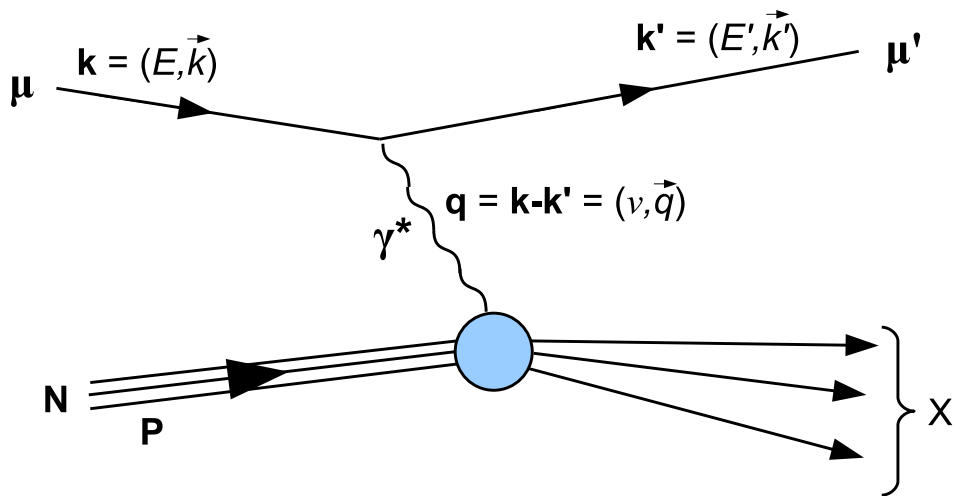


Figure 1.1: Diagram of the inclusive inelastic μN scattering in the one photon exchange approximation.

muon its momentum four-vector is defined as:

$$\mathbf{k} = (E, \vec{k}) \stackrel{LAB}{=} (E, 0, 0, |\vec{k}|) \quad (1.1)$$

Here E and $\vec{k}$ are energy and momentum vector of the incoming muon. The momentum four-vector of the target nucleon, at rest in the LAB system, is given by:

$$\mathbf{P} \stackrel{LAB}{=} (M, 0, 0, 0) \quad (1.2)$$

where M is the nucleon mass. The $\mathbf{q}$ is a four-momentum transfer from the lepton to the hadronic system:

$$\mathbf{q} = \mathbf{k} - \mathbf{k}' \quad (1.3)$$

We choose the following Lorentz invariants to describe the interaction: Q^2 , x and y . They are defined as:

$$Q^2 = -\mathbf{q}^2 = -(\mathbf{k} - \mathbf{k}')^2 \stackrel{LAB}{=} -2(m_\mu^2 - EE' + |\vec{k}||\vec{k}'|\cos\theta) \quad (1.4)$$

$$y = \frac{\mathbf{P} \cdot \mathbf{q}}{\mathbf{P} \cdot \mathbf{k}} \stackrel{LAB}{=} \frac{\nu}{E} \quad (1.5)$$

$$x = \frac{Q^2}{2\mathbf{P} \cdot \mathbf{q}} \stackrel{LAB}{=} \frac{Q^2}{2M\nu} \quad (1.6)$$

where $\nu = E - E'$ and m_μ is the muon mass. The Q^2 variable is a photon virtuality and the Bjorken scaling variable x can be treated as a measure of the elasticity of the process, in the Quark Parton Model in the Breit frame² it is interpreted as a fraction of the nucleon momentum carried by the struck quark [14]. The y is the fraction of the incoming lepton energy carried by the photon. At a given interaction energy only two of the above variables are independent.

The analysis presented in this thesis is based on the COMPASS ability to measure

²Breit frame is defined with: $\vec{q} + 2x\vec{P} = 0$. The Z -axis coincides with the nucleon-photon axis.

at least a part of the final hadronic system. For a description of such a semi-inclusive process another Lorentz invariant variable, called z , is defined:

$$z = \frac{\mathbf{P} \cdot \mathbf{P}_h}{\mathbf{P} \cdot \mathbf{q}} \quad (1.7)$$

where $\mathbf{P}_h$ is a momentum four-vector of a hadron that is measured in the final hadronic state. In the laboratory system z can be rewritten as:

$$z \stackrel{LAB}{=} \frac{E_h}{\nu} \quad (1.8)$$

It describes a fraction of the energy of the interacting photon carried by a given hadron.

1.2 The Cross-Section

The differential cross-section for the inclusive scattering is given by the following formula [15]:

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{e^4}{16\pi^2 Q^4} \frac{E'}{ME} L_{\mu\nu} W^{\mu\nu} \quad (1.9)$$

where $L_{\mu\nu}$ is a leptonic tensor corresponding to a virtual photon emission from the lepton line, and $W^{\mu\nu}$ is a hadronic tensor which represents the virtual photon-hadron interaction. The former is well described by the **Q**uantum **E**lectro**D**ynamics (QED) while the latter cannot be calculated directly (*e.g.* in QCD) since it depends also on the non-perturbative dynamics. For inclusive scattering involving the projectile and the target polarisations, the tensors depend on the momenta and spins four-vectors of particles taking part in the interaction: $L_{\mu\nu}(\mathbf{s}, \mathbf{k}, \mathbf{k}')$, $W^{\mu\nu}(\mathbf{S}, \mathbf{P}, \mathbf{q})$. For simplicity we will discuss the formalism for spin $\frac{1}{2}$ target first, and then the considerations will be broaden to cover also spin 1 case.

Both tensors, $L_{\mu\nu}$ and $W_{\mu\nu}$, can be split into two parts – symmetric and an anti-symmetric with respect to the interchange of $\mu\nu$ indices. Only the anti-symmetric parts depend on the polarisation:

$$L_{\mu\nu}(\mathbf{s}, \mathbf{k}, \mathbf{k}') = L_{\mu\nu}^S(\mathbf{k}, \mathbf{k}') + iL_{\mu\nu}^A(\mathbf{s}, \mathbf{k}, \mathbf{k}') \quad (1.10)$$

$$W^{\mu\nu}(\mathbf{S}, \mathbf{P}, \mathbf{q}) = W_S^{\mu\nu}(\mathbf{P}, \mathbf{q}) + iW_A^{\mu\nu}(\mathbf{S}, \mathbf{P}, \mathbf{q}) \quad (1.11)$$

The $L_{\mu\nu}^S$ and $L_{\mu\nu}^A$ can be calculated in the QED:

$$L_{\mu\nu}^S(\mathbf{k}, \mathbf{k}') = 2(k'_\mu k_\nu + k'_\nu k_\mu + (m^2 - \mathbf{k}' \cdot \mathbf{k})g_{\mu\nu}) \quad (1.12)$$

$$L_{\mu\nu}^A(\mathbf{s}, \mathbf{k}, \mathbf{k}') = -2m\epsilon_{\mu\nu\rho\sigma}q^\rho s^\sigma \quad (1.13)$$

where $\epsilon_{\mu\nu\rho\sigma}$ is the fully anti-symmetric Levi-Civita tensor defined by $\epsilon_{1234}=1$ and $g_{\mu\nu}$ is the diagonal metric tensor.

The $W_S^{\mu\nu}$ and $W_A^{\mu\nu}$ can be parameterised in the following way (cf. [16]):

$$W_S^{\mu\nu}(\mathbf{P}, \mathbf{q}) = -g^{\mu\nu}F_1 + \frac{F_2}{\mathbf{P} \cdot \mathbf{q}} P^\mu P^\nu \quad (1.14)$$

$$W_A^{\mu\nu}(\mathbf{S}, \mathbf{P}, \mathbf{q}) = g_1 \frac{M}{\mathbf{P} \cdot \mathbf{q}} \epsilon^{\mu\nu\lambda\delta} q_\lambda S_\delta + g_2 \frac{M}{(\mathbf{P} \cdot \mathbf{q})^2} \epsilon^{\mu\nu\lambda\delta} q_\lambda (\mathbf{P} \cdot \mathbf{q} S_\delta - \mathbf{S} \cdot \mathbf{q} p_\delta) \quad (1.15)$$

where F_1 , F_2 , g_1 , g_2 are functions of x and Q^2 and contain information on the internal structure of the target nucleon. They are called structure functions and have to be measured in experiments. After the contraction of the $L_{\mu\nu} W^{\mu\nu}$ tensors the formula (1.9) for the cross-section can be decomposed into a sum of two terms, the first one proportional to $L_{\mu\nu}^S W_S^{\mu\nu}$ and the other proportional to $L_{\mu\nu}^A W_A^{\mu\nu}$. The differential cross-section can be rewritten as:

$$\frac{d^3\sigma}{dx dQ^2 d\vartheta} = \frac{d^3\bar{\sigma}}{dx dQ^2 d\vartheta} - \frac{1}{2} h \frac{d^3\Delta\sigma}{dx dQ^2 d\vartheta} \quad (1.16)$$

where the first part is independent of the spin orientations of the interacting particles while the second part depends on the relative spin orientation of the target and of the projectile. The angle ϑ is an angle between the projections of $\vec{k}'$ and $\vec{S}$ onto the XY plane, transverse to the direction of the incoming lepton, Fig. 1.2. The h is the lepton's helicity. The second term in this equation can be further decomposed into two parts:

$$\frac{d^3\Delta\sigma}{dx dQ^2 d\vartheta} = \cos\alpha \frac{d^3\Delta\sigma_{\parallel}}{dx dQ^2 d\vartheta} + \sin\alpha \frac{d^3\Delta\sigma_T}{dx dQ^2 d\vartheta} \quad (1.17)$$

where α is an angle between $\vec{S}$ and $\vec{k}$. Here the first term describes the case when the spin of the interacting lepton is parallel to the spin of the target particle while the other corresponds to the projectile spin oriented transversely with respect to the spin of the nucleon. For a discussion of the presented decomposition and relations between the cross-section and the structure functions see *e.g.* [17].

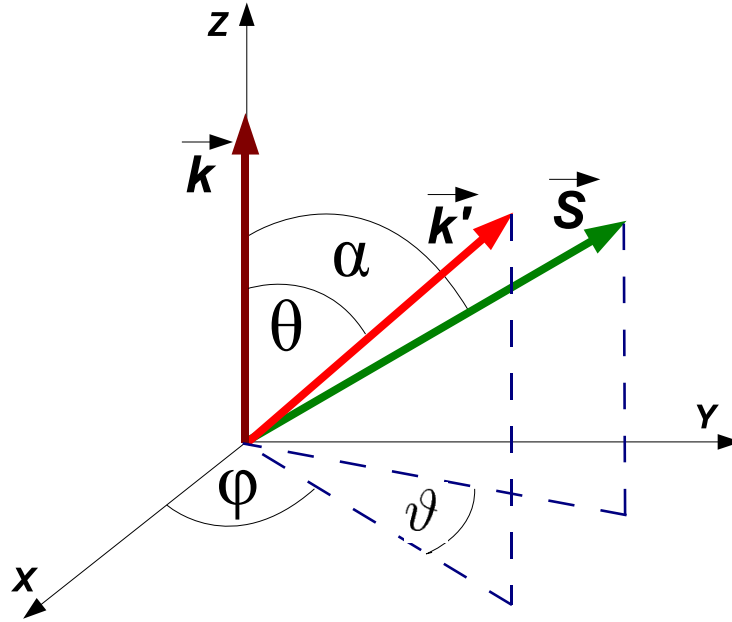


Figure 1.2: Definition of the angles used for the description of polarised scattering.

1.3 The Nucleon Structure Functions

The four structure functions: F_1 , F_2 , g_1 and g_2 , that parameterise the structure of the nucleon cannot be derived from theory. They have to be measured in experiments.

1.3.1 Structure Functions in the Quark Parton Model

The Quark Parton Model describes the internal nucleon structure in terms of the non-interacting, pointlike and massless particles called partons. It is defined in the nucleon's infinite momentum frame. In this frame partons do not carry transverse momenta. The photon probing the nucleon structure is thus interacting with a given parton which during the interaction does not feel the existence of other surrounding partons. The interaction can occur only if a parton carries an electric charge. The charged partons are identified with quarks.

In the QPM the structure functions depend only on x , a fraction of a nucleon momentum carried by a struck quark. The structure functions can be related to the functions that define quark distributions in the nucleon, $q_f^+(x)$ and $q_f^-(x)$, where f denotes the quark flavour while “+” and “−” refer to the quark spin orientation, parallel and anti-parallel to the spin of the nucleon respectively. The distribution functions are the probability densities of finding a quark of a given flavour, spin orientation and momentum fraction x in the nucleon. The F_1 structure function in the QPM can be expressed as:

$$F_1(x) = \frac{1}{2} \sum_f e_f^2 (q_f^+(x) + q_f^-(x)) = \frac{1}{2} \sum_f e_f^2 q_f(x) \quad (1.18)$$

where e_f is an electric charge, in units of the elementary charge, carried by a quark of a flavour f . The summation is over all flavours. The F_2 in the QPM can be obtained from F_1 function using the Callan-Gross relation [18]:

$$F_2(x) = 2xF_1(x) = x \sum_f e_f^2 (q_f^+(x) + q_f^-(x)) \quad (1.19)$$

The experiments performed in the sixties at SLAC confirmed an approximate dependence of F_1 and F_2 on x only. A discovery of this effect, called the Bjorken scaling, was a stunning success of the QPM. The next experiments have shown that the scaling is not complete and a weak F_1 and F_2 dependence on Q^2 , of the order of 10%, appears. It will be a subject of the next section. The F_2 structure function for the proton was thoroughly measured in various experiments, Fig. 1.3.

The g_1 structure function in the QPM has a form similar to that of F_1 . It is a square of electric charge weighted difference of distributions of quarks with spin parallel and anti-parallel to the spin of the nucleon:

$$g_1(x) = \frac{1}{2} \sum_f e_f^2 [q_f^+(x) - q_f^-(x)] = \frac{1}{2} \sum_f e_f^2 \Delta q_f(x) \quad (1.20)$$

where $\Delta q_f(x) = q_f^+(x) - q_f^-(x)$. The measured values of g_1 for proton are presented in Fig. 1.4. In the QPM the g_2 structure function is equal to 0 at all x .

For the spin 1 target the hadronic tensor is parameterised by eight structure functions. Apart from the spin-independent F_{1-2} and the spin-dependent g_{1-2} structure functions, four additional structure functions b_{1-4} are needed (cf. [27]). All these functions depend on x and Q^2 . The b_{1-4} are predicted to be small and can be neglected at the precision at which the target is probed in COMPASS [28,29]. Neglecting those functions makes the formalism introduced for spin $\frac{1}{2}$ hold also for the spin 1 target.

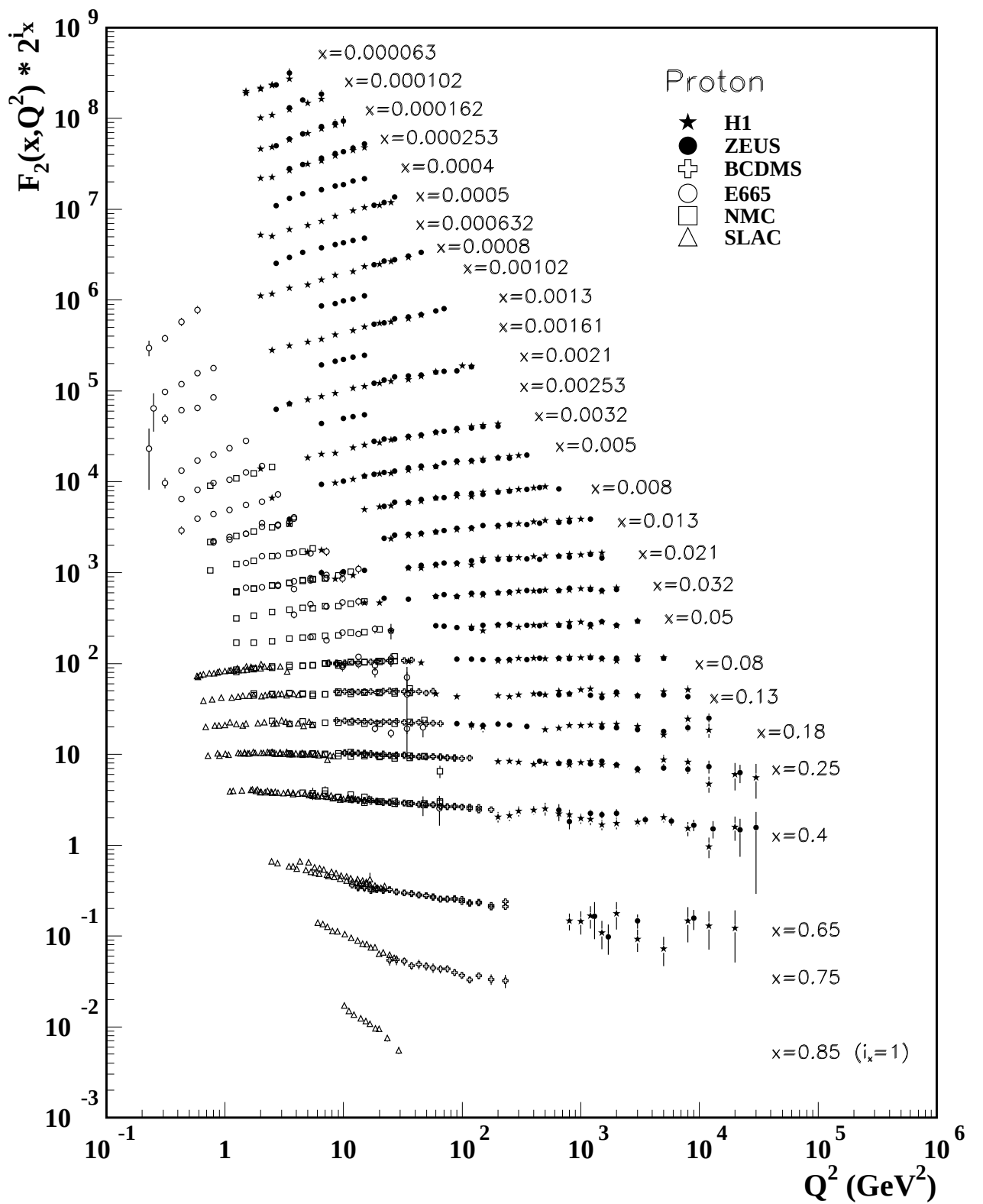


Figure 1.3: The proton F_2^p structure function measured in the scattering of positrons on protons at ZEUS [19] and H1 [20] at the HERA collider, and in the scattering of electrons and muons on fixed proton targets at BCDMS [21], E665 [22], NMC [23] and SLAC [24]. Errors are statistical and systematic uncertainties added in quadratures. For the purpose of clarity the F_2^p was multiplied by 2^{i_x} , where i_x is the x -bin number (for $x = 0.85$ the $i_x = 1$, for $x = 0.000063$ the $i_x = 28$). Plot taken from [25].

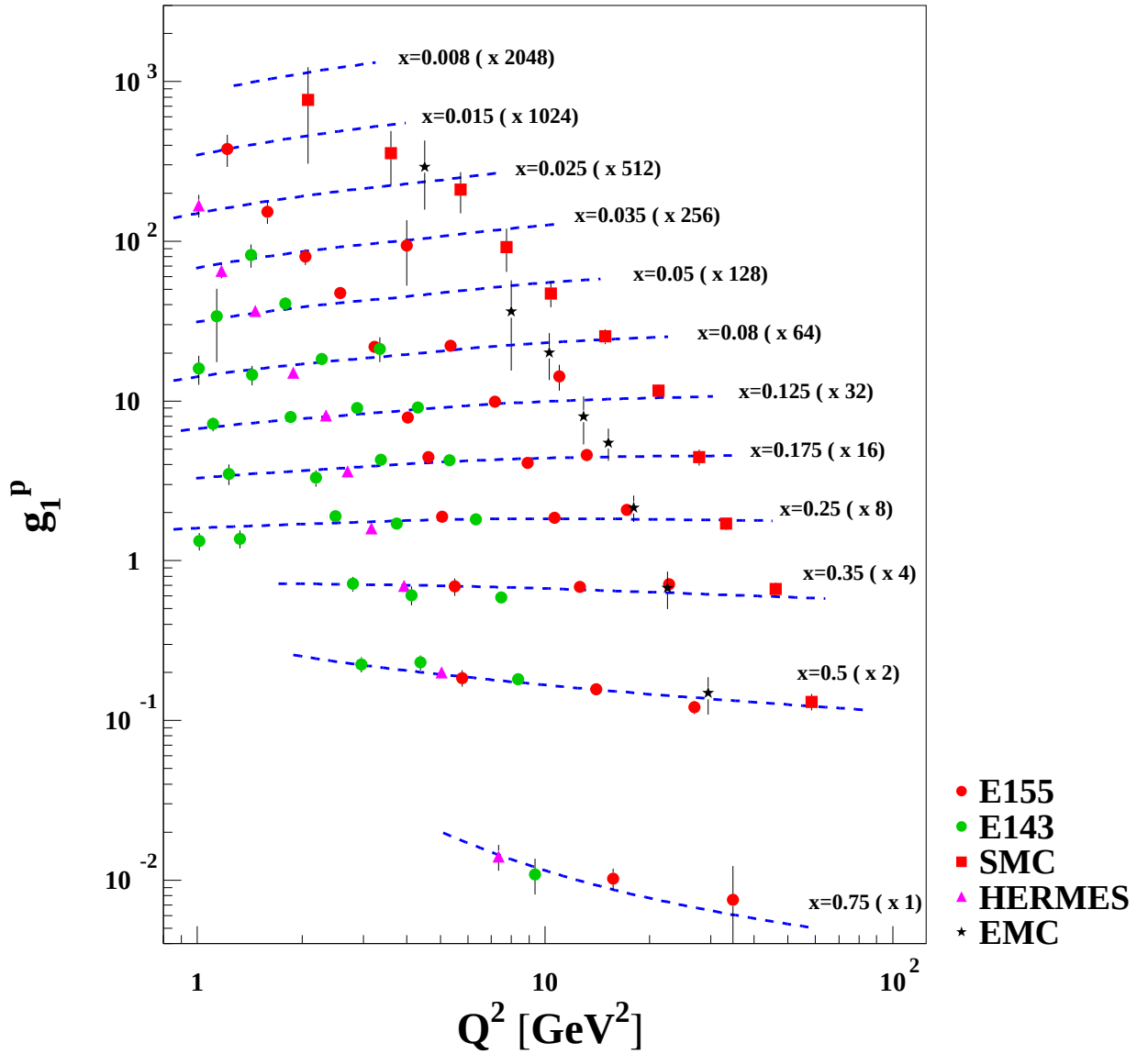


Figure 1.4: The proton spin dependent structure function, g_1^p , measured in the scattering of charged leptons on fixed proton targets. The dashed lines are from a functional fit to the world g_1^p data. The points and lines were scaled by the factors in parentheses. Plot taken from [26].

1.3.2 QCD Improved Parton Model

The QCD model of strong interactions enriched the simple picture of the nucleon with gluons. Gluons are massless bosons responsible for the mediation of the strong forces between partons. Unpolarised inclusive inelastic lepton-nucleon scattering have shown that quarks carry only about a half of the total nucleon momentum. The rest of it is attributed to gluons. The gluons are thus as important as quarks when the internal structure of the nucleon is considered.

The presence of the strong interactions between partons introduces the Q^2 dependence to the structure functions. A quark can emit a gluon, a gluon can split into a $q\bar{q}$ pair. A quark from that pair can subsequently emit another gluon and so on. Increasing the Q^2

of the interaction, increases the resolution of the nucleon probing. Therefore at higher Q^2 a parton reveals its QCD structure of a compound of quarks and gluons. The photons of higher Q^2 can resolve the gluon emissions from the quarks and thus the observed quarks momenta are reduced (cf. Fig. 1.5). Therefore a probability of finding a quark of small x increases with increasing Q^2 , while a probability of finding a quark with large x decreases at the same time. The effect of the Q^2 dependence of the structure functions is called a violation of the Bjorken scaling and is well documented in experiments (cf. Fig. 1.3). Distributions of quarks q_f are thus functions of two independent variables $q_f = q_f(x, Q^2)$. Distribution of gluons also depends on x and Q^2 : $G = G(x, Q^2)$. For fixed x the dependence of quark and gluon distribution functions on Q^2 is given by the Dokshitzer–Gribov–Lipatov–Altarelli–Parisi (DGLAP) equations [30–32]:

$$\frac{dq_f(x, Q^2)}{d\ln Q^2} = \frac{\alpha_S(Q^2)}{2\pi} \int_x^1 \frac{dx'}{x'} \left[q_f(x', Q^2) P_{qq}\left(\frac{x}{x'}\right) + G(x', Q^2) P_{qG}\left(\frac{x}{x'}\right) \right] \quad (1.21)$$

$$\frac{dG(x, Q^2)}{d\ln Q^2} = \frac{\alpha_S(Q^2)}{2\pi} \int_x^1 \frac{dx'}{x'} \left[\sum_f q_f(x', Q^2) P_{Gq}\left(\frac{x}{x'}\right) + G(x', Q^2) P_{GG}\left(\frac{x}{x'}\right) \right] \quad (1.22)$$

where α_S is a running coupling constant of strong interactions and P_{ij} are the splitting functions describing the probability of a parton j having a momentum fraction x' to become a parton i with a momentum fraction x (cf. Fig. 1.6).

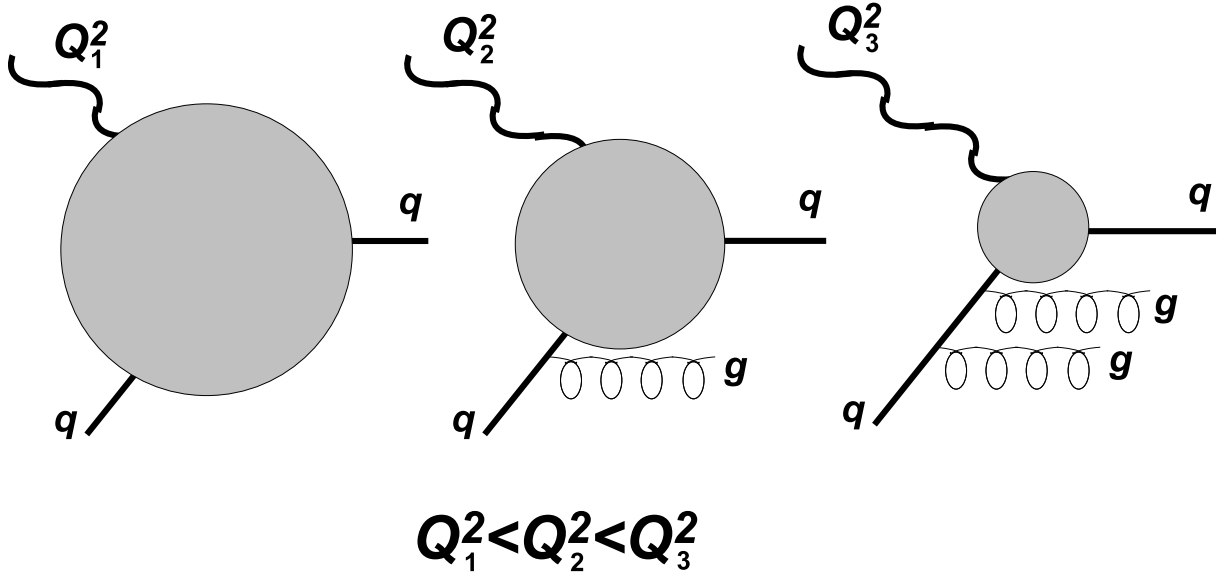


Figure 1.5: Probing quark distributions with photons of different Q^2 resolves the gluons emissions and results in decreasing the quark momenta.

The DGLAP equations describe the evolution of partons densities in Q^2 at a fixed x . They are the differential equations and require a knowledge of the distributions at certain Q_0^2 at $0 \leq x \leq 1$ which has to be obtained from measurements and extrapolated to the unmeasured region of small and large x .

As the measurements are more scarce for the polarised case, in this case only the fol-

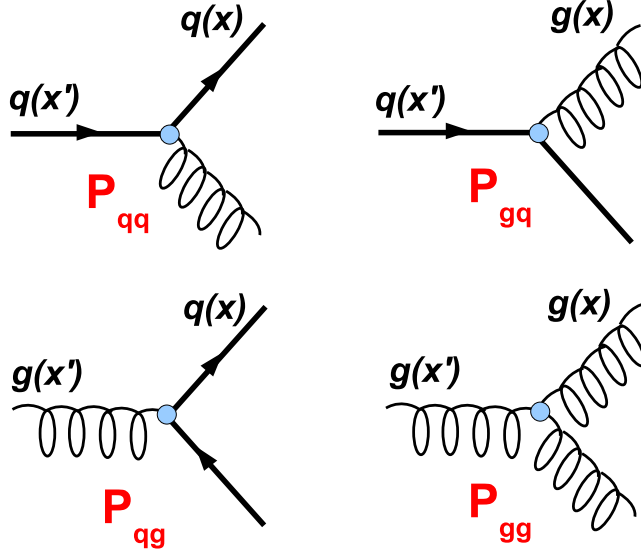


Figure 1.6: Splittings described by DGLAP equation. Upper: quark splitting; bottom: gluon splitting.

lowing DGLAP equations are used to describe the Q^2 evolution [33]:

$$\frac{d}{d\ln Q^2} \Delta q^{NS}(x, Q^2) = \frac{\alpha_S(Q^2)}{2\pi} \Delta P_{qq}^{NS} \otimes \Delta q^{NS}(x, Q^2) \quad (1.23)$$

$$\frac{d}{d\ln Q^2} \begin{pmatrix} \Delta \Sigma(x, Q^2) \\ \Delta G(x, Q^2) \end{pmatrix} = \frac{\alpha_S(Q^2)}{2\pi} \begin{pmatrix} \Delta P_{qq}^S & 2n_f \Delta P_{qg}^S \\ \Delta P_{gq}^S & \Delta P_{gg}^S \end{pmatrix} \otimes \begin{pmatrix} \Delta \Sigma(x, Q^2) \\ \Delta G(x, Q^2) \end{pmatrix} \quad (1.24)$$

A convolution of functions is given by:

$$(A \otimes B)(x) = \int_x^1 \frac{dx'}{x'} A\left(\frac{x}{x'}\right) B(x') \quad (1.25)$$

The Δq^{NS} and $\Delta \Sigma$ are the flavour non-singlet and flavour singlet distributions defined as:

$$\Delta q^{NS}(x, Q^2) = \sum_f \left(\frac{e_f^2}{\frac{1}{n_f} \sum_f e_f^2} - 1 \right) \Delta q_f(x, Q^2) \quad (1.26)$$

$$\Delta \Sigma(x, Q^2) = \sum_f \Delta q_f(x, Q^2) \quad (1.27)$$

and $\Delta G(x, Q^2)$ is a distribution of gluon polarisation. The integral of $\Delta G(x, Q^2)$ over x at a fixed Q^2 gives a contribution of gluon polarisation to the nucleon spin at that Q^2 .

The flavour non-singlet distribution evolves independently of the gluon distribution, while the evolution of the flavour singlet and of the gluon distribution depend on both these distributions at a given Q_0^2 scale. The ΔP_{ij} are defined through the splitting functions for the unpolarised case: $\Delta P_{ij} = P_{i+j+} - P_{i-j+}$, where “+” and “-” correspond to the helicities of the j -th and i -th parton.

With the introduction of the DGLAP evolution equations the simple formula for g_1 , (Eq. (1.20)), becomes:

$$g_1(x, Q^2) = \left[\frac{1}{2n_f} \sum_f e_f^2 \right] \cdot \left[\begin{array}{l} C_q^{NS}(x, Q^2) \otimes \Delta q^{NS}(x, Q^2) \quad + \\ C_q^S(x, Q^2) \otimes \Delta \Sigma(x, Q^2) \quad + \\ C_g(x, Q^2) \otimes \Delta G(x, Q^2) \end{array} \right] \quad (1.28)$$

The C_g , C_q^{NS} and C_q^S are the coefficient functions. Their dependence on Q^2 is through $\alpha_S(Q^2)$: $C_i(x, Q^2) = C_i(x, \alpha_S(Q^2))$. It implies that the C_i functions can be expanded in the powers of α_S . This treatment is restricted to the perturbative regime, that is for high Q^2 , where the expansion takes form:

$$C_i(x, \alpha_S(Q^2)) = C_i^0(x) + \frac{\alpha_S(Q^2)}{2\pi} C_i^1(x) + \mathcal{O}(\alpha_S^2(Q^2)) \quad (1.29)$$

The splitting functions can also be expanded in the power series of α_S :

$$\Delta P(x, \alpha_S(Q^2)) = \Delta P^0(x) + \frac{\alpha_S(Q^2)}{2\pi} \Delta P^1(x) + \mathcal{O}(\alpha_S^2(Q^2)) \quad (1.30)$$

First elements in both expansions do not depend on Q^2 . They are called the Leading Order (LO) elements. The splitting functions as well as coefficient functions are known to the Next-to-Leading Order (NLO) accuracy [34,35]. Recently also the first results on the Next-to-Next-to-Leading Order (NNLO) were obtained [36].

1.4 The First Moment of the g_1 Distribution

We will come back now to the QPM, where dependence on Q^2 is not present. In this model the g_1 function is given by the formula (1.20). Its first moment is equal to:

$$\begin{aligned} \Gamma_1 &= \int_0^1 g_1(x) dx = \int_0^1 \frac{1}{2} \sum_f e_f^2 [q_f^+(x) - q_f^-(x)] dx = \frac{1}{2} \sum_f e_f^2 \int_0^1 [q_f^+(x) - q_f^-(x)] dx = \\ &= \frac{1}{2} \sum_f e_f^2 \Delta q_f \end{aligned} \quad (1.31)$$

Here $\Delta q_f = \int_0^1 (q_f^+(x) - q_f^-(x)) dx$. In the proton case the first moment is given by:

$$\Gamma_1^p = \frac{1}{2} \left(\frac{4}{9} \Delta q_u + \frac{1}{9} \Delta q_d + \frac{1}{9} \Delta q_s \right) \quad (1.32)$$

The Γ_1^n for the neutron can be obtained from Γ_1^p by assuming the isospin symmetry, *i.e.* exchanging: $\Delta q_u \leftrightarrow \Delta q_d$.

The Δq_f defined as above, are related to the weak axial-vector couplings a_0 , a_3 and a_8 :

$$a_0 = (\Delta q_u + \Delta q_d + \Delta q_s) \quad (1.33)$$

$$a_3 = (\Delta q_u - \Delta q_d) \quad (1.34)$$

$$a_8 = (\Delta q_u + \Delta q_d - 2\Delta q_s) \quad (1.35)$$

The couplings are calculated from the hadron matrix elements of the $SU(3)$ flavour octet axial-vector currents $J_{5\mu}^j$ ($j = 1, \dots, 8$) and of the flavour singlet axial current $J_{5\mu}^0$ defined as [37]:

$$J_{5\mu}^j = \bar{\Psi} \gamma_\mu \gamma_5 \frac{\lambda_j}{2} \Psi \quad (1.36)$$

$$J_{5\mu}^0 = \bar{\Psi}\gamma_\mu\gamma_5\Psi \quad (1.37)$$

where Ψ is a flavour vector:

$$\begin{pmatrix} \Psi_u \\ \Psi_d \\ \Psi_s \end{pmatrix} \quad (1.38)$$

and λ_j are the Gell-Mann matrices. The matrix elements are given by:

$$Ma_j S_\mu = \langle P, S | J_{5\mu}^j | P, S \rangle \quad (1.39)$$

$$2Ma_0 S_\mu = \langle P, S | J_{5\mu}^0 | P, S \rangle \quad (1.40)$$

In this equation P is the nucleon momentum four-vector and S is its spin.

For the neutron the equations similar to (1.33–1.35), but with Δq_u and Δq_d interchanged are valid. The Γ_1^p and Γ_1^n take form:

$$\Gamma_1^p = \frac{1}{9}a_0 + \frac{1}{12}(a_3 + \frac{1}{3}a_8) \quad (1.41)$$

$$\Gamma_1^n = \frac{1}{9}a_0 + \frac{1}{12}(-a_3 + \frac{1}{3}a_8) \quad (1.42)$$

The a_3 and a_8 are related to parameters which describe beta decays of neutrons and hyperons. The value of the a_3 is expressed as the ratio of the axial vector and vector coupling constants:

$$a_3 = \left| \frac{g_A}{g_V} \right| \quad (1.43)$$

Values of the a_3 and a_8 have been measured directly in many experiments with high accuracy: $a_3 = 1.2695 \pm 0.0029$ and $a_8 = 0.579 \pm 0.025$ [25]. Therefore, from the knowledge of Γ_1^p or Γ_1^n and using Eq. (1.41) or (1.42), one find a_0 . Here a_0 is equal to $\Delta\Sigma$, Eq. (1.33). Another conclusion is the Bjorken sum rule [38]:

$$\Gamma_1^p - \Gamma_1^n = \frac{1}{6}a_3 = \frac{1}{6} \left| \frac{g_A}{g_V} \right| \quad (1.44)$$

This sum rule establishes a link between the beta decays, the right hand side of the equation, with the integrated structure functions of both, the neutron and the proton, the left hand side of the equation.

In the QCD improved parton model the first moment of g_1 has a form:

$$\Gamma_1(Q^2) = \left[\frac{1}{2n_f} \sum_f e_f^2 \right] \cdot [C_q^{NS}(Q^2)\Delta q^{NS}(Q^2) + C_q^S(Q^2)\Delta\Sigma(Q^2) + C_g(Q^2)\Delta G(Q^2)] \quad (1.45)$$

Each of the three components of the above formula has two separate parts – the hard and the soft. The former parts encompass coefficient functions $C_i(Q^2)$ while the latter the polarised quarks and gluons distributions. The soft parts cannot be calculated directly from QCD and have to be determined by experiments. Separation between the soft and the hard parts is not strict, and different factorisation and renormalisation schemes can be introduced. The schemes vary by the contributions which are absorbed into hard and soft parts. Two common choices are the Modified **M**inimal **S**ubtraction ($\overline{\text{MS}}$) [39] and the **A**dler-**B**ardeen (AB) [40] schemes.

The coefficient functions C_i can be expanded in power series of α_S . In this expansion in the LO approximation the ΔG does not enter the g_1 nor Γ_1 irrespectively of the applied QCD scheme. In the NLO the expansion terms differ in $\overline{\text{MS}}$ and AB. In the former scheme the ΔG does not enter NLO term either, while this term in the latter scheme does depend on ΔG . As a consequence $\Delta\Sigma$ becomes scheme dependent:

$$\Delta\Sigma(Q^2)_{\overline{\text{MS}}} = \Delta\Sigma_{AB} - n_f \frac{\alpha_S(Q^2)}{2\pi} \Delta G(Q^2) \quad (1.46)$$

while in both schemes ΔG is defined in the same way:

$$\Delta G(Q^2)_{\overline{\text{MS}}} = \Delta G(Q^2)_{AB} \quad (1.47)$$

The a_0 now becomes:

$$a_0(Q^2) = \Delta\Sigma(Q^2)_{\overline{\text{MS}}} = \Delta\Sigma_{AB} - n_f \frac{\alpha_S(Q^2)}{2\pi} \Delta G(Q^2) \quad (1.48)$$

The gluon contribution to the $a_0(Q^2)$ is called the Adler–Bell–Jackiw anomaly [41, 42]. In both schemes a_0 is a function of Q^2 : through $\Delta\Sigma(Q^2)$ in $\overline{\text{MS}}$ or through $\Delta G(Q^2)$ in AB. As a consequence also the Bjorken sum rule has to be modified. With $C_q^{NS}(Q^2)$ calculated in the $\overline{\text{MS}}$ scheme it takes a form:

$$\Gamma_1^p(Q^2) - \Gamma_1^n(Q^2) = \frac{1}{6} \left| \frac{g_A}{g_V} \right| C_q^{NS}(Q^2) \quad (1.49)$$

and the first moments of g_1 for the proton and the neutron are given with:

$$\Gamma_1^p(Q^2) = \frac{1}{9} a_0(Q^2) C_q^S(Q^2) + \frac{1}{12} (a_3 + \frac{1}{3} a_8) C_q^{NS}(Q^2) \quad (1.50)$$

$$\Gamma_1^n(Q^2) = \frac{1}{9} a_0(Q^2) C_q^S(Q^2) + \frac{1}{12} (-a_3 + \frac{1}{3} a_8) C_q^{NS}(Q^2) \quad (1.51)$$

They differ from Eq. (1.41) and (1.42) by the coefficient functions, C_q , and the explicit Q^2 dependence of the a_0 . A measurement of the first moment of g_1 at a given Q^2 allows to extract a_0 at the same Q^2 which is immediately translated to $\Delta\Sigma(Q^2)_{\overline{\text{MS}}}$, Eq. (1.48). The knowledge of $\Delta G(Q^2)$ allows the calculation of $\Delta\Sigma_{AB}$.

1.5 Cross-Section Asymmetries

The spin effects are studied in the experiments measuring the cross-sections for interactions occurring with a given relative spin orientation of the projectile and of the target. These cross-sections change with a change of the spin orientation.

1.5.1 The Lepton-Nucleon and the Virtual Photon-Nucleon Asymmetries

The main observables in the spin dependent inelastic lepton-nucleon scattering are the cross-section asymmetries for different relative polarisations. In COMPASS the polarisation of the lepton beam is fixed while the direction of the deuteron target polarisation can be changed. To probe different aspects of the nucleon structure the polarisation

of the target can be set to parallel (anti-parallel) or transverse to the beam direction. As a consequence the longitudinal and the transverse cross-section asymmetries for the lepton-deuteron interactions are measured:

$$A_{\parallel} = \frac{\sigma_{\Rightarrow}^{\leftarrow} - \sigma_{\Leftarrow}^{\leftarrow}}{\sigma_{\Rightarrow}^{\leftarrow} + \sigma_{\Leftarrow}^{\leftarrow}} \quad (1.52)$$

$$A_{\perp} = \frac{\sigma^{\leftarrow\Downarrow} - \sigma^{\leftarrow\Uparrow}}{\sigma^{\leftarrow\Downarrow} + \sigma^{\leftarrow\Uparrow}} \quad (1.53)$$

where $\leftarrow$ and $\Leftarrow$ represent polarisations directions of the muon beam and of the deuteron target, respectively. The longitudinal and transverse virtual photon-deuteron asymmetries, A_1 and A_2 , are defined via the asymmetry of absorption cross-sections of transversely polarised photon as:

$$A_1 = \frac{\sigma_0^T - \sigma_2^T}{2\sigma^T} \quad (1.54)$$

$$A_2 = \frac{\sigma_0^{TL} + \sigma_1^{TL}}{2\sigma^T} \quad (1.55)$$

where σ_J^T is the virtual photon-deuteron absorption cross-section for a total spin projection J in the photon direction, σ_J^{TL} results from the interference between transverse and longitudinal amplitudes for $J = 0, 1$, and σ^T is the total transverse photoabsorption cross-section. The experimental asymmetries $A_{\parallel}$ and $A_{\perp}$ are related with A_1 and A_2 through equations:

$$A_{\parallel} = D(A_1 + \eta A_2) \quad (1.56)$$

$$A_{\perp} = d(A_2 - \xi A_1) \quad (1.57)$$

where D , d , η and ξ are kinematical factors depending on Q^2 and y , see *e.g.* [43]. The virtual photon-deuteron asymmetries can be translated into g_1 and g_2 according to³:

$$A_1 = \frac{g_1 - \gamma^2 g_2}{F_1} \quad A_2 = \gamma \frac{g_1 + g_2}{F_1} \quad (1.58)$$

where $\gamma = \sqrt{Q^2}/\nu$. Bringing together equations (1.56–1.57), (1.58) and eliminating A_1 and $A_{\perp}$ the formulas for g_1 and g_2 give:

$$g_1 = \frac{F_1}{1 + \gamma^2} \left[\frac{A_{\parallel}}{D} + (\gamma - \eta) A_2 \right] \quad (1.59)$$

$$g_2 = \frac{F_1}{1 + \gamma^2} \left[-\frac{A_{\parallel}}{D} + \left(\frac{1}{\gamma} + \eta \right) A_2 \right] \quad (1.60)$$

The structure functions g_1 and g_2 can be obtained from these equations provided all the kinematical factors are known and $A_{\parallel}$, A_2 , F_1 were measured.

1.5.2 Approximate Formula for g_1

The A_2 asymmetry was measured for the proton as well as for the deuteron in an x range between 0.003 and 0.8 cf. [44]. The measurements have shown that the A_2 is small. Moreover the factors γ^2 and η in the COMPASS kinematics also are small: below

³Note that here when talking about lepton-deuteron scattering the structure functions are defined for the deuteron. They are denoted usually with d index: g_1^d , g_2^d , F_1^d . Here the index was omitted for simplicity.

10^{-3} and 10^{-2} respectively. Therefore the terms γA_2 and ηA_2 can be neglected. Then the expression (1.59) becomes:

$$g_1 \approx \frac{F_1}{1 + \gamma^2} \frac{A_{\parallel}}{D} \approx F_1 \frac{A_{\parallel}}{D} \quad (1.61)$$

Under the same approximations Eq. (1.56) and (1.58) lead to:

$$A_{\parallel} \approx D A_1 \quad g_1 \approx A_1 F_1 \quad (1.62)$$

The first formula gives a simple interpretation of the D factor. It describes the polarisation transfer from the polarised lepton to the virtual photon and is thus called a depolarisation factor. It is defined as:

$$D = \frac{y \left[(1 + \gamma^2 y/2)(2 - y) - 2y^2 m_{\mu}^2 / Q^2 \right]}{y^2 (1 - 2m_{\mu}^2 / Q^2)(1 + \gamma^2) + 2(1 + R)(1 - y - \gamma^2 y^2 / 4)} \quad (1.63)$$

where R is the ratio of longitudinal (σ^L) and transverse photoabsorption cross-sections, $R = \sigma^L / \sigma^T$. For the analysis performed in LO QCD $R = 0$. Observe that $0 < D < 1$.

The results on A_1 measured for deuteron are presented in Fig. 1.7.

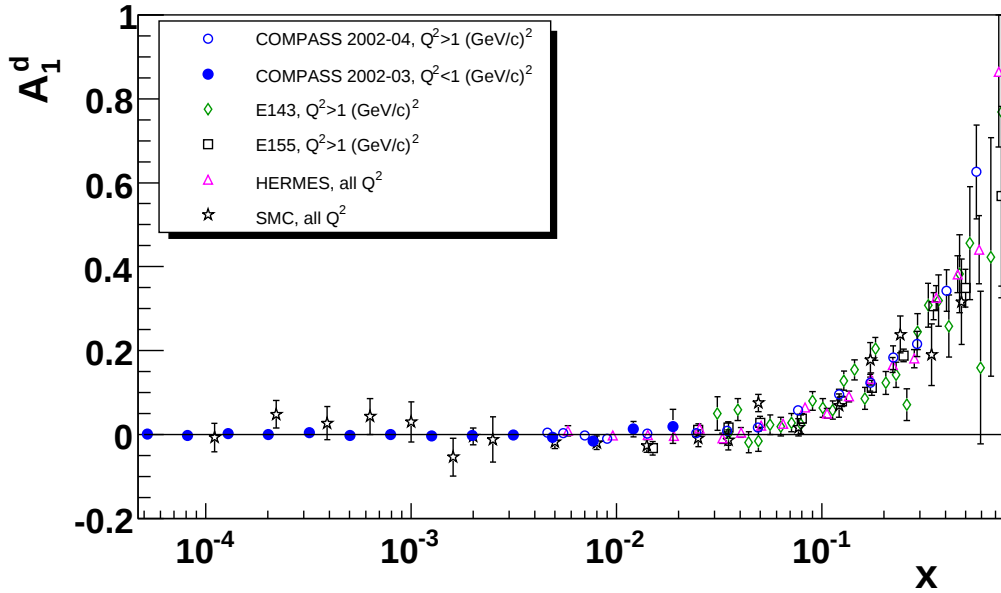


Figure 1.7: The asymmetry A_1 for a deuteron as a function of x at the measured values of Q^2 from COMPASS, SMC, HERMES, E143 and E155. For details see [43] from which the plot was taken.

1.6 Experimental Methods and Results on ΔG

Experiments with the inelastic polarised lepton scattering have been collecting data over the last 30 years. Spin studies of protons and neutrons were performed. As there are no purely neutron polarised targets, for the neutron studies deuterium or helium-3 was used. To measure the polarised effects on neutrons it is then necessary to subtract the

effects coming from protons⁴. The compilation of data from neutrons and protons is required *e.g.* for tests of the Bjorken sum rule, cf. Eq. (1.49), and for the flavour dependent polarised partons distribution studies. Here we will present the polarised measurements from which conclusions on the ΔG can be drawn.

1.6.1 Results on the Quarks Polarisation

Experiments that measured the polarisation effects in inelastic lepton-nucleon scattering were conducted for the first time in mid-seventies at SLAC in USA. These pioneering experiments (E80 [2] and later E130 [45]) provided results on A_1 for the electron-proton scattering at $x \in (0.1, 0.7)$. In the eighties the kinematical range for the measurement of A_1 on proton was extended to $x = 0.01$ by the European Muon Collaboration (EMC) [3] at CERN.

The g_1 for proton measured by the EMC permitted to calculate Γ_1^p . In the unmeasured range of small and large x the g_1 was extrapolated. For small x phenomenological models were used. The uncertainty that was introduced due to the extrapolation was included into the systematic error. Then the a_0 was calculated taking known a_3 and a_8 . Finally $\Delta\Sigma$ was derived with $\Delta\Sigma = a_0$. The obtained value was $\Delta\Sigma = 0.12 \pm 0.09 \pm 0.14$ [3], far from the naïve expectation of $\Delta\Sigma \approx 0.6$. The number of the EMC followers: SMC [4] and COMPASS [46] at CERN, HERMES [47, 48] at DESY, E142 [6], E143 [7], E155 [8] at SLAC confirmed the EMC result. The recent analysis of the world data [46] gave $\Delta\Sigma$ at $Q^2 = 3 \text{ GeV}^2$ equal to:

$$\Delta\Sigma(Q^2 = 3 \text{ GeV}^2) = 0.30 \pm 0.01 \pm 0.03 \quad (1.64)$$

The result was obtained in the NLO with $\overline{\text{MS}}$ scheme, that is $\Delta\Sigma(Q^2) = a_0(Q^2)$. The obtained value does not fulfil the sum rule (1). The missing fraction of the nucleon spin may be carried by gluons or it may arise from the orbital angular momenta of partons moving inside the nucleon.

The flavour dependent polarisation of the sea quarks can be measured studying semi-inclusive channels where a particle of a given type is detected. The results from these studies done at HERMES are presented in Tab. 1.1. In the SMC the flavour independent sea quarks polarisation analysis was performed. It gave $\Delta\bar{q} = 0.01 \pm 0.04 \pm 0.03$ [49], where $\Delta\bar{q} = \Delta\bar{u} = \Delta\bar{d} = \Delta\bar{s} = \Delta s$ was assumed. The SMC and HERMES analyses were performed at the LO QCD accuracy. Their results are compatible with the zero polarisation of the sea quarks. Two independent NLO analyses based on the world data gave results for the sea quarks polarisation slightly negative: $\Delta\bar{q} = -0.062 \pm 0.023$ [50] and $\Delta\bar{q} = -0.074 \pm 0.017$ [51]. The deviations from zero are at the level of 3–4 σ .

1.6.2 The ΔG from the QCD Evolution

Evolution of the $\Delta\Sigma(x, Q^2)$, $\Delta q^{NS}(x, Q^2)$ and $\Delta G(x, Q^2)$ in Q^2 at fixed x is described by the DGLAP equations (1.23–1.24). The $g_1(x, Q^2)$ structure function is related with

⁴For ^3He the orbital angular momentum of the 3-body system (2 protons and 1 neutron) is predominantly 0. In this state, due to Pauli exclusion principle, protons are anti-aligned. The spin effects observed in ^3He should therefore come from neutron. For studies on the deuteron both nucleons give contribution to the spin effects. However for deuteron the percentage of neutrons in the material is higher than for ^3He .

Flavour	Polarisation	Statistical and systematic errors
Δu	0.601	$0.039 \oplus 0.049$
Δd	-0.226	$0.039 \oplus 0.050$
$\Delta \bar{u}$	-0.002	$0.036 \oplus 0.023$
$\Delta \bar{d}$	-0.054	$0.033 \oplus 0.011$
Δs	0.028	$0.033 \oplus 0.009$
$\Delta u_{\text{valence}}$	0.603	$0.071 \oplus 0.040$
$\Delta d_{\text{valence}}$	-0.172	$0.068 \oplus 0.045$

Table 1.1: HERMES results for the quarks polarisation for different flavours, at $Q^2=2.5$ GeV^2 and in $0 \leq x \leq 1$. The sea quarks polarisation for u (d) is a difference between the total u (d) polarisation and the corresponding valence quarks polarisation. Taken from [48].

$\Delta\Sigma(x, Q^2)$, $\Delta q^{NS}(x, Q^2)$, $\Delta G(x, Q^2)$ through Eq. (1.28). Using DGLAP and Eq. (1.28) the predictions on $\Delta\Sigma(x, Q^2)$, $\Delta q^{NS}(x, Q^2)$, $\Delta G(x, Q^2)$ can be derived. The procedure is the following. First an initial parameterisation of the $\Delta\Sigma(x, Q^2)$, $\Delta q^{NS}(x, Q^2)$ and $\Delta G(x, Q^2)$ functions at a fixed reference value of $Q^2 = Q_0^2$ and at all x is made. Then the parameterised distributions are evolved according to DGLAP equations and the resulting values of $g_1(x, Q^2)$ are calculated for each (x_i, Q_i^2) where the experimental measurements of this structure function exist. The calculated and measured $g_1(x, Q^2)$ values are compared and using the χ^2 minimisation method the parameters of the initial parameterisation are optimised. The number of $g_1(x, Q^2)$ data points is presently about 230 (including data for proton, deuteron and helium targets). However as the lepton-nucleon polarised measurements were done exclusively by the fixed target experiments, they cover much smaller region of (x, Q^2) as compared with the unpolarised case, where also data from collider experiments are available (compare Figs. 1.3 and 1.4). As a consequence the predictions for $\Delta\Sigma$, Δq^{NS} and ΔG are only weakly constrained. In particular the uncertainty of the ΔG is large. In the recent COMPASS DGLAP evolution analysis [46] performed in the NLO, two solutions for ΔG were found, one positive and one negative. Both of them result in a rather small $|\Delta G| \sim 0.2 - 0.3$ for $Q^2 = 3$ GeV^2 , cf. Fig. 1.8.

There are two ways to improve the knowledge on ΔG . The first one is to enlarge the kinematic range of the g_1 measurements. This implies the data taking with the polarised beams at colliders. It would be possible within the polarised HERA project at DESY. Unfortunately the project was abandoned. There are plans for the upgrade of the RHIC at Brookhaven to eRHIC, where an additional polarised electron ring will be added to the existing hadron collider [52]. The timescale for this project is 10–20 years. Thus perspectives of the g_1 measurements in a wider x range are rather dim. The other method that leads to an improvement of the knowledge on ΔG is a direct measurement of this quantity in the process called Photon–Gluon Fusion.

1.6.3 Photon–Gluon Fusion

The **Photon–Gluon Fusion** (PGF) process gives a direct insight into the gluon distribution in the nucleon. With an additional knowledge of $G(x, Q^2)$ coming from the unpolarised measurements, Fig. 1.9, the studies of the PGF process in the experiments with a polarised target and a polarised beam reveal the polarised gluon distribution

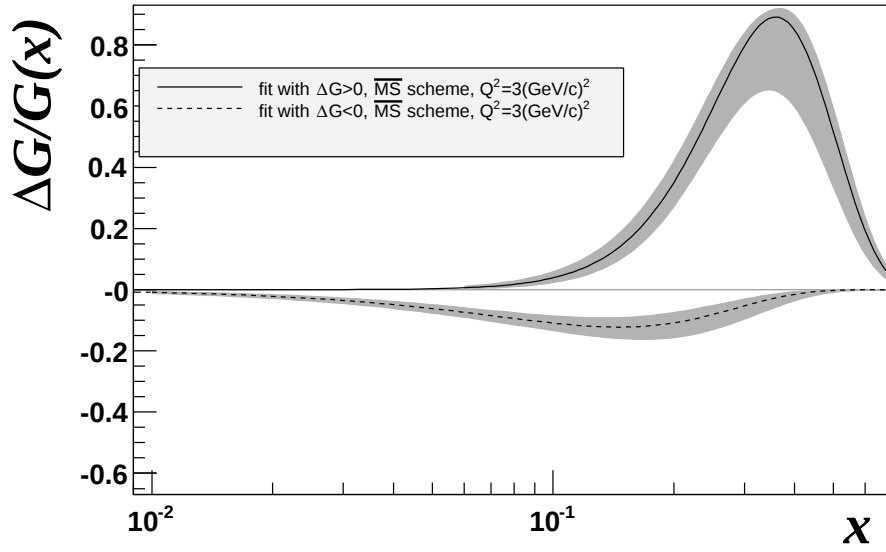


Figure 1.8: Distribution of the gluon polarisation $\Delta G/G(x)$ at $Q^2 = 3\text{GeV}^2$ from the recent COMPASS NLO QCD analysis [46]. Two solutions were found, one positive and one negative. The error bands correspond to the statistical error on $\Delta G(x)$ at a given x .

$\Delta G(x, Q^2)$. The PGF is an interaction of a virtual photon coming from the lepton with a gluon embedded in the nucleon, occurring through the exchange of a virtual quark and resulting in a $q\bar{q}$ pair production, Fig. 1.10. To enhance the amount of the PGF processes in the studied data sample two different methods can be used. The first one is based on the PGF tagging via the detection of the charmed quarks. It is called the open charm method as the tagging means reconstruction of the D^0 mesons in the final state. The other approach relies on the selection of hadron pairs with high transverse momenta with respect to the virtual photon direction [55]. The advantage of this method is a much higher statistics comparing to the open charm method, as it is not restricted to charmed quark pairs in the final state only. However, as it will be shown, it relies extensively on the Monte Carlo simulations.

1.6.4 The Open Charm Method

The mass of the charm quark, $m_c \approx 1.5\text{ GeV}$, is much larger than those of the u , d and s quarks. Therefore the charm content of the nucleon for the measurements at COMPASS kinematics can be neglected. Also the creation of the charm quarks in the fragmentation process is highly suppressed. Thus the only reaction that has a significant contribution to the charm production is the PGF process. The contribution from the resolved photon processes at COMPASS kinematics in the charm production was estimated with RAPGAP [56] Monte Carlo simulation, using different parameterisations of the photon structure. The contribution is of the order of a few percent [57] and is neglected in the analysis. The presented studies are performed in the LO QCD. Therefore also the description of the method will be limited to LO. The method for the introduction to the open charm analysis the NLO corrections is still a subject of studies in COMPASS. The impact of these corrections is not yet known.

The charmed quarks produced in the interactions, fragment subsequently into charmed

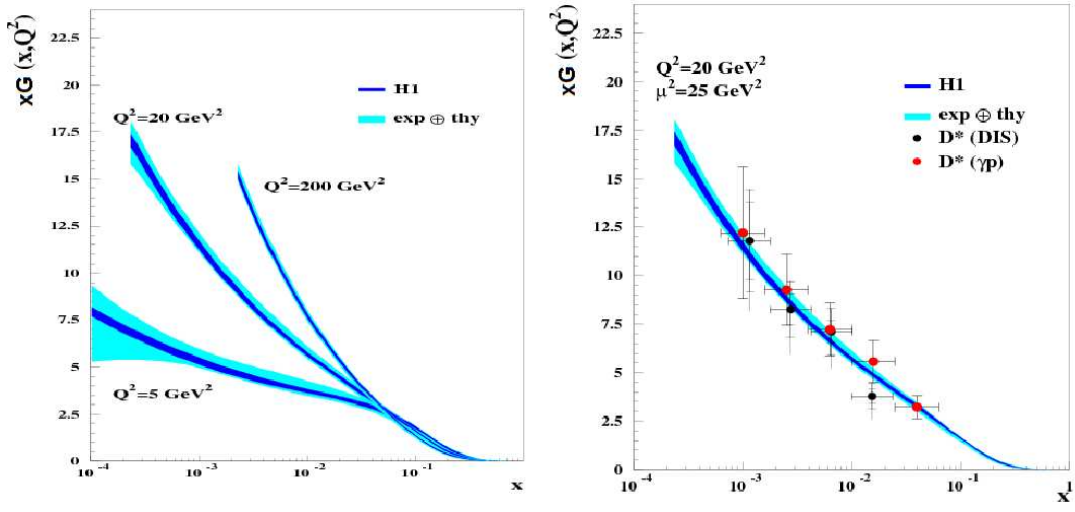


Figure 1.9: Left: determination of $xG(x, Q^2)$ in the NLO QCD by H1 at HERA using NMC and H1 lepton-proton data. Right: comparison of $xG(x, Q^2)$ obtained from scaling violation with the direct H1 measurement using the open charm method. Two subsamples were studied: DIS ($Q^2 > 2 \text{ GeV}^2$) and photo-production ($Q^2 < 0.01 \text{ GeV}^2$). The plot is taken from [53]. See also [54]

hadrons. The detection and identification of them provides a clear tag for the PGF process. From all known charmed particles, the one that can be most clearly reconstructed in the COMPASS kinematics, is a D^0 , “open charm”, meson ($c\bar{u}$ quark content). On average 1.2 D^0 mesons are produced per each $c\bar{c}$ pair [9]. The method of gluon polarisation measurement which base on the PGF tagging via charmed hadrons is for the first time implemented in COMPASS. It has never been used before in other experiments.

The observable that is measured in the experiment is the asymmetry defined as:

$$A^{exp} = \frac{N_{D^0}^{\leftarrow\rightarrow} - N_{D^0}^{\leftarrow\leftarrow}}{N_{D^0}^{\leftarrow\rightarrow} + N_{D^0}^{\leftarrow\leftarrow}} \quad (1.65)$$

where N_{D^0} are numbers of D^0 mesons produced with different relative target-beam spin orientations. The above experimental asymmetry can be translated into the spin dependent asymmetry of the lepton-nucleon interactions (A^{lN}) by dividing it by several dilution factors. These are: the beam polarisation P_B , the target polarisation P_T and the target material dilution factor f . The f factor accounts for the fraction of polarisable nucleons in the target material. All these factors will be discussed later. They give:

$$A^{lN} = \frac{1}{P_B P_T f} A^{exp} \quad (1.66)$$

The A^{lN} is related to the virtual photon-nucleon asymmetry A^{γ^*N} :

$$A^{\gamma^*N} = \frac{1}{D} A^{lN} = \frac{1}{P_B P_T f D} A^{exp} \quad (1.67)$$

where D is a depolarisation factor introduced in Sec. 1.5.1. Formula (1.67) holds only if the data sample contains exclusively the open charm events. If the background is also present, the formula should be rewritten as:

$$A^{\gamma^*N} = \frac{1}{P_B P_T f D \frac{S}{S+B}} A^{exp} - A^{BG} \quad (1.68)$$

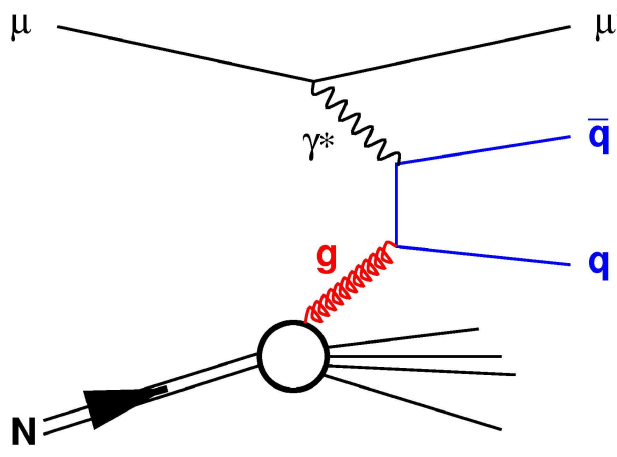


Figure 1.10: The Photon–Gluon Fusion process in LO.

The $S/(S + B)$ is an additional dilution factor with S and B being a number of signal and background events in the studied open charm sample. The A^{BG} is a background asymmetry arising from other spin dependent processes present in the sample. They are expected to have a negligible contribution comparing to the statistical error of the measurement, as discussed later in this work. Therefore the $A^{BG} = 0$ is assumed.

The virtual photon-nucleon asymmetry can be presented as:

$$A^{\gamma^*N}(x_g) = \frac{\int_{4m_c^2}^{2M\nu} d\hat{s} \Delta\sigma^{\gamma^*g \rightarrow c\bar{c}X}(\hat{s}) \Delta G(x_g, \hat{s})}{\int_{4m_c^2}^{2M\nu} d\hat{s} \sigma^{\gamma^*g \rightarrow c\bar{c}X}(\hat{s}) G(x_g, \hat{s})} \quad (1.69)$$

where the $\Delta\sigma^{\gamma^*g \rightarrow c\bar{c}X}(\hat{s})$ and $\sigma^{\gamma^*g \rightarrow c\bar{c}X}(\hat{s})$ are the cross-sections for the interactions leading to the PGF with $c\bar{c}$ production for the helicity dependent and helicity averaged cases. In the limit $Q^2 \rightarrow 0$ and in the LO, they are given by:

$$\Delta\sigma^{\gamma^*g \rightarrow c\bar{c}X}(\hat{s}) = \frac{4}{9} \frac{2\pi\alpha_e\alpha_s(\hat{s})}{\hat{s}} \left[3\beta - \ln \frac{1+\beta}{1-\beta} \right] \quad (1.70)$$

$$\sigma^{\gamma^*g \rightarrow c\bar{c}X}(\hat{s}) = \frac{4}{9} \frac{2\pi\alpha_e\alpha_s(\hat{s})}{\hat{s}} \left[-\beta(2 - \beta^2) + \frac{1}{2}(3 - \beta^4) \ln \frac{1+\beta}{1-\beta} \right] \quad (1.71)$$

In the above equations $\beta = \sqrt{1 - 4m_c^2/\hat{s}}$ and $\hat{s}$ is a centre-of-mass energy of the photon-gluon system⁵. The x_g variable is the fraction of the nucleon momentum carried by the gluon:

$$x_g = x \left(\frac{\hat{s}}{Q^2} + 1 \right) \approx \frac{\hat{s}}{2M\nu} \quad (1.72)$$

Where the approximation holds at low x , that is for instance for COMPASS. Integration limits in Eq. (1.69) are from the $c\bar{c}$ threshold energy squared ($4m_c^2$) to the square of the total energy available in the interaction at a given ν ($2M\nu$). The parton asymmetry for the photon-gluon interactions $\hat{a}_{LL}$ is defined as:

$$\hat{a}_{LL}(\hat{s}) = \frac{\Delta\sigma^{\gamma^*g \rightarrow c\bar{c}X}(\hat{s})}{\sigma^{\gamma^*g \rightarrow c\bar{c}X}(\hat{s})} \quad (1.73)$$

⁵Hats over variables, *e.g.* $\hat{s}$, mean that they are defined at the parton level of the interaction.

Substituting $\hat{a}_{LL}$ to Eq. (1.69) one gets:

$$A^{\gamma^*N}(x_g) = \frac{\int_{4m_c^2}^{2M\nu} d\hat{s} \hat{a}_{LL}(\hat{s}) \frac{\Delta G(x_g, \hat{s})}{G(x_g, \hat{s})} \sigma^{\gamma^*g \rightarrow c\bar{c}X}(\hat{s}) G(x_g, \hat{s})}{\int_{4m_c^2}^{2M\nu} d\hat{s} \sigma^{\gamma^*g \rightarrow c\bar{c}X}(\hat{s}) G(x_g, \hat{s})} \approx \langle \hat{a}_{LL} \rangle \times \left\langle \frac{\Delta G}{G} \right\rangle(x_g) \quad (1.74)$$

The above equation together with formula (1.68) and $A_{BG} = 0$ give:

$$\left\langle \frac{\Delta G}{G} \right\rangle = \frac{1}{P_B P_T f D \langle \hat{a}_{LL} \rangle \frac{S}{S+B}} A^{exp} \quad (1.75)$$

where $\langle \frac{\Delta G}{G} \rangle$ and A^{exp} are the average values for the measured x_g range.

The differential cross-section for the $c\bar{c}$ production in a lepton-nucleon interactions is a product of a virtual photon flux (defined with a Hand convention [58]), Γ , and of the cross-section for the $\gamma^*N \rightarrow c\bar{c}X$ process:

$$\frac{d^2\sigma^{lN \rightarrow c\bar{c}X}}{dQ^2 d\nu} = \Gamma(E; Q^2, \nu) \sigma^{\gamma^*N \rightarrow c\bar{c}X}(Q^2, \nu) \quad (1.76)$$

where E is an incoming lepton energy. The virtual photon flux is:

$$\Gamma(E; Q^2, \nu) = \frac{\alpha_e}{2\pi} \frac{2(1-y) + y^2 + Q^2/2E^2}{Q^2 \sqrt{(Q^2 + \nu^2)}} \quad (1.77)$$

At a given ν and y , the flux increases when Q^2 decreases. Therefore a substantial fraction of D^0 mesons is produced at small Q^2 . For the PGF process studied via the open charm mesons, the QCD scale of the interaction is set by a high mass of charmed quark and not by Q^2 . The scale is equal to $4(m_c^2 + p_T^2)$, where p_T is the charmed quark transverse momentum with respect to the virtual photon. In what follows that scale is denoted with μ^2 .

1.6.5 The Method of High- p_T Hadron Pairs

Another method to study the polarised PGF process is a measurement of the cross section asymmetries for the production of two hadrons of high transverse momenta relative to the virtual photon direction. In the γ^*g centre-of-mass quarks are produced back-to-back. In the process where a quark is struck directly by a photon the quark inherits the direction of the momentum from the γ^* . After the fragmentation hadrons usually preserve the direction of motion of the quarks they originate from. Therefore selection of two high- p_T hadrons strongly enhances a fraction of PGF events. Simulations performed with PYTHIA and LEPTO showed that this fraction is about 30% in the COMPASS case.

The High- p_T Method for $Q^2 > 1 \text{ GeV}^2$.

Apart from the PGF the high- p_T events with $Q^2 > 1 \text{ GeV}^2$ contain a large fraction of the leading processes ($\gamma^*q \rightarrow q$) and of the QCD-Compton interactions ($\gamma^*q \rightarrow gq$). There are hints coming from the PYTHIA Monte Carlo simulation, that the contribution of the resolved photon processes in the region of high Q^2 is smaller than 10% [59].

Thus they are neglected. With the R_{PGF} , R_{LP} and R_{QCDC} being respectively fractions of events with PGF, leading and QCD–Compton scattering the asymmetry reads:

$$A^{\gamma^*N \rightarrow hh} = R_{PGF} \langle \hat{a}_{LL}^{PGF} \rangle \frac{\Delta G}{G} + [R_{LP} \langle \hat{a}_{LL}^{LP} \rangle + R_{QCDC} \langle \hat{a}_{LL}^{QCDC} \rangle] \frac{\Delta q}{q} \quad (1.78)$$

In this equation both sides are averaged over the experimentally accessible x_g range. In the analysis performed at COMPASS an additional cut rejecting events with $x > 0.05$ is imposed. This ensures that the measured A_1 asymmetry is small which corresponds to the smallness of the $\Delta q/q$. Therefore the terms describing leading and QCDC interactions can be dropped from the above equation retaining:

$$A^{\gamma^*N \rightarrow hh} \approx R_{PGF} \langle \hat{a}_{LL}^{PGF} \rangle \frac{\Delta G}{G} \quad (1.79)$$

The R_{PGF} cannot be extracted directly from the QCD. It has to be estimated from the simulations. Therefore its value is model dependent which introduces an additional systematic uncertainty to the analysis.

The High- p_T Method for $Q^2 < 1 \text{ GeV}^2$.

For the fixed target experiments the bulk of events with two high- p_T hadrons is at small Q^2 . At COMPASS about 90% of events have $Q^2 < 1 \text{ GeV}^2$. In this kinematic region apart from the direct processes (PGF, LP and QCDC) an important contribution, more than 50%, comes from the resolved photon interactions. The asymmetry introduced with these interactions, A_{RP} , cannot be neglected in contrast to the $Q^2 > 1 \text{ GeV}^2$ analysis. The measured asymmetry is thus:

$$A^{\gamma^*N \rightarrow hh} = R_{PGF} \langle \hat{a}_{LL}^{PGF} \rangle \frac{\Delta G}{G} + [R_{LP} \langle \hat{a}_{LL}^{LP} \rangle + R_{QCDC} \langle \hat{a}_{LL}^{QCDC} \rangle] \frac{\Delta q}{q} + A_{RP} \quad (1.80)$$

In the resolved photon interactions a photon first fluctuates into a hadronic structure, then a parton from this structure interacts with another parton coming from the nucleon. The interaction can occur in a number of channels each having its separate contribution to the $A^{\gamma^*N \rightarrow hh}$ asymmetry:

- $qq^\gamma \rightarrow qq$ where q is a nucleon quark and q^γ is a resolved photon quark. The contribution from this process to $A^{\gamma^*N \rightarrow hh}$ is:

$$R_{qq} \langle \hat{a}_{LL}^{qq} \rangle \frac{\Delta q}{q} \left(\frac{\Delta q}{q} \right)^\gamma \quad (1.81)$$

- $qg^\gamma \rightarrow qg$ where q is a nucleon quark and g^γ is a gluon coming from the hadronic structure of the photon. The contribution is given by:

$$R_{qg} \langle \hat{a}_{LL}^{qg} \rangle \frac{\Delta q}{q} \left(\frac{\Delta G}{G} \right)^\gamma \quad (1.82)$$

- $gq^\gamma \rightarrow qg$ where g is a gluon from a nucleon and q^γ is a quark coming from the hadronic structure of the photon. The contribution is given by:

$$R_{gq} \langle \hat{a}_{LL}^{gq} \rangle \frac{\Delta G}{G} \left(\frac{\Delta q}{q} \right)^\gamma \quad (1.83)$$

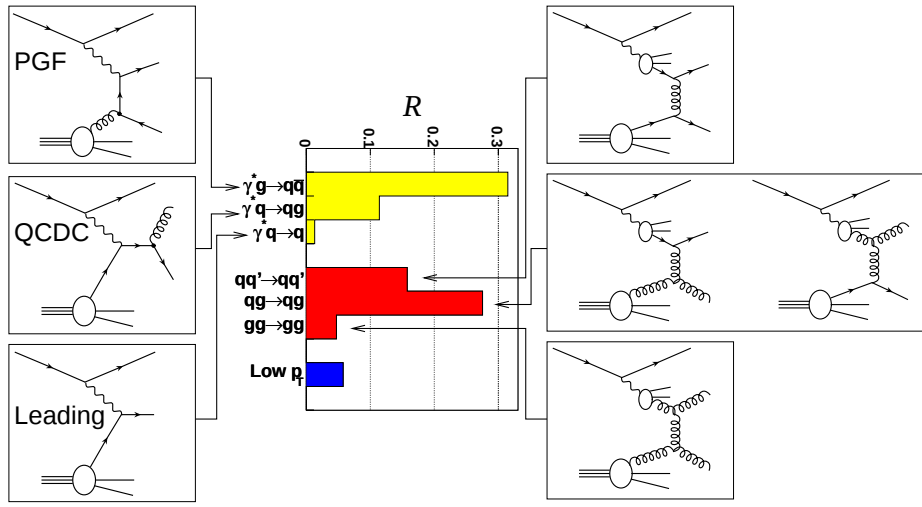


Figure 1.11: Processes contributing to the high- p_T sample with $Q^2 < 1 \text{ GeV}^2$ as obtained for COMPASS analysis with PYTHIA. On the left the direct processes and on the right the resolved photon contributions are presented. Diagrams of processes with contributions smaller than 1% were omitted.

- $gg^\gamma \rightarrow gg$ where one gluon comes from the nucleon and the other from the resolved photon. The contribution to $A^{\gamma^* N \rightarrow hh}$ is equal to:

$$R_{gg} \langle \hat{a}_{LL}^{gg} \rangle \frac{\Delta G}{G} \left(\frac{\Delta G}{G} \right)^\gamma \quad (1.84)$$

- $q\bar{q}^\gamma \rightarrow q\bar{q}$, $\bar{q}q^\gamma \rightarrow q\bar{q}$, $q\bar{q}^\gamma \rightarrow gg$, $\bar{q}q^\gamma \rightarrow gg$, $gg^\gamma \rightarrow q\bar{q}$ processes account only for a very small fraction of high- p_T events (0.6% in total) and can be neglected.

The total asymmetry produced by the interactions involving resolved photons is:

$$A_{RP} = \left[R_{qq} \langle \hat{a}_{LL}^{qq} \rangle \left(\frac{\Delta q}{q} \right)^\gamma + R_{qg} \langle \hat{a}_{LL}^{qg} \rangle \left(\frac{\Delta G}{G} \right)^\gamma \right] \frac{\Delta q}{q} + \left[R_{gg} \langle \hat{a}_{LL}^{gg} \rangle \left(\frac{\Delta G}{G} \right)^\gamma + R_{gq} \langle \hat{a}_{LL}^{gq} \rangle \left(\frac{\Delta q}{q} \right)^\gamma \right] \frac{\Delta G}{G} \quad (1.85)$$

where the superscript γ denotes the parton distributions describing the resolved photon hadronic structure. This structure is known only for the unpolarised case: q^γ and G^γ were measured experimentally while the Δq^γ and ΔG^γ polarised distributions are not known. They can only be estimated as theoretical considerations provide for them an upper and lower limits [60]. The uncertainty arising from this procedure has to be included in the systematic error of the final result. As it can be seen from Eq. (1.85) the resolved photon contributions not only dilute the measured $\Delta G/G$ but also through the $gg^\gamma \rightarrow gg$ and $gq^\gamma \rightarrow gq$ channels are sensitive to it. Finally the total asymmetry reads:

$$A^{\gamma^* N \rightarrow hh} = \left[R_{PGF} \langle \hat{a}_{LL}^{PGF} \rangle + R_{qg} \langle \hat{a}_{LL}^{qg} \rangle \left(\frac{\Delta G}{G} \right)^\gamma + R_{gq} \langle \hat{a}_{LL}^{gq} \rangle \left(\frac{\Delta q}{q} \right)^\gamma \right] \frac{\Delta G}{G} + \left[R_{LP} \langle \hat{a}_{LL}^{LP} \rangle + R_{QCDC} \langle \hat{a}_{LL}^{QCDC} \rangle + R_{qq} \langle \hat{a}_{LL}^{qq} \rangle \left(\frac{\Delta q}{q} \right)^\gamma + R_{qg} \langle \hat{a}_{LL}^{qg} \rangle \left(\frac{\Delta G}{G} \right)^\gamma \right] \frac{\Delta q}{q} \quad (1.86)$$

Fractions of processes as well as average $\hat{a}_{LL}$ for each process have to come from simulation. A large number of parameters not measured directly but estimated from the simulation entails a strong model dependence of the resulting $\Delta G/G$ value. It is included in the systematic error.

1.7 Direct Measurements of $\Delta G/G$

Up to now the $\Delta G/G$ values for different x_g have been determined by the HERMES, SMC and COMPASS Collaborations. Measurements by the first two were based on the high- p_T approach. In HERMES the analysis was focused on the quasi-real photoproduction ($Q^2 \ll 1 \text{ GeV}^2$) while in SMC on the DIS ($Q^2 > 1 \text{ GeV}^2$) region. COMPASS is the first one to perform the measurements in both Q^2 ranges. In addition in COMPASS the $\Delta G/G$ is measured in the open charm channel. STAR and PHENIX experiments, located at RHIC, have also developed spin physics programmes and their first results are now available.

1.7.1 The HERMES Experiment

HERMES (**H**ERA **M**Easurement of **S**pin) is an experiment situated in the DESY laboratory at the HERA collider. It is a fixed target setup with a forward spectrometer. The beam is either electrons or positrons of 27.5 GeV from HERA. It is polarised transversely to the beam plane in the Sokolov–Ternov process [61]. Before the interaction point the polarisation of the beam is rotated into the longitudinal direction. The polarisation is measured continuously with the Compton back-scattering process. Its average value is 0.55 ± 0.02 . As the target HERMES uses a polarised gas. The gas is injected directly into a dedicated part of the beam pipe. As no target walls confining the gas are used, it leaks to the beam pipe from which it is pumped away by a set of high speed pumps. The vacuum in the HERA ring is not affected. The HERMES spectrometer is equipped with a magnet of 1.3 Tm integrated field used for the particles momenta measurement. The particle identification relies on a set of detectors, including the RICH and the calorimeter. A description of the detector setup can be found in [62].

The HERMES high- p_T hadron pairs analysis uses events registered on the hydrogen target and containing at least two oppositely charged hadrons. These hadrons are required to have momenta larger than 4.5 GeV and transverse momenta with respect to the beam exceeding 0.5 GeV. As a bulk of the selected events has $Q^2 \approx 0 \text{ GeV}^2$ the transverse momenta from the above requirement are approximately equal to the transverse momenta calculated with respect to the photon direction. The invariant mass of the system of hadrons, assuming they are pions, has to be larger than 1 GeV. This cut removes the background arising from the ρ meson production. The fraction of the PGF process is estimated with the PYTHIA generator. This generator is also used for the estimation of the fractions of other direct processes: $\gamma^* q \rightarrow q$ and $\gamma^* q \rightarrow gq$, partonic asymmetries $\hat{a}_{LL}$ and the virtual photon depolarisation factor. Possible asymmetries arising from the resolved photon interactions are neglected.

The result of the analysis is:

$$\left\langle \frac{\Delta G}{G} \right\rangle = 0.41 \pm 0.18 \pm 0.03 \quad (1.87)$$

while the average x_g is 0.17 and the scale at which the nucleon structure was probed is given by the average p_T^2 equal to 2.1 GeV². For more details on the HERMES analysis see [63].

Recently HERMES presented a new result on $\Delta G/G$ [64]. It is based on the measurement of the inclusive hadron production asymmetry. The target was the deuteron and the events selected for the analysis had at least one high- p_T hadron of $1.05 < p_T < 2.5$ GeV. The preliminary result of this analysis is:

$$\left\langle \frac{\Delta G}{G} \right\rangle = 0.071 \pm 0.034 \begin{smallmatrix} +0.127 \\ -0.105 \end{smallmatrix} \quad (1.88)$$

with the average x_g equal to 0.22 and the scale of 1.35 GeV².

1.7.2 The SMC Experiment

The SMC (**S**pin **M**uon **C**ollaboration) experiment, NA47, was the predecessor of COMPASS. It was located at CERN North Area and used the M2 positive muon beam of the energy 190 GeV. The beam was naturally polarised to -0.795 ± 0.019 . The polarisation was measured in the $\mu e \rightarrow \mu e$ scattering and through the observation of the energy spectrum of the positrons from the muon decays. The SMC was a fixed target experiment. The target was composed of two solid state cells, each 60 cm long and filled with deuterated butanol or with ammonia. The first material was used for the studies of the interactions on the deuterium, the second on the hydrogen. The target material was polarised to 50% or 90% for deuterium and hydrogen, respectively. The cells were polarised in opposite directions enabling the measurement of interactions with both beam-target spin configurations at the same time. The SMC spectrometer was built around a 4.4 Tm magnet. The tracks were registered with over 100 multiwire proportional chamber detector planes. Scattered muons were identified detecting their tracks behind the 2 m thick iron filter. As no hadrons identification was done in SMC, efficient open charm reconstruction was not possible. Therefore the $\Delta G/G$ was determined only with the high- p_T hadron pairs. A description of the spectrometer can be found in [65].

The SMC analysis was restricted to the sample with $Q^2 > 1$ GeV². The subsample of the events with two hadrons was selected with the cuts:

- hadron candidates tracks were not found behind the muon filter;
- the contribution from the target fragmentation region was removed with $x_F > 0.1$ and $z > 0.1$ cuts for both hadron candidates⁶.

A neural network was used to select the PGF events. The input information for the network were the global parameters describing an event (x , y , Q^2) and the parameters characterising hadronic tracks (transverse and longitudinal momenta, energy fractions etc.). The output of the network was a single number from the (0,1) range. Events described by a high value of this number were more likely to come from the PGF process, while these with a small value originated from the background. The choice of the cut-off value was done taking into account the purity (the ratio of the PGF to non-PGF processes) and the cut's efficiency (the fraction of PGF processes kept in the sample by the cut). The neural network was prepared and optimised on events generated with

⁶The $x_F \approx 2p_{Z'}^{\text{cms}}/\sqrt{s}$, where $p_{Z'}^{\text{cms}}$ is a hadron momentum along Z' axis pointing along the virtual photon momentum vector and $\sqrt{s}$ is the photon-nucleon centre-of-mass energy.

LEPTO. The Monte Carlo was also used for the partonic asymmetry $\langle \hat{a}_{LL}^{PGF} \rangle$ estimation.

The final value from the SMC analysis is [66]:

$$\left\langle \frac{\Delta G}{G} \right\rangle = -0.20 \pm 0.28 \pm 0.10 \quad (1.89)$$

The average x_g is 0.07 and the scale at which the nucleon structure was probed is 3 GeV².

1.7.3 The COMPASS Experiment

The basic layout of the COMPASS spectrometer is similar to that of the SMC. The main difference is a particle identification system consisting of a Cherenkov detector supplemented with electromagnetic and hadronic calorimeters. Also the structure of the tracking detectors is more complex, able to sustain much higher event rates compared to the SMC experiment. The particle identification together with the energy of interactions (the muon-nucleon centre-of-mass energy is ~ 17 GeV) enable studies in the open charm channel. Apart of the open charm, COMPASS is also extracting $\Delta G/G$ using the high- p_T method. The analysis is performed separately in the DIS ($Q^2 > 1$ GeV²) and in the quasi-real photoproduction ($Q^2 < 1$ GeV²) kinematic regions. The cuts selecting high- p_T hadrons are the following:

- hadron candidates are detected in the hadronic calorimeters;
- $p_{T_1} > 0.7$ GeV, $p_{T_2} > 0.7$ GeV where p_{T_1} and p_{T_2} are hadron transverse momenta relative to the virtual photon direction;
- $p_{T_1}^2 + p_{T_2}^2 > 2.5$ GeV²;
- invariant mass of the two hadron system, assuming the hadrons are pions, is larger than 1.5 GeV; this cut removes the resonances;
- contribution from the target fragmentation events is removed by demanding: $x_F > 0.1$ and $z > 0.1$ for both hadrons.

LEPTO 6.5.1 [67] generator is used to estimate the R_{PGF} and $\hat{a}_{LL}^{PGF}$ for $Q^2 > 1$ GeV². For the $Q^2 < 1$ GeV² events PYTHIA 6.2 [68] is used. In the latter case not only R_{PGF} but also the fractions of other processes are taken from simulation.

A preliminary result from the high- p_T analysis of the 2002–2003 data at $Q^2 > 1$ GeV² is:

$$\left\langle \frac{\Delta G}{G} \right\rangle = 0.06 \pm 0.31 \pm 0.06 \quad (1.90)$$

The fraction of R_{PGF} is equal to 0.34 ± 0.07 , the average x_g for the sample is 0.13 with RMS of 0.08 while the scale is 3 GeV².

The result from the high- p_T analysis of the 2002–2003 sample at $Q^2 < 1$ GeV² is:

$$\left\langle \frac{\Delta G}{G} \right\rangle = 0.024 \pm 0.089 \pm 0.057 \quad (1.91)$$

The average x_g is $0.095_{-0.04}^{+0.08}$ and the scale is equal to 3 GeV² [69]. A preliminary result for the whole 2002–2004 data set is:

$$\left\langle \frac{\Delta G}{G} \right\rangle = 0.016 \pm 0.058 \pm 0.055 \quad (1.92)$$

with the same x_g and scale.

1.7.4 Experiments at RHIC

Relativistic Heavy Ion Collider (RHIC) is a hadron collider located at Brookhaven National Laboratory (BNL) in USA. Its primary goal is to explore the matter at the extreme conditions of temperature and density, *i.e.* to produce and probe the **Quark Gluon Plasma (QGP)**. Another physics programme at RHIC is dedicated to the measurements of gluon polarisation. The programme is based on the observation of the polarised proton-proton collisions in two RHIC experiments: **Solenoid TrAcKER at RHIC (STAR)** and **Pioneering High Energy Nuclear Interaction eXperiment (PHENIX)**.

The protons in RHIC are accelerated to 100 or 250 GeV (other energies are also possible). They are polarised at an early stage of acceleration. Special magnets called Siberian Snakes are installed to overcome the proton depolarisation during acceleration. The magnetic field in the Snakes flips the protons polarisation and at the same time averages out the effects leading to the depolarisation. The proton spin orientation inside the rings is vertical. Before interaction points spins are rotated to the longitudinal orientation. For 2003–2006 data taking periods the polarisation of protons increased from 30% to the current 65%.

STAR is a detector which is optimised for the charged particles tracking and identification. It is well suited for the hadronic jet reconstruction. PHENIX specialises in the lepton and photon registration while the jet reconstruction is more difficult. A discussion of the STAR and PHENIX detectors can be found in [70] and [71].

In the RHIC experiments the gluon structure of the interacting protons can be probed through the reactions: $qg \rightarrow \gamma q$, $qg \rightarrow gq$, $gg \rightarrow gg$, cf. Fig. 1.12. In the final state either a photon accompanied by one jet or two jets are observed. The proton-proton interactions provide a much higher statistics of gluon interactions as compared to lepton-nucleon scattering. However, the background of other processes is large.

The observable measured in the experiments is a double spin cross-section asymmetry for a production of a given final state:

$$A^{exp} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \quad (1.93)$$

where σ^{++} and σ^{+-} are the cross-sections for reactions with the colliding beams having polarisations mutually parallel or anti-parallel. A given final state (*e.g.* jet–jet) can be produced not only through the reactions in which a gluon from a proton is participating, but also through reactions with quarks only ($qq \rightarrow qq$). This second kind of reactions is considered a background. For a given partonic reaction the asymmetry, A_i , is given by:

$$A_i = \hat{a}_{LLi} \epsilon \frac{\Delta f_{i1}}{f_{i1}} \cdot \frac{\Delta f_{i2}}{f_{i2}} \quad (1.94)$$

where Δf_{i1-2} and f_{i1-2} are the polarised and unpolarised distributions of partons taking part in the interaction ($\Delta f = \Delta G$ and $f = G$ in case of gluons), $\hat{a}_{LLi}$ is a parton asymmetry for this reaction and ϵ stands for dilution factors. The experimental asymmetry, A^{exp} , is a sum of all A_i for reactions leading to a given final hadronic state. The asymmetries in the sum should be taken with weights corresponding to a fraction of a given reaction in the studied sample. Disentangling the $\Delta G/G$ from this sum is a complex and difficult task. Therefore another method is elaborated. Different scenarios of ΔG distribution are assumed and the corresponding expected experimental double

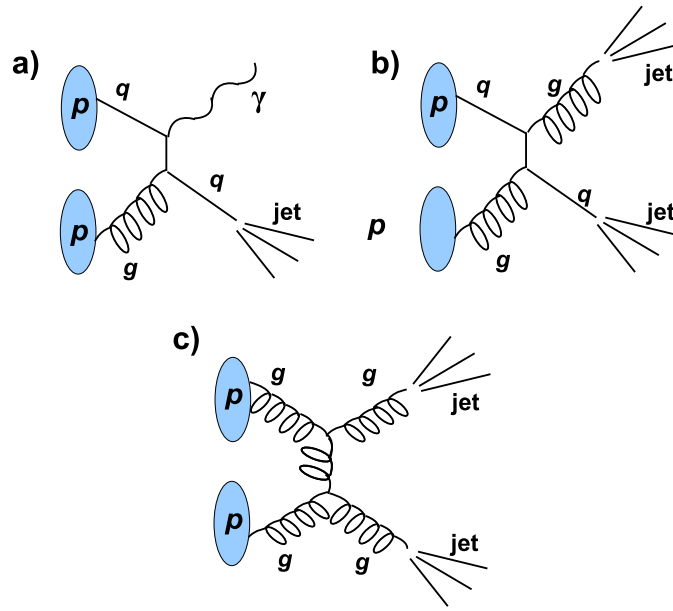


Figure 1.12: Partonic interaction channels in which $\Delta G/G$ can be probed at RHIC:
a) $qq \rightarrow \gamma q$, b) $qg \rightarrow qg$, c) $gg \rightarrow gg$.

spin asymmetry for a production of a given final state are calculated. They are then compared with the measured value. Scenarios that do not agree with the measurement are discarded. The validation for the calculations used to interpret the observed spin asymmetries comes from the spin independent measurements of the cross-sections for production of different final states. The theory predictions and the data are here in a good agreement [72].

Measurements done at RHIC cover a wide x_g range, $0.01 < x_g < 0.3$. The final statistical errors are smaller than in the lepton-nucleon scattering. However the complexity of the hadron-hadron interactions makes the analysis extremely difficult and strongly model dependent.

The results from lepton-nucleon and nucleon-nucleon experiments are complementary. The measurements of $\Delta G/G$ in the former are much more direct, especially the open charm channel, but statistically limited, while the latter are based on a much larger event samples but have to take into account a greater number of the background processes.

Chapter 2

The COMPASS

The **C**ommon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy, COMPASS (NA58)¹, is a Collaboration of more than 250 physicists from 27 institutes from Europe, Russia, Japan and India. The experiment is a successor of a long chain of muon scattering experiments² located in the same hall in the previous 30 years. COMPASS is a result of merging two other originally planned experiments – HMC and CHEOPS. Consequently the COMPASS physics programme has two parts. The first is focused on the spin dependent observables and the other mainly on the hadron spectroscopy. In the former a polarised target and a polarised muon beam are used while the latter is based on different nuclear targets and hadron beams. The experiment was approved in 1998 and the spectrometer became operational in 2001 when a commissioning run was taken. In 2002 first physics data with a muon beam were recorded. The muon data taking programme continued in 2003 and 2004. In 2006 the muon programme was resumed after a one year break when the beam was not delivered due to the shutdown of the SPS at CERN. The analysis presented in this thesis concerns data taken in 2002–2004 with a muon beam. The main features of the spectrometer that was on the floor during that time are presented in this chapter. Also the software packages aiming at the reconstruction of the events and at the physics analysis are briefly described. Two topics are discussed in more details. The first one is the RICH detector and the particle identification based on it. Particle identification is crucial for the analysis presented here. The other topic is an example of Monte Carlo studies leading to the optimisation of the detector performance, here the studies of the Scintillating Fibers tracking station are presented. More specific information on the COMPASS detector configuration can be found in [73].

2.1 The Beam

The COMPASS detector is located in the CERN North Area, EHN2 hall. It uses a high-intensity muon M2 beam line (Fig. 2.1). The beam is produced in three subsequent steps. Protons of 400 GeV energy, coming from the **S**uper **P**roton **S**ynchrotron (SPS), collide with a solid, 500 mm thick, beryllium target (T6) generating a secondary beam which consists mainly of π^+ , K^+ , π^- and K^- mesons. Positive beam particles are then selected with bending magnets and directed into 600 meters long decay tunnel where about 7% of them decay into $\mu^+\nu_\mu$ pairs. At the end of the tunnel a heavy absorber is placed. It stops the remaining hadrons, while μ^+ pass it, losing only a

¹CERN code number of the experiment is NA58. COMPASS is a common name of both, the detector and the Collaboration.

²EMC (NA2, NA2', NA9, NA28), NMC (NA37) and SMC (NA47).

small fraction of their initial energy. Then the μ^+ beam enters a 400 meters long section where particles of a given energy are selected and focused in a set of magnets (B6–B9). This results in a final μ^+ beam of RMS ~ 0.8 cm at target with $2 \cdot 10^8$ particles per spill (the SPS spill contains about $1.2 \cdot 10^{13}$ protons) and an angular divergence of 0.4×0.8 mrad. The contamination of hadrons is smaller than 10^{-6} . Spills last 4.8 s each and are separated by 12 s time windows when the beam is not delivered. The energy of the final beam can be selected in a range of about 60–200 GeV.

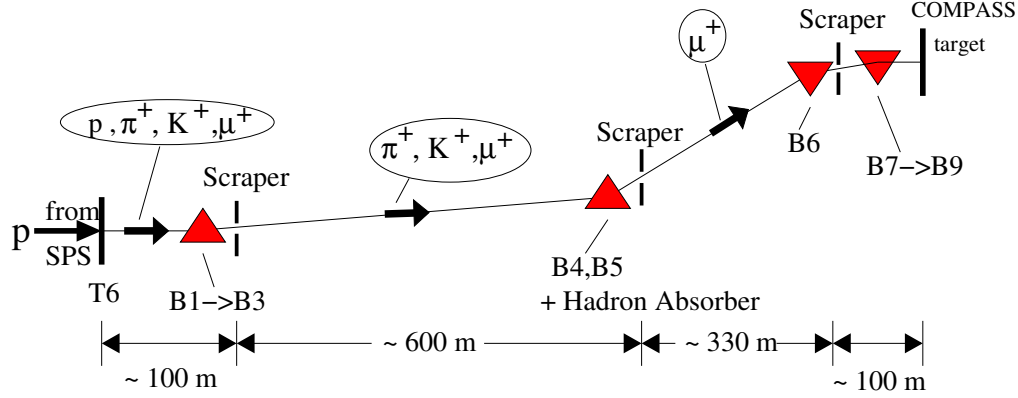


Figure 2.1: Sketch of the COMPASS M2 beam line. B1–9 are magnet stations, T6 is the hadron production target. Plot taken from [74]

Muons coming from the π and K decays are naturally polarised. In the rest frame of the decaying particle muons are 100% polarised and the μ^+ helicity is negative. This fact arises from the left-handedness of neutrinos and the angular momentum conservation. In the laboratory frame the polarisation of muons is no longer 100% due to the Lorentz boost. It depends on the ratio of the decaying meson energy ($E_{\pi,K}$) to the muon energy (E_μ) and is given by the formula:

$$P_\mu = -\frac{m_{\pi,K}^2 + (1 - 2E_{\pi,K}/E_\mu)m_\mu^2}{m_{\pi,K}^2 - m_\mu^2} \quad (2.1)$$

The highest polarisation ($P_\mu = -1$) is for $E_\mu = E_{\pi,K}$. There are three additional parameters that have to be taken into account when choosing the muon energy for the experiment: the beam intensity, the cross-section for the PGF process and the experimental acceptance which vary with the muon beam energy. Monte Carlo simulations prepared with the AROMA generator³ were analysed to obtain the optimal beam energy for the studies of the spin dependent asymmetries [75]. For the 2002–2004 data taking the energy of 160 GeV was chosen. This corresponds to the beam polarisation of -0.76 (for 2002 and 2003) and -0.81 (for 2004 when the secondary π , K beam energy was changed). Momenta of the beam particles are measured to 0.5% accuracy with the **B**eam **M**omentum **S**tation (BMS) placed along the beam line. The RMS of the beam momentum spread is $\sim 3\%$.

Apart from the μ^+ beam also a hadron beam can be delivered via the M2 line to the COMPASS experimental hall. In this case the hadron filter is removed which lets the

³AROMA is a Monte Carlo generator tailored for the simulations of the heavy quark production through the PGF process. More details concerning this generator are given in Sec. 6.1.1.

π^+ and K^+ to reach the target. The identification of the beam hadrons is performed by Cherenkov CEDAR detectors placed along the beam line. The hadron programme of COMPASS is not covered by this thesis, therefore the details of its setup will be omitted.

For more information on the COMPASS beam line cf. [76].

2.2 The Target

For the muon programme in 2002–2004 COMPASS uses a target composed of two cylindrical cells each 60 cm long and 3 cm in a diameter separated by a 10 cm gap (cf. Fig. 2.2). Cells are filled with a solid lithium deuteride, ^6LiD . They are located inside a superconducting solenoid which provides a homogenous 2.5 T longitudinal magnetic field. The homogeneity $\Delta B/B$ in the cell region is of the order of $3.5 \cdot 10^{-5}$. The COMPASS solenoid magnet is the one used previously by the SMC Collaboration. It provides ± 70 mrad angular acceptance. In 2006 it is replaced by a new one with an aperture of ± 180 mrad.

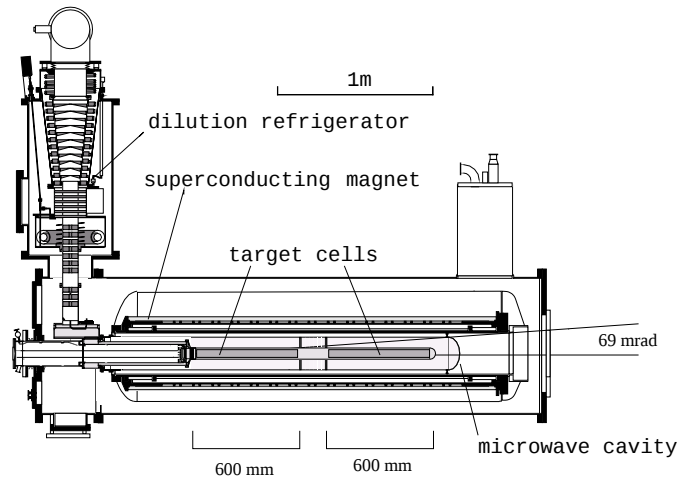


Figure 2.2: Setup of the COMPASS target that was used in 2002–2004 data taking period. Plot taken from [77].

The nuclear spins of the material in the two parts of the target are polarised in opposite directions – parallel and anti-parallel to the magnetic field direction. For the studies of the spin effects a very high level of the target nuclear polarisation is required. This cannot be achieved through the method based on a Zeeman effect. Using this method, even with a 2.5 T magnetic field and in 1 K temperature, polarisation of the deuterons would be only 0.05%⁴ while in the same conditions the electrons polarisation is 96%. This difference is due to a much smaller magnetic moment of the nuclei in comparison with the electrons. In order to polarise nuclei a technique based on the **D**ynamic **N**uclear **P**olarization phenomenon (DNP) [78] is used. It may be described as an induced transfer of a large polarisation from the electrons to the nuclei. The electrons and the nuclei cannot be considered separately as they interact with each another via the electromagnetic field. Instead they should be treated as one complex quantum system.

⁴The level of polarisation for spin 1 target is defined as: $P = \frac{N_+ - N_-}{N_+ + N_0 + N_-}$ where N_+ , N_- and N_0 are populations of a spin projection: +1, -1 and 0, respectively.

For simplicity let us consider a system composed of a spin $\frac{1}{2}$ nucleus and an electron. A target is then composed of the nucleus-electron pairs each being in one of the following states: $|A\rangle = (+\frac{1}{2}, +\frac{1}{2})$, $|B\rangle = (+\frac{1}{2}, -\frac{1}{2})$, $|C\rangle = (-\frac{1}{2}, +\frac{1}{2})$, $|D\rangle = (-\frac{1}{2}, -\frac{1}{2})$; where the first number corresponds to the nucleus and the second to the electron spin projection. In a strong magnetic field almost all the nucleus-electron pairs will be in the quantum states with given spin orientation of the electron, for instance in $|B\rangle$ and $|D\rangle$ (see Fig. 2.3). Then the target is irradiated with a microwave radiation. A frequency of the radiation is exactly equal to the frequency needed to a simultaneous flip of both spins from a given pair. By choosing a proper frequency, $\omega_e + \omega_p$ or $\omega_e - \omega_p$, $|C\rangle$ and $|A\rangle$ states can be filled selectively. Electron spins relax within milliseconds to a lower state and the nucleus-electron systems end in a state $|D\rangle$ or $|B\rangle$ (double spin transitions are highly suppressed) and thus the initial $|B\rangle$ states are transferred to $|D\rangle$ or $|D\rangle$ are transferred to $|B\rangle$, depending on the used microwave frequency. Once the microwave radiation is switched off the temperature of the target is lowered by an order of magnitude and the achieved nuclear polarisation level can be maintained for a long period.

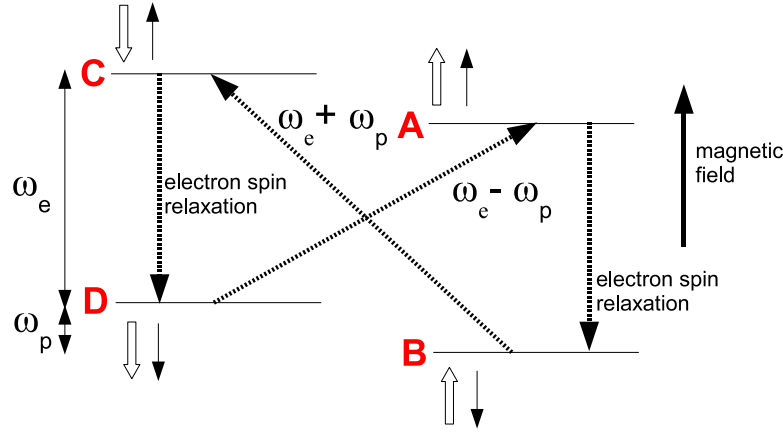


Figure 2.3: Energy levels and transitions between them used for the nucleus polarisation in the DNP method. The microwave frequencies are: $\omega_e + \omega_p$ or $\omega_e - \omega_p$. Arrows $\uparrow\uparrow$ and $\uparrow$ represent the nucleus and electron spin projections.

The DNP method requires the target cells to be enclosed in a microwave cavity and separated by a microwave stopper. Building up polarisation lasts for about 2–3 days. The maximal polarisation obtained was +57% and –53% (average about 50%). The polarisation is measured by the **N**uclear **M**agnetic **R**esonance method (NMR). The NMR is also used to estimate the amount of impurities in the ^6LiD material, especially the contamination coming from ^7Li and H isotopes. Another important contamination is due to the cooling system enclosing the ^6LiD material and consisting of ^4He and ^3He atoms. The amount of impurities has an influence on the spin asymmetry measurements. For the composition of the target material see Tab. 2.1. Directions of the target cells polarisation are flipped every 8 hours by applying an additional magnetic field of a maximal induction 0.5 T perpendicular to the solenoid field. The polarisation reversal lasts for about 30 minutes and preserves its initial level. The reversal is needed to cancel false asymmetries originating from different spectrometer acceptances for the two target halves. It also reduces the error from time dependent variations of the spectrometer efficiency. In order to sustain the polarisation level for a long time the target material is cooled down to the temperature of 50 mK. Cooling is done with a help of ^3He – ^4He

dilution refrigerator. For more information on the COMPASS target setup see [79].

Element	No. of mols	Atomic mass	Element	No. of mols	Atomic mass
H	0.1019	1	⁷ Li	1.7950	7
D	44.5370	2	C	0.0080	12
³ He	3.6207	3	F	0.0160	19
⁴ He	10.9118	4	Ni	0.0057	58.6
⁶ Li	42.8429	6	Cu	0.0136	63.6

Table 2.1: Composition of the target material in 2002.

The nucleons in a deuteron are in the spin triplet state. They can be in a mutual S -state ($L = 0$) or D -state ($L = 2$), with the probabilities of $P_S = 0.951$ and $P_D = 0.049$, respectively [80]. In the S -state the polarisation of the nucleons is simply parallel to that of the deuteron and both spins add up to form spin 1. For D -state the picture is more complex. If m , m_L and m_S denote the total, orbital and spin magnetic quantum numbers in the system, then the following states $|m_L, m_S; m\rangle$ are possible for $m = 1$: $|2, -1; 1\rangle$, $|1, 0; 1\rangle$ and $|0, 1; 1\rangle$. The corresponding Clebsch-Gordan coefficients are $\sqrt{3/5}$, $\sqrt{3/10}$ and $\sqrt{1/10}$. Therefore the nucleon spins are in net 50% cases aligned opposite to the deuteron polarisation. The total number of nucleons in the COMPASS target with spins parallel to the deuteron polarisation is thus:

$$N_{\uparrow\uparrow} = N_S - 1/2N_D = N - 3/2N_D = (1 - 3/2P_D)N = \Omega N = (0.926 \pm 0.016)N \quad (2.2)$$

where N_S and N_D are the numbers of nucleons in the S -state and D -state, while $N = N_S + N_D$. The nucleon polarisation in the target should be thus reduced by the Ω factor with respect to the deuteron polarisation. To be compatible with other COMPASS analyses, which use deuteron as a whole, it was decided to first calculate the $\Delta G/G$ for deuteron, *i.e.* without Ω , and then divide the final result of the analysis by 0.926 to get the $\Delta G/G$ for a nucleon.

2.3 The Spectrometer

The COMPASS detector consists of two separate spectrometers – **L**arge **A**ngle **S**pectrometer (LAS) and **S**mall **A**ngle **S**pectrometer (SAS), Fig. 2.4. This construction allows to perform accurate measurements of tracks of particles emitted at large and small angles with respect to the beam direction. LAS is optimised for angles larger than 30 mrad while SAS is made for smaller angle, high momentum tracks. Both spectrometers contain dipole magnets, SM1 and SM2, located in LAS and SAS respectively. The first magnet, 4 m downstream the target centre, has the field integral along the beam equal to 1 Tm. In order to have a wide angular acceptance it has a large, $2.29 \times 1.52 \text{ m}^2$, central gap. This leads to a non-negligible fringe field in the zone between SM1 and the target solenoid. It is taken into account during track reconstruction. A charged particle has to carry momentum larger than 0.4 GeV to cross the magnet and be recorded downstream. For a particle slower than 0.4 GeV its momentum can be estimated from the measurement of the track deviation in the fringe field. The SM2 magnet is located 18 m downstream the target centre and has a field integral of 4.4 Tm. It has a central gap of $2 \times 1 \text{ m}^2$. The minimal momentum for charged particles that can pass SM2 is 4 GeV. Zones before and after SM1 and SM2 are equipped with a number of tracking detectors

which allow to reconstruct tracks in a magnetic field-free regions. Segments of the reconstructed tracks are then bridged through magnetic field and the final 3-momentum vectors are estimated.

The first spectrometer is equipped with a **R**ing **I**maging **C**herenkov (RICH) detector which provides hadron identification in a wide momentum range. It measures particle velocity from the corresponding Cherenkov emission angle. Combining this information with the knowledge of momentum, the particle type can be determined. More detailed description of the RICH is presented in Sec. 2.5. The RICH detector is not well suited for the distinction between pions and muons. Therefore for muon identification the drift tubes detectors installed at the end of LAS and SAS are used. In front of them 60 cm iron and 2.4 m concrete walls are placed, respectively. The walls work as filters absorbing all charged particles but muons.

Both spectrometers contain hadronic calorimeters (HCAL1 and HCAL2). They have a sandwich construction of alternate scintillators and iron plates. Their task is to help the distinction between muons and hadrons. They are also used in the trigger system. SAS is additionally equipped with an electromagnetic calorimeter (ECAL2) made of lead glass blocks. Another electromagnetic calorimeter (ECAL1) has been added to the experiment setup in 2006. Both may be used for the detection and the energy measurement of neutral particles, *e.g.* photons.

Positions of all the detectors are defined in the COMPASS reference system. Its Z axis is along the beam direction, X axis is pointing horizontally towards the Jura mountains and Y axis is pointing upwards. The upstream target cell is placed between $Z=-100$ cm and $Z=-40$ cm while the downstream one between $Z=-30$ cm and $Z=30$ cm.

2.4 Tracking Detectors

Several kinds of tracking detectors are placed along both stages of the COMPASS. The purpose of using various detectors is to match different particle fluxes in different parts of the spectrometer. In general the detectors can be divided into three groups according to their position with respect to the beam axis. These are: **V**ery **S**mall **A**rea **T**rackers (VSAT), **S**mall **A**rea **T**rackers (SAT) and **L**arge **A**rea **T**rackers (LAT).

VSAT detectors work efficiently in a high particle intensity region, close to the beam. This group consists of eight **S**CIntillating **F**ibers stations (SCIFI) [81] of various sizes (from 4×4 cm² up to 12×12 cm²) and of the **S**ilicon trackers (SI) [82]. Two SCIFI stations and all SI detectors are installed upstream the target and are responsible for a measurement of the direction of the incident muon (first detectors are placed 7.5 m upstream the target). The rest of SCIFI stations are located downstream the target. As the muon scattering angle is usually small these detectors are used for the muon track reconstruction. In Sec. 2.11 a more detailed discussion of SCIFI detectors is presented.

Further away from the beam region the SAT detectors are placed. Between the target and SM1 three **M**icro**M**egas stations (MM) [83], each equipped with three active layers, are located. These provide tracking in a zone highly populated with short hadron tracks outgoing from the primary interaction point. The active area of MM detectors is 40×40 cm² while the central part of 5 cm diameter is deactivated to avoid discharges caused by a high particle flux. Downstream SM1 ten stations of the **G**as **E**lectron **M**ultipliers

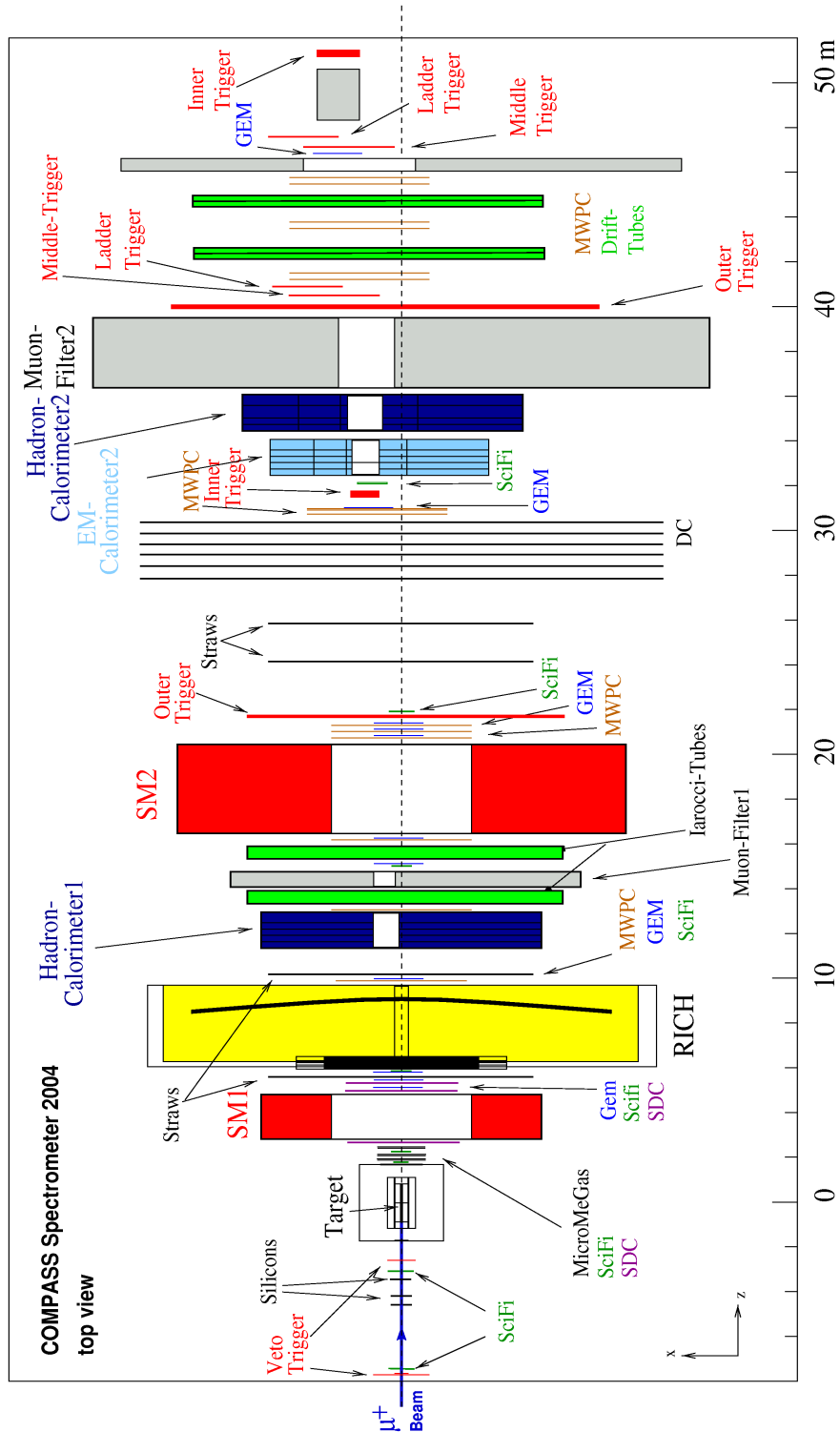


Figure 2.4: Sketch of the COMPASS spectrometer in 2004. The muon beam coming from the left and drawn in blue, before hitting the target is tracked by a set of Silicon and Scintillating Fiber stations. SM1 and SM2 magnets around which LAS and SAS spectrometers are built are marked red. The first spectrometer is equipped with RICH (yellow) while the second with Electromagnetic Calorimeter (light blue). Both stages contain Hadronic Calorimeters (dark blue) and Muon Filters (grey). A number of various tracking devices are also marked. In the SAS four pairs of trigger hodoscopes are placed: Inner, Middle, Outer and Ladder. Plot taken from [73].

(GEM) [84] trackers are installed. Each station consists of four planes rotated by 45° with respect to the other. Their dimensions are $31.6 \times 31.6 \text{ cm}^2$ and the dead zones are the same as for the MM detectors.

The large area tracking is based on the **S**mall area **D**rift **C**hambers (SDC), **M**ulti **W**ires **P**roportional **C**hambers (MWPC) [85], **S**Traw drift chambers (ST) [86] and large area **D**rift **C**hambers (DC) [87]. There are three SDC stations each with eight active planes. One station is placed before SM1 and two just behind it. Their task is to enable track bridging of the particles outgoing from the interaction point at large angles with respect to the beam direction. The active area of SDC planes is $1.8 \times 1.3 \text{ m}^2$ with a central dead zone of 30 cm diameter. The MWPC modules, 11 in total, provide the tracking in a region of a low track occupancy. The modules are installed throughout the SAS spectrometer. The last module is set about 46 m downstream the target. The size of MWPC is $1.8 \times 1.2 \text{ m}^2$ while the dead zone diameter varies from 16 cm to 22 cm depending on the position of the module⁵. Tracking far from the beam area is also due to 15 double layer ST stations. Their sizes are $3.2 \times 2.8 \text{ m}^2$ with the insensitive zones $20 \times 20 \text{ cm}^2$ at the centres. Two of the modules are placed after SM1 and enable the tracking of slow hadrons which are strongly deflected in the magnetic field. The other two are placed after SM2 and help with the reconstruction of muon tracks, scattered at large angles. Downstream SM2 four DC modules are installed. They have active areas of $5 \times 2.5 \text{ m}^2$ with diameters of the dead zones 0.5 m or 1.0 m. They provide tracking in the outermost regions of the spectrometer.

Detector	Active area [mm^2]	Dead zone [mm]	Resolution [mm]
SCIFI	$39 \times 39 \div 123 \times 123$	–	$0.13 \div 0.21$
SI	50×70	–	0.010
MM	400×400	$r = 50$	0.09
GEM	316×316	$r = 50$	0.07
SDC	1800×1275	$r = 300$	0.19
MWPC	$1780 \times 900 \div 1780 \times 1200$	$r = 160 \div 220$	1.6
ST	3230×2800	197×197	0.19
DC	5000×2500	$r = 500 \div 1000$	0.5

Table 2.2: Characteristics of tracking detectors.

2.5 The RICH

The first spectrometer is equipped with a **R**ing **I**maging **C**herenkov detector (RICH)⁶ responsible for the charged hadrons identification [88]. It is capable to separate pions kaons and protons in a wide range of their momenta starting from a threshold of a few GeV (2.5 GeV, 9 GeV, 17 GeV for π , K and p respectively) up to 50 GeV. It can work in a high-intensity particle environment and is able to register and record a great amount of data. It has a wide acceptance: $\pm 250 \text{ mrad}$ in horizontal and $\pm 200 \text{ mrad}$ in vertical directions in order to cover full acceptance range provided by the new COMPASS target solenoid that was installed in 2006. The amount of the material the particle has

⁵The sizes of the detectors are approximate. For actual sizes cf. Tab. 2.2 and [73].

⁶In what follows RICH detector configuration from 2002–2004 period is described. For 2006 run a number of RICH subsystems were upgraded.