Measurement of the gluon polarization in the nucleon via spin asymmetries of charmed mesons at COMPASS

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This article discusses a measurement of the gluon polarization in the nucleon, $\Delta g/g$. It concentrates on the most direct and cleanest way, the measurement of double spin asymmetries of charmed mesons produced in deep inelastic muon-nucleon scattering. The method, the experimental set-up and the analysis leading to the result

$$\frac{\Delta g}{g} = -0.39 \pm 0.24(\text{stat.}) \pm 0.11(\text{syst.})$$

at an average gluon momentum fraction $x_g \approx 0.11$ and a scale $\mu^2 \approx 13\ \text{GeV}^2$ are presented.

1 Introduction: The Nucleon Spin Puzzle

One of the open questions in hadron physics is the decomposition of the nucleon spin of 1/2 among helicity and orbital angular momentum contributions of its constituents. The naive expectation, supported by the static quark model, is that the valence quarks are responsible for the spin of the nucleon. Results from deep inelastic scattering show that the helicity contribution of quarks to the nucleon spin, $\Delta\Sigma$, is only ≈ 30 % [1] by interpreting the matrix element of the singlet axial current, a_0, as $\Delta\Sigma$.

This interpretation is not free of ambiguities. It depends on the renormalization scheme used. In schemes where $\Delta\Sigma$ does not depend on the renormalization scale, a large helicity contribution of gluons, $\Delta G = 2 - 3$, would lead to a much higher value of $\Delta\Sigma$, consistent with quark models [2].

Here ΔG denotes the first moment of the gluon helicity distribution, $\Delta g(x_g)$, i.e. $\Delta G \equiv \int_0^1 \Delta g(x_g)\mathrm{d}x_g = \int_0^1 g^{\uparrow}(x_g) - g^{\downarrow}(x_g)\mathrm{d}x_g$. $g^{\uparrow}$ ($g^{\downarrow}$) is the number density of gluons with spin parallel (antiparallel) to the nucleon spin at a momentum fraction x_g. The unpolarized gluon distribution is thus given by $g(x_g) = g^{\uparrow}(x_g) + g^{\downarrow}(x_g)$.

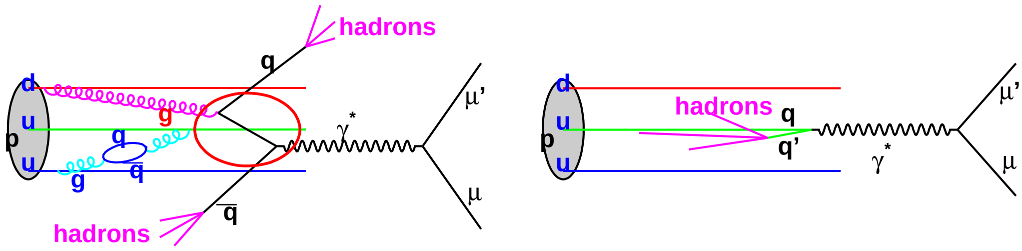

Figure 1: Deep inelastic μ-proton event with the photon-gluon-fusion process (left) and the absorption of the virtual photon by a quark (right) as the underlying partonic subprocess.

2 How to measure ΔG?

2.1 Tagging the gluon

The main tool to study the partonic structure of the nucleon is deep inelastic lepton nucleon scattering (DIS). In the quark parton model, deep inelastic scattering is interpreted as an incoherent sum of scattering processes off partons inside the nucleon. Of particular interest for the discussion here is the process shown in Figure 1, left. It shows a deep inelastic event in the proton-photon center of mass system where the participating parton is a gluon. The partonic subprocess $\gamma^* g \to q\bar{q}$ (indicated by the red ellipse) is called photon-gluon-fusion (PGF). Identifying this process among the much more abundant leading processes where the virtual photon is directly absorbed by one of the quarks inside the nucleon (Fig. 1, right) is the main difficulty. The cleanest way to tag the PGF process is to especially look for the production of charm quarks in the PGF process, i.e. $\gamma^* g \to c\bar{c}$. This process can be identified by the observation of charmed mesons produced in the fragmentation of the c and $\bar{c}$ quarks. At lepton energies considered here, intrinsic charm in the nucleon can be neglected and the production of charmed mesons in the fragmentation process is also strongly suppressed, i.e. the PGF process $\gamma^* g \to c\bar{c}$ is the dominating process for the production of charmed hadrons. They are identified experimentally via the invariant mass of their decay products.

The cross section is schematically given by

$$\sigma^{\mu N \to \mu' DX} \propto \int \sigma^{\mu g} \, D_c^D \, g(x_g) \, \mathrm{d}x_g \, ,$$

where $g(x_g)$ is the gluon distribution, $\sigma^{\mu g}$ the cross section for the partonic process $\mu g \to \mu' c\bar{c}$ and D_c^D a fragmentation function describing the probability for a c quark to fragment into a D meson. To simplify the formula the dependence of the quantities on various kinematic variables was omitted. The integral indicates that for a fixed event kinematics the gluon density is probed in a given range of the gluon momentum fraction x_g. This is in contrast to the leading process where the quark momentum fraction is identical to the Bjorken variable x_{Bj} accessible from the event kinematics.

2.2 Learning about the helicity contribution of gluons

To investigate the helicity contribution of the gluons to the nucleon spin, in addition to identifying processes where the gluon participated, a longitudinally polarized beam and target are needed. The polarized lepton-nucleon cross section is related to the gluon distribution in the following way:

$$\sigma^{\mu(\uparrow)N(\downarrow)} \quad \propto \quad \int (\sigma^{\mu(\uparrow)g(\downarrow)} g^{\uparrow} + \sigma^{\mu(\uparrow)g(\uparrow)} g^{\downarrow})\, D_c^D \,\mathrm{d}x_g\,, \tag{1}$$

$$\sigma^{\mu(\uparrow)N(\uparrow)} \quad \propto \quad \int (\sigma^{\mu(\uparrow)g(\uparrow)} g^{\uparrow} + \sigma^{\mu(\uparrow)g(\downarrow)} g^{\downarrow})\, D_c^D \,\mathrm{d}x_g\,. \tag{2}$$

The arrows indicate the spin direction.

The muon-nucleon asymmetry, $A^{\mu N\to\mu' DX}$, gives access to the gluon helicity distribution $\Delta g = g^{\uparrow} - g^{\downarrow}$.

$$\begin{aligned} A^{\mu N\to\mu' DX} &= \frac{\sigma^{\mu(\uparrow)N(\downarrow)} - \sigma^{\mu(\uparrow)N(\uparrow)}}{\sigma^{\mu(\uparrow)N(\downarrow)} + \sigma^{\mu(\uparrow)N(\uparrow)}} \\ &= \frac{\int \left(\sigma^{\mu(\uparrow)g(\downarrow)} - \sigma^{\mu(\uparrow)g(\uparrow)}\right)\, (g^{\uparrow} - g^{\downarrow}) D_c^D \,\mathrm{d}x_g}{\int \left(\sigma^{\mu(\uparrow)g(\downarrow)} + \sigma^{\mu(\uparrow)g(\uparrow)}\right)\, (g^{\uparrow} + g^{\downarrow}) D_c^D \,\mathrm{d}x_g} \\ &= \frac{\int \frac{\Delta g}{g}\, a_{LL}\, \sigma^{\mu g}\, g\, D_c^D \mathrm{d}x_g}{\int \sigma^{\mu g}\, g\, D_c^D \,\mathrm{d}x_g} \end{aligned} \tag{3}$$

where the partonic asymmetry

$$a_{LL} = \frac{\sigma^{\mu(\uparrow)g(\downarrow)} - \sigma^{\mu(\uparrow)g(\uparrow)}}{\sigma^{\mu(\uparrow)g(\downarrow)} + \sigma^{\mu(\uparrow)g(\uparrow)}} \tag{4}$$

has been introduced. It depends on the photon-gluon kinematics. At leading order [1] (LO) QCD an expression can be found in [3]. Finally one arrives at

$$A^{\mu N\to\mu' DX}(X) = \langle a_{LL}\rangle(X)\, \langle \Delta g/g\rangle_x \tag{5}$$

where

$$\langle a_{LL}\rangle = \frac{\int\, a_{LL}\, \sigma^{\mu g}\, g\, D_c^D \,\mathrm{d}x_g}{\int \sigma^{\mu g}\, g\, D_c^D \,\mathrm{d}x_g}\,.$$

and

$$\langle \Delta g/g\rangle_x = \frac{\int \Delta g/g\, a_{LL} \sigma^{\mu g} \mathrm{d}x_g}{\int a_{LL} \sigma^{\mu g} \mathrm{d}x_g}\,.$$

The argument X for $\langle a_{LL}\rangle$ indicates the dependence on kinematic variables, like for example the photon virtuality Q^2, the energy of the virtual photon divided by the energy of the incoming lepton in the target rest system, y, the energy of the D-meson divided by the energy of the virtual photon, z_{D^0}, and the transverse momentum of the D meson with respect to the virtual photon axis, p_T. The measurement of the double spin asymmetry, $A^{\mu N\to\mu' DX}$, gives thus access to the gluon polarization in the nucleon, $\langle \Delta g/g\rangle_x$, averaged over a certain range in x_g.

[1] Note that the terminology is sometimes confusing. For the open charm analysis presented here the PGF process shown in Fig. 1, left is leading order (LO) since it is the process with the lowest order in α_s where charm quarks are produced. Whereas in an inclusive analysis the process shown in Fig. 1, right is LO and the left diagram is next-to-leading order (NLO).

3 The COMPASS experiment at CERN

From the discussion in the previous section one can read off the main requirements for the measurement of $\Delta g/g$. These are

- a high energetic polarized lepton beam
- a polarized target
- good particle identification to identify the decay products of D mesons.

The COMPASS experiments meets these requirements. COMPASS is a fixed target experiment at CERN using hadron and muon beams to study the structure of the nucleon and spectroscopy of hadrons. For the subject discussed here, a 160 GeV naturally polarized positively charged muon beam is used. Its polarization is -0.80 ± 0.04. ^{6}LiD serves as target material. The target material is placed in a superconducting solenoid and is polarized via dynamic nuclear polarization. ^{6}Li can be considered as a helium nucleus plus a deuteron. Thus 4 out of the 8 nucleons in ^{6}LiD are polarizable. This would lead to a so called dilution factor of $4/8 = 0.5$. Talking into account additional non polarizable material in the target leads to a dilution factor of approximately 0.4. The exact value depends on the kinematics and is calculated event by event. Its relative uncertainty is 5%. The target polarization reached is 50% with a relative error of 5%. For the years 2002-2004 two target cells oppositely polarized were in use. In 2006, 3 target cells were used, the outer two had opposite polarization compared to the central cell. The use of 2 (or 3) target cells oppositely polarized and simultaneously exposed to the muon beam is mandatory for the extraction of asymmetries. Combining data sets with two different polarizations with respect to the muon polarization, allows, to a large extend, a cancellation of possible acceptance variations during the data taking.

The scattered muon and the produced hadrons are detected and identified in a two stage magnetic spectrometer. Of special importance for this analysis is the Ring Imaging Cherenkov Detector for charged particle identification. It allows a pion-kaon separation from threshold (9 GeV) up to momenta of 40 GeV at a 2.5 σ level. For a more detailed description of the experimental setup see [4].

4 Analysis

4.1 Event selection

For the present analysis events with an incoming muon, a scattered muon and at least two additional reconstructed tracks of opposite charge are selected. Note that the event sample comprises events from quasi-real photon production $Q^2 \approx m_\mu^2 y^2/(1-y)$ to the maximum Q^2 of about 100 GeV^2 attainable at this beam energy. Even events at very low Q^2 can be interpreted in perturbative QCD since a hard scale, μ, is given by $\mu^2 \approx 4m_c^2$ and not simply by the virtuality of the photon Q^2. All events are in the deep inelastic region, i.e. the invariant mass of the hadronic final state, W, is larger than 4 GeV^2.

The D mesons are reconstructed via their decay in $K\pi$ pairs. The analysis is performed independently for the following decay channels (charge conjugate channels are always implied)

1. $D^0 \to K^-\pi^+$

2. $D^{*+} \to D^0\, \pi^+$
   $\hookrightarrow D^0 \to K^-\pi^+$

3. $D^{*+} \to D^0\, \pi^+$
   $\hookrightarrow D^0 \to K^-\pi^+(\pi^0)$,
   π^0 is not reconstructed.

4. $D^{*+} \to K^-\pi^+\pi^+$
   kaons below the threshold of RICH,
   kaons are identified by neither giving a signal corresponding to a pion or an electron in the RICH.

The corresponding invariant mass spectra are shown in Fig. 2. The channel $D^0 \to K^-\pi^+(\pi^0)$, where the π^0 is not reconstructed shows up in Figure 2 (center) as a shoulder at $M(K\pi) - M(D^0) \approx 0.250$ GeV. The final event samples amount to 37400, 8700, 6200, 1800 for the four samples, respectively.

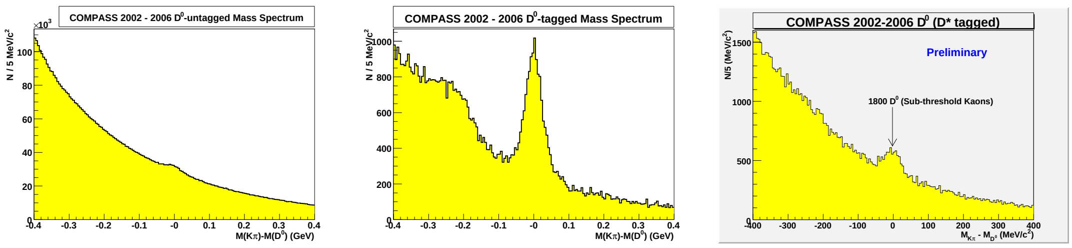

Figure 2: Invariant mass distributions of the $K\pi$ pairs for channel 1 (left), channel 2 and 3 (center) and channel 4 (right).

4.2 Determination of $\Delta g/g$

As derived in section 2.2, information on the gluon polarization is contained in the asymmetry

$$A^{\mu N \to \mu' D^0 X} = \frac{\sigma^{\mu(\uparrow)N(\downarrow)} - \sigma^{\mu(\uparrow)N(\uparrow)}}{\sigma^{\mu(\uparrow)N(\downarrow)} + \sigma^{\mu(\uparrow)N(\uparrow)}} \, .$$

This asymmetry is related to the number of observed events by

$$\frac{\mathrm{d}^k N}{\mathrm{d}m\,\mathrm{d}X} = a\phi n(s+b)\left[1 + P_\mathrm{t} P_\mu f\left(\frac{s}{s+b} A^{\mu N \to \mu' D^0 \mathrm{X}} + \frac{b}{s+b} A_\mathrm{B}\right)\right] \, . \tag{6}$$

Here a, Φ and n are the spectrometer acceptance, the time integrated muon flux and the number of target nucleons, respectively. P_t, P_μ denote the target and beam polarizations and f the dilution factor. The factor $s/(s+b)$ is the ratio of signal (s) to signal plus background (b) events. It can be obtained as a function of the invariant mass from Fig. 2. The term $b/(s+b)\, A_B$ takes into account a possible asymmetry of the combinatorial background.

In a LO QCD analysis $A^{\mu N \to \mu' D^0 \mathrm{X}}$ is replaced by $< a_{LL} > (X)\, \langle \Delta g/g \rangle_x$ according Eq. 5. To make best use of the data in terms of the statistical error, $\langle \Delta g/g \rangle_x$ is not simply determined from the counting rate asymmetry of the number of observed events but rather with a weighting procedure where every event is weighted by its analyzing power which is essentially [2] the factor in front of $\langle \Delta g/g \rangle_x$, i.e. $w_S = P_\mu f \frac{s}{s+b} < a_{LL} >$. Introducing a similar weight for the background allows a simultaneous extraction of signal and background asymmetries. It can be shown that this methods provides the smallest possible statistical error [5].

To evaluate $\langle \Delta g/g \rangle_x$, apart from the number of (weighted) events, the various factors $P_\mathrm{t}, P_\mu, f, \frac{s}{s+b}$ and a_{LL} have to be known. Whereas this is straight forward for the two polarizations and the dilution factor, it is much more difficult for $\langle a_{LL} \rangle$ and $\frac{s}{s+b}$. $\langle a_{LL} \rangle$ depends on the partonic event kinematics and is thus not known event by event. With the help of a neural network it is parameterized in terms of the known event kinematics. The neural network is trained on an AROMA MC sample and uses a leading order QCD expression for a_{LL}. The a_{LL} parameterizations for the different decay channels are almost identical. Figure. 3 shows a correlation of 81% between the generated and the parameterized a_{LL}.

The dependence on the invariant mass of $s/(s+b)$ can be directly obtained from the plots in Fig. 2. However it turns out that there is a strong anti-correlation between $s/(s+b)$ and a_{LL}. This means that it is not sufficient to determine $s/(s+b)$ as a function of the invariant mass, it is also necessary to include the dependence on the other kinematic variables. Moreover this provides a smaller statistical error.

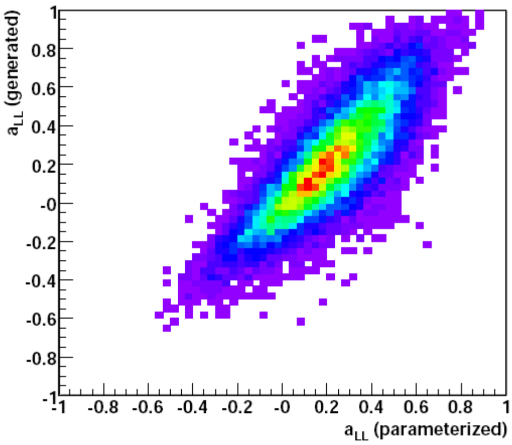

Figure 3: Correlation between the generated and reconstructed a_{LL}.

This is achieved with an iterative multivariate procedure, where $s/(s+b)$ is build as a function of kinematic variables and the response of the RICH detector [6, 7]. For the decay channels with less statistics (no. 3) and 4)) this method has difficulties and a new way to determine s/(s+b) was invented. Here a neural network (NN) is trained on kinematic variables and the information from the RICH. A training set is obtained from wrong charge combinations (wcc), $K^-\pi^+\pi^-$, for the background and good charge combinations (gcc), $K^-\pi^+\pi^+$, for the signal. Figure 4 shows one of the input variables of the NN, namely the polar angle of the kaon in the rest system of the D^0, $|\cos\theta^*|$, in the peak region and outside the peak region, once for the good and once for the wrong charge combination. One clearly observes the different shape for the events with the good charge combination in the peak region.

In both methods the parameterization is validated by verifying that the signal purity, $s/(s+b)$, obtained by the procedure in a given bin in $s/(s+b)$ agrees with the value obtained from a fit to the invariant mass spectrum in this bin. Combining data taken with two oppositely polarized target cells before and after a reversal of the target spin allows to extract $\langle \Delta g/g \rangle_x$ and A_B largely independent of acceptance and flux variations as explained in [7].

[2] The target polarization, P_T, is not included in the weight since it changes with time and may lead to a bias in the asymmetry extraction.

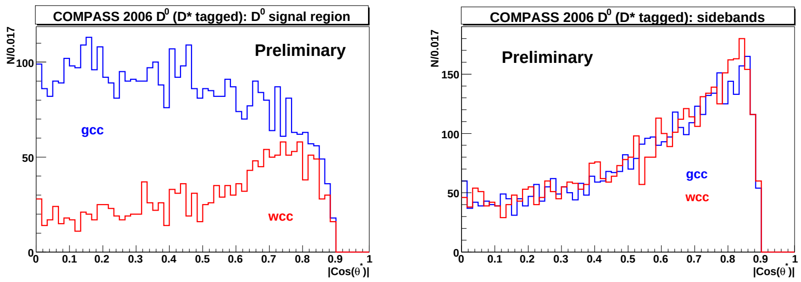

Figure 4: Distribution of $|\cos\theta^*|$ in the signal region (left) and in the sidebands (right) for the good charge combination (gcc) and the wrong charge combination (wcc).

5 Results

Figure 5 shows the results obtained for the four decay channels used in the analysis. The right most point is the weighted average. The gluon distribution is probed at an average momentum fraction $\langle x_g \rangle = 0.11^{+0.11}_{-0.05}$ and at a scale $\mu^2 \approx 4m_c^2 + p_T^2 = 13\,\text{GeV}^2$. The background asymmetries come out to be consistent with 0.

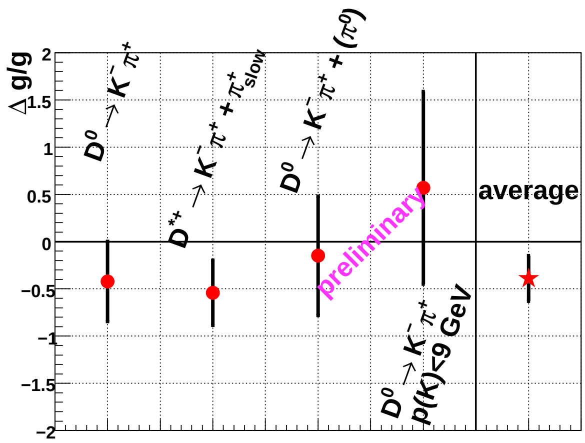

Figure 5: Results on $\langle \Delta g/g \rangle_x$ for the different decay channels used in the analysis. Only the statistical error is shown.

5.1 Systematic Error

Tab. 1 shows a detailed list of systematic errors for channel 1) and 2). The largest contribution to the systematic error comes from the parameterization of the signal purity in the case of the D^0 sample (channel 1) and possible experimental false asymmetries in the D^* sample (channel 2). The systematic error of the other two channels are of similar size. To be conservative a fully correlated systematic error of 0.11 is assigned to all four decay channels. Note that the

source	$\langle \Delta g/g \rangle_x$	source	$\langle \Delta g/g \rangle_x$
False asymmetry	0.05(0.05)	Beam polarization P_μ	0.02
$S/(S+B)$	0.07(0.01)	Target polarization $P_{\rm t}$	0.02
$a_{\rm LL}$	0.05(0.03)	Dilution factor f	0.02
Total error	0.11(0.07)		

Table 1: Systematic error contributions to $\langle \Delta g/g \rangle_x$ for $D^0(D^*)$ channels.

major contributions to the systematic error can be lowered with more statistics.

5.2 Final result

The final result is

$$\langle \Delta g/g \rangle_x = -0.39 \pm 0.24(\text{stat.}) \pm 0.11(\text{syst.})$$

at an average gluon momentum fraction $x_g \approx 0.11$ and a scale $\mu^2 \approx 13$ GeV^2.

This result is obtained in LO QCD analysis. In Ref. [7] also photon-nucleon asymmetries defined by $A^{\gamma N \to DX} = A^{\mu N \to \mu' DX}/D$, where D is the depolarization factor describing the polarization transfer from the muon to the virtual photon, are published. This asymmetry is independent of the interpretation in LO QCD.

5.3 Comparison to other results

Figure 6 shows the open charm result in comparison with other results obtained by using hadrons with large transverse momentum with respect to the virtual photon to tag the PGF process. In this method the signal purity has to be determined in a model dependent way from MC simulations in contrast to the open charm method where the signal purity is obtained from the invariant mass spectra.

The results clearly favor a small value of $\Delta g/g$ at $x \approx 0.1$ and exclude first moments of $\Delta G = 2-3$. This is also supported by results obtained from polarized proton-proton scattering at RHIC [11] and NLO fits to inclusive DIS data [1].

6 Summary & Outlook

The measurement presented here together with other measurements shows that the polarization of gluons around $x_g \approx 0.1$ is consistent with 0 and incompatible with large contribution of the first moment $\Delta G = \int g(x_g) \mathrm{d}x_g = 2-3$, though still consistent with $\Delta G = \int g(x_g) \mathrm{d}x_g = 0.5$, i.e. the gluons carrying 100% of the nucleon spin. The next steps are the inclusion of data taken in 2007 in the analysis and an analysis in next-to-leading order QCD.

At present COMPASS is the only experiment being able to use charmed meson for the determination of $\Delta g/g$. In the future, a polarized electron nucleon collider would offer much better opportunities for this method. One would not suffer from the absorption of hadrons in a solid state target. This will increase the number of reconstructed D mesons. Moreover it will offer the possibility to reconstruct both charmed particles produced in one event. This gives a better access to the gluon momentum fraction x_g.

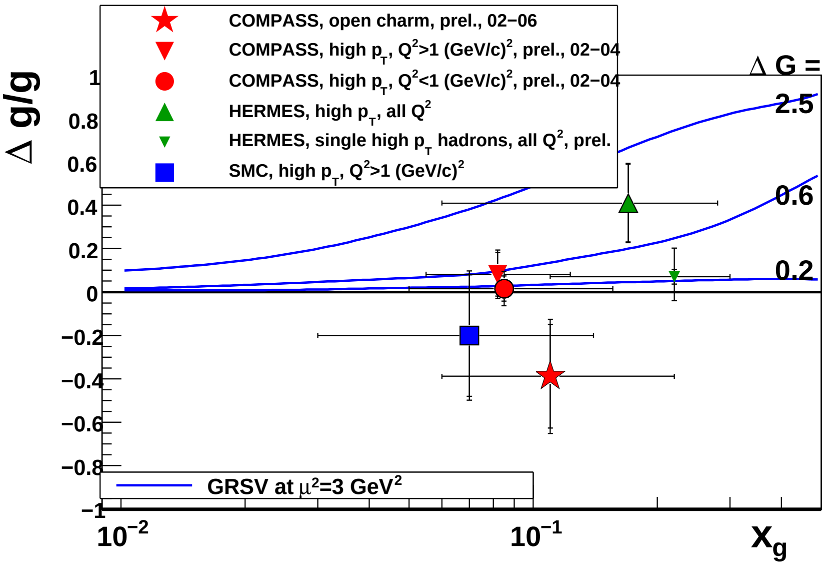

Figure 6: Comparison of the $\Delta g/g$ measurements from open charm and high p_T hadron production by COMPASS, SMC [8] and HERMES [9] as a function of x_g. Horizontal bars indicate the range in x_g for each measurement, vertical ones give the statistical and the total errors (if available). The open charm measurement is at a scale of about 13 GeV^2, other measurements and curves at 3 GeV^2. The solid (blue) curves are a parameterizations [10] with a first moment $\Delta G = \int_0^1 \Delta g(x_g) \mathrm{d}x_g = 0.2, 0.6, 2.5$.

7 Bibliography

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