

Leading and next-to-leading order gluon polarization in the nucleon and longitudinal double spin asymmetries from open charm muoproduction

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The gluon polarization in the nucleon was measured using open charm production by scattering 160 GeV/c polarized muons off longitudinally polarized protons or deuterons. The data were taken by the COMPASS Collaboration between 2002 and 2007. A detailed account is given of the analysis method that includes the application of neural networks. Several decay channels of D^0 mesons are investigated. Longitudinal spin asymmetries of the D meson production cross sections are extracted in bins of D^0 transverse momentum and energy. At leading order QCD accuracy, the average gluon polarization is determined as $\langle \Delta g/g \rangle^{\text{LO}} = -0.06 \pm 0.21(\text{stat.}) \pm 0.08(\text{syst.})$ at the scale $\langle \mu^2 \rangle \approx 13 \text{ (GeV/c)}^2$ and an average gluon momentum fraction $\langle x \rangle \approx 0.11$. The average gluon polarization is also obtained at next-to-leading order QCD accuracy as $\langle \Delta g/g \rangle^{\text{NLO}} = -0.13 \pm 0.15(\text{stat.}) \pm 0.15(\text{syst.})$ at the scale $\langle \mu^2 \rangle \approx 13 \text{ (GeV/c)}^2$ and $\langle x \rangle \approx 0.20$.

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I. INTRODUCTION

The decomposition of the nucleon spin projection of $1/2$ (in units of \hbar) into contributions from helicities and orbital angular momenta of partons became a topic of major interest in experimental and theoretical hadron physics after the European Muon Collaboration at CERN had published the surprising result that quark helicities contribute only an unexpectedly small fraction [1]. Extensive nucleon spin studies were carried out at CERN [2,3], SLAC [4], DESY [5], JLAB [6], and BNL [7,8]. From the data, parton helicity distributions of the nucleon were extracted using the framework of perturbative QCD. By now, the contribution of the quark helicities to the nucleon spin is known to be about 30%, significantly smaller than the value of 60% expected from the Ellis-Jaffe sum rule [9]. Relativistic quark motion is responsible for the reduction from the value of 100%, expected in the naïve quark-parton model [10]. In spite of the ongoing theoretical debate on how to correctly

perform a gauge-invariant decomposition of the nucleon spin, agreement exists that besides the contributions of the quark helicities, the gluon helicity contribution ΔG is also a measurable, gauge-invariant observable (see, e.g., Ref. [11]).

The data of present inclusive polarized deep-inelastic scattering experiments cover a narrower range in the photon virtuality, Q^2 , as compared to unpolarized ones, and hence their QCD analyses (e.g., Ref. [12]) show only limited sensitivity to the gluon helicity distribution as a function of the gluon momentum fraction x ,¹ $\Delta g(x)$, and to its first moment, ΔG . Such a determination of $\Delta g(x)$ from QCD evolution has therefore to be complemented by direct, dedicated measurements.

Direct determinations of the average gluon polarization in a limited interval of x , $\langle \Delta g/g \rangle$, were performed in a model-dependent way using the photon-gluon fusion (PGF) process by SMC [13], Hermes [14] and Compass [15]. These analyses used events containing hadrons or hadron pairs with high transverse momenta, typically 1 to 2 GeV/c. This method provides good statistical precision but relies on Monte Carlo generators simulating QCD processes. PYTHIA [16] was used by Hermes and by Compass for the analysis of small Q^2 events, and LEPTO [17] by SMC and Compass for $Q^2 > 1 \text{ (GeV/c)}^2$ events [18]. All measurements yield a small value of the gluon polarization at $x \approx 0.1$. This is consistent with recent

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¹Throughout this paper, x denotes the gluon momentum fraction, while x_B stands for the Bjorken scaling variable.

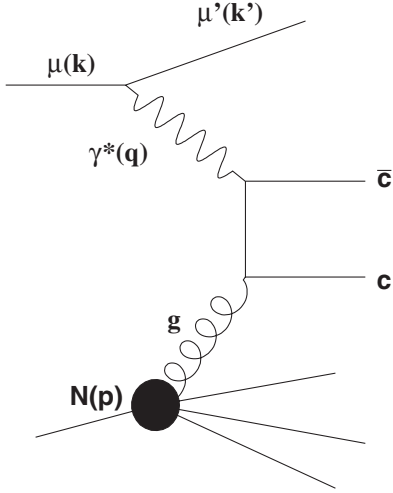


FIG. 1. Photon-Gluon Fusion into a pair of charm quarks, $c\bar{c}$. Symbols in parentheses denote four-vectors.

results from Phenix [7] and Star [8] at RHIC, where the production of inclusive π^0 or high-transverse momentum jets led to constraining the magnitude of $\langle \Delta g/g \rangle$.

In this paper, we present new results on $\langle \Delta g/g \rangle$ and the virtual photon-nucleon asymmetries obtained from charm production tagged by D meson decays in 160 GeV/ c polarized muon-nucleon scattering. The data were collected by the Compass Collaboration at CERN in the 2002–2004 and 2006–2007 running periods. The results supersede the ones given in Ref. [19], since they are based on the full data sample and an improved analysis method; additional final state channels are added as well. The gluon polarization is determined assuming that open charm

production is dominated by the PGF mechanism, $\gamma^* g \rightarrow c\bar{c}$, as depicted in Fig. 1. The subsequent fragmentation of the $c\bar{c}$ pair, mainly into D mesons, is assumed to be spin independent. The dominance of the PGF mechanism in the Compass kinematic region is supported by the EMC results on $F_2^{c\bar{c}}$ (Ref. [20], further discussed in Ref. [21]), and by a Compass study of charm meson production [22]. The determination of the gluon polarization based on this assumption, although limited statistically, has the advantage that in lowest order of the strong coupling constant, there are no other contributions to the cross section.

In the present analysis, only one charmed meson is required in every event. This meson is selected through its decay in one of the following channels: $D^*(2010)^+ \rightarrow D^0 \pi_s^+$ or $D^0 \pi_s^+ \rightarrow (K^- \pi^+ / K^- \pi^+ \pi^0 / K^- \pi^+ \pi^+ \pi^-) \pi_s^+$ or $D^0 \rightarrow K^- \pi^+$, as well as their charge conjugates (the subscript “s” refers to “slow”). The former samples are called “tagged” ones, while the latter is denoted “untagged.” Virtual photon cross section asymmetries, $A^{\gamma N \rightarrow D^0 X}$, and the average gluon polarization $\langle \Delta g/g \rangle$ are extracted from these open charm events. In Table I, the kinematic variables describing the μN scattering process are listed. In this analysis we have also employed, for the first time, next-to-leading order QCD calculations for the determination of the gluon polarization. Since the PGF process is dominated by quasireal photoproduction ($Q^2 \rightarrow 0$), the perturbative scale for the selected events, μ^2 , cannot be set to Q^2 as in the QCD analyses of inclusive data. Instead, this scale is chosen to be the transverse mass of the charmed quarks, $\mu^2 \equiv 4M_T^2 = 4[m_c^2 + (p_T^{D^0})^2]$, where the D meson transverse momentum, $p_T^{D^0}$, is defined with respect to the virtual photon.

TABLE I. Kinematic variables used to describe the muon-nucleon interaction, see Fig. 1.

Variable	Symbol	Definition
Nucleon (muon) mass	$M(m_\mu)$	
Four vector of incoming (outgoing) muon	$k(k')$	
Four vector of target nucleon	p	
Four vector of outgoing hadron final state	p_X	
Four vector of virtual photon	q	$q = k - k'$
Four vector of a final state hadron	p'_h	
Negative four momentum transfer squared (photon virtuality)	Q^2	$Q^2 = -q^2$
Muon laboratory incident (final) energy	$E(E')$	$E = \frac{p \cdot k}{M}$ ($E' = \frac{p \cdot k'}{M}$)
Polar angle of kaon in the D^0 centre-of-mass relative to the D^0 laboratory momentum	θ^*	
Virtual photon energy	ν	$\nu = \frac{p \cdot q}{M} = \text{lab } E - E'$
Bjorken scaling variable	x_B	$x_B = \frac{Q^2}{2p \cdot q} = \frac{Q^2}{2M\nu}$
Virtual photon fractional energy	y	$y = \frac{p \cdot q}{p \cdot k} = \text{lab } \frac{\nu}{E}$
Final state hadron fractional energy	z_h	$z_h = \frac{p \cdot p'_h}{p \cdot q} = \text{lab } \frac{E_h}{\nu}$
Transverse momentum of D^0 meson with respect to the virtual photon direction	$p_T^{D^0}$	
Energy of D^0 meson in laboratory	E_{D^0}	

The paper starts with a brief presentation of the experiment in Sec. II. In Sec. III the data selection is reported in detail. The evaluation of the asymmetries and the corresponding results are described in Sec. IV. The determinations of the gluon polarization $\langle \Delta g/g \rangle$ at leading (LO) and next-to-leading (NLO) QCD accuracies are presented in Sec. V. Concluding remarks are given in Sec. VI.

II. EXPERIMENTAL SETUP

The Compass spectrometer is a fixed target setup situated at the M2 beam line of the CERN super proton synchrotron (SPS) using muon or hadron beams. For the present measurement, longitudinally polarized positive muons of 160 GeV/ c momentum were scattered off a large polarized solid state target. A detailed description of the setup can be found in Ref. [23].

The muons originate from the weak decay of 175 GeV/ c pions and kaons produced by the 400 GeV/ c SPS proton beam impinging on a primary beryllium target and are thus naturally polarized. The beam polarization, P_μ , is about 0.8 at 160 GeV/ c with a relative uncertainty of 5% [24]. A beam intensity of about 4×10^7 muons/s was used, with the spill length between 4.8 and 9.6 s for SPS cycles between 16.8 and 48 s, respectively. The beam is focused onto the target center with a spread of 7 mm (rms) and a momentum spread of 5% for the Gaussian core. The momentum of each incoming muon is measured with a precision better than 1% upstream of the experimental hall using a beam momentum station. Before the target, the trajectory of each beam particle is determined with an angular precision of 30 μ rad using a set of scintillating fiber and silicon detectors.

The solid state target is housed in a large superconducting solenoid, providing a field of 2.5 T with field uniformity, $\delta B/B$, better than 10^{-4} . From 2002 to 2004, the angular acceptance was ± 69 mrad at the upstream edge and ± 170 mrad at the downstream edge of the target material. From 2006 onwards, a new target magnet with a larger aperture solenoid was used [23]. It yields an angular acceptance of ± 180 mrad for the upstream target edge, resulting in a much improved hadron acceptance and matching the ± 180 mrad acceptance of the spectrometer.

The target material consisted of ${}^6\text{LiD}$ beads in 2002 to 2006 and NH_3 beads in 2007, in a bath of ${}^3\text{He-}^4\text{He}$. The target was cooled down to a temperature below 100 mK by a ${}^3\text{He-}^4\text{He}$ dilution refrigerator. The target polarization was accomplished using the method of dynamic nuclear polarisation (DNP) and measured continuously by a set of NMR coils surrounding the target material. The achieved polarization, P_t , was about 0.5 for deuterons (${}^6\text{LiD}$) and 0.9 for protons (NH_3) with a relative uncertainty of 5% and 2%, respectively.

In 2002 to 2004, the target material was contained in two 60-cm-long cells that were polarized in opposite directions. The polarization was reversed three times per day by

rotating the field of the target magnet. From 2006 onwards, a three-cell target setup was used with a central 60-cm-long cell placed between two 30-cm-long ones. The material inside the central cell was polarized oppositely to that of the outer ones. The use of this new target arrangement allows for further reduction of the systematic uncertainty due to the variation of the spectrometer acceptance along the target, so that only one field rotation per day was performed. In order to minimize possible acceptance effects related to the orientation of the solenoid field, the sign of the polarization in each target cell was reversed several times per year by changing the DNP microwave frequencies.

As not all nucleons in the target material are polarized, the so-called dilution factor, f , is introduced. It is expressed in terms of the numbers n_A of nuclei with mass number A and the corresponding total (i.e., including radiative effects) spin-independent cross sections, σ_A^{tot} , per nucleon for all the elements involved,

$$f_{\text{H,D}} = \frac{n_{\text{H,D}} \cdot \sigma_{\text{H,D}}^{\text{tot}}}{\sum_A n_A \cdot \sigma_A^{\text{tot}}}.$$

In the present analysis, the dilution factor is modified by a correction factor $\rho = \sigma_{\text{p,d}}^{1\gamma} / \sigma_{\text{p,d}}^{\text{tot}}$ accounting for the dilution due to radiative events on unpolarized protons (deuterons) [25]. A correction for polarization of the deuteron in the ${}^6\text{Li}$ nucleus is also applied.

The dilution factor depends on x_B . At low x_B , it is larger for events containing hadrons in the final state due to the absence of radiative elastic tails. Its values at medium x_B for ${}^6\text{LiD}$ and NH_3 are about 0.37 and 0.14 with relative uncertainties of 2% and 1%, respectively.

The two stages of the Compass setup are open dipole spectrometers for large and small angle tracks, respectively. Each dipole magnet is surrounded by tracking detectors. Compass uses various types of them in order to match the expected particle flux at various locations in the spectrometer. In high-flux regions close to the beam, tracking is provided by arrays of scintillating fibers, silicon detectors, micromesh gaseous chambers and gas electron multiplier chambers. Further away from the beam, larger-area tracking devices as multiwire proportional chambers, drift chambers and straw detectors are used. In 2006 the tracking system in the first stage of the spectrometer was adapted to match the increased aperture of the superconducting solenoid.

Muons are identified in large area tracking detectors and scintillators downstream of concrete or iron muon filters. Hadrons are detected by two scintillator-iron sandwich calorimeters installed in front of the muon filters. Electromagnetic lead glass calorimeters are placed in front of the hadron ones. The data recording system is activated by triggers indicating the presence of a scattered muon and/or energy deposited by hadrons in the calorimeters. Both inclusive and semi-inclusive triggers are used. In the former, the scattered muon is identified by coincident signals

in the trigger hodoscopes, and in the latter the energy deposited in calorimeters is demanded in addition. Moreover, a calorimetric trigger with a high-energy threshold is implemented to extend the acceptance. In order to suppress triggers due to halo muons, veto counters upstream of the target are used. The Compass trigger system covers a wide range in Q^2 , from quasireal photo-production to the deep inelastic region.

For charged particle identification in the first stage of the setup, a ring imaging Cherenkov detector (RICH) is installed [26]. It is a gas RICH with a 3-m-long C_4F_{10} radiator. Two spherical mirror surfaces reflect and focus the Cherenkov photons on two sets of detectors situated above and below the acceptance of the tracking detectors, respectively. The photon detection uses MWPCs with segmented CsI photocathodes which detect photons in the UV region. In 2006, the central part of the RICH was upgraded replacing the MWPCs by multianode photomultiplier tubes, yielding a considerably higher number of detected photons and a much faster response. For the outer parts, the readout electronics was refurbished allowing a significant reduction of the background.

The particle identification procedure relies on a likelihood function based on information on the photons detected in the RICH and associated with a charged particle trajectory. The likelihood function uses the photons of the signal and a theoretical expectation of their distribution, taking into account possible signal losses due to dead zones in the detector. For the description of the background photons, the experimental occupancy of the photon detectors is used. For each track, likelihood values are computed for different particle mass hypotheses and the background hypothesis. Identification of a pion (kaon) is possible for momenta between 2.5 GeV/c (9 GeV/c) and 50 GeV/c.

The performance of the detectors as well as the stability of the reconstructed data was carefully monitored and all spills not fulfilling stability requirements were excluded from further analysis. Time intervals selected for asymmetry measurements correspond to periods of stable spectrometer performance. In total, data taking amounted to 48 weeks in the years 2002 to 2007.

III. DATA SELECTION

In order to extract information about the gluon polarization, events with D mesons have to be selected from the data. This is accomplished by requiring every event containing an incoming and outgoing muon together with at least two outgoing charged tracks. Furthermore, only events with the incoming muon potentially crossing the whole target and with an interaction point (or “vertex”) within the target were retained.

The direction of tracks reconstructed at an interaction point in the target is determined with a precision better than 0.2 mrad and the momentum resolution for charged tracks detected in the first (second) spectrometer stage is about 1.2% (0.5%). The longitudinal vertex resolution varying from 5 to 25 mm along the target permits assigning each event to a particular target cell, i.e., to a specific target spin direction. In Fig. 2 are shown the distributions of the reconstructed vertex position z_{vtx} along the beam axis for events remaining after applying the aforementioned selection criteria. The relative increase of the number of events in the upstream and central target cells, seen in the right panel, reflects the acceptance increase due to the upgrade of the target magnet in 2006. Due to multiple Coulomb scattering in the solid state target, the spatial resolution of the vertex reconstruction is not sufficient to separate production and decay points of charmed mesons. As a result,

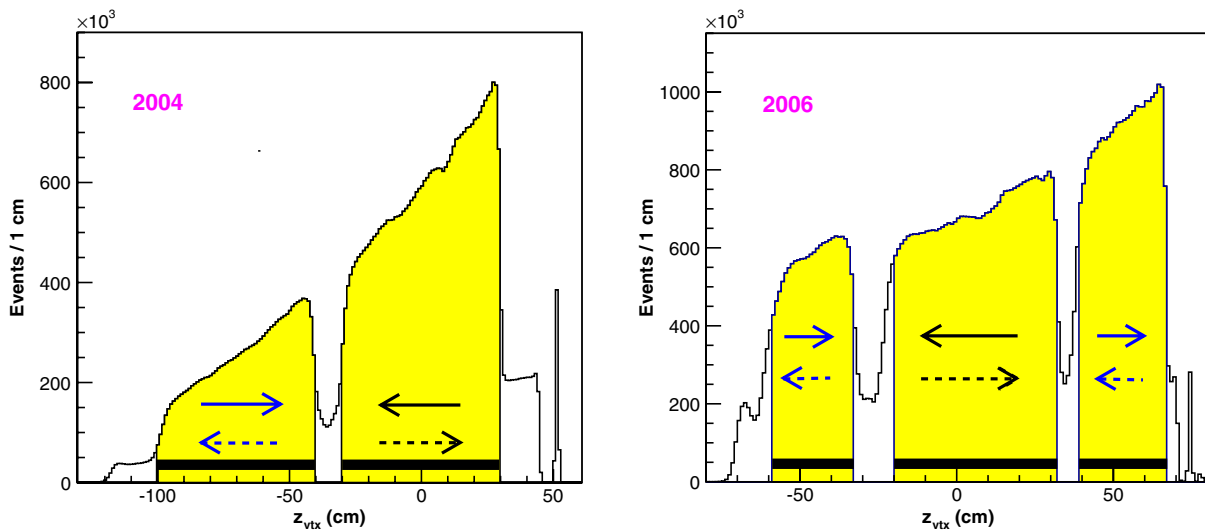


FIG. 2 (color online). Distribution of reconstructed vertex positions z_{vtx} along the beam axis for the target with two (left) and three (right) cells. Dark horizontal bars at the bottom mark the target fiducial regions, arrows denote the target polarization directions. See text for details.

TABLE II. Charmed D^0 meson decay modes, together with their branching ratios, considered in this analysis. The charge conjugate (c.c.) final states from \bar{D}^0 decays are also included.

Reaction number	D^0 decay mode
1	$D^0 \rightarrow 3.89\% K^- \pi^+ + \text{c.c.}$
2	$D^0 \rightarrow 13.9\% K^- \pi^+ \pi^0 + \text{c.c.}$
3	$D^0 \rightarrow 8.09\% K^- \pi^+ \pi^+ \pi^- + \text{c.c.}$

TABLE III. Event samples used in the analysis. For each sample, the corresponding reactions from Table II are indicated. In the tagged samples, the D^0 is assumed to originate from D^* decay and the final state of the D^0 decay is indicated by the subscript where ‘ K_{sub} ’ stands for a kaon with momentum below the RICH threshold. Throughout this paper, each sample will be referred to using the above notation.

	Untagged sample	Tagged samples			
Sample	$D_{K\pi}^0$	$D_{K\pi}^*$	$D_{K_{\text{sub}}\pi}^*$	$D_{K\pi\pi^0}^*$	$D_{K\pi\pi\pi}^*$
Reaction number	1	1	1	2	3

such mesons can only be reconstructed using the invariant mass of their decay products. Their decay modes considered in this analysis are listed in Table II. Those D^0 decays which involve the same set of final state particles cannot be distinguished event by event. Therefore five independent data samples with different final states are defined for this analysis, see Table III. In the four tagged samples, i.e., $D_{K\pi}^*$, $D_{K_{\text{sub}}\pi}^*$, $D_{K\pi\pi^0}^*$, and $D_{K\pi\pi\pi}^*$, the D^0 meson is assumed to originate from a D^* decay into a D^0 meson and a slow pion, $D^* \rightarrow 67.7\% D^0 \pi_s$ (here ‘‘ K_{sub} ’’ stands for a kaon with momentum below the RICH threshold). The kinematic selection criteria, which are tuned to reduce the combinatorial background without affecting the D^0 meson signal, are listed in Table IV.

Particles are identified using the RICH detector. Using the measured momentum of a charged particle and the distributions of Cherenkov photons, likelihood values for different mass hypotheses and for the background

hypothesis are computed. A particle is identified as kaon or pion if the likelihood value is larger than those for all remaining hypotheses. This procedure is very efficient in reducing the combinatorial background of two particles other than π and K . A detailed description of the identification procedure is given in Ref. [27].

The following selection criteria were applied to obtain the final event samples. The untagged sample $D_{K\pi}^0$ contains events with $K\pi$ pairs in the reconstructed mass range given in Table IV; these events do not stem from decays of reconstructed D^* mesons. Due to large combinatorial background, this sample requires more restrictive cuts for the identification of pion and kaon: a pion momentum above 7 GeV/ c is required to avoid contamination from electrons. For the four tagged samples, a D^* meson is selected by requiring the presence of a slow pion, $p_{\pi_s} < 8$ GeV/ c , in addition to a D^0 candidate. The presence of the slow pion permits the application of two additional cuts. The first one uses the RICH detector to reject electrons that mimic slow pion candidates and reduces the combinatorial background by a factor of two. The second one is a cut on the mass difference, $\Delta M = M_{K\pi\pi_s}^{\text{rec}} - M_{K\pi}^{\text{rec}} - M_{\pi}$, where $M_{K\pi\pi_s}^{\text{rec}}$ and $M_{K\pi}^{\text{rec}}$ are the reconstructed masses of the D^* and the D^0 candidates, respectively. This mass difference can be measured with very good precision and thus the cut on ΔM results in a significant reduction of the combinatorial background in the tagged samples.

In addition to the cuts described above, further kinematic cuts were applied to all samples. It is demanded that $|\cos \theta^*| < 0.9$ for the tagged $D_{K\pi}^*$ and $D_{K\pi\pi^0}^*$ samples, $|\cos \theta^*| < 0.65$ for the sample $D_{K\pi}^0$ and $|\cos \theta^*| < 0.85$ for the remaining samples. This cut suppresses mainly background events and improves the significance of the signal. Finally, all events have to satisfy a cut on z_{D^0} . Since a pair of charmed quarks is produced in the center of mass of the $\gamma^* g$ system, each quark receives on average half of the virtual photon energy. Indeed, the measured z_{D^0} distribution and the one simulated assuming a pure PGF process (with parton showers included) are very similar and have a

TABLE IV. List of kinematic cuts used for each data sample. An event is considered (and called a ‘‘ D^0 candidate’’) if it fulfills all conditions in a corresponding column. Here $\Delta M = M_{K\pi\pi_s}^{\text{rec}} - M_{K\pi}^{\text{rec}} - M_{\pi}$, where the superscript ‘‘rec’’ denotes the reconstructed mass.

Variables	Kinematic cut intervals				
	Untagged sample	Tagged samples			
	$D_{K\pi}^0$	$D_{K\pi}^*$	$D_{K\pi\pi^0}^*$	$D_{K_{\text{sub}}\pi}^*$	$D_{K\pi\pi\pi}^*$
$(M_{K\pi}^{\text{rec}} - M_{D^0})$ [MeV/ c^2]	[-400, +400]	[-600, +600]		[-400, +400]	
$ \cos \theta^* $	<0.65	<0.90		<0.85	
z_{D^0}	[0.20, 0.85]	[0.20, 0.85]	[0.20, 0.85]	[0.20, 0.85]	[0.30, 0.85]
p_K [GeV/ c]	[9.5, 50]	[9.5, 50]	[9.5, 50]	[2.5, 9.5]	[9.5, 50]
p_{π} [GeV/ c]	[7, 50]			[2.5, 50]	
ΔM [MeV/ c^2]	...		[3.2, 8.9]		[4.0, 7.5]
p_{π_s} [GeV/ c]	...			<8	

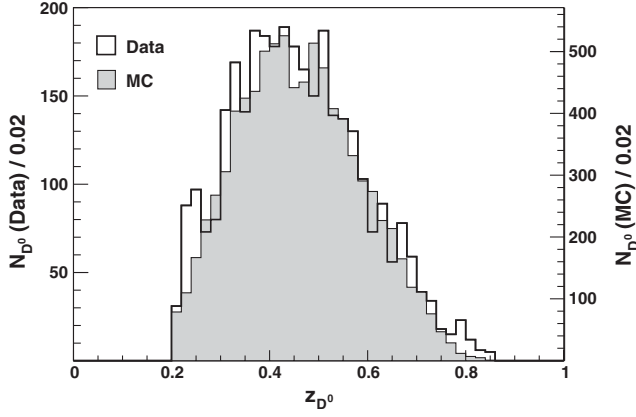


FIG. 3. Distribution of z_{D^0} for the $D_{K\pi}^*$ data sample (background is subtracted using the background model described in Sec. IV A 2) and corresponding Monte Carlo events. D^0 mesons are selected in the $\pm 80 \text{ MeV}/c^2$ mass window around the D^0 mass.

most probable value close to 0.5; see Fig. 3. This fact strongly supports the assumption on PGF dominance in charm production.

Final mass spectra for the $D_{K\pi}^0$ and $D_{K\pi}^*$ samples, selected according to kinematic cuts listed in Table IV, are shown in Fig. 4. For the latter, a most pronounced signal is visible at the D^0 mass with a mass resolution of about $27 \text{ MeV}/c^2$. In this mass spectrum, also a second structure is visible at about $-250 \text{ MeV}/c^2$, which is due to the events with $D^0 \rightarrow K^- \pi^+ \pi^0$ decays with the neutral pion not reconstructed in the analysis. Thus the $K\pi$ spectrum is shifted to lower mass as compared to $D^0 \rightarrow K^- \pi^+$ decays. The purity of this signal is much worse due to the non-reconstructed neutral pion.

Further improvement of the significance of the signal is accomplished by applying the Neural Network method described in Sec. IV A 2, which leads to a considerable reduction of the combinatorial background in the tagged samples. The resulting mass spectrum for $D_{K\pi\pi^0}^*$ is shown in Fig. 5, with an improvement of the signal strength by 15% while for the $D^0 \rightarrow K^- \pi^+$ the signal and the background are reduced in a similar way so that the significance of the signal stays unchanged. Therefore, only the criteria from Table IV are used to select the final $D_{K\pi}^*$ sample; see Fig. 4.

Results on channels with a weaker D^0 signal, like $D_{K\pi\pi\pi}^*$ and $D_{K_{\text{sub}}\pi}^*$, are also shown in Fig. 5. The sample $D_{K_{\text{sub}}\pi}^*$ contains events where the momentum of the kaon candidate is below the limit of $9.5 \text{ GeV}/c$ for kaon identification by the RICH detector. Simulations using a Monte Carlo generator for heavy flavors, AROMA [28], and a full spectrometer description based on GEANT [29] have shown that about 30% of the kaons coming from D^0 decays have their momenta below this RICH threshold. Therefore, it is only required that those particles, K_{sub} , are not identified as pions or electrons.

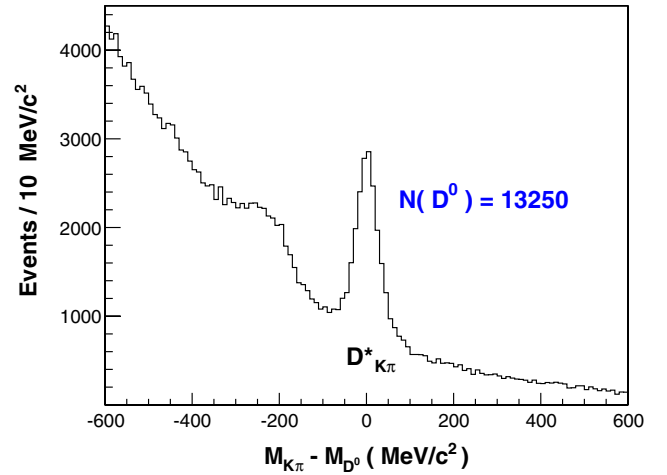
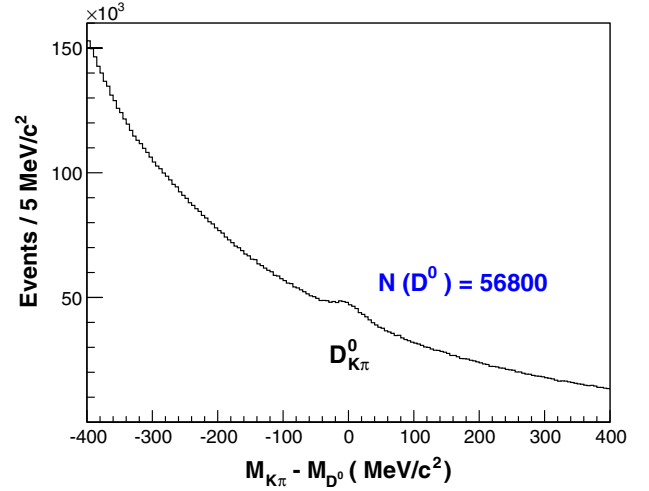


FIG. 4 (color online). Invariant mass spectra for the $D_{K\pi}^0$ and $D_{K\pi}^*$ samples with the approximate number of D^0 mesons above background. Events in the spectra fulfill all the cuts in Table IV. The structure visible at about $-250 \text{ MeV}/c^2$ is due to events with $D^0 \rightarrow K^- \pi^+ \pi^0$ decays with the neutral pion not reconstructed in the analysis.

In the case the two D^0 candidates are found in the same event, only one of them, chosen randomly, is considered in the analysis. If two channels contribute with a D^0 candidate to the same event, only one of them is accepted according to the following priority rule: $D_{K\pi\pi\pi}^*$, $D_{K\pi}^*$ or $D_{K\pi\pi^0}^*$, $D_{K_{\text{sub}}\pi}^*$ (see Ref. [27]).

Distributions of x_B , Q^2 and y variables for the $D_{K\pi}^*$ candidates from 2006, and from the D^0 signal region, are presented in Fig. 6. For those events, x_B values range from about 10^{-5} to 0.1 with $\langle x_B \rangle = 0.004$, Q^2 values from 10^{-3} to $30 (\text{GeV}/c)^2$ with $\langle Q^2 \rangle = 0.6 (\text{GeV}/c)^2$ and y values from 0.1 to 1 with $\langle y \rangle = 0.63$.

IV. ASYMMETRY EVALUATION

In this section, we describe the determination of the virtual photon asymmetry for D^0 production, $A^{\gamma N} \equiv A^{\gamma N \rightarrow D^0 X}$, from the event samples defined in Table III.

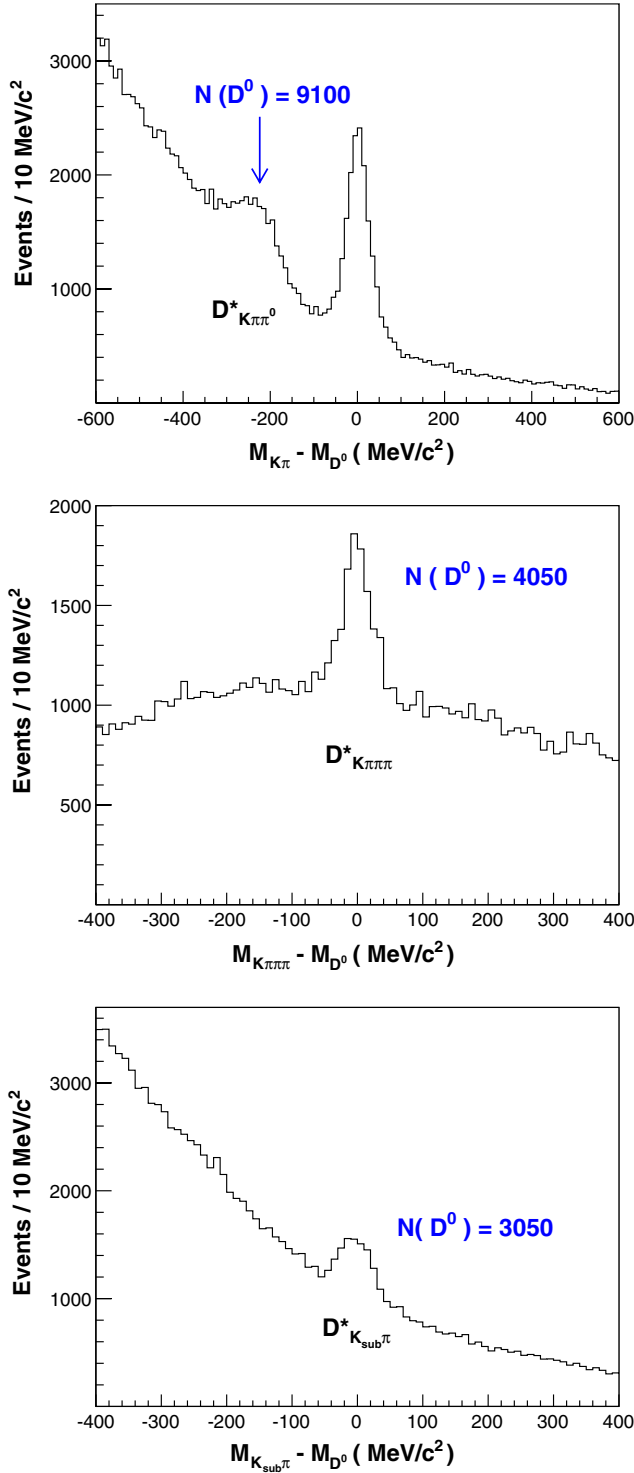


FIG. 5 (color online). Invariant mass spectra for the $D_{K\pi\pi^0}^*$, $D_{K\pi\pi\pi}^*$ and $D_{K_{sub}\pi}^*$ samples. The purity of the samples was improved using the Neural Network. The approximate number of D^0 mesons above background is given.

The method is similar to the one used in our previous publication [19]. The asymmetry $A^{\gamma N}$ can be used in various ways to evaluate the gluon polarisation $\langle \Delta g/g \rangle$ at LO or NLO QCD accuracy.

A. Analysis method

1. Asymmetries

The number of events collected in a given target cell and time interval is given by

$$\frac{d^k N}{dm dX} = a \phi n (s + b) \left[1 + P_t P_\mu f \left(\frac{s}{s + b} A^{\mu N \rightarrow \mu' D^0 X} + \frac{b}{s + b} A_B \right) \right]. \quad (1)$$

Here, $A^{\mu N \rightarrow \mu' D^0 X}$ is the longitudinal double spin asymmetry of the differential cross section for events with a D^0 or \bar{D}^0 in the final state, and A_B is the corresponding asymmetry originating from background events. Furthermore, $m \equiv M_{K\pi}$ (or $m \equiv M_{K\pi\pi\pi}$) and the symbol X denotes a set of $k - 1$ kinematic variables describing an event ($p_T^{D^0}$, E_{D^0} , Q^2 , y , ...), while a , ϕ and n are the spectrometer acceptance, the incident muon flux integrated over the time interval and the number of target nucleons, respectively. The differential unpolarized cross sections for signal and background, folded with the experimental resolution as a function of m and X , are represented by $s = s(m, X)$ and $b = b(m, X)$, respectively. The ratio $s/(s + b)$ will be called ‘‘signal purity’’ and the ratio $b/(s + b)$ ‘‘background purity.’’ The information on the gluon polarization is contained in the virtual photon asymmetry $A^{\gamma N} = A^{\mu N \rightarrow \mu' D^0 X}/D$. Similarly, the background asymmetry can be written as $A_B^{\gamma N} = A_B/D$. Here, D is the so-called depolarization factor accounting for the polarization transfer from lepton to virtual photon (terms negligible in our kinematic region are disregarded),

$$D = \frac{y \left[2 - y - \frac{2y^2 m_\mu^2}{Q^2} \right]}{y^2 \left(1 - \frac{2m_\mu^2}{Q^2} \right) + 2(1 - y)}. \quad (2)$$

A straightforward way to extract $A^{\gamma N}$ would be the following: Equation (1) is integrated over the variables X to obtain the number of events in both spin configurations as a function of the invariant mass m . Next, the event number asymmetry in the D^0 signal region is extracted, and a possible background asymmetry, determined from the asymmetries in sidebands to the left and right from the signal region, is subtracted.

For this analysis, however, we choose the method of event weighting, which is advantageous in terms of statistical precision. Compared to previous Compass analyses where weighting procedures were applied [3], here the weighting procedure is extended to determine the background asymmetry $A_B^{\gamma N}$ simultaneously with $A^{\gamma N}$ [30]. In order to achieve this, every event is weighted once with a signal weight, w_S , and once with a background weight, w_B ,

$$w_S = P_\mu f D \frac{s}{s + b}, \quad (3)$$

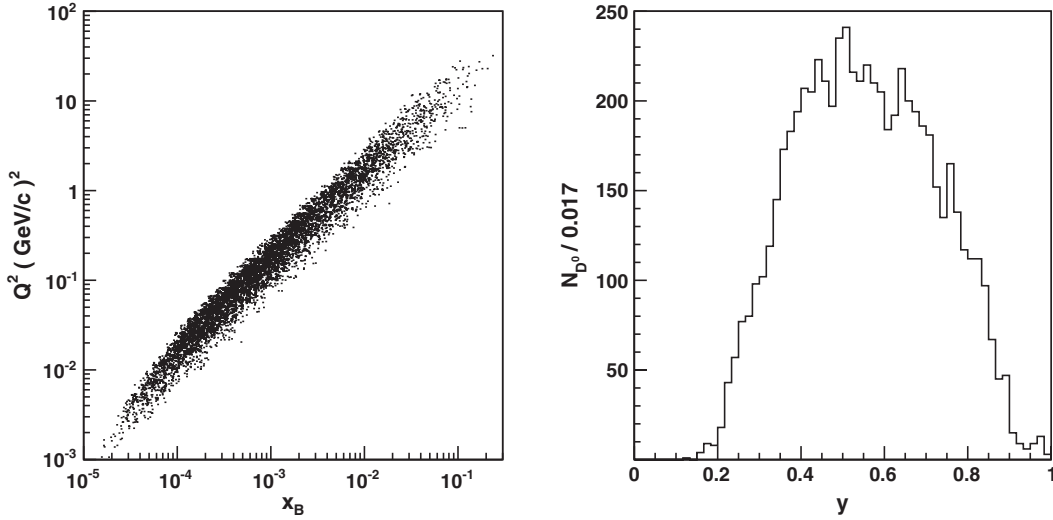


FIG. 6. A scatter plot of Q^2 vs x_B and a distribution of y for the 2006 $D_{K\pi}^*$ sample selected as in Fig. 3 except that the background is not subtracted.

$$w_B = P_\mu f D \frac{b}{s+b}. \quad (4)$$

Except for the target polarization P_t , these weights are the prefactors of the asymmetries $A^{\gamma N}$ and $A_B^{\gamma N}$; see Eq. (1). The target polarization is not included in the weights because its time dependence would lead to an increase in false asymmetries. The signal and background purities are included in the respective weights. This procedure leads to the highest possible statistical precision which would also be obtained in the unbinned maximum likelihood method [30,31]. Note that the unbinned maximum likelihood method cannot be applied here because the acceptance and flux factors in Eq. (1) are not known with sufficient precision, only their ratios for different spin states and target cells are known. These ratios will be used for the extraction of $A^{\gamma N}$ and $A_B^{\gamma N}$.

The asymmetry $A^{\gamma N}$ is extracted in bins of D^0 transverse momentum with respect to the virtual photon, $p_T^{D^0}$, and D^0 energy in the laboratory system, E_{D^0} . These variables and their binning were chosen to minimize the influence of the experimental acceptance on the asymmetry. As $A^{\gamma N}$ does not contain the depolarization factor D , its remaining dependence on the inclusive variables y and Q^2 is very weak. The expectation value of the sum of signal weights in a given target cell is obtained as

$$\begin{aligned} \left\langle \sum_{i=1}^{N_i} w_{S,i} \right\rangle &= \int w_S(X, m) \frac{d^k N}{dmdX} dmdX \\ &= \alpha_{S,t} [1 + \langle \beta_S \rangle_{w_S} \langle A^{\gamma N} \rangle_{w_S \beta_S} + \langle \beta_B \rangle_{w_S} \langle A_B^{\gamma N} \rangle_{w_S \beta_B}]. \end{aligned} \quad (5)$$

The symbols used are defined as

$$\alpha_{S,t} = \int w_S a_t \phi_t n_t (s+b) dmdX, \quad (6)$$

$$\langle \eta \rangle_w = \frac{\int \eta w a_t \phi_t n_t (s+b) dmdX}{\int w a_t \phi_t n_t (s+b) dmdX}, \quad (7)$$

with $\beta_S = w_S P_t$, $\beta_B = w_B P_t$, $\eta \in [\beta_S, \beta_B, A^{\gamma N}, A_B^{\gamma N}]$ and $w \in [w_S, w_S \beta_S, w_S \beta_B]$. The index t denotes the target cell before ($t = u, d$) or after ($t = u', d'$) spin rotation, and N_t is the number of events observed in a given target cell.² An equation analogous to Eq. (5) holds for the sum of background weights ($\sum_{i=1}^{N_i} w_{B,i}$), with analogous definition of symbols. In total, eight equations similar to Eq. (5) are obtained for every $(p_T^{D^0}, E_{D^0})$ bin—for the signal and background weights in two target cells and for two spin configurations. These eight equations contain 12 unknowns: $\langle A^{\gamma N} \rangle_{w_S \beta_S}$, $\langle A_B^{\gamma N} \rangle_{w_S \beta_B}$, $\langle A^{\gamma N} \rangle_{w_B \beta_S}$, $\langle A_B^{\gamma N} \rangle_{w_B \beta_B}$, four acceptance factors $\alpha_{S,t}$ and four acceptance factors $\alpha_{B,t}$.

The expectation values of the sum of weights on the left-hand side of Eq. (5) are identified with the measured sums of weights. In order to extract $A^{\gamma N}$ and $A_B^{\gamma N}$ from the measured sums of weights, one proceeds as follows. The factors $\langle \beta_{S,B} \rangle_{w_S, w_B}$ are evaluated from data, e.g.,

$$\langle \beta_S \rangle_{w_S} \approx \frac{\sum_{i=1}^{N_i} \beta_S w_S}{\sum_{i=1}^{N_i} w_S}. \quad (8)$$

The expectation values appearing in Eq. (7) contain the spin-averaged cross section, while the sum over events in Eq. (8) used to evaluate these expectation values runs over

²In 2006–2007 d and u stand for the central target cell and the sum of the outer ones, respectively.

the spin-dependent events. This has a negligible effect on the result because the raw asymmetry $P_t P_\mu f D \langle A^{\gamma N} \rangle$ is very small. This smallness makes sure that neither the result nor its statistical error are sensitive to the fact that the same data which are used to determine the asymmetries are also used to evaluate the expectation values above.

The acceptance factors $\alpha_{S,t}$ and $\alpha_{B,t}$ cannot be determined with sufficient precision to extract $A^{\gamma N}$ and $A_B^{\gamma N}$ directly from the set of eight equations. By assuming that for both signal and background possible acceptance variations affect the upstream and downstream cells in the same way, i.e., $\alpha^u/\alpha^d = \alpha^{u'}/\alpha^{d'}$, the number of unknowns is reduced to ten. With an extra, much weaker assumption that signal and background events from the same target cell are affected in the same way by the acceptance variations, one arrives at a system of eight equations with nine unknowns. Possible deviations from the above assumptions may generate false asymmetries which are included in the systematic uncertainty, see Sec. VA.

The number of unknowns is reduced to seven with two additional assumptions,

$$\langle A^{\gamma N} \rangle_{w_S \beta_S} = \langle A^{\gamma N} \rangle_{w_B \beta_S} = A^{\gamma N}$$

and

$$\langle A_B^{\gamma N} \rangle_{w_S \beta_B} = \langle A_B^{\gamma N} \rangle_{w_B \beta_B} = A_B^{\gamma N}, \quad (9)$$

which are satisfied for constant values of $A^{\gamma N}$ and $A_B^{\gamma N}$ in a given bin. The uncertainty on the gluon polarization introduced by this assumption will be discussed in Sec. VB. Using the set of eight equations, the asymmetry $A^{\gamma N}$ and the background asymmetry $A_B^{\gamma N}$ are determined simultaneously by a standard least square minimization procedure, which takes into account the statistical correlation between $\sum w_S$ and $\sum w_B$ in the same target cell. The correlation factor $\text{cov}(\sum w_S, \sum w_B)$ is given in Ref. [31]. The analysis is performed independently for each $(p_T^{D^0}, E_{D^0})$ bin and D meson decay channel. Observe that for the $K\pi\pi^0$ channel the kinematic variables are computed for a $K\pi$ subsystem as the π^0 is not reconstructed in the analysis.

For determinations of average values of kinematic variables in each $(p_T^{D^0}, E_{D^0})$ bin, a weight equal to w_S^2 is used, in accordance with Eq. (5).

2. The signal purity

The signal purity $s/(s+b)$ can be extracted from a fit to the invariant mass distribution of D^0 candidates. It depends on kinematic variables; for instance, it is large at high transverse momenta $p_T^{D^0}$ of the $K\pi$ system and small at low $p_T^{D^0}$. In order to implement the kinematic dependence of the signal purity in the weights given by Eqs. (3) and (4), one would naively proceed by performing fits to the corresponding invariant mass distributions in bins of kinematic variables. This procedure is not feasible in our case because of limited statistics. Instead, in this

analysis a classification based on a Neural Network is employed [27,32].

Here, the aim of the Neural Network is to distinguish signal from background events using only data. The network consists of information processors (neurons), which are interconnected and organized into layers. The external information fed into the input layer is processed in the hidden layers and the result produced by the output layer is a classification of the event by the network. In the present case, the input layer contains a set of kinematic observables: ratios of RICH likelihoods, $\cos \theta^*$, z_D and kaon momentum. There are two hidden layers and the number of neurons in them varies during the training process (dynamic network). For each event, the network tunes the strength of each variable-neuron and neuron-neuron connection. The strengths are obtained by minimising the squared deviation between the expected output and the actual Neural Network prediction. This training process stops when the deviation reaches a stable minimum [32].

For each event sample (see Table III), two data sets are used as inputs to the Neural Network. The first one contains the D^0 signal and the combinatorial background events. These events are called ‘‘good charge combination’’ ones (gcc) referring to the charges of particles from D^0 decays, and they are selected as described in Sec. III. The second set, the ‘‘wrong charge combination’’ events (wcc), is selected in a similar way except that the sum of charges of corresponding particles should not be zero. It contains only background events and is used as a background model (see Fig. 7). The Neural Network performs a multidimensional comparison of gcc and wcc events in a ± 40 MeV/ c^2 mass window around the D^0 mass.³ Within the gcc set, signal events are distinguished from combinatorial background by exploiting differences between the gcc and wcc sets in the shapes of distributions of kinematic variables as well as multidimensional correlations between them. An example of a properly chosen variable for the network is $\cos \theta^*$, as shown in Fig. 8. The reconstructed mass cannot be used because it would enhance the probability of a background event in the signal region to be a true D meson.

The network classifies all the gcc events according to their similarity in kinematics with respect to the wcc ones, and to each event it assigns a probability of being a signal. A probability of 0.5 is assigned to indistinguishable events. If the network is trained with proper input samples, i.e., a correct background model and a sufficiently strong signal, the network output, $[s/(s+b)]_{\text{NN}}$, can be directly interpreted as an estimate of the signal purity in the corresponding mass window. This is the so-called ‘‘pure’’ Neural Network method, applicable to the $D_{K\pi\pi^0}^*$, $D_{K\pi}^*$ and

³A mass window of ± 30 MeV/ c^2 is used for the sample $D_{K\pi}^0$ and ± 40 MeV/ c^2 around -250 MeV/ c^2 for the sample $D_{K\pi\pi^0}^*$.

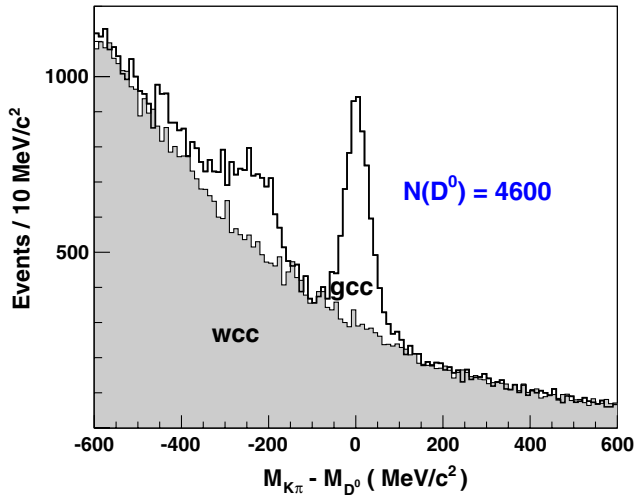


FIG. 7 (color online). Example of the $K\pi$ -invariant mass spectrum for the $D_{K\pi\pi}^*$ sample with good (gcc) and wrong (wcc) combination of pion and kaon charge signs. See text for details. Data were collected in 2007 with the proton (NH_3) target.

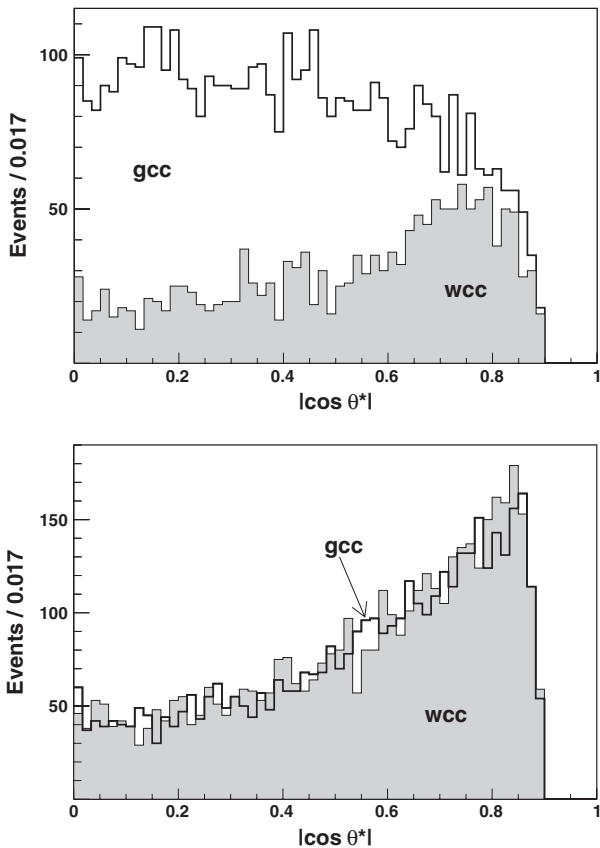


FIG. 8. Example of the distribution of $|\cos \theta^*|$ (polar angle of kaon in the D^0 center of mass relative to the D^0 momentum) for the gcc and wcc events ($D_{K\pi\pi}^*$ sample, 2006 data). Top: region of the D^0 signal. Bottom: outside the D^0 signal.

$D_{K\pi\pi}^*$ samples collected in 2004–2007, where event statistics and signal purities are large.

The mass dependence of signal and background $s(m)$ and $b(m)$, which cannot be obtained from the Neural Network in an unbiased way, is determined from a fit to the mass spectra in bins of $[s/(s+b)]_{\text{NN}}$. In order to describe the signal, a Gaussian distribution is used for all samples, while for the background the following fitting functions are employed: two exponential distributions for the $D_{K\pi}^0$ channel and one exponential for the D^* tagged channels. An exception is the $D_{K\pi\pi}^*$ sample, for which a second-degree polynomial is used. From those fits, corrections λ to the signal purity are obtained in the mass windows defined above,

$$\lambda = \left\langle \left(\frac{s}{b} \right)_{\text{NN}} \right\rangle \frac{\int b(m) dm}{\int s(m) dm}, \quad (10)$$

so that

$$\frac{s}{s+b} = \frac{\lambda s(m)}{\lambda s(m) + b(m)}. \quad (11)$$

The fit of the invariant mass spectra in bins of the NN signal purity can also be used to validate the classification obtained by the Neural Network. For each bin, the signal purity is determined from an integration of the signal and background fits over the same mass windows as in the NN parametrizations. Good agreement between signal purities from the NN and the fit is found for all samples, which confirms that the Neural Network does not introduce any bias in the analysis. As an illustration, the mass spectra in bins of the NN signal purity together with a comparison of the two signal purities are shown for the $D_{K\pi}^*$ sample in Fig. 9. The signal purity clearly increases with increasing $[s/(s+b)]_{\text{NN}}$. Equally good agreement is found when comparing $s/(s+b)$ between NN and data in bins of (p_T^D, E_{D^0}) .

The signal purity can be parametrized in various ways, provided it correctly reproduces the data. Several parametrizations were found to indeed yield asymmetries compatible within statistical uncertainties. In order to achieve the statistically most precise result on the gluon polarization, we chose the method described in Sec. VB. As a special feature in this method, the signal weight contains the product of the signal purity and a_{LL} , which is the muon-gluon asymmetry for the PGF process. Observation shows that a_{LL} is strongly anticorrelated with the signal purity. Therefore a parametrization of a_{LL} , validated as described in Ref. [27], was additionally included in the training of the NN.

For the low purity sample $D_{K\pi}^0$ collected in 2002–2007, and for all samples collected in 2002 and 2003, the extraction of the signal purities from the network is more complicated since the anticorrelation mentioned above cannot be accounted for because of weak signals. Therefore a “hybrid” method is employed. Similar to the method

used in Refs. [19,33], this approach uses fits to the mass spectra which are sampled in bins of two variables, NN signal purity (from a parametrization without a_{LL} in the training) and $fP_\mu a_{LL}$. The former sorts the events according to their similar kinematic dependences, while the latter is used to ensure the anticorrelation between a_{LL} and the

signal purity. The signal and background distributions belonging to the mass spectra sampled in the bins are fitted by the same fitting functions as defined above for describing the mass dependence of signal and background. Integrating the fits within the same mass windows as used for the NN training procedure yields the signal

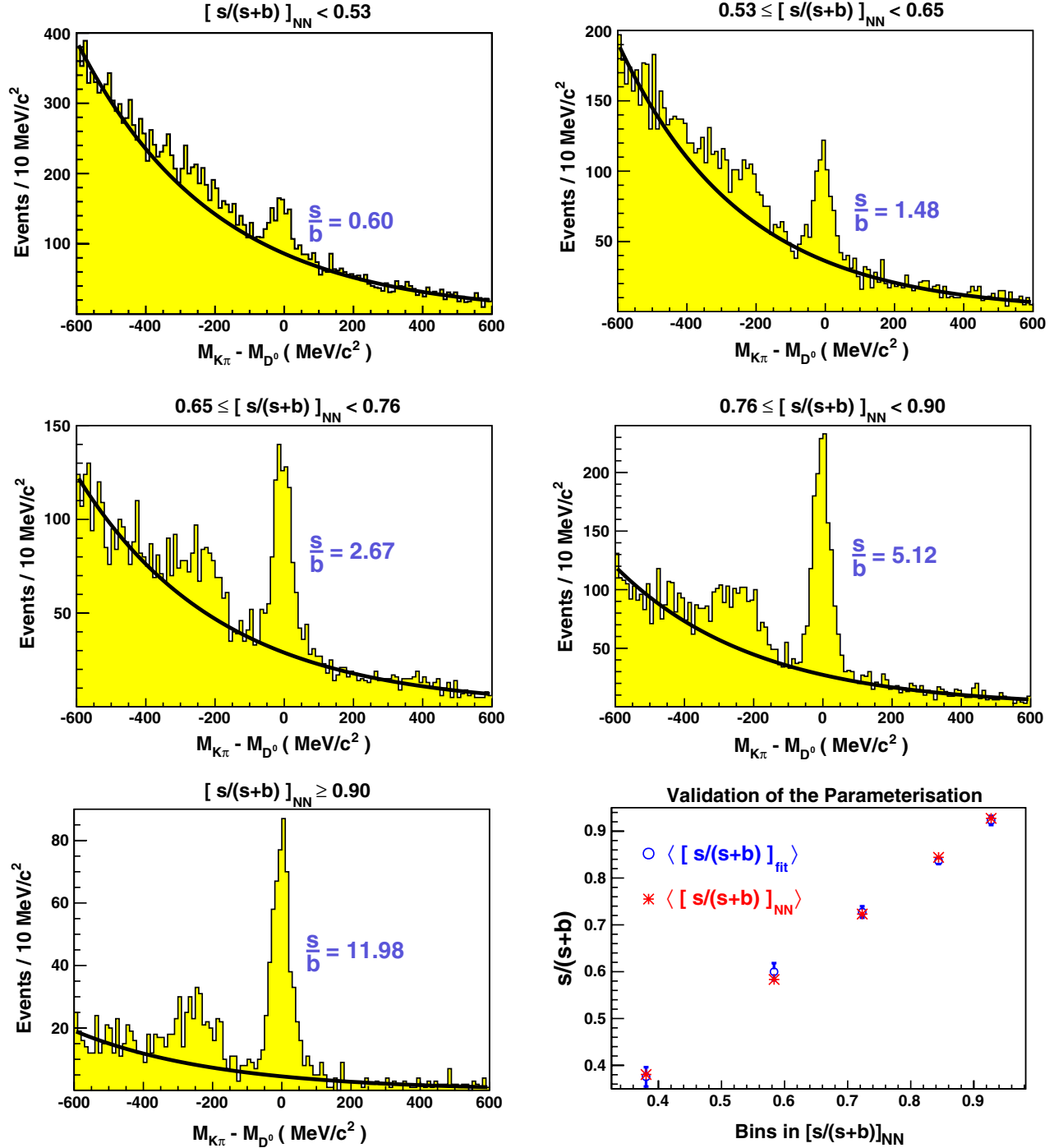


FIG. 9 (color online). The $K\pi$ -invariant mass spectra in bins of the NN signal purity $[s/(s+b)]_{NN}$ for the $D_{K\pi}^*$ sample. The last panel shows a comparison of the two purities, $[s/(s+b)]_{NN}$ and $[s/(s+b)]_{fit}$ (see text for details). Curves show the background component of the invariant mass fits described in the text. The significance of the $D_{K\pi}^*$ signal is shown as ratio s/b . Signal purities are defined in a ± 40 MeV/c^2 mass window around average mass values from the measured D^0 signals.

purities extracted from the fit. For each of the two variables, a function is built using linear interpolations between the fit results. An iterative procedure is used to obtain a stable result on these two functions simultaneously, and thereafter the correction λ is applied to the signal purity. Due to the statistical limitations, only one parametrization was built for each decay channel and year.

As the hybrid method can be used for both, low purity and high purity channels, it was decided to use it for all parametrizations of signal purities. Although more complex than the pure NN method, the hybrid method results in a comparable statistical precision.

B. Results on asymmetries

The asymmetry $A^{\gamma N}$ is extracted simultaneously with the background asymmetry $A_B^{\gamma N}$ for each bin, channel and year of data taking, except for low purity samples where some data taking years of the same target setup are merged. Final results sorted by D^0 decay mode are shown in Tables V, VI, and VII, where $A^{\gamma N}$ is given in each $(p_T^{D^0}, E_{D^0})$ bin together with average values of kinematic variables. All averages are calculated with the weight w_S^2 . The muon-nucleon asymmetry $A^{\mu N \rightarrow \mu' D^0 X}$ can be obtained from $A^{\gamma N}$ by multiplying it by $\langle D \rangle$, also given in Tables V, VI, and VII.

As the extraction of $A^{\gamma N}$ is performed based on event weights, uncertainties introduced into the determination of the asymmetry by each contribution to the weight have to be accounted for. The uncertainty of $A^{\gamma N}$ is acquired from a spread of weighting factors w , Eq. (4), which is obtained by comparing the default analysis with weight w_0 to other analyses with different weight, w . The expectation value of

the weighted asymmetry is $\langle A_{w_0}^{\gamma N} \rangle = \langle w w_0 \rangle / \langle w_0^2 \rangle A^{\gamma N}$, as shown in Ref. [27]. The spread of $\langle w w_0 \rangle / \langle w_0^2 \rangle$ gives the relative systematic uncertainty of $A^{\gamma N}$.

The major sources of systematic uncertainties in the measurement of $A^{\gamma N}$ are discussed below. The contributions from P_μ , P_t and f are taken conservatively as 5%, 5% and 2%, respectively, for both deuteron and proton targets. In order to study the contribution of $s/(s+b)$ to the systematic uncertainty, three tests are performed. In one of them, different fitting functions are used for the functional form of the background. In the other two, different mass windows are investigated concerning the Neural Network parametrization and the choice of the binning used in the reconstruction of the D^0 spectra. Note that each of these tests leads to several new values of $s/(s+b)$ and, consequently, new weights w are obtained. The resulting spread of weights is computed for each year of data taking, each sample and each bin with respect to the default weight w_0 . Thereafter, the weighted average of all spreads is determined separately for each of the three systematic tests considered. The combined uncertainty on $s/(s+b)$ is obtained from a quadratic superposition of these three uncertainties. The resulting average value over all bins is 7% of the measured asymmetries.

The contribution of D to the uncertainty of $A^{\gamma N}$ is obtained as follows. According to the experimental uncertainty of 1% in the measurement of the mean value of the scattered muon momentum, shifted values of y are calculated for every event. Thereafter, new values of D are computed from Eq. (2). The resulting spread of $\langle w w_0 \rangle / \langle w_0^2 \rangle$ gives a systematic uncertainty of 1.6%.

TABLE V. Combined asymmetries $A^{\gamma N \rightarrow D^0 X}$ for the $D_{K\pi}^0$, $D_{K\pi}^*$ and $D_{K_{\text{sub}}\pi}^*$ samples in bins of $(p_T^{D^0}, E_{D^0})$, together with the weighted (with w_S^2) averages of several kinematic variables. First uncertainty is statistical, second is systematic.

Bin limits		$A^{\gamma N \rightarrow D^0 X}$	$\langle y \rangle$	$\langle Q^2 \rangle$ (GeV/c) ²	$\langle p_T^{D^0} \rangle$ (GeV/c)	$\langle E_{D^0} \rangle$ (GeV)	$\langle D \rangle$
$p_T^{D^0}$ (GeV/c)	E_{D^0} (GeV)						
0–0.3	0–30	$-0.90 \pm 0.63 \pm 0.11$	0.50	0.46	0.19	24.3	0.62
0–0.3	30–50	$-0.19 \pm 0.48 \pm 0.06$	0.60	0.69	0.20	39.1	0.74
0–0.3	>50	$+0.07 \pm 0.68 \pm 0.06$	0.69	1.17	0.20	59.2	0.84
0.3–0.7	0–30	$-0.18 \pm 0.37 \pm 0.04$	0.51	0.47	0.51	24.6	0.63
0.3–0.7	30–50	$+0.10 \pm 0.26 \pm 0.04$	0.60	0.62	0.51	39.5	0.75
0.3–0.7	>50	$-0.04 \pm 0.36 \pm 0.05$	0.69	0.73	0.51	59.0	0.83
0.7–1	0–30	$-0.42 \pm 0.44 \pm 0.05$	0.50	0.45	0.85	24.7	0.62
0.7–1	30–50	$-0.36 \pm 0.29 \pm 0.04$	0.61	0.60	0.85	39.2	0.75
0.7–1	>50	$+1.49 \pm 0.42 \pm 0.15$	0.69	0.76	0.84	58.6	0.83
1–1.5	0–30	$-0.30 \pm 0.35 \pm 0.03$	0.54	0.41	1.23	25.3	0.66
1–1.5	30–50	$+0.13 \pm 0.23 \pm 0.01$	0.64	0.55	1.24	39.2	0.77
1–1.5	>50	$-0.20 \pm 0.33 \pm 0.02$	0.71	0.73	1.24	58.3	0.85
>1.5	0–30	$+0.38 \pm 0.49 \pm 0.04$	0.56	0.47	1.84	25.6	0.69
>1.5	30–50	$0.00 \pm 0.25 \pm 0.02$	0.65	0.70	1.92	39.9	0.79
>1.5	>50	$+0.36 \pm 0.33 \pm 0.04$	0.69	0.60	1.95	59.9	0.86

TABLE VI. Asymmetries $A^{\gamma N \rightarrow D^0 X}$ for the $D_{K\pi\pi^0}^*$ sample in bins of $(p_T^{D^0}, E_{D^0})$ together with the weighted (with w_S^2) averages of several kinematic variables (here $p_T^{D^0}$ and E_{D^0} are computed for the $K\pi$ subsystem). First uncertainty is statistical, second is systematic.

Bin limits		$A^{\gamma N \rightarrow D^0 X}$	$\langle y \rangle$	$\langle Q^2 \rangle$ (GeV/c) ²	$\langle p_T^{D^0} \rangle$ (GeV/c)	$\langle E_{D^0} \rangle$ (GeV)	$\langle D \rangle$
$p_T^{D^0}$ (GeV/c)	E_{D^0} (GeV)						
0–0.3	0–30	$-0.63 \pm 1.29 \pm 0.08$	0.52	0.75	0.19	24.4	0.65
0–0.3	30–50	$+0.27 \pm 1.17 \pm 0.06$	0.67	0.65	0.20	38.8	0.81
0–0.3	>50	$-2.55 \pm 2.00 \pm 0.27$	0.72	1.12	0.19	59.3	0.86
0.3–0.7	0–30	$-0.24 \pm 0.80 \pm 0.04$	0.53	0.51	0.52	24.3	0.65
0.3–0.7	30–50	$+0.49 \pm 0.69 \pm 0.06$	0.65	0.65	0.51	39.0	0.79
0.3–0.7	>50	$-1.28 \pm 1.03 \pm 0.14$	0.72	0.77	0.51	59.1	0.86
0.7–1	0–30	$+0.55 \pm 0.95 \pm 0.06$	0.53	0.41	0.84	24.6	0.65
0.7–1	30–50	$-0.53 \pm 0.76 \pm 0.06$	0.63	0.53	0.86	39.4	0.77
0.7–1	>50	$-0.17 \pm 1.00 \pm 0.03$	0.73	0.80	0.85	58.2	0.88
1–1.5	0–30	$+1.35 \pm 0.86 \pm 0.14$	0.54	0.38	1.24	25.4	0.67
1–1.5	30–50	$-0.11 \pm 0.51 \pm 0.01$	0.64	0.59	1.25	39.6	0.78
1–1.5	>50	$-0.05 \pm 0.78 \pm 0.01$	0.74	0.62	1.25	58.3	0.88
>1.5	0–30	$-0.19 \pm 1.14 \pm 0.03$	0.56	0.52	1.80	25.7	0.70
>1.5	30–50	$-0.23 \pm 0.51 \pm 0.03$	0.66	0.66	1.88	40.0	0.80
>1.5	>50	$+0.26 \pm 0.90 \pm 0.04$	0.74	0.88	1.92	57.3	0.88

TABLE VII. Asymmetries $A^{\gamma N \rightarrow D^0 X}$ for the $D_{K\pi\pi\pi}^*$ sample in bins of $(p_T^{D^0}, E_{D^0})$ together with the weighted (with w_S^2) averages of several kinematic variables. First uncertainty is statistical, second is systematic.

Bin limits		$A^{\gamma N \rightarrow D^0 X}$	$\langle y \rangle$	$\langle Q^2 \rangle$ (GeV/c) ²	$\langle p_T^{D^0} \rangle$ (GeV/c)	$\langle E_{D^0} \rangle$ (GeV)	$\langle D \rangle$
$p_T^{D^0}$ (GeV/c)	E_{D^0} (GeV)						
0–0.3	0–30	$+7.03 \pm 4.74 \pm 0.71$	0.46	0.38	0.22	27.7	0.58
0–0.3	30–50	$-2.05 \pm 1.10 \pm 0.21$	0.60	0.72	0.20	40.6	0.74
0–0.3	>50	$+0.17 \pm 1.83 \pm 0.05$	0.69	0.88	0.20	59.1	0.84
0.3–0.7	0–30	$-0.59 \pm 1.74 \pm 0.06$	0.52	0.31	0.53	27.8	0.71
0.3–0.7	30–50	$+1.00 \pm 0.54 \pm 0.11$	0.61	0.44	0.52	39.7	0.80
0.3–0.7	>50	$-1.75 \pm 0.84 \pm 0.18$	0.68	0.70	0.51	60.2	0.84
0.7–1	0–30	$+2.91 \pm 2.61 \pm 0.30$	0.45	0.26	0.84	27.7	0.61
0.7–1	30–50	$+1.42 \pm 0.57 \pm 0.15$	0.64	0.57	0.85	40.9	0.81
0.7–1	>50	$+1.69 \pm 0.81 \pm 0.17$	0.69	0.58	0.86	60.9	0.84
1–1.5	0–30	$-1.89 \pm 2.64 \pm 0.19$	0.46	0.31	1.22	27.7	0.64
1–1.5	30–50	$-0.45 \pm 0.51 \pm 0.05$	0.63	0.58	1.23	41.1	0.79
1–1.5	>50	$+1.06 \pm 0.66 \pm 0.11$	0.71	0.77	1.24	61.8	0.86
>1.5	0–30	$+1.64 \pm 3.52 \pm 0.17$	0.46	0.40	1.84	28.1	0.72
>1.5	30–50	$+0.44 \pm 0.68 \pm 0.05$	0.65	0.75	1.95	42.2	0.78
>1.5	>50	$+0.08 \pm 0.63 \pm 0.02$	0.74	0.77	2.03	64.4	0.88

Systematic uncertainties of $A^{\gamma N}$ arising from false asymmetries and from the assumptions specified in Eq. (9) can be best estimated using the statistically optimized method (see Sec. VB). First, they are determined for the gluon polarization $\Delta g/g$, and then they are translated to $A^{\gamma N}$ in bins of $(p_T^{D^0}, E_{D^0})$ employing $\langle a_{LL}/D \rangle$. Averaging over all bins, the resulting absolute values of the uncertainties due to false asymmetries and the assumptions in Eq. (9) are 0.022 and 0.007, respectively.

The total systematic uncertainties of $A^{\gamma N}$, as given in Tables V, VI, and VII, are obtained by adding all contributions in quadrature.

V. DETERMINATION OF THE GLUON POLARIZATION

In this section we present the results of our measurement of the gluon polarization. The extraction of $\Delta g/g$ from $A^{\gamma N}$ at LO QCD accuracy is discussed in Sec. VA. The LO determination of the gluon polarization by a statistically optimized method is described in Sec. VB. The extraction of $\Delta g/g$ from $A^{\gamma N}$ at NLO accuracy is presented in Sec. VC.

This analysis neglects any contribution from ‘‘intrinsic charm,’’ i.e., nonperturbative charm quark or charmed hadron components of the nucleon wave function. Such

contributions, estimated to be $\leq 1\%$ [34,35], are fundamentally different from the perturbative splitting of a gluon into a $c\bar{c}$ pair; the latter decreases strongly with x_B . In the EMC measurement of the charm component in the nucleon structure function $F_2^{c\bar{c}}$ [20], a possible intrinsic charm contribution of about 1% at $x_B \sim 0.4$ could not be excluded [20,21]. Up to now, the estimates of Refs. [34,35] cannot be experimentally verified due to the poor statistics of the EMC measurement at large x_B , too low values of x_B in the Hera $F_2^{c\bar{c}}$ measurements [36], and kinematic acceptance limited to the region $x_B \leq 0.1$ for open charm production in Compass.

The contribution of resolved-photon interactions was estimated using the RAPGAP generator [37] and found to be negligible in our kinematic domain.

A. Leading-order results from the asymmetries

The information on the gluon polarization contained in $A^{\mu N}$ can be decomposed at LO accuracy as

$$A^{\mu N} = DA^{\gamma N} = a_{LL} \frac{\Delta g}{g}, \quad (12)$$

assuming photon-gluon fusion as the underlying partonic process. Here a_{LL} is the analyzing power of the $\mu g \rightarrow \mu' c\bar{c}$ process.

The analyzing power a_{LL} depends on partonic kinematics. It is not accessible experimentally on an event-by-event basis. It is obtained using the Monte Carlo generator AROMA [28] in leading-order QCD approximation, i.e., with parton showers switched off. The generated D^0 events are processed with GEANT [29] to simulate the full response of the Compass spectrometer, and then are reconstructed with the same analysis chain as used for

real events. In order to provide a_{LL} values for real data, a Neural Network with the same architecture as described in Sec. IV is used to parametrize the generated a_{LL} in terms of measured kinematic variables X . Here the input layer contains the following observables: $X = \{Q^2, y, x, p_T^{D^0}, E_{D^0}\}$. As a result, $a_{LL}(X)$ is obtained for real data on an event-by-event basis.

Contrary to the parametrization of $s/(s+b)$, the Neural Network predicts values for a_{LL} based on event kinematics. For each generated event, the network tunes the strength of each variable-neuron and neuron-neuron connection. The strengths are obtained by minimizing the squared deviation between the expected output, i.e., the generated a_{LL} and the actual Neural Network prediction for a_{LL} based on X . This training process stops when the deviation between generated and parametrized a_{LL} reaches a stable minimum. Six separate $a_{LL}(X)$ parametrizations were built—for three D meson decay channels ($K\pi$, $K\pi\pi^0$, $K\pi\pi\pi$), each for two experimental configurations (2002–2004 and 2006–2007). The correlation achieved between the generated and the parametrized analyzing powers is 77% for the $D_{K\pi\pi^0}^*$ channel and 82% for the remaining channels. The trained network is applied to real data.

Knowing that $A^{\mu N} = DA^{\gamma N}$, the determination of the gluon polarization from Eq. (12) is straightforward. The extraction of $\Delta g/g$ from $A^{\gamma N}$ in bins of $(p_T^{D^0}, E_{D^0})$ is performed using the values of $\langle a_{LL}/D \rangle$ shown in Table VIII.

The gluon polarization in LO QCD, obtained from $A^{\gamma N}$, amounts to

$$\left\langle \frac{\Delta g}{g} \right\rangle = -0.10 \pm 0.22(\text{stat.}) \pm 0.09(\text{syst.}), \quad (13)$$

TABLE VIII. The average LO photon-gluon asymmetries, $\langle a_{LL}/D \rangle$, in bins of $(p_T^{D^0}, E_{D^0})$ for each D^0 decay mode studied in the analysis. The averages use a_{LL}^{LO}/D from data events, obtained from the Neural Network parametrization; they are weighted with w_S^2 .

Bin limits		Photon-gluon asymmetries		
$p_T^{D^0}$ (GeV/ c)	E_{D^0} (GeV)	$D_{K\pi}^0, D_{K\pi}^*$ and $D_{K_{\text{sub}}\pi}^*$ samples combined	$D_{K\pi\pi^0}^*$ sample	$D_{K\pi\pi\pi}^*$ sample
0–0.3	0–30	0.65	0.62	0.64
0–0.3	30–50	0.68	0.65	0.63
0–0.3	>50	0.76	0.74	0.74
0.3–0.7	0–30	0.46	0.42	0.38
0.3–0.7	30–50	0.50	0.46	0.41
0.3–0.7	>50	0.56	0.53	0.52
0.7–1	0–30	0.26	0.19	0.25
0.7–1	30–50	0.26	0.21	0.25
0.7–1	>50	0.29	0.26	0.30
1–1.5	0–30	0.00	–0.06	0.02
1–1.5	30–50	0.01	–0.05	0.04
1–1.5	>50	0.05	–0.02	0.08
>1.5	0–30	–0.23	–0.29	–0.26
>1.5	30–50	–0.26	–0.31	–0.23
>1.5	>50	–0.27	–0.31	–0.22

TABLE IX. Contributions to the systematic uncertainty of $\langle\Delta g/g\rangle^{\text{LO}}$ obtained from $A^{\gamma\text{N}}$.

Source	$\delta(\langle\Delta g/g\rangle)$	Source	$\delta(\langle\Delta g/g\rangle)$
Beam polarisation P_μ	0.005	$s/(s+b)$	0.007
Target polarisation P_t	0.005	False asymmetry	0.080
Dilution factor f	0.002	a_{LL}	0.015
Assumption, Eq. (9)	0.025	Depolarisation factor D	0.002
Total uncertainty 0.086			

in the range of $0.06 < x < 0.22$ with a weighted $\langle x \rangle \approx 0.11$, and a scale $\langle \mu^2 \rangle \approx 13$ (GeV/c)². The range of x is determined by the rms value of a Gaussian distribution in $\log_{10}x$. Assuming that $\Delta g/g(x)$ is approximately a linear function of x in the range covered by the present data, the above result corresponds to the gluon polarization $\Delta g/g$ at the value $\langle x \rangle$.

The sources of systematic uncertainties in the measurement of $\Delta g/g$ are listed in Table IX. The contributions from P_μ , P_t , f , $s/(s+b)$ and D are the same as discussed in Sec. IV B. Contributions from false asymmetries and from the assumption given in Eq. (9), the same as in the statistically optimized method, are discussed in Sec. V B. In order to estimate the influence of the simulation parameters on the determination of a_{LL} , Monte Carlo samples with different parameter sets are generated and the analyzing power is recalculated. In these parameter sets, the mass of the charm quark is varied between 1.3 and 1.6 GeV/c², and the parton distribution functions as well as the factorization scale are varied by a factor of eight. From each of these systematic tests a new value of $\langle a_{\text{LL}}/D \rangle$ is obtained, and thereafter $\Delta g/g$ is recalculated for each ($p_{\text{T}}^{\text{D}^0}$, E_{D^0}) bin by dividing $A^{\gamma\text{N}}$ by $\langle a_{\text{LL}}/D \rangle$. The systematic uncertainty in each bin is determined from the average spread of $\Delta g/g$ compared to the result of the default analysis. The value for the systematic uncertainty of gluon polarization is obtained as a weighted average of the systematic uncertainty in each bin. The relative uncertainty introduced by a_{LL} alone is 15%.

The final systematic uncertainty of $\langle\Delta g/g\rangle$ is obtained as a quadratic sum of all contributions.

B. Statistically optimized determination of the gluon polarization at LO

The data described in Sec. III allow for the determination of $\langle\Delta g/g\rangle$ in a different, statistically optimized way. Practically it means that the gluon polarization is obtained

by replacing the factor D with a_{LL} in the definition of w_S : $w_S = P_\mu f a_{\text{LL}} s/(s+b)$. The use of this weight allows us to reproduce the results on $\langle\Delta g/g\rangle$ obtained from $A^{\gamma\text{N}}(\langle p_{\text{T}}^{\text{D}^0} \rangle, \langle E_{\text{D}^0} \rangle)$ with about 6% gain in the statistical precision. This gain is due to a wide range of a_{LL} values but the observed (anti)correlation between the signal purity and the parametrized a_{LL} has to be accounted for in the parametrization of $s/(s+b)$. This fact is crucial to obtain an unbiased result of $\langle\Delta g/g\rangle$ with this statistically optimized method.

Values for $\langle\Delta g/g\rangle$ and the background asymmetry $\langle A_{\text{B}}^{\gamma\text{N}} \rangle$ were obtained for each of the 48 weeks of data taking and separately for each of the five event samples. The results shown in Table X are the weighted means of those values.

The value of the gluon polarization is obtained as the weighted mean of the five results shown in Table X and amounts to

$$\left\langle \frac{\Delta g}{g} \right\rangle = -0.06 \pm 0.21(\text{stat.}) \pm 0.08(\text{syst.}), \quad (14)$$

in the range of $0.06 < x < 0.22$ with a weighted $\langle x \rangle \approx 0.11$, and a scale $\langle \mu^2 \rangle \approx 13$ (GeV/c)².

The major contributions for the systematic uncertainty given in Eq. (14) are presented in Table XI. They were estimated as follows. In addition to P_μ , P_t , f and $s/(s+b)$, the uncertainty of a_{LL} was also determined from the spread of weights $\langle w w_0 \rangle / \langle w_0^2 \rangle$ (where w_0 stands for the default analysis). The use of different sets of parameters as described in Sec. V A gives rise to a relative systematic uncertainty of 9% of the $\langle\Delta g/g\rangle$ value originating from a_{LL} . The relative systematic uncertainty introduced by $s/(s+b)$ is 7%.

In order to study the influence of false asymmetries, the $\text{D}_{\text{K}\pi}^*$ sample was divided into two subsamples using criteria related to the experimental apparatus, e.g., the slow pion going to the left or to the right side of the incoming muon. The resulting asymmetries were found to be compatible within their statistical accuracies, i.e., no false asymmetries were observed. An upper limit of the contribution of time-dependent acceptance effects to the systematic uncertainty was derived from the dispersion of $\langle\Delta g/g\rangle$ and $\langle A_{\text{B}}^{\gamma\text{N}} \rangle$ in the 48 weeks of data taking. The study was performed using the background asymmetry, profiting from the large statistics. Then the obtained results were translated to $\langle\Delta g/g\rangle$, using the method described in Ref. [27]. An uncertainty of 0.024 was obtained assuming that possible detector instabilities are similar for background and signal events. Notice that the same assumption

TABLE X. Results for $\langle\Delta g/g\rangle$ and $\langle A_{\text{B}}^{\gamma\text{N}} \rangle$ for each data sample. Errors are statistical.

	$\text{D}_{\text{K}\pi}^*$	$\text{D}_{\text{K}\pi\pi^0}^*$	$\text{D}_{\text{K}\pi\pi\pi}^*$	$\text{D}_{\text{K}_{\text{sub}}\pi}^*$	$\text{D}_{\text{K}\pi}^0$
$\langle\Delta g/g\rangle$	-0.192 ± 0.305	-0.414 ± 0.575	0.614 ± 0.667	0.497 ± 0.995	0.020 ± 0.415
$\langle A_{\text{B}}^{\gamma\text{N}} \rangle$	$+0.019 \pm 0.029$	$+0.051 \pm 0.035$	$+0.004 \pm 0.036$	$+0.004 \pm 0.047$	-0.005 ± 0.004

TABLE XI. Contributions to the systematic uncertainty of $\langle \Delta g/g \rangle^{\text{LO}}$ obtained in a statistically optimized method.

Source	$\delta(\langle \Delta g/g \rangle)$	Source	$\delta(\langle \Delta g/g \rangle)$
Beam polarisation P_μ	0.003	$s/(s+b)$	0.004
Target polarisation P_t	0.003	a_{LL}	0.005
Dilution factor f	0.001	False asymmetry	0.080
Assumption, Eq. (9)	0.025		
Total uncertainty 0.084			

was used to reduce the number of unknowns in Eq. (5) from 12 to 9. Therefore, a more conservative approach is taken: the double ratio of acceptances for the signal, $\alpha_S^u \cdot \alpha_S^d / \alpha_S^d \cdot \alpha_S^u$, is assumed to be uncorrelated with the corresponding one for the background events. The combination of these two cases leads to an upper limit of 0.08 for the possible contribution of false asymmetries. This contribution is also used in Secs. IV B and VA.

An uncertainty originating from the assumption for $\Delta g/g$, analogous to that given in Eq. (9) and valid for $\Delta g/g$ constant in the measured interval, $0.06 < x < 0.22$, is estimated as follows. First a pair of extremal values of $\Delta g/g$ in that interval is selected as those given by the Compass NLO QCD fit with $\Delta g > 0$; see Sec. VC. This fit is chosen to maximize a potential influence of the above assumption. Next, a difference between these two $\Delta g/g$ values is used as a bias in the system of equations from which $\Delta g/g$ and $A_B^{\gamma\text{N}}$ are determined. The bias is added to all $\langle \Delta g/g \rangle_{w_B \beta_S}$ terms, while the $\langle \Delta g/g \rangle_{w_S \beta_S}$ ones are left unchanged. The $\Delta g/g$ interval resulting from the equations gives a relative systematic uncertainty due to the assumption. Possible variations of $A_B^{\gamma\text{N}}$ are studied in a similar way using a parametrization of the inclusive asymmetry, A_1^d , [38]. The systematic uncertainty on $\Delta g/g$ is taken as the largest difference between the result obtained in the default analysis and results of those tests.

The result given in Eq. (14) is shown in Fig. 10 together with a compilation of other LO gluon polarization measurements from high- p_T hadron production by Compass [15,18], SMC [13] and Hermes [14]. The present measurement is at a scale of about $13 \text{ (GeV}/c)^2$ while other measurements are at $3 \text{ (GeV}/c)^2$.

C. Next-to-leading order results

The extraction of the gluon polarization as described in Secs. VA and VB was performed at LO where the only process leading to open-charm production is PGF. This requires knowledge of the analyzing power a_{LL} and the signal strength on a bin-by-bin or event-by-event basis. Only the combinatorial background was considered in the LO analysis.

In this section a brief outline of a method of computing the NLO QCD corrections to the a_{LL} calculation in our analysis is given; see also Ref. [39]. Examples of the NLO

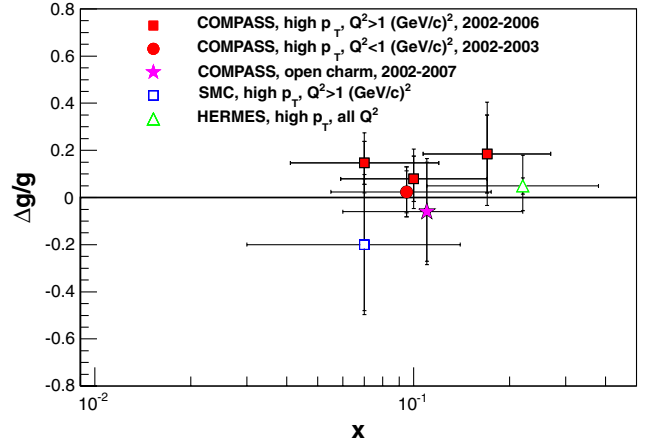


FIG. 10 (color online). A compilation of gluon polarization measurements from open charm and high- p_T hadron production. The star denotes a result of the present, open charm analysis, Eq. (14), obtained at LO accuracy, 2002–2007 data and all values of Q^2 . Full squares denote a Compass result [18] for high- p_T hadron production on 2002–2006 data, for $Q^2 > 1 \text{ (GeV}/c)^2$ while a full circle corresponds to 2002–2003 data and $Q^2 < 1 \text{ (GeV}/c)^2$ [15]. The empty square shows the SMC measurement [13] for $Q^2 > 1 \text{ (GeV}/c)^2$ and the empty triangle the Hermes result [14] obtained for all values of Q^2 . The horizontal bars mark the range in x for each measurement, the vertical ones give the statistical precision or the total uncertainties.

processes contributing to the muoproduction of the $c\bar{c}$ pair are shown in Fig. 11. Apart from the NLO corrections to the PGF mechanism, Figs. 11(a)–11(c), there exists other NLO contributions to muoproduction of open charm, initiated by light quarks; as an example a process where a gluon emitted by a light quark creates the $c\bar{c}$ pair is shown

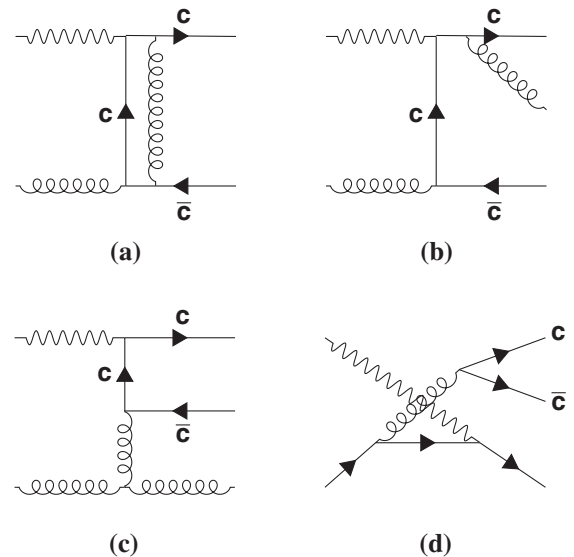


FIG. 11. Examples of the NLO processes contributing to the muoproduction of the $c\bar{c}$ pair: (a) virtual correction, (b), (c) gluon bremsstrahlung, (d) light quark background.

in Fig. 11(d). Such processes do not probe the gluons inside the nucleon albeit they contribute to the D meson signal. Therefore, in the extraction of the gluon polarization at NLO accuracy from the signal asymmetries, a correction term has to be taken into account,

$$A^{\gamma N} = \frac{a_{LL}}{D} \frac{\Delta g}{g} + A_{\text{corr}}.$$

Here, a_{LL} is calculated at NLO accuracy and is different from the corresponding one at LO.

The QCD calculations at NLO accuracy for spin averaged [40] as well as polarization dependent cross sections for open charm production [41] are available only at the photoproduction limit, i.e., for $Q^2 = 0$. They are used in our analysis to estimate the value of the NLO corrections to a_{LL} and the light quark contribution. The average value of Q^2 in the kinematic region of our measurement is about $0.6 \text{ (GeV}/c)^2$. It was confirmed by a direct check at LO accuracy that the $Q^2 = 0$ limit used in the calculation is a very good approximation in our kinematic domain.

Note that only one D meson is registered in the Compass data, while the second charm particle is unobserved. Also the NLO calculations of Refs. [40,41] represent integrated cross sections for a single charm quark (meson) observed in the final state. The cross sections are integrated over the kinematic variables of the ‘‘unobserved’’ second charm quark and radiated hard gluon, present in NLO processes. The limits of the integration depend on the available phase space left for ‘‘unobserved’’ partons which is determined by x and the kinematics of the D-tagged c quark.

In order to obtain a_{LL} in NLO accuracy on an event-by-event basis, the AROMA generator (which is based on a LO matrix element) with parton showers included is used, followed by a full simulation of the detector. In this way an approximation to the phase space needed for NLO QCD corrections is provided.

For every simulated event, the upper limit of the integration over the energy of the unobserved gluon in the NLO emission process, $\gamma^* g \rightarrow c\bar{c}g$, is obtained from the partonic Mandelstam variables, \hat{s} and \hat{t} . Both variables are calculated from the kinematics of simulated events. In particular \hat{s} is determined from x , x_B and Q^2 , while \hat{t} is related to the kinematics of the D-tagged charm quark. The integration over unobserved NLO real gluon emission

reduces a differential cross section for a three-body final state ($c\bar{c}g$) to that for a two-body one ($c\bar{c}$), which has to be added to the LO cross section ($c\bar{c}$, PGF) and the two-body virtual corrections (see e.g., diagram (a) in Fig. 11). In this way a correct infrared divergence cancellation is achieved [41]. The semi-inclusive partonic cross section at NLO accuracy is calculated on an event-by-event basis for both the spin-averaged and spin-dependent case using formulas of Ref. [41], and consequently a_{LL} at NLO accuracy is obtained. The same procedure is applied for the correction originating from a light quark. It should be stressed that in this method of a_{LL} estimation at NLO, only the values of \hat{s} and \hat{t} are taken from AROMA simulated events.

To obtain the gluon polarization at NLO accuracy, the measured asymmetry for D meson production has to be combined with the a_{LL} calculated at NLO. The kinematic variables $p_T^{D^0}$, E_{D^0} and gluon momentum fraction x define the total energy of all particles produced in the final state of the partonic process, including unobserved gluons emitted at NLO accuracy, $\gamma^* g \rightarrow c\bar{c}g$. However, in a_{LL} calculations, simulated events at given x values are used and the integration over energy of the unobserved gluon is performed to obtain divergence-free a_{LL} , which depends on \hat{s} and \hat{t} only. Therefore, to be consistent with the NLO method of calculating a_{LL} , the asymmetry measured in $(p_T^{D^0}, E_{D^0})$ intervals is binned into five one-dimensional intervals of $p_T^{D^0}$ only.

In each $p_T^{D^0}$ bin, the weighted averages of a_{LL}/D and A_{corr} are calculated, Table XII, and the gluon polarization is evaluated from the $A^{\gamma N \rightarrow D^0 X}$ asymmetries. The NLO light quark contribution to the D meson asymmetry, A_{corr} , is small, less than 5%, compared to the measured asymmetries. The gluon polarization at NLO accuracy, obtained as weighted average over all $p_T^{D^0}$ bins, is

$$\left\langle \frac{\Delta g}{g} \right\rangle^{\text{NLO}} = -0.13 \pm 0.15(\text{stat.}) \pm 0.15(\text{syst.}). \quad (15)$$

It is determined in the interval $0.12 < x < 0.33$ with a weighted $\langle x \rangle \approx 0.20$, at the scale $\langle \mu^2 \rangle \approx 13 \text{ (GeV}/c)^2$. The gluon momentum fraction x is taken from the simulations.

For a given experimental acceptance for open charm tagging, the average value of x depends on the order of

TABLE XII. The average values of the $\langle a_{LL}/D \rangle$ and A_{corr} , at NLO and in bins of $p_T^{D^0}$ for each D^0 decay mode studied in the analysis.

$p_T^{D^0}$ (GeV/c)	$D_{K\pi}^0, D_{K\pi}^*$ and $D_{K_{\text{sub}}\pi}^*$ samples combined		$D_{K\pi\pi^0}^*$ sample		$D_{K\pi\pi\pi}^*$ sample	
	$\langle a_{LL}/D \rangle$	A_{corr}	$\langle a_{LL}/D \rangle$	A_{corr}	$\langle a_{LL}/D \rangle$	A_{corr}
0.0–0.3	−0.130	0.001	−0.127	0.002	−0.097	0.000
0.3–0.7	−0.241	0.003	−0.263	0.003	−0.240	0.001
0.7–1.0	−0.419	0.005	−0.460	0.004	−0.404	0.002
1.0–1.5	−0.574	0.008	−0.607	0.008	−0.572	0.006
>1.5	−0.679	0.027	−0.710	0.020	−0.719	0.021

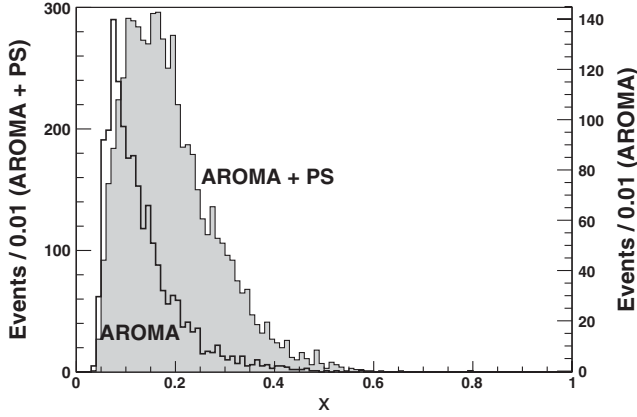


FIG. 12. Distributions of the gluon momentum fractions x for the simulated $D_{K\pi}^*$ events at the LO accuracy (marked “AROMA”) and at LO with parton shower (AROMA + PS). Note different normalizations of the samples.

the QCD calculations used in the analysis. At the same time the energy in the photon-gluon center-of-mass system required to produce a D^0 meson is higher with parton shower simulation as compared to the case of LO where parton shower is not simulated. Therefore a value of $\langle x \rangle$ at which the gluon polarization is determined at NLO $\langle x \rangle^{\text{NLO}} \approx 0.20$, is higher than $\langle x \rangle^{\text{LO}} \approx 0.11$; see for example Fig. 12 (where “PS” stands for parton shower).

A systematic uncertainty of the result in Eq. (15) is estimated as follows; see Table XIII. Contributions from P_μ , P_t , f , $s/(s+b)$, and D are the same as discussed in Sec. IV B, i.e., 5%, 5%, 2%, 7%, and 1.6%, respectively. Contributions from false asymmetries and the assumption given in Eq. (9), the same as in the statistically optimized method at LO, are discussed in Sec. V B. Concerning the analyzing power a_{LL} , the following contributions resulting from the NLO determination of a_{LL} were studied: its dependence on scale, the charm mass value and the Monte Carlo mode (with or without PS). The renormalization scale (here chosen equal to the factorization one, Ref. [41]) varied from m_c to $3m_c$. This changes the gluon polarization at most by a factor of two, leading to a conservative contribution to the systematic uncertainty of 0.1. The variation of the charm quark mass between 1.3 and 1.6 GeV/c^2 results in a contribution of 0.05. The

TABLE XIII. Contributions to the systematic uncertainty of $\langle \Delta g/g \rangle^{\text{NLO}}$.

Source	$\delta(\langle \Delta g/g \rangle)$	Source	$\delta(\langle \Delta g/g \rangle)$
Beam polarisation P_μ	0.006	$s/(s+b)$	0.009
Target polarisation P_t	0.006	a_{LL}	0.119
Dilution factor f	0.003	False asymmetry	0.080
Assumption, Eq. (9)	0.025	Depolarisation factor D	0.002
Total uncertainty 0.146			

systematic uncertainty contribution from the simulation method was estimated using AROMA with and without parton showers. Note, that measured D meson spectra are described reasonably well by AROMA both with and without parton showers, and the difference in a_{LL} between both cases is mainly due to the different phase space available for “unobserved” partons. Such comparison allows us to give a conservative estimate of uncertainty due to the simulation method equal to 0.04. The total systematic uncertainty of $\langle \Delta g/g \rangle^{\text{NLO}}$ is obtained by adding all the contributions in quadrature and amounts to 0.15.

The result on $\langle \Delta g/g \rangle^{\text{NLO}}$, Eq. (15), was included in NLO QCD fits of polarized parton distributions; see the Appendix for details. The fitted distributions of $\Delta g(x)/g(x)$, evolved to $Q^2 = 13 (\text{GeV}/c)^2$, are shown in Fig. 13 together with error bands corresponding to the statistical errors as derived from the error matrix of the fitted parameters. The present NLO open charm result agrees within 0.5 standard deviation with the fitted Compass curve for $\Delta g(x) < 0$ and within 2σ with the one for $\Delta g(x) > 0$. It significantly influences the $\Delta g(x) > 0$ fit, reducing the value of ΔG from $0.39 \pm 0.07(\text{stat.})$ to $0.22 \pm 0.08(\text{stat.})$ at $Q^2 = 3 (\text{GeV}/c)^2$.

The results of two other global fits, DSSV [42] and LSS [12], which employ both DIS and SIDIS asymmetries are also shown in the same figure. In the DSSV fit, $\Delta g(x)$ changes sign at $x \approx 0.1$ and is about 1.5σ above the Compass open charm value. In the case of LSS, two solutions, with positive and sign-changing $\Delta g(x)$ are quoted. Our measurement cannot distinguish between these two functions. Both solutions give a positive $\Delta g(x)$

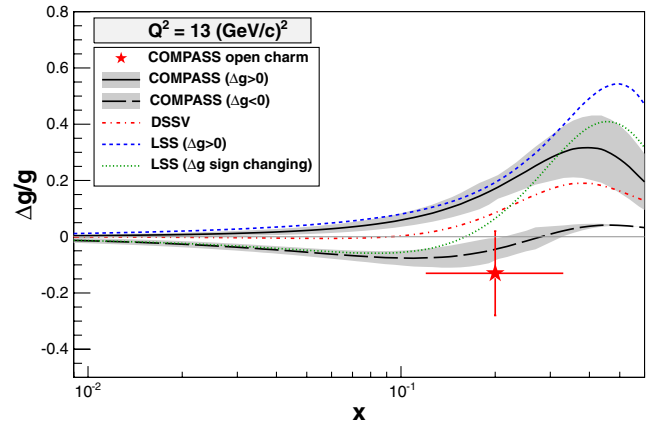


FIG. 13 (color online). The present NLO measurement of the gluon polarization $\langle \Delta g(x)/g(x) \rangle$ at $\langle \mu^2 \rangle = 13 (\text{GeV}/c)^2$, compared to the NLO QCD fits of Compass with $\Delta g(x) > 0$ (continuous line) and $\Delta g(x) < 0$ (long-dashed) with their respective error bands, of LSS [12] (dashed and dotted curves, respectively, with $\Delta g > 0$ and Δg changing sign) and of DSSV [42] (dashed-dotted curve), all at the same value of $Q^2 = 13 (\text{GeV}/c)^2$. The measurement error and the error bands are statistical only; the horizontal bar marks the range of x in which $\langle \Delta g(x)/g(x) \rangle$ is determined.

at the (x, Q^2) of the present measurement, about 2 and 1.3σ above the measured value.

VI. CONCLUSIONS

We have presented new results on the gluon polarization in the nucleon $\langle \Delta g/g \rangle$ and the virtual photon-nucleon asymmetries $A^{\gamma N}$ obtained from charm production tagged by D-meson decays in 160 GeV/c polarized muon scattering off polarized proton and deuteron targets. The results are based on a data sample collected between 2002 and 2007 and supersede the previously published ones [19] as they are based on an improved analysis method and on the full data sample; additional final state channels are added as well. Most of the data were collected with the deuteron target. Those collected with the proton one improve the statistical precision of dg/g by about 9% but otherwise practically do not influence the results.

The gluon polarization is determined with open charm production dominated by the photon-gluon fusion mechanism followed by a spin-independent charm quark fragmentation into D mesons. This analysis neglects any contributions from the intrinsic charm; a contribution of resolved photon interactions was found negligible.

Only one charmed meson is required in every event. This meson is selected through its decay in one of the following channels: $D^*(2010)^+ \rightarrow D^0 \pi_s^+ \rightarrow (K\pi/K\pi\pi^0/K\pi\pi\pi)\pi_s^+$ or $D^0 \rightarrow K\pi$. The decays are selected using the invariant mass distributions of identified kaons and pions. A Neural Network is used to distinguish signal from background events in the data. The asymmetries $A^{\gamma N}$ are extracted from these open charm events in bins of D^0 transverse momentum and laboratory energy. The average gluon polarization obtained from these asymmetries at LO QCD accuracy amounts to $\langle \Delta g/g \rangle^{\text{LO}} = -0.10 \pm 0.22(\text{stat.}) \pm 0.09(\text{syst.})$. This result is confirmed and statistically improved by employing a statistically optimized method of extracting the gluon polarization,

$$\left\langle \frac{\Delta g}{g} \right\rangle^{\text{LO}} = -0.06 \pm 0.21(\text{stat.}) \pm 0.08(\text{syst.}).$$

Both results are obtained in the range $0.06 < x < 0.22$ of the gluon momentum fraction with $\langle x \rangle \approx 0.11$ and a scale $\langle \mu^2 \rangle \approx 13 \text{ (GeV}/c)^2$.

In this analysis, next-to-leading order QCD calculations for the determination of the gluon polarization are employed for the first time. Using asymmetries $A^{\gamma N}$ the gluon polarization is obtained as

$$\left\langle \frac{\Delta g}{g} \right\rangle^{\text{NLO}} = -0.13 \pm 0.15(\text{stat.}) \pm 0.15(\text{syst.}).$$

In this case the range of x , $0.12 < x < 0.33$ leads to a higher average value, $\langle x \rangle \approx 0.20$, while the scale is approximately the same, $\langle \mu^2 \rangle \approx 13 \text{ (GeV}/c)^2$.

The present measurement at LO QCD accuracy of the gluon polarization in the nucleon, together with other

measurements of SMC, Compass and Hermes, all situated around $x \sim 0.1$, points towards a small gluon polarization at that value of x . This may be a hint for a small value of the first moment, ΔG , of the gluon helicity distribution, although it in principle does not exclude a large value of ΔG .

The $\langle \Delta g/g \rangle^{\text{NLO}}$ result was included in NLO QCD fits of polarized parton distributions. It significantly influences a fit in which $\Delta g(x) > 0$ was assumed, reducing the value of ΔG from $0.39 \pm 0.07(\text{stat.})$ to $0.24 \pm 0.09(\text{stat.})$ at $Q^2 = 3 \text{ (GeV}/c)^2$, after it is included.

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APPENDIX: NLO QCD FITS

In this appendix, new NLO QCD fits of polarized parton distributions, including the $\langle \Delta g/g \rangle^{\text{NLO}}$ result of Eq. (15) are presented. In our previous fit [3] the gluon helicity distribution is parametrized at a reference Q^2 of $3 \text{ (GeV}/c)^2$ in the form

$$\Delta g(x) = \frac{\eta_g x^{\alpha_g} (1-x)^{\beta_g}}{\int_0^1 x^{\alpha_g} (1-x)^{\beta_g} dx}. \quad (\text{A1})$$

Here η_g is the integral of $\Delta g(x)$, $\eta_g \equiv \Delta G$. The same parametrizations, Eq. (A1), are used for the singlet, nonsinglet quark and gluon helicity distributions except for the singlet quark in the fit with $\eta_g > 0$, where a factor $(1 + \gamma x)$ is added in order to allow a change of sign. The high x parameter of the gluon helicity distribution is fixed to $\beta_g = 10$ in this $\eta_g > 0$ fit so that the total number of free parameters remained equal to 10. Two fits, in NLO QCD approximation and using all inclusive data with $Q^2 > 1 \text{ (GeV}/c)^2$, are performed: one with $\eta_g > 0$, the other with $\eta_g < 0$. Both of them gave a comparable χ^2 probability.

In the new fit all the data used in Ref. [3] are employed with an addition of the 15 Compass values of A_1^p published

later [43]. As in the previous fit, only statistical errors are considered. The reference Q^2 is kept at 3 (GeV/c)² and the same parametrizations, Eq. (A1), are used. The total number of free parameters is also equal to 10.

The new open charm result is not attached to a precise value of x and thus its contribution is taken into account by the average

$$\langle R_g \rangle = \frac{1}{(0.33 - 0.12)} \int_{0.12}^{0.33} \left[\frac{\Delta g}{g}(x, Q^2 = 13) \right] dx, \quad (\text{A2})$$

which is reevaluated during the fit for any modification of one of the gluon or singlet quark parameters. The obtained value of $\langle R_g \rangle$ is compared to the open charm result $\nu_{\text{OC}} = -0.13$ with the statistical error $\sigma_{\text{OC}} = 0.15$ and the χ^2 of the fit is incremented by $(\langle R_g \rangle - \nu_{\text{OC}})^2 / \sigma_{\text{OC}}^2$.

The unpolarized gluon distribution $g(x, Q^2)$ in Eq. (A2) is taken from the MRST04 parameterization [44]. It was also used in Ref. [3]. In contrast to previous parametrizations of the same group, MRST04 predicts

a slower decrease of the gluon distribution at high x , $(1-x)^\beta$ with $\beta \sim 3-4$. For this reason the choice of $\beta_g = 10$ for the fit with $\eta_g > 0$ in Ref. [3] leads to a strongly peaked distribution of $\Delta g/g$ which in turn generates a dip in the fitted distribution of $g_1^d(x)$ around $x = 0.25$ for low values of Q^2 and leads in some cases to very asymmetric errors due to the limits imposed by the positivity condition $|\Delta g(x)| \leq g(x)$. To avoid these unphysical features, β_g is now fixed to 6 in the fit with $\eta_g > 0$.

The present open charm result has practically no effect on the fit for $\Delta g(x) < 0$, where $\eta_g = -0.34 \pm 0.12$ with and without that measurement, while it reduces significantly the positive η_g , from $\eta_g = 0.39 \pm 0.07(\text{stat.})$ to $\eta_g = 0.22 \pm 0.08(\text{stat.})$ at $Q^2 = 3$ (GeV/c)², after it is included. Similarly, the values of α_g for the fits including the open charm point are $\alpha_g = 1.31 \pm 0.47(\text{stat.})$ for $\Delta g(x) > 0$ and $\alpha_g = 0.26 \pm 0.48(\text{stat.})$ for $\Delta g(x) < 0$, both at $Q^2 = 3$ (GeV/c)².

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