# Nucleon spin studies at COMPASS

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**Abstract.** An overview of the muon part of the COMPASS results related to the spin structure of the nucleon is given.

**Keywords:** Polarised electroproduction, nucleon spin structure, QCD
**PACS:** 13.60Le, 13.88.+e

## INTRODUCTION

The structure of the most common of hadrons, the nucleon, is still largely unknown, in particular in its spin-dependent aspects. Their intensive studies have commenced after the European Muon Collaboration, 20 years ago, had published a surprising result that total quark spin constitutes a rather small fraction of the spin of the proton, [1]. This result has been later confirmed by several experiments using polarised electrons (muons), different polarised nucleon targets and incident energies from few to few hundred GeV. Possible other nucleon spin carriers, gluons and the parton angular momenta, should thus be investigated. The latter are presently inaccessible experimentally. As for the former, the QCD evolution of the polarised inclusive DIS measurements has a limited sensitivity to the gluon helicity distribution, $\Delta g(x)$, due to the limited range in the $Q^2$ values covered by the data. Direct measurements of the gluon polarisation in the nucleon, through final states which select processes with gluons, have thus become an imperative.

The nucleon quark structure at the twist-two level and in the absence of (or after intergating over) the quark transverse momentum, $k_T$, is fully determined by a set of quark momentum ($q(x)$), helicity ($\Delta q(x)$), and transversity ($\Delta_T q(x)$) distributions. Helicity distribution is a difference of probabilities of quarks having spins parallel and antiparallel to the nucleon spin when the latter is oriented along the virtual photon. Definition of the transversity is similar but refers to the transverse polarisation of the nucleon. Since boosts and rotations do not commute, helicity and transversity need not to be the same in the relativistic (high energy beam) case. The transversity distributions, ($\Delta_T q(x)$), are C-odd and chiral-odd, thus they may only be measured with another chiral-odd partner, e.g. the fragmentation function. They have very interesting properties: their QCD evolution is simple since it does not involve gluons, they are related to the Generalised Parton Distributions and finally their first moment gives the nucleon tensor charge, now being studied on the lattice. Allowing for twists higher than two or for the non-zero $k_T$ of quarks, results in additional distributions needed to describe the quark structure of the nucleon.

The COMPASS (COmmon Muon and Proton Apparatus for Structure and Spectroscopy) collaboration at CERN pursues extended studies of the nucleon spin structure. They include: a direct mesurement of the gluon polarisation, extraction of the flavour-separated quark helicity distributions, $\Delta q(x)$, and of the quark transverse spin distributions, $\Delta_T q(x)$.

## THE EXPERIMENT

COMPASS runs a fixed target experiment [2] situated at the M2 muon beam line of the CERN SPS. In 2002 it started to take data with a 160 GeV naturally polarised beam of positive muons, incident on a large, longitudinally or transversally polarised deuteron target of solid $^6$LiD (in 2007 replaced by the solid ammonia, $NH_3$, as a proton target). The target container has two (three since 2006), oppositely polarised cells, for simultaneous recording of events with different spin orientations. A large, two-stage spectrometer determines the momenta of the scattered muon and of the final state hadrons. Charged particles are identified in the RICH counter and in the hadron calorimeters. In 2006 several elements of the spectrometer were upgraded. The experimental acceptance extends to very small values of $x$, albeit at low values of $Q^2$.

## LONGITUDINALLY POLARISED NUCLEON

### Inclusive measurements – spin dependent structure functions

COMPASS has performed precise measurements of the longitudinal virtual photon–deuteron and (recently) photon–proton asymmetries covering the region of $0.004 < x < 0.7$ at $Q^2 > 1$ (GeV/$c$)$^2$ (based on the data collected in 2002–2004, [3] and 2007, [4] respectively), as well as the virtual photon–deuteron asymmetry at $Q^2 < 1$ (GeV/$c$)$^2$ and $0.00004 < x < 0.025$, based on the data collected in 2002–2003, [5]. All those measurements improve the precision at low $x$ about 2-3 times ($Q^2 > 1$ (GeV/c)$^2$) or even about 10 times ($Q^2 < 1$ (GeV/c)$^2$) with respect to the only other results in this region, those of the SMC [6]. The nucleon- and proton spin structure functions, $g_1^N(x,Q^2)$ and $g_1^p(x,Q^2)$, extracted from the COMPASS measurements are shown in Fig.1. Here

$$g_1^N(x,Q^2) = \frac{g_1^d(x,Q^2)}{1-1.5\omega_D}$$

and the deuteron D-state probability, $\omega_D$ is 0.05±0.01. The $g_1^N$ values are consistent with zero for $x < 0.03$, independently of the $Q^2$ interval, an important conclusion in view of the less accurate results of the SMC suggesting that $g_1^N < 0$ at low $x$. The $g_1^p$ for $0.004 < x < 0.04$ is compatible with a constant, found to be $g_1^p = 0.48 \pm 0.03 \pm 0.04$ at $Q^2 = 3$ (GeV/$c$)$^2$.

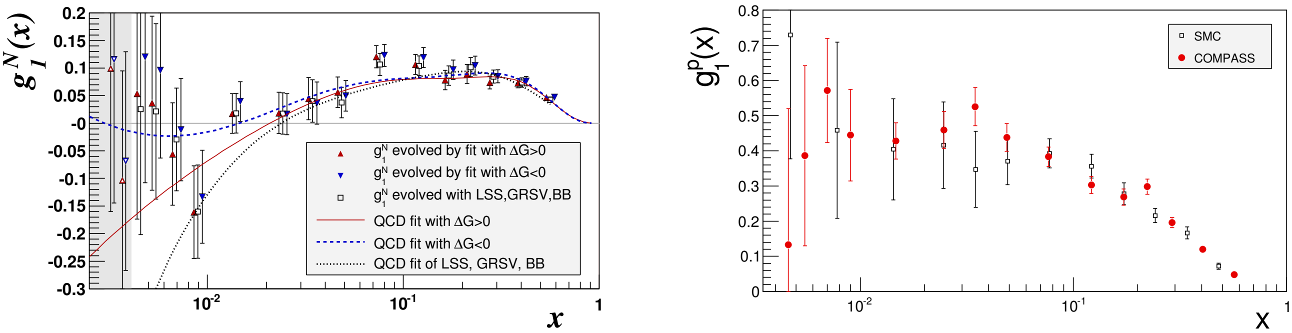


**FIGURE 1. Left:** COMPASS values of $g_1^N(x)$ evolved to $Q^2 = 3$ (GeV/$c$)$^2$. The open triangles at low $x$ correspond to $Q^2 > 0.7$ (GeV/$c$)$^2$, the other symbols to $Q^2 > 1$ (GeV/$c$)$^2$. Results of the QCD fits are shown by curves. Symbols 'LSS', 'GRSV' and 'BB' refer to published polarised parton distribution functions parameterisations. Errors are statistical. See [3] for further details. **Right:** $g_1^p(x)$ at the $Q^2$ of the measurements, for $Q^2 > 1$ (GeV/$c$)$^2$. Errors are statistical.

A QCD fit of the world $g_1^d$ data at NLO was performed and yielded two solutions: $\Delta g(x) > 0$ or $\Delta g(x) < 0$, equally well describing the data, cf. Fig.1. In both cases, the first moment of $\Delta g(x)$ is of the order 0.2 – 0.3 in absolute value at $Q^2 = 3(\text{GeV}/c)^2$ but the shapes of the distributions are very different. An accurate evaluation of the first moment of $g_1^d(x)$, and of the matrix element of the singlet axial current, $a_0$, were also obtained. In the $\overline{\text{MS}}$ renormalisation scheme the $a_0$ is the same as the quark spin contribution to the nucleon spin. At $Q^2 = 3$ (GeV/$c$)$^2$ it is equal to $a_0 = 0.30 \pm 0.01$ (stat.) $\pm$ 0.02 (evol.). It was also found that the first moment of the strange quark distribution in the $Q^2 \to \infty$ limit, $(\Delta s(x) + \Delta\bar{s}(x))$, is –0.08 ± 0.01 (stat.) ± 0.02 (syst.).

The new COMPASS proton asymmetries [4] were combined with those previously published for the deuteron [3] to extract the non-singlet spin-dependent structure function,

$$g_1^{NS}(x,Q^2) = g_1^p(x,Q^2) - g_1^n(x,Q^2) = 2\left[g_1^p(x,Q^2) - g_1^N(x,Q^2)\right]$$

The $g_1^{NS}$ is of special interest since its $Q^2$ dependence is decoupled from the singlet and the gluon spin densities. The NLO QCD fit of $g_1^{NS}$ was performed to extract the isovector quark density. Its first moment corresponds to a ratio of the axial and vector coupling constants $|g_A/g_V| = 1.28 \pm 0.07 \pm 0.10$, within one standard deviation from the value predicted by the fundamental Bjorken sum rule.

## Semi-inclusive measurements – flavour helicity distributions

Quarks and antiquarks of the same flavour equally contribute to $g_1$ and thus the inclusive data do not allow to separate valence and sea contributions to the nucleon spin. Therefore additional, semi-inclusive spin asymmetries for positive and negative hadrons in the final state, $h^+$ and $h^-$ were measured on the same data set as the inclusive deuteron results mentioned above [7].

In the LO QCD the difference asymmetry, $A^{h^+-h^-}$, measures the valence quark polarisation and provides an evaluation of the first moment of $\Delta u_v + \Delta d_v$ which was found to be $0.41 \pm 0.07 \pm 0.06$ at $Q^2 = 10(\mathrm{GeV}/c)^2$ and over the measured range of $x$. When combined with the first moment of $g_1^d$, this result favours a non-symmetric polarisation of light quarks, $\Delta\bar{u}(x) = -\Delta\bar{d}(x)$ at a confidence level of two standard deviations, in contrast to the often assumed symmetric scenario $\Delta\bar{u}(x) = \Delta\bar{d}(x) = \Delta\bar{s}(x) = \Delta s(x)$.

Recently the whole deuteron sample, collected in 2002 – 2006 has been used to extract the semi-inclusive asymmetries for the RICH identified positive and negative pions and kaons, down to $x = 0.004$ [8]. These asymmetries, together with the inclusive ones were used to evaluate the LO helicity densities of valence, $\Delta u_v + \Delta d_v$, non-strange sea, $\Delta\bar{u}_v + \Delta\bar{d}_v$, and strange quarks, $\Delta s$ (assumed to be equal to $\Delta\bar{s}$), at the LO accuracy. Both non-strange densities are found to be in a good agreement with previous measurements and are weakly denepedent on the selected parameterisation of the fragmentation fuctions. The distribution of $\Delta s(x)$ is compatible with zero in the whole measured range, in contrast to the shape of the strange quark helicity distribution obtained in most LO and NLO QCD fits. The values of the first moment of $\Delta s(x)$ and its error are very sensitive to the assumed value of the ratio of the $\bar{s}$-quark to $u$-quark fragmentation functions into positive kaons. These conclusions are confirmed after the full flavour separation of the LO helicities distributions was performed by combining the (inclusive and semi-inclusive) deuteron and the new proton sample asymmetries, Fig.2.

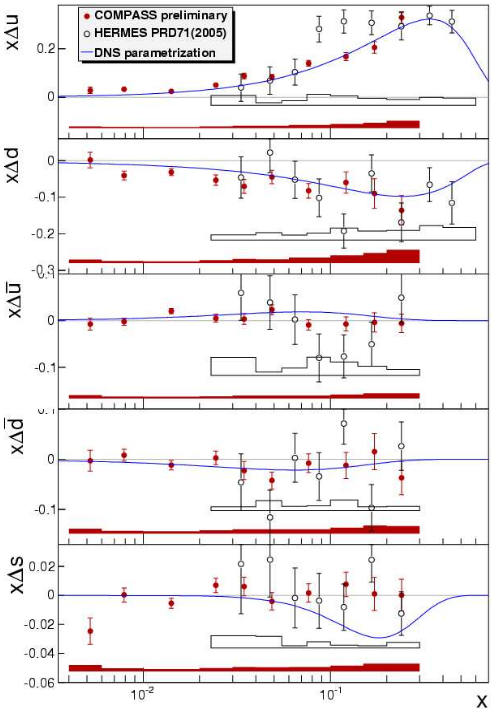


**FIGURE 2.** COMPASS and HERMES quark helicity distributions evaluated at a common value $Q^2 = 3(\mathrm{GeV}/c)^2$ for the DSS fragmentation functions [9]. Bands at bottom represent systematic uncertainties. The curves correspond to the LO DNS parameterisation of polarised parton distribution functions [10].

## Measurement of the gluon polarisation and the "nucleon spin puzzle"

The gluon polarisation in the nucleon is determined from the cross-section for the virtual photon–gluon fusion (PGF), $\gamma^{*}g \rightarrow q\bar{q}$. The PGF process was selected depending on the products of the $q\bar{q}$ pair fragmentation, either through production of hadron pairs with high transverse momenta, $p_T$ (typically 1–2 GeV/$c$), with respect to the virtual photon direction or through the open-charm production, *i.e.* when $q \equiv c$ and the $c\bar{c}$ pair fragments into a pair of the $D$ mesons. The former process results in a very high statistics but relies heavily on the Monte Carlo generators simulating the QCD processes; the latter provides the cleanest sample of interesting events albeit at a low rate.

The average gluon polarisation in a limited range of $x$, $\langle \Delta g/g \rangle_x$ (here $g \equiv g(x)$ is the spin-averaged gluon distribution in the nucleon), has been determined for the 2002–2006 sample, assuming that the $D$ meson production is dominated by the PGF mechanism, [11]. The assumption is supported by measurements of $F_2^c$ in the COMPASS kinematic domain. The method has the advantage that in the lowest order of the $\alpha_s$ there are no other contributions to the cross section. Only one charmed meson was required in every event. It was selected through its decay in one of the two channels: $D^{*}(2010)^{+} \rightarrow D^0\pi^{+}_{slow} \rightarrow K^{-}\pi^{+}\pi^{+}_{slow}$($D^{*}$ sample) and $D^0 \rightarrow K^{-}\pi^{+}$ ($D^0$ sample) and their charge conjugates. To reduce the large combinatorial background only the RICH–identified $K\pi$ pairs were used. In this analysis the perturbative scale $\mu^2$ for the selected events is not given by $Q^2$ but by the $4(m_c^2 + p_T^2)$, $m_c$ being the mass of the charm quark and $p_T$ its transverse momentum with respect to the virtual photon.

Later the $D^0 \rightarrow K\pi\pi^0$ events as well as the kaon candidates not identified by the RICH (but not positively identified as pions or electrons) were included in the $D^{*}$ sample from the 2002–2006 data set. Also a neural network was employed to separate the charm signal from the uncorrelated background. This analysis resulted in an average gluon polarisation of $\langle \Delta g/g \rangle_x$ = –0.39 ± 0.24 ± 0.11 at a scale $\mu^2 \approx 13$ (GeV/$c$)$^2$ and at an average gluon momentum fraction $\langle x \rangle \approx 0.11$.

The $\langle \Delta g/g \rangle_x$ has also been determined from the events which contain at least two high-$p_T$ hadrons in addition to the incoming and outgoing muon. The cross-section helicity asymmetry for those events contains an asymmetry from the background processes in addition to the contribution from the PGF. This background asymmetry as well as the PGF contribution were estimated by a simulation which introduces a model dependence in the evaluation of $\langle \Delta g/g \rangle_x$. The $Q^2 > 1(\mathrm{GeV}/c)^2$ and the $Q^2 < 1(\mathrm{GeV}/c)^2$ events were considered separately since different generators (LEPTO and PYTHIA respectively) were used to model the interactions. In the latter case, the hard scale was set by the (high) $p_T$ value of the final state hadrons, $\mu^2 \approx 3$ (GeV/$c^2$) and apart of the direct processes also the resolved photon reactions were simulated. The $Q^2 < 1(\mathrm{GeV}/c)^2$ results based on the 2002–2003 data were published, [12]; including the 2004 measurements gave $\langle \Delta g/g \rangle_x$ = 0.016 ± 0.058 (stat.) ± 0.014 (syst. exp.) ± 0.052 (syst. MC) ± 0.013 (syst.resolved photons) at an average gluon momentum fraction $\langle x \rangle \approx 0.08$. Corresponding result for the $Q^2 > 1(\mathrm{GeV}/c)^2$ and 2002–2004 data reads: $\langle \Delta g/g \rangle_x$ = 0.08 ± 0.10 (stat.) ± 0.05 (syst.), consistent with that at low $Q^2$.

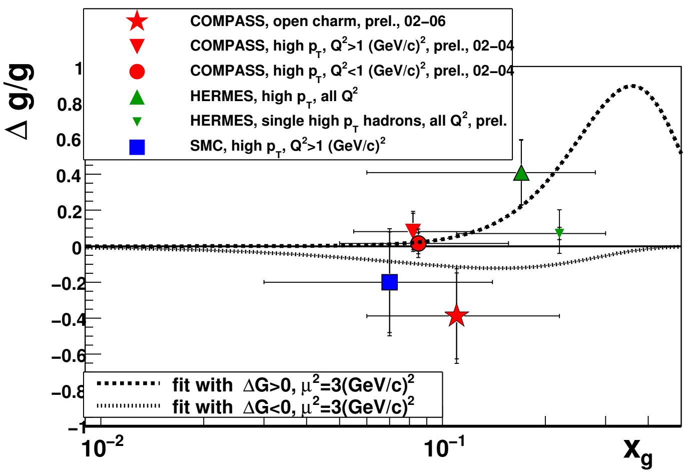


**FIGURE 3.** Compilation of the $\langle \Delta g/g \rangle_x$ measurements from the open charm and high $p_T$ hadron pair production. The curves display two parametrisations from the COMPASS NLO QCD analysis, [3].

COMPASS results on $\langle \Delta g/g \rangle_x$ for the nucleon are collected in Fig. 3 where also the measurements by SMC and HERMES are shown. The horizontal bars mark the range in $x$ for each mesurement, the vertical ones give the statistical precision and the total errors (if available). All measurements are situated around $x \sim$0.1 and point towards a small gluon polarisation at that value of $x$. This, in principle, does not exclude a large value of the first moment of the gluon helicity distribution.

In QCD the nucleon spin decomposition into the quark and gluon helicites, $\Delta\Sigma$ and $\Delta G$, and orbital angular momenta, $L_q$ and $L_g$, may be expressed as follows:

$$\frac{\hbar}{2} = J_q + J_g = \left(\frac{1}{2}\Delta\Sigma + L_q\right) + (\Delta G + L_g)$$

where each term is renormalisation scale–dependent and the $J_g = \Delta G + L_g$ decomposition is not gauge–invariant. Here $\Delta G$ is the first moment of $\Delta g(x)$.

In the Quark Parton Model the nucleon spin is given by the quark spins, $\Delta\Sigma$, while $\Delta G$ and $L_{q,g}$ vanish. The quark contribution is now confirmed to be around 0.3, smaller than the expected value of 0.6 [13] which keeps the “nucleon spin puzzle” alive, 20 years after its discovery [1].

In principle the puzzle can still be solved by the QCD axial (or U(1)) anomaly, steming from the axial vector current nonconservation. The anomaly generates a gluonic contribution to the measured singlet axial coupling, $a_0(Q^2)$, which does not vanish at $Q^2 \to \infty$. As a result, $\Delta\Sigma(Q^2)$ becomes scheme dependent and may differ from the observable $a_0$ while $\Delta G$ is scheme–independent at least up to the NLO. In the Adler–Bardeen factorisation scheme, $\Delta\Sigma^{AB}$ is independent of $Q^2$. As a consequence, the measured quantity is in fact not the $\Delta\Sigma$ but

$$a_0(Q^2) = \Delta\Sigma^{AB} - \left(\frac{n_f \alpha_s}{2\pi}\right)\Delta G(Q^2)$$

Restoring the Ellis–Jaffe value of $\Delta\Sigma^{AB} \sim 0.6$ (or solving the “spin puzzle”) would thus require a value of $\Delta G(Q^2) \sim 2.2$ and $L = L_q + L_g \sim -2$ at $Q^2 \approx 3$ (GeV/$c$)$^2$. If indeed the $\Delta G$ is close to zero as all the measurements seem to point to, then the axial anomaly plays only a marginal role in the nucleon spin balance. Further, if $a_0 = 0.30 \pm 0.01$(stat.)$\pm$0.05 (evol.) as *e.g.* the COMPASS fit at $Q^2$ = 3 (GeV/$c$)$^2$ shows [3] then the only way out is through a large orbital angular momentum contributions, $L_{q,g}$. The $L_q$ may in principle be accessed through the Generalised Parton Distribution functions measured in the Deeply Virtual Compton Scattering. Several DVCS data have already been taken and are being analysed; several other measurements are expected to be performed in the next few years, including COMPASS.

## TRANSVERSALLY POLARISED NUCLEON

A full sample of the data taken with a transversally polarised deuteron target has been analysed. Several asymmetries (*e.g.* $\Lambda$ polarisation, hadron pair production) were measured in this configuration. The respective distribution functions are sensitive to such quantities as spin dependent fragmentation functions, interference fragmentation function, *etc*. Particularly important are asymmetries due to the Collins and Sivers mechanisms, the former being due to the combined effect of the chirally-odd $\Delta_T q$ and a chirally–odd spin–dependent fragmentation function and the latter to a correlation between the intrinsic transverse momentum of a quark and the transverse polarisation of the nucleon.

For the deuteron target and for the identified final state hadrons (charged pions, charged kaons, neutral kaons) both Collins and Sivers asymmetries are small, compatible with zero within the statistical errors, [14]. This result is in line with the previously published results, [15] for not identified hadrons, and with the expected cancellation between the $u$- and $d$-quark contributions but it is at variance with the signal of both Collins and Sivers effects seen by HERMES at lower energies and on the proton target[1].

Preliminary results obtained by COMPASS for the data taken in 2007 with the transversely polarised proton target show a hint of a nonzero Collins asymmetry at the $x \gtrsim$ 0.1, Fig.4. The Sivers asymmetries stay compatible with zero which await a confirmation with a larger statistics.

Finally it should be mentioned that first global analyses of the transverse parton distributions have already been performed and point towards small values of $\Delta_T q$ as compared to $\Delta q$ [16].

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[1] Recently also the BELLE Collaboration observed a signal of the Collins effect by the azimuthal correlations in $e^+e^- \to$ hadrons.

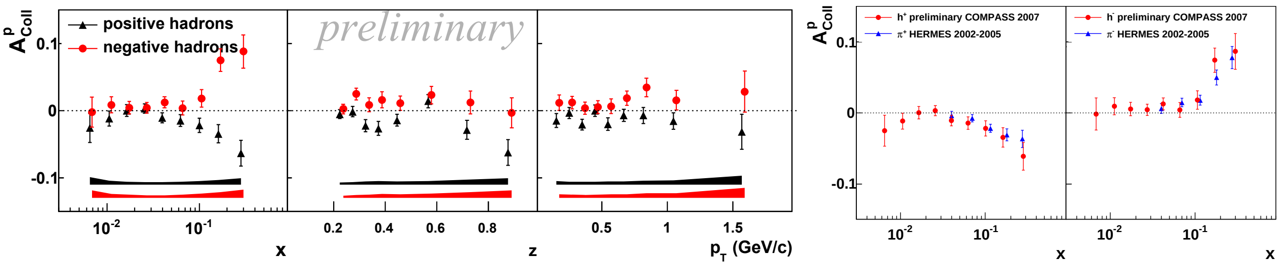


**FIGURE 4.** COMPASS preliminary results for the Collins asymmetry for the proton.

## OUTLOOK AND PLANS

Polarised muon–proton and muon–deuteron scattering studied by COMPASS resulted in a wide spectrum of new information on the longitudinal and transverse spin phenomena. Average gluon polarisation around $x \sim 0.1$ is small and its first moment is limited to about 0.2–0.3 in absolute value by the scaling violation in the $g_1^d$. A large value of first moment of the gluon polarisation, i.e. a large gluon polarisation contribution to the nucleon spin, is thus unlikely. Flavour symmetric polarised sea seems disfavoured. Flavour separation of quark helicities, down to low values of $x$, is progressing; the case of the strange sea where the strong dependence on the assumed fragmentation functions seems to exist, needs special attention. Transversity effects appear weak, especially for the deuteron but nonetheless may substantially influence global analyses of the transverse parton distributions.

COMPASS plans for the longitudinal and transverse proton target running with the muon beam in 2010 and 2011 have just been approved, [17]. For its more distant future, $\gtrsim$ 2012, the Collaboration is preparing a proposal to study the Generalised Parton Distribution functions via measurements of the Deeply Virtual Compton Scattering and to study the Transverse Momentum Dependent distributions via measurements of the Drell–Yan process, [18].

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