 DOI: 10.1051/epjconf/201716401007

COMPASS results on proton longitudinal spin structure function g_1 and quark fragmentation functions

Fabienne Kunne[1]

[1] IRFU, CEA Saclay, Université Paris-Saclay, France

On behalf of the COMPASS Collaboration

Abstract. We present a few recent highlights from the COMPASS experiment at CERN, related to the nucleon spin and structure: the proton spin structure function $g_1^p(x)$ measured using 200 GeV polarized muons, together with a QCD fit of g_1 world data; pion and kaon multiplicities in DIS in view of constraining quark fragmentation functions.
The statistical precision on g_1^p is improved by a factor of ~2 at low x. A re-evaluation of the Bjorken sum rule based on COMPASS data alone confirms its validation within 9% accuracy. An NLO QCD fit to g_1 world data leads to a value of the quark spin contribution to the nucleon spin $\Delta\Sigma$, between 0.26 and 0.36 at $Q^2 = 3$ (GeV/c)^2, the size of the uncertainty being driven by the unknown shape of the polarized parton distributions.
The results on pion and kaon multiplicities produced in DIS of muons off an isoscalar target constitute an impressive data set of more than 400 points in π and 400 in K, covering a large kinematical domain in (x, z, Q^2), which will be used in future NLO QCD fits to extract quark fragmentation functions into π and K. A LO fit is performed to extract the favoured and unfavoured quark fragmentation functions into pions.

1 Measurements of g_1^p proton spin structure function at 200GeV

The 1/2 nucleon spin can be decomposed along the longitudinal projection as follows

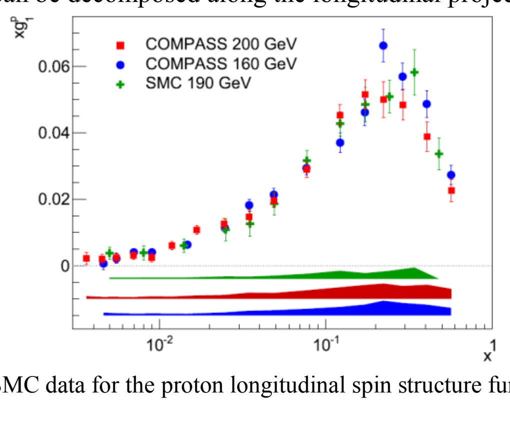

Fig. 1. COMPASS and SMC data for the proton longitudinal spin structure function g_1^p.

1/2 = ½ ΔΣ + ΔG + L_z, where ΔΣ represents the quark spin contribution, ΔG the gluon spin one and L_z the contribution from the orbital angular momenta of quarks and gluons. We present here COMPASS results on the proton longitudinal spin structure function $g_1^p(x)$ [1]. The measurements were performed using 200 GeV polarized muons from the CERN SPS (tertiary beam), scattered off a longitudinally polarized NH_3 target [2]. Results [1] are shown in Fig.1 together with previous results taken at 160 GeV [3] and earlier results from SMC [4]. The new data cover smaller *x* values, down to 0.0036. They improve the statistical precision of previous COMPASS data by a factor of about 2.

2 Test of the Bjorken Sum Rule

The Bjorken sum rule is a fundamental QCD prediction relating the difference of first moment of the proton and the neutron spin structure functions to the ratio of the axial-vector to vector weak coupling constants g_A/g_V assuming SU(2) flavour symmetry. It can be tested by combining the COMPASS proton [1] and deuteron [5] results to calculate the non-singlet spin structure function $g_1^{NS}(x) = g_1^p(x) - g_1^n(x)$, and compare its first moment to the prediction.

Preliminary results for $g_1^{NS}(x)$ are shown in Fig.2 *left*, and the corresponding truncated integral values (integrated from the minimum $x=x_{min}$ to 1), are shown versus x_{min} in Fig.2 *right*. The full integral corresponds to a value of g_A/g_V = 1.220 ± 0.053(stat) ± 0.095(syst). Comparing this result [1] to the value obtained from neutron decay measurements, 1.2701 ± 0.0025 [6], we can say that the Bjorken sum rule is validated within 9% accuracy. The dominant uncertainty comes from systematic uncertainties on beam and target polarisation and target dilution factor (fraction of polarisable material in the target). Note that the data cover 94% of the contribution to the integral, a remarkable feature compared to other evaluations.

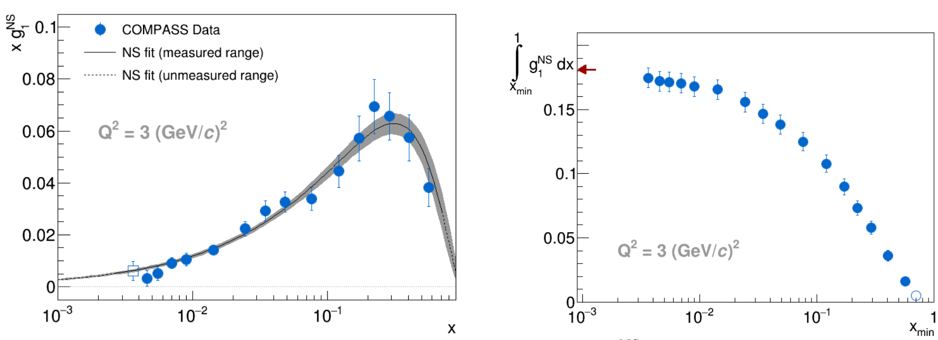

Fig. 2. *Left:* The nucleon non-singlet spin structure function g_1^{NS} vs *x*, measured from COMPASS p and d data. *Right:* truncated integral of g_1^{NS} from x_{min} to 1, vs x_{min}. The arrow shows the value extrapolated to x_{min}=0.

3 NLO QCD fit of g_1 world data

The COMPASS g_1^p and g_1^d measurements are shown in Fig. 3 as a function of Q^2 for various *x* values, together with other world data. The COMPASS coverage is very significant in the low *x* and large Q^2 regions. To extract quark and gluon helicity distributions, we have performed a global NLO QCD fit to all these and existing neutron data. A functional form is assumed at an initial Q_0^2 scale for the singlet, the triplet and the octet SU(3) flavour combinations of the quark distributions as well as for the gluon distribution. The first moments of the non

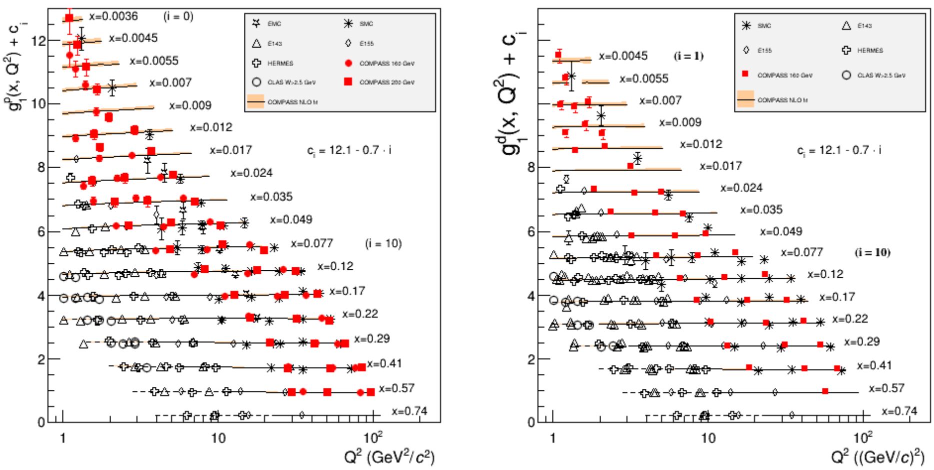

Fig. 3. World data on g_1 proton *(left)* and deuteron *(right)* vs Q^2, for various x. COMPASS data are in red. The dotted lines represent the solutions of a COMPASS global NLO QCD fit (see text)..

singlet distributions are fixed to the values of the axial-vector weak coupling constants measured in neutron and hyperon β-decay. The x-Q^2 evolution is made in the MS factorisation scheme (program #1 taken from [7]). Depending on the choice of the functional forms at the initial Q_0^2 scale, two classes of possible solutions are found. They correspond to a positive and negative ΔG value and values in between are allowed. The value of ΔΣ, correlated to ΔG, ranges between 0.26 and 0.36 at the same scale. The dominant uncertainty in the extraction comes from the choice of the functional forms chosen at the initial Q_0^2 scale. Results for the two solutions are shown in Fig.4 at Q^2 = 3 (GeV/c)^2, with on top the quark singlet helicity $\Delta q^S(x)$ (the integral of which gives ΔΣ) and the gluon helicity $\Delta G(x)$ distributions. In Fig.4 bottom, the quark helicity distributions are shown separately for the u, d and s flavours. The solid and dashed lines correspond to positive and negative ΔG solutions of the NLO QCD fit. The dark and light bands correspond respectively to the propagation of the statistical error from the data and to the combined statistical and systematic uncertainties. The latter largely dominates and comes mainly from the choice of functional forms.

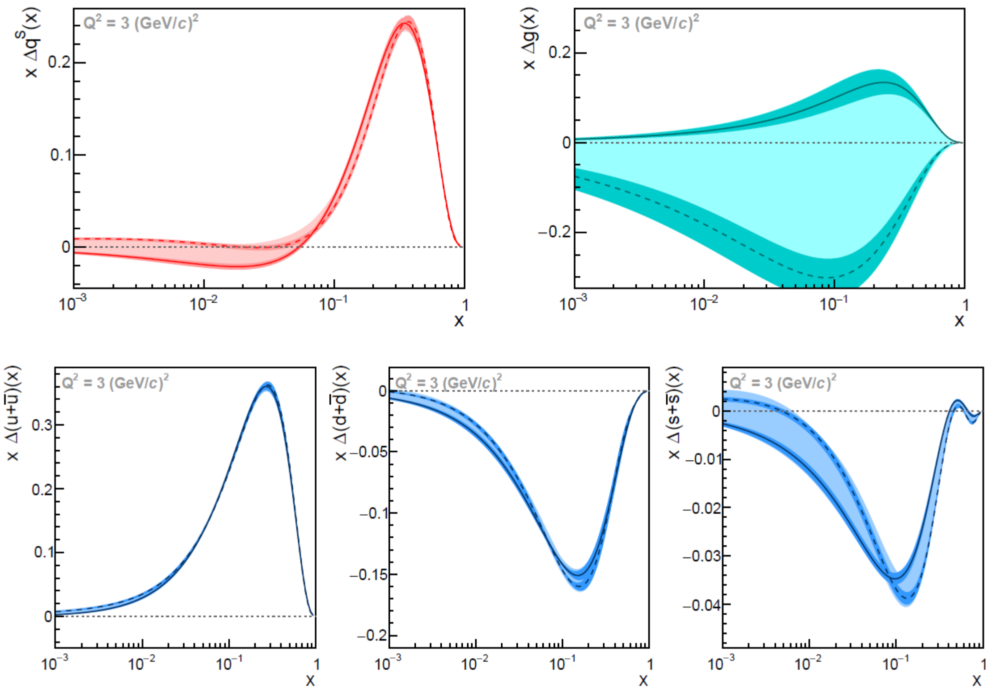

Fig. 4. *Top:* Helicity distributions of the quarks *(left)* and the gluons (*right*) at 3 (GeV/c)2 in MS scheme [1]. *Bottom:* Helicity distributions per flavour. The solid and dashed lines correspond to the solutions with positive and negative ΔG. Dark bands correspond to propagation of statistical errors, and the light bands to the combined statistical and systematic uncertainties (dominating and mainly attributed to choice of functional forms).

4 Measurement of π and K multiplicities in semi inclusive DIS

Parton fragmentation functions (FFs), like parton distribution functions (PDFs), are non-perturbative objects. They describe the hadronization of partons. The FFs are process independent and are used to describe the probability that a quark of flavor q fragments into a hadron of type *h* (D_q^h). They are needed e.g. for the extraction of flavor dependent quark helicity distributions Δq(*x*) [8,9] from semi-inclusive polarized deep inelastic scattering. In particular, to access the strange quark polarization Δs from polarized SIDIS, the strange quark FF into kaon D_s^K is needed and it constitutes by far the largest contribution to the uncertainty in the extraction. Data sensitive to FFs exist from e^+e^- and p p(bar) reactions, but they are insufficient for a good flavor separation; they also lie at relatively too high Q^2 values. This is why it was decided to measure charged hadron multiplicities in SIDIS with a high precision and a fine binning in several variables.
At leading order (LO), the hadron multiplicities $M(x,Q^2,z)$, defined as the mean number of hadrons *h* produced in a semi inclusive deep inelastic scattering event $\mu\, p \rightarrow \mu\, h\, X$, are simply related to PDFs, $q(x, Q^2)$ (for flavour *q)*, and quark FFs, $D_q^h(z,Q^2)$:

$$\frac{\mathrm{d}M^{\mathrm{h}}(x,z,Q^2)}{\mathrm{d}z} = \frac{\mathrm{d}^3\sigma^{\mathrm{h}}(x,z,Q^2)/\mathrm{d}x\mathrm{d}Q^2\mathrm{d}z}{\mathrm{d}^2\sigma^{\mathrm{DIS}}(x,Q^2)/\mathrm{d}x\mathrm{d}Q^2} \tag{1}$$

$$\frac{\mathrm{d}^2\sigma^{\mathrm{DIS}}}{\mathrm{d}x\mathrm{d}Q^2} = C(x,Q^2)\sum_{\mathrm{q}} e_{\mathrm{q}}^2 q(x,Q^2), \qquad \frac{\mathrm{d}^3\sigma^{\mathrm{h}}}{\mathrm{d}x\mathrm{d}Q^2\mathrm{d}z} = C(x,Q^2)\sum_{\mathrm{q}} e_{\mathrm{q}}^2 q(x,Q^2) D_{\mathrm{q}}^{\mathrm{h}}(z,Q^2) \tag{2}$$

where x is the Bjorken variable, *i.e.* the fraction of momentum carried by the struck quark, Q^2 is the momentum transfer and z is the energy fraction taken by the hadron. C depends on kinematics and e_q is the quark fractional charge. Note that apart from the Q^2 dependence, PDFs depend upon x, while FFs depend upon z. This will be useful in the disentanglement of FFs from PDFs, while only the product of both is measured.

The π [10] and K multiplicities [11] were measured using COMPASS SIDIS data taken in 2006 with an isoscalar target (^{6}LiD). They were corrected by the value of the global acceptance of the apparatus estimated in each (x, y, z) bin, where y is the lepton energy fraction carried by the virtual photon. The acceptance of the spectrometer was evaluated from a Monte Carlo simulation, comparing the number of generated and reconstructed events in the whole chain of analysis. For this study, the y variable is chosen instead of the Q^2 one, since Q^2 is too much correlated to x. For the π and K identification a RICH detector is used. Additional corrections including RICH unfolding and radiative corrections were applied. As an illustration, final multiplicities for positive charge kaons are shown in Fig.5 in the three dimensional binning. Similar data were obtained for negative charge kaons, as well as for positive and negative charge pions.

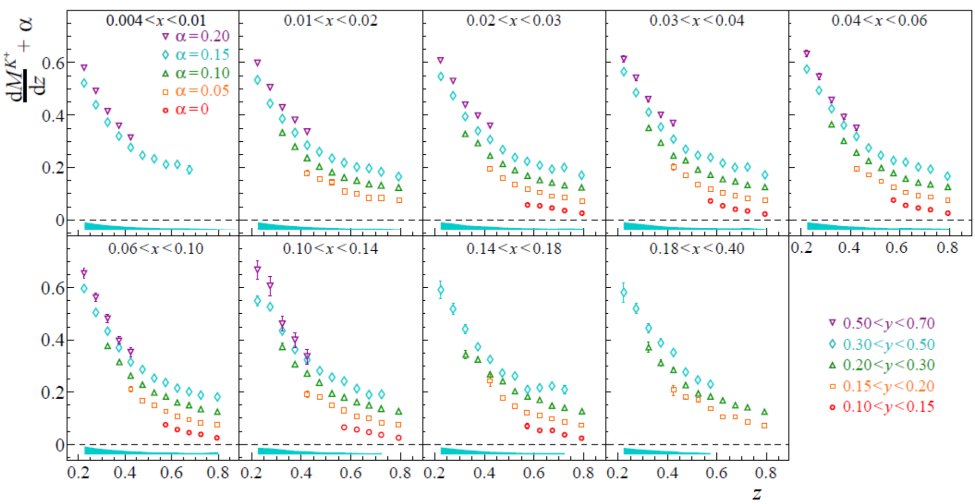

Fig. 5. K$^+$ multiplicities [11] shown vs z for nine x ranges and 5 y ranges (for better visibility shifted vertically by a constant α). Statistical errors are small and hardly visible. The bands correspond to the total systematic uncertainty for the range 0.3 < y < 0.5.

The sum of positively and negatively charged hadron multiplicities integrated over z is of special interest. For kaon multiplicities the sum is used by HERMES [12] to extract at LO pQCD the product of the strange quark distribution and the fragmentation function of strange quarks into kaons. For pions, the sum allows one to verify the applicability of the LO pQCD formalism in the COMPASS kinematic domain. In Fig. 5 COMPASS results are compared to HERMES ones [12] for pions on the left and kaons on the right. Results differ significantly in both cases. However they were taken in different kinematic ranges, COMPASS data covering higher energies than HERMES. NLO QCD analyses of the data should help understanding the discrepancy.

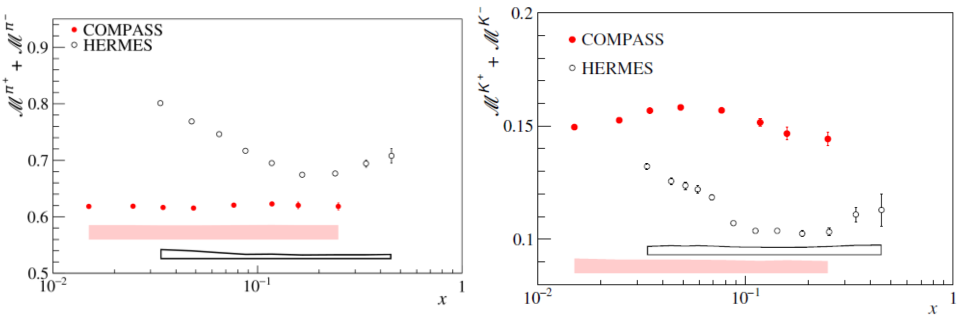

Fig. 6. Sum of positive and negative charge hadron multiplicities integrated over *z* and plotted vs *x*. COMPASS data (full points) are compared to HERMES ones (open points). The bands show the total systematic uncertainties.

5 Extraction of quark fragmentation functions into pions from a LO fit to pion multiplicities

Starting from the equation (1) given at LO, FFs can be extracted once PDFs are taken from the literature. In each (*x,y,z*) bin, two equations are given by the π^+ and π^- multiplicity measured in that bin. We can extract two FFs, namely the favored and unfavored quark FFs into pions. They correspond to pion valance and sea quarks respectively, and are the two independent pion FFs left after applying isospin and charge symmetry relations between FFs, and assuming in addition that the strange quark FF is equal to the unfavored one. In order to use simultaneously all data measured at various Q^2, a LO fit is performed. For this, functional forms are chosen for the shape of the two FFs at an initial Q_0^2 value, and the DGLAP equations are used for the evolution to the measured Q^2 of each data point. Results for the favored and unfavored quark FF into pions obtained from the fit of the pion multiplicities are shown in Fig.6. The statistical error band was obtained with a replica method, varying the data points within their error. Our result [10] is in fair agreement with fits realized at NLO on similar SIDIS data [13]. They differ, as expected from fits including only $e^+ e^-$ data [7].

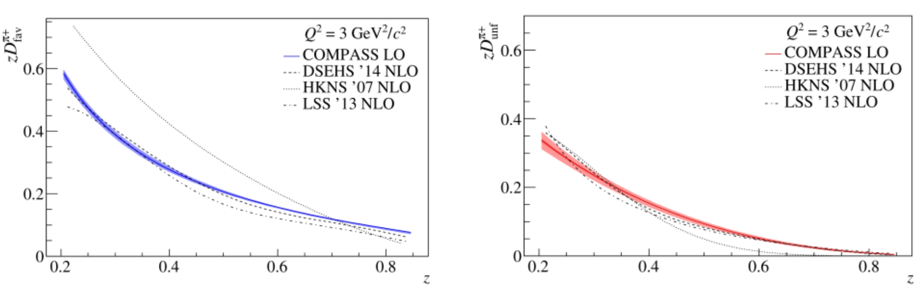

Fig. 6. Favored *(left)* and unfavored *(right)* quark fragmentation functions into pions extracted from a LO fit to COMPASS π multiplicities [10].

6 Conclusion

Recent COMPASS results are show on the spin structure function $g_1^p(x)$ measured using a 200 GeV polarized muon beam. They improve the statistical precision by a factor of ~2 at low x. A re-evaluation of the Bjorken sum rule based on COMPASS data alone confirms its validation within 9% accuracy. The NLO QCD fit was performed to g_1 proton, deuteron and neutron world data. It leads to a value of the quark spin contribution to the nucleon spin $\Delta\Sigma$, between 0.26 and 0.36 at Q^2 = 3 $(\text{GeV/c})^2$. The rather large uncertainty comes essentially from the unknown shape of the polarized parton distributions. The Bjorken sum rule was verified within 9% accuracy using COMPASS data alone, which cover 94% of the contribution to the integral, a remarkable fact compared to other measurements.
Precise results on pion and kaon multiplicities produced in DIS of muons off an isoscalar target were presented. They constitute an impressive data set covering a large kinematical domain, which will be used in future global NLO QCD fits to extract quark fragmentation functions into π and K. A first LO fit was performed to extract the favoured and unfavored quark fragmentation functions into pions. Results agree with previous NLO fits which included a preliminary subset of the present data. The sum of positively and negatively charged hadron multiplicities integrated over z is found in significant disagreement with HERMES data, both for pions and kaons.
The results presented here were previously discussed in a preliminary form [15, 16]. More data on the spin structure function of the deuteron will soon be published by COMPASS, together with an update on the verification of the Bjorken sum rule [17].

References

1. COMPASS Collab., C.Adolph et al., PLB **753**,18 (2016)
2. COMPASS Collab., P.Abbon el al., NIM A **517**, 455 (2007).
3. COMPASS Collab., M. G. Alekseev et al., PLB **690**, 466 (2010)
4. SMC Collab., B. Adeva et al., Phys. Rev. D 58, 11201 (1998)
5. COMPASS Collab., V. Alexakhin et al., PLB **647**, 8 (2007)
6. J. Beringer et al.,, Particle Data Group, Phys. Rev. D86, 010001 (2012)
7. M. Hirai, S. Kumano, T.-H. Nagal and K. Sudoh, Phys. Rev. D **75**,094009 (2007)
8. COMPASS Collab., M. G. Alekseev et al., Phys. Lett. B **693** (2010) 227
9. COMPASS Collab., M. G. Alekseev et al., Phys. Lett. B **680** (2009) 217
10. COMPASS Collab., C.Adolph et al., arXiv 1604.02695, Phys. Lett. B to be published
11. COMPASS Collab., C.Adolph et al., arXiv 1608.06760, subm. to Phys. Lett. B
12. HERMES Collab., A. Airapetian et al., Phys. Rev.D **89** (2014) 097101
13. D. de Florian, et al., Phys. Rev. D **91** (2015) 014035.
14. E. Leader et al., arXiv 1312.5200, Proceedings of DSPIN-13, Dubna, Russia (2013)
15. F. Kunne, Proceedings of SPIN2014, Int. Journal of Modern Physics A: Conf. Series Vol. **40** (2016) 1660017
16. F. Kunne, Proceedings of SPIN2014, Int. Journal of Modern Physics A: Conf. Series Vol. **40** (2016) 1660027
17. M.Wilfert, Contribution to SPIN2016 "Final COMPASS results on the spin dependent structure functions g_1^d and g_1^p"