

# Single hadron multiplicities in SIDIS @ COMPASS

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**Abstract.** Single hadron multiplicities in Semi-Inclusive Deep Inelastic Scattering (SIDIS) provide an important input for the understanding of the hadronisation process and its description in terms of Fragmentation Functions (FFs). COMPASS collaboration has undertaken a programme of measurements of these observables. I first give an overview of the results obtained in the range  $0.20 < z < 0.85$  for the fraction  $z$  of the virtual photon energy carried by the hadron. And I then focus on the multiplicity charge ratio,  $h^-/h^+$ , at large  $z$ , which results challenge the conventional picture of a factorisation between FFs and Parton Distribution Functions (PDFs).

## 1. Introduction

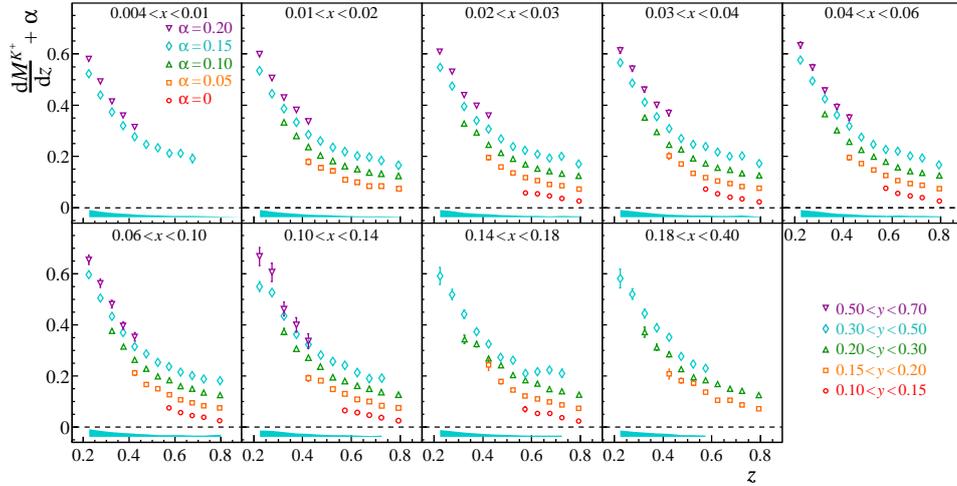
Quark and gluon fragmentation into hadrons is a core ingredient of a QCD-based analysis of hard scattering. In the framework of perturbative QCD (pQCD) with independent fragmentation, the fragmentation process is universal, *i.e.* the hadronisation of a parton does not depend on how it was produced. It is described by non-perturbative objects called Fragmentation Functions. While these functions cannot be presently predicted by theory, their  $Q^2$  evolution can be, using time-like DGLAP evolution equations [1]. At leading order in pQCD, FFs have a probabilistic interpretation, *viz.* the FF  $D_i^h(z, Q^2)$  represents the probability density of the collinear transition of parton  $i$  into a hadron  $h$  carrying energy fraction  $z = E_h/E_i$ . The cleanest way to access FFs is  $e^+e^-$  annihilation. This, however, lacks sensitivity to charge and flavour. SIDIS,  $lN \rightarrow lhX$ , is a complementary approach, better sensitive to both charge and flavour, but depending upon the PDFs in the nucleon  $N$ . The relevant observable is the hadron multiplicity as a function of  $z$ , parton momentum fraction  $x$  and hard scale  $Q^2$ :

$$\frac{dM^h(x, z, Q^2)}{dz} = \frac{d^3\sigma^h(x, z, Q^2)/dx dz dQ^2}{d^2\sigma^{DIS}/dx dQ^2}$$

## 2. $\pi^\pm$ and $K^\pm$ multiplicities

The COMPASS collaboration at CERN has undertaken a programme of measurements of these multiplicity observables in  $\mu N \rightarrow \mu hX$  reactions, where a hadron  $h$  is observed in the final state. Its spectrometer is designed to reconstruct scattered muons and charged hadrons in a wide kinematic range. It is equipped with a RICH for particle identification. It fulfils hence all the requirements. Results have been published for  $\pi^\pm$  [2] and  $K^\pm$  [3] on an isoscalar target. The corresponding data were obtained with a 160 GeV  $\mu^+$  beam impinging on a  ${}^6\text{LiD}$  target. They are corrected for instrumental and radiative effects and, based on event generator HEPGEN[4],



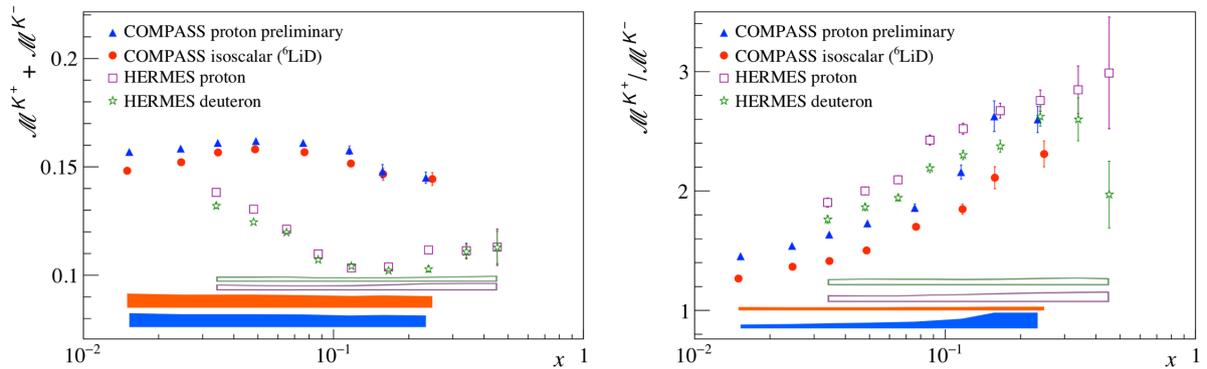


**Figure 1.** COMPASS Multiplicities for  $K^+$  [3] on isoscalar  ${}^6\text{LiD}$  target shown *vs.*  $z$  in bins of  $x$  and virtual photon energy fraction  $y$ , staggered by a constant  $\alpha$ . The bands correspond to the total systematic uncertainty for the range  $0.30 < y < 0.50$ .

for the contamination by the decay of diffractively produced vector mesons. As an illustration,  $K^+$  multiplicities are shown in Fig. 1. Preliminary results have been obtained for  $K^\pm$  on a proton target [5].

The extraction of the FFs is best performed by QCD fits taking into account a large number of hadron production datasets. For example, DEHSS [6, 7] consider  $e^+e^-$  and  $pp$  data in addition to SIDIS. SIDIS, in particular from COMPASS and HERMES [8], plays there a crucial role in the flavour and charge separation [7].

In [2, 3, 5], we compare our results with those from other DIS experiments, *viz.* HERMES [8], EMC [9] and JLab [10]. While reasonable agreement is obtained with the latter two, discrepancies are observed with respect to HERMES, see Fig. 2 as an example. The comparison is done in terms of multiplicities integrated over the measured  $z$  range,  $\mathcal{M}$ .



**Figure 2.** Comparison of  $z$ -integrated multiplicities  $\mathcal{M}^K$  in COMPASS [3, 5] *vs.* HERMES [8]. The charge sum and ratio are shown for  $K^\pm$  produced on proton and isoscalar targets, as indicated in the legends. Systematics are shown by the bands. While both experiments are individually consistent with expectations based on the isospin content of the two targets, significant discrepancies are found between them.

The kinematics are different for the two experiments, with lower centre of mass energy for HERMES. But this alone cannot easily account for the discrepancies [11], particularly so for the  $\mathcal{M}$  observable selected *supra* to evidence the problem, since it is little sensitive to the  $Q^2$  scale.

Several approaches have been pursued to handle the discrepancies. In DEHSS, they are absorbed in uncertainties arising in part from the normalisations of the datasets and otherwise, from the input PDFs. This latter observation underlines the sensitivity of the analysis of SIDIS data to the PDFs. The best way to deal with the fact is to take advantage of it to simultaneously fit FFs and PDFs. Two groups of global fits have started to implement the idea, *viz.* the above-mentioned DEHSS [12] and the JAM group [13]. In [14], the authors explore the impact of target and hadron mass corrections. These are all the more pronounced as the mass of the produced hadron is large and decrease with  $Q^2$ . Their conclusion is that mass effects partially account for the discrepancy observed on the kaons, and that other corrections, possibly from higher twist effects, as well as from unquantified systematic uncertainties are otherwise at play.

### 3. $h^-/h^+$ multiplicity ratio at high $z$

The pQCD framework whereby SIDIS cross-section factorises into a hard scattering, PDFs and FFs is only applicable in the kinematical region of the current fragmentation [15]. This is usually taken into account by restricting the  $z$  range, typically  $z > 0.2$ . COMPASS explored other limitations to this validity domain by investigating fragmentation in the high  $z$  region. For this, we determined the hadron multiplicity ratio:

$$R_h(x, Q^2, z) = \frac{dM^{h^-}(x, z, Q^2)/dz}{dM^{h^+}(x, z, Q^2)/dz}$$

where the observed hadron  $h$  is either a kaon,  $h = K$ , or a proton  $h = p$ .

In this ratio, systematics connected to the instrumental apparatus and to radiative corrections cancel out, which allows to carry out this otherwise experimentally difficult investigation of the high  $z$  region. However, in the pion case, the contamination by decay products of diffractive  $\rho$  vector mesons,  $\rho^0 \rightarrow \pi^+\pi^-$ , prevents us from getting reliable results, since they dominate the high  $z$  region. Instead, for the two selected hadrons, the contamination is either totally absent, in the proton case, or stays within  $0.3 < z < 0.7$  in the kaon case, because of the small break-up momentum of the  $\phi$  meson decay,  $\phi \rightarrow K^+K^-$ .

Results for kaons, obtained on the  ${}^6\text{LiD}$  isoscalar target, are published in [16]. They are shown in Fig. 3, for one  $x$ -bin with  $\langle x \rangle = 0.030$ , as a function of  $z^1$ . Expectations from pQCD calculations based on the DEHSS set of FFs and from the LEPTO Monte Carlo generator [17] are superimposed on the data points. To serve as a guidance, we also show a lower limit obtained using LO pQCD, isospin symmetry and reasonable assumptions on the PDFs, *viz.*:

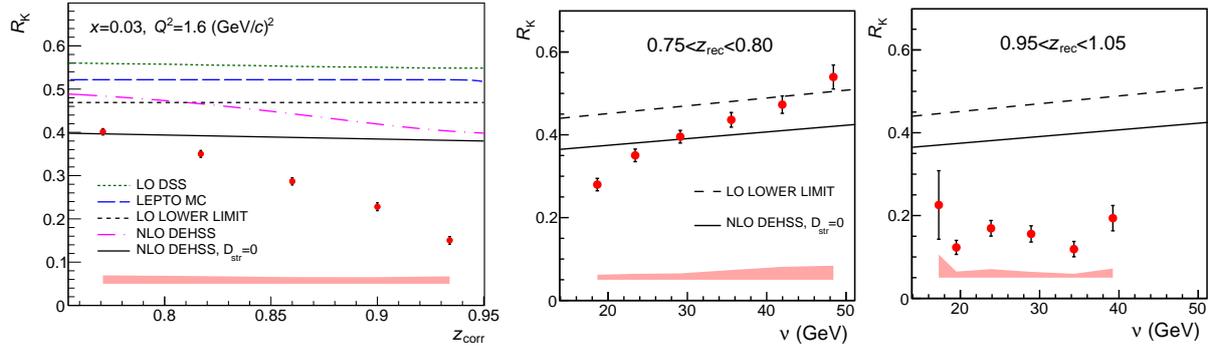
$$R_K > \frac{\bar{u} + \bar{d}}{u + d} \quad (1)$$

and a lower next-to-leading order (NLO) limit obtained by setting  $D_s^{K^+} = D_s^{K^-} = 0$ .

It is observed that with increasing  $z$ , the values of  $R_K$  are increasingly disagreeing with calculations and even with LO and NLO lower limits. A second  $x$  bin with  $\langle x \rangle = 0.094$ , not shown on Fig. 3, is found to exhibit the same departure from expectations, within experimental uncertainties. The discrepancy between the COMPASS results and the NLO predictions reaches a factor of about 2.5 at the largest value of  $z$ . As the difference between the LO and NLO calculations is never larger than 20%, it is very unlikely that any prediction obtained at even higher order would be able to account for such a large disagreement. Higher-twist effects cannot

<sup>1</sup> Note that various estimators of  $z$  are used in the legend of the figures throughout these proceedings: refer to [16] for their exact definition.

account either, since they are proportional to  $1/Q^2$ , and therefore should be smaller by a factor of about three in the second  $x$ -bin. It is worth mentioning that the factorisation approach used for string hadronisation in the LEPTO generator, in spite of its considerably higher flexibility in comparison to the independent fragmentation approach of pQCD, appears also incapable to describe the data at high  $z$ .



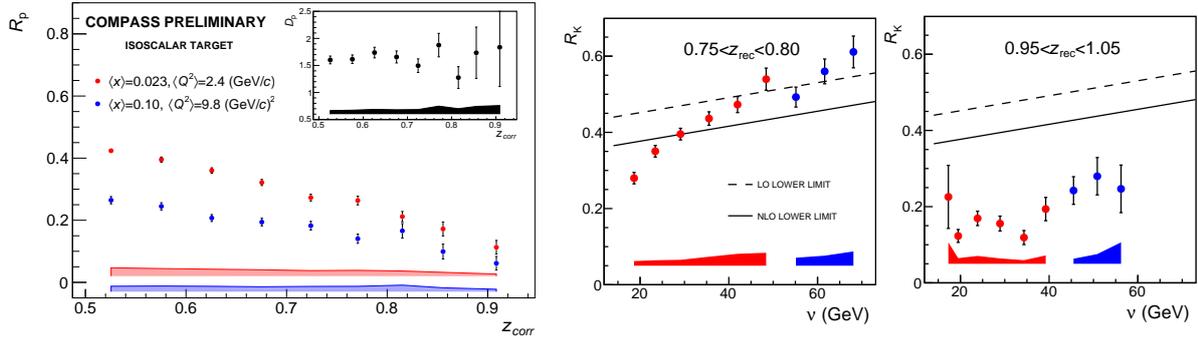
**Figure 3.** *Left:*  $R_K$  (*i.e.*  $K^-/K^+$  multiplicity ratio) as a function of  $z_{\text{corr}}$  ( $\simeq z$ ) [16], compared to predictions. *Centre and right:*  $R_K$  as a function of the energy of the virtual-photon,  $\nu$ , in two bins of  $z_{\text{rec}}$  ( $\simeq z$ ). Statistical uncertainties are shown by error bars, systematic uncertainties by bands at the bottom. LO and NLO pQCD lower limits, defined in the body of these proceedings (see Eq. (1) and text thereafter), are indicated respectively by solid and dashed black lines.

$R_K$  exhibits a strong dependence on the virtual-photon energy  $\nu$ , except at the highest  $z$ . This is illustrated on the centre and right panels of Fig. 3. Note that at most 15% of the observed variation of  $R_K$  with  $\nu$  can be explained by the fact that in a given  $z$ -bin events at different  $\nu$  have somewhat different values of  $x$  and  $Q^2$ . The observed trends suggest that at even lower values of  $\nu$ , like those accessible at fixed target experiments other than COMPASS, a larger range of  $z$  becomes problematic.

Further results, still preliminary, have been extracted from the very same  $^6\text{LiD}$  measurements, complementing those reported above.

Firstly, the  $\bar{p}/p$  ratio,  $R_p$ , has been determined [18]. The results are shown in Fig. 4 for two bins in  $x$ , with  $\langle x \rangle = 0.023$  and  $\langle x \rangle = 0.10$ , respectively. The corresponding LO pQCD limits, calculated with Eq. (1), are about 0.51 and 0.28. Therefore,  $R_p$  ratio falls below limit over the whole kinematical domain considered. Note that the discrepancy shows up at much lower  $z$  than in the kaon case. The double ratio from the two studied  $x$ -bins is shown as an inset. Within uncertainties, it agrees with LO pQCD expectations. The same behaviour was earlier observed for kaons [16]. Conversely, the behaviour of  $R_p$  as a function of  $\nu$ , not illustrated here, exhibits a strong dependence similarly to that of  $R_K$  in Fig. 3. With respect to  $R_K$ , the departure from the LO pQCD limit is stronger and persists up to a higher value of  $\nu$ . It should be noted that  $R_p$  is determined at higher values of  $Q^2$ , because of the constraint imposed on the kinematics of the measurement by the RICH-based identification of  $p$  and  $\bar{p}$ .

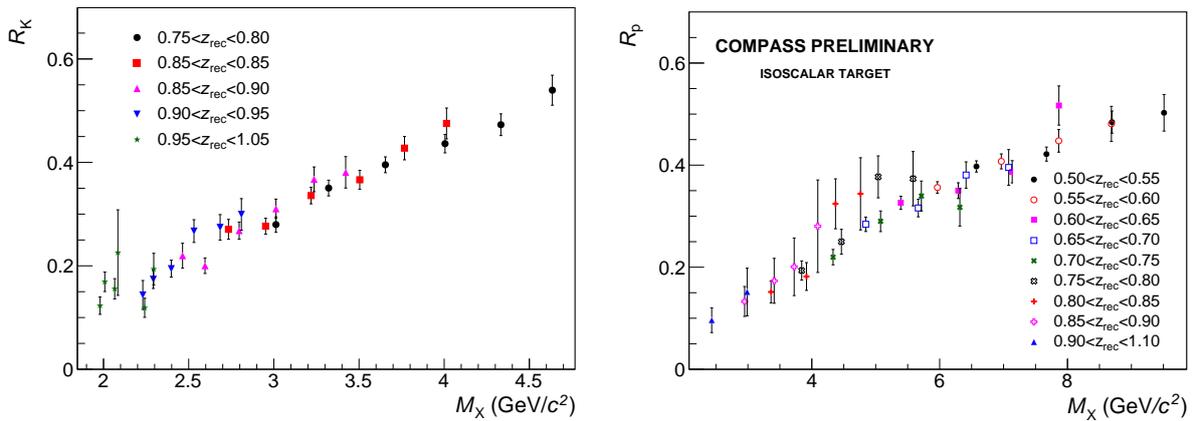
Secondly, the momentum range used in the determination of  $R_K$  has been extended thanks to an improved processing of the RICH information based on neural networks. This allowed in turn to extend the determination of  $R_K$  to higher values of  $\nu$ . The obtained results are shown in the centre and right panels of Fig. 4. At the highest  $\nu$  and lowest  $z$ ,  $R_K$  reaches an asymptotic regime and regains compatibility with the NLO pQCD limit.



**Figure 4.** Left:  $R_p$  as a function of  $z_{\text{corr}}$  ( $\simeq z$ ) for two  $x$  bins [18]. The ratio of ratios for the two  $x$  bins,  $D_p$ , is drawn in the inset. Centre and right:  $R_K$  as a function  $\nu$ , in two bins of  $z_{\text{rec}}$  ( $\simeq z$ ).  $R_K$  is here presented over an extended kinematical domain, as indicated by the blue data points complementing the red ones already shown in Fig.3. Statistical and systematic uncertainties, as well as the LO and NLO pQCD limits are as in Fig 3.

One possible explanation of the phenomenon reported here is that when a high  $z$  hadron is produced, little phase-space is left to the target remnants for the conservation of baryon and strangeness quantum numbers. The relevant variable to study this aspect is the missing mass,  $M_X = |\mathbf{p} + \mathbf{q} - \mathbf{p}_h|$ , where  $\mathbf{p}$ ,  $\mathbf{q}$  and  $\mathbf{p}_h$  are the four-vectors of target, virtual photon and produced high  $z$  hadron. Fig. 5 shows that  $R_K$  and  $R_p$  as a function of  $M_X$  follow a remarkably smooth behaviour.  $M_X$ , which is approximately given by  $M_X^2 = M_p^2 + 2M_p\nu(1-z) - Q^2(1-z)^2$  and which dominant term is  $\propto \sqrt{\nu(1-z)}$ , thus simultaneously expresses both to the  $z$  and  $\nu$  dependences described *supra*. This strongly suggests that  $M_X$  is in fact the prime mover, while the observed  $z$  and  $\nu$  dependences simply result from the correlation of  $z$  and  $\nu$  with  $M_X$ .

Our conclusion is that within the pQCD formalism an additional correction may be required, which takes into account the phase space available for hadronisation. Or else care should be applied to limit its kinematical domain of applicability when analysing SIDIS data obtained at low energy.



**Figure 5.** Ratio  $R_h$  binned in  $z$  and  $\nu$  as a function of the missing mass  $M_X$ . Left:  $R_K$  results from [16]. Right: Preliminary  $R_p$  results [18].

#### 4. Conclusions and outlook

COMPASS has collected SIDIS data on a liquid hydrogen target in 2016 and 2017. Multiplicities extracted from these data will provide interesting information on the FFs, complementary to that obtained on an isoscalar target and published in [2, 3]. An improved treatment of radiative corrections, based on the event generator DJANGO [19], is expected to help reduced systematic uncertainties.

Our results on the charge ratio of single hadron multiplicities,  $R_h = M_{h^-}/M_{h^+}$ , show that the applicability of the pQCD formalism to SIDIS becomes questionable at high  $z$  and low values of the virtual photon energy,  $\nu$ . The effect is all the more pronounced as the mass of the observed hadron is larger. In COMPASS, the problematic domain is restricted to a corner region of phase space. However, with experiments at lower centre of mass energy, this should not be the case, and problems with the pQCD description of the data should already show up at lower values of  $z$ . Moreover, protons and kaons add up together to about 25% of all produced hadrons. Thus, when performing phenomenology studies of non-identified hadrons one should be quite careful, as the presence of kaons and protons may introduce bias in the obtained results.

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