Next to Leading Order Semi-inclusive Spin Asymmetries

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Abstract

We have computed semi-inclusive spin asymmetries for proton and deuteron targets including next to leading order (NLO) QCD corrections and contributions coming from the target fragmentation region. These corrections have been estimated using NLO fragmentation functions, parton distributions and also a model for spin dependent fracture functions which is proposed here. We have found that NLO corrections are small but non-negligible in a scheme where gluons are polarised and that our estimate for target fragmentation effects, which is in agreement with the available semi-inclusive data, does not modify significantly charged asymmetries but is non negligible for the so called difference asymmetries.

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Introduction:

Recently, the Spin Muon Collaboration (SMC) [1] have presented a measurement of semi-inclusive spin asymmetries for positively and negatively charged hadrons from deep inelastic scattering of polarised muons on polarised protons and deuterons. This data, combined with previous measurements [2–4] of this kind can be used to determine polarised valence and non-strange sea quark distributions.

Up to now, the analyses [1–4] of semi-inclusive spin asymmetries have been performed in the naive quark-parton model, neglecting higher order corrections and trying to avoid contributions coming from the target fragmentation region imposing kinematical cuts. This procedure simplifies greatly the extraction of parton distributions and seems to be adequate given the present accuracy of the data and the restriction to high hadron energy fractions.

However, taking into account that the most recent analyses of parton distributions [5–7], which are performed in the NLO approximation from totally inclusive data, have shown the importance of including these effects, and that the forthcoming semi-inclusive experiments [8] promise better accuracy than the obtained so far, it is worthwhile analysing the size of these hitherto neglected contributions.

Higher order corrections can be non-negligible if gluons are polarised in the proton and, in the case of semi-inclusive processes, require a non trivial treatment of collinear divergences related to the target fragmentation region. This has been addressed in references [10] and [11]. In this last reference, the concept of fracture functions has been introduced as a mean to describe target fragmentation phenomena. The full NLO contributions to semi-inclusive cross-sections, including those related to fracture functions, have been calculated recently in references [12] and [13] for unpolarised and polarised deep inelastic scattering, respectively.

As the parton distributions and the fragmentation functions, fracture functions are non-pertubative objects that have to be extracted from semi-inclusive high precision experiments. This task is not possible yet, however one can estimate the size of the target fragmentation corrections effects using a sensible model for fracture functions based on parton model ideas.

In order to establish our notation, in the next section we show the naive quark parton model expressions for the semi-inclusive cross sections and the full NLO ones. We also remind the definition of the spin asymmetries in terms of the former cross sections. In the following section we present our choice for parton distributions, fragmentation functions and the main features of the model proposed for fracture functions. In the last section we show results and present our conclusions.

NLO Cross Sections

In the naive quark-parton model, the semi-inclusive cross section for the production of a hadron h from polarised deep inelastic scattering of charged leptons carring momentum l on nucleons with momentum P, is usually written as [13]:

$$\frac{d\Delta\sigma_N^h}{dx\,dy\,dz} = \lambda Y_P \sum_{i=q,\bar{q}} c_i\,\Delta q_i(x)\,D_{h/i}(z) \tag{1}$$

where λ is the helicity of the lepton, $c_i = 4\pi e_{q_i}^2 \alpha^2/x(P+l)^2$, and $\Delta\sigma_N^h$ denotes the difference between cross sections of targets with opposite helicities. This cross section is differential in the variables x, y and z defined by

$$x = \frac{Q^2}{2P\cdot q}, \quad y = \frac{P\cdot q}{P\cdot l}, \quad z = \frac{E_h}{E_N(1-x)} \tag{2}$$

where q is the transfered momentum ($-q^2 = Q^2$) and E_h and E_N are the produced hadron and target nucleon energies, respectively. The unpolarised cross section can easily be obtained changing the kinematical factor $\lambda Y_P = \lambda(2-y)/y$ for $Y_M = (1+(1-y)^2)/2y^2$ and removing the Δ's, which denote differences in polarization. Δq_i is the spin-dependent parton distribution of flavour i and $D_{h/i}$ is the fragmentation function of a hadron h from a parton i.

It is customary to define spin asymmetries A_{1N}^h, proportional to the difference between the number of events for antiparallel and parallel orientation of the lepton and the nucleon spins, which in our notation are given by

$$A^h_{1\,N} = \frac{Y_M}{\lambda Y_P}\frac{\Delta\sigma^h_N}{\sigma^h_N} \tag{3}$$

and in the naive parton model reduce to

$$A^h_{1\,N} = \frac{\sum_i e_i^2 \Delta q(x) D_{h/i}(z)}{\sum_i e_i^2 q(x) D_{h/i}(z)} \tag{4}$$

Actually, the data on these asymmetries is restricted to positively and negatively charged hadrons with the cross section integrated over some range of the variable z.

The difference asymetries [14], $A_N^{h^+-h^-}$ are given by

$$A_N^{h^+-h^-} = \frac{Y_M}{\lambda Y_P}\frac{\Delta\sigma_N^{h^+} - \Delta\sigma_N^{h^-}}{\sigma_N^{h^+} - \sigma_N^{h^-}} \tag{5}$$

and in this approximation have no dependence on the fragmentation functions, leading to expressions like

$$A_D^{\pi^+-\pi^-} = \frac{\Delta u_v + \Delta d_v}{u_v + d_v}, \qquad A_p^{\pi^+-\pi^-} = \frac{4\Delta u_v - \Delta d_v}{4 u_v - d_v} \tag{6}$$

for pion production on deuterium and proton targets respectively. In the next to leading order approximation, the polarised cross sections have the following expression

$$\begin{aligned}
\frac{d\Delta\sigma^h_N}{dx\,dy\,dz} = \lambda_P \sum_{i=q,\bar{q}} c_i \Bigg\{ \int\int_A \frac{du}{u}\frac{d\rho}{\rho} \; \Bigg\{ & \Delta q_i(\frac{x}{u},Q^2)\, D_{h/i}(\frac{z}{\rho},Q^2)\, \delta(1-u)\delta(1-\rho) \\
& + \Delta q_i(\frac{x}{u},Q^2)\, D_{h/i}(\frac{z}{\rho},Q^2)\, \Delta C_{qq}(u,\rho) \\
& + \Delta q_i(\frac{x}{u},Q^2)\, D_{h/g}(\frac{z}{\rho},Q^2)\, \Delta C_{qg}(u,\rho) \\
& + \Delta g(\frac{x}{u},Q^2)\, D_{h/i}(\frac{z}{\rho},Q^2)\, \Delta C_{gq}(u,\rho) \Bigg\} \\
+ \int_B \frac{du}{u}(1-x) \; \Bigg\{ & \Delta M^h_{q_i}(\frac{x}{u},(1-x)z,Q^2) \Big(\delta(1-u) \; + \Delta C_q(u) \Big) \\
& + \Delta M^h_g(\frac{x}{u},(1-x)z,Q^2)\, \Delta C_g(u) \Bigg\}\Bigg\}
\end{aligned} \tag{7}$$

where the ΔC's are the NLO coefficient functions [15], which are proportional to α_s, and ΔM^h_i are the spin dependent fracture functions. Details about the convolution variables and integration limits can be found in references [12,13]. Notice that the difference between equations (1) and (7) is not only proportional to α_s, but there is a leading order fracture contribution which is neglected in the most naive approximation. Obviously, the spin asymmetries develop much more complicated expressions, particularly, the difference asymmetries do not reduce just to combinations of partons distributions as in equation (6), and depend on the variable z. Notice that the variable z defined in equation (2) and used in equation (7) coincides with the one used in the analyses performed up to now, $z_h = P.P_h/P.q$ [10] in the naive approximation but they differ for higher order processes, in which the hadron may be produced at an arbitrary angle θ with respect to the beam direction

$$z_h = z\,\frac{1+\cos\theta}{2} \tag{8}$$

The z variable so defined is much more convenient for factorization purposes [12].

Inputs

In order to feed equation (7) with parton distributions and fragmentation functions, we have chosen two sets of NLO parametrizations for polarised parton distributions [16], one for unpolarised distributions [17] and one for NLO fragmentation functions [18]. The polarised sets reproduce the main features of the available inclusive data and are defined within a physical factorization presciption ($\overline{MS_p}$), the same chosen for the coefficients in equation (7). In one of these sets (set 1) the gluons are polarised whereas in the other (set 2), the strange sea quarks are responsible for the low value of Ellis-Jaffe integral [19]. Both sets satisfy positivity constraints with respect to the unpolarised sets, something that is crucial for computing asymmetries. The fragmentation functions do not imply the full flavour symmetry relations between hadrons that were assumed in reference [1]. These functions were obtained as NLO fits to charged pion and kaon production in e^+e^- annihilation.

Fracture functions are a relatively new concept and have not been measured yet, so there are not parametrisations available for them. However, taking into account that these functions measure the probability for finding a hadron and a struck parton in a target nucleon, one can approximate them as a simple convolution products between known distributions.

These are the probabilities for finding the struck parton in a nucleon carrying a fraction x of its momentum, the one for finding another parton in the target remnant (with momentum fraction constrained to the interval $[0, 1-x]$) and that for its fragmentation in the observed hadron with momentum fraction $z(1-x)$. Assuming that the correlation between both subprocesses is dominated by the momentum balance, a tipically partonic assumption, our proposal for the fracture functions reads as

$$M_j^h(x, z(1-x)) = q_j(x)\,\frac{1}{N(x)}\int_z^1 \frac{dt}{t}\sum_k q_k(t(1-x))D_{h/k}(z/t) \tag{9}$$

The index j reffers to the struck parton (quark or gluon), and k denotes an intermediate parton which undergoes hadronization into a particle h. A sum over all possible intermediate flavors and momentum fractions is implied. The function $N(x)$, given by

$$N(x) = \frac{\int_0^{1-x} dy\, y\, q(y)}{(1-x)}, \tag{10}$$

normalizes the full remnant momentum to $(1-x)$, as required for consistency, and guarantees the momentum sum rule fulfilment [11]

$$\sum_h \int dz\, z\, M_j^h(x, z(1-x)) = \frac{q_j(x)}{(1-x)} \tag{11}$$

provided

$$\sum_h \int dz\, z\, D_{h/j}(z) = 1 \tag{12}$$

Analogously, spin dependent fracture functions can be modelized using spin dependent parton distributions for the struck parton and unpolarized distributions for the remaining part. The normalization function is the same as in equation (10), which also guarantees the analogous sum rule

$$\sum_h \int dz\, z\, \Delta M_j^h(x, z(1-x)) = \frac{\Delta q_j(x)}{(1-x)} \tag{13}$$

In the next section we estimate the higher order corrections to the semi-inclusive charged and difference spin asymetries using the distributions presented here and our model for fracture functions.

Results:

In order to compare with the available data on semi-inclusive spin asymmetries, we compute them taking into account the production of charged pions and kaons and we integrate the cross sections in the variable z over the measured range. Charged kaon production adds negligible contributions to charged asymmetries, which are dominated by pion production, however we take them into account because of its role in difference asymmetries as it will be discussed later.

In figure (1) we show positively (1a,1b) and negatively (1c,1d) charged hadron asymmetries on protons using both sets for polarised parton distributions. The solid lines correspond to the most naive contribution $-\mathcal{O}(\alpha_s^0)$ and without target fragmentation effects-, long-dashed lines include NLO corrections to fragmentation processes, short-dashed lines (almost overlapping with the solid ones) takes into account fragmentation and fracture but at LO, finally the dotted lines (overlapping with the long dashes) show the result of the full NLO computation (equation 7).

These figures show clearly that target fragmentation effects are negligible in the charged asymmetries for $z > 0.2$. This is due, at small x ($x < 0.1$) where the contributions from target fragmentation to cross sections are large, to the suppression of the full asymmetries caused by the increase of the unpolarised cross section. At intermediate x ($x \sim 0.3$), the dominance of current fragmentation over target fragmentation is the main reason for the smallness of the correction. At larger values of x ($x \geq 0.5$), target fragmentation becomes again of the same order of current fragmentation, however both hadronization contributions tend to be cancelled in the asymmetry due to the fact that those considered here -producing spinless final states- are essentially independent of the initial state polarisation (that of the struck parton). The model accounts for this fact because it defines fracture functions in which the hadronization part is the same for the polarised and the unpolarised case, being the spin dependence restricted to the probability of finding the struck parton. In other words,

$$\frac{\Delta M_i^h}{M_i^h} = \frac{\Delta q_i}{q_i} \tag{14}$$

Next to leading order corrections are small but non negligible for sets with gluon polarization, as can be seen in figures (1a) and (1c), if the forthcoming experiments reach the expected accuracy. As these corrections are dominated by those of gluon origin, they have no significant consequences for set 2, figures (1b) and (1d).

The same features are observed for deuterium targets, figures (2a), (2b), (2c) and (2d). We also show the most recent SMC proton and deuterium data [2], and that presented by EMC [1].

In figures (3a) and (3b) we show the curves of figure (1a) and (1c) but only for charged pion production against the accuracy expected from Compass [8,9] for two years running at 100 GeV.

It is interesting to notice that the cancellation of fracture function contributions in charged asymmetries allows a naive interpretation for them with less stringent cuts in z than those used up to now. This choice would eventually allow a substantial improvement of the experimental statistics. In figure (4) we show the corrections exhibited in figure (1a) but for $z > 0.1$ instead of $z > 0.2$ as in the previous figures.

A completely different situation is observed for the difference asymetries, figures (5) and (6), in this case calculated for values of z greater than 0.25 in order to compare with the experimental data presented in reference [4]. In these asymmetries the suppression due to the unpolarised cross sections is not present at small x so target fragmentation effects are then quite significant (short dashes for LO and dots for NLO) particularly for proton targets. This is related to the fact that the asymmetries depend on the differences between the probabilities for positive and negative hadron production. This also affects the intermediate x region, where the differences are comparable in the current and target fragmentation cases.

Regarding the differences between the prediction of both sets of parton distributions in figures (5,6), it can be noticed that these are less conspicuos due to the cancellation of the gluon initated contributions in the numerators.

Corrections to equation (1) have also other serious consequences in difference asymmetries. Notice that the passage from equation (5) to equation (6) implies the cancellation of a factor, both in the numerator and the denominator of these equations, like

$$\left[D_{\pi^+/u}(z) - D_{\pi^-/u}(z)\right] \tag{15}$$

which is found to be zero around $z \sim 0.2$ in different experiments [18]. The above mentioned corrections, however, shift the zeros of numerator and denominator in a different way causing large distortions (even divergencies) from the naive expectation [14]. These distortions make pointless a naive interpretation of the difference asymmetries, at least for values of z of the order or lower than 0.2. In figure (7) we show the more recent data [9] on difference asymmetries applying cuts for $z < 0.2$. The solid lines correspond to the naive expectation for them and the dotted line includes all the corrections. Figure (7a.) shows an impressive agreement between the data and the corrected prediction. Corrections are larger than the ones obtained for more restricted cuts. The deuteron asymmetry seems to be particularly sensitive to the effect when the data around $z \sim 0.2$ is included, as it can be seen in a comparasion between figures (6a.) and (7.b). We have omitted the corrections in the last figure because they are not well defined, specifically, they diverge for $x \sim 0.02$ and depend strongly on the fragmentation functions used.

At variance with the charged asymmetries, difference asymmetries only allow analyses with a lower cut in z if large corrections are taken into account. This fact by no means challenges difference asymmetries. On the contrary, the comparison between the results comming from them and those from inclusive and the other semi-inclusive observables allows one to explore new aspects of the parton model, in particular fracture function contributions to cross sections.

Conclusions:

In this paper we have found that that NLO corrections to semi-inclusive spin asymmetries, particularly those related to target fragmentation effects, are not negligible and can be treated quantitatively using a sensible model for fracture functions.

Taking into account these corrections, one can safely reduce the kinematical cuts used in the analysis of the experimental data on charged asymmetries, correct the naive interpretation of the difference asymmetries for $z > 0.25$, and give an explanation to the features of the data for lower z cuts. We expect that these issues will be relevant in the analyses of the forthcoming semi-inclusive experiments.

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Figure Captions:

Figure 1: Semi-inclusive asymmetries for muoproduction of charged pions and kaons on a proton target with $z > 0.2$; a) and b) for positive hadrons calculated with sets 1 and 2, respectively, c) and d) for negative hadrons. The curves correspond to the naive estimate (solid), adding target fragmentation effects al LO (short dashes almost superimposed with the previous), current fragmentation at NLO (long dashes), and the full NLO prediction. The data correspond to EMC and SMC experiments.

Figure 2: The same as in figure (1) but for deuterium targets.

Figure 3: The same as in figures (1a) and (1c) but for charged pion production. The error bars represent the expected accuracy for two years of running of the Compass experiment.

Figure 4: The same as in figure (1a) but for $z > 0.1$

Figure 5: Naive estimate of the difference asymmetry and corrections, calculated with $z > 0.25$ for porton targets.

Figure 6: The same as in figure 5 but for deuteron targets.

Figure 7: Recent SMC data [9] on difference asymmetries applying cuts for $z < 0.2$.

FIGURES

FIGURE 1

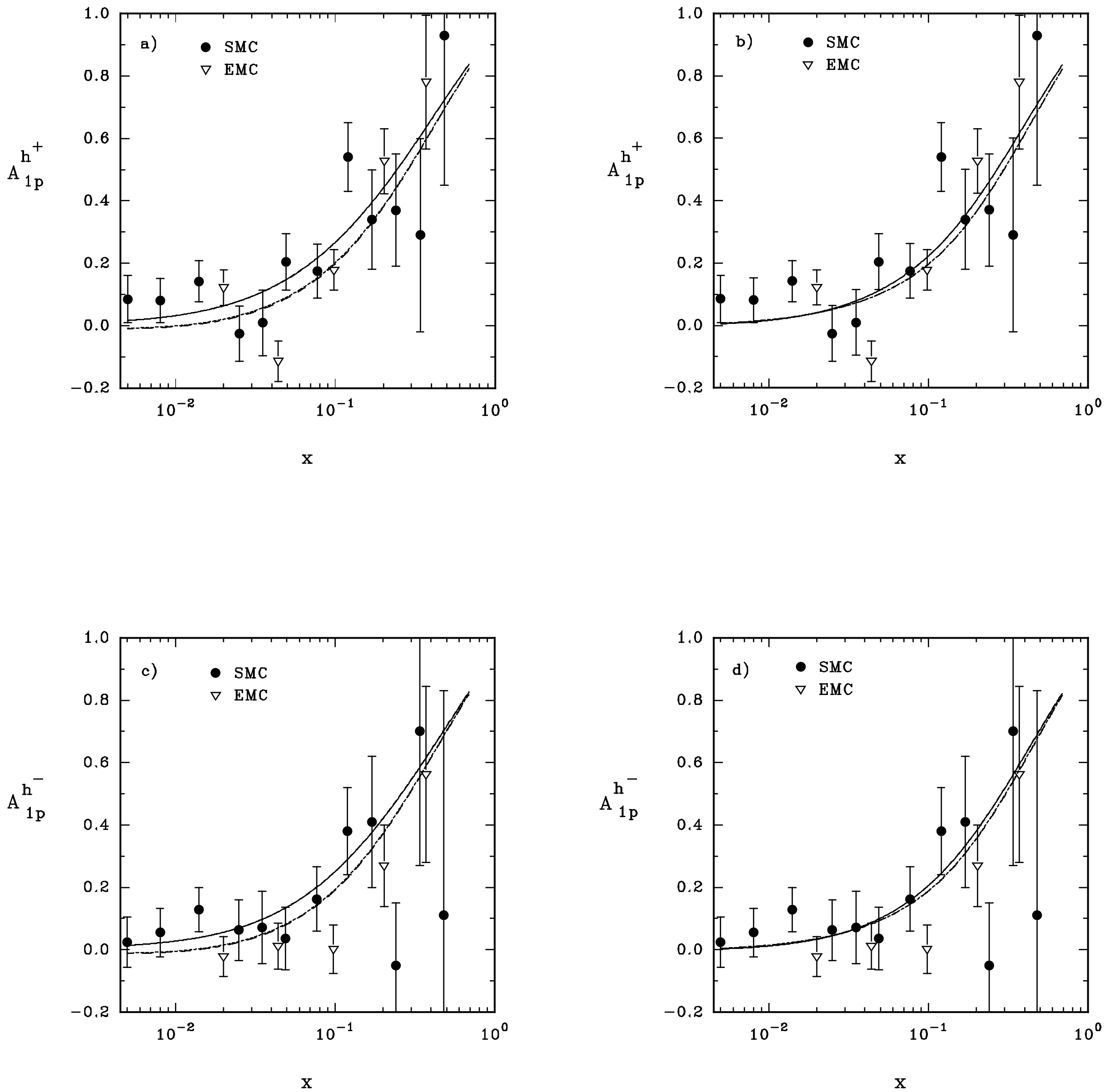


FIGURE 2

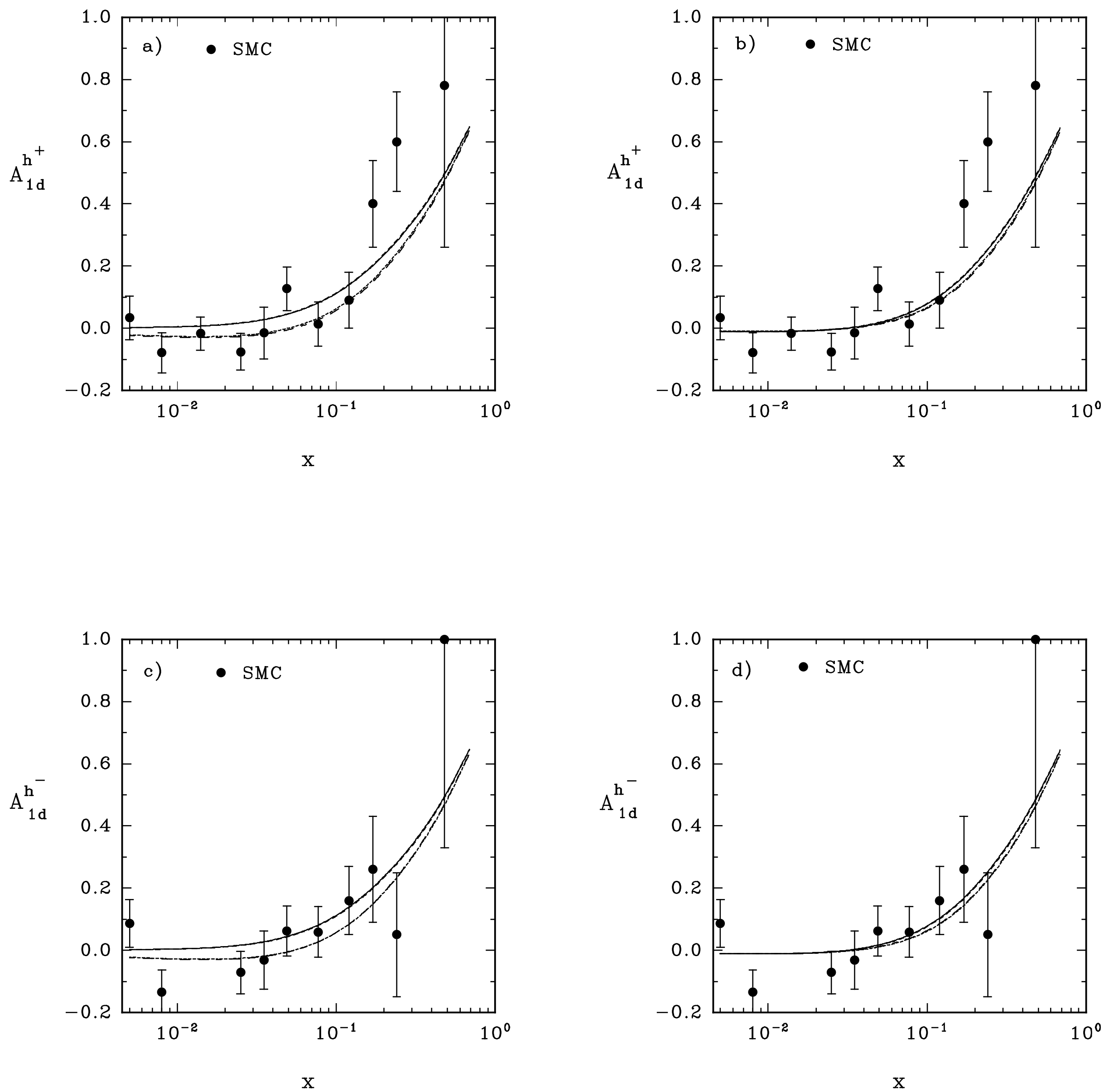


FIGURE 3

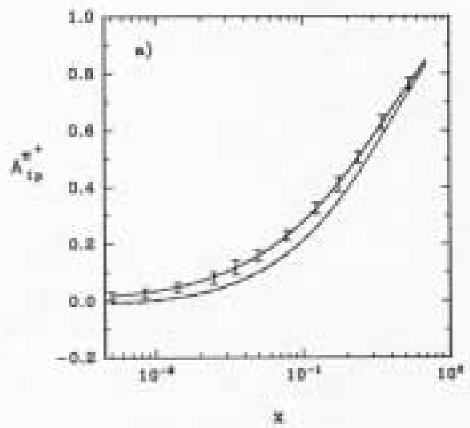


FIGURE 4

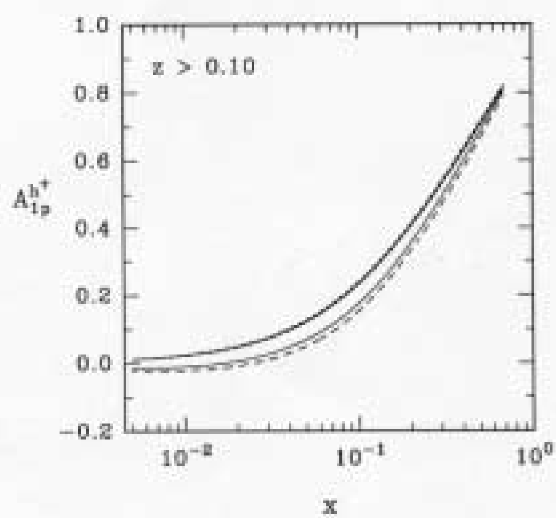


FIGURE 5

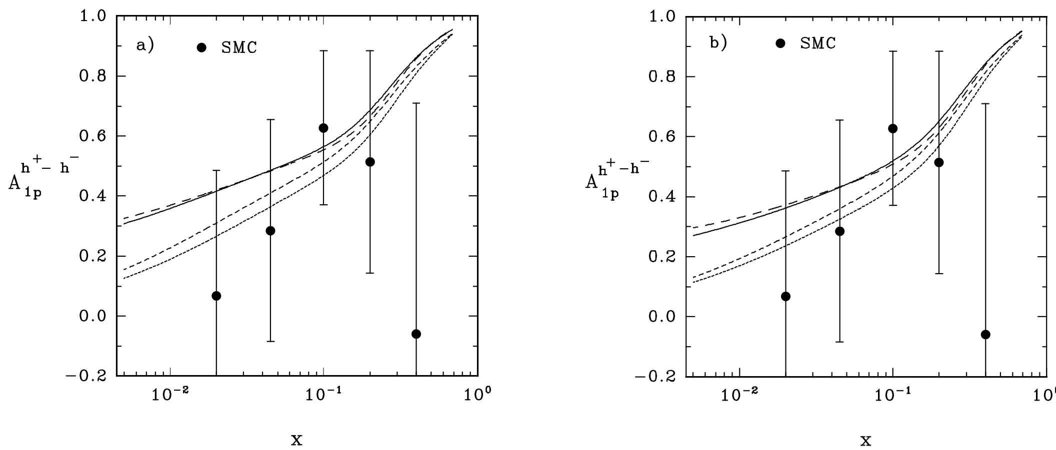


FIGURE 6

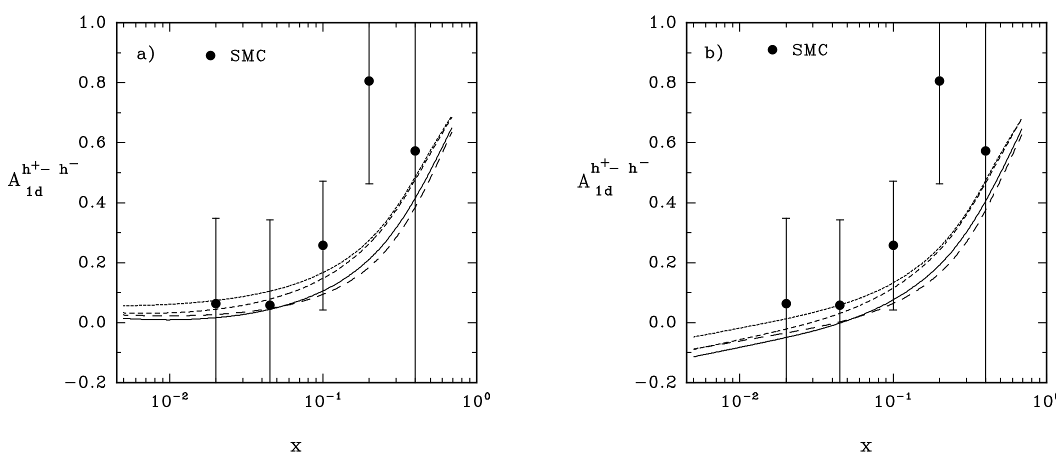
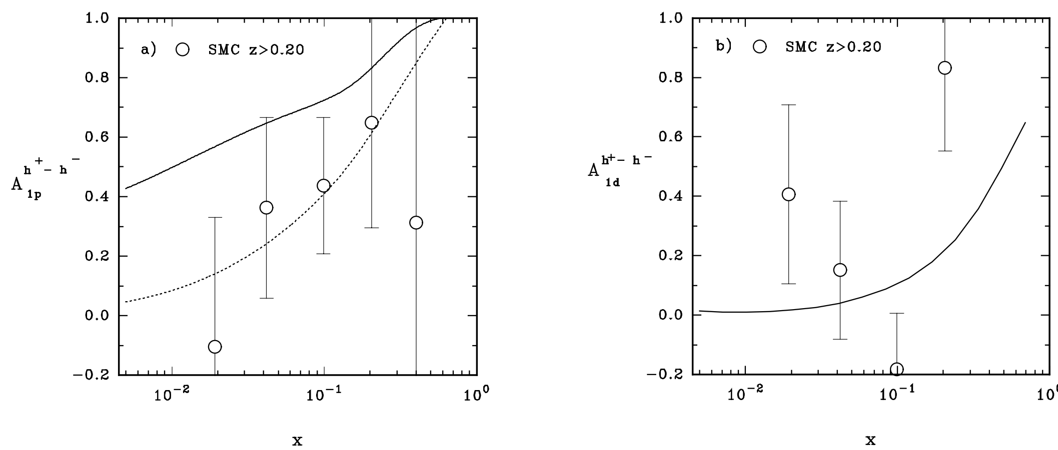


FIGURE 7



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