Target mass correction, based on the re-scaled parton densities

M. M. Yazdanpanah¹, R. Mohammadi pour¹, and A. Mirjalili²a

¹ Faculty of physics, Shahid Bahonar University of Kerman, Kerman, Iran
² Physics Department, Yazd University, P.O. Box 89195-741, Yazd, Iran

Received: date / Revised version: date

Abstract. Target mass correction (TMC) is being used to improve the theoretical results for the nucleon structure functions. This improvement makes the fitting more reliable with the available experimental data in lepton scattering off the nucleon. The recent relations, using the Georgi and Politzer approach indicate that employing TMC effect are cumbersome, long and contains complicated integrals. Some of these integrals can not be solved exactly and people are forced to use approximate methods which seems not to give sufficient and precise results. On the other hand on analysing the TMC effect we encounter with the threshold problem for nucleon structure which results to have the structure function in a regions which are physically forbidden. Here we render a new solution way, based on the re-scaled parton densities to resolve the difficulty, relating to the TMC effect. Our solution way can be employed directly and easily to the parton distribution rather than to the nucleon structure function. There are different options to amend the parton densities. What we call as third re-scaling is the best one. Using it we are able to discard the threshold problem for the nucleon structure function without resorting to apply some auxiliary mathematical tools like the step function which is plausible by people. On this way we obtain a better agreement for the nucleon structure function with the available experimental data in comparison with the ordinary TMC results, based on Georgi and Politzer approach and some other approaches.

PACS. 12.38.Bx, 12.38.Aw, 12.38.Qk, 14.65.Bt

1 Introduction

For the very small size of dimension, smaller scale than nuclei size, there are some specific theories to investigate the parton interaction dynamic [1,2,3]. However there is not any completed and exclusive theory to describe exactly what are being happened inside the nucleon. To recognize the subatomic structure better we need to resort the deep inelastic scattering (DIS) process for leptons off the nucleon as a sufficient and rich investigating instrument. The DIS experiment can be used to investigate the dynamical behavior which are govern the quarks and gluons interactions inside the nucleon.

To analysis the experimental data of DIS, there are different models. But these models are not exact and need some corrections to yield us reliable results. In the related approximations the forces between the partons which are infinitesimal and do not leak out at any place, are usually ignored. If we wish to achieve more exact relations for describing the subatomic particles, we need to consider the effect of these forces in the interval which are more effective. As a result we should employ the TMC effect which can be applied in the naive quark-parton model.

TMC is in fact to consider the effect of mass for the particles in DIS experiment which people usually ignore it. The history of considering TMC is too long and back essentially to 1976 when Georgi and Politzer took it into account to the nucleon structure function which is relating as well the electro-weak force [4]. TMC in DIS scale, includes the effects resulted from massive quarks. This correction was followed latter on by Elice, Formansky and Petronzio, based on quark-parton model [5]. All the calculations have been done in the leading order(LO) approximation which then extended to the next-to-leading-order(NLO) approximation by De Rujula, Georgi and Politzer [6]. Recently some investigations have been done by Kretzer and Reno in the NLO approximation, considering the charged current which exists when the partons are assumed to interact with each other [7,8].

The method which was introduced by Georgi and Politzer, was in fact based on operator product expansion (OPE) theorem [9]. Latter on Nachtmann [10] showed that using OPE theorem in terms of $\frac{1}{Q^2}$ expansion, only a twist two operators are needed where twist is defined as dimension minus spin. The dimension means the naive canonical dimension of an operator and spin relates to its transformation properties under the Lorentz group. In general, power-suppressed contributions are referred as higher-twist contributions. TMC consists of power-suppressed twist-2...
operators that occurs in the expansion when the target mass is not set to zero. Those corrections can be exactly taken into account by expressing the structure functions in terms of Nachtmann variable, $\xi$, rather than the $x$-Bjorken variable. At a specific $Q^2$, this variable is defined by a four vector which is relating to the momentum fraction of nucleon ($p$), carried by parton ($k$) [9]:

$$\xi (x, Q^2) = \frac{k^0 + k^z}{p^0 + p^z} = \frac{2x}{1 + \sqrt{1 + \frac{4x^2M^2}{Q^2}}}.$$  \hspace{1cm} (1)

Using this variable, there are some difficulties whose famous one is called “threshold problem”. When nucleon structure function is written in terms of Nachtmann variable, the maximum value of $\xi$ at a specified value of $Q^2$ is $\xi_0 = \xi (x = 1) < 1$ which causes the parton distribution and finally nucleon structure function appear on the physical range of $\xi = 0$ to $\xi = \xi_0$. For the interval in which $\xi_0 < \xi < 1$, the Bjorken variable $x$ exceeds its maximum value $x = 1$ which is physically forbidden. To overcome this difficulty, some solution ways are suggested which by themselves makes other difficulties [9,11,12]. On the other hand if someone wishes to follow the Georgi and Politzer approach then the main relations to consider the TMC effect for the structure function involve many complex integrals which we are not able to calculate them easily.

Here we first introduce the recent relations which exist for TMC and then express our idea to resolve the difficulty which we referred it. Finally we present the result of this difficulty, some solution ways are suggested which by themselves makes other difficulties [9][11][12]. On the other hand if someone wishes to follow the Georgi and Politzer approach then the main relations to consider the TMC effect for nucleon structure function by this approach, is a long equation and involves complicated integrals, given by Eqs.(3,4). So employing the TMC equation, Eq.(2), is a long equation and involves complicated integrals, given by Eqs.(3,4). So employing the TMC effect for nucleon structure function by this approach, is a tedious task. Sometime due to the unsolvable integrals, achieving the correction, using this approach is impossible. On this base, some people are trying to use the approximate relations [6]. But these approximations would yield us reliable results just at some specific energy scales. This is why people are encouraging to seek the other approaches, based on the modified parton densities to employ the TMC effect for nucleon structure function by this approach, is a tedious task. Sometime due to the unsolvable integrals, achieving the correction, using this approach is impossible. On this base, some people are trying to use the approximate relations [6]. But these approximations would yield us reliable results just at some specific energy scales.

2 Revisiting the TMC; Georgi and Politzer approach

Here we intend to consider where the TMC has been ignored in which we need to amend the nucleon structure function to involve the mass corrections. In fact we are looking for where the required forces in interaction between partons have been existed in which we need to employ the corrections. If we use Lorentz frame in which $|p| \gg m, M$, i.e. the frame where parton has infinite momentum then we can take the nucleon and its parton as massless particles. In this frame, the relativistic delay time, possesses low rate for parton interactions. Therefore virtual photon interacts in a short time with quarks which seems like free particles. So in a naive theoretical consideration of DIS processes, quarks do not interact with each other. In a real case when partons are constrained to be inside the nucleon, they interact to each other. Effect of the forces which quarks make to each other, would causes to produce some small mass effect which is related to TMC. The relations of the nucleon structure function should be amended, considering the required mass effect of target.

According to Ref.[9], the TMC effect for nucleon structure functions can be related to the limit of these functions when we do not consider any mass effect. The related equation is called “master equation”. This equation was first obtained by Georgi and Politzer (GP) [4]. This equation is written for the unpolarized case at twist 2 order by:

$$F_{TMC}^2(x, Q^2) = \frac{x^2}{\xi r v} F_2^0(\xi, Q^2) + \frac{6M^2x^3}{Q^2v^4} h_2(\xi, Q^2) + \frac{12M^4x^4}{Q^4v^4} g_2(\xi, Q^2).$$  \hspace{1cm} (2)

The related expressions in above equation are as following:

$$h_2(\xi, Q^2) = \int^{\xi_1}_\xi du \frac{2F_2^0(u, Q^2)}{u^2},$$ \hspace{1cm} (3)

$$g_2(\xi, Q^2) = \int^{\xi_1}_\xi du x h_2(u, Q^2) = \int^{\xi_1}_\xi dv (-\xi) \frac{F_2^0(v, Q^2)}{v^2}.$$ \hspace{1cm} (4)

The ‘r’ variable in these equations is given by:

$$r = \sqrt{1 + \frac{4x^2M^2}{Q^2}}.$$ \hspace{1cm} (5)

We should note that the coefficients which exist in Eq.(2) like $\frac{x^2}{\xi r v}$, $\frac{6M^2x^3}{Q^2v^4}$ and $\frac{12M^4x^4}{Q^4v^4}$ are identical at all LO, NLO and higher approximations. As can be seen the master equation, Eq.(2), is a long equation and involves complicated integrals, given by Eqs.(3,4). So employing the TMC effect for nucleon structure function by this approach, is a tedious task. Sometime due to the unsolvable integrals, achieving the correction, using this approach is impossible. On this base, some people are trying to use the approximate relations [6]. But these approximations would yield us reliable results just at some specific energy scales. This is why people are encouraging to seek the other approaches, based on the modified parton densities to employ the TMC effect as we discuss them in the next section.

3 Parton densities and TMC, motivations

Here we intend to express the motivations which make the people to consider the TMC effect through the parton densities. Before that we need to some basic definitions.
The two standard moments of structure functions which are used in the literature are the Cornwall-Norton (CN) and Nachtmann moments \([13]\). The CN moments of \(F_2\) are given by:

\[
M_2^n(Q^2) = \int_0^1 dx \, x^{n-2} \, F_2(x, Q^2),
\]  

(6)

which are appropriate for the region \(Q^2 \gg M^2\).

On the other hand, the Nachtmann moment contains \(M^2/Q^2\) corrections to the Bjorken limit, and are given by:

\[
\mu_2^n(Q^2) = \int_0^1 dx \, \frac{\xi^{n+2}}{x^3} \left[ \frac{3 + 3(n + 1)r + n(n + 2)r^2}{(n + 2)(n + 3)} \right] F_2(x, Q^2),
\]  

(7)

where \(r\) is defined by Eq.\((5)\) and \(\xi\) is representing as before the Nachtmann variable. A particular feature of these Nachtmann moments is that they are supposed to factor out the target mass dependence of the structure functions in a way such that its moments would equal the moments of the corresponding parton distributions.

Recent experimental data includes the region of large Bjorken \(x\). Therefore we need to achieve a better control to employ parton distributions in this region. This region contains higher twist contributions and also the corrections which are relating to the mass of target. So we should be careful in the meaning of parton distributions for such case.

There are different approaches to prescript the inclusion of TMC to extract parton distributions from the measured structure functions. One of them as was referred before, is the Georgi and Politzer approach which is based on the operator product expansion where in the product of currents, the terms proportional to \(\frac{1}{Q^2}\) are kept \((n\) is the mass of target\). The problem with this prescription is that it uses parton distributions in an un-physical region. This happens because in the presence of a target mass, the distributions are not defined up to 1 in the momentum fraction. Instead, the maximum value for the momentum fraction is:

\[
\xi_0 = \xi(x = 1) = \frac{2}{1 + \sqrt{1 + \frac{4M^2}{Q^2}}}.
\]  

(8)

which is smaller than 1 for any finite \(Q^2\). It seems that if TMC are included, one loses the partonic interpretation: no parton distribution with TMC can be really defined. Given the importance of the potential consequences, it is urged that more investigation on this fascinating subject be made.

4 TMC, based on the re-scaled partons

As was discussed in above, however GP approach give us reliable results for nucleon structure function (SF) but when people are intending to re-express this effect in this approach in terms of parton densities, they encounter with parton densities in an un-physical region. Additionally this approach by itself contains cumbersome and unsolvable analytical integrals which forces people to use the approximation methods to consider this approach. In order to discard this deficiencies, it is better to do directly the mass correction on parton distributions rather than to use Eq.\((2)\). In Eq.\((2)\) the TMC is done only on the nucleon SFs, and the mass correction has not been done by parton densities.

The main question is how the mass correction can be done on parton distributions in which the resulted correction is equal to what have been obtained, using Eq.\((2)\) such that there is not the threshold problem for the nucleon structure functions. Therefore we are going to employ the mass correction on parton distributions in which the nucleon structure function, \(F_2\), resulted from this correction, is very similar to what is obtained from Eq.\((2)\). The suggested solution is that to do the mass correction for parton distributions, using a method which is called re-scaling. We mean from re-scaling to substitute new variable instead of the variable which is usually used to describe the parton distributions. In fact we replace the Bjorken variable-\(x\) with the new one in parton distributions and investigate the changes which are resulted.

Now we use the parametrization of Ref.\([14]\) for the parton distributions, and then employing the re-scaling prescription. We could get finally the mass correction for the nucleon structure function. But what is the proper re-scaling and what variable should be replaced instead of \(x\)-Bjorken variable?.

There are three types of re-scaling:

I) Replacement the \(x\) Bjorken variable with the Nachtman variable, \(\xi\), in the whole part of the parton distributions. If we assume the following form for the parton densities:

\[
q(x, Q^2) = ax^b(1 - x)^c(1 - dx^{0.5} + ex)
\]  

(9)

then the re-scaled presentation for parton densities in this type of re-scaling, is appeared as

\[
a\xi^b(1 - \xi)^c(1 - d\xi^{0.5} + e\xi)
\]  

(10)

II) Replacement the \(x\) Bjorken variable with the Nachtmann variable, \(\xi\), in the whole part of the parton distributions but substituting the maximum value of transferred momentum fraction, 1, by \(\xi_0(x = 1)\). So the re-scaled presentation of the second type for parton densities will be as

\[
a\xi^b(\xi_0(x = 1) - \xi)^c(1 - d\xi^{0.5} + e\xi)
\]  

(11)

III) Replacement the \(x\) Bjorken variable with the Nachtmann variable, \(\xi\), in all parts of the parton distributions except for the \((1-x)\) part.

We believe that the third type of re-scaling is the best one as the results which are arising out from this re-scaling confirm this reality. In this case the threshold problem would be solved automatically and the nucleon structure...
function goes to zero when the $x$ is approaching to 1. By keeping the $(1-x)$ term without any change in parton distribution function, in fact we do not allow the structure function achieves numerical values when $x$-Bjorken variable is greater than 1. It is because that the unchanged $(1-x)$ term implies this fact that maximum value of $x$ is 1. Our justification for this re-scaling is that when the transferred momentum fraction which is carried by partons achieves its maximum value, 1, only the three valence quarks exist and there is no chance for sea quarks and gluons to be appeared. On the other hand, if there is not any partonic interactions to produce sea quarks and gluons. If such interactions do not exist it means that there is not any mass effect. In this case we can assume that $x$ and $x$ variables are equal to each other. This is why we keep the $(1-x)$ term in this re-scaling without any change.

In summary, if we consider the expression $a g^2(1-x)^c(1-d x^{0.5} + c x)$ as the parameterized form for parton distribution then the re-scaled form would be as:

$$a g^2(1-x)^c(1-d x^{0.5} + c x).$$

In this expression the first term is controlling the behavior of parton distribution at low $x$ values. The second term is relating to behavior of parton distribution at large values of $x$ which we keep it not to change. The last term is controlling the behavior of parton distribution at medium values of $x$ variable which changes to $x$ during the re-scaling processes. When this type of re-scaling is used, we do not need to use the step function to discard the threshold problem as has been used in Ref.[9]. On the other hand, the unchanged $(1-x)$ term which is used in the third type of re-scaling, will guarantee to yield us a proper result for the structure function with acceptable threshold behavior.

After employing the proper re-scaling on the parton densities, it is now turn to construct the nucleon structure function, $F_2$, which at LO and NLO approximations are given respectively by [13]:

$$F_{2,LO}(x) = \sum_i (e_i^2 x f_i(\xi))$$

$$F_{2,NLO}(x, Q^2) = \sum_q e_q^2(q(\xi, Q^2) + \pi(\xi, Q^2))$$

$$+ \frac{\alpha_s(Q^2)}{2\pi}[C_{q,2} \otimes (q + \bar{q}) + 2C_{g,2} \otimes \bar{g})].$$

In above equations, $q$ and $\bar{q}$ refer to quark and anti-quark distributions with different flavours and electric charge, $e_q$. The gluon distribution is representing by $g(x, Q^2)$. Wilson coefficients, $C_{q,2}(z)$, $C_{g,2}(z)$ and also the convolution integral $C \otimes q$ are given by [13]:

$$C_{g,2}(z) = \frac{4}{3} \frac{(z^2 + (1-z)2ln \frac{1-z}{z} - \frac{3}{4}(1+49+5z)+}{ln \frac{1-z}{z}},$$

$$C_{g,2}(z) = \frac{1}{2}[(z^2 + (1-z)2ln \frac{1-z}{z},$$

$$-1 + 8z(1-z)]].$$

The plus sign in Eqs.(15,16) would be appeared in the convolution integral as in following:

$$\int_x^1 \frac{dy}{y} C_{q,2} \otimes F(x)+g(y)$$

$$= \int_x^1 \frac{dy}{y} f(x)[g(y) - \frac{x}{y^2}(x)]$$

$$- g(x) \int_0^x \frac{dy}{y^2}(y).$$

Now we can use the re-scaled parton densities to make the improved SF at different approximations. In this case we do not need to use Eq.(2) to employ the TMC effect. All the required considerations to take into account the mass effects are done by the re-scaled parton densities.

5 Discussions and results

Here we try to use the re-scaled parton densities instead of Eq.(2) to get the mass effects for the SF. First we do employ on parton densities the mass correction, using the three type re-scaling and then we obtain SF at LO and NLO approximations. We plot in Fig.1 and 2 the results for SF in NLO approximation at $Q^2 = 2, 3, 5, 4.5$ and $15 \text{GeV}^2$. In these figures we use three re-scaled prescriptions as we dealt with them in section 4. We have added as well in these figures the plots for nucleon SF, $F_2$, resulted from Eq.(3) at the NLO approximations. The results which are obtained from the third type of re-scaling are in good agreements with GP approach.

A comparison with the available experimental data has also been done [15,16,17,18,19]. As can be seen, what we get from the third type of re-scaled parton densities for SF is in better agreement with GP approach and also the available experimental data. To show how much the results from GP approach and the third type of re-scaled parton densities are near to each other, we plot in Fig.3 the ratio of structure function using the GP approach and the third re-scaling method for parton densities which is the best re-scaling.

However based on the first type re-scaling, there is threshold problem in Fig.1 and 2 but in order to indicate this problem more clearly we depict in Fig.4 the nucleon structure function in LO and NLO approximations at typical energy scale $Q^2 = 4.5 \text{GeV}^2$ by considering their behavior at large values of $x$ variable. So in this figure we choose the interval of $x$-Bjorken variable, for instance, from 0.8 to maximum value which it can get according to the relation between Nachtmann variable, $\xi$, and $x$-variable in Eq.(4). We mean that we put the maximum value of $\xi$ which is 1 in Eq.(4) and then depend on the value of $Q^2$, the maximum value of $x$-variable is obtained respectively. This maximum value of $x$ is used in depicting the plots of Fig.4.

As can be seen the second and third type of re-scaling does not contain the threshold problem. The reason for
Fig. 1. The nucleon structure function at NLO approximations, resulted from GP approach [3] and the re-scaled parton densities at $Q^2 = 2.7$ and $3.5 \text{ GeV}^2$. In the legends of these figures $r_1$, $r_2$ and $r_3$ refers to the first, second and third type of re-scaled parton densities. A comparison with the available experimental data has also been done [15,16,17,18,19].

Fig. 2. As Fig.1 but at $Q^2 = 4.5$ and $15 \text{ GeV}^2$. 
Fig. 3. The ratio of the nucleon structure function at NLO approximation, resulted from GP approach [4] and the third re-scaled parton densities at $Q^2 = 2.7$ and 4.5 GeV$^2$.

Fig. 4. The LO and NLO results for the nucleon structure function at $Q^2 = 4.5$ GeV$^2$, resulted from GP approach [4] and the re-scaled parton densities for the interval of $0.8 < x < x_{max} (\xi = 1)$. 
the third re-scaling is obvious as we explained in Sec.4. For the second type of re-scaling the \( (\xi_0 (x = 1) - \xi) \) term forbids the \( x \)-variable to achieve values greater than 1. In our suggested third scaling, again the unchanged \( (1 - x) \) term in parton distribution function would prevent the \( x \)-variable to get values greater than 1. Therefore only for the first type of re-scaling, the \( x \)-variable can get the amounts greater than 1 by considering the maximum value of \( \xi \) in Eq.\( \text{[1]} \) in correspond to what we described in above.

As referred in above, two solutions are suggested to discard the threshold problem. The first solution which is given by the second type re-scaling, contains the \( (\xi_0 (x = 1) - \xi) \) term in parton densities and as can be seen in Fig.1 and 2 and more clearly in Fig.4, involves the results which are not compatible with the GP approach and the first and third re-scalings. The reason is that when in this type of re-scaling, we change the \( x \)-variable to \( \xi \) and in following do not allow it to get its maximum value \( (\xi = 1) \) but to get only the maximum value \( \xi = \xi_0 (x = 1) \) which obviously is less than 1, we should be precise to the correlation which exist between the mass term, \( M \), and energy scale, \( Q^2 \) according to Eq.\( \text{[1]} \). By replacing the \( x \) variable by \( \xi \), we let \( \xi \) take its maximum value, 1, when the mass effect has dominant effect. On the other hand when we have \( \xi = \xi_0 (x = 1) \) as in Eq.\( \text{[1]} \), it means that we prevent the mass effect are appeared, since as discussed in previous section the condition \( x = 1 \) implies that we just encounter with valence quarks and there are not any other partons like sea quarks and gluon. On the other hand, there is not any interaction in this limit and therefore we do not expect to have in this case any mass effect. So the expression \( (\xi_0 (x = 1) - \xi) \) denotes to two conditions which in fact contradicts each other according to what we explained in above. This is why in spite that this re-scaling does not involve threshold problem but its behavior is not compatible with other scaling and GP approach. In conclusion we can say that this type of re-scaling (second type) is not a proper one. The first re-scaling should also be discarded since it contains the threshold problem. So the only acceptable re-scaling is our suggested scaling which was called third re-scaling.

To confirm the validity of discussion in connection to the deficiency of the second type re-scaling, we can refer to the Ref.\( \text{[2]} \) where by looking at Fig.1 and Fig.2 of this reference, it can be seen that the behavior of momentum ratio of nucleon structure function, resulting from the second type of re-scaling which was denoted there as “Threshold dependent (TD)” is different with respect to the other used re-scalings in that paper. Looking as well at Fig.3 of this reference which is depicting the structure function, based on different re-scalings, once again confirms what is expecting from the second type re-scaling in which indicates different behavior for SF with respect to the other used re-scalings in that paper. Fig.5 of this reference, which is relating to longitudinal structure function, once again indicates a different behavior of TD re-scaling (second type of re-scaling in our paper) and therefore can be used as an another evidence to approve our reasons why this type of re-scaling presents such different behavior. Consequently we can now claim that the best candidate for re-scaled parton densities is the third type re-scaling which we suggested in this paper.

6 Conclusions

In this paper we investigated a new method to do the mass correction for the nucleon structure function, rather than to use the Eq.\( \text{[2]} \) which contains cumbersome calculations. In this case the mass correction has been employed directly by parton densities rather than the SF as was done by the Georgi and Politzer approach \( \text{[3]} \). Three prescriptions for the re-scaled parton densities were introduced. Using the third type of the re-scaled parton densities, the threshold problem has been removed properly, so as the SF would be existed only in the physical region of \( x \)-Bjorken variable. As we can see from the related figures, what we got for the corrected SF considering the TMC effect, using the third type re-scaling, are very similar to the result of GP approach and even better than the results when we employ the other types of the re-scaling. In fact, first type re-scaling was discarded since contains the threshold problem. The second type re-scaling indicated un-compatible results with respect to the other re-scaling types. The best candidate for re-scaling IS the third type re-scaling which was suggested and we described it extensively in the article.

As a further research task, the TMC effect can be extended to the polarized case and then to the nuclear matter which we hope to give a report on them in future.

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