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Quark shapes of most modern parton distribution functions

Hasan OĞUL*
Department of Nuclear Engineering, Faculty of Engineering and Architecture, Sinop University, Sinop, Turkey

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Abstract: Parton distribution functions (PDFs) describe the internal structure of the proton and are necessary inputs to almost all theory predictions of hadron colliders. One way to do a precise measurement of a PDF is to measure the lepton charge asymmetry of W boson where $u\bar{d} \rightarrow W^{+}$ and $d\bar{u} \rightarrow W^{-}$. Therefore, u, d, $\bar{u}$, and $\bar{d}$ quark shapes of the most modern PDF models (NNPDF3.1, NNPDF3.0, CT14, MMHT2014, and HERAPDF2.0) are inspected using the APFEL online cluster in this paper. The ratio of d to u is further investigated since the charge asymmetry is sensitive to the value of d over u momentum distributions in the proton. Q scale dependence of PDFs are further studied in a range from 1 to 100 GeV.

Key words: High energy physics, parton distribution functions, NNPDF3.1, quarks

1. Introduction

Quarks and gluons are collectively referred to as partons. The parton name is a generic description of any particle constituent within hadrons such as protons and neutrons. There are six type of quarks (up (u), down (d), charm (c), strange (s), top (t), and bottom (b)) and six types of antiquarks ($\bar{u}$, $\bar{d}$, $\bar{c}$, $\bar{s}$, $\bar{t}$, and $\bar{b}$). Quantum chromodynamics (QCD) and parton distribution functions (PDFs) describe the interactions between quarks and the internal structure of the hadrons, respectively. Therefore, QCD calculation of any particle and the PDF of any hadron provide crucial information about their properties. The measurement of W boson charge asymmetry (A_W) originating from pp, $p\bar{p}$, and ep collisions provides important information about the proton structure as described by PDFs. One way to extract W boson charge asymmetry is the calculation of W^{+} and W^{-} boson production cross-sections. Any calculation of production cross-section with hadrons in the initial state involves PDFs as an input. If A and B hadrons produce X, the cross-section for the process $\sigma_{AB\longrightarrow X}$ can be determined from the convolution of the cross-section of the intervening partons a and b, $\hat{\sigma}_{ab\longrightarrow X}$:

$$\sigma_{AB\longrightarrow X} = PDF?\sigma_{ab\longrightarrow X} = \sum\int dx_a dx_b f_{a/A}(x_a) f_{b/B}(x_b)\,\hat{\sigma}_{ab\longrightarrow X}, \tag{1}$$

where $f_{a/A}(x_a)$ and $f_{b/B}(x_b)$ are parton distribution functions, and $x_{a,b}$ is the momentum fractions of hadrons A and B carried by partons a and b. An inaccurate PDF prediction can lead to an erroneous result or a false claim of discovery since all production cross-sections for SM and new physics alike depend on PDFs.

Another remark that should be underlined here is the definition of W boson charge asymmetry. Its simple definition can be given as the difference between W^{+} and W^{-} bosons, normalized to the sum. Eq. (2) provides

*Correspondence: hogul@sinop.edu.tr

the mathematical statement of the definition. A_W is sensitive to the value of d over u momentum distributions in the proton [1]; therefore, the ratios of d to u PDF shapes are explored in Bjorken parameter x [2] ranging from 0.00001 to 1 at different QCD energy scales (Q).

$$A_W = \frac{W^+ - W^-}{W^+ + W^-} = \frac{u\bar{d} - d\bar{u}}{u\bar{d} + d\bar{u}} \tag{2}$$

There are many PDF models provided by PDF analysis groups. Although the PDF models might have many differences, such as different input data, treatments of heavy quarks, values of heavy quark masses, and ways of parameterizing PDFs, studies on QCD predictions proved that the calculations based on different PDF models result in good agreement with each other [3,4]. This motivates us to study quark NNPDF3.1, NNPDF3.0, CT14, MMHT2014, and HERAPDF2.0 PDF shapes to understand their agreement with each other at the parton level.

2. Quark PDF shapes

$u, d, \bar{u}$, and $\bar{d}$ quarks are considered to compare different PDF models since $u\bar{d} \to W^+$ and $d\bar{u} \to W^-$. The APFEL online cluster (https://apfel.mi.infn.it) is used to extract the PDF shape of the quarks. To plot the shapes as a function of Bjorken parameter x, the x-axis is divided into 100 bins and ranged from 10^{-5} to 1. Then the Q scale is set to W boson mass (M_W = 80.403 GeV) and the considered quark shapes are calculated and compared in Figure 1.

Here, NNPDF3.1 [5], NNPDF3.0 [6], CT14 [7], MMHT2014 [8], and HERAPDF2.0 [9] NNLO PDF models are used to make comparisons of quark PDFs. NNPDF3.1 is the improved version of NNPDF3.0 and became available recently. As shown in the figures, the most noticeable improvement over NNPDF3.0 involves the uncertainty of the predictions. For all considered quark types, the uncertainties in NNPDF3.1 are smaller than the uncertainties in NNPDF3.0 at low x region. On the other hand, the figures also show that all PDF predictions are in good agreement over the entire range of x. NNPDF3.0 and HERAPDF2.0 have the biggest and smallest uncertainties, respectively, and the uncertainties on the PDFs are bigger at low x values.

Figure 2 presents the ratio of d to u quarks. On the left-hand side, the ratios are provided with the uncertainties on the quark PDFs while only the central value of the ratio is plotted on the right-hand side. Overall, the ratio predictions are within the uncertainty band; however, the central value of HERAPDF2.0 is significantly different from others in the range from 10^{-3} to 10^{-1}. A similar ratio difference is also presented by the CT14 model in the range of 10^{-4} to 10^{-2}.

In general, it is not expected to have significant differences in the central values of quark PDF shapes; however, the ratios of d to u for the CT14 and HERAPDF2.0 models introduce remarkable differences in specific x ranges from what NNPDF and MMHT2014 predict. These differences may lead to the inadequacy of predictions to describe the experimental results in the corresponding x ranges.

3. The impact of Q scale on quark PDF shapes

Quarks are stated in the form of $q(x, Q)$ so that it is clearly seen that they are a function of Q scale as much as x. Therefore, the predictions are performed at different Q values to understand how the shapes are changed by the increase of the Q scale. This study is focused on CT14, HERAPDF2.0, and NNPDF3.1 predictions in the Bjorken parameter range from 10^{-5} to 10^{-1}.

Figure 3 shows the results of u and d quark PDF shapes by varying the Q scale from 1 GeV to 100 GeV. The plots are placed from left to right for NNPDF3.1, CT14, and HERAPDF2.0. The upper and lower plots

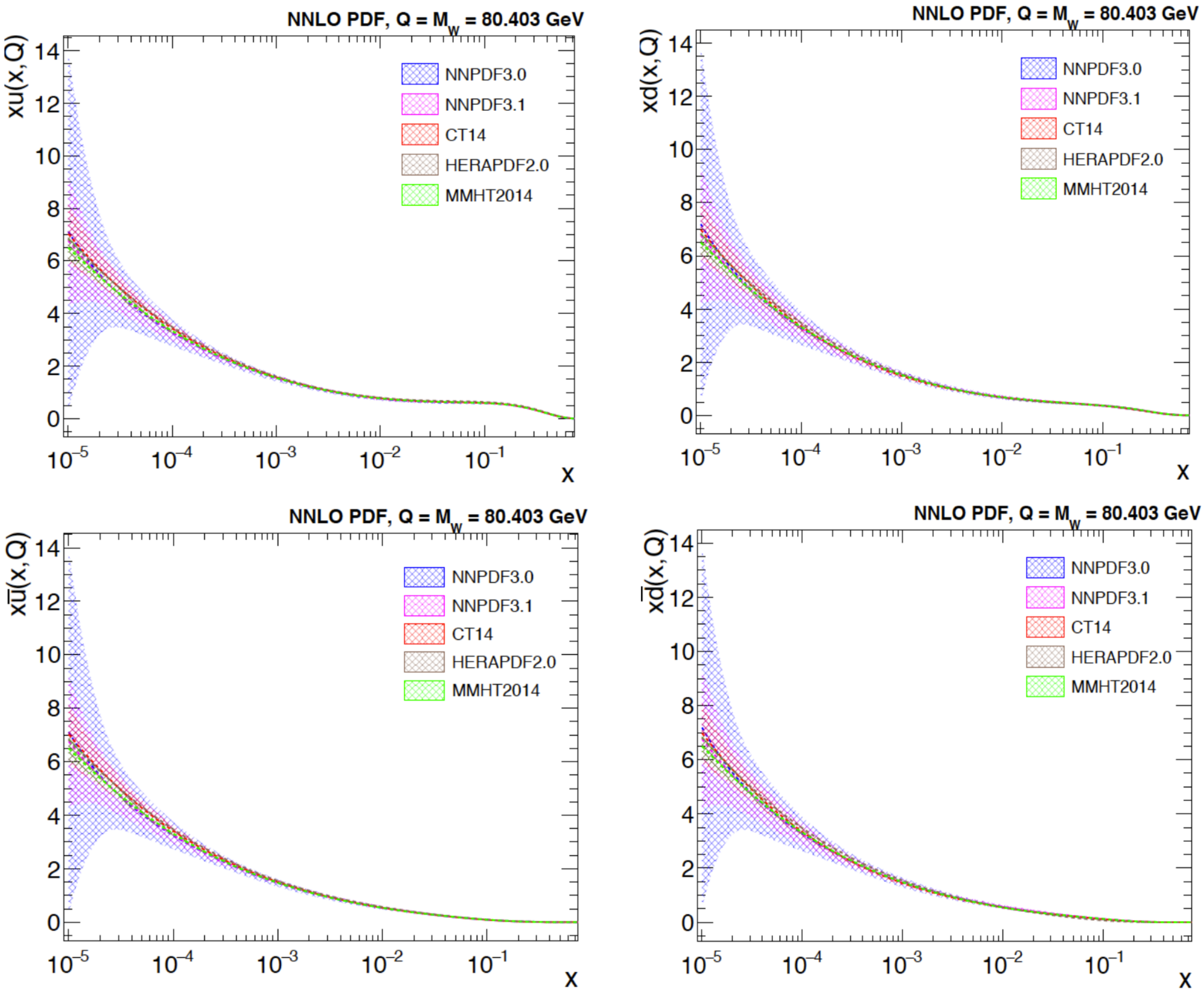

Figure 1. $u, d, \bar{u}$, and $\bar{d}$ quark shapes as a function of Bjorken scale.

present the results of u and d quarks, respectively. It is observed that the values on the distributions increase by increase of Q scale. The ratios of these quarks are further plotted as a function of x at different Q scales. Figure 4 illustrates the predictions of d/u ratio based on NNLO NNPDF3.1, CT14, and HERAPDF2.0 PDF models. The ratios for NNPDF3.1 and HERAPDF2.0 do not change significantly by change of Q scale except the prediction at $Q = 1$ GeV. However, significant differences are observed in CT14 predictions at different Q values in the range of 10^{-5} to 10^{-2}.

4. Results and discussion

PDFs are essential inputs for the theoretical predictions of any particle in any hadron collider. Therefore, many groups are motivated to study PDFs and they provide different models of PDFs by using different approaches and parameters. In this paper, some of the latest PDF models (NNPDF3.1, NNPDF3.0, CT14, MMHT2014, and HERAPDF2.0) are taken into account to inspect their behaviors on different quark momentum distributions (u, d, $\bar{u}$, and $\bar{d}$) and the ratio of d to u quarks. In terms of u, d, $\bar{u}$, and $\bar{d}$ quark PDFs, there is good

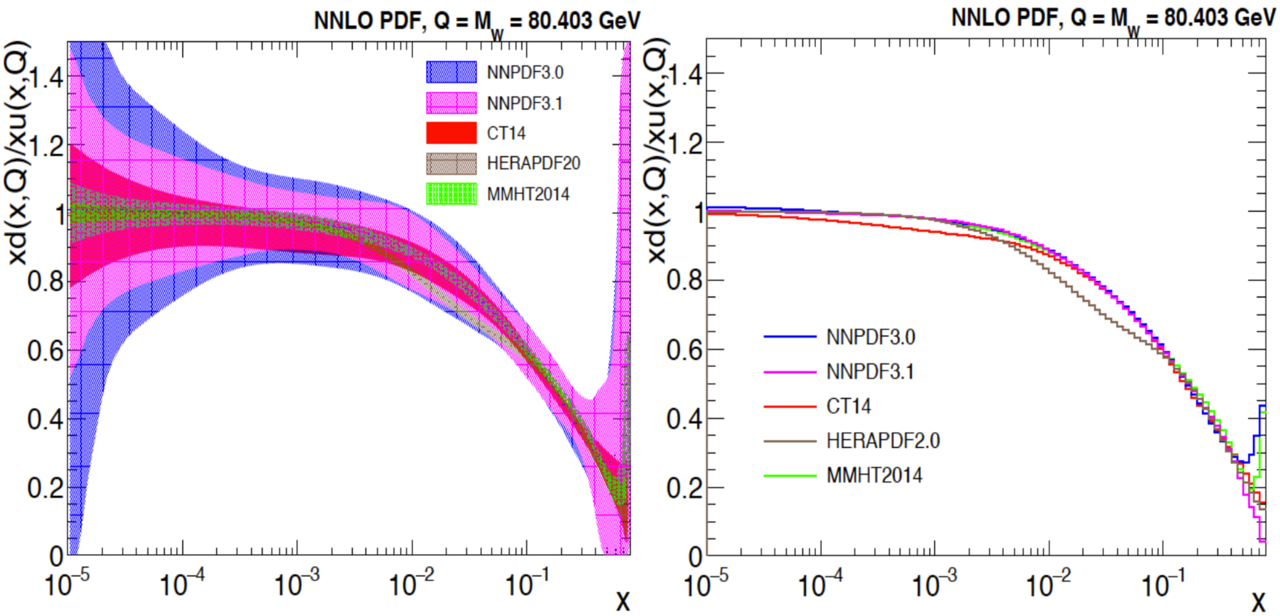

Figure 2. The ratio of d to u as a function of Bjorken parameter x at $Q = M_W$.

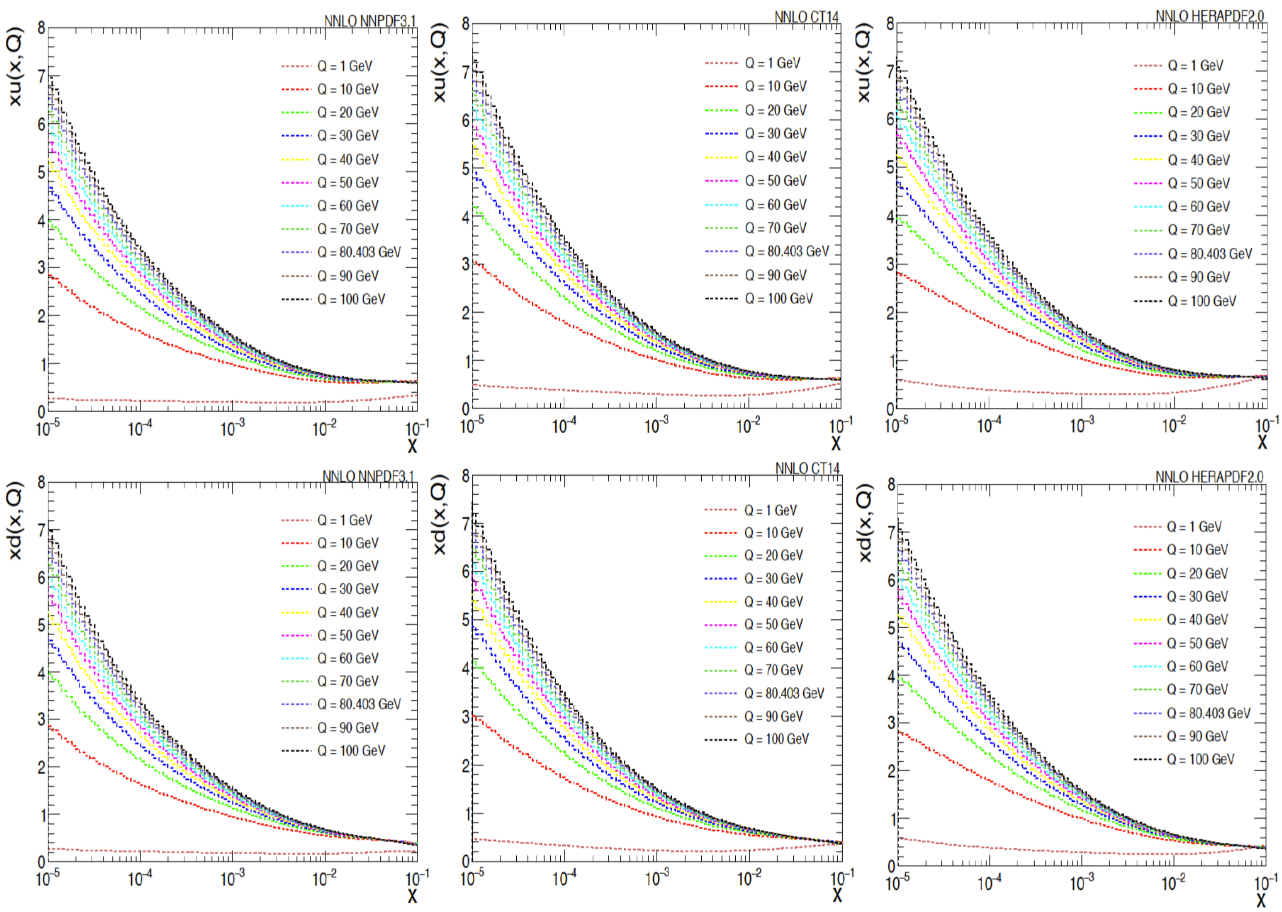

Figure 3. u and d quark PDF shapes at different Q levels in x range of 10^{-5} to 10^{-1}.

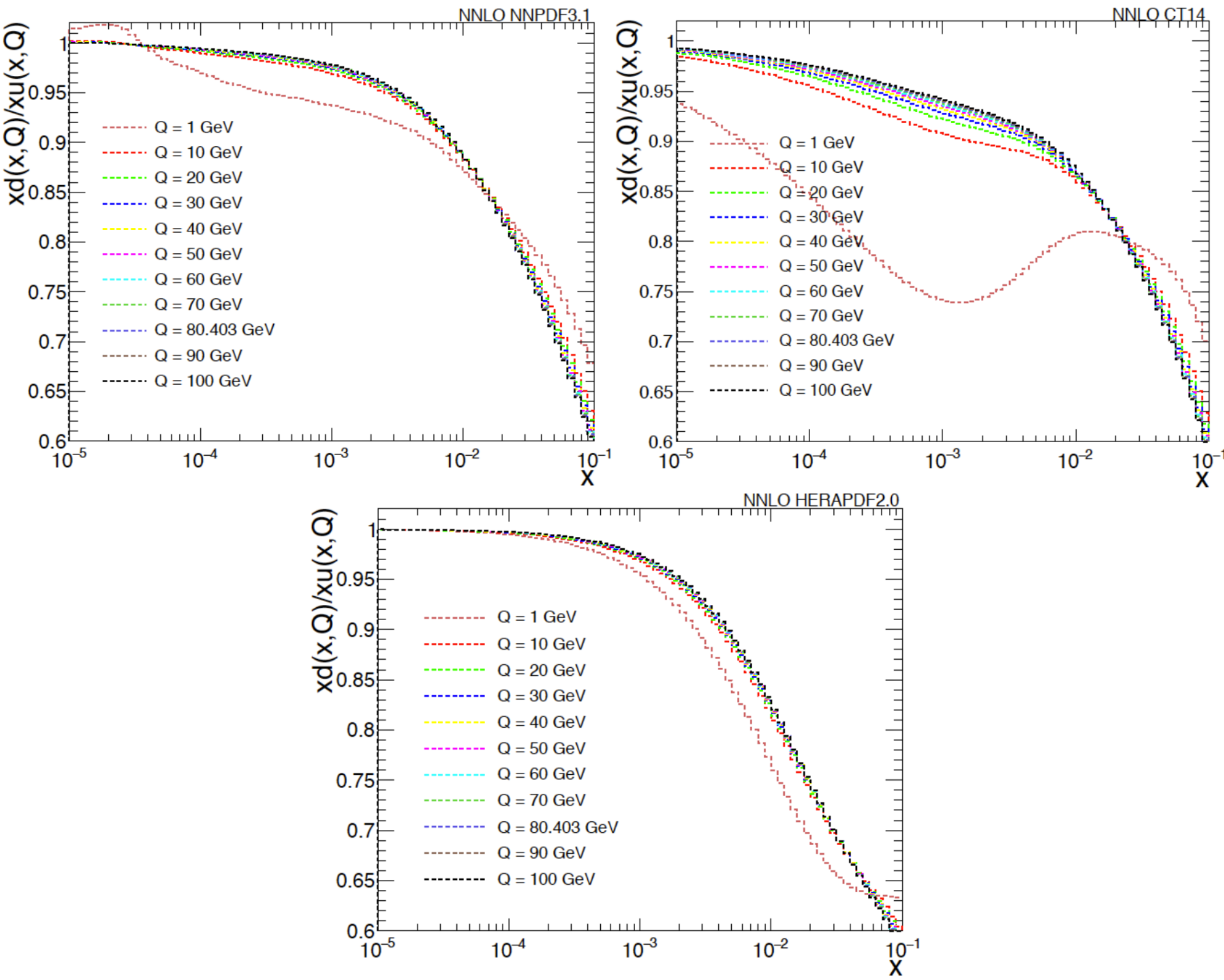

Figure 4. The ratio of d to u as a function of x parameter at different Q scales.

agreement in the entire range of x except for HERAPDF2.0 prediction in the range from 10^{-3} to 10^{-1} and CT14 prediction in the range from 10^{-4} to 10^{-2} at $Q = M_W$. Since x is equal to $\frac{M_W}{\sqrt{s}}e^{\pm y}$ (where $\sqrt{s}$ is the collision energy of hadrons and y is the rapidity of the observable), the predictions of CT14 and HERAPDF may lead to wrong judgments for particles in the corresponding collision energy. For example, one of the Large Hadron Collider (LHC: http://home.cern/topics/large-hadron-collider) measurements at $\sqrt{s} = 7$ TeV states that the results may provide additional constraints on the parton distribution functions of the proton in the range of the Bjorken scaling variable x from 10^{-3} to 10^{-1} [10]. Therefore, it can be safely claimed that the charge asymmetry prediction of HERAPDF2.0 at 7 TeV may not describe the LHC measurement well since the charge asymmetry is sensitive to the d over u ratio and this ratio is different from other PDF groups' ratios in this region.

The impact of Q scale on PDFs is further studied. Figures 3 and 4 are indicative of the impact of Q scale on the quark PDFs. The Q scale is ranged from 1 to 100 GeV: 1, 10, 20, 30, 40, 50, 60, 70, 80.403, 90, 100. The quark PDFs at small Q scale (Q = 1 GeV) are significantly different than the PDF shapes at other considered Q scales. In particular, CT14 differs considerably from the other two at $Q = 1$ GeV. On the other hand, the predictions for $Q \geq 10$ cases have similar shapes but they might differ from each other. One thing needing to be underlined here for Figure 4 is that the momentum distribution ratios of CT14 in the range of 10^{-5} to 10^{-2} present bigger differences for different Q values and this behavior needs to be further investigated by the CT14 PDF group.

References

[1] Aaltonen, T.; Adelman, J.; Akimoto, T.; Alvarez Gonzalez, B.; Amerio, S.; Amidei, D.; Anastassov, A.; Annovi, A.; Antos, J.; Apollinari, G. et al. *Phys. Rev. Lett.* **2009**, *102*, 181801.

[2] Bjorken, J. D.; Paschos, A. E. *Phys. Rev.* **1969**, *185*, 1975-1982.

[3] Ogul, H.; Dilsiz, K.; Tiras, E.; Tan, P.; Onel, Y.; Nachtman, J. *Adv. High Energy Phys.* **2016**, *2016*, 7865689.

[4] Ogul, H.; Dilsiz, K. *Adv. High Energy Phys.* **2017**, *2017*, 8262018.

[5] Ball, R. D.; Bertone, V.; Carrazza, S.; Debbio, L. D.; Forte, F.; Groth-Merrild, P.; Guffanti, A.; Hartland, N. P.; Kassabov, Z.; Latorre, J. I. et al. *arXiv* 1706.00428, 2017.

[6] Ball, R. D.; Bertone, V.; Carrazza, S.; Deans, C. S.; Debbio, L. D.; Forte, F.; Guffanti, A.; Hartland, N. P.; Kassabov, Z.; Latorre, J. I. et al. *J. High Energ. Phys.* **2015**, *2015*, 040-148.

[7] Dulat, S.; Hou, T. J.; Gao, J.; Guzzi, M.; Huston, J.; Nadolsky, P.; Pumplin, J.; Schmidt, C.; Stump, D.; Yuan, C. P. *Phys. Rev. D* **2016**, *93*, 033006.

[8] Harland-Lang, L. A.; Martin, A. D.; Motylinski, P.; Thorne, R. S. *Eur. Phys. J. C* **2015,** *75*, 204-253.

[9] Abramowicz, H.; Abt, I.; Adamczyk, L.; Adamus, M.; Andreev, V.; Antonelli, S.; Antunović, B.; Aushev, V.; Aushev, Y.; Baghdasaryan, A. et al. *Eur. Phys. J. C* **2015**, *75*, 580-598.

[10] Chatrchyan, S.; Khachatryan, V.; Sirunyan, A. M.; Tumasyan, A.; Adam, W.; Bergauer, T.; Dragicevic, M.; Erö, J.; Fabjan, C.; Friedl, M. et al. *Phys. Rev. D* **2014**, *90*, 032004.