Inclusive Higgs boson production at LHC within the k_T-factorization approach

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We study the inclusive Higgs boson production with its subsequent decay to diphoton pair at LHC energies in the k_T-factorization QCD approach. We take into account the off-shell gluon fusion subprocess $g^*g^* \to H \to \gamma\gamma$. As unintegrated (or transverse momentum dependent) gluon distributions we use densities obtained with CCFM evolution equation and KMR prescription. We evaluate the theoretical uncertainties of our calculations and compare them with the results of traditional pQCD calculations. We find good agreement between our predictions and first experimental data of the ATLAS Collaboration.

The recent discovery of the Higgs boson [1,2] has become a triumph of the Glashow-Salam-Weinberg theory of electroweak interactions and simultaneously marks the commencement of a new era in high energy physics. Spin and relative production rates of the observed particle in different decay modes are in very good agreement with the SM expectations for the Higgs boson.

The subprocess of gluon-gluon fusion, $gg \to H$, is the basic mechanism of inclusive Higgs boson production in proton-proton collisions at the LHC energy. The ggH effective interaction is mediated in the lowest order by a triangle loop of heavy (primarily t) quark. In the conventional collinear QCD approach NNLO calculations [3–8] matched mith NNLL resumation [9,10] are performed to describe experimental data [11].

An alternative approach is based on the k_T-factorization of QCD[2]. One of the advantages of the method is that one can obtain good description of experimental data even in LO due to partial incorporating of higher orders corrections in unintegrated (or transverse momentum dependent) parton distributions. Investigation of Higgs boson production in the k_T-factorization approach has its own history. The process was studied in [15] and p_T-distributions were presented. Reasonable agreement with collinear NNLO results was achieved in the lowest perturbative order. Further, the finite top quark mass was correctly introduced in [16]. Concerning justifying the k_T-factorization formula for Higgs boson production, big progress has been made in the last few years [17] (see also a review [18] and references therein).

Recently the ATLAS Collaboration has reported first measurements of the Higgs boson differential cross sections in the diphoton decay mode [11]. In particular, the distributions with respect to the diphoton transverse momentum p_T, rapidity y and helicity angle $|\cos\theta^*|$ have been presented. The goal of this work is to describe those data in the k_T-factorization QCD approach.

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[2] Detailed description of the k_T-factorization approach can be found in reviews [12–14].

Now we shortly describe our calculation steps. Our consideration is based on the off-shell gluon fusion subprocess $g^*g^* \to H \to \gamma\gamma$. In the limit of large top quark mass $m_t \to \infty$ the effective Lagrangian for the Higgs boson coupling to gluons reads [19,20]:

$$\mathcal{L}_{ggH} = \frac{\alpha_s}{12\pi}(G_F\sqrt{2})^{1/2}G^a_{\mu\nu}G^{a\mu\nu}H, \tag{1}$$

where G_F is the Fermi constant, $G^a_{\mu\nu}$ is the gluon field strenth tensor and H is the scalar field. Then one can easily obtaine the triangle vertex for two off-shell gluons having four-momenta k_1 and k_2 and color indices a and b:

$$T^{\mu\nu,ab}_{ggH}(k_1,k_2) = i\delta^{ab}\frac{\alpha_s}{3\pi}(G_F\sqrt{2})^{1/2}(k_2^\mu k_1^\nu - (k_1k_2)g^{\mu\nu}). \tag{2}$$

The triangle vertex for $\gamma\gamma H$ is derived analogously. One just needs to take into account also W boson loop. Then one has [19,20]:

$$\mathcal{L}_{ggH} = \frac{\alpha_s}{8\pi}\mathcal{A}(G_F\sqrt{2})^{1/2}F_{\mu\nu}F^{\mu\nu}H, \tag{3}$$

where $F_{\mu\nu}$ is the electromagnetic field strength tensor. The triangle vertex for two photons with four-momenta p_1 and p_2 reads:

$$T^{\mu\nu}_{\gamma\gamma H}(p_1,p_2) = i\frac{\alpha_s}{2\pi}\mathcal{A}(G_F\sqrt{2})^{1/2}(p_2^\mu p_1^\nu - (p_1p_2)g^{\mu\nu}), \tag{4}$$

where

$$\mathcal{A} = \mathcal{A}_W(m_H^2/4m_W^2) + N_c\sum_f Q_f^2\mathcal{A}_f(m_H^2/4m_W^2), \tag{5}$$

$$\mathcal{A}_W(\tau) = -[2\tau^2 + 3\tau + 3(2\tau-1)f(\tau)]/\tau^2, \tag{6}$$

$$\mathcal{A}_f(\tau) = 2[\tau + (\tau-1)f(\tau)]/\tau^2, \tag{7}$$

$$f(\tau) = \begin{cases} \arcsin^2(\sqrt{\tau}), & \tau \le 1; \\ -\frac{1}{4}\left[\log\frac{1+\sqrt{1-1/\tau}}{1-\sqrt{1-1/\tau}} - i\pi\right]^2, & \tau > 1. \end{cases} \tag{8}$$

Here N_c is the color factor and Q_f is the electric charge of the fermion f.

Using the effective vertices (2), (4) one can easily obtain the off-shell matrix element for gluon-gluon fusion subprocess $g^*g^* \to H \to \gamma\gamma$. The only difference with the traditional calculations comes in so-called k_T-factorization prescription for summation over polarizations of incoming gluons:

$$\sum \epsilon^\mu\epsilon^{*\nu} = \frac{\mathbf{k}_T^\mu\mathbf{k}_T^\nu}{\mathbf{k}_T^2}. \tag{9}$$

In the collinear limit ($k_T \to 0$) this expression converges to the ordinary one after averaging on the azimuthal angle. So, the matrix element squared takes the following form:

$$\overline{|\mathcal{M}|}^2 = \frac{1}{1152\pi^4}\alpha^2\alpha_S^2G_F^2|\mathcal{A}|^2\frac{\hat{s}^2(\hat{s}+\mathbf{p}_T^2)^2}{(\hat{s}-m_H^2)^2+m_H^2\Gamma_H^2}\cos^2\phi, \tag{10}$$

where Γ_H is the Higgs boson decay width, $\hat{s} = (k_1+k_2)^2$, the transverse momentum of the Higgs particle $\mathbf{p}_T = \mathbf{k}_{1T} + \mathbf{k}_{2T}$, and ϕ is the azimuthal angle between the transverse momenta of the initial gluons. The expression (10) is fully consistent with the one obtained in [15].

The cross-section for the inclusive Higgs boson production in proton-proton collision in the k_T-factorization approach is calculated as convolution of the off-shell partonic cross-section with the unintegrated gluon distributions in the proton:

$$\sigma = \int \frac{\overline{|\mathcal{M}|}^2}{16\pi(x_1x_2s)^2} f_g(x_1, \mathbf{k}_{1T}^2, \mu^2) f_g(x_2, \mathbf{k}_{2T}^2, \mu^2) d\mathbf{p}_{1T}^2 d\mathbf{k}_{1T}^2 d\mathbf{k}_{2T}^2 dy_1 dy_2 \frac{d\phi_1}{2\pi}\frac{d\phi_2}{2\pi}, \quad (11)$$

where s is the total centre-of-mass energy, $y_{1,2}$ are the rapidities of the produced photons, and the $\phi_{1,2}$ and $x_{1,2}$ are the azimuthal angles and colliding proton longitudinal momenta fractions of the incoming gluons respectively. $f_g(x, \mathbf{k}_T^2, \mu^2)$ is the unintegrated gluon density in the proton. In our numerical calculations we tested two sets of such distributions. First, CCFM A0 set [21], is obtained as a numerical solution of the CCFM gluon evolution equation, where all input parameters were fitted in a way to describe the proton structure function $F_2(x, Q^2)$. The second set was obtained with Kimber-Martin-Ryskin (KMR) prescription [22, 23]. In this method the unintegrated distributions can be calculated from the conventional collinear ones. As the input we used leading order MSTW set [24]. Following [25], we also multiply the KMR based distributions by special K-factor, absorbing the main part of non-logarithmic loop corrections to the gluon fusion cross-section:

$$K = \exp\left(C_A \frac{\alpha_s(\mu^2)}{2\pi}\pi^2\right), \quad (12)$$

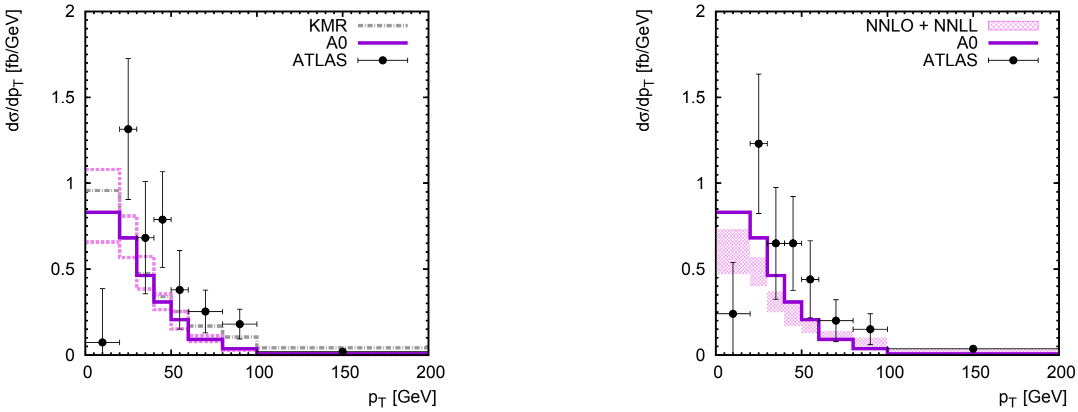
where the color factor $C_A = 3$, and the scale $\mu^2 = p_T^{4/3} m_H^{2/3}$ allows to eliminate certain subleading logarithms [26].

Now we turn to results of our simulations [27]. We set the renormalization and factorization scales equal to $\mu_R = \mu_F = \xi m_H$. We vary the parameter ξ between 1/2 and 2 about the default value $\xi = 1$ in order to estimate the scale uncertainties of our calculations[3]. We set $m_H = 126.8$ GeV and $\Gamma_H = 4.3$ MeV. We use the leading order formula for the strong coupling constant $\alpha_S(\nu^2)$ with $n_f = 4$ active quark flavors at $\Lambda_{QCD} = 200$ MeV, so that $\alpha_S(m_Z^2) = 0.1232$. We also use the running QED coupling constant $\alpha(\mu^2)$. The multidimensional integration in (11) was performed by the means of Monte-Carlo technique, using the routine VEGAS [28].

The results of our calculations [27] are presented in Figs. 1—3 in comparison with the ATLAS data. The ATLAS kinematical region is defined by $|\eta^\gamma| < 2.37$, $105 < M < 160$ GeV and $E_T^\gamma/M > 0.35(0.25)$ for the leading (subleading) photon, where M is the invariant mass of produced photon pair. In left panels, the solid histograms are obtained with the CCFM A0 gluon density by fixing both the factorization and renormalization scales at the default value, whereas the upper and lower dashed histograms correspond to the scale variation as described above. The dash-dotted histograms correspond to the predictions obtained with the KMR gluon distribution. We find that the ATLAS data are reasonably well described by the k_T-factorization approach.

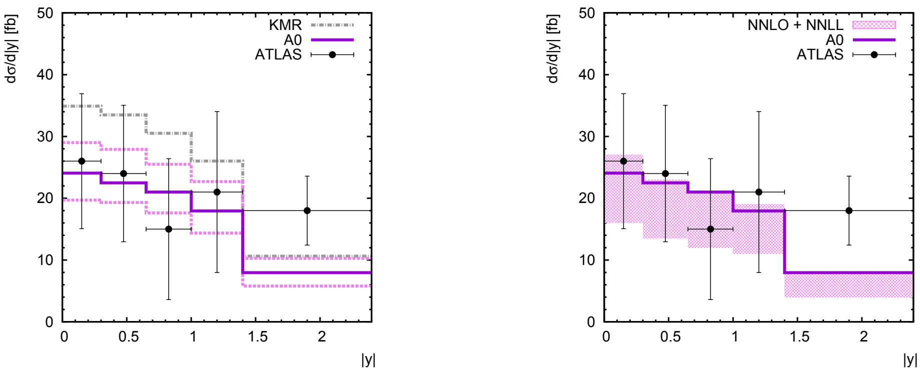
In right panels of Figs. 1—3 we plot the matched NNLO + NNLL pQCD predictions [9,10] (or NLO ones for $|\cos\theta^*|$ distribution) taken from [11] in comparison with our results and the ATLAS data. One can see that the measured cross sections are typically higher than the collinear QCD predictions, although no significant deviation within the theoretical and experimental uncertainties is observed. However, the k_T-factorization predictions at the default scale are rather similar to upper bound of collinear QCD results, providing us better agreement with the ATLAS data. Higher order corrections are known to be large in the collinear factorization: their effect increases the leading order cross section by about 80—100% [4, 5]. So, Figs. 1—3 illustrate the main advantage of the k_T-factorization approach: it is possible to obtain in a straightforward

[3] In the case of CCFM parton distribution such a variation leads to the usage of separate sets of gluon distribution — A0+ set (for $\xi = 2$) and A0– ($\xi = 1/2$) [21].



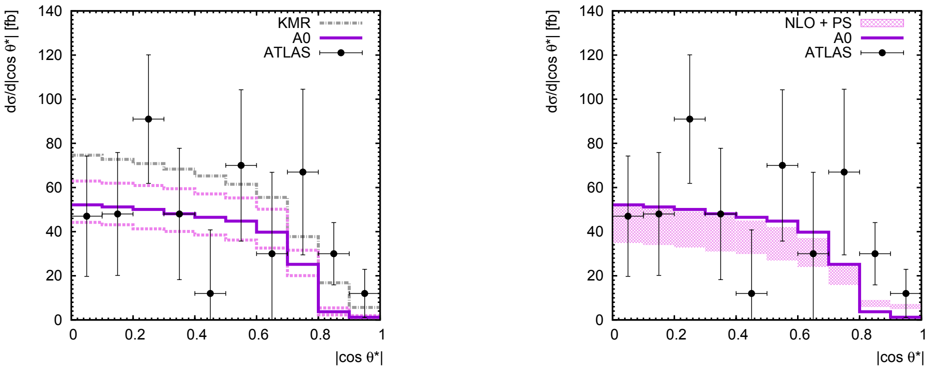
(a) (b)

Figure 1: *The differential cross section of the Higgs boson production in pp collisions at the LHC as a function of diphoton transverse momentum. Left panel: the solid and dash-dotted histograms correspond to the CCFM A0 and KMR predictions, respectively; and the upper and lower dashed histograms correspond to the scale variations in the CCFM-based calculations, as it is described in the text. Right panel: the solid histogram corresponds to the CCFM A0 predictions, and the hatched histogram represent the NNLO + NNLL predictions obtained in the collinear QCD factorization (taken from [11]). The experimental data are from ATLAS [11].*



(a) (b)

Figure 2: *The differential cross section of the Higgs boson production in pp collisions at the LHC as a function of diphoton rapidity. Notation of all histograms are the same as in Fig. 1. The NNLO + NNLL predictions are taken from [11]. The experimental data are from ATLAS [11].*



(a) (b)

Figure 3: *The differential cross section of the Higgs boson production in pp collisions at the LHC as a function of the helicity angle. Notation of all histograms are the same as in Fig. 1. The NLO predictions are taken from [11]. The experimental data are from ATLAS [11].*

manner analytic description which reproduces the main features of rather cumbersome higher order pQCD calculations.

In conclusion, the inclusive Higgs boson production with its subsequent decay to diphoton pair in the k_T-factorization QCD approach at LHC energies has been studied for the first time. The off-shell matrix element for $g^*g^* \to H \to \gamma\gamma$ subprocess has been evaluated. Reasonably good description of ATLAS data for the inclusive production of Higgs boson, decaying to diphoton pair, at LHC has been obtained. The results give the upper limit of NNLO+NNLL predictions, which shows the effective including of higher orders corrections in the k_T-factorization approach. We have demonstrated that the k_T-factorization approach can be used to study processes incorporating Higgs bosons decays and that the experimental data give limitations on the transverse momentum dependent. Future experimental analyses are necessary in order to discriminate between NNLO+NNLL and k_T-factorization predictions.

M.A.M. is very grateful to the organizing committee for their really helpful support. A.V.L. and N.P.Z. would also appreciate DESY Directorate for the support in the framework of Moscow — DESY project on Monte-Carlo implementation for HERA — LHC.

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