HIGGS PRODUCTION VIA GLUON FUSION WITH $K_T$ FACTORIZATION

A.V. LIPATOV, N.P. ZOTOV
SINF, Moscow State University,
119992 Moscow, Russia

We consider the Higgs boson production at high energy hadron colliders in the framework of the $k_T$-factorization approach. The attention is focused on the dominant gluon-gluon fusion subprocess. We show that $k_T$-factorization gives a possibility to investigate the associated Higgs boson and jets production.

1 Introduction

The search for the Higgs boson takes important part at the Fermilab Tevatron experiments and will be one of the main fields of study at the CERN LHC collider. In QCD the gluon-gluon fusion $gg \rightarrow H$ is the dominant inclusive Higgs production mechanism at LHC conditions. In this process, the Higgs production occurs via triangle heavy (top) quark loop.

It is obvious that the gluon-gluon fusion contribution to the Higgs production at LHC is strongly dependent on the gluon density $xG(x, \mu^2)$ in a proton. Usually gluon density are described by the Dokshitzer-Gribov-Lipatov-Altarelli-Parizi (DGLAP) evolution equation, where large logarithmic terms proportional to $\ln \mu^2$ are taken into account. However, at the LHC energies typical values of the incident gluon momentum fractions $x \sim m_H/\sqrt{s} \sim 0.008$ (for Higgs boson mass $m_H = 120$ GeV) are small, and another large logarithmic terms proportional to $\ln 1/x$ become important. These contributions can be taken into account using Balitsky-Fadin-Kuraev-Lipatov (BFKL) evolution equation. Just as for DGLAP, in this way it is possible to factorize an observable into a convolution of process-dependent hard matrix elements with universal gluon distributions. But as the virtualities (and transverse momenta) of the propagating
gluons are no longer ordered, the matrix elements have to be taken off-shell and the convolution made also over transverse momentum $k_T$ with the unintegrated ($k_T$-dependent) gluon distribution $F(x, k_T^2)$. This generalized factorization is called $k_T$-factorization.

In the collinear factorization, the calculation of Higgs production processes is quite complicated even at lowest order because of the heavy quark loops contribution. For example, in Higgs + one jet production, triangle and box loops occur, and in Higgs + two jet production the pentagon loops occur (see [1] and references therein). However, the calculations of the Higgs production rates can be simplified in the limit of large top quark mass $m_t \to \infty$. In this approximation the coupling of the gluons to the Higgs via top-quark loop can be replaced by an effective coupling. Thus it reduces the number of loops in a given diagram by one. The large $m_t$ approximation is valid to an accuracy of $\sim 5\%$ in the intermediate Higgs mass range $m_H < 2m_t$, as long as transverse momenta of the Higgs or final jets are smaller than of the top quark mass ($p_T < m_t$).

A particularly interesting quantity is the transverse momentum distribution of the produced Higgs boson. It is well-known that the fixed-order perturbative QCD is applicable when the Higgs transverse momentum is comparable to the $m_H$. However, the main part of the events is expected in the small-$p_T$ region ($p_T \ll m_H$), where the coefficients of the perturbative series in $\alpha_s$ are enhanced by powers of large logarithmic terms proportional to $\ln m_H^2/p_T^2$. Therefore reliable predictions at small $p_T$ can only be obtained if these terms will be resummed to all orders. Recently it was shown [2] that in the framework of $k_T$-factorization approach the soft gluon resummation formulas are the result of the approximate treatment of the solutions of the CCFM evolution equation (in the $b$-representation).

There are several additional motivations for our study of the Higgs production in the $k_T$-factorization approach. First of all, in the standard collinear approach, when the transverse momentum of the initial gluons is neglected, the transverse momentum of the final Higgs boson in $gg \to H$ subprocess is zero. Therefore it is necessary to include an initial-state QCD radiation to generate the $p_T$ distributions. In the $k_T$-factorization approach the underlying partonic subprocess is $gg \to H$ and the $k_T$-factorization naturally includes a large part of the high-order perturbative QCD corrections. Since the upper gluon in the parton ladder is not included in the hard interaction, its transverse momentum is now determined by the properties of the evolution equation only. It means that in the $k_T$-factorization approach the study of transverse momenta distributions in the Higgs production via gluon-gluon fusion will be direct probe of the unintegrated gluon distributions in a proton. In this case the transverse momentum of the produced Higgs should be equal to the sum of the of the initial gluons. Therefore future experimental studies at LHC can be used as further test of the non-collinear parton evolution.

In the previous studies [3,5,6] the $k_T$-factorization formalism was applied to calculate transverse momentum distribution of the inclusive Higgs production. The calculations were done using the on-mass shell (independent from the gluon $k_T$) matrix element of the $gg \to H$ subprocess and rather the similar results have been obtained. In Ref. [5] in the framework of MC generator CASCADE the off-mass-shell matrix element obtained by F. Hautmann [9] has been used with full CCFM evolution. In our paper [8] we have investigated Higgs production at hadron colliders using the full CCFM-evolved unintegrated gluon densities. Here in order to illustrate the fact that in the $k_T$-factorization approach the main features of collinear higher-order pQCD corrections are taken into account effectively, we give theoretical predictions for the Higgs + one jet and Higgs + two jet production processes.

## 2 Basic formulas

The effective Lagrangian for the Higgs boson coupling to gluons [1] is

$$
\mathcal{L}_{\text{eff}} = \frac{\alpha_s}{12\pi} \left( G_F \sqrt{2} \right)^{1/2} G_{\mu\nu} G^{\mu\nu} H,
$$

(1)
where $G_F$ is the Fermi coupling constant, $G^a_{\mu\nu}$ is the gluon field strength tensor and $H$ is the Higgs field. The triangle vertex $T^{\mu\nu}(k_1, k_2)$ for two off-shell gluons having four-momenta $k_1$ and $k_2$ and color indexes $a$ and $b$ respectively, can be obtained easily from the Lagrangian (1):

$$T^{\mu\nu}(k_1, k_2) = i\delta^{ab}\alpha_s(\mu)\left(\frac{G_F}{\sqrt{2}}\right)^{1/2} \left[ k_2^\mu k_1^\nu - (k_1 \cdot k_2) g^{\mu\nu} \right].$$

The differential cross section of inclusive Higgs production $p\bar{p} \rightarrow H + X$ in the $k_T-$factorization approach has been calculated in [8] and can be written as:

$$\frac{d\sigma(p\bar{p} \rightarrow H + X)}{dy_H} = \int \frac{\alpha_s^2(\mu^2)}{288\pi} \frac{G_F\sqrt{2}}{x_1 x_2 m_H^2 s} \left[ m_H^2 + p_T^2 \right]^2 \cos^2(\Delta\varphi) \times$$

$$\times A(x_1, k_{1T}^2, \mu^2) A(x_2, k_{2T}^2, \mu^2) \frac{d\Delta\varphi}{2\pi},$$

where $A(x, k_T^2, \mu^2)$ is the unintegrated gluon distribution, $\Delta\varphi$ the azimuthal angle between the initial gluon momenta $k_{1T}$ and $k_{2T}$, and the transverse momentum of the produced Higgs boson is $p_T = k_{1T} + k_{2T}$. It should be noted that this process is particularly interesting in $k_T-$factorization, as the transverse momenta of the gluons are in the same order as their longitudinal momenta ($\sim (10 \text{ GeV})$).

### 3 Numerical results

![Figure 1: Differential cross section $d\sigma/dp_T$ for Higgs + one jet production at $\sqrt{s} = 14 \text{ TeV}$: solid, dashed, dash-dotted and dotted curves correspond to $m_H = 125, 100, 150, 200 \text{ GeV}$, respectively (left column). The jet-jet azimuthal angle distribution in the Higgs + two jet production: solid and dashed curves correspond to the J2003 set 1 and J2003 set 2 unintegrated gluon distributions, respectively (right column).](image)

Our prediction for the total cross section and the transverse momentum and rapidity distributions of the inclusive Higgs production at the LHC ($\sqrt{s} = 14 \text{ TeV}$) were done in Ref. [8]. The calculations were fulfilled for four choices of the Higgs boson mass ($m_H = 100, 125, 150, 200 \text{ GeV}$) under interest in the Standard Model with default scale $\mu^2 = m_H^2$. We used LO formula for the strong coupling constant $\alpha_s(\mu^2)$ with $n_f = 4$ active quark flavours and $\Lambda_{\text{QCD}} = 200 \text{ MeV}$, such that $\alpha_s(M_Z^2) = 0.1232$.

Here we illustrate how $k_T-$factorization approach can be used to calculate the semi-inclusive Higgs production rates. We choose the one carrying the largest transverse momentum, and then compute Higgs with an associated jet cross sections at the LHC energy. We have applied the usual cut on the final jet transverse momentum $|p_{\text{jet}T}| > 20 \text{ GeV}$. Our predictions for the transverse momentum distribution of the Higgs + one jet production are shown in Fig. 1 (left column). One can see the shift of the peak position in the $p_T$ distributions in comparison with...
inclusive production, which is a direct consequence of the $|p_{\text{jet}} T| > 20$ GeV cut. To demonstrate the possibilities of the $k_T$-factorization approach, we calculate azimuthal angle distributions between the two final jet transverse momenta in the Higgs + two jet production process, where the kinematical cut $|p_{\text{jet}} T| > 20$ GeV was applied for both final jets. Studying of these quantities is important to clean separation of weak-boson fusion and gluon-gluon fusion contributions. Our results are shown in Fig. 1 (right column), where a dip at 90 degrees is seen. This dip at $\Delta \phi \simeq \pi/2$ comes from the $\cos(\Delta \phi)$ in eq. (3). In the approach presented here, the $k_T$ of the initial gluons is approximately compensated by the transverse momenta of the jets, $k_T \simeq p_{\text{jet}} T$ and, consequently, $\Delta \phi \simeq \Delta \varphi$. This dip is characteristic for the loop-induced Higgs coupling to gluons in the framework of fixed-order pQCD calculations. Thus, we illustrate that the features usually interpreted as NNLO effects are reproduced in the $k_T$-factorization with LO matrix elements.

However, we see a very large difference between the predictions based on the J2003 gluon densities set 1 and set 2, showing the sensitivity to the shape of the unintegrated gluon distribution.

4 Conclusions

The predictions in the $k_T$-factorization approach are very close to NNLO pQCD results for the inclusive Higgs production at the LHC, since the main part of high-order collinear pQCD corrections is already included in the $k_T$-factorization. In the $k_T$-factorization approach the calculation of the associated Higgs+ jets production is much simpler than in the collinear factorization approach. However, the large scale dependence of our calculations (of the order of 20 - 50%) probably indicates the sensitivity to the unintegrated gluon distributions.

Acknowledgments

N.Z. thanks J. Tran Thanh Van and B. Nicolescu for financial support and kindly and friendly atmosphere during the Workshop.

References

1. V. Del Duca, W. Kilgore, C. Olear, C. Schmidt and D. Zeppenfeld, *Nucl. Phys.* B 616, 367 (2001); *Phys. Rev.* D 67, 073003 (2003); V. Del Duca, [hep-ph/0312184](http://arxiv.org/abs/hep-ph/0312184).
2. J.R. Ellis, M.K. Gaillard and D.V. Nanopoulos, *Nucl. Phys.* B 106, 292 (1976); M.A. Shifman, A.I. Vainstein, M.B. Voloshin and V.I. Zakharov, * Yad. Fiz.* 30, 1368 (1979).
3. A. Gawron and J. Kwiecinski, *Phys. Rev.* D 70, 014003 (2004).
4. M.G. Ryskin, A.G. Shuvaev and Y.M. Shabelski, *Phys. Atom. Nucl.* 64, 120 (2001).
5. H. Jung, *Mod. Phys. Lett.* A 19, 1 (2004), [hep-ph/0311249](http://arxiv.org/abs/hep-ph/0311249).
6. G. Watt, A.D. Martin and M.G. Ryskin, *Phys. Rev.* D 70, 014012 (2004), [hep-ph/0309096](http://arxiv.org/abs/hep-ph/0309096).
7. H. Jung, *Comp. Phys. Comm.* 143, 100 (2002).
8. A.V. Lipatov, N.P. Zotov, DESY 05-020, [hep-ph/0501172](http://arxiv.org/abs/hep-ph/0501172).
9. F. Hautmann, *Phys. Lett.* B 535, 159 (2002).
10. S.P. Baranov, N.P. Zotov, *Phys. Lett.* B 491, 111 (2000).
11. R.V. Harlander and W.B. Kilgore, *Phys. Rev. Lett.* 88, 201801 (2002); C. Anastasiou and K. Melnikov, *Nucl. Phys.* B 646, 220 (2002); V. Ravindran, J. Smith and W.L. van Neerven, *Nucl. Phys.* B 665, 325 (2003).