Resummed transverse momentum distribution of Pseudo-scalar Higgs boson at NNLO$_A$+NNLL

Neelima Agarwal,[a] **Pulak Banerjee,**[b,c] **Goutam Das,**[d] **Prasanna K. Dhani,**[b,c] **Ayan Mukhopadhyay**[e] **V. Ravindran**[b,c] **and Anurag Tripathi**[e]

[a] *Department of Physics, Chaitanya Bharathi Institute of Technology, Gandipet, Hyderabad, Telangana State 500075, India*
[b] *The Institute of Mathematical Sciences, IV Cross Road, CIT Campus, Chennai 600 113, India*
[c] *Homi Bhabha National Institute, Training School Complex, Anushakti Nagar, Mumbai 400085, India*
[d] *Theory Group, Deutsches Elektronen-Synchrotron (DESY), Notkestrasse 85, D-22607 Hamburg, Germany*
[e] *Department of Physics, Indian Institute of Technology Hyderabad, Kandi, Sangareddy, Telangana State 502285, India*

E-mail: neel1dph@gmail.com, bpulak@imsc.res.in, goutam.das@desy.de, prasannakd@imsc.res.in, ayanmukhopadhyay5@gmail.com, ravindra@imsc.res.in, tripathi@iith.ac.in

Abstract: In this article we have studied the transverse momentum distribution of the pseudo-scalar Higgs boson at the Large Hadron Collider (LHC). The small p_T region which provides the bulk of the cross-section is not accessible to fixed order perturbation theory due to the presence of large logarithms in the series. Using the universal infrared behaviour of the QCD we resum these large logarithms upto next-to-next-to leading logarithmic (NNLL) accuracy. We observe a significant reduction in theoretical uncertainties due to the unphysical scales at NNLL level compared to the previous order. We present the p_T distribution matched to NNLO$_A$+NNLL, valid for the whole p_T region and provide a detailed phenomenological study in the context of 14 TeV LHC using different choices of masses, scales and parton distribution functions which will be useful for the search of such particle at the LHC in near future.

Keywords: Perturbative QCD, Resummation

Contents

1 Introduction

The Standard Model (SM) of particle physics has been very successful in explaining the properties of the fundamental particles and the interactions among them. After the discovery of the Higgs boson by the ATLAS [1] and the CMS [2] at the Large Hadron Collider (LHC), the SM has become the most accepted theory of particle physics. The measured properties of this new boson are in full agreement with the SM predictions so far. However SM is not the compete theory of the nature as it can not describe many things including baryogenesis, neutrino masses, hierarchy problem to name a few. Many of these issues can be addressed by going beyond the SM often by invoking some extended sectors. A lot of the effort is recently being made towards the discovery of such new physics beyond the SM (BSM). A plethora of models exist in this context; a large class of which predicts an extended scalar sector containing multiple scalar or pseudo-scalar Higgs particles. Extended models like the Minimal Supersymmetric Standard Model (MSSM) or Next-to-Minimal Supersymmetric Standard Model (NMSSM) etc., predict a larger variety of Higgs bosons which differ among each other for example by their mass, charge, CP-parity and couplings. A simple example contains an additional Higgs doublet along with the usual Higgs doublet of the SM. After the symmetry breaking this gives rise to two CP-even (scalar) Higgs bosons (h, H), one of which is identified with the SM Higgs boson (h), a CP-odd (pseudo-scalar) Higgs boson (A) as well as a pair of charged scalars $(H^{\pm})$. This allows phenomenologically interesting scenarios particularly with pseudo-scalar resonances. One of the important goal at the LHC Run-II is to search for such resonances which requires a precise theoretical predictions for both inclusive as well as for exclusive observables.

Similar to the SM scalar Higgs production, the dominant production channel for pseudo-scalar Higgs is through the gluon fusion. Therefore at the LHC the large gluon flux can boost its production cross-section to a great extent. Like the scalar Higgs boson, the leading order (LO) prediction of the pseudo-scalar production at the hadron colliders suffers from large theoretical uncertainties due to dependence on renormalisation scale μ_R through the strong coupling constant. The next-to-leading order (NLO) correction [3–6] is known to increase the cross-section as high as 67% compared to the born with scale uncertainty varying about 35%. This essentially calls for higher order corrections beyond NLO. The total inclusive cross-section at next-to-next-to leading order (NNLO) has been known for quite a long time [7–11]. The NNLO correction increases the cross-section further by 15% and reduces the scale uncertainties to 15%. To further reduce the scale dependences one has to go even higher order considering full next-to-next-to-next-to leading order (N^{3}LO) corrections. The complexity in full N^{3}LO correction is even higher and only recently full N^{3}LO correction [12] has been obtained for the SM Higgs productions with infinite top mass limit approximation which reduces the scale uncertainty to 3%. The large top mass approximations turned out to be a good approximation for the scalar Higgs case and the predictions are found to be within 1% [13–15] and one could expect similar behaviour in pseudo-scalar production as well.

The first attempt towards the N^{3}LO corrections is made through the calculation of threshold enhanced soft-virtual (SV) corrections. For scalar Higgs productions these are known for a long time upto N^{3}LO$_{SV}$ [16–21]. Associated production [22] and bottom annihilation [23] are also known at the same accuracy. The soft gluons effect at threshold for pseudo-scalar Higgs has been computed in [24] at N^{3}LO$_{SV}$ level on the subsequent computation of its form factor at three loops [25]. Inclusive cross-section may however give unreliable results in certain phase space (PSP) region due to large logarithms arising from soft gluon emission and needs to be resummed to all orders. The soft gluon resummation for inclusive scalar Higgs production has been known upto next-to-next-to leading logarithm (NNLO+NNLL) [26] for a long time. The full N^{3}LO result [12] enables to perform soft gluon resummation at next-to-next-to-next-to leading logarithm (N^{3}LO+N^{3}LL) [27–29] (see also [30] for renormalisation group improved prediction.). For pseudo-scalar Higgs production, an approximate N^{3}LO$_A$ result has been matched with N^{3}LL threshold resummation in [31] (see [32, 33] for earlier works in this direction).

Recently there have been a renewed interest in the resummed improved prediction for exclusive observables as well. Higgs [34] and Drell-Yan [35] rapidity distributions are predicted at NNLO+NNLL accuracy resumming large threshold logarithms using double Mellin space formalism (see [36–38] for earlier works)[1]. The resummation in transverse momentum distribution is also well studied in the past. The small p_T region (defined by $p_T \ll M$, M being typical hard scale of the theory) often spoils the fixed order (FO) predictions due to the presence of large logarithms of the type $\ln(M^2/p_T^2)$. By resumming these large logarithms [47–59], the predictivity of the QCD can be recovered in the full PSP region for p_T distribution. Such resummation of large logarithms can be obtained by exploiting the universal properties of QCD in the infrared region [48–54, 57, 60, 61]. Recently a powerful and elegant technique is provided using soft-collinear effective theory (SCET) by

[1] Also see [39–43] for a different QCD approach and [44–46] for SCET approach.

exploiting only the soft and collinear degrees of freedom in an effective field theory set up (see [62–66]). These approaches have been applied to obtain the scalar Higgs boson p_T spectrum in gluon fusion upto NNLO+NNLL [67–75] and through bottom annihilation upto NNLO+NNLL [76, 77]. Recently the p_T distribution for Higgs boson has been achieved to NNLO+N^{3}LL accuracy [78, 79]. Another approach to resum these large logarithms is through the parton shower (PS) simulations which has been also successful in recent times through the implementation in monte-carlo generators like MadGraph5_aMC@NLO [80], POWHEG [81] etc. mostly upto NLO+PS accuracy. However the accuracy of PS prediction is often not clear and has remained an active topic of research these days[2]. In all these approaches, there is an effective matching scale (resummation scale or shower scale) which defines the infrared region and the hard region. Although its dependence is of higher logarithmic order, a suitable choice is needed to properly describe the full p_T spectrum in a meaningful way.

A clear understanding of the pseudo-scalar Higgs boson properties is also based on the precise knowledge of such differential observables like transverse momentum, rapidity etc. For pseudo-scalar production in association with a jet, the two loop virtual amplitudes can be found in [83], which is important to predict the differential distribution of A. The small p_T region of pseudo-scalar transverse momentum distribution renders the FO prediction due to the large logarithms in this PSP region. These logarithms have to be resummed in order to get a realistic distribution. This has been achieved at next-to-leading logarithm (NLO+NLL) [84] accuracy for a long time[3] using universal infrared behaviour of QCD. The scale uncertainty in the peak region at NLO+NLL was found to be 25% when the scale is varied simply by a factor of two. Along with the PDF uncertainty, the total theoretical uncertainties reach as large as 35% near the peak. This necessitates the correction at the next order. In this article we extend this accuracy to NNLL. We obtained different pieces necessary for p_T resummation of a pseudo-scalar Higgs boson upto NNLL accuracy. The resummed contribution has to be matched with FO in order to get a realistic distribution valid in the full p_T spectrum. We use the ansatz prescribed in [31] to obtain the NNLO piece to a very good approximation. Finally the matched prediction is presented upto NNLO$_A$+NNLL for the pseudo-scalar Higgs p_T spectrum for phenomenological study at 14 TeV LHC.

The paper is organised as follows: in section-2 we set up the theoretical framework for the resummation of large logarithms for small p_T region relevant for pseudo-scalar Higgs production. In section-3, we will provide a detailed phenomenological study of the p_T spectrum for different masses, scales and PDFs relevant at the LHC. Finally we draw our conclusion in section-4.

[2] For a recent study see [82] and references therein.

[3] Through this paper we take $gg \to A$ as the LO for p_T distribution even though its contribution is $\sim \delta(p_T)$.

2 Theoretical Framework

In this section we give the formula that carries out resummation and present the various coefficients that enter it.

Resummation formula: If we calculate the distribution of a colorless final state of mass M and if p_T is significantly smaller than M, large logarithms of p_T/M arise in the distribution $\mathrm{d}\sigma/\mathrm{d}p_T$ due to an incomplete cancellation of soft and collinear contributions. At each successive order in α_s the highest power of the logarithm that appears increases which renders the naïve perturbative expansion in α_s invalid as $p_T \to 0$. However, factorization of soft and collinear radiation from the hard process allows us to resum the logarithms to all orders in α_s. This factorization occurs in the Fourier space conjugate to p_T called impact parameter space; the variable conjugate to $\vec{p_T}$ is denoted by $\vec{b}$:

$$f(\mathbf{p}_T) = \frac{1}{(2\pi)^2} \int \mathrm{d}^2\mathbf{b}\; e^{-i\mathbf{b}\cdot\mathbf{p}_T} f(\mathbf{b})\,, \tag{2.1}$$

implying that the limit $p_T \to 0$ corresponds to $b \to \infty$. The momentum conservation relates $\mathbf{p}_T$ to the sum of the transverse momenta $\mathbf{k}_T = \sum_i \mathbf{k}_{i,T}$ of the outgoing partons which is factorized in b space using

$$\delta(\mathbf{p}_T + \mathbf{k}_T) = (2\pi)^{-2} \int \mathrm{d}\mathbf{b} \exp[-i\mathbf{b}\cdot\mathbf{p}_T] \exp[-i\mathbf{b}\cdot\mathbf{k}_T]. \tag{2.2}$$

Using rotational invariance around the beam axis the angular integration can be performed which gives Bessel function J_0. The distribution at low p_T values compared to M has the following behaviour which is obtained by resumming the large logarithms to all orders in perturbation theory.

$$\frac{\mathrm{d}\sigma^{F,(\mathrm{res})}}{\mathrm{d}p_T^2} = \tau \int_0^\infty \mathrm{d}b\, \frac{b}{2}\, J_0(bp_T)\, W^F(b, M, \tau)\,, \tag{2.3}$$

with the Bessel function $J_0(x)$, $\tau = M^2/S$, and S the hadronic center-of-mass energy. The proper inclusion of terms $p_T \gtrsim M$ will be described in Section 2.1. Here and in what follows, the superscript F is attached to final state specific quantities. It is convenient to consider the Mellin transform with respect to the variable τ:

$$W_N^F(b, M) = \int_0^1 \mathrm{d}\tau \tau^{N-1} W^F(b, M, \tau)\,, \tag{2.4}$$

which has the following form for Higgs and Pseudo-scalar Higgs production [54, 57][4]

$$\begin{aligned} W_N^F(b, M) = \hat{\sigma}^{F,(0)} \exp\left\{ -\int_{b_0^2/b^2}^{M^2} \frac{\mathrm{d}k^2}{k^2} \Big[A_g(\alpha_s(k)) \ln \frac{M^2}{k^2} + B_g(\alpha_s(k)) \Big] \right\} \\ \times \sum_{i,j} \left[H_g^F C_1 C_2 \right]_{gg;ij} f_{i,N}(b_0/b)\, f_{j,N}(b_0/b)\,, \end{aligned} \tag{2.5}$$

[4]Throughout this paper the parameters that are not crucial for the discussion will be suppressed in function arguments.

where $\hat{\sigma}^{F,(0)}_{c\bar{c}}$ is the Born factor which is the parton level cross section at LO. Unless indicated otherwise, the renormalization and factorization scales have been set to $\mu_f = \mu_r = M$. The sum over c, in general, runs over all relevant quark flavors $c = q \in \{u, d, s, c, b\}$ and their charge conjugates as well as gluons ($\bar{g} \equiv g$). It takes into account that, already at LO, different initial states can contribute.[5] In this study we will only consider contributions arising from the operator O_G in the effective Lagrangian and will not include the contributions arising from O_J operator and hence $c = g$ only.

The function $f_{i,N}(q)$ in Eq. (2.5) is the Mellin transform of the density function $f_i(x, q)$ of parton i in the proton, where x is the momentum fraction and q the momentum transfer. The numerical constant $b_0 = 2\exp(-\gamma_E)$, with Euler's constant $\gamma_E = 0.5772\ldots$, is introduced for convenience.

The born cross section at the parton level including the finite top mass dependence is given by

$$\sigma^{A,(0)}(\mu_R^2) = \frac{\pi\sqrt{2}G_F}{16} a_s^2 \cot^2\beta \left|\tau_A f(\tau_A)\right|^2. \tag{2.6}$$

Here $a_s = \alpha_s/4\pi$, $\tau_A = 4m_t^2/m_A^2$ and the function $f(\tau_A)$ is given by

$$f(\tau_A) = \begin{cases} \arcsin^2 \frac{1}{\sqrt{\tau_A}} & \tau_A \geq 1\,, \\ -\frac{1}{4}\left(\ln\frac{1-\sqrt{1-\tau_A}}{1+\sqrt{1-\tau_A}} + i\pi\right)^2 & \tau_A < 1\,. \end{cases} \tag{2.7}$$

All the coefficients that appear in the resummation formula have series expansions in α_s:

$$C_{ga}(z;\alpha_s) = \delta_{ga}\delta(1-z) + \sum_{n=1}^{\infty}\left(\frac{\alpha_s}{\pi}\right)^n C^{(n)}_{ga}(z) \tag{2.8}$$

$$G_{ga}(z;\alpha_s) = \sum_{n=1}^{\infty}\left(\frac{\alpha_s}{\pi}\right)^n G^{(n)}_{ga}(z) \tag{2.9}$$

$$H^F_c(\alpha_s) = 1 + \sum_{n=1}^{\infty}\left(\frac{\alpha_s}{\pi}\right)^n H^{F,(n)}_c \tag{2.10}$$

$$A_g(\alpha_s) = \sum_{n=1}^{\infty}\left(\frac{\alpha_s}{\pi}\right)^n A^{(n)}_g \tag{2.11}$$

$$B_g(\alpha_s) = \sum_{n=1}^{\infty}\left(\frac{\alpha_s}{\pi}\right)^n B^{(n)}_g \tag{2.12}$$

The order at which these coefficients are taken into account in Eq. (2.5) determines the *logarithmic accuracy* of the resummed cross section; *leading logarithmic* (LL) means that all higher order coefficients except for $A^{(1)}_c$ are neglected, *next-to-LL* (NLL) requires $A^{(2)}_c$, $B^{(1)}_c$, $C^{(1)}_{ci}$, and $H^{F,(1)}_c$, etc. The coefficients required for the pseudo-scalar Higgs boson at next-to-NLL (NNLL) accuracy are given in Section 2.2.

[5] For example, the LO DY process receives contributions from all light quark flavors.

The coefficients A_g, B_g, and C_{gi} that enter the resummation formula for Higgs production with $H_g^{Higgs} = 1$ can be used for the pseudo-scalar Higgs as well. This choice of resummation coefficients will be termed Higgs resummation scheme in this paper. See [85] for details on resummation schemes. The information of pseudo-scalar Higgs is contained in the *hard coefficient* H_c^F and the Born factor $\hat{\sigma}_{c\bar{c}}^{F,(0)}$.

All resummation coefficients are known in the Higgs scheme up to the order required in this paper (see Section 2.2), with the exception of $H_g^{A,1}$ and $H_g^{A,2}$ whose evaluation through NNLO will also be presented in Section 2.2.

Perturbative expansion of resummation formula: Evolving the parton densities from b_0/b to μ_f in Eq. (2.5) (see Ref.[85]), one can define the partonic resummed cross section $\mathcal{W}_{ij,N}^F$ through

$$W_N^F(b, M) = \sum_{i,j} \mathcal{W}_{ij,N}^F\,(b, M, \mu_f)\, f_{i,N}(\mu_f) f_{j,N}(\mu_f)\,. \tag{2.13}$$

From a perturbative point of view, $\mathcal{W}^F$ can be cast into the form

$$\mathcal{W}_{ij,N}^F\,(b, M, \mu_f) = \sum_c \hat{\sigma}_{c\bar{c}}^{F,(0)} \left\{ \mathcal{H}_{c\bar{c}\leftarrow ij,N}^F(M, Q, \mu_f) + \Sigma_{c\bar{c}\leftarrow ij,N}^F(L, M, Q, \mu_f) \right\}, \tag{2.14}$$

where $L = \ln(Q^2 b^2/b_0^2)$ denotes the logarithms that are being resummed in $\mathcal{W}^F$, and Q is an arbitrary *resummation scale*. While $\mathcal{W}^F$ is formally independent of Q, truncation of the perturbative series will introduce a dependence on this scale which is, however, of higher order. The b dependence is contained entirely in the functions $\Sigma_{c\bar{c}\leftarrow ij}^F$ which are *defined* to vanish at $L = 0$; for the perturbative expansions upto NNLO please refer to Ref.[85].

2.1 Matching the cross-section across the large and small p_T regions

The resummed result given in the previous section is valid at small values of transverse momentum where the logarithms of p_T are summed to all orders, and to emphasize that these results are accurate to a certain logarithmic accuracy such as NLL or NNLL we attach a subscript to the resummed cross-section: $\left(\mathrm{d}\sigma^{(\mathrm{res})}/\mathrm{d}p_T^2\right)_{\mathrm{l.a.}}$. At high values of transverse momentum fixed order results accurately describe the distribution which we will denote by $\left(\mathrm{d}\sigma/\mathrm{d}p_T^2\right)_{\mathrm{f.o.}}$. To match the cross-section across the entire p_T region we will follow the additive matching procedure defined below:

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right)_{\mathrm{f.o.+l.a.}} = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right)_{\mathrm{f.o.}} + \left(\frac{\mathrm{d}\sigma^{(\mathrm{res})}}{\mathrm{d}p_T^2}\right)_{\mathrm{l.a.}} - \left(\frac{\mathrm{d}\sigma^{(\mathrm{res})}}{\mathrm{d}p_T^2}\right)_{\mathrm{f.o.}}. \tag{2.15}$$

When at low p_T the divergences in p_T arising due to the fixed order result in the first term are subtracted by the last term, which is nothing but the expansion of the resummation formula in α_s truncated to appropriate order. At large values of p_T we can reduce the effect of the last term by making the replacement [85]

$$L \to \tilde{L} \equiv \ln\left(\frac{Q^2 b^2}{b_0^2} + 1\right). \tag{2.16}$$

2.2 Resummation coefficients and determination of $H_g^{A,(2)}$

Here we list down the A, B and C coefficients that enter the computation. Whenever, a coefficient is scheme dependent we have given it in the Higgs scheme.

$$
\begin{aligned}
A_g^{(1)} &= C_A\,, \\
A_g^{(2)} &= \frac{1}{2}\,C_A\left[\left(\frac{67}{18}-\frac{\pi^2}{6}\right)C_A-\frac{5}{9}N_f\right]\,, \\
A_g^{(3)} &= C_A\Bigg[C_A^2\left(\frac{11\pi^4}{720}-\frac{67\pi^2}{216}+\frac{245}{96}+\frac{11}{24}\zeta_3\right)+C_AN_f\left(\frac{5\pi^2}{108}-\frac{209}{432}-\frac{7}{12}\zeta_3\right) \\
&\quad +C_FN_f\left(-\frac{55}{96}+\frac{1}{2}\zeta_3\right)-\frac{1}{108}N_f^2+8\beta_0\left(C_A\left(\frac{101}{216}-\frac{7}{16}\zeta_3\right)-\frac{7}{108}N_f\right)\Bigg] \\
B_g^{(1)} &= -\frac{1}{6}\,(11C_A-2N_f) \\
B_g^{(2)} &= C_A^2\left(\frac{23}{24}+\frac{11}{18}\pi^2-\frac{3}{2}\zeta_3\right)+\frac{1}{2}C_FN_f-C_AN_f\left(\frac{1}{12}+\frac{\pi^2}{9}\right)-\frac{11}{8}C_FC_A \\
C_{gg}^{(1)} &= \frac{1}{4}\left((5+\pi^2)C_A-3C_F\right)\delta(1-z) \\
C_{gq}^{(1)} &= \frac{1}{2}C_Fz \\
G_{gg}^{(1)} &= C_A\frac{1-z}{z} \\
G_{gq}^{(1)} &= C_F\frac{1-z}{z}
\end{aligned}
\tag{2.17}
$$

where $\beta_0 = (11\,C_A - 2\,N_f)/12$, $C_F = 4/3$, $C_A = 3$, and $N_f = 5$ is the number of active quark flavors.

The coefficients $A_g^{(i)}$, $B_g^{(1)}$, off-diagonal coefficient $C_{gq}^{(1)}$, and $G_{gg}^{(1)}$ and $G_{gq}^{(1)}$ are scheme independent. The coefficients $B^i(2)_g$ and C_{gg}^1 have been given above in Higgs scheme.

3 The results: Hard coefficients and matched distributions

In this section we will first calculate the hard coefficients $H_g^{A,1}$ and $H_g^{A,2}$, then we will describe how we obtain the fixed order p_T distribution that we need for the matching, and finally obtain the distributions.

3.1 Evaluation of Hard coefficient

The only coefficients that remain to be determined are the first and second order hard coefficients. These can be extracted from the knowledge of form factors upto 2-loop for the pseudoscalar Higgs. The unrenormalized form factor $\hat{\mathcal{F}}_g^{A,(n)}$ up to 2-loop are given reproduced here

$$
\mathcal{F}_g^A \equiv \sum_{n=0}^{\infty}\left[\hat{a}_s^n\left(\frac{Q^2}{\mu^2}\right)^{n\frac{\epsilon}{2}} S_\epsilon^n\hat{\mathcal{F}}_g^{A,(n)}\right]\,. \tag{3.1}
$$

We present the unrenormalized results for the choice of the scale $\mu_R^2 = \mu_F^2 = q^2$ as follows:

$$
\begin{aligned}
\hat{\mathcal{F}}_g^{A,(1)} &= C_A \Bigg\{ -\frac{8}{\epsilon^2} + 4 + \zeta_2 + \epsilon\Bigg(-6 - \frac{7}{3}\zeta_3\Bigg) + \epsilon^2\Bigg(7 - \frac{\zeta_2}{2} + \frac{47}{80}\zeta_2^2\Bigg)\Bigg\}\,, \\
\hat{\mathcal{F}}_g^{A,(2)} &= C_F n_f \Bigg\{ -\frac{80}{3} + 6\ln\left(\frac{q^2}{m_t^2}\right) + 8\zeta_3 + \epsilon\Bigg(\frac{2827}{36} - 9\ln\left(\frac{q^2}{m_t^2}\right) - \frac{19}{6}\zeta_2 - \frac{8}{3}\zeta_2^2 \\
&\quad - \frac{64}{3}\zeta_3\Bigg) + \epsilon^2\Bigg(-\frac{70577}{432} + \frac{21}{2}\ln\left(\frac{q^2}{m_t^2}\right) + \frac{1037}{72}\zeta_2 - \frac{3}{4}\ln\left(\frac{q^2}{m_t^2}\right)\zeta_2 + \frac{64}{9}\zeta_2^2 + \frac{455}{9}\zeta_3 \\
&\quad - \frac{10}{3}\zeta_2\zeta_3 + 8\zeta_5\Bigg)\Bigg\} \qquad (3.2)
\end{aligned}
$$

The strong coupling constant $a_s \equiv a_s\left(\mu_R^2\right)$ is renormalised at the mass scale μ_R and is related to the unrenormalised one, $\hat{a}_s \equiv \hat{g}_s^2/16\pi^2$, through

$$
\hat{a}_s S_\epsilon = \left(\frac{\mu^2}{\mu_R^2}\right)^{\epsilon/2} Z_{a_s} a_s \qquad (3.3)
$$

with $S_\epsilon = \exp\left[(\gamma_E - \ln 4\pi)\epsilon/2\right]$ and the scale μ is introduced to keep the unrenormalized strong coupling constant dimensionless in $d = 4 + \epsilon$ space-time dimensions. The renormalisation constant Z_{a_s} up to $\mathcal{O}(a_s^3)$ is given by

$$
Z_{a_s} = 1 + a_s\left[\frac{2}{\epsilon}\beta_0\right] + a_s^2\left[\frac{4}{\epsilon^2}\beta_0^2 + \frac{1}{\epsilon}\beta_1\right] + a_s^3\left[\frac{8}{\epsilon^3}\beta_0^3 + \frac{14}{3\epsilon^2}\beta_0\beta_1 + \frac{2}{3\epsilon}\beta_2\right]. \qquad (3.4)
$$

The coefficient of the QCD β function β_i are given by [86]

$$
\begin{aligned}
\beta_0 &= \frac{11}{3}C_A - \frac{2}{3}n_f\,, \\
\beta_1 &= \frac{34}{3}C_A^2 - 2n_f C_F - \frac{10}{3}n_f C_A\,, \\
\beta_2 &= \frac{2857}{54}C_A^3 - \frac{1415}{54}C_A^2 n_f + \frac{79}{54}C_A n_f^2 + \frac{11}{9}C_F n_f^2 - \frac{205}{18}C_F C_A n_f + C_F^2 n_f \qquad (3.5)
\end{aligned}
$$

with the SU(N) QCD color factors

$$
C_A = N, \qquad C_F = \frac{N^2-1}{2N}\,. \qquad (3.6)
$$

n_f is the number of active light quark flavors. The operator renormalization is needed to remove the additional UV divergences and UV finite formfactor is obtained is given by

$$
[\mathcal{F}_g^A]_R = Z_g^A \mathcal{F}_g^A\,. \qquad (3.7)
$$

where the operator renormaliztion factor is given by

$$
\begin{aligned}
Z_g^A &= 1 + a_s \left[\frac{22}{3\epsilon} C_A - \frac{4}{3\epsilon} n_f \right] + a_s^2 \left[\frac{1}{\epsilon^2} \left\{ \frac{484}{9} C_A^2 - \frac{176}{9} C_A n_f + \frac{16}{9} n_f^2 \right\} + \frac{1}{\epsilon} \left\{ \frac{34}{3} C_A^2 \right.\right. \\
&\quad \left.\left. - \frac{10}{3} C_A n_f - 2 C_F n_f \right\} \right] + a_s^3 \left[\frac{1}{\epsilon^3} \left\{ \frac{10648}{27} C_A^3 - \frac{1936}{9} C_A^2 n_f + \frac{352}{9} C_A n_f^2 - \frac{64}{27} n_f^3 \right\} \right. \\
&\quad + \frac{1}{\epsilon^2} \left\{ \frac{5236}{27} C_A^3 - \frac{2492}{27} C_A^2 n_f - \frac{308}{9} C_A C_F n_f + \frac{280}{27} C_A n_f^2 + \frac{56}{9} C_F n_f^2 \right\} \\
&\quad \left. + \frac{1}{\epsilon} \left\{ \frac{2857}{81} C_A^3 - \frac{1415}{81} C_A^2 n_f - \frac{205}{27} C_A C_F n_f + \frac{2}{3} C_F^2 n_f + \frac{79}{81} C_A n_f^2 + \frac{22}{27} C_F n_f^2 \right\} \right] .
\end{aligned}
\tag{3.8}
$$

Using the above form factor which is completely free of any ultraviolet divergences and contains only infrared singularities we can obtain the the hard fuction by removing them by multiplying the IR subtraction operators. This gives the hard function in what is called hard scheme. We would use the same B and C functions that appear in the Higgs process and this choice we would name as Higgs scheme. So, we need to find hard function H in the Higgs scheme and this can be done by the following relations:

$$
\begin{aligned}
H_g^{A,(1)} &= H_{g,\text{hard}}^{A,(1)} - H_{g,\text{hard}}^{H,(1)} , \\
H_g^{A,(2)} &= H_{g,\text{hard}}^{A,(2)} - H_{g,\text{hard}}^{H,(2)} + \left(H_{g,\text{hard}}^{H,(1)} \right)^2 - H_{g,\text{hard}}^{A,(1)} H_{g,\text{hard}}^{H,(1)}
\end{aligned}
\tag{3.9}
$$

The first and second order coefficients that appear in the expansion of the hard function when calculated in the Higgs scheme are

$$
H_g^{A,1} = \frac{3}{2} C_F - \frac{1}{2} C_A \tag{3.10}
$$

$$
\begin{aligned}
H_g^{A,2} &= \frac{1}{12} C_F + \frac{5}{96} C_A + \frac{41}{144} C_A n_f + \left(-\frac{13}{8} + \frac{1}{4} \log \frac{m_A^2}{m_t^2} \right) C_F n_f \\
&\quad + \left(\frac{37}{24} + \frac{11}{8} \log \frac{m_A^2}{m_t^2} \right) C_A C_F + \left(\frac{137}{288} - \frac{7}{8} \log \frac{m_A^2}{m_t^2} \right) C_A^2 .
\end{aligned}
\tag{3.11}
$$

3.2 Fixed order distribution at NNLO

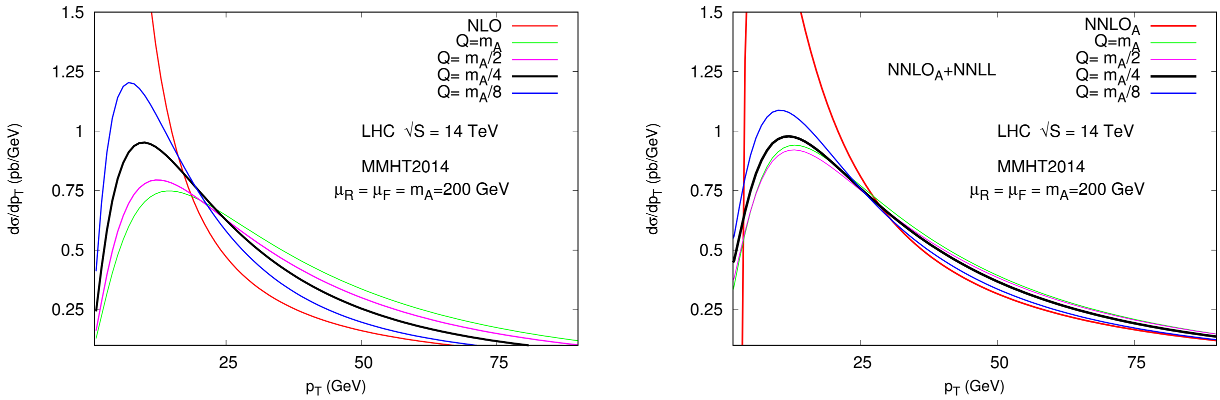
It has been long observed that the inclusive pseudo-scalar Higgs coefficient can be obtained from the Higgs coefficient at each order of perturbation theory by a simple rescaling (see Eq. 13-16 of [31]) after factoring out the born cross-section. One may expect that since the rescaling is independent of kinematics the same will hold for the p_T distributions as well. Therefore we use the same rescaling to find out fixed order NNLO piece (denoted as NNLO$_A$) for pseudo-scalar Higgs from the scalar one. We have performed an extensive checks on this ansatz at the small q_T region where the pseudo-scalar spectrum is known completely accurate upto NNLL from the knowledge of exact hard function that we have computed above. We find a very good agreement within 1%.

3.3 Matched distributions

In this subsection we present distributions that we have obtained using our FORTRAN code which we created by modifying the publicly available code HqT [85, 87, 88]. Our default choices for different quantities in this study are:

1. LHC with centre-of-mass energy 14 TeV,
2. Pseudo-scalar Higgs mass $m_A = 200$ GeV,
3. Resummation scale $Q = m_A$,
4. MMHT 2014 parton density sets with the corresponding α_s.

First and foremost we note that the divergent behaviour of the distribution at fixed order is cured upon resummation. In Fig. 1 we note that at NLO the distribution diverges to positive infinity and at NNLO to negative infinity. Upon resummation a regular behaviour is displayed in both the cases.



(a) (b)

Figure 1. Resummation scale variation for (a) NLL and (b) NNLL.

Uncertainty due to Q: In Fig. 1 we also show the sensitivity of the results to the choice of resummation scale Q. In the left panel we see the results are quite sensitive to the choice and, not surprisingly, upon going to the next logarithmic accuracy (right panel) the sensitivity is significantly reduced around the peak region and the results at moderate values of p_T are almost insensitive to the choice. It is reassuring that in the right panel at moderate and large values of p_T the resummed curve is coincident with the fixed order curve as desired. We note that the position of the peak is unchanged in going to the next order. For $Q = m_A$ we see that the peak value changes by 25% in going from NLO+NLL to NNLO+NNLL.

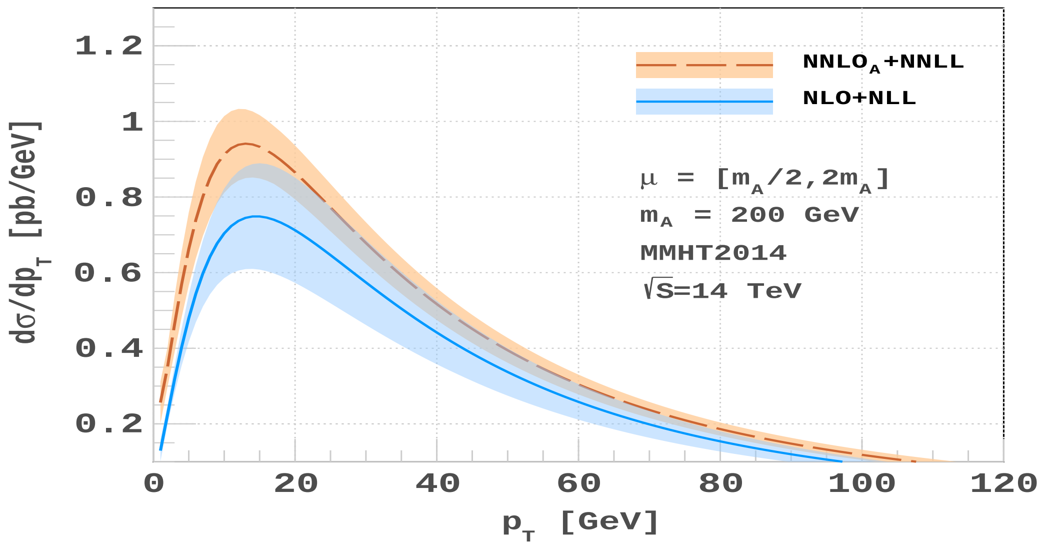


Figure 2. Renormalization and factorization scale variation at NNLO$_A$+NNLL and NLO+NLL

Uncertainty due to μ_r and μ_f: In Fig. 2 we show the sensitivity of our results to the renormalization and factorization scales μ_r and μ_f on the distribution. The bands in this figure show independent variation of μ_r and μ_f in the range $[m_A/2, 2m_A]$ excluding the regions where $\mu_r/\mu_f > 2$ or $\mu_r/\mu_f < 1/2$. This figure shows again that the sensitivity to these arbitrary scales has reduced significantly upon carrying out the next order calculation. More specifically, we see that at the peak the variation is 38% at NLO+NLL which gets reduced to 19% upon going to the next level of accuracy. We have also studied individual variation of μ_r and μ_f by varying one while fixing other at m_A in Fig. 3 and Fig. 4.

Combined uncertainty due to Q, μ_r and μ_f: In Fig. 5 we show the sensitivity of our results to the resummation (Q), renormalization (μ_r) and factorization (μ_f) scale on the distribution. The bands in this figure show independent variation of Q, μ_r and μ_f in the range $[m_A/2, 2m_A]$ with constraints $\mu_r/\mu_f \in [1/2, 2]$, $Q/\mu_r \in [1/2, 2]$ and $Q/\mu_f \in [1/2, 2]$. This figure shows the sensitivity to these arbitrary scales has reduced significantly upon carrying out the next order calculation.

Uncertainty due to parton density sets: As there are several PDF groups in the literature, it is necessary to estimate the uncertainty resulting from the choice of PDFs within each set of a given PDF group. Using PDFs from different PDF groups namely MMHT2014 [89], ABMP [90], NNPDF3.1 [91] and PDF4LHC [92] we have obtained the differential q_T distributions along with the corresponding PDF uncertainty. In Fig. 6, we have demonstrated the uncertainty bands for various PDF sets as a function of q_T in order to demonstrate the correlation of PDF uncertainty with the q_T values and in Table 1, we have tabulated the corresponding results for few benchmark values of q_T along with percentage uncertainties.

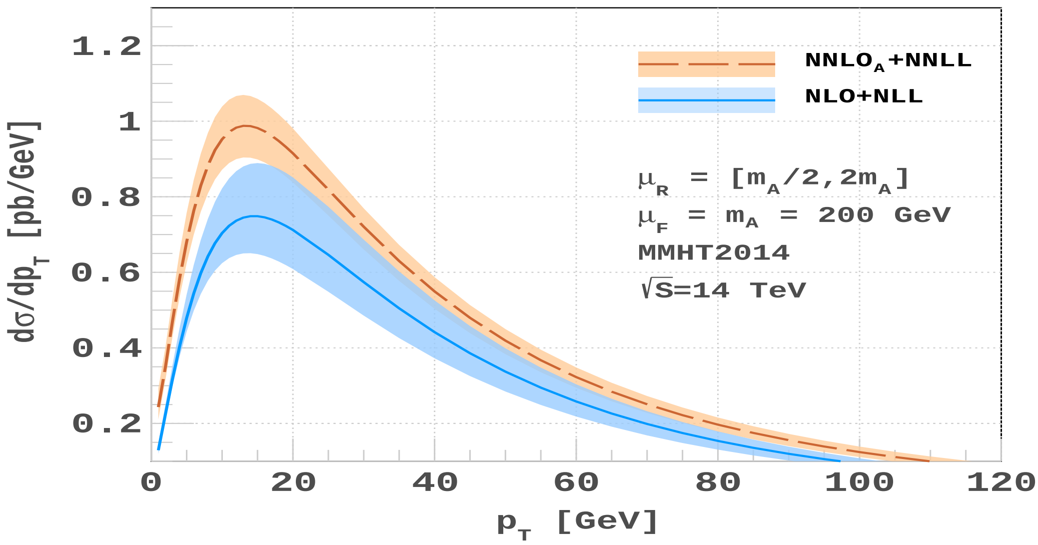


Figure 3. Variation of renormalization scale at NNLO$_A$+NNLL and NLO+NLL keeping factorization scale fixed at m_A.

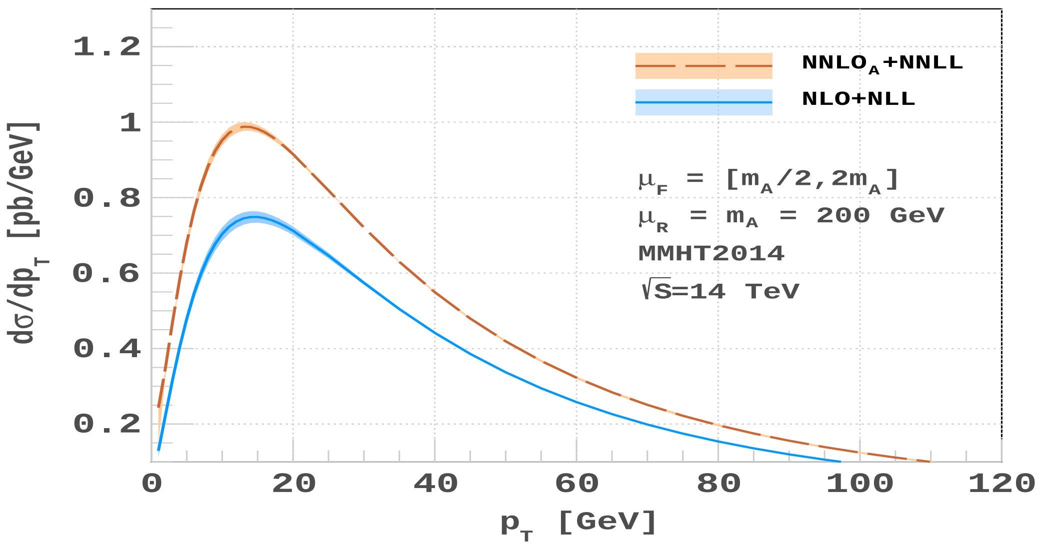


Figure 4. Variation of factorization scale at NNLO$_A$+NNLL and NLO+NLL keeping renormalization scale fixed at m_A.

Pseudo-scalar Higgs mass variation: In Fig. 7 we show how the distribution behaves as the mass of the final state is changed, where we see that the cross-section decreases with the increase in the mass of the final state. We have kept the renormalization and factorizaiton scales fixed at 200 GeV and varied m_A from 100 to 250 GeV.

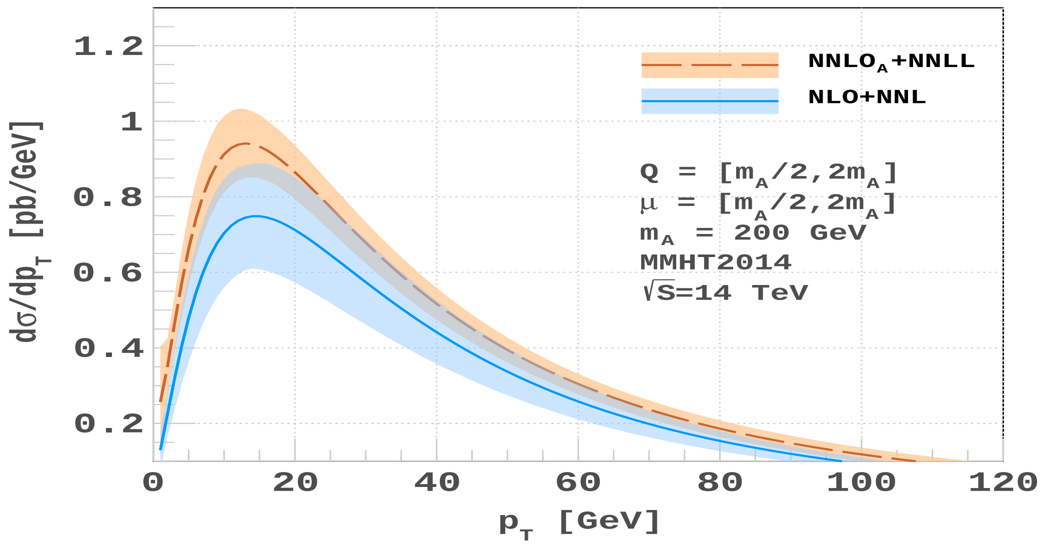


Figure 5. Resummation, renormalization and factorization scale variation at NNLO$_A$+NNLL and NLO+NLL

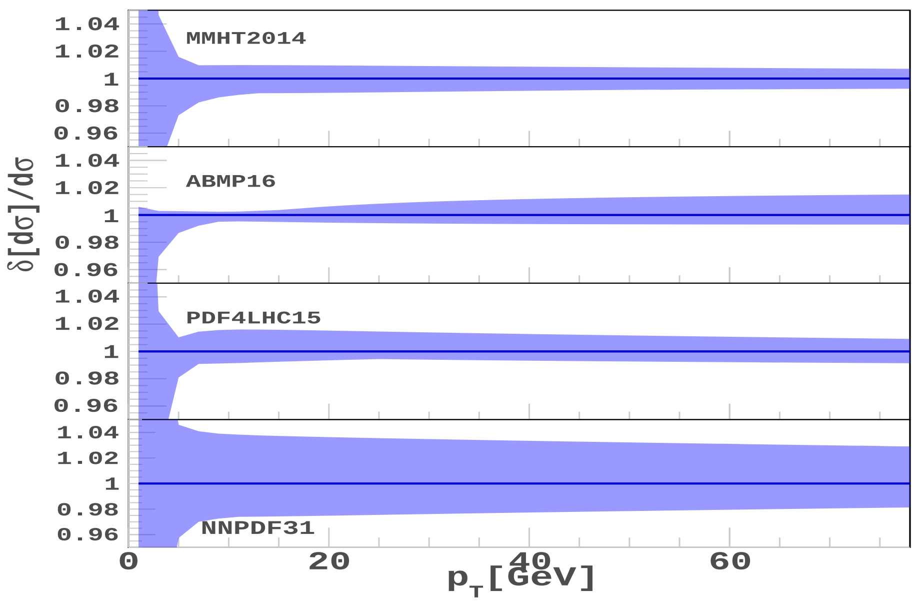


Figure 6. PDF variation at NNLO$_A$+NNLL using various sets. The y-axis represents the ratio of extremum variation over the central PDF set.

4 Conclusion

In this study we obtained the resummed p_T distribution for pseudo-scalar Higgs bosons at the LHC at a center of mass of 14 TeV at next-to-next-to-leading logarithmic accuracy by matching the resummed curve with fixed order next-to-next-to-leading order result.

q_T	MMHT	ABMP	NNPDF	PDF4LHC
7.0	$0.802^{+1.00\%}_{-1.75\%}$	$0.828^{+0.24\%}_{-0.85\%}$	$0.821^{+4.02\%}_{-3.05\%}$	$0.804^{+1.49\%}_{-0.87\%}$
13.0	$0.941^{+0.96\%}_{-1.06\%}$	$0.928^{+0.32\%}_{-0.43\%}$	$0.960^{+3.75\%}_{-2.60\%}$	$0.943^{+1.59\%}_{-0.74\%}$
19.0	$0.882^{+0.91\%}_{-1.13\%}$	$0.847^{+0.59\%}_{-0.59\%}$	$0.897^{+3.68\%}_{-2.56\%}$	$0.884^{+1.47\%}_{-0.68\%}$
25.0	$0.772^{+0.91\%}_{-1.04\%}$	$0.729^{+0.82\%}_{-0.55\%}$	$0.783^{+3.58\%}_{-2.43\%}$	$0.774^{+1.42\%}_{-0.65\%}$
31.0	$0.660^{+0.91\%}_{-0.91\%}$	$0.616^{+0.97\%}_{-0.65\%}$	$0.669^{+3.44\%}_{-2.39\%}$	$0.662^{+1.36\%}_{-0.60\%}$

Table 1. q_T distributions at NNLO$_A$+NNLL using different PDF sets along with percentage uncertainties for $q_T = 7.0, 13.0, 19.0, 25.0, 31.0$.

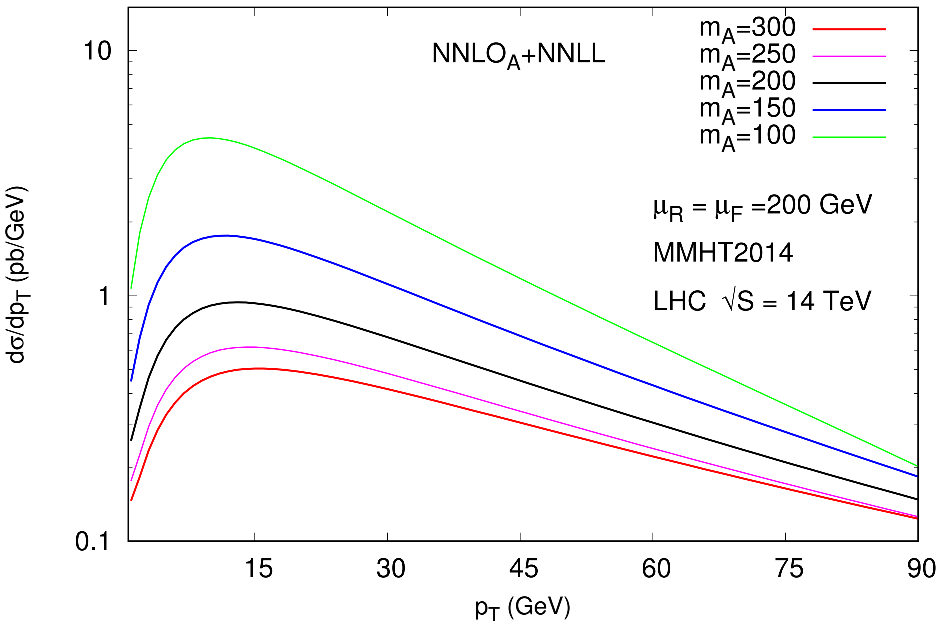


Figure 7. Pseudo-scalar Higgs mass variation at NNLO$_A$+NNLL .

We showed that we achieve a very significant reduction in sensitivity to the choices of resummation, renormalization and factorization scales that are artefact of perturbation theory. We also studied the uncertainty due to different choices of parton density sets. This results provides us with precise estimates for the distribution especially in the region around 15 GeV where the cross-section is large and the fixed order results are completely unreliable due to the breakdown of fixed order perturbation series.

Acknowledgments

AT would like to thank G. Ferrera for very helpful discussions, and would also like to thank the Department of Physics of the University of Turin for hospitality during the last stages of this work. NA would like to thank B. L. Reddy for his support. GD would like to thank F. J. Tackmann for stimulating discussions and suggestions on the manuscript.

References

[1] ATLAS collaboration, G. Aad et al., *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, *Phys. Lett.* **B716** (2012) 1–29, [1207.7214].

[2] CMS collaboration, S. Chatrchyan et al., *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, *Phys. Lett.* **B716** (2012) 30–61, [1207.7235].

[3] R. P. Kauffman and W. Schaffer, *QCD corrections to production of Higgs pseudoscalars*, *Phys. Rev.* **D49** (1994) 551–554, [hep-ph/9305279].

[4] A. Djouadi, M. Spira and P. M. Zerwas, *Two photon decay widths of Higgs particles*, *Phys. Lett.* **B311** (1993) 255–260, [hep-ph/9305335].

[5] M. Spira, A. Djouadi, D. Graudenz and P. M. Zerwas, *Higgs boson production at the LHC*, *Nucl. Phys.* **B453** (1995) 17–82, [hep-ph/9504378].

[6] M. Spira, A. Djouadi, D. Graudenz and P. M. Zerwas, *SUSY Higgs production at proton colliders*, *Phys. Lett.* **B318** (1993) 347–353.

[7] R. V. Harlander and W. B. Kilgore, *Next-to-next-to-leading order Higgs production at hadron colliders*, *Phys. Rev. Lett.* **88** (2002) 201801, [hep-ph/0201206].

[8] R. V. Harlander and W. B. Kilgore, *Production of a pseudoscalar Higgs boson at hadron colliders at next-to-next-to leading order*, *JHEP* **10** (2002) 017, [hep-ph/0208096].

[9] C. Anastasiou and K. Melnikov, *Higgs boson production at hadron colliders in NNLO QCD*, *Nucl. Phys.* **B646** (2002) 220–256, [hep-ph/0207004].

[10] C. Anastasiou and K. Melnikov, *Pseudoscalar Higgs boson production at hadron colliders in NNLO QCD*, *Phys. Rev.* **D67** (2003) 037501, [hep-ph/0208115].

[11] V. Ravindran, J. Smith and W. L. van Neerven, *NNLO corrections to the total cross-section for Higgs boson production in hadron hadron collisions*, *Nucl. Phys.* **B665** (2003) 325–366, [hep-ph/0302135].

[12] C. Anastasiou, C. Duhr, F. Dulat, F. Herzog and B. Mistlberger, *Higgs Boson Gluon-Fusion Production in QCD at Three Loops*, *Phys. Rev. Lett.* **114** (2015) 212001, [1503.06056].

[13] R. V. Harlander and K. J. Ozeren, *Top mass effects in Higgs production at next-to-next-to-leading order QCD: Virtual corrections*, *Phys. Lett.* **B679** (2009) 467–472, [0907.2997].

[14] R. V. Harlander and K. J. Ozeren, *Finite top mass effects for hadronic Higgs production at next-to-next-to-leading order*, *JHEP* **11** (2009) 088, [0909.3420].

[15] A. Pak, M. Rogal and M. Steinhauser, *Finite top quark mass effects in NNLO Higgs boson production at LHC*, *JHEP* **02** (2010) 025, [0911.4662].

[16] C. Anastasiou, C. Duhr, F. Dulat, E. Furlan, T. Gehrmann, F. Herzog et al., *Higgs boson gluon?fusion production at threshold in N^{3}LO QCD*, *Phys. Lett.* **B737** (2014) 325–328, [1403.4616].

[17] S. Moch and A. Vogt, *Higher-order soft corrections to lepton pair and Higgs boson production*, *Phys. Lett.* **B631** (2005) 48–57, [hep-ph/0508265].

[18] E. Laenen and L. Magnea, *Threshold resummation for electroweak annihilation from DIS data*, *Phys. Lett.* **B632** (2006) 270–276, [hep-ph/0508284].

[19] V. Ravindran, *On Sudakov and soft resummations in QCD*, *Nucl. Phys.* **B746** (2006) 58–76, [hep-ph/0512249].

[20] V. Ravindran, *Higher-order threshold effects to inclusive processes in QCD*, *Nucl. Phys.* **B752** (2006) 173–196, [hep-ph/0603041].

[21] A. Idilbi, X.-d. Ji, J.-P. Ma and F. Yuan, *Threshold resummation for Higgs production in effective field theory*, *Phys. Rev.* **D73** (2006) 077501, [hep-ph/0509294].

[22] M. C. Kumar, M. K. Mandal and V. Ravindran, *Associated production of Higgs boson with vector boson at threshold N^{3}LO in QCD*, *JHEP* **03** (2015) 037, [1412.3357].

[23] T. Ahmed, N. Rana and V. Ravindran, *Higgs boson production through $b\bar{b}$ annihilation at threshold in N^{3}LO QCD*, *JHEP* **10** (2014) 139, [1408.0787].

[24] T. Ahmed, M. C. Kumar, P. Mathews, N. Rana and V. Ravindran, *Pseudo-scalar Higgs boson production at threshold N^3 LO and N^3 LL QCD*, *Eur. Phys. J.* **C76** (2016) 355, [1510.02235].

[25] T. Ahmed, T. Gehrmann, P. Mathews, N. Rana and V. Ravindran, *Pseudo-scalar Form Factors at Three Loops in QCD*, *JHEP* **11** (2015) 169, [1510.01715].

[26] S. Catani, D. de Florian, M. Grazzini and P. Nason, *Soft gluon resummation for Higgs boson production at hadron colliders*, *JHEP* **07** (2003) 028, [hep-ph/0306211].

[27] S. Catani, L. Cieri, D. de Florian, G. Ferrera and M. Grazzini, *Threshold resummation at N^{3}LL accuracy and soft-virtual cross sections at N^{3}LO*, *Nucl. Phys.* **B888** (2014) 75–91, [1405.4827].

[28] M. Bonvini and S. Marzani, *Resummed Higgs cross section at N^{3}LL*, *JHEP* **09** (2014) 007, [1405.3654].

[29] M. Bonvini, S. Marzani, C. Muselli and L. Rottoli, *On the Higgs cross section at N^{3}LO+N^{3}LL and its uncertainty*, *JHEP* **08** (2016) 105, [1603.08000].

[30] T. Ahmed, G. Das, M. C. Kumar, N. Rana and V. Ravindran, *RG improved Higgs boson production to N^{3}LO in QCD*, 1505.07422.

[31] T. Ahmed, M. Bonvini, M. C. Kumar, P. Mathews, N. Rana, V. Ravindran et al., *Pseudo-scalar Higgs boson production at N^3 LO$_A$ +N^3 LL ′*, *Eur. Phys. J.* **C76** (2016) 663, [1606.00837].

[32] T. Schmidt and M. Spira, *Higgs Boson Production via Gluon Fusion: Soft-Gluon Resummation including Mass Effects*, *Phys. Rev.* **D93** (2016) 014022, [1509.00195].

[33] D. de Florian and J. Zurita, *Soft-gluon resummation for pseudoscalar Higgs boson production at hadron colliders*, *Phys. Lett.* **B659** (2008) 813–820, [0711.1916].

[34] P. Banerjee, G. Das, P. K. Dhani and V. Ravindran, *Threshold resummation of the rapidity distribution for Higgs production at NNLO+NNLL*, *Phys. Rev.* **D97** (2018) 054024, [1708.05706].

[35] P. Banerjee, G. Das, P. K. Dhani and V. Ravindran, *Threshold resummation of the rapidity distribution for Drell-Yan production at NNLO+NNLL*, 1805.01186.

[36] G. F. Sterman, *Summation of Large Corrections to Short Distance Hadronic Cross-Sections*, *Nucl. Phys.* **B281** (1987) 310–364.

[37] S. Catani and L. Trentadue, *Resummation of the QCD Perturbative Series for Hard Processes*, *Nucl. Phys.* **B327** (1989) 323–352.

[38] S. Catani and L. Trentadue, *Comment on QCD exponentiation at large x*, *Nucl. Phys.* **B353** (1991) 183–186.

[39] E. Laenen and G. F. Sterman, *Resummation for Drell-Yan differential distributions*, in *The Fermilab Meeting DPF 92. Proceedings, 7th Meeting of the American Physical Society, Division of Particles and Fields, Batavia, USA, November 10-14, 1992. Vol. 1, 2*, pp. 987–989, 1992.

[40] G. F. Sterman and W. Vogelsang, *Threshold resummation and rapidity dependence*, *JHEP* **02** (2001) 016, [hep-ph/0011289].

[41] A. Mukherjee and W. Vogelsang, *Threshold resummation for W-boson production at RHIC*, *Phys. Rev.* **D73** (2006) 074005, [hep-ph/0601162].

[42] P. Bolzoni, *Threshold resummation of Drell-Yan rapidity distributions*, *Phys. Lett.* **B643** (2006) 325–330, [hep-ph/0609073].

[43] M. Bonvini, S. Forte and G. Ridolfi, *Soft gluon resummation of Drell-Yan rapidity distributions: Theory and phenomenology*, *Nucl. Phys.* **B847** (2011) 93–159, [1009.5691].

[44] M. A. Ebert, J. K. L. Michel and F. J. Tackmann, *Resummation Improved Rapidity Spectrum for Gluon Fusion Higgs Production*, *JHEP* **05** (2017) 088, [1702.00794].

[45] T. Becher and M. Neubert, *Threshold resummation in momentum space from effective field theory*, *Phys. Rev. Lett.* **97** (2006) 082001, [hep-ph/0605050].

[46] T. Becher, M. Neubert and G. Xu, *Dynamical Threshold Enhancement and Resummation in Drell-Yan Production*, *JHEP* **07** (2008) 030, [0710.0680].

[47] Y. L. Dokshitzer, D. Diakonov and S. I. Troian, *On the Transverse Momentum Distribution of Massive Lepton Pairs*, *Phys. Lett.* **79B** (1978) 269–272.

[48] Y. L. Dokshitzer, D. Diakonov and S. I. Troian, *Hard Processes in Quantum Chromodynamics*, *Phys. Rept.* **58** (1980) 269–395.

[49] G. Parisi and R. Petronzio, *Small Transverse Momentum Distributions in Hard Processes*, *Nucl. Phys.* **B154** (1979) 427–440.

[50] G. Curci, M. Greco and Y. Srivastava, *QCD Jets From Coherent States*, *Nucl. Phys.* **B159** (1979) 451–468.

[51] J. C. Collins and D. E. Soper, *Back-To-Back Jets in QCD*, *Nucl. Phys.* **B193** (1981) 381.

[52] J. Kodaira and L. Trentadue, *Summing Soft Emission in QCD*, *Phys. Lett.* **112B** (1982) 66.

[53] J. Kodaira and L. Trentadue, *Single Logarithm Effects in electron-Positron Annihilation*, *Phys. Lett.* **123B** (1983) 335–338.

[54] J. C. Collins, D. E. Soper and G. F. Sterman, *Transverse Momentum Distribution in Drell-Yan Pair and W and Z Boson Production*, Nucl. Phys. **B250** (1985) 199–224.

[55] S. Catani, E. D'Emilio and L. Trentadue, *The Gluon Form-factor to Higher Orders: Gluon Gluon Annihilation at Small Q^-transverse*, Phys. Lett. **B211** (1988) 335–342.

[56] D. de Florian and M. Grazzini, *Next-to-next-to-leading logarithmic corrections at small transverse momentum in hadronic collisions*, Phys. Rev. Lett. **85** (2000) 4678–4681, [hep-ph/0008152].

[57] S. Catani, D. de Florian and M. Grazzini, *Universality of nonleading logarithmic contributions in transverse momentum distributions*, Nucl. Phys. **B596** (2001) 299–312, [hep-ph/0008184].

[58] H. X. Zhu, C. S. Li, H. T. Li, D. Y. Shao and L. L. Yang, *Transverse-momentum resummation for top-quark pairs at hadron colliders*, Phys. Rev. Lett. **110** (2013) 082001, [1208.5774].

[59] H. T. Li, C. S. Li, D. Y. Shao, L. L. Yang and H. X. Zhu, *Top quark pair production at small transverse momentum in hadronic collisions*, Phys. Rev. **D88** (2013) 074004, [1307.2464].

[60] J. C. Collins and D. E. Soper, *Back-To-Back Jets: Fourier Transform from B to K-Transverse*, Nucl. Phys. **B197** (1982) 446–476.

[61] G. Altarelli, R. K. Ellis, M. Greco and G. Martinelli, *Vector Boson Production at Colliders: A Theoretical Reappraisal*, Nucl. Phys. **B246** (1984) 12–44.

[62] C. W. Bauer, S. Fleming and M. E. Luke, *Summing Sudakov logarithms in B —¿ X(s gamma) in effective field theory*, Phys. Rev. **D63** (2000) 014006, [hep-ph/0005275].

[63] C. W. Bauer, S. Fleming, D. Pirjol and I. W. Stewart, *An Effective field theory for collinear and soft gluons: Heavy to light decays*, Phys. Rev. **D63** (2001) 114020, [hep-ph/0011336].

[64] C. W. Bauer and I. W. Stewart, *Invariant operators in collinear effective theory*, Phys. Lett. **B516** (2001) 134–142, [hep-ph/0107001].

[65] C. W. Bauer, D. Pirjol and I. W. Stewart, *Soft collinear factorization in effective field theory*, Phys. Rev. **D65** (2002) 054022, [hep-ph/0109045].

[66] M. Beneke, A. P. Chapovsky, M. Diehl and T. Feldmann, *Soft collinear effective theory and heavy to light currents beyond leading power*, Nucl. Phys. **B643** (2002) 431–476, [hep-ph/0206152].

[67] G. Bozzi, S. Catani, D. de Florian and M. Grazzini, *Higgs boson production at the LHC: Transverse-momentum resummation and rapidity dependence*, Nucl. Phys. **B791** (2008) 1–19, [0705.3887].

[68] G. Bozzi, S. Catani, G. Ferrera, D. de Florian and M. Grazzini, *Transverse-momentum resummation: A Perturbative study of Z production at the Tevatron*, Nucl. Phys. **B815** (2009) 174–197, [0812.2862].

[69] S. Catani and M. Grazzini, *QCD transverse-momentum resummation in gluon fusion processes*, Nucl. Phys. **B845** (2011) 297–323, [1011.3918].

[70] S. Catani, M. Grazzini and A. Torre, *Soft-gluon resummation for single-particle inclusive hadroproduction at high transverse momentum*, Nucl. Phys. **B874** (2013) 720–745, [1305.3870].

[71] P. F. Monni, E. Re and P. Torrielli, *Higgs Transverse-Momentum Resummation in Direct Space*, *Phys. Rev. Lett.* **116** (2016) 242001, [1604.02191].

[72] M. A. Ebert and F. J. Tackmann, *Resummation of Transverse Momentum Distributions in Distribution Space*, *JHEP* **02** (2017) 110, [1611.08610].

[73] I. W. Stewart, F. J. Tackmann, J. R. Walsh and S. Zuberi, *Jet p_T resummation in Higgs production at $NNLL' + NNLO$*, *Phys. Rev.* **D89** (2014) 054001, [1307.1808].

[74] M. Grazzini, S. Kallweit, D. Rathlev and M. Wiesemann, *Transverse-momentum resummation for vector-boson pair production at NNLL+NNLO*, *JHEP* **08** (2015) 154, [1507.02565].

[75] G. Ferrera and J. Pires, *Transverse-momentum resummation for Higgs boson pair production at the LHC with top-quark mass effects*, *JHEP* **02** (2017) 139, [1609.01691].

[76] A. Belyaev, P. M. Nadolsky and C. P. Yuan, *Transverse momentum resummation for Higgs boson produced via b anti-b fusion at hadron colliders*, *JHEP* **04** (2006) 004, [hep-ph/0509100].

[77] R. V. Harlander, A. Tripathi and M. Wiesemann, *Higgs production in bottom quark annihilation: Transverse momentum distribution at NNLO+NNLL*, *Phys. Rev.* **D90** (2014) 015017, [1403.7196].

[78] X. Chen, T. Gehrmann, E. W. N. Glover, A. Huss, Y. Li, D. Neill et al., *Precise QCD Description of the Higgs Boson Transverse Momentum Spectrum*, 1805.00736.

[79] W. Bizo?, X. Chen, A. Gehrmann-De Ridder, T. Gehrmann, N. Glover, A. Huss et al., *Fiducial distributions in Higgs and Drell-Yan production at N^3LL+NNLO*, 1805.05916.

[80] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer et al., *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, *JHEP* **07** (2014) 079, [1405.0301].

[81] S. Alioli, P. Nason, C. Oleari and E. Re, *A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX*, *JHEP* **06** (2010) 043, [1002.2581].

[82] M. Dasgupta, F. A. Dreyer, K. Hamilton, P. F. Monni and G. P. Salam, *Logarithmic accuracy of parton showers: a fixed-order study*, 1805.09327.

[83] P. Banerjee, P. K. Dhani and V. Ravindran, *Two loop QCD corrections for the process Pseudo-scalar Higgs $\to$ 3 partons*, *JHEP* **10** (2017) 067, [1708.02387].

[84] B. Field, *Next-to-leading log resummation of scalar and pseudoscalar Higgs boson differential cross-sections at the CERN LHC and Tevatron*, *Phys. Rev.* **D70** (2004) 054008, [hep-ph/0405219].

[85] G. Bozzi, S. Catani, D. de Florian and M. Grazzini, *Transverse-momentum resummation and the spectrum of the Higgs boson at the LHC*, *Nucl. Phys.* **B737** (2006) 73–120, [hep-ph/0508068].

[86] O. V. Tarasov, A. A. Vladimirov and A. Yu. Zharkov, *The Gell-Mann-Low Function of QCD in the Three Loop Approximation*, *Phys. Lett.* **93B** (1980) 429–432.

[87] G. Bozzi, S. Catani, D. de Florian and M. Grazzini, *The q(T) spectrum of the Higgs boson at the LHC in QCD perturbation theory*, *Phys. Lett.* **B564** (2003) 65–72, [hep-ph/0302104].

[88] D. de Florian, G. Ferrera, M. Grazzini and D. Tommasini, *Transverse-momentum resummation: Higgs boson production at the Tevatron and the LHC*, *JHEP* **11** (2011) 064, [1109.2109].

[89] L. A. Harland-Lang, A. D. Martin, P. Motylinski and R. S. Thorne, *Parton distributions in the LHC era: MMHT 2014 PDFs*, *Eur. Phys. J.* **C75** (2015) 204, [1412.3989].

[90] S. Alekhin, J. Blmlein, S. Moch and R. Placakyte, *Parton Distribution Functions, α_s and Heavy-Quark Masses for LHC Run II*, *Phys. Rev.* **D96** (2017) 014011, [1701.05838].

[91] NNPDF collaboration, R. D. Ball et al., *Parton distributions from high-precision collider data*, *Eur. Phys. J.* **C77** (2017) 663, [1706.00428].

[92] J. Butterworth et al., *PDF4LHC recommendations for LHC Run II*, *J. Phys.* **G43** (2016) 023001, [1510.03865].