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Threshold resummation in rapidity for colorless particle production at LHC

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We present a formalism to resum large threshold logarithms to all orders in perturbative QCD for the rapidity distribution of any colorless particle at the hadron colliders. Using the derived resummed coefficients in two dimensional Mellin space, we present the rapidity distributions for the Higgs as well as for the Drell-Yan production to NNLO+NNLL accuracy at the LHC. The resummed distributions give stable prediction against the variation of unphysical renormalisation and factorisation scales in both the cases. Perturbative convergence is also improved with the inclusion of the resummed result.

Loops and Legs in Quantum Field Theory (LL2018)
29 April 2018 - 04 May 2018
St. Goar, Germany
Preprint: DESY 18-115

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arXiv:1807.04583v1 [hep-ph] 12 Jul 2018

1. Introduction

Resummation of large logarithms for rapidity distribution has been an interesting topic over the years and several results are already available to a very good accuracy for different processes. The fixed order (f.o) predictions are often not reliable in certain regions of phase space where large logarithms of some kinematic variables appear. For example, at the partonic threshold, where the initial partons have just enough energy to produce the final state such as a Higgs boson or $Z/W^{\pm}$ boson or a pair of leptons in addition to soft gluons, the phase-space available for the gluons become severely constrained which results in large logarithms. In a truncated f.o calculation, these large logarithms give unreliable result and needs to be systematically resummed to all orders in perturbation theory for reliable predictions.

When talking about resummation of rapidity, two distinct approaches can be observed in QCD. One we call Catani & Trentadue approach (or Mellin-Mellin (M-M) approach) [1] which was proposed for the x_F distribution but can easily be extended to rapidity distribution. In this approach threshold limit is taken using both partonic scaling variable z_1, z_2 simultaneously going to threshold limit 1. This basically resums all the delta ($\delta(1-z_i)$) and distributions ($\left[\frac{\ln^n(1-z_i)}{1-z_i}\right]_+$) arising in z_1 and z_2. Using this approach lepton pair resummation is performed at NLL accuracy [2]. The other approach, we call by Laenen & Sterman approach (or Mellin-Fourier (M-F) approach) [3]. Here partonic cross-section is written in terms of scaling variable z and partonic rapidity y_p and finally threshold limit is taken *only* for $z \to 1$ which resums delta ($\delta(1-z)$) and distributions ($\left[\frac{\ln^n(1-z)}{1-z}\right]_+$) in z. However for partonic y_p only delta ($\delta(y_p)$) piece is taken. Using this approach, resummation has been performed for $W^{\pm}$ production [4] as well as Drell-Yan (DY) rapidity upto NNLL accuracy [5, 6].

We follow the M-M approach and derive an all order resummed result in two dimensional Mellin space for rapidity distribution of any colourless state F that can be produced in hadron colliders. We present our results in terms of Mellin variables N_1 and N_2 corresponding to z_1 and z_2 respectively. In the Mellin space, the limits $z_i \to 1$ translate into $N_i \to \infty$ and large logarithms proportional to $\ln(N_i)$ are resummed to all orders in perturbation theory. We present numerical results for resummed rapidity distributions for Higgs [7] and DY [8] productions at the LHC.

2. Theoretical Framework

The rapidity distribution of a colorless state F can be written as

$$\frac{d\sigma^I}{dy} = \sigma^I_{\rm B}(x_1^0, x_2^0, q^2) \sum_{ab=q,\bar{q},g} \int_{x_1^0}^1 \frac{dz_1}{z_1} \int_{x_2^0}^1 \frac{dz_2}{z_2} \times \mathscr{H}^I_{ab}\left(\frac{x_1^0}{z_1}, \frac{x_2^0}{z_2}\right) \Delta^I_{d,ab}(z_1, z_2, q^2). \tag{2.1}$$

For brevity, the renormalization scale (μ_R) and the factorisation scale (μ_F) dependences are kept implicit in the above equation. Here the hadron level rapidity is $y = \frac{1}{2}\ln(p_2.q/p_1.q) = \frac{1}{2}\ln\left(x_1^0/x_2^0\right)$; $\tau = q^2/S = x_1^0 x_2^0$, q being the momentum of the final state F, $S = (p_1+p_2)^2$, where p_i are the momenta of incoming hadrons P_i $(i=1,2)$. For the DY process, the state F is a pair of leptons with invariant mass q^2 $(I=q)$, $\sigma^I = d\sigma^q(\tau, q^2, y)/dq^2$ whereas for the Higgs boson production through gluon (bottom anti-bottom) fusion, $I = g(b)$ and $\sigma^I = \sigma^{g(b)}(\tau, q^2, y)$. The luminosity $\mathscr{H}^I_{ab}$ in Eq.2.1 is given by the product of parton distribution functions (PDFs) $f_a^{P_1}(x_1, \mu_F^2)$ and

$f_b^{P_2}(x_2,\mu_F^2)$, renormalized at μ_F. The partonic coefficient functions denoted by $\Delta^I_{d,ab}$ depend on the parton level scaling variables $z_i,(i=1,2)$. Using factorization properties of the cross sections and renormalization group invariance, the threshold enhanced contribution to the $\Delta^I_{d,ab}$ denoted by $\Delta^{\rm SV}_{d,I}$ was shown to exponentiate [9] as

$$\Delta^{\rm SV}_{d,I} = \mathscr{C}\exp\Big(\Psi^I_d(q^2,\mu_R^2,\mu_F^2,\bar z_1,\bar z_2,\varepsilon)\Big)\Big|_{\varepsilon=0}, \tag{2.2}$$

where the exponent Ψ^I_d is both ultraviolet and infrared finite to all orders in perturbation theory. It contains finite distributions computed in $4+\varepsilon$ space-time dimensions expressed in terms of two shifted scaling variables $\bar z_1 = 1-z_1$ and $\bar z_2 = 1-z_2$ and takes the following form:

$$\begin{aligned}\Psi^I_d =& \Big(\ln\Big(Z^I(\hat a_s,\mu_R^2,\mu^2,\varepsilon)\Big)^2 + \ln\big|\hat F^I(\hat a_s,Q^2,\mu^2,\varepsilon)\big|^2\Big)\delta(\bar z_1)\delta(\bar z_2)\\ &-\mathscr{C}\Big(\ln\Gamma_{II}(\hat a_s,\mu^2,\mu_F^2,\bar z_1,\varepsilon)\ \delta(\bar z_2)+(\bar z_1\leftrightarrow\bar z_2)\Big)+2\ \Phi^I_d(\hat a_s,q^2,\mu^2,\bar z_1,\bar z_2,\varepsilon).\end{aligned} \tag{2.3}$$

We have defined, $Q^2=-q^2$ and the scale μ is introduced to define the dimensionless strong coupling constant $\hat a_s = \hat g_s^2/16\pi^2$ in dimensional regularization, which is related to renormalised a_s through the renormalization constant $Z(a_s(\mu_R^2))$ *i.e.*, $\hat a_s = (\mu/\mu_R)^\varepsilon Z(\mu_R^2)S_\varepsilon^{-1}a_s(\mu_R^2)$, $S_\varepsilon = \exp[(\gamma_E - \ln 4\pi)\varepsilon/2]$, $\gamma_E = 0.57721566\cdots$ is Euler-Mascheroni constant. The definition of double Mellin convolution $\mathscr{C}$ is given in [9], and it is understood that the regular functions resulting from various convolutions are dropped. The overall operator renormalization constant Z^I renormalizes the bare form factor $\hat F^I$; the corresponding anomalous dimension is denoted by γ_I. The diagonal mass factorization kernels Γ_{II} remove the initial state collinear singularities. We have factored out the form factor and the mass factorization kernels in $\Delta^I_{d,ab}$ in such a way that the remaining soft distribution function Φ^I_d contains only soft gluon contributions. Both the form factor $\hat F^I$ and the soft distribution function Φ^I_d satisfy Sudakov type differential equations (see [10, 11]) which is straightforward to solve in powers of strong coupling constant and they can be found in [9, 10, 11, 12]. In terms of these solutions we arrive at the following expression (setting $\mu_R^2=\mu_F^2$):

$$\begin{aligned}\Psi^I_d =& \delta(\bar z_2)\left(\frac{1}{\bar z_1}\left\{\int_{\mu_F^2}^{q^2\ \bar z_1}\frac{d\lambda^2}{\lambda^2}A_I\left(a_s(\lambda^2)\right)+D^I_d\left(a_s(q^2\ \bar z_1)\right)\right\}\right)_+ + \frac{1}{2}\left(\frac{1}{\bar z_1\bar z_2}\left\{A^I(a_s(z_{12}))\right.\right.\\ &\left.\left.+\frac{dD^I_d(a_s(z_{12}))}{d\ln z_{12}}\right\}\right)_+ + \frac{1}{2}\delta(\bar z_1)\delta(\bar z_2)\ln\Big(g^I_{d,0}(a_s(\mu_F^2))\Big)+(\bar z_1\leftrightarrow\bar z_2)\end{aligned} \tag{2.4}$$

Here $z_{12}=q^2\bar z_1\bar z_2$ and A^I are the cusp anomalous dimensions which are known upto four loops [13]. The finite function D^I_d can be expanded order by order in strong coupling and can be found from inclusive counterpart with the use of following identity [9, 14]:

$$\int_0^1 dx_1^0\int_0^1 dx_2^0\,(x_1^0x_2^0)^{N-1}\frac{d\sigma^I}{dy} = \int_0^1 d\tau\ \tau^{N-1}\ \sigma^I\,, \tag{2.5}$$

where the σ^I is the inclusive cross section. Comparing against D^I from the inclusive cross section, we obtain

$$\begin{aligned}D^I_{d,1} =& D^I_1\ ;\ D^I_{d,2}=D^I_2-\zeta_2\beta_0A^I_1\ ;\ D^I_{d,3}=D^I_3+\zeta_2(-\beta_1A^I_1-2\beta_0A^I_2-2\beta_0^2f^I_1)-4\zeta_3\beta_0^2A^I_1\\ D^I_{d,4} =& D^I_4+\zeta_2(-2\beta_1A^I_2-\beta_2A^I_1-\beta_0(3A^I_3+5\beta_1f^I_1)-6\beta_0^2f^I_2-12\beta_0^3\overline{\mathscr{G}}^{I,1}_1)-\frac{57}{5}\zeta_2^2\beta_0^3A^I_1\\ &-\beta_0\zeta_3(12\beta_0A^I_2+10\beta_1A^I_1+12\beta_0^2f^I_1)\,.\end{aligned} \tag{2.6}$$

After taking the double Mellin moments [15] of Eq. 2.2 we arrive at the N_1-N_2 space cross-section:

$$\tilde{\Delta}^{(res)}_{d,I}(N_1,N_2) \equiv \tilde{\Delta}^{SV}_{d,I}(\omega) = \int_0^1 dx_1^0 \left(x_1^0\right)^{N_1-1} \int_0^1 dx_2^0 \left(x_2^0\right)^{N_2-1} \Delta^{SV}_{d,I} \equiv g^I_{d,0}(a_s)\exp\left(g^I_d(a_s,\omega)\right) \quad (2.7)$$

where $\omega = a_s\beta_0 \ln(\overline{N}_1\overline{N}_2)$ (where $\overline{N}_i = e^{\gamma_E}N_i, i = 1,2$). Eq. 2.7 is organised in such a way that $g^I_d(a_s,\omega)$ contains only N_1,N_2 dependent terms whereas $g^I_{d,0}(a_s)$ are N_1,N_2 independent. The N_i independent coefficients $g^I_{d,0}(a_s)$ can be expanded in powers of a_s as $\ln(g^I_{d,0}) = \sum_{i=0}^{\infty} a_s^i l^{I,(i)}_{g_0}$. The exponent $g^I_d(a_s,\omega)$ takes the canonical form:

$$g^I_d(a_s,\omega) = g^I_{d,1}(\omega)\ln(\overline{N}_1\overline{N}_2) + \sum_{i=0}^{\infty} a_s^i g^I_{d,i+2}(\omega)\,. \quad (2.8)$$

To perform resummation at NNLO+NNLL accuracy, we need resummed coefficients upto $g^I_{d,3}$ and the prefactors upto $l^{I,(2)}_{g_0}$ and those can be found in [7][1]. Exponentiation of the coefficients $g^I_{d,i}$ resums the terms $a_s\beta_0\ln(\overline{N}_1\overline{N}_2)$ systematically to all orders in perturbation theory. The resummed result has to be properly matched with the fixed order avoiding any double counting of the logarithms. The matched cross-section takes the following form:

$$\frac{d\sigma^{I,(res)}}{dy} = \frac{d\sigma^{I,(f.o)}}{dy} + \sigma^I_B \int_{c_1-i\infty}^{c_1+i\infty} \frac{dN_1}{2\pi i} \int_{c_2-i\infty}^{c_2+i\infty} \frac{dN_2}{2\pi i} e^{y(N_2-N_1)} \left(\sqrt{\tau}\right)^{c_I-N_1-N_2} \tilde{f}_I(N_1)\tilde{f}_I(N_2) \times \left[\tilde{\Delta}^{(res)}_{d,I}(N_1,N_2) - \tilde{\Delta}^{(res)}_{d,I}(N_1,N_2)\Big|_{\rm tr}\right], \quad (2.9)$$

Here $c_I = -4(I = g)$ and $2(I = q)$. The subscript tr refers to the result obtained from Eq.(2.7) by truncating at desired accuracy in a_s. Note that the coefficients $g^I_{d,0}$ and $g^I_{d,i}$ are functions of cusp (A^I_i), collinear (B^I_i), soft (f^I_i), UV (γ^g_i) anomalous dimensions and universal soft terms $G^{I,i}_{d,j}$ and process dependent constants $G^{I,i}_j$ of virtual corrections. These constants are known to sufficient order to perform resummation to NNLL accuracy. The N_i dependent terms inside the square bracket appropriately multiplied with N_i dependent PDFs, namely $\tilde{f}_I(N_i)$ have to undergo two Mellin inversions to obtain the final result in terms of τ and y. We have used minimal prescription advocated in [16] to perform the Mellin inversion to finally get resummed rapidity distribution.

3. Results

3.1 Higgs rapidity distribution

To perform numerical analysis for the Higgs rapidity distribution, we have adopted following choice of parameters: $\sqrt{S} = 13$ TeV, $M_H = 125$ GeV, $n_f = 5$, $M_t = 173$ GeV and used MMHT2014 [17] PDF set with corresponding value of strong coupling constant at each order in perturbation theory. While f.o results up to NNLO are obtained using publicly available code FEHIP [18], the resummed contributions are included up to NNLL using an in-house Fortran code. To assess remaining scale uncertainty due to unphysical renormalisation and factorisation scale, we vary them between $[M_H/2, 2M_H]$ around the central scale $\mu_R = \mu_F = M_H$ with the constraint $1/2 \leq \mu_R/\mu_F \leq 2$.

[1]The $g^I_{d,4}$ and $l^{I,(3)}$ coefficients can also be found in the first arXiv version of [7].

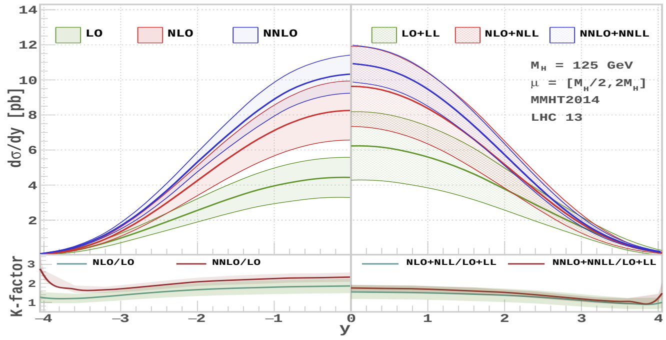

Figure 1: Higgs rapidity distributions for fixed order (left panel) upto NNLO and resummed (right panel) contributions upto NNLO+NNLL are presented with scale variation around central scale choice M_H. The respective K-factors are shown at the bottom panel.

In Fig. 1, we have plotted production cross section for the Higgs boson as a function of its rapidity y up to NNLO in left panel and to NNLO+NNLL in right panel along with respective K-factors. We observe (see Fig. 1) that the extent of overlap between consecutive orders in resummed case is better compared to fixed order indicating the fact that inclusion of higher order corrections has improved the convergence of the perturbation series. In particular, NNLO+NNLL increases approximately by 13% with respect to NLO+NLL whereas corresponding number for NNLO over NLO is approximately 25%. We also found that the choice of different central scales has minimum effect on the resummed result at NNLO+NNLL level (see Fig. 2 left). The scale uncertainties coming from the variation of μ_F and μ_R are also reduced by the inclusion of resummed contributions (Fig. 2 right).

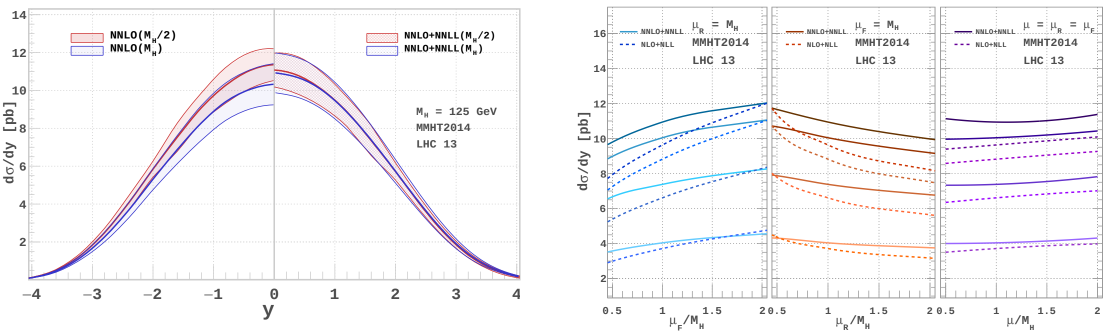

Figure 2: (Left) Higgs rapidity distributions for fixed order and resummed contributions are presented with scale variation around central scale choices $M_H/2$ and M_H at NNLO+NNLL. (Right) μ_F, μ_R scale variations for different benchmark y values (starting from the top $y = 0, 0.8, 1.6, 2.4$).

3.2 Drell-Yan rapidity distribution

For DY rapidity distribution we choose to work at 14 TeV LHC and focus mainly the Z-peak region. The NNLO contributions are obtained from Vrap-0.9 [20]. We performed a detailed analysis on the choice of central scale and found the best prediction for the f.o case is $(\mu_r, \mu_f) =$

$(\frac{\mu_R}{M_Z}, \frac{\mu_F}{M_Z})$	LO	$\text{LL}_{\text{M-F}}$	$\text{LL}_{\text{M-M}}$	NLO	$\text{NLL}_{\text{M-F}}$	$\text{NLL}_{\text{M-M}}$	NNLO	$\text{NNLL}_{\text{M-F}}$	$\text{NNLL}_{\text{M-M}}$
(2, 2)	72.626	+0.988	+3.219	73.450	+1.639	+1.796	70.894	+0.630	+0.646
(2, 1)	63.197	+0.768	+2.595	70.625	+0.761	+1.017	70.360	+0.292	+0.317
(1, 2)	72.626	+1.095	+3.577	73.535	+1.912	+1.760	70.509	+0.510	+0.395
(1, 1)	63.197	+0.851	+2.887	71.395	+0.858	+0.901	70.537	+0.248	+0.167
(1, 0.5)	53.241	+0.621	+2.216	67.581	+0.156	+0.140	69.834	- 0.001	- 0.094
(0.5, 1)	63.197	+0.953	+3.278	72.355	+0.945	+0.681	70.266	+0.091	- 0.015
(0.5, 0.5)	53.241	+0.695	+2.504	69.259	+0.102	- 0.154	70.283	- 0.039	- 0.146

Table 1: Comparison of resummed results between M-F and M-M approach in the minimal prescription scheme at $y = 0$ for various choices of scales.

$(1,1)M_Z$ whereas in resummed case it is $(\mu_r, \mu_f) = (1/2, 1)M_Z$ (see Fig. 3 left). In DY case also we see a better perturbative convergence compared to the f.o. The scale uncertainty however is more in the resummed case compared to the f.o (Fig. 3 right). The reduced scale uncertainty at f.o is due to the large cancellation of the contributions from different partonic channels which could be accidental and might not hold at higher orders. Resummation only takes care of the large logarithms coming from the distribution in the $q\bar{q}$ channel; therefore considering only $q\bar{q}$ channel, we get less scale uncertainty compared to the f.o as expected. The PDF uncertainties are also consistent among different groups and remains within 2% at NNLO+NNLL. We also made a numerical comparison between the M-F and M-M approaches keeping parameters for both cases same as in [6]. We found a significant difference at LO+LL level; though at higher orders the differences are not much at the level of cross-section. The M-M approach however provides a better perturbative convergence (see Table-1). Finally we stress that at this accuracy the electro-weak (EW) corrections are important. Using publicly available code Horace [21] we have included the EW corrections at NLO accuracy with q-integrated NNLO+NNLL QCD result at 8 TeV LHC (Fig. 4 left). Moreover we compare our prediction with CDF data [19] for $\sqrt{S} = 1.8$ TeV integrated over q in the range $66 < q < 116$ GeV and find a very good agreement (Fig. 4 right).

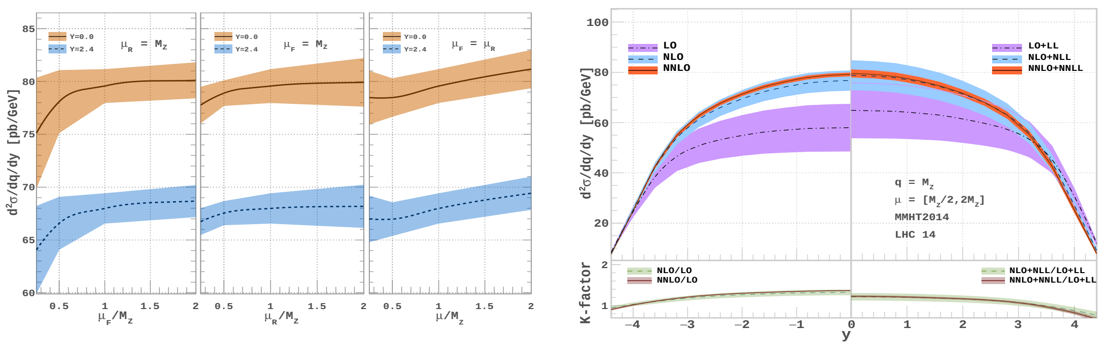

Figure 3: (Left) DY cross sections against μ_F(left), μ_R(middle) and μ(right) variations at NNLO+NNLL for 14 TeV LHC. (Right) Rapidity distribution for 14 TeV LHC at $q = M_Z$ with bottom panels representing the K-factors.

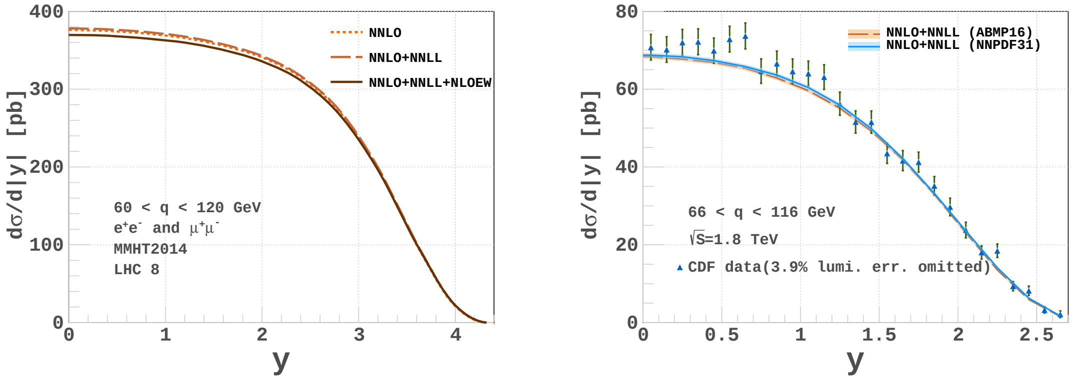

Figure 4: (Left) DY rapidity distribution at NNLO+NNLL for 8 TeV LHC in the invariant mass range $60 < q < 120$ GeV. (Right) Comparison between resummed results and the CDF data [19] at $\sqrt{s} = 1.8$ TeV in the invariant mass range $66 < q < 116$ GeV for two different PDF sets.

4. Conclusion

We have developed a formalism to resum threshold logarithms in double Mellin space for the rapidity distribution of a colorless final state F produced at the hadron collider. An analytic expression of the resummed coefficients upto N^{3}LL has been presented in terms of double Mellin variables N_1 and N_2. As an application we have studied the role of the resummed threshold logarithms for the rapidity distribution for Higgs and DY productions at the LHC. We have performed a detailed study on scale variations and central scale choice as well as estimated uncertainty coming from PDFs. Numerical impact of our resummation in double Mellin space has significant differences at the leading logarithmic accuracy compared to the existing results in literature; however we found agreement at NNLO+NNLL level. Our resummed coefficients can be used for rapidity distribution of any colorless final state produced at the LHC. The numerical analysis presented here would be useful to understand the properties of the Higgs boson as well as will be very useful for precise determination of PDFs at the LHC.

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