PROCEEDINGS OF SCIENCE

Precision prediction for the jet mass spectrum in one-jet inclusive production at the LHC

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The jet mass is an useful variable to distinguish the interesting signal jets formed by highly boosted massive paricles from the purely QCD background, so the QCD jet mass needs to be understood very precisely. We present precision prediction for the jet mass spectrum in one-jet inclusive production at the LHC with soft-collinear effective theory. The large logarithms $\ln^n(m_J^2/p_T^2)$ in the process are resummed to all order in α_s. The peak of the spectrum is enhanced by about 23% from the next-to-leading logarithmic level to next-to-next-to-leading logarithmic level. Our results agree with PYTHIA and ATLAS data at the 7 TeV LHC after considering the non-perturbative effects. We also present the predictions at the 13 TeV LHC.

XXVII International Symposium on Lepton Photon Interactions at High Energies
17-22 August 2015
Ljubljana, Slovenia

*Speaker.

PoS(LeptonPhoton2015)103

1. Introduction

The LHC has finished running with the collision energy of 7 and 8 TeV. The current searches for the signals of new physics have not made any discovery, which indicates that the possible new physics may reside in very high energy scale. Upgraded to the 13 TeV collision, the LHC continues probing the unexplored energy regions from this year. If any new heavy resonance is produced at the LHC and decays into massive electroweak gauge bosons or top quarks, which are highly boosted, the final state would contain very fat jets. It is necessary to use certain techniques of jet substructures to distinguish them from ordinary QCD jets. A very simple jet substructure is the invariant mass of the jet. However, a precise prediction for the QCD jet mass is not simple because the fixed order results in QCD suffer from the large logarithms of the form $\alpha_s^n \ln^m(m_J^2/p_T^2)/m_J^2$ with $m \leq 2n-1$, which would be divergent and make the fixed order results unreliable as $m_J \to 0$. After taking into account the parton shower effect, the event generators, such as `SHERPA` [1], `PYTHIA` [2] and `HERWIG++` [3] can give convergent predictions. But the parton shower is performed in different evolution schemes, for example, $p_\perp$-ordered and angular-ordered, respectively. The predictions from these event generators are thus different. More precise predictions can be obtained by resummation of the large logarithms analytically in traditional perturbative QCD formalism [4, 5] or the soft-collinear effective theory (SCET) [6, 7]. Given that the one-jet inclusive production at the LHC has large cross sections and thus is the main background, it is of great importance to study the jet mass spectrum in this process.

2. Definition of the threshold variable and factorization formalism

The one-jet inclusive process is depicted as in Figure 1. Experimentally, the two initial protons collide to produce two jets as well as many soft and collinear radiations. However, only one leading jet is required to be measured. On the theoretical side, one can calculate the cross section of the dijet production $pp \to j_1 j_2$. Since one can not determine whether the measured jet comes from j_1 or j_2, one needs to average the jet mass spectra of the leading two jets j_1 and j_2. The jets are constructed through sequential, iterative jet clustering algorithms. We adopt the anti-k_T clustering algorithm [8], which builds jets with a very regular shape.

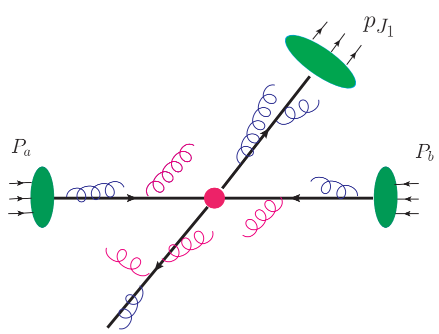

Figure 1: The illustrative picture for dijet production at the LHC. The blue and red arcs denote the collinear and soft gluons, respectively.

At LO in QCD, the partonic processes are $2 \to 2$, e.g., $q\bar{q} \to gg$, and the jet is massless. At NLO in QCD, the real corrections are $2 \to 3$, where the final state may contain a jet consisting of two partons. However, at the region with $m_J \to 0$, the two partons become collinear to each other or one of them is soft, and thus the amplitude for the real corrections is divergent. This special phase space is called the threshold region. More specifically, we denote the sum of the momenta of all the collinear particles as p_{J_1} and the sum of momenta of all the soft particles inside the jet as $k_{\rm in}$. The threshold variable is

$$m_J^2 = (p_{J_1} + k_{\rm in})^2 = m_{J_1}^2 + 2k_{\rm in} \cdot p_{J_1}. \tag{2.1}$$

The same situation happens for the recoiling jet thought it is not observed. We make use of another threshold variable

$$s_4 = (p_{J_2} + k_{\rm out})^2 = m_{J_2}^2 + 2k_{\rm out} \cdot p_{J_2} \tag{2.2}$$

to describe the special phase space. Here $k_{\rm out}$ represents the sum of momenta of all the soft particles outside the jet. Other useful kinematical variables are defined as

$$\hat{s} = (p_a + p_b)^2, \quad \hat{t}_1 = (p_a - p_{J_1})^2 - m_{J_1}^2, \quad \hat{u}_1 = (p_b - p_{J_1})^2 - m_{J_1}^2. \tag{2.3}$$

In the threshold region $m_J \to 0$ and $s_4 \to 0$, the cross section is factorized as [9]

$$\frac{d\sigma}{dp_T dy dm_J^2} = \frac{p_T}{8\pi s} \sum_{i,j} \int_{x_a^{\rm min}}^1 \frac{dx_a}{x_a} \int_{x_b^{\rm min}}^1 \frac{dx_b}{x_b} f_i(x_a,\mu_f) f_j(x_b,\mu_f) C_{ij}(\hat{s},\hat{t}_1,\hat{u}_1,m_J^2,R,\mu_f), \tag{2.4}$$

where $f_i(x,\mu_f)$ is the parton distribution function and C_{ij} is the hard-scattering kernel

$$C_{ij}(\hat{s},\hat{t}_1,\hat{u}_1,m_J^2,R) = \sum_{I,J} \int dm_{J_1}^2\, dm_{J_2}^2\, dk_{\rm in}\, dk_{\rm out}\, H_{IJ}(\hat{s},\hat{t}_1,\hat{u}_1)\, S_{JI}(k_{\rm in},k_{\rm out}) \tag{2.5}$$

$$\times J_1(m_{J_1}^2) J_2(m_{J_2}^2) \delta(m_J^2 - m_{J_1}^2 - 2E_J k_{\rm in})\, \delta(s_4 - m_{J_2}^2 - 2E_J k_{\rm out}). \tag{2.6}$$

The above H_{IJ}, S_{JI} and J_i are hard function, soft function and jet function, respectively [1]. They are evaluated in their intrinsic scales so that no large logarithms appear. Then all of them can be evolved to the factorization scale by renormalization group (RG) equations respectively. Since the RG equations are integro-differential equations, the solutions contain no large logarithms. Especially, the prediction in the region $m_J \to 0$ is finite.

Meanwhile, if we take the limit that all scales are equal, the RG improved result is expanded in the strong coupling constant α_s and reproduce the fixed-order result. This agreement can serve as a nontrivial check on the correctness of the components in the factorization formalism, in particular, the soft function, which we have calculated for the first time.

In reality, the soft function is very complicated at higher orders since each soft particle can be clustered inside or outside the jet. This kind of phase space constraint becomes more and more intricate with the increasing of the number of final-state soft particles. As a consequence, additional large logarithms of the form $\ln^n(k_{\rm in}/k_{\rm out})$ emerge, which depend on the specified phase space regions and thus are called the non-global logarithms. In our study, we adopt an approximate factorization form of the soft function, i.e., $\mathbf{S}(k_{\rm in},k_{\rm out}) \approx \mathbf{S}(k_{\rm in}) \cdot \mathbf{S}(k_{\rm out})$ [9].

[1]The variables $k_{\rm in}$ and $k_{\rm out}$ have been redefined by $k_{\rm in} \equiv n_J \cdot k_{\rm in}$ and $k_{\rm out} \equiv \bar{n}_J \cdot k_{\rm out}$.

3. Numerical results

We use the MSTW2008 PDF sets [10] and associated strong coupling α_s to perform numerical calculations. We present results with different precisions which are defined as [2]

Precision	Γ_{cusp}	γ	H_{IJ}, S_{JI}, J_i
NLL	2-loop	1-loop	tree
NNLL$_\text{p}$	3-loop	2-loop	1-loop

There are five matching scales μ_h, $\mu_{s_{\text{in}}}$, $\mu_{s_{\text{out}}}$, μ_{j_1} and μ_{j_2}, which are chosen as

$$\mu_h = 1.4\, p_T\,, \quad \mu_{s_{\text{out}}} = 0.2\, p_T + 80\,\text{GeV}\,, \quad \mu_{j_2} = 0.5\, p_T\,, \quad \mu_{j_1} = 3m_J, \quad \mu_{s_{\text{in}}} = \frac{{\mu_*}^2}{c_R}\frac{p_T^*}{p_T}\,, \tag{3.1}$$

where c_R is an R (jet radius)-dependent parameter, $p_T^* = 400\text{GeV}$ and $\mu_* = 1.67 m_J^{1.47}$. We first show the resummation results for the jet mass spectrum at the 7 TeV LHC in the left plot of Figure 2. Though the scale uncertainties are slightly decreased and the peak positions are almost the same, the shapes of the distributions are significantly changed and the spectrum at the peak region is enhanced by about 23% from NLL to NNLL$_\text{p}$. This improvement is mainly caused by inclusion of the one-loop hard function.

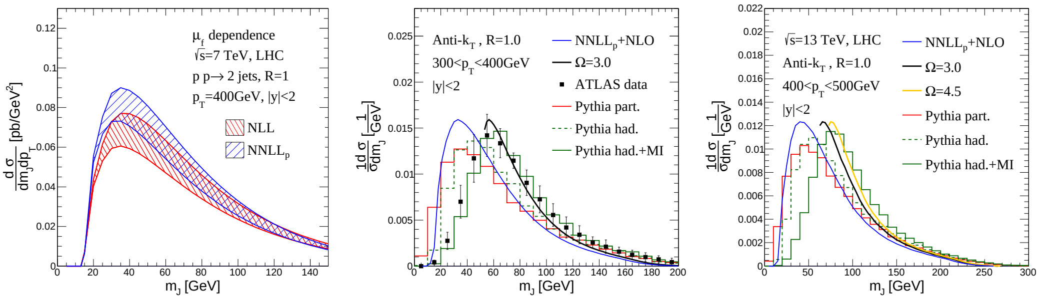

Figure 2: *Left plot:* The resummation results for $p_T = 400$ GeV and $R = 1$ at the LHC. The bands denote the uncertainties from varying the factorization scale by a factor of 2. *Middle plot:* Comparison of the RG improved results with PYTHIA and ATLAS data. *Right plot:* Predictions at the 13 TeV LHC.

We can compare our predictions with PYTHIA and ATLAS data, as shown in the middle plot of Figure 2. Without the effect of hadronization, the peak position agrees with the result of PYTHIA but the peak is higher due to the reason discussed above. After including the effects of hadronization and multiparton interaction, PYTHIA can describe the ATLAS data. These effects involve QCD non-perturbative region and thus are hard to be predicted analytically. Instead, we would simulate the effects by simply shifting the spectrum in the form $m_J^2 \to m_J^2 + 2\Omega R\, p_T$, where Ω accounts for the non-perturbative effects, chosen to be 3.0 GeV in this case. This shift is not applicable in the small jet mass region, so only part of the spectrum is shown, which illustrates that our result is in agreement with the data. The predictions for the jet mass spectrum at the 13 TeV LHC are shown in the right plot of Figure 2. Since gluon jets will be more dominant at higher

[2] For the R-dependent pieces, only the one-loop soft anomalous dimensions are used at NNLL$_\text{p}$.

energy collisions, the hadronization effect is expected to be more significant at the 13 TeV LHC. Therefore, we see that the spectrum with $\Omega = 4.5$ GeV is closer to the result of PYTHIA than that with $\Omega = 3$ GeV.

4. Conclusion

The jet mass is an useful variable to distinguish the interesting signal jets formed by highly boosted massive paricles from the purely QCD background, so the QCD jet mass needs to be understood very precisely. We present precision prediction for the jet mass spectrum in one-jet inclusive production at the LHC with soft-collinear effective theory. The large logarithms $\ln^n(m_J^2/p_T^2)$ in the process are resummed to all order in α_s. The peak of the spectrum is enhanced by about 23% from the next-to-leading logarithmic level to next-to-next-to-leading logarithmic level. Our results agree with PYTHIA and ATLAS data at the 7 TeV LHC after considering the non-perturbative effects. We also present the predictions at the 13 TeV LHC.

Acknowledgments

We would like to thank Hua Xing Zhu, Ding Yu Shao, Zhao Li and Hsiang-nan Li for helpful discussions. This work was supported in part by the National Natural Science Foundation of China under Grants No. 11375013 and No. 11135003. The research of J.W. has been supported by the Cluster of Excellence *Precision Physics, Fundamental Interactions and Structure of Matter* (PRISMA-EXC 1098).

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