Summary report for the CERN-KEK Committee 2010

Hiroshi Yokoya (Physics Department, Theory Unit)

Overview

Since the first year of my fellowship at the CERN, I have been working on the bound-state effects in pair production of heavy colored particles, such as top-quarks, at the LHC. In the first and second years, in collaboration with K. Hagiwara and Y. Sumino, I have worked on the bound-state effects on the pair invariant-mass distributions of the top-quark pair, as well as the gluino pair production at hadron colliders [1, 2]. We unveiled that the all-order Coulomb corrections can be significant at the LHC, since gluon-fusion process dominates the production cross-section where a certain fraction of the pairs of the heavy particles are color-singlet.

In this year, in collaboration with Y. Sumino, I further proceed the project to formulate the bound-state effects on kinematical distributions of the top-quarks, or the differential cross-sections at hadron colliders [3]. For the numerical calculation and simulation study, I developed a Monte-Carlo event generator which implement the formula to include all-order Coulomb corrections.

In addition, in collaboration with J. Kanzaki and under fruitful discussions with M. Mangano, I have been working on proposing methods to probe the color of $t\bar{t}$ pairs using jet-shape variables and accompanied jets distributions. I plan to publish these studies soon [4, 5].

Bound-state effects on kinematical distributions of top-quarks

The method to incorporate bound-state effects to the fully differential cross sections has been developed mostly in e^+e^- collision. In contrast to the e^+e^- collision, at hadron colliders, the (partonic) collision energy is not fixed. Therefore, we have to set up a framework which is valid both in the threshold region ($m_{t\bar{t}} \simeq 2m_t$) and in the high-energy region ($m_{t\bar{t}} \gg 2m_t$). The former region is where the bound-state effects (Coulomb corrections) become significant and where the non-relativistic approximation is valid. On the other hand, in the latter region, the bound-state effects are not significant and the top quarks are relativistic. We considered a framework which takes into account all the leading-order (LO) corrections in both regions. Namely, we incorporate all the $(\alpha_s/\beta)^n$ terms in the threshold region, while we include all the β^n terms in the relativistic region.

To take into account off-shellness of the top quarks, we constructed full amplitudes for the $bW^+\bar{b}W^-$ final-state. In the $bW^+\bar{b}W^-$ production, there also exist non-resonant diagrams where bW^+ and $\bar{b}W^-$ are not produced from the decay of t and $\bar{t}$, respectively. In the threshold region, either of t and $\bar{t}$ tends to be off-shell due to the restricted phase-space and the binding effects, and the non-resonant diagrams can give non-negligible contributions compared to the resonant diagrams. Since these contributions interfere with each other, all the diagrams have to be taken into account at the amplitude level.

The formula to incorporate bound-state effects in the resonant amplitudes is given by;

$$\mathcal{M}^{(c)}_{t\bar{t}} = \mathcal{M}^{(c)}_{t\bar{t},\mathrm{tree}} \times \frac{G^{(c)}(E' + i\Gamma_t, \vec{p})}{G_0(E' + i\Gamma_t, \vec{p})}, \tag{1}$$

with $E' = E + E^2/(4m_t)$, and $E = m_{t\bar{t}} - 2m_t$. The momentum-space Green functions are defined as

$$G^{(c)}(E + i\Gamma_t, \vec{p}) = \int d^3\vec{r} e^{-i\vec{p}\cdot\vec{r}} \widetilde{G}^{(c)}(E + i\Gamma_t, \vec{r}). \tag{2}$$

The use of the modified energy E' in the formula turns out to be indispensable to extrapolate the Green function formalism to the high-energy region. It is motivated by the fact that the Green function, which dictates the time evolution of the $t\bar{t}$ system, is identified as a part of the Feynman amplitudes for $i \to t\bar{t} \to bW^+\bar{b}W^-$. The advantage of using $\widetilde{G}^{(c)}(E' + i\Gamma_t, \vec{p})$ is that one can obtain it from the conventional non-relativistic Green function with a minimal modification $E \to E' = E + E^2/(4m_t)$.

For the numerical calculation, we develop a Monte-Carlo event-generator which implements the ingredients explained above. The helicity amplitudes for $bW^+\bar{b}W^-$ resonant and non-resonant diagrams are calculated by using `HELAS`, based on the `MadGraph` output. We modified them to implement the

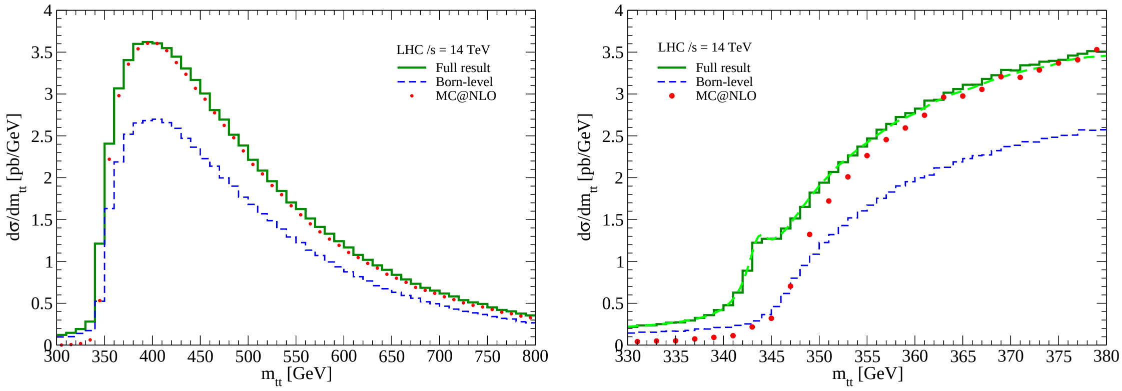

Figure 1: $t\bar{t}$ invariant-mass distribution in $pp \to bW^+\bar{b}W^-$ production at $\sqrt{s} = 14$ TeV. Green solid line is the full cross-section and blue dashed line is the result in Born-level. The NLO $t\bar{t}$ production computed by using `MC@NLO` is also plotted in red dots.

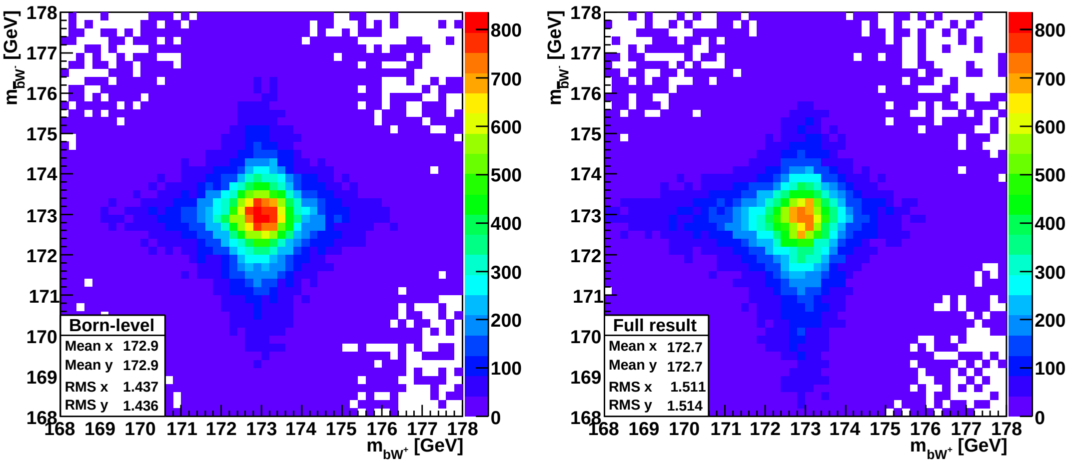

Figure 2: Two-dimensional distribution histogram in the bW^+ and $\bar{b}W^-$ invariant-masses, for the events with $m_{t\bar{t}} \leq 370$ GeV at the LHC $\sqrt{s} = 14$ TeV. Left figure is the Born-level prediction and right figure is the full result (including the Coulomb corrections and K-factors).

color-decomposition and to include the bound-state effects via the Green functions. The phase-space integrations are performed by using `BASES/SPRING`, and alternatively by adapting our code to `MadEvent`. The ISR effects are partly incorporated by connecting our framework to parton-shower simulators, such as `Pythia` or `Herwig`. In addition, we include "K-factors" as the normalization constants of the cross-section for each individual channel. They are determined such that the $m_{t\bar{t}}$ distribution for each channel matches the corresponding NLO prediction in the threshold region.

As an example, I present two distributions which indicates the importance of the bound-state effects at the LHC. Fig. 1 (left) shows the $t\bar{t}$ invariant-mass distribution in $pp \to bW^+\bar{b}W^-$ production at $\sqrt{s} = 14$ TeV. The green solid line represents the full result which includes the bound-state effects as well as the K-factors, and the blue dashed line represents the Born-level result (the LO prediction in the conventional perturbative QCD approach). Fig. 1 (right) shows a magnification of the same cross sections in the threshold region. Theoretically the bound-state effects can be seen most clearly in the shape of the $m_{t\bar{t}}$ distribution in the threshold region. Far above the threshold, the bound-state effects disappear and the cross section approaches the Born-level distributions, up to the K-factor normalization.

Fig. 2 shows the density plots of the invariant-masses of the bW^+ and $\bar{b}W^-$ systems, given by the Born-level prediction (left) and our full prediction (right). The Born-level prediction is essentially determined by the product of the Breit-Wigner functions, hence the distribution is almost reflection symmetric with respect to the on-shell lines $(p_b + p_{W^+})^2 = m_t^2$ and $(p_{\bar{b}} + p_{W^-})^2 = m_t^2$. By contrast, the distribution by our full prediction is not symmetric and biased towards the configuration, where one of t or $\bar{t}$ is on-shell and the other has an invariant-mass smaller than m_t. We observed a characteristic bound-state effect in the (bW^+)-$(\bar{b}W^-)$ double-invariant-mass distribution, which should be important for the precise mass determination of the top-quark using threshold events.

For more realistic predictions, one has to take into account the decay of W-boson including spin correlations. For this purpose, we also developed a matrix-element for the process with six-body final-state including the decay of W-bosons, where the core $t\bar{t}$ production part is unchanged. We found however that the angular distributions of leptons from W-boson decay are not much affected by the bound-state effects.

Probing the color of top-quark pairs at the LHC

In addition to the above project, I have been working on proposing methods to probe the color of $t\bar{t}$ pairs produced at the LHC. At the LHC, gluon fusion process dominates the $t\bar{t}$ production cross-section, and therefore a certain fraction of the $t\bar{t}$ pairs would be color-singlet. On the other hand, at the Tevatron, $q\bar{q}$ annihilation process dominates, therefore $t\bar{t}$ pairs are almost always color-octet. By observing the color of the $t\bar{t}$ pairs, one can check the detailed mechanism of $t\bar{t}$ production and also the color dynamics of the events at the hadron collider.

(1) Jet-shape angular-correlation

The first proposal is to observe the color-flow structure in the hard scattering process by analyzing the the hadronic energy-energy correlations in the event. It is known theoretically and experimentally that due to the string-like nature of the quark-gluon splittings, final-state hadrons would emerge preferably along the color-flow among partons in the hard scatterings. For example, there would be many particles between the jets if the two jets are connected in color. On the other hand, there would be many particles between the jet and the beam remnant direction if color-flow exists between the initial-state and final-state partons.

In collaboration with J. Kanzaki, I found that a kind of jet-shape variables, called "pull-vector", is good to measure the direction of the color-flow from the jet, i.e. the direction of the color partner. Using the angular correlation of "pull-vectors" of two b-jets in $t\bar{t}$ events, it is possible to observe the evidence of the color-singlet $t\bar{t}$ production at the LHC. I plan to publish a paper on this study soon (within one month). It would be applicable to study the color structure of unknown heavy particles (resonances), observed in future at the LHC.

(2) Accompanied jets distribution

The second proposal is to use the accompanied jet distribution in $t\bar{t}$ production. Suppose $t\bar{t}$ is produced with large transverse momentum, then $t\bar{t}$ is not back-to-back but close to each other. If the $t\bar{t}$ is color-singlet, the gluon radiation from the $t\bar{t}$ is suppressed due to the destructive interference between the diagrams with gluon radiation from t and $\bar{t}$. On the other hand, if the $t\bar{t}$ is color-octet, the gluon radiation amplitudes are not canceled. Thus, by looking at the hard-jet distributions accompanied with the $t\bar{t}$ pair, one can observe the difference between the color-singlet and octet $t\bar{t}$ productions.

Under close discussions with M. Mangano, I am performing a phenomenological study for the possibility of measuring significant difference at the LHC. I plan to publish a report of this study within two months.

References

Papers

[1] K. Hagiwara, Y. Sumino and H. Yokoya, "Bound-state Effects on Top Quark Production at Hadron Colliders," Phys. Lett. B **666** (2008) 71 [arXiv:0804.1014 [hep-ph]].

[2] K. Hagiwara and H. Yokoya, "Bound-state effects on gluino-pair production at hadron colliders," JHEP **0910** (2009) 049 [arXiv:0909.3204 [hep-ph]].

[3] Y. Sumino and H. Yokoya, "Bound-state effects on kinematical distributions of top quarks at hadron colliders," JHEP **1009** (2010) 034 [arXiv:1007.0075 [hep-ph]].

[4] J. Kanzaki and H. Yokoya, "Probing the color of top-quark pairs using angular correlations of jet-shape variables", in preparation.

[5] H. Yokoya, "Probing the color of top-quark pairs using kinematical distributions of accompanied jets", in preparation.

Conferences

[6] "Bound-state effects in ttbar production at hadron colliders"
Invited talk at 3rd International workshop on Top Quark Physics (TOP2010),
Bruges, Belgium, 31 May - 4 June 2010.
Proceedings to appear in Nouvo Cim. C.

[7] "Bound-state effects on gluino-pair production"
18th International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY 10), Bonn, 23-27 August, 2010.

[8] "Bound-state effects on kinematical distributions of top quarks at hadron colliders"
The 3rd International Workshop on High Precision for Hard Processes at the LHC (HP2.3rd), GGI, Florence, 14-17 September 2010.