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以MadGraph比較重夸克對伴隨希格斯粒子產生的兩個不同處理方法

Comparison of Two Schemes For Higgs Production Associated with Heavy Quark Pairs using MadGraph

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本論文係王柏庭君在國立臺灣大學物理學系、所完成之碩士學位論文，於民國 102 年 6 月 11 日承下列考試委員審查通過及口試及格，特此證明

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Chung Kao

陳傳仁

[illegible]

中文摘要

在一些超越標準模型中，希格斯粒子在大強子對撞器目前研究的能量範圍內可能和其他粒子有很強的交互作用，重夸克伴隨希格斯粒子產生過程的研究有助於我們蒐尋這些超越標準模型。我們用MadGraph接口PYTHIA結合矩陣元方法和部分子簇射方法，比較處理這個過程的兩個不同方法(四風味方法和五風味方法)在領頭階加上數個噴流的精確度下的模擬結果。我們的研究顯示在考慮領頭階加上數個噴流的情況下，四風味方法比五風味方法結果更爲精確。

關鍵字: 希格斯，底夸克。

Abstract

Some Beyond the Standard Model (BSM) Higgs particle may interact strongly with other particles at energy scales presently studied at the LHC, the study of Higgs production associated with heavy quark pairs may help us search for these BSMs. We compare two different schemes, the 4 flavour scheme and the 5 flavour scheme, to describe this process at LO + n jet by merging matrix element method and parton shower approach on MadGraph 5 interface to PYTHIA. We show that the 4 flavour scheme may provide better description than the 5 flavour scheme at LO + n jet level.

keywords: Higgs, Bottom, Matching, Four Flavour, Five Flavour, MadGraph.

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Chapter 1

Introduction

Some Beyond the Standard Models (BSM) such as SUSY, Little Higgs models, some extra dimension models and technicolor models have strongly interating particles with mass at the TeV scale [1]. Since strong Higgs couplings enhance the amplitude of Higgs production processes, the inclusive Higgs production process is sensitive to these models at Large Hadron Collider (LHC). By analyzing these models, we will be able to search for signals of new physics.

We shall focus on inclusive Higgs production associated with bottom quarks. There are two different schemes for inclusive Higgs production with bottom quarks. The first scheme is the 4 flavour scheme which uses $pp \to hb\bar{b}$ as leading order (LO). The second scheme is the 5 flavour scheme which uses $pp \to h$ as LO. These two schemes should approach each other at higher order. In simulation, we take much time on the higher order term (especially the loop term), so we might hope that we can get acceptable results with lower order calculation.

In this paper, we want to compare the two different schemes with the inclusive Higgs production process at LO including the radiation term, to learn which scheme gives better description at lower order.

In the past, there are two extreme methods to deal with multi-jet simulation in proton-proton collisions: matrix element (ME) method and parton shower (PS) approach. ME method considers amplitudes of every Feynman diagram, combining them to calculate the cross section and other physical observables. PS approach, however, treats parton radiation by soft and collinear approximation. ME results diverge at soft and collinear limit (angle between two partons is small). On the other hand, PS approach fails at hard limit. We can combine the two methods: in soft limit we use PS approach and in hard limit we use ME method. This combination of phase space is the so-called matching method. Many studies show that the effect of matching is important for multi-jet simulation. So we study which scheme has higher simulation accuracy at lower order by comparing LO + n jet results of two schemes to NLO + n jet results in the matching algorithm framework.

The outline of this thesis is as follows: in Section 2, we discuss the 4 flavour and the 5 flavour schemes, including their properties, advantages and faults. At the same time, we review ME method and PS approach, then introduce how to generate a matching scheme and briefly explain how does this matching scheme solve faults arising from ME and PS approaches. Then we introduce MadGraph [2]: the tool we use in our study. Section 3 is our data analysis results and Section 4 is our conclusion.

Chapter 2

Matching scheme for multi-jet simulation

2.1 Introduction to two flavour schemes

The 4 flavour scheme and the 5 flavour scheme are two schemes used to calculate inclusive Higgs production in association with heavy quarks. The 4 flavour scheme uses $gg \to hb\bar{b}$ as LO, which yields collinear logarithms $\ln(m_h/m_b)$. The 5 flavour scheme uses $b\bar{b} \to h$ as LO. When higher-and-higher order terms are considered, the two schemes should be the same, since they are just different orderings of the same terms.

With logarithms $\ln(m_h/m_b)$, the 4 flavour scheme is less convergent than the 5 flavour scheme [3, 4]. On the other hand, the 5 flavour scheme sums logarithms into b-quark distribution function via the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) equations [5–7], so it is more convergent. In addition, with simpler LO ($b\bar{b} \to h$) process, higher order consideration for the 5 flavour scheme is easier than the 4 flavour scheme.

2.2 Two approaches of multi-jet simulation

In high energy hadronic collision, parton final states radiate continuously and when energy is low enough (about 1 GeV), partons begin to hadronize. We see jets in experimental detector finally.

There are two methods that can be used to simulate multi-jet processes. The first method uses LO matrix elements with coupling α_s. One can furthermore consider next to leading order (NLO) or higher order Feynman diagrams. Alternatively, one can use the parton shower (PS) approach. PS approach sums collinear and soft radiation of a parton into one parton branch, giving logarithmic order of amplitude.

The ME method diverges in the case when two partons are soft and collinear, while PS approximation loses efficacy when the angle between the two partons is large and the process is hard. Another problem is double counting: when we consider LO and NLO diagrams, NLO diagrams (for example: tree level plus a radiated particle) may be the same as LO process plus a showered hard particle.

To accurately describe phase space of both hard and soft regions, we need to combine two approaches with no double counting or gaps between different parton multiplicities, correctly matching PS and ME descriptions. Besides these, we give two further restrictions to this combined method:

1. Procedure should give smooth distributions between ME and PS region.

2. When we change scale separating ME and PS, the physical description should be stable.

2.3 Matrix element method

The idea of matrix element method is to calculate Feynman diagram amplitude then using amplitude to get total cross section of a process. By Fermi's Golden Rule, the differential cross section of process: particle $1, 2 \rightarrow 3, 4, ...n$ can be written as follows:

$$d\sigma = \frac{(2\pi)^4 |\mathcal{M}|^2}{4\sqrt{(p_1 \cdot p_2)^2 - (m_1^2 m_2^2)}} d\Phi_{n-2}, \tag{2.1}$$

where $\mathcal{M}$ is the amplitude of this process, p_i and m_i are four momentum and mass of the i-th particle, $d\Phi_{n-2}$ is Lorentz invariant phase space volume for $n-2$ particles. Integrating over all phase space, we get the total cross section.

2.4 Parton shower approach

2.4.1 Introduction

In hard processes, the coloured partons (quarks and gluons) radiate virtual gluons. Unlike photon in QED, gluons carry colour charge, which can radiate further gluons or produce quark-antiquark pairs, resulting in parton showers. The dominant contribution of parton shower is associated with collinear parton splittings or soft gluon emissions. We consider correct contribution of initial and final state particle radiations from different possible branchings, including $q \to qg$, $g \to gg$, $g \to q\bar{q}$. The branching rate $I_{a\to bc}$ is proportional to the integral: $\int P_{a\to bc}(z)dz$, where $P_{a\to bc}(z)$ is the splitting function of these branchings, describing the probability that b carries energy fraction z from a, another particle c, of course, carries $1-z$ fraction energy from a.

It is convenient to define t by virtuality scale:

$$t = \ln(\frac{Q^2}{\Lambda^2}), dt = dQ^2/Q^2, \tag{2.2}$$

where Λ is QCD scale of α_s. We can estimate the probability that a parton does not split between t_1 and t_2, which is given by Sudakov form factor [8]:

$$P_{\mathrm{no-splitting}} = \exp(-\int_{t_1}^{t_2} \sum_{b,c} I_{a\to bc}(t)dt). \tag{2.3}$$

A feature of PS approach is the evolution variable, describing how partons radiated in order. Commonly used evolution variables are angular order [9], k_T order [10] or virtuality (Q^2) order.

2.4.2 Final state parton shower

Parton shower of the final state is as follows: the final state partons start at a high energy and a large time-like virtuality scale Q^2, gradually losing energy and virtuality. How to define Q^2 is not unique. Definition of Q^2 decides how parton shower evolves. For example, in k_T order, parton with largest k_T will radiate first, and then k_T of emitted partons becomes smaller gradually. At about 1 GeV, these partons and their descendants stop splitting. And at this scale hadronization takes place.

2.4.3 Initial state parton shower

Two initial partons from incoming hadrons start at high energy and radiate, losing energy and acquiring virtuality, until they scatter in hard process. Parton distribution function in hadron, which is used to describe probability a parton carries momentum fraction x, may change by energy scale as a result of soft radiation. We can not see bare parton distribution function actually. What we can see is parton distribution function at scale Q^2 in hard process. We can describe virtuality scale dependence of parton distribution function which is governed by DGLAP equation:

$$\frac{df_{j/H}(x,\mu)}{d\ln\mu} = 2\sum_{j'}\int_x^1 \frac{\alpha_s(\mu)}{2\pi} P_{jj'}(z) f_{j'/H}(x/z,\mu)\frac{dz}{z}, \tag{2.4}$$

where $f_{j/H}(x,\mu)$ is parton distribution function of parton j, which depends on energy scale μ in a hadron. The no-splitting probability is given by modified Sudakov form factor which includes parton distribution.

2.4.4 Hadronization

When final state partons of a process experience parton shower, they lose energy and virtuality Q^2. In QCD, the β function of the strong coupling constant α_s is negative, which means that at low energy scale, the strong coupling constant increases. It is shown that at about 1 GeV, non-pertubative effects dominate the process, and at this energy scale, partons begin to hadronize. String model [11] and Cluster model [12] are two mainstream models used to describe processes of hadronization.

2.5 Matching approach

Motivation for constructing a matching algorithm is because neither the ME method nor the PS approach can give good description in all phase space. The matrix element approach causes divergence of amplitude at soft and collinear phase regions. To see this, we can focus on amplitude of process: $a \to bc$. This process contribute a $\frac{1}{(P_b+P_c)^2}$ term, which is approximate to $\frac{1}{E_bE_c(1-cos\theta_{bc})}$. We can easily see that in soft and collinear limit this description diverges. The PS approach ignores inner structure of radiated partons, so quantum interference of these radiations is not considered. We imagine a gluon radiated from one of b, c dipole in process: $a \to bc$. If a radiated gluon is soft and large angle, then this gluon could not "see" (resolve) this b, c dipole, as if it is radiated by particle a. In this case, these different radiation orders of gluon give the contribution which could be seen as sequential emission of angular-ordered partons, so we can treat interference effect by angular order approximation [9]. This approximation fails if showered partons are hard.

To test if a matching algorithm work, we usually check the smoothness of the differential jet rate. The $N \to N-1$ differential jet rate is distribution of the resolution parameter (in k_T clustering algorithm [13]), make jet multiplicities transit from N to $N-1$. If a matching algorithm gives good description, the transition of differential jet rate between two phase spaces separated by $Q_{\rm match}$, which is a scale in a matching algorithm used to define hard phase space and soft $\&$ collinear phase space, should be smooth. Therefore, when we run a matching algorithm simulation, we choose a matching scale $Q_{\rm match}$ that gives a smooth differential jet rate distribution.

The first matching method is the CKKW algorithm [14, 15], but now there are several schemes that match ME and PS, such as Lönnblad [16] and Mangano schemes [17] [18]. In our simulation, we use Mangano (MLM) algorithm in MadGraph 5. The MLM algorithm is described as follows:

1. Using Monte Carlo method to generate multi-jet matrix element events (initial state $\to n$ jets, $n = 2, 3, ..., N$) which has hard enough and non-collinear jets . We require that p_T, ΔR and η should be larger than some cut parameters ($p_t > p_t^{\rm ME}$, $\Delta R > \Delta R_{\rm ME}$, $\eta > \eta_{\rm ME}$).

2. Running parton shower on genetated matrix element.

3. Using the cone jet algorithm to cluster partons into jets. This algorithm uses $E_{T_{\rm min}}$, $E_{T_{\rm cluster}}$ and $R_{\rm cluster}$ to define jets.

4. In this step, we merge partons at matrix element level and jets in parton shower level. The purpose is that a matrix element level parton corresponds to a jet. The procedure is as follows:

   (a) Beginning from high p_t ME parton and in order, if a jet with parameter $R_{\rm match}$

larger than ΔR between jet and parton, then we say a jet merged to the parton. We then remove this jet from the jet list.

(b) If not all ME partons merge with a jet, we then discard this event.

5. If we consider $n = 2, 3, \ldots, N$ jets final state, then for $n < N$, we pick up inclusive events and reject other events. In other words, we reject events with jet number larger than N. If $n = N$, then we consider exclusive events.

This algorithm avoids double counting problem from collinear partons in matched events [19]. An example for events must be rejected is that a ME parton is too soft so that it could not spray jets. Another example is when the angle between two ME partons is too small so that after parton shower partons sprayed from two ME partons may be defined as one jet. The most important is that events with hard jets generated by parton shower are rejected. MLM scheme algorithm successfully merges the two methods by assigning hard processes to matrix element, and soft processes to parton shower, with no double counting.

2.6 MadGraph approach

MadGraph 5 is an event generator tool used to simulate Matrix Element level hard process in the SM and some BSM (MSSM, 2HDM, HEFT) frameworks, which now also supports some matching algorithms. We generate MLM matching algorithm in our analysis by MadGraph 5. Detailed analysis is stated in the next section.

The approach of the MLM algorithm in MadGraph [20] [21] is a little different from the original paper. MadGraph uses different jet algorithms for jet matching and to define scales of coulping α_s. The phase-space separation between the different multi-jet processes is achieved using the k_T-measure as in SHERPA [22], while the Sudakov reweighting is performed by rejecting showered events that do not match to the parton-level jets, as in ALPGEN, which is described in Ref. [23].

MadGraph 5 matching algorithm uses PYTHIA [24] as parton shower generator. MadGraph 5 supports PYTHIA interface included in Pythia-PGS package for running parton shower in MLM matching algorithm.

Chapter 3

Simulation

3.1 Parameter setting and results

To compare accuracy of the 4 flavour scheme and the 5 flavour scheme on Higgs production process associated with b-quark pairs at lower order, we generate $pp \to h + n$ jets process with the 4 flavour (LO: $pp \to hb\bar{b} + 0$ jet) and the 5 flavour (LO: $pp \to h + 0$ jet, using b mass zero approxmation) scheme on MadGraph 5 with energy scale 7 GeV, factorization scale and renormalization scale is mass of Higgs (120 GeV in our setting), $p_T(\mathrm{jet}) > 20$ GeV, consider $h \to \tau^+\tau^-$ decay mode, including parton level results and matching results. We consider LO plus 1 jet for the 4 flavour scheme and LO plus 3 jets for the 5 flavour scheme. There are different kinds of parton shower procedures, we use p_T-order parton shower. We use b-tagging technique to find b-hadron information in events and check that in most events there are two b-hadrons in final states, consistent with intuition. And then we

1. Compare the 4, 5 flavour schemes PL (parton level) results in MadGraph with MC@NLO's (a matrix element event generator with NLO considered [25]) PL LO results. We must confirm that PL results are similar for different simulations.

2. Compare the 4, 5 flavour schemes matched (parton shower part generated by PYTHIA [24]) results in MadGraph with MC@NLO results (which include parton shower by interfacing to HERWIG, a parton shower event generator [26]) [25]. We compare what's different between the 4, 5 flavour results in MadGraph and MC@NLO re-

sults, which are NLO (tree, gluon emission and loop diagram) processes with best accuracy.

Where MC@NLO uses $pp \to hb\bar{b}$ and $h \to \tau^+\tau^-$ decay mode in it's PL LO process.

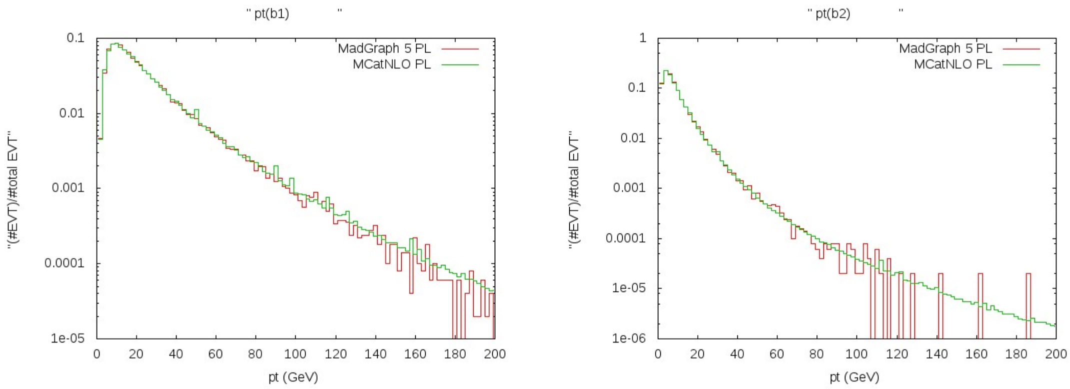
In the 4 flavour approximation, final state includes two b-quarks, and in the 5 flavour approximation, two initial particles may radiate partons. Mostly, an initial particle radiates one b-quark. Finding a b-hadron from string shows that there is a hard b-quark before hadronization. Therefore, we tag b-hadron in final state to confirm that in most events, there are two b-quarks in final state for the 4 flavour and the 5 flavour approximation. For tagging b-hadron, we change code hep2lhe.f under Pythia-PGS package which is used to transform events from StdHep (.hep) format to lhe format.

After generating processes on MadGraph 5, we mainly compare physical observables which are relevant to b-quark in PL and b-hadron in MC (Monte Carlo, in this place it means Monte Carlo simulation of matrix element + parton shower) level final state, and compare results in LO and NLO PDFsets (we use MSTW2008lo68cl_nf4, MSTW2008nlo68cl_nf4 for the 4 flavour process and MSTW2008lo68cl, MSTW2008nlo68cl for the 5 flavour process [27–29]). What is worth to mention is that: in MadGraph 5, whether to turn on matching algorithm has nothing to do with running of PYTHIA, in other words, we can turn off matching in MC level or turn on matching in PL. For not to confuse readers, if we do not mention, PL in MadGraph means PL with matching algorithm turn off, and MC level in MadGraph means MC level with matching turn on.

We normalize these spectra by generated event number and show in plots. We compare transverse momentum, pseudo rapidity, invariant mass, ΔR and $\Delta\phi$ spectra of b-hadron for study.

3.2 Parton level comparison

As we talked in the previous section, we first check whether two ME event generators get the same prediction on PL LO b-quark spectra. We compare PL results of $Hb\bar{b}$ + 0 jet in MadGraph with PL LO results in MC@NLO, and PL result plots fit very well, which is what we expect (Fig. 3.1 to Fig. 3.5).



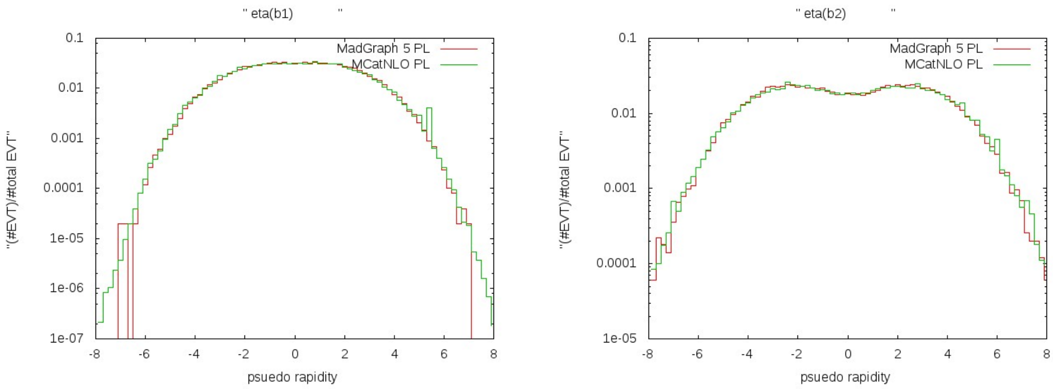
(a) plot of $p_T(b1)$ (b) plot of $p_T(b2)$

Figure 3.1: Histogram to compare p_T of b-quark of PL LO result of $Hb\bar{b}$ + 0 jet by the 4 flavour scheme on MadGraph 5 and by MC@NLO, red is by MadGraph 5, green is by MC@NLO result.

3.3 The influence of jet number and PDF

We also study the influence of considering different jet number in process and impact of using parton density functions fitted by LO or NLO Feynman diagrams at MC level in MadGraph. We get the same conclusion on studying of the 4 favour scheme and the 5 flavour scheme: using parton distribution functions fitted by LO or NLO Feynman diagram does not affect result too much, and taking account of different jet number in our process does not affect result, either (Fig. 3.6 to Fig. 3.10 for plots of the 4 flavour scheme and Fig. 3.11 to Fig. 3.15 for plots of the 5 flavour scheme).

Intuitely, hard jets can boost b-hadron (b-quark) in transverse direction, so we expect that with more hard jets in configuration, we observe harder b-spectra. But we do not observe the phenomenon in MC LO of the 4, 5 flavour schemes. This is because in MC level, the configuration of two processes are more similar after matching events of matrix element to parton shower. For example, in PL of the 4 flavour process, $Hb\bar{b}$ + 0 jet have no jet in final state, so $Hb\bar{b}$ + 0,1 jet considers more configurations than $Hb\bar{b}$ + 0 jet. However, after matching to parton shower, n jets final state are considered in both processes, so effect of hard jets is not obvious in matching algorithm.



(a) $\eta(b1)$ (b) $\eta(b2)$

Figure 3.2: Histogram to compare pseudo rapidity of b-quark of PL LO result of $Hb\bar{b}$ + 0 jet by the 4 flavour scheme on MadGraph 5 and by MC@NLO, red is by MadGraph 5, green is by MC@NLO result.

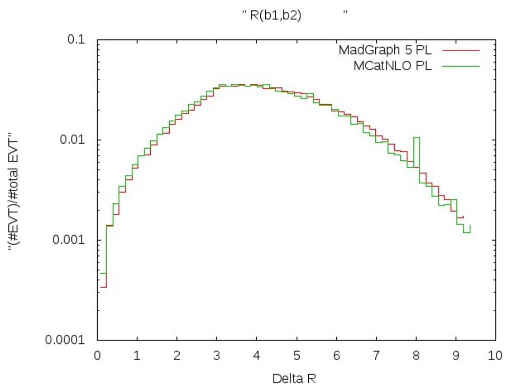


Figure 3.3: Histogram to compare $\Delta R(b1, b2)$ of PL LO result of $Hb\bar{b}$ + 0 jet by the 4 flavour scheme on MadGraph 5 and by MC@NLO, red is by MadGraph 5, green is by MC@NLO result.

3.4 Comparison of two schemes

Now we study b-hadron spectra of the two schemes by comparing their MC results with MC NLO calculation generated by MC@NLO. Since NLO calculation has higher accuracy, we expect a scheme with better description on inclusive Higgs production should have higher agreement with MC@NLO results. In general, the 4 flavour scheme results look more like MC NLO results of MC@NLO, illustrating that the 4 flavour scheme is more convergent to real solution than the 5 flavour approximation (Fig. 3.16 to Fig. 3.20). In histogram of $p_T(b)$, MC NLO results of MC@NLO are obviously different to results of the 4 flavour and the 5 flavour schemes (Fig. 3.16). And in histogram of pseudo rapid-

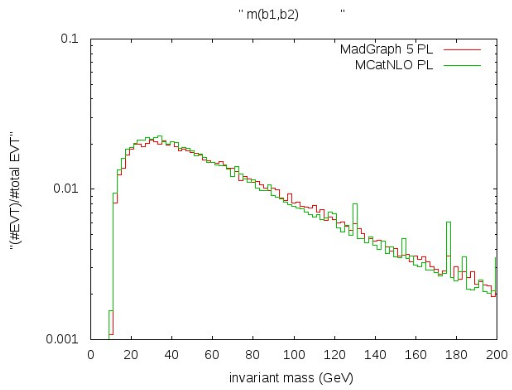


Figure 3.4: Histogram to compare two b-quarks invariant mass, $m(b1, b2)$, of PL LO result of $Hb\bar{b}$ + 0 jet by the 4 flavour scheme on MadGraph 5 and by MC@NLO, red is by MadGraph 5, green is by MC@NLO result.

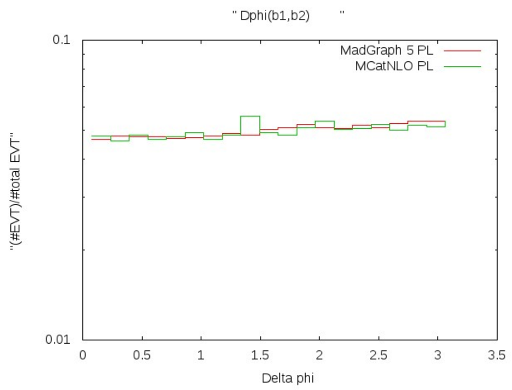
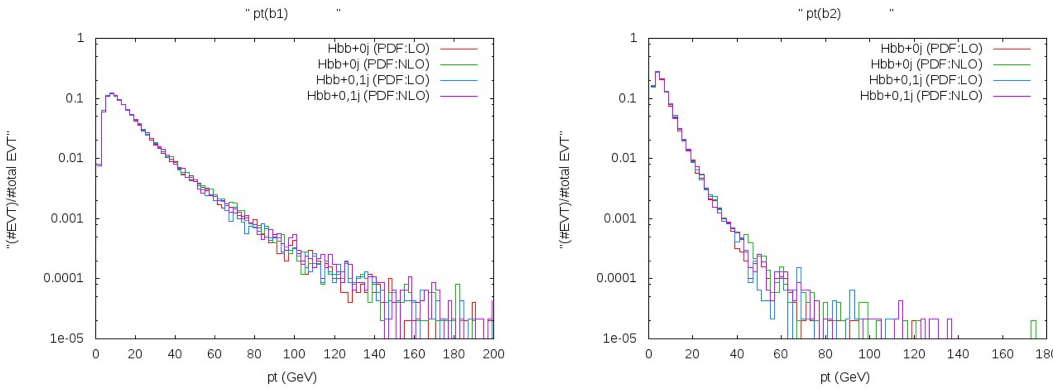


Figure 3.5: Histogram to compare two b-quarks $\Delta\phi$ of PL LO result of $Hb\bar{b}$ + 0 jet by the 4 flavour scheme on MadGraph 5 and by MC@NLO, red is by MadGraph 5, green is by MC@NLO result.

ity of b-hadron, we find results of the 4 flavour scheme and which of MC@NLO fit very well (Fig. 3.17). In $\Delta R(b1, b2)$, curve of the 4 flavour scheme is very close to which of MC@NLO (Fig. 3.18). In invariant mass spectrum of first two b-hadrons, an interesting result is that the 4 flavour scheme results fit well to MC@NLO's results with only LO considered rather than NLO considered (Fig. 3.19), which shows that effects of some loop diagrams on invariant mass spectrum can not be ignored, so $m(b1, b2)$ spectrum in LO + n jets and in NLO are different. In $\Delta\phi(b1, b2)$ all results fit well except LO results of MC@NLO (Fig. 3.20).

More interesting problems arise from Fig. 3.16 to Fig. 3.20: the first problem is what's the difference between the two schemes at LO + n jets that yields their different b-hadron spectra, and the second problem is that in Fig. 3.16 to Fig. 3.20, $Hb\bar{b}$ of MC LO



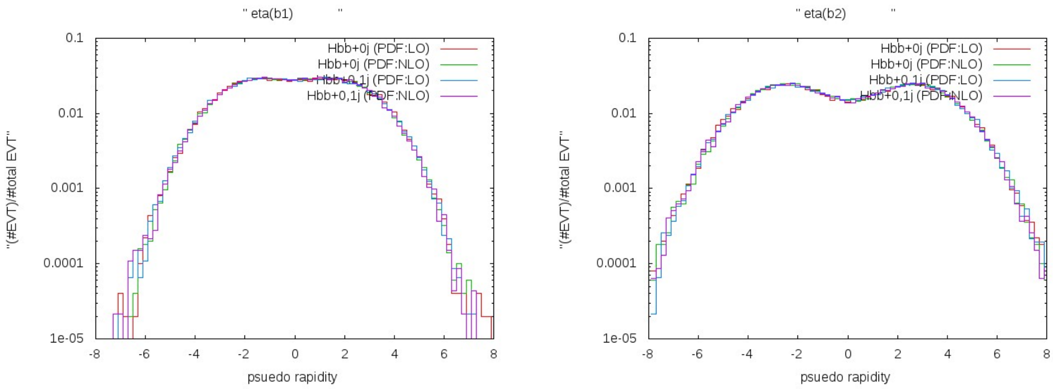
(a) plot of $p_T(b1)$ (b) plot of $p_T(b2)$

Figure 3.6: Histogram of p_T of b-hadrons for the 4 flavour scheme generated by MadGraph 5 with matching algorithm, normalized by total event number, red: LO, PDF using MSTW2008lo68cl_nf4, green: LO, PDF using MSTW2008nlo68cl_nf4, blue: LO + 0,1 jet, PDF using MSTW2008lo68cl_nf4, purple: LO + 0,1 jet, PDF using MSTW2008nlo68cl_nf4.

in MC@NLO and in MadGraph 5 both consider the configuration to $Hb\bar{b}$ + n jets, then why their results are so different?

About the first problem, we find that different results of the 4 flavour and the 5 flavour schemes mainly come from high pseudo rapidity of b-hadron (see Fig. 3.17). We show that many 4 flavour scheme and 5 flavour scheme plots look similar after cutting events with pseudo rapidity of the first and the second b-hadrons larger than 3 (in Fig. 3.21 to Fig. 3.25). We can see that b-hadron pseudo rapidity histogram of the 4, 5 flavour schemes different in high pseudo rapidity part, after cutting that part, b-hadron property of left events via two schemes is similar. We think this difference is due to some b-hadrons in the 5 flavour scheme actually come from parton shower. In the 5 flavour scheme, if in ME level $H + n$ jets final state, every parton is not b-quark, then b-hadrons come from initial parton shower, which results in larger number of high pseudo rapidity b-hadrons. We also compare the 4, 5 flavour schemes MC results in MadGraph with MC NLO results in MC@NLO, with cuts of soft and near beam-direction b-hadrons (Fig. 3.26 to Fig. 3.30), which show that after cutting events with soft and near beam-direction b-hadrons, b-hadron spectra from using matching algorithm at LO + n jets processes are similar to NLO results.

To study the second problem, we notice that MC@NLO interface to HERWIG does



(a) $\eta(b1)$ (b) $\eta(b2)$

Figure 3.7: Histogram of pseudo rapidity of b-hadrons for the 4 flavour scheme generated by MadGraph 5 with matching algorithm, normalized by total event number, red: LO, PDF using MSTW2008lo68cl_nf4, green: LO, PDF using MSTW2008nlo68cl_nf4, blue: LO + 0,1 jet, PDF using MSTW2008lo68cl_nf4, purple: LO + 0,1 jet, PDF using MSTW2008nlo68cl_nf4.

not reweight coupling constants and parton distribution functions as MadGraph does. We want to check whether the difference comes from the reweighting of matching algorithm. So we compare:

1. PL results of the 4 flavour scheme with matching & with no matching algorithm by MadGraph to PL LO results by MC@NLO.

2. MC results of the 4 flavour scheme with matching & with no matching algorithm by MadGraph to MC LO results by MC@NLO.

As shown in Fig. 3.31 and Fig. 3.32 in PL and MC level, if we turn off matching algorithm, b-hadron (or b-quark) p_T spectra of MadGraph become harder and fix well with b-hadron (or b-quark) p_T spectra of MC@NLO, both for MC LO and for PL LO. This is because, when we turn on the matching algorithm in MadGraph, we turn on the reweighting of coupling constants and PDFs at the same time, which increases the probability of radiating low p_T particles via higher strong coupling at low energy scale. However, even if we turn off matching algorithm in MC LO level, other b-hadron spectra in MadGraph such as pseudo rapidity are not similar to MC LO results of MC@NLO (in Fig. 3.33 and Fig. 3.34). So we can conclude that the difference of b-hadron p_T spectra of MC LO in MadGraph and in MC@NLO are dominated by effect of reweighting, and cause of differ-

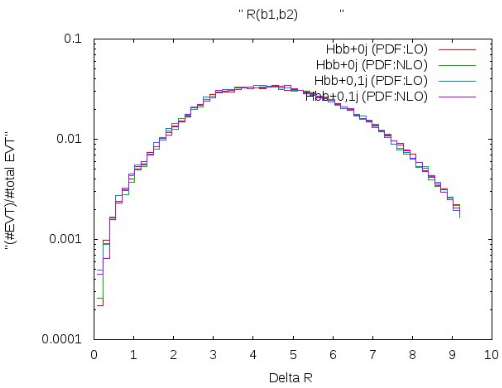


Figure 3.8: Histogram of $\Delta R(b1, b2)$ for the 4 flavour scheme generated by MadGraph 5 with matching algorithm, normalized by total event number, red: LO, PDF using MSTW2008lo68cl_nf4, green: LO, PDF using MSTW2008nlo68cl_nf4, blue: LO + 0,1 jet, PDF using MSTW2008lo68cl_nf4, purple: LO + 0,1 jet, PDF using MSTW2008nlo68cl_nf4.

ence of pseudo rapidity and ΔR b-hadron spectrum (in Fig. 3.33 and Fig. 3.34) is perhaps that PYTHIA and HERWIG use different way to generate parton shower (PYTHIA: p_T order parton shower, HERWIG: angular order parton shower).

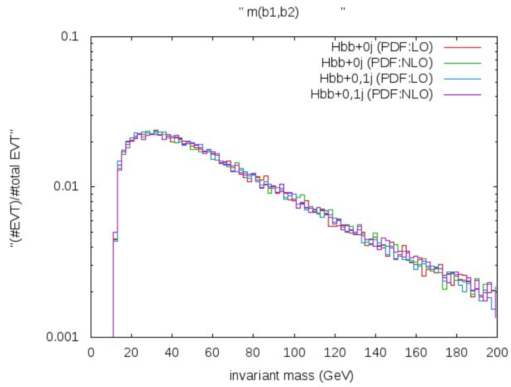


Figure 3.9: Histogram of invariant mass of two b-hadrons, $m(b1, b2)$, for the 4 flavour scheme generated by MadGraph 5 with matching algorithm, normalized by total event number, red: LO, PDF using MSTW2008lo68cl_nf4, green: LO, PDF using MSTW2008nlo68cl_nf4, blue: LO + 0,1 jet, PDF using MSTW2008lo68cl_nf4, purple: LO + 0,1 jet, PDF using MSTW2008nlo68cl_nf4.

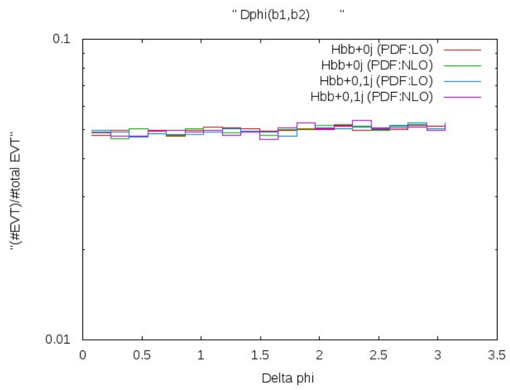
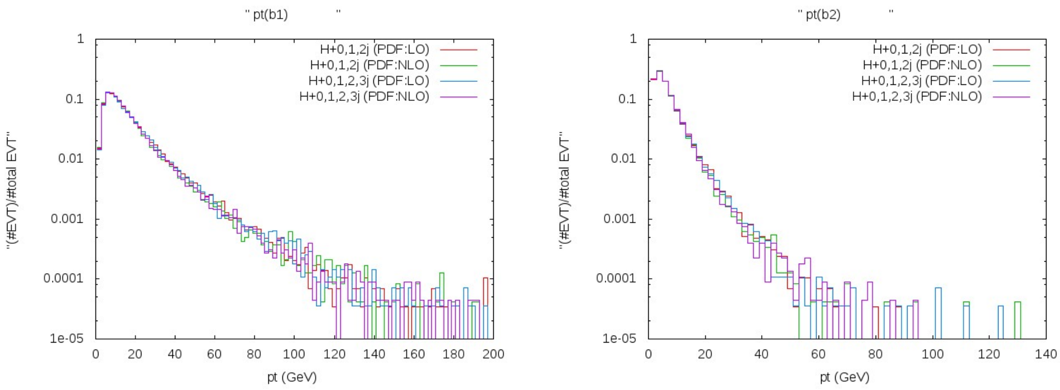
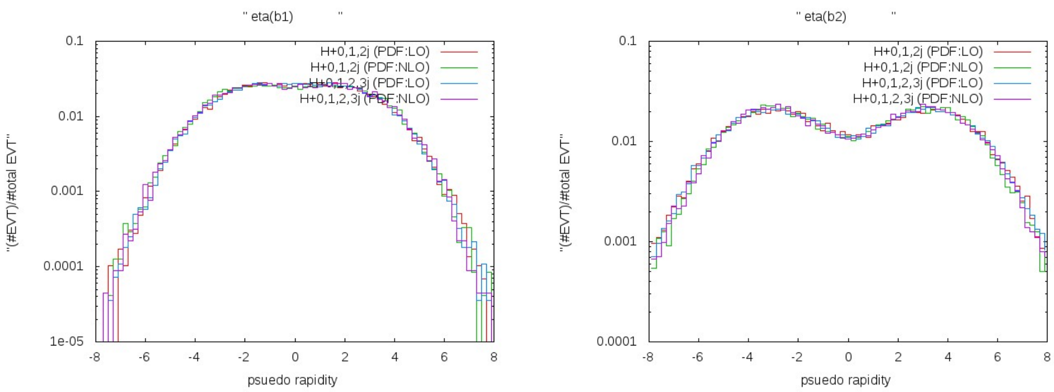


Figure 3.10: Histogram of $\Delta\phi$ of two b-hadrons, Dphi(b1,b2), for the 4 flavour scheme generated by MadGraph 5 with matching algorithm, normalized by total event number, red: LO, PDF using MSTW2008lo68cl_nf4, green: LO, PDF using MSTW2008nlo68cl_nf4, blue: LO + 0,1 jet, PDF using MSTW2008lo68cl_nf4, purple: LO + 0,1 jet, PDF using MSTW2008nlo68cl_nf4.



(a) plot of $p_T(b1)$ (b) plot of $p_T(b2)$

Figure 3.11: Histogram of p_T of b-hadrons for the 5 flavour scheme generated by MadGraph 5 with matching algorithm, normalized by total event number, red: LO, PDF using MSTW2008lo68cl, green: LO, PDF using MSTW2008nlo68cl, blue: LO + 0,1 jet, PDF using MSTW2008lo68cl, purple: LO + 0,1 jet, PDF using MSTW2008nlo68cl.



(a) $\eta(b1)$ (b) $\eta(b2)$

Figure 3.12: Histogram of pseudo rapidity of b-hadrons for the 5 flavour scheme generated by MadGraph 5 with matching algorithm, normalized by total event number, red: LO, PDF using MSTW2008lo68cl, green: LO, PDF using MSTW2008nlo68cl, blue: LO + 0,1 jet, PDF using MSTW2008lo68cl, purple: LO + 0,1 jet, PDF using MSTW2008nlo68cl.

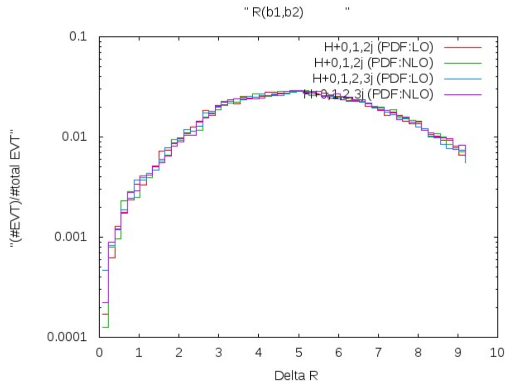


Figure 3.13: Histogram of $\Delta R(b1, b2)$ for the 5 flavour scheme generated by MadGraph 5 with matching algorithm, normalized by total event number, red: LO, PDF using MSTW2008lo68cl_nf4, green: LO, PDF using MSTW2008nlo68cl_nf4, blue: LO + 0,1 jet, PDF using MSTW2008lo68cl_nf4, purple: LO + 0,1 jet, PDF using MSTW2008nlo68cl_nf4.

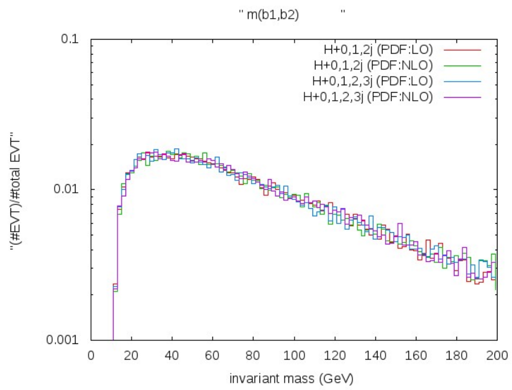


Figure 3.14: Histogram of invariant mass of two b-hadrons, $m(b1, b2)$, for the 5 flavour scheme generated by MadGraph 5 with matching algorithm, normalized by total event number, red: LO, PDF using MSTW2008lo68cl, green: LO, PDF using MSTW2008nlo68cl, blue: LO + 0,1 jet, PDF using MSTW2008lo68cl, purple: LO + 0,1 jet, PDF using MSTW2008nlo68cl.

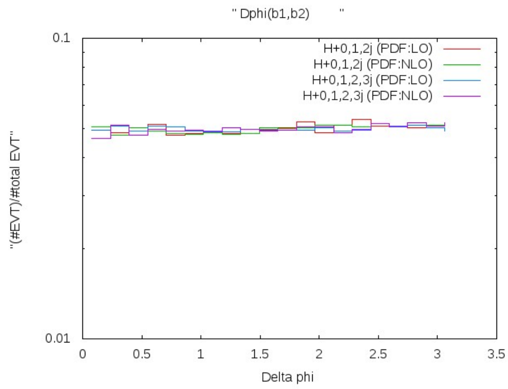
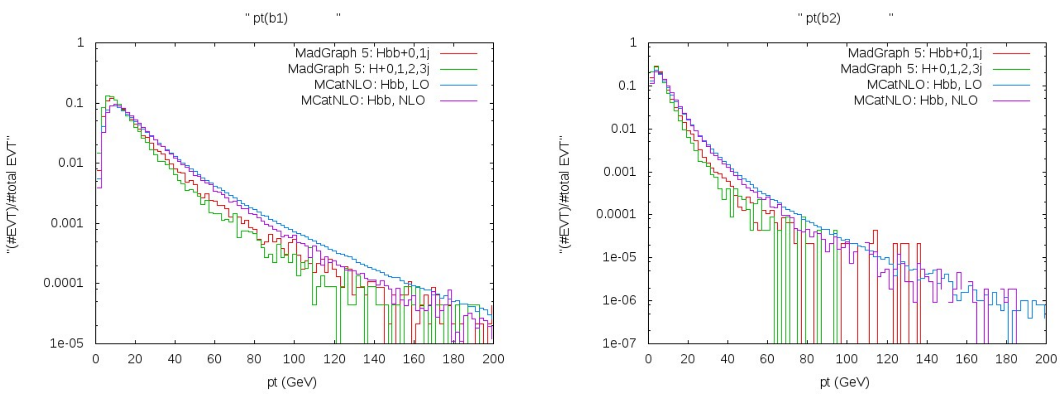
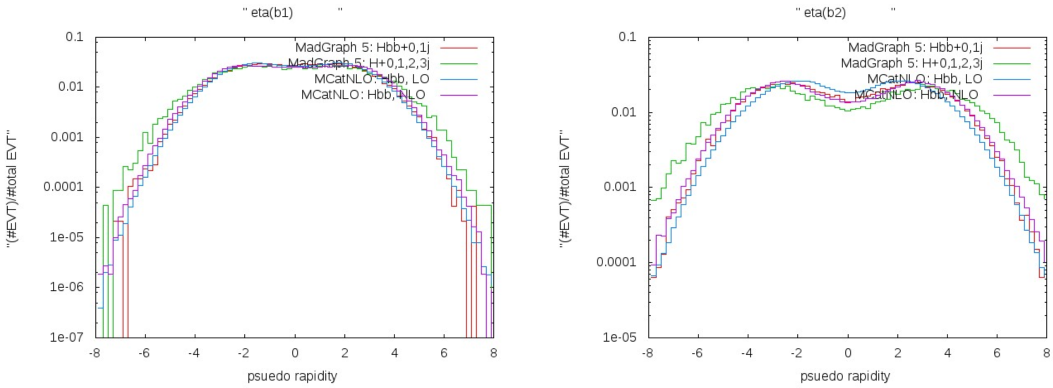


Figure 3.15: Histogram of $\Delta\phi$ of two b-hadrons, Dphi(b1,b2), for the 5 flavour scheme generated by MadGraph 5 with matching algorithm, normalized by total event number, red: LO, PDF using MSTW2008lo68cl, green: LO, PDF using MSTW2008nlo68cl, blue: LO + 0,1 jet, PDF using MSTW2008lo68cl, purple: LO + 0,1 jet, PDF using MSTW2008nlo68cl.



(a) plot of $p_T(b1)$ (b) plot of $p_T(b2)$

Figure 3.16: Histogram of p_T of b-hadron by the 4 flavour scheme, the 5 flavour scheme by MadGraph 5 with matching algorithm and by MC@NLO MC LO $\&$ MC NLO, red is the 4 flavour scheme, PDF using MSTW2008nlo68cl_nf4, LO + 0,1 jet, green is the 5 flavour scheme, PDF using MSTW2008nlo68cl, LO + 0,1 jet, blue is by MC@NLO MC LO, purple is by MC@NLO MC NLO.



(a) $\eta(b1)$ (b) $\eta(b2)$

Figure 3.17: Histogram of pseudo rapidity of b-hadron by the 4 flavour scheme, the 5 flavour scheme by MadGraph 5 with matching algorithm and by MC@NLO MC LO $\&$ MC NLO, red is the 4 flavour scheme, PDF using MSTW2008nlo68cl_nf4, LO + 0,1 jet, green is the 5 flavour scheme, PDF using MSTW2008nlo68cl, LO + 0,1 jet, blue is by MC@NLO MC LO, purple is by MC@NLO MC NLO.

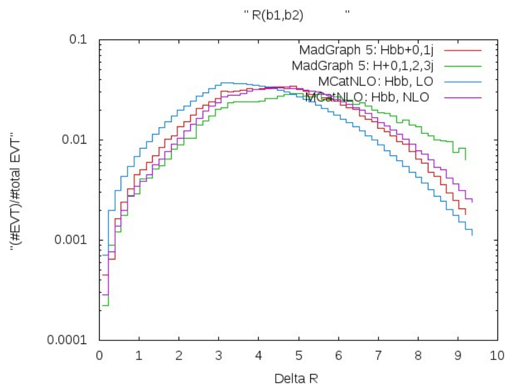


Figure 3.18: Histogram of $\Delta R(b1, b2)$ by the 4 flavour scheme, the 5 flavour scheme by MadGraph 5 with matching algorithm and by MC@NLO MC LO $\&$ MC NLO, red is the 4 flavour scheme, PDF using MSTW2008nlo68cl_nf4, LO + 0,1 jet, green is the 5 flavour scheme, PDF using MSTW2008nlo68cl, LO + 0,1 jet, blue is by MC@NLO MC LO, purple is by MC@NLO MC NLO.

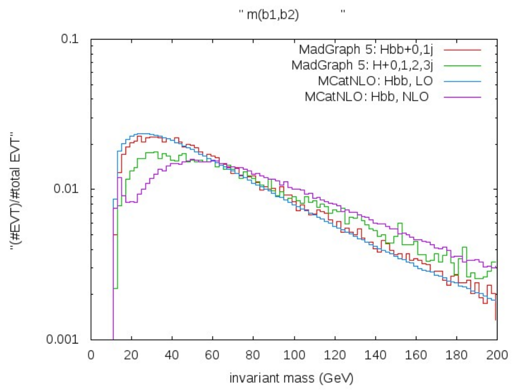


Figure 3.19: Histogram of invariant mass, $m(b1, b2)$, by the 4 flavour scheme, the 5 flavour scheme by MadGraph 5 with matching algorithm and by MC@NLO MC LO & MC NLO, red is the 4 flavour scheme, PDF using MSTW2008nlo68cl_nf4, LO + 0,1 jet, green is the 5 flavour scheme, PDF using MSTW2008nlo68cl, LO + 0,1 jet, blue is by MC@NLO MC LO, purple is by MC@NLO MC NLO.

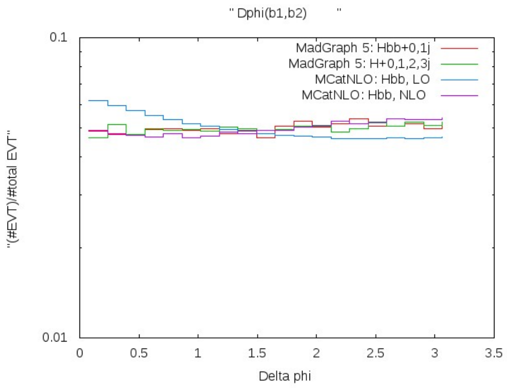
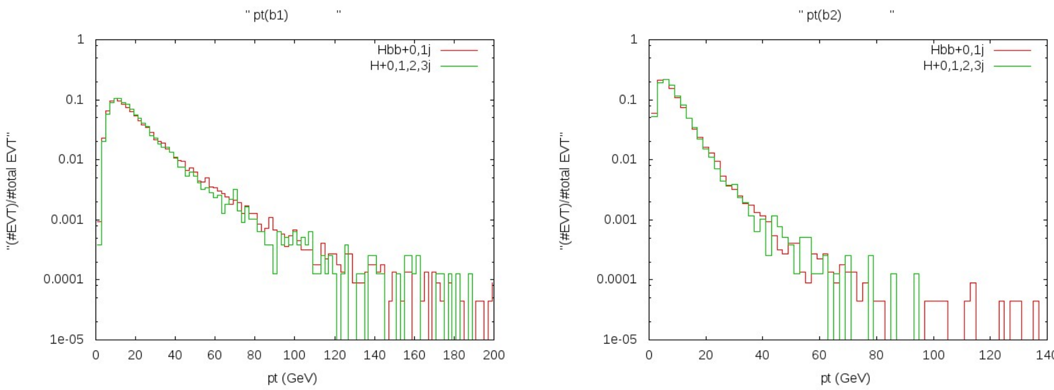
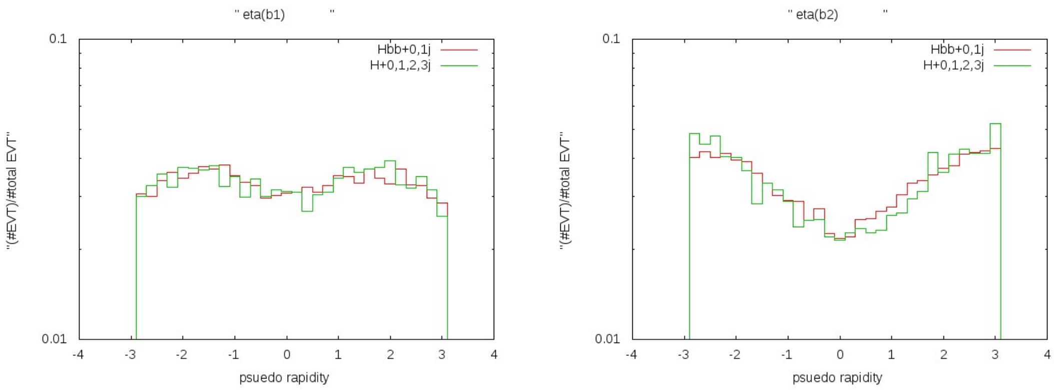


Figure 3.20: Histogram of $\Delta\phi$ of two b-hadrons, Dphi(b1,b2), by the 4 flavour scheme, the 5 flavour scheme by MadGraph 5 with matching algorithm and by MC@NLO MC LO & MC NLO, red is the 4 flavour scheme, PDF using MSTW2008nlo68cl_nf4, LO + 0,1 jet, green is the 5 flavour scheme, PDF using MSTW2008nlo68cl, LO + 0,1 jet, blue is by MC@NLO MC LO, purple is by MC@NLO MC NLO.



(a) plot of $p_T(b1)$ (b) plot of $p_T(b2)$

Figure 3.21: Histogram of comparing p_T of b-hadron of the 4, 5 flavour schemes by MadGraph 5 with matching algorithm, cutting $|\eta(b1)| > 3$ and $|\eta(b2)| > 3$ events, red is the 4 flavour result, green is the 5 flavour result.



(a) plot of $\eta(b1)$ (b) plot of $\eta(b2)$

Figure 3.22: Histogram of comparing pseudo rapidity of b-hadron of the 4, 5 flavour schemes by MadGraph 5 with matching algorithm, cutting $|\eta(b1)| > 3$ and $|\eta(b2)| > 3$ events, red is the 4 flavour result, green is the 5 flavour result.

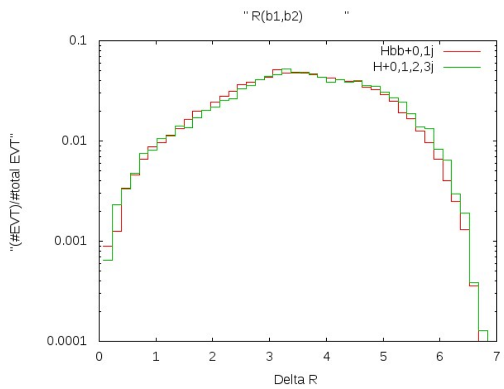


Figure 3.23: Histogram of $\Delta R(b1, b2)$ by the 4, 5 flavour schemes by MadGraph 5 with matching algorithm, cutting $|\eta(b1)| > 3$ and $|\eta(b2)| > 3$ events, red is the 4 flavour result, green is the 5 flavour result.

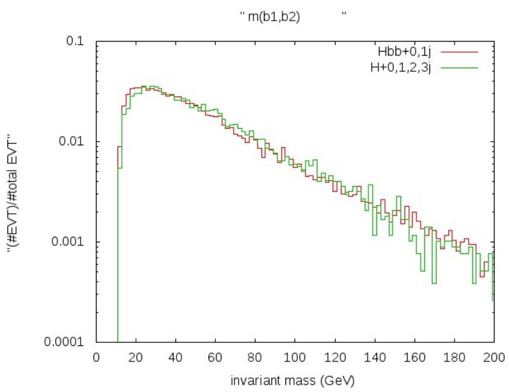


Figure 3.24: Histogram of invariant mass, $m(b1, b2)$, by the 4, 5 flavour schemes by MadGraph 5 with matching algorithm, cutting $|\eta(b1)| > 3$ and $|\eta(b2)| > 3$ events, red is the 4 flavour result, green is the 5 flavour result.

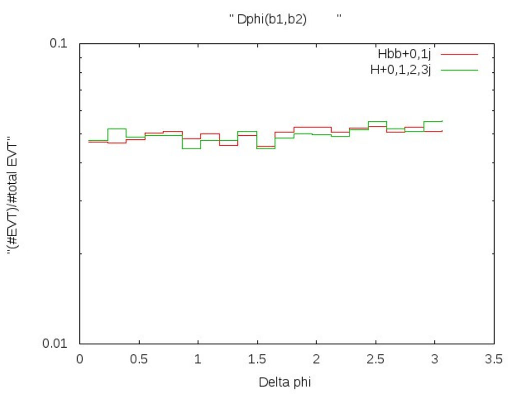
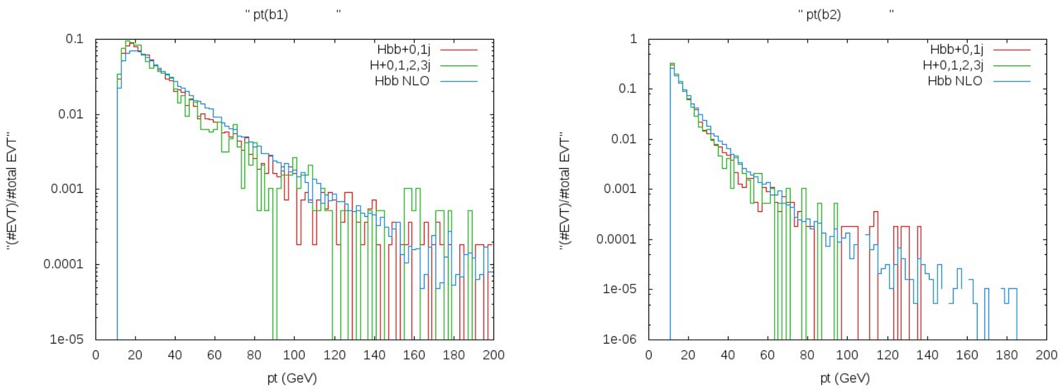
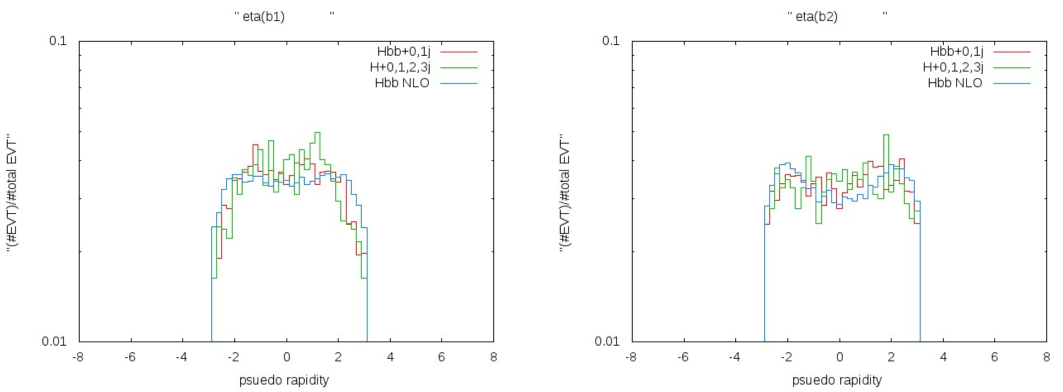


Figure 3.25: Histogram of $\Delta\phi$ of two b-hadrons, Dphi(b1,b2), by the 4, 5 flavour schemes by MadGraph 5 with matching algorithm, cutting $|\eta(b1)| > 3$ and $|\eta(b2)| > 3$ events, red is the 4 flavour result, green is the 5 flavour result.



(a) plot of $p_T(b1)$ (b) plot of $p_T(b2)$

Figure 3.26: Histogram of comparing p_T of b-hadron of the 4, 5 flavour schemes by MadGraph 5 with matching algorithm to MC NLO result by MC@NLO, cutting $|\eta(b1)| > 3$, $|\eta(b2)| > 3$, $p_T(b1) < 10$ GeV and $p_T(b2) < 10$ GeV events, red is the 4 flavour result, green is the 5 flavour result, blue is MC NLO result by MC@NLO.



(a) plot of $\eta(b1)$ (b) plot of $\eta(b2)$

Figure 3.27: Histogram of comparing pseudo rapidity of b-hadron of the 4, 5 flavour schemes by MadGraph 5 with matching algorithm to MC NLO result by MC@NLO, cutting $|\eta(b1)| > 3$, $|\eta(b2)| > 3$, $p_T(b1) < 10$ GeV and $p_T(b2) < 10$ GeV events, red is the 4 flavour result, green is the 5 flavour result, blue is MC NLO result by MC@NLO.

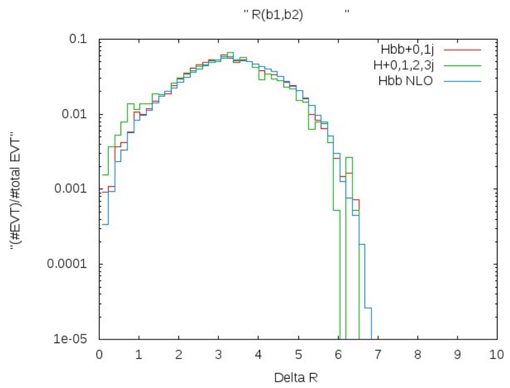


Figure 3.28: Histogram of $\Delta R(b1, b2)$ by the 4, 5 flavour schemes by MadGraph 5 with matching algorithm to MC NLO result by MC@NLO, cutting $|\eta(b1)| > 3$, $|\eta(b2)| > 3$, $p_T(b1) < 10$ GeV and $p_T(b2) < 10$ GeV events, red is the 4 flavour result, green is the 5 flavour result, blue is MC NLO result by MC@NLO.

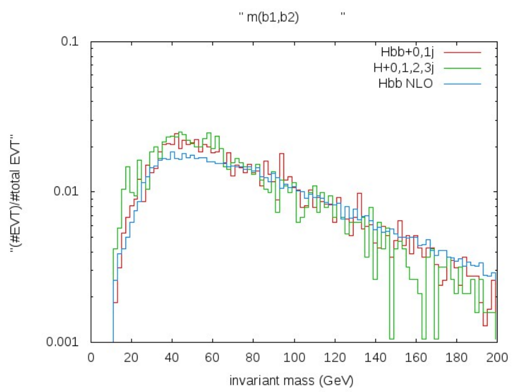


Figure 3.29: Histogram of invariant mass, $m(b1, b2)$, by the 4, 5 flavour scheme by MadGraph 5 with matching algorithm to MC NLO result by MC@NLO, cutting $|\eta(b1)| > 3$, $|\eta(b2)| > 3$, $p_T(b1) < 10$ GeV and $p_T(b2) < 10$ GeV events, red is the 4 flavour result, green is the 5 flavour result, blue is MC NLO result by MC@NLO.

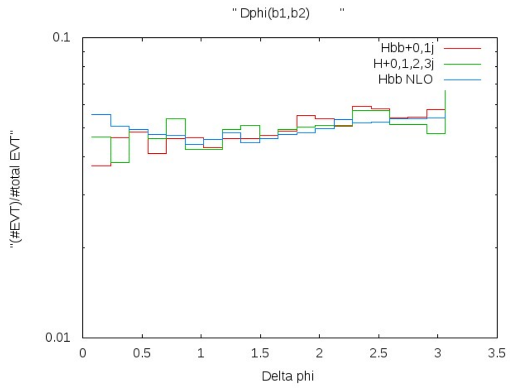
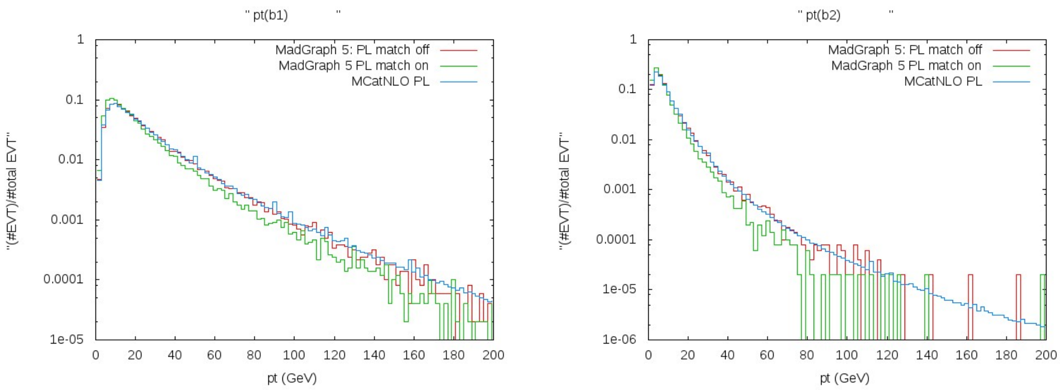


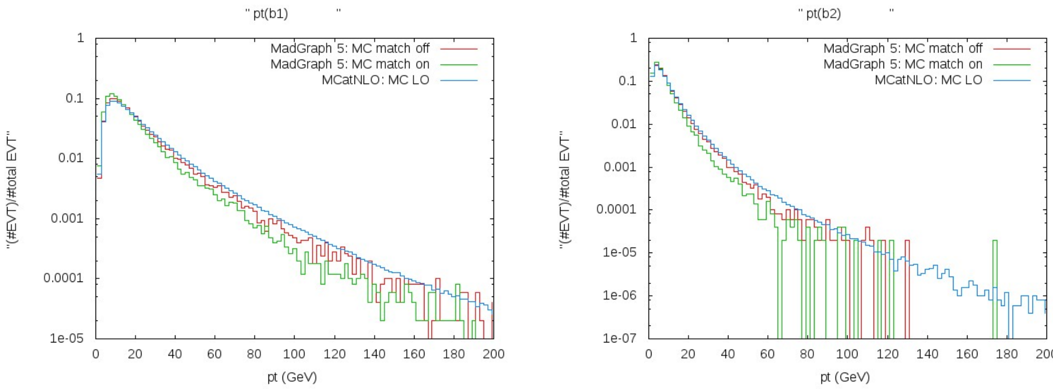
Figure 3.30: Histogram of $\Delta\phi$ of two b-hadrons, Dphi(b1,b2), by the 4, 5 flavour schemes by MadGraph 5 with matching algorithm to MC NLO result by MC@NLO, cutting $|\eta(b1)| > 3$, $|\eta(b2)| > 3$, $p_T(b1) < 10$ GeV and $p_T(b2) < 10$ GeV events, red is the 4 flavour result, green is by the 5 flavour result, blue is MC NLO result by MC@NLO.



(a) plot of $p_T(b1)$

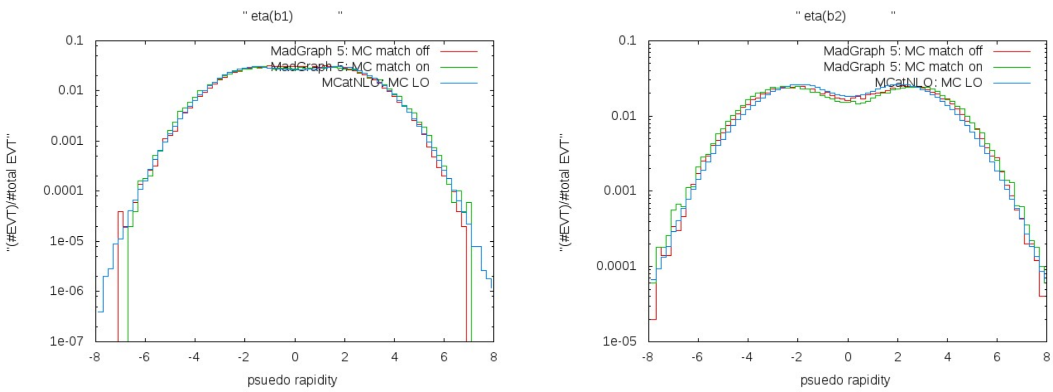
(b) plot of $p_T(b2)$

Figure 3.31: Histogram of comparing p_T of b-quark of the 4 flavour scheme ($Hb\bar{b}$) PL LO by MadGraph 5 with p_T of b-quark by PL LO of MC@NLO, red is the PL in MadGraph with matching turn off, green is the PL in MadGraph with matching turn on, blue is PL LO of MC@NLO.



(a) plot of $p_T(b1)$ (b) plot of $p_T(b2)$

Figure 3.32: Histogram of comparing p_T of b-hadron of the 4 flavour scheme ($Hb\bar{b}$) MC LO level by MadGraph 5 with p_T of b-hadron by LO of MC@NLO, red is the MC in MadGraph with matching turn off, green is the MC in MadGraph with matching turn on, blue is MC LO of MC@NLO.



(a) plot of $\eta(b1)$ (b) plot of $\eta(b2)$

Figure 3.33: Histogram of pseudo rapidity of b-hadron of the 4 flavour scheme ($Hb\bar{b}$) MC LO by MadGraph 5 with pseudo rapidity of b-hadron by MC LO of MC@NLO, red is the MC in MadGraph with matching turn off, green is the MC in MadGraph with matching turn on, blue is MC LO of MC@NLO.

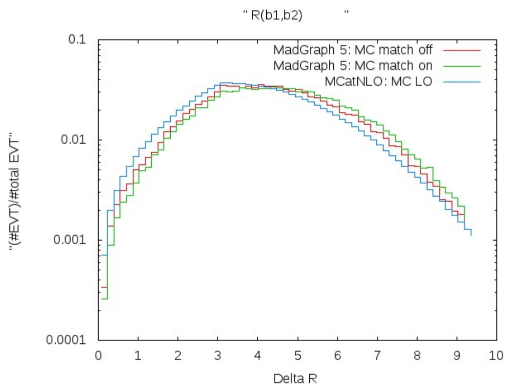


Figure 3.34: Histogram of comparing $\Delta R(b1, b2)$ of b-hadron of the 4 flavour scheme ($Hb\bar{b}$) MC LO by MadGraph 5 with $\Delta R(b1, b2)$ of b-hadron by MC LO of MC@NLO, red is the MC in MadGraph with matching turn off, green is the MC in MadGraph with matching turn on, blue is MC LO of MC@NLO.

Chapter 4

Conclusion

In conclusion, we merge parton shower approach and matrix element method by interfacing MadGraph 5 to PYTHIA 6 [24] to study the comparison of the two schemes describing inclusive Higgs production associated with heavy quark (bottom quark) pairs and find that the 4 flavour scheme behaves better than the 5 flavour scheme, since spectra of b-hadron in LO + n jets of the 4 flavour scheme is closer to MC@NLO result (including loop level and radiation level) than those of the 5 flavour scheme. Besides, we find the difference between two schemes is mainly on number of small angle (near the beam direction) b-hadrons. Thanks to parton shower, there are more b-hadrons near the beam direction in the 5 flavour scheme than in the 4 flavour scheme in inclusive $Hb\bar{b}$ production process. Our result improves our realization of the 4, 5 flavour schemes on Higgs production process and may help the search for some Beyond the Standard Models (BSMs) that couple strongly to the Higgs boson.

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