Scale Choices in Electroweak Higgs plus Jets Production

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Abstract

In this work we investigate the dependence of the electroweak Higgs plus jet production on the scale choice. Different methods of choosing a scale will be compared and also the effect of the renormalization and factorization scale separately. To improve the scale choice a MINLO-type alogrithm was implemented in the Herwig++ Monte Carlo generator and the result of these computations were compared to the standard approach.

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1 Introduction

The next uprade of the LHC will increase the center of mass energy to 14 TeV. One goal is to investigate the properties of the Higgs-like particle which has been found at an energy around 125 GeV. In the standard model there some possible production channels for the Higgs boson. One possible channel is the vector boson fusion (VBF). This kind of process is represented by the Feynman diagram shown in figure (1). This is in third order of the electroweak coupling and in this case 2 jets in the final state besides the Higgs-particle. One special feature of these process is that we need to choose all lot scales for the event simulation. And because of that the LO calculations have a large dependence. Because of the higher Luminosity in the future LHC, we get better measurements and so we need to improve the theoretical predictions. The matrixelements for the α^3 Higgs plus 2,3 and 4 jet production has been calculated up to NLO [CFPS13]. Which have a strong dependence of the phase space. In this work we investigate the scale dependence at least for LO and want to use a MINLO-type algorithm [HNZ12] to improve scale choices. We will use the Monte Carlo generator Herwig++ [BGG+08] to produce the the Monte Carlo events and also implement the MINLO-type algorithm for Herwig++.

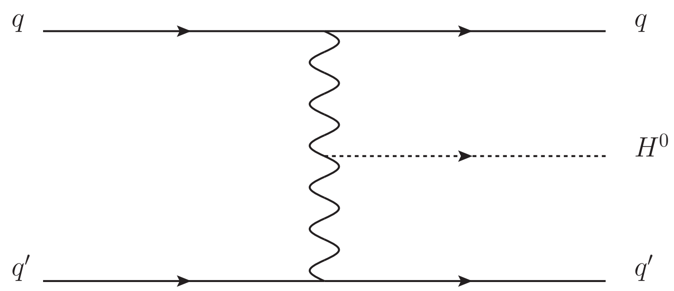


Figure 1: Vector Boson Fusion plus 2 Jets

To study the production of the Higgs-boson in VBF, we concentrate on underlying processes with a Higgs and two, three or four partons in the final state in leading order in perturbation theory. In order to have a cleaner view on these underlying processes, we switch off some parts of the Monte Carlo simulation. First of all there is no parton shower simulation and hadronization and so the final state partons were identified as jets. Also there is no multiple parton interaction and the Higgs is treated as a stable particle.

2 Higgs plus jet production

For Higgs plus 2 two jets there are two kinds of diagrams. In addition to the mentioned VBF diagram in figure (1), there are contribution to the full $O(\alpha^3)$ calculations by quark antiquark annihilation to a Z boson which radiate a Higgs and then decays in a quark pair. This s-channel diagram is viewed in figure (2). Both kind of diagrams are also possible with a W^+ and or W^-.

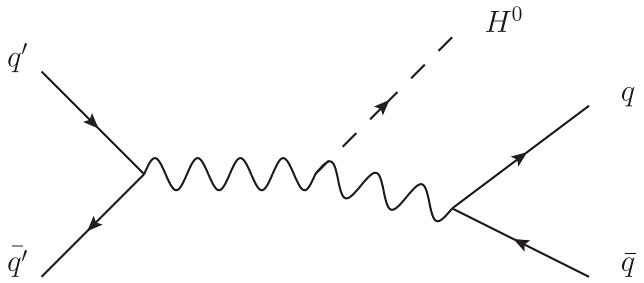
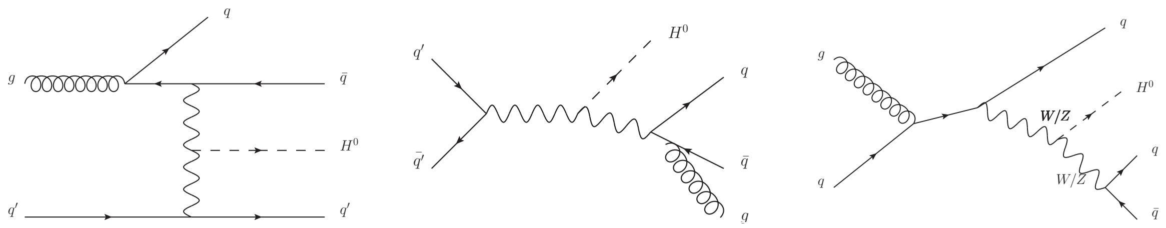


Figure 2: Higgs-Strahlung plus 2 Jets

For the case of 3 jets there are a some contributions of the Higgs plus 2 jets diagrams with a additional radiation of gluon in the final or initial state (see figure (3(b))). For Higgs plus 2 jets there are no gluons in initial state, but with three jets this is possible because of a gluon splitting in a quark pair. One of this quarks will take place in the hard subprocess and the other will be radiated and form a jet, like in figure (3(a)). Another contribution are diagrams with a s-channel quark which radiate a Z or W boson which then radiate a Higgs and decay in quarks like in figure 3(c). But the contribution is very small due to the large virtuality of the s-channel quark.



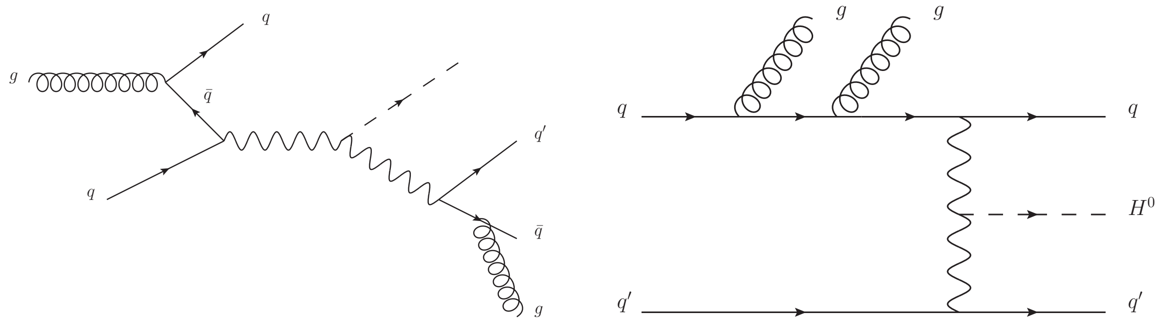
(a) Initialstate radiation (b) Finalstate radiation (c) s-channel quark

Figure 3: Feynman diagrams for Higgs plus 3 Jets production.

The processes of Higgs and four jets are represented by a large number of diagrams. Of course there a lot contributions of the already mentioned diagrams with one more radiated gluon, but there are a lot of other possibilities to get a final state with four partons and one Higgs. A few chosen examples are in figure 4.

3 Scales and Scale Choices

To calculate this processes we need to get the initial state parton from the parton-distribution-function. Therefore we have to choose an Energy scale called the factorization scale to evaluate them. This factorization scale have to choose in such a way that it correspond to the interaction energy of the partons. And in addition to that there are some strong-coupling constants in the matrixelements which also depend on the energyscale of the interaction. This scale is called the renormalization scale. There



(a) Example 1: s-channel (b) Example 2: t-channel

Figure 4: Feynman diagrams for Higgs plus 4 Jets production.

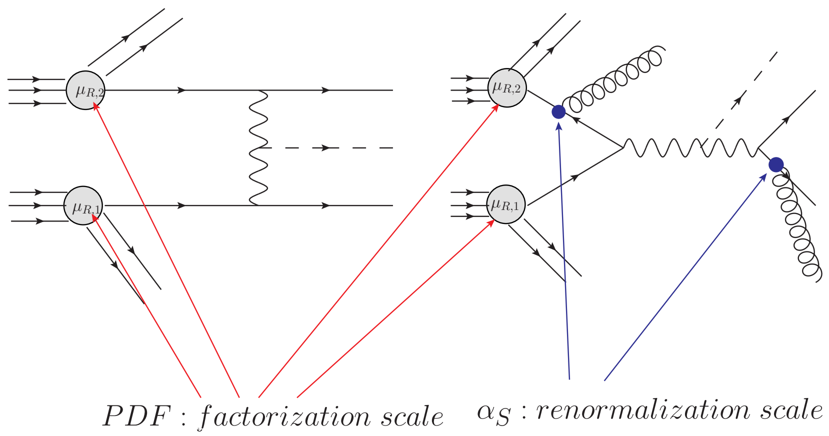


Figure 5: Appearing scales in elektroweak Higgs plus jets production.

is no easy and clear way of choosing this scales, because for each diagram you need a different scale choice due to the topology of the diagram to take the most appropriate. There are some standard approaches to choice the renormalization and factorization scale. Some of them choose the scale in a dynamic way for each generated event using the transverse momentum or the center-of-mass energy. Other approaches use some fixed predefined value of the scale for all events. For studying the scale dependence of the Higgs production in VBF we discuss four different scale choices, three dynamical ones and one fixed scale. In all cases is the value for both scales the same. We see the visualized dynamic scale choices in figure 6.

3.1 Fixed Scale

For the fixed scale choice we use the W-mass $m_W = 81.188$ GeV. This value is for the factorization scale quite intuitive for processes in the figure 1. But for Diagrams with a higher order in α_S like in figure 3(a) it will more difficult to justify this choice, because of the additional initial state radiation of the gluon will not necessary be around a energy of the W-mass. Therefore may this static choice here not appropriate. So we expect some issues with this choice in higher order diagrams.

3.2 MaxPt Scale

Another possible reasonable choice is the the highest jet transverse momentum. When we consider the initial state radiation of a gluon or the gloun splitting in a quark-pair and look on the scale for the strong coupling and the factorization scale, we may like to choose the transverse momentum of the radiated parton. This radiated parton will be most likely the jet with the highest p_T. So we get an appropriate choice for both scales in this case. But for the other parton it is not. It's factorization scale correspond more to the radiation of the vector boson then to the parton radiation.

3.3 SHatScale

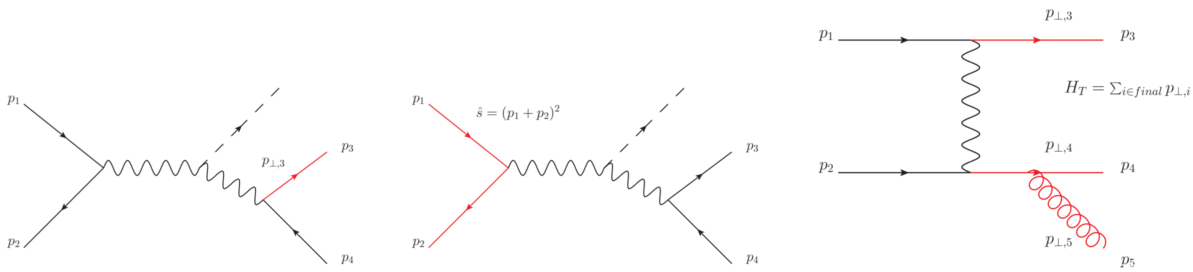
The t-channel diagrams interfere with some s-channel diagrams with the same particles in the final state. In the s-channel diagrams with no initial state radiation is center-of-mass energy the natural choice for the factorization scale. But this may not an appropriate choice for the strong coupling in eventually occurring final or initial state radiation.

3.4 HTScale

A slightly different option is the HT of an Event. The HT is defined as the sum over all transverse jet momenta.

$$H_T = \sum_{j \in (jets)} {p_j}_T^2 \tag{1}$$

This scale like the MaxPt-scale correspond to the energy of the strong interaction.



(a) MaxPt (b) SHat (c) HT

Figure 6: Different Scale Choices.

4 VBF and Higgs-Strahlung cuts

The VBF diagrams interfere with Higgs radiation processes. To study only the VBF process we need cuts which terminate the s-channel contributions but leaves the VBF contributions untouched. First get stick to Higgs plus 2 jets. A way to pick out the s-channel contribution is the invariant mass of the jet-pair. Both jets belong to the decay of the vector-boson and because of that their invariant mass should be around the bosons mass. For this s-channel cut we choose a window of 70 GeV to 110 GeV for the invariant mass of the two leading jets. To pick out the VBF or t-channel diagrams one can use that the two jets are in the opposite direction and have a large invariant mass. To pick up this t-channel diagram we require a invariant mass of the two jets above 600 GeV and that the jets have a rapidity difference greater than 4.

5 Scale dependence

Because it is not always clear which is the appropriate scale for a certain process we investigate the effects of choose one particular method of choose a scale on the result. First of all we compare some differential cross sections between the different mentioned methods of choosing a scale. And then we look for each scale (renormalization or factorization) at the dependence of the results on the scale by the variation of the scale factor. The scale factors are a dimensionless factor in front of the scale and usually set to 1. We repeat this for all methods mentioned above.

5.1 Scale choices

For the different final states Higgs plus 2,3 and 4 jets we compare different methods of figuring out the scale . For the inclusive process Higgs plus 2 jets are the distributions of the traverse momenta of the first and second jet for different cuts shown in figure 7. We use the fixed scale as a reference in all ratio plots. For the inclusive Higgs production in figure 7(a) and 7(b) we can see that all methods reproduce more or less the same, particular in the region of the peak are the result very equal. But for low p_T and very high p_T the differences grow. In figure 7(c) and 7(c) we had produced only events which will pass the s-channel cut. Now are in the region of the peak slightly higher differences as for the inclusive distributions and we can see that the sHat scale produce the highest cross-section. For the t-channel cut in figure 7(e) and 7(f) are the differences much more obvious. The sHat scale reproduce here a significant smaller cross-section than the other ones.

In figure 8 are the same plots for the Higgs plus 3 jets processes than for 2 jets with two exceptions, the s-channel cut reduce the statistics in such a way that we get large bin errors. Because of that a rebinning was necessary to increase the weights per bin. And the second difference is that we use here the HT scale as the reference for the ratios. For 3 jets is a additional scale choice for the renomalization necessary, so we can expect greater differences in the results. For the inclusive process is the p_T of the first and second leading jet in figure 8(a). Here the result depends much more on the method of choice than before. It is remarkable that the sHat scale produce the lowest cross-section and that the fixed scale produce a lot more high p_T jets than the other ones. This is quite reasonable because the strong coupling becomes weak at high energies. A high p_T jet will produced through a interaction at a high energy scale and because of that the dynamic scale choices will pick up a high energy scale which make α_S small. For the fixed scale the interaction energy doesn't matter. In the case of the t-channel cut in figures 8(c) and 8(d) we observe that that the Maxpt, HT and the fixed scale reproduce more or less the same and only the sHat scale method generates a lower cross-section but with same shape corresponding to the flat ratio plot.

5.2 Factorization Scale

For each scale choice and process type (Higgs plus n jets, with and without t- or s-channel cut) we investigate the effects of scaling up or down the factorization scale by a factor of 2. We use the untouched scale as the reference for the ratios always. Because there a lot of plots and results of this investigation there are only some examples which give a good insight.
For Higgs plus two jets is the effect very small for kind of scale choices. In figure 9 we can see the dependence in the inclusive case for the fixed and the H_T scale. For the t-channel cut is the result the same, only small deviations. In the case of the s-channel cut, shown in figure 10, we can see a little bit stronger influence of the variation. In some cases are the shapes more or less the same and the variation correspond to an offset for the hole distribution. But in some distributions like leading jet p_T we observe that the for a scale factor < 1 the differential cross section is smaller than the reference for small p_T but is higher for high p_T. For a scale factor > 1 we get the opposite behavior.
For the processes with higher jet multiplicities we can observe the same behavior. The influences increase slightly but there are no different effects on the shapes.

5.3 Renormalization Scale

To study the effects of the renomalization scale factor we do the same as for the factorization scale and used a factor of 0.5 and 2. The Higgs plus 2 jets processes doesn't have any factor of α_S so there is no effect from the renormalization scale. For Higgs plus 3 jets is again the p_T of the leading jet in figure 11 for the MaxPt and SHat scale choice. The variation of the scale doesn't effect the shape but generates an off-set. This behavior reflect the running of the strong coupling constant. The strength of the off-set variate for the different scale choices. The strongest effect was observed with the MaxPt scale and the smallest effect with the sHat-scale.
The Higgs plus 4 Jet events have an additional strong coupling. Because of that the dependence of the renormalization scale increases. In figure 12 is an example plot. If we compare it with the Higgs plus 3 Jet results we can see the increasing effect. In addition to that we can see a small shape variation due to the scaling of the renormalization scale.

6 MINLO-type algorithm

We saw that for inclusive processes it is not a priori clear which method of choosing a scale we want to use. Recall that for s-channel diagrams with Higgs radiation we would use the center of mass energy and for t-channel diagrams the momentum transfer of for each parton as the scale for the factorization scale. But in a inclusive Higgs with 2 jets process both kind of diagrams are included and we would need to choose one of this methods for each generated event. In higher order processes with more partons in the final state this issue even more complicated because of the renormalization scale for additional parton radiation. One option to handle this problems is the MINLO algorithm [HNZ12]. This algorithm choose the scales individual for each event using its structure. We doesn't use the full MINLO algorithm here and leave out the Sudakov form factors which take place in the MINLO. The algorithm figure out the an appropriate value for the scales and reweight the events accordingly with the help of the scale factors.

6.1 Concept of the MINLO-type algorithm

In order to describe the algorithm we refer the various steps to an example in figure 13. For an general event with n partons in the final state the algorithm searches for quark-antiquark pairs which came from a gluon-splitting or a quark-gluon pairs which inherits from a gluon radiation and for particles belong to a initial state radiation. In the first step the algorithm figures out which partons belong to a pair or the initial state using the Monte Carlo information of the particles which include mother-child relation. For each pair ij it calculates the quantity $d_{ij} = \min p_{Tj}^2, p_{Ti}^2 \cdot \frac{\Delta R_{ij}}{R}$, with a dimensionless parameter R. R refer to the cone size of the jets. For initial state radiated particles it calculates the transverse momentum. If there are more than one possible pair, the algorithm choose the pair which minimize value of d_{ij} and respectively $p_\perp^2$. In the second step this pair will be erased and the mother particle will be added to the final state, which now contains $n-1$ particles. The square root of d_{ij} will be the renormalization scale for the α_S belonging to the splitting. If the pair inherits from a initial state interaction the incoming and outgoing parton will be erased and the remaining daughter-particle will be added to the incoming partons. In this case the factorization scale will be also set to $p_\perp^2$. This will be repeated onetime per order in α_S, which correspond to step 3 in the example. When all renormalization scale has been chosen we get a Higgs plus 2 jets diagram. The last and forth step is to choose the remaining factorization scales dependent on the topology of the diagram. For the s-channel diagram it chooses the center of mass energy and for the t-channel diagram the momentum transfer.
One additional remark for the diagrams with an s-channel quark. For this special cases we cannot repeat the algorithm for all order α_S because the α_S in the gluon-quark fusion. For these Diagrams we stop the procedure after we reconstruct the s-channel quark diagram. And choose the gluon-quark center of mass energy as the factorization scale.

6.2 Comparison with other scale choices

Lets compare the results of the MINLO-type algorithm with other scale choices. In figure 14 are the different scale choice methods compared with the MINLO for the Higgs plus 2 jets case. The $\hat{s}$ scale have strong deviations from the MINLO-type algorithm but the HT and MaxPt scale reproduce more or less the same results with no large differences. The fixed scale deviate from the MINLO-type strongly in the high p_T regime. That the HT and MaxPt can reproduce the result is not very surprising. For Higgs plus 2 jets we only have to choose the factorization scale. The MINLO-type will choose s-channel processes the center of mass energy and for t-channel the momentum transfer which corresponds here directly to the p_T of the outgoing parton.
For Higgs plus 3 jets we expect much larger deviations between the choices because of the additional α_S. The distribution of the leading jet p_T is compared between the MINLO-type and standard scale choices in figure 15. The fixed scale produce a to low cross-section in the small p_T regime and a to high cross-section in the high p_T. This reasonable because low p_T can inherit from a low energy strong interaction where α_S is strong. This events will be reweighted by the MINLO-type algorithm with a higher value and high p_T jets with a small value. Here also deviate the MaxPt and HT scale choice from the MINLO and again have the SHat scale the largest differences.
Because of some computational problems there are no MINLO results for Higgs plus 4 jets jet. But one would expect even larger differences.

6.3 Scale variations

Like for the standard scale choices we variate the scale by a scaling factor of 2. The result are in figure 16 for Higgs plus 2 jets and in figure 17 for Higgs plus 3 jets. From this plots we can get the same conclusions as for the standard scale choices.

7 Summary

He have seen that the Higgs plus jet production in electroweak processes is very sensitive on the chosen scales. Standard scale choices give quite different results in the inclusive processes. To differentiate between the VBF and the Higgs-Strahlung we found cuts that can filter out the process type of interest. For the resuts after these cuts we again found scale dependencies. By variation of the scale we found that the effect of the factorization scale is quite low, but the renormalization scale have a large effect of the differential cross-section distributions. It have effect on the bin height as well as the shape of some distributions. To improve the scale choice the MINLO-type algorithm was implemented in Herwig++. And it was found that the MINLO-type algorithm has in some cases large difference to the standard scale choices.

References

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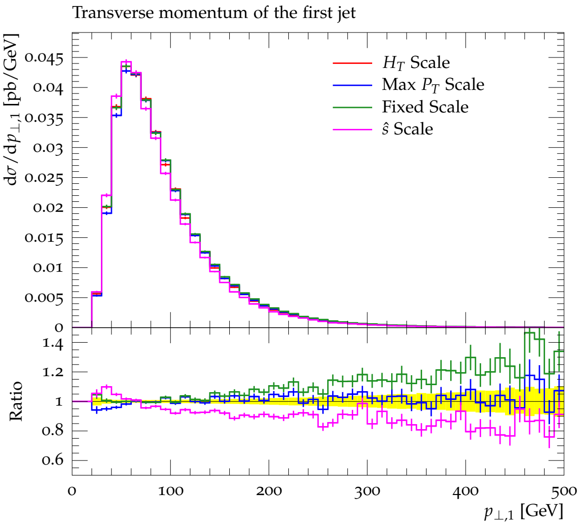
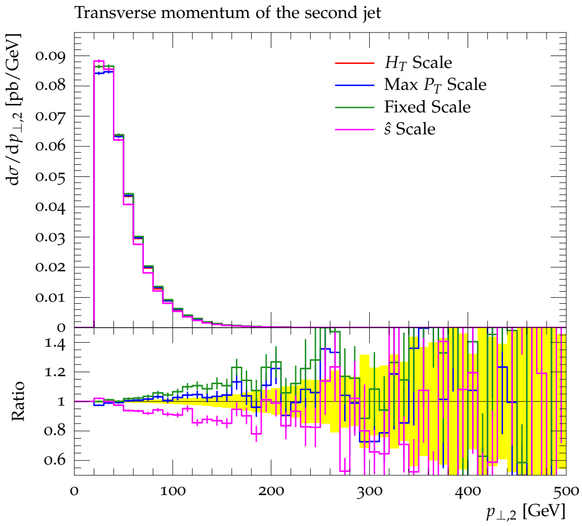
[CFPS13] F. Campanario, T. Figy, S. Pltzer and M. Sjdahl, *Electroweak Higgs plus Three Jet Production at NLO QCD*, (2013), 1308.2932.

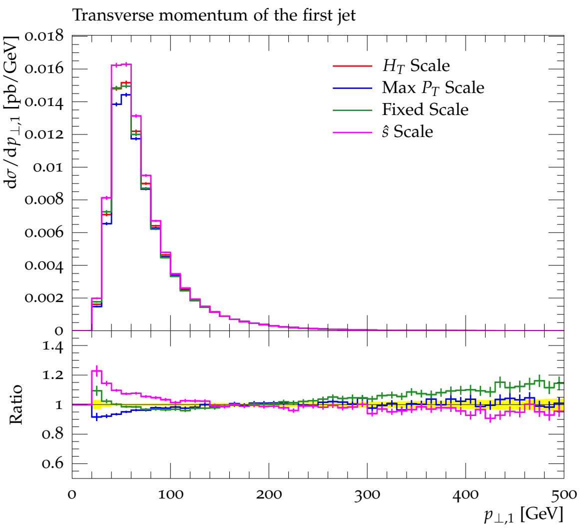
[HNZ12] K. Hamilton, P. Nason and G. Zanderighi, *MINLO: Multi-Scale Improved NLO*, JHEP **1210**, 155 (2012), 1206.3572.



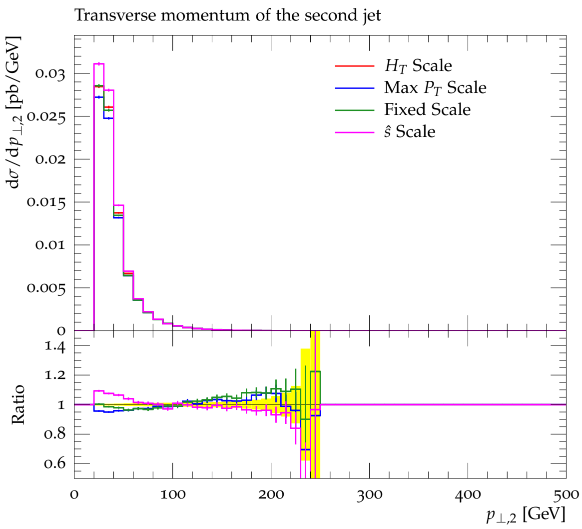
(a) First leading Jet p_T, inclusive



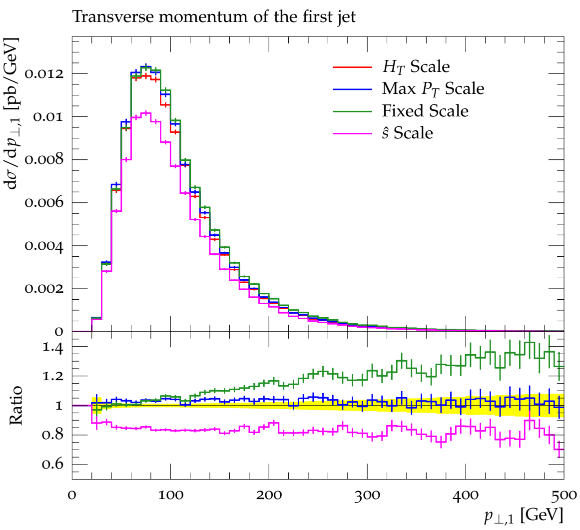
(b) Second leading Jet p_T, inclusive



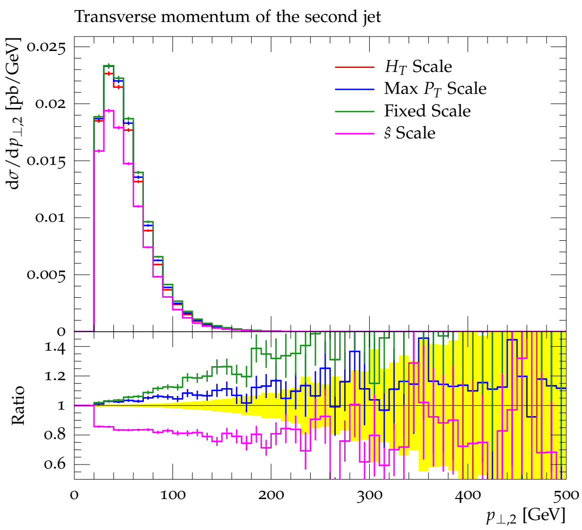
(c) First leading Jet p_T, Higgs-radiation



(d) Second leading Jet p_T, Higgs-radiation

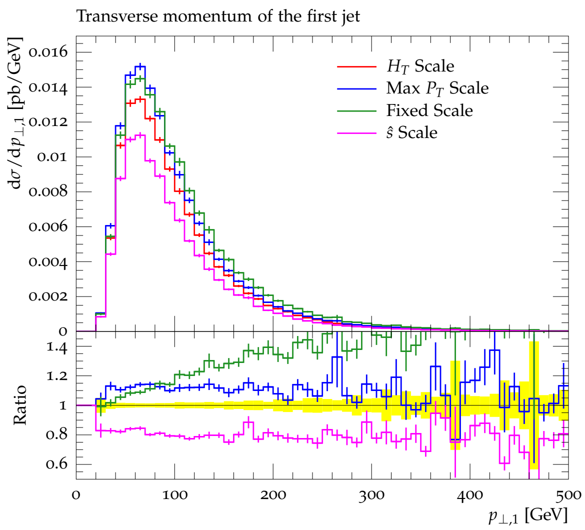


(e) First leading Jet p_T, VBF

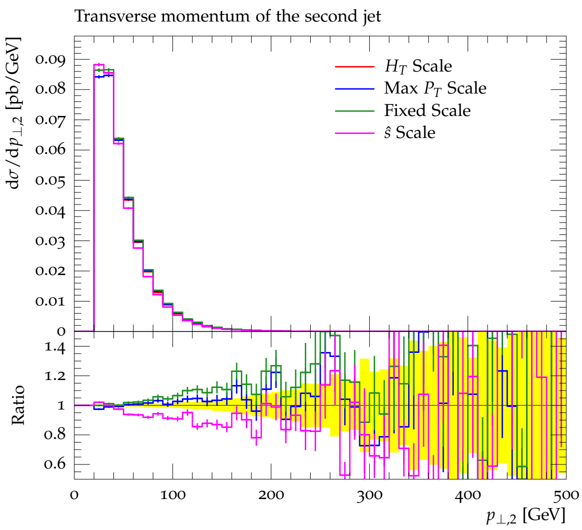


(f) Second leading Jet p_T, VBF

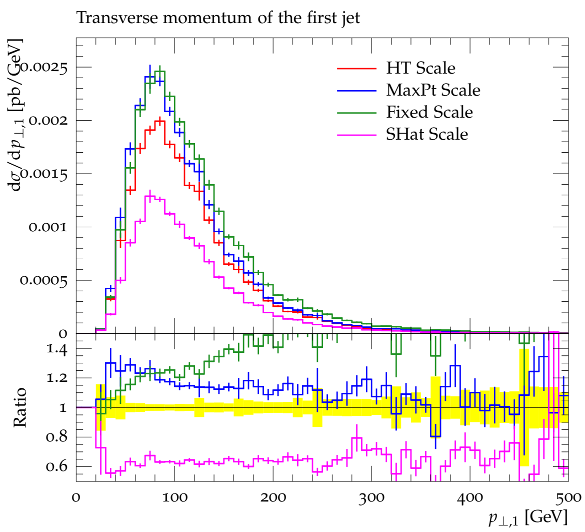
Figure 7: Higgs with 2 jets, p_T of first and second leading jet for different cuts.



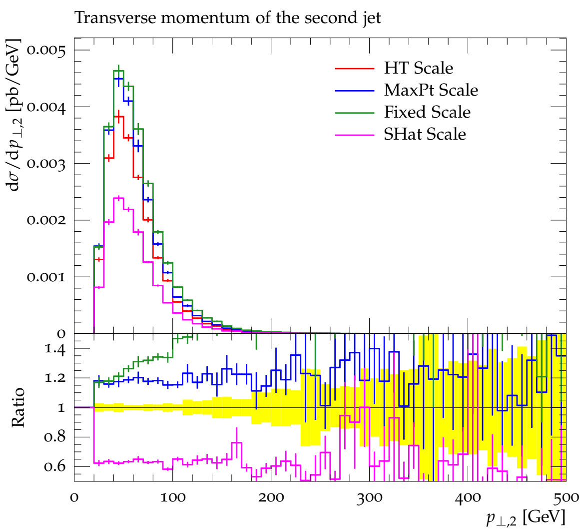
(a) First leading Jet p_T, inclusive



(b) Second leading Jet p_T, inclusive

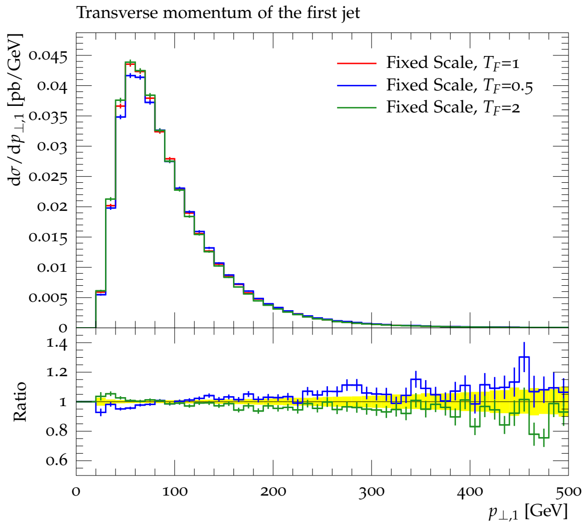


(c) First leading Jet p_T, VBF

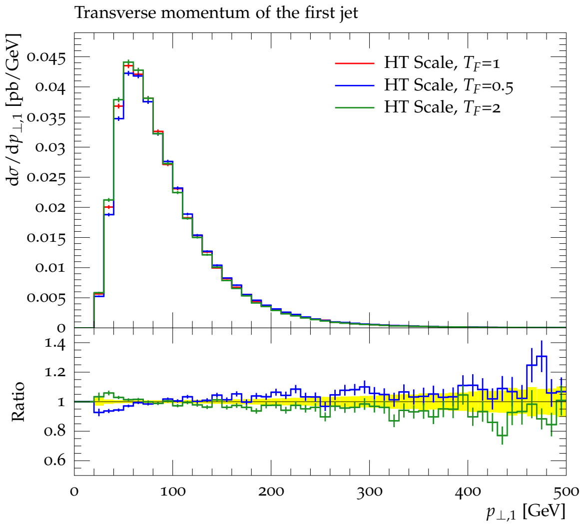


(d) Second leading Jet p_T, VBF

Figure 8: Higgs with 3 jets, p_T of first and second leading jet for different cuts.

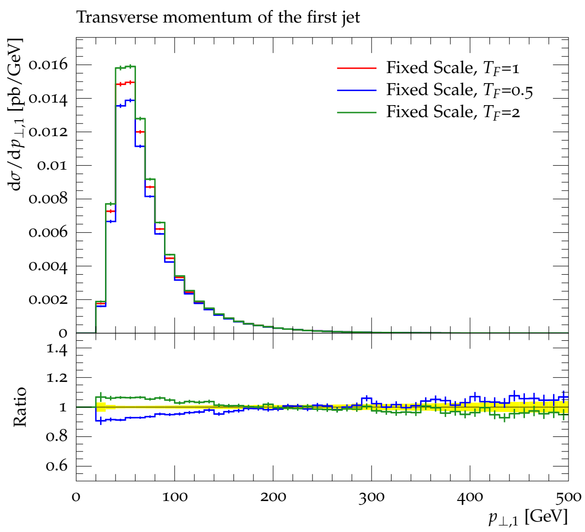


(a) Fixed scale

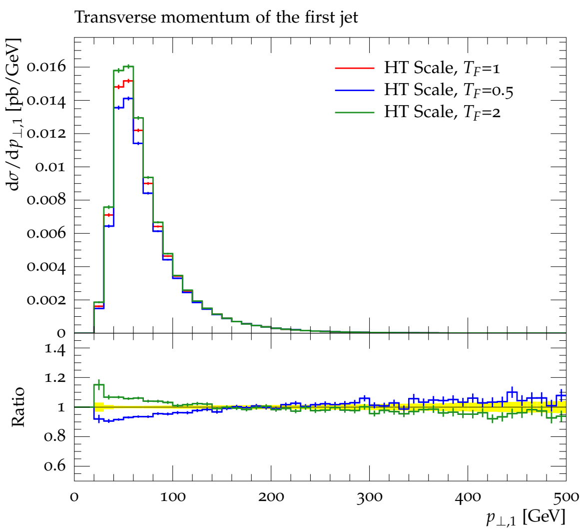


(b) HT scale

Figure 9: Factorization scale variation for inclusive Higgs with 2 jets, in the p_T-distribution of the first leading jet.

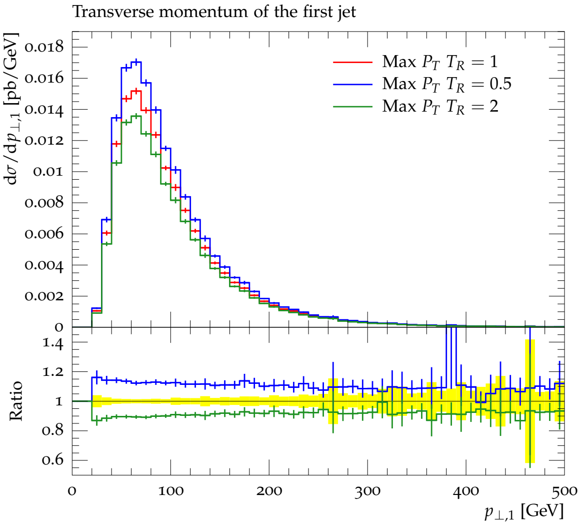


(a) Fixed scale

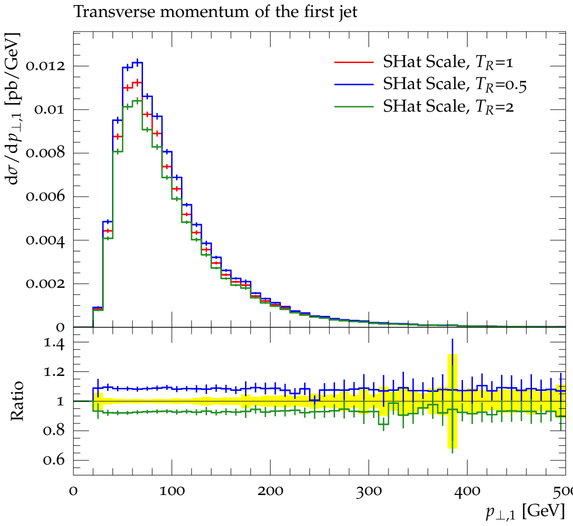


(b) HT scale

Figure 10: Factorization scale variation for Higgs with 2 jets after the s-channel cut, in the p_T-distribution of the first leading jet.



(a) MaxPt scale



(b) SHat scale

Figure 11: Renormalization scale variation for inclusive Higgs with 3 jets processes, in the p_T-distribution of the first leading jet.

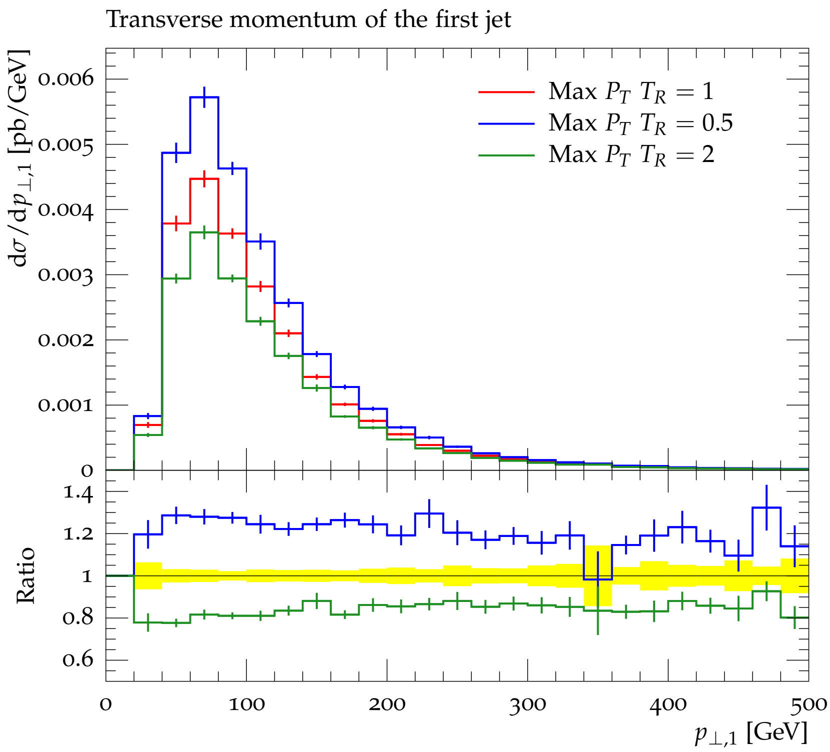


Figure 12: Renormalization scale variation for inclusive Higgs plus 4 Jets using the MaxPt scale choice, in the p_T-distribution of the first leading jet.

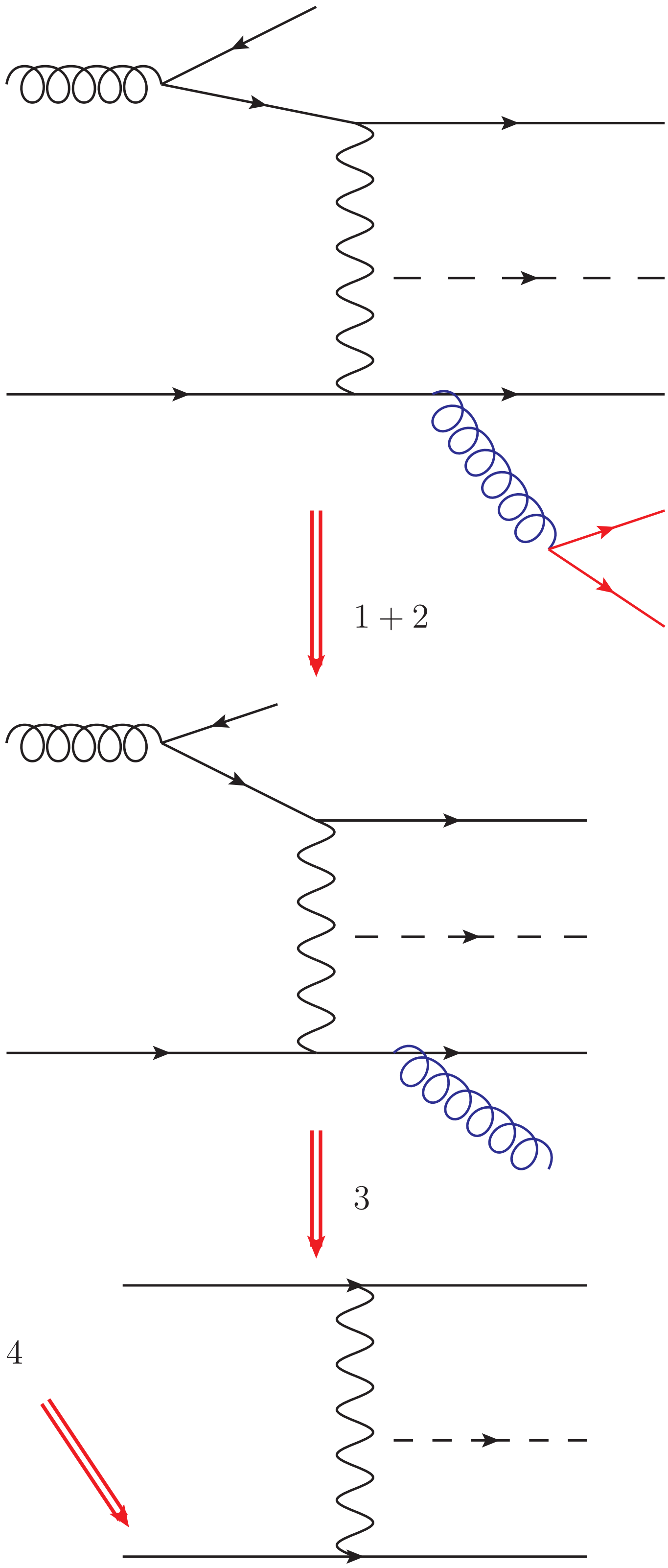
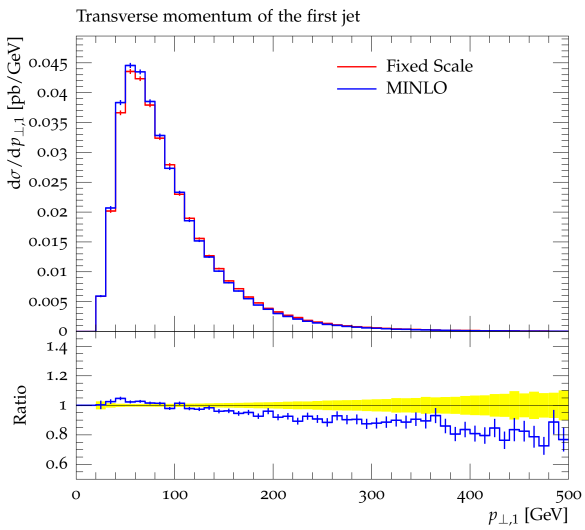
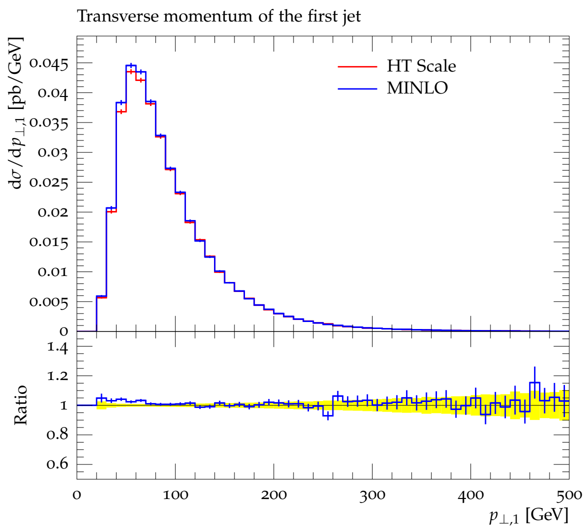


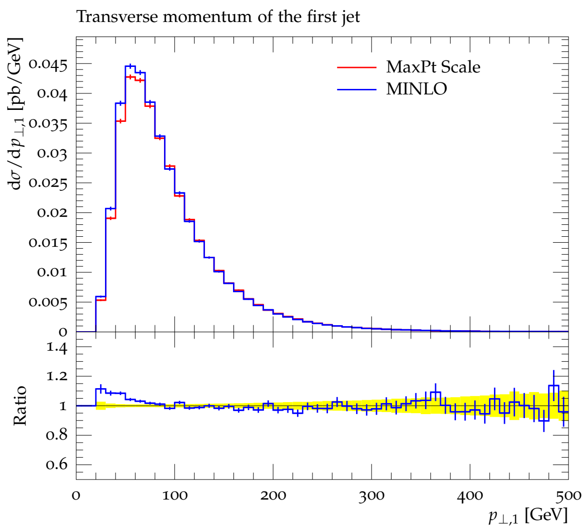
Figure 13: Schematic example for the MINLO-type algorithm.



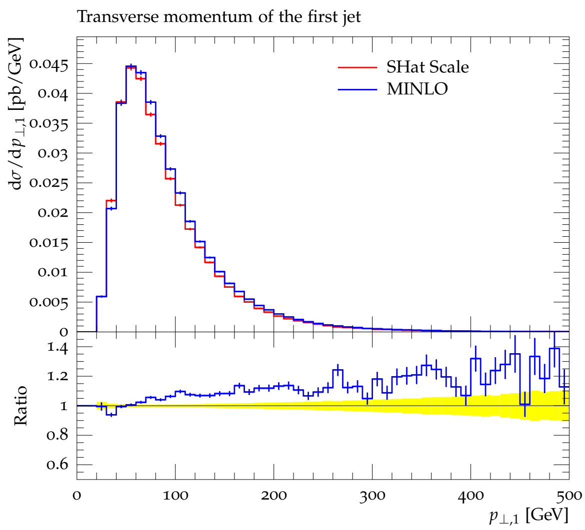
(a) Fixed Scale



(b) HT Scale

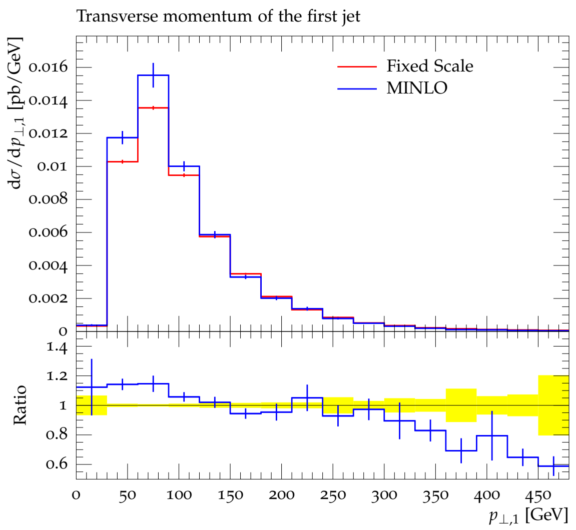


(c) MaxPt Scale

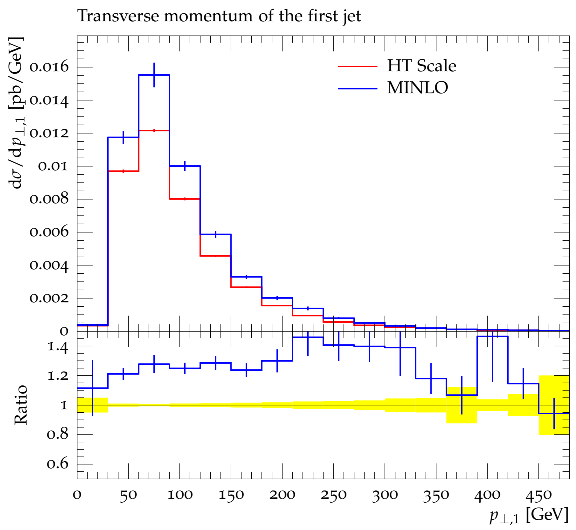


(d) SHat Scale

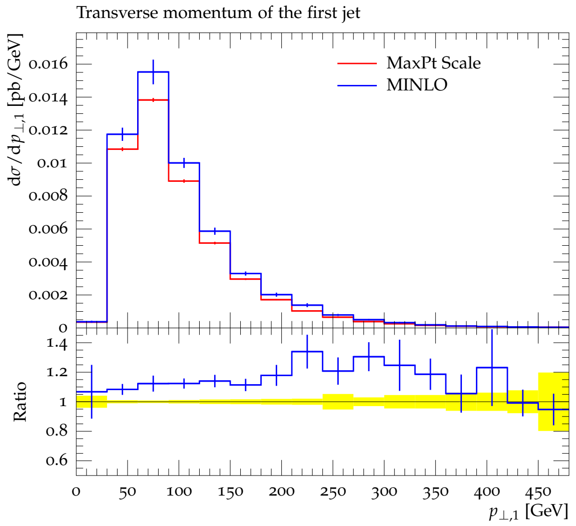
Figure 14: Scale choice in comparison to the MINLO-type, inclusive Higgs plus 2 jets.



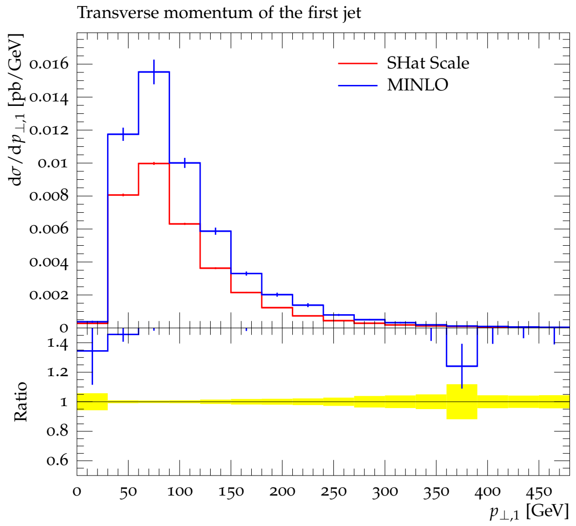
(a) Fixed Scale



(b) HT Scale

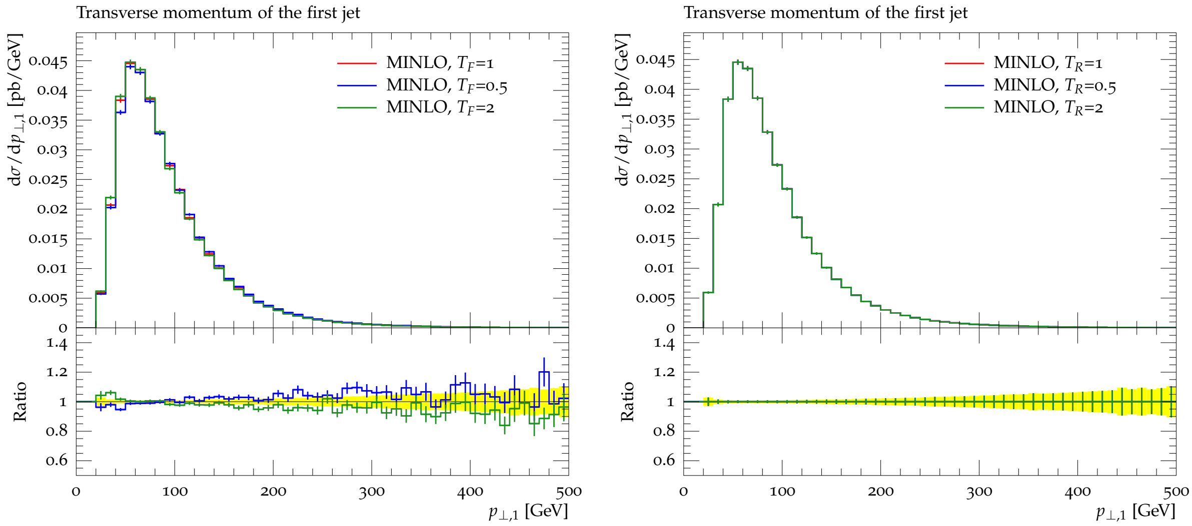


(c) MaxPt Scale



(d) SHat Scale

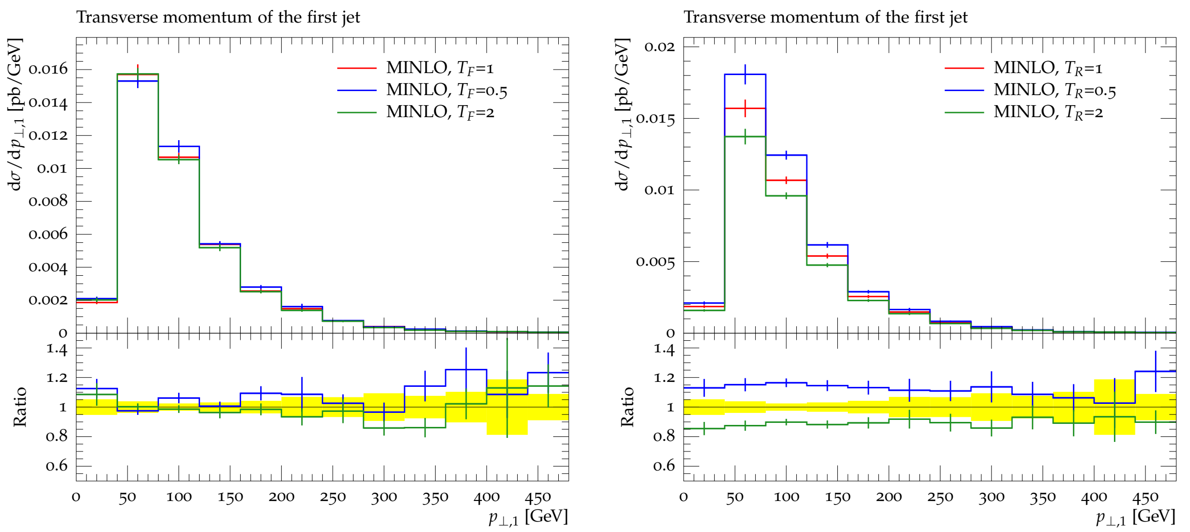
Figure 15: Scale choice in comparison to the MINLO, inclusive Higgs plus 3 jets.



(a) Factorization scale.

(b) Renormalization scale.

Figure 16: Scale variation for inclusive Higgs with 2 jets with MINLO, in the p_T-distribution of the first leading jet.



(a) Factorization scale.

(b) Renormalization scale.

Figure 17: Scale variation for inclusive Higgs with 3 jets with MINLO, in the p_T-distribution of the first leading jet.