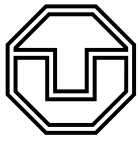
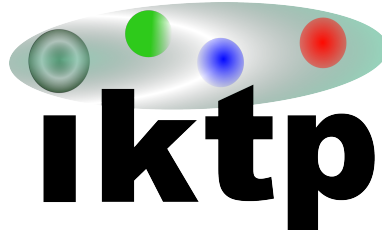




CERN-THESIS-2016-441
06/05/2016



TECHNISCHE
UNIVERSITÄT
DRESDEN



Determination of non-perturbative correction factors in jet production at the LHC using iterative methods

Bachelor-Arbeit
zur Erlangung des Hochschulgrades
Bachelor of science
im Bachelor-Studiengang Physik

vorgelegt von

David Tucholski
geboren am 31.01.1995 in Herdecke

Institut für Kern- und Teilchenphysik
Fachrichtung Physik
Fakultät Mathematik und Naturwissenschaften
Technische Universität Dresden
2016

Eingereicht am 28.Juni 2016

1. Gutachter: Dr. Frank Siegert
2. Gutachter: Prof. Dr. Arno Straessner

Summary

Abstract

English:

Predictions for the measurements at the LHC come from Monte Carlo simulations. Some generators for them do not include the hadronisation and the detector effects so that their results can not be compared to measured data directly. Commonly those incomplete simulations are corrected for these effects with *bin-by-bin unfolding*. The idea in this work is to apply the technique of *iterative unfolding* to such simulations of jet production to describe the hadronisation. With the Sherpa event generator correlated simulations are created that are then analyzed in the Rivet framework. For the unfolding the RooUnfold library is used. For the validation of the performance and for the determination of the uncertainties of this method pseudoexperiments and a fake simulation are done.

Zusammenfassung

Deutsch

Theorievorhersagen für die Messungen am LHC werden mit Monte Carlo Simulationen erzeugt. Manche der dafür verwendeten Generatoren beinhalten keine Hadronisierungs- und Detektoreffekte, sodass ihre Ergebnisse nicht direkt mit Messdaten verglichen werden können. Gewöhnlicherweise werden diese unvollständigen Simulationen mit *bin-by-bin Unfolding* um diese Effekte korrigiert. Die Idee dieser Arbeit ist, die Methode des *iterativen Unfolding* auf solche Simulationen von Jet-Produktion anzuwenden, um die Hadronisierung zu beschreiben.. Mit dem Sherpa Ereignisgenerator werden korrelierte Simulationen erzeugt und dann in der Rivet Umgebung analysiert. Das Unfolding erfolgt mit der RooUnfold Bibliothek, die Validierung der Performance und die Bestimmung der Unsicherheiten mit Pseudoexperimenten und einer verfälschten Simulation.

Contents

1	Introduction	1
2	Short summary of the theory	3
2.1	Simulation of jets	3
2.2	Observables	4
2.3	Unfolding	5
3	Method and implementation	7
3.1	Setup of the simulation	7
3.2	Creation of responses and unfolding	8
4	Results and evaluation	11
4.1	Comparison with data	11
4.2	Properties of the responses and effects of hadronisation	12
4.3	Unfolding results	14
4.4	Validation and determination of uncertainties	15
5	Conclusion, Summary and Outlook	17
A	Appendix	19
A.1	Simulation	19
A.2	Additional plots	19
B	Bibliography	23

1 Introduction

At the Large Hadron Collider at CERN collisions of high energy proton beams are studied to increase knowledge of high energy particle physics. Nearly all of the processes at such a hadron collider involve the production of jets, the most prominent example of this being the Higgs boson production, for which jet production also is a very important classification mechanism.

The theoretical predictions for these measurements are obtained with Monte-Carlo (MC) simulations, which consist of three steps. The first step in this simulation is covering the physics from the incoming protons to the central scattering of partons and gluons and its produced particles. Later this will be referred to as *parton level*, as it contains free quarks. The result of the hadronisation of the particles in the second step is referred to as *hadron level*. The third step then is the simulation of the detector effects, which are separate from the hadronisation.

Such simulation allow for the *unfolding* technique to be employed, which basically is to apply the knowledge of the changes between the steps of the simulation in an inverted way. This is commonly used to estimate the "true" distribution of an observable from a biased one, which is *smeared* by the detector effects. The idea in this work is now to use unfolding on a simulated parton level to get the respective hadron level. This allows to apply non-perturbative effects to calculations done at the parton level, which is the aimed area of application.

Commonly, for this a rather simple unfolding technique is used by just determining the correction factors between bins of distributions in parton and hadron level. This work is about extending that method with a matrix containing beforehand neglected correlations between the bins, which is then employed in an iterative procedure.

The outline of this work is as follows:

First a short summary of the simulation of jets (section 2.1) and its physical background and unfolding (section 2.3) is given. In chapter 3 the way to the correction factors is shown. After the presentation of the results of the simulation (also considering the hadronisation effects) in chapter 4 in section 4.4 the validation and evaluation of the results are done. The results are discussed and summarized in section 5. Here also all the things beyond the scope of this bachelor thesis are looked at.

2 Short summary of the theory

2.1 Simulation of jets

This section gives a basic knowledge of the underlying principles of the simulation of jet production, mostly due to QCD effects. It is not aiming at discussing the theory in details but only the main effects in a rather qualitative approach. So this part of the summary will be a compact overview and leave out most formalism. Fig. 2.1 shows only a model of a simulated collision event, but is suitable to illustrate the main principles.

The software used for the simulation is the Sherpa event generator [5]. A feature of it is the possibility to generate weighted events, i.e. that the phase-space of generation is not equally used, to have more events in regions of low statistics, for instance. Its Monte Carlo simulation of jets consists of mainly two steps, leaving out the detector simulation.

The first one is the perturbative calculation of matrix elements for the desired process with Feynman graphs until a certain order and after that parton showers for an approximative resummation of higher order QCD corrections. With them, events on parton level are generated. The Feynman Graphs reflect the core process, which is the collision of two protons (dark green, incoming from left and right), more precisely, of constituent quarks or gluons (blue and purple lines and spirals originating from the protons).

This collision creates high energy particles (red as the process of interest), in this example event top quarks and a Higgs boson are produced, which undergo QCD bremsstrahlung calculated non perturbatively with parton showers and decays (blue and red particles spreading from the central interaction). The effect of confinement appears when these high energy quarks are torn away from each other by the high energies of the collision. The potential energy rises until it is high enough to produce another quark pair, which then also might have enough energy to undergo the same effect. This spray of more and more partons is focused because of relativistic effects. After the loss of enough energy these partons bound together as hadrons. The emphasis of this work is this hadronisation, the second step, which is modelled non-perturbatively. It can not be accessed perturbatively because the strong coupling constant gets too big in the domain of the hadronisation, so that the summation over the Feynman Graphs does not converge. Most important for this non-perturbative approach is the so called fragmentation, the pendant of the actual hadronisation. Additional to parton level the hadron

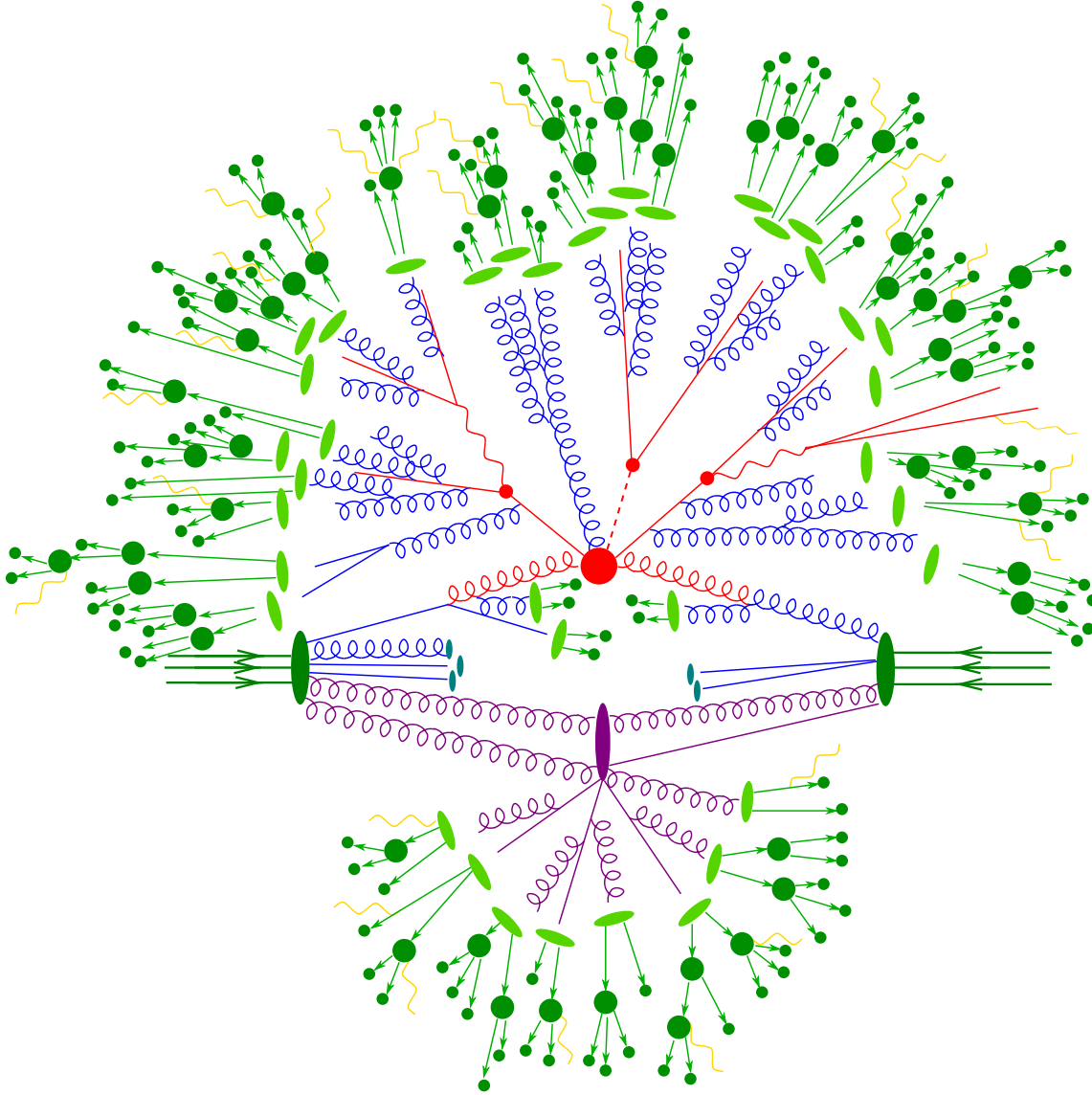


Figure 2.1: A visualization of the model event structure used in the Sherpa event generator [9]. The big nodes include multiple vertices. In red the central interaction is depicted, including the most inner decays, e.g. of top-quarks or a Higgs boson. The blue particles originating from the red ones are the parton shower and the purple structure is the underlying event. Green nodes are the beginning of the hadronisation, which is the formation of hadrons (bright green) and decays of them (dark green).

level also takes into account the multiple parton interactions¹, also known as the underlying event, and the inner transverse momenta of the partons. This is not related to the physical hadronisation, but neglected at the parton level to have a pure look at the core processes there. The effects of this hadronisation are looked at in section 4.2.

Also worth mentioning is the algorithm used for identification of the jets. A main feature of this anti-kt jet clustering algorithm (for this, see [4]) is, that it is applicable to all states. It can work with parton level events, with final states such as the hadron level and even with energy deposits in a detector [1]. The procedure to identify jets is as follows, close to [4], using the transverse momentum k_{ti} , the rapidity y_i and azimuthal angle Φ_i of the input four momenta i (particles or pseudo-jets):

1. Calculate the 'distances' $d_{ij} = \min(k_{ti}^{-1}, k_{tj}^{-1}) \frac{\Delta_{ij}^2}{R^2}$ and $d_{iB} = k_{ti}^{-1}$ with $\Delta_{ij}^2 = (y_i - y_j)^2 + (\Phi_i - \Phi_j)^2$ and the jet radius parameter R from the inputs.
2. If the smallest of these distances is a d_{ij} , recombine entities i and j , or if it is a d_{iB} , define i as jet and remove it from the list of inputs.
3. If inputs left, repeat procedure.

2.2 Observables

The observables looked at in this work are the jet transverse momentum p_T , the jet mass m and the absolute rapidity $|y|$.

The jet mass is given by the four momentum of the jet constituents p^μ

$$p^\mu p_\mu = E^2 - \vec{p}^2 = m^2. \quad (2.1)$$

Similarly, the transverse momentum is the transverse component of p^μ .

Because many outgoing particles of an event are scattered close to the beam axis, the detector cannot detect their momenta and therefore it is not possible to use full momentum conservation, but only of transverse momentum, since the detector encloses the beam axis radially.

The rapidity is defined using the jet energy E and the z component of the momentum p_z as

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}, \quad (2.2)$$

¹This is counted as a hadronisation effect, to have a more pure core process in the parton level. Actually the multiparton interactions are part of the central interaction.

giving a quantity that is related to the angle between the beam axis and the transverse plane. An absolute rapidity of 0 means a jet in the x - y -plane, while a value of ∞ means the jet coincides with the beam axis. Due to detector restrictions mentioned above, absolute rapidity is only examined for $0 \leq |y| \leq 3.0$.

2.3 Unfolding

Here the concepts and methods of unfolding are briefly reviewed, very close to the outline of D'Agostini [2], in a shortened way.

Unfolding is the technique of reversing biases on a distribution, which come from hadronisation or detector effects, for instance. Applied to the biased distribution, e.g. a measured one, it yields the underlying unbiased, *true* distribution.

A simple introduction into the unfolding world are bin-by-bin correction factors. These basically come from the bin-wise division of two distributions, one being the *true* distribution, the other the *measurement* which is to be unfolded. The area of applicability are distributions with the same binning, where bin migrations are small compared to the bin widths. This work uses the same binnings for correlated histograms to make this unfolding possible, while the binnings are chosen to be very fine to show the limitations of the procedure. The correction factors C_i are calculated from the contents of the *true* bins T_i and those of the *measurement* M_i simply as

$$C_i = \frac{T_i}{M_i}. \quad (2.3)$$

Now the iterative approach proposed by D'Agostini in [2] is described. D'Agostini begins by considering n_C different causes (C_i) for one effect (E). The causes themselves have initial probabilities of appearing ($P_0(C_i)$) and a conditional probability to cause the effect ($P(E|C_i)$). With n_E different effects E_j he then introduces as the *smearing matrix*. This matrix is later also referred to as *response matrix* ² containing the conditional probabilities of the causes to have produced the effects, $P(C_i|E_j)$ is stated with Bayes' theorem as

$$P(C_i|E_j) = \frac{P(E_j|C_i) P_0(C_i)}{\sum_{l=1}^{n_C} P(E_j|C_l) P_0(C_l)}. \quad (2.4)$$

This equation includes the normalization of the initial probabilities of the causes and of all causes to one effect. This means that no additional causes appear, that causes initially being

²Not to confound with the later used *response histogram*, which consists of values of observables in both levels in the x - y -plane and their cross section in the z -axis

zero do not contribute and that an effect can be caused only by the causes. Also it is stated, that a cause does not have to result in an effect, while the cumulative probability of causing effects, also referred to as an efficiency ϵ_i for that,

$$\epsilon_i = \sum_{j=1}^{n_E} P(E_j|C_i), \quad (2.5)$$

must be between zero and one. With this, the true number in the i-th bin due to each cause could be expressed as

$$\hat{n}(C_i) = \frac{1}{\epsilon_i} \sum_{j=1}^{n_E} P(C_i|E_j). \quad (2.6)$$

The iterative procedure of unfolding is then:

1. Start with the initial distribution to be unfolded as $P_0(C_i) = \frac{n_0(C_i)}{N_{\text{Obs}}}$, with the observed number of events for each cause $n_0(C_i)$ ³ and totally observed events N_{Obs} .
2. Use equation 2.6 to get the estimated $\hat{n}$
3. Do a χ^2 comparison of n_0 and $\hat{n}$
4. Repeat with $\hat{n}$ in 1. until 3. is satisfactory

One sees after short consideration, that the smearing matrix, in this work describing the hadronisation effects, is independent from the initial probabilities. This means, that later even with arbitrary changes of the simulation at the parton level the smearing matrix is the same in the limit of a large number of generated events, if the hadronisation in this changed simulation is not changed. Also, this method does not require the same binning of the histograms, though in this work it is used to apply the bin-by-bin unfolding for comparison purposes.

³For concrete unfolding in this first step later the parton level distribution is used.

3 Method and implementation

3.1 Setup of the simulation

To get the final result of a response matrix, which will be needed for the unfolding, a series of steps has to be taken. This will be the structure of the next sections.

Crucial for the response histograms is, that they have to be filled with the same event on parton level and hadron level. This gives insight to the migrations due to hadronisation.

At first, one has to set up the two correlated Sherpa Monte Carlo simulations. Setting the same seed for each event in both runs assures the correlation of the events.

This simulation is compared to the measured data of jet transverse momentum [1], using the same binning as the publication for that.

An important parameter in this is the minimum transverse momentum, which at least one jet in the event must have. This cut to the jets is done twice, first in the simulation, after that again in the analysis. Setting this to 100 GeV as in the later analysis results in the loss of approx. 20 % of the events in the first bin of the hadron level (this depends on the rapidity region and jet radius parameter) due to transverse momentum shifts during the hadronisation. At the same time, with a high transverse momentum cut, a large part of the generated events passes the cut in the analysis. A lower cut in the simulation leads to a correct reproduction of the first bin, but makes the simulation inefficient for the later analysis. After a few runs of the simulation using the analysis of [1], this cut is set to require at least one jet with at least 80 GeV, where the reduction in the first bin is negligible and after all at least a third of the events passes the cut of the analysis. A plot of this is Fig. 3.1. Jets passing the cut before hadronisation in the parton-level and not in hadron level are later recognised as fakes in the processing of the response matrix. The order of the analytical calculation of the hadronisation is set to the lowest order, as the parton shower alone yields good agreement with data. Some other details of the setup of the simulation are described in section A.1.

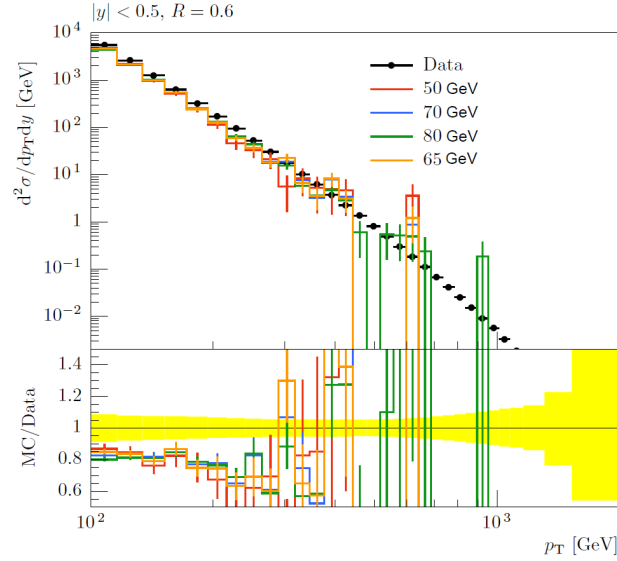


Figure 3.1: An example histogram from the calibration of the minimum transverse momentum parameter. Plotted are the distributions for several values against measured data. The simulations used 10000 events each, which explains the low statistics in the upper transverse momentum.

3.2 Creation of responses and unfolding

For using the aforementioned output files for an analysis one combines them to a single file that is then analyzed using the rivet-framework [6]. In the file the correlated events from the different levels are merged to a new single event by setting the particle status value to indicate the level of each particle.

In the analysis the anti-kt algorithm is used as a first step to construct jets from the final state particles in the event using radius parameters of 0.4, 0.6 and 1.0. Filling the response histograms, the jets are separated into the six rapidity regions with corresponding jets in same regions being inserted into the histogram.

Besides this one dimensional histograms for parton- and hadron-level of the observables are filled, exclusively containing entries with same level but different absolute rapidity that are later recognized and treated in the unfolding.

For the binning of the histograms a logarithmic binning is used, leading to equally spaced histograms, when plotting on a logarithmic scale.

This binning is the same for both levels of each observable, to allow the method of bin-by-bin unfolding to be used and, with 40 bins for each histogram, is chosen to show the limitations of this method.

This histograms are used for the unfolding using the RooUnfold libraries with most interest in the implemented iterative unfolding based on Bayes' theorem and in bin-by-bin unfolding.

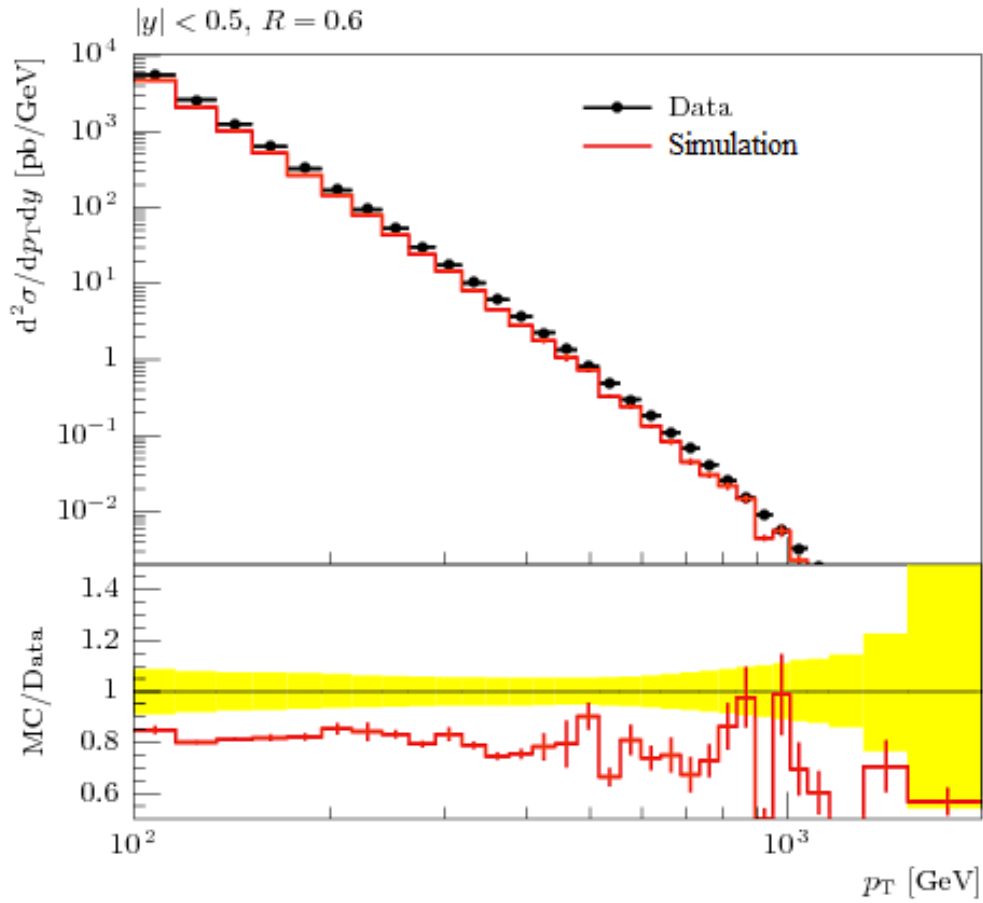
Before this a routine is passed the histograms of both levels and the response histograms, determining fakes¹, and the response matrices. Then the actual unfolding happens by passing the response matrix to the Bayesian unfolding algorithm with a parton level histogram to be unfolded, specifying the number of iterations to perform to get out the unfolded distribution.

¹events from both 1D histograms not contributing to the response histogram

4 Results and evaluation

4.1 Comparison with data

The data from the measurement of inclusive jet production [1] is only for transverse momentum, so the simulation is not compared to jet mass. The correctness of the simulation as a whole is assumed, as it fits the data for transverse momentum, as shown in Fig. 4.1. The cross section is a bit lower than the measurement, as the simulation of the jet production is only in the lowest order. Nevertheless that is enough to study the effects of the hadronisation.



(a)

Figure 4.1: Comparison of simulation with data from measurement [1], using the same analysis as the paper. The cross section is lower due to the low order of the simulation.

4.2 Properties of the responses and effects of hadronisation

In the following the effects of the hadronisation are discussed with a look at the response histograms. For different configurations of parameters and observables the strength of these effects varies. The response matrices of the transverse momentum consist of a diagonal which is a few bins wide, containing most of the entries, and a slight asymmetry towards the hadron-side of the diagonal. Comparing the both distributions in one plot (see figure 4.1) there is no big difference either.

On the other hand, in the jet mass responses there are clearly off-diagonal elements. The region up to about 10 GeV at the parton level is shifted into a broadly smeared horizontal. The two significantly higher bins matching masses of around 1.3 and 4.2 GeV in parton level appearing in Fig. 4.2 (d) are interpreted as charm and bottom quarks. In the response histogram these peaks are broadly smeared. A good view of this is given in figure 4.4 (c) for the charm peak. Also, plotted together the levels show great differences here (see figure A.1 (b) and (d)).

With a growing jet radius parameter the peak of the distribution of the jet mass is shifted to higher values while its tail towards high masses is getting more flat. This is due to the greater radius of the jet cone, as more particles are counted into the jet and mostly the angle between two four momenta is increasing and thus the mass m increases as the scalar product $\vec{p}^2$ in equation 2.1 decreases.

The smaller deviation between the levels in transverse momentum for a jet radius parameter R of 0.4 comes from a combination of hadronisation and underlying event effects. $R = 0.4$ is often chosen for jets as a compromise to be less sensitive to these effects.

A rising jet radius parameter is found to increase the non diagonal character for both observables. This non diagonal character raises with lower rapidity (see Fig. A.1), not that much for transverse momentum, as for mass.

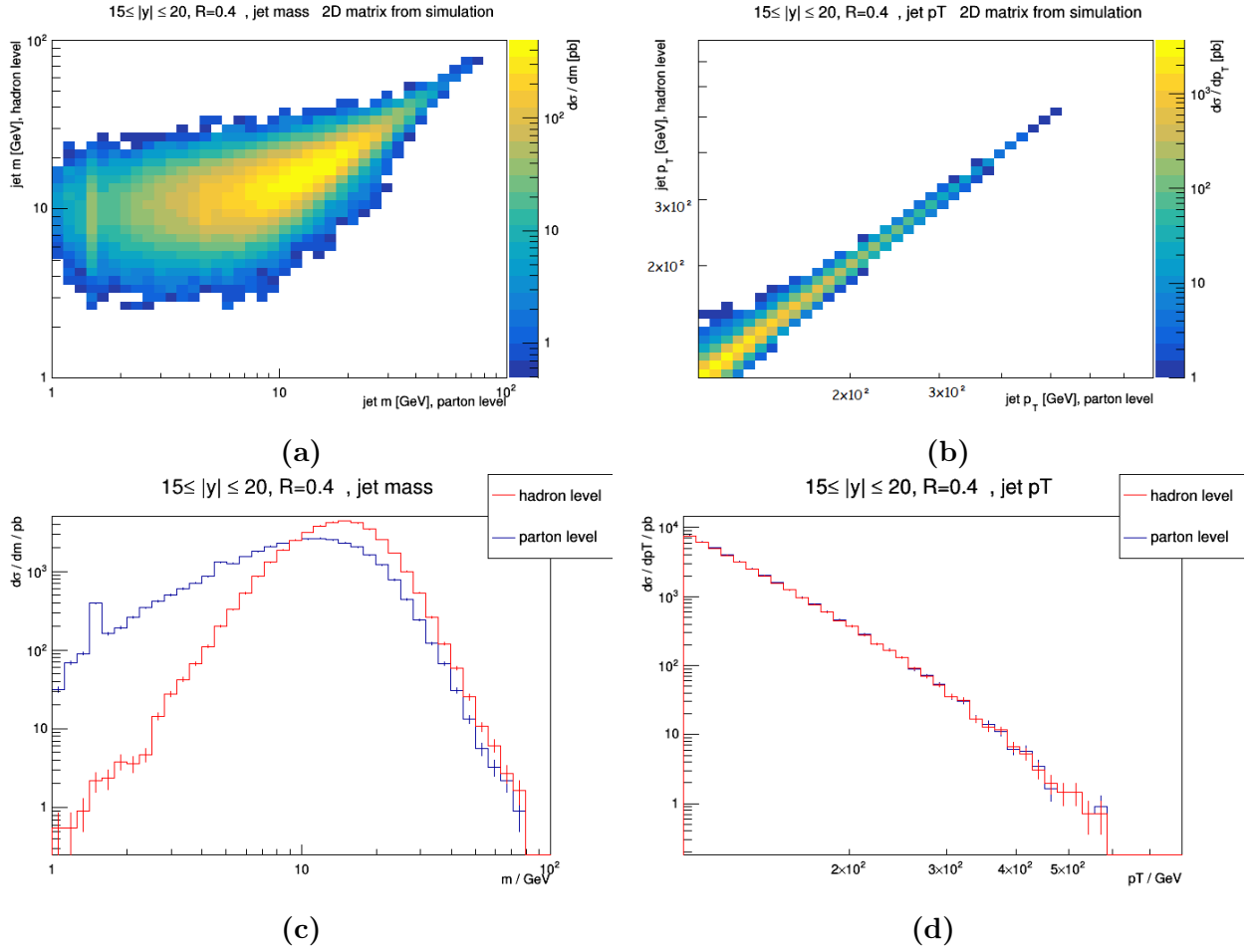


Figure 4.2: Response histograms and distributions in both levels. a) and c): The charm quark peak is visible. For transverse momentum the hadronisation effects are smaller.

4.3 Unfolding results

Now a look at the results of the unfolding is taken, leading over to the determination of its uncertainties with pseudoexperiments and the validation of its performance. To get an independent parton level for the testing of the unfolding, a faked simulation is created. For this, 100000 events are created in the weighted generation mode. Then their weights are set to 1 thus creating an independent parton level.

The number of iterations to perform is determined by comparison of the performance of one to four iterations. D'Agostini [2] proposes to run a χ^2 -test between the steps to give a criterion of convergence.

Since after more than five iterations instabilities appear and the chi-square value cannot be accessed easily, a visual comparison between the performance using one to four iterations, respectively, is done in Fig. 4.3. Also the divergent behavior for too many iterations for three, six and eleven iterations is visible as well.

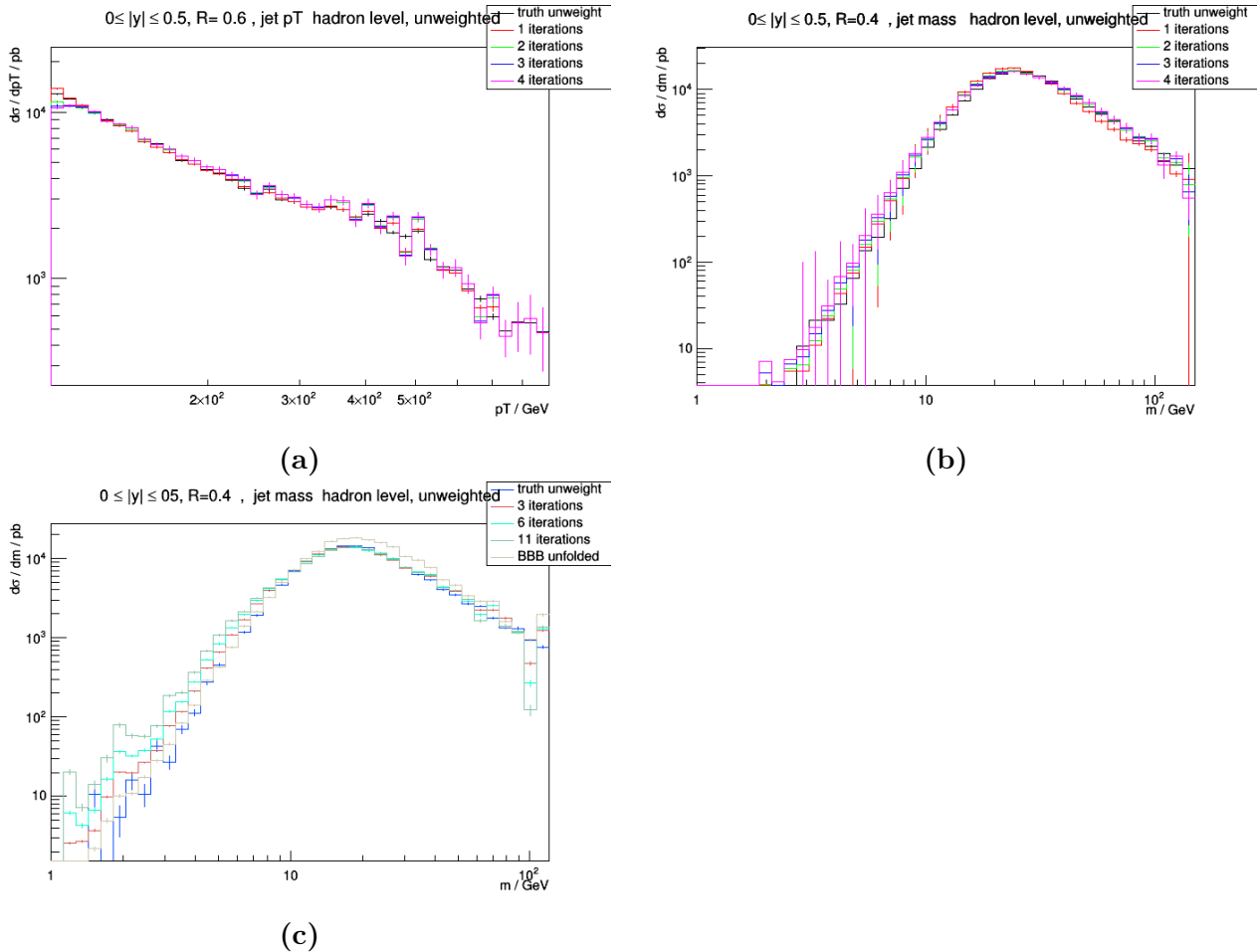


Figure 4.3: a) Plot of one to four iterations, with the bin-by-bin (BBB) unfolded distribution for comparison. The big errors in the lower cross section come from the fourth iteration mainly. The errors in a) and b) are calculated with pseudoexperiments, as described in section 4.4. Those in c) are the statistical errors from the analysis, because no pseudoexperiments for those iterations were done.

Three iterations are chosen as a compromise between fluctuations and too few iterations for the iterative character of the unfolding. It can be seen that the unfolded distributions have a higher cross section in the first bins, but describe the hadronisation very good in the bins for masses.

4.4 Validation and determination of uncertainties

Uncertainties of the unfolded distribution don't come from the statistical uncertainty of determined entries in each bin but from those within the response matrices, the *measured* distribution (hadron level in this work) and the unfolding itself.

With a fluctuation¹ of the response and the hadron level histogram before unfolding and the difference to the unfolding with three more iterations the total statistical uncertainty on the unfolded result is determined.

A test for the performance of the unfolding is done using histograms filled without event weights, to get distributions of the same observables independent from the generation of the responses. This creates a distribution differing in the parton level, which undergoes the same effects of hadronisation. This simulation will be referred to as unweighted. For a large number of events the response matrix is expected to be independent from such changes of the weights, as discussed in the summary of theory in section 2.3.

Below in Fig. 4.4 the response histograms for both observables and the actual and the fake run are plotted. Looking at the differences in the distributions in the plots below, they do not reflect the differences in the runs, but those in the number of generated events.

¹For the 1D histograms each bin is set as random from a Gaussian distribution around its value with a width of its statistical error, for 2D there is a build-in toy for this in the RooUnfold package. After unfolding with them, the root-mean-square error of 2000 such pseudoexperiments is assigned as an uncertainty.

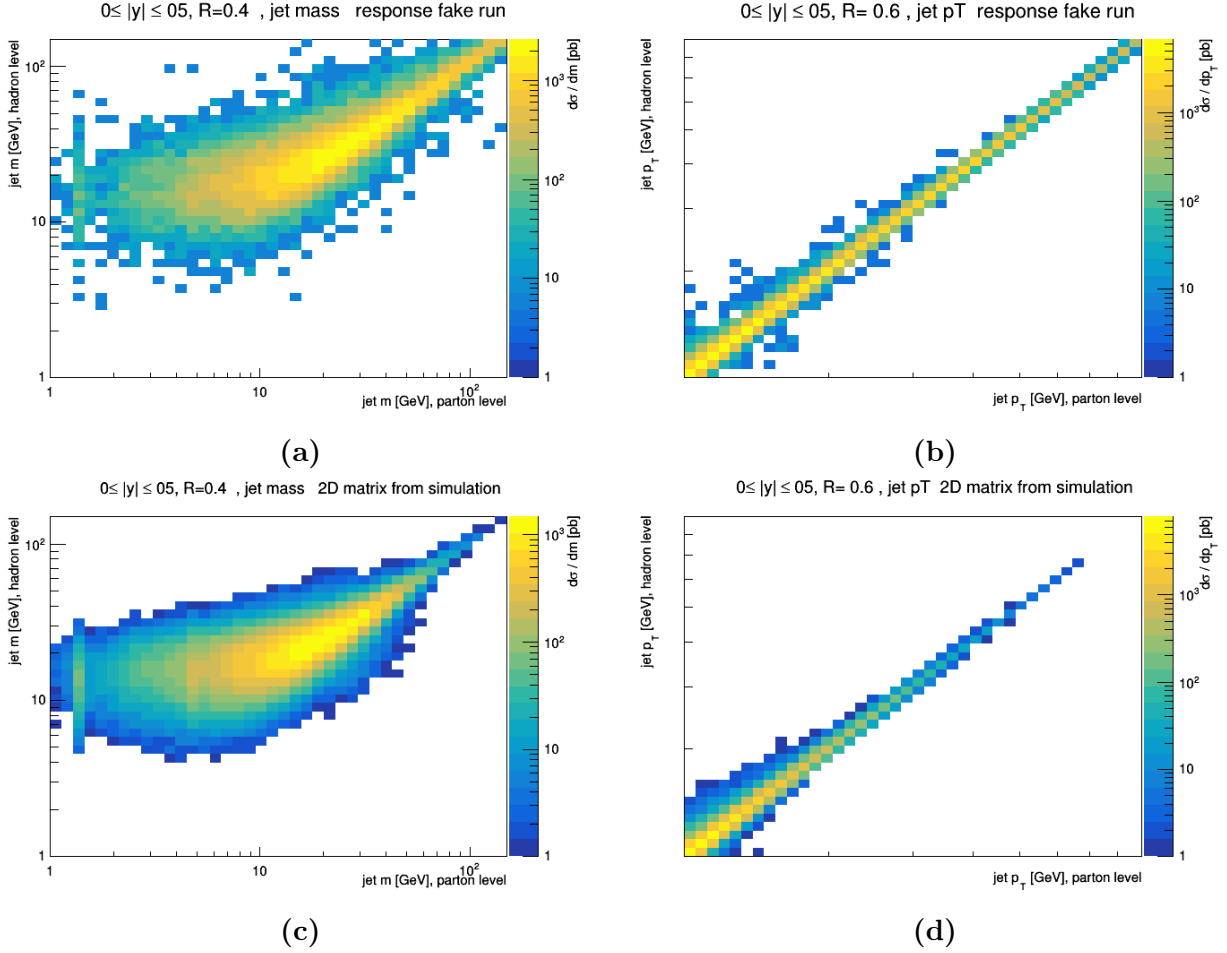


Figure 4.4: Examples for weighted and unweighted distributions in both levels and observables. The weighted and the unweighted response histograms show that despite great differences in the weighted and unweighted distributions (c) and (d) the response matrices (a) and (b) remain practically same. The unweighted response histogram differs due to low statistics (just 100 000 generated unweighted events vs. 3 million weighted ones.). Another effect is the rise of cross section in regions of higher mass and transverse momentum leading to the greater cross section in the response histograms. Properly normalized, the responses are even more similar.

5 Conclusion, Summary and Outlook

This work has shown the advantages of the iterative unfolding method proposed by D’Agostini applied to the unfolding from parton to hadron level of jet production. This is achieved by producing correlated simulations of each level to directly get the response matrix describing the hadronisation. Pseudoexperiments then have been used for both the determination of correction factors and the determination of the uncertainties.

The non-diagonal character of the response matrices for the jet mass is much greater than for jet transverse momentum, which shows the unapplicability of bin-by-bin unfolding for jet mass. Despite the very diagonal response matrices for transverse momentum, iterative unfolding with them can be an improvement compared to bin-by-bin unfolding, as shown in Fig. 4.4. A simple consideration about the nature of bin-by-bin unfolding shows its disadvantages here: If one applies the bi-by-bin correction factor from the weighted distributions on the same bin of the faked distribution, especially in the regions of high, the resulting values may differ drastically from the respective truth.

Nevertheless bin-by-bin unfolding can be a choice for jet transverse momentum, when the distributions of the parton level simulation are not differing much from the ones used to produce the correction factors.

The determined response matrices used are found to be mostly independent from parton level, thus describing the pure hadronisation.

The limitations of iterative unfolding are the errors occurring in bins with too few events, for instance. One way to avoid this is to change the binning. Because the focus here is on simulations, larger numbers of events can be also easily achieved.

Beyond the scope of this work is the consideration of further influences and steps. First of all, the discussed method was just tested with a distorted distribution and not with another simulation generator, as the aim is, but the feaking of a simulation is a good replacement for testing. It is possible to use the rapidity as another dimension, since the method of D’Agostini allows for multidimensional unfolding [2]. This would require more rapidity bins, and for that, more events to be generated for the responses. Influences that could be examined (or examined more detailed) for instance are the cuts in the analysis and the influence of the binning on the performance of the unfolding. Finally, since only one parameter is to change for the simulation, one could easily expand this procedure e.g. on up-to-date $\sqrt{s}$.

A Appendix

A.1 Simulation

The central steering element for the Sherpa simulation [5] is the Runcard, a file containing all the main parameters. The three sections begin with the run-part, where the number of events to generate, the output format of the events, the beam energies, the seed for the random numbers and the hadronisation parameters are set. The hadronisation parameters allow to switch off the features of the hadronisation to generate a parton level. In this part also the mode of weighing is set.

The next section is used to set the processes to do, with e.g. parameters for the error tolerance of the generation, the particles to collide and to produce and the orders in the perturbative calculation.

In the next section cuts can be applied to the generation, in this work this is the aforementioned minimal transverse momentum that at least one jet has to have. Figure ?? shows the influence of the cut used in this work.

The last section allows to bind in a rivet analysis to analyze the events directly after the simulation.

A.2 Additional plots

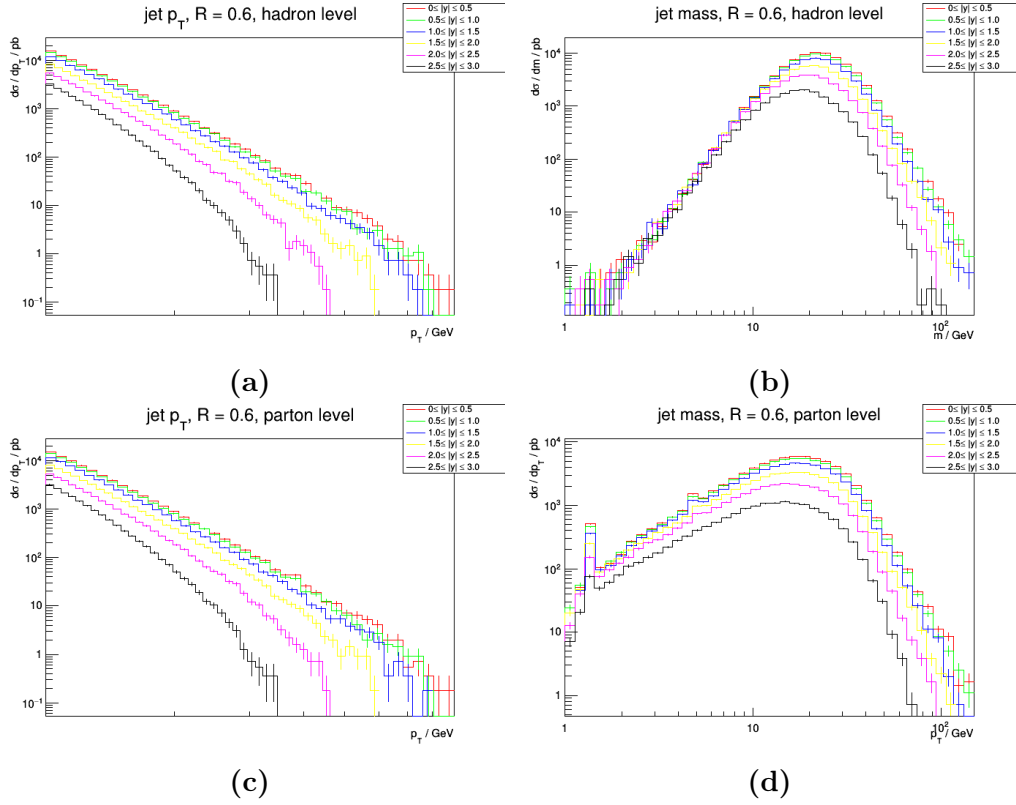


Figure A.1: The changes within the regions of rapidity for both levels and observables. The vertical bars of uncertainties are the statistical error from the number of events per bin. With rising rapidity the cross section is sinking and shifting to lower values of the respective observable.

(b) : In hadron level there are no peaks of the charm and bottom quark. This is due to their decay and hadronisation. (c): With rising rapidity the peaks shrink, in the last rapidity region the bottom quark peak is not visible anymore.

Erklärung

Hiermit erkläre ich, dass ich diese Arbeit im Rahmen der Betreuung am Institut für Kern- und Teilchenphysik ohne unzulässige Hilfe Dritter verfasst und alle Quellen als solche gekennzeichnet habe.

David Tucholski

Dresden, 27. Juni 2016

B Bibliography

- [1] ATLAS Collaboration, *Measurement of the inclusive jet cross-section in proton-proton collisions at $s = \sqrt{7}\text{TeV}$ using 4.5fb^{-1} of data with the ATLAS detector*, arXiv:1410.8857.
- [2] G. D' Agostini, *A Multidimensional Unfolding Method Based On Bayes' Theorem* , Nucl. Instr. and Meth. in Phys. Res. A362 (1995) 487.
- [3] Georgios Choudalakis, *Unfolding in ATLAS* , arXiv:1104.2962.
- [4] Gavin P. Salam, Gregory Soyez, Matteo Cacciari, *The anti-kt jet clustering algorithm* , arXiv:0802.1189.
- [5] T. Gleisberg, Stefan. Hoeche, F. Krauss, M. Schonherr, S. Schumann, F. Siegert, and J. Winter.
Event generation with SHERPA, 1.1. JHEP, 02:007, 2009.
- [6] Andy Buckley, Jonathan Butterworth, David Grellscheid, Hendrik Hoeth, Leif Lonnblad, James Monk, Holger Schulz, Frank Siegert, *Rivet user manual*, arXiv:1003.0694.
- [7] Tim Adye, *Unfolding algorithms and tests using RooUnfold*, arXiv: 1105.1160.
- [8] Jennifer Archibald, Timo Fischer, Tanju Gleisberg, Stefan Hoeche, Hendrik Hoeth, Frank Krauss, Ralf Kuhn, Silvan Kuttimalai, Thomas Laubrich, Radoslaw Matyszkiewicz, Andreas Schaelicke, Marek Schoenherr, Steffen Schumann, Frank Siegert, Jennifer Thompson, Jan Winter, and Korinna Zapp, *Sherpa 2.2.0 Manual*, August 2015.
- [9] T. Gleisberg, S. Hoeche, F. Krauss, M. Schoenherr, S. Schumann, F. Siegert, J. Winter
Event generation with SHERPA 1.1, arXiv:0811.4622.
- [10] ATLAS collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, J. Instrum. 3 (2008) S08003.