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High p_T jets in RunII of the ATLAS Experiment

MASTER'S DEGREE PROJECT

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Zadani prace

Statement

Prohlasuji. . .

V Praze dne ....

Jan Lochman

Acknowledgment

Dekuji. . .

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Název práce:
Jety s vysokou příčnou hybností v RunII experimentu ATLAS
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High p_T jets in RunII of the ATLAS Experiment
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Abstract: This thesis deals with the meassurement of the inclusive jet double differential cross section in p_T and rapidity using PYTHIA8 generated events of pp colisions at $\sqrt{s} = 13\,\text{TeV}$ with the ATLAS detector response reconstructed by GEANT4 detector simulation. Differential cross section obtained from the detector level is unfolded on the particle level and compared with the parton level cross section prediction of the NLO pQCD. Both PYTHIA8 and NLO pQCD have used CT10 PDFs and ATLAS underlying event tune AU2.
Key words: Keywords

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Introduction

Search for the superior equation which would be able to explain all about the physical universe we do observe, sometimes called the Theory of Everything, led physicists to the concept of elementary particles some of which define the building blocks of our observable universe whereas the remaining govern the way how they interact.

From the beginning of the 20^{th} century, the term of elementary particles was redefined with new generation of physicists as is illustrated in Figure 1. The latest reform was caused by quarks and the invention of Quantum Chromodynamics describing its strong interaction which is next to the electromagnetic and weak interactions encapsulated by the present theory of elementary particles called the Standard Model.

Although Standard Model contains mechanism for assigning elementary particles masses, gravity was not included in Standard Model up to date because the present attempts of quantization gravity and description gravity as the interaction mediated by the quanta of gravity, known as graviton, led to the unrenormalizable theories.

Humans have build large particle accelerators to verify, if the Standard Model is the correct theory of particle physics. Next to these experiments, the huge telescopes on the Earth as well as in the orbit are looking to the distant galaxies. Although Standard Model have with the help of supercomputers succeeded in explanation of the structure and origin of recently observed objects (pulsars, neutron stars) and the description of Supernovas, the new yet unexplained phenomenons emerged including dark matter and dark energy.

Standard Model in its present form is not able to explain what these dark substances of our universe are. Fortunately there are some theories or better - some extensions of Standard Model - which could have answer. These include the Supersymmetry or the theories of Extra Dimensions.

The LHC run II which will start in June 2015 could find one of these expansions of the Standard Model is correct. This thesis deals with the measurement of inclusive jets double differential cross section in p_T and rapidity. Inclusive jets are the dominant objects observed on hadron colliders dominating any other observable physics process in orders of magnitude and could thus be the one of the first indicators that there is a new theory emerging.

First Chapter deals with the Quantum Chromodynamics and follows the historical development including experiments which led to the removing proton from the list of elementary particles and replacing it by the quarks. QCD will be formulated as the quantum field theory and the phenomenon known as the running coupling constant will be discussed. This will lead to the division of the QCD into perturbative and non-perturbative regions.

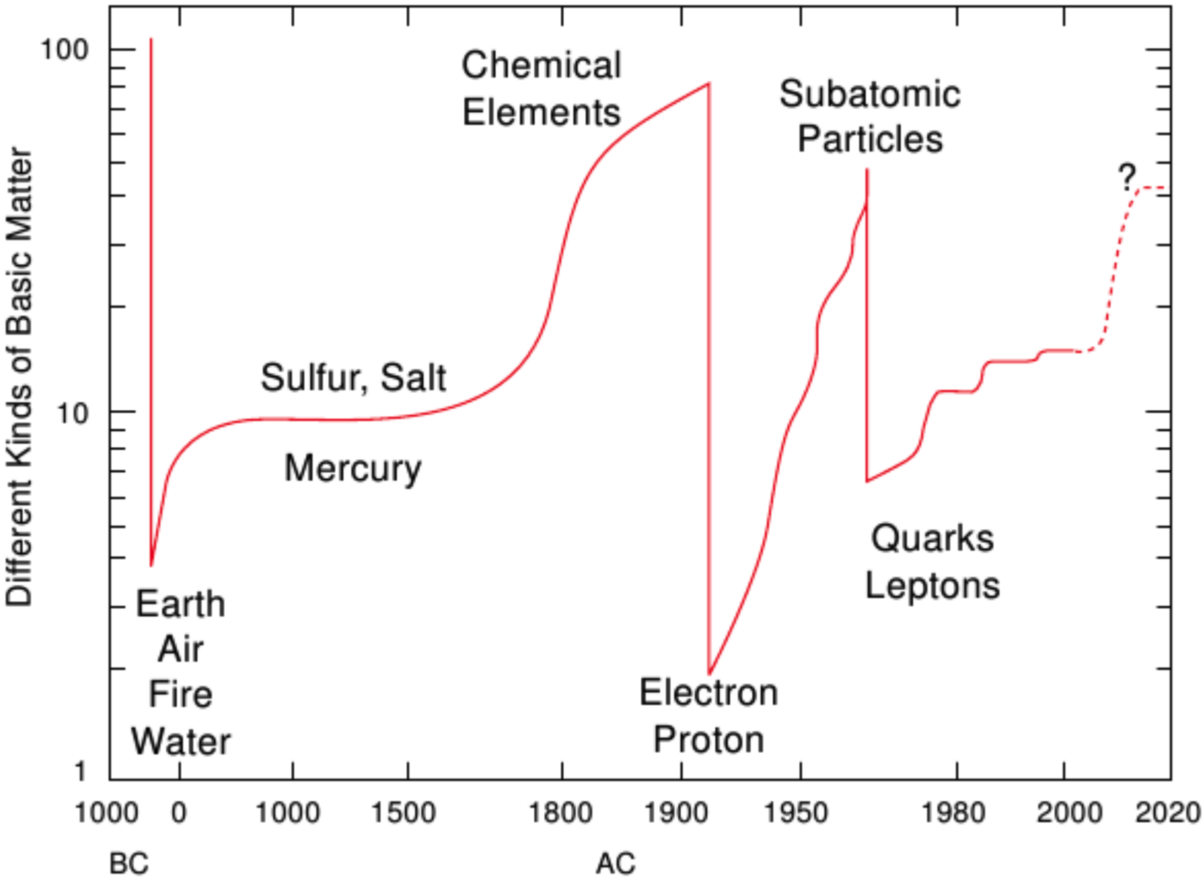


Figure 1: History of elementary particle physics. Figure From [?].

In the second Chapter, the Large Hadron Collider will be encountered with detailed description of its largest ATLAS detector. The basic features of QCD introduced in the previous chapter will be used to define jets - objects we do dominantly observe on hadron colliders. The jet reconstruction on ATLAS detector including description of jet calibration and unfolding of observed spectra will be presented in this chapter as well.

Third chapter describes the steps of analysis.

Chapter 1

QCD

Is the purpose of theoretical physics to be no more than a cataloging of all the things that can happen when particles interact with each other and separate? Or is it to be an understanding at a deeper level in which there are things that are not directly observable (as the underlying quantized fields are) but in terms of which we shall have a more fundamental understanding?

Julian Schwinger

The theoretical framework of particle physics is called the Standard Model (SM). The SM describes the way how the fundamental components of matter interact with each other through strong, weak and electromagnetic interactions. Mathematically the SM is gauge quantum field theory with local internal symmetries of the direct product group $SU(3) \times SU(2) \times U(1)$. Gauge bosons are assigned to generators of this symmetry - there are 8 massless gluons from $SU(3)$ and 3 massive $W^{\pm}, Z$ bosons with 1 massless boson γ from electroweak $SU(2) \times U(1)$ sector. Higgs mechanism has to be introduced in the electroweak sector to assign $W^{\pm}, Z$ bosons mass and as consequence the new particle - Higgs boson - emerges in the SM theory. All bosons have integer spin.

In addition to the bosons the SM introduces spin1/2 fermions which are divided into three quark and three lepton families. Fermions are assumed to be point-like because there is no evidence for their internal structure to date. All fermions interact weakly, if they have electrical charge, they interact electromagnetically as well. Quarks are the only fundamental fermions which do interact strongly. System of fundamental particles of the SM is shown in Figure 1.1.

Quarks bind together to form hadrons and there are hundreds [**?**] of known hadrons up to date. Hadrons are divided into baryons (3 quarks) and mesons (quark and anti-quark pairs). Theory describing the interaction between quarks is called Quantum Chromodynamics (QCD) which key features will be discussed in this chapter. The reasoning for quark existence and for the description their strong interaction as $SU(3)$ gauge theory will be presented. Running coupling constant will be discussed to split QCD into perturbative and non-perturbative regions

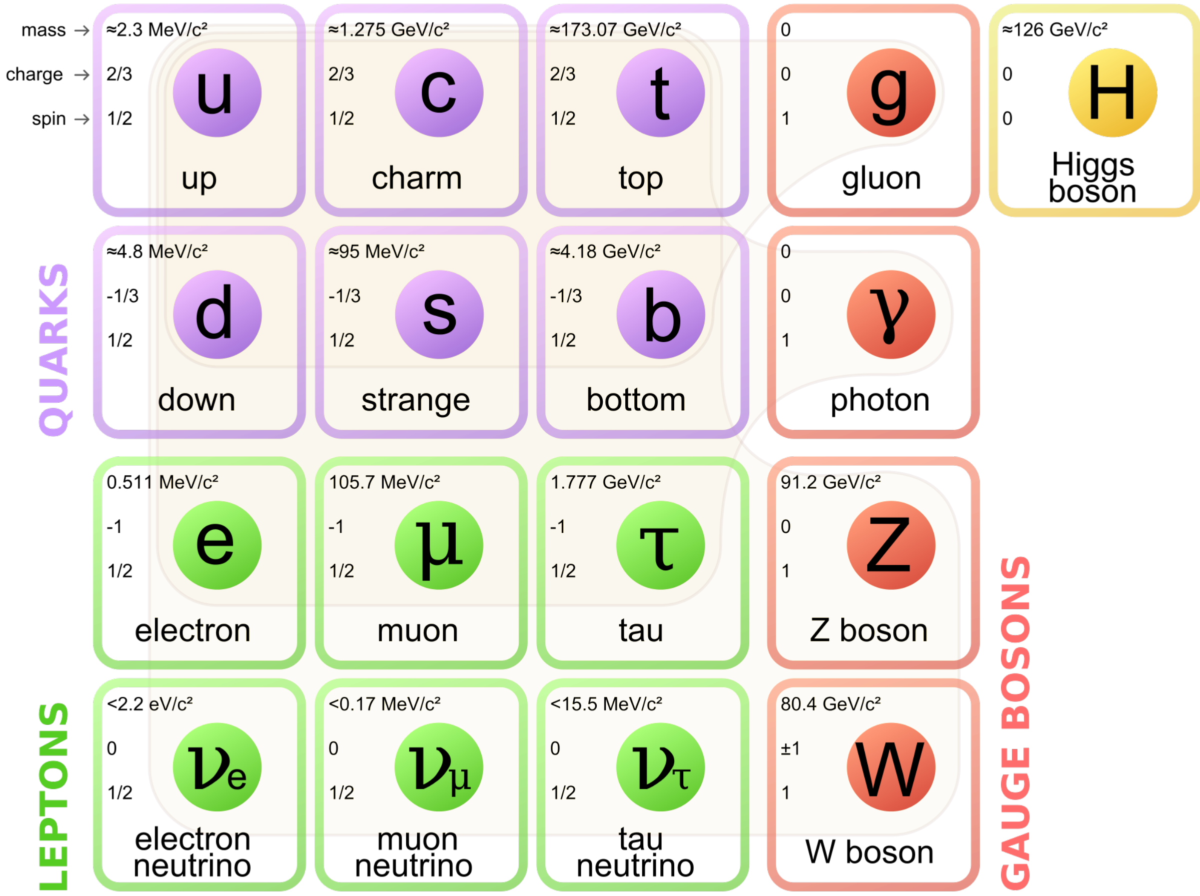


Figure 1.1: The system of fundamental particles of the SM. Figure from [1]

- two regions, where QCD has to use different mathematical approach for the description of strong interaction. Most of ideas presented here is overtaken from the following textbook [4]. Electroweak sector of the SM is described in [10]. For more concise information about the SM the following textbooks can serve [11, 12].

1.1 Theoretical Ansatz

In 1950s, there have already been discovered tens of new hadrons thanks to new particle accelerators and a lot of effort was exerted to categorize them. To each particle there was assigned a series of quantum numbers including isospin T with its third component T_3, hypercharge Y, electrical charge Q, strangeness S, baryon number B and others. Soon it was recognized, that there are some symmetries between these quantum numbers, like famous Gell-Mann–Nishijima relation [13, 14]

$$Q = T_3 + 1/2Y \quad , \quad Y = B + S + \ldots , \tag{1.1}$$

	S	Y	T	T_3	Q
p	0	1	1/2	1/2	1
n				-1/2	0
Σ^+	-1	0	1	1	1
Σ^0				0	0
Σ^-				-1	-1
Λ			0	0	0
Ξ^0	-2	-1	1/2	1/2	0
Ξ^-				-1/2	-1

Table 1.1: Quantum numbers of selected baryons known in 1950s. S strangeness, Y hypercharge, T isospin, T_3 third component of isospin, Q electrical charge.

where dots denote charm, bottomness and topness and were introduced after work of Gell-Mann and Nishijima. Some of the baryons known by then are shown in table 1.1. In 1960s, the known hadrons were successfully categorized with the so called Eightfold Way, which was published independently by Murray Gell-Mann [15] and George Zweig [16] in 1964. The Eightfold Way successfully predicted the existence of new particle Ω^- including its mass. Basic ideas of Eightfold way will be discussed in this section.

The key feature of Eightfold Way is to understand hadrons as the part of different representations of infinitesimal generators of $SU(3)$ flavor symmetry group. These infinitesimal generators of $SU(3)$ form the real eight-dimensional Lie algebra $\mathfrak{su}(3)$ which fundamental representation is usually derived from Gell-Mann matrices

$$\begin{aligned}
&\lambda_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \\
&\lambda_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \quad \lambda_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix} \\
&\lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \quad \lambda_7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix} \quad \lambda_8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}.
\end{aligned} \tag{1.2}$$

The generators are usually chosen $g_a = \frac{1}{2}\lambda_a$ and obey the commutation relation $[g_a, g_b] = i f_{abc} g_c$ with f_{abc} being structure constants. Cartan subalgebra of fundamental representation of $\mathfrak{su}(3)$ is generated by $H_1 = g_3$ and $H_2 = g_8$. The eigenstates of three-dimensional representation of $\mathfrak{su}(3)$ can be chosen

$$u = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \leftrightarrow \left(\frac{1}{2}, \frac{\sqrt{3}}{6} \right), \quad d = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \leftrightarrow \left(-\frac{1}{2}, \frac{\sqrt{3}}{6} \right), \quad s = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \leftrightarrow \left(0, -\frac{\sqrt{3}}{3} \right), \tag{1.3}$$

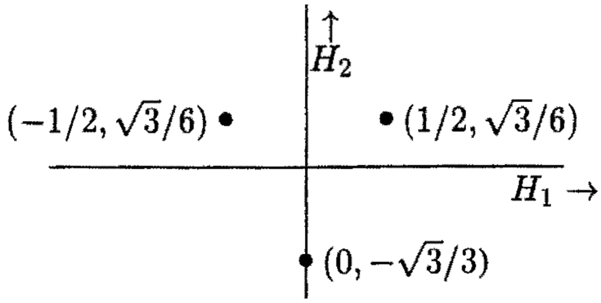


Figure 1.2: Eigenvalues of 3-dimensional representation of $\mathfrak{su}(3)$ Lie algebra. Figure from [2].

<table>
<tr><th></th><th>S</th><th>Y</th><th>T</th><th>T_3</th><th>Q</th></tr>
<tr><td>u</td><td rowspan="2">0</td><td rowspan="2">1/3</td><td rowspan="2">1/2</td><td>1/2</td><td>2/3</td></tr>
<tr><td>d</td><td>-1/2</td><td rowspan="2">-1/3</td></tr>
<tr><td>s</td><td>-1</td><td>-2/3</td><td>0</td><td>0</td></tr>
</table>

Table 1.2: Quantum numbers of three quarks which existence was predicted by Gell-Mann and Zweig in 1964.

where the eigenvalues to generators of the Cartan subalgebra was assigned $H_1 u = \frac{1}{2}u$, $H_2 u = \frac{\sqrt{3}}{6}u$ and similarly for d and s eigenstates. These eigenvalues are shown in Figure 1.2. Other important representation of $\mathfrak{su}(3)$ is eight-dimensional adjoint representation. This representation has the following eigenstates and corresponding eigenvalues

$$
\begin{aligned}
&\frac{1}{\sqrt{2}}\left(g_1 \pm i g_2\right) \leftrightarrow (\pm 1, 0)\,, \\
&\frac{1}{\sqrt{2}}\left(g_4 \pm i g_5\right) \leftrightarrow \left(\pm\frac{1}{2}, \pm\frac{\sqrt{3}}{2}\right), \\
&\frac{1}{\sqrt{2}}\left(g_6 \pm i g_7\right) \leftrightarrow \left(\mp\frac{1}{2}, \pm\frac{\sqrt{3}}{2}\right),
\end{aligned}
\tag{1.4}
$$

where again when denoting $A = \frac{1}{\sqrt{2}}(g_1 + i g_2)$ then the upper sign of the first expression reads $[H_1, A] = A$ and $[H_2, A] = 0$ and similarly for remaining 5 eigenstates. Defining

$$
H_1 = T_3 \quad \text{and} \quad H_2 = \frac{\sqrt{3}}{2} Y \tag{1.5}
$$

one can easily assign hadrons from table 1.1 to corresponding eigenvalues of adjoint representation in (1.4) according to its third component of isospin T_3 and its hypercharge Y. This is depicted in Figure 1.3.

When the same redefinition is done to the eigenstates of three-dimensional representation in (1.3), one can assign to eigenstates the hypercharge Y and strangeness S as well. The concrete values for states u, d, s are shown in table 1.2.

It is possible to find another representations of Lie algebra, to which the observed hadrons can be assigned. The simplest way seems to be through highest weight defining representa-

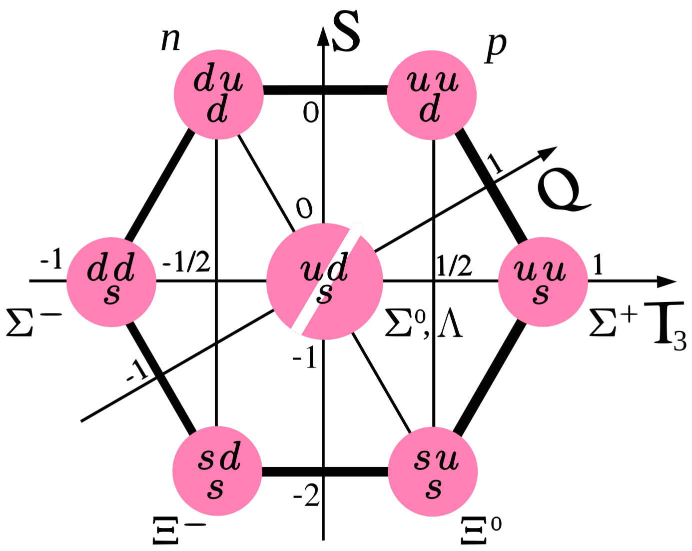


Figure 1.3: Baryonic octuplet encapsulating baryons from table 1.1. For baryons in this diagram, the relation $Y = S + 1$ holds. Figure from [3].

tion. From eigenvalues of adjoint representation (1.4) one can find simple roots $\alpha^1 = \left(\frac{1}{2}, \frac{\sqrt{3}}{2}\right)$, $\alpha^2 = \left(\frac{1}{2}, -\frac{\sqrt{3}}{2}\right)$, which are defining the highest weights $\mu^1 = \left(\frac{1}{2}, \frac{\sqrt{3}}{6}\right)$, $\mu^2 = \left(\frac{1}{2}, -\frac{\sqrt{3}}{6}\right)$. New representation of Lie algebra can be constructed from highest weight. This procedure is described in [2] in detail.

Representations defined by highest weight μ^1 or μ^2 respectively are called fundamental. Fundamental representation defined by μ^1 is usually denoted **3** and was encountered already by expressions (1.3) with weight diagram at Figure 1.2, corresponding to three different quark states. The second fundamental representation corresponds to three anti-quark states and is usually denoted $\bar{\mathbf{3}}$. Representation depicted in Figure 1.3 is defined by the highest weight $\mu^1 + \mu^2$.

Special interest is in representations with dimensions 10 and 8. These are present in decompositions $\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} = \mathbf{10} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{1}$, which correspond to the baryons composed of three quarks, and $\mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{8} \oplus \mathbf{1}$ corresponding to mesons from quark and anti-quark.

Important feature of quark model just presented is its capability to predict hadron masses. This is done using Gell-Mann–Okubo mass formula [17, 18]

$$M = a_0 + a_1 S + a_2 \left(T(T+1) - \frac{1}{4} S^2 \right), \tag{1.6}$$

where a_0, a_1 and a_2 are free parameters which are common for all hadrons in one multiplet.

In 1970 Sheldon Lee Glashow, John Iliopoulos and Luciano Maiani proposed [19] an extension which predicted existence of fourth flavor of quark - charm quark. In 1973 the Makoto Kobayashi and Toshihide Moskawa proposed [20] that the existence of 6 different quark flavors could explain the experimental observation of CP violation.

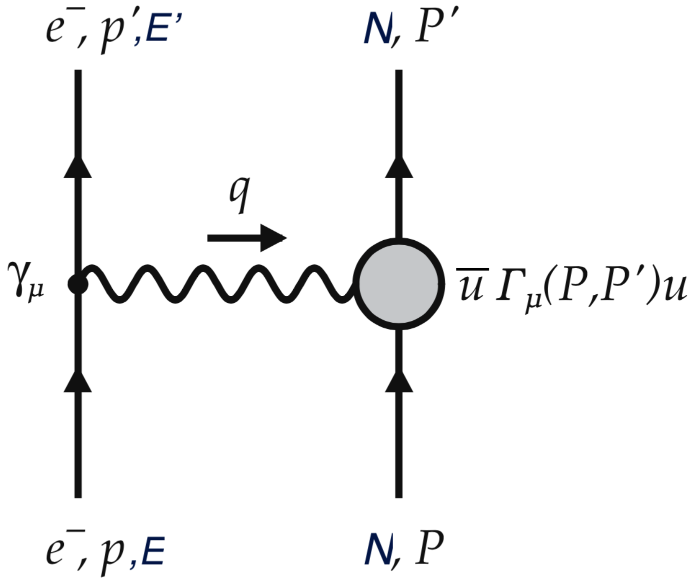


Figure 1.4: Scattering reaction $e^-N \to e^-N$ with kinematics variables and algebraic structures of vertices. Figure from [4].

1.2 Experimental Ground

In the previous section it was shown the hadrons can be categorized using representations of $\mathfrak{su}(3)$ Lie algebra. This lead to the model, where baryons were composed of three quarks whereas the mesons of quark and anti-quark. In this section, some experimental evidences will be presented to support quark model. First the scattering reactions will be discussed. It will be shown, that the lepton scattering on nucleons can be explained by assumption, that nucleons are composed of point-like spin-1/2 particles. Next discussion will address the fact, that there are three color charges - this will encounter the question, why the group $SU(3)$ is connected to the theory of strong interaction.

1.2.1 Scattering Reactions

One of the possibilities, how to find out, if there is some inner structure in nucleon N, are the scattering reactions

$$e^- \, (E \gg 1\,\mathrm{GeV}) + N \to e^- + N, \tag{1.7}$$

$$\nu_e \, (E \gg 1\,\mathrm{GeV}) + N \to \nu_e + N, \tag{1.8}$$

where the condition $E \gg 1\,\mathrm{GeV}$ is explicitly written to ensure the wavelength of lepton being $< 0.2\,\mathrm{fm}$. By the first scattering reaction, the information about electric charge distribution in nucleon can be extracted, whereas the second scattering reaction informs us about weak charge distribution. Further only (1.7) will be discussed. Feynmann diagram of this process is depicted with kinematics variables and vertex algebraic structures in Figure 1.4.

Because of Lorentz-invariance of QED, the matrix element of the nucleon vertex $\bar{u}(P', S')\Gamma_\mu u(P, S)$

has to be a Lorentz-vector. This restricts the possible form of Γ_μ to the following algebraic structure

$$\Gamma_\mu = A\gamma_\mu + BP'_\mu + CP_\mu + iDP'^\nu\sigma_{\mu\nu} + iEP^\nu\sigma_{\mu\nu}, \tag{1.9}$$

where $A,\ldots,E$ depend only on Lorentz-invariant quantities. Next condition which has to be taken into account, is gauge invariance of matrix element, which can be written in the form

$$q^\mu \bar{u}(P', S')\Gamma_\mu u(P, S). \tag{1.10}$$

The further computation of cross section is straightforward and the result can be easily generalized to non-elastic scattering by which the nucleon in final state decays. The result is usually written using inelasticity parameter $y = \frac{E-E'}{E}$, $0 \le y \le 1$, $y = 0$ corresponding to the elastic scattering, Bjorken variable $x = \frac{Q^2}{2P\cdot q}$, $0 < x \le 1$, $x = 1$ denoting elastic scattering and finally instead of negative value q^2 the $Q^2 = -q^2$ is used. Final result can be than written in the form

$$\left.\frac{d^2\sigma}{dxdy}\right|_{eN} = \frac{8\pi M_N E\alpha^2}{Q^4}\left[xy^2F_1^{eN}(Q^2,x) + (1-y)F_2^{eN}(Q^2,x)\right]. \tag{1.11}$$

The eN sub(super)script stresses the fact, we are dealing with scattering (1.7). F_1^{eN} and F_2^{eN} are the so called structure functions, which are not determinable by the theory just presented - they have to be measured experimentally.

Structure constants were first measured by eP scattering at SLAC in 1968 [21] and shown the following results

1. for $Q^2 \ge 1\,\mathrm{GeV}$, there is no significant dependence of structure functions on Q^2 and
2. for $Q^2 \ge 1\,\mathrm{GeV}$, $F_2 \approx 2xF_1$.

These results can be explained by assumption nucleon being composed of point-like spin-1/2 constituents, for which R. P. Feynmann used term partons. In the following basic ideas of parton model will be presented. To ith parton, it is possible to assign momentum $P_{i,\xi}$

$$P_{i,\mu} = \xi_i P_\mu + \Delta P_{i,\mu} \quad , \quad \max_\mu(\Delta P_\mu) \ll \max_\mu P_\mu, \tag{1.12}$$

where $\xi_i \in \langle 0, 1\rangle$ and $\Delta P_{i,\mu}$ comes from the interaction between partons and it is assumed, the momentum coming from this interaction is much smaller than the total nucleon momentum P_μ. In addition, probabilities $f_i(\xi_i)$ that ith parton will carry ξ_i fraction of total momentum fulfilling

$$\int d\xi_i f_i(\xi_i) = 1 \tag{1.13}$$

must be defined. Then for scattering reaction (1.7) the total cross section formula can be derived

$$\left.\frac{d^2\sigma}{dxdy}\right|_{eN} = \frac{4\pi M_N E\alpha^2}{Q^4}\left[y^2 + 2(1-y)\right]\sum_i f_i(x)q_i^2 x. \tag{1.14}$$

where for ith parton its electrical charge q_i was introduced. The last expression and (1.11) can be compared as polynomials in y resulting in

$$F_1^{eN}(x) = \frac{1}{2}\sum_i f_i(x)q_i^2 \quad , \quad F_2^{eN}(x) = \sum_i f_i(x)q_i^2 x. \tag{1.15}$$

It can be easily checked, that $F_2^{eN}(x) = 2xF_1^{eN}(x)$. Functions $f_i(x)$ just introduced are called Parton Distribution Functions (PDFs) and their important role in QCD will be discussed in (?somewhere?) in more details.

Important conclusion from analyzing of scattering reactions is, that the experimental results can be explained by assumption nucleons being composed of spin-1/2 point-like partons, now called quarks.

1.2.2 Number of Colors

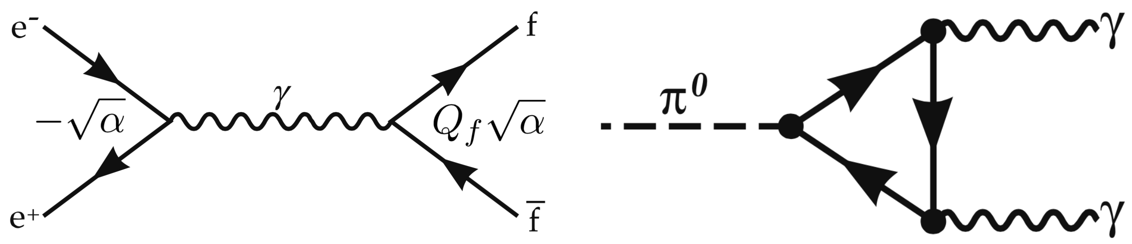
Despite the strong confidence in the parton model, a theory which would describe the interaction between partons was still missing. There was no direct evidence on how the theory would look like at the beginning of 1970s. The theory of electroweak unification successfully suggested, that the gauge theories are the right theories for the description of our world at the subatomic level, but to construct gauge theory of strong interaction the number of colors first had to be known.

Number of colors N_C is the number of different kinds of quarks of the same flavor with respect to the new interaction. In this part, three arguments will be presented to demonstrate, that $N_C = 3$.

The first argument is the analysis of the electron-positron anihilation into the pair of fermion and anti-fermion

$$e^+e^- \to f\bar{f}. \tag{1.16}$$

Feynmann diagram of this reaction is shown in Figure 1.5a, where constants sitting in two vertices are empahised. α stands for fine structure constants and Q_f for charge of fermion f in units of positron charge. Total cross section has to be proportional to



(a) $e^+e^- \to f\bar{f}$ (b) $\pi^0 \to 2\gamma$

Figure 1.5: (a) e^-e^+ annihilation itno the pair of fermion anti-fermion. Constants siting in both vertices are dented with α being the fine structure constant and Q_f the charge of fermion f in units of positron charge. (b) π^0 meson decay into pair of photons with closed fermion loop.

$$\sigma(e^- e^+ \to f\bar{f}) \sim Q_f^2 \alpha^2. \tag{1.17}$$

In the case fermion f being quark, there is new degeneracy in final state coming from different colors of quarks in final state - the total cross section has to be multiplied by factor N_C. Experimentally, the so called R-factor is measured

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = \left(\sum_q Q_q^2\right) N_C, \tag{1.18}$$

where sum on the left hand side is over all possible quark states. When the quark model proposed by Gell-Mann a Zweig is used, then for the quark charges in table 1.2

$$R = \left[\left(\frac{2}{3}\right)^2 + \left(\frac{-1}{3}\right)^2 + \left(\frac{-1}{3}\right)^2\right] N_C = \frac{2}{3} N_C. \tag{1.19}$$

Experimental results for R-ratio have shown [22], that $N_C = 3$.

The second argument is the measurement of decay width of π_0 meson. Decay is depicted in Figure 1.5b. For decay width Γ it can be derived

$$\Gamma = 7.63 \left(\frac{N_C}{3}\right)^2 \text{eV}, \tag{1.20}$$

which, compared to the experimental value $\Gamma = 7.57 \pm 0.32\,\text{eV}$ [22] leads again to $N_C = 3$.

The third argument is purely theoretical and states, that the SM is internally consistent only if there are three colors [4]. This indicates that there is some linking between electroweak and strong sector of SM and motivates the search for Grand Unified Theories.

1.3 QCD as a Gauge Theory

Putting arguments of previous section all together, there is strong experimental evidence, that nucleons consist of point-like spin-1/2 particles called quarks and that quarks bring into the theory new degeneracy factor $N_C = 3$, which can be understood as three different strong charges called colors.

Nowadays the quark-quark strong interaction is understood as an $SU(3)$ gauge theory in a degree of freedom called color. Gell-Mann matrices (1.2) can be chosen as generators of $SU(3)$. These matrices act on quark color triplets wave functions

$$\psi(x) = \begin{pmatrix} \psi_r(x) \\ \psi_g(x) \\ \psi_b(x) \end{pmatrix}. \tag{1.21}$$

Following the Yang-Mills theory [23], to each generator $\frac{\lambda^a}{2}$ gluon field $A_\mu^a(x)$ and gluon file strength tensor

$$F_{\mu\nu}^a = \left(\partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g f^{abc} A_\mu^b A_\nu^c\right) \tag{1.22}$$

is assigned where g denotes the coupling constant of strong interaction and f^{abc} are structure constant defined in section 1.1. QCD Lagrangian

$$\mathscr{L}_{\mathrm{QCD}} = \bar{\psi}\left(-i\partial_\mu + g\frac{\lambda}{2}A^a_\mu(x)\right)\gamma^\mu\psi - \frac{1}{4}F^a_{\mu\nu}F^{\mu\nu}_a \tag{1.23}$$

is invariant under local transformation

$$\begin{aligned}\psi(x) \; &\to \psi'(x) = \mathrm{e}^{ig\Theta(x)}\psi(x), \\ A_\mu(x) &\to \mathrm{e}^{ig\Theta(x)}\left(A_\mu(x) + \frac{i}{g}\partial_\mu\right)\mathrm{e}^{-ig\Theta(x)},\end{aligned} \tag{1.24}$$

where

$$\Theta(x) = \frac{1}{2}\lambda^a\Theta^a(x) \quad , \quad A_\mu(x) = \frac{1}{2}\lambda^a A^a_\mu(x). \tag{1.25}$$

There is no mass term in Lagrangian (1.23) because mass term $m\bar{\psi}\psi$ vary under gauge transformation (1.24). Origin of mass term lies in Higgs mechanism [24] which is explained in [10] in details.

QCD Lagrangian (1.23) together with gauge transformations (1.24) are sufficient for determination of Feynman rules - key ingredient in perturbative QCD which will be discussed in next section.

By derivation of gluon propagator, one has to add to the QCD Lagrangain the so called gauge-fixing term

$$\mathscr{L}^{\text{gauge-fixing}}_{\mathrm{QCD}} = -\frac{1}{2\xi}\left(\partial_\mu A^\mu_a\right)^2, \tag{1.26}$$

which confines the possible gauges to one class parametrized by real parameter ξ. In non-Abelian gauge theories this term must be supplemented by the so called ghost term which brings into the theory new unphysical scalar particle obeying fermionic statistics. More details on so called Faddev-Popov ghost filed can be found in [25].

1.4 Perturbative QCD

Quantum Electrodynamics (QED) and QCD are both quantum filed gauge theories, but they differ in one killing feature - the former is Abelian whereas the latter is not. The non-Abelian character of QCD leads to new phenomenons which have the origin in QCD Lagrangian (1.23) directly leading to triple and quartic gluonic interactions. In this section one remarkable consequence will be discussed - the running coupling constant.

Assume scattering process

$$q\bar{q} \to q\bar{q}, \tag{1.27}$$

which is depicted in the lowest order of perturbation theory by the Feynman graph in Figure 1.6. Except contribution of this graph to the scattering amplitude (which is the only contribution

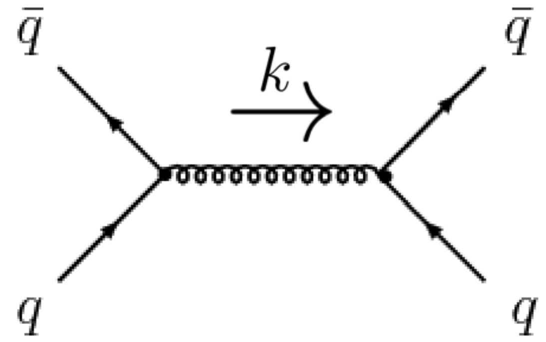


Figure 1.6: Leading order Feynmann diagrams in scattering reaction $q\bar{q} \to q\bar{q}$ with denoted transfered momentum k.

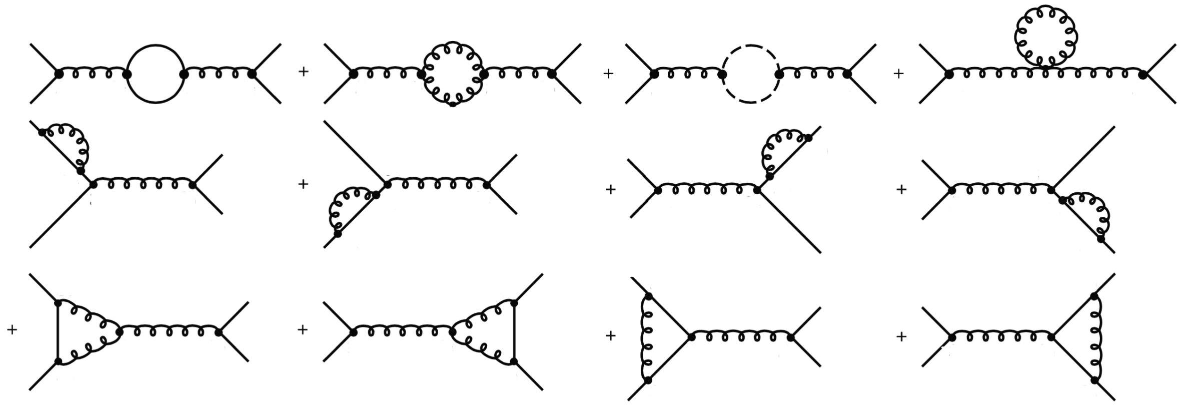


Figure 1.7: Next to the leading order Feynmann diagrams in scattering reactions $q\bar{q} \to q\bar{q}$. Dashed line represents scalar ghost particle.

$\sim g^2$) there are 12 other Feynman diagrams with contributions $\sim g^4$. These are depicted in Figure 1.7.

The contributions from new Feynman diagrams are calculated in [4] in detail. There is shown, that all this contributions together are logarithmically divergent. This divergence can be removed, when from the scattering amplitude for arbitrary momentum transfer k^2 scattering amplitude for fixed momentum transfer $k^2 = -M^2$ is subtracted. This is how the renormalized coupling constant g_R is obtained and here is its final expression

$$g_R = g_0 - \frac{g_0^3}{16\pi^2}\left(\frac{11}{2} - \frac{1}{3}N_F\right)\ln\left(\frac{-k^2}{M^2}\right) + \mathscr{O}(g_0^5). \tag{1.28}$$

g_0 stands for the coupling constant measured at the renormalization scale $k^2 = -M^2$ and N_F is the number of different quark flavors with mass $m^2 \ll |k^2|$. Dependence of g_R on transfered momentum k^2 is evident, but there are another two intertwined dependences - on normalization scale M and on coupling constant at renormalization scale $g_0 = g_R|_{k^2=-M^2}$. For next purpose, it is convenient to use the dependence schema

$$g_R = g_R(-k^2, g_0(M)) \tag{1.29}$$

which allows the use of advantages of β-function and when the equation (1.28) is used, then the differential equation for $g_0(M)$ can be obtained

$$\beta(g_0) \equiv M \left(\frac{\partial g_R}{\partial M}\right)_{-k^2=M^2} = M \left(\frac{dg_0}{dM}\right)_{-k^2=M^2} \tag{1.30}$$

$$= -b_0 g_0^3 + \mathscr{O}(g_0^5), \quad b_0 = \frac{1}{16\pi^2}\left(11 - \frac{2N_F}{3}\right), \tag{1.31}$$

which can be solved directly to obtain coupling constant g_0 for arbitrary scale $-k^2$

$$\int_{g_0(M^2)}^{g_0(-k^2)} \frac{dg_0}{g_0^3} = -b_0 \int_{M^2}^{-k^2} \frac{dM}{M} \tag{1.32}$$

with solution

$$\alpha_S(-k^2) = \frac{\alpha_S(M^2)}{1 + \frac{\alpha_S(M^2)}{4\pi}\left(11 - \frac{2N_F}{3}\right)\ln\left(\frac{-k^2}{M^2}\right)}, \quad g_0^2(-k^2) = 4\pi\alpha_S(-k^2), \tag{1.33}$$

which is the final expression for running coupling constant up to one-loop order. This dependence corresponds to experimental data which are depicted in Figure 1.8. Coupling constant decreases with increasing momentum transfer allowing the use of the perturbation theory. This is known as Asymptotic Freedom [26].

On the other hand, when the momentum transfer decreases, there is special value $-k^2 = \Lambda^2$ for which the last expression diverges

$$-1 = \frac{\alpha_S(M^2)}{4\pi}\left(11 - \frac{2N_F}{3}\right)\ln\left(\frac{\Lambda^2}{M^2}\right). \tag{1.34}$$

Experimental value is $\Lambda = 213^{+38}_{-35}\,\mathrm{MeV}$ [27] and demonstrates, that perturbative QCD cannot be used at low energy transfers. In fact, the running coupling constant $\alpha_S(-k^2)$ reaches value ~ 1 on momenta transfers $\sqrt{|k^2|} \sim 500\,\mathrm{MeV}$.

The behaviour of coupling constant at low energy transfers is not explainable in the language of perturpative QCD just presented. It is non-perturbative effect known as the principle of color confinment, which states, that quarks when seperate, the gluon force field between them becomes stronger and its energy is consumed by the creation of quark anti-quark pair. This continues until there is no free color charge left. This principle forbids us from observing free quarks.

To understand e.g. structure of proton with rest mass $< 1\,\mathrm{GeV}$ it is clear non-perturbative QCD has to be used. The ideas of non-perturbative QCD will be introduced in next section.

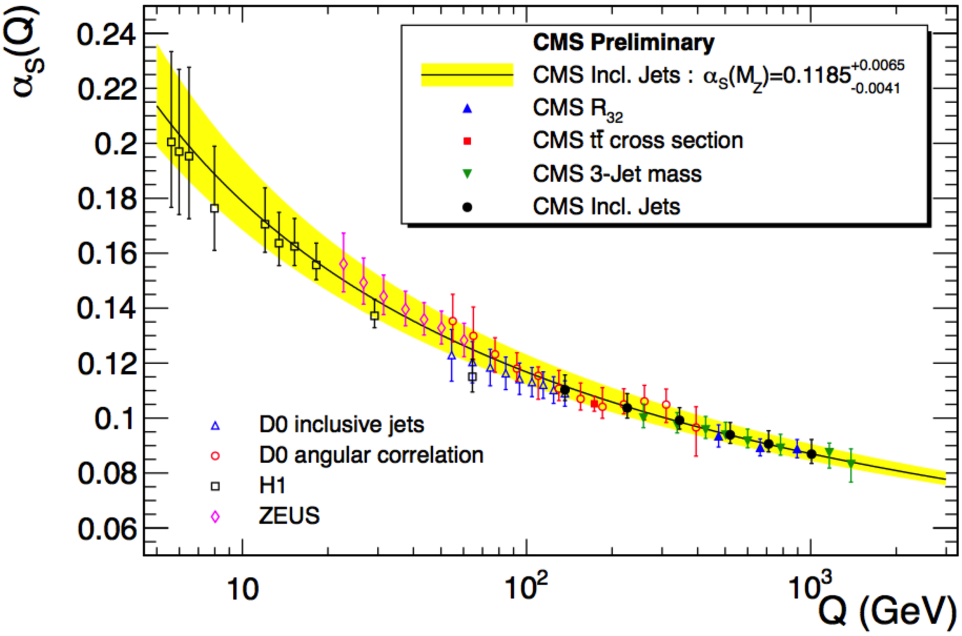


Figure 1.8: Experimental measurements of running coupling constant $\alpha_S(Q)$ (solid line) and its uncertainty (yellow band). $Q = \sqrt{|k^2|}$ in comparison to (1.33). Figure from [5].

1.5 Non-Perturbative QCD

The most well established non-perturbative approach to QCD is the lattice QCD (LQCD). In this section basic features of the LQCD will be presented. More informations on this extended topic can be found in [4, 28].

LQCD is QCD formulated on a hypercubic equally spaced lattice in space and time with lattice parameter a denoting the distance between neighboring sites. Quark fields are placed on sites whereas the gluon fields sit on the links between neighboring sites. From QCD it inherits the gauge invariance which has to be formulated on lattice structure. For $a \to 0$ action of LQCD coincides with that of QCD. LQCD contains 6 parameters - strong coupling constant and masses of 5 quarks (the top quark with lifetime $\sim 10^{-24}$ s is not assumed by the theory).

Unlike perturbative expansion used in continuous QCD, numerical evaluation of the path integral defining LQCD allows non-perturbative calculations. Practical LQCD calculations are limited by the availability of computational resources and the efficiency of algorithms. LQCD suffers with both statistical and systematic errors, the former arising from the use of Monte-Carlo integration, the latter, e.g. from the use of non-zero values of a.

Present LQCD calculations are made on supercomputers like the QCDCQ supercomputer [29] with peak speed of 500 TFlops using lattice spacing $a \sim 0.05 - 0.15\,\mathrm{fm}$ in lattice volume $V \sim (2 - 6\,\mathrm{fm})^3$.

The Importance of LQCD lies in its ability to predict mass spectrum of observed mesons and baryons, including quark masses itself, and in investigation of topological structure of QCD vacuum. LQCD can be used to obtain PDFs (1.13) helping us to understand the structure of hadrons. Phenomenology of LQCD explains also the principle of color confinment.

Chapter 2

Experimental Framework

What we observe is not nature itself, but nature exposed to our method of questioning.

Werner Heisenberg

In the previous chapter, the key features of QCD - today's theory of strong interaction - were introduced. The predictions of QCD are tested at particle accelerators persistently with no signs for new physics so far. Large Hadron Collider which will open energy regions not observed yet can change this very soon.

Jets are the most important objects observed on hadron colliders, which allows the QCD predictions being confronted with the experiment. In this chapter, after the introduction of the Large Hadron Collider and the ATLAS detector, jet algorithms and the way how jets are reconstructed on the ATLAS detector will be described.

2.1 The Large Hadron Collider and The ATLAS Detector

2.1.1 The Large Hadron Collider

The Large Hadron Collider (LHC) [30,31] is a charged particle accelerator located on the border of France and Switzerland, near Geneva. Built using the areas of the Large Electron-Positron collider, the main accelerator ring, of a 27 km circumference, is located around 100 m below the surface. There are four main experiments located around the ring: A Large Ion Collider Experiment (ALICE), A Toroidal LHC ApparatuS (ATLAS), Compact Muon Solenoid (CMS) and Large Hadron Collider beauty (LHCb). The complete accelerator and detector system is shown in Figure 2.1.

LHC started to operate on November 23, 2009 and soon thereafter (March 30, 2010) the proton-proton collisions achieved the center-of-mass energy $\sqrt{s} = 7\,\mathrm{TeV}$, which is a half of the design energy of the machine. On April 5, 2012, the machine started its successful $\sqrt{s} = 8\,\mathrm{TeV}$ run.

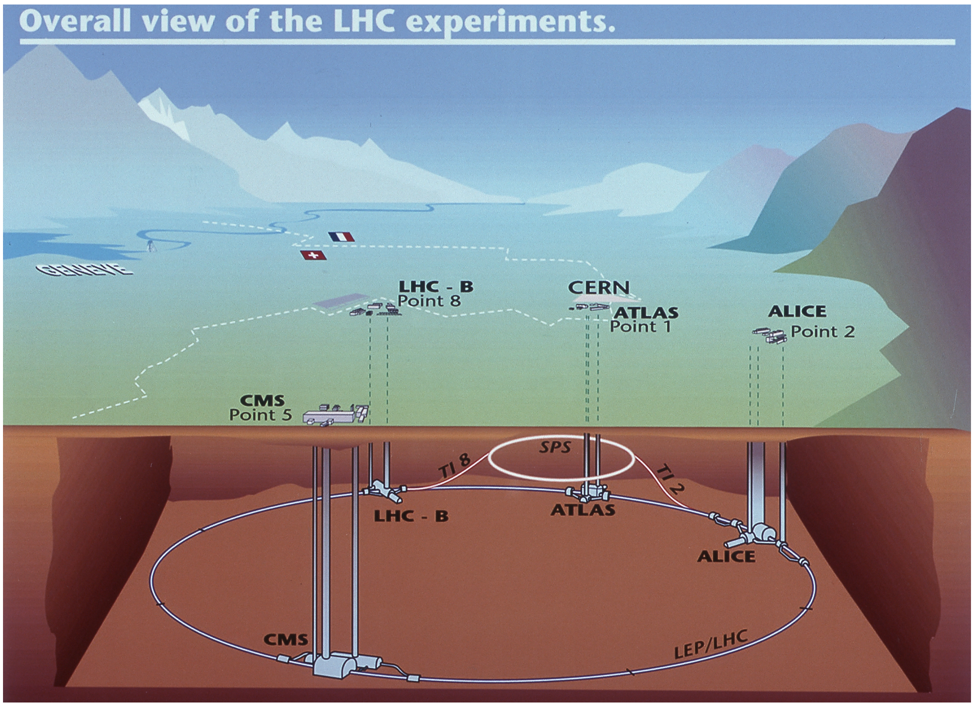


Figure 2.1: This diagram shows the locations of the four main experiments (ALICE, ATLAS, CMS and LHCb) that take place at the LHC. Located between 50 m and 150 m underground, huge caverns have been excavated to house the giant detectors. The Super Proton Synchotron (SPS), the final link in the pre-acceleration chain, and its connection tunnels to the LHC are also shown. Figure from [6].

Next to the proton-proton collisions, first heavy-ion Pb-Pb collisions took place in 2010 at a center of mass energy per pair of colliding nucleons $\sqrt{s} = 2.76\,\text{TeV}$. Proton-Pb collisions at $\sqrt{s} = 5.02\,\text{TeV}$ occurring on LHC during 3 weeks of 2013 successfully demonstrated LHC capability to provide asymmetric collisions.

The first running period of the LHC, Run I, was very successful and resulted in the discovery of the Higgs boson on July 4, 2012 [32]. The accelerator complex including its experiments has been upgraded for two years and the Run II is expected to start in summer 2015 [33, 34]. In Run II the center-of-mass energy of proton-proton collisions will be raised to $\sqrt{s} = 13\,\text{TeV}$ and the beam crossing time will be reduced from the current 50 ns to 25 ns. The expected integrated luminosity is $\sim 100\,\text{fb}^{-1}$.

2.1.2 The ATLAS Detector

The ATLAS detector [35] is a general-purpose detector surrounding one of the interaction points of the LHC and with $\sim$ 100 million of individual electronic channels it is the most complicated instrument ever created. The purpose of the ATLAS detector is to record particle collisions up to the center-of-mass energy per pair of colliding nucleons $\sqrt{s} = 14\,\text{TeV}$. A detector overview is shown in Figure 2.2a, where the main sub-detector systems can be seen: the inner detector, used to reconstruct charged-particle tracks, the electromagnetic calorimeters, the hadronic calorimeters, and the muon spectrometer.

ATLAS uses a right-handed coordinate system with its origin at the interaction point in the center of the detector and the z axis along the beam pipe. The x axis points from the interaction point to the center of the LHC ring, and the y axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. Instead of polar angle θ, pseudorapidity η is often used. In this thesis the rapidity y is used as the polar angle coordinate. In following definitions of pseudorapidity η and rapidity y, E stands for the total energy and p for size of total momentum:

$$\eta = -\frac{1}{2}\ln\left(\frac{p+p_z}{p-p_z}\right) = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right], \tag{2.1}$$

$$y = -\frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right). \tag{2.2}$$

The transverse momentum $p_T = \sqrt{p_x^2 + p_y^2}$ presents the component of momentum perpendicular to the beam line.

The main detector system relevant to this thesis is the ATLAS calorimeter, which is emphasized in Figure 2.2b. The calorimeter is divided into sub-detectors, providing overall coverage up to $|\eta| < 4.9$. The electromagnetic calorimeter, covering region $|\eta| < 3.2$, is a high-granularity sampling detector in which the liquid argon (LAr) active medium is interspaced with layers of lead absorber. The hadronic calorimeters are divided into three sections: a tile scintillator/steel calorimeter is used in both the barrel ($|\eta| < 1.0$) and extended barrel cylinders ($0.8 < |\eta| < 1.7$) while the hadronic endcap ($1.5 < |\eta| < 3.2$) consists of LAr/copper calorimeter modules. The forward calorimeter measures both electromagnetic and hadronic energy in the range $3.2 < |\eta| < 4.9$ using LAr/copper and LAr/tungsten modules.

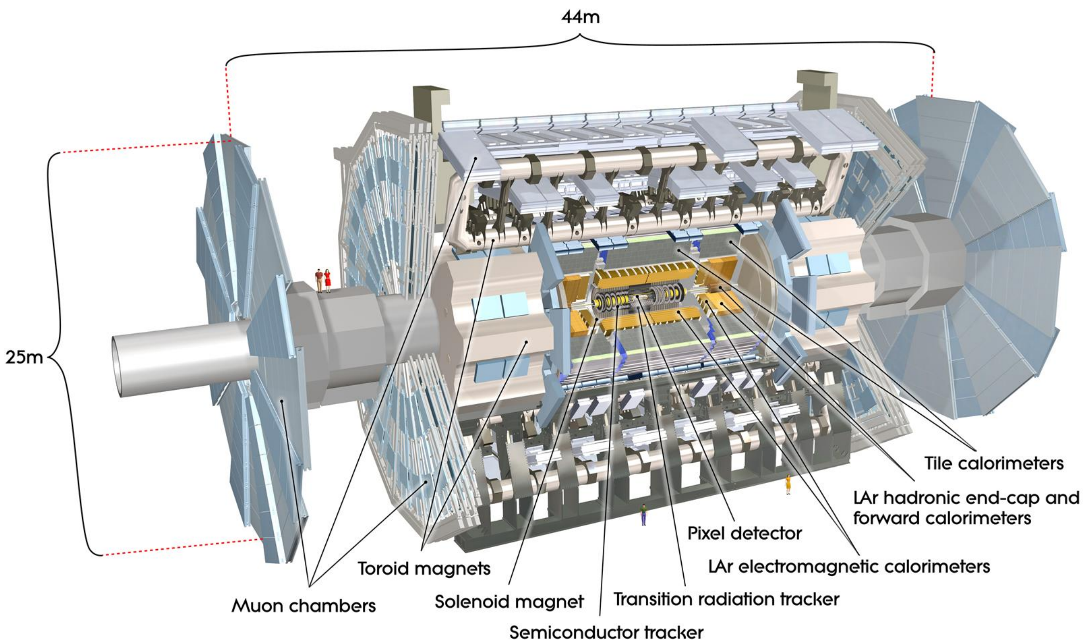
2.2 Hadron Collision at LHC

In this section the phenomenological description of proton-proton collisions will be presented following Figure 2.3 and Reference about Monte Carlo event generators [22].

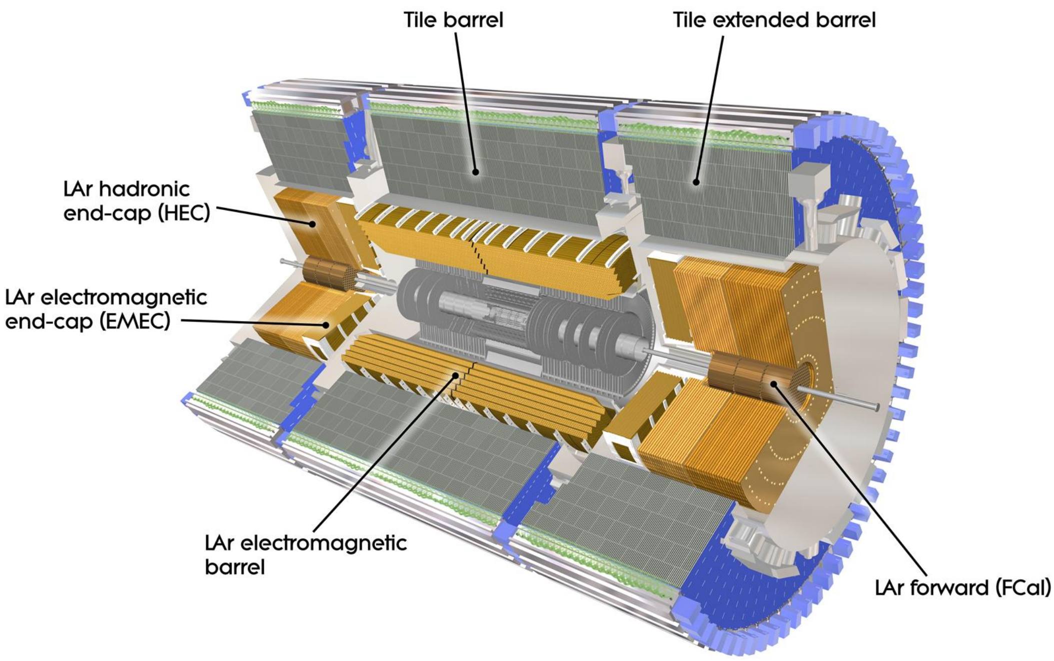
Two incoming protons can be understood as two bags of partons. The collision is dominated by the strong interaction of two partons - one from each of the colliding hadrons. These partons are called incoming partons and the momentum transfer by their interaction is $Q \gg \Lambda$, so the perturbative QCD can be used to describe the process of hard scattering. The remaining energy is carried by the remaining partons, which create the so called underlying event - particles, which do not come from the hard QCD processes.

When partons are sufficiently from each other, the non-perturbative QCD has to be used to describe the process of hadronisation, by which a set of colored partons is transformed into a set of colorless primary hadrons which may then decay further.

During the collision, the electric and color charges of partons interact resulting in radiation of photons $q \to q\gamma$ and gluons $q \to qg$. These processes are described by perturbative QCD and lead



(a) ATLAS detector



(b) Inner detector and calorimeter systems

Figure 2.2: (a) an overview of the ATLAS detector (b) detail on the inner detector and the calorimeters - the dominant sub-detector systems used in this thesis. Figures taken from [7].

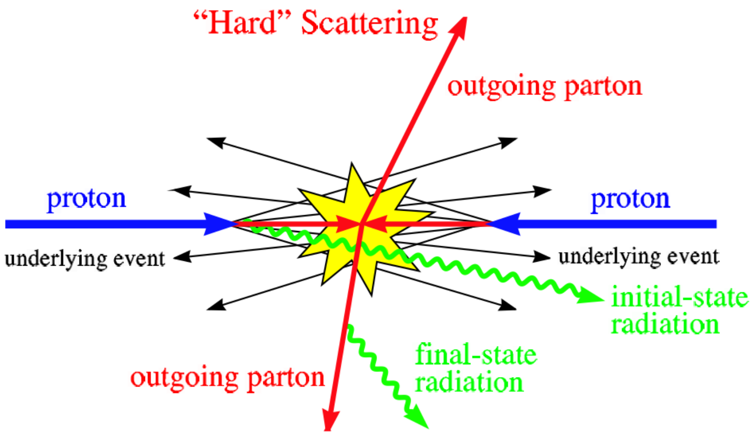


Figure 2.3: Schematic representation of a hard scattering proton-proton collision. Figure taken from [8].

to infrared and collinear divergences. However, infrared divergences are canceled by Kinoshita–Lee–Nauenberg theorem [36, 37], so only collinear divergences remain. There is no mechanism known up to date, which would solve the problem with collinear divergence. However, observables inclusive enough to be insensitive to processes that distinguish between different numbers of partons are not affected by infrared divergences. There is no possibility how to theoretically predict the energy of hardest outgoing particle, but it is possible to predict the energy flow in a cone from the point of scattering.

This is where the term jet comes to play. A jet can be naively seen as a group of collimated particles generated by the hadronisation of a parton in the scattering process and is the most important object used on hadron colliders for analysis of QCD processes.

2.3 Jet Algorithms

Jet algorithm is a generic "recipe" which takes a set of particles (or other objects with defined four-momenta) and returns jets created from them. The jet algorithm usually involves a set of parameters which the algorithm fully specify the jet definition. According to the remarks at the end of the previous section, jet algorithms should fulfill the following conditions

1. Infrared safety - the presence of additional soft particles should not affect the recombination of these particles into a jet.
2. Collinear safety - jet reconstruction should not depend on the fact, if the transverse momentum is carried by one particle, or if the particle is split into two collinear particles.

Two important steps must be defined in each jet algorithm

1. Clustering - description how the input objects are clustered into jets.
2. Recombination - determination of physical quantities of jets.

Additional steps may include the preclustering reducing the number of input objects for jet algorithm.

Two jet algorithms are described here - fixed cone algorithm and k_t algorithm. First of these algorithms is more illustrative, the second one is used in ATLAS. These algorithms use two different recombination schemes which description will follow. Detailed description as well as other jet algorithms can be found in [?, 38]. After definitions of jet algorithms it is shortly described, how the objects (not necessary particles) with defined four-momenta are constructed from the signal observed on the ATLAS detector.

2.3.1 Fixed cone algorithm

The first step of this algorithm is to order all input objects (reconstructed detector objects with four-momentum representation) in decreasing order of transverse momentum p_T. If the object with the highest p_T is above the seed threshold, all objects within a cone in rapidity y and azimuth ϕ with $\Delta R = \sqrt{\Delta y^2 + \Delta\phi^2} < R_{cone}$, where R_{cone} is the fixed cone radius, are recombined using Snowmass recombination scheme (see Section 2.3.3). A new cone is centered around a new direction and the objects in the new cone are recombined and again the direction is updated. This process continues until the direction of the cone does not change anymore after recombination, at which point the cone is considered stable and is called a proto-jet.

At this point, the next seed is taken from the input list and a new proto-jet is formed with the same iterative procedure. This continues until no more seeds are available.

The proto-jets found by this procedure can share some constituents. Constituents shared between two proto-jets are recombined into new proto-jet and if the ratio $E_T^{shared}/\min(E_T^{neighbor}) > f$ is over the certain threshold $f = 0.5$ the neighboring proto-jets are recombined into one proto-jet (shared constituents are taken only once). If this condition is not satisfied, the shared constituents are assigned to the nearest proto-jet. When proto-jet does not share constituents it is recombined into the jet using four-momentum recombination (see Section 2.3.3).

This algorithm is both not infrared safe (Figure 2.4a) and not collinear safe (Figure 2.4b). The infrared sensitivity can be improved by adding the midpoints between pairs of proto-jets fulfilling $R_{cone} < \Delta R < 2R_{cone}$ and repeating the iterative procedure with midpoints being new seeds. Since the collinear unsafety arises from the use of seed towers, Seedless cone algorithm was developed, which searches the entire detector to find all stable proto-jets.

Parameters used by fixed cone algorithm are a seed threshold of $p_T > 1\,\mathrm{GeV}$, and a narrow ($R_{cone} = 0.4$) or a wide cone jet ($R_{cone} = 0.7$) option.

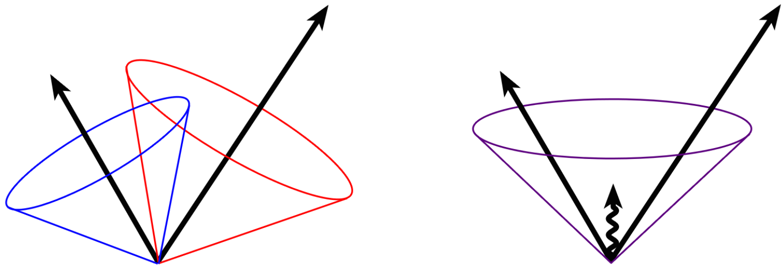
2.3.2 k_t algorithms

In this class of algorithms all pairs (i, j) of input objects are analyzed with respect to their relative transverse momentum squared, defined by

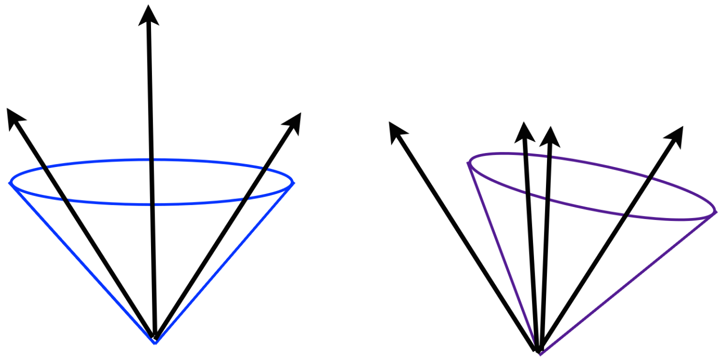
$$d_{ij} = \min\left(p_{T,i}^{2p}, p_{T,j}^{2p}\right)\frac{\Delta R_{ij}^2}{R^2} \tag{2.3}$$

and the squared p_T of object i relative to the beam axis

$$d_i = p_{T,i}^{2p}. \tag{2.4}$$



(a) Infrared unsafety



(b) Collinear unsafety

Figure 2.4: Illustration of (a) infrared unsafety and (b) collinear unsafety of fixed cone jet algorithm. Figures from [9].

Here $\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$ and $p_{T,i}$, y_i and ϕ_i are respectively the transverse momentum, rapidity and azimuth of particle i. In addition to the radius parameter R, parameter p was added to split k_t algorithms into three categories.

- $p = 1$ k_t algorithm,
- $p = 0$ Cambridge/Aachen algorithm,
- $p = -1$ anti-k_t jet-clustering algorithm.

The differences between these algorithms are detailed described in [39]. Recombination of calorimeter signal towers (see Section 2.3.4) in jets is for k_t and anti-k_t algorithms shown at Figure 2.5.

These algorithms first find the minimum d_{min} of all d_{ij} and d_i. If d_{min} is in d_{ij}'s, the corresponding objects i and j are combined into a new object k using four-momentum recombination. Both objects i and j are removed from the list, and the new object k is added to it. If d_{min} is in d_i's, the object i is considered to be a jet by itself and is removed from the list.

This means that all original input objects end up to be either part of a jet or to be jets by themselves. Contrary to the cone algorithm described earlier, no objects are shared between jets and the procedure is both infrared and collinear safe.

ATLAS uses anti-k_t algorithm with $R = 0.4$ for narrow and $R = 0.6$ for wide jets.

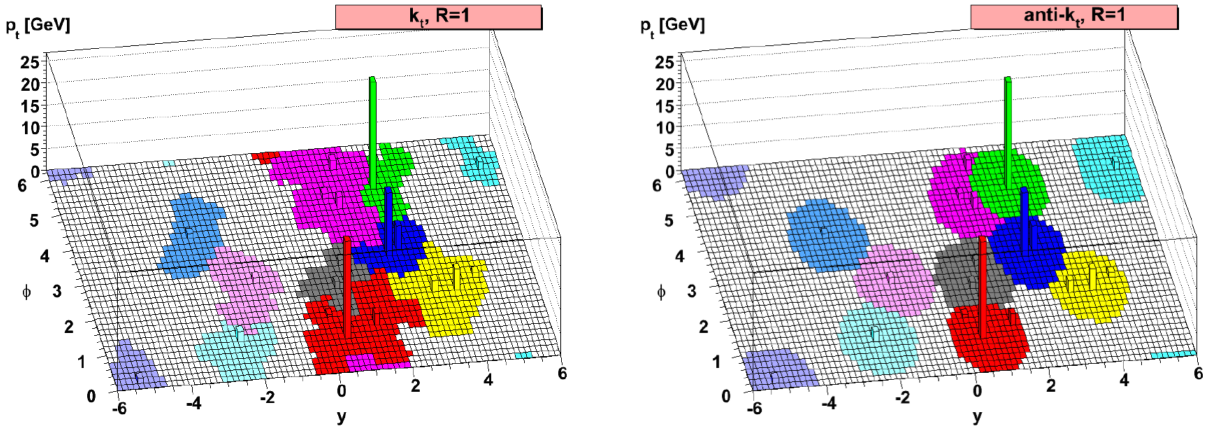


Figure 2.5: Illustration of k_t and anti-k_t jet algorithms with $R = 1$ for calorimeter signal towers in azimuth Φ and pseudorapidity y. Towers of the same color were recombined to one jet. Figure taken from [9].

2.3.3 Recombination

Let J be the index set of the input objects with the defined four-momenta $(E^i, p_x^i, p_y^i, p_z^i)$, $i \in J$ which has to be recombined into the jet with new kinematic quantities E^J, $\mathbf{p}^j$, p_T^J, y^J, ... Possible recombination schemes are

- **Snowmass Scheme**
  Used by fixed cone algorithm when finding proto-jets.

$$E_T^J = \sum_{i \in J} E_T^i \quad , \quad \eta^J = \frac{1}{E_T^J} \sum_{i \in J} E_T^i \eta^i \quad , \quad \phi^J = \frac{1}{E_T^J} \sum_{i \in J} E_T^i \phi^i. \tag{2.5}$$

- **Four-Momentum Recombination (E-Scheme)**
  Used by k_t-algorithms and in fixed cone algorithm to final recombination of proto-jets into jets.

$$p^J = (E^J, \mathbf{p}^J) = \sum_{i \in J} (E^i, p_x^i, p_y^i, p_z^i), \tag{2.6}$$

$$p_T^J = \sqrt{(p_x^J)^2 + (p_y^J)^2} \quad , \quad y^J = \frac{1}{2} \ln \frac{E^J + p_z^J}{E^J - p_z^J} \quad , \quad \phi^J = \tan^{-1} \frac{p_y^J}{p_x^J}. \tag{2.7}$$

2.3.4 Calorimeter jets

The most important detectors for the jet reconstruction are the ATLAS calorimeters. The ATLAS calorimeter system has about 200,000 individual cells of various sizes and with different readout technologies and cell geometries. For jet finding it is necessary to first combine these cell signals into larger signal object with physically meaningful four-momenta. The two concepts available are the calorimeter signal towers and the topological cell clusters.

In the case of calorimeter signal towers, the cells are projected onto a fixed grid in pseudorapidity η and azimuth ϕ. The tower bin size is $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ in the whole acceptance region of the calorimeters, i.e. in $|\eta| < 5$ and $-\pi < \phi < \pi$ with approximately $100 \times 64 = 6,400$ towers in total.

The alternative representation of the calorimeter signals for jet reconstruction are topological cell clusters, which are basically an attempt to reconstruct three-dimensional "energy blobs" representing the showers developing for each particle entering the calorimeter. The clustering starts with seed cells with a signal-to-noise ratio, or signal significance $\Gamma = E_{cell}/\sigma_{noise,cell}$, above a certain threshold S, i.e. $|\Gamma| > S = 4$. All directly neighboring cells of these seed cells, in all three dimensions, are collected into the cluster. Neighbors of neighbors are considered for those added cells which have Γ above a certain secondary threshold N ($|\Gamma| > N = 2$). Finally, a ring of guard cells with signal significances above a basic threshold $|\Gamma| > P = 0$ is added to the cluster. After the initial clusters are formed, they are analyzed for local signal maxima by a splitting algorithm, and split between those maxima.

2.4 Jet corrections

Before jets can proceed to the data analysis, corrections have to be applied to minimize detector effects including calorimeter non-compensation, noise, losses in dead material and cracks, longitudinal leakage and particle deflection in the magnetic field. Indispensable tool for jet corrections are Monte Carlo event generators - PYTHIA8 [?] generating high-energy-physics events and GEANT4 [?] or ATLFASTII [?] detector simulations for simulating the ALTAS detector response on PYTHIA8 generated events.

Using these tools it is possible to reconstruct jets from Monte Carlo events on three different stages of collision indicated in Figure 2.6. First there are parton jets which are reconstructed from the quarks, gluons and other elementary particles created just after the collision. Stable particles (with lifetime $c\tau \sim 10^{-15}$ m) created by hadronization are recombined into the truth jets. When collision reaches the detector, the detector simulation is used and the recorded signal is reconstructed into reco jets.

First, the signal jets are corrected to the particle jets leading to modification of kinematic properties of individual signal jet in the process called calibration.

2.4.1 Jet Energy Scale Calibration

Energy E_{reco} of the jet measured by the detector may differ from the energy E_{truth} of the corresponding particle jet. The goal of the jet energy scale calibration is to remove some detector effects and correct E_{reco} to E_{truth}. The detector effects can be summarized by the formula

$$E_{truth} = \frac{E_{reco} - O}{R \cdot S}, \tag{2.8}$$

where O is the offset representing subtraction of additional energy, which is represented by the detector noise and pile-up with contributions from other pp collisions occurring during beam crossing. Hadronic character of jets observed at LHC is the reason why the response R is the

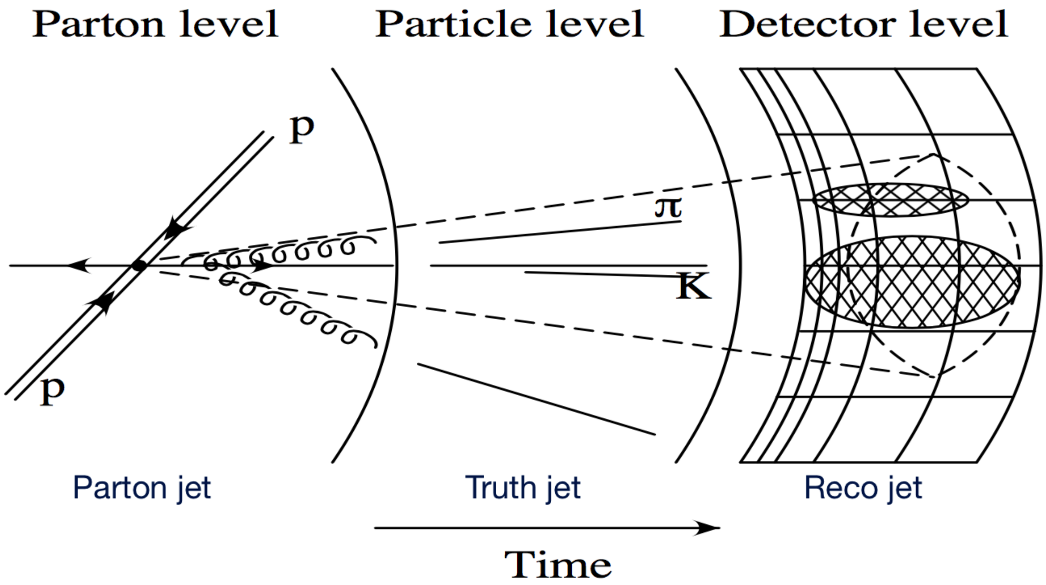


Figure 2.6: Three levels of jet reconstruction. Figure from [?]

largest correction. Showering factor S describes the particle flow out/from jet recombination cells. More concise information about the parameters just introduced can be found in [?].

Because the calibration is persistently evolving, each jet analysis uses as the input the uncalibrated reco jets which are then easily calibrated using standard library ApplyJetCalibration [?].

However, there are some detector effects which can't be fixed by the calibration. These effects include the limited detector resolution (detector cells have finite dimensions) and the limited acceptance (not all events are recorded). The former leads to the smearing of jet kinematic properties wheres the later to lowering of observed cross section against the value theoretically predicted. Both of these effects are negatively influencing the observables and can be partially removed by the unfolding procedure, which unlike the jet calibration, is analysis dependent.

2.4.2 Unfolding

In this analysis, the distribution $f(p_T)$ of inclusive jet p_T is measured for $p_T \in \langle a, b \rangle$. Thanks to the detector imperfections, instead of physical variable p_T new variable x and its distribution $g(x)$ are measured. New distribution can be expressed as

$$g(x) = \int_a^b A(x, p_T) f(p_T) dp_T, \tag{2.9}$$

with the function $A(x, p_T)$ describing the detector response as can be seen when the detector is exposed to a particle beam with well known $p_T = p'_T$ meaning $f(p_T) = \delta(p_T - p'_T)$, leading to $g(x) = A(x, p'_T)$. The reconstruction of $f(p_T)$ from measured $g(x)$ is called unfolding.

For practical purposes the equation (2.9) should be discretized so instead of continuous distribution $g(x)$ the discretized values $g_i = \int_{N(i)} g(x)dx$ of discretized observable $f_i = \int_{N(i)} f(p_T)dp_T$ are measured, where the integration is done over measurable $N(i) \subset \langle a, b \rangle$. For simplicity assume $x \in \langle a, b \rangle$ is discretized in the same way as the physical p_T. Equation (2.9) then reads

$$g = Af, \tag{2.10}$$

with g and f being vectors of g_i's and f_i's respectively and A matrix derived from $A(x, p_T)$, later in Section 3.3 called the transfer matrix. If the limited acceptance would be the only detector problem, then A would be diagonal matrix with some elements < 1. When the limited resolution comes to play, the diagonal entries starts to smear out of the diagonal and the matrix A starts to complicate.

The unfolding result which offers the solution of (2.10) by inversion of matrix A is mostly disappointing as is illustrated e.g. in [?]. For result improvement, different unfolding methods were developed including Iterative Bayesian Unfolding [?], Singular Value Decomposition [?], or Iterative, Dynamically Stabilized (IDS) method [?], which is the method used in this thesis.

Chapter 3

Data Analysis

In physics, you don't have to go around making trouble for yourself - nature does it for you.

Frank Wilczek

QCD jets are the most common hard objects observed at hadron colliders, with their cross section exceeding any other physics process by orders of magnitude. Measurement of inclusive jet cross section thus provide the first test for both QCD predictions and the detector performance. LHC Run II should open new kinematic region with expectation of observation of jets with p_T in TeV region.

This chapter describes the details of the inclusive jet double cross section analysis.

3.1 Data Characteristics

Data used in this thesis are Monte Carlo generated events of pp collisions at the center-of-mass energy $\sqrt{s} = 13\,\text{TeV}$ by PYTHIA8 [?] event generator using CT10 PDFs [?] and ATLAS underlying event tune AU2 [?]. QCD calculations are done only to the leading order in PYTHIA8. The response of the ATLAS detector on these events was calculated with ?GEANT4? (?citace?) software toolkit.

Particles were recombined using anti-k_t jet algorithm with parameter $R = 0.4$. There are parton jets reconstructed from the PYTHIA8 output, which further in this thesis are denoted truth jets, and next to them, there are the signal jets reconstructed from the output of GEANT4 detector simulation from the topological cell clusters.

Signal jets were calibrated using APPLYJETCALIBRATION [?] library version 3.28 and configuration parameters were loaded from the `JES_Full2012dataset_May2014.config` with calibration sequence `JetArea_Residual_EtaJES`. In next signal jets denotes the signal calibrated jets.

Generated events are divided into JZXW samples according to the leading truth jet p_T. These samples differ in event weight which is for the whole event calculated as the product of cross

JZXW	p_T range (GeV)	Cross-section (fb)	Filter Efficiency	# envents
JZ0W	0 - 20	7.8420e+13	9.7193e-01	3498000
JZ1W	20 - 80	7.8420e+13	2.7903e-04	2998000
JZ2W	80 - 200	5.7312e+10	5.2261e-03	500000
JZ3W	200 - 500	1.4478e+09	1.8068e-03	499500
JZ4W	500 - 1000	2.3093e+07	1.3276e-03	477000
JZ5W	1000 - 1500	2.3793e+05	5.0449e-03	499000
JZ6W	1500 - 2000	5.4279e+03	1.3886e-02	493500
JZ7W	2000 +	9.4172e+02	6.7141e-02	497000

Table 3.1: The cross-sections, filter efficiency and number of events for the JZXW samples which differ in the leading truth jet p_T.

section, filter efficiency, inverse number of events and additional weight factor which is for each event stored in `EventInfoAux` container. Concrete values for datasets used in this theses are given in Table 3.1.

Analysis uses jets with transverse momentum $p_T > 15\,\mathrm{GeV}$ and rapidity $|y| < 4$ and is done in double binning in p_T and $|y|$ with the following edges

$$\begin{aligned} p_T =& 15 : 20 : 25 : 35 : 45 : 55 : 70 : 85 : 100 : 116 : 134 : 152 : 172 : 194 : 216 : 240 : 264 : 290 : \\ & 318 : 346 : 376 : 408 : 442 : 478 : 516 : 556 : 598 : 642 : 688 : 736 : 786 : 838 : 894 : 952 : \\ & 1012 : 1076 : 1162 : 1310 : 1530 : 1992 : 2300 : 2800 : 3400 : 4100 : 5000 : 6000 : 7200\,\mathrm{GeV} \\ |y| =& 0.0 : 0.5 : 1.0 : 1.5 : 2.0 : 2.5 : 3.0 : 3.5 : 4.0 \end{aligned} \tag{3.1}$$

3.2 Event Selection

In this section the jet selection criteria and matching of truth with signal jets are described. The former is needed to cut those jets (or those events) off, which were misinterpreted by the detector, by the later the inputs for the unfolding procedure are obtained. Description of the unfolding procedure will follow in the next section. More details including graphical display and numerical results for procedures described in this section are given in Appendix A.

3.2.1 Jet Cuts

- **$\mathbf{p_T}$ Cut**

  By this cut those signal and truth jets with $p_T < 15\,\mathrm{GeV}$ were removed from the list.

- **y Cut**

  By this cut those signal and truth jets with $|y| > 4$ were removed from the list.

- **Zero jet (0jet) Cut**

If there was no signal or truth jet left in the event after previous cuts, the whole event was skipped.

- **Leading Ration (LR) Cut**

  In this cut the signal and truth jets with the highest p_T were used. If there were only one signal jet left, the ratio $LR = p_T^{signal,leading}/p_T^{truth,leading}$ was calculated. If there were two signal jets, instead of $p_T^{signal,leading}$ the average p_T of two leading signal jets was calculated. If $LR > 1$, LR was replaced by its inverse value. If $LR < 0.6$ the whole event was skipped.

Numbers of signal and truth jets removed in each step are shown in Table A.1, where also the cut efficiencies for individual JZXW samples are shown. The impact of each cut on jet p_T spectrum of signal and truth jets is displayed in Figure A.1.

It can be seen that the most important cut is the 0jet cut which removes approximately 80 % of signal jets in JZ0W sample whereas the truth jets remain intact. According to Table 3.1 for event from the JZ0W sample the leading truth jet $p_T < 20\,\text{GeV}$ which has no longer to hold for signal jets which were in some cases reconstructed with $p_T \sim 100\,\text{GeV}$. Because of Monte Carlo event weight of events from JZ0W sample is dominant over event weights of other JZXW samples by several orders, the misreconstructed signal jets from JZ0W sample were parasitizing on the observed p_T spectrum of signal jets as can be seen from top of the Figure A.1.

3.2.2 Jet Matching

To find, how the truth jets are reconstructed by the detector, the jet matching has to be done, i.e. for each truth jet it is needed to find signal jet whom could the original truth jet become.

For each pair (i, j) of signal and truth jet, the quantity $dR_{ij} = \sqrt{d\phi_{ij}^2 + dy_{ij}^2}$ was calculated with $d\phi_{ij} = \phi_i^{signal} - \phi_j^{truth}$ and $dy_{ij} = y_i^{signal} - y_j^{truth}$. The minimum was found between all of dR_{ij}'s. If this minimum led under the defined cutoff $\min(dR_{ij}) = dR_{pq} < dR^{cutoff} = 0.2$, the jets (p, q) were matched and further not assumed in matching procedure. This continued until condition $\min(dR_{ij}) < dR^{cutoff}$ was not satisfied or all of the signal or truth jets were matched.

Numbers of signal and truth jets, both matched and unmatched are shown in Table A.1 where also the matching efficiencies for individual JZXW samples are shown. In Figure A.2 there are compared p_T spectra of matched and unmatched signal and truth jets with p_T spectra of all signal and truth jets respectively, whereas in Figure A.3 the comparison between p_T spectra of signal and truth jets are shown for matched and unmatched jets separately.

It can be seen that for JZ(1-7)W samples, there is much more unmatched signal jets, than is the unmatched truth jets. Looking back at the statistics of the p_T cut, the reason is, that more than a half of truth jets has $p_T < 15\,\text{GeV}$ in every JZXW sample, which does not hold for the signal jets. There is much more signal jets in statistics than is the truth jets.

From the top of the figure A.3 showing the contribution of matched jets to p_T spectra, it can be seen, that starting with $p_T > 25\,\text{GeV}$, p_T spectra of signal jets overwhelms those of truth jets. Taking into account the fact, that p_T spectra of matched signal and matched truth jets are obtained from the same number of jets, this can seem to be a little bit confusing. The reason is, that some signal jets overflow the p_T range defined by the JZXW sample and that each event is filled with weight defined by the JZXW sample, which with increasing p_T falls down.

3.3 Unfolding

Summarizing the results of the previous section, all events saved in Monte Carlo simulated data firstly underwent the series of four cutoffs to obtain the set of jets denoted signal and truth jets. Both signal and truth jets were split into two categories depending on successful matching - there is correspondence 1 : 1 between matched signal and matched truth jets. Signal jets, which were not matched, formed the unmatched signal jets, and similarly set of unmatched truth jets was created. All these 6 sets of jets are needed by the unfolding procedure which description follows in this section.

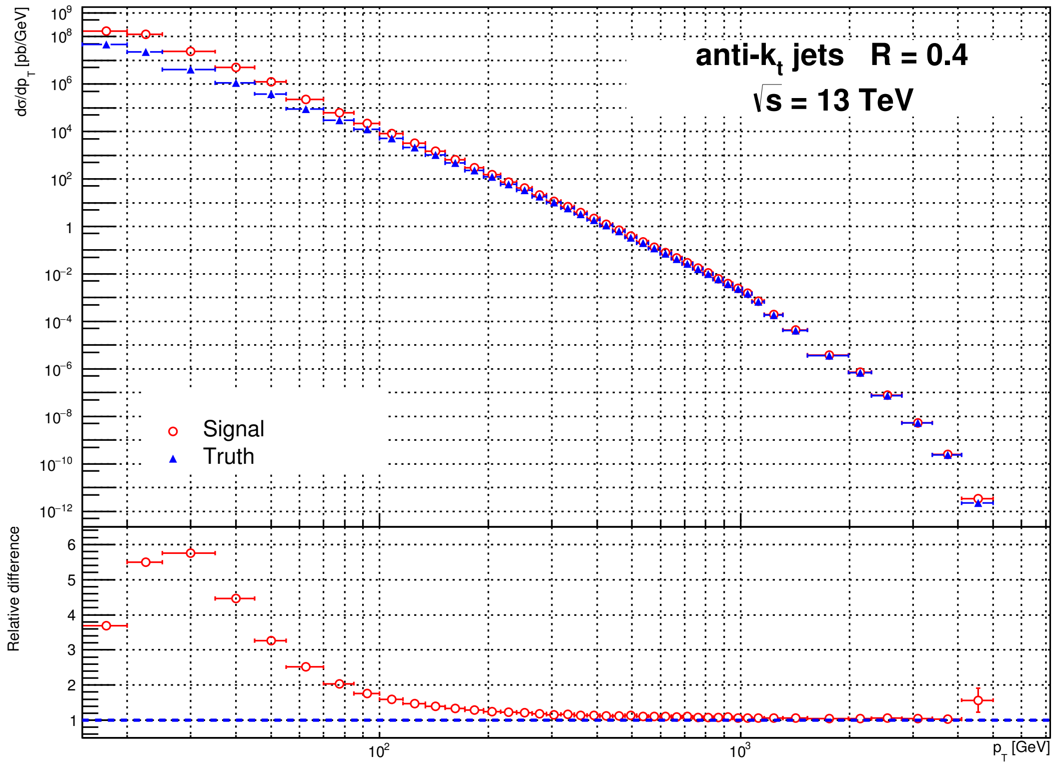


Figure 3.1: Comparison of p_T spectra of signal and truth jets, which survived four steps of cutoff. Each bin was divided by its width so y-axis has physical meaning of differential cross section in p_T. Bottom graph contains the relative difference between signal and truth differential cross section in p_T.

Figure 3.1 shows the p_T spectra of signal and truth jets. It can be seen, that observed p_T spectrum, represented by the signal jets, differs from the p_T spectrum theoretically expected which is represented by the p_T spectrum of truth jets. Unfolding should transform the observed p_T spectrum to the spectrum theoretically expected. If this transformation would be done on real data, it should preserve additional structures, which are presented in data, but not included by the theory.

The main ingredient for the unfolding procedure is the transfer matrix A_{ij} which cells are proportional to number of signal jets in bin i with a matched truth jet that was generated in bin j. Example of unfolding matrix is shown in Figure 3.2 where only matched signal and truth jets both with rapidity $|y| < 0.5$ were used.

In this thesis the double binning 3.1 is used which complicates the situation because the matched signal jet can simply migrate of the transfer matrix from Figure 3.2, when its rapidity $|y| > 0.5$ and when it was matched with truth jet with $|y| < 0.5$. To these cases could be treat, the transfer matrix was redefined in a way which can be easily seen from Figure 3.3 where the marked square represents the previous unfolding matrix from Figure 3.2.

The main diagonal of the unfolding matrix contains the dominant elements corresponding to the correct reconstruction of the truth jet and meaning that there is no significant bias in p_T of matched signal and matched truth jets. Next to the main diagonal, there are two minor diagonals representing the migration of matched jets between different rapidity bins. All of these three diagonals are smeared thanks to the final detector resolution in p_T.

Next to the transfer matrix, numbers of matched and unmatched signal and truth jets are needed for each (y, p_T) bin by unfolding procedure. These serve for calculation of matching efficiency which is the key ingredient for final reweighting of reconstructed p_T spectrum. The Iterative Dynamical Stabilized (IDS) [**?**] unfolding method was used in this thesis and the unfolding procedure was iterated once.

Comparison of unfolded p_T spectrum for $|y| < 0.5$ rapidity bin is compared with p_T spectra of signal and truth jets in Figure 3.4, results for other rapidity bins are shown in Appendix B. It can be seen, that the unfolded spectrum match the truth spectrum up to the systematic error less than 5 %.

3.4 Comparison with Prediction

Unfolded p_T spectrum obtained by the way described in previous section, was compared with p_T spectrum obtained by the NLO QCD calculations ?(?citace?)? using ?PDF?. The result is for rapidity bin $|y| < 0.5$ shown at Figure 3.5, results for other rapidity bins are shown in Appendix C.

From the figures it follows, that there will be more jets observed with $p_T < 500$ GeV than it is theoretically expected. This is because the reduced bunch crossing time and increased luminosity will lead to increase of both underlying events and pileup. This will increase the electronic noise in detector cells, which will be misinterpreted by the detector either as increased jet energy or as completely new unphysical jet.

This effect becomes negligible as jet p_T increases. For jets with rapidity $|y| < 2$ and $p_T > 500$ GeV there is deviation < 10 % between the p_T spectra obtained by the Monte Carlo simulations and the theoretical prediction. For higher rapidity region $|y| > 2$ there is significant drop-off in Monte Carlo prediction against the theoretical prediction about more than > 10 %.

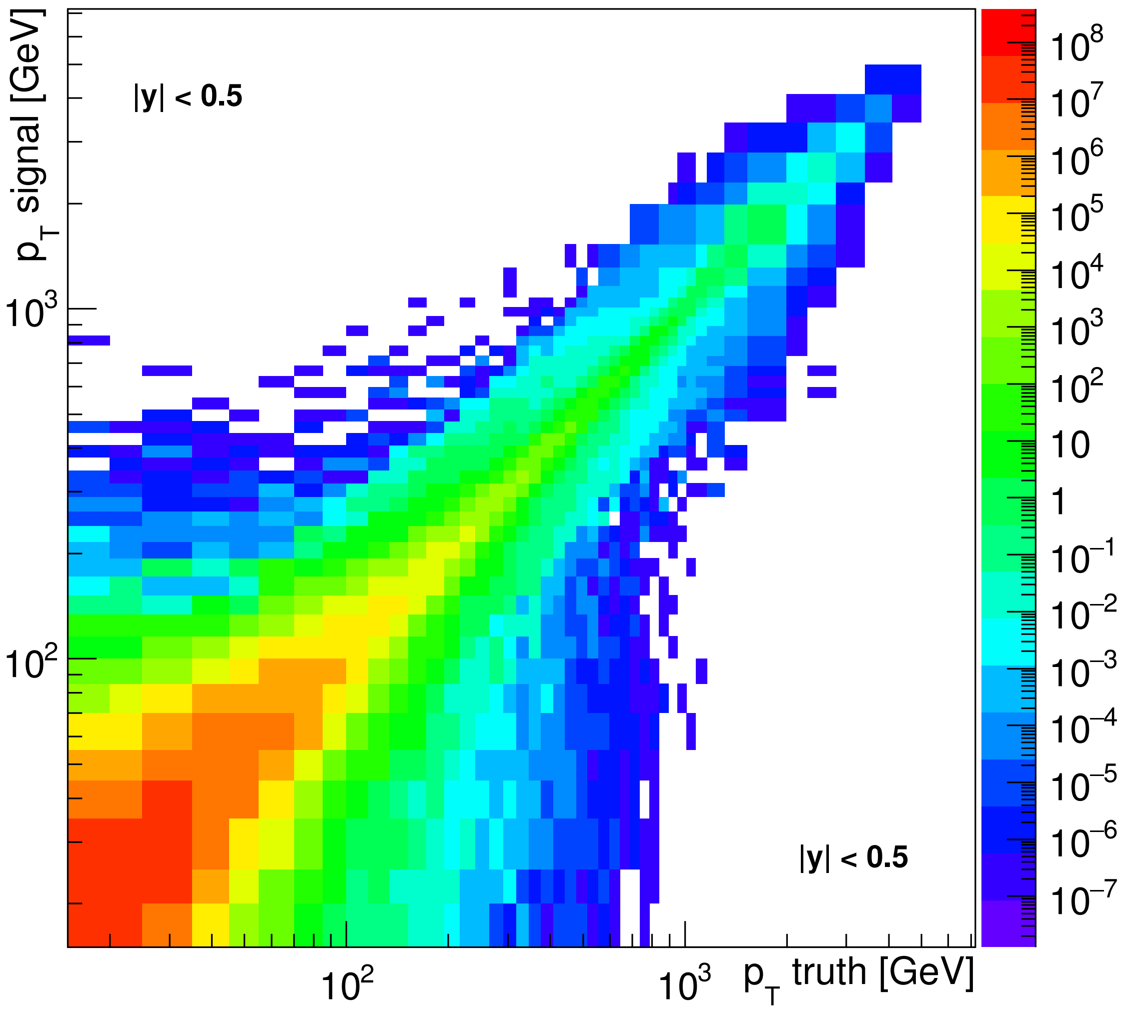


Figure 3.2: Unfolding matrix for matched signal and truth jets with rapidity $|y| < 0.5$. Each cell is proportional to the number of jets with truth p_T in range determined by the x-axis which were reconstructed to the signal jets with p_T determined by the y-axis. White space signalize no input.

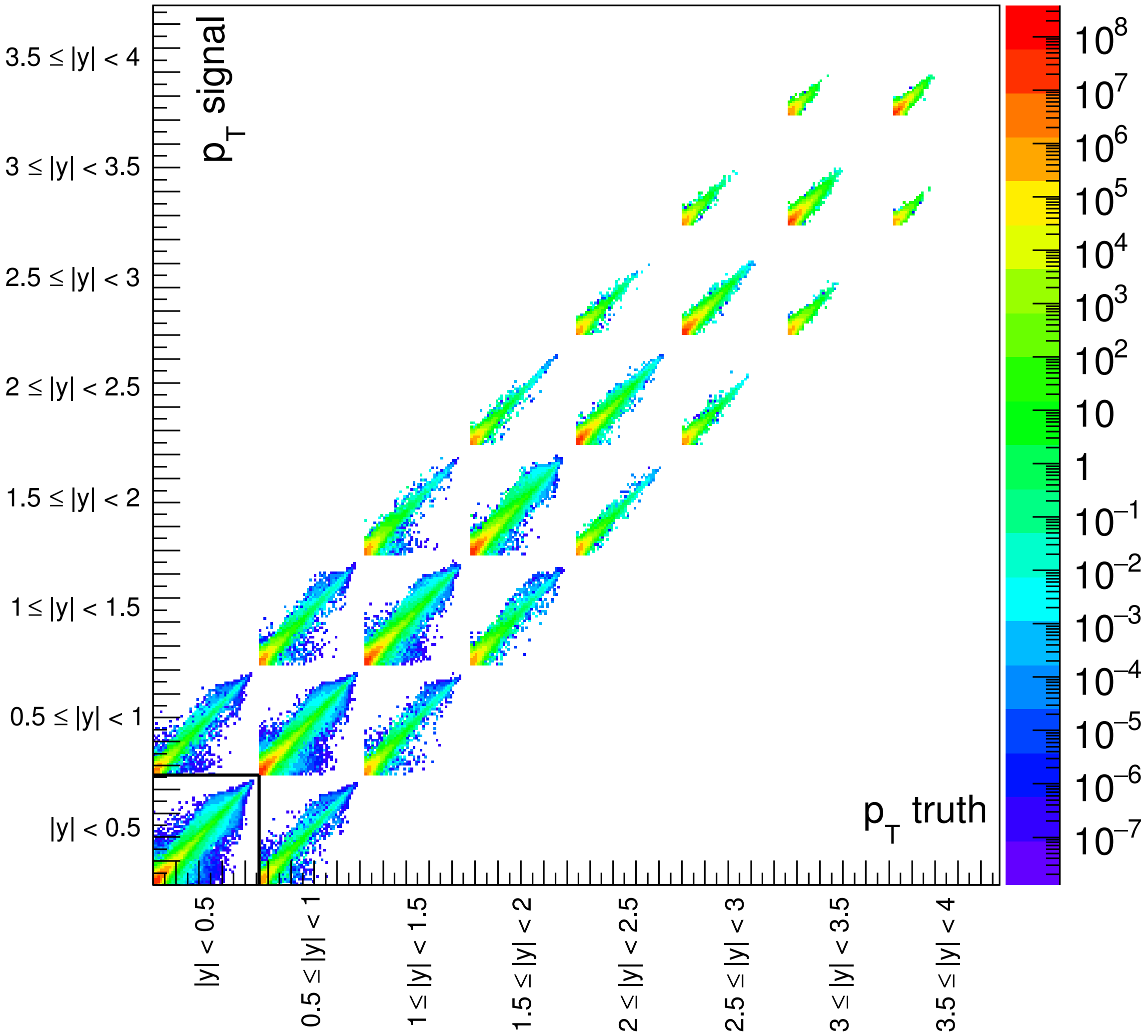


Figure 3.3: Unfolding matrix for all matched signal and truth jets. Each cell is proportional to the number of jets with truth p_T and rapidity y determined by the x-axis, which were reconstructed to the signal jets with p_T and y determined by the y-axis. Marked square in $|y| < 0.5$ region is shown in Figure 3.2. Projection of this matrix on the x and y-axis corresponds to the p_T spectrum of truth and signal jets for corresponding rapidity bin respectively.

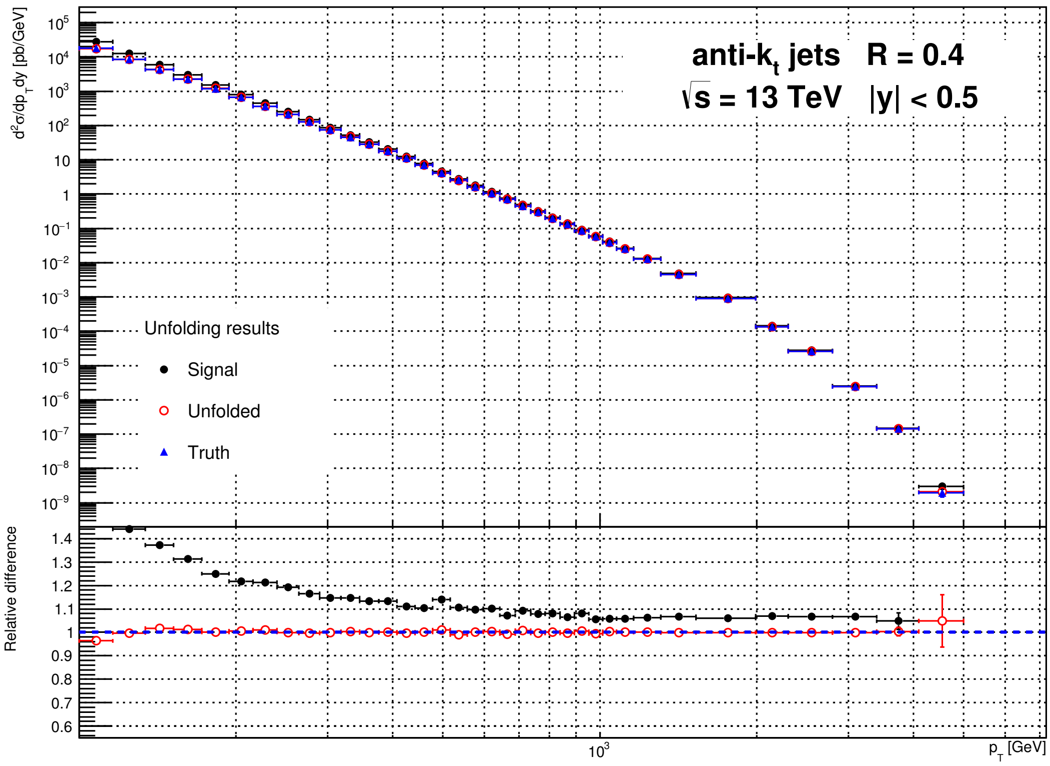


Figure 3.4: Comparison of spectra of signal jets and unfolded spectra of signal jets with the spectrum of truth jets for $|y| < 0.5$ rapidity bin. Each bin was divided by its width so the y-axis has meaning of double differential cross section in p_T and y. The graph at bottom shows the relative difference between signal or unfolded spectrum and the truth spectrum.

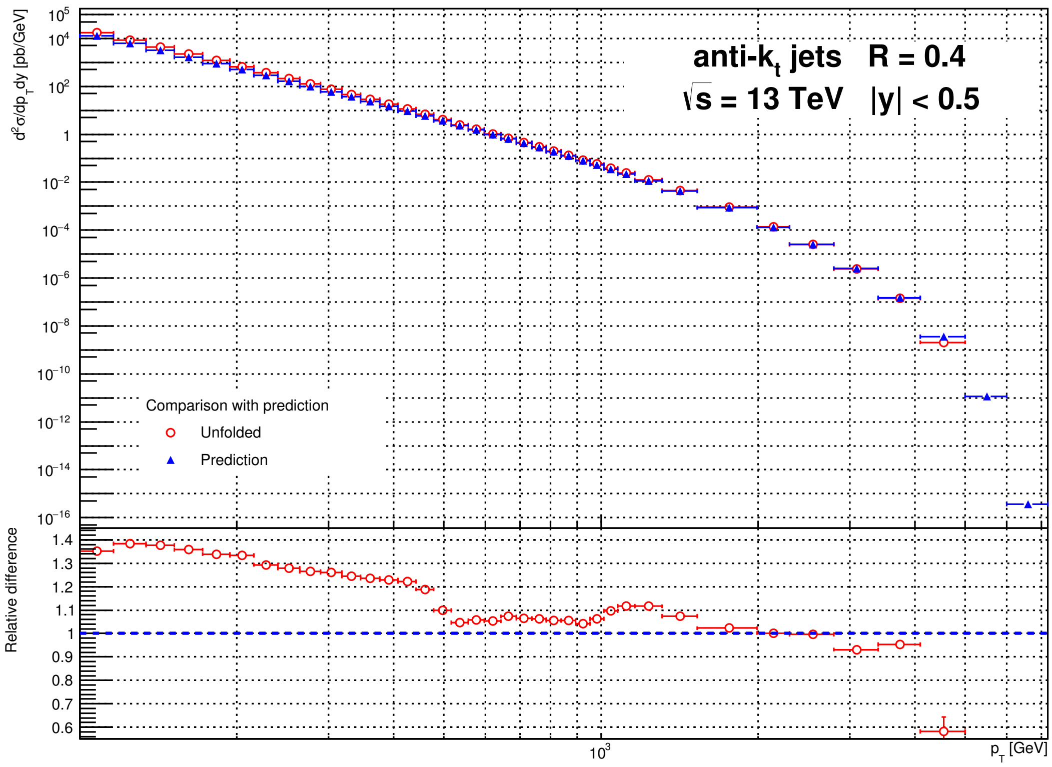


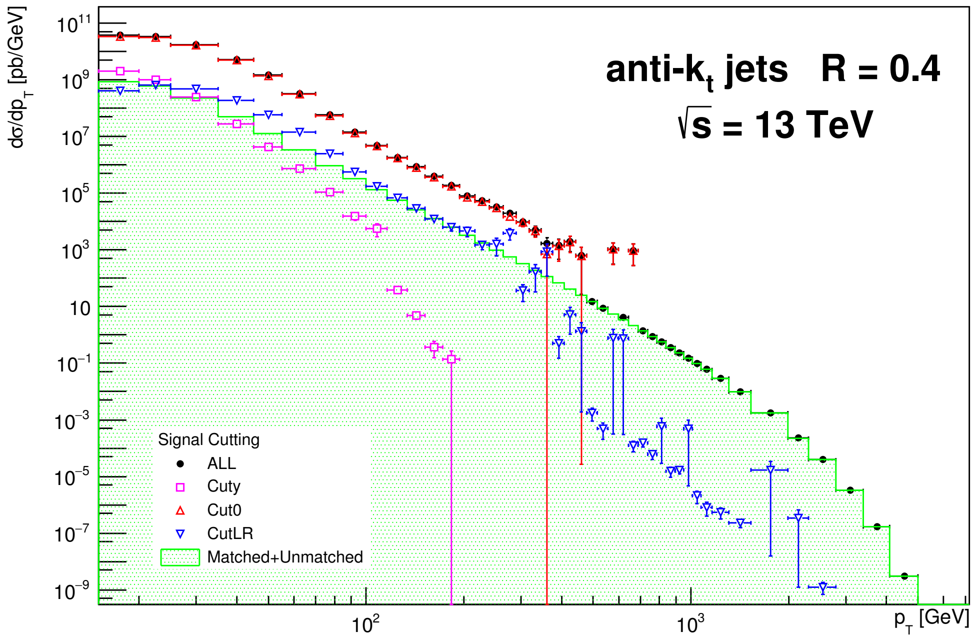
Figure 3.5: Unfolded double differential cross section of inclusive jets in p_T and rapidity y compared to the NLO QCD prediction for $|y| < 0.5$ rapidity bin. At the bottom the relative difference between unfolded and predicted cross section is shown.

Conclusion

Appendices

Appendix A

Cut and Matching Results



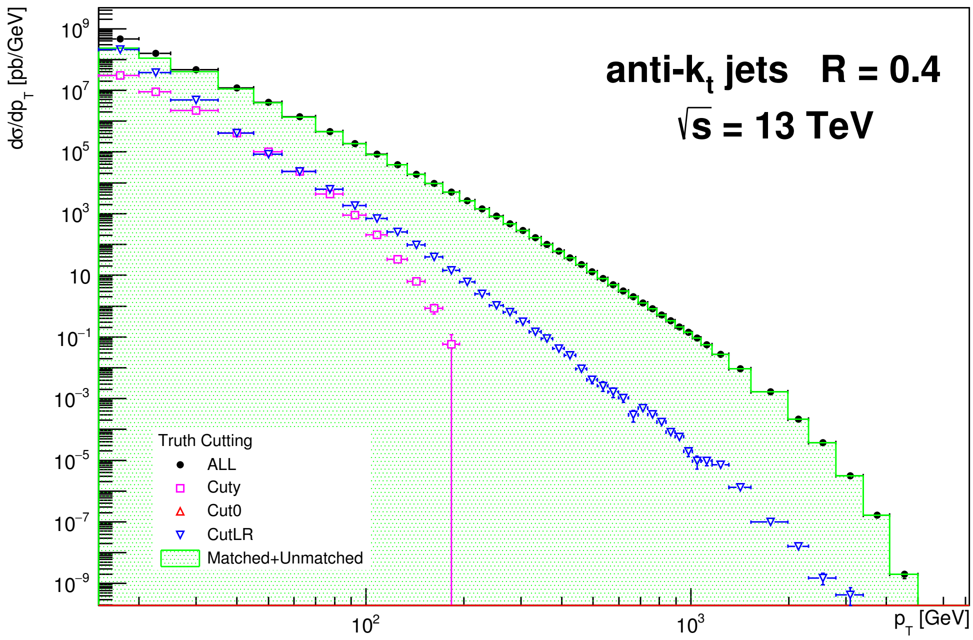


Figure A.1: Impact of 4 cuts defined in Section 3.2.1 on differential cross section in p_T of signal jets (top) and truth jets (bottom). Black dots represent the original uncutted spectrum, green area then these jets, which survived all four cutoffs.

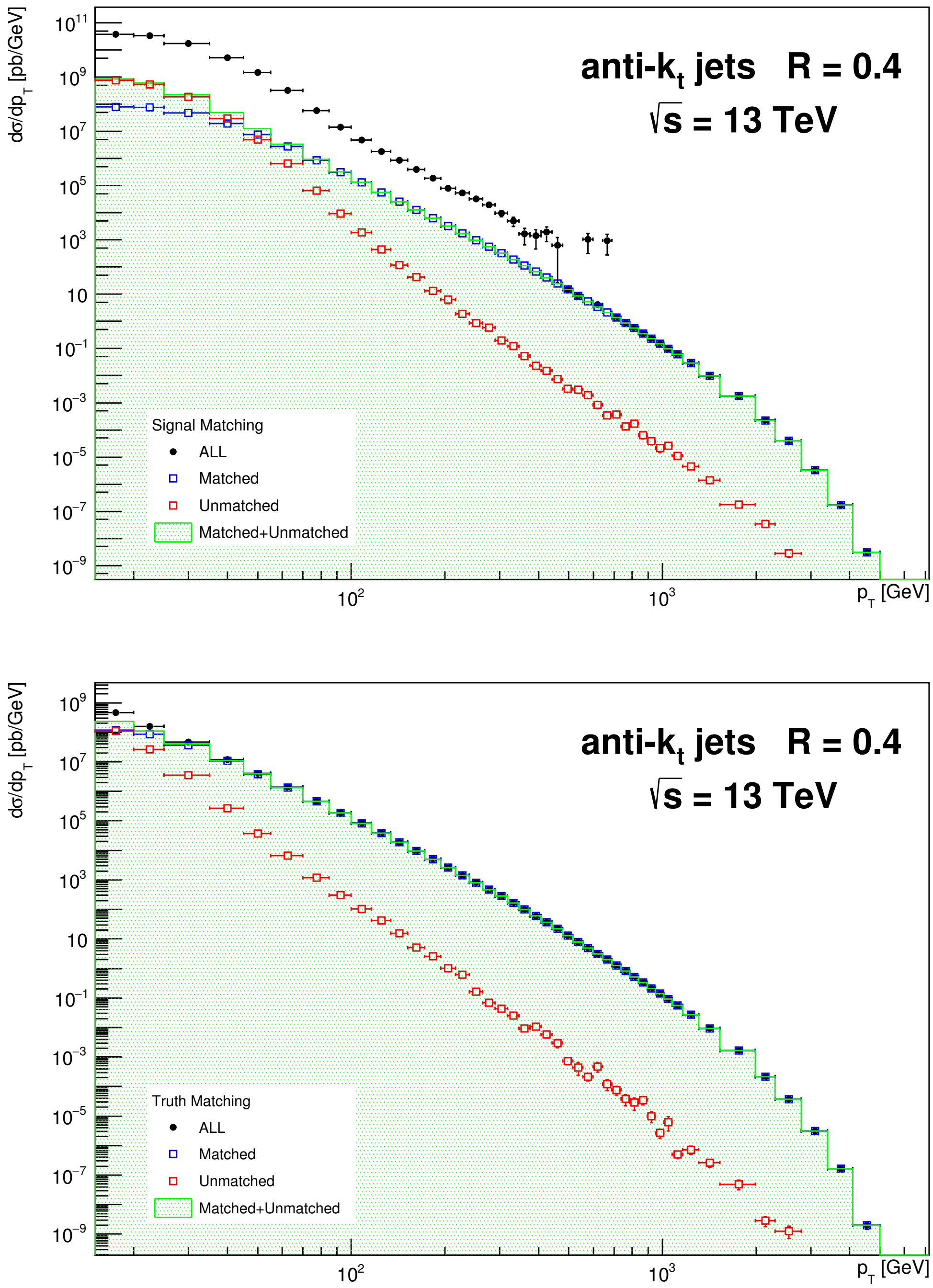


Figure A.2: Results of matching procedure described in Section 3.2.2 demonstrated on differential cross section in p_T of signal (top) and truth (bottom) jets. Black dots represent the original uncutted spectrum. The contribution of matched and unmatched jets to green area representing all jets which survived cutoffs is shown.

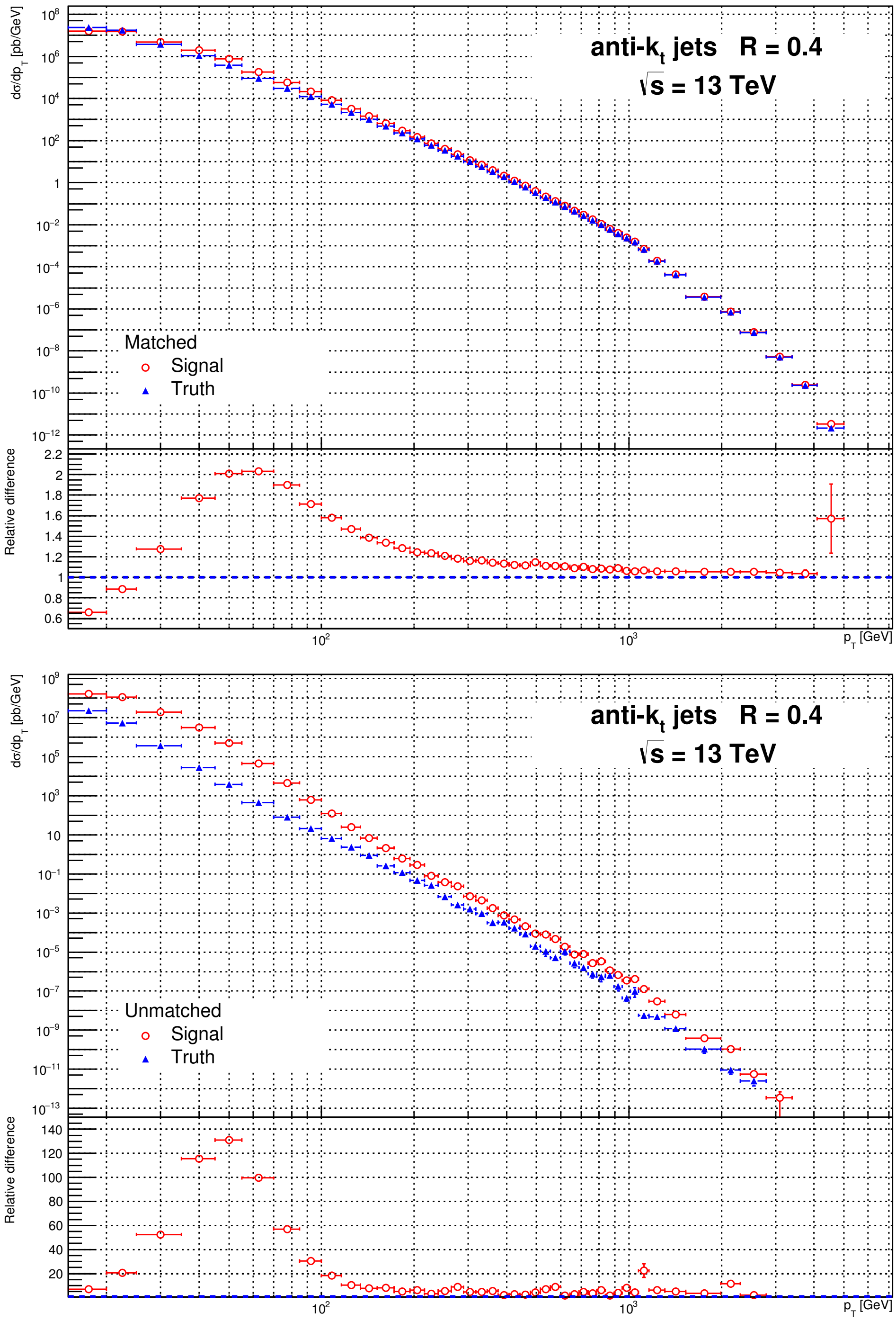


Figure A.3: Comparison of p_T spectra of matched (top) and unmatched (bottom) signal and truth jets. The p_T spectra are the same as those at Figure A.2. Only difference is, that there are compared spectra of signal and truth jets. The bottom part both of these graphs shows the relative difference between signal and truth spectrum.

# jets		**ALL**	JZ0W	JZ1W	JZ2W	JZ3W	JZ4W	JZ5W	JZ6W	JZ7W
Signal		**1.10e+08**	3.22e+07	3.59e+07	6.67e+06	7.07e+06	6.28e+06	7.29e+06	7.13e+06	7.11e+06
Truth		**7.22e+07**	3.15e+06	3.00e+07	6.17e+06	6.91e+06	6.20e+06	6.98e+06	6.53e+06	6.25e+06
CutPt	Signal	**1.32e+07** **12.1 %**	5.45e+06 17.0 %	4.38e+06 12.2 %	6.50e+05 9.7 %	5.87e+05 8.3 %	4.76e+05 7.6 %	5.48e+05 7.5 %	5.52e+05 7.7 %	5.63e+05 7.9 %
	Truth	**4.67e+07** **64.7 %**	3.11e+06 98.7 %	2.20e+07 73.1 %	3.86e+06 62.6 %	4.00e+06 57.8 %	3.42e+06 55.1 %	3.74e+06 53.6 %	3.43e+06 52.5 %	3.23e+06 51.6 %
Cuty	Signal	**2.46e+06** **2.2 %**	8.02e+05 2.5 %	9.54e+05 2.7 %	1.42e+05 2.1 %	1.28e+05 1.8 %	1.03e+05 1.6 %	1.16e+05 1.6 %	1.10e+05 1.5 %	1.08e+05 1.5 %
	Truth	**5.03e+05** **0.7 %**	3.14e+03 0.1 %	3.19e+05 1.1 %	4.54e+04 0.7 %	3.79e+04 0.5 %	2.88e+04 0.5 %	2.78e+04 0.4 %	2.22e+04 0.3 %	1.83e+04 0.3 %
Cut0jet	Signal	**2.62e+07** **23.9 %**	2.56e+07 79.6 %	5.49e+05 1.5 %	0.00e+00 0.0 %	0.00e+00 0.0 %	0.00e+00 0.0 %	0.00e+00 0.0 %	0.00e+00 0.0 %	0.00e+00 0.0 %
	Truth	**0.00e+00** **0.0 %**	0.00e+00 0.0 %	0.00e+00 0.0 %	0.00e+00 0.0 %	0.00e+00 0.0 %	0.00e+00 0.0 %	0.00e+00 0.0 %	0.00e+00 0.0 %	0.00e+00 0.0 %
CutLR	Signal	**3.64e+06** **3.3 %**	2.27e+05 0.7 %	3.37e+06 9.4 %	2.99e+04 0.4 %	7.07e+03 0.1 %	2.33e+03 0.0 %	1.63e+03 0.0 %	7.14e+02 0.0 %	6.31e+02 0.0 %
	Truth	**5.21e+05** **0.7 %**	2.15e+04 0.7 %	4.74e+05 1.6 %	1.82e+04 0.3 %	4.45e+03 0.1 %	1.33e+03 0.0 %	9.03e+02 0.0 %	4.37e+02 0.0 %	2.78e+02 0.0 %
Matched	Signal	**2.13e+07** **19.5 %**	7.95e+03 0.0 %	5.99e+06 16.7 %	1.95e+06 29.3 %	2.54e+06 36.0 %	2.46e+06 39.1 %	2.88e+06 39.5 %	2.78e+06 38.9 %	2.72e+06 38.2 %
	Truth	**2.13e+07** **29.5 %**	7.95e+03 0.3 %	5.99e+06 19.9 %	1.95e+06 31.7 %	2.54e+06 36.8 %	2.46e+06 39.6 %	2.88e+06 41.3 %	2.78e+06 42.5 %	2.72e+06 43.5 %
Unmatched	Signal	**4.28e+07** **39.0 %**	6.15e+04 0.2 %	2.06e+07 57.5 %	3.89e+06 58.4 %	3.81e+06 53.8 %	3.24e+06 51.6 %	3.75e+06 51.4 %	3.69e+06 51.8 %	3.72e+06 52.3 %
	Truth	**3.14e+06** **4.4 %**	7.51e+03 0.2 %	1.30e+06 4.3 %	2.89e+05 4.7 %	3.29e+05 4.8 %	2.95e+05 4.8 %	3.29e+05 4.7 %	3.03e+05 4.6 %	2.88e+05 4.6 %

Table A.1: Statistics for matching and cutting procedures described in Sections jets which were (un)matched.

Appendix B

Unfolding Results

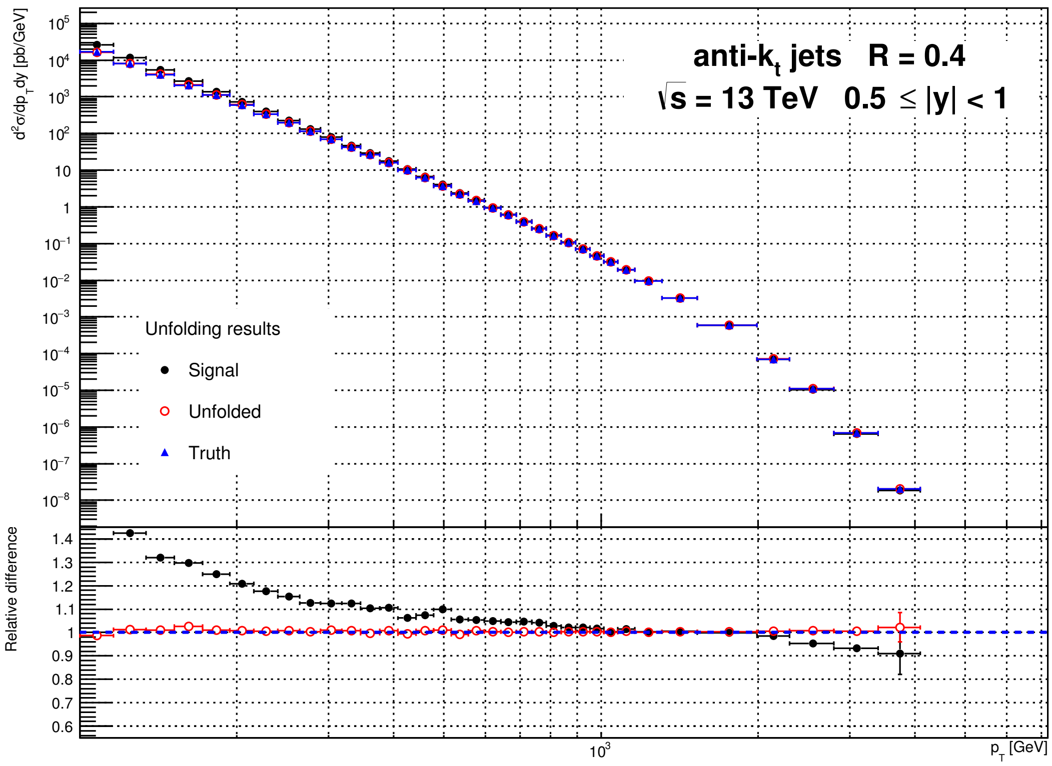
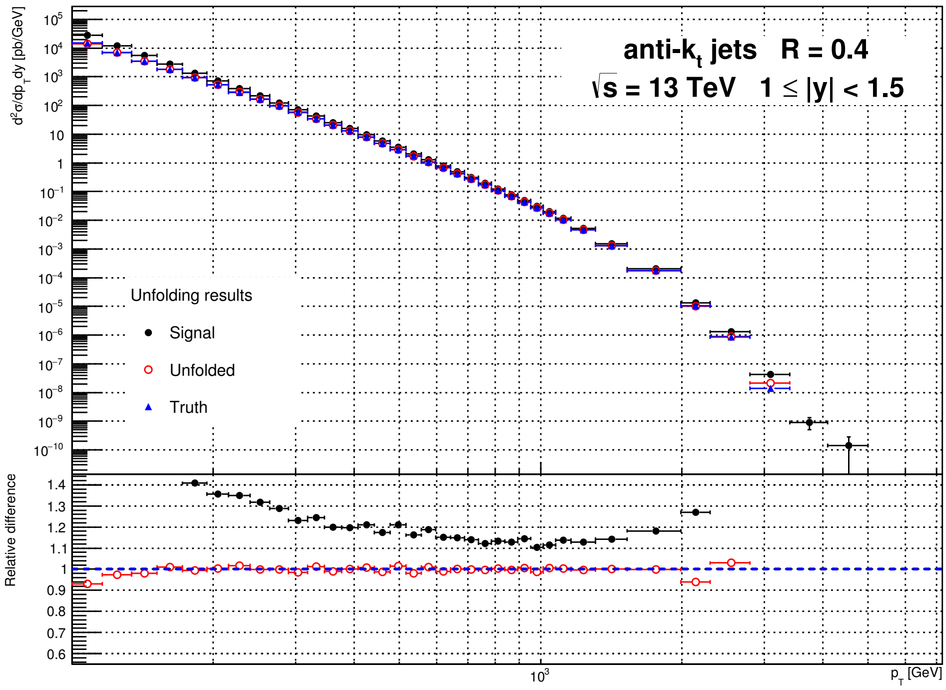


Figure B.1: Comparison of spectra of signal jets and unfolded spectra of signal jets with the spectrum of truth jets for $0.5 \leq |y| < 1$ rapidity bin. Each bin was divided by its width so the y-axis has meaning of double differential cross section in p_T and y. The graph at bottom shows the relative difference between signal or unfolded spectrum and the truth spectrum.



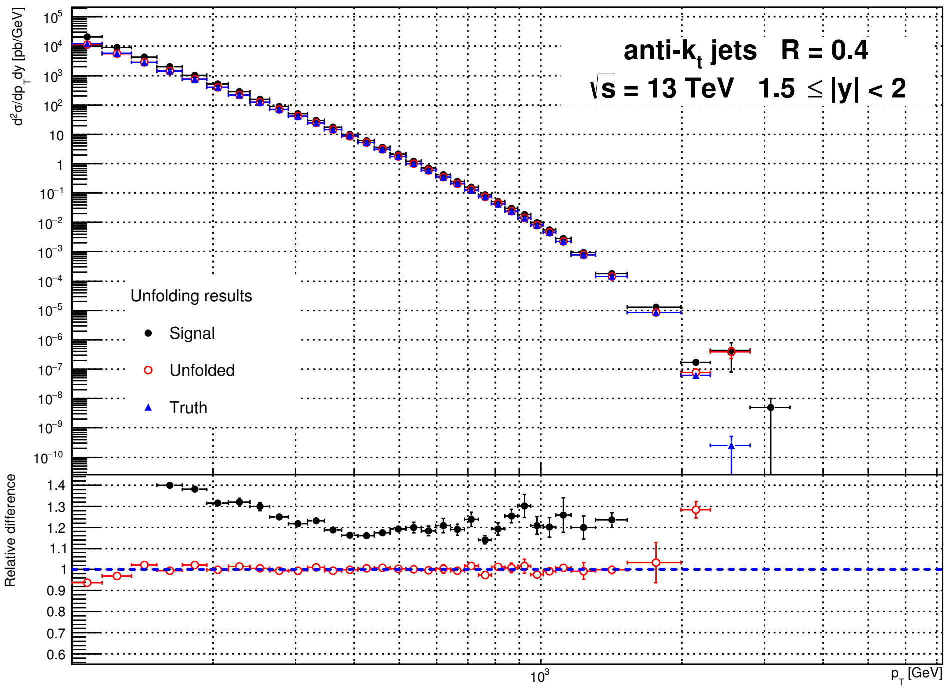


Figure B.2: Comparison of spectra of signal jets and unfolded spectra of signal jets with the spectrum of truth jets for $1 \leq |y| < 1.5$ (top) and $1.5 \leq |y| < 2$ (bottom) rapidity bin. Each bin was divided by its width so the y-axis has meaning of double differential cross section in p_T and y. The graph at bottom shows the relative difference between signal or unfolded spectrum and the truth spectrum.

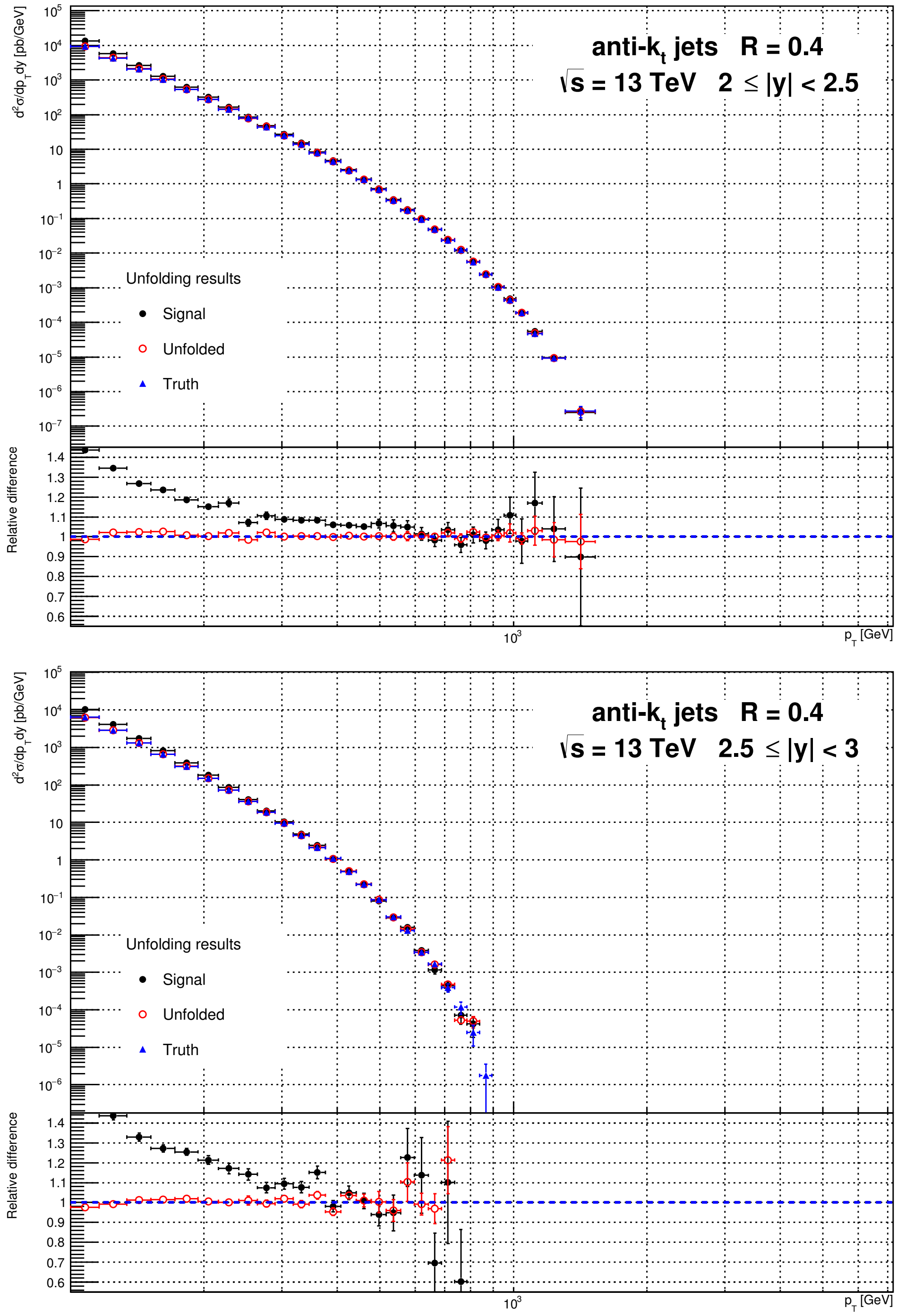


Figure B.3: Comparison of spectra of signal jets and unfolded spectra of signal jets with the spectrum of truth jets for $2 \leq |y| < 2.5$ (top) and $2.5 \leq |y| < 3$ (bottom) rapidity bin. Each bin was divided by its width so the y-axis has meaning of double differential cross section in p_T and y. The graph at bottom shows the relative difference between signal or unfolded spectrum and the truth spectrum.

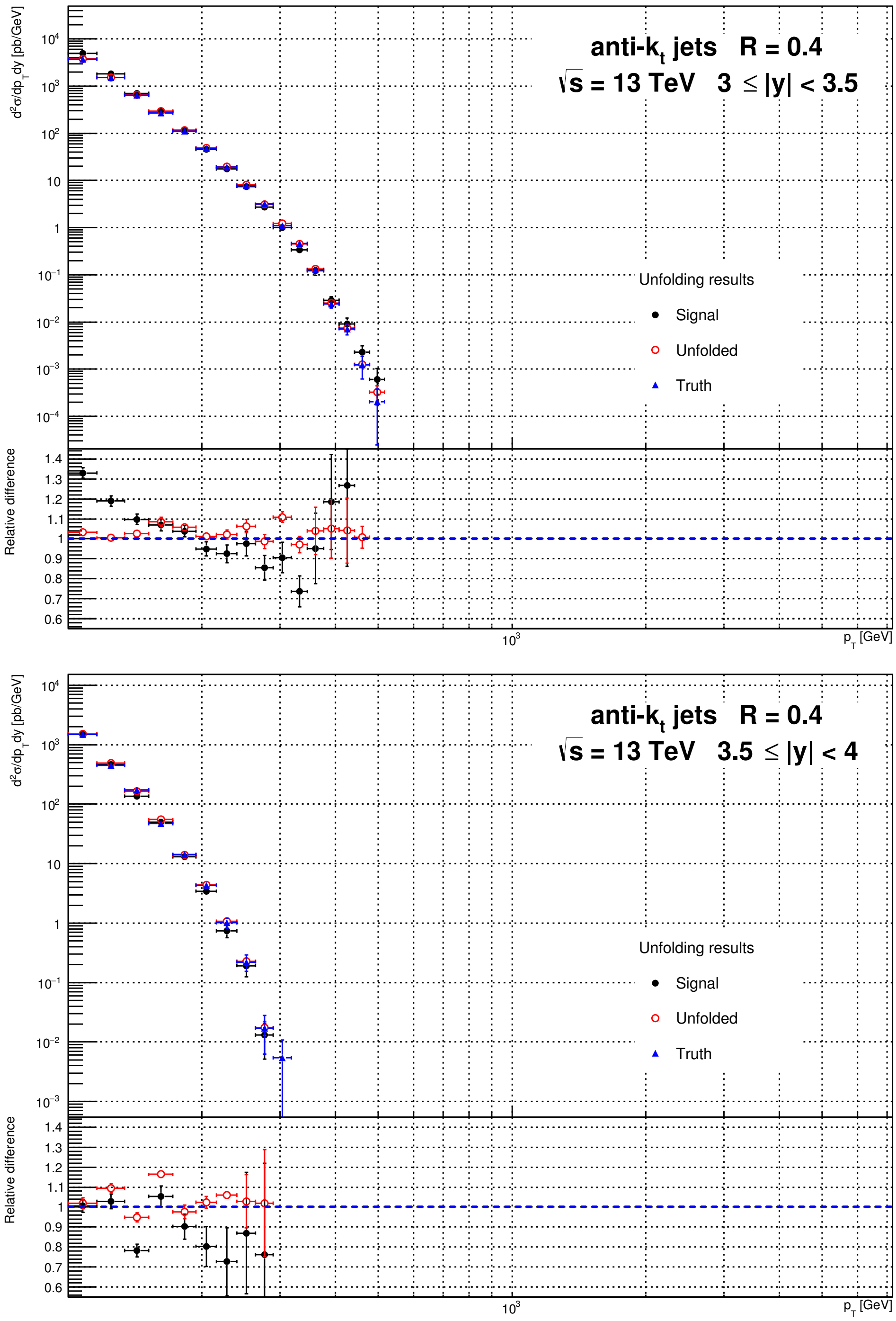


Figure B.4: Comparison of spectra of signal jets and unfolded spectra of signal jets with the spectrum of truth jets for $3 \leq |y| < 3.5$ (top) and $3.5 \leq |y| < 4$ (bottom) rapidity bin. Each bin was divided by its width so the y-axis has meaning of double differential cross section in p_T and y. The graph at bottom shows the relative difference between signal or unfolded spectrum and the truth spectrum.

Appendix C

Unfolding and Prediction

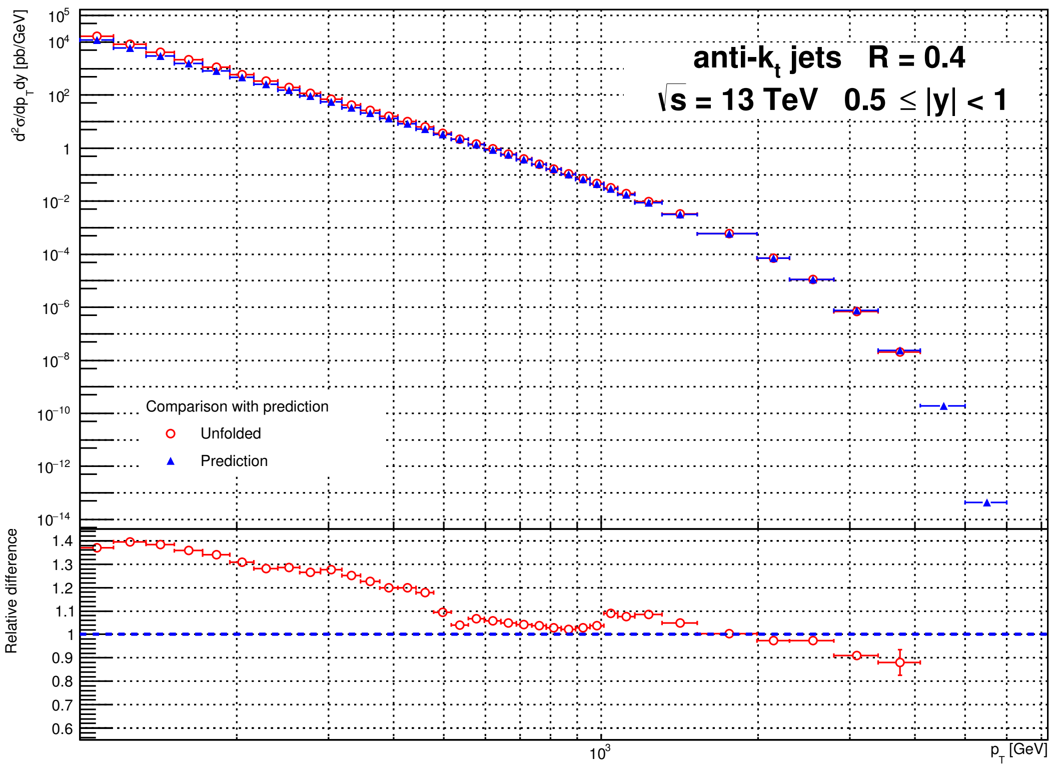


Figure C.1: Unfolded double differential cross section of inclusive jets in p_T and rapidity y compared to the NLO QCD prediction for $0.5 \leq |y| < 1$ rapidity bin. At the bottom the relative difference between unfolded and predicted cross section is shown.

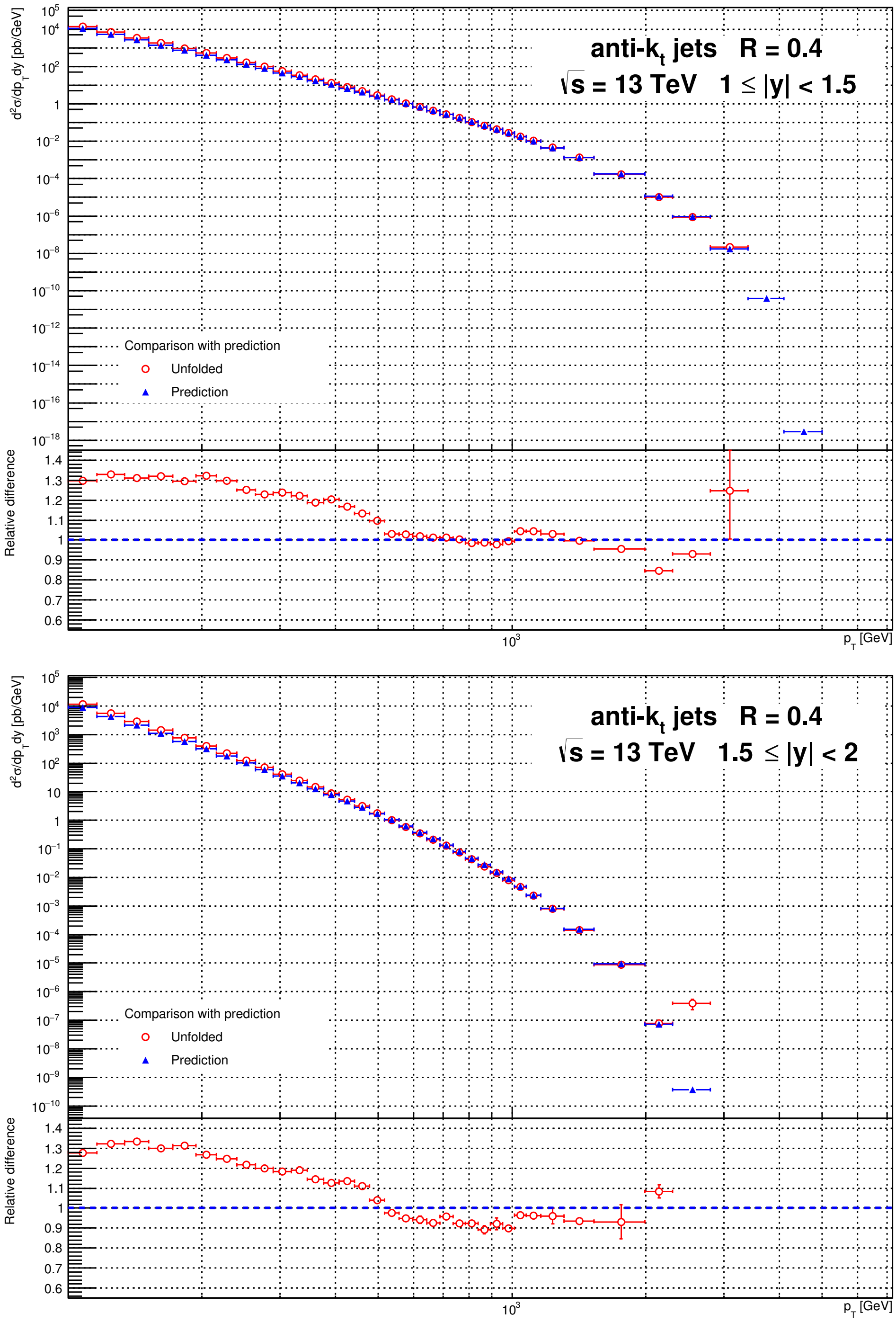


Figure C.2: Unfolded double differential cross section of inclusive jets in p_T and rapidity y compared to the NLO QCD prediction for $1 \leq |y| < 1.5$ (top) and $1.5 \leq |y| < 2$ (bottom) rapidity bin. At the bottom the relative difference between unfolded and predicted cross section is shown.

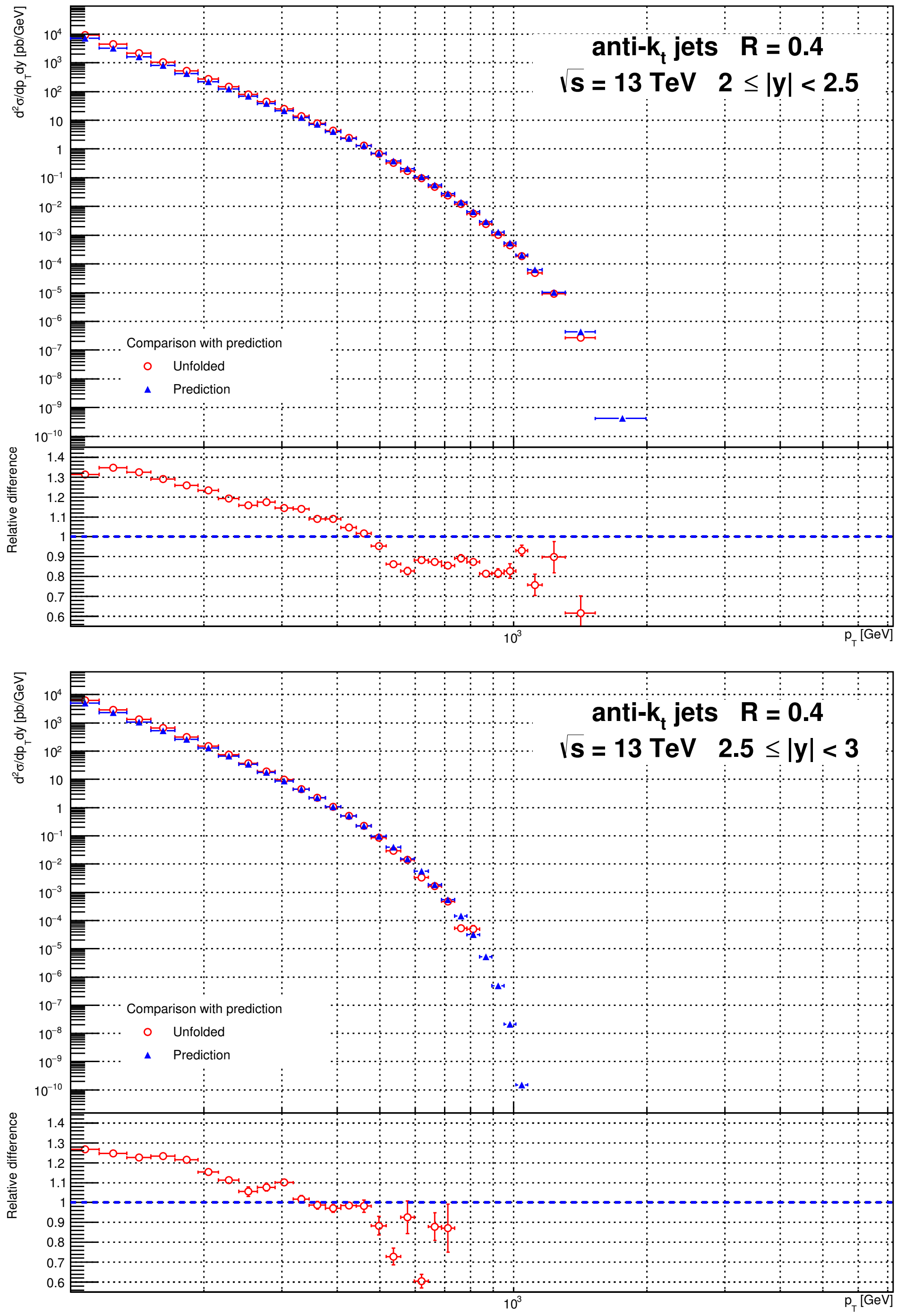


Figure C.3: Unfolded double differential cross section of inclusive jets in p_T and rapidity y compared to the NLO QCD prediction for $2 \leq |y| < 2.5$ (top) and $2.5 \leq |y| < 3$ (bottom) rapidity bin. At the bottom the relative difference between unfolded and predicted cross section is shown.

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