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## **Zusammenfassung**

### **Abstract**

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# **1 Introduction**

## 2 Theory

### 2.1 Standard model of particle physics

The standard models of particles is a quantum field theory describing elementary particles and their interaction. All particles contained in this theory have been discovered and experiments have confirmed predictions of the standard model at very high precision. In Fig. 2.1 all elementary particles and their basic properties are displayed. The particles can be ordered in groups by their properties. Firstly one distinguishes particles depending on their spin. Spin- $\frac{1}{2}$  particles are called fermions, Spin-1 and Spin-0 particles represent the bosons. Fermions are the building block of matter while bosons carry the fundamental forces included in the standard model. Quarks and leptons are sub groups of the fermions are divided by their possible interaction with forces. While the quarks are affected by the strong force, carried by the gluon, the leptons are not. Three fundamental forces are introduced in this theory. The strong force is carried by the gluon and affects quarks and the gluon itself. The charge of the strong interaction is called colour.

#### 2.1.1 Top quark

The top quark is the heaviest particle in the standard model and therefore offers a large phase space for decays and has a life time of approximately  $0.5 \times 10^{-24}$  s. Because of the short life time the top quark does not form bound hadronic states and thus measurement of the bare quark are possible. This provides a special access to parameters of the standard model. Especially the top quark mass is an essential parameter to check the standard model for consistency. The Higgs mechanism relates the masses of the top quark with the masses of the W and Higgs boson. Measuring these masses with high precision gives the possibility to check the standard model for consistency.

Additionally the top quark is important for searches of new physics since is is often part of the final state and/or a relevant background.

#### Top quark mass

### 2.2 Unfolding

Most analyses at LHC measure distributions of appropriate variables and then compare the obtained results in data with event simulations. In this method the MC samples also include detector effects. What one measures in this case is the real distribution on particle level folded

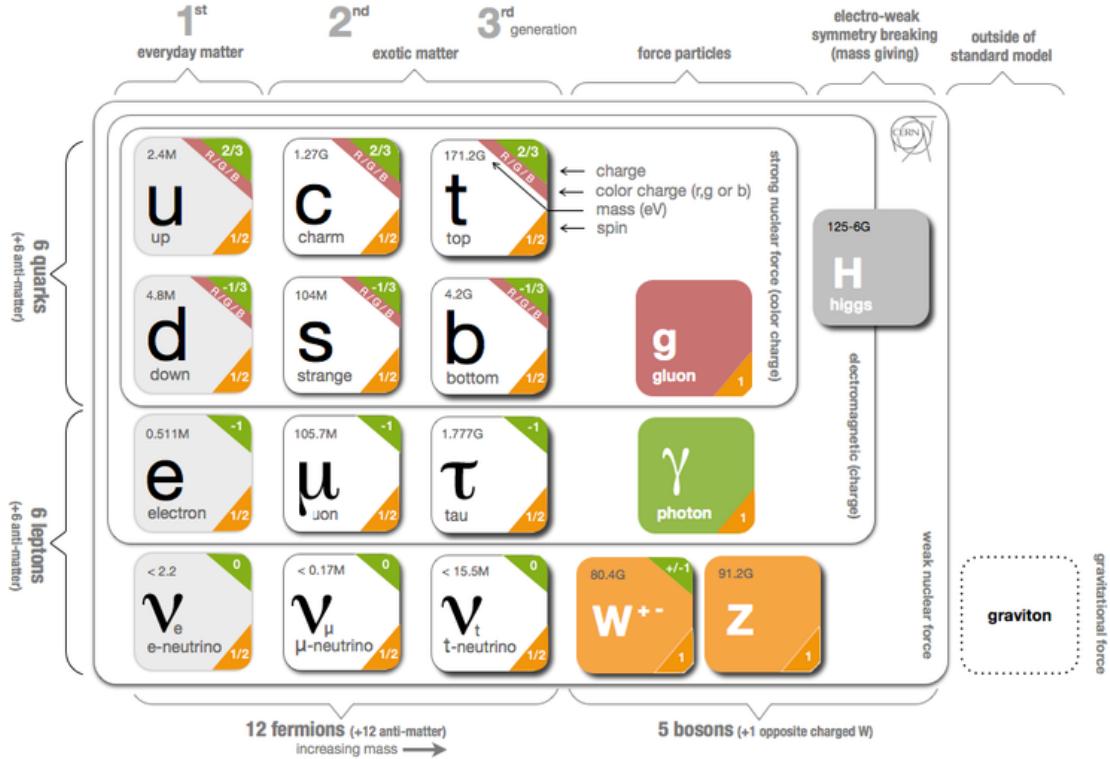


Figure 2.1

with an unknown detector function. Studying the difference in MC between particle level and reconstruction level it is possible to calculate the probabilities that a measured value in a bin  $x_i$  is originating from bin  $y_i$  on particle level. The resulting matrix can then be applied to real data to obtain data on particle level. This can then be compared with theory calculations.

## 3 Experiment

### 3.1 Large Hadron Collider

The Large Hadron Collider (LHC) is a circular particle collider with a circumference of 27 km.

Four Experiments are placed at the interaction points of LHC.

### 3.2 CMS detector

#### 3.2.1 Tracker

The purpose of the tracking system is to measure the momentum of created particles. It is taken advantage of the Lorentz force which changes the momentum of charged particles in a magnetic field. Paths of those particles are therefore bended with a bending radius proportional to the momentum in a constant magnetic field. Therefore a solenoid provides a constant magnetic field of about 4 T inside the tracker. Per path one spatial point per layer is measured. These points are the input for a track finding algorithm.

#### 3.2.2 Calorimeters

To define the type of particle one has to measure not only momentum but also energy. Therefore outside the tracker are two types of calorimeters installed.

##### Electromagnetic Calorimeter

##### Hadronic Calorimeter

#### 3.2.3 Solenoid

Outside the hadronic calorimeter a superconducting solenoid is installed and provides a magnetic field of about 4 T inside the tracking system. The solenoid has a length of 13 m and a diameter of 6 m. The purpose of the magnetic field is to bend paths of charged particles due to the Lorentz force. The bending radius then is directly connected to the momentum of the particle.

#### 3.2.4 Muon system

Because muons are not absorbed in the calorimeters, it is possible to use an additional tracking detector for muons at the very outside of the detector. Muon chambers are embedded in the

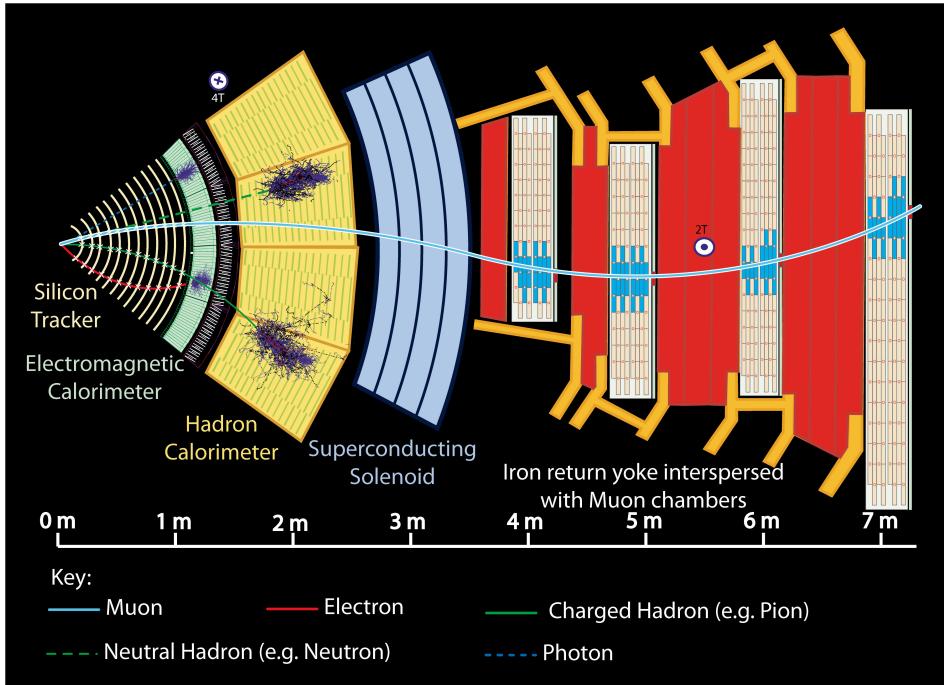


Figure 3.1

iron return yoke of the magnet. Thus a magnetic field of about 2 T is present. In cooperation with the inner tracker it is possible to reconstruct muon momenta with high precision.

### 3.2.5 Trigger

At the interaction point centred in the CMS detector every ??? proton bunches cross. Per crossing about ??? interactions take place. This adds up to about ??? interactions per second. This huge collision rate makes it impossible to store information of every event on disk. Additionally it would need a tremendous number of computing cores to analyse this data. Therefore a trigger system is installed to select the most interesting events to reduce the amount of data. For the computation system it is required to reduce the amount from ??? to ??. To decide which events are worth storing and which will be neglected different criteria are defined.

## 4 Reconstruction

### 4.1 Coordinate system

The coordinate system used in the CMS experiment is based on cartesian and right-handed coordinates. The origin is set in the center of the CMS detector. To define the direction of the axes other fix points are set. The  $x$ -axis point in the direction of the center of the LHC ring, the  $y$ -axis points up and the  $z$ -axis is defined parallel to the beam axis. Important variables used in analysis of CMS data are the angles  $\phi$  and  $\theta$ .  $\phi$  is defined as the angle in the  $x$ - $y$ -plane measured from the  $x$ -axis and  $\theta$  describes the angle from a given point to the beam axis. Because the LHC is a hadron collider and physical events are therefore not symmetric in  $\theta$  it is useful to construct the Lorentz invariant variable  $\eta$ :

$$\eta = -\ln \left[ \tan \left( \frac{\theta}{2} \right) \right] \quad (4.1)$$

The distance  $\Delta R$  between two objects  $i$  and  $j$  is calculated using the differences  $\Delta\phi = \phi_i - \phi_j$  and  $\Delta\eta = \eta_i - \eta_j$ :

$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} \quad (4.2)$$

An important quantity used in this analysis is the transversal momentum  $p_T$  which is constructed out of the  $x$  and  $y$ -components ( $p_x$  and  $p_y$ ) of the total momentum of an object:

$$p_T = \sqrt{p_x^2 + p_y^2} \quad (4.3)$$

It is practical to not consider the  $z$  component in a hadron collider because it depends on the initial state of interacting partons which is unknown. The  $p_T$  sum of all objects is expected to be 0 in every event. If it is not the  $p_T$  may be reconstructed wrong for some objects or objects left the CMS experiment undetected.

### 4.2 Particle Flow

### 4.3 Electrons

Electrons are reconstructed in the tracker and electromagnetic calorimeter.

## 4.4 Muons

Since the energy of muons cannot be measured in the calorimeters, a muon is identified by hits in the muon chambers. Combining informations from the muon system and the inner tracker leads to a very precise measurement of muons in the CMS detector. Therefore muons are very reliable objects in CMS data analyses. An object is announced a muon if

## 4.5 Jets

Jets are objects to reconstruct quarks. Because of confinement quarks cannot exist isolated but hadronize. This results in an particle shower consisting of hadrons. To reconstruct the initial quark one needs to sum up all particles from the final shower. This is done using different jet algorithms.

### 4.5.1 Anti- $k_T$ Jet Algorithm

[1]

Here  $d_{ij}$  describes a effective distance between two objects  $i$  and  $j$ ,  $d_{iB}$  is a distance measure from object to beam axis.

$$d_{ij} = \min(k_{T,i}^{-2}, k_{T,j}^{-2}) \frac{\Delta R_{ij}^2}{R^2} \quad (4.4)$$

$$d_{iB} = k_{T,i}^{-2} \quad (4.5)$$

### 4.5.2 XCone Jet Algorithm

XCone [2] is an exclusive jet algorithm, returning conical jets. It is well suited for analysis where the final state and therefore the expected number of jets is known since it returns a fixed number of jets. Thus, a physical final state has direct influence on the jet finding.

Starting with a fixed number of jet axes  $N$  the algorithm calculates the direction of these axes by minimizing the N-jettiness variable. N-jettiness is a measure for how N-jet-like an event looks. The definition is written down in Eq. 4.6.

$$\tilde{\tau}_N = \sum_i \min\{\rho_{\text{jet}}(p_i, n_1), \dots, \rho_{\text{jet}}(p_i, n_N), \rho_{\text{beam}}(p_i)\} \quad (4.6)$$

Once the minimizing process converges, all particles inside a radius  $R$  from a jet axis are added to one jet.

### 4.5.3 b-Jets

In this analysis jets originating from a bottom quark are identified to reduce background. To identify a jet as an b-jet the "Combined Secondary Vertex" (CSV) algorithm is used. Since b-hadrons have a large lifetime of 1.5 ps they travel about 450  $\mu\text{m}$  in the detector before decaying. This leads to a secondary vertex at the spatial point where the hadron decays which can be reconstructed in the tracking system. Additionally the composition of hadrons in a b-jet is different from other jets. These properties are taken advantage of in the CSV algorithm.

## 4.6 $E_T$ and $S_T$

With the information of mentioned objects two important variables are defined. The missing transverse energy  $\cancel{E}_T$  is defined to estimate the energy carried away by particles which leave the experiment undetected, like neutrinos. Summing up all transverse momenta of each particle in the final state returns the  $p_T$  of the system in the initial state which is  $p_T = 0$ . Thus the transverse energy of all undetected particles is defined as the absolute value of the negative sum over all transverse momenta of detected objects (Eq. 4.7). Since every object, independent from its  $\eta$ , has to be taken into account for this variable,  $\cancel{E}_T$  is independent from the selection applied.

$$\cancel{E}_T = \left| - \sum_{\text{leptons, jets}} \vec{p}_T \right| \quad (4.7)$$

Another important variable to describe an event is  $S_T$ .  $S_T$  is defined to be the scalar sum of all transverse momenta of reconstructed objects plus the missing transverse energy mentioned above (Eq. 4.8). Different from  $\cancel{E}_T$  only objects surviving the selection are considered.

$$S_T = \left( \sum_{\text{leptons, jets}} |\vec{p}_T| \right) + \cancel{E}_T \quad (4.8)$$

Additionally, a definition for  $S_T$  which just takes leptonic activity into account is used in this analysis. It is similarly defined and referred to as  $S_T^{\text{lep}}$  (see Eq. 4.9).

$$S_T^{\text{lep}} = \left( \sum_{\text{leptons}} |\vec{p}_T| \right) + \cancel{E}_T \quad (4.9)$$

## 5 Analysis

### 5.1 Selection

A pre-selection is applied to obtain a clean  $t\bar{t}$  data set with a low fraction of background processes. An event must contain a muon or electron.

### 5.2 Jet studies

For this analysis it is crucial to choose a suitable jet algorithm and cone size. A similar analysis has been performed by CMS on LHC’s 2012 data set with a center-of-mass energy of 8 TeV with Cambridge-Aachen jets with a radius parameter of  $R = 1.2$ . This large radius was chosen to compensate for low statistics in the boosted  $t\bar{t}$  regime. Since the cross-section of  $t\bar{t}$  production is much higher at a center-of-mass energy of 13 TeV it has to be studied, how the jet radius parameter  $R$  influences the measured distribution and what influence different jet algorithms have.

#### 5.2.1 XCone strategy

The XCone jet algorithm has already been tested resolving  $t\bar{t}$  decays. Studies for hadronically decaying top quark pairs are presented in a paper from Thaler and Wilkason [3]. Here, the XCone algorithm is tuned to the  $t\bar{t}$  final state, expecting six jets. Using the information that it is expected to find three jets from each top quark, a promising approach to reconstruct the top quark decays was made with a strategy using two clustering steps. Firstly, the event is divided in two parts. This is done by require the XCone algorithm to find exactly two jets with a radius parameter  $R = \infty$ . Thus, every particle in the event is clustered into one of the jets. The goal of this first step is to separate the two top quarks into independent jets. Now, a second clustering step finding three jets is run where separate lists of particles from each fat jet are used as an input. Thus, in each fat jet, three smaller jets with  $R = 0.4$  are found. These three small jets are then combined and used as the final top jets.

In this analysis the lepton+jets channel is used. Therefore the jet originating from the hadronically decaying top quark is identified while calculating the distance between each jet and the lepton. Additionally studies with a method where the fat jet originating from the leptonically decaying top quark is divided into two instead of three jets is presented. This approach was made because the neutrino from the  $W$  decay cannot be seen in the detector. Nevertheless it proved to be handy to use the  $3 + 3$  method for data and therefore also for MC samples after detector simulation.

### **5.2.2 Comparison of different jet algorithms**

## **5.3 Unfolding**

## References

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- <sup>2</sup>I. W. Stewart, F. J. Tackmann, J. Thaler, C. K. Vermilion, and T. F. Wilkason, “Xcone: n-jettiness as an exclusive cone jet algorithm”, (2015) 10.1007/JHEP11(2015)072.
- <sup>3</sup>J. Thaler and T. F. Wilkason, “Resolving boosted jets with xcone”, (2015) 10.1007/JHEP12(2015)051.



Hiermit bestätige ich, dass die vorliegende Arbeit von mir selbststandig verfasst wurde und ich keine anderen als die angegebenen Hilfsmittel – insbesondere keine im Quellenverzeichnis nicht benannten Internet-Quellen – benutzt habe und die Arbeit von mir vorher nicht einem anderen Prüfungsverfahren eingereicht wurde. Die eingereichte schriftliche Fassung entspricht der auf dem elektronischen Speichermedium. Ich bin damit einverstanden, dass die Masterarbeit veröffentlicht wird.

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## **Danksagung**