Perspectives on measuring the tau lifetime at CMS

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1 Introduction

The Large Hadron Collider (LHC), the highest-energetic particle collider in the world, has been running and collecting data from November 2009 to February 2013. This first LHC running period was greatly successful including the discovery of a boson with a mass between 125 and 127 GeV/c$^2$ [1] which seems to be the Higgs boson and the highest luminosity ever reached by a hadron collider [2].

A measurement which has not been performed yet is the measurement of the tau lifetime at the Compact Muon Solenoid (CMS), one of the two large multi-purpose detectors at the LHC. The tau lepton is the heaviest of all leptons. Due to its high mass it decays very fast and is therefore almost never detected directly but only reconstructed by considering its decay products. The precise measurement of the tau lepton’s lifetime is useful for testing charged lepton universality, an assumption which is part of the standard model (SM) of particle physics. Since this measurement would be useful, in this thesis I will try to figure out if competing with the currently most precise measurements of the tau lifetime is feasible. For this, after a brief introduction to theoretical foundations, different methods used to perform the currently most precise measurements as well as their results are summarized. This is followed by a description of the experimental setup and of the procedure including the input used for this study. The procedure, in general, begins with applying defined selections on 2012 CMS data and afterwards calculating as well as recording tau lifetime distributions from the amount of data which passed the selections. The selections are applied in order to reject events that unlikely have a certain decay topology. Particularly, this topology contains a Z boson decaying into two tau leptons where one of these tau leptons decays into a muon and the other one decays into three charged pions. The main part of the procedure is to extract the tau lifetime from random generated distributions that are taken as idealized measurements as well as from actual CMS data and corresponding Monte Carlo (MC) simulations. Outcomes of both of these lifetime extractions are considered to draw conclusions in terms of feasibility of measuring the tau lifetime at CMS.
2 Theory

2.1 The standard model of elementary particle physics

The standard model (SM) of particle physics describes the elementary particles which matter is made of and how these particles interact.

In the SM, interactions between elementary particles are transferred by bosons which are exchanged between particles and have a spin of 1. The three types of interactions are the weak interaction, the electromagnetic interaction and the strong interaction. In the upper part of table 1 an overview of the basic properties of the bosons transferring the interactions and the type of particles the interactions are acting on are given. Besides the mentioned interactions there is the so called Higgs mechanism which is used to explain how particles obtain their masses. The coupling to the Higgs boson, a resonance state particle of the Higgs field, gives the particles their masses.

The particles forming matter are fermions and have a spin of 1/2. They can be divided into two sorts: quarks and leptons. There are six different particles of each of these sorts. Both sets of six particles are divided into three generations. There are two different particles in each quark and lepton generation differing by charge and mass.

Quarks are the only elementary matter particles which interact through the strong interaction. The strong interaction is described by the theory of quantum chromodynamics (QCD). Complying with QCD, every quark has a dedicated color charge. Quarks always have to form compound states being color singlets. In particular, these are mesons formed by quark-antiquark pairs and baryons formed by quark triplets.

Each of the lepton generations contains a charged lepton and a corresponding neutrino that has a very small mass and no electric charge. Neutrinos only interact weakly and therefore have a small cross section. The leptons of each generation have a dedicated flavor that is empirically observed to be conserved. In the lower part of table 1, all important properties of the elementary fermions are given.
### 2.2 The tau lepton

The tau lepton is the heaviest of all leptons in the SM. The tau lepton’s mass and lifetime are given in Table 1. It is the only lepton that can decay hadronically due to its high mass. For the present analysis the crucial decay modes and the associated branching ratios of the tau lepton are: $\tau^- \to \mu^- + \nu_\tau + \bar{\nu}_\mu$, (17.41(4)%), $\tau^- \to 2\pi^- + \pi^+ + \nu_\tau$, (9.31(6)%), where charge conjugation is implied. Further information on decay modes and other properties of the tau lepton can be found in the 2012 PDG [5].

#### 2.3 Charged-lepton universality

One of the fundamental assumptions within the SM is charged-lepton universality. It states that the coupling between a charged lepton and the charge weak current is independent of the lepton’s flavor, more specifically, it has the same value for all charged leptons. The coupling constants $g_e$, $g_\mu$, and $g_\tau$ signify the strength of the weak interaction with the termed lepton concerned.
in a weak-interaction process. In figure 1 the Feynman-diagrams for the decays of the muon and tau lepton are shown with the coupling constants indicated at the decay vertices they are affecting.

\[ \Gamma(L^- \rightarrow l^- + \nu_L + \bar{\nu}_l) = \frac{m^5 g^2_l g^2_\tau c^2}{6144 \cdot \pi^3 \cdot m^4_W} \cdot f \left( \frac{m^2_L}{m^2_W} \right) r^L_W r^L_\gamma \]  

(1)

with tau and W boson masses \( m_{\tau} \) and \( m_W \), and coupling constants \( g_\tau \) and \( g_W \) and the speed of light \( c \). The last two factors in equation 1 are corrections for

Figure 1: Feynman diagrams for muon and tau decay [9]
2.3 *Charged-lepton universality*

Radiation which can be found at [12] and the function $f$ is [11]:

$$f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x$$  \hspace{1cm} (2)

Thus, having general expressions for the widths of muon and tau decays, one can calculate the ratio of the widths of different types of the muon and tau decays to get the corresponding ratios of the leptons’ coupling constants which are simply proportionality factors for the decay width. The ratio has to be corrected by the factors that do not cancel out, especially the masses. Assuming charged-lepton universality is valid, the ratios of all pairs of coupling constants are exactly 1. Different calculations to test tau-muon universality, and thereby charged-lepton universality from the Heavy Flavour Averaging Group (HFAG) Tau Summer 2011 Web Report [13] are summarized in the plot shown in figure 2. This test of tau-muon universality is only one of several tests of charged-lepton universality since it is also possible to calculate the ratios between the electron’s weak coupling constant and the weak coupling constant of one of the heavier charged leptons. However, this test uses the tau lifetime and includes the currently most precise universality test so it sufficiently motivates measuring the tau lifetime.

![Figure 2: Muon-tau universality tests by HFAG [14]. Single decays in brackets represent corresponding branching ratios. Multiple decays in brackets denote which fits were used to calculate the average.](image-url)
The currently most precise test uses the calculation

\[ BR(\tau \rightarrow e\overline{\nu}_e\nu_\tau) \cdot \frac{\tau_\mu}{\tau_\tau} \]  

which is displayed in the second line of the plot in figure 2. For this test, the electroweak tau decay and the lifetimes of the muon and tau are used. The general relation between a particle’s lifetime, the branching ratio and decay width of a certain decay “a → b” can be calculated directly from the energy-time uncertainty relation [15]:

\[ \tau = \frac{\hbar \cdot BR(a \rightarrow b)}{\Gamma(a \rightarrow b)} \]  

where \( \tau \) is the lifetime, \( BR \) is the branching ratio, \( \Gamma \) is the decay width and \( \hbar \) is the Planck constant. With this relation, the measured branching ratios and lifetimes shown in figure 2 can be related to widths which are calculated accordingly as already shown in equation 1 so the coupling constant ratios can be calculated. Several measurements of the different weak coupling constants of the charged leptons can be found in the HFAG-Tau Summer 2011 Web Report [13]. As listed in table 1, the tau lifetime has a much higher relative uncertainty than its mass and also than the lifetimes and masses of the muon and the W boson. Thus, reducing the tau lifetime uncertainty is a necessary step to test tau-muon universality and thereby charged-lepton universality.

Since charged-lepton universality is a fundamental part of the SM, testing this assumption is a way to search for new physics or to improve precision of the model’s limits.
3 Tau lifetime measurements at LEP and Belle

The four Large Electron-Positron Collider (LEP) collaborations ALEPH [17], DELPHI [18], L3 [19] and OPAL [20] as well as the Belle [21] collaboration published results of their tau lifetime measurements where they used different methods and algorithms to obtain the lifetime. The Belle results in this section are preliminary and it is stated that further systematic calculation has to be done [21]. In the next subsections, an overview of the used methods and obtained results for measuring the tau lifetime at the LEP experiments and at Belle is given. These methods are the impact parameter (IP) method, the impact parameter difference (IPD) method, the impact parameter sum (IPS) method and the decay length (DL) method.

3.1 Impact parameter method

A signed impact parameter (IP) is defined by having the value of the distance of closest approach to the primary vertex and the sign according to the side at which the primary vertex is lying relatively to the bending direction of the particle's track. The sign is positive if the vertex is lying inside the circle the track would form if it would be continuous. Otherwise, the sign is negative. Figure 3 is an illustration of how the signed IP is defined.

\[ \alpha < \pi/2 \rightarrow \delta = +|\delta| \]
\[ \alpha > \pi/2 \rightarrow \delta = -|\delta| \]

![Figure 3: Definition of the signed IP [16]](image)

The mean signed impact parameter is assumed to be proportional to the tau lifetime. To get the proportionality factor a Monte Carlo (MC) simulation is done in which the tau lifetime and the mean signed impact parameter are known. Then, the measured lifetime from data calculates as follows:

\[ \tau_{\text{data}} = \frac{\delta_{\text{data}} \tau_{\text{MC}}}{\delta_{\text{MC}}} \]  \hspace{1cm} (3)

Figure 4 contains plots from the OPAL tau lifetime measurement [20] in which the IP method is used.
Figure 4: OPAL IP distribution plots. The arrows mark IP trimming points. Only the area between the arrows is taken into account for the results [20, Fig 1]

The IP distribution looks basically like a Gaussian convolved with a decay function. Since the IP is proportional to the lifetime, this functional behavior could already be expected before. As visible in the logarithmic plot, the cuts are made for ignoring the non-Gaussian tails.

The first part of table 2 shows the results of the tau lifetime measurement at OPAL. The main systematic uncertainty sources and their contribution to the total systematic uncertainty.

3.2 Impact parameter difference method

The impact parameter difference (IPD) method is used when 1-1 topology events are considered, which means that there is a one-prong tau decay on each side of a $Z\to\tau\tau$ event. The IPD is defined as $Y = \delta_+ - \delta_-$ where $\delta$ is the IP of a track corresponding to a one-prong tau decay. Another quantity, the acoplanarità, can be defined as $X = \Delta\Phi \cdot \sin\Theta$, where $\Delta\Phi$ is the difference of the azimuthal angles of the tracks minus $\pi$ because $X$ is supposed to be larger if the decay
products travel away from each other in planes with a larger azimuthal angle between them and $\Theta_\tau$ is the polar angle of the tau estimated by the polar angle of the event’s thrust axis. For small decay angles, which are a good approximation since the momenta of the decay products are much higher than the mass of the tau in the LEP experiments, the relation between the IPD $Y$ and the acoplanarity $X$ is estimated as being

$$Y = LX$$  \hspace{1cm} (6)

with the flight length $L$ of the tau. By measuring $Y$ and $X$ one can get a value for $L$ from which the tau lifetime can be calculated as follows:

$$\tau_\tau = \frac{L}{\beta \gamma c}$$  \hspace{1cm} (7)

with $\beta$ and $\gamma$ as the parameters of relativistic boost and $c$ as the speed of light. The parameters of the relativistic boost are calculated from the beam energy with the formula

$$\beta \gamma = \frac{p}{mc}$$  \hspace{1cm} (8)

with corrections from inertial and final state radiation which causes lose of energy and therefore a smaller boost than one could expect from the beam energy naively.

In figure 5 the IPD distributions as a function of the acoplanarity from the ALEPH [17] and DELPHI [18] experiment, at which the tau lifetime was measured using the IPD method, are shown.

![Figure 5: The ALEPH [17, Figure 2] & DELPHI [18, Figure 2] IPD plots show the measured IPD as a function of acoplanarity](image)

Especially for the central region, the linear relation fits well to data and MC (white in the DELPHI plot).

The second part of table 2 contains results and a deployment of systematic uncertainty sources from the ALEPH and DELPHI IPD measurement.
3.3 Impact parameter sum method

The impact parameter sum (IPS) method is used for 1-1-topology events just as the IPD method. The IPS $\Delta$ is defined as

$$\Delta = \delta_+ + \delta_-$$

(9)

with the impact parameters $\delta$ of the event’s tracks corresponding to the taus. The tau lifetime is proportional to the width of the IPS distribution so that one can calculate the lifetime analogously to the way it can be done with the IP method, given in equation 5:

$$\tau_{\text{data}} = \sigma_{\text{data}} \cdot \frac{\tau_{MC}}{\sigma_{MC}}$$

(10)

where $\sigma$ is the width of the IPS distribution and $\tau$ the tau lifetime.

In figure 6 the plots from measuring the tau lifetime at ALEPH [17] and DELPHI [18] using the IPS method are shown.

![Figure 6: The IPS plots from measuring the tau lifetime at ALEPH & DELPHI using the IPS method.](image)

As one would expect, the distributions look symmetric due to the fact that in the required 1-1-topology events there is always one positively charged and one negatively charged track which have opposite bending directions due to the constant magnetic field. Since the sign of the IP is defined according to the bending direction, the IPSs of the oppositely charged tracks tend to cancel each other out in sum which produces the symmetry. Both distributions have tails being flatter than the central region and are therefore modeled with a linear combination of various Gaussians.

The third part of table 2 contains results and a deployment of systematic uncertainty sources from the ALEPH and DELPHI IPD measurement.
3.4 Decay length method

The decay length (DL) method is used for events containing at least one 3-prong tau decay. The DL is defined as the distance between the production vertex and the decay vertex of the tau lepton decaying in a 3-prong topology.

At LEP, not the whole DL was directly measured but only the decay length in transverse direction with respect to the beam spot since the transverse component of the beam spot is very well known and can be assumed being the transverse component of the production point of the tau. The decay vertex of the tau lepton is also in the first step only measured in transverse direction and estimated as the point where the three tracks corresponding to the decay products are intersecting. An exact intersection of all three reconstructed tracks is very unlikely, so a vertex fit to the measured tracks has to be performed. Besides the transverse DL the polar angle $\Theta_z$ was taken into account. It was assumed to be the polar angle of the event’s thrust axis and used to calculate the z-coordinate of the DL by just multiplying the transverse DL with $\cot(\Theta_z)$ so that the whole DL can be used to calculate the tau lifetime as in equation 7 where the DL has to be inserted for $L$.

At Belle, the laboratory frame is not equal to the center of mass frame. Because of this, it uses an analogous method with modifications to take into account the difference between the centre of mass frame and the laboratory frame [21]. Also, only events with both taus decaying in a 3-prong topology were taken into account at Belle. This is done because taking into account two decays in one event makes crosschecks on the decays possible. However, the Belle results for the lifetime are not published yet but only the precision which is given in table 2.

In figure 7 there are plots shown from measuring the tau lifetime at ALEPH [17], DELPHI [18], OPAL [20] and Belle [21] using the DL method.
Figure 7: ALEPH [17, Figure 3], Belle [21, Figure 5], DELPHI [18, Figure 1] & OPAL [20, Fig. 2] plots for the tau lifetime measurements using the DL method. The gray filled distribution in the Belle plot (upper right) corresponds to u, d, s and and \gamma\gamma background, the red distribution corresponds to charm background and the blue one to beauty background.

Similarly to the IP distributions in figure 4, the DL distributions look like Gaussians convolved with exponential decay functions. The results of the lifetime measurements using the DL method are shown in the last part of table 2. As mentioned, the Belle results are preliminary.

### 3.5 Results of previous tau lifetime measurements

In table 2 all results of the mentioned measurements at LEP and Belle are summarized. The amount of tracks or vertices respectively is given for the measurements as well as the actual lifetime results, relative systematic uncertainties and the types and contributions of systematic uncertainty sources for the different experiments.
### 3.5 Results of previous tau lifetime measurements

<table>
<thead>
<tr>
<th></th>
<th>IP measurement at OPAL [20]</th>
<th>Beam properties</th>
</tr>
</thead>
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<tr>
<td>number of tracks measured</td>
<td>62885</td>
<td>4.2% 3.9% 3.4%</td>
</tr>
<tr>
<td>systematic uncertainty</td>
<td>290.4±3.5±2.2</td>
<td></td>
</tr>
<tr>
<td><strong>IP resolution</strong></td>
<td><strong>MC statistics</strong></td>
<td><strong>Beam properties</strong></td>
</tr>
<tr>
<td>IPD measurement</td>
<td>ALEPH [17]</td>
<td>DELPHI [18]</td>
</tr>
<tr>
<td>number of tracks measured</td>
<td>80484</td>
<td>520/2</td>
</tr>
<tr>
<td>result for $\tau_\ell$ [6]</td>
<td>290.4±3.5±1.3</td>
<td>291.4±3.5±1.3</td>
</tr>
<tr>
<td>systematic uncertainty</td>
<td>4.3%</td>
<td>5.1%</td>
</tr>
<tr>
<td>Cut data / MC agreement</td>
<td>3.8%</td>
<td>4.6%</td>
</tr>
<tr>
<td>IPS measurement</td>
<td>ALEPH [17]</td>
<td>DELPHI [18]</td>
</tr>
<tr>
<td>number of tracks measured</td>
<td>80484</td>
<td>520/2</td>
</tr>
<tr>
<td>result for $\tau_\ell$ [6]</td>
<td>289.0±3.5±3.5</td>
<td>292.0±2.3±2.1</td>
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<tr>
<td>systematic uncertainty</td>
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<td>IP resolution parameters</td>
<td>Event selection Method bias</td>
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<tr>
<td>DL measurement</td>
<td>ALEPH [17]</td>
<td>Belle [21]</td>
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<tr>
<td>number of vertices fitted</td>
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<td>- 10</td>
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<tr>
<td>result for $\tau_\ell$ [6]</td>
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<td>Detector alignment</td>
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<td>n/a</td>
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<tr>
<td>Detector alignment</td>
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<td></td>
</tr>
<tr>
<td>background</td>
<td>3.5% 2.8% 0.7% 3.5% 4.0% 2.0%</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: LEP results for the tau lifetime measurements

The statistical uncertainties obtained with the IPS measurement are smaller than the ones of the IPD measurement but the systematic uncertainties are distinctly increased in size and diversity which makes it more difficult to avoid them. Especially, in the IPS measurement the IP resolution parametrization becomes important since the width of the IPS is considered directly for calculating the results, so the IP resolution has a wide influence on it. The DL measurements generally yield results with lower statistics in the LEP experiments due to the lower branching ratios for the required decay topologies but as a compensation for that they have lower systematic uncertainties. The systematic uncertainties from Belle are still to be calculated, so the value in table 2 is not confirmed yet. However, the statistical uncertainty is very low due to the large amount of events so if the systematic uncertainties finally stay at such a low level the Belle tau lifetime result will be a crucial contribution to the world average.
4 Experimental setup

4.1 The Large Hadron Collider

The Large Hadron Collider (LHC) is the particle accelerator with the highest energy worldwide. In particular, it has run at center-of-mass energies of 900 GeV, 7 TeV and 8 TeV and is expected to run at 14 TeV in the next running period [22]. The storage ring of the accelerator has a perimeter of about 26.7 kilometers and is located at the France-Switzerland border near Geneva. There are four main experiments based at the storage ring using the hadron collisions in the LHC: ALICE, ATLAS, CMS and LHCb. CMS and ATLAS are general purpose detectors while ALICE is built for studying heavy-ion collisions and LHCb for studying hadronic decays related to beauty and charm quarks.

LHC is a discover machine which uses proton-proton collisions because this way higher center-of-mass energies can be obtained than with e⁺-e⁻ storage rings which emit more synchrotron radiation causing energy loss. Since protons have a substructure in which different quarks and gluons are statistically distributed, the exact initial state for an event is not trivially known. A strength of the LHC is the high luminosity which had a peak of \( \lambda = 7.73 \cdot 10^{33} \text{cm}^{-2}\text{s}^{-1} \) in August 2012 [23] currently being the world record for proton colliders. The luminosity is planned to be raised to about \( 10^{34} \text{cm}^{-2}\text{s}^{-1} \) [24].

At the LHC, the colliding hadrons are delivered from pre-accelerators to the main storage ring in bunches and are therefore statistically distributed when the bunches are crossing each other. Also, there is a varying amount of typically about 20 collisions in every bunch-crossing while the bunch-crossings appear every 50 ns. These effects combined are called “pile-up”. Having pile-up in a bunch-crossing means that it can be difficult to distinguish which tracks are coming from which vertex.

4.2 The Compact Muon Solenoid

The Compact Muon Solenoid (CMS) experiment is a multi-purpose detector at the LHC. It is generally arranged in an azimuthal symmetric way with the symmetry axis lying in the middle of the beam pipe as shown in figure 8. All in all it has a diameter of 15 m, a length of 28.7 m and a weight of 14,000 tons [26].

There are several coordinates commonly used for the CMS detector. Three coordinates refer to a Cartesian coordinate system. In this system, the x-axis points to the center of LHC, the y-axis points upward and the z-axis points into the counterclockwise beam direction so the coordinate system is right-handed. The azimuthal angle \( \phi \) is measured in transverse plane relatively to the x-axis. The polar angle \( \theta \) is measured relatively to the z-axis and lies in any plane determined by the azimuthal angle. The polar angle can be converted into a Lorentz-invariant quantity, the pseudorapidity, which is \( \eta = -\ln \left( \tan \left( \frac{\theta}{2} \right) \right) \).

The detector is composed of different components which together allow for the energy and momentum of different particles to be measured and give the ability to distinguish between particle types. Figure 8 gives an overview of the com-
ponents, the way they are assembled and their basic properties.

The most inner component is the silicon tracker. It consists of silicon pixel and strip detectors which both are used to measure the tracks of charged particles traveling through the tracker. Silicon is used for detection because of its high energy and time resolution since in this part of the detector the amount of particle flow is much higher than anywhere else in the detector. The large number and the arrangement of layers gives the possibility to have an up to 14-hit coverage high precision track measurement for $\eta \leq 2.4$ [28]. To measure the track with high precision is generally useful because the momentum and charge of a particle can be calculated from its track’s curvature due to the magnetic field and also eventual vertices can be measured using tracker information. For more information on the CMS tracker and its performance the tracking performance paper from the CMS collaboration can be consulted [28].

The next component of the CMS detector is the electromagnetic calorimeter (ECAL) which is constructed directly around the tracker. It consists of scintillating lead-tungstate (PbWO$_4$) crystals, used because of their high density, since they are supposed to absorb all the energy of electrons and photons traveling through the ECAL. Electrons and photons traveling through the ECAL produce showers which cause scintillation in the crystals which are transparent to the produced frequencies of light. The amount of light produced in this way is proportional to the particle’s energy and therefore measured. Moreover, there are preshower detectors within the endcap region which have a finer granularity than the rest of the ECAL. They are used to e.g. distinguish one high energy photon from two photons with a lower energy which are not well separated and
would therefore be identified as one high energy photon. The finer granularity gives the ability to distinguish these cases because the energy deposits of the two photons are made separately if the crystals are smaller. For more information on the CMS ECAL and its performance the ECAL performance and operation paper from the CMS collaboration can be consulted [29].

The next component of the detector is the hadronic calorimeter (HCAL). It consists of brass plates which cause showers, if hadrons travel through it. Between the brass plates, there are plastic scintillators, used to measure the showers’ properties. In the HCAL the showers are only samples, which means that not the whole amount of the hadronic energy is absorbed in the HCAL but still the total hadronic energy is measurable by proper calibration. For more information on the CMS HCAL and its performance the HCAL performance paper from the CMS collaboration can be consulted [30].

Outside of the HCAL there is a superconducting solenoid, providing a magnetic field of about 3.8 T inside and about 2 T in the opposite direction at the outside. The magnetic field is used in the tracker and muon system for bending tracks of charged particles which is necessary to calculate the charge and momentum from the track’s curvature. More information on the CMS solenoid is available in the magnet technical design report [31].

The outermost component is the muon detection system. It consists of a large steel return yoke and muon chambers. The yoke is there to absorb all particles except muons and neutrinos and also for forming the magnetic field. The different types of muon chambers are all consisting of anodes and cathodes, separated by gas which is partly ionized when a muon travels through it. The ions and electrons travel away from each other to the electrodes. The traveling distance and the place of impact of multiple chambers are used to measure a track and together with the magnetic field to calculate a momentum and match it with tracker information. More information on the CMS muon chambers is available in the muon detector performance report [32].

Figure 9 illustrates how the components are used in combination to identify particles and measure their charges, momenta and masses.
The basic principle is that every sort of particles has its own signature depending on its properties: Charged particles have bended tracks, electrons and photons generally deposit their energy in the ECAL, hadrons leave samples in the HCAL and muons in the muon chambers. The curvature of all charged particles is proportional to the momentum and the particle’s charge determines the curvature’s direction according to the Lorentz force. Particularly, electrons have an associated curved track in the silicon tracker and leave a shower in the ECAL. Muons also have an associated curved track in the silicon tracker but they pass the ECAL, reach the muon chambers and are detected there because they ionize gas which causes a measurable electric current between voltage-carrying electrodes. Charged hadrons also have an associated curved track in the silicon tracker, pass the ECAL and finally leave sample showers in the HCAL. Photons only leave showers in the ECAL and neutral hadrons only in the HCAL.
5 Procedure and results

The general procedure of this analysis consists of multiple steps. First, lifetime distributions are reconstructed and calculated in the way it is described in subsection 5.1. Specifications of the used data and MC are given in subsection 5.2 and selection criteria applied to clean the data sample from backgrounds are listed in subsection 5.3. In order to decide which of several possible fit methods to take for further fitting, tests with toy MC are done and described in subsection 5.4. In subsection 5.5, fits to measured flight-length, momentum, and lifetime resolutions are shown and their results are associated with different methods of reconstructing the tau lifetime which can be compared in this way. Considering this comparison, one appropriate of the differently obtained lifetime distributions is shown in subsection 5.6 in order to substantiate and elucidate details of further procedure. This procedure generally consists of studying the feasibility of actual tau lifetime measurements at CMS in terms of statistics by using toy MC and, analogously to that, performing probabional fits to actual data and MC. The feasibility study for statistics is performed in subsection 5.7 and the probabilional fits in subsection 5.8. The probabilional fits are done to see roughly what is already obtainable with an effort appropriate for the scope of this thesis. Further details on the individual steps are stated in the corresponding mentioned subsections.

5.1 Lifetime reconstruction

The signal type data and MC for measuring the tau lifetime, which is specified in subsection 5.2, is required being only from Drell-Yan→ττ events. A Drell-Yan (DY) event is an event in which a quark and an antiquark annihilate and form a photon or Z boson. This decays into two same-flavoured leptons with opposite charge. As it is included in the selection criteria, described in subsection 5.3, the final states of the DY events in the present analysis are reconstructed as 3π± vs μ states. This is done for using the muon as a tag due to its clear signature in the detector and the 3π± tracks for fitting a secondary vertex to get a decay length. All quantities are calculated in the transverse plane and in 3d to allow for a comparison between these two cases.

The algorithm taking into account all detector information to obtain vertices and momenta of all particles and jets in an event as well as missing transverse energy (MET) is called particle flow (PF) algorithm [38]. The primary vertex (PV) of each event is fitted from the tracks of all charged final state particles assumed to belong to the affected collision. In this analysis, the secondary vertex (SV) is fitted to the point where the tracks of the three charged pions, into which the tau decayed, most likely come from.

Moreover, at LHC, the tau momentum can not be calculated by nominal quantities of the accelerator. It has to be determined on an event by event basis. Also, for the hadronic tau decays, there is always one neutrino escaping the detector without being measured which means the momentum of the tau is estimated by the PF algorithm, is missing the neutrino contribution. Therefore,
an invariant mass and a direction constraint is used, taking into account the four-momenta of the hadronically decaying tau’s decay products event by event. The mass constraint is represented by the formula:

\[ m_\tau = \sqrt{(p_{\mu}^a + p_{\mu}^h)^2} \]  \hspace{1cm} (11)

where \( p^\mu \) denotes the momentum four-vector and \( a_l \) is the resonance state of decaying taus indicating the required 3-charged-pion topology. The tau momentum itself can be extracted from the mass constraint in equation 11 and \( p_T \) balance only to a twofold ambiguity. In this case, \( p_T \) balance means that the momentum components of \( a_l \) and of the neutrino, measured transversely with respect to the tau, have to sum up to zero. The quadratic expression for the tau momentum is not exactly symmetric. This leads to two different approaches getting an estimate for the tau momentum: taking the average of the two solutions as the tau momentum; or taking the apex of the asymmetric parabola as the tau momentum. In this analysis, both approaches are used parallel for measuring the momenta of the taus to compare the resolution.

The method itself, besides obtaining the tau PV, SV and momentum, operates as follows: The absolute value of the decay length is calculated by subtracting the three vector of every 3-prong decaying tau’s PV from the three vector of its SV. To get a signed decay length the sign is calculated as follows:

\[ sgn_{DL} = \frac{\vec{p}_{a_l} \cdot (\vec{x}_{SV} - \vec{x}_{PV})}{|\vec{p}_{a_l} \cdot (\vec{x}_{SV} - \vec{x}_{PV})|} \]  \hspace{1cm} (12)

where \( \vec{x} \) is the spatial position of the respective vertex. Finally, the signed decay length is simply the product of the sign for the decay length and its absolute value. Another necessary quantity for getting the lifetime is the tau momentum which is obtained in the two different ways for comparison of the methods as described in the last paragraph. The tau lifetime is calculated analogously to the way it was done for the DL method which leads to a calculation as follows:

\[ \tau_\tau = \frac{L \cdot m_\tau}{p_T} \]  \hspace{1cm} (13)

In the present analysis, for both of the possible ways to obtain the momentum as well as for the transverse and the 3d case, all distributions are recorded. This means there are different resolutions to be compared in order to decide which one to take for the best estimate of the tau lifetime. This is done in subsection 5.5. The efficiency is always assumed to be constant over the whole range of the measured quantity.

5.2 Data and Monte Carlo

This analysis uses data from the LHC 2012 run at 8 TeV which has a total integrated luminosity of 23.3 fb\(^{-1}\) [34]. The MC dataset contains background MC belonging to the following types: W+Jet events; Drell Yan events which decay
into muon or electron pairs; and ttbar events. Also, there is background from QCD contribution. To estimate the QCD background the amount of events from data and from MC where the reconstructed charge has the same sign on each side (muon and 3-prong tau) is recorded separately. The difference of these amounts is assumed to be the QCD contribution. QCD backgrounds are assumed to have approximately as much events with same charge as with opposite charge on each side, so the QCD contribution in oppositely charged data events should be exactly the calculated difference of the amounts which were reconstructed to have same signed charge on each side. In MC, DY→ττ events are assumed to be signal events. All MC events are processed with the detector simulator Geant4 [35] to get a data-like sample which is afterwards treated exactly as the real data. The true information of the MC events is also stored. The files containing the data and MC events with all the necessary information for the performed reconstructions are listed in table 9 in the appendix.

5.3 Selection

To select a clean sample of DY→ττ→3π±µ events, reducing background and increasing the purity of the signal for the final result is necessary. Therefore, selections are applied to data as well as to MC events. The selections are applied pursuing the following strategy:

- **muon selection**
  - Trigger requiring isolated muon is applied
  - muon is “good”, basically meaning that the muon measurements from the muon chambers and the other detector parts have to be compatible at least to a minimal level
  - muon p_T > 20 GeV/c
  - muon is isolated, more specifically \( \frac{p_{T,ECAL} + p_{T,HCAL} + p_{T,tracker}}{p_{T}} < 0.2 \)
  - only one muon is allowed to pass the cuts, otherwise the whole event is discarded

- **tau selection**
  - tau p_T > 20 GeV/c
  - tau \( \eta < 2.0 \)
  - tau is isolated (result from PF algorithm)
  - tau has to have the correct decay mode, a clear SV and a dedicated al momentum reconstructed by PF algorithm
  - only one tau candidate is allowed to pass the cuts, otherwise the whole event is discarded
5.4 Fit procedure validation with toy Monte Carlo

- event cuts
  - \( \Delta \phi (\text{tau, muon}) > \frac{\pi}{4} \)
  - \( |\Delta \text{charge(tau, muon)}| < 0.5 \text{ e} \)
  - transverse mass \( M_T < 40 \text{ GeV/c}^2 \)

The transverse mass is defined as \( M_T \)

\[
M_T = \sqrt{2p_T^\mu \cdot \mathcal{E}_{T}^{\text{missing}} \cdot (1 - \cos(\phi(p_T^\mu) - \phi(E_{T}^{\text{missing}})))}
\]  

(14)

where \( \varphi \) denotes the polar angle of the muon four-momentum and of the missing transverse energy.

There are 15603 data events in the sample that passed these selection criteria and had associated lifetimes in the recorded range which was from -0.5 ps to 2 ps. The estimated number of background events is 5627 so there are 9976 data events associated with signal. The background event number estimation is the number of events from MC backgrounds plus the number of QCD control sample events which are estimated from same-signed charged data events, both passing all selection criteria. After applying the trigger, there is a decrease of total integrated luminosity to 19.789 fb\(^{-1}\).

5.4 Fit procedure validation with toy Monte Carlo

To compare different fitting methods and validate the fitting procedures, fits to toy Monte Carlo (MC) were performed. In theory, the tau lifetime is an exponential decay function. The detector resolution can be emulated with a Gaussian function. Therefore, initially, toy MC is generated by adding a Gaussian distributed to an exponential distributed random variable, generated with the Root data analysis framework [36], and the distribution of this sum is stored. As the fitting function probability density function (p.d.f), a convolution of an exponential decay function with a Gaussian is used. The first tests with toy MC are done to find biases and difficulties in fitting convolved functions with RooFit [37], a data fitting package for Root. The fits performed to the histogrammed toy data were least-chi-square (\( \chi^2 \)) fits and maximum-likelihood (LL) fits for binned versions and maximum-likelihood fits for unbinned versions of the stored distributions. In figure 10 example plots of the convolved distributions are shown for the three different fitting procedures. The blue lines represent the best fit function obtained with the fitting method indicated in the respective plots.
Figure 10: Fitting to distributions of toy data to test the fitting process. Left: χ² fit; middle: binned LL fit; right: unbinned LL fit

The plots basically look all the same. Therefore, to test the fitting methods for biases, the whole fitting procedure has been executed 10,000 times for every method while every fit itself has been made with a set of 10,000 random data points. Until this point, there are 10,000 single fit results obtained for the width parameter σ of the Gaussian and the mean life parameter of the exponential τ. The distributions of these fit parameter results should be Gaussian with mean values equal to the values the parameters have been set to for generating the toy MC (true values). Therefore, the distributions of the fit results for the width σ of the Gaussian resolution function and for the mean-life parameter τ of the exponential decay function were recorded and Gaussians were fitted to them. The absolute values of the differences between the true values and the reconstructed mean values of this Gaussians and their relative uncertainties represent the biases of the fitting procedures and the corresponding relative uncertainties on bias. In table 3 the results of the fits of the parameters are shown.

<table>
<thead>
<tr>
<th></th>
<th>χ² fit</th>
<th>binned LL fit</th>
<th>unbinned LL fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>bias (σ) * 1000</td>
<td>0.6898±0.0123</td>
<td>0.9619±0.0114</td>
<td>0.0199±0.0111</td>
</tr>
<tr>
<td>bias (τ) * 1000</td>
<td>4.243±0.034</td>
<td>0.029±0.025</td>
<td>0.030±0.024</td>
</tr>
</tbody>
</table>

Table 3: Toy MC parameter distribution fit results. The true value for σ is always 0.04, the true value for τ is always 0.2

For the χ² fit, there is a significant bias in the lifetime fit while for the binned LL fit, the bias on the lifetime is very small and not significant with respect to its uncertainty. The unbinned LL fit result for the mean-life parameter τ is similar to the corresponding result from the binned LL fit. However, the binned LL fits are significantly faster than the unbinned LL fits. Moreover, the binned LL fits are precise enough for the purpose of this analysis. For this reason, all fits to data and MC as well as the feasibility study for statistics are only be performed using binned LL fits.
5.5 Resolution

Following the procedure described in subsection 5.1, one obtains distributions for the flight-length, momentum and lifetime. As mentioned, all distributions were recorded in transverse plane and in 3d and also with different solutions of the momentum fit from mass and direction constraints.

The resolution for the different types of MC and for data, both described in subsection 5.2, is determined in different ways. For signal MC (DY→ττ), the resolution of any quantity is measured by subtracting the true value from the reconstructed value event by event and storing the result in a distribution. Then, Gaussians are fitted to these distributions to get corresponding resolutions. The MC backgrounds belonging to prompt decays can also be taken into account. Prompt decays are decays that correspond to negligible lifetimes compared to the scale of the tau lifetime. In this analysis, these backgrounds are W+Jet and DY→μμee events. Since these decays are prompt, their resolutions are obtained by fitting Gaussians to distributions of these backgrounds. For a data-driven resolution estimate, the QCD control sample is handled the same way as the prompt decay MC backgrounds are. More specifically, Gaussians are fitted to the flight-length and lifetime distributions of the QCD contribution. This can be done because the QCD contribution is also a prompt decaying one.

All resolution plots are corrected for biases so the quantities are centered around zero. The bias is always given in the table referring to the respective resolution measurement.

Figures 11 - 13 show the signal MC resolution distributions for the following quantities in 3d and transverse plane: The tau flight-length; the tau momentum from the apex solution obtained as described in the beginning of this section of the thesis; and the tau lifetime only using the apex solution since this solution yields the best resolution for the lifetime which can be seen in table 6 and also already the best resolution for the momentum which can be seen in table 5.
Figure 11: Fitted resolution of the signal MC flight-length in transverse plane and in 3d.

The signal MC flight-length resolution distributions both look symmetric. They can be fitted well with Gaussian functions which have the fit parameter values shown in table 4, where $\sigma$ is the Gaussian width parameter and the bias is the shift into the right direction which the plot in figure 11 is already corrected for. The same fitting procedure was applied for prompt decay background flight-lengths and QCD flight-lengths. The results of these fits are shown in the second and third part of table 4.

<table>
<thead>
<tr>
<th></th>
<th>transverse</th>
<th>3d</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signal MC</strong></td>
<td>$\sigma$ [\mu m]</td>
<td>bias [\mu m]</td>
</tr>
<tr>
<td></td>
<td>489.37$\pm$4.29</td>
<td>18.02$\pm$5.46</td>
</tr>
<tr>
<td><strong>Prompt decay background MC</strong></td>
<td>$\sigma$ [\mu m]</td>
<td>bias [\mu m]</td>
</tr>
<tr>
<td></td>
<td>583.93$\pm$8.31</td>
<td>60.83$\pm$9.54</td>
</tr>
<tr>
<td><strong>Data estimate (QCD control sample)</strong></td>
<td>$\sigma$ [\mu m]</td>
<td>bias [\mu m]</td>
</tr>
<tr>
<td></td>
<td>459.03$\pm$11.89</td>
<td>43.77$\pm$11.97</td>
</tr>
</tbody>
</table>

Table 4: Flight-length resolution Gaussian fit parameter results
As already visible in figure 11, the transverse resolutions have smaller widths than the 3d resolutions. The bias for signal MC is small in comparison to the resolution width. The width parameters for data estimate from QCD are differing significantly from the ones from the prompt MC background distributions. The uncertainty on the signal MC resolution parameters is way smaller than the uncertainty on the other resolution parameters. Also, considering the $\chi^2$ values, the fits themselves seem to work better for signal MC.

Figure 12 shows the momentum resolution fits for the apex solution of the momentum fit in transverse plane and 3d using signal MC.

![MC Momentum Resolution](image)

Figure 12: Fitted resolutions of the tau momentum using the apex solution of the kinematic momentum fit

One general feature of the momentum resolution is that it is not symmetric. In the plot in figure 12 it can be seen especially at the left flank of the Gaussians where there are more points below the fit function than at the right flank. This may be due to the fact that taus from $\text{DY} \rightarrow \tau\tau$ events that decay in a $3\pi^\pm + \pi^0$ (4-pion) topology can pass all the cuts not being distinguished from events without a $\pi^0$ (3-pion). The 4-pion decays have other decay kinematics than the 3-pion decays. More specifically, they do not decay through the a1-channel to 3 charged pions which means the $p_T$ balance between the charged pions and the neutrino can not be assumed for this case. An attempt to compensate for this issue in estimating the momentum resolution is taking only the inner part (peak region) of the momentum resolution distributions for fitting a Gaussian which indicates the resolution quantitatively. This is reasonable since larger differences between true and measured momentum might have more likely been
caused by the reconstruction of 4-pion decays as by 3-pion ones. By fitting only the peak region of the momentum resolution distribution, a large amount of 4-pion decays should not be taken into account. The momentum resolution fits already are applied only on the peak region of the distributions.

Also, the mean values of all signal MC momentum resolution fits originally are significantly different from zero. For all following lifetime fits this bias will be taken into account, so the distributions will be corrected for this bias. The fit parameter values for the signal MC momentum resolution fit are shown in table 5.

<table>
<thead>
<tr>
<th>Apex momentum solution</th>
<th>3d</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.03±0.10</td>
<td>6.30±0.12</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Average momentum solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>transverse</td>
</tr>
<tr>
<td>10.63±0.14</td>
</tr>
</tbody>
</table>

Table 5: Momentum resolution Gaussian fit parameter results

Like the flight-length resolution function, the momentum resolution function in 3d is wider than in transverse plane. Furthermore, the momentum obtained with the apex solution has a better resolution than the one obtained with the average solution since all relative uncertainties are smaller for the apex solution. For this reason, only the apex solution will be used as the momentum from this point on.

Figure 13 shows the resolution fits for the signal MC lifetime where only the apex momentum solution is applied.
Figure 13: Fitted resolution of the tau lifetime in transverse plane and 3d using the apex momentum solution

The mentioned asymmetry from the momentum resolution is also visible in the lifetime resolution plots. On the left side, the points tend to be more likely below the fit function than on the right side. The results of this fit are shown together with the prompt decay background and QCD lifetime resolution in table 6. As a reminder, to get the parameters for these resolutions, Gaussians were fitted to prompt decay background lifetime distributions and to the QCD lifetime distribution.
Table 6: Lifetime resolution Gaussian fit parameter results using different estimations for different types of MC and data

The non-zero mean values of the Gaussians are small due to the already applied bias corrections. They are not significant with respect to their uncertainties. The fit function for signal MC seems to fit very well. It can be seen that for the lifetime resolution the values and the uncertainties for the QCD control sample estimating a resolution for data and the prompt background coincide while they do not do so for the flight-length. However, the resolution width parameters from the prompt decays and the QCD control sample estimated from data are smaller than the signal MC resolution. Generally, a reason for this difference could be the smaller lifetime than the common signal-like data or signal MC lifetime. Taking into account the differences between the data estimate from the QCD control sample and the prompt backgrounds in the flight-length resolution, it is clear that for an actual lifetime measurement the resolutions of backgrounds have to be modeled with more complex models. Another disadvantage of the data estimate and prompt decay MC parameters are their large uncertainties. For the probabilistic fits, the lifetime is fitted to signal-like data and signal MC to obtain the lifetime. Thus, only the resolution parameters from signal MC, shown in the first part of table 6, will be taken into account and applied for both, signal MC and data. Besides of that, the backgrounds will not be fitted but taken into account for the data fit as the histogrammed distributions they originally are.

5.6 The lifetime distribution

The differently obtained momenta yield different resolutions as shown in subsection 5.5. Since the apex solution yields a better resolution, it is the only momentum used for all following lifetime plots, fits and results.

The transverse lifetime distribution of all MC types taken into account, including background, and of the complete data sample, is shown in figure 14 with linear y-scale in the upper plot and logarithmic y-scale in the lower plot.
5.6 The lifetime distribution

![Lifetime distribution graph](image)

Figure 14: Lifetime distribution of data and MC in transverse plane using the apex momentum solution. The lifetime is rebinned by a factor of 8 to provide better readable histograms.

The background distributions are almost all located closely to zero whereas the signal and the ttbar contribution reach much farer to the right side. This
can be related to the fact that the backgrounds, except t\bar{t}, are associated with prompt decays and are therefore distributed very closely to zero relatively to the scale of the tau lifetime. The contribution of t\bar{t} background is assumed to be negligible. Based on this lifetime distribution, the following approaches for the feasibility study with toy MC as well as for the probational lifetime fit will be tested and validated: To avoid having a high amount of background in the fitted distribution, for a first approach, the lifetime in transverse plane is fitted only from 0.15 ps on. The fits are performed only until 0.6 ps because using a fine binning well fittable bin contents can be obtained until approximately 0.6 ps without containing large contributions of non-Gaussian tails which are visible in the lower plot of figure 14. The second approach will be the same as the first one with the exception that the fit is performed on the whole recorded range which is 0.5 until 2 ps. The distributions for this approach have more statistics but they contain a region which is dominated by background which causes necessity to estimate systematic uncertainties with more effort than for the limited range when this is done for an actual lifetime measurement. While for the full range fits the Gaussian parameters are free for fitting, they are fixed to the resolution values for the limited range fits. This is because the Gaussian parameters and the lifetime parameter are highly correlated when fitting on such a small range on the right side of the Gaussian which is also the tail of the exponential decay function because these functions are convolved. For the 3d lifetime fits, which will not be performed in the toy MC feasibility study, the ranges are always the same as for the transverse plane fits since the distributions are very similar.

5.7 Feasibility study on statistics

As contrasted with the toy fits for validating the fitting procedure in subsection 5.4, for the feasibility study in this subsection, there are the following considered toy MC contributions for fitting: a background distribution containing 5627 background entries, randomly Gaussian distributed with a width parameter set to 0.07 ps and centered around zero; a signal distribution containing 9976 signal entries, distributed exactly like the toy MC in subsection 5.4, so the random variable for signal is a Gaussian plus an exponential distributed variable. The width parameter for the signal distribution is set to 0.08 ps and the lifetime parameter is 0.2906 ps which is equal to the PDG tau lifetime value [5]. The signal and background distributions are added and a Gaussian plus an exponential distribution convolved with another Gaussian is fitted to this sum. For the full range approach, all Gaussian parameters are free; for the limited range approach, all Gaussian parameters are fixed to their true values. Since the true Gaussian parameter values in reality (and also for the probational fit in the next subsection) are not determinable with arbitrary precision, the limited range approach for this toy MC study does not include any uncertainty from backgrounds. The number of entries for background and signal toy MC are multiplied by several scale factors in order to estimate the behavior of statistical uncertainties for higher CMS luminosities. These different results for different scale factors are shown in table 7.
Figure 15 shows fits using both approaches described in the last paragraph.

![Toy MC lifetime fit](image1)

**Toy MC lifetime fit**

![Toy MC lifetime fit](image2)

**Toy MC lifetime fit**

Figure 15: Fitted toy MC lifetime for the limited range approach with resolution parameters fixed to their true values (upper plot) and for the full range approach with free resolution parameters (lower plot). The scale factor for the amount of signal and background entries is 1.
Table 7 shows the results of the fits for both approaches and for different scale factors.

<table>
<thead>
<tr>
<th>Luminosity scale factor</th>
<th>limited fit range $\tau$ [fs]</th>
<th>$\chi^2$</th>
<th>full fit range $\tau$ [fs]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>297.848±10.475</td>
<td>0.80</td>
<td>289.026±4.092</td>
</tr>
<tr>
<td>2</td>
<td>292.791±7.149</td>
<td>0.70</td>
<td>287.332±2.676</td>
</tr>
<tr>
<td>5</td>
<td>289.873±4.481</td>
<td>1.13</td>
<td>287.729±1.849</td>
</tr>
<tr>
<td>10</td>
<td>286.640±3.099</td>
<td>0.85</td>
<td>288.910±1.249</td>
</tr>
<tr>
<td>25</td>
<td>289.056±2.001</td>
<td>1.03</td>
<td>289.956±0.827</td>
</tr>
<tr>
<td>50</td>
<td>289.047±1.417</td>
<td>0.89</td>
<td>290.290±0.586</td>
</tr>
<tr>
<td>100</td>
<td>289.393±1.063</td>
<td>0.93</td>
<td>290.021±0.416</td>
</tr>
<tr>
<td>1000</td>
<td>290.856±0.319</td>
<td>1.13</td>
<td>290.587±0.132</td>
</tr>
</tbody>
</table>

Table 7: Results of both approaches for the toy MC lifetime fit for different integrated luminosity scale factors. Uncertainties are statistical only.

The $\chi^2$ values for the full range fit are not given because they are not meaningful. They are always larger than 500 due to bins with zero content. However, the fits themselves all worked well. Further discussion of the results will be done in section 6.

5.8 Probational data and MC lifetime fits

In the course of fitting the lifetime to signal MC, a convolution of a Gaussian resolution function and an exponential decay function as it was tested in subsection 5.4 is used. To fit the convolved function to data, the MC background distributions, shown in figure 14, are taken into account. They are fixed and added to the convolved function. This sum is then fitted to the total data lifetime distributions which still include backgrounds.

For the approach with limited range, the Gaussian parameters are fixed at the values they have from the signal MC resolution in subsection 5.5 due to the already mentioned fact that the resolution from prompt decay backgrounds and the QCD control sample is not suitable for signal events. For the approach with full range, the Gaussian parameters are free since the full range lifetime distributions are sensitive to the resolution and the lifetime parameters in a less correlated way than for the limited range region chosen for this analysis.

In figure 16, the signal MC and data lifetime distributions in transverse plane and in 3d, corrected for bias and fitted on the limited range with fixed Gaussian parameters, are shown.
5.8 Probational data and MC lifetime fits

Figure 16: Fitted lifetime of signal MC (upper plot) and of data (lower plot) using the apex solution for tau momenta and a Gaussian-exponential convolution with fixed parameters on the range from 0.15 ps to 0.6 ps.

The background contribution in the data fit is indirectly visible in the fit function which fluctuates due to the background. The actual convolved decay
function itself is recognizable by considering only the bottom points of the fluctuations in the solid lines representing the fit as these points have almost no background contribution. The results for the fit parameters of this first approach are shown in the first part of table 8 where $\tau$ is the mean-life parameter of the exponential function.

Figure 17 shows the signal MC and data lifetime distributions in transverse plane and in 3d, corrected for bias and fitted on the whole recorded lifetime range with free Gaussian parameters.
Figure 17: Fitted lifetime of signal MC (upper plot) and of data (lower plot) using the apex solution for tau momenta and a Gaussian-exponential convolution with fixed parameters.

The results and statistical uncertainties for the fit parameters of this approach are shown in the second part of table 8 where $\tau$ is the mean-life parameter.
of the exponential function.

<table>
<thead>
<tr>
<th>signal MC lifetime - limited fit range</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>transverse</td>
<td>3d</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \tau ) [fs]</td>
<td>( \chi^2 )</td>
<td>( \tau ) [fs]</td>
<td>( \chi^2 )</td>
</tr>
<tr>
<td>264.113( \pm )8.127</td>
<td>1.20</td>
<td>265.007( \pm )8.195</td>
<td>1.13</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>data lifetime - limited fit range</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>transverse</td>
<td>3d</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \tau ) [fs]</td>
<td>( \chi^2 )</td>
<td>( \tau ) [fs]</td>
<td>( \chi^2 )</td>
</tr>
<tr>
<td>282.176( \pm )9.921</td>
<td>1.24</td>
<td>275.162( \pm )9.559</td>
<td>1.18</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>signal MC lifetime - total fit range</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>transverse</td>
<td>3d</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>( \chi^2 )</td>
<td>( \tau ) [fs]</td>
<td>( \chi^2 )</td>
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<tr>
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<td>230.815( \pm )3.304</td>
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<td>3d</td>
<td></td>
<td></td>
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<td>( \tau ) [fs]</td>
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<td>242.822( \pm )3.936</td>
<td>2.40</td>
<td>242.178( \pm )3.939</td>
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Table 8: Results of all fits of the convolution of a Gaussian and an exponential decay function to signal MC and data lifetime

The worse \( \chi^2 \) values for the total range approach do not necessarily mean that the fit is worse because they partly originate from zero bins which are stored with very small uncertainties. These uncertainties increase the \( \chi^2 \) heavily.
6 Conclusions

6.1 Validation of fitting procedures
Several fitting procedures were tested for biases and general working properties applying fits to toy Monte Carlo. Based on the precision and runtime for the lifetime extraction using the different fitting procedures, the binned LL method was chosen as the method further fitting is performed with.

6.2 Resolution
A significant discrepancy between the flight-length resolutions of prompt decay background MC and the QCD control sample was noticed. This already implies a limitation of the probational lifetime measurement since this discrepancy indicates that much more detailed studies on background estimation have to be done. However, the resolution of the flight-length, momentum and lifetime could be measured well for signal MC with lower uncertainty than for the prompt decay background and QCD resolution. The data estimate and prompt decay background resolutions were not taken into account for further lifetime measurement due to their differing values and the therefore suspected insufficiency of the resolution modeling. As a workaround for this problem, for the probational fits, the backgrounds were taken into account as histogrammed distributions without modeling them. In contrast to that, p.d.f.s were used to model the backgrounds for the toy MC feasibility study as stated in subsection 5.7. Since the signal data should have similar energy spectra as signal MC and the signal MC resolution measurement worked well, the resolution parameters from signal MC were used for the probational lifetime measurement.

An interesting conclusion to draw from the momentum resolution measurements is that the apex solution yields a better resolution in terms of wideness of the distribution but also in terms of relative uncertainties on the resolution parameters as shown in table 5. This is interesting because, as an example, for the SV fit the average solution is assumed to be the better one.

Another interesting outcome of the resolution studies is that the 3d resolution for the flight-length and for the momentum is significantly worse than for the corresponding transverse quantities but for the lifetime it is not. This suggests that the effects widening the 3d resolution distributions cancel out due to the analogous angular dependence of the flight-length and the momentum which are divided by one another to get the lifetime according to equation 13.

6.3 Reconstructed lifetime distributions
The reconstructed lifetime distributions have a good agreement between data and MC as visible in figure 14. Also the general shapes of the background and the signal MC contributions look reasonable. The 3d and transverse lifetime distributions are very similar which is the reason why they are treated exactly the same for the probational fit. Furthermore, the selection of the range of
the limited range approach for fitting the lifetime bases on considering the reconstructed lifetime distributions.

### 6.4 Feasibility study on statistics

The results of the toy MC lifetime fits and their uncertainties are shown in Table 7. A statistical lifetime uncertainty of about 3 fs can be accepted as competitive with respect to the several LEP results summarized in subsection 3.5. Taking this into account, one can see from the results of this feasibility study that the integrated CMS luminosity has to be at least twice as high as it was in 2012 considering the full range fit. However, as mentioned, for the full range fit studies on background have to be done which are not that substantial for the limited range fit. For getting a competitive statistical lifetime uncertainty from this fit, the integrated CMS luminosity has to be more than ten times as high as for the 2012 run. This means, on the long term, the limited range approach may become more promising than the full range approach due to smaller systematic uncertainties. Still, for both approaches there have to be much further studies on systematic uncertainties which is not in the scope of this thesis so these scale factors might even be underestimated. One more reason for a possible underestimation is that the resolution width values were set to 0.07 ps for background and 0.08 ps for signal which are not necessarily the actual true values. This means, disentangling background from signal may even be more difficult as the values used in the toy study may suggest. In any case, with these approaches, no competitive results in terms of statistics can be expected before the next running period of CMS which starts in 2015 [39]. To even compete with the statistical uncertainty from Belle which is also given in subsection 3.5, the integrated luminosity has to be increased by a factor of more than 100; for the limited range approach it would be about 1000. Such increases are far beyond current accessibility so this is an issue for time scales of the order of decades.

### 6.5 Probational data and MC lifetime fits

The results of the probational data and MC lifetime fits and their uncertainties are shown in Table 8. As mentioned, due to missing resolution, background and other systematic uncertainty studies, the probational fit results can not be taken as actual measurement results. Anyway, the simple analysis already seems to work in general since all results are in the correct order of magnitude and all fits to data and MC look reasonable. Interesting outcomes are the statistical uncertainties which are similar to the ones from the toy MC study, shown in the first result line of Table 7. This substantiates the estimations of the statistical uncertainties for higher integrated CMS luminosities which are also shown in that table.

In general, possible further improvements to be investigated and applied are: more complex resolution models; bias estimations from the selection criteria and from the fit limits; and studies on proper momentum reconstruction.
7 Appendix

7.1 Files containing data and MC

In Table 9 all data and MC containing sets of files the analyses uses are listed.

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<table>
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<th>MC samples</th>
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</tbody>
</table>

Table 9: Summary of all data and MC files used for the analysis

7.2 Acknowledgements

I would like to give thanks to all the people who supported me elaborating and writing this thesis during the last three months.

First of all, I am grateful to Prof. Dr. Achim Stahl for offering me such an interesting topic for my Bachelor’s Thesis.

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[34] CMS Luminosity - Public Results. https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults#2012_Proton_Proton_Collisions (called on August 7th, 2013)


