

Bachelorarbeit

Selection of the Sample for Data-Driven $Z \rightarrow \nu\bar{\nu}$ Background Estimation in SUSY-Searches



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The topic of this study was to improve the selection of the sample for data-driven $Z \rightarrow \nu\bar{\nu}$ background estimation, which is a major contribution in supersymmetric searches in a no-lepton search mode. The data is based on $Z \rightarrow \ell^+\ell^-$ samples using data created with ATLAS simulation software. This method works if two leptons are reconstructed, but using cuts that are typical for SUSY searches reconstruction efficiency for electrons and muons is rather low. For this reason it was tried to enhance the data sample. Therefore events were considered, where only one electron was reconstructed. In this case the invariant mass for the electron and each jet was computed to select the jet with the best match for the Z boson mass as not reconstructed electron. This way the sample can be extended but significantly loses purity because of also reconstructed background events. To improve this method other variables have to be considered which were not available for this study.

Applying a similar method to muons using tracks instead of jets as probe one obtains again poor purity. Furthermore only a few additional events are added to the sample leading to neglectable increase in efficiency. To understand this the distribution of the pseudorapidity $|\eta|$, the transverse momentum p_T and the muon isolation ΔR were studied for true and reconstructed muons. This led to the conclusion that most muons which are not reconstructed have too large pseudorapidity. Since the tracker does not cover this region either, using it for a tag and probe approach does not increase the efficiency of the selection of the sample.

Thema dieser Arbeit war die Verbesserung der Auswahl des Samples für die datengestützte Abschätzung des $Z \rightarrow \nu\bar{\nu}$ -Hintergrunds, der bei der Suche nach supersymmetrischen Teilchen in Fällen ohne Leptonen im Endzustand eine große Rolle spielt. Die verwendeten Daten stammen von $Z \rightarrow \ell^+\ell^-$ -Ereignissen und wurden mit Simulations-Software für ATLAS erzeugt. Diese Methode erweist sich bei zwei rekonstruierten Leptonen als sehr erfolgreich, aber unter Verwendung von Selektionsparametern, die in SUSY-Suchen üblich sind, ist die Rekonstruktionseffizienz für Elektronen und Myonen eher gering. Aus diesem Grund wurde versucht eine höhere Statistik zu erzielen. Hierfür wurden Ereignisse betrachtet bei denen nur ein Elektron rekonstruiert wurde. Anschließend wurde die invariante Masse für das Elektron und jeden Jet berechnet und derjenige, für den das Ergebnis der Z -Boson-Masse am nächsten kam, als nicht-rekonstruiertes Elektron ausgewählt. Auf diese Weise kann der Datensatz erweitert werden, verliert aber erheblich an Reinheit wegen der ebenfalls rekonstruierten Hintergrundereignisse. Zur Verbesserung dieser Methode sind weitere Variablen einzubeziehen, die in den verwendeten Datensätzen nicht verfügbar waren.

Wendet man eine ähnliche Methode auf Myonen an, indem man Tracks an Stelle von Jets verwendet, erhält man wiederum geringe Reinheit. Darüber hinaus werden nur wenige zusätzliche Ereignisse zum Sample hinzugefügt. Dies führt zu einer vernachlässigbaren Steigerung der Effizienz. Um die Gründe hierfür zu verstehen, wurden die Verteilungen der Pseudorapidität $|\eta|$, des Transversalimpulses und der Isolationsbedingung ΔR für wahre und rekonstruierte Myonen untersucht. Dies führte zu dem Ergebnis, dass die meisten der nicht rekonstruierten Myonen eine zu große Pseudorapidität haben. Da auch der Tracker diesen Bereich nicht abdeckt, kann dieser nicht verwendet werden, um die Effizienz der Auswahl zu verbessern.

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1 Introduction

After the LHC start-up energies of up to 10 TeV and 14 TeV will be available for the first time. Hence physicists hope to discover many phenomena of new physics. This includes also supersymmetric theories, that could help to overcome some difficulties of the Standard Model of particle physics.

One of the possible backgrounds for SUSY events is the $Z \rightarrow \nu\bar{\nu}$ decay. Since Monte Carlo data has large errors a data-driven approach using $Z \rightarrow \ell^+\ell^-$ samples is considered.

Simulations with ATLAS software help to study the data samples. It is possible to analyze methods to increase the selection efficiency with these programs.

The data-driven method works if two leptons are reconstructed. However, typical cuts for SUSY searches result in low reconstruction efficiency for electrons and muons. To enhance the data sample also events were considered, where only one electron was reconstructed. Therefore a “tag and probe” method was used to increase the number of events. For electrons jets were considered as probe and tracks were considered for muons. In the case of muons the reason for failed reconstruction was studied, too.

Results show that in both cases the background is too large to take advantage of this method using the given samples.

2 LHC and ATLAS

2.1 LHC

The “Large Hadron Collider” (LHC) is an accelerator for protons and lead ions located at the European Organization for nuclear research CERN near Geneva [1]. It re-uses the tunnel of the LEP experiment, which was in operation between 1989 and 2002. The circumference of this tunnel is 26.7 km and it is located between 45 m and 170 m below ground (Fig. 2.1).

There are two rings for the two counter-rotating beams. Because of limited space the rings are not completely separated and use a so called “twin-bore” magnet design. The accelerator was designed to achieve center of mass collision energies of up to 14 TeV. The expected maximal luminosity is $10^{34} \text{ cm}^{-2}\text{s}^{-1}$. The integrated luminosity gives information about the amount of collected data. Early data will have about 200 pb^{-1} .

As mentioned above, the space constraints due to the use of the existing LEP tunnel require the use of a “twin-bore” design for the superconducting magnets. This means the rings for both beams are placed in a common cryostat. As a result both are magnetically coupled.

Because the LHC is a proton-proton collider, the particles in the two beam channels have the same charge. Therefore the magnetic fields have to be orientated opposite, which makes the construction more difficult considering the coupling.

Like other detectors the LHC uses NbTi superconductors but at fields above 8 T.

Acceleration and stabilization of the beam is accomplished by a system of superconducting cavities operating at up to 400 MHz.

The superconducting magnets are cooled in a bath of superfluid helium at maximal 1.9 K. Because of its special properties the superfluid helium can permeate the magnet windings. The cooling power is distributed via a compound cryogenic distribution line (QRL). Several layers of shielding, containing liquid nitrogen or vacuum, enclose the magnets.

Before the protons are injected into the LHC they are pre-accelerated by Linac2, the Proton Synchrotron Booster (PSB), Proton Synchrotron (PS) and Super Proton Synchrotron (SPS). These are all accelerators which were previously used at CERN in order to save costs. They were upgraded to meet the demands of the LHC.

There are several detectors which are either highly specialized or were designed for general new physics searches. The four principal detectors at LHC are LHCb, ALICE, CMS and ATLAS [2].

At the **LHCb** events involving bottom quarks are studied in order to get a better understanding of CP violation. Its objective is to find an explanation for the fundamental fact that matter is preferred to antimatter. Without our existence would be impossible.

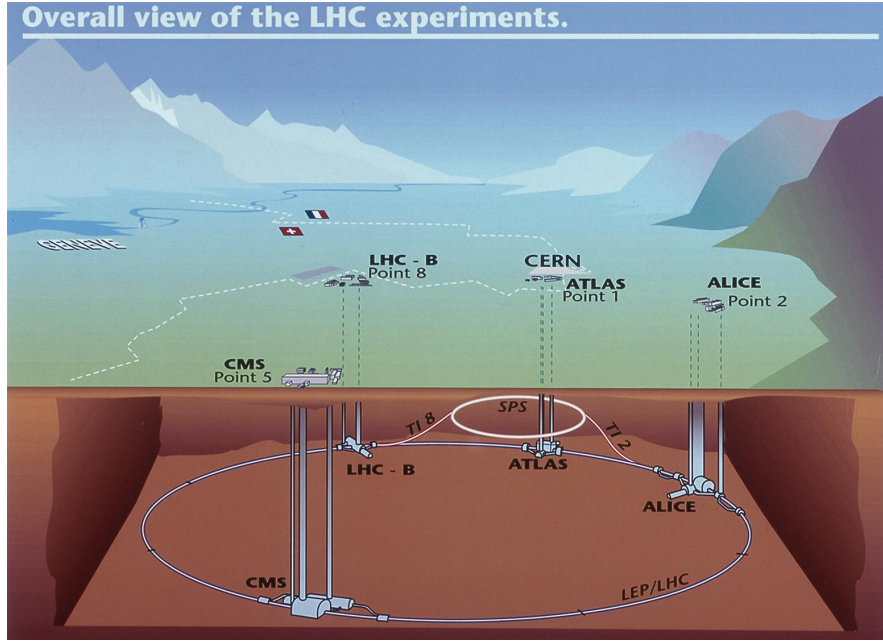


Figure 2.1: Schematics of the tunnel for the Large Hadron Collider under the Swiss-French border near Geneva showing the locations of the four big experiments LHCb, ALICE, CMS and ATLAS. [3]

ALICE (*A Large Ion Collider Experiment*) makes use of the possibility to run the LHC also with lead ions instead of protons. In the collision of those a quark-gluon plasma is created. This condition is believed to have existed shortly after the Big Bang.

The *Compact Muon Solenoid* **CMS** is a more universal detector searching for new physics like the Higgs boson, supersymmetric particles or extra dimensions. It is the counterpart to ATLAS, which has the same purpose but another technical layout. The intention for this duplicity is to obtain redundancy and control.

As this study focuses on the **ATLAS** detector it will be explained in more detail below.

2.2 ATLAS

2.2.1 Overview

The ATLAS detector (*A Toroidal LHC ApparatuS*) has a large spectrum of different subsystems (Fig. 2.2) to make an accurate study in many fields of particle physics possible [4]. There are electromagnetic calorimeters for photon and electron identification and hadronic calorimeters to measure jet and missing transverse energy (E_T^{miss}). Furthermore muon spectrometers are used to determine the momentum of muons. With trackers the lepton momentum can be measured.

One of the most important design criteria is high acceptance. This means that as

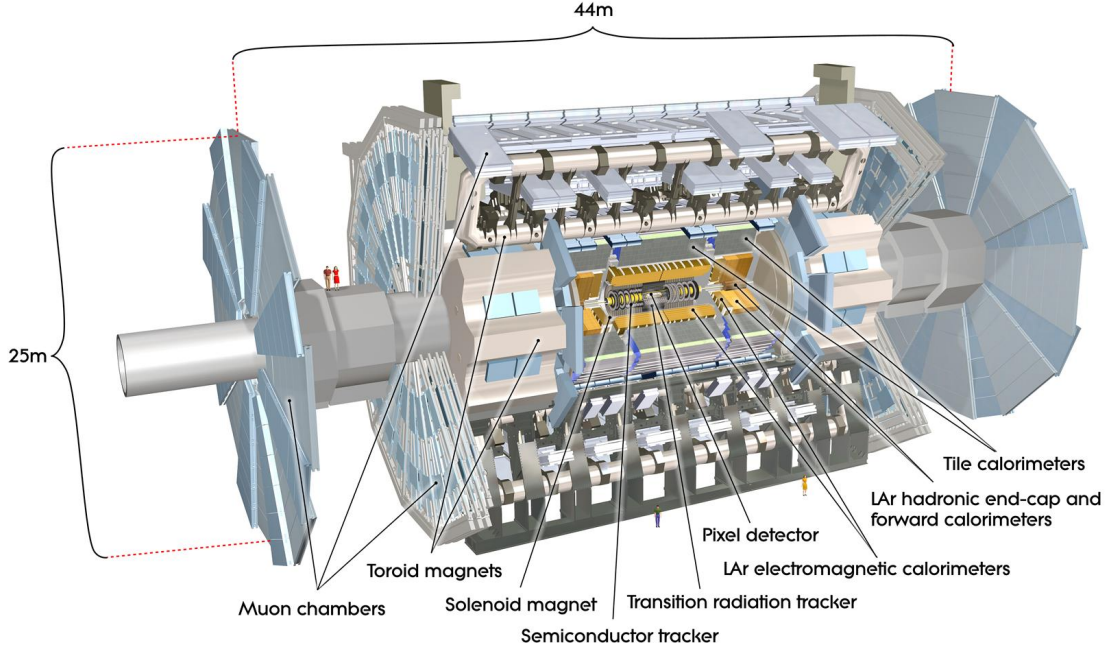


Figure 2.2: Schematics of the ATLAS detector showing its several subsystems [3].

much decay products as possible should be detected. Hence the systems should cover any possible direction in regard to the collision point and have a small lower limit for the momentum of the final state particles.

2.2.2 Detector parameters and nomenclature

As some geometric parameters of the detector will be used later on to describe event signatures, they will be discussed here [4]:

One can define a Cartesian system for detector coordinates where the z -axis is the beam-line. Hence the x - y plane is orthogonal to the beam. The x -axis originates from the interaction point and points to the center of the accelerator ring. Finally the y axis is pointing upwards.

However in most cases a spherical coordinate system is more convenient. The azimuthal angle ϕ is measured in the x - y -plane and is defined as $\tan \phi \equiv p_y/p_x$. θ is the polar angle starting from the z -axis.

In particle physics θ is often replaced by the pseudorapidity $\eta = -\ln \tan(\theta/2)$. Another parameter which will be used is $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

If not defined differently transverse variables (e.g. transverse momentum p_T) are the components of a vector in the x - y -plane.

In addition one should note that there are some naming conventions that might differ from their typical usage. As it is often difficult or irrelevant to distinguish detected

particles and antiparticles, the name of a particle refers often to both, e.g. electron or e means e^- or e^+ . If speaking of leptons (ℓ) usually only muons and electrons are meant. Especially neutrinos ν are excluded.

2.2.3 Detector subsystems

To understand samples produced by ATLAS or ATLAS simulation software some knowledge of its subsystems is helpful [4].

The **magnetic fields**, which are necessary to determine the momentum of charged particles, are generated by several components. For the Inner Detector a central solenoid operates with a peak performance of 2.6 T. The magnetic field for the muon spectrometer with maximal 3.9 T is provided by air-core toroids. In addition there are two end-cap toroids with a peak magnetic field of 4.1 T.

The **Inner Detector** ($|\eta| < 2.5$) is composed of tracking elements and high-resolution detectors near the interaction point. The **pixel detector** is closest to the vertex and is needed to identify particles like B hadrons and τ leptons with a short lifetime. To be still working after ten years of direct exposure to ionizing radiation (> 300 kGy) and neutrons ($5 \cdot 10^{14}$ per cm^2) the electronics have to be radiation hard.

The **semiconductor tracker** is build of silicon microstrips and helps to measure momentum, impact parameter and vertex position. It has a tangential resolution of $16 \mu\text{m}$ and an axial resolution of $580 \mu\text{m}$.

The **transition radiation tracker** uses straw detectors with very small diameter. Its sense wires are isolated in separate gas volumes designed for operation at high rates.

The **electromagnetic calorimeter** ($|\eta| < 3.2$) has accordion geometry and is a lead/liquid-argon (LAr) detector. The hadronic barrel calorimeter ($|\eta| < 1.7$) uses plastic scintillator plates and an iron absorber. There is also a hadronic end-cap calorimeter ($1.5 < |\eta| < 3.2$, cooper LAr) and a forward calorimeter ($3.1 < |\eta| < 4.9$, tungsten LAr), which are exposed to higher radiation levels.

The **muon spectrometer** is composed of trigger and precision tracking chambers. It makes use of the magnetic field of the toroids to measure the (transverse) momentum of muons. The main tracking components of the spectrometer are Monitored Drift Tubes (MDTs). For $2 < |\eta| < 2.7$ Cathode Strip Chambers (CSCs) are used in the innermost plane. To allow high precision measurements the chambers are equipped with optical alignment systems. The trigger system is composed of Resistive Plate Chambers (RPCs) in the barrel and Thin Gap Chambers in the end cap regions.

The muon drift tubes have a diameter of 30 mm diameter with a central W-Re wire ($50 \mu\text{m}$ diameter). They are filled with 93% Ar and 7% CO_2 . Their resolution is about $80 \mu\text{m}$. The MDT chambers contain three to four mono-layers of tubes and have a support structure to make accurate positioning possible. The CSCs are multi-wire proportional chambers.

Because of the 40 million bunch crossings per second at the interaction points the interaction rate at full luminosity is about 10^9 Hz. It is the purpose of the **triggers** to select only interesting events from that large amount of data, thereby reducing the rate of selected events to about 100 Hz.

3 Supersymmetry

3.1 Theoretical background

As the topic of this study is the estimation of the background for SUSY searches, in this section an overview on supersymmetric theories will be given [5], [6].

SUSY is motivated by its ability to explain some problems of the Standard Model (SM) of particle physics. The standard model has been tested very successfully, but problems are expected at high energy scales.

One of its limitations is the **hierarchy problem**: Calculations of higher order corrections of the Higgs-boson mass lead to quadratic diverging terms. To obtain accordance with experimental restraints one has to assume very exact fine tuning of parameters in nature.

Another problem is that the extrapolations of the **coupling constants** for electromagnetic, weak and strong interaction do not match at one point for high energies. This is required, and expected by many physicists, to obtain a unified theory of the fundamental interactions (grand unified theory, GUT).

Supersymmetry is a possible extension of the standard model that can solve these problems. In SUSY theories all particles are associated to sparticles that have the same quantum numbers but differ in 1/2 unit of spin. The generator of this symmetry is the operator Q :

$$Q|\text{fermion}\rangle = |\text{boson}\rangle; \quad Q|\text{boson}\rangle = |\text{fermion}\rangle \quad (3.1)$$

If one associates all chiral fermions $f_{L/R}$ to scalar sfermions $\tilde{f}_{L/R}$ and the massless gauge bosons A_μ with helicity ± 1 to gauginos with spin 1/2, helicity $\pm 1/2$ and no mass, one obtains the Minimal Supersymmetric extension of the Standard Model (MSSM).

In supersymmetry the three coupling constants cross at the same point at high energies. Also the hierarchy problem can be solved since loop corrections for the sparticles introduce negative weighted terms that counter act the terms of the particles and minimize divergence.

To avoid so called “triangle anomalies” one has to assume four Higgs bosons in contrast to only one in the Standard Model: H_1^+ , H_1^0 , H_2^0 , H_2^- . After electroweak symmetry breaking the W^0 and B particles mix to the Z boson and the photon using the Higgs mechanism.

The remaining Higgs fields mix to physical observable Higgs bosons:

$$h^0, H^0, A, H^+, H^- \quad (3.2)$$

The superpartners of the Higgs bosons are the higgsinos ($\tilde{H}_1^+$, $\tilde{H}_1^0$, $\tilde{H}_2^0$, $\tilde{H}_2^-$). They mix with the winos $\tilde{W}^\pm$ to charginos ($\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^\pm$) whereas the neutral higgsinos mix with

Chiral super-multiplets

Name	Spin 0	Spin 1/2
squarks, quarks	$\tilde{Q} = (\tilde{u}_L, \tilde{d}_L)$ $\tilde{u}_R^*$ $\tilde{d}_R^*$	$Q = (u_L, d_L)$ $\bar{u}_R$ $\bar{d}_R$
sleptons, leptons	$\tilde{L} = (\tilde{\nu}, \tilde{e}_L)$ $\tilde{e}_R^*$	$L = (\nu, e_L)$ $\bar{e}_R$
Higgs, Higgsinos	$H_1 = (H_1^+, H_1^0)$ $H_2 = (H_2^0, H_2^-)$	$\tilde{H}_1 = (\tilde{H}_1^+, \tilde{H}_1^0)$ $\tilde{H}_2 = (\tilde{H}_2^0, \tilde{H}_2^-)$

Vector super-multiplets

Name	Spin 1/2	Spin 1
gluino, gluon	$\tilde{g}$	g
winos, W's	$\tilde{W}^\pm, \tilde{W}^0$	$W^\pm, W^0$
bino, B	$\tilde{B}$	B

Table 3.1: Particle content of the MSSM. There are three generations of squarks and sleptons. After symmetry breaking the physical states of the Higgs bosons are h, H, A and $H^\pm$. W^0 and B particles mix to the Z boson and the photon. The neutralinos $\tilde{\chi}_i^0$ and charginos $\tilde{\chi}_i^\pm$ are a mixture of the Higgsinos with the winos and binos.[6]

the gauginos $\tilde{W}^0, \tilde{B}$ to four neutralinos ($\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$). The particle content of the MSSM is listed in Tab. 3.1.

Since superpartners of normal particles with the same mass are not observed, supersymmetry must be broken so that sparticles can only be observed at energies which are not available yet, but will be provided after the LHC start-up.

Unlike in the Standard Model baryon (B) and lepton number (L) are not conserved by theoretical constraints. A consequence of this is the possibility of proton decay. Since for protons a large minimum lifetime has been measured, it is necessary to guarantee the conservation of B and L in another way. Therefore one can introduce R-parity:

$$R = (-1)^{3(B-L)+2S} \quad (3.3)$$

where S is the spin. R-parity therefore is always 1 for normal particles and -1 for their superpartners. As a consequence SUSY particles are produced in pairs. Furthermore the lightest supersymmetric particle (LSP) is stable. The LSP is also a possible candidate for dark matter. This is another advantage compared to the SM.

Symmetry breaking can be introduced adding mass terms for the SUSY particles by hand. However it would be more likely that SUSY is broken spontaneously. This can be accomplished by introducing a “hidden sector” where the symmetry is broken and is

communicated to the MSSM sector by a messenger interaction.

In models for supergravity (SUGRA) the messenger is gravity. There are 5 parameters added to those of the SM for minimal supergravity (mSUGRA) which is a significant reduction compared to MSSM with 105 additional parameters. The first two parameters are the common mass m_0 of scalar and $m_{1/2}$ of spin 1/2 sparticles at high energies (GUT-scale). The masses of the sparticles at low energy can be obtained from those two parameters using renormalization group equations (RGE). The other parameters are A_0 , a value for Higgs-sfermion-sfermion couplings, the ratio of the vacuum expectation values of Higgs $\tan \beta = v_+/v_-$ and the sign of the higgsino mass $\text{sgn } \mu = \pm 1$. In SUGRA the LSP is the neutralino $\tilde{\chi}_1^0$.

For studies benchmark points in the parameter space have been selected. Those were chosen according to restrictions due to experimental results and providing interesting events. Those benchmark points are described in Tab. 3.2. The mass spectrum for these benchmark points can be found in [7]. All masses of the sparticles are below 1 TeV for the chosen parameters. The LSP is 171.9 GeV for SU3 and 59.84 GeV for SU4.

As the LSP is a possible candidate for dark matter also cosmological considerations have been taken into account.

There is also a large variety of other possible SUSY models including Gauge Mediated SUSY Breaking (GMSB) and R-Parity breaking models [6]. In this study only mSUGRA has been considered.

3.2 Characteristics and search strategies

Besides for SU2 the squark and gluino mass is similar and below 1 TeV. Therefore large amounts of gluinos and squarks are likely to be produced at ATLAS, which cause signatures with high p_T jets. As mentioned before all supersymmetric particles will decay into the LSP, the $\tilde{\chi}_1^0$ neutralino, which barely interacts with the detector. Therefore large missing transverse energy E_T^{miss} is typical for mSUGRA events, too.

There are several search modes for SUSY analysis [7], depending on the number of reconstructed leptons. The one lepton search mode is used to suppress QCD background and requires one electron or muon ($p_T > 10$ GeV) where a second reconstructed lepton ($p_T > 10$ GeV) is vetoed.

There are also possible multi lepton and tau search modes, but this study focuses on the no-lepton search mode. In this mode all events with a reconstructed muon or electron ($p_T > 20 \text{ GeV}$) are rejected. Additionally four jets ($|\eta| < 2.5$) with $p_T > 50$ GeV and one with $p_T > 100$ GeV are required.

The backgrounds in the no-lepton search mode are from $t\bar{t}$ events, W and Z boson decays and single top and QCD events. There are cuts on transverse sphericity ($S_T > 0.2$) and missing transverse Energy ($E_T^{\text{miss}} > 100$ GeV and $> 0.2 M_{\text{eff}}$) to reduce those backgrounds. These variables are defined as follows[7]:

Transverse sphericity

One can define the 2×2 sphericity tensor $S_{ij} = \sum_k p_{ki} p_{kj}$ where all jets with $|\eta| < 2.5$ and $p_t > 20$ GeV and all selected leptons are taken into account. Transverse sphericity can then be derived from the eigenvalues λ_1 and λ_2 of this tensor:

	$m_0(\text{GeV})$	$m_{1/2}(\text{GeV})$	A_0	$\tan\beta$	μ
SU1	70	350	0	10	>0
	<i>Coannihilation region where $\tilde{\chi}_1^0$ annihilate with near-degenerate $\tilde{\ell}$.</i>				
SU2	3550	300	0	10	>0
	<i>Focus point region near the boundary where $\mu^2 < 0$. This is the only region in mSUGRA where the $\tilde{\chi}_1^0$ has a high higgsino component, thereby enhancing the annihilation cross-section for processes such as $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow WW$.</i>				
SU3	100	300	-300	6	>0
	<i>Bulk region: LSP annihilation happens through the exchange of light sleptons.</i>				
SU4	200	160	-400	10	>0
	<i>Low mass point close to Tevatron bound.</i>				
SU6	320	375	0	50	>0
	<i>The funnel region where $2m_{\tilde{\chi}_1^0} \approx m_A$. Since $\tan\beta \gg 1$, the width of the pseudo-scalar Higgs boson A is large and τ decays dominate.</i>				
SU8.1	210	360	0	40	>0
	<i>Variant of coannihilation region with $\tan\beta \gg 1$, so that only $m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0}$ is small.</i>				
SU9	300	425	20	20	>0
	<i>Point in the bulk region with enhanced Higgs production.</i>				

Table 3.2: The mSUGRA benchmark points. [7]

$$S_T \equiv \frac{2\lambda_2}{\lambda_1 + \lambda_2} \quad (3.4)$$

Since in SUSY events sparticles with large masses are produced, those are usually at rest. Therefore their decay products can be measured in any direction ($S_T \sim 1$). QCD events in contrast have a back-to-back topology ($S_T \sim 0$). This way QCD background can be suppressed using cuts on S_T .

Effective mass

Effective mass characterizes the activity of an event. All reconstructed leptons and the four jets ($|\eta| < 2.5$) with highest p_T are considered:

$$M_{\text{eff}} \equiv \sum_{i=1}^4 p_T^{\text{jet},i} + \sum_i p_T^{\text{lep},i} + E_T^{\text{miss}} \quad (3.5)$$

Missing transverse energy

Since E_T^{miss} is very characteristic for SUSY events a measurement as precise as possible is required. It is caused by undetected particles like neutrinos or the LSP. It can be computed since the initial transverse energy of the protons before collision is neglectable. The energy in the final state can be obtained from calorimeter data. Because of the detector geometry, limited resolution, dead regions and noise, fake E_T^{miss} has to be considered.

To obtain a good measurement on E_T^{miss} sophisticated methods have been developed. These are presented in detail in [7].

Furthermore the minimal $\Delta\phi$ between p_T^{miss} and the three highest- p_T jets is required to be larger than 0.2.

4 Selection of a $Z \rightarrow \ell^+ \ell^-$ sample for background estimation

4.1 $Z \rightarrow \nu \bar{\nu}$ as background process in SUSY searches

Besides the two charged vector bosons W^+ and W^- the Z boson is the third carrier of electroweak interaction. Because of their high masses ($m_W = 80.398 \pm 0.025$ GeV and $m_Z = 91.1876 \pm 0.0021$ GeV [8]) interactions involving these vector bosons are very short ranged. They are also historically known as charged-current and neutral-current. The first neutral current in the reaction $\bar{\nu}_\mu + e \rightarrow \nu_\mu + e$ was observed at the “Gargamelle” bubble chamber at CERN [9].

The Z boson has the leptonic decay channels $Z \rightarrow \ell^+ \ell^-$ and $Z \rightarrow \nu \bar{\nu}$ as well as hadronic decay channels $Z \rightarrow q \bar{q}$ [10].

4.2 Replace method for $Z \rightarrow \nu \bar{\nu}$ events

As neutrinos interact only very weakly, they escape undetected from the experiment just like the LSP. So both particles lead to large E_T^{miss} . This explains why $Z \rightarrow \nu \bar{\nu}$ events are a major background for SUSY searches in the no lepton mode. The Feynman diagram for this process is shown in Fig. 4.1.

Because of the above mentioned properties of neutrinos, $Z \rightarrow \nu \bar{\nu}$ events can also not be measured directly to correct SUSY samples for the background. However considering that Monte Carlo generators can only produce approximate results, it is preferred to estimate backgrounds from real data. The data-driven approach in the case of $Z \rightarrow \nu \bar{\nu}$

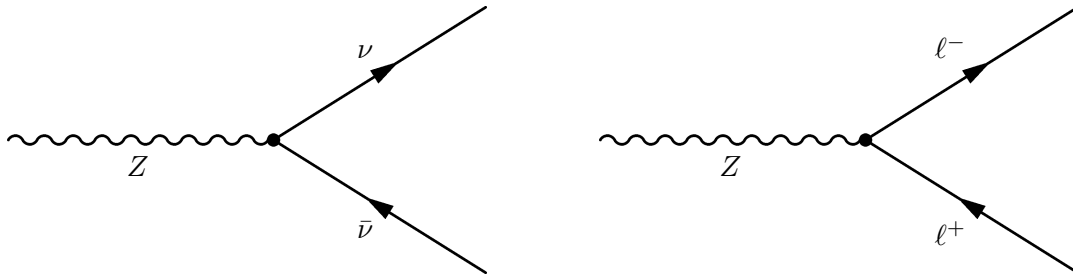


Figure 4.1: Feynman diagram of a $Z \rightarrow \nu \bar{\nu}$ and a $Z \rightarrow \ell^+ \ell^-$ decay. Both have the same topology and coupling constant. The mass difference between leptons and neutrinos gives only a minor contribution at high particle energies. Hence $Z \rightarrow \nu \bar{\nu}$ events can be approximated by $Z \rightarrow \ell^+ \ell^-$ events.

events makes use of experimental $Z \rightarrow \ell^+ \ell^-$ data [7]. By replacing the leptons with neutrinos one should obtain the correct signatures of $Z \rightarrow \nu \bar{\nu}$ events if some corrections are considered. The number $N_{Z \rightarrow \nu \bar{\nu}}$ of $Z \rightarrow \nu \bar{\nu}$ events can be calculated from the number $N_{Z \rightarrow \ell^+ \ell^-}$ of $Z \rightarrow \ell^+ \ell^-$ events in the following way:

$$N_{Z \rightarrow \nu \bar{\nu}} = N_{Z \rightarrow \ell^+ \ell^-}(p_T(\ell^+ \ell^-)) \times c_A \times c_{\text{eff}} \times \frac{\text{Br}(Z \rightarrow \nu \bar{\nu})}{\text{Br}(Z \rightarrow \ell^+ \ell^-)} \quad (4.1)$$

where the fraction of the branching ratios $(\text{Br}(Z \rightarrow \nu \bar{\nu})) / (\text{Br}(Z \rightarrow \ell^+ \ell^-))$ can be calculated theoretically. The correction constant c_A takes the acceptance of the detector into account and can be obtained from Monte Carlo data. c_{eff} is a further correction because of identification efficiency, which also depends on selection cuts and reconstruction efficiency.

4.3 Object definition and identification

As the identification of an object is never free of doubt one has to decide under which circumstances an object has to be rejected or not. The aim of this is to increase efficiency and suppress background. There are typical parameters used by the ATLAS reconstruction algorithms [7], which will be defined. Some of them have been changed in regard to the topic of this study.

Jets

For the reconstruction of jets the ATLAS cone algorithm was used. SUSY searches always require a large number of jets, so a narrow cone $R < 0.4$ is used to reconstruct jets. Otherwise it would be difficult to separate the different jets. Only jets with $p_T > 20$ GeV are considered. The jet is rejected, if a reconstructed electron is close to the jet ($\Delta R < 0.2$).

Missing transverse energy

As mentioned before, a characteristic of the SUSY models which are studied in this thesis is large E_T^{miss} due to the undetected LSP. Furthermore E_T^{miss} could be useful to identify background events involving neutrinos, that also cannot be detected, like in $t\bar{t}$ events.

We know that the initial transverse momentum before the proton collision is neglectable. Hence we can calculate the missing transverse energy considering conservation laws and the information of energy deposited in the calorimeters.

Leptons

Since we are interested in $Z \rightarrow \nu \bar{\nu}$ events in the no-lepton search mode, lepton definition has principally not to be affected by SUSY concerns. Instead the leptons have to be identified in a way that provides a clean $Z \rightarrow \ell^+ \ell^-$ sample for data-driven background estimation.

- **Electrons**

To reject background events “tight” cuts have been applied for electrons.

This cuts are applied on data from the hadronic and electromagnetic calorimeters, including shower-shape. Further data is obtained from the strip and pixel detectors. Also information of the transition radiation tracker (TRT) is used. Finally isolation cuts are applied on energy deposited in a cone around the electron. The parameters for those cuts and a more detailed description can be found in [7].

As objects with too small p_T are difficult to reconstruct electrons with low p_T are rejected. To get as much events as possible in this study a soft cut ($p_T < 10$ GeV) was used. The cut for E_T in the cone around the electron has been set to $p_T < 10$ GeV.

- **Muons**

Reconstruction algorithms use information from the muon spectrometer as well as tracks from the inner detector to identify a muon. To avoid fake muons and muons produced in hadronic decays additional isolation cuts have been applied. The energy in a cone ($\Delta R < 0.2$) around the muon measured by the calorimeter has to be less than 10 GeV. Also muons close to a jet ($\Delta R < 0.4$) are rejected. As with electrons a cut on $p_T < 10$ GeV was used.

4.4 Selection cuts

As we want to estimate data for $Z \rightarrow \nu\bar{\nu}$ events as a background for supersymmetric events, we have to apply similar cuts on the $Z \rightarrow \ell^+\ell^-$ sample as in the no-lepton mode SUSY searches. However we have to consider the later replacement of the leptons with neutrinos.

To select an event a minimum of four jets with $p_T > 50$ GeV and at least one of them with $p_T > 100$ GeV are required. There are also cuts on transverse sphericity ($S_T > 0.2$), on the azimuthal angle between the vector of the p_T of all jets and the vector of the missing transverse energy ($\Delta\phi > 0.2$) and a cut ($E_T^{miss}/M_{\text{eff}} > 0.2$).

A cut on E_T^{miss} , which is also typical for SUSY searches, has not been applied, because E_T^{miss} will of course change significantly after the replacement of leptons with neutrinos.

4.5 Backgrounds for the $Z \rightarrow \ell^+\ell^-$ sample

In general all events with two leptons in the final state contribute to the background for the $Z \rightarrow \ell^+\ell^-$ sample. But there are also events of interest with only one lepton in the final state since a “tag and probe” method was used to improve efficiency. The exact influence of the background on the sample will be studied in detail in section 4.7 et seq. In this subsection the topologies of the background processes will be explained [7].

W decays

The W is charged and as said before can decay either hadronically ($W \rightarrow q\bar{q}$) or leptonically ($W \rightarrow e\nu$ or $W \rightarrow \mu\nu$) (Fig. 4.2). With a lepton and a neutrino, that causes large E_T^{miss} in the final state, it is a possible background for tag and probe methods.

The channel $W \rightarrow \tau \nu$ was not considered since it has low statistics due to the higher mass of the τ . W boson events usually have additional jets which allow them to pass SUSY selection cuts.

Top-Antitop pair production

At the LHC top quark pairs ($m_t = 171.2 \pm 2.1$ GeV [8]) are produced in gluon-gluon and quark-antiquark scattering at large numbers. The almost only decay channel for the top quark is $t \rightarrow Wb$. A W boson decays either hadronically ($W \rightarrow q\bar{q}$) or leptonically ($W \rightarrow \ell \nu$). Combining those events we obtain several topologies for the final states in the $t\bar{t}$ decay. For these states the dileptonic mode ($t\bar{t} \rightarrow b\bar{b}\ell^+\nu\ell^-\bar{\nu}$) and the semileptonic mode ($t\bar{t} \rightarrow b\bar{b}\ell\nu q\bar{q}$) are of interest for this study. Both have large E_T^{miss} because of the neutrinos in the final states. The Feynman graph of the semileptonic mode is shown in Fig. 4.3 a).

Z decay into tau pairs

The decay of the Z boson into $\tau^+\tau^-$ can also contribute to the background. The taus decay via W bosons ($\tau \rightarrow W\nu$). The W bosons then decay either leptonically leading to $\nu_\tau\nu_\mu\mu$ or $\nu_\tau\nu_e e$ (Fig.4.3 b)) or hadronically leading to $\nu_\tau q\bar{q}$. As each of the produced taus can decay both ways, this is a possible background for events with two or one reconstructed electron.

QCD background

The effects of Quantum Chromo Dynamics (QCD) will be studied at ATLAS not only to test theoretical predictions but also because this is a large background to most of the other studied signals. They are caused by the strong interaction of the quarks and gluons of the colliding protons. There is a large variety of possible event topologies and with an average number of inelastic collisions in each bunch-crossing of up to 25, it is understandable why QCD events are such a major background to other samples.

4.6 Simulation and analysis tools

Several Monte Carlo Generators were used to create the data samples:

W and Z events were created with ALPGEN v 2.11 [11], QCD events with PYTHIA v 6.412 [12] and top anti-top events with MC@NLO v 3.3.1 [13].

For the tracing of the particles through the detector GEANT 4 was used. Further steps include the simulation of detector response by a set of dedicated packages and finally the reconstruction of events using common ATLAS reconstruction packages.

The detector simulations are in principle of two kinds [4]:

Full simulation and **Fast Simulation**. Fast simulation is used when it is not possible to simulate enough data with full simulation, but high statistics are required. The data studied in this thesis was produced with full simulation.

The data obtained this way is very similar to the expected real data from the ATLAS detector. This way methods to analyze the experimental samples can already be studied. In addition the Monte Carlo data also contains true level information. Thus one can compare the real event to the reconstructed one. This is useful to study reconstruction efficiency and to optimize selection cuts for example.

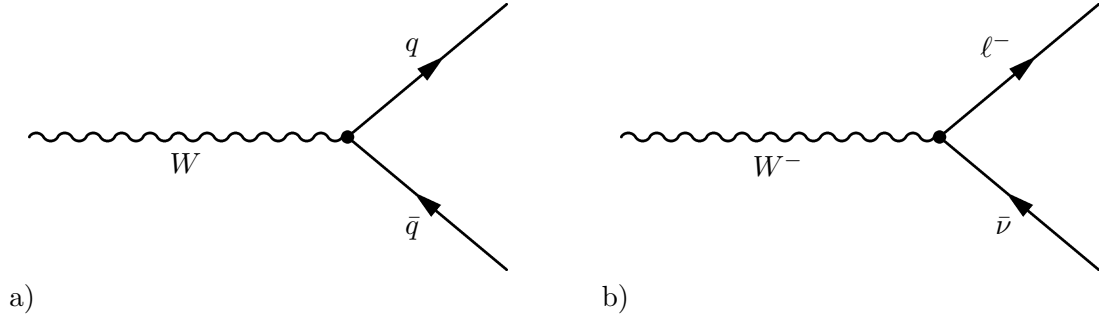


Figure 4.2: The Feynman graph of a decaying W boson. a) The hadronic decay with the final state $q\bar{q}$. b) The leptonic decay of a W^- boson with the final state $\ell^-\bar{\nu}$.

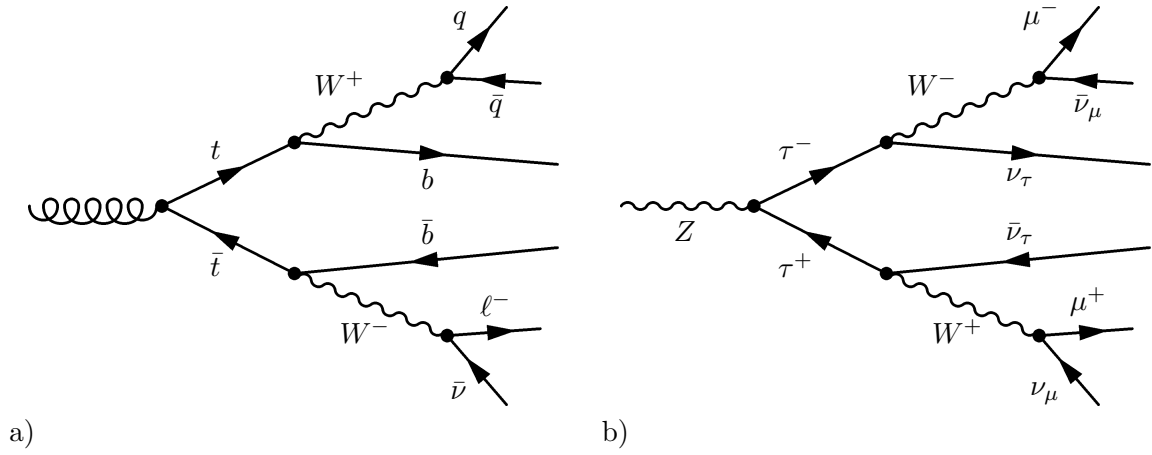


Figure 4.3: a) Feynman graph of the semileptonic top pair decay with the final state $b\bar{b}q\bar{q}\ell^-\bar{\nu}$. b) Feynman graph of a Z boson decaying via $\tau^+\tau^-$ and with a muon pair and neutrinos in the final state, which cause high E_T^{miss} .

A pre-existing program package for SUSY search has been used to analyze the data. The biggest part of the code is used to define object properties and apply selection cuts. (see 4.3 and 4.4). It has also algorithms implemented to calculate more complex variables like sphericity or transverse mass. Finally there are reconstruction algorithms which are used for data-driven background estimation. The complete code is included in the digital version of this thesis. The excerpts of the code which are of central interest for this study are shown in App. A. A class for data-driven $Z \rightarrow \nu \bar{\nu}$ background estimation has been implemented during the work for this study (excerpts in App. A.1).

The program package is written in C++ using the ROOT environment (version 5.16/00). ROOT is composed of a command line interpreter (CINT) and a large number of packages which provide tools for data analysis and presentation. It is very common in the particle physics community. More information can be found at the projects homepage [14].

All data used in this thesis has been scaled to a integrated luminosity of 200 pb^{-1} . This value corresponds to the early data from LHC. The samples have been created for a center of mass energy of 10 TeV.

4.7 Selection of the $Z \rightarrow e^+ e^-$ sample

4.7.1 Two reconstructed electrons

The algorithm used to reconstruct the Z boson for two electrons is described below:

- Select an event with two reconstructed electrons e^+ and e^- .
- Determine the four-vectors $p_a(|p_T|, \eta, \phi)$ and $p_b(|p_T|, \eta, \phi)$ for both electrons.
- Reconstruct the momentum four-vector of the Z boson from the vector sum $p_Z = p_a + p_b$.

All other values of interest can be obtained from p_Z . For example E_T^{miss} of the corresponding $Z \rightarrow \nu \bar{\nu}$ event can be estimated from $p_{Z,T}$. The most important value for this study is the invariant mass of the Z boson:

$$m_Z = p_Z^2 = (p_a + p_b)^2 \quad (4.2)$$

To select only events which are really from $Z \rightarrow e^+ e^-$ decays the invariant mass of both electrons (i.e. reconstructed m_Z) should be close to the true mass of the Z boson. To reject background also p_T^{miss} (of the $Z \rightarrow e^+ e^-$ sample) was studied.

m_Z and p_T^{miss} are shown in Fig. 4.4. The default cuts have been applied. Additional cuts on the mass of the Z boson ($81 \text{ GeV} < m_Z < 101 \text{ GeV}$) and transverse momentum ($p_T > 40 \text{ GeV}$) have been used to reduce the remaining background, which is mostly composed of dileptonic top events (Tab. 4.1). Also semileptonic top events appear (before m_Z cut). As only one true electron is created in these events, there have to be fake electrons.

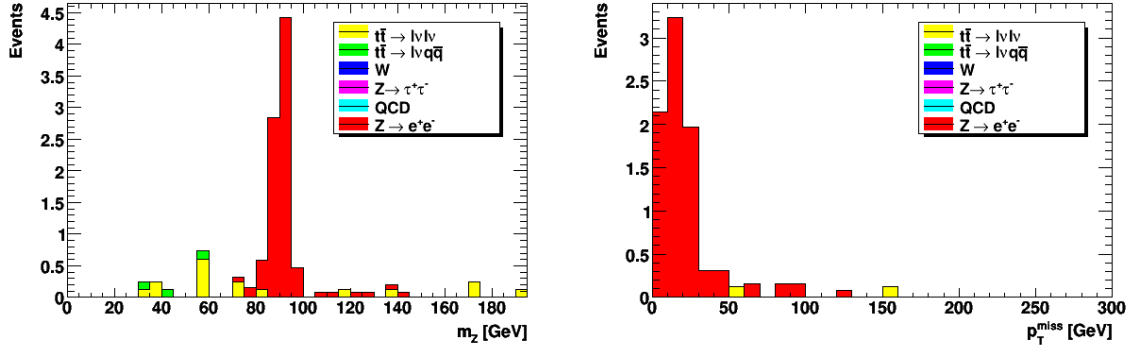


Figure 4.4: Distribution of the reconstructed mass of the Z boson and p_T^{miss} for two reconstructed electrons. Beside the usual SUSY selection cuts two additional cuts $81 \text{ GeV} < m_Z < 101 \text{ GeV}$ and $p_T^{miss} < 40 \text{ GeV}$ have been applied. The cut on the plotted variable has been omitted in each case.

The quality of the cuts is indicated by purity and efficiency. Purity is the ratio of the signal to the sum of signal and background. Efficiency is the ratio of the signal after cuts to the signal before cuts.

The cuts have not been optimized and are almost unnecessary in this case because of the purity of the given signal. However they are still applied to make it possible to compare the 2 electron case with the case of only one reconstructed electron (4.7.2).

event	before cuts		after cuts	
$Z \rightarrow ee$	9.55	(71.0%)	7.66	(100%)
$t\bar{t} \rightarrow \ell\nu qq$	0.37	(2.7%)	0	(0%)
$t\bar{t} \rightarrow \ell\nu\ell\nu$	3.54	(26.3%)	0	(0%)

Table 4.1: Composition of the $Z \rightarrow e^+e^-$ sample with two reconstructed electrons before and after the cuts on invariant mass ($81 \text{ GeV} < m < 101 \text{ GeV}$) and $p_T^{miss} < 40 \text{ GeV}$. This selection cuts have an efficiency of 80.3%. The purity before cuts is 71.0% and 100% after cuts.

4.7.2 One reconstructed electron

As shown in Tab. 4.2 only in 8.9% of $Z \rightarrow e^+e^-$ events both true electrons are reconstructed. Therefore a method that makes it possible to use also the events with one reconstructed electron would significantly increase efficiency. A procedure of this kind is the “tag and probe method”. The tag is the reconstructed electron and the probe is a possible electron candidate, assuming that the missing electron was mistakenly reconstructed as jet.

Therefore an algorithm can be created, that tries to reconstruct the Z boson using the tag and the best matching candidate:

N_e	0	1	2	all
events	49.91 (46.7%)	47.50 (44.4%)	9.55 (8.9%)	106.96 (100.0%)

Table 4.2: Number of Events for zero, one or two reconstructed electrons for an integrated luminosity of 200 pb^{-1} with SUSY selection cuts for a $Z \rightarrow e^+ e^-$ sample.

- Select an event with one reconstructed electron e_{tag} .
- Determine the momentum four-vector p_a of e_{tag} .
- Determine the momentum four-vectors $p_{b,i}$ of all jets ($i = 1, 2, \dots, N_{jet}$).
- Calculate the invariant mass $m_i = (p_a + p_{b,i})^2$ for all candidates.
- Select the candidate for which the invariant mass is closest to the Z boson mass m_Z and choose it as the second four-vector p_b .
- Reconstruct the momentum four-vector of the Z boson from the vector sum $p_Z = p_a + p_b$.
- Calculate all interesting properties of the Z boson ($m, p_T, \dots$) from p_Z .

The results for m_Z using this method are shown in Fig. 4.5. Also p_T^{miss} of the original sample is shown. It can be easily seen that also a large background is measured this way. Part of it can be rejected by applying cuts on m_Z and p_T^{miss} . However one still obtains bad results for purity (see Tab. 4.3). Therefore possible ways to reject this background have to be considered.

4.7.3 Transverse mass

Transverse mass M_T is defined as [7]:

$$M_T^2(\mathbf{p}_T^\alpha, \mathbf{p}_T^{miss}, m_\alpha, m_\chi) \equiv m_\alpha^2 + m_\chi^2 + 2(E_T^\alpha E_T^{miss} - \mathbf{p}_T^\alpha \cdot \mathbf{p}_T^{miss}) \quad (4.3)$$

$$E_T^\alpha \equiv \sqrt{(\mathbf{p}_T^\alpha)^2 + m_\alpha^2} \quad (4.4)$$

$$E_T^{miss} \equiv \sqrt{(\mathbf{p}_T^{miss})^2 + m_\chi^2} \quad (4.5)$$

Where m_α and p_T^α are the mass and transverse momentum of a visible particle, which is the electron in our case. m_χ is the mass of the invisible particle (e.g. neutrino or LSP) which can be neglected.

The distribution of M_T with cuts on m_Z and p_T is shown in Fig. 4.6. As can be seen in the plot a cut on $M_T < 30 \text{ GeV}$ removes the QCD background. This is because there are no neutrinos produced in QCD events. The results on the composition of the sample are listed in Tab. 4.4.

event	before cuts		after cuts	
$Z \rightarrow ee$	47.5	(2.5%)	32.2	(8.0%)
$Z \rightarrow \tau\tau$	0.2	(<0.1%)	0.1	(<.1%)
$W + \text{jets}$	176.4	(9.2%)	21.3	(5.3%)
QCD	1180.8	(61.9%)	276.1	(68.3%)
$t\bar{t} \rightarrow \ell\nu q\bar{q}$	454.3	(23.8%)	71.6	(17.7%)
$t\bar{t} \rightarrow \ell\nu\ell\nu$	48.2	(2.5%)	3.2	(0.8%)

Table 4.3: Composition of the $Z \rightarrow e^+e^-$ sample (see Fig. 4.5) with one reconstructed electron using the tag and probe method before and after the cuts on invariant mass ($81 \text{ GeV} < m < 101 \text{ GeV}$) and $p_T^{\text{miss}} < 40 \text{ GeV}$. This selection cuts have an efficiency of 68.5%. The purity before cuts is 2.5% and 8.0% after cuts.

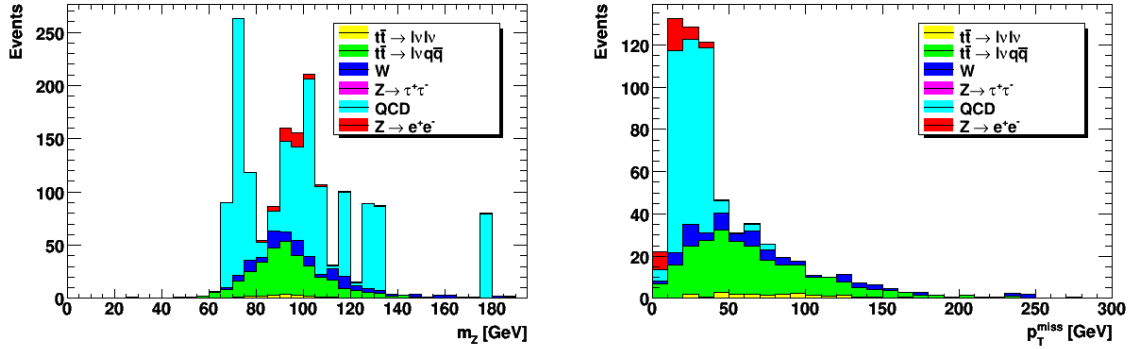


Figure 4.5: Distribution of the reconstructed mass of the Z boson and p_T^{miss} for one reconstructed electron. m_Z was reconstructed using a “tag and probe” method. Beside the usual SUSY selection cuts two additional cuts $81 \text{ GeV} < m < 101 \text{ GeV}$ and $p_T^{\text{miss}} < 40 \text{ GeV}$ have been applied. The cut on the plotted variable has been omitted in each case.

event		
$Z \rightarrow ee$	16.1	(18.7%)
$Z \rightarrow \tau\tau$	0	(0%)
$W + \text{jets}$	13.9	(16.2%)
QCD	0	(0%)
$t\bar{t} \rightarrow \ell\nu q\bar{q}$	53.2	(62.1%)
$t\bar{t} \rightarrow \ell\nu\ell\nu$	2.6	(3.0%)

Table 4.4: Composition of the sample after cut $M_T > 30$ GeV. The selection efficiency of this cut is 50%. The purity can be increased from 8.0% to 18.7%.

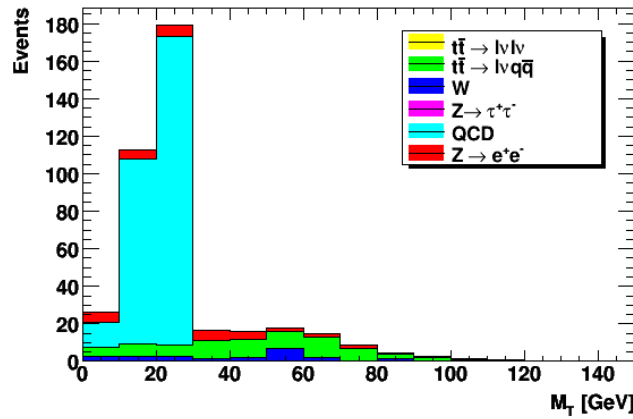


Figure 4.6: Distribution of the transverse mass M_T . A cut at 30 GeV can remove most of the QCD background.

Using this cut we loose 50% of the events of interest, but by rejecting QCD events purity can be increased to 18.7% compared to 8.0% before the cut. The number of events after the cut is still more than twice the number of events for the case with two reconstructed electrons (Tab. 4.3). Therefore in the further progress of this study the M_T cut will always be used. The m_Z and p_T^{miss} distribution after this cut are shown in Fig. 4.7.

4.7.4 Angle between jet and electron

In Fig. 4.8 the $\Delta\phi$ distribution between the electron and the jet which was selected as electron candidate is plotted.

In theory for pure $Z \rightarrow e^- e^+$ one can expect that the angle between the two produced electrons is close to π . This is because conservation of momentum, assuming that the initial momentum of the Z boson is low.

But one also has additional jets from gluon radiation and underlying events which originate in the proton collision, which soften this limitation. This has to be considered,

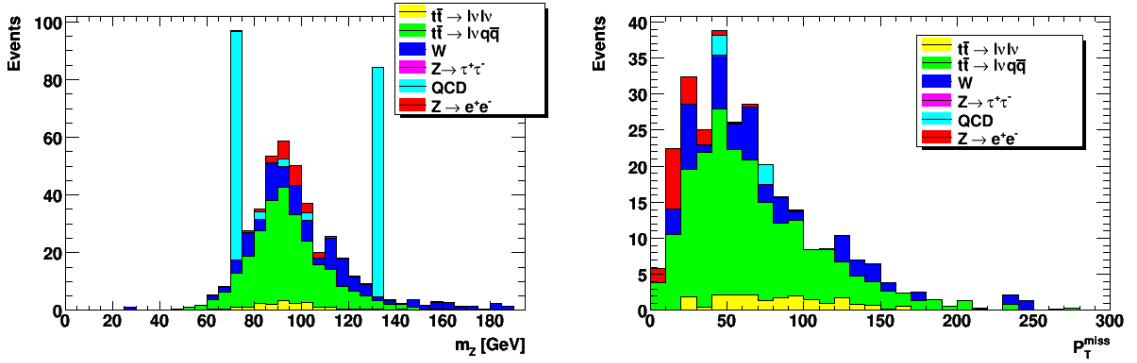


Figure 4.7: Sample after cut on $M_T < 30$ GeV. Most of the QCD background has been removed. The remaining QCD peaks can be explained, because only some single events with high weight pass the tight selection cuts. Hence this phenomenon is due to too low statistics.

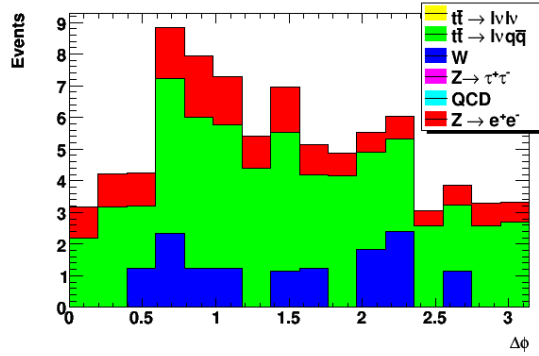


Figure 4.8: Distribution of the azimuthal angle $\Delta\phi$ between the tag and the probe electron. Background can not be separated using this parameter.

since we select only events with large jet multiplicity.

Nevertheless the angle between tag and probe still should differ for various event topologies. However the results of the plot show no special characteristic for the $Z \rightarrow e^- e^+$ sample. Apparently the large number of jets prevents any preference for the direction of the two electrons.

4.7.5 Mass of the top quark

The program package that was used for this study also contained a class for reconstruction of $t\bar{t} \rightarrow \ell\nu q\bar{q}$ events in a similar way like for $Z \rightarrow \ell^+ \ell^-$ events in this study (excerptst in App. A.2). Since we have a large background of semileptonic $t\bar{t}$ events we can try to reconstruct the top quark. One could expect that only true $t\bar{t}$ events are correctly reconstructed and $Z \rightarrow \ell^+ \ell^-$ events are rejected or lead to bad results.

The pre-existing class had to be modified because only events which pass the cuts on m_Z and p_T^{miss} are of interest. So before reconstructing top quarks the Z boson reconstruction algorithm (subsection 4.7.2) was used to select events of interest.

Topbox method

There are two different methods that were used to reconstruct the top quark mass (171.2 ± 2.1 GeV). The first algorithm uses the so called “topbox” method. It starts with the reconstruction of the leptonically decaying top quark:

- First look at $W \rightarrow \ell \nu$.
- Assume that all E_T^{miss} is produced by the neutrino, hence $p_{\nu,x} = E_T^{miss}$, $p_{\nu,y} = E_{T,y}^{miss}$.
- Select the lepton with highest p_T .
(In our case only events with one e are of interest.)
- Estimate $p_{\nu,z}$ using conservation of momentum, p_ℓ and the W boson mass.
($m_W = 80.398 \pm 0.025$ GeV ([8])).
- Since a quadratic equation is used, one obtains two possible neutrino candidates, ν_1 and ν_2 .
- Calculate the momentum four-vector $p_{W,1/2}$ of the W boson for each candidate.
- Find the jet of the b quark: Loop over all jets and use p_{jet} and $p_{W,1/2}$ to calculate the invariant top quark mass.
- Select the result with the best match for the true top quark mass.

It is also possible to limit the number of jets by applying a cut on $p_{T,jet}$ or the number of leading jets (i.e jets with largest p_T), which was not used in this study.

Then the algorithm calculates the mass of the second top quark, which has decayed hadronically:

- Look at $W \rightarrow q\bar{q}$.
- Combine the two four-vectors of all remaining jet pairs.
- Select those two whose invariant mass is the best match for m_W to reconstruct the four-vector of the W boson.
- The rest of jets are the candidates for the second b quark. Calculate the sum of the four-vectors of the W boson and the b quark candidates. Select the one with the best match for m_t .

A more detailed description of the topbox method can be found in [7]. The plots for hadronic and leptonic top quark mass are shown in Fig. 4.9. The composition of the sample is listed in Tab. 4.5. One can see that the ratio of $Z \rightarrow e^+ e^-$ to background

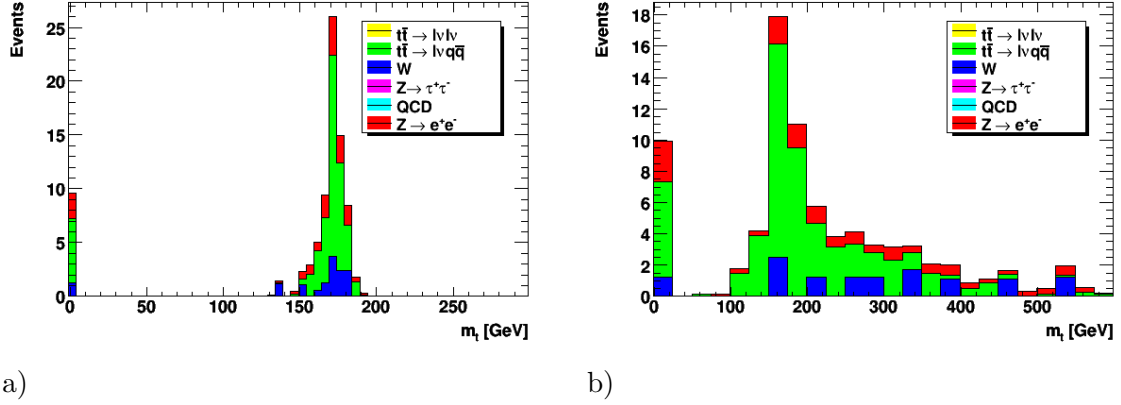


Figure 4.9: Reconstructed mass of the top quark using the topbox method for a) the leptonically decaying top quark and b) the hadronically decaying top quark. In the first bin all rejected events are shown. For these it was not possible to reconstruct m_t .

	leptonic top				hadronic top			
	rejected		reconstructed		rejected		reconstructed	
$Z \rightarrow ee$	2.41	(25.4%)	13.6	(17.9%)	2.58	(26.3%)	13.5	(17.8%)
$Z \rightarrow \tau\tau$	0	(0%)	0	(0%)	0	(0%)	0	(0%)
$W + \text{jets}$	1.25	(13.1%)	12.6	(16.5%)	1.25	(12.7%)	12.6	(16.6%)
QCD	0	(0%)	0	(0%)	0	(0%)	0	(0%)
$t\bar{t} \rightarrow \ell\nu qq$	5.98	(62.8%)	47.3	(62.0%)	6.11	(62.2%)	47.1	(62.1%)
$t\bar{t} \rightarrow \ell\nu\ell\nu$	-0.12	(-1.3%)	2.7	(3.5%)	-0.12	(-1.2%)	2.7	(3.5%)

Table 4.5: Composition of the mass distribution for the hadronically and leptonically decaying top quark. The reconstructed and rejected events are compared to show possible ways to increase purity.

processes is larger for rejected events than for reconstructed ones. However the purity of the remaining sample would still be insufficient.

Alternative method

There is also a second way to calculate the hadronic top quark mass. It is based on the assumption, that jets originating from the same mother particle are close together (i.e. ΔR between them is small). This is very probable if the initial momentum of the mother particle was large compared to its mass.

The algorithm works as follows:

- First look at $W \rightarrow q\bar{q}$.
- Select the two jets with minimal ΔR .
- Use those jets to reconstruct the W boson.

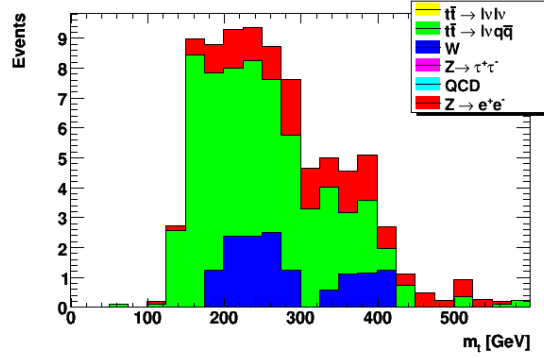


Figure 4.10: Reconstructed mass of the top quark using the alternative method for the hadronically decaying top quark.

- Then look at $t \rightarrow Wb$.
- Find jet with minimal ΔR to the reconstructed W boson.
- Use the sum of the four-vectors of the three selected jets to calculate m_t .

The results for m_t using this method are shown in Fig. 4.10. The composition of this distribution is listed in Tab. 4.6. This algorithm rejects no events. Assuming top quark events are close to the true top quark mass one could add cuts to remove most of the top event background. However it can be seen clearly from the plot that the purity of the sample can not be increased that way.

Because the selected events already had to pass the reconstruction algorithm for m_Z one can assume that they have already very similar signatures. This possibly explains the difficulty in distinguishing them using the reconstruction algorithms for the top quark mass.

	reconstructed	
$Z \rightarrow ee$	16.1	(18.7%)
$Z \rightarrow \tau\tau$	0	(0%)
$W + \text{jets}$	13.9	(16.2%)
QCD	0	(0%)
$t\bar{t} \rightarrow \ell\nu qq$	53.2	(62.1%)
$t\bar{t} \rightarrow \ell\nu\ell\nu$	2.6	(3.0%)

Table 4.6: Composition of the mass distribution using the alternative reconstruction method for the hadronically decaying top quark.

Summing up the tag and probe method can not yet be used to increase reconstruction efficiency because of the large number of background events. Since we require a large number of jets it is understandable that among the many W boson and $t\bar{t}$ pair production

events a probe matching the Z boson mass can be easily found due to high statistics. Without requiring high jet multiplicity the tag and probe method is considered very effective and is used to study electron reconstruction efficiency of the ATLAS detector for example [7].

Better results could possibly be obtained if one were able to distinguish between the jets which are not reconstructed electrons and real jets. A way to do this is to calculate the ratio of the energy deposited in the electromagnetic and the hadronic calorimeter. This fraction should be large for true electrons. Unfortunately data of this kind was not available during this study but could help to make use of the tag and probe method in the future.

4.8 Selection of the $Z \rightarrow \mu^+ \mu^-$ sample

4.8.1 Two reconstructed muons

The algorithm used to reconstruct the Z boson for events with two reconstructed muons is almost identical to the one for two reconstructed electrons:

- Select an event with two reconstructed muons μ^+ and μ^- .
- Determine the momentum four-vectors p_a and p_b for both muons.
- Reconstruct the momentum four-vector of the Z boson from the vector sum $p_Z = p_a + p_b$.
- Calculate all interesting properties of the Z boson (m , p_T , ...) from p_Z .

p_T^{miss} and reconstructed m_Z for the $Z \rightarrow \mu^+ \mu^-$ sample are shown in Fig. 4.11. The default SUSY selection cuts have been used. Again cuts on the mass of the Z boson ($81 \text{ GeV} < m_Z < 101 \text{ GeV}$) and missing transverse momentum ($p_T^{miss} > 40 \text{ GeV}$) have been used to reduce the remaining background. It is composed of mostly dileptonic top quark events and semileptonic top quark events, too (Tab. 4.7).

event	before cuts		after cuts	
$Z \rightarrow \mu^+ \mu^-$	15.8	(61.5%)	12.4	(99.0%)
$t\bar{t} \rightarrow \ell \nu q q$	2.6	(10.0%)	0.1	(1.0%)
$t\bar{t} \rightarrow \ell \nu \ell \nu$	7.3	(28.5%)	0	(0%)

Table 4.7: Composition of the $Z \rightarrow \mu^+ \mu^-$ sample with two reconstructed muons before and after the cuts on invariant mass ($81 \text{ GeV} < m < 101 \text{ GeV}$) and $p_T^{miss} < 40 \text{ GeV}$. This selection cuts have an efficiency of 78.5%. The purity before cuts is 61.5% and 99.0% after cuts.

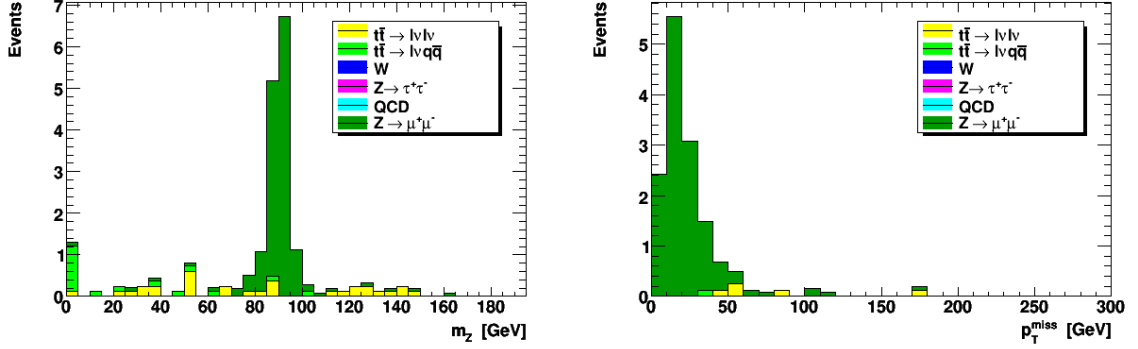


Figure 4.11: Distribution of the reconstructed mass of the Z boson and p_T^{miss} for two reconstructed muons. Beside the usual SUSY selection cuts two additional cuts $81 \text{ GeV} < m < 101 \text{ GeV}$ and $p_T^{miss} < 40 \text{ GeV}$ have been applied. The cut on the plotted variable has been omitted in each case.

4.8.2 One reconstructed muon

As shown in Tab. 4.8 the ratio of events with two reconstructed muons to the events with at least one not reconstructed muon is smaller than for electrons. However the efficiency could still be increased significantly if it were possible to use also the events with only one reconstructed muon.

N_μ	0	1	2	all
events	4.97	16.43	15.79	37.2
	(13.4%)	(44.2%)	(42.5%)	(100.0%)

Table 4.8: Number of Events for zero, one or two reconstructed muons for an integrated luminosity of 200 pb^{-1} with SUSY selection cuts.

Since muons do not produce jets, tracks have to be used for a similar “tag and probe” method as for electrons. Hence the algorithm has to be corrected for muons:

- Select an event with one reconstructed muon μ_{tag} .
- Determine the momentum four-vector p_a of μ_{tag} .
- Discard tracks which are too close to the tag muon ($\Delta R < 0.02$).
- Reject tracks with $(p_T^{track}/p_T^{jet}) < 0.6$, which are most likely tracks of electrons.
- Determine the momentum four-vector $p_{b,i}$ of all remaining tracks ($i = 1, 2, \dots, N_{track} - 1$).
- Calculate the invariant mass $m_i = (p_a + p_{b,i})^2$ for all candidates.

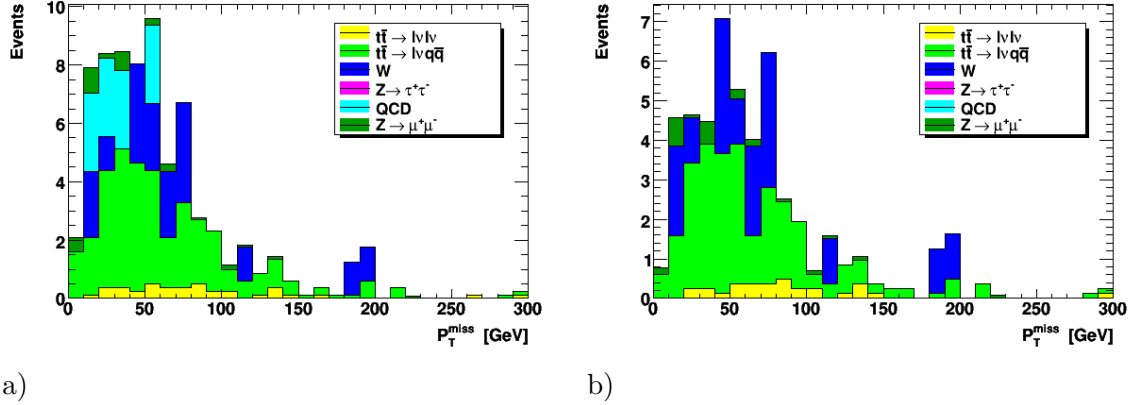


Figure 4.12: p_T^{miss} distribution of the $Z \rightarrow \mu^+ \mu^-$ sample. A cut has been applied on $81 \text{ GeV} < m < 101 \text{ GeV}$. For b) an additional cut on the transverse mass ($M_T < 30 \text{ GeV}$) has been used.

- Select the candidate for which the invariant mass is closest to the Z boson mass m_Z and choose it as the second momentum four-vector p_b .
- Reconstruct the momentum four-vector of the Z boson from the vector sum $p_Z = p_a + p_b$.
- Calculate all interesting properties of the Z boson ($m, p_T, \dots$) from p_Z .

The p_T^{miss} distributions of the $Z \rightarrow \mu^+ \mu^-$ sample for events passing the cuts on the reconstructed Z boson mass ($81 \text{ GeV} < m < 101 \text{ GeV}$) are shown in Fig. 4.12 with and without an additional cut on transverse mass ($M_T < 30 \text{ GeV}$). The composition of the sample is listed in Tab. 4.9.

One can see that there is again a large background. But for muons the results are even worse, because only a small number of events is being reconstructed. Apparently there are only few events with one reconstructed muon where the other muon is reconstructed as track only. The reason for this will be studied in more detail below.

	before cuts		after cuts		after M_T cut	
$Z \rightarrow \mu\mu$	12.7	(0.9%)	2.2	(8.1%)	1.5	(10.6%)
$Z \rightarrow \tau\tau$	0.3	(<0.1%)	0	(0%)	0	(0%)
$W + \text{jets}$	174.7	(12.5%)	3.4	(12.7%)	1.25	(12.7%)
QCD	772.8	(55.3%)	8.1	(30.0%)	3.4	(23.5%)
$t\bar{t} \rightarrow \ell\nu q\bar{q}$	395.3	(28.3%)	12.3	(46.0%)	9.0	(62.5%)
$t\bar{t} \rightarrow \ell\nu\ell\nu$	40.7	(2.9%)	0.9	(3.2%)	0.5	(3.4%)

Table 4.9: Composition of the sample with one reconstructed muon before and after cuts on m_Z and p_T^{miss} . Also an additional cut on transverse mass has been applied.

4.8.3 η distribution

The distribution of the pseudorapidity η is shown in Fig. 4.13 a). The binning has been matched to the geometry of the muon spectrometer (Fig. 4.13 b)). An additional intersection has been added at $|\eta| = 2.5$ since leptons are only reconstructed for smaller pseudorapidity. The number of entries per bin varies largely because of the different bin size.

4.8.4 p_T distribution

The transverse momentum p_T is also of interest because the muon definition for reconstruction includes only muons with $p_T > 10$ GeV. Muons with lower p_T cannot be reconstructed. The plot (Fig. 4.14 a)) shows that the number of true muons with low p_T is very small and therefore this cut has only a small effect on reconstruction efficiency.

4.8.5 ΔR between jet and muon

For muon identification an isolation requirement is made. This means that a muon which is close to a jet ($\Delta R < 0.4$) is rejected. The reason for this is to reject muons which are produced in the jet. The ΔR distribution between each muon and the closest jet is shown in Fig. 4.14 b), where events with too large η and too small p_T already have been removed (for both, true and reconstructed muons). One can see that the remaining number of muons that have not been reconstructed are the ones with small ΔR whereas the muons with large enough ΔR are very often reconstructed.

4.8.6 Comparison of true and reconstructed events

It is very easy to calculate the number of true events from the number of true muons for a $Z \rightarrow \mu^+ \mu^-$ sample. As in each event two muons are produced the number of events is half the number of muons. For reconstructed events however, this is not as simple any more. Since in each event two, one or no lepton might be detected the number of events has to be calculated independently. These results are shown in Tab. 4.10.

Only in 42.5% of true events both muons are detected. The remaining events with at least one not reconstructed muon (57.5%) are rejected. The table shows that this is mostly (50.3% of true events) the case if at least one muon has either too large pseudorapidity, too small p_T or is close to a jet.

This means that also for muons the tag and probe method cannot yet be used to increase reconstruction efficiency. This is because a large part of the muons is not reconstructed because of large $|\eta|$. For this region also no data of tracks is available due to the detector geometry. The remaining missing muons are mainly reconstructed but rejected if they are close to a jet which cannot be improved by a tag and probe method.

In any case there are nearly no muons which have a track and are not reconstructed. So a tag and probe method using muon tracks cannot be used to increase reconstruction efficiency.

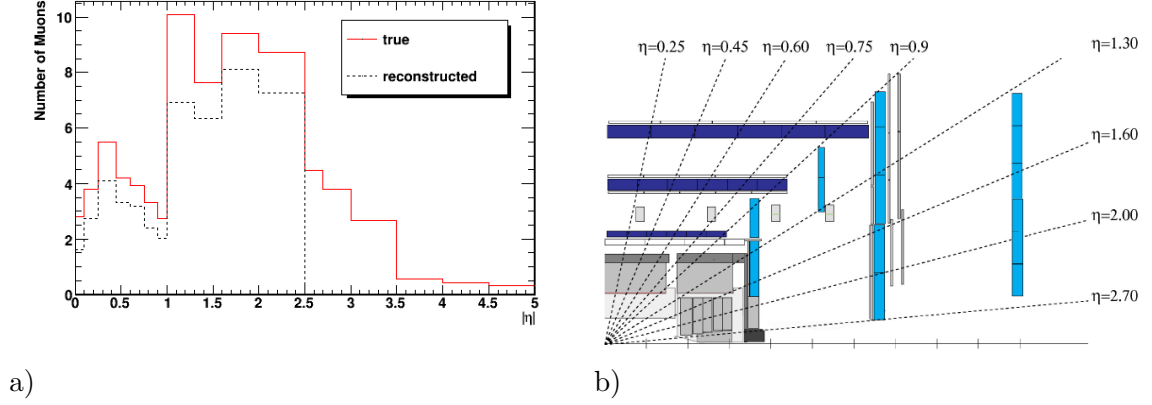


Figure 4.13: a) Muon counts in regard to the pseudorapidity $|\eta|$ for true muons and reconstructed muons. A dynamic binning has been chosen to take the detector geometry in account. An additional intersection has been added at $|\eta| = 2.5$ because leptons can not be reconstructed for larger values (due to the tracker geometry) b) Geometry of the ATLAS muon spectrometer showing the η values for the edges of the muon chambers.

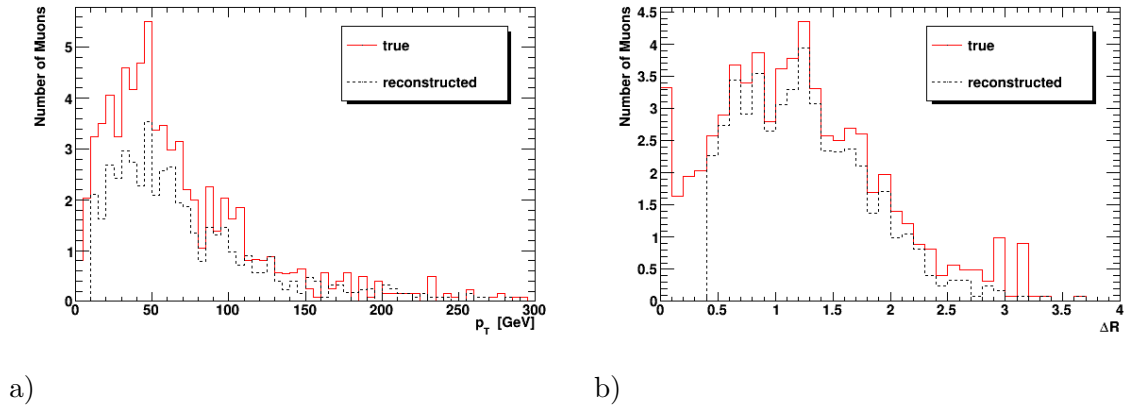


Figure 4.14: a) Distribution of the transverse momentum p_T of true and reconstructed muons. Muons with $p_T < 10$ GeV are not reconstructed. Only a small fraction of muons is lost because of this. b) Distribution of ΔR between muons (true and reconstructed) and the closest jet. Only muons with $|\eta| < 2.5$ and $p_T < 10$ GeV are considered. The remaining muons are mainly not reconstructed if $\Delta R < 0.4$. This is due to isolation requirements for muon reconstruction.

	true muon events	
true events	37.2	(100.0%)
2 μ reconstructed	15.8	(42.5%)
<2 μ reconstructed	21.4	(57.5%)
too high $ \eta $	8.8	(23.8%)
too low p_T (rest)	1.5	(4.0%)
not isolated (rest)	8.4	(22.6%)
all	18.7	(50.3%)

Table 4.10: Table of true events and events with two reconstructed muons. Also the number of events is listed with at least one muon with too high $|\eta|$, the number of *remaining* events with at least one muon with too low p_T and of the *then remaining* events the ones with at least one muon that is too close to a jet.

5 Conclusion

Possible methods were studied to improve the selection of a $Z \rightarrow \ell^+ \ell^-$ sample which is used for data-driven estimation of the $Z \rightarrow \nu \bar{\nu}$ background in SUSY searches. Therefore a “tag and probe” method was used to include also events with only one reconstructed lepton.

In the case of electrons jets have been used as probe. The results for this procedure show that a large background mostly composed of QCD and $t\bar{t}$ events makes a use of this method impossible.

A cut on M_T removes the QCD background but the remaining background is still larger than the signal. No possibility was found to remove $t\bar{t}$ events. Neither the distribution of the angle between the tag electron and the probe jet nor top quark reconstruction algorithms were helpful.

This method can be improved if more detailed information on the jets will be available.

For muons a neglectable number of events can be reconstructed with a track as probe. This can be explained by studying the reasons for the not reconstructed electrons. One part of the muons is not reconstructed if they have too large pseudo-rapidity, because neither the muons-spectrometer nor the tracker cover this region. Furthermore muons are rejected if they are close to a jet. Muons with too low p_T make only a minor contribution.

To sum up, for electrons as well as for muons the selection of the sample could not be improved by using a tag and probe method.

A Program code excerpts

A.1 Zll.C

```
1 \label{app_Zll}
2 Int_t Zll::reconstruct(Int_t method){
3
4     // method = 0
5     // 1. reconstruct Z:
6     //     - select 2 leptons same flavour opposite sign
7     //     - reconstructed vector of Z = vector sum of
8       leptons
9     //     - calculate massZ and other values of Z from
10      vector
11
12     if (debug) cout << "In reconstruct(), method = " <<
13       method << endl;
14
15     // set default values
16     massZ = -1;
17     deltaR_TrackJet = -1;
18     ptTrackSelected = -1;
19     leptonModeUsed = -1;
20     nTrackWOMu = -1;
21     nTrackCone = -1;
22     ptTrackCone = -1;
23     ptJetCone = -1;
24     etTrackSelCone = -1;
25
26     if (method == 0){
27
28         // Lorentz vectors for the two leptons
29         TLorentzVector *tmp1 = new TLorentzVector();
30         TLorentzVector *tmp2 = new TLorentzVector();
31
32         // (leptons used to reconstruct Z must be replaced to
33           estimate Znunu)
34         vector<Int_t>* leptonsReplaced = new vector<Int_t>();
35         vector<Int_t>* jetsReplaced = new vector<Int_t>();
```

```

32
33 // TWO ELECTRON MODE
34 // (leptonRecMode e2, leptonModeUsed 1)
35 // the vectors of the two electrons are used to
   reconstruct Z
36
37 if(NElectron()==2 && strstr(leptonRecMode,"e2")){ //2
   electrons
38   leptonModeUsed = 1;
39   if ((ChargeElectron(0)+ChargeElectron(1))==0){ //
   check opposite sign
40     if(debug) cout << "In Zll::reconstruct(), 2
   electrons " << endl;
41     tmp1->SetPtEtaPhiM(PtElectron(0), EtaElectron(0)
   , PhiElectron(0), 0);
42     tmp2->SetPtEtaPhiM(PtElectron(1), EtaElectron(1)
   , PhiElectron(1), 0);
43
44     leptonsReplaced->push_back(0);
45     leptonsReplaced->push_back(1);
46   }
47
48 }
49
50 // TWO MUON MODE
51 // (leptonRecMode mu2, leptonModeUsed 2)
52 // the vectors of the two muons are used to
   reconstruct Z
53 if(NMuon()==2 && strstr(leptonRecMode,"mu2")){ //2
   muons
54   leptonModeUsed = 2;
55   if ((ChargeMuon(0)+ChargeMuon(1))==0){ // check
   opposite sign
56     if(debug) cout << "In Zll::reconstruct(), 2
   muons " << searchMode << endl;
57     tmp1->SetPtEtaPhiM(PtMuon(0), EtaMuon(0),
   PhiMuon(0), 0);
58     tmp2->SetPtEtaPhiM(PtMuon(1), EtaMuon(1),
   PhiMuon(1), 0);
59
60     leptonsReplaced->push_back(10);
61     leptonsReplaced->push_back(11);
62
63   }
64

```

```
65     }
66
67     // ONE ELECTRON MODE
68     // (leptonRecMode e1, leptonModeUsed 3)
69     // vectors used to reconstruct Z: one electron and jet
70     //   (electron which was not reconstructed)
71     // select jet with best match for mZ
72     if(NElectron()==1 && NJet() > 0 && strstr(
73         leptonRecMode,"e1")){ //1 electron, 1 jet as
74         electron
75         leptonModeUsed = 3;
76         if(debug) cout << "In Zll::reconstruct(), electron
77             + jet " << endl;
78
79         tmp1->SetPtEtaPhiM(PtElectron(0), EtaElectron(0),
80             PhiElectron(0), 0);
81
82         // Select jet with best results vor mZ
83         int countJet = -1;
84         Float_t deltaM0 = 1e6;    // differnece of
85             calculated and true mZ
86
87         for(int k = 0; k < NJet(); k++){
88             TLorentzVector *tmpA2 = new TLorentzVector();
89             tmpA2->SetPtEtaPhiM(PtJet(k), EtaJet(k), PhiJet(
90                 k), 0);
91             Float_t deltaM = fabs((*tmp1+*tmpA2).M()-m_Z);
92             if(deltaM < deltaM0){
93                 countJet=k;
94                 deltaM0 = deltaM;
95                 tmp2->SetPtEtaPhiM(PtJet(k), EtaJet(k),
96                     PhiJet(k), 0);
97             }
98         }
99     }
100
101     leptonsReplaced->push_back(0);
102     jetsReplaced->push_back(countJet);
103     deltaPhi_eJet = DeltaPhi(tmp1->Phi(),tmp2->Phi());
104 }
```

```

102
103
104     // ONE MUON MODE
105     // (leptonRecMode mu1, leptonModeUsed 4)
106     // vectors used to reconstruct Z: one muon and track (
107         muon which was not reconstructed)
108     // select track with best match for mZ
109     if(NMuon()==1 && NTrack() > 1 && strstr(leptonRecMode,
110         "mu1")){ //1 muon, 1 additional(!) track as muon
111
112         leptonModeUsed = 4;
113         if(debug) cout << "In Zll::reconstruct(), muon +
114             track " << endl;
115         tmp1->SetPtEtaPhiM(PtMuon(0), EtaMuon(0), PhiMuon
116             (0), 0);
117
118         TLorentzVector *tmp1 = new TLorentzVector();
119
120         // calculate mZ for each track
121         // and Select track with best results vor mZ
122         int countTrack = -1;
123
124         Float_t deltaM0 = 1e6;    // differnece of
125             calculated and true mZ
126         if(NTrack() > 1){
127             for(int k = 0; k < NTrack(); k++){
128                 TLorentzVector *tmpA2 = new TLorentzVector();
129                 tmpA2->SetPtEtaPhiM(PtTrack(k), EtaTrack(k),
130                     PhiTrack(k), 0);
131                 Float_t deltaM = fabs((*tmp1+*tmpA2).M()-m_Z)
132                     ;
133                 if(deltaM < deltaM0){
134                     // if track matches muon continue
135                     Float_t deltaRMuonTrack = DeltaR(DeltaPhi(
136                         PhiMuon(0),PhiTrack(k)),(EtaMuon(0)-
137                         EtaTrack(0)));
138                     if(deltaRMuonTrack < .02) continue;
139                     // check opposite charge
140                     if(ChargeMuon(0)+ChargeTrack(k) != 0)
141                         continue;
142                     // reject track from e
143                     if(PtJetOverPtTrack(k) > .6) continue;
144                     // otherwise tmp2 is track with best match
145                     for mZ

```

```

136         countTrack=k;
137         deltaM0 = deltaM;
138         tmp2->SetPtEtaPhiM(PtTrack(k), EtaTrack(k)
            , PhiTrack(k), 0);
139     }
140     if(countTrack == -1){
141         return -1;
142     }
143
144 }
145

```

(...)

```

1
2     leptonsReplaced->push_back(10);
3
4     //---DeltaR for track and closest Jet---
5
6     if(debug) cout << "In Zll::reconstruct(), DeltaR "
7         << endl;
8     Float_t deltaR0 = 1e6;
9     for(int k = 0; k < NJet(); k++){
10         // calculate DeltaR for each jet
11         Float_t tmpDeltaR = DeltaR(DeltaPhi(PhiTrack(
12             countTrack),PhiJet(k)),(EtaTrack(countTrack)-
13             EtaJet(k)));
14         // select closest Jet
15         if(tmpDeltaR < deltaR0){
16             deltaR0 = tmpDeltaR;
17         }
18     }
19     if(deltaR0 < 1e6) deltaR_TrackJet = deltaR0;
20
21     //-----PtTrackSelected-----
22     ptTrackSelected = PtTrack(countTrack);
23     //-----NTrackWOMu-----
24     nTrackWOMu = NTrack()-1;
25

```

```

24
25     // RECONSTRUCT Z
26
27     // checks if mZ was reconstructed
28     // (massZ is -1 if not reconstructed)
29     if(leptonModeUsed<0){
30         return -1;
31     }
32
33     // reconstructed Lorentz vector of Z
34     TLorentzVector* tmpZ = new TLorentzVector();
35     *tmpZ = *tmp1+*tmp2;
36
37     // reconstructed values of Z / estimated values for
38     // Znunu
39     massZ = tmpZ->M();
40     ptMiss_Zll = tmpZ->Pt();
41     phiMiss_Zll = tmpZ->Phi();
42
43     return 1;
44 }
45 return -1;
}

```

A.2 semileptonic_top_Zll.C

```

1  Int_t semileptonic_top_Zll::reconstruct(Int_t method){
2      // return value:
3      // -1: if the event can not be reconstructed
4      // 0: if reconstructed but the jet pairing is not correct
5      // 1: reconstructed with correct jet paring
6      // method = 0 TopBox method:
7      // 1. find z-component of neutrino
8      // 2. find jet with M(jet, nu, lep) = M_top
9      // 3. find jet pair with M(jet, jet) = M_W
10     // 4. find jet with M(W, jet) = M_top
11
12     // method = 1 ATL-COM-PHYS-2008-044
13     // 1. recontruct hadronic W:
14     // - select 2 jets with min delta_R(jet,jet)
15     // - select jet with min delta_R(jet, W)
16
17     // method = 2 same as 1 plus misidentified electron (jet)

```

```

18 // method = 3 same as 1 plus misidentified lepton (track)
19
20 Int_t w_jet1 = -1;
21 Int_t w_jet2 = -1;
22 Int_t leptonic_jet = -1;
23 Int_t hadronic_jet = -1;
24 Int_t lepton_charge = 0;
25 TLorentzVector lepton;
26
27 if (debug) cout << "In reconstruct(), method = " << method
    << endl;
28
29 massTopLep = -1;
30 massTopHad = -1;
31 massW = -1;
32 JetMatchElectron = false;
33 leptonCandidateJet = -1;
34 leptonCandidateTrack = -1;
35 // find z-component of neutrino momentum
36 // lepton momentum, take lepton with largest Pt
37 Float_t ptmax = 0;
38 for (Int_t i=0; i<NElectron(); i++){
39     if (PtElectron(i)>ptmax){
40         ptmax = PtElectron(i);
41         lepton.SetPtEtaPhiM(PtElectron(i), EtaElectron(i),
            PhiElectron(i), 0);
42         if (ChargeElectron(i)>0) lepton_charge = 1;
43         else lepton_charge = -1;
44     }
45 }
46 for (Int_t i=0; i<NMuon(); i++){
47     if (PtMuon(i)>ptmax){
48         ptmax = PtMuon(i);
49         lepton.SetPtEtaPhiM(PtMuon(i), EtaMuon(i), PhiMuon(i),
            0);
50         if (ChargeMuon(i)>0) lepton_charge = 1;
51         else lepton_charge = -1;
52     }
53 }
54
55 if (method == 0){
56     Float_t p = lepton.P();
57     Float_t pz = lepton.Pz();
58     Float_t pt = lepton.Pt();
59     Float_t MEt = PtMiss();

```

```

60
61     Float_t mt = Mt(PtMiss(), PhiMiss(), &lepton);
62
63
64     Float_t m2 = 0.5*(m_W*m_W - mt*mt);
65     Float_t A = m2+MEt*pt;
66
67     // // solve quadratic equation
68     Float_t a = pt*pt;
69     Float_t b = -2*pz*A;
70     Float_t c = MEt*MEt*p*p-A*A;
71
72     Float_t D = b*b-4*a*c;
73     if (D<0 || a==0) return -1; // no solutions...
74     Float_t z1 = (-b-sqrt(D))/(2*a);
75     Float_t z2 = (-b+sqrt(D))/(2*a);
76     TLorentzVector neutrino1;
77     TLorentzVector neutrino2;
78     neutrino1.SetXYZM(PtMiss()*cos(PhiMiss()), PtMiss()*sin(
        PhiMiss()), z1, 0);
79     neutrino2.SetXYZM(PtMiss()*cos(PhiMiss()), PtMiss()*sin(
        PhiMiss()), z2, 0);
80     // find a jet which make top invariant mass
81     // loop over 4 leading jets
82     // momentum of the 4-th jet
83     vector<Float_t> Pt_sorted;
84     for (int i=0; i<NJet(); i++){
85         Pt_sorted.push_back(PtJet(i));
86     }
87     std::sort(Pt_sorted.begin(),Pt_sorted.end());
88     Float_t pt4 = 0;
89     // Int_t leptonic_jet = -1;
90     Int_t solution = -1;
91     Float_t deltaM = 1000.0*GeV; // M(jet, neutrino, lepton)
        -m_W
92     TLorentzVector jet;
93     if (nLeadingJetCut>0)
94         if (NJet() > nLeadingJetCut) pt4 = 0.5*(Pt_sorted[
            NJet()- nLeadingJetCut] + Pt_sorted[NJet()-
            nLeadingJetCut-1]);
95
96     if (ptBjetMinCut>0) pt4 = ptBjetMinCut;
97
98     // leptonic top
99     for (Int_t i=0; i<NJet(); i++){

```

```
100     if (PtJet(i)<pt4) continue;
101     // calculate invariant mass
102     jet.SetPtEtaPhiM(PtJet(i), EtaJet(i), PhiJet(i), 0);
103     if (fabs((jet+neutrino1+lepton).M()-m_top) < deltaM){
104         deltaM = fabs((jet+neutrino1+lepton).M()-m_top);
105         leptonic_jet = i;
106         solution = 1;
107     }
108     if (fabs((jet+neutrino2+lepton).M()-m_top) < deltaM){
109         deltaM = fabs((jet+neutrino2+lepton).M()-m_top);
110         leptonic_jet = i;
111         solution = 2;
112     }
113 }
114 if (leptonic_jet == -1) return -1;
115 jet.SetPtEtaPhiM(PtJet(leptonic_jet), EtaJet(
    leptonic_jet), PhiJet(leptonic_jet), 0);
116 if (solution == 1) massTopLep = (jet+lepton+neutrino1).M
    ();
117 if (solution == 2) massTopLep = (jet+lepton+neutrino2).M
    ();
118 if (solution<0) return -1;
119
120 // reconstruct hadronic W
121 deltaM = 1000.0*GeV;
122 TLorentzVector jet1;
123
124 //     Int_t w_jet1 = -1; // index of hadronic w-jet
125 //     Int_t w_jet2 = -1; // index of hadronic w-jet
126 // loop over all pairs
127 Int_t count = 0;
128 for (Int_t i=0; i<NJet(); i++){
129     if (PtJet(i)<pt4 || i==leptonic_jet) continue;
130     for (Int_t j=i+1; j<NJet(); j++){
131         if (PtJet(j)<pt4 || j==leptonic_jet) continue;
132         jet.SetPtEtaPhiM(PtJet(i), EtaJet(i), PhiJet(i), 0);
133         jet1.SetPtEtaPhiM(PtJet(j), EtaJet(j), PhiJet(j), 0)
            ;
134         count++;
135         if ( fabs((jet+jet1).M()-m_W)<deltaM){
136             deltaM = fabs((jet+jet1).M()-m_W);
137             w_jet1 = i;
138             w_jet2 = j;
139         }
140     }
```

```

141     }
142     if (w_jet1<0 || w_jet2<0) return -1;
143
144     jet.SetPtEtaPhiM(PtJet(w_jet1), EtaJet(w_jet1), PhiJet(
145         w_jet1), 0);
146     jet1.SetPtEtaPhiM(PtJet(w_jet2), EtaJet(w_jet2), PhiJet(
147         w_jet2), 0);
148     massW = (jet+jet1).M();
149
150     // reconstruct hadronic top mass
151     TLorentzVector jet2;
152     deltaM = 1000.0*GeV;
153     // Int_t hadronic_jet = -1;
154     for (Int_t i=0; i<NJet();i++){
155         if (i==leptonic_jet || i==w_jet1 || i==w_jet2)
156             continue;
157         jet2.SetPtEtaPhiM(PtJet(i), EtaJet(i), PhiJet(i), 0);
158         if (fabs((jet+jet1+jet2).M()-m_top) < deltaM ){
159             deltaM = fabs((jet+jet1+jet2).M()-m_top);
160             hadronic_jet = i;
161         }
162     }
163     if (hadronic_jet < 0) return -1;
164     jet2.SetPtEtaPhiM(PtJet(hadronic_jet), EtaJet(
165         hadronic_jet), PhiJet(hadronic_jet), 0);
166     massTopHad = (jet+jet1+jet2).M();
167 }
168 else if (method == 1 || method == 2 || method == 3){
169     // 1. hadronic w
170     TLorentzVector jet;
171     TLorentzVector jet1;
172     // Int_t w_jet1 = -1; // index of hadronic w-jet
173     // Int_t w_jet2 = -1; // index of hadronic w-jet
174     Float_t dr = 100000.;
175     // loop over jet pairs
176     for (Int_t i=0; i<NJet(); i++){
177         for (Int_t j=i+1; j<NJet(); j++){
178             if (PtJet(j)<JetLowPtCut) continue;
179             if (DeltaR( EtaJet(i)-EtaJet(j), DeltaPhi(PhiJet(i),
180                 PhiJet(j)))< dr){
181                 dr = DeltaR( EtaJet(i)-EtaJet(j), DeltaPhi(PhiJet(
182                     i), PhiJet(j)));
183                 w_jet1 = i;
184                 w_jet2 = j;
185             }
186         }
187     }

```

```
180     }
181   }
182
183   if (w_jet1<0 || w_jet2<0){
184     return -1;
185   }
186   jet.SetPtEtaPhiM(PtJet(w_jet1), EtaJet(w_jet1), PhiJet(
187     w_jet1), 0);
187   jet1.SetPtEtaPhiM(PtJet(w_jet2), EtaJet(w_jet2), PhiJet(
188     w_jet2), 0);
188   TLorentzVector W=(jet+jet1);
189   massW = W.M();
190
191   if (debug){
192     cout << "jets:" << endl;
193     for (Int_t i=0; i<NJet(); i++){
194       cout << PtJet(i)/GeV << " GeV, KF = "
195         << KFJet(i)
196         << endl;
197     }
198     cout << "semileptonic_top_Zll::reconstruct():"
199       << " W jet1 = " << w_jet1
200       << " W jet2 = " << w_jet2
201       << " massW = " << massW/GeV
202       << endl;
203   }
204
205   //   Int_t hadronic_jet = -1;
206   // find the jet closest to W
207   dr = 100000.;
208   for (Int_t i=0; i<NJet(); i++){
209     if (i==w_jet1 || i==w_jet2) continue;
210     if (PtJet(i)<JetLowPtCut) continue;
211     Float_t etaW = W.Eta();
212     Float_t phiW = W.Phi();
213     if (DeltaR(EtaJet(i)-etaW, DeltaPhi(PhiJet(i), phiW))<
214       dr){
215       dr = DeltaR(EtaJet(i)-etaW, DeltaPhi(PhiJet(i), phiW
216         ));
217       hadronic_jet = i;
218     }
219   }
220   if (hadronic_jet < 0) return -1;
221   jet.SetPtEtaPhiM(PtJet(hadronic_jet), EtaJet(
222     hadronic_jet), PhiJet(hadronic_jet), 0);
```

```

220     massTopHad = (jet+W).M();
221     if (debug) cout << "hadronic b-jet: "
222                     << hadronic_jet
223                     << " Hadronic Top Mass: "
224                     << massTopHad/GeV
225                     << endl;
226
227     // find z-component of neutrino momentum
228     // lepton momentum, take lepton with largest Pt
229     vector <TLorentzVector>* leptonList = new vector <
        TLorentzVector>();
230     vector <Int_t>* jetIndex = new vector <Int_t>(); //
        indice if electron candidates
231     TLorentzVector lepton;
232     bool leptonFound = false;
233     Float_t ptmax = 0;
234     for (Int_t i=0; i<NElectron(); i++){
235         if (PtElectron(i)>ptmax){
236             ptmax = PtElectron(i);
237             lepton.SetPtEtaPhiM(PtElectron(i), EtaElectron(i),
                PhiElectron(i), 0);
238             leptonFound = true;
239         }
240     }
241     for (Int_t i=0; i<NMuon(); i++){
242         if (PtMuon(i)>ptmax){
243             ptmax = PtMuon(i);
244             lepton.SetPtEtaPhiM(PtMuon(i), EtaMuon(i), PhiMuon(i),
                0);
245             leptonFound = true;
246         }
247     }
248     if (leptonFound){
249         leptonList->push_back(lepton);
250         jetIndex->push_back(-1);
251     }

```

(...)

```

1     if (debug) cout << "leptonList length: " << leptonList->
        size() << endl;

```

```
2 // loop over leptonList
3 Float_t deltaM = 1000.0*GeV; // M(jet, neutrino, lepton)
   -m_top
4 for (UInt_t ilep=0; ilep<leptonList->size(); ilep++){
5     lepton = (*leptonList)[ilep];
6     Float_t p = lepton.P();
7     Float_t pz = lepton.Pz();
8     Float_t pt = lepton.Pt();
9     Float_t MEt = PtMiss();
10    if (debug) cout << "ilep = " << ilep
11                  << " Pt = " << pt/GeV << endl;
12
13
14    Float_t mt = Mt(PtMiss(), PhiMiss(), &lepton);
15
16
17    Float_t m2 = 0.5*(m_W*m_W - mt*mt);
18    Float_t A = m2+MEt*pt;
19
20    // // solve quadratic equation
21    if (debug) cout << "solve quadratic equation" <<
22                  endl;
23    Float_t a = pt*pt;
24    Float_t b = -2*pz*A;
25    Float_t c = MEt*MEt*p*p-A*A;
26
27    Float_t D = b*b-4*a*c;
28    if (D<0 || a==0) return -1; // no solutions...
29    Float_t z1 = (-b-sqrt(D))/(2*a);
30    Float_t z2 = (-b+sqrt(D))/(2*a);
31    TLorentzVector neutrino1;
32    TLorentzVector neutrino2;
33    neutrino1.SetXYZM(PtMiss()*cos(PhiMiss()), PtMiss()*
34                      sin(PhiMiss()), z1, 0);
35    neutrino2.SetXYZM(PtMiss()*cos(PhiMiss()), PtMiss()*
36                      sin(PhiMiss()), z2, 0);
37
38    // find a jet which make top invariant mass
39    // Int_t leptonic_jet = -1;
40    Int_t solution = -1;
41
42    // leptonic top
43    if (debug) cout << "leptonic top" << endl;
44    for (Int_t i=0; i<NJet(); i++){
45        if (PtJet(i)<JetLowPtCut) continue;
46        if (i==w_jet1 || i==w_jet2 || i==hadronic_jet)
```

```

43         continue;
44         if (i == (*jetIndex)[ilep]) continue; // exclude the
45         jet which is electron candidate
46         // calculate invariant mass
47         if (debug) cout << "calculate invariant mass 1" <<
48         endl;
49         jet.SetPtEtaPhiM(PtJet(i), EtaJet(i), PhiJet(i), 0);
50         if (fabs((jet+neutrino1+lepton).M()-m_top) < deltaM)
51         {
52             deltaM = fabs((jet+neutrino1+lepton).M()-m_top);
53             leptonic_jet = i;
54             solution = 1;
55             leptonCandidateJet = (*jetIndex)[ilep];
56             leptonCandidateTrack = ilep;
57         }
58         if (debug) cout << "calculate invariant mass 2" <<
59         endl;
60         if (fabs((jet+neutrino2+lepton).M()-m_top) < deltaM)
61         {
62             deltaM = fabs((jet+neutrino2+lepton).M()-m_top);
63             leptonic_jet = i;
64             solution = 2;
65             leptonCandidateJet = (*jetIndex)[ilep];
66             leptonCandidateTrack = ilep;
67         }
68         if (debug) cout << "calculate invariant mass 3" <<
69         endl;
70     }
71     if (leptonic_jet == -1) continue;
72     if (debug) cout << "leptonic b-jet: " << leptonic_jet
73     << endl;
74     jet.SetPtEtaPhiM(PtJet(leptonic_jet), EtaJet(
75     leptonic_jet), PhiJet(leptonic_jet), 0);
76     if (solution == 1) massTopLep = (jet+lepton+neutrino1)
77     .M();
78     if (solution == 2) massTopLep = (jet+lepton+neutrino2)
79     .M();
80 }
81 if (debug) cout << "calculate invariant mass -
82 before delete" << endl;
83 // delete leptonList;
84 // delete jetIndex;
85 if (debug) cout << "calculate invariant mass - after
86 delete" << endl;
87 if (debug) cout << "leptonCandidateJet = " <<

```

```

    leptonCandidateJet << endl;
75 // check if the this jet match the true electron
76 if (method == 2 || leptonCandidateJet >= 0){
77     for (Int_t i=0; i<NTrueElectron(); i++){
78         if (abs(MotherTrueElectron(i)) != 24) continue;
79         Float_t r = DeltaR(DeltaPhi(PhiTrueElectron(i),
80                                 PhiJet(leptonCandidateJet)),
81                                 EtaTrueElectron(i) - EtaJet(
82                                     leptonCandidateJet));
83         if (r<0.4) JetMatchElectron = true;
84     }
85 }
86 else {
87     cout << "Warning in semileptonic::reconstruct(): unknown
88         method = " << method << endl;
89     return -1;
90 }
91 // check if 2 b-quark and 2 w-jets attributed to the jets
92 if (debug){
93     cout << "***** ttbar Id's ***** " << endl;
94     for (Int_t i=0; i<NJet(); i++){
95         cout << TtbarIdJet(i) << " ";
96     }
97     cout << "Lepton charge: " << lepton_charge << endl;
98     cout << "w_jet1 = " << w_jet1 << endl;
99     cout << "w_jet2 = " << w_jet2 << endl;
100     cout << "hadronic_jet = " << hadronic_jet << endl;
101     cout << "leptonic_jet = " << leptonic_jet << endl;
102 }
103 if ( hadronic_jet < 0 ||
104     w_jet1 < 0 || w_jet2 < 0 ) return -1;
105 if (abs(TtbarIdJet(hadronic_jet)+TtbarIdJet(w_jet1)+
106     TtbarIdJet(w_jet2))==(24+24+5)) return 1;
107 return 0;
108 }

```

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Eidesstattliche Erklärung

Gemäß §21 Absatz 10 der allgemeinen Studien- und Prüfungsordnung für die Bachelor- und Masterstudiengänge an der Julius-Maximilians-Universität Würzburg erkläre ich hiermit, dass ich diese Arbeit selbstständig verfasst, keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe und die Arbeit bisher keiner anderen Prüfungsbehörde unter Erlangung eines akademischen Grades vorgelegt habe.

Würzburg, den 1. Juli 2009

Martin Krauß