To the bottom of the stop: calibration of bottom-quark jets identification algorithms and search for scalar top-quarks and dark matter with the Run I ATLAS data
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Citation for published version (APA):
Pani, P. (2014). To the bottom of the stop: calibration of bottom-quark jets identification algorithms and search for scalar top-quarks and dark matter with the Run I ATLAS data
Summary

The Standard Model and beyond

In the last century high energy physics has made incredible steps forward toward the comprehension of the nature of our universe, its matter content and the interactions of that matter. The SM provides a cogent description of all known subatomic particles and their quantum interactions (strong, weak and electromagnetic). The SM predictive power has been tested to unprecedented precision, with the recent discovery of a Higgs boson by the LHC experiments completing the last piece of the particles puzzle. Despite its success, the SM is not considered to be the conclusive theory of elementary particles due to its inability to explain a number of open questions about our universe, such as the nature of Dark Matter and Dark Energy that compose 96% of the universe content or the relation of gravity with the other three interactions. These and many more open questions about nature call for theories that extend the the SM.

Among these theories, Supersymmetry is one of the most compelling ideas. It is grounded on a generalisation of space-time transformations linking fermions and bosons and it predicts the existence of a supersymmetric partner for every known particle with half a unit of spin difference, but otherwise with the same properties and quantum numbers. Supersymmetry is one of the main focuses of the research program at the LHC experiments.

The LHC and the ATLAS experiment during Run I

The Large Hadron Collider (LHC) is currently the most powerful proton-proton collider in the world and it is located at CERN near Geneva in Switzerland. The first Run of data-taking lasted from 2010 to 2012. The A Toroidal LHC ApparatuS (ATLAS) experiment is one of four experiments recording the collisions delivered by the LHC.
Summary

This thesis is based on the data recorded by ATLAS during Run I, which correspond to a total integrated luminosity of $pp$ collisions of 5 and 20 fb$^{-1}$ at a centre-of-mass energy of 7 and 8 TeV, respectively.

The ATLAS detector is often denoted as a general purpose experiment, with the aim to express that behind its design lies the purpose of performing a large variety of very different measurements with the data collected in the next twenty years of data taking.

For this reason, it is of utmost importance to ensure that the detector reaches, and if possible outperforms, its design requirements. This can be summarised in three different key points of action:

(a) Guarantee that the detector efficiently records high quality data.

(b) Increase the understanding of the detector in order to improve the performance and achieve a precise simulation description;

(c) Evaluate the time evolution of the detector’s performance, both in the long and in the short term, to ensure the detector’s health throughout the experiment lifetime.

A section of this thesis is focused on two examples of performance monitoring and improvement, namely the alignment of the inner tracker, which was achieved with a precision of the order of 10 μm and the monitoring of one of its sub detectors, the SCT, which achieved data taking efficiencies of 99.9%, 99.6% and 99.1% in 2010, 2011 and 2012 respectively [95].

Calibration of bottom-quark jets identification algorithms

In 2011, the main focus of the ATLAS experiment has been not only to probe for the first time physics at the energy frontier, but also to improve the understanding and calibration of the detector and the tuning and validation of the Monte Carlo simulation used to model the SM (and new physics) processes.

A large number of measurements and new physics searches performed in ATLAS rely on the identification of jets originating from $b$-quarks, which is performed by means of dedicated $b$-tagging algorithms. The aim of the first analysis presented in this thesis is to investigate the reliability of the Monte Carlo simulation in describing the quantities exploited directly and indirectly by these $b$-tagging algorithms. This is achieved by studying a $b$-jet enriched sample from fully reconstructed $B^+ \rightarrow J/\psi K^*$
Summary, Figure 1: Angular distance between the hadronization tracks of the jet and the jet axis.

decays. The study is based on the 5 fb$^{-1}$ of data collected in 2011 at centre-of-mass energy of $\sqrt{s} = 7$ TeV and it was driven by the need of understanding the calibration factors of the $b$-tagging algorithms needed to match the simulation to the experimental data. $B$-jets properties and the performance of the tagging algorithms are studied in data and compared to the Monte Carlo simulation. The majority of the observables are found to be well described by the simulation and the $b$-tagging performance has been found to be in agreement to the Monte Carlo at the few percent level. Fig. 1 compares the angular distance between the hadronization tracks in a $b$-jet and the jet axis$^{1}$. The solid line represents the distribution from the Monte Carlo simulation that is compared to the same distribution from data (indicated with points). The points in the lower panel of the figure show the ratio between the

$^{1}$defined as $\Delta R(\text{jet, trk}) = \sqrt{(\phi_{\text{jet}} - \phi_{\text{trk}})^2 + (\eta_{\text{jet}} - \eta_{\text{trk}})^2}$
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data and the Monte Carlo simulation. The two distributions agree at a few percent level, proving a good modelling of the $b$-jets hadronization track topology by the simulation. The distributions of the transverse and longitudinal impact parameters of hadronization tracks have shown instead up to 20% disagreement between the data and the Monte Carlo simulation.

Search for scalar top-quarks and Dark Matter

The dataset collected by ATLAS in 2012 is four times bigger than the one in 2011 and the higher centre-of-mass energy results in a higher production cross section for one of the most intriguing particles predicted by Supersymmetry: a scalar top quark (top squark).

The SUSY analysis presented in this thesis is a search for top squarks in final states with one isolated lepton, $b$-jets and missing transverse momentum. Since R-parity is assumed to be conserved, top squarks are always produced in pairs. Of all the possible top squark decay modes, three are considered:

\begin{itemize}
  \item[a)] $\tilde{t} \rightarrow t \tilde{\chi}^0$ (with subsequent decay $t \rightarrow W b$)
  \item[b)] $\tilde{t} \rightarrow b \tilde{\chi}^\pm \rightarrow b W^\pm \tilde{\chi}^0$ (with $W^\pm \rightarrow \ell \nu$ or $W^\pm \rightarrow \bar{q} q'$)
  \item[c)] $\tilde{t} \rightarrow b W^\pm \tilde{\chi}^0$ (via off-shell top and $W^\pm \rightarrow \ell \nu/\bar{q} q'$)
\end{itemize}

The neutralino ($\tilde{\chi}^0$) is assumed to be the lightest supersymmetric particle and due to the conservation of R-parity it is stable and escapes the detector without interacting. The masses of the top squark and the other supersymmetric particles in the decay chain (charginos and neutralinos) are unknown.

In order to achieve a good sensitivity for the three top squark decay modes and the widest range of assumptions for $m_{\tilde{t}}$, $m_{\tilde{\chi}^\pm}$, $m_{\tilde{\chi}^0}$ we exploit two different strategies to define the signal enriched regions:

\begin{itemize}
  \item Selections defined by requirements on a number of quantities with high discrimination power between signal and background. The final discrimination is achieved by counting and comparing the number of signal and background events passing all requirements, and therefore these selections are called cut-and-count selections.
  \item A simultaneous likelihood fit of multi-bin selections (*shape fits*). The binning is defined in the two most discriminating quantities and allows to exploit the
Summary, Figure 2: Event display of a $t \rightarrow b \chi^\pm$ candidate event. This event has a $E_T^{\text{miss}}$ value of 609 GeV (red dashed line). It has four jets of transverse momenta of 424, 199, 130 and 99 GeV, respectively. Jets are indicated as cones with area proportional to the jet transverse momentum. The second and the third most energetic jets are identified as $b$-jets using the MV1 $b$-tagging algorithm (blue lines). One muon is identified in the event and it has a transverse momentum of 51 GeV (yellow line). Tracks with transverse momentum of at least 0.5 GeV are shown in the inner tracker.
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difference in shape between the background and the signal in order to increase the discriminating potential.

A total of seven cut-and-count selections and four shape fit selections are defined for this analysis.

A $\tilde{t} \rightarrow b \tilde{\chi}^\pm$ candidate event display is shown in Fig. 2. This event has a $E_T^{\text{miss}}$ value of 609 GeV, indicated with a red dashed line in the figure. It has four selected jets of transverse momenta of 424, 199, 130, and 99 GeV, respectively. Jets are indicated as cones and the area of the cone is proportional to the jet transverse momentum. The second and the third most energetic jets are identified as $b$-jets using the MV1 $b$-tagging algorithm (blue lines). One muon is identified in the event and it has a transverse momentum of 51 GeV (yellow line).

The data yield observed in each signal region are compatible with the SM-only hypothesis, hence the results have been interpreted in terms of upper limits on the

Summary, Figure 3: Exclusion limits 95% CL in the $(m_{\tilde{t}}, m_{\tilde{\chi}^0})$ plane. The two decay modes $\tilde{t} \rightarrow b \tilde{\chi}^\pm$ and $\tilde{t} \rightarrow t \tilde{\chi}^0$ are assumed with a branching ratio of $(100 - x)\%$ and $x\%$, respectively for each line in the plot. $m_{\tilde{\chi}^\pm} = 2m_{\tilde{\chi}^0}$ is assumed.
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three top squark decay modes.

Fig. 3 shows the result in the \((m_\tilde{t}, m_\chi^0)\) mass plane obtained for models where two decay modes of the top squark are allowed in the same event. Each line in the plot represents the exclusion curve for a different branching ratio in the two decay modes, \(x\%\) in \(\tilde{t} \rightarrow t \tilde{\chi}^0\) and \((100 - x)\%\) in \(\tilde{t} \rightarrow b \tilde{\chi}^\pm \rightarrow b W^\pm \tilde{\chi}^0\). \((m_\tilde{t}, m_\chi^0)\) mass assumptions inside the solid line have been excluded at 95\% CL. Dashed lines indicate the expected exclusion contours. Branching ratios of 0-100\%, 25-75\%, 50-50\%, 75-25\%, and 100-0% have been tested. All signal selections presented in this analysis have been combined to obtain this exclusion. The combination was obtained by selecting a-priori the signal region with the best expected limit for each \((m_\tilde{t}, m_\chi^0)\) point. Top squark masses between 290 and 530 GeV are excluded for all branching ratios in the case of a neutralino mass of 100 GeV.

Neutralinos are excellent candidates for WIMP Dark Matter. In the context of an Effective Field Theory description of DM [76, 77], certain Lagrangian operators describing the contact interaction between DM particles and quarks are proportional to the quark masses, being therefore possibly enhanced for bottom and top quarks. The results of the top squark analysis were interpreted in terms of DM associate production with top quarks \((pp \rightarrow t\bar{t}\chi\chi)\), that has the same final state as the \(\tilde{t} \rightarrow t \tilde{\chi}^0\) decay. The combined exclusion curves at 95\% CL for the DM-nucleon scattering cross section are given in Figure 4, for contact operators D1 (Dirac scalar DM) and C1 (complex scalar DM). Values above the curve are excluded. The results are compared with limits obtained by the ATLAS mono-jet analysis using the 7 TeV data set and the exclusion limits (at 90\% CL) recently set by the LUX and Super-CDMS collaborations. Assuming a DM mass of 1 GeV, DM-nucleon scattering cross sections above \(3 \cdot 10^{-41}\) cm\(^2\) and \(7 \cdot 10^{-43}\) cm\(^2\) are excluded for complex scalar and Dirac DM contact operators, respectively. The exclusion limits resulting from this analysis are currently the world strongest constraints on scalar coupling of Dark Matter for operators involving heavy quarks.
Summary, Figure 4: Exclusion curves at 95% CL for DM-nucleon scattering cross section for operators D1 and C1. The results are compared with 90% CL exclusion curves from the Super-CDMS and the LUX Collaborations and values above the curves are excluded.