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Ruth Pöttgen

Search for Dark Matter with ATLAS

Using Events with a Highly Energetic Jet and Missing Transverse Momentum in Proton-Proton Collisions at $\sqrt{s} = 8$ TeV

Doctoral Thesis accepted by
the Johannes Gutenberg University, Mainz, Germany

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Für meine Großeltern

Supervisor's Foreword

One of the biggest present mysteries in fundamental science is the so far unknown nature of Dark Matter, which amounts to about one-quarter of the energy–matter density of our universe. So far no unambiguous direct detection of Dark Matter has been made in laboratory on earth. A favourite candidate for dark matter particles is the so-called weakly interacting massive particle (WIMP), behaving in several ways similar to neutrinos (albeit possibly having a much larger mass).

This thesis addresses the hunt for Dark Matter in the laboratory, making use of the Large Hadron Collider (LHC) as the energy frontier machine of this decade, to possibly produce and study candidates for Dark Matter under controlled conditions. If these were to be produced in proton-proton collisions, they would however escape a direct detection by the LHC experiments. The question thus arises: how to detect the undetectable in an experiment such as the ATLAS detector? The answer is given by the so-called "mono–X" signature, which implies the (pair) production of WIMPs together with another (detectable) object X in the final state of the reaction. There are several possibilities for the object X, however, in most cases the largest sensitivity is obtained when X is a hadronic jet. One of the major challenges in this search is the careful estimation of irreducible backgrounds, dominated by the production of Z-boson together with jets, where the former decay in neutrino-antineutrino pairs. As part of this thesis a detailed, data-driven determination has been performed, together with a thorough determination of systematic uncertainties.

The results are interpreted in two different but related theoretical frameworks: One is the canonical approach of an effective field theory that allows for a straightforward comparison to other searches for Dark Matter. The other is a new approach with respect to previous LHC searches: using a simplified model, which is more robust at LHC energies than the effective theory ansatz. The absence of an observed excess in the full data set at a centre-of-mass energy of 8 TeV as recorded by ATLAS in 2012 was used to set more stringent bounds on relevant parameters of both models, compared to earlier results from LHC.

Furthermore, this book describes major contributions to the understanding and the improvement (as well as its operation) of a crucial component of the ATLAS experiment for its full physics program: the ATLAS trigger system. Without its reliable and efficient trigger ATLAS would not be able to select the interesting events out of the huge rate of inelastic proton-proton collisions delivered by the LHC, i.e. the necessary search for the needle in the haystack.

In 2015, the LHC resumed its operation (in the so-called "run II") providing proton-proton collisions at the unprecedented centre-of-mass energy of 13 TeV. Part of this book contains a sensitivity study made in the context of this thesis, clearly showing the significantly enlarged discovery potential for WIMPs.

The analysis in this thesis documents the state-of-art results from run-I of the LHC in the search for WIMPs as candidates for Dark Matter in the mono-jet signature. The results are complementary to those of direct detection experiment, aiming at e.g. recording the recoil of a nucleus when hit by a WIMP. These are presented in a thorough scientific manner and in an extremely comprehensible way, embedded in the overall scientific context also beyond particle physics. This book will surely serve as a compendium for future young research students in the analysis of run-II data from ATLAS (and other experiments).

Mainz, Germany
June 2016

Prof. Stefan Tapprogge

Abstract

Any physics analysis at a collider experiment heavily relies on an efficient trigger system to filter out potentially interesting events. To ensure stable operation, a continuous and detailed real-time monitoring is essential. Two such online monitoring features for the Central Trigger of the ATLAS experiment at the Large Hadron Collider (LHC) at the European centre for particle physics, CERN, are developed as part of this thesis and are presented in detail. To prepare the ATLAS experiment for the second run of the LHC starting in 2015, among other systems the Central Trigger hardware will be upgraded to remove resource limitations and allow for the connection of newly installed systems. This thesis reports on the corresponding changes and extensions in the simulation of the Central Trigger, the implementation of which is part of this work.

A further part of this thesis presents a search for Dark Matter candidates. Cosmological observations indicate that about 80 % of the matter content of the universe consist of a form of non-luminous matter which is traceable only due to its gravitational interaction and for which the Standard Model of particle physics does not provide a viable candidate. A number of experiments searches for evidence of Weakly Interacting Massive Particles (WIMPs), that in a natural way could account for the observed present day abundance of this Dark Matter. In recent years, also the search for WIMP pair production at hadron colliders has gathered momentum. A possible signal signature at a collider is a jet originating from initial state radiation and recoiling against a pair of WIMPs, leading to events with a highly energetic jet and a large amount of missing transverse momentum due to the WIMPs leaving the detector without interacting. The signal is thus expected to manifest itself as an excess above the Standard Model prediction at large missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$).

The search for WIMP candidates presented in this thesis uses such mono-jet events, based on 20 fb^{-1} of proton-proton collision data collected in 2012 with the ATLAS detector at a centre-of-mass energy of $\sqrt{s} = 8$ TeV. The main Standard Model backgrounds are estimated in a semi-data driven way. The event selection is optimized with respect to the sensitivity for a WIMP signal and the search is

performed in eight signal regions of increasing $E_{\mathrm{T}}^{\mathrm{miss}}$. No significant excess is observed and model independent limits both at 90 % and 95 % confidence level (CL) are set on the cross section for new physics. In addition, 90 % CL limits are derived on the suppression scale of an effective field theory (EFT) for various operators and compared to the results from other search experiments. The collider limits for all considered effective operators are stronger than the bounds from other experiments at low WIMP masses in the case of spin-independent interactions, and over a large mass range for spin-dependent interactions. In the light of concerns about the applicability of an EFT at LHC energies, the results are furthermore interpreted in terms of a simplified model with an *s*-channel vector mediator.

A simulation based sensitivity study on the prospects of the Dark Matter search with mono-jet events at a centre-of-mass energy of 14 TeV is presented and expected limits at 95 % CL as well as discovery potentials are given. It is found that already with the first few fb^{-1} of $\sqrt{s} = 14$ TeV data the expected limits can improve by a factor of 2. The discovery potential ultimately reaches up to suppression scales of 2.6 TeV, while for $\sqrt{s} = 8$ TeV it is of the order of 700 GeV.

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