Search for dark matter production in association with top quarks in the dilepton final state at $\sqrt{s} = 13$ TeV

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CMS

Outline

Introduction

A search for the production of dark matter particles in association with either one or two top quarks is presented:

- We study the pp collisions produced by the LHC at $\sqrt{s} = 13$ TeV;
- Reconstruction performed by the CMS detector;
- Legacy analysis, considering the full Run II dataset (data collected in 2016, 2017 and 2018 and summing around 136 fb^{-1}).

Motivation

- Several (mostly astrophysical) evidences for the existence of dark matter, but **no direct nor direct detection** so far;
- We hope to be able to produce such particles in the high energy collisions produced by the LHC if they exist.

Main objective

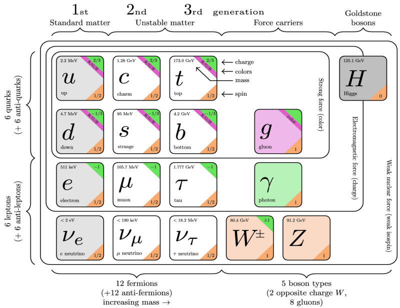
- Consider different dark matter production models to eventually exclude some of them or at least **put upper limits on their cross section of production**.

The dark matter case

The Standard Model

The most accepted model to describe the elementary particles and some of the fundamental interactions between them is the Standard Model:

- Contains 26 free parameters, among which the masses of the **12 predicted fermions**;
- Many **successful predictions** made over the years, such as the existence of the top quark, and the W, Z and Higgs bosons [1].



However, this model has several shortcomings: eventual exotic particles which do not fit within this model (such as dark matter) are extensively searched for nowadays.

At the origins of dark matter I

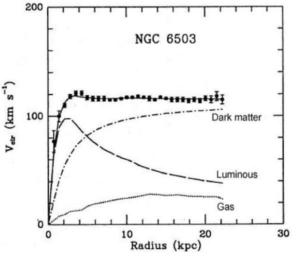
The concept of dark matter can be traced back to the 19th century, and was introduced to **explain several astrophysical evidences**, among which:

Zwicky's calculations

- Measurement of the mass of the Coma Cluster using the virial theorem;
- Concluded that its mass was **400-500 times larger** than the value obtained by Hubble, considering only visible galaxies [2].

Spiral galaxies rotation curves

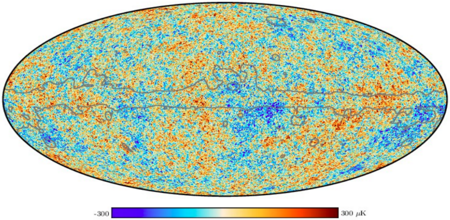
- Stars within spiral galaxies should rotate with a velocity depending on the radius to the galactic center, but **this is not what is observed experimentally** [3];
- Either our understanding of gravity at large scales or our basic understanding of galaxies as a celestial body made of stars has to be revised.

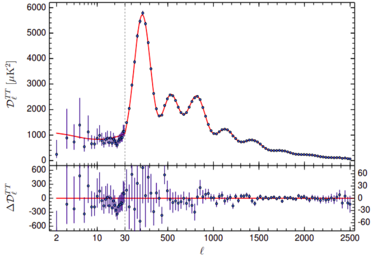


K.G. Begeman, A.H. Broels, R.H. Sanders. 1991. Mon.Not.RAS 249, 523.

CMB anisotropies

- Background of primary radio waves emitted when the Universe became transparent around 380 000 years after the Big Bang;
- Can be considered as emitting a black body spectrum with a temperature of (2.72548 ± 0.00057)K [4], but small anistropies at the 10^{-5} level are observed;
- Implies that dark matter accounts for $\sim 27\%$ of the total mass of the Universe.





Other observations, such as the gravitational lensing effect, **also tend to further support the existence of dark matter** (cf. backup).

Several fundamental properties of dark matter are nowadays known or assumed:

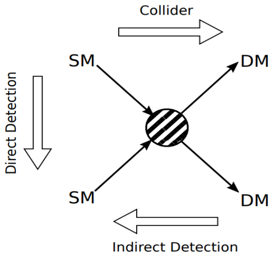
- Dark matter is a particle, given that it is assumed to have a certain mass;
- It should be dark, unable to interact with electromagnetic radation, otherwise we would have seen it already. It should then also be **electrically neutral**;
- It is non-baryonic, because the energy density for the baryonic matter estimated from the CMB is too low to account for dark matter;
- We only consider cold dark matter since the widely accepted Λ_{CDM} model is based on this assumption and this helps explaining the presence of large scale structures in the Universe;
- It should have a mass in the electroweak scale, between 10 GeV and 1 TeV, because of the relic density obtained from the thermal freeze-out mechanism [5].
- Finally, it should be long-lived, since we expect them to have been produced during the Big Bang and they are still present in the Universe.

Weakly Interactive Massive Particles

The WIMPs are the dark matter candidates considered in this work, because of the so-called **WIMP miracle**. Indeed, they:

- Are expected to interact very weakly with ordinary baryonic matter;
- Have a mass in the 100 GeV-1 TeV range for reasonable electroweak production cross-section values;
- Give us a dark matter while being able to solve the **hierarchy problem**.

Search strategies



Different strategies are used:

- The **direct and indirect searches**, relying on the production of baryonic matter from the interaction between two DM particles or on the observation of the interaction between the dark and baryonic sectors;
- And the **collider production**, able to probe lower dark matter candidates masses.

Focus of this thesis

Yukawa

Previous relevant results

The experimental setup

The Large Hadron Collider I

The Large Hadron Collider II

The CMS detector I

The CMS detector II

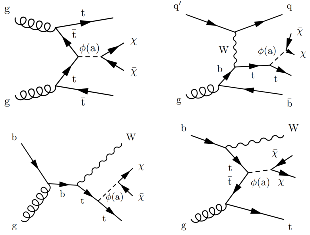
Analysis reminder

Analysis reminder

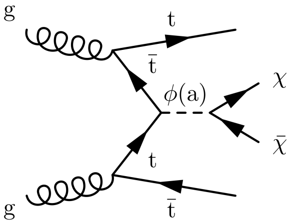
Simplified model considered:

- Spin 1/2 DM χ ($\in [1, 55]$ GeV, Dirac fermion)
- Spin 0 scalar (S)/pseudoscalar (PS) mediator ϕ (Yukawa-like structure of such interactions $\rightarrow$ gain from the coupling of the mediator to top quarks)
- Mediator mass $\in [10, 1000]$ GeV
- Coupling g_χ mediator/DM set to 1 (same for all g_q couplings)

$t/\bar{t}$+DM models



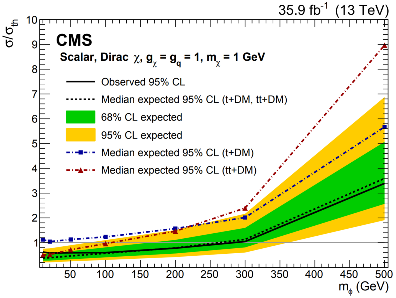
$t\bar{t}$+DM model

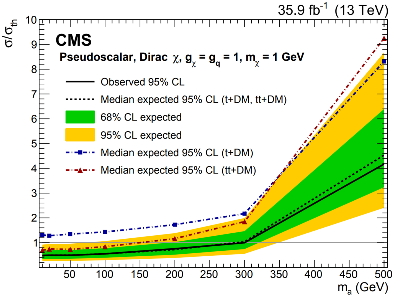


2016 results

The inclusion of the $t/\bar{t}$+DM process improves up to a factor 2 the limits obtained by the $t\bar{t}$ analysis on its own. Published in 2016 as CMS-EXO-18-010.

- Only considering semi-leptonic and hadronic final states
- Scalar (pseudoscalar) mediators excluded up to 290 (300) GeV at 95% CL.





Analysis strategy

Run II legacy paper expected to combine both the t+DM and $t\bar{t}$+DM analyses, and the 3 different final states (hadronic, one and two leptons).

This talk mostly focuses on:

- Explaining the global strategy and status of the analysis
- Show the latest news and plans for each final state
- Display the two leptons final state latest distributions for 2016, 2017 and 2018

The effort is globally common between the groups:

- Objects will be defined in a common way
- Control and signal region orthogonal between the channels
  - Number of leptons and b-jet categorization to improve the sensitivity by defining enriched single top/$t\bar{t}$ regions

Dilepton final state

Global strategy

Frameworks

Two different frameworks currently used in coordination:

- Both frameworks use nanoAODv7 and the same samples
- A synchronization exercise has been performed in the different control and signal regions, in 2016, 2017 and 2018, as documented in our twiki [1].

[1] `https://twiki.cern.ch/twiki/bin/view/CMS/TopPlusDMRunIILegacy`

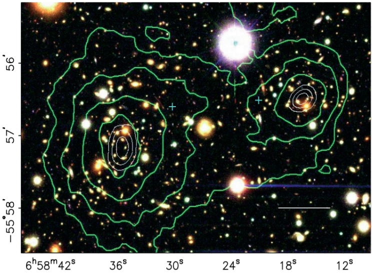
Conclusions

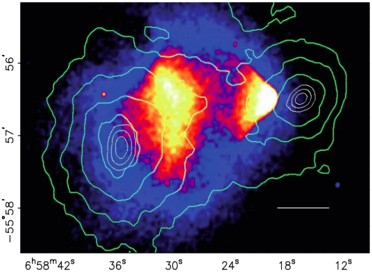
Back up

Gravitational lensing

Consequence of the general relativity: massive objects placed between distant sources and the observer should be able to **act as lenses and bend the light of the source**.

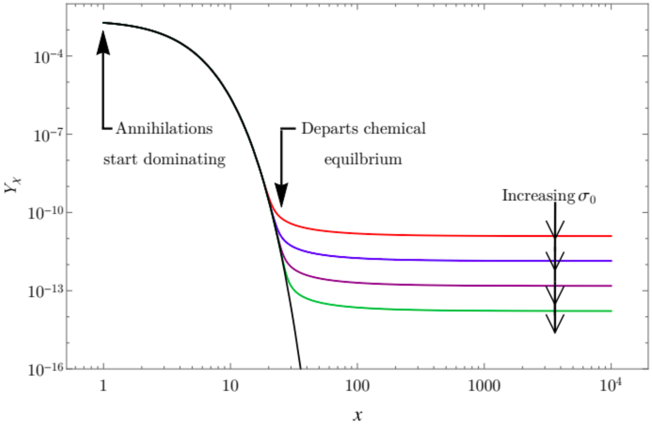
- The deviation of the light is **proportional to the mass of the intermediate object**, giving us a way to measure its mass;
- The mass distribution obtained has been compared to the luminous distribution of several galaxies, leading to 8σ discrepancies [6].





Thermal freeze-out

Schematic representation of the freeze-out process, representing the abundance of a 500 GeV dark matter with respect to the time and the impact of increasing cross-section annihilation values on this freeze-out abundance.



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