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

A thesis submitted in fulfillment of the requirements for the

Degree of Doctor of Philosophy

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Abstract

Resumen

Acknowledgments

Acronyms used

SM Standard Model

DM Dark Matter

LHC Large Hadron Collider

CMS Compact Muon Solenoid

ATLAS A Toroidal LHC ApparatuS

CERN European Council for Nuclear Research

QFT Quantum Field Theory

CMB Cosmic Microwave Background

ML Machine Learning

MFV Minimal Flavour Violation

WIMP Weakly Interactive Massive Particle

PF Particle Flow

BSM Beyond the Standard Model

MACHO Massive Compact Halo Object

MSSM Minimal Supersymmetric Standard Model

SI Spin Independent

SD Spin Dependent

CL Confidence Level

QCD Quantum ChromoDynamics

ADMX Axion Dark Matter Experiment

CAST CERN Axion Solar Telescope

IAXO International Axion Observatory

LNGS Laboratori Nazionali del Gran Sasso

UED Universal Extra Dimensions

NFW Navarro-Frenk-White

LAT Fermi Large Telescope

IACT Imaging Atmospheric Cherenkov Telescopes

CTA Cherenkov Telescope Array

AMS Alpha Magnetic Spectrometer

EFT Effective Field Theory

ISR Initial State Radiation

FSR Final State Radiation

DMWG Dark Matter Working Group

MET Missing Transverse Energy

VBF Vector Boson Fusion

BR Branching Ratio

LEP Large Electron Positron collider

ALICE A Large Ion Collider Experiment

PS Proton Synchrotron

SPS Super Proton Synchrotron

PU Pile Up

PV Primary Vertex

ECAL Electromagnetic Calorimeter

HCAL Hadronic Calorimeter

DT Drift tube

CSC Cathode Strip Chamber

RPC Resistive Plate Chamber

TIB/TBD Tracker Inner Barrel and Disks

TOB Tracker Outer Barrel

TEC Tracker EndCap

HO Hadron Outer

LS Long Shutdown

GEM Gas Electron Multiplier

L1 Level-1 Trigger

HLT High-Level Trigger

DAQ Data Acquisition System

DQM Data Quality Monitoring

DCS Detector Control System

WP Working Point

SC Super Cluster

KF Kalman Filter

GSF Gaussian Sum Filter

MVA Multi-Variate Analysis

CSV Combined Secondary Vertex

DNN Deep Neural Network

PUPPI Pileup Per Particle Identification

BW Breit-Wigner

MC Monte Carlo

UE Underlying Event

PDF Parton Density Function

LO Leading Order

NLO Next to Leading Order

MPI Multiple Parton Interaction

SF Scale Factors

AOD Analysis Object Data

EDM Event Data Model

DY Drell-Yan

DAS Data Aggregation System

Contents

Chapter 1

Data, signals and backgrounds

In order to find a possible hint of the production of Dark Matter (DM) in the Large Hadron Collider (LHC) collisions considering our signal models of interest, briefly described in Section **??**, the data collected needs to be compared with Monte Carlo (MC) simulations produced in a central way for each Standard Model (SM) process. Indeed, any deviation of the data observed with respect to what we expect to see, obtained from these MC simulations, might be the sign of some Beyond the Standard Model (BSM) physics. All of the steps needed to mathematically simulate the *pp* collisions of the LHC and to take into account the effect of the detector on the particles produced will first of all be introduced in Section 1.1.

Then, the different formats of files available to perform the analysis and the code used will be briefly introduced in Sections 1.2 and 1.3 and the different data samples collected during the Run II of operation of the LHC will be then detailed in Section 1.4, while the signal models and samples considered in this particular analysis along with the MC samples used for the simulation of the different backgrounds will be introduced in Sections 1.5 and 1.6 respectively.

1.1 The Monte Carlo (MC) simulation method

As previously explained, the generation of MC simulations for the most common SM processes is a crucial step of any analysis because they are considered to be the reference to which the data collected is compared in order to try and find some discrepancies, which could the sign of the existence of BSM physics. Searches for exotic physics therefore heavily depend on these simulations, which need to be generated with great care and to which a large uncertainty is typically associated since the collision between the partons of two protons and the interaction between the particles produced and the detector itself are extremely complex by nature.

The basic idea of the MC simulation consists in using a random number generator to simulate the randomness of nature and produce as many events as computationally possible for all the SM processes, taking into account the probability density functions of these processes. This is performed by specific softwares called **event generators** and it is important to note that since we usually don't know everything about the SM or BSM process being generated, the perfect event generator does not exist.

To make the generation of such simulations a bit easier, the description of a typical pp collision can usually be divided into several steps that will now be described, as shown with the color code used in Figure 1.1. The typical approximations used to make this kind of simulation possible from the computational point of view will also be briefly introduced at this point.

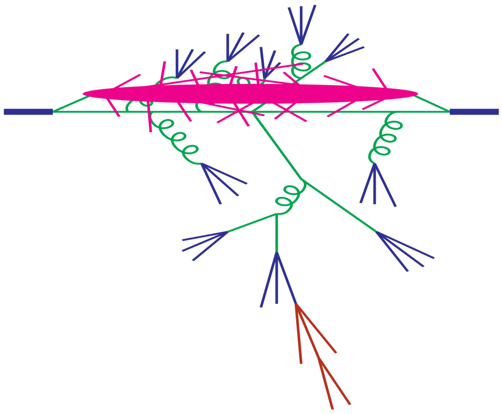

Figure 1.1: Structure of a pp collision and different steps of the MC simulation used by the event generators, such as the parton shower (in green), the UE (in pink), the hadronization (in blue) and the decay of unstable particles (in red) [101].

Hard scattering

A typical pp collision at a center of mass energy $\sqrt{s}$ is usually described by an event generator as the interaction between a parton i coming from one proton with a parton j coming from the other, leading to the production of a final state A, made out of n different particles. The total cross section of such process can be expressed with Equation 1.1 [102].

$$\sigma_A(s) = \sum_{i,j} \iint dx1\ dx2\ f_i(x_1, \mu^2)\ f_j(x_2, \mu^2)\ \hat{\sigma}_{ij \to A}(\hat{s}, \mu^2) \tag{1.1}$$

In this equation, several variables have been introduced, such as:

- The artificial parameter μ^2 used as the delimitation between short and long range physics.
- The Parton Density Functions (PDFs) $f_i(x, \mu^2)$ of both partons involved in the collision, giving the probability of finding in the proton a parton of flavor i (quark or gluon) carrying a fraction x of the proton momentum.
- The integrated parton-level cross section $\hat{\sigma}_{ij \to A}$ describing the short range physics between the partons, taking into account the phase space and the matrix element obtained considering all the Feynman diagrams of a given process.
- The square invariant mass of the two partons $\hat{s} = (p_i + p_j)^2$.

Many algorithms have been developed in order to select a hard process $ij \to A$ and determine its kinematics by solving this equation using different methods. The samples used in this work have actually been produced at different orders and by different hard scattering generators, such as MADGRAPH [104] (at LO) and POWHEG [105] and MC@NLO [106] (at NLO).

Parton showers

The parton shower phase is then used to describe what happens to the incoming and outgoing partons after the initial collision that has just been described. The hard process induce by definition a large acceleration to the partons involved, which then tend to emit Quantum ChromoDynamics (QCD) radiation under the forms of gluons, just like accelerated electric charges do by emitting photons. However, the gluons emitted do have a color charge and can therefore emit further radiation until reaching such a low energy that they are able to form colourless hadrons, as discussed in Section **??**. This process typically leads to the creation of the so-called **parton showers**, approximate higher-order real-emission corrections to the hard scattering, that need to be simulated by the event generators as well since they are an important part of the kinematics of the collision.

The parton showering then consists in simulating these showers for not only the final state particles produced by the hard scattering, but also for the particles in the initial state and for the remnants of the colliding protons, since gluons can actually be emitted by Initial State Radiation (ISR) and by these remnants themselves.

Underlying Event (UE)

Once the hard scattering and all the possible gluon emissions simulated, the next step consists in considering the so-called **Underlying Event (UE)** arising from the parton showers just described and from the secondary collisions between partons not involved in the primary hard process, the so-called Multiple Parton Interactions (MPIs). The UE is usually responsible for the production of particles at low transverse momenta p_T that cannot be experimentally distinguished from particles produced from initial or final state radiation but still need to be simulated.

These secondary collisions typically lead to the production of extra hadrons and therefore need to be simulated as well by events generators, usually by distributing the partons of the incoming protons in an area of 1fm^2: an increased UE will be obtained when the so-called impact parameter, the distance between the parton and the centre of this area, is decreased, making the collision mostly central and almost head-on [107]. The UE is typically well simulated using softwares such as Herwig [108] and PYTHIA [109]. The spectrum for the generation of some variables in a top enriched sample can be found in Figure 1.2.

Hadronization

Once all the primary and secondary collisions simulated, it is time for the event generators to simulate the **hadronization** and binding processes of the different coloured partons emitted into colourless hadrons, as explained in Section **??**. This hadronization process happen at low energies, when the perturbation theory becomes invalid and the dynamics enter a non-perturbative phase,

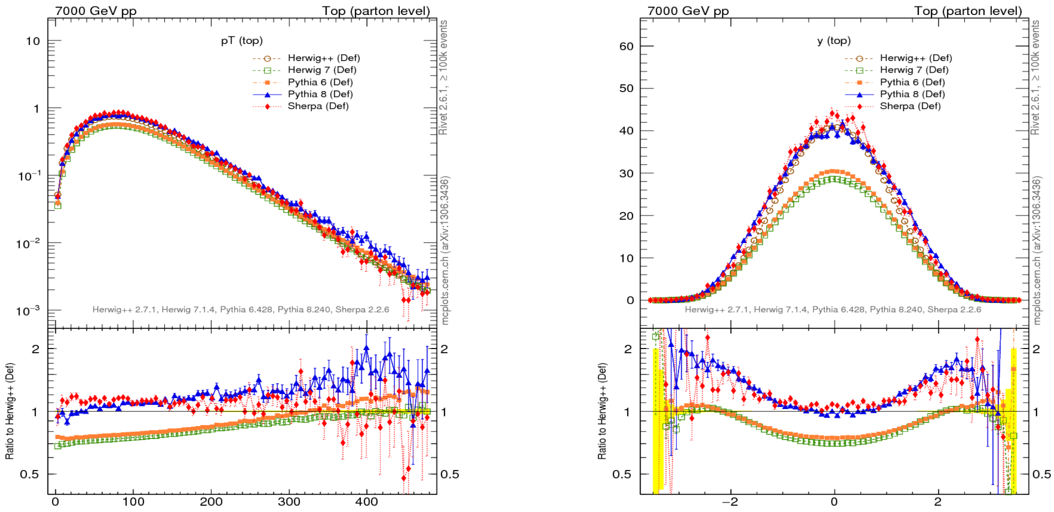

Figure 1.2: Top p_T (on the left) and rapidity (on the right) distributions obtained using different MC generators [110].

which leads to the formation of the observed final-state hadrons. Non-perturbative calculations then have to be used by the event generators in order to simulate this effect.

Unstable particle decays

The last step of the MC generation consists in finding a model allowing the unstable hadrons created in the hadronization process to decay, and to study these decays. This is extremely important because experimental data clearly shows that a large fraction of the observed final state particles come from the decays of such excited hadronic states.

Detector simulation

Once the event completely simulated using the event generators and the Pile Up (PU) taken into account by reproducing the hard scattering process several times, another step is required: simulating the interaction between the "perfect" particles previously created and the "imperfect" Compact Muon Solenoid (CMS) detector.

This is typically done by the GEANT4 software [111], able to model different effects, such as:

- Modeling of the interaction region
- Modeling of the particle passage through the volumes that compose CMS detector and of the accompanying physics processes
- Modeling of the effect of multiple interactions per beam crossing and/or the effect of events overlay (PU simulation)
- Modeling of the detector's electronics response

This modeling accounts for all the cracks and for the disposition of the subsystems inside of the CMS detector. This software is for example able to model the interaction of the electrons with the tracker, responsible for the emission of bremsstrahlung photons, as explained in Section ??.

The results of the comparison between the output of two different versions of the GEANT4 software and prototypes of the CMS calorimeter in the test beam facility at European Council for Nuclear Research (CERN) lead to comparable results, as shown in Figure 1.3.

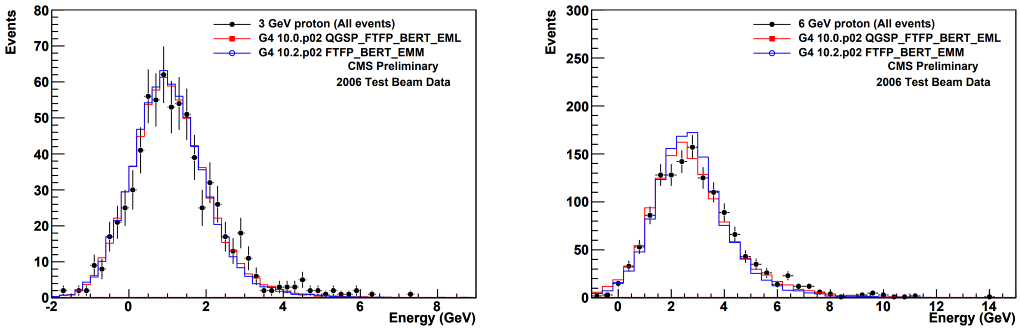

Figure 1.3: Proton energy distribution at 3 (on the left) and 6 (on the right) GeV compared for the test beam data (in black) and two different GEANT4 versions [112].

However, the modeling of the detector is not perfect and not all the inefficiencies can be accounted for. In some cases, Scale Factors (SF) are then used to correct the MC simulations and correct some expected discrepancies between data and MC. This will be detailed later on.

1.2 Files format

Once recorded (or simulated), the data (or MC) still needs to go under a complete post-processing in order to change its format and reduce the total size of the samples to be considered in the analyses. Different types of analysis are expected to need different levels of data reduction, so the data is usually accessible at different levels [113]:

- Virgin-RAW: used only in low rate runs with heavy ions collisions (10-15Mb/event)
- RAW : standard raw data event content (1Mb/event)
- RECO: detailed information on reconstructed physics objects (3Mb/event)
- Analysis Object Data (AOD): physics objects used in analysis (400-500kB/event)

Two additional formats were introduced since the end of the Run I. First of all the MiniAOD was introduced to reduce the size of the AOD by a factor 10 while retaining most of the information about all the particles that were created, without applying any further selection.

Because of the increased integrated luminosity collected by CMS over the last few years, a brand new file format featuring another reduction of the file size of a factor ~ 50 was recently introduced:

the nanoAOD, able to retain most of the information of each collision in around 1kB of data per event only. This reduction in size was achieved by optimizing the floating point of the variables, by not storing quantities that can be recomputed from the available information and by limiting the number of physics objects available, for example. This means that some low-level analyses cannot use this format to work, but it has been estimated that around 50-70% of the analyses performed at CMS can rely on such files in order to work.

In this particular case, the 6th version of the nanoAOD, introducing a series of bug fixes and the latest jet energy corrections, was used for both the data and the MC samples (signal and backgrounds) that will now be listed in the next sections.

1.3 Analysis code

The code used for the event generation, simulation and reconstruction is the version 10_2_X of the official software of the CMS collaboration, called CMSSW [115]. This software contains the CMS Event Data Model (EDM) which is able to describe every event as a C++ object containing all the RAW and reconstructed information related to the collision. These object are stored using the ROOT file format [116], an analysis package writen in C++.

Once all the different samples produced centrally up to the nanoAOD stage, another framework was put in place in order to do a post-processing of such samples, by selecting objects interesting for different dileptonic analyses, reducing therefore even more the size of the samples to be considered by selecting only events having 2 tight leptons. This selection will be detailed in Chapter 2. This *Latino* framework, written in phyton, is common to several different analyses and has been developed by tens of different people over the past few years, providing several tools to produce samples, read the files, apply different corrections to the MC samples and produce the histograms needed to perform a search such as this one.

1.4 Data samples

As already explained in Section **??**, the data analyzed in this work has been taken at a center of mass energy of 13 TeV during the second part of the Run II of operation of the LHC.

During this period, an integrated luminosity of 35.9 ± 0.9 fb^{-1} (2016) [117], 41.5 ± 1.0 fb^{-1} (2017) [118] and 59.7 ± 1.5 fb^{-1} (2018) [119] has been collected, resulting in a total dataset of 137.1 ± 2.0 fb^{-1} recorded by the CMS detector and ready to be analyzed. This data has been obtained by combining a set of single and double lepton triggers that will be described in Section 2.1.1 by taking care of avoiding any eventual double counting due to events present in different triggers. All the data samples considered for this analysis are listed in Section A.1.

1.5 Signal samples

To be completed once the files are actually available Listed in Section A.2.

1.6 Backgrounds prediction

Several different SM background processes have been considered for this analysis, all listed in Section A.3 and mostly estimated directly from MC. In this section, the main backgrounds to consider for this particular analysis will be quoted, such as:

- The major background for the $t\bar{t}$+DM analysis is the SM $t\bar{t}$, kinematically close to the signal searched for (Section 1.6.1).
- On the other hand, the major background for the $t/\bar{t}$ analysis is the single top production, which has an even higher cross section than the $t\bar{t}$ (Section 1.6.1).
- Then, mainly because of its huge cross section shown in Figure 1.4, the Drell-Yan (DY) process is usually quite important, even in the signal regions (Section 1.6.2).
- The non-prompt background, or fakes, is another important piece of this analysis mainly because of the particular data-driven method used to compute them (Section 1.6.3).
- Fianlly, the $t\bar{t}+V$ ($t\bar{t}+Z$ and $t\bar{t}+W$) may have a kinematics even closer to our signal than the $t\bar{t}$ process and is therefore extremely important in our signal regions, even though its low cross section does limit its impact (Section 1.6.4).

Add percentage of each background once known

Finally, some smaller backgrounds will be introduced in Section 1.6.5 and the weights and corrections aplied to all these MC samples will be detailed in Section 1.6.6.

TALK ABOUT SINGLE TOP?

1.6.1 Top production

Dominant in both searches

The main background: $t\bar{t}$

This background is the most relevant for this analysis because of its large cross section (as seen in Appendix A, it is actually between ~ 4 and ~ 250.000 times larger than the expected cross section of our signal, depending on the mass point considered!) and kinematics quite close to the expected one for our signal when consider the possible decay of the top quarks into two leptons.

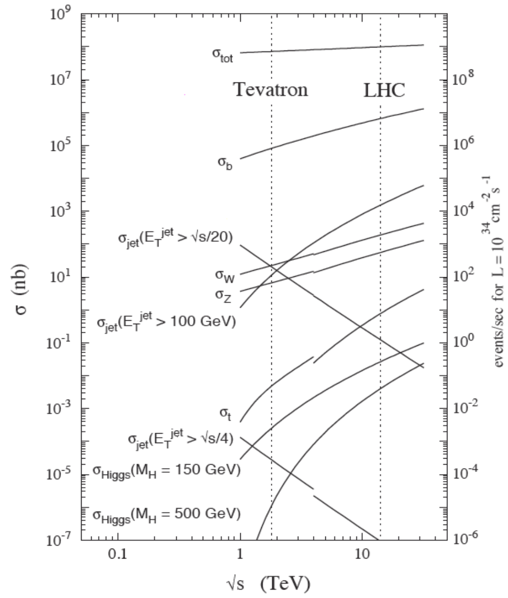

Figure 1.4: Production cross section of the most common SM processes considering different center of mass energies, such as the 13 TeV of the LHC.

Different Feynman diagrams contribute to this process at Leading Order (LO), as shown in Figure 1.5.

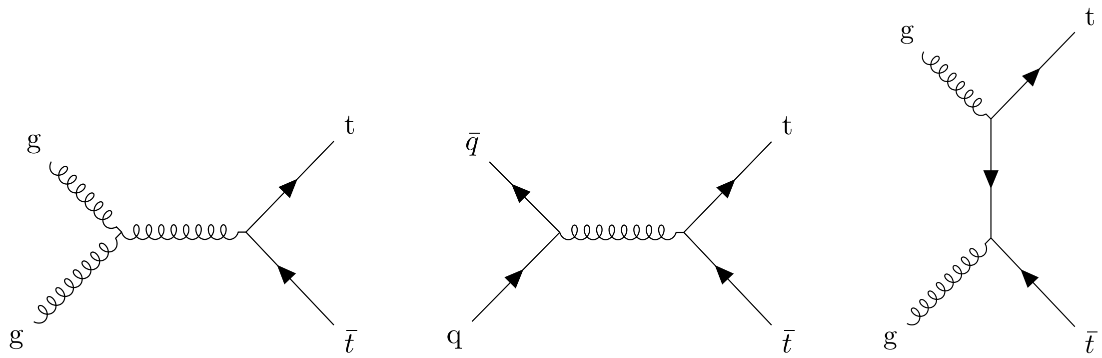

Figure 1.5: Main feynman diagrams for the production of the SM $t\bar{t}$ process.

This background is so similar to the signal searched for that some Machine Learning (ML) techniques had to be developed in order to find some discrimination between the two processes.

Single top

s-channel in Figure 1.6 other in Figure 1.7

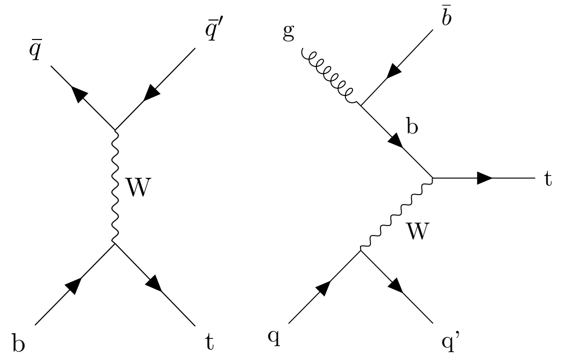

Figure 1.6: Feynman diagrams for s-channel production mode of a single top quarks.

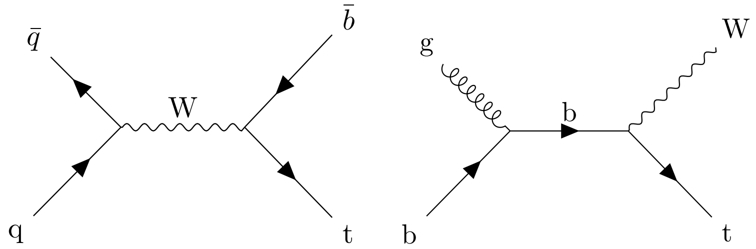

Figure 1.7: Feynman diagrams for t-channel (on the left) and tW (on the right) production modes of a single top quarks.

Top decay

1.6.2 Drell-Yan estimation

Figure 1.9.

1.6.3 Non prompt contamination

qcd? w+jets and z+jets in Figure 1.10

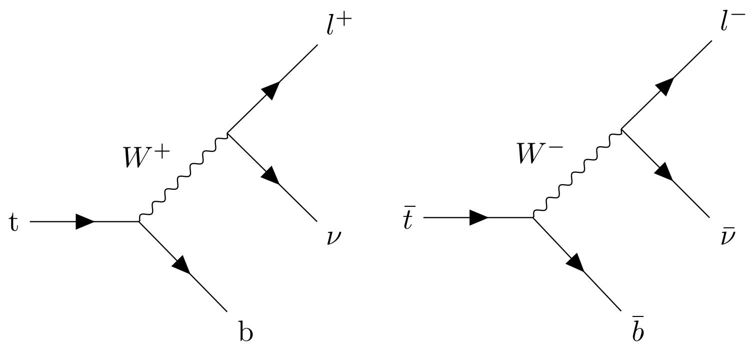

Figure 1.8: Feynman diagrams for the leptonic decay of the top (on the left) and antitop (on the right) quarks.

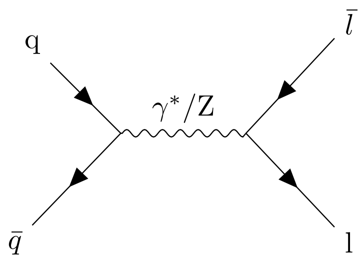

Figure 1.9: Feynman diagram for the DY process involving a virtual γ^* or Z boson.

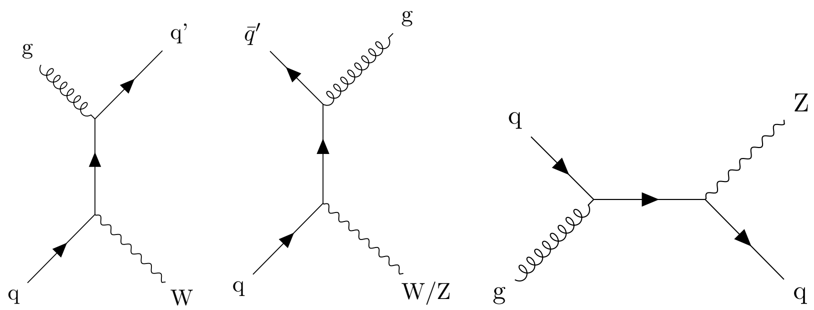

Figure 1.10: Possible Feynman diagrams for the production of a W/Z boson in association with a jet.

1.6.4 $t\bar{t} + V$

Figure 1.11

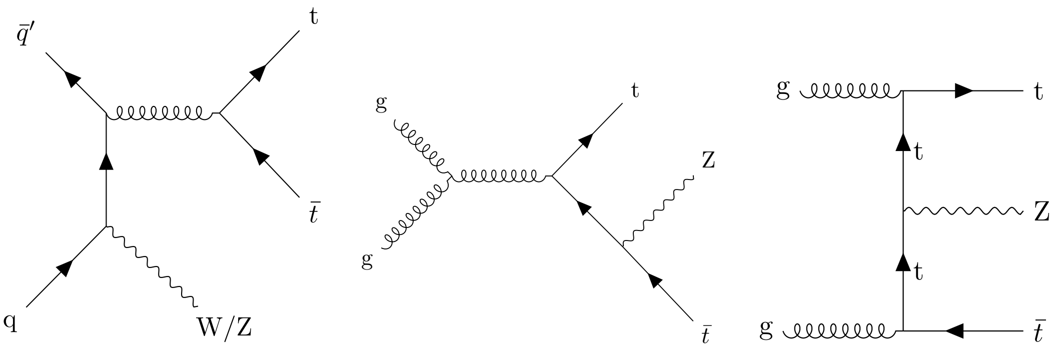

Figure 1.11: Possible Feynman diagrams for the Initial State Radiation (ISR) $t\bar{t}$ with a W/Z boson (on the left) and for the production of an Final State Radiation (FSR) ttZ (on the center and right).

1.6.5 Smaller backgrounds

Diboson contamination Figure 1.12.

1.6.6 Weights and corrections applied

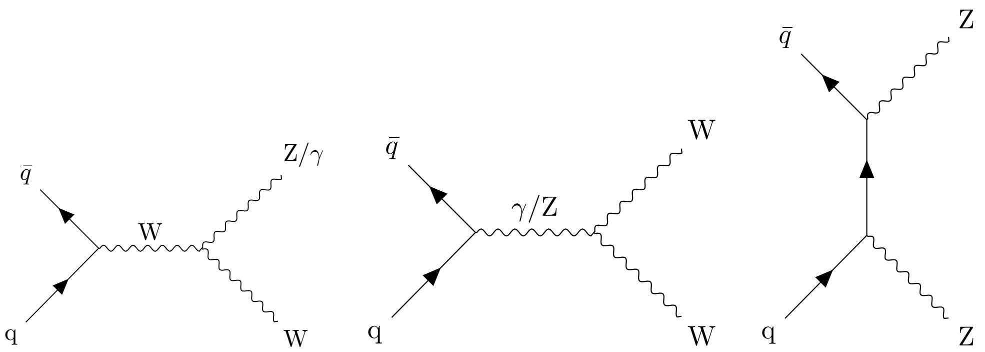

Figure 1.12: Possible Feynman diagrams for smaller backgrounds of this analysis: WW (on the left), Wγ and WZ (on the center) and ZZ (on the right).

Chapter 2

Event selection

2.1 Objects selection

2.1.1 Triggers selection

2.1.2 Electron selection

2.1.3 Muon WP

2.1.4 Jet WP

2.2 Signal regions

It is important to note that a strict **blinding policy** has been followed for this search, in order to avoid optimizing the analysis based on what has already seen. The data available to be ploted in the following signal regions has therefore been limited to 1 fb^{-1} for each year.

2.3 Control regions

2.4 Background-signal discrimination

2.4.1 Discriminating variables

Missing Transverse Energy (MET)

This variable has already been defined in Section **??**, and corresponds to the imbalance in transverse momentum which can be left by different phenomena, such as the apparition of a SM neutrino or the existence of DM particles, able to escape the detector without being detected.

This variable is expected to induce some discrimination between the signal and the backgrounds because, even tough the $t\bar{t}$ in the dilepton final state is expected to produce two neutrinos and therefore some MET, the $t\bar{t}$+DM signal model is expected to have mostly the same contribution to the MET from its own two neutrinos, and an additional contributions from the pair $\chi\bar{\chi}$ produced. The MET spectrum is therefore expected to reach higher values for the signal than the backgrounds.

TALK ABOUT SINGLE TOP?

Stransverse mass

The m_{T2} variable, also called **stransverse mass**, is an extension of the definition of the transverse mass m_T to cases when pairs of particles with the same flavor decay into one visible and one invisible particle, such as what happens in the $W \to l\nu$ decay, for example.

In this particular case, two particles contribute to the presence of Missing Transverse Energy (MET) and the individual contribution of each particle ($\not{\boldsymbol{p}}_{\boldsymbol{T_1}}$ and $\not{\boldsymbol{p}}_{\boldsymbol{T_2}}$) to this missing energy cannot be inferred. The stransverse mass is then defined according to Equation 2.1, where $\boldsymbol{p_{T_i}} = \overrightarrow{p_{T_i}}$ is the (visible) transverse momentum of the particle i and α is the angle between the visible and invisible p_T of the decay considered [114].

$$\begin{cases} M_{T2}^2 = \min\limits_{\not{\boldsymbol{p}}_{\boldsymbol{T_1}} + \not{\boldsymbol{p}}_{\boldsymbol{T_2}} = \not{\boldsymbol{p}}_{\boldsymbol{T}_{\text{tot}}}} \left(\max \left(m_T^2(\boldsymbol{p_{T_1}}, \not{\boldsymbol{p}}_{\boldsymbol{T_1}}), m_T^2(\boldsymbol{p_{T_2}}, \not{\boldsymbol{p}}_{\boldsymbol{T_2}}) \right) \right) \\ m_T^2(\boldsymbol{p_T}, \not{\boldsymbol{p}}_{\boldsymbol{T}}) = 4\, |\boldsymbol{p_T}||\not{\boldsymbol{p}}_{\boldsymbol{T}}|\, \sin^2\left(\frac{\alpha}{2}\right) \end{cases} \tag{2.1}$$

This equation can be understood in the following way: to compute the m_{T2} variable, different combinations ($\not{\boldsymbol{p}}_{\boldsymbol{T_1}}$, $\not{\boldsymbol{p}}_{\boldsymbol{T_2}}$) satisfying the condition $\not{\boldsymbol{p}}_{\boldsymbol{T_1}} + \not{\boldsymbol{p}}_{\boldsymbol{T_2}} = \not{\boldsymbol{p}}_{\boldsymbol{T}_{\text{tot}}}$ need to be probed, keeping only the combination which results in the lowest value.

In this particular analysis, $M_{T2}(ll)$ is calculated, since the role of the visible particles is played by the two final state leptons. This variable is expected to introduce some discrimination because, according to the definition just given, the $M_{T2}(ll)$ variable for a SM $t\bar{t}$ process is expected to have an endpoint exactly at the mass of the W boson, while an eventual $t\bar{t}$+DM signal does not have this limitation in the $M_{T2}(ll)$ spectrum because of the pair of DM particles produced, which also contributes to the total MET of the event.

However, in practice, we do observe a tail in this spectrum even for SM $t\bar{t}$ without DM, because of the instrumental MET sometimes observed or the fact that some selected leptons are not actually prompt leptons but can be jets misidentified as leptons by the detector.

TALK ABOUT SINGLE TOP?

2.4.2 Neural network

Chapter 3

Results and interpretations

3.1 Systematics and uncertainties

3.2 Results

Chapter 4

Conclusions

4.1 Future prospects

Appendices

Appendix A

Samples used

A.1 Data samples

All the data samples considered for this analysis are listed in Tables A.1, A.2 and A.3. The luminosity of each dataset has been computed using the Brilcalc tool provided by CMS [120], while the number of generated events has been obtained using the CERN official Data Aggregation System (DAS).

A.2 Signal samples

To be completed once the files are actually available

A.3 Backgrounds samples

To be completed once the analysis actually performed LO/NLO Generator used

Dataset	Events (size)	$\mathcal{L}$ [fb^{-1}]
Run 2016B		
/DoubleEG/Run2016B_ver2-Nano1June2019_ver2-v1/NANOAOD	143073268 (99.4Gb)	
/DoubleMuon/Run2016B_ver2-Nano1June2019_ver2-v1/NANOAOD	82535526 (53.2Gb)	
/MuonEG/Run2016B_ver2-Nano1June2019_ver2-v1/NANOAOD	32727796 (26.8Gb)	5.8
/SingleElectron/Run2016B_ver2-Nano1June2019_ver2-v1/NANOAOD	246440440 (167.8Gb)	
/SingleMuon/Run2016B_ver2-Nano1June2019_ver2-v1/NANOAOD	158145722 (96.4Gb)	
Run 2016C		
/DoubleEG/Run2016C-Nano1June2019-v1/NANOAOD	47677856 (35.3Gb)	
/DoubleMuon/Run2016C-Nano1June2019-v1/NANOAOD	27934629 (19.7Gb)	
/MuonEG/Run2016C-Nano1June2019-v1/NANOAOD	15405678 (12.8Gb)	2.6
/SingleElectron/Run2016C-Nano1June2019-v1/NANOAOD	97259854 (69.3Gb)	
/SingleMuon/Run2016C-Nano1June2019-v1/NANOAOD	67441308 (42.4Gb)	
Run 2016D		
/DoubleEG/Run2016D-Nano1June2019-v1/NANOAOD	53324960 (39.6Gb)	
/DoubleMuon/Run2016D-Nano1June2019-v1/NANOAOD	33861745 (24.1Gb)	
/MuonEG/Run2016D-Nano1June2019-v1/NANOAOD	23482352 (19.4Gb)	4.2
/SingleElectron/Run2016D-Nano1June2019-v1/NANOAOD	148167727 (104.4Gb)	
/SingleMuon/Run2016D-Nano1June2019-v1/NANOAOD	98017996 (61.3Gb)	
Run 2016E		
/DoubleEG/Run2016E-Nano1June2019-v1/NANOAOD	49877710 (37.9Gb)	
/DoubleMuon/Run2016E-Nano1June2019-v1/NANOAOD	28246946 (20.8Gb)	
/MuonEG/Run2016E-Nano1June2019-v2/NANOAOD	22519303 (19.0Gb)	4.0
/SingleElectron/Run2016E-Nano1June2019-v1/NANOAOD	117321545 (86.5Gb)	
/SingleMuon/Run2016E-Nano1June2019-v1/NANOAOD	90984718 (58.7Gb)	
Run 2016F		
/DoubleEG/Run2016F-Nano1June2019-v1/NANOAOD	34577629 (26.9Gb)	
/DoubleMuon/Run2016F-Nano1June2019-v1/NANOAOD	20329921 (15.3Gb)	
/MuonEG/Run2016F-Nano1June2019-v1/NANOAOD	16002165 (13.6Gb)	3.1
/SingleElectron/Run2016F-Nano1June2019-v1/NANOAOD	70593532 (51.4Gb)	
/SingleMuon/Run2016F-Nano1June2019-v1/NANOAOD	65489554 (42.4Gb)	
Run 2016G		
/DoubleEG/Run2016G-Nano1June2019-v1/NANOAOD	78797031 (61.6Gb)	
/DoubleMuon/Run2016G-Nano1June2019-v1/NANOAOD	45235604 (34.2Gb)	
/MuonEG/Run2016G-Nano1June2019-v1/NANOAOD	33854612 (29.0Gb)	7.6
/SingleElectron/Run2016G-Nano1June2019-v1/NANOAOD	153363109 (109.2Gb)	
/SingleMuon/Run2016G-Nano1June2019-v1/NANOAOD	149912248 (94.6Gb)	
Run 2016H		
/DoubleEG/Run2016H-Nano1June2019-v1/NANOAOD	85388734 (67.7Gb)	
/DoubleMuon/Run2016H-Nano1June2019-v1/NANOAOD	48912812 (37.3Gb)	
/MuonEG/Run2016H-Nano1June2019-v1/NANOAOD	29236516 (26.0Gb)	8.6
/SingleElectron/Run2016H-Nano1June2019-v1/NANOAOD	128854598 (93.8Gb)	
/SingleMuon/Run2016H-Nano1June2019-v1/NANOAOD	174035164 (110.2Gb)	

Table A.1: Datasets collected in 2016 and considered for this analysis.

Dataset	Events (size)	$\mathcal{L}$ [fb^{-1}]
Run 2017B		
/DoubleEG/Run2017B-Nano1June2019-v1/NANOAOD	58088760 (46.6Gb)	
/DoubleMuon/Run2017B-Nano1June2019-v1/NANOAOD	14501767 (10.8Gb)	
/SingleElectron/Run2017B-Nano1June2019-v1/NANOAOD	60537490 (42.2Gb)	4.8
/SingleMuon/Run2017B-Nano1June2019-v1/NANOAOD	136300266 (86.2Gb)	
/MuonEG/Run2017B-Nano1June2019-v1/NANOAOD	4453465 (4.1Gb)	
Run 2017C		
/DoubleEG/Run2017C-Nano1June2019-v1/NANOAOD	65181125 (53.8Gb)	
/DoubleMuon/Run2017C-Nano1June2019-v1/NANOAOD	49636525 (39.5Gb)	
/SingleElectron/Run2017C-Nano1June2019-v1/NANOAOD	136637888 (102.5Gb)	9.7
/SingleMuon/Run2017C-Nano1June2019-v1/NANOAOD	165652756 (109.5Gb)	
/MuonEG/Run2017C-Nano1June2019-v1/NANOAOD	15595214 (15.0Gb)	
Run 2017D		
/DoubleEG/Run2017D-Nano1June2019-v1/NANOAOD	25911432 (21.6Gb)	
/DoubleMuon/Run2017D-Nano1June2019-v1/NANOAOD	23075733 (18.6Gb)	
/SingleElectron/Run2017D-Nano1June2019-v1/NANOAOD	51526710 (38.5Gb)	4.2
/SingleMuon/Run2017D-Nano1June2019-v1/NANOAOD	70361660 (47.2Gb)	
/MuonEG/Run2017D-Nano1June2019-v1/NANOAOD	9164365 (8.9Gb)	
Run 2017E		
/DoubleEG/Run2017E-Nano1June2019-v1/NANOAOD	56233597 (49.8Gb)	
/DoubleMuon/Run2017E-Nano1June2019-v1/NANOAOD	51589091 (44.4Gb)	
/SingleElectron/Run2017E-Nano1June2019-v1/NANOAOD	102121689 (81.3Gb)	9.3
/SingleMuon/Run2017E-Nano1June2019-v1/NANOAOD	154630534 (111.0Gb)	
/MuonEG/Run2017E-Nano1June2019-v1/NANOAOD	19043421 (19.2Gb)	
Run 2017F		
/DoubleEG/Run2017F-Nano1June2019-v1/NANOAOD	74307066 (67.1Gb)	
/DoubleMuon/Run2017F-Nano1June2019-v1/NANOAOD	79756560 (68.0Gb)	
/SingleElectron/Run2017F-Nano1June2019-v1/NANOAOD	128467223 (105.2Gb)	13.5
/SingleMuon/Run2017F-Nano1June2019-v1/NANOAOD	242135500 (178.3Gb)	
/MuonEG/Run2017F-Nano1June2019-v1/NANOAOD	25776363 (26.3Gb)	

Table A.2: Datasets collected in 2017 and considered for this analysis.

Dataset	Events (size)	$\mathcal{L}$ [fb^{-1}]
Run 2018A		
/DoubleMuon/Run2018A-Nano25Oct2019-v1/NANOAOD	75499908 (62.6Gb)	13.5
/EGamma/Run2018A-Nano25Oct2019-v1/NANOAOD	327843843 (261.8Gb)	
/SingleMuon/Run2018A-Nano25Oct2019-v1/NANOAOD	241608232 (167.7Gb)	
/MuonEG/Run2018A-Nano25Oct2019-v1/NANOAOD	32958503 (32.3Gb)	
Run 2018B		
/DoubleMuon/Run2018B-Nano25Oct2019-v1/NANOAOD	35057758 (28.3Gb)	6.8
/EGamma/Run2018B-Nano25Oct2019-v1/NANOAOD	153822427 (123.1Gb)	
/SingleMuon/Run2018B-Nano25Oct2019-v1/NANOAOD	119918017 (82.3Gb)	
/MuonEG/Run2018B-Nano25Oct2019-v1/NANOAOD	16211567 (15.8Gb)	
Run 2018C		
/DoubleMuon/Run2018C-Nano25Oct2019-v1/NANOAOD	34565869 (27.6Gb)	6.6
/EGamma/Run2018C-Nano25Oct2019-v1/NANOAOD	147827904 (119.2Gb)	
/SingleMuon/Run2018C-Nano25Oct2019-v1/NANOAOD	110032072 (75.7Gb)	
/MuonEG/Run2018C-Nano25Oct2019-v1/NANOAOD	15652198 (15.3Gb)	
Run 2018D		
/DoubleMuon/Run2018D-Nano25Oct2019_ver2-v1/NANOAOD	168605834 (128.6Gb)	32.0
/EGamma/Run2018D-Nano25Oct2019-v1/NANOAOD	751348648 (583.6Gb)	
/SingleMuon/Run2018D-Nano25Oct2019-v1/NANOAOD	513867253 (344.5Gb)	
/MuonEG/Run2018D-Nano25Oct2019_ver2-v1/NANOAOD	71961587 (68.6Gb)	

Table A.3: Datasets collected in 2018 and considered for this analysis.

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