



FACULTAD DE CIENCIAS
UNIVERSIDAD DE CANTABRIA

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

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**Búsqueda de materia oscura en
asociación con quarks top en el estado
final dileptónico a $\sqrt{s} = 13$ TeV**

Memoria para optar al

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Escrita por

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Abstract

Resumen

Acknowledgments

Acronyms used

SM Standard Model	LAT Fermi Large Telescope
DM Dark Matter	IACT Imaging Atmospheric Cherenkov Telescopes
LHC Large Hadron Collider	CTA Cherenkov Telescope Array
CMS Compact Muon Solenoid	AMS Alpha Magnetic Spectrometer
ATLAS A Toroidal LHC ApparatuS	EFT Effective Field Theory
CERN European Council for Nuclear Research	ISR Initial State Radiation
QFT Quantum Field Theory	FSR Final State Radiation
CMB Cosmic Microwave Background	DMWG Dark Matter Working Group
ML Machine Learning	MET Missing Transverse Energy
MFV Minimal Flavour Violation	VBF Vector Boson Fusion
WIMP Weakly Interactive Massive Particle	BR Branching Ratio
PF Particle Flow	LEP Large Electron Positron collider
BSM Beyond the Standard Model	ALICE A Large Ion Collider Experiment
MACHO Massive Compact Halo Object	PS Proton Synchrotron
MSSM Minimal Supersymmetric Standard Model	SPS Super Proton Synchrotron
SI Spin Independent	PU Pile Up
SD Spin Dependent	PV Primary Vertex
CL Confidence Level	ECAL Electromagnetic Calorimeter
QCD Quantum ChromoDynamics	HCAL Hadronic Calorimeter
ADMX Axion Dark Matter Experiment	DT Drift tube
CAST CERN Axion Solar Telescope	CSC Cathode Strip Chamber
IAOX International Axion Observatory	RPC Resistive Plate Chamber
LNGS Laboratori Nazionali del Gran Sasso	TIB/TBD Tracker Inner Barrel and Disks
UED Universal Extra Dimensions	TOB Tracker Outer Barrel
NFW Navarro-Frenk-White	TEC Tracker EndCap
	HO Hadron Outer
	LS Long Shutdown

GEM Gas Electron Multiplier	UE Underlying Event
L1 Level-1 Trigger	PDF Parton Density Function
HLT High-Level Trigger	LO Leading Order
DAQ Data Acquisition System	NLO Next to Leading Order
DQM Data Quality Monitoring	MPI Multiple Parton Interaction
DCS Detector Control System	SF Scale Factors
WP Working Point	AOD Analysis Object Data
SC Super Cluster	EDM Event Data Model
KF Kalman Filter	DY Drell-Yan
GSF Gaussian Sum Filter	SR Signal Region
MVA Multi-Variate Analysis	CR Control Region
CSV Combined Secondary Vertex	PR Prompt Rate
DNN Deep Neural Network	FR Fake Rate
PUPPI Pileup Per Particle Identification	SS Same Sign
BW Breit-Wigner	EWK Electroweak
MC Monte Carlo	DAS Data Aggregation System

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Chapter 1

Event selection

This Chapter will be dedicated to the analysis itself, by defining first of all the different objects actually used in this case, along with the actual selection that has been applied to enhance the quality of such objects in this particular search in Section 2.1. Then, the different Signal Regions (SRs) defined in which a high purity of signal is expected are defined in Section 2.2 while all the different Control Regions (CRs) defined in order to check the behavior of the MC simulation performed for the major backgrounds on this analysis, such as the single top or Standard Model (SM) $t\bar{t}$ production, will be introduced in Section 2.3.

Finally will come a description about the different variables expected to naturally introduce some discrimination of the t/\bar{t} and $t\bar{t}$ +DM signals with respect to the different backgrounds in Section 2.4, along with a global description of the Machine Learning (ML) techniques employed in order to optimize the discriminating power of these variables in the best way possible.

1.1 Objects selection

We already described what to expect from a typical t/\bar{t} or $t\bar{t}$ +DM signal: the typical signature of such signals is made out of a certain number of b tagged jets along with two leptons (electrons and/or muons) and some Missing Transverse Energy (MET) coming from the two Dark Matter (DM) particles created along the way. It is therefore extremely important to describe the Working Point (WP) chosen and the selection applied in order to select the objects of the analysis, such as the leptons and the jets used, in such a way to optimize the lepton reconstruction efficiency while reducing as much as possible the possible misidentification rates of such objects.

First of all, the different triggers used to collect the data will be detailed in Section 2.1.1. Then, the leptons used in this analysis will be introduced in Sections 2.1.2 (for electrons) and 2.1.3 (for muons). Finally, given the nature of the DM signal searched for, a complete description of the jets selected in the analysis will be necessary and performed in Section 2.1.4.

1.1.1 Triggers selection

The triggers, described in Section ??, and particularly the trigger paths chosen are an important part of each analysis since they will describe the kind of data that can be collected and therefore analyzed. The triggers used in this analysis for the years 2016, 2017 and 2018 can be found in Tables 2.1, 2.2 and 2.1 respectively.

Dataset	Run range	High-Level Trigger (HLT) trigger path
SingleMu	[273158,284044]	HLT_IsoMu24_v* HLT_IsoTkMu24_v*
SingleEle	[273158,284044]	HLT_Ele27_WPTight_Gsf_v* HLT_Ele25_eta2p1_WPTight_Gsf_v*
DoubleEG	[273158,284044]	HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v*
DoubleMu	[273158,281612]	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_v* HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_v*
	[281613,284044]	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_v* HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_DZ_v*
MuonEG	[273158,278272]	HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL
	[278273,284044]	HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ_v* HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v*

Table 1.1: 2016 trigger paths considered for this analysis.

Dataset	Run range	HLT trigger path
SingleMu	[297046,306462]	HLT_IsoMu27_v*
EGamma	[297046,306462]	HLT_Ele35_WPTight_Gsf_v* HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_v*
DoubleMu	[297046,299329]	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_v*
	[299368,306462]	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass8_v*
MuonEG	[297046,306462]	HLT_Mu12_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ_v*
	[297046,299329]	HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v*
	[299368,306462]	HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_v*

Table 1.2: 2017 trigger paths considered for this analysis.

Dataset	Run range	HLT trigger path
SingleMu	[315252,325172]	HLT_IsoMu24_v*
	[314859,325175]	HLT_Mu5_v*
EGamma	[315252,325172]	HLT_IsoMu27_v*
		HLT_Ele32_WPTight_Gsf_v*
		HLT_Ele35_WPTight_Gsf_v*
DoubleMu	[315252,325172]	HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_v*
		HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass3p8_v*
MuonEG	[315252,325172]	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass8_v*
		HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_v*
MuonEG	[315252,325172]	HLT_Mu12_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ_v*
		HLT_Mu12_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ_v*

Table 1.3: 2018 trigger paths considered for this analysis.

Our analysis relying on the dilepton final state, the single lepton trigger are only considered in order to recover some of the efficiency lost in some cases when one lepton passes the tight identification criteria while the second one does not, and does therefore not trigger the event. The logical *or* of all the trigger paths are usually considered. Eventual events passing several triggers is taken into account as well to make sure to avoid any double counting due to this effect.

These triggers have been studied in order to make sure that they are efficient enough in the p_T region of the leptons of the analysis to avoid any undesired effect due to the turn-on of any trigger. These trigger efficiencies, calculated using a general tag and probe method and found for example for different runs of the 2017 data taking period in Figure 2.1 for a DoubleEG trigger, are then used to reweight the simulated samples.

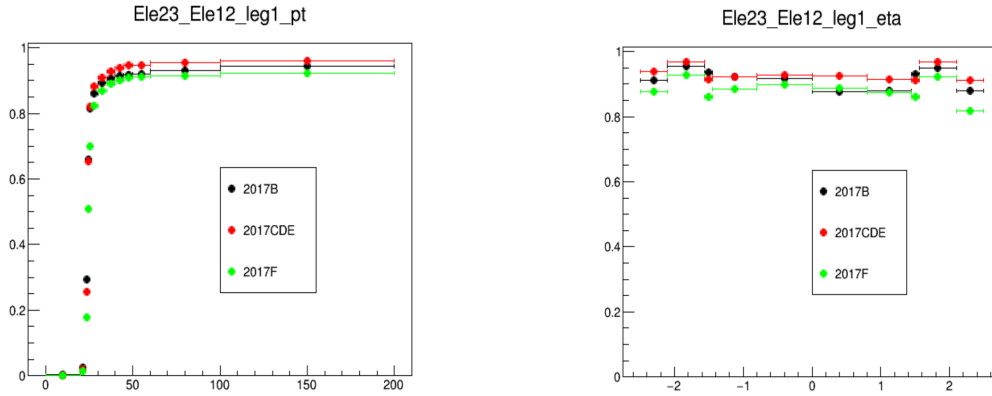


Figure 1.1: DoubleEG trigger efficiencies with respect to the p_T (on the left) and η (on the right), computed using a tag and probe method, for the 2017 data taking period.

1.1.2 Electrons selection

1.1.3 Muons selection

1.1.4 Jet selection

1.2 Signals 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 plotted in the following signal regions has therefore been limited to 1 fb^{-1} for each year.

1.3 Control regions

1.3.1 Same Sign (SS) CR

1.4 Background-signal discrimination

1.4.1 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 though 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 contribution 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 $W \rightarrow l\nu$ 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 ($\not{\mathbf{p}}_{T_1}$ and $\not{\mathbf{p}}_{T_2}$) to this missing energy cannot be inferred. The stransverse mass is then defined according to Equation 2.1, where $\mathbf{p}_{T_i} = \vec{p}_{T_i}$ 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].

$$\begin{cases} M_{T_2}^2 = \min_{\not{\mathbf{p}}_{T_1} + \not{\mathbf{p}}_{T_2} = \not{\mathbf{p}}_{T_{\text{tot}}}} \left(\max \left(m_T^2(\mathbf{p}_{T_1}, \not{\mathbf{p}}_{T_1}), m_T^2(\mathbf{p}_{T_2}, \not{\mathbf{p}}_{T_2}) \right) \right) \\ m_T^2(\mathbf{p}_T, \not{\mathbf{p}}_T) = 4 |\mathbf{p}_T| |\not{\mathbf{p}}_T| \sin^2 \left(\frac{\alpha}{2} \right) \end{cases} \quad (1.1)$$

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

In this particular analysis, $M_{T_2}(ll)$ 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 $M_{T_2}(ll)$ 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 $M_{T_2}(ll)$ 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?

1.4.2 Neural network

Chapter 2

Results and interpretations

2.1 Systematics and uncertainties

2.2 Results

Chapter 3

Conclusions

3.1 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 Compact Muon Solenoid (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)	5.8
/DoubleMuon/Run2016B_ver2-Nano1June2019_ver2-v1/NANOAOD	82535526 (53.2Gb)	
/MuonEG/Run2016B_ver2-Nano1June2019_ver2-v1/NANOAOD	32727796 (26.8Gb)	
/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)	2.6
/DoubleMuon/Run2016C-Nano1June2019-v1/NANOAOD	27934629 (19.7Gb)	
/MuonEG/Run2016C-Nano1June2019-v1/NANOAOD	15405678 (12.8Gb)	
/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)	4.2
/DoubleMuon/Run2016D-Nano1June2019-v1/NANOAOD	33861745 (24.1Gb)	
/MuonEG/Run2016D-Nano1June2019-v1/NANOAOD	23482352 (19.4Gb)	
/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)	4.0
/DoubleMuon/Run2016E-Nano1June2019-v1/NANOAOD	28246946 (20.8Gb)	
/MuonEG/Run2016E-Nano1June2019-v2/NANOAOD	22519303 (19.0Gb)	
/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)	3.1
/DoubleMuon/Run2016F-Nano1June2019-v1/NANOAOD	20329921 (15.3Gb)	
/MuonEG/Run2016F-Nano1June2019-v1/NANOAOD	16002165 (13.6Gb)	
/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)	7.6
/DoubleMuon/Run2016G-Nano1June2019-v1/NANOAOD	45235604 (34.2Gb)	
/MuonEG/Run2016G-Nano1June2019-v1/NANOAOD	33854612 (29.0Gb)	
/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)	8.6
/DoubleMuon/Run2016H-Nano1June2019-v1/NANOAOD	48912812 (37.3Gb)	
/MuonEG/Run2016H-Nano1June2019-v1/NANOAOD	29236516 (26.0Gb)	
/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)	4.8
/DoubleMuon/Run2017B-Nano1June2019-v1/NANOAOD	14501767 (10.8Gb)	
/SingleElectron/Run2017B-Nano1June2019-v1/NANOAOD	60537490 (42.2Gb)	
/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)	9.7
/DoubleMuon/Run2017C-Nano1June2019-v1/NANOAOD	49636525 (39.5Gb)	
/SingleElectron/Run2017C-Nano1June2019-v1/NANOAOD	136637888 (102.5Gb)	
/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)	4.2
/DoubleMuon/Run2017D-Nano1June2019-v1/NANOAOD	23075733 (18.6Gb)	
/SingleElectron/Run2017D-Nano1June2019-v1/NANOAOD	51526710 (38.5Gb)	
/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)	9.3
/DoubleMuon/Run2017E-Nano1June2019-v1/NANOAOD	51589091 (44.4Gb)	
/SingleElectron/Run2017E-Nano1June2019-v1/NANOAOD	102121689 (81.3Gb)	
/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)	13.5
/DoubleMuon/Run2017F-Nano1June2019-v1/NANOAOD	79756560 (68.0Gb)	
/SingleElectron/Run2017F-Nano1June2019-v1/NANOAOD	128467223 (105.2Gb)	
/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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