Measurement of the cross section (σ_{W^*}) of the process $\mathrm{W}^* \to \mu\nu$

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Abstract

The Standard Model (SM) of particle physics has successfully predicted many phenomena up to the $\mathcal{O}(1\ \text{TeV})$ energy scale. The high p_T region of the phase-space can offer sensitivity to physical effects that are not yet explainable, offering hints for new physics beyond the SM. This leads to an interest in the reconstruction and identification of objects with high transverse momentum ("high" in this work means $p_T > 100$ GeV), for example the tau lepton. The process $W^* \to \tau\nu$ with a virtual W-boson ($m_W > 200$ GeV) decaying to τ leptons is an optimal candidate for our signal region.
To accomplish this, three major steps need to be performed:

- Measurement of σ_{W^*} of the process $W^* \to \mu\nu$ (This has been done in this project).
- Data-driven estimation of the $j \to \tau_{fake}$ background (I added some useful tools related to this).
- Extraction of the energy scale (ES) and identification (ID) scale factors (SFs) via simultaneous fit to data in the sample $W^* \to \tau\nu$ events (This is the final goal for which this project has laid the foundations).

The first step is done since the $W^* \to \mu\nu$ signal process is affected by MC statistical fluctuations and theoretical uncertainties that can be constrained by measuring the cross section (σ_{W^*}) of the virtual W-boson production. All the work done in this project was performed inside the Tau framework (TauFW) in which I added several modules and some tools useful for the analysis in question and for future measurements. The FIT was performed using the COMBINE tool yielded a result of $\sigma_{W^*} = (7.4 \pm 0.2)$pb. In this project I also introduced some useful tools for the future measurement of tau identification efficiency and ES SFs at high p_T.

Contents

1 Introduction

The Standard Model (SM) of particle physics has successfully predicted many phenomena up to the $\mathcal{O}(1\text{ TeV})$ energy scale. The high p_T region of the phase-space can offer sensitivity to physical effect are not yet explainable, that could offer hints at new physics beyond the SM. This leads to an interest in the reconstruction and identification of objects with high transverse momentum ("high" in this work means $p_T > 100$ GeV) , for example the tau lepton. The final goal of this project is to correct the τ identification efficiency and four-momenta with identification (ID) and Energy Scale (ES) Scale Factors (SFs). In order to perform this measurement, we need to choose a process where τ candidates can be reliably reconstructed and identified. In this analysis we are interest only in τs that decay hadronically which will be labeled "τ" for simplicity. The process $W^* \rightarrow \tau\nu$ with a W-boson ($m_W > 200$ GeV) decaying to τ leptons is a good candidate for our signal region. Unfortunately the τ can be mimicked by strongly collimated jets ($j \rightarrow \tau_{fake}$) creating a background for this measurement. This means that major background that we need to account for comes from QCD events that are notoriously difficult to simulate via Monte Carlo (MC). To constrain the uncertainties that afflict this major background a data-driven estimation is implemented: the background from the anti-isolated region is scaled to the signal region using the fake factor method with a jet-jet and a $W^* \rightarrow \mu\nu + \text{jet}$ determination region. The measurement is made more complex because we also have to constrain the normalization of the $W^* \rightarrow \tau\nu$ process. This signal process is affected by MC statistical fluctuations and theoretical uncertainties that can be constrained by measuring the cross section (σ_{W^*}) of the process virtual W boson production. This can be done with $W^* \rightarrow \mu\nu$ decays on account of the lepton flavor universality principle. So to accomplish this analysis these three major steps need to be performed:

- Measurement of σ_{W^*} of the process $W^* \rightarrow \mu\nu$.
- Data-driven estimation of the $j \rightarrow \tau_{fake}$ background.
- Extraction of the ES and ID SFs via simultaneous fit of the $W^* \rightarrow \mu\nu$ signal to data and corresponding side band regions.

The aim on my project is to prepare the measurement, starting with the first step: the measurement of σ_{W^*} of the process.

2 Methodology

In order to perform the analysis the first thing needed is the NanoAODs constructed from the raw data. These are then *skimmed* in order to create *skimmed-NanoAODs* from which flat n-tuples, that are used for the analysis, are obtained. The raw data consists of simulated MC samples based on the CMS detector and real data collected by the CMS experiment. The skimming is done with the following main criteria:

- Select only those events, that might be interesting, e.g. would enter the signal region or one of the relevant sidebands.
- Store only the information from NanoAOD that is relevant, i.e. drop from the *ROOT Trees* unused branches.

The work done in this project is based on the τ analysis framework (TauFW) and builds upon 2018 NanoAOD datasets. The statistical inference is performed with CombinedLimit, CombineHarvester and analysis CMS software CMSSW10_6_13. My work was also used as validation for a new tool under development aiming at producing NanoAODs (v10) from the MiniAOD datasets.
The TauFW consists of three main packages:

- PicoProducer: Tools to process nanoAOD (currently up to v9) and make custom analysis tuples named PicoTuples.
- Plotter: Tools for further analysis, auxiliary measurements, validation and plotting.
- Fitter: Tools for measurements and fits using the Combine statistical toolkit.

Most modules in TauFW inherit from ModuleTauPair. In this analysis we do not have two objects, but a Particle Flow Candidate + MET system so I created a new ModuleHighPT class (for a brief explanation of the Particle Flow Algorithm and MET see Appendix A A.3). I added three new Modules and three TreeProducers, the former are used to preselect with some preliminar cuts the events we are interested in and compute some variables, the others store these quantities into ROOT files by actually creating the picotuples.

The Modules and the corresponding TreeProducer are:

- ModuleHighPT: the main module from which the others inherit, it stores the fuctions and the general variables that are needed by all modules.
- TreeProducerHighPT: the main treeproducer from which the others inherit, it stores the fuctions and the general variables that are needed by all treeproducers
- ModuleTauNu: module that take care of the $W^* \rightarrow \tau\nu$ process.
- TreeProducerTauNu: treeproducer that makes the ROOT file of the $W^* \rightarrow \tau\nu$ process.
- ModuleMuNu: module that take care of the $W^* \rightarrow \mu\nu$ process.
- TreeProducerMuNu: treeproducer that makes the ROOT file of the $W^* \rightarrow \mu\nu$ process.

The preselection cuts in the ModuleMuNu are done looping over μ collection with the idea of choosing the highest p_T muon:

- $p_T > 50$ GeV
- $|\eta| < 2.4$
- $|d_z| < 0.2$ cm
- $|d_{xy}| < 0.045$ cm
- the muon candidate needs to pass mediumId
- pfRelIso04_all < 0.5

- Trigger: HLT_IsoMu24 or HLT_IsoMu27.

The preliminar cuts in the ModuleTauNu are done looping over τ collection with the idea of choosing the most isolated τ:

- $p_T > 40$ GeV
- $|\eta| < 2.3$
- $|d_z| < 0.2$ cm
- decayMode in [0,1,10,11] (to learn more about decayMode see A.4.)
- idDeepTau2017v2p1VSe $>= 1$
- idDeepTau2017v2p1VSmu $>= 1$
- idDeepTau2017v2p1VSjet $>= 1$
- Trigger : HLT_PFMETNoMu120_PFMHTNoMu120_IDTight

In both Modules the MET is required to be greater than 50 GeV.
In order to take care of possible extra taus or jets in an event I added two new vetos, the extratau_veto and the extrajet_veto, with the following requirements:
Extra tau veto:

- $p_T > 100$ GeV
- $|\eta| < 2.3$
- $|d_z| < 0.1$ cm
- $|d_z| < 0.045$ cm
- DeltaR(tau) > 0.4
- idDeepTau2017v2p1VSjet $>= 1$
- idDeepTau2017v2p1VSe $>= 128$
- idDeepTau2017v2p1VSmu $>= 8$

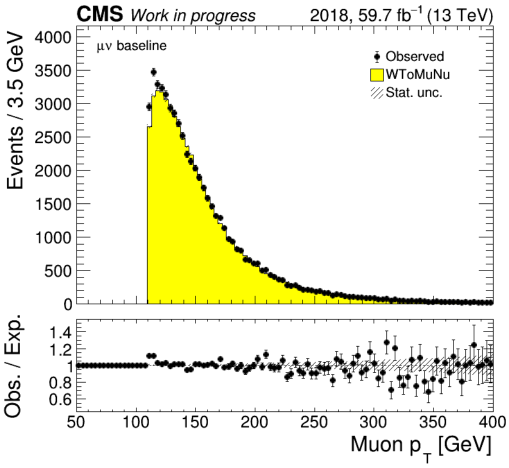
Extra jet veto :

- $p_T > 30$ GeV
- $|\eta| < 4.7$
- jetId ≥ 1 (era 2016)
- jetId ≥ 2 (era 2017 and 2018)
- DeltaR(tau) > 0.5

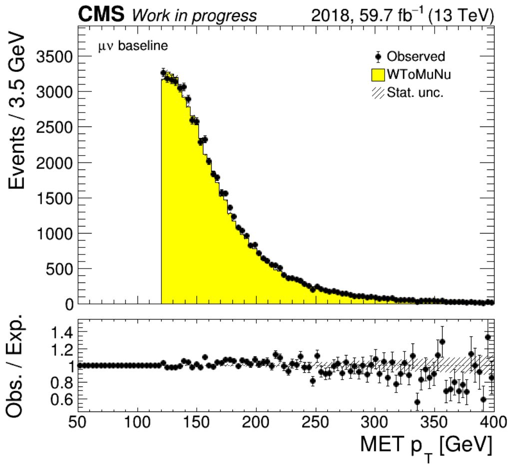
The last requirement is performed as the jet that seeded the tau reconstruction is stored in the jet collection within NanoAODs and should not trigger the veto.

3 Data/MC plots and histogram inputs for datacards

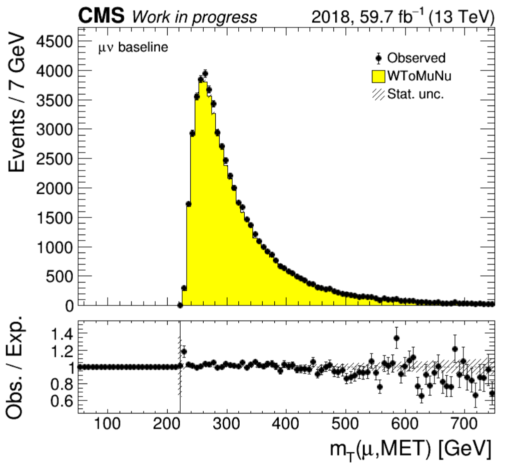
I used the picotuples to make some data/MC plots.
In order to do it I added into the Plotter package of the TauFW a script called Wstarplot-Pico in order to make the plots in figure:1.



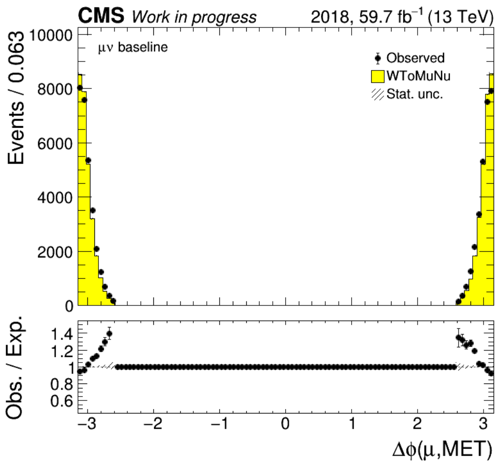
(a) Muon transverse momentum



(b) Missing transverse energy



(c) Muon + MET transverse mass system

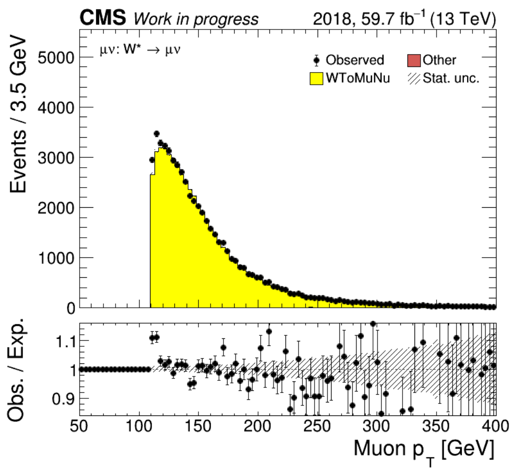


(d) $\Delta\Phi$ between muon and MET

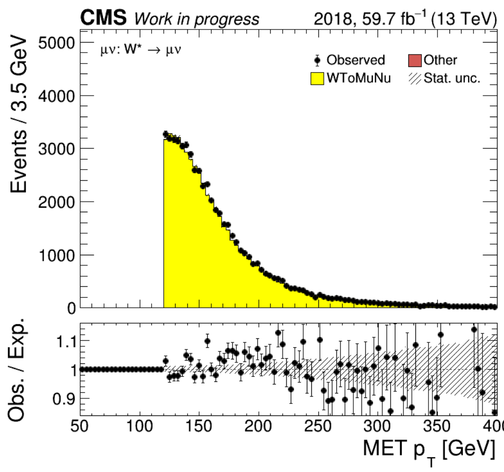
Figure 1: Distributions of data/MC for $W^* \to \mu\nu$, the negligiable background is not shown.

These plots include the full SingleMuon dataset for Ultra Legacy 2018 (Runs A, B, C and D) plotted against the $W^* \to \mu\nu$ Monte Carlo (MC) samples; Fig. 1a is the transverse momentum of the muon, Fig. 1b is the transverse momentum of the MET, Fig. 1c is the transverse mass of the muon and MET system and Fig. 1d is the angular azymuthal difference between muon and MET.

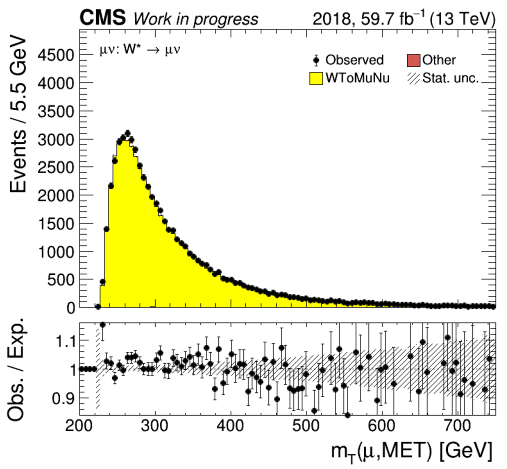
I also created a new createinputs module in order to create the input histograms for the datacards, shown in Fig. 2). The cuts required for the histograms 1 and 2 are the



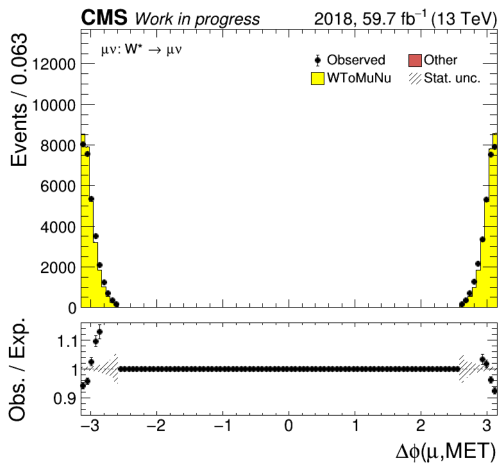
(a) Muon transverse momentum



(b) Missing transverse energy



(c) Muon + MET transverse mass system



(d) $\Delta\Phi$ between muon and MET

Figure 2: Input histograms for $W^* \to \mu\nu$ process

following:

- n_{jets}=0
- MET $>$ 120 GeV
- $p_{T\_1} > 110$
- $|\Delta\Phi(\mu, \text{MET})| > 2.6$
- extramuon_veto $<$ 0.5 (that means exactly one muon)
- extraelec_veto $<$ 0.5 (that means no electrons)

The weight used is the product between genweight, trigweight, puweight, idisoweight_1. There is also another multiplicative factor, the kfactor_mu that i have extracted from a

ROOT file thanks to a piece of code I added to the ModuleMuNu. The kfactor_mu is not used in this work but it will be useful for future measurements.
As we can clearly see, the histograms made with the WstraplotPico module and createinputs are exactly the same. This is a cross check between two scripts that are made for different purposes but they are meant to generate the same histograms.

4 Measurement of σ_{W^*} of $W^* \rightarrow \mu\nu$ process and results

Using the distribution of the transverse mass of the muon and MET system (2c), we were able to perform a statistical inference using the COMBINE statistical toolkit and perform a maximum likelihood fit to the spectrum of $m_T(\mu, MET)$ to retrieve the virtual W production cross-section: σ_{W^*}.
The following uncertainties affecting signal model are taken into account in the fit so far:

- luminosity uncertainty : 2%;
- muon ID efficiency : 2%;
- trigger : 1%;
- MC statistical bin-by-bin uncertainties in the signal template

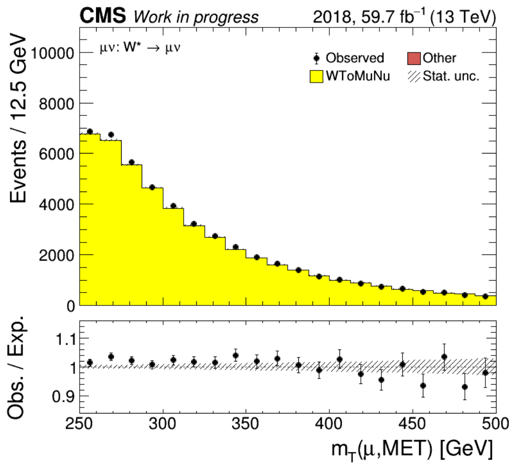
Additional uncertainties to be included in the future studies:

- luncertainty in the muon momentum scale (affects muon p_T and $m_T(\mu, MET)$);
- uncertainty in the unclustered energy scale (affects missing p_T and $m_T(\mu, MET)$);
- uncertainty in the jet energy scale (affects missing p_T and $m_T(\mu, MET)$)

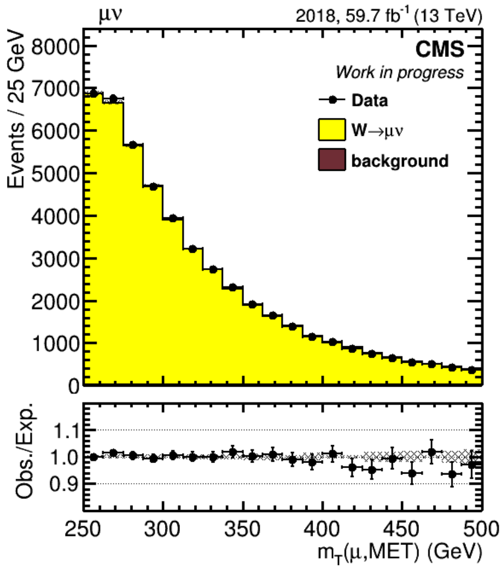
The fit result is 1.02±0.03 (68% CL) which, multiplied by the cross-section of the WToMuNu process ($\sigma^{theo}_{W^*(m>200\ GeV)} = 7.273$), gives :

$$\sigma_{W^*} = (7.4 \pm 0.2)\text{pb} \tag{1}$$

In figure (3a) the $m_T^{(\mu+MET)}$ is shown before performing the FIT and in figure (3b) the same distribution is shown after the FIT. In the postfit figure the agreement between data and MC looks better.



(a) Pre-fit μ + Met transverse mass



(b) Post-fit μ + Met transverse mass

Figure 3: Pre-fit and post-fit distribution of transverse mass of the muon + MET system

5 Conclusions

In this Summer Student project, I managed to lay the foundations for what will be the measurement of tau momentum scale and identification efficiency scale factors at high p_T. I introduced some new modules inside the Tau Framework and I helped to validate a new tool, currently under development, in the TauCQM group, aiming at producing NanoAODs (v10) from the MiniAOD datasets (Appendix B). I have also made the necessary preparations in order to measure the cross section that will be used to constrain the normalization of the $W^* \to \tau\nu$ process. The fit I performed yielded a measured cross-section of $\sigma_{W^*} = (7.4 \pm 0.2)$pb.
The first step has been taken, only two more are missing. Rearranging and distorting the words of Niel Armstrong, I claim the right to say: "That's one small step for TauFW, but a giant leap for a young physicist".

Appendix A CMS workflow

A.1 CMS Trigger

At the LHC collision points proton bunches cross once every 25 ns and for each bunch crossing there can be over 50 primary interactions, with potentially hundreds of particles produced per collision. Storing all the data produced by each subdetector for each bunch crossing is nearly impossible taking into account both the amount of data and the rate at which it should be stored. This presents a challenge for the data storage at CMS. Of the proton-proton collisions most can be classified as almost elastic or diffractive events, which correspond to interactions where the colliding protons either recoil from each other without being destroyed in the process, or the proton structure is broken leading to the emission of highly forward jets. These events present low transverse transferred momentum and therefore are of minor interest when looking at processes involving exchange of on-shell gauge boson, or Higgs physics. Only a fraction of these minimum bias events are written on disk, and are mainly used for detector calibration or luminosity measurements. To reconstruct a statistically significant number of events with signatures of interest a more elaborate system is required. This system is named trigger, as it stores data based on specific inputs received by some of the CMS detectors. The trigger system is divided into two parts: Level 1 Trigger (L1) and High Level Trigger (HLT). The L1 is a hardware based trigger which is needed to reduce the flow of information from 40 MHz to 100 kHz. Event selection is based only on inputs from calorimeters and muon chambers and has the task of identifying whether in an event a high energy electron, muon, photon or jet has been identified. The HLT is designed to reduce the output rate of L1 to about 800 events/s. Events that pass the HLT are written to disk and stored in the CMS computing center at CERN, called Tier 0. HLT corresponds to a software level selection, which uses all the information coming from the subdetectors reducing the rate of minimum bias events while prioritising high transverse momenta objects. To process the events effectively, the HLT must have a good rejection rate of minimum bias events while keeping a good efficiency in the selection of other, rarer, phenomena. This is also required to be done in a limited amount of time, for this purpose the HLT code is organized on multiple levels:

- Level 2 trigger uses the full information gathered from calorimeters and muon chambers;
- Level 2.5 trigger adds to the algorithm the information from the pixel detector;
- Level 3 trigger uses the data collected by all subdetectors.

The events which pass the HLT selection are then saved on mass storage and become available for offline data analysis.

A.2 Data processing

The raw data from the detectors are processed and analyzed to reconstruct physical events. This requires to combine the information gathered by each subdetector in order to identify the particles produced in each pp collision (event), and reconstruct and store their properties. In CMS, events are stored in datasets which are processed in multiple successive steps. Starting from raw data (RAW), these are combined in order to have higher level information: for example separate hits in the tracker are combined in order to reconstruct tracks and energy deposits in the calorimeters are combined in the form of clusters. These reconstructed objects form the RECO data tier, muons, electrons and jets are also reconstructed at this stage. The Analysis Object Data (AOD) is a subset of the RECO dataset, obtained by keeping only the information on higher level reconstructed objects, like track, vertices, muons, jets etc. Most analyses use further subsets of the AOD datasets, called miniAOD and nanoAOD, which store only a fraction of the reconstructed objects. This thesis work uses miniAODs, where the data stored for each event is kept to less than 100 kB.

A.3 Particle Flow Algorithm

The physics object reconstruction in CMS is accomplished using an algorithm called Particle Flow (PF). It uses the whole information gathered by the subdetectors to reconstruct energy, momentum and trajectory of each stable particle. First, the PF algorithm identifies the quantities measured by each subdetector, like charged particles tracks in the silicon tracker, energy clusters in calorimeters or muon tracks in the outer section of the detector. The algorithm groups these signatures into blocks according to whether they could be associated to the same particle. As an example, a charged particle track pointing to an energy cluster in a section of the electromagnetic calorimeter could be associated to an electron or positron candidate. Once these initial blocks are constructed the algorithm proceeds to identify the particles in the following order:

- Muons: they are identified using the hits in the muon chambers and in the silicon tracking system, and by ECAL and HCAL clusters compatible with minimum ionizing particle (MIP) signatures. The requirements for a track to be assigned to a muon is that at least a hit in a muon chamber was found. After the track hits are assigned to a muon, they are removed from other blocks.
- Electrons: the algorithm tries to pair together tracks in the silicon tracker with energy clusters in ECAL and HCAL. The matching tracks and energy deposits are removed before proceeding to the next step.
- Charged hadrons: the remaining tracks in the tracker are associated with this type of particles. The tracks are matched to energy clusters in ECAL and HCAL and then removed from the list of objects.
- Neutral hadrons and photons: energy deposits in HCAL, which have not been matched before, are marked as neutral hadrons, while those in ECAL are assigned to photons.

The last step of the PF algorithm involves the measurement of the total transverse energy of the event. In a pp collision the total momenta in the transverse plane must sum up to 0. When this is not verified it means that some energy in the transverse plane is missing in the event. This missing transverse energy (MET) could be linked to inefficiencies in the detector or to particles which travelled through the subdetectors without interacting, like the neutrinos.

A.4 The Hadron-Plus-Strip algorithm

Reconstruction of hadronically decaying tau leptons is operated in CMS with the hadron-plus-strip (HPS) algorithm. Candidate jets, photons and electrons reconstructed by the

PF algorithm are tested for compatibility with hadronic decay channels of tau leptons. A typical τ_h candidate is an isolated collimated jet with low multiplicity. The HPS algorithm aims at identifying τ_h candidates with high efficiency while rejecting the main background: quark and gluon jets coming from the QCD multijet production.
The HPS algorithm is seeded by PF jet candidates identified by the anti-kt algorithm [1] with a cone size of $\Delta R < 0.4$. Particles in the jets are then tested as candidates for:

- prongs are charged particles depositing their energy in both ECAL and HCAL;
- strips are clusters of electrons and photons producing in ECAL signatures compatible with a π^0 decays.

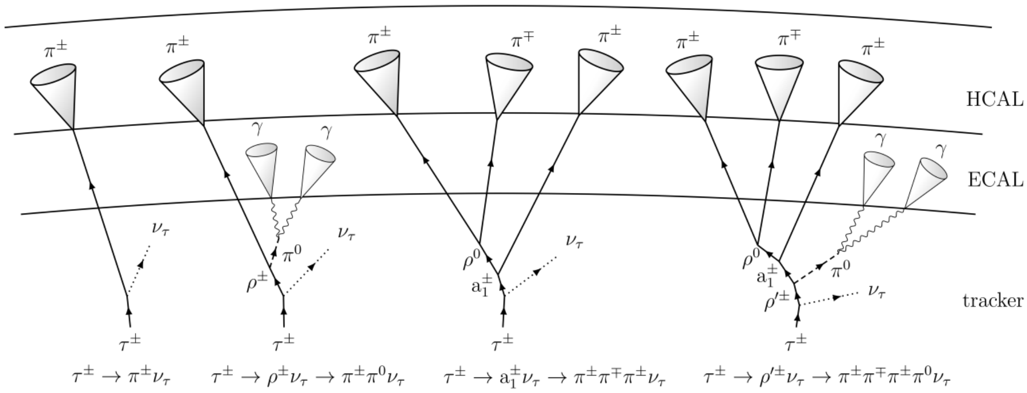


Figure 4: Schematic representation of the four HPS-DMs considered at analysis level. From left to right the DMs shown are: one prong (DM=0), one prong plus π^0s (DM=1), three prong (DM=10) and three prong plus π^0 (DM=11). Thanks to Andrea Cardini for the picture that is taken from his PhD Thesis [2].

It is common to label the tau hadronic decays with an integer index based on the number of prongs ($\mathrm{n_{prongs}}$) and strips ($\mathrm{n_{strip}}$):

$$\mathrm{DM} = 5 \times (\mathrm{n_{prongs}} - 1) + \mathrm{n_{strip}}. \quad (2)$$

Appendix B Validation of nanoAODs

My work was also used as validation for a new tool, currently under development in the TauCQM group, aiming at producing NanoAODs (v10) from the MiniAOD datasets. I made some plots of the most interesting variables stored in the flat n-tuples obtained after applying the ModuleMuNu to the NanoAOD. The plots includes $\mathrm{m_T}$, muon $\mathrm{p_T}$, MET $\mathrm{m_T}$, η and $\Delta\Phi(\mu, \mathrm{MET})$ for each data and MC sample. The data samples are the SingleMuonA (5),SingleMuonB (6),SingleMuonC (7) and SingleMuonD (8). The MC samples are WToMuNu (9), WJToLNu inclusive (10), WJToLNu100to200 (11), WJToLNu200to400 (12), WJToLNu400to600 (13), WJToLNu600to800 (14), WJToLNu800to1200 (15), WJToLNu1200to2500 (16) and WToTauNu (17).
All plots looks fine; for example the SingleMuonA (5) m_T is roughly peak at 200 GeV as we expect for a W^* decaying with $m_W > 200$ GeV. To point another feature that behaves as expected we can take a look at the $\Delta\Phi(\mu, MET)$ distribution for increasing value of hadron activity (HT) in the transverse plane; the azymuthal angular difference between muon and MET plots: 11, 12, 13,14, 15 and 16 the more HT increase the more they look peaked at 0. This is because by increasing hadronic activity, the only way they have neutrino and lepton to compensate the jet, is to be producted parallel to each other and opposite to the latter.

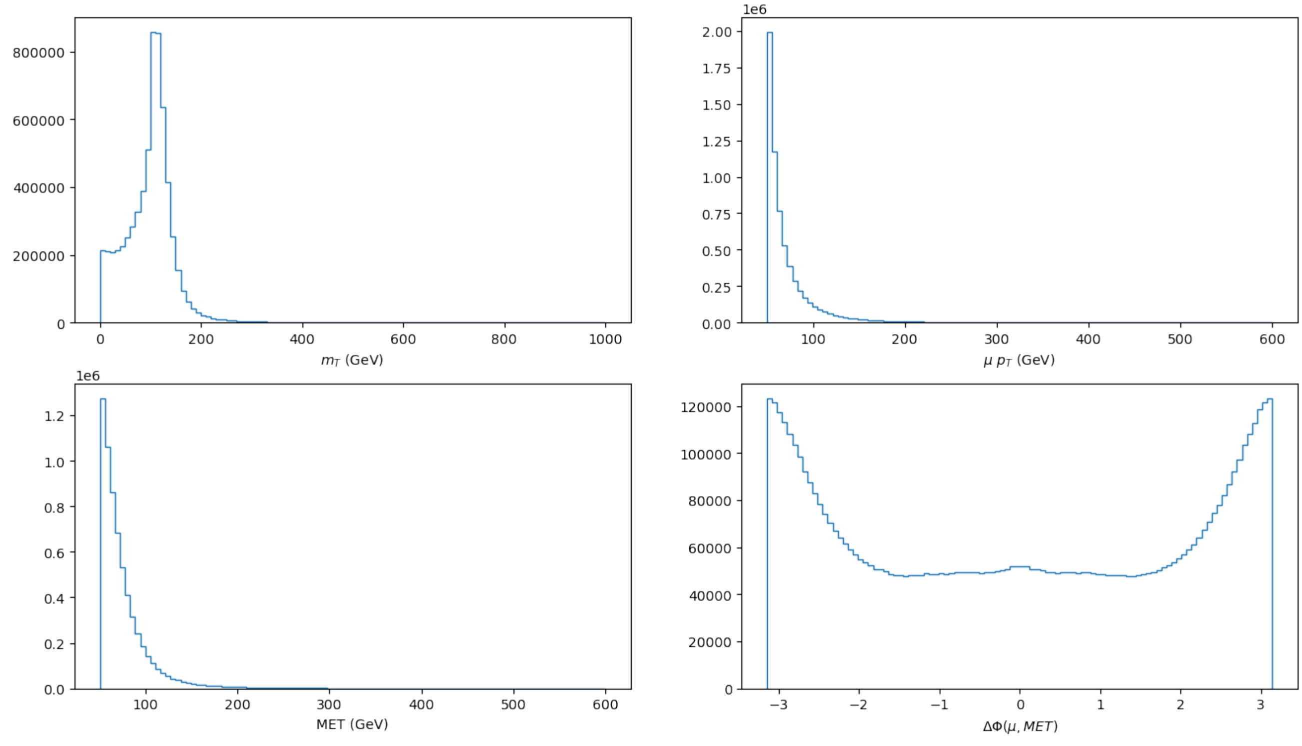


Figure 5: SingleMuonA flat n-tuples distributions

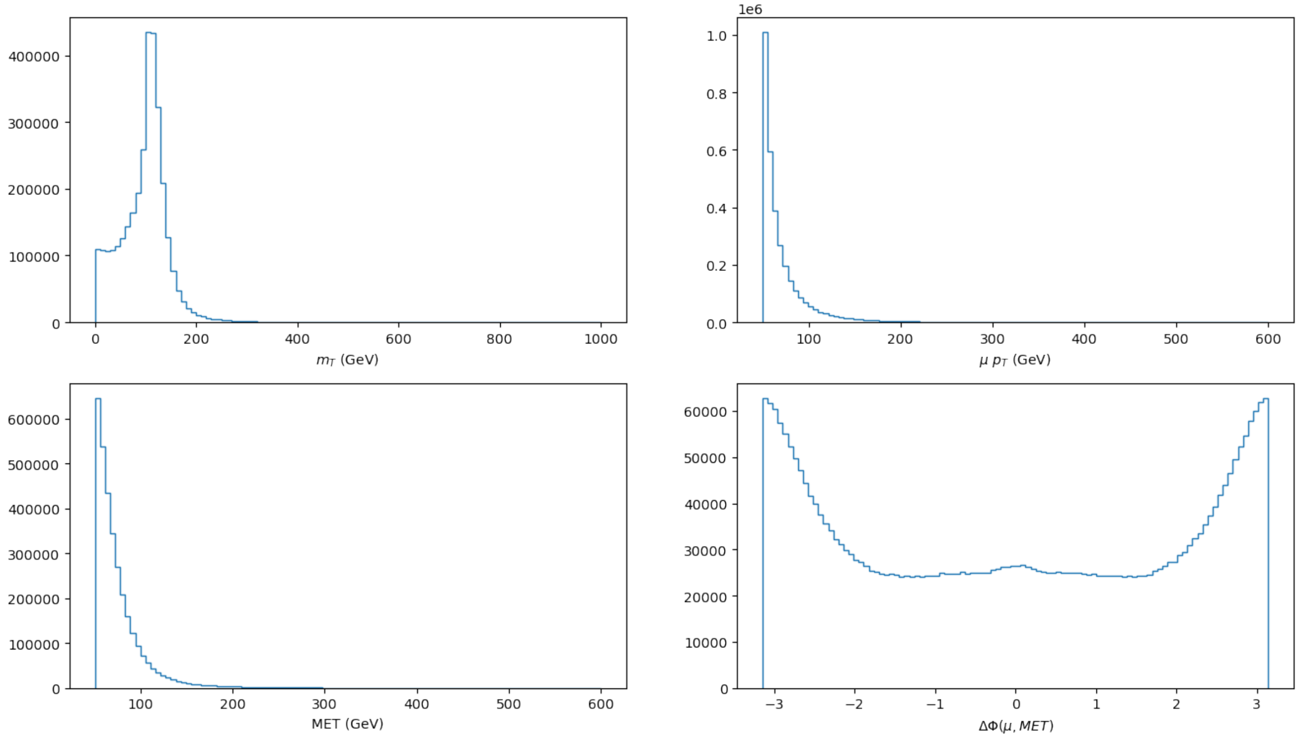


Figure 6: SingleMuonB flat n-tuples distributions

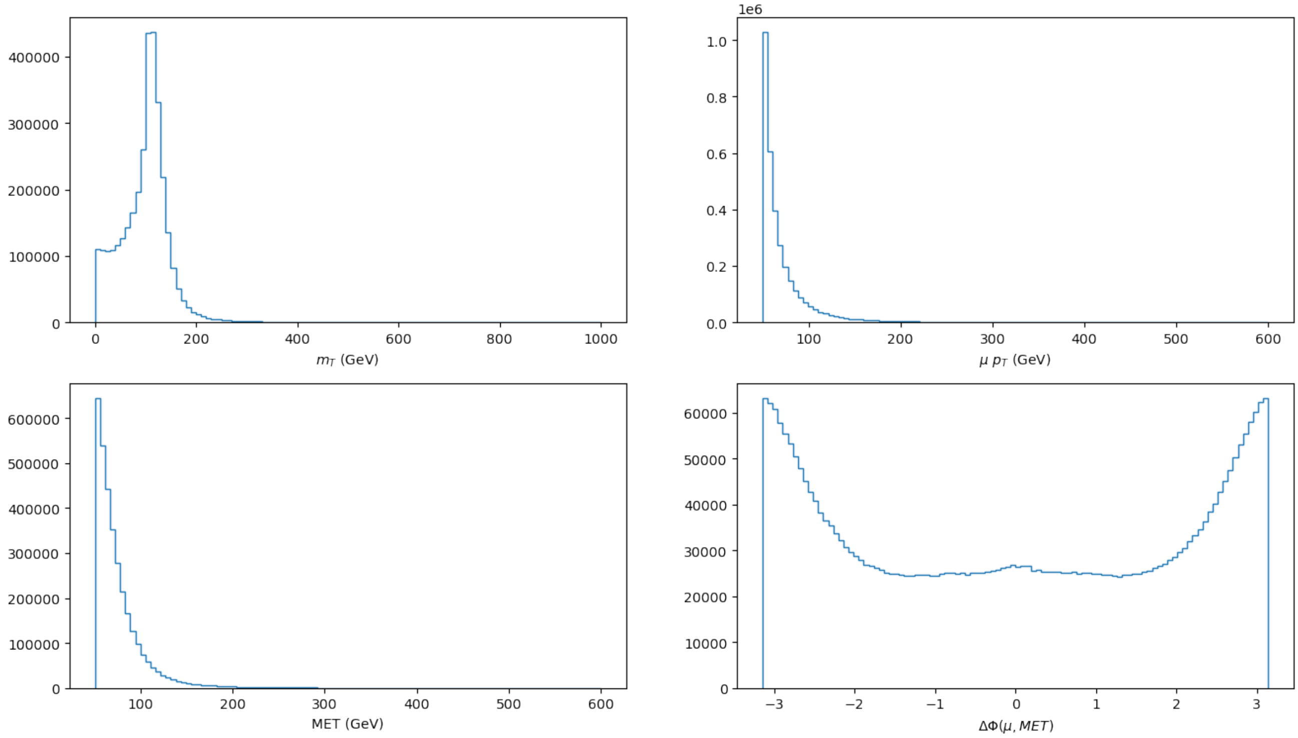


Figure 7: SingleMuonC flat n-tuples distributions

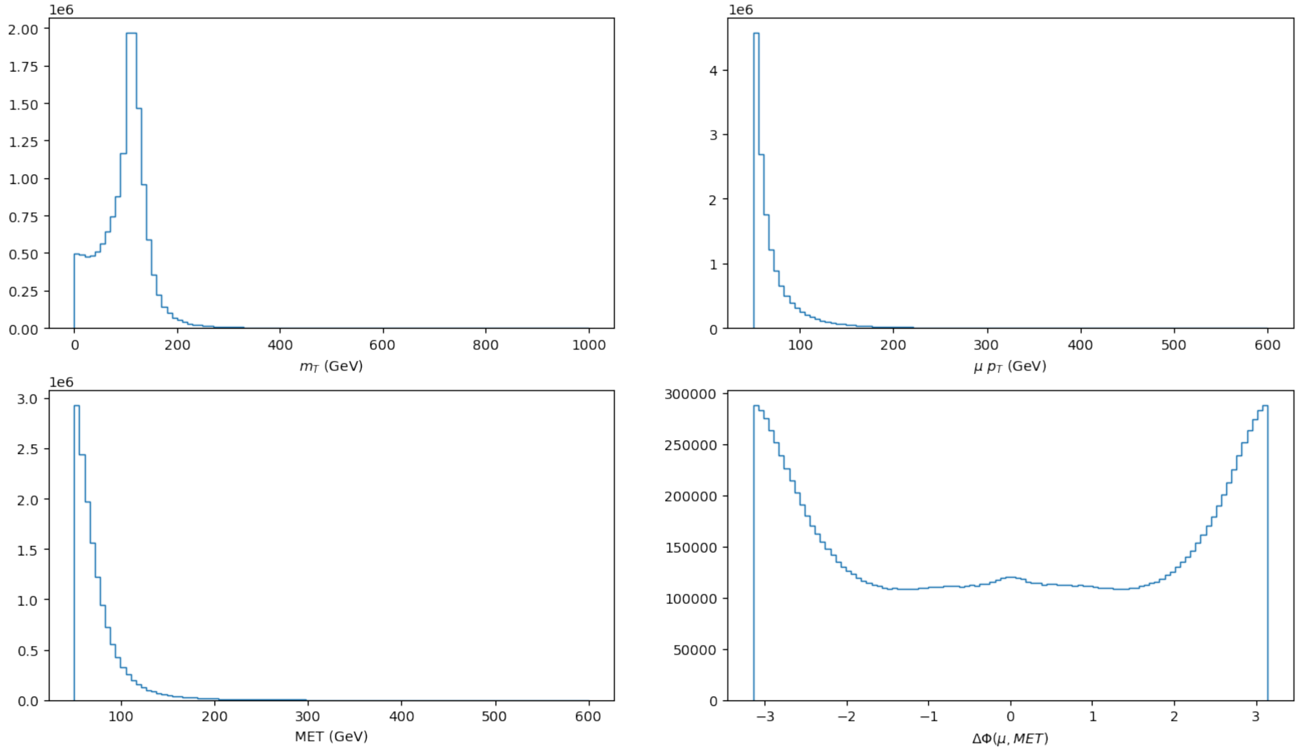


Figure 8: SingleMuonD flat n-tuples distributions

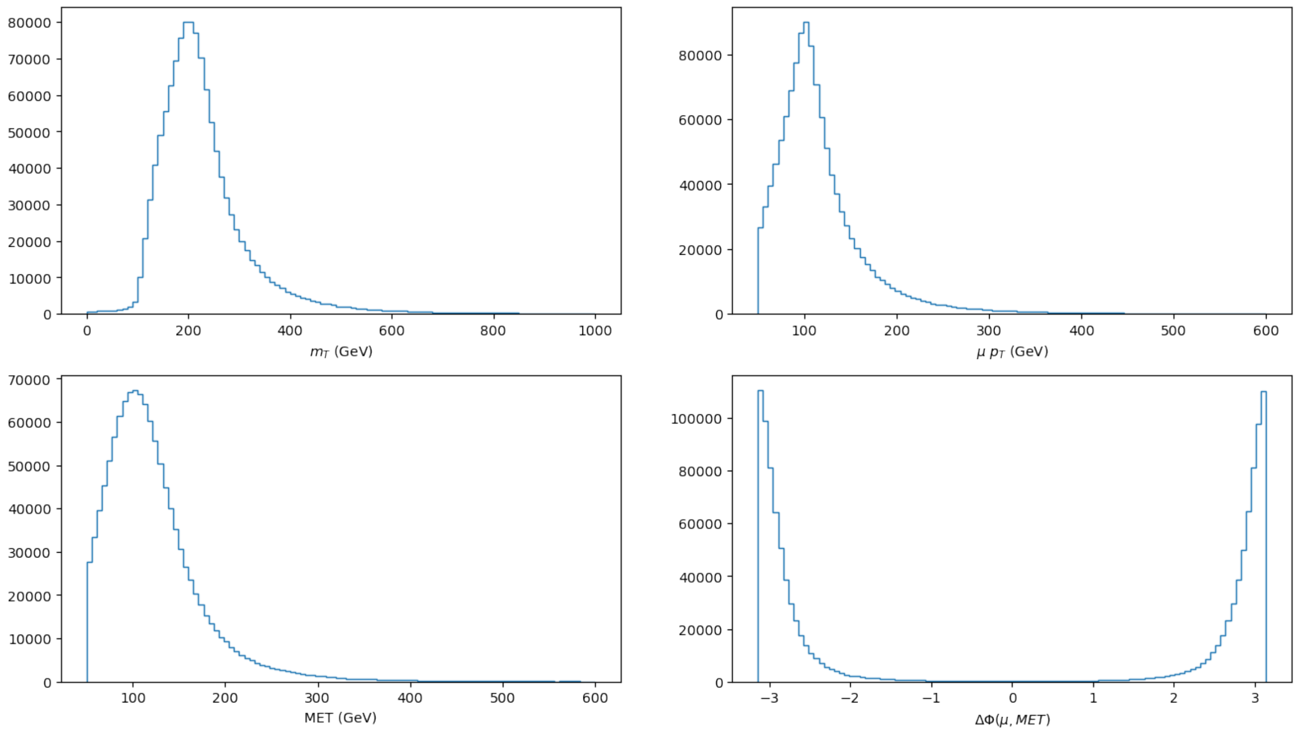


Figure 9: WToMuNu flat n-tuples distribution

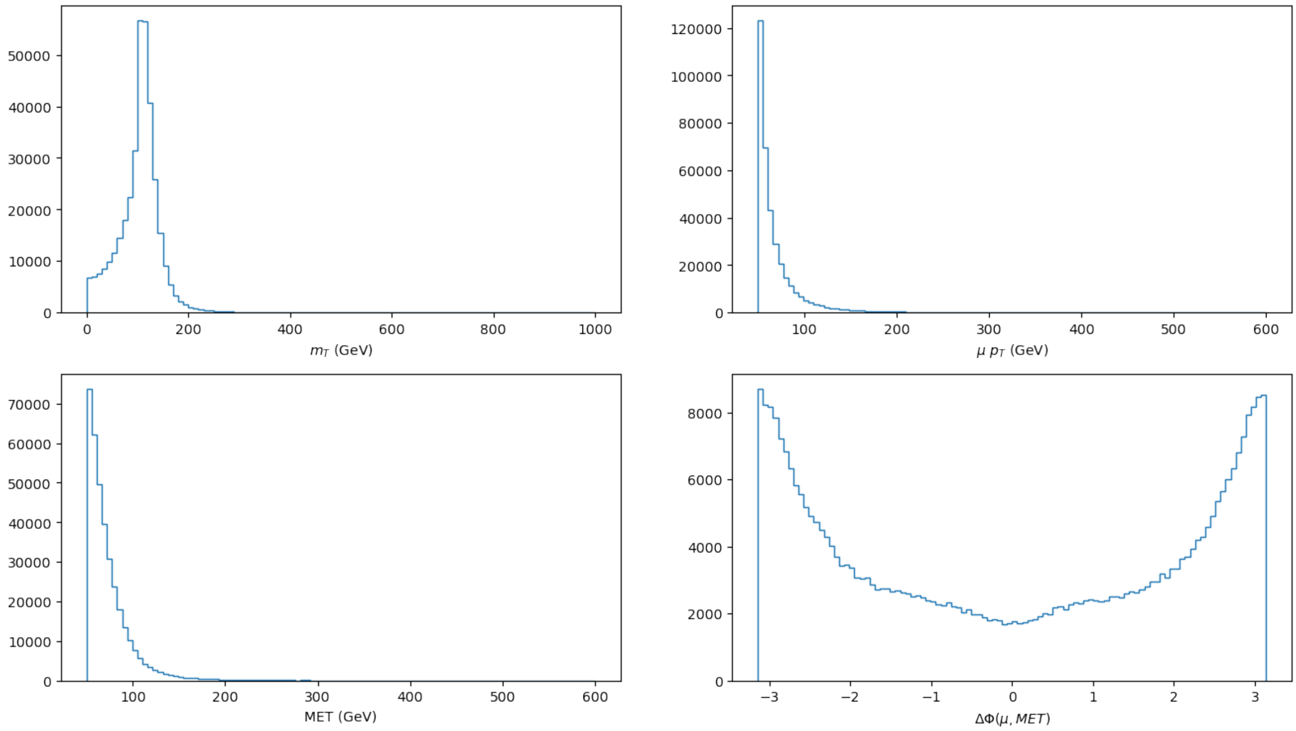


Figure 10: WJToLNu inclusive flat n-tuples distributions

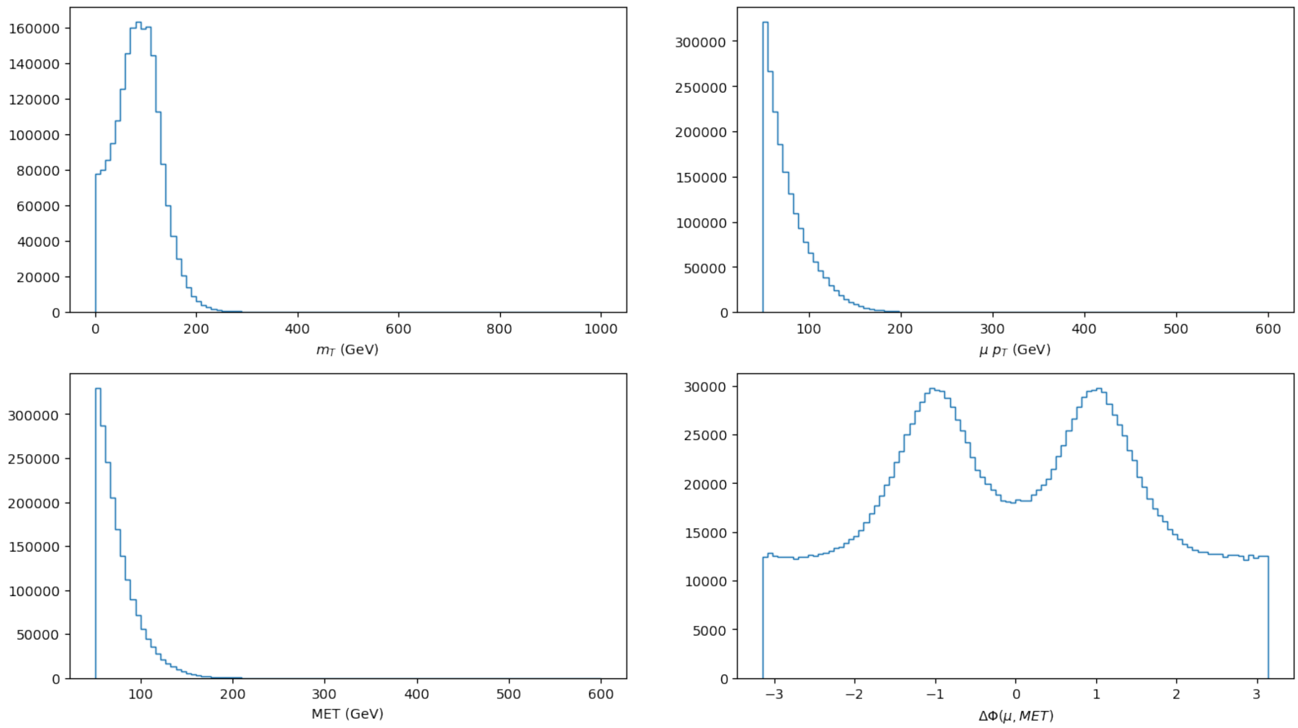


Figure 11: WJToLNu100to200 flat n-tuples distributions

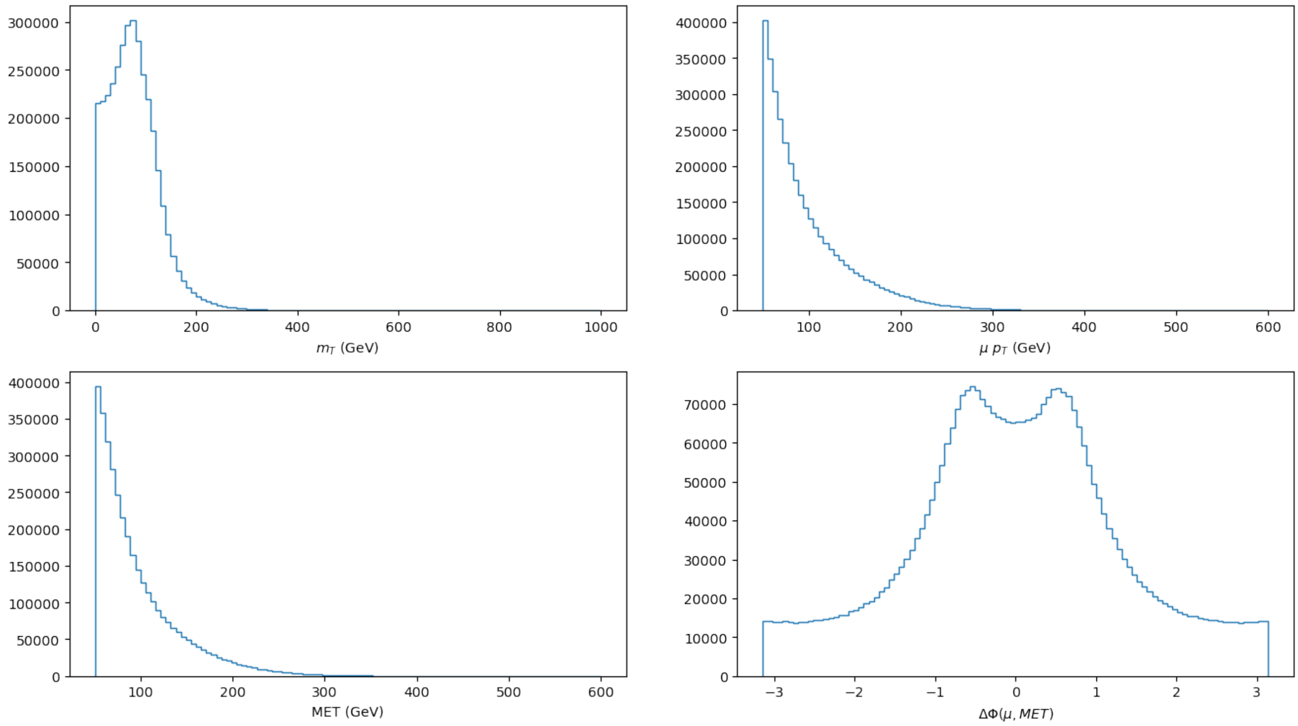


Figure 12: WJToLNu200to400 flat n-tuples distributions

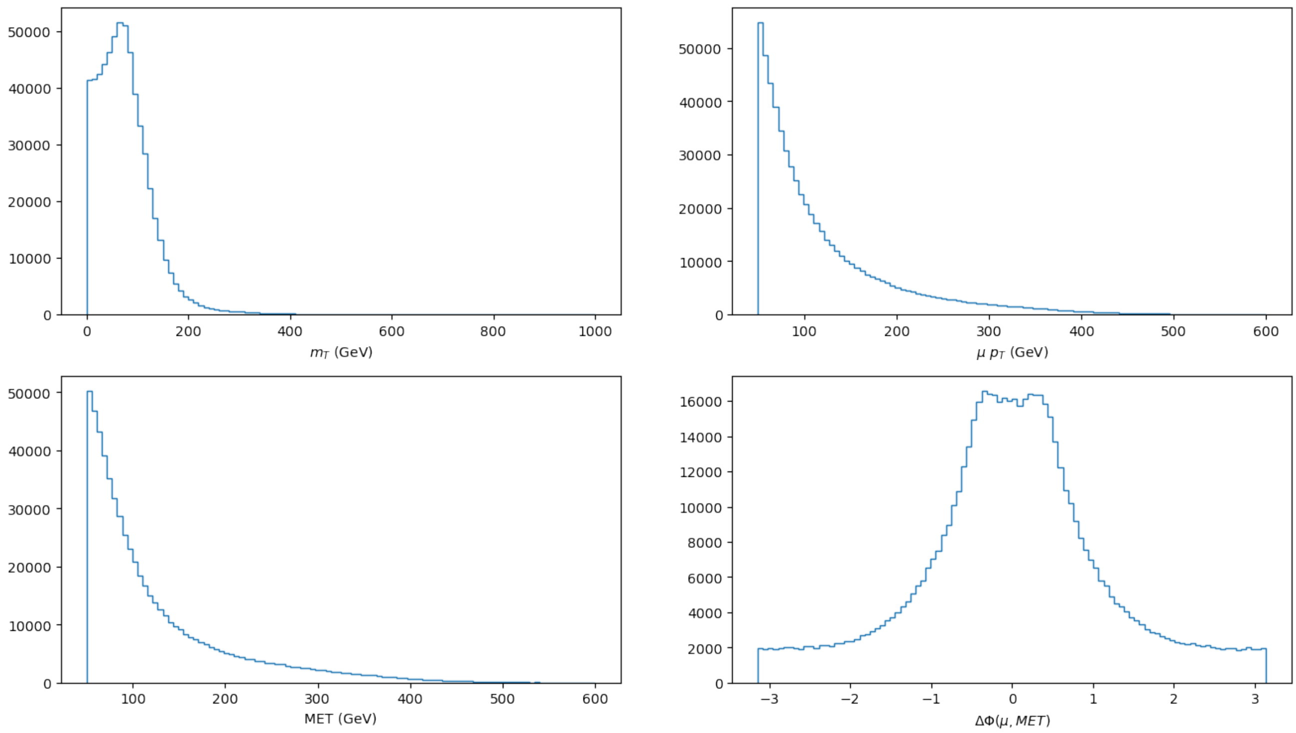


Figure 13: WJToLNu400to600 flat n-tuples distributions

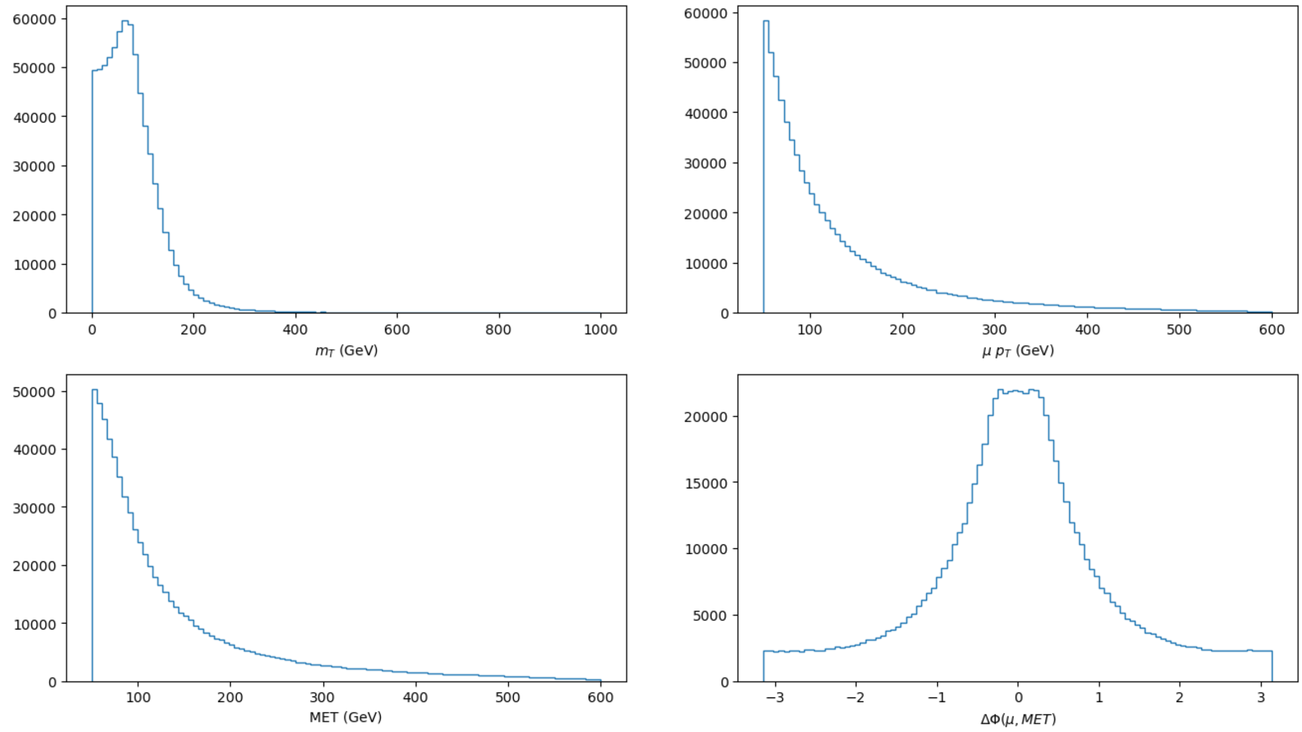


Figure 14: WJToLNu600to800 flat n-tuples distributions

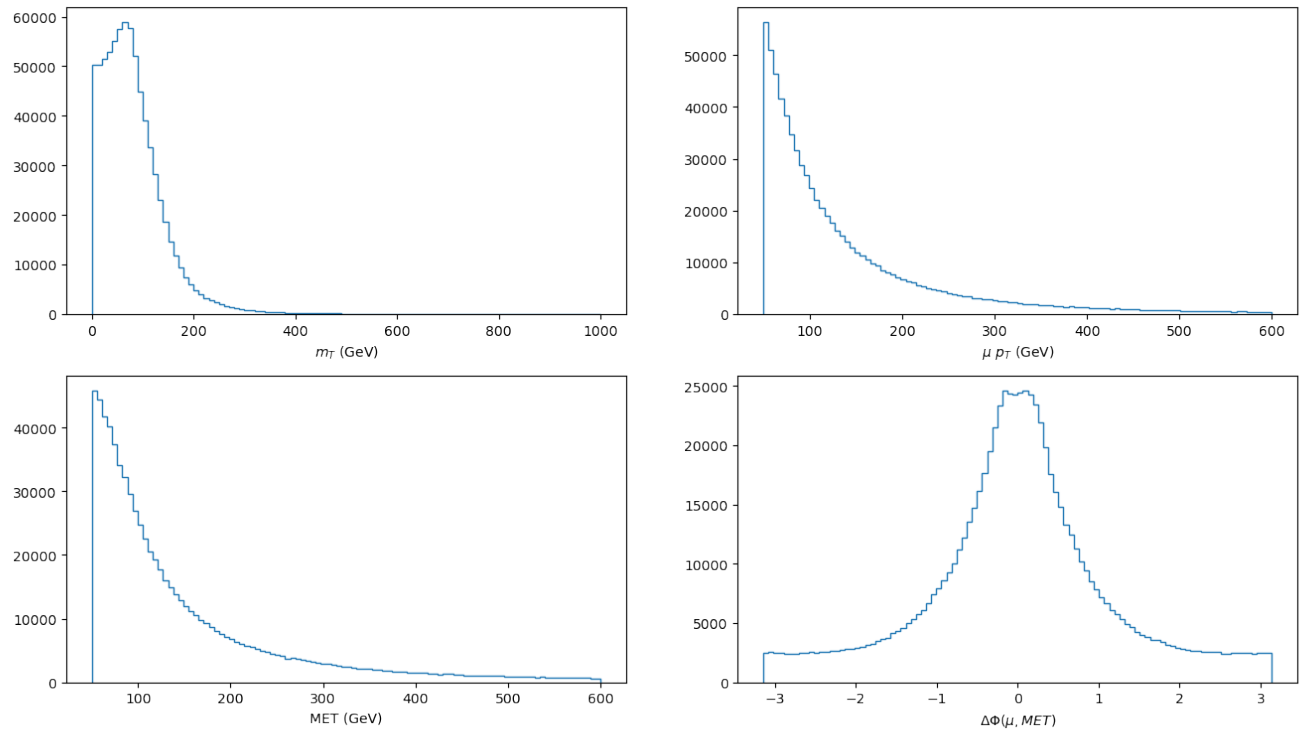


Figure 15: WJToLNu800to1200 flat n-tuples distributions

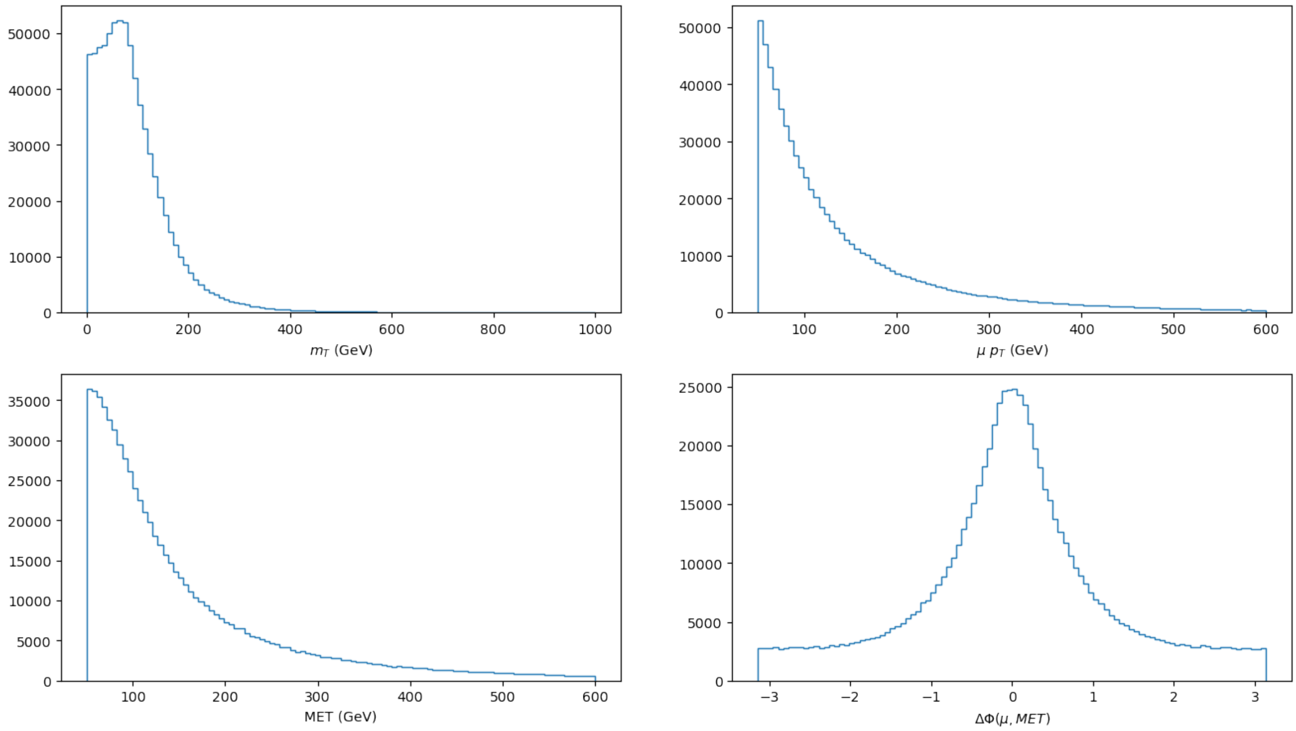


Figure 16: WJToLNu1200to2500 flat n-tuples distributions

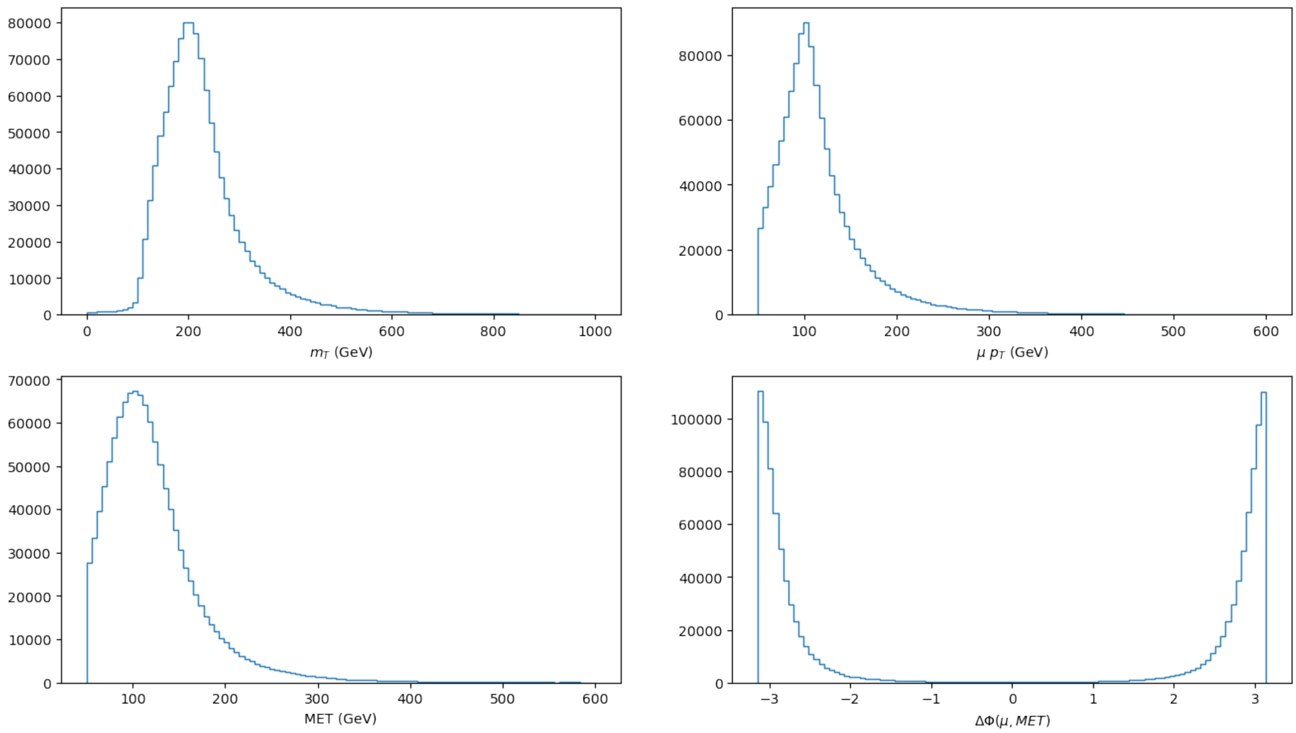


Figure 17: WToTauNu flat n-tuples distribution

Appendix C Classified

C.1 Project codenamed - CApyBARA

The capybara or greater capybara (Hydrochoerus hydrochaeris) is a giant cavy rodent native to South America. It is the largest living rodent and a member of the genus Hydrochoerus. The only other extant member is the lesser capybara (Hydrochoerus isthmius). Its close relatives include guinea pigs and rock cavies, and it is more distantly related to the agouti, the chinchilla, and the nutria. The capybara inhabits savannas and dense forests and lives near bodies of water. It is a highly social species and can be found in groups as large as 100 individuals, but usually lives in groups of 10–20 individuals. The capybara is hunted for its meat and hide and also for grease from its thick fatty skin. Luckily it is not considered a threatened species. Why do other animals like capybaras so much?

Figure 18: **CApyBARA** = **C**ms **A**dvanced **py**thon **BA**sed **R**epository (of) **A**lgorithms, picture taken by me at Hamburg Zoo Tierpark Hagenbeck.

The photo evidence(19) of the capybara's friendliness and the animal friendships they can form was more than convincing. Each and every one of domestic and wild animals seems to like hanging out with this friendly creature that looks like a rat-pig hybrid. Even the crocodiles! The answer? It probably lies in some capybara facts. First of all, these cute animals are very social and often live in groups of 10-20 individuals. Second, this lovable creature is the largest rodent in the world, growing to a size of up to 134 cm and weighing up to 66 kg. Third, native to South America, capybaras are semi-aquatic mammals that prefer to live near bodies of water; in fact, they are excellent swimmers, can avoid predators by staying submerged for up to 5 minutes, and mate only in water. Moreover, the most important fact is that we'd sure love to have a capybara pet! For all these reasons and for many others I decided to baptize my Summer Student Project: **CApyBARA**.

(a) Capybara sleeping with water turtles and ducks, so sleepy.

(b) Capybara pampered by monkeys, so friendly.

(c) Capybara alongside a crocodile, so brave.

(d) Capybara with a bird of prey that wants to take it away, so fat that it is not liftable.

(e) Capybara with a purring cat, so lovable.

(f) Capybara playining with some puppies, so playful.

Figure 19: Some pictures of capybaras enjoying their life without worrying about what is happening around them.

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I will try, as far as possible, to express my gratitude to my supervisors Andrea Cardini and Aliaksei Raspiareza. Andrea was the one who followed me more closely, helping me daily to solve problems from the most trivial to the most complex. In addition to being magnificently competent in what he does he is also able to explain it to those who, like me, are beginners. Allow me to say that for me he was like an older brother with whom I could joke, have fun and spend almost two months in which I learned so much, both in the field of Physics and in everything else. I spent less time with Aliaksei but it was still precious, confronting him has always been pleasant. He does not lack of availability, friendliness and exposition skills. His contribution to the success of the project was fundamental. I sincerely hope to have the honor of working or collaborating with both of them again in the near future. It is also necessary to thank the organizers, I will just extend my gratitude to Olaf Benhke as a representative of the aforementioned. His availability and his knowledge of "beautiful things to do in Germany" are comparable only to the enthusiasm with which he tries to convince you to do them. I really appreciated the scientific approach used in proposing the activities: always photos and always links to support his statements. And now we must also thank the summer students who accompanied me on this phantasmagoric adventure, I'll just mention their names or nicknames and that's it: Matteo, Francy, Francesco, Beppo, Edo, Kerby, Max, Alain, Paul and Eric. Thank you all for these unforgettable months.

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