Search for $\tau \to 3\mu$ decay at the CMS experiment in Run-II

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1 Introduction

In the Standard Model (SM), lepton flavour violation (LFV) involving charged leptons is allowed by neutrino oscillations; it can therefore occur only through loop processes which are stronghly suppressed and not accessible at present day experiments [1]. Several extensions of the SM, however, allow for LFV in the charged sector with sizeable branching fractions. In particular, some models based on Supersimmetry (SUSY) have strongly enhanced rates for such decays ($\mathcal{O}(10^{-8})$) [2, 3]; this makes LFV an ideal playground to search for beyond the SM physics (BSM).
The neutrinoless decay of the tau lepton into three muons ($\tau \to 3\mu$) is a promising LFV decay channel for the LHC experiments, since it has a clear signature given by the three muons in the final state, it is strongly enhanced by BSM theories since they typically couple through the higher mass particles and it is feasible at pp colliders given the high number of tau leptons produced.
The more relevant source of τ leptons at the LHC are decays of c- and b-hadrons, dominated by the $D_s \to \tau\nu$, $B \to \tau\nu$ and referred as heavy flavour channel (HF), followed by $W \to \tau\nu$ and $Z \to \tau\tau$ decays. Despite τ produced in the HF channel are the most abundant, they are significantly boosted in the forward direction thus being more difficult to reconstruct because of the higher background.

2 State of the art

The search for this decay has already been carried out by several experiments and no evidence has been observed so far. The stricter limit on the branching fraction has been set by the Belle collaboration with $\mathcal{B}(\tau \to 3\mu) < 2.1 \cdot 10^{-8}$ at 90% confidence level [4]. This search in the HF channel has been performed at the CMS experiment using pp collision data collected at $\sqrt{s} = 13\,\text{TeV}$ in 2016, corresponding to an integrated luminosity of 33 fb^{-1}. The upper limit on the brancing fraction set by the 2016 data analysis is $\mathcal{B}(\tau \to 3\mu) < 8.8 \cdot 10^{-8}$ at 90% confidence level [5], while the search for the $\tau \to 3\mu$ in the W channel using 2016 data is being finalized.
Extending the search for the $\tau \to 3\mu$ decay to the full Run II data taking corresponding to ~ 120 fb^{-1} would exploit an increased statistics thus possibly providing a stricter upper limit on the branching fraction. This PhD research aims to analyse the full Run II data (i.e. including data collected in 2017 and 2018) using τ leptons from B and D decays to search for the $\tau \to 3\mu$ decay.

3 Report on progress: 2017 analysis

3.1 Datasets and simulated samples

The analysis is based on pp collision data at a center-of-mass energy of 13 TeV collected in 2017 with the CMS detector corresponding to an integrated luminosity of $\mathcal{L} = 38$ fb^{-1}. The collision data sets, run ranges, and integrated luminosity per data set, are listed in Table 1.

2017 Datasets	Run range	$\mathcal{L}(\text{fb}^{-1})$
/DoubleMuonLowMass/Run2017B-17Nov2017-v1/AOD	297046-299329	4.79
/DoubleMuonLowMass/Run2017C-17Nov2017-v1/AOD	299368-302029	9.63
/DoubleMuonLowMass/Run2017D-17Nov2017-v1/AOD	302030-303434	4.24
/DoubleMuonLowMass/Run2017E-17Nov2017-v1/AOD	303824-304797	9.30
/DoubleMuonLowMass/Run2017F-17Nov2017-v1/AOD	305040-306462	10.04
Total	**297046-306462**	**38.00**

Table 1

The High Level Trigger (HLT) used for this search requires 2 muons with $p_T > 3.0$ GeV and one additional track with $p_T > 1.2$ GeV in the final state. The invariant mass of the three objects is required to be within 1.60 and 2.02 GeV and their common vertex is displaced from the beam-spot by more than two sigmas.

Monte Carlo (MC) simulated samples are used to model the $\tau \to 3\mu$ decay in the more relevant τ production channels, namely the $D_s \to \tau\nu_\tau$, $B^\pm \to \tau\nu_\tau$ and $B^0 \to D^{-(*)}\tau^+\nu_\tau$. The events are generated with PYTHIA. The full simulation and reconstruction reproducing the 2017 data taking conditions is then performed for the events containing at least 2 generated muons with $p_T > 2.7$ GeV and $|\eta| < 2.4$. These requirements match the CMS detector acceptance for muon reconstruction while being looser than the requirement at HLT level.

The $D_s \to \phi(\mu\mu)\pi$ decay is used to measure signal event rate associated with hadronically produced τ-leptons. Moreover, this decay is used to compare data with MC simulation to evaluate systematic uncertainties on the final signal yields and to monitor the data taking during 2017 as it shares the same trigger as used for the $\tau \to 3\mu$ search. For this reason a MC sample for the $D_s \to \phi(\mu\mu)\pi$ decay is generated with similar settings as the signal samples.

3.2 Event selection

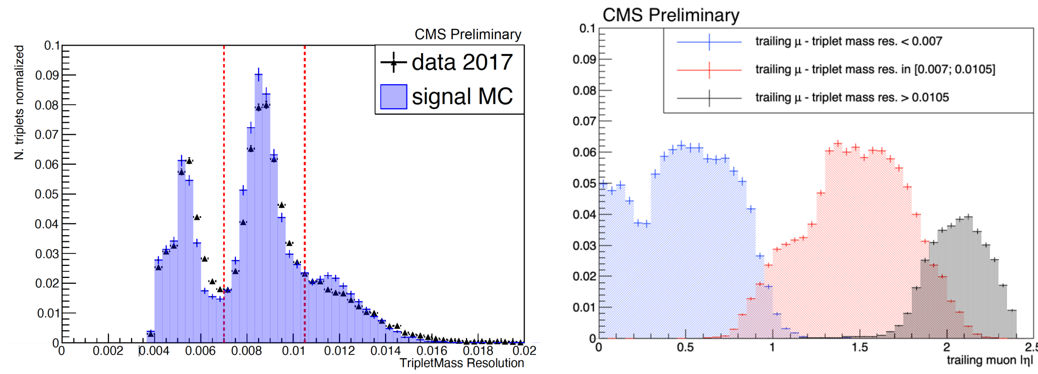
The event are required to pass the HLT and at least one of its related L1 seeds. For the $\tau \to 3\mu$ search, events containing 3 reconstructed muons having $p_T > 2$ GeV and $|\eta| < 2.4$ which released at least 1 hit in the inner tracker and having total electric charge of ± 1 are selected. The three μ tracks are fitted to a common vertex through a kinematic fit and the these tracks are removed for the primary vertex position re-computation. The thus formed 3μ candidate is then required to pass additional selections on the vertex quality, event topology, trigger matching:

- χ^2 of the 3μ common vertex in (0, 15) range
- three muon reconstructed as global muon having $p_T > 2$ GeV and $|\eta| < 2.4$
- 3μ invariant mass in $(1.62, 2)$ GeV
- all muon pairs have $\Delta R < 0.8$ and $\Delta Z < 0.5$
- Veto on ϕ meson mass and veto on ω meson mass on the invariant mass of all opposite-charge muon pairs
- Each muon matches with one "leg" of the HLT object within $\Delta R < 0.03$

In order to improve the search sensitivity, all the candidate events are sorted into three exclusive categories based on the expected resolution of the three-muons system invariant mass, showed in Fig. 1a, which depends on the lowest-p_T muon pseudorapidity, as showed in Fig. 1b.

3.3 D_s yield evaluation and Data-MC comparison

The $D_s \to \phi(\mu\mu)\pi$ analysis is performed with a set of selections similar to the one used for the signal search. In this case, two reconstructed muons are required to have opposite charge, while loose requirements are applied to the additional track (i.e. the pion candidate). The invariant mass of the 2μ+1track system, showed in Fig. 2, is used to extract the D_s yield.



(a) Mass resolution of the muon triplet per event in signal MC (blue) and data events (black dots).

(b) Pseudorapidity value of the most forward muon of the 3μ, for events in category A (blue), B (red), C (black)

Figure 1: The 3μ events are categorized based on the invariant mass resolution "m". Category A: $m < 0.0070$, category B: $0.0070 < m < 0.0105$, category C: $m > 0.0105$.

Run	Ds yield per fb^{-1}	Data/MC Ds yield
2017 B	1022.0 ± 26.2	0.345 ± 0.0009
2017 C	2642.9 ± 74.7	0.892 ± 0.025
2017 D	2724.0 ± 119.6	0.919 ± 0.040
2017 E	2584.5 ± 72.1	0.872 ± 0.024
2017 F	1779.1 ± 26.2	0.600 ± 0.009
Total	2182.6 ± 15.4	0.737 ± 0.005

Table 2: Fitted $D_s \to \phi(\mu\mu)\pi$ yields for each of the 2017 runs and data/MC ratio

The D_s yield is measured for each of the 2017 run era separately and compared with the prediction from the Monte Carlo simulation based on the integrated luminosity and on the $D_s \to \phi(\mu\mu)\pi$ decay branching fraction. The results are showed in Table 2. This study allow us to find an anomaly in the run B and F. In fact, the monitoring of the D_s yield during the 2017 data taking runs compared with the delivered luminosity (Fig. 3) shows a drop in run B and F which is presently under investigation.

The $D_s \to \phi(\mu\mu)\pi$ channel is also used to compare distributions of relevant variables in both data and Monte Carlo. The distributions in MC are scaled by a factor f_{MC} given by:

$$f_{MC} = \frac{\mathcal{L} \cdot \sigma(pp \to D_s) \cdot \mathcal{B}(D_s \to \phi(\mu\mu)\pi)}{N_{MC}} \tag{1}$$

Since the $D_s \to \phi(\mu\mu)\pi$ MC sample only contains decay events, the background contribution is subtracted from data exploiting the fitting procedure showed in Fig. 2. Distributions of relevant variables, such as the 2 muons and track transverse momentum and pseudorapidity, are compared in data and MC and they are shown in Fig. 4. The goal is to evaluate how well the simulated events reproduce the detector response, since MC simulation will be used to model the $\tau \to 3\mu$ signal.

3.4 Multi-variate analysis for background rejection

On the set of the events passing all the selections in both MC and data, the signal-background discrimination cannot be performed using a single variable, so a multivariate analysis (MVA) is required. The MVA for background rejection is implemented using the TMVA toolkit, and Boost Decision Tree (BDT) algorithm is chosen. The BDT is trained using MC events as signal, data from the 3μ invariant mass region $[1.65, 1.73] \cup [1.82, 1.90]$ GeV (referred as sidebands - SB) as background. Half of the events are used for training the BDT.

The input variables given to the BDT for a first iteration are the following:

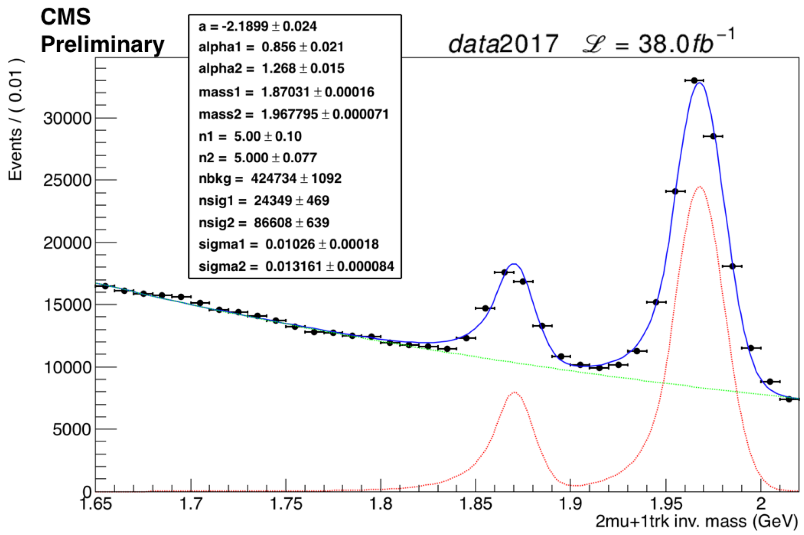


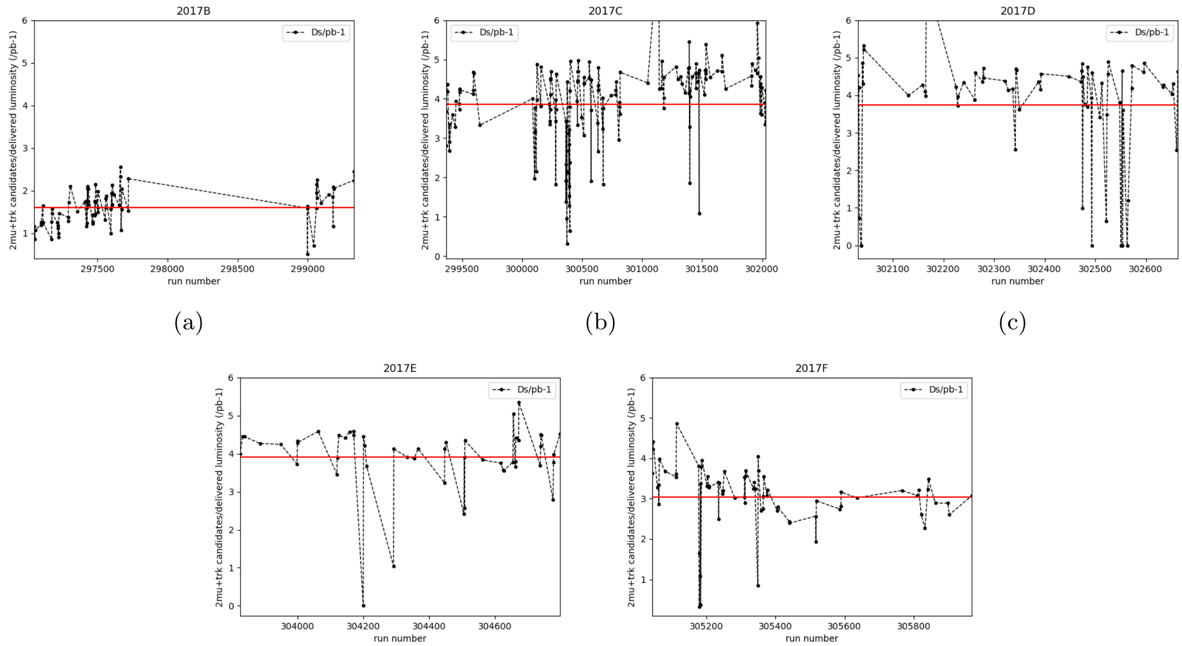
Figure 2: Invariant mass of the two muons + 1 track system measured in the 2017 data. The D_s and D^+ peaks are fitted with Crystall Ball functions (red line), while the background is fitted with an exponential (green line). The combination of the two fits (blue line) is used to model the data (black dots).

- Pmu3: the momentum of the trailing muon of the triplet;
- cLP: χ^2 for the position matching between the muon inner track and the outer track. The maximum value among the ones of the three muons is used;
- tKink: kink algorithm applied to the muon inner track (maximum of the three muons);
- segmComp: the value of the position compatibility between the inner track and muon segment;
- fv_nC: normalized χ^2 for the 3μ vertex;
- fv_dphi3D: angle between the 3μ momentum vector and the PV-SV vector;
- fv_d3Dsig: significance of the 3D displacement of the 3μ vertex with respect to the primary vertex (PV);
- d0sig: significance of the transverse impact parameter of the muon track with respect to the PV;
- mindca_iso: the minimum of the distance of closest approach to the 3μ vertex to any other track in the event having $p_T > 1$ GeV.

The BDT is trained separately in the three events categories defined based on the invariant mass resolution. Fig. 5 shows the distributions for all input variables for both signal and background events in category A. Based on the BDT decision, an additional categorisation is done for background rejection so that the combined signal significance in the best two categories is maximised, while the worst one is discarded. The signal significance as a function of the boundaries for categorisation is shown in Fig. 6 for the three categories, while the BDT decision distributions on the test samples for the three categories, together with the boundaries maximising the signal significance, are shown in Fig. 7.

3.5 Preliminary results

The signal yields in each of the six categories is obtained by normalizing the number of events for each production mode to the related cross section. The signal yield is then corrected for the discrepancy in the number of D_s observed in data and MC. Finally, the 3μ mass spectra are parameterized with a fitting procedure for both signal (crystal ball function) and background (exponential).



(a) (b) (c)

(d) (e)

Figure 3: Number of $2\mu + 1track$ candidates with invariant mass in $[1.93, 2.01]$ GeV, per fb^{-1} per run. The red line shows the average D_s yield for each 2017 run period.

The CMS Higgs Combined Limit tool is used to perform statistical analysis. Upper limits on branching fraction $\tau \to 3\mu$ are set using the modified frequentist CLs criterion. The chosen test statistic which is used to determine how signal or background-like the data are, is based on the profile likelihood ratio. Systematic uncertainties are incorporated in the analysis via nuisance parameters and are treated according to the frequentist paradigm.

The expected upper limit obtained is:

$$\mathcal{B}(\tau \to 3\mu) = 1.16 \times 10^{-7} \text{at } 90\%\text{C.L.} \tag{2}$$

4 Future plans

Extending the search for the $\tau \to 3\mu$ decay to the full Run II data taking corresponding to $\sim 120\ \text{fb}^{-1}$ would exploit an increased statistics thus possibly providing a stricter upper limit on the branching fraction. My PhD research aims to analyse the full Run II data (i.e. including data collected in 2017 and 2018) using τ leptons from B and D decays to search for the $\tau \to 3\mu$ decay.

Most of the systematic uncertainties have been evaluated and the results are not discussed in this report for brevity. The evaluation of the uncertainty on the BDT response has to be evaluated using the $D_s \to \phi(\mu\mu)\pi$ control channel while the evaluation of the contribution from B meson decays, which cannot be directly normalized to $D_s \to \phi(\mu\mu)\pi$, is ongoing.

A key point of the search is the multi-variate analysis for the background rejection, which has to be optimized to get a higher rejection and increase the search sensitivity. For this reason I propose to study the impact of Machine Learning based discriminators, such has Deep Neural Networks, to better fit the background. An additional possible improvement for the analysis is the implementation of a dedicated muon identification algorithm specifically conceived to discriminate low transverse momentum muons from wrongly reconstructed kaons and pions.

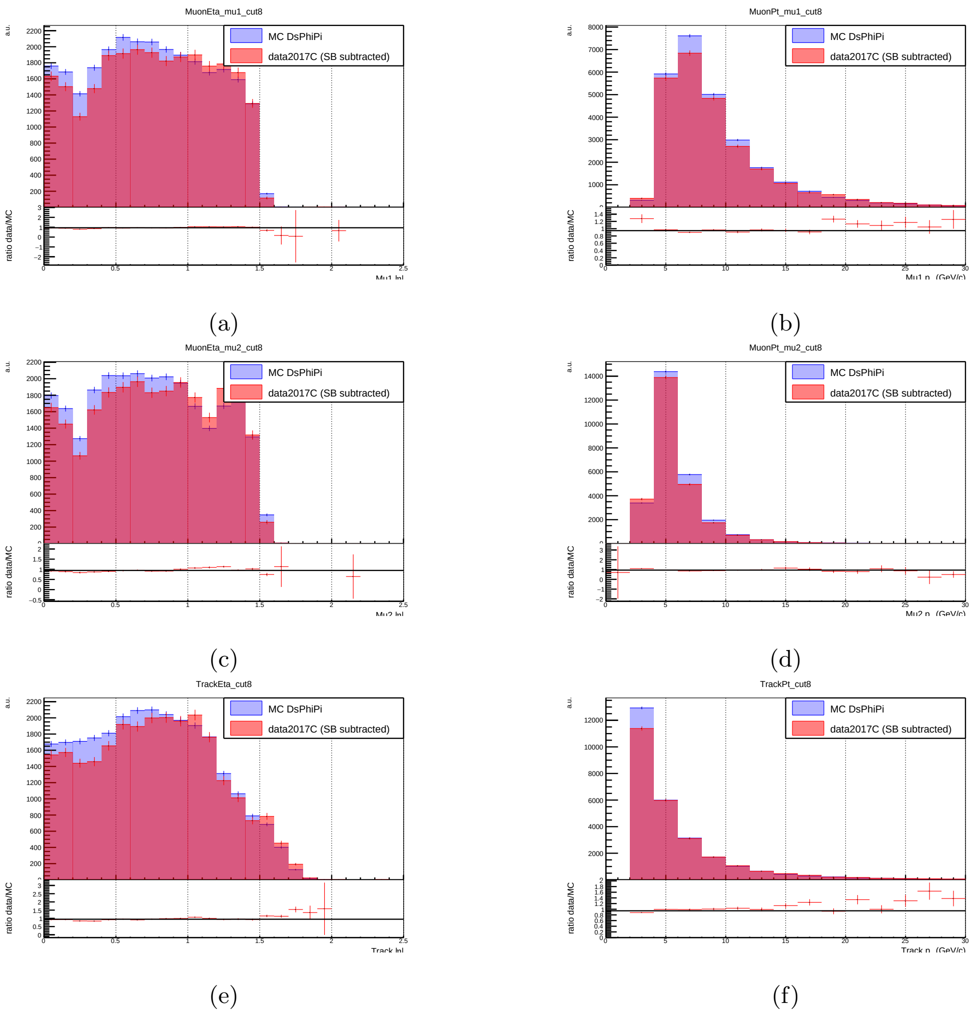


Figure 4: Distributions of transverse momentum and pseudorapidity for the 2 muons and 1 track from the $D_s \to \phi(\mu\mu)\pi$ candidate in Monte Carlo simulation (blue) and run C data (red).

References

[1] A. Soffer. *B-meson decays into final states with a τ lepton*. Modern Physics Letters A 29.07 (2014): 1430007. doi: 10.1142/s0217732314300079. arXiv:1401.7947

[2] K.S. Babu and C. Kolda. *Higgs-Mediated $\tau \to \mu\mu\mu$ in the Supersymmetric See-saw Model*. Phys. Rev. Lett., 89 (2002), 241802, doi:10.1103/PhysRevLett.89.241802, arXiv:hep-ph/0206310v2.

[3] R. Barbier et al. *R-parity violating supersymmetry*. Physics Reports, 420 (2005), 1, doi:10.1016/j.physrep.2005.08.006, arXiv:hep-ph/0406039.

[4] Belle Collaboration. *Search for Lepton Flavor Violating Tau Decays into Three Leptons with 719 Million Produced Tau+Tau- Pairs*. Phys. Lett. B 687 (2010) 139, doi:10.1016/j.physletb.2010.03.037, arXiv:1001.3221.

[5] CMS Collaboration. *Search for $\tau \to 3\mu$ decays using leptons produced in D and B mesons decays*. CMS-PAS-BPH-17-004, http://cds.cern.ch/record/2668282?ln=en.

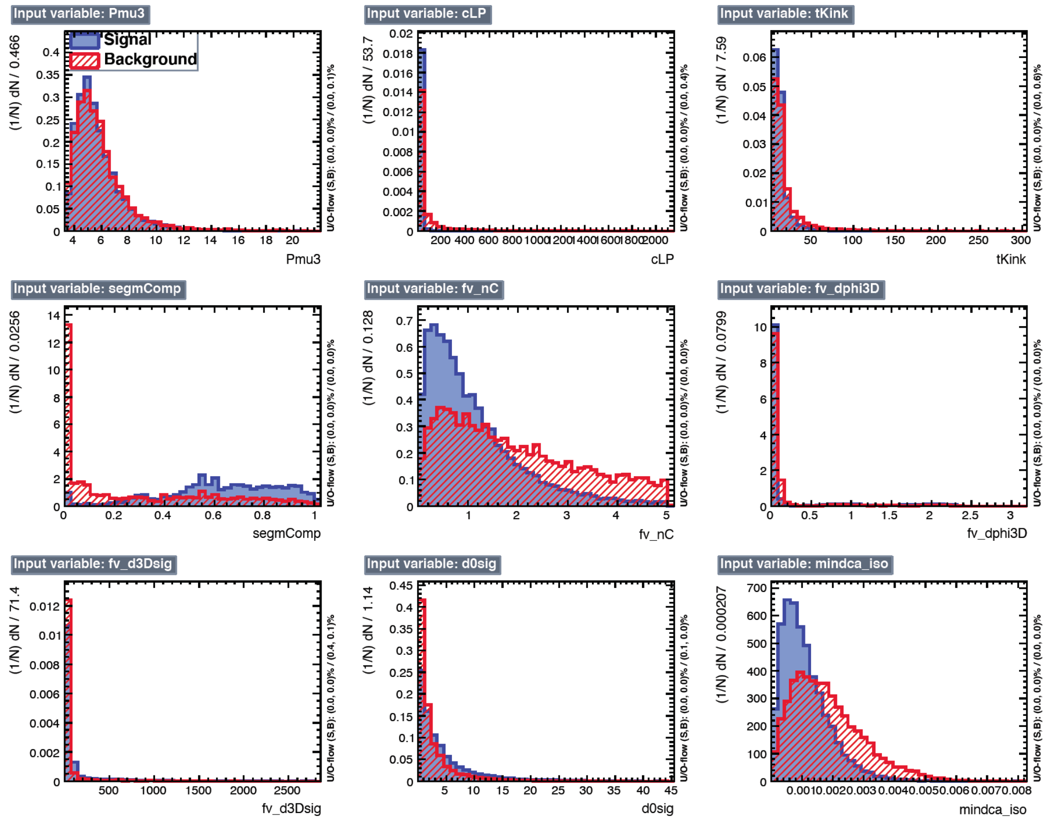
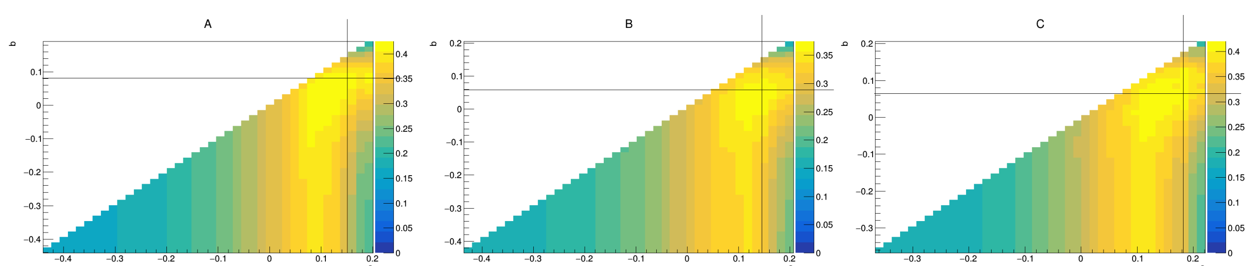
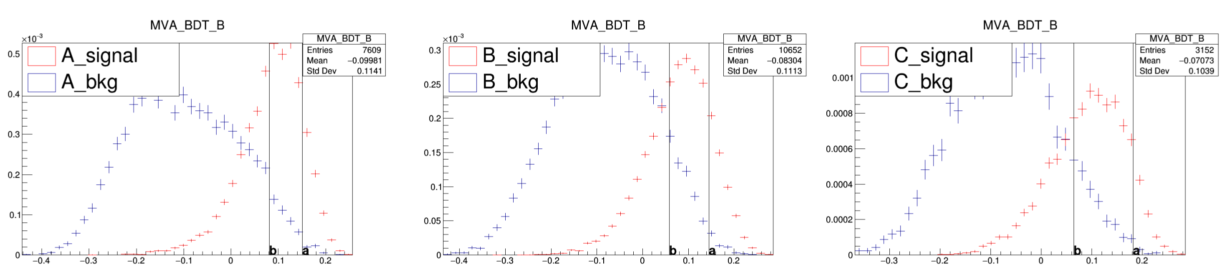


Figure 5: Signal (blue) and background (red) comparison of the variables used for the BDT training for event category A (i.e. invariant mass resolution $m < 0.0070$).



(a) (b) (c)

Figure 6: Combined signal significance in each category shown as a function of the values of the 2 cuts.



(a) (b) (c)

Figure 7: BDT response for the three categories of events. The 2 vertical bars indicate the cuts for sub-categories definition.

5 Exams taken

1. Machine Learning Techniques in High Energy Physics
2. Programming with Python
3. How to prepare a technical speech in English
4. Promozione della Ricerca (Percorso formativo in Comunicazione e Promozione della Ricerca)

6 Schools and workshops

- Joint 9th IDPASC School and XXXI International Seminar of Nuclear and Subnuclear Physics ”Francesco Romano”, Otranto, Italy, May 27 - June 4 2019.
- CMS Data Analysis School (CMSDAS) 2019, Pisa, Italy, Jan 28 - Feb 1 2019.

7 Conference talks and posters

7.1 Conference talks

- “Ricerca del decadimento $\tau \to 3\mu$ all’esperimento CMS”, 105^o National Congress of the Italian Physics Society, L’Aquila, Italy, Sept 23-27 2019.
- “Design e prestazioni dei rivelatori a tripla GEM per la stazione GE1/1 dell’esperimento CMS a LHC”, 105^o National Congress of the Italian Physics Society, L’Aquila, Italy, Sept. 23-27, 2019.
- “Upgrade of the CMS Muon System with Triple-GEM detectors”, IEEE International Workshop on Advances in Sensors and Interfaces (IWASI), Otranto, Italy, June 13-14 2019.
- “Upgrade del Sistema per Muoni dell’esperimento CMS con rivelatori a Tripla GEM”, IFAE2019: Incontri di Fisica delle Alte Energie 2019, Napoli, Italy, April 8-10 2019.

7.2 Conference posters

- “CMS GEM front-end electronics operational experience”, 2019 Winter LHCC meeting, CERN, Geneva, Switzerland, Feb 27 2019.

7.3 Expert talks

- “GEM sparks and VFAT protection”, CMS Muon Annual Review, CERN, Geneva, Switzerland, Oct 15 2019.

8 Publications

1. **"Measurement of properties of $\mathrm{B}_s^0 \to \mu^+\mu^-$ decays and search for $\mathrm{B}^0 \to \mu^+\mu^-$ with the CMS experiment"**
   A. M. Sirunyan *et al.* [CMS Collaboration].
   arXiv:1910.12127 [hep-ex]
   CMS-BPH-16-004, CERN-EP-2019-215

2. **"Search for supersymmetry with a compressed mass spectrum in events with a soft τ lepton, a highly energetic jet, and large missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV"**
   A. M. Sirunyan *et al.* [CMS Collaboration].
   arXiv:1910.01185 [hep-ex]
   CMS-SUS-19-002, CERN-EP-2019-196

3. **"Running of the top quark mass from proton-proton collisions at $\sqrt{s} = 13$ TeV"**
   A. M. Sirunyan *et al.* [CMS Collaboration].
   arXiv:1909.09193 [hep-ex]
   CMS-TOP-19-007, CERN-EP-2019-189

4. **"Search for long-lived particles using delayed photons in proton-proton collisions at $\sqrt{s} = 13$ TeV"**
   A. M. Sirunyan *et al.* [CMS Collaboration].
   arXiv:1909.06166 [hep-ex]
   CMS-EXO-19-005, CERN-EP-2019-185

5. **"Search for electroweak production of a vector-like T quark using fully hadronic final states"**
   A. M. Sirunyan *et al.* [CMS Collaboration].
   arXiv:1909.04721 [hep-ex]
   CMS-B2G-18-003, CERN-EP-2019-174

6. **"Measurements of differential Z boson production cross sections in proton-proton collisions at $\sqrt{s} = 13$ TeV"**
   A. M. Sirunyan *et al.* [CMS Collaboration].
   arXiv:1909.04133 [hep-ex]
   CMS-SMP-17-010, CERN-EP-2019-175

7. **"Searches for physics beyond the standard model with the M_{T2} variable in hadronic final states with and without disappearing tracks in proton-proton collisions at $\sqrt{s} = 13$ TeV"**
   A. M. Sirunyan *et al.* [CMS Collaboration].
   arXiv:1909.03460 [hep-ex]
   CMS-SUS-19-005, CERN-EP-2019-180

8. **"Search for production of four top quarks in final states with same-sign or multiple leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV"**
   A. M. Sirunyan *et al.* [CMS Collaboration].
   arXiv:1908.06463 [hep-ex]
   CMS-TOP-18-003, CERN-EP-2019-163

9. **"Search for supersymmetry in proton-proton collisions at 13 TeV in final states with jets and missing transverse momentum"**
   A. M. Sirunyan *et al.* [CMS Collaboration].
   arXiv:1908.04722 [hep-ex]
   CMS-SUS-19-006, CERN-EP-2019-152

10. **"Search for dark photons in decays of Higgs bosons produced in association with Z bosons in proton-proton collisions at $\sqrt{s} = 13$ TeV"**
A. M. Sirunyan *et al.* [CMS Collaboration].
arXiv:1908.02699 [hep-ex]
DOI:10.1007/JHEP10(2019)139
JHEP **1910**, 139 (2019)
CMS-EXO-19-007, CERN-EP-2019-159

11. **"Diamond-Like Carbon for the Fast Timing MPGD"**
A. Colaleo *et al.*.
arXiv:1907.13559 [physics.ins-det]

12. **"Tests and investigation towards the final design of the GEM front-end electronics"**
C. Aruta, F. Simone, F. Ivone, B. L. Domey, J. A. Merlin and E. R. Starling.
DOI:10.1109/IWASI.2019.8791335

13. **"Upgrade of the CMS Muon system with Triple-GEM detectors"**
F. M. Simone, R. Venditti and E. Soldani.
DOI:10.1109/IWASI.2019.8791422

14. **"Layout and Assembly Technique of the GEM Chambers for the Upgrade of the CMS First Muon Endcap Station"**
D. Abbaneo *et al.* [CMS Muon Collaboration].
arXiv:1812.00411 [physics.ins-det]
DOI:10.1016/j.nima.2018.11.061
Nucl. Instrum. Meth. A **918**, 67 (2019)

15. **"Operational Experience With the GEM Detector Assembly Lines for the CMS Forward Muon Upgrade"**
D. Abbaneo *et al.*.
DOI:10.1109/TNS.2018.2871428
IEEE Trans. Nucl. Sci. **65**, no. 11, 2808 (2018).