Study of CMS sensitivity to neutrinoless τ decay at LHC

R.Santinelli [a]

[a]Physics Department, University of Perugia and INFN Perugia,
1 via Pascoli, 06100 Perugia, Italy

The Large Hadron Collider (LHC), scheduled to start operation in 2006, is foreseen to provide in the first year of running a total of $\sim 10^{12}$ τ leptons.

CMS (Compact Muon Solenoid) is a general-purpose experiment designed to study proton-proton and heavy-ion collisions at LHC. Even if the Susy particles and Higgs searches together with the B-physics provide its main goal, the large number of τ-leptons provided, could allow a systematic study of tau-physics. We have performed a full simulation of CMS using GEANT 3 package and the object-oriented reconstruction program ORCA to study the sensitivity to neutrinoless tau decay $\tau \to \mu^+\mu^-\mu^-$ and $\tau \to \mu\gamma$. We present the analysis developed for these channels and the results obtained.

1. THEORETICAL INRODUCTION

In the Standard Model the neutrinoless decay of tau leptons are not foreseen because they would violate the *Charged Lepton Flavour* and/or the *Baryonic Number*. Until now there is no experimental evidence for such processes. The Noether theorem states that for every conservation law there must be an associated symmetry, with the converse also true. In the Standard Model we do not have a symmetry associated to the Charged Lepton Flavor Conservation law. It is simply a built in characteristic of the theory. Beyond the SM, a large number of existing theories can explain and accomodate them. An incomplete list will include the Standard Model with right handed neutrinos, the Fourth generation neutrino theory, See-Saw type II models, GUT-theory, Susy with R-parity broken, Super Strings theories, Leptoquarks, Technicolor.

Every model in the above list typically provides either a too optimistic or a too pessimistic expectation of the neutrinoless decay Branching Ratios. Nevertheless, from the experimental point of view, the mSUGRA scenario with right handed neutrinos offers the closest forecast to the future experimental sensitivity. In this theory the vertices causing the violation of charged lepton flavour are due to non diagonal terms in the slepton mass matrix which cannot be diagonalized simultaneously with the mass matrix of the neutrinos. Mixing vertices arise at 1-loop radiative corrections from Yukawa couplings between sleptons and neutrinos.[1] With an opportune choice of the input universal parameters and with a texture describing the mixing in neutrino sector in accordance with the Super Kamiokande experiment, it is possible to find a value of the Branching Ratio for the $\tau \to \mu\gamma$ around 10^{-7} while a 200 times lower value is expected for the $\tau \to \mu^+\mu^-\mu^-$.

2. CMS

The main features of this detector are the strong (4 Tesla) magnetic field, ensuring high momentum resolution for charged tracks, the efficient muon system, providing a very good reconstruction of muons and the very small global size.

The detector consists of a silicon tracker with an embedded pixel detector, a crystal $PbWO_4$ electromagnetic calorimeter (ECAL) and a copper-scintillator hadron calorimeter(HCAL). A sophisticated four station muon system made of tracking chambers, the drift tube (DT) and the cathode strip chamber (CSC) and of dedicated trigger chamber (the resistive plate chamber or RPC), is located outside the solenoidal magnetic field. The overall dimensions of the CMS detector are: 21.6 m in length, 14,6 m in diameter with a total weight of 14,500 tons. The analysis I will present here will rely heavily on the performance of the muon subdetector for its high efficiency to detect isolated muons (95%) and its low probability to misindentify pions or kaons as muons.

Another very important component of the CMS detector is its tracking system. The performance of the CMS tracker plays a fundamental role in the improvement of the Branching Ratio sensitivity for the tau to three muons decay channel.

The main requirements for the tracker are:

- high radiation resistance because the tracker will be the part of CMS closest to the primary interaction point and it will be therefore operating in a very high radiation enviroment
- a low material budget, to minimize the photon conversion and bremsstrahlung.
- high momentum resolution
- high secondary vertex reconstruction efficiency

The expected resolution on the transverse momentum of muons will be $\frac{\sigma_{Pt}}{Pt}$ =1.5% for 10 GeV muons and the resolution on the secondary vertex reconstruction about 200 μm. The particle detection efficiency is expected to be 95% for isolated charged tracks and 90% for tracks inside a jet.

As for what regards the calorimeters, they become of the utmost importance in the $\tau \to \mu\gamma$ analysis, where we require a good photon reconstruction.

The transverse energy resolution for electron/photon could be parameterized as:

$$\frac{\sigma_E^{ECAL}}{E} = \frac{a}{\sqrt{E}} \otimes b \otimes \frac{c}{E} \quad (1)$$

The "stochastic term" a arises from photoelectron statistics and shower fluctuations. The "constant term" b has contributions from non-uniformities and from shower leakage. The "noise term" c is due to electronics noise and pile-up. The design goal for the CMS ECAL barrel and endcaps are a = 2.7% and a = 5.7% respectively and b < 0.55% for both sections of the detector. Expressing the noise as traverse energy, the goals for the c term are at low luminosity c=155MeV for the barrel part and 205MeV for the end-caps. The phi-angle resolution is expected to be 1.3 mrad.

3. $\tau \to \mu^+\mu^-\mu^-$

In Table 1 we summarize the main sources of tau leptons at LHC as we have found using PYTHIA 6.152 generator and the branching ratios listed in the PDG tables.

The total cross section will be around 120 μb for a total number of taus produced after one year of low luminosity of LHC (integrated luminosity of 10 fb^{-1}) of 10^{12} tau lepton. Because we will only be capable to trigger on the higt p$_t$ particles, we have concentrated on the following signal sources:

- W source, $\sigma(pp \to W \to \tau\nu_\tau)$=19 nb [2]
- Z source, $\sigma(pp \to Z \to \tau\tau)$=3nb
- B source, $\sigma(pp \to B \to \tau D\nu$=24$\mu$b

The W source, as we shall see, represents the best source for the signal.

3.1. The background

The presence of three well reconstructed, collimated and isolated muons offers a very clear signature for the signal. According to the results of [3] the main sources of μ that could contribute to the background will be:

- heavy quark mesons (D & B)
- pile-up effects from primary interactions
- Gauge bosons and Drell Yan (Z,W)
- τ production
- cosmic rays
- Susy Particles
- Higgs decay
- non prompt muons (punchthrough pions non interacting in the calorimeters)

Table 1
Main sources of τ-leptons at LHC

Meson (M)	D_S	D^+	B^0	B_S	B^+
$BR(M \to \tau + X)$	7.0%	0.2%	2.7%	1.5%	2.7%
$\sigma(M \to \tau + X)/\sigma(pp \to \tau + X)$	77%	3%	9%	2%	9%

Pile-up effects from primary interactions and tau source of muons are not considered for their low probability to have a final three muons topology. The cosmic rays will be removed by timing. W and Z source will give negligible contribution due to their distinctive high mass. Susy particles and Higgs sources present a too low total production cross section to be really dangerous at the present sensitivity attainable.

We focused then on heavy quarks mesons and on unphysical background. Events were simulated using the PYTHIA [6] kinematics generation followed by the GEANT3 ([8]) based simulation program CMSIM ([7]) and the reconstruction program ORCA ([9]).

3.2. Heavy quarks mesons events

We focus our investigations on events with only 3 muons in the final state. This kind of event can occur in two different ways as depicted in fig. 1.

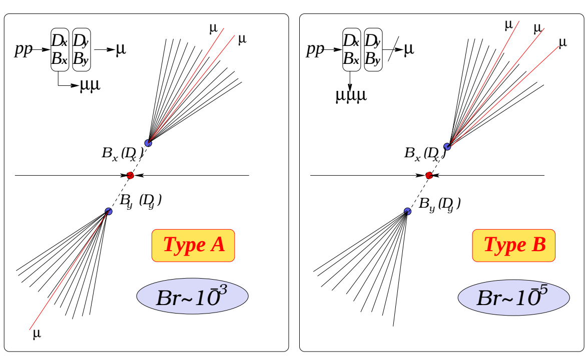

Figure 1. Three muons from $b\bar{b}$ and $c\bar{c}$ events

A preliminary study, conducted at kinematic generation level, has shown that an upper cut on the angle between two muons removes completely events of type A, leaving almost all the events of type B. These can be generated by forcing decay cascades where some resonance rare decays should be included like $\phi \to \mu\mu$ For the background we forced the following decays

- $pp \to D_X D_S \to D_X \mu\nu_\mu \phi \to D_X \mu\nu_\mu \mu\mu$
- $pp \to B_X B_S \to B_X \mu\nu_\mu D_S \to B_X \mu\nu_\mu \mu\mu K$

It is worthwhile to note that the choice of the ϕ as the resonance decaying into 2 μ is not unique, but one of the most important. We could use other resonances like ω, η, η' but their contribution will be too small. Moreover, to increase the final statistics, we required, at the generation level, three muons with a transverse momentum greater than 3 GeV. We will refer to these events as *preselected*. Finally, we obtained from a fast simulation, the very important information that the $b\bar{b}$ events are negligible if compared with $c\bar{c}$. This is true because the reconstructed final three muons mass for $b\bar{b}$ events is shifted toward 4-5GeV values while the one from $c\bar{c}$ is peaked around 1.5 GeV.

We will consider then the events $pp \to D_X D_S \to D_X \mu\nu_\mu \phi \to D_X \mu\nu_\mu \mu\mu$ as the main source of background (*main background*)

3.3. Signal and analysis

Different τ-sources give rise to different signal signatures. We have therefore adopted three different sets of cuts appropriate for the different sources of signal.

3.3.1. τ from W

These events are mainly characterized by a high value of missing energy. Indeed the tau coming from W decay shares half of the initial boson's energy with the corresponding neutrino and this will be detected as an high missing energy, (see fig. 2).

Here we have for the signal from W the typical Jacobian peak around 35 GeV while the distribution is shifted toward low values for the main background and for the signal from Z. The complete analysis implemented for these events require:

- trigger

  1. at least 3 muons passing the CMS trigger level 1 (L1)
  2. 2 or more CMS level 3 muons (the final CMS trigger level for muons) (L3)

- identification

  1. only 3 well reconstructed and close muon candidates from tracker with a Pt>4GeV in the barrel region and Pt>2.5GeV in the endcaps
  2. total charge equal ± 1

- topology

  1. Common secondary vertex (not necessary to implement!)
  2. no charged tracks inside a cone of $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta} = 0.4$ around the μ tracks. (ϕ is the azimuthal angle and η is the pseudorapidity).

- missing transverse energy >20GeV

- veto on phi-mass region (1020±25)MeV for any couple of muons

- reconstructed three muons mass =1778±20MeV

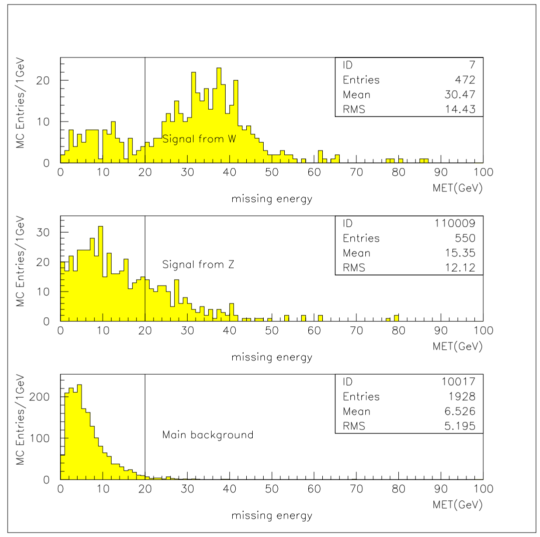

Figure 2. Transverse missing energy

The isolation cut is justified by the high multiplicity of background events and the low number of tracks for this kind of signal. In figure 3 we compare the number of tracks around the three muons for the signal from W, for the background and for the signal from B. Once again we would remove a large number of events from this source by excluding the events with other charged tracks around the three muons.

In figures 4 and 5 we illustrate the secondary vertex cut and the veto on phi mass. The probability to have three muons from a common secondary vertex is shown in figure 4. From this figure we also see how signal and cc events present the same distribution while, as expected, the bb events have a peak at zero. In this case the muon pair originating from Ds decay presents a vertex position distinct from the origin position of the third muon coming directly from Bs decay. The dimuon-mass plot for signal and main background are self-explanatory and do not need any other comment. Finally we remove all the background events by applying the three muons mass cut where the resolution found for the signal is 15MeV. At the end of the analysis, with

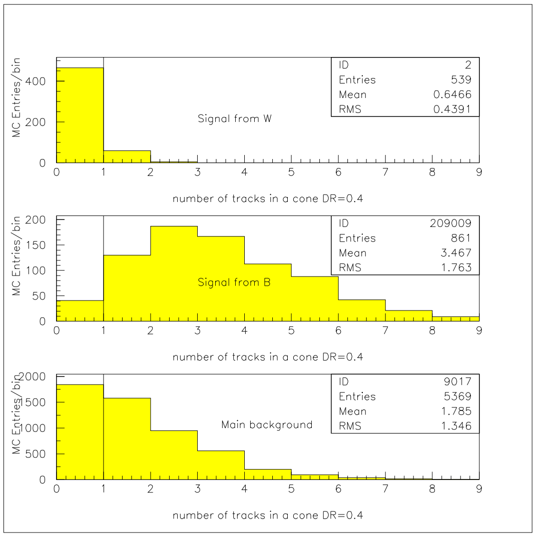

Figure 3. Number of track inside a cone of opening =0.4 around the three muons

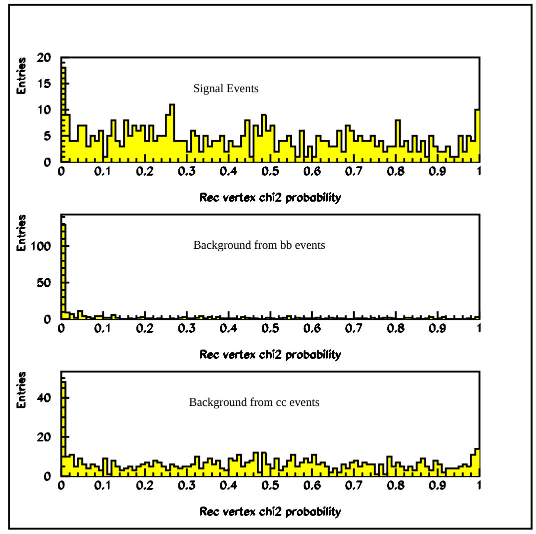

Figure 4. Reduced chi squared probability of three muons to belong to same vertex

the hypothesis that the BR of tau in three muons is the actual experimental limit set by CLEO II (1.9×10^{-6}), we expect after one year 44±2 signal events against 1±1 of the background. In fig 6 we illustrate the plot of the signal plus background and background as expected with an integrated luminosity of $10fb^{-1}$ (available after one year of LHC running at $\mathcal{L} = 10^{33}cm^{-2}s^{-1}$) and assuming the Branching Ratio to be equal to the present CLEOII experimental limit. This will correspond to an upper limit on the BR (at 90% CL) of 8.4×10^{-8}.

3.3.2. τ from Z and from B

In this case we can exploit the second tau which is selected by applying a second isolation criterion based on the fact that the tau usually decays into one or three well collimated charged tracks. Moreover this tau and the tau signal will give the reconstructed Z-mass. The analysis used for this source is quite similar to that of the W source with the main difference that we do not apply the missing energy cut but we require the following additional cuts:

- second tau isolation (1 to 3 tracks inside a narrow cone of 0.03 aperture and no other tracks inside a broader and complementary cone of opening 0.4 with Pt>1.5
- Pt_τ >23GeV
- reconstructed mass of the tau-jet+ missing energy+three muons greater than 70GeV

In figure 7 we have a summary of the Z-dedicated set of cuts. In the upper part we have the distribution for the signal while in the bottom that for the main background.

Because of the lower Z production cross section, the final number of events from Z surviving our analysis will be 4±1 with 0.8±1 background events for $10fb^{-1}$. The corresponding sensitivity if no signal is detected will be 7.6×10^{-7}.

The final source of signal considered was the B. At low luminosity running of the collider this could be a very important source of signal. These

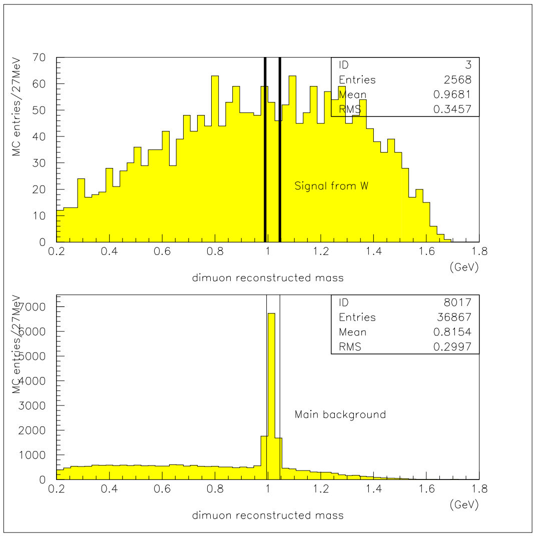

Figure 5. Combinatorial dimuon mass

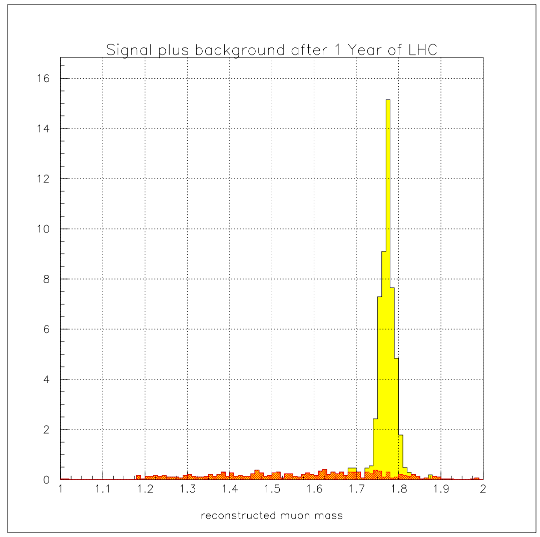

Figure 6. Signal plus background after one year of luminosity of LHC assuming a BR equal to the CLEOII limit

events present a signature completely different from the previous ones. First, their multiplicity is too high to apply an isolation cut and the missing energy selection can not be applied. Second the energy of the tau is not so high to be a good cut candidate. In this case after the trigger and the identification criteria, we therefore require two consecutive b-tag for the two b-jet candidate. The b-tag algorithm considered was the simplest possible one by requiring some track for each event inside a jet with a significance of the transverse impact parameter greater than a given value, which can be tuned. In figure 8 we show this variable for the three muons jet for signal events (top) and main background (bottom). We cut out events presenting less than 3 tracks with significance of impact parameter greater than 2. With this analysis we can to reach a sensitivity of BR at 90% equal 3.8×10^{-7}.

3.4. Instrumental background

Till now we estimated the sensitivity by considering only physical channels whose experimental signature is closest to that of the signal. However, given the very low sensitivity we want to reach, it is dangerous to exclude a priori other sources of background arising in an experimental environment. Although,(see [4]), the estimation of the probability to mistag at CMS trigger level 1 a light meson (pion or kaon) as a muon is very low ($\sim \frac{1}{100}$) and decreases with the threshold on the roughly reconstructed level 1 transverse momentum of the particle, we have done a systematic analysis to evaluate their contribution. First we generated 500 events, as kinematically close as possible to the signal, and considered the decay $\tau \to \pi\pi\pi\nu_\tau$ (with the tau from W) replacing two pions with two real muons. In this way we are able to estimate the probability to mistag the third π as μ by simply counting how many close muons have been reconstructed by our simulation program at level 1 or 2 or 3. In figure 9 we show these numbers.

We found at level-1 that 5 events (among 500) present 3 μ. We can then estimated a 1% misidentification probability.

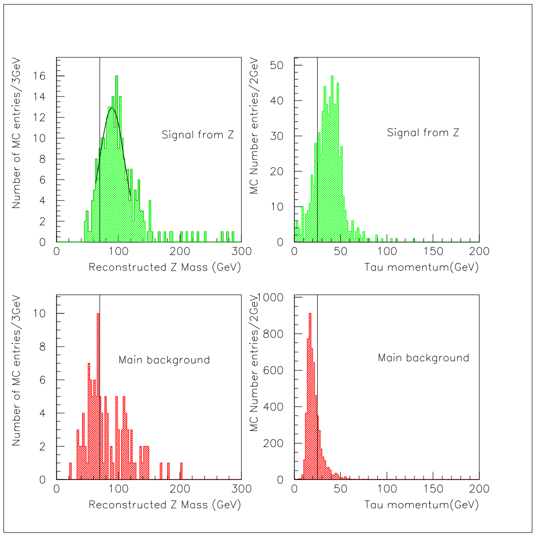

Figure 7. Main kinematical variables used for the Z-dedicated analysis

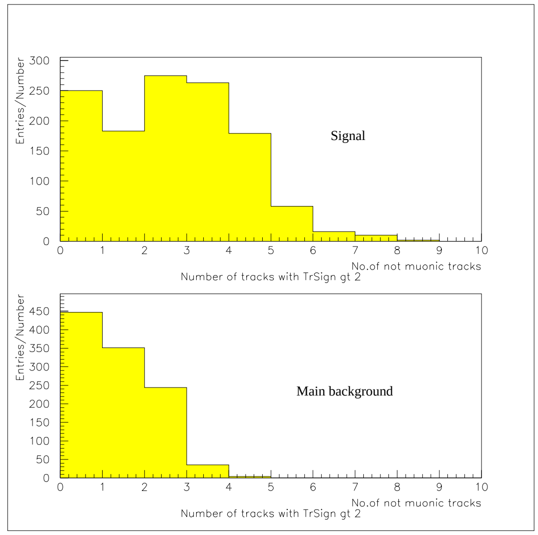

Figure 8. Number of tracks with a significance of IP greater than 2

After this cross-check, we have considered as background the following channel, $\tau \rightarrow \pi\pi\pi\nu_\tau$, with all the three pions misidentified as muons. The expected number of events passing after one year the analysis (W dedicated) is given by the formula:

$$N_{1year} = \mathcal{L} \times BR(pp \rightarrow W \rightarrow \tau\nu) \times$$
$$BR(\tau \rightarrow \pi\pi\pi\nu) \times P(\pi \rightarrow \mu)^3 \times \epsilon_{analysis} \qquad (2)$$

With $\epsilon_{analysis} \simeq 10^{-3}$ and BR$\sim$ 9%, we found for these events an expected rate negligible compared with the physical background.

4. $\tau \rightarrow \gamma\mu^-$

Encouraged by the previous results we have undertaken a preliminary study of the possibility to detect the $\tau \rightarrow \mu\gamma$ decay channel, which is expected to be much higher even if much harder to be detected experimentally. We have focused on the τ source which allows to exploit the large missing energy expected. So the background has to be sought inside muons sources with high missing energy. The same background should have a very hard and well isolated muon. From these preliminary considerations we focused our attention to the following events:

- $pp \rightarrow W \rightarrow \mu\nu_\mu$ (SAMPLE A $\sigma = 19nb$)
- $pp \rightarrow W\gamma \rightarrow \mu\gamma\nu_\mu$ (SAMPLE B $\sigma = 0.18nb$)
- $pp \rightarrow W \rightarrow \tau\nu_\tau \rightarrow \mu\nu_\mu\nu_\tau\nu_\tau$ (SAMPLE C $\sigma = 2.1nb$)

These events present similar kinematical features although some important differences arise. The sample A present the highest cross section. The photon presence is not assured and eventually it could come from some π^0. The sample B, with a photon radiated from primary interaction, present a cross section 100 times smaller. The muon is very hard and the photon is not always close to the muon. The sample C is expected to have the most signal like distributions and then the rejection power to be the poorest among the channels considered. The analysis steps are the following:

- Level 1 trigger

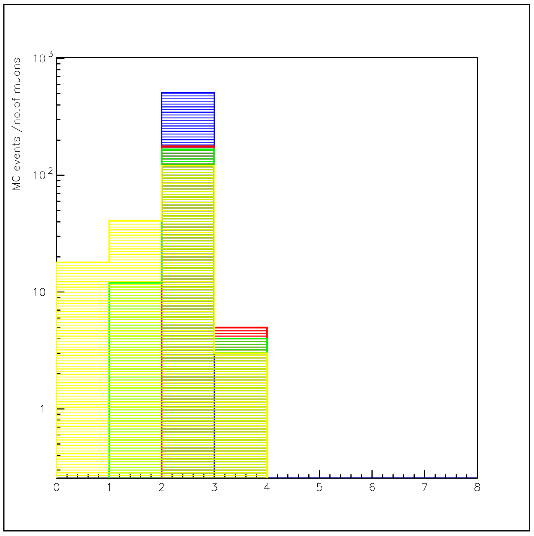

Figure 9. Number of real, L1, L2 and L3 reconstructed muons

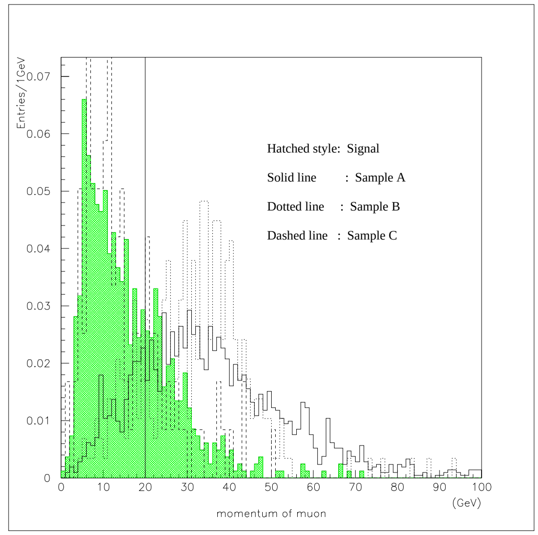

Figure 10. Muon momentum distribution

1. 1 photon with L1 $E_T > 25$ GeV or
2. 1 muon with L1 $p_T > 20$GeV or
3. 1 muon with L1 $p_T > 5$GeV and 1 photon with L1 $E_T > 15$ GeV

- high level trigger:1 well reconstructed photon (level 2) and one muon L3 or just one high transverse momentum track close to the photon
- reconstructed transverse energy of photon greater than 18 GeV
- missing transverse energy greater than 20 GeV
- candidate muon momentum less than 20 GeV
- angular distance between muon and photon greater than 008 and less than 0.15
- significance of impact parameter of muon greater than 2
- reconstructed mu-gamma mass equal the tau mass $\pm$ 60MeV

In figure from 10 to 12 we illustrate the distributions of the quantities used in the analysis. The sample C of background is shown as a dashed line in figures 10 and 11. In solid line we plotted the same variables for sample A events and in dotted line for sample B. We note that the sample C shows distributions for the μ momentum and transverse impact parameter closest to these for the signal. In figure 12 and 13 we plotted the transverse energy of the photon for the signal (filled area) and for the background (solid line) and angular distance between muon and photon. We do not show for these quantities the distribution for sample B and C whose shape is similar to the sample A.

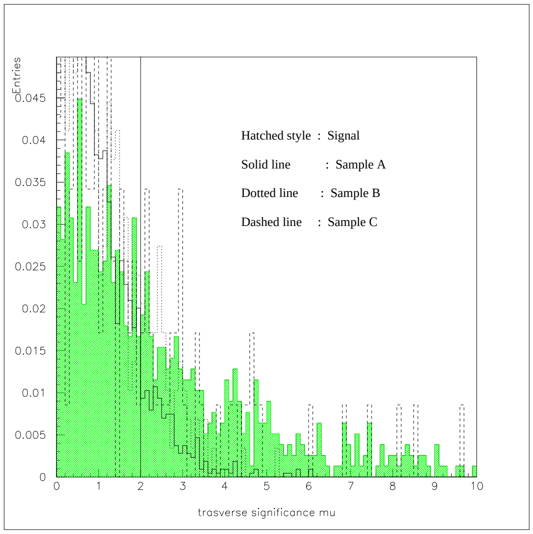

Figure 11. Muon transverse impact parameter significance distribution

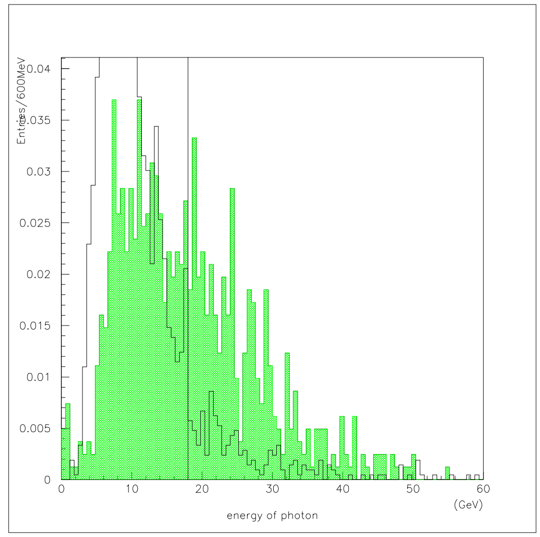

Figure 12. Photon transverse impact energy distribution (filled area for the signal)

In figure 14 we present the photon-muon reconstructed mass for the signal events. We also plot the mass region around the tau mass which shows a resolution of around 40 MeV. (this is worse than one found in CLEOII and Atlas collaboration [5]) At the end of the analysis we still remain with around 6% of MonteCarlo initial signal events produced and we remove all the initial 40000 events of sample A and 3500 events of sample B and C. The normalized number of background events expected after one year is 13 from sample A, less than 1 from B and 18 events from sample C which is confirmed to be the most dangerous background. To find these numbers we adopted the hypothesis the mass distribution for the background is uniform in the range between 0 to 3 GeV. This is a rather pessimistic hypothesis, because the mass for the background (upper box in fig. 15) is peaked below 1 GeV/c^2 and in the interesting region (τ-mass $\pm$ 60MeV/c^2) the number of events is smaller than the one foreseen with a flat distribution assumed. With these assumptions we evaluated the BR to be less than 10^{-6} for the $\tau \rightarrow \mu\gamma$ after one year of low luminosity of LHC taking data.(10 fb^{-1})

5. Conclusion

We have presented the MonteCarlo based analysis of neutrinoless decays channel $\tau \rightarrow \mu^+\mu^-\mu^-$ and $\tau \rightarrow \mu\gamma$ using the CMS object-oriented reconstruction program ORCA. We isolated and analysed three important sources of signal. We found that the most dangerous background for the first channel is represented by $c\bar{c}$ events with three muons coming from a common meson. After one year of low luminosity of LHC we could improve by a factor 25 the actual experimental sensitivity to this channel by using only the W source. Other channels (Z and B) give a minor contribution in the present analysis. For the $\tau \rightarrow \mu\gamma$ channel the most dangerous background arises from leptonic decays of W boson and a first study confirms the results of ATLAS. The signal is background limitated and the CMS sensitivity for this analysis will be similar to that expected at the B factories.

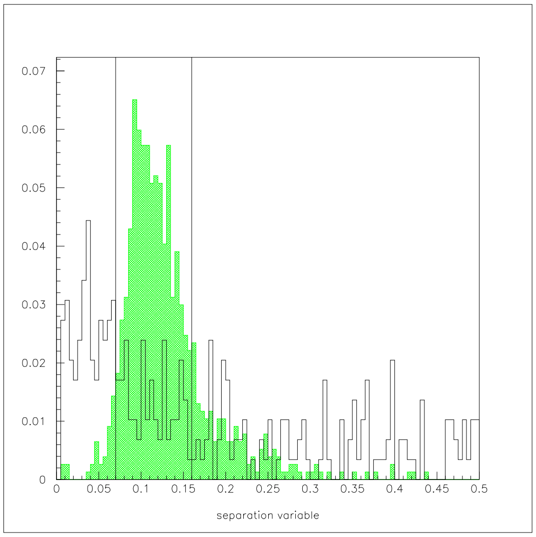

Figure 13. Photon-muon angular distance distribution (filled area for the signal)

Nevertheless, more detailed studies of pile-up effects are required to extend the analysis to higher luminosity.

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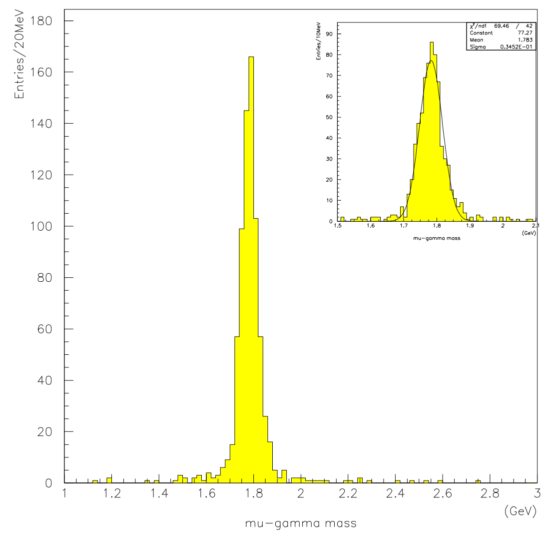

Figure 14. Signal muon-photon reconstructed mass

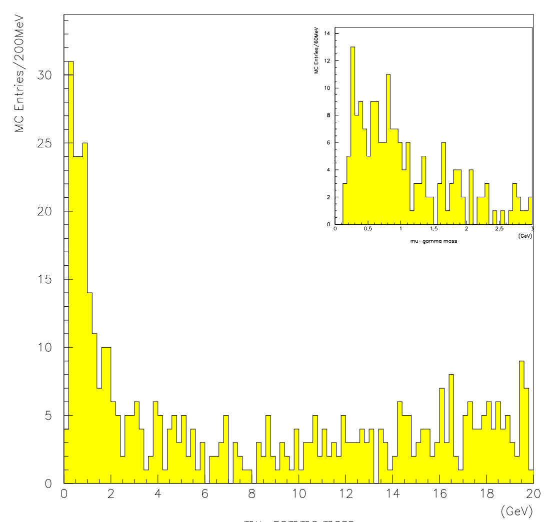

Figure 15. Background muon-photon reconstructed mass