Study of the inclusive four-lepton productions at LHC

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1. Introduction:

My project in this summer is using MCFM program to do Monte Carlo simulation of data coming from world's largest and most powerful collider-LHC.

My main work is to:

1. Study using Monte Carlo simulation about proton-proton collision of the four-lepton final states.
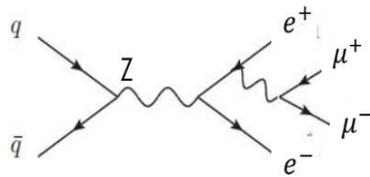
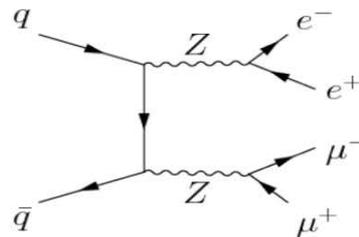2. Calculate the cross sections of the following 4 different processes:

qq->Z->eeµµ,
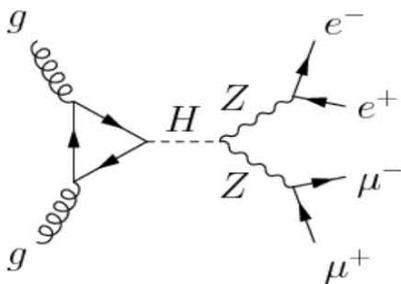
qq->ZZ->eeµµ,

gg->H->ZZ->eeµµ,
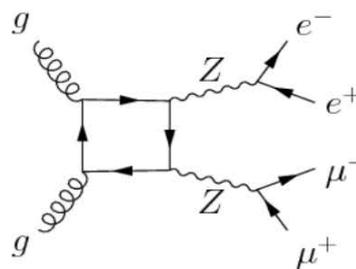
gg->ZZ->eeµµ,

FIG.1 Main processes of four-lepton final states

3. Study the interference between Higgs-mediated and continuum processes of four-lepton final states.

4. Study the difference of cross sections between two-electron-two-muon final state and four-electron final state in qq process.

5. Bound the Higgs width in high mass of four-lepton.

2. Study of the four-lepton mass spectra at CMS cuts

My first work is reproducing the work in arXiv: 1311.3589 which used CMS cuts to calculate the cross-sections of processes I have mentioned above.

I present the 4l mass spectra at 8TeV and 13TeV in Figs. 2 and 3. These plots have been applied to the CMS cuts which are detailed as follow:

$$P_{T,\mu} > 5GeV, \quad \left|\eta_\mu\right| > 2.4$$

$$P_{T,e} > 7GeV, \quad \left|\eta_e\right| > 2.5$$

$$m_{ll} > 4GeV, \quad m_{4l} > 100GeV$$

In addition, the transverse momentum of the hardest lepton should be larger than 20GeV and that of the next hardest lepton should be larger than 10GeV. The invariant mass of the pair of same-flavor leptons closer to the Z-mass among the 2 pairs should be in the interval $40GeV < m_{ll} < 120GeV$ and that of the other pair should be in the interval $12GeV < m_{ll} < 120GeV$. What is more, for the input of MCFM program, the QCD renormalization and factorization scale has been set equal to $m_H/2$, and the PDF (parton distribution function) has been set to MSTW2008.
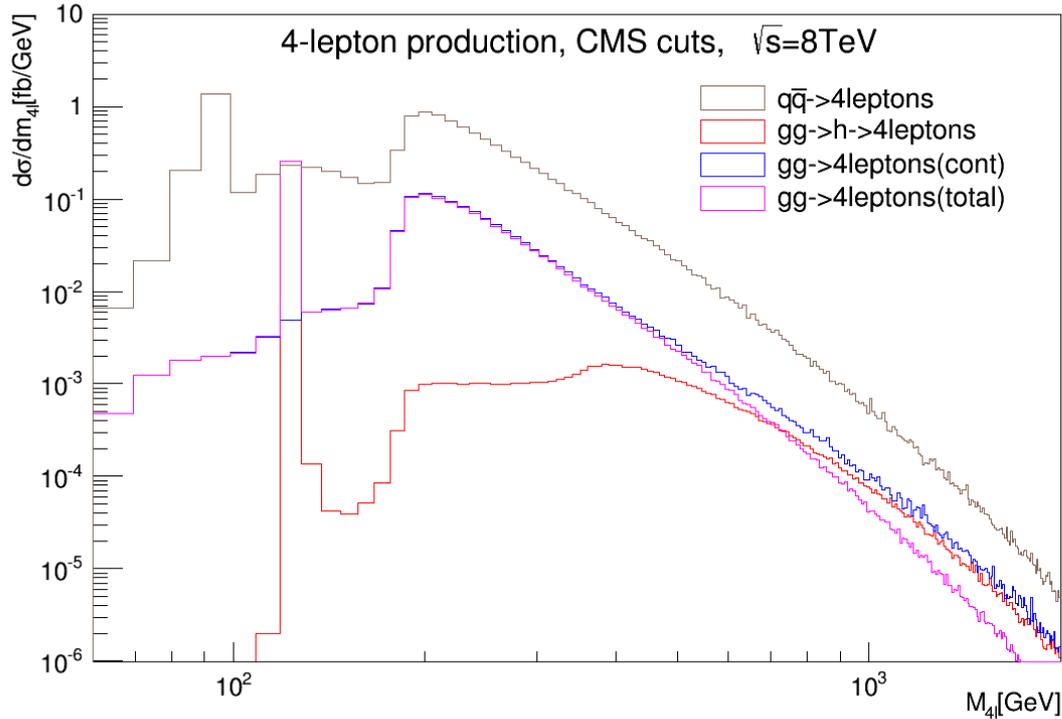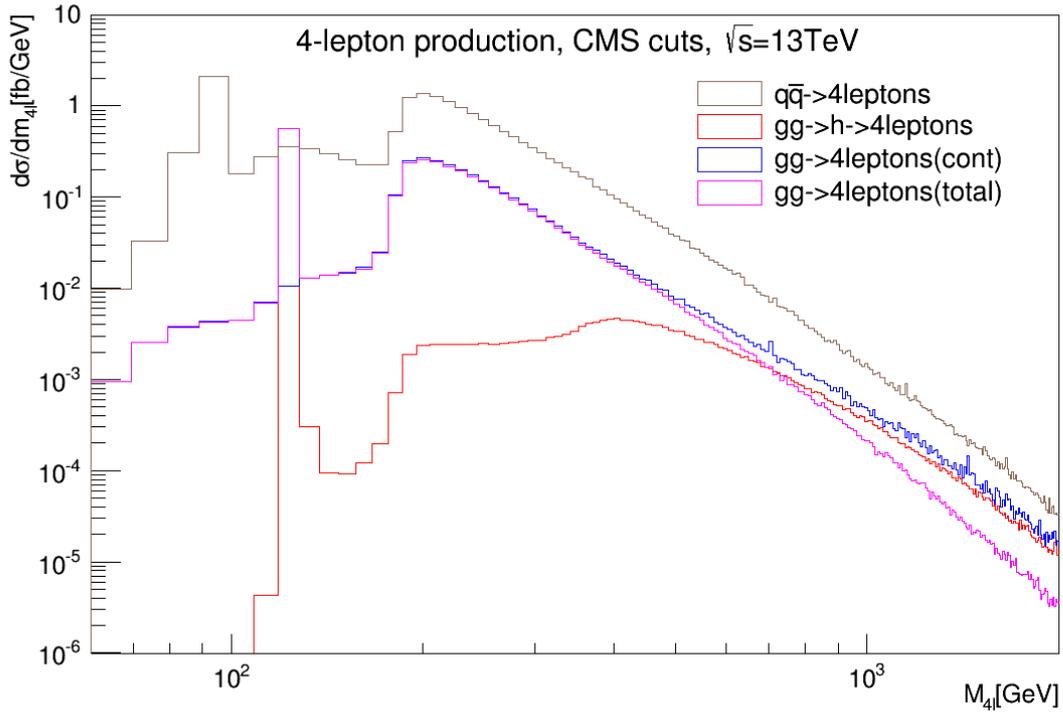

FIG. 2 4l mass spectra at 8TeV

FIG. 3 4l mass spectra at 13TeV

Process	MC Produced Events	Total Cross-section (fb)	Cross-section in CMS cuts (fb)
qq->ZZ->eeμμ	18600000	199.17	11.35
gg->H->ZZ->eeμμ	22500000	0.64	0.32
gg->ZZ->eeμμ (cont.)	19800000	25.18	1.16
gg->ZZ->eeμμ (total)	24000000	25.61	1.36

TABLE 1 Cross sections for different processes at 8TeV.

Process	MC Produced Events	Total Cross-section (fb)	Cross-section in CMS cuts (fb)
qq->ZZ->eeμμ	29900000	329.13	18.02
gg->H->ZZ->eeμμ	28000000	1.59	0.75
gg->ZZ->eeμμ (cont.)	19500000	51.29	2.89
gg->ZZ->eeμμ (total)	28000000	52.42	3.29

TABLE 2 Cross section for different processes at 13TeV.

Energy	Process	$m_{4l} < 130GeV$	$m_{4l} > 130GeV$		$m_{4l} > 300GeV$	
		σ^H_{peak} (fb)	σ^H_{off} (fb)	σ^I_{off} (fb)	σ^H_{off} (fb)	σ^I_{off} (fb)
8TeV	gg->H->ZZ->eeμμ	0.26	0.06	-0.12	0.05	-0.07
	gg->ZZ->eeμμ (cont.)	0.27	1.09		0.21	
	gg->ZZ->eeμμ (total)	0.01	1.15		0.23	
13TeV	gg->H->ZZ->eeμμ	0.56	0.19	-0.34	0.16	-0.23
	gg->ZZ->eeμμ (cont.)	0.04	2.85		0.66	
	gg->ZZ->eeμμ (total)	0.60	2.65		0.59	

TABLE 3 Interferences of gg processes at 8TeV and 13TeV.

Tables 1 and 2 show the cross sections of the four processes, and Table 3 shows the interference between Higgs-mediated and continuum productions. All these numbers are calculated from data of MCFM. From the Cross sections in CMS cuts, one can find that the gg processes cross sections increase faster from 8TeV to 13TeV than the background (qq processes), which means at higher energy the gg-initial processes are more sensitive than the background. So it is easier to observe more Higgs events at 13TeV.

3. Extracting Higgs width

In order to study the relationship between Higgs width and cross sections at different regions of gg->H->ZZ->eeμμ process, here I need to verify that in on-peak region the cross section is inversely proportional to the Higgs width, while in off-peak region the cross section is independent with Higgs width:

$$\begin{cases} \text{On} - \text{peak}: \sigma_{i \to H \to f} \sim \frac{g_i^2 g_f^2}{\Gamma_H} \\ \text{Off} - \text{peak}: \sigma_{i \to H \to f} \sim g_i^2 g_f^2 \end{cases}.$$

I set different values of ξ in the input file of MCFM program based on the rescaling: $g_x \to \xi\, g_x$, $\Gamma_H \to \xi^4\, \Gamma_H$. Here g_x is Higgs coupling and Γ_H is Higgs width. FIG. 4 shows the 4l mass spectra at different ξs. The Higgs widths in this spectra are as follow:

$$\Gamma_H = 0.004307\text{GeV (mH=126 GeV)} \quad \text{(SM)}$$
$$\Gamma_H 1 = 0.004307 GeV \ (\xi_1^4 = 1)$$
$$\Gamma_H 2 = 0.107675 GeV \ (\xi_2^4 = 25)$$

From Fig. 4 one can clearly see that at the peak of Higgs, the difference between two histogram is small, however, at high mass of 4l region which belongs to off-peak region, the difference is really big.
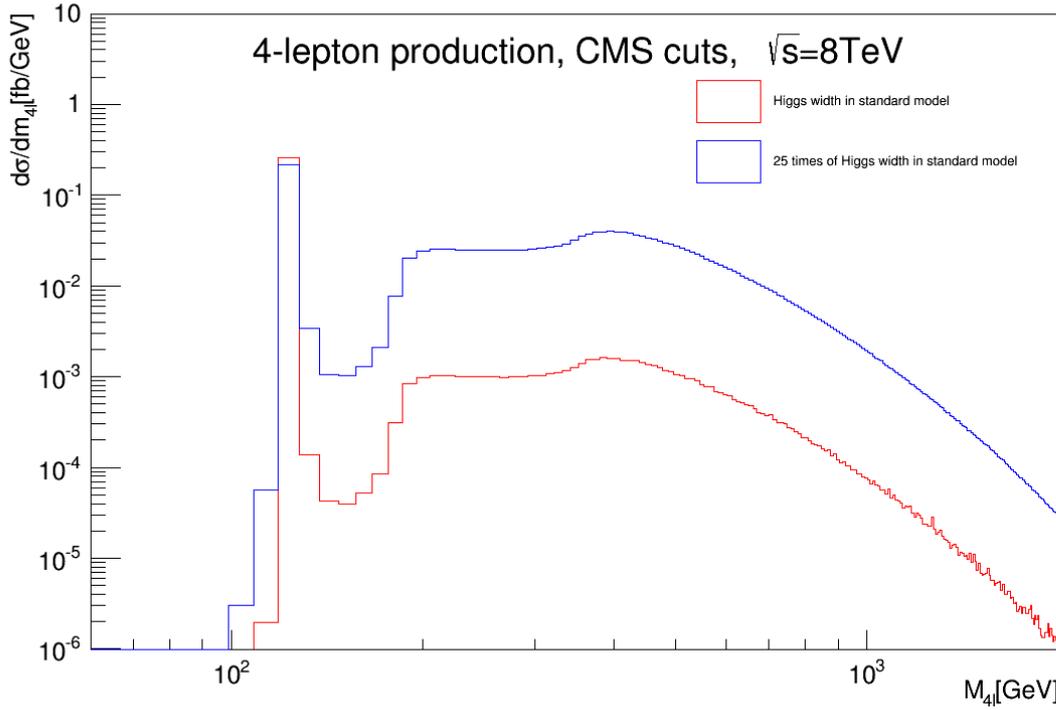
FIG. 4 4l mass spectra at different Higgs width of process gg->H->ZZ->eeμμ at 8TeV

Energy	ξ^4	$\sigma_{on-peak}$ (fb)	$\sigma_{off-peak}$ (fb)
8TeV	1	0.26	0.06
	25	0.26	1.53
13TeV	1	0.56	0.19
	25	0.56	4.68

TABLE 4 Cross sections at different Higgs width of process gg->H->ZZ->eeμμ at 8TeV.

Table 4 shows the cross sections at both 8TeV and 13TeV with different rescaling, from which the ratio of cross sections in both on-peak region and off-peak region are calculated:

At 8TeV : $\begin{cases} \dfrac{\sigma_{off-peak}\ (\xi^4=25)}{\sigma_{off-peak}\ (\xi^4=1)} = \dfrac{1.53}{0.06} = 25.5 \sim 25 = \dfrac{\Gamma_H 2}{\Gamma_H 1} \\ \\ \dfrac{\sigma_{on-peak}\ (\xi^4=25)}{\sigma_{on-peak}\ (\xi^4=1)} = \dfrac{0.26}{0.26} = 1 \end{cases}$

At 13TeV: $\begin{cases} \dfrac{\sigma_{off-peak}\ (\xi^4=25)}{\sigma_{off-peak}\ (\xi^4=1)} = \dfrac{4.68}{0.19} = 24.6 \sim 25 = \dfrac{\Gamma_H 2}{\Gamma_H 1} \\ \\ \dfrac{\sigma_{on-peak}\ (\xi^4=25)}{\sigma_{on-peak}\ (\xi^4=1)} = \dfrac{0.56}{0.56} = 1 \end{cases}$

From the results of the calculation above, one can find that the cross section at Higgs resonance region (on-peak region) is independent on Higgs width, but in off-peak region they

are strongly dependent. So it is easier to extract Higgs width at off-peak region than in on-peak region.

4. Study of the four-lepton mass spectra at ATLAS cuts

After the study of CMS cuts by reproducing the paper, I change the event selection from CMS cuts to ATLAS cuts. The detail of ATLAS cuts are as follows:

$$\left|\eta_\mu\right| > 2.7, \quad \left|\eta_e\right| > 2.5$$
$$m_{ll} > 4GeV, \quad m_{4l} > 70GeV$$
$$\Delta R(l, l') > 0.2, \quad \Delta R(l, l) > 0.1$$
$$P_{T,z} > 2GeV$$

In addition, the transverse momentum of the first and second hardest leptons should be larger than 20GeV and 15GeV respectively. And if the transverse momentum of the third and forth hardest lepton are electrons, they should be larger than 10GeV and 7GeV respectively, if they are muons, they should be larger than 8GeV and 6GeV respectively. What is more, the invariant mass of the pair of same-flavor leptons closer to the Z-mass should be in the interval 50GeV $< m_{ll} <$ 120GeV, and the other pair should be in the interval 12GeV $< m_{ll} <$ 120GeV.
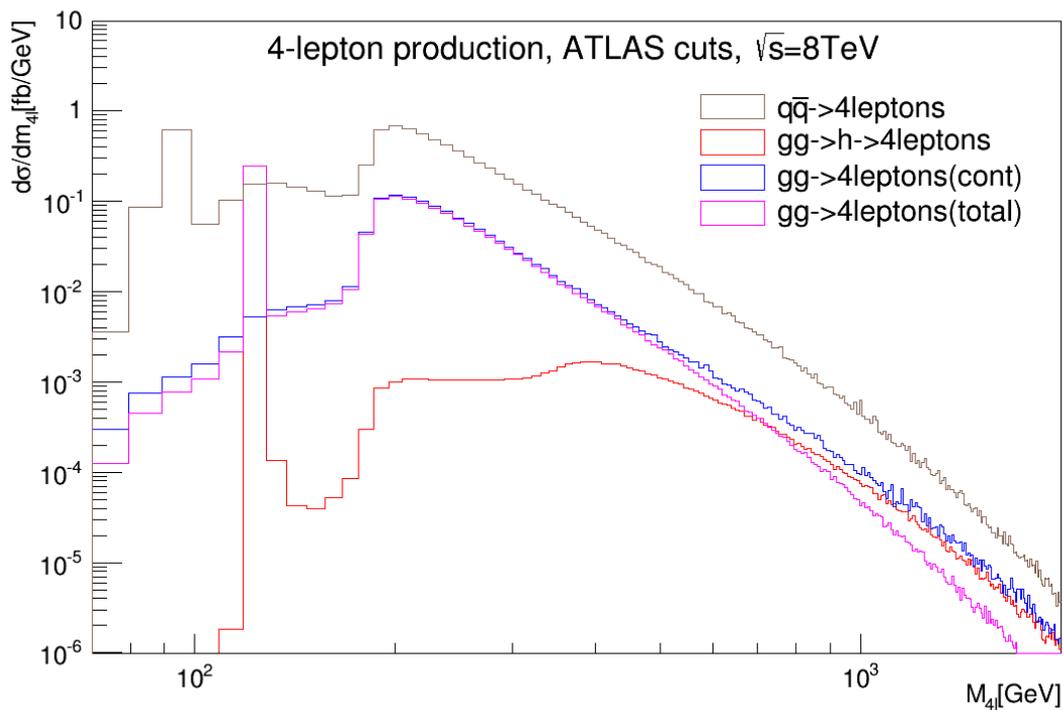
FIG. 5 4l mass spectra of ATLAS cuts at 8TeV.
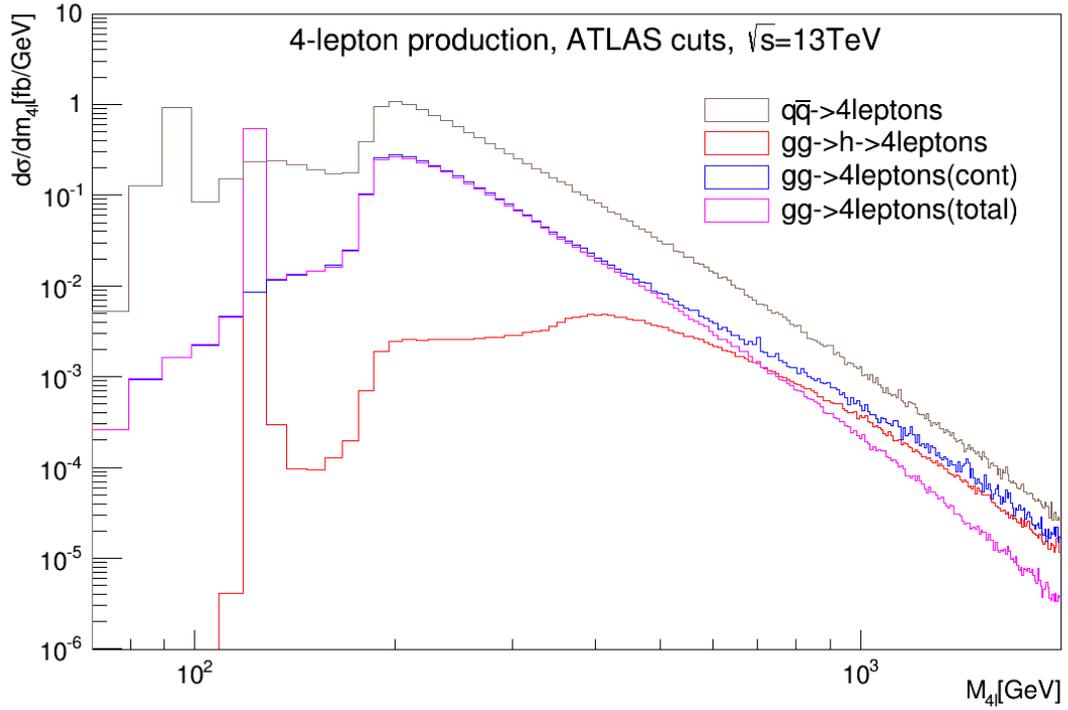
FIG. 6 4l mass spectra of ATLAS cuts at 13TeV.

Process	MC Produced Events	Total Cross-section (fb)	Cross-section in ATLAS cuts (fb)
qq->ZZ->eeμμ	18600000	199.17	11.31
gg->H->ZZ->eeμμ	22500000	0.64	0.31
gg->ZZ->eeμμ (cont.)	19800000	25.18	1.23
gg->ZZ->eeμμ (total)	24000000	25.61	1.41

TABLE 1 Cross section for different processes at 8TeV.

Process	MC Produced Events	Total Cross-section (fb)	Cross-section in ATLAS cuts (fb)
qq->ZZ->eeμμ	29900000	329.13	17.96
gg->H->ZZ->eeμμ	28000000	1.59	0.74
gg->ZZ->eeμμ (cont.)	19500000	51.29	3.04
gg->ZZ->eeμμ (total)	28000000	52.42	3.42

TABLE 2 Cross section for different processes at 13TeV.

Figs. 5 and 6 are the 4l mass spectra of ATLAS cuts at 8 and 13TeV. Tables 5 and 6 are the cross-sections of ATLAS cuts at 8 and 13TeV. One can find that the figures of CMS cuts and ATLAS cuts are basely the same. A little bit difference can be found is that the cross sections of ATLAS cuts in qq process and gg->H->ZZ->eeμμ process are a little bit smaller than that of CMS cuts, and the cross sections of ATLAS cuts in continuum and total gg process are a little bigger than those of CMS cuts. However, the conclusion is the same: it is easier to observe Higgs signal at 13TeV than at 8TeV.

5. Study of spectra of qq-initial process.

In this part, I study the cross sections of qq->ZZ->eeee process and qq->ZZ->eeμμ process, and make 5 spectra with different parameters to compare the difference of two processes. Here I still use ATLAS cuts.

FIG. 7 4l mass spectra of qq process at 8TeV

4-lepton production, ATLAS cuts, $\sqrt{s}=13\text{TeV}$
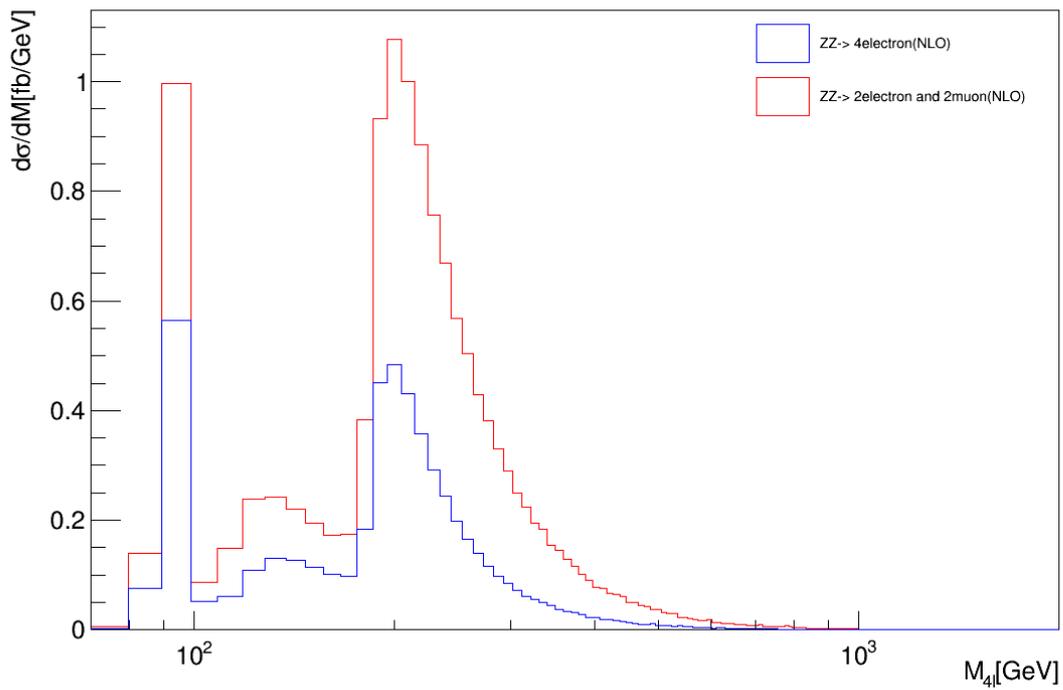
FIG. 8 4l mass spectra of qq process at 13TeV.

Compare the Transverse Momentum of leptron 3 and 4 between ZZ->4e and ZZ->2e2m $\sqrt{s}$=8TeV
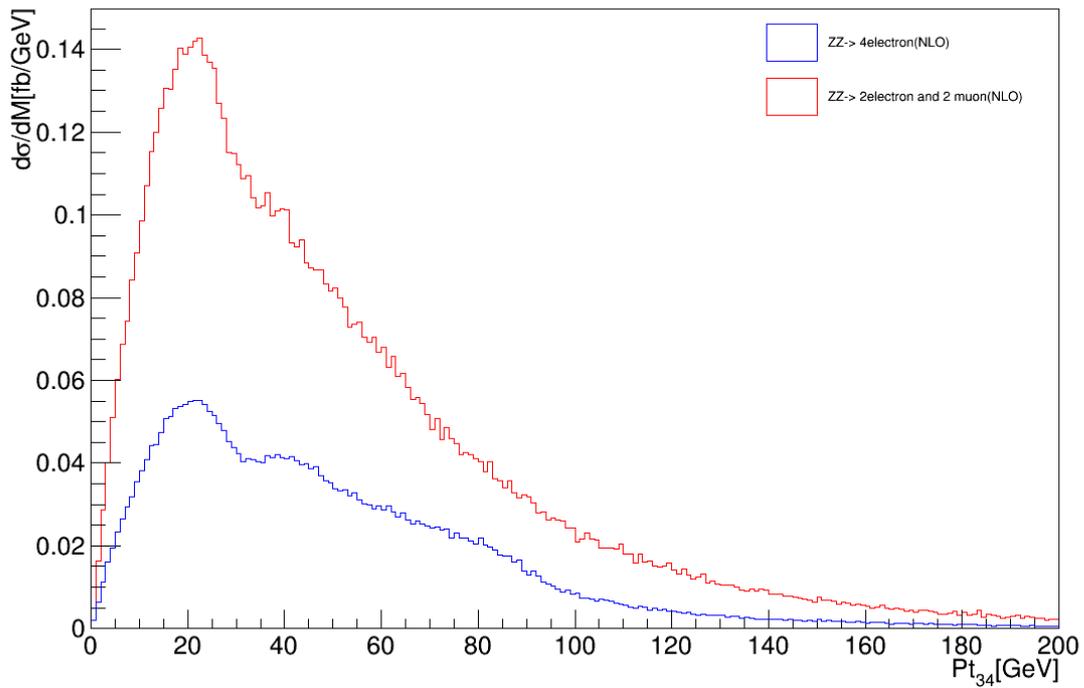
FIG. 9 Transvers momentum of Z-boson at 8TeV.

FIG. 10 Transvers momentum of Z-boson spectra at 13TeV.

FIG. 11 Invariant mass of Z-boson spectra at 8TeV.

FIG. 12 Invariant mass of Z-boson spectra at 13TeV.

FIG. 13 Eta angle of Z-boson spectra at 8TeV.
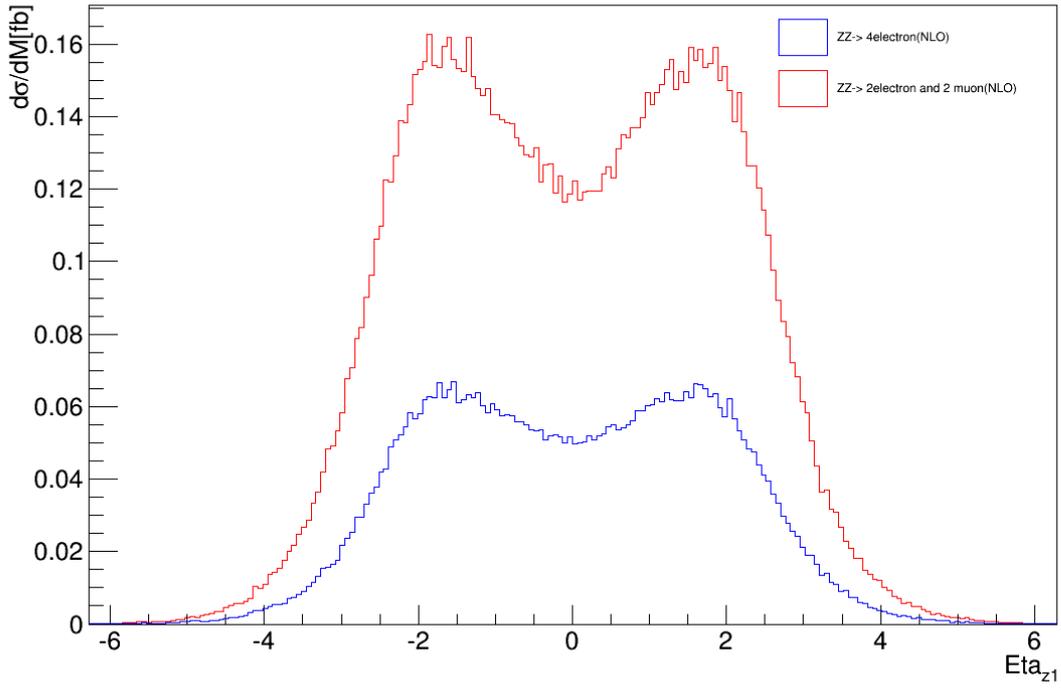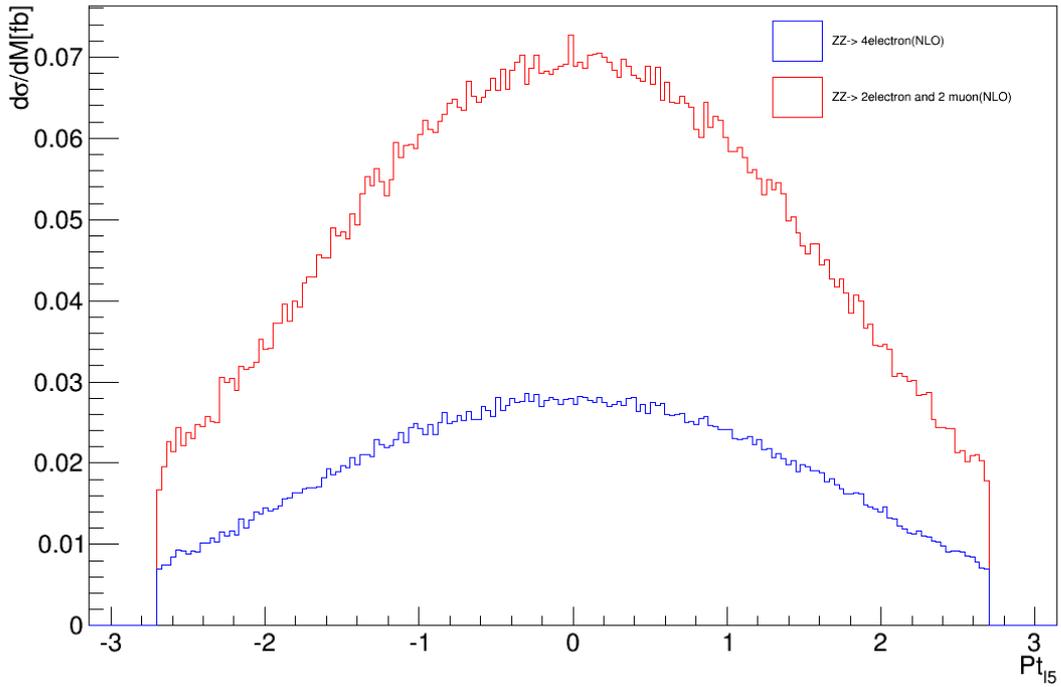
FIG. 14 Eta angle of Z-boson spectra at 13TeV.
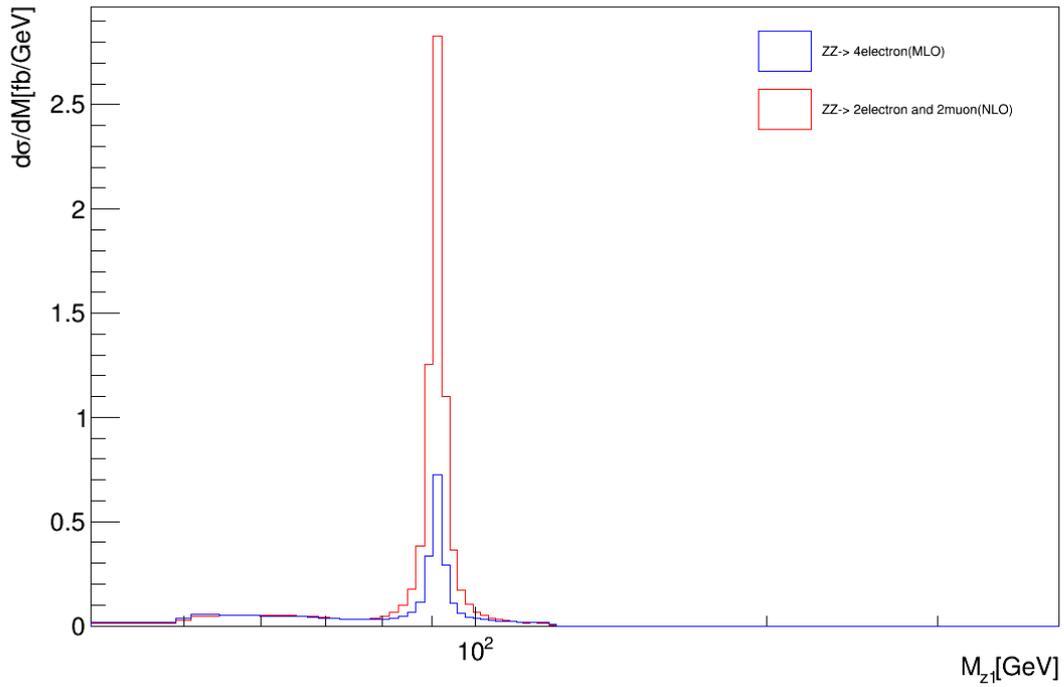
FIG. 15 Eta angle of one lepton spectra at 8TeV.

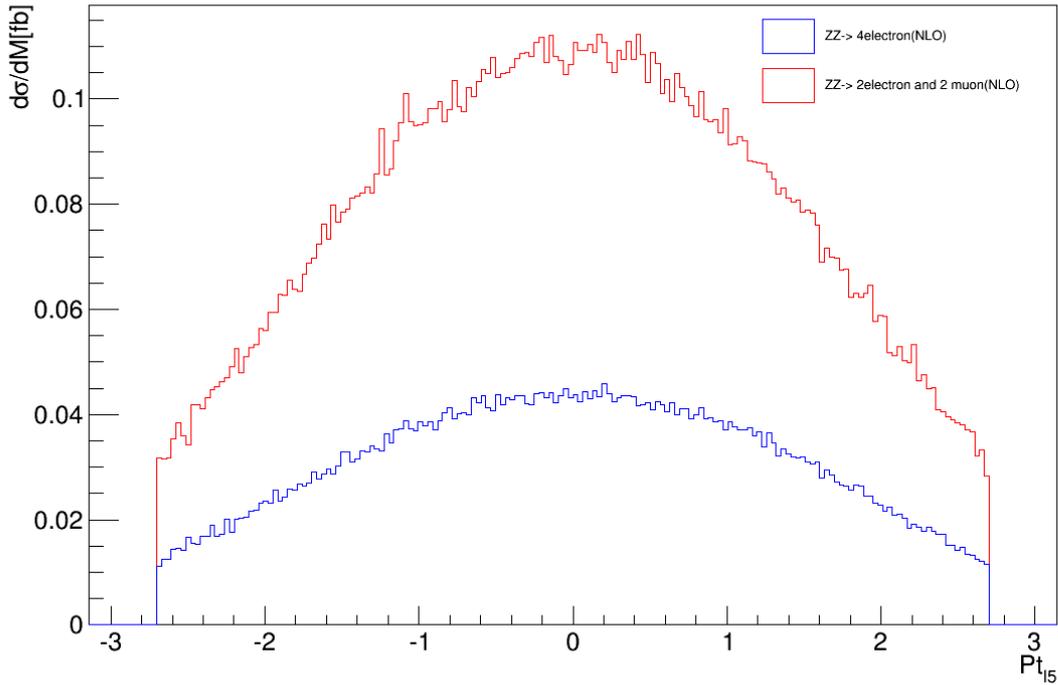Compare the Eta Angle of e5 between ZZ->4e and ZZ->2e2m   √s=13TeV

FIG. 16 Eta angle of one lepton spectra at 13TeV.

These 10 figures show the distinction between 4-electron final state and 2-electron-2-muon final state of qq processes. In these figures one can clearly see that the cross section of 2e2m process is larger than that of 4e process. Actually the cross section of 2e2m process is about twice as large as that of 4e process. The 4 cases of qq->ZZ->4leptons processes are shown as follow:
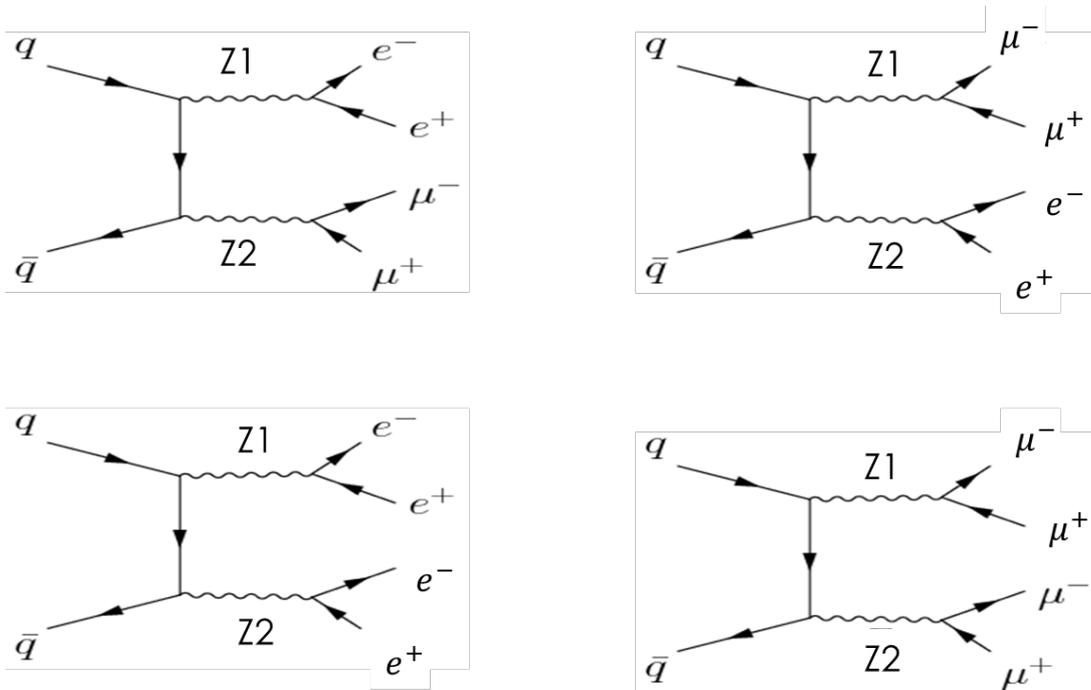

FIG. 17 qq->ZZ->4leptons process Feynman diagram

In Fig. 17 one can find that the probability of getting 2e2m final states is twice as large as that of 4e final state. That is why the cross section of 2e2m is larger.

6. Acknowledgement

7. Reference

[1] J. M. Campbell, R. K. Ellis, and C. Williams, arXiv:1311.3589 [hep-ph] (2013).