

# Search for new physics in the 2011 opposite sign dilepton sample

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## **Abstract**

We present the results of a search for new physics in the opposite-sign leptons + jets + missing transverse energy final state based on  $349 \text{ pb}^{-1}$  of 2011 CMS data. We observe no evidence for an excess of events with large hadronic activity and missing transverse energy, and place upper limits on the non-SM contributions to the signal regions.

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# 1 Changes since Last Version of AN

- Version v2
  - Update results to  $349 \text{ pb}^{-1}$
  - Switch to signal regions in  $E_T^{\text{miss}}$  vs.  $H_T$  plane
- Version v1
  - Add OF subtraction studies for low lepton  $p_T$  sample
  - Add LM1, change MC normalization for data/MC plots in appendix
  - Several minor editorial comments

## 2 Introduction

In this note we describe a search for new physics in the opposite sign isolated dilepton sample ( $ee$ ,  $e\mu$ , and  $\mu\mu$ ) based on  $349 \text{ pb}^{-1}$  of 2011 data. The main sources of isolated dileptons at CMS are Drell Yan and  $t\bar{t}$ . Here we concentrate on dileptons with invariant mass inconsistent with  $Z \rightarrow ee$  and  $Z \rightarrow \mu\mu$ , thus  $t\bar{t}$  is the most important background. A separate search for new physics in the  $Z$  sample is described in another note [1]. This is an update of a (soon to be) published analysis performed on 2010 data [2, 3].

The search strategy is the following

- We start out with a pre-selection which is as close as possible to the published  $t\bar{t}$  dilepton analysis [4] (same lepton ID, same jet definitions, etc.). We do make a couple of substantive modifications:
  1. The top analysis requires two leptons of  $P_T > 20 \text{ GeV}$ . In this analysis we search for new physics in 2 data samples. The first data sample is collected with high  $p_T$  dilepton triggers; for this sample we require leptons with  $p_T > (20, 10) \text{ GeV}$  (leading lepton  $p_T > 20 \text{ GeV}$ , trailing lepton  $p_T > 10 \text{ GeV}$ ). The second data sample is collected with dilepton- $H_T$  cross triggers. For this sample we require  $ee$  dileptons with  $p_T > (10, 10) \text{ GeV}$ ,  $\mu\mu$  dileptons with  $p_T > (10, 5) \text{ GeV}$ , and for  $e\mu$  dileptons we require  $p_T > (10, 5) \text{ GeV}$  and that the electron has  $p_T > 10 \text{ GeV}$ . This is motivated by our desire to maintain sensitivity to possible SUSY signals with relatively low  $p_T$  leptons generated in the cascade decays of heavy objects.
  2. The top analysis requires at least two jets of  $p_T > 30 \text{ GeV}$  with  $E_T^{\text{miss}} > 30 \text{ GeV}$  ( $ee$  and  $\mu\mu$ ) or  $E_T^{\text{miss}} > 20 \text{ GeV}$  ( $e\mu$ ). We tighten the  $E_T^{\text{miss}}$  cut to  $50 \text{ GeV}$  and we also require that the scalar sum of the  $p_T$  of all jets with  $p_T > 30 \text{ GeV}$  be  $> 100 \text{ GeV}$ . These requirements considerably reduce backgrounds to the  $t\bar{t}$  sample, *e.g.*, backgrounds from Drell Yan and  $W$ +jets.
- The pre-selection consists mostly of  $t\bar{t}$  events. Kinematic distributions in data are compared against Monte Carlo. Assuming reasonable agreement for the bulk of  $t\bar{t}$  we move on to a search for new physics in the tails of the  $t\bar{t}$   $E_T^{\text{miss}}$  and  $H_T$  distributions.
- Our prejudice is that new physics would manifest itself in an excess of events with high  $E_T^{\text{miss}}$  and significant hadronic activity. We define search regions a-priori by tightening the  $E_T^{\text{miss}}$  and hadronic activity requirements.
- We perform a counting experiment in the signal regions. We compare observed yields with expectations from Monte Carlo and with three independent data driven techniques (see Sections 11.1, 11.3 and 11.4).

## 3 Datasets, Triggers, Luminosity

$349 \text{ pb}^{-1}$  of data was analyzed, corresponding to the events included in the official May10ReReco and June 3rd PromptReco json files:

- Cert\_160404-163869\_7TeV\_May10ReReco\_Collisions11\_JSON
- Cert\_160404-165970\_7TeV\_PromptReco\_Collisions11\_JSON

We use two data samples, one collected with high  $p_T$  dilepton triggers and the other with dilepton- $H_T$  cross triggers. These samples are complementary, since the dilepton- $H_T$  trigger sample extends to lower lepton  $p_T$ , while the high  $p_T$  dilepton trigger sample does not include requirements on the hadronic activity in the event.

Currently we use data reconstructed in CMSSW 4.2.X and Spring11 MC reconstructed in CMSSW 3.11.X. We will update the MC when the Summer11 madgraph MC samples become available.

- Datasets

- High  $p_T$  dilepton trigger sample

- \* DoubleElectron\_Run2011A-May10ReReco-v1\_AOD
    - \* DoubleMu\_Run2011A-May10ReReco-v1\_AOD
    - \* MuEG\_Run2011A-May10ReReco-v1\_AOD
    - \* DoubleElectron\_Run2011A-PromptReco-v4\_AOD
    - \* DoubleMu\_Run2011A-PromptReco-v4\_AOD
    - \* MuEG\_Run2011A-PromptReco-v4\_AOD

- Dilepton- $H_T$  cross trigger sample

- \* ElectronHad\_Run2011A-May10ReReco-v1\_AOD
    - \* MuHad\_Run2011A-May10ReReco-v1\_AOD
    - \* ElectronHad\_Run2011A-PromptReco-v4\_AOD
    - \* MuHad\_Run2011A-PromptReco-v4\_AOD

- Monte Carlo samples

- TTJets\_TuneZ2\_7TeV-madgraph-tauola\_Spring11-PU\_S1\_START311\_V1G1-v1
  - DYToEE\_M-10To20\_TuneZ2\_7TeV-pythia6\_Spring11-PU\_S1\_START311\_V1G1-v1
  - DYToMuMu\_M-10To20\_TuneZ2\_7TeV-pythia6\_Spring11-PU\_S1\_START311\_V1G1-v1
  - DYToTauTau\_M-10To20\_CT10\_TuneZ2\_7TeV-powheg-pythia-tauola\_Spring11-PU\_S1\_START311\_V1G1-v2
  - DYToEE\_M-20\_CT10\_TuneZ2\_7TeV-powheg-pythia\_Spring11-PU\_S1\_START311\_V1G1-v1
  - DYToMuMu\_M-20\_CT10\_TuneZ2\_7TeV-powheg-pythia\_Spring11-PU\_S1\_START311\_V1G1-v1
  - DYToTauTau\_M-20\_CT10\_TuneZ2\_7TeV-powheg-pythia-tauola\_Spring11-PU\_S1\_START311\_V1G1-v1
  - DYJetsToLL\_TuneD6T\_M-50\_7TeV-madgraph-tauola\_Spring11-PU\_S1\_START311\_V1G1-v1
  - WWTo2L2Nu\_TuneZ2\_7TeV-pythia6\_Spring11-PU\_S1\_START311\_V1G1-v1
  - WZtoAnything\_TuneZ2\_7TeV-pythia6-tauola\_Spring11-PU\_S1\_START311\_V1G1-v1
  - ZZtoAnything\_TuneZ2\_7TeV-pythia6-tauola\_Spring11-PU\_S1\_START311\_V1G1-v1
  - WJetsToLNu\_TuneZ2\_7TeV-madgraph-tauola\_Spring11-PU\_S1\_START311\_V1G1-v1
  - TToBLNu\_TuneZ2\_s-channel\_7TeV-madgraph\_Spring11-PU\_S1\_START311\_V1G1-v1
  - TToBLNu\_TuneZ2\_t-channel\_7TeV-madgraph\_Spring11-PU\_S1\_START311\_V1G1-v1
  - TToBLNu\_TuneZ2\_tW-channel\_7TeV-madgraph\_Spring11-PU\_S1\_START311\_V1G1-v1

## 4 Event Preselection

The purpose of the preselection is to reject backgrounds other than  $t\bar{t} \rightarrow$  dileptons. We compare the kinematical properties of this sample with expectations from  $t\bar{t}$  Monte Carlo.

The preselection is based on the  $t\bar{t}$  analysis [4]. We select events with two opposite sign, well-identified and isolated leptons ( $ee$ ,  $e\mu$ , or  $\mu\mu$ ); one of the leptons must have  $p_T > 20$  GeV, the other one must have  $p_T > 10$  GeV. Events with dilepton mass consistent with  $Z \rightarrow ee/\mu\mu$  are rejected. In case of events with more than two such leptons, we select the pair that maximizes the scalar sum of lepton  $p_T$ 's. There must be at least two pfjets of  $p_T > 30$  GeV and  $|\eta| < 3.0$ ; jets must pass loose `pfJetId` and be separated by  $\Delta R > 0.4$  from any lepton with  $p_T > 10$  GeV passing the selection. The scalar sum  $H_T$  of the  $p_T$  of all such jets must exceed 100 GeV, for the dilepton- $H_T$  sample this requirement is increased to 200 GeV since these triggers have large inefficiency below this threshold. Finally, we require  $E_T^{\text{miss}} > 50$  GeV (pfmet). More details are given in the subsections below.

## 4.1 Event Cleanup

- Require at least one good deterministic annealing (DA) vertex
  - not fake
  - $\text{ndof} > 4$
  - $|\rho| < 2 \text{ cm}$
  - $|z| < 24 \text{ cm}$ .

## 4.2 Muon Selection

Muon candidates are RECO muon objects passing the following requirements:

- $p_T > 5 \text{ GeV}$  and  $|\eta| < 2.4$
- Global Muon and Tracker Muon
- $\chi^2/\text{ndof}$  of global fit  $< 10$
- At least 11 hits in the tracker fit
- Impact parameter with respect to the first DA vertex  $d_0 < 200 \mu\text{m}$  and  $d_z < 1 \text{ cm}$
- $I_{\text{so}} \equiv E_T^{\text{iso}}/p_T < 0.15$ ,  $E_T^{\text{iso}}$  is defined as the sum of transverse energy/momentum deposits in ecal, hcal, and tracker, in a cone of 0.3
- At least one of the hits from the standalone muon must be used in the global fit
- Tracker  $\Delta p_T/p_T < 0.1$

## 4.3 Electron Selection

Electron candidates are RECO GSF electrons passing the following requirements:

- $p_T > 10 \text{ GeV}$  and  $|\eta| < 2.5$ .
- Veto electrons with a supercluster in the transition region  $1.4442 < |\eta| < 1.556$ .
- VBTF90 identification[5] with requirements tightened to match the CaloIdT and TrkIdVL HLT requirements:
  - $\sigma_{i\eta i\eta} < 0.01 \text{ (EB)}, 0.03 \text{ (EE)}$
  - $\Delta\phi < 0.15 \text{ (EB)}, 0.10 \text{ (EE)}$
  - $\Delta\eta < 0.007 \text{ (EB)}, 0.009 \text{ (EE)}$
  - $H/E < 0.1 \text{ (EB)}, 0.075 \text{ (EE)}$
- Impact parameter with respect to the first DA vertex  $d_0 < 400 \mu\text{m}$  and  $d_z < 1 \text{ cm}$ .
- $I_{\text{so}} \equiv E_T^{\text{iso}}/p_T < 0.15$ .  $E_T^{\text{iso}}$  is defined as the sum of transverse energy/momentum deposits in ecal, hcal, and tracker, in a cone of 0.3. A 1 GeV pedestal is subtracted from the ecal energy deposition in the EB, however the ecal energy is never allowed to go negative.
- Electrons with a tracker or global muon within  $\Delta R$  of 0.1 are vetoed.
- The number of missing expected inner hits must be less than two [6].
- Conversion removal via partner track finding: any electron where an additional GeneralTrack is found with  $\text{dist} < 0.02 \text{ cm}$  and  $\Delta \cot \theta < 0.02$  is vetoed [6].

We estimate the contributions from fake leptons using the data-driven fake rate (FR) method [12]. The requirements defining the fakeable objects are listed in App. A.

## 4.4 Invariant mass requirement

We remove  $e^+e^-$  and  $\mu^+\mu^-$  events with invariant mass between 76 and 106 GeV. We also remove events with invariant mass  $< 12$  GeV, since this kinematical region is not well reproduced in CMS Monte Carlo and to remove events with Upsilon's.

In addition, we remove  $Z \rightarrow \mu\mu\gamma$  candidates with the  $\gamma$  collinear with one of the muons. This is done as follows: if the ecal energy associated with one of the muons is greater than 6 GeV, we add this energy to the momentum of the initial muon, and we recompute the  $\mu\mu$  mass. If this mass is between 76 and 106 GeV, the event is rejected.

## 4.5 Trigger Selection

We do not make any requirements on HLT bits in the Monte Carlo. Instead, as discussed in Section 5, a trigger efficiency weight is applied to each event, based on the trigger efficiencies measured on data (see Sec. 5).

We select data events using the following triggers. An event in the  $ee$  channel is required to pass a DoubleElectron trigger, an event in the  $\mu\mu$  channel is required to pass a DoubleMu trigger, and an event in the  $e\mu$  channel is required to pass a Ele-Mu trigger.

- High  $p_T$  dilepton trigger sample

- HLT\_Ele17\_CaloIdL\_CaloIsoVL\_Ele8\_CaloIdL\_CaloIsoVL
- HLT\_DoubleMu7
- HLT\_Mu13\_Mu7
- HLT\_Mu17\_Ele8\_CaloIdL
- HLT\_Mu8\_Ele17\_CaloIdL

- Lepton  $H_T$  cross trigger sample

- HLT\_DoubleMu3\_HT150
- HLT\_DoubleMu3\_HT160
- HLT\_Mu3\_Ele8\_CaloIdL\_TrkIdVL\_HT150
- HLT\_Mu3\_Ele8\_CaloIdT\_TrkIdVL\_HT150
- HLT\_Mu3\_Ele8\_CaloIdL\_TrkIdVL\_HT160
- HLT\_Mu3\_Ele8\_CaloIdT\_TrkIdVL\_HT160
- HLT\_DoubleEle8\_CaloIdL\_TrkIdVL\_HT150
- HLT\_DoubleEle8\_CaloIdT\_TrkIdVL\_HT150
- HLT\_DoubleEle8\_CaloIdL\_TrkIdVL\_HT160
- HLT\_DoubleEle8\_CaloIdT\_TrkIdVL\_HT160

## 5 Trigger efficiency

For the high  $p_T$  dilepton triggers, the efficiencies have been measured to be approximately 100% (DoubleEle), 90% (DoubleMu), and 95% (Mu-Ele) [7]. In the following, unless otherwise specified we weight the  $ee$ ,  $\mu\mu$  and  $e\mu$  MC events by these efficiencies. We do not apply any efficiency correction for the hadronic part of the dilepton- $H_T$  triggers. We have verified that the efficiencies for these triggers with respect to an offline selection of  $H_T > 200$  GeV is high ( $\sim 90$ – $95\%$ ), as shown in Fig. 1.

## 6 Dilepton Yields

The data and MC dilepton mass distributions for events with 2 leptons passing the dilepton triggered  $p_T > (20, 10)$  GeV selection are displayed in Fig. 2. The yields of  $Z$  events in the mass range 76–106 GeV are indicated in Table 1. In data we observe a slight excess with respect to MC expectations, of 3% (11%) in the  $ee$  ( $\mu\mu$ ) channel, which we attribute to uncertainties in trigger efficiency, lepton selection efficiency, and integrated luminosity. We use the ratio of  $Z \rightarrow \mu^+\mu^-$  to  $Z \rightarrow e^+e^-$  yields in data to estimate the ratio of muon to electron selection efficiencies, and find  $R_{\mu e} = \text{eff}(\mu)/\text{eff}(e) = 1.13$ .

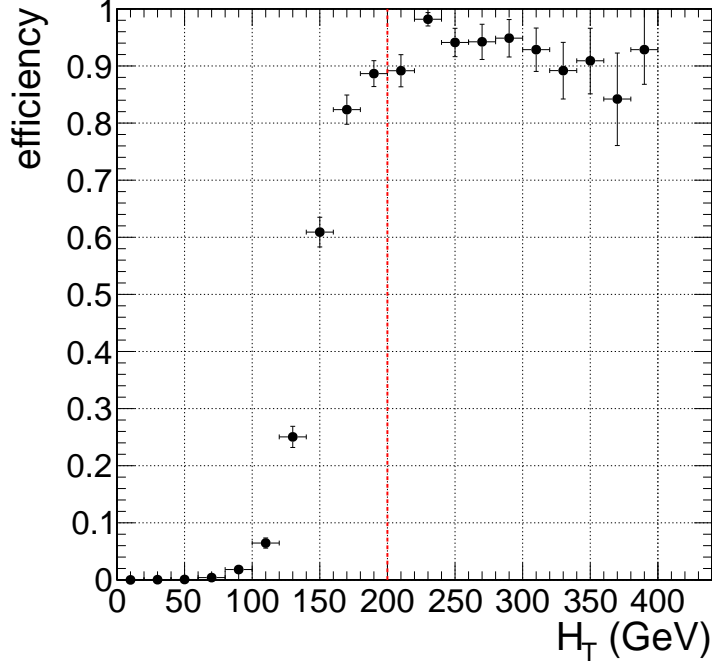


Figure 1: Efficiency for the dimuon- $H_T$  trigger HLT\_DoubleMu3\_HT150 as a function of the offline  $H_T$ . Events are selected with the high  $p_T$  dilepton trigger HLT\_DoubleMu7 and required to have 2 muons passing analysis selection. The vertical dashed line indicates the requirement  $H_T > 200$  GeV, which is used in the preselection for the dilepton- $H_T$  trigger sample.

Table 1: The data and MC yields in the  $ee$  and  $\mu\mu$  final states for events with 2 selected leptons with invariant mass 76–106 GeV.

Sample	$ee$	$\mu\mu$
data	110402	140191
MC	107089	125998
data/MC	1.03	1.11

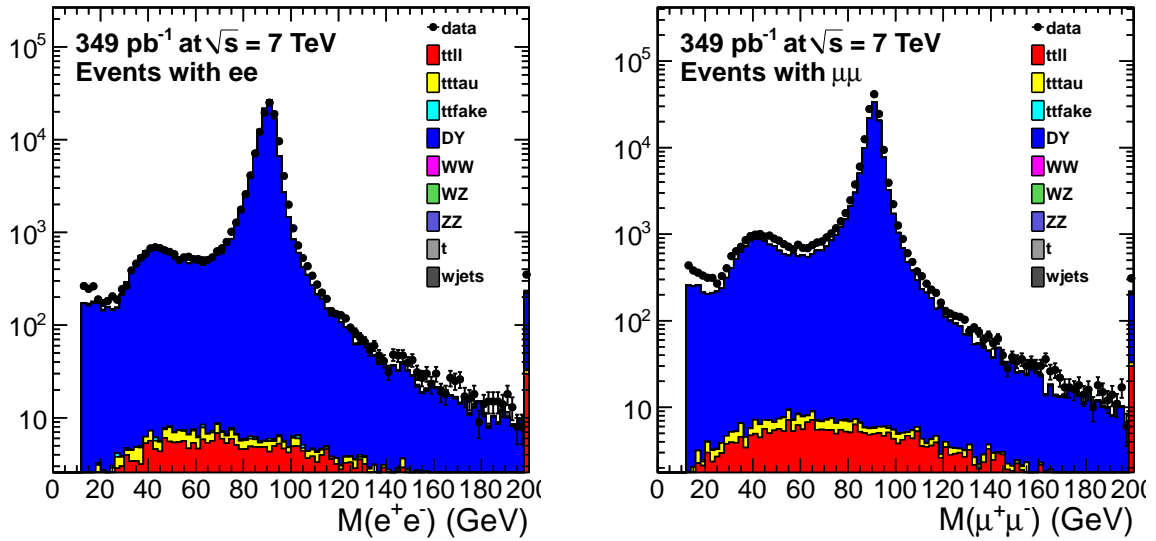


Figure 2: Distributions of dilepton mass in data and MC, in the  $ee$  channel (left) and  $\mu\mu$  channel (right).



## 7 Preselection yields: Data/MC Comparison

The data yields and the MC predictions for the dilepton trigger sample are given in Table 2. As anticipated, the MC predicts that the preselection is dominated by  $t\bar{t}$ . We observe a slight excess in data with respect to MC expectations. We also look for an excess of low lepton  $p_T$  events using the dilepton- $H_T$  trigger sample. In this sample the leptons are required have  $p_T > (10,5)$  GeV and not to have  $p_T > (20,10)$  GeV. This is done to remove overlap with the dilepton trigger sample, as summarized in Table 3. We observe reasonable agreement between the data and MC yields in this region. Finally, we compare in Table 4 the data samples collected with high  $p_T$  dilepton triggers and lepton- $H_T$  cross triggers, including the requirements  $H_T > 200$  GeV and lepton  $p_T > (20,10)$  GeV. We find slightly fewer events in the dilepton- $H_T$  trigger sample, consistent with the small inefficiency of the hadronic part of the trigger for an offline selection of  $H_T > 200$  GeV.

The MC yields are normalized to  $349 \text{ pb}^{-1}$  using the cross-sections from Reference [8]. The final luminosity measurement for CMS is anticipated to increase by a few percent from  $349 \text{ pb}^{-1}$ . The MC is scaled by the approximate trigger efficiency (100% for  $ee$ , 95% for  $\mu\mu$ , and 95% for  $e\mu$ ) and has been reweighted such that the distribution of reconstructed DA vertices matches that in data. The DY contribution is dominated by  $\text{DY} \rightarrow \tau^+\tau^-$ , and we have verified with the data-driven  $R_{out/in}$  method [4] that the contributions from  $\text{DY} \rightarrow e^+e^-$  and  $\text{DY} \rightarrow \mu^+\mu^-$  are negligible. Also shown are the yields for LM1 and LM3, two of the LM points which are benchmarks for SUSY analyses at CMS. The LM yields are calculated at NLO using process-dependent k-factors computed from Prospino.

Table 2: High  $p_T$  dilepton trigger data and Monte Carlo yields for the preselection ( $n_{\text{jets}} \geq 2$ ,  $H_T > 100$  GeV,  $E_T^{\text{miss}} > 50$  GeV, lepton  $p_T > (20,10)$  GeV).

Sample	$ee$	$\mu\mu$	$e\mu$	tot
$t\bar{t} \rightarrow \ell^+\ell^-$	$120.1 \pm 2.9$	$133.1 \pm 2.9$	$320.3 \pm 4.6$	$573.5 \pm 6.1$
$t\bar{t} \rightarrow \ell^\pm\tau^\mp/\tau^+\tau^-$	$27.5 \pm 1.4$	$33.3 \pm 1.4$	$71.5 \pm 2.2$	$132.3 \pm 3.0$
$t\bar{t} \rightarrow \text{fake}$	$4.5 \pm 0.6$	$1.3 \pm 0.3$	$8.1 \pm 0.7$	$13.9 \pm 1.0$
DY	$6.6 \pm 1.8$	$9.5 \pm 2.1$	$13.4 \pm 2.6$	$29.6 \pm 3.8$
$W^+W^-$	$1.4 \pm 0.2$	$1.5 \pm 0.2$	$3.4 \pm 0.2$	$6.3 \pm 0.3$
$W^\pm Z^0$	$0.3 \pm 0.0$	$0.4 \pm 0.0$	$0.7 \pm 0.1$	$1.3 \pm 0.1$
$Z^0 Z^0$	$0.1 \pm 0.0$	$0.1 \pm 0.0$	$0.2 \pm 0.0$	$0.4 \pm 0.0$
single top	$4.5 \pm 0.2$	$5.0 \pm 0.2$	$11.9 \pm 0.3$	$21.4 \pm 0.5$
$W + \text{jets}$	$4.5 \pm 1.9$	$0.0 \pm 0.0$	$2.8 \pm 1.7$	$7.3 \pm 2.6$
tot SM MC	$169.7 \pm 4.2$	$184.3 \pm 3.9$	$432.2 \pm 6.0$	$786.1 \pm 8.3$
data	193	201	485	879

Table 3: Dilepton- $H_T$  trigger data and Monte Carlo yields for the preselection ( $n_{\text{jets}} \geq 2$ ,  $H_T > 200$  GeV,  $E_T^{\text{miss}} > 50$  GeV, lepton  $p_T > (10,5)$  GeV and not lepton  $p_T > (20,10)$  GeV).

Sample	$ee$	$\mu\mu$	$e\mu$	tot
$t\bar{t} \rightarrow \ell^+\ell^-$	$0.6 \pm 0.2$	$3.7 \pm 0.5$	$4.1 \pm 0.5$	$8.4 \pm 0.7$
$t\bar{t} \rightarrow \ell^\pm\tau^\mp/\tau^+\tau^-$	$0.6 \pm 0.2$	$3.9 \pm 0.5$	$3.5 \pm 0.5$	$8.0 \pm 0.7$
$t\bar{t} \rightarrow \text{fake}$	$0.1 \pm 0.1$	$1.3 \pm 0.3$	$1.5 \pm 0.3$	$2.9 \pm 0.4$
DY	$0.0 \pm 0.0$	$3.7 \pm 1.4$	$0.6 \pm 0.6$	$4.3 \pm 1.5$
$W^+W^-$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
$W^\pm Z^0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
$Z^0 Z^0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
single top	$0.0 \pm 0.0$	$0.3 \pm 0.1$	$0.3 \pm 0.1$	$0.6 \pm 0.1$
$W + \text{jets}$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
tot SM MC	$1.3 \pm 0.3$	$12.9 \pm 1.6$	$10.1 \pm 1.0$	$24.3 \pm 1.9$
data	1	9	8	18

Table 4: Comparison of data yields in the high- $p_T$  dilepton and dilepton- $H_T$  trigger samples, passing the selection  $n_{\text{jets}} \geq 2$ ,  $E_T^{\text{miss}} > 50$  GeV,  $H_T > 200$  GeV, lepton  $p_T > (20, 10)$  GeV.

Sample	$ee$	$\mu\mu$	$e\mu$	tot
high- $p_T$ dilepton trigger	88	75	190	353
dilepton- $H_T$ trigger	85	74	185	344

## 8 Properties of data passing the preselection

A number of kinematical distributions for events passing the preselection in data are compared with MC in Appendix C. Although we observe a slight overall excess of data, in general we find that the MC does a good job of reproducing the shapes of the kinematical distributions. We keep in mind that the CMS luminosity estimate is expected to increase by a few percent. Given good observed agreement between data and expectation, we turn our attention to events in the tails of the  $t\bar{t}$  distributions.

## 9 Definition of the signal region

We define signal regions to look for possible new physics contributions in the opposite sign isolated dilepton sample. The choice of signal region is driven by three observations:

1. astrophysical evidence for dark matter suggests that we concentrate on the region of high  $E_T^{\text{miss}}$ ;
2. new physics signals should have high  $\sqrt{s}$ ;
3. observable high cross section new physics signals are likely to be produced strongly; thus, we expect significant hadronic activity in conjunction with the two leptons.

Following these observations, we define the following 3 signal regions ( shown in figure 3 ) by adding requirements of large hadronic activity and missing transverse energy to the preselection of Section 4.

- 2010 signal region:  $H_T > 300$  GeV and  $y > 8.5$  GeV $^{1/2}$ .
- high  $E_T^{\text{miss}}$  signal region:  $H_T > 300$  GeV and  $E_T^{\text{miss}} > 275$  GeV
- high  $H_T$  signal region:  $H_T > 600$  GeV and  $E_T^{\text{miss}} > 200$  GeV

In our 2010 analysis, we cut on the quantity  $y \equiv E_T^{\text{miss}}/\sqrt{H_T}$  rather than  $E_T^{\text{miss}}$  because the variables  $H_T$  and  $y$  are largely uncorrelated for the dominant  $t\bar{t}$  background. This allows us to use a data-driven ABCD method to estimate the background (see Section 11.1). Here, we include 2 additional tighter signal regions using requirements on  $E_T^{\text{miss}}$  and  $H_T$ , since we observe that  $E_T^{\text{miss}}$  is a better discriminant between  $t\bar{t}$  vs. SUSY. We have developed a novel technique, which is a variation of the ABCD method, to estimate the background in a signal region defined by  $E_T^{\text{miss}}$  and  $H_T$  requirements (see App. B).

The 2010 signal region is the same as the one used in the 2010 analysis, and was chosen to preserve about 1% of the  $t\bar{t}$  sample. The additional signal regions (high  $E_T^{\text{miss}}$  and high  $H_T$ ) have tightened requirements on  $E_T^{\text{miss}}$  and  $H_T$ , respectively, which reduce the expected background by roughly an order of magnitude.

For each signal region, we search in the high  $p_T$  dilepton trigger sample requiring lepton  $p_T > (20, 10)$  GeV, and separately in the dilepton- $H_T$  trigger sample requiring lepton  $p_T > (10, 5)$  GeV and not passing lepton  $p_T > (20, 10)$  GeV, to remove overlap with the high  $p_T$  dilepton trigger sample. For the high  $p_T$  dilepton sample, for which we have prior experience with the 2010 analysis, we apply the ABCD,  $p_T(\ell\ell)$ , and OF subtraction background estimates. For the dilepton- $H_T$  sample we currently apply only the OF subtraction background estimate.

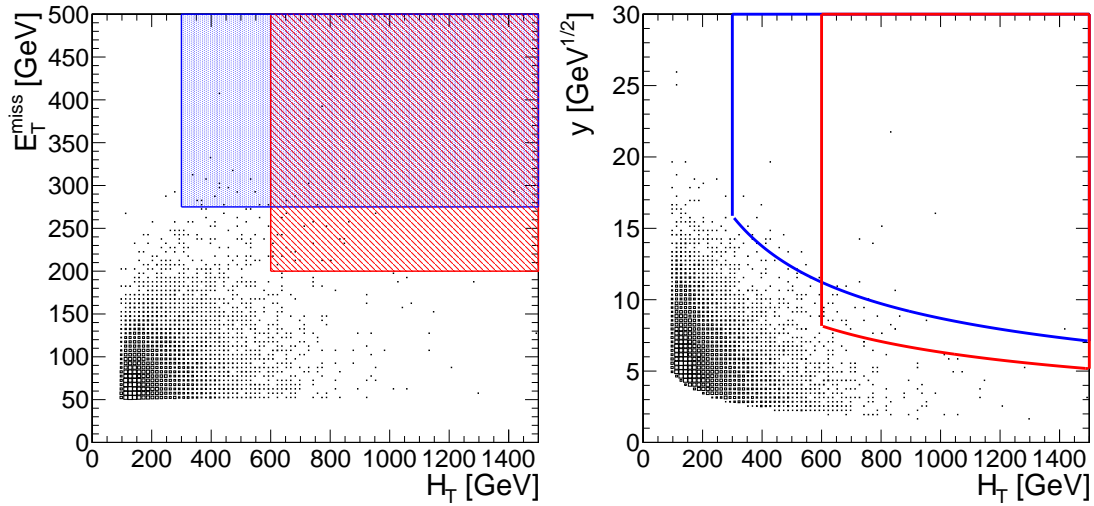


Figure 3: Illustration of signal regions for the 2011 analysis;  $t\bar{t}$  MC is plotted. Left:  $E_T^{\text{miss}}$  vs.  $H_T$ . The high  $E_T^{\text{miss}}$  signal region (  $E_T^{\text{miss}} > 275$  GeV,  $H_T > 300$  GeV) is shown in blue. The high  $H_T$  signal region (  $E_T^{\text{miss}} > 200$  GeV,  $H_T > 600$  GeV) is shown in red. Right: The 2011 signal regions shown on the left are represented in the  $y$  vs.  $H_T$  plane.

Data yields are compared against Monte Carlo expectations in the following tables:

- High  $p_T$  dilepton trigger sample:
  - Table 5: 2010 signal region
  - Table 6: 2011 high  $E_T^{\text{miss}}$  signal region
  - Table 7: 2011 high  $H_T$  signal region
- Dilepton- $H_T$  cross trigger sample ( events with  $p_T > (20,10)$  are excluded ):
  - Table 8: 2010 signal region
  - Table 9: 2011 high  $E_T^{\text{miss}}$  signal region
  - Table 10: 2011 high  $H_T$  signal region

Yields for the 2010 signal regions are presented in tables 5 and 8 to ensure that results from the 2011 analysis are consistent with the 2010 results.

Table 5: High  $p_T$  dilepton trigger data and MC yields in the 2010 signal region. MC errors are statistical only.

Sample	$ee$	$\mu\mu$	$e\mu$	tot
$t\bar{t} \rightarrow \ell^+\ell^-$	$1.6 \pm 0.3$	$2.5 \pm 0.4$	$4.5 \pm 0.5$	$8.5 \pm 0.7$
$t\bar{t} \rightarrow \ell^\pm\tau^\mp/\tau^+\tau^-$	$0.7 \pm 0.2$	$0.7 \pm 0.2$	$2.0 \pm 0.4$	$3.4 \pm 0.5$
$t\bar{t} \rightarrow \text{fake}$	$0.2 \pm 0.1$	$0.0 \pm 0.0$	$0.3 \pm 0.1$	$0.4 \pm 0.2$
DY	$0.3 \pm 0.3$	$0.7 \pm 0.7$	$0.7 \pm 0.7$	$1.7 \pm 1.0$
$W^+W^-$	$0.1 \pm 0.0$	$0.1 \pm 0.0$	$0.1 \pm 0.0$	$0.3 \pm 0.1$
$W^\pm Z^0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
$Z^0 Z^0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
single top	$0.1 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.1 \pm 0.0$
$W + \text{jets}$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
tot SM MC	$2.9 \pm 0.5$	$4.0 \pm 0.8$	$7.7 \pm 1.0$	$14.5 \pm 1.4$
data	4	4	11	19
LM1	$11.0 \pm 0.4$	$13.0 \pm 0.4$	$6.7 \pm 0.3$	$30.7 \pm 0.7$
LM3	$3.2 \pm 0.2$	$3.8 \pm 0.2$	$5.4 \pm 0.2$	$12.4 \pm 0.4$

Table 6: High  $p_T$  dilepton trigger data and MC yields in the high  $E_T^{\text{miss}}$  signal region. MC errors are statistical only.

Sample	$ee$	$\mu\mu$	$e\mu$	tot
$t\bar{t} \rightarrow \ell^+\ell^-$	$0.4 \pm 0.2$	$0.4 \pm 0.1$	$0.8 \pm 0.2$	$1.6 \pm 0.3$
$t\bar{t} \rightarrow \ell^\pm\tau^\mp/\tau^+\tau^-$	$0.1 \pm 0.1$	$0.0 \pm 0.0$	$0.1 \pm 0.1$	$0.3 \pm 0.1$
$t\bar{t} \rightarrow \text{fake}$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
DY	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.7 \pm 0.7$	$0.7 \pm 0.7$
$W^+W^-$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.1 \pm 0.0$
$W^\pm Z^0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
$Z^0 Z^0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
single top	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
$W + \text{jets}$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
tot SM MC	$0.6 \pm 0.2$	$0.4 \pm 0.1$	$1.6 \pm 0.8$	$2.6 \pm 0.8$
data	2	0	2	4
LM1	$6.2 \pm 0.3$	$7.3 \pm 0.3$	$3.9 \pm 0.2$	$17.4 \pm 0.5$
LM3	$1.7 \pm 0.1$	$2.1 \pm 0.1$	$2.6 \pm 0.2$	$6.4 \pm 0.3$

Table 7: High  $p_T$  dilepton trigger data and MC yields in the high  $H_T$  signal region. MC errors are statistical only.

Sample	$ee$	$\mu\mu$	$e\mu$	tot
$t\bar{t} \rightarrow \ell^+\ell^-$	$0.2 \pm 0.1$	$0.3 \pm 0.1$	$0.7 \pm 0.2$	$1.1 \pm 0.3$
$t\bar{t} \rightarrow \ell^\pm\tau^\mp/\tau^+\tau^-$	$0.1 \pm 0.1$	$0.2 \pm 0.1$	$0.4 \pm 0.2$	$0.7 \pm 0.2$
$t\bar{t} \rightarrow \text{fake}$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
DY	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.7 \pm 0.7$	$0.7 \pm 0.7$
$W^+W^-$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
$W^\pm Z^0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
$Z^0 Z^0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
single top	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
$W + \text{jets}$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
tot SM MC	$0.3 \pm 0.1$	$0.5 \pm 0.2$	$1.8 \pm 0.8$	$2.5 \pm 0.8$
data	1	0	2	3
LM1	$5.3 \pm 0.3$	$5.7 \pm 0.3$	$2.5 \pm 0.2$	$13.5 \pm 0.4$
LM3	$1.9 \pm 0.1$	$2.1 \pm 0.1$	$2.8 \pm 0.2$	$6.7 \pm 0.3$

Table 8: Dilepton- $H_T$  trigger data and MC yields in the 2010 signal region. MC errors are statistical only.

Sample	$ee$	$\mu\mu$	$e\mu$	tot
$t\bar{t} \rightarrow \ell^+\ell^-$	$0.0 \pm 0.0$	$0.2 \pm 0.1$	$0.4 \pm 0.2$	$0.5 \pm 0.2$
$t\bar{t} \rightarrow \ell^\pm\tau^\mp/\tau^+\tau^-$	$0.0 \pm 0.0$	$0.2 \pm 0.1$	$0.1 \pm 0.1$	$0.3 \pm 0.1$
$t\bar{t} \rightarrow \text{fake}$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.1 \pm 0.1$	$0.1 \pm 0.1$
DY	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
$W^+W^-$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
$W^\pm Z^0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
$Z^0 Z^0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
single top	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
$W + \text{jets}$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
tot SM MC	$0.0 \pm 0.0$	$0.4 \pm 0.1$	$0.6 \pm 0.2$	$1.0 \pm 0.2$
data	0	1	0	1
LM1	$0.3 \pm 0.1$	$2.7 \pm 0.2$	$2.1 \pm 0.2$	$5.1 \pm 0.3$
LM3	$0.0 \pm 0.0$	$0.4 \pm 0.1$	$0.4 \pm 0.1$	$0.8 \pm 0.1$

Table 9: Dilepton- $H_T$  trigger data and MC yields in the high  $y$  signal region. MC errors are statistical only.

Sample	$ee$	$\mu\mu$	$e\mu$	tot
$t\bar{t} \rightarrow \ell^+\ell^-$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
$t\bar{t} \rightarrow \ell^\pm\tau^\mp/\tau^+\tau^-$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.1 \pm 0.1$	$0.1 \pm 0.1$
$t\bar{t} \rightarrow \text{fake}$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
DY	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
$W^+W^-$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
$W^\pm Z^0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
$Z^0 Z^0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
single top	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
$W + \text{jets}$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
tot SM MC	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.1 \pm 0.1$	$0.1 \pm 0.1$
data	0	0	0	0
LM1	$0.2 \pm 0.0$	$1.6 \pm 0.1$	$1.3 \pm 0.1$	$3.0 \pm 0.2$
LM3	$0.0 \pm 0.0$	$0.3 \pm 0.0$	$0.2 \pm 0.0$	$0.5 \pm 0.1$

Table 10: Dilepton- $H_T$  trigger data and MC yields in the high  $H_T$  signal region. MC errors are statistical only.

Sample	$ee$	$\mu\mu$	$e\mu$	tot
$t\bar{t} \rightarrow \ell^+\ell^-$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
$t\bar{t} \rightarrow \ell^\pm\tau^\mp/\tau^+\tau^-$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
$t\bar{t} \rightarrow \text{fake}$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
DY	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
$W^+W^-$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
$W^\pm Z^0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
$Z^0 Z^0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
single top	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
$W + \text{jets}$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
tot SM MC	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
data	0	0	0	0
LM1	$0.2 \pm 0.1$	$1.3 \pm 0.1$	$0.7 \pm 0.1$	$2.2 \pm 0.2$
LM3	$0.0 \pm 0.0$	$0.3 \pm 0.1$	$0.1 \pm 0.0$	$0.5 \pm 0.1$

These results are summarized as:

- High  $p_T$  dilepton trigger sample
  - 2010 signal region ( $y > 8.5 \text{ GeV}^{1/2}$ ,  $H_T > 300 \text{ GeV}$ )
    - \* observed yield : 19
    - \* MC prediction :  $14.5 \pm 1.4$
  - high  $E_T^{\text{miss}}$  signal region ( $E_T^{\text{miss}} > 275 \text{ GeV}$ ,  $H_T > 300 \text{ GeV}$ )
    - \* observed yield : 4
    - \* MC prediction :  $2.6 \pm 0.8$
  - high  $H_T$  signal region ( $E_T^{\text{miss}} > 200 \text{ GeV}$ ,  $H_T > 600 \text{ GeV}$ )
    - \* observed yield : 3
    - \* MC prediction :  $2.5 \pm 0.8$
- Dilepton- $H_T$  trigger sample ( events with  $p_T > (20,10)$  are excluded )
  - 2010 signal region ( $y > 8.5 \text{ GeV}^{1/2}$ ,  $H_T > 300 \text{ GeV}$ )
    - \* observed yield : 1
    - \* MC prediction :  $1.0 \pm 0.2$
  - high  $E_T^{\text{miss}}$  signal region ( $E_T^{\text{miss}} > 275 \text{ GeV}$ ,  $H_T > 300 \text{ GeV}$ )
    - \* observed yield : 0
    - \* MC prediction :  $0.1 \pm 0.1$
  - high  $H_T$  signal region ( $E_T^{\text{miss}} > 200 \text{ GeV}$ ,  $H_T > 600 \text{ GeV}$ )
    - \* observed yield : 0
    - \* MC prediction :  $0.0 \pm 0.0$

For all signal regions, we observe reasonable agreement between data and MC expectations. A data/MC comparison of the kinematic distributions of the 19 events passing the 2010 signal region selection is presented in App. D.

## 10 Estimation of Drell Yan and QCD backgrounds

For the 2010 signal region, we observe 1  $ee$  and 2  $e\mu$  events in the  $Z$  mass window, confirming the expectation from MC that the DY background is negligible. We also confirm the MC expectation that the contribution of fake leptons is small, using the data-driven fake rate method [12]. The results are summarized as:

- High  $p_T$  dilepton trigger sample
  - 2010 signal region ( $y > 8.5 \text{ GeV}^{1/2}$ ,  $H_T > 300 \text{ GeV}$ )
    - \* single fakes :  $0.6 \pm 0.6$
    - \* double fakes :  $0.0 \pm 0.0$
  - high  $E_T^{\text{miss}}$  signal region ( $E_T^{\text{miss}} > 275 \text{ GeV}$ ,  $H_T > 300 \text{ GeV}$ )
    - \* single fakes :  $0.0 \pm 0.0$
    - \* double fakes :  $0.0 \pm 0.0$
  - high  $H_T$  signal region ( $E_T^{\text{miss}} > 200 \text{ GeV}$ ,  $H_T > 600 \text{ GeV}$ )
    - \* single fakes :  $0.5 \pm 0.5$
    - \* double fakes :  $0.0 \pm 0.0$

- Dilepton- $H_T$  trigger sample ( events with  $p_T > (20,10)$  are excluded )
  - 2010 signal region ( $y > 8.5 \text{ GeV}^{1/2}$ ,  $H_T > 300 \text{ GeV}$ )
    - \* single fakes :  $0.2 \pm 0.2$
    - \* double fakes :  $0.1 \pm 0.1$
  - high  $E_T^{\text{miss}}$  signal region ( $E_T^{\text{miss}} > 275 \text{ GeV}$ ,  $H_T > 300 \text{ GeV}$ )
    - \* single fakes :  $0.0 \pm 0.0$
    - \* double fakes :  $0.0 \pm 0.0$
  - high  $H_T$  signal region ( $E_T^{\text{miss}} > 200 \text{ GeV}$ ,  $H_T > 600 \text{ GeV}$ )
    - \* single fakes :  $0.0 \pm 0.0$
    - \* double fakes :  $0.0 \pm 0.0$

Based on these results, we treat the contributions from fakes leptons in our signal regions as negligible.

## 11 Data Driven Background Estimation Methods for $t\bar{t}$

For the high  $p_T$  dilepton trigger sample, we use 3 data-driven methods to estimate the background in the signal regions. In the first method, ABCD, one exploits the fact that  $H_T$  and  $y$  are nearly uncorrelated for the  $t\bar{t}$  background. When predicting the backgrounds in the signal regions defined in the  $E_T^{\text{miss}}$  vs.  $H_T$  plane, we use a variation of the ABCD method which we refer to as the ABCD' method (see Appendix B). The second method,  $p_T(\ell\ell)$ , is based on the fact that in  $t\bar{t}$  the  $p_T$  of the dilepton pair is on average nearly the same as the  $p_T$  of the pair of neutrinos from  $W$ -decays, which is reconstructed as  $E_T^{\text{miss}}$  in the detector. The third method exploits the fact that in  $t\bar{t}$  events the rates of same-flavor vs. opposite-flavor dilepton events are the same. For the low lepton  $p_T$  events collected by the dilepton- $H_T$  triggers, we use the opposite-flavor subtraction technique only.

We study the closure of these methods using our madgraph  $t\bar{t}$  sample, as well as the powheg sample TTTto2L2Nu2B\_7TeV-powheg-pythia6\_Spring11-PU\_S1\_START311\_V1G1-v1 which has approximately 10 times more events in the dilepton channel than the madgraph sample. We use these samples to estimate correction factors and systematic uncertainties for the background predictions. However, the final choice of correction factors and uncertainties will be extracted from the Summer11  $t\bar{t}$  madgraph sample which will have 50 times as many events as the current madgraph sample. For the studies presented in this section, we do not apply trigger efficiency corrections or reweighting for number of reconstructed vertices since are not comparing MC to data.

### 11.1 ABCD method

We find that in  $t\bar{t}$  events  $H_T$  and  $y$  are nearly uncorrelated, as demonstrated in Fig. 4 (left). Thus, we can use an ABCD method in the  $y$  vs.  $H_T$  plane to estimate the background in a data driven way. We define 4 regions in the plane of  $y$  vs.  $H_T$ , as shown in Fig. 4 (right). The region D is the signal region, and the regions A, B and C are control regions. The predicted background in region D is given by  $N_A \times N_C / N_B$ .

In Table 11, we quote the  $t\bar{t}$  MC expected results for  $1 \text{ fb}^{-1}$ . We find that the prediction agrees with the observed yield in the signal region within  $\sim 20\%$ , and we assign a corresponding systematic uncertainty. We also study the dependence of the ratio of observed to predicted signal yields, as a function of the  $y$  and  $H_T$  requirements used to define the signal region, shown in Fig. 5.

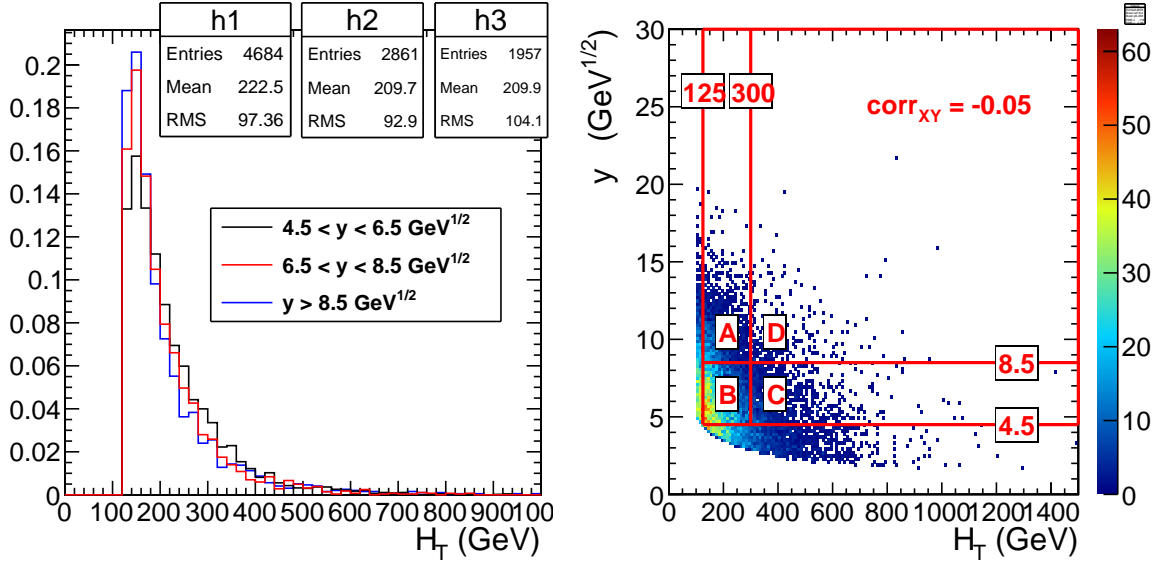


Figure 4: Illustration that  $y$  and  $H_T$  are not very correlated in MC for the 2010 signal region. Left: distributions of  $H_T$  in MC  $t\bar{t}$  events for different intervals of  $y$ . h1, h2, and h3 refer to the  $y$  intervals 4.5 - 6.5, 6.5 - 8.5 and  $> 8.5$ , respectively. Right: Distributions of  $y$  vs.  $H_T$  for  $t\bar{t}$  MC. Here we also show our choice of ABCD regions. The correlation coefficient  $\text{corr}_{XY}$  is computed for events falling in the ABCD regions.

Table 11: Expected yields from  $t\bar{t}$  MC in  $1 \text{ fb}^{-1}$  in the four ABCD regions for the signal region depicted in Figs. 8, as well as the predicted yield in region D given by  $N_A \times N_C / N_B$  and the ratio of the observed signal yield to the prediction. The quoted uncertainties are statistical only.

signal region	sample	A	B	C	D	$N_A \times N_C / N_B$	obs/pred
2010 signal region	madgraph	$251.3 \pm 6.1$	$951.5 \pm 11.9$	$165.2 \pm 4.9$	$38.3 \pm 2.4$	$43.6 \pm 1.8$	$0.88 \pm 0.07$
	powheg	$231.7 \pm 2.0$	$850.6 \pm 3.7$	$157.8 \pm 1.6$	$37.0 \pm 0.8$	$43.0 \pm 0.6$	$0.86 \pm 0.02$

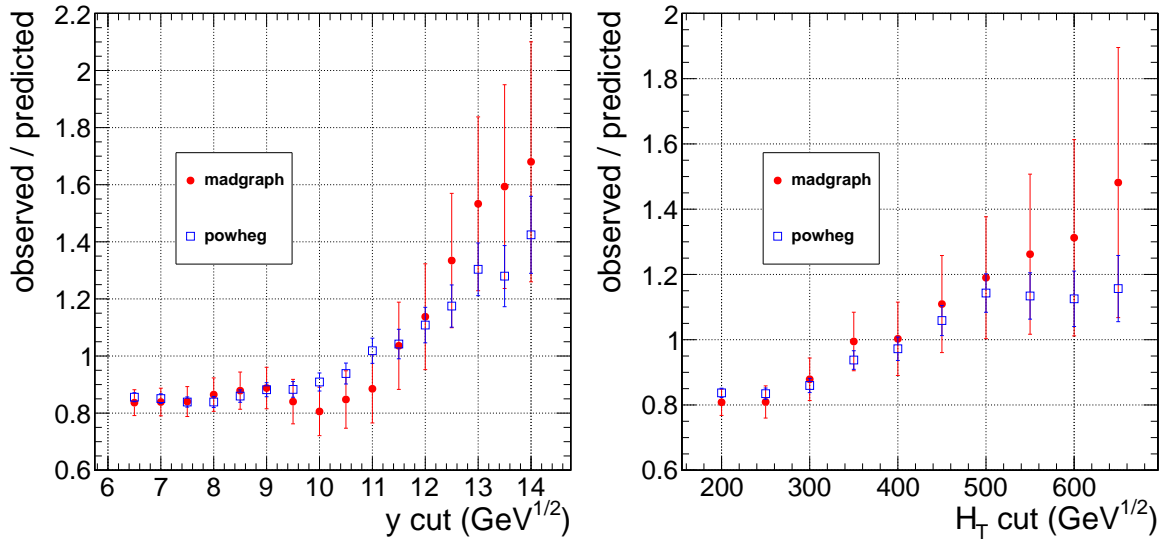


Figure 5: Variation of observed/predicted for the ABCD method as a function of the  $y$  ( for  $H_T > 300 \text{ GeV}$  ) and  $H_T$  ( for  $y > 8.5 \text{ GeV}^{1/2}$  ) cuts defining the signal region.



## 11.2 ABCD' Method

To estimate the background in a signal region defined in the  $E_T^{\text{miss}}$  vs.  $H_T$  plane, we perform a variant of the ABCD method which we refer to as the ABCD' method. This method is discussed in detail in App. B. Based on these results, we apply the scale factors and systematic uncertainties summarized in Table 15 to the background prediction of the ABCD' method.

## 11.3 Dilepton $p_T$ method

This method is based on a suggestion by V. Pavlunin [9], and was investigated by our group in 2009 [10] and in our 2010 analysis [3]. The idea is that in dilepton  $t\bar{t}$  events the lepton and neutrinos from  $W$  decays have the same  $p_T$  spectrum (modulo  $W$  polarization effects). One can then use the observed  $p_T(\ell\ell)$  distribution to model the sum of neutrino  $p_T$ 's which is identified with the  $E_T^{\text{miss}}$ .

Then, in order to predict the  $t\bar{t} \rightarrow$  dilepton contribution to a selection with  $E_T^{\text{miss}} + X$ , one applies a cut on  $p_T(\ell\ell) + X$  instead. In practice one has to rescale the result of the  $p_T(\ell\ell) + X$  selection to account for the fact that any dilepton selection must include a moderate  $E_T^{\text{miss}}$  cut in order to reduce Drell Yan backgrounds. This is discussed in Section 5.3 of Reference [10]; for a  $E_T^{\text{miss}}$  cut of 50 GeV, the rescaling factor is obtained from the MC as

$$K = \frac{\int_0^\infty \mathcal{N}(p_T(\ell\ell)) dp_T(\ell\ell)}{\int_{50}^\infty \mathcal{N}(p_T(\ell\ell)) dp_T(\ell\ell)} = 1.5.$$

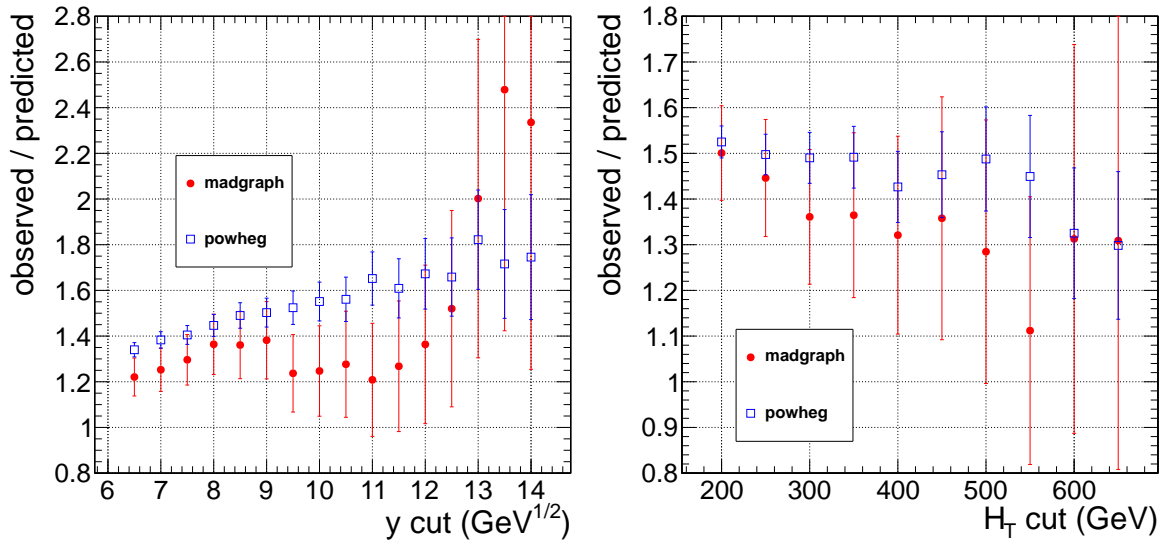


Figure 6: Variation of observed/predicted for the  $p_T(\ell\ell)$  method as a function of the  $y$  ( for  $H_T > 300$  GeV ) and  $H_T$  ( for  $y > 8.5$  GeV $^{1/2}$  ) cuts defining the signal region.

We summarize the expected results of the  $p_T(\ell\ell)$  method in 1 fb $^{-1}$   $t\bar{t}$  MC in Table 12, and we show the dependence of observed/predicted vs. the signal region requirements in Fig. 6. Based on these results, we apply the scale factors and uncertainties summarized in Table 15 to the predicted background from the  $p_T(\ell\ell)$  method. In [2], we have studied extensively the origin of the excess of observed vs. predicted events from this method. We found that it is due mostly to the  $W$  polarization, which results in a harder  $p_T$  distribution for the  $W$  neutrinos than charged leptons.

As a validation of the  $p_T(\ell\ell)$  method, we also apply the background estimate to the  $H_T$  sideband region 125–300 GeV, where we expect the events to be dominated by background and where the higher event yields allow us to test the method with higher statistical precision. The results of the  $p_T(\ell\ell)$  method applied to  $t\bar{t}$  MC in the  $H_T$  sideband region with the requirements corresponding to the 2010 signal region ( $y > 8.5$  GeV $^{1/2}$ ) and the high  $E_T^{\text{miss}}$  region ( $E_T^{\text{miss}} > 200$  GeV) are given in Table 13. Based on these results we will apply a correction factor  $K_C = 1.4 \pm 0.1$  ( $K_C = 1.3 \pm 0.2$ ) to data for the  $y > 8.5$  GeV $^{1/2}$  ( $E_T^{\text{miss}} > 200$  GeV) requirements in the  $H_T$  sideband region.

Table 12: Expected observed and predicted yields in  $1 \text{ fb}^{-1}$  for  $t\bar{t}$  MC for the  $p_T(\ell\ell)$  method applied to the 3 signal regions, and the ratio of the observed signal yield to the prediction. The quoted uncertainties are statistical only. Based on these results, we will apply the correction factor  $K_C$  to the prediction in data.

signal region	sample	predicted	observed	obs/pred	$K_C$
2010 signal region	madgraph	$28.2 \pm 2.5$	$38.3 \pm 2.4$	$1.36 \pm 0.15$	$1.4 \pm 0.2$
	powheg	$24.8 \pm 0.8$	$37.0 \pm 0.8$	$1.49 \pm 0.06$	
high $E_T^{\text{miss}}$ signal region	madgraph	$2.7 \pm 0.8$	$4.6 \pm 0.8$	$1.72 \pm 0.59$	$1.5 \pm 0.3$
	powheg	$3.3 \pm 0.3$	$4.5 \pm 0.3$	$1.39 \pm 0.15$	
high $H_T$ signal region	madgraph	$4.7 \pm 1.0$	$5.5 \pm 0.9$	$1.17 \pm 0.31$	$1.3 \pm 0.2$
	powheg	$4.7 \pm 0.3$	$6.2 \pm 0.3$	$1.33 \pm 0.11$	

Table 13: Expected observed and predicted yields in  $1 \text{ fb}^{-1}$  for  $t\bar{t}$  MC for the  $p_T(\ell\ell)$  method for the control regions in the  $H_T$  sideband region  $125 < H_T < 300 \text{ GeV}$ , and the ratio of the observed signal yield to the prediction. The quoted uncertainties are statistical only, assuming Gaussian errors.

control region	sample	predicted	observed	obs/pred
$125 < H_T < 300 \text{ GeV}, y > 8.5 \text{ GeV}^{1/2}$	madgraph	$35.8 \pm 1.3$	$51.3 \pm 1.2$	$1.43 \pm 0.06$
	powheg	$33.4 \pm 0.4$	$47.3 \pm 0.4$	$1.42 \pm 0.02$
$125 < H_T < 300 \text{ GeV}, E_T^{\text{miss}} > 200 \text{ GeV}^{1/2}$	madgraph	$6.4 \pm 1.3$	$9.9 \pm 1.2$	$1.54 \pm 0.36$
	powheg	$6.6 \pm 0.4$	$8.4 \pm 0.4$	$1.27 \pm 0.10$

Table 14: Dependence of the correction factor  $K_C$  on the hadronic energy scale. Based on these results, we apply the uncertainty in the rightmost column to  $K_C$  for the given signal region.

Signal Region	sample	nominal	+5%	-5%	uncertainty
2010 signal region	madgraph	$1.36 \pm 0.15$	$1.66 \pm 0.17$	$1.07 \pm 0.12$	0.3
	powheg	$1.49 \pm 0.06$	$1.82 \pm 0.07$	$1.18 \pm 0.05$	
high $E_T^{\text{miss}}$ signal region	madgraph	$1.72 \pm 0.59$	$2.34 \pm 0.76$	$1.11 \pm 0.41$	0.4
	powheg	$1.39 \pm 0.15$	$1.83 \pm 0.18$	$1.05 \pm 0.12$	
high $H_T$ signal region	madgraph	$1.17 \pm 0.31$	$1.42 \pm 0.36$	$1.07 \pm 0.29$	0.3
	powheg	$1.33 \pm 0.11$	$1.58 \pm 0.13$	$1.11 \pm 0.10$	

Table 15: Summary of correction factors and systematic uncertainties for the ABCD' and  $p_T(\ell\ell)$  methods in the 3 signal regions. For the  $p_T(\ell\ell)$  method, the correction factor is from Table 12, with the additional uncertainty from hadronic energy scale of Table 14.

signal region	ABCD'	$p_T(\ell\ell)$
2010 signal region	$1.0 \pm 0.2$	$1.4 \pm 0.4$
high $E_T^{\text{miss}}$ signal region	$1.2 \pm 0.5$	$1.5 \pm 0.5$
high $H_T$ signal region	$1.0 \pm 0.5$	$1.3 \pm 0.4$

## 11.4 Opposite-Flavor Subtraction

The opposite-flavor subtraction technique exploits the fact that in  $t\bar{t}$ , the flavor of the 2 leptons from  $W$  decay are uncorrelated. Hence we expect equal rates of same-flavor (SF)  $ee$  or  $\mu\mu$  vs. opposite-flavor (OF)  $e\mu$  lepton pairs. In SUSY, the lepton flavors may be correlated, producing an excess of SF over OF events. We use the observed yield in the OF final state to predict the yields in the SF final state according to:

$$N(ee) = \frac{1}{2R_{\mu e}}N(e\mu) \text{ and } N(\mu\mu) = \frac{R_{\mu e}}{2}N(e\mu)$$

where  $R_{\mu e}$  is the ratio of muon to electron selection efficiencies. This quantity is evaluated by taking the ratio of the number of observed  $Z \rightarrow \mu^+\mu^-$  to  $Z \rightarrow e^+e^-$  events, in the mass range 76-106 GeV with no jets or  $E_T^{\text{miss}}$  requirements (see Fig. 2). Alternatively, we can quantify the excess of SF vs. OF events with the quantity:

$$\Delta = R_{\mu e}N(ee) + \frac{1}{R_{\mu e}}N(\mu\mu) - N(e\mu), \quad (1)$$

which is predicted to be 0 for processes with uncorrelated lepton flavors. In order for this technique to work, the kinematic selection applied to events in all dilepton flavor channels must be the same, which is not the case for our default selection because the  $Z$  mass veto is applied only to same-flavor channels. Therefore when applying the OF subtraction technique we also apply the  $Z$  mass veto also to the  $e\mu$  channel.

We will apply this technique to both the high  $p_T$  dilepton trigger and dilepton- $H_T$  trigger data samples. In the following, we first apply the technique to  $t\bar{t}$  MC with high  $p_T$  leptons, and then to  $t\bar{t}$  MC with low  $p_T$  leptons.

### 11.4.1 OF subtraction: Application to high $p_T$ lepton sample

We begin by applying the OF subtraction technique to  $t\bar{t}$  MC with leptons passing  $p_T > (20,10)$  GeV. Here we extract  $R_{e\mu}$  by taking the ratio of  $Z \rightarrow \mu^+\mu^-$  vs.  $Z \rightarrow e^+e^-$  events in the window 76–106 GeV in DY MC. For data, we have verified that the contribution from fake leptons in the high lepton  $p_T$  signal regions is small using the data-driven fake rate method, hence we do not need to correct for fake leptons here. The results are summarized in Table 16, where we find values of  $\Delta$  consistent with 0, as expected.

Table 16: Expected yields in  $1 \text{ fb}^{-1}$   $t\bar{t}$  MC for the OF subtraction method, and the quantity  $\Delta$ , defined in Eq. 1. The quoted systematic uncertainty refers to that of  $R_{\mu e}$ .

region	sample	$N(ee)$	$N(\mu\mu)$	$N(e\mu)$	$\Delta$
preselection region	madgraph	$431.1 \pm 8.0$	$531.3 \pm 8.9$	$945.8 \pm 11.8$	$11.8 \pm 16.8 \text{ (stat)} \pm 1.1 \text{ (syst)}$
	powheg	$383.1 \pm 2.5$	$492.9 \pm 2.9$	$876.2 \pm 3.8$	$-7.0 \pm 5.4 \text{ (stat)} \pm 0.8 \text{ (syst)}$
2010 signal region	madgraph	$7.4 \pm 1.0$	$10.7 \pm 1.3$	$14.5 \pm 1.5$	$3.3 \pm 2.2 \text{ (stat)} \pm 0.04 \text{ (syst)}$
	powheg	$7.2 \pm 0.3$	$8.6 \pm 0.4$	$16.8 \pm 0.5$	$-1.1 \pm 0.7 \text{ (stat)} \pm 0.03 \text{ (syst)}$

### 11.4.2 OF subtraction: Application to low $p_T$ lepton sample

In this section, we apply the OF subtraction technique to  $t\bar{t}$  MC with leptons passing  $p_T > (10,5)$  GeV but not passing  $p_T > (20,10)$  GeV (in order to remove overlap with the high lepton  $p_T$  sample). The OF subtraction in the low lepton  $p_T$  regime is complicated by 2 factors:

- The ratio of muon to electron selection efficiencies  $R_{\mu e}$  increases significantly at low  $p_T$ , due to a drop in the electron selection efficiency.
- We reconstruct muons down to  $p_T > 5$  GeV but electrons only to  $p_T > 10$  GeV.

Our strategy is the following:

- Evaluate  $R_{\mu e}$  from  $t\bar{t}$  MC.

- Parameterize  $R_{\mu e}$  as a function of lepton  $p_T$ . For now we split in 2 bins,  $10 < p_T < 20$  GeV and  $p_T > 20$  GeV.
- For data, we will apply to  $R_{\mu e}$  a trigger efficiency correction and subtract the expected contribution from fake leptons from the data-driven fake rate method (but neither correction is performed for the MC studies in this section).
- We first apply the OF subtraction to the preselection region, and then to the signal region.

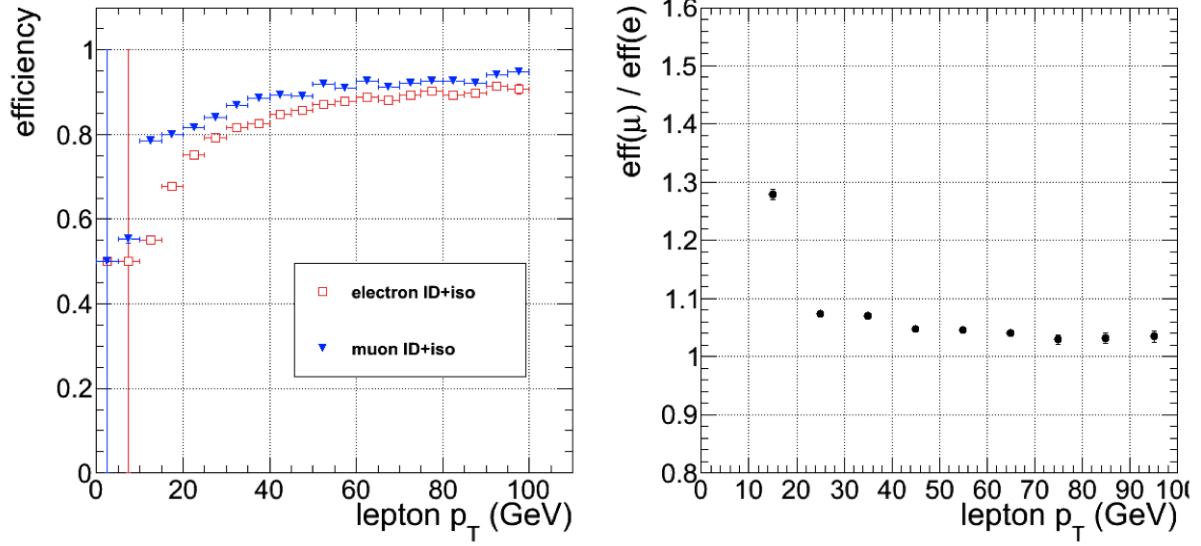


Figure 7: Left: the electron and muon selection efficiencies, as a function of lepton  $p_T$ , extracted from  $t\bar{t}$  MC. Right: the ratio  $R_{\mu e}$  of muon to electron selection efficiencies as a function of lepton  $p_T$ .

We begin by examining the dependence of  $R_{\mu e}$  on lepton  $p_T$ , as shown in Fig. 7. We find that  $R_{\mu e}$  increases in the region  $p_T$  10–20 GeV, but is roughly constant for  $p_T > 20$  GeV. Hence we take  $R_{\mu e}^{10-20} = 1.28$  for  $p_T$  10–20 GeV and  $R_{\mu e}^{>20} = 1.08$  for  $p_T > 20$  GeV, and assign a 5% systematic uncertainty.

Next, to take into account the fact the electrons and muons have a different  $p_T$  range, we split the low  $p_T$  sample into events with leptons passing  $p_T > (10,10)$  GeV, denoted in the following as (10,10), and events with leptons passing  $p_T > (10,5)$  GeV but not passing  $p_T > (10,10)$  GeV, denoted in the following as (10,5). We find the following relations, expected for backgrounds with uncorrelated lepton flavors:

- $N(ee)(10,10) = 1/(2R_{\mu e}^{10-20})N(e\mu)(10,10)$
- $N(\mu\mu)(10,10) = (R_{\mu e}^{10-20}/2)N(e\mu)(10,10)$
- $N(\mu\mu)(10,5) = R_{\mu e}^{>20}N(e\mu)(10,5)$

Note that for (10,10) events, both leptons are in the range  $p_T$  10–20 GeV, hence the relevant efficiency ratio is  $R_{\mu e}^{10-20}$ . For (10,5) events, both  $ee$  and  $\mu\mu$  events have a muon with  $p_T$  5–10 GeV and an additional lepton with  $p_T > 10$  GeV. In most cases the leading lepton has  $p_T > 20$  GeV, hence we use  $R_{\mu e}^{>20}$  for these events.

In this case we find the following expression for  $\Delta$ , quantifying the excess of SF vs. OF yields:

$$\Delta = R_{\mu e}^{10-20}N(ee)(10,10) + 1/R_{\mu e}^{10-20}N(\mu\mu)(10,10) + 1/R_{\mu e}^{>20}N(\mu\mu)(10,5) - N(e\mu)(10,10) - N(e\mu)(10,5) \quad (2)$$

In Table 17 we apply this technique to  $t\bar{t}$  MC. As expected, we find  $\Delta$  consistent with 0.

Table 17: Expected yields in  $1 \text{ fb}^{-1} t\bar{t}$  MC for the OF subtraction method in the low lepton  $p_T$  regime, and the quantity  $\Delta$ , defined in Eq. 2. The quoted systematic uncertainty refers to that of  $R_{\mu e}$ .

region	sample	$N(ee)(10, 10)$	$N(\mu\mu)(10, 10)$	$N(e\mu)(10, 10)$	$N(\mu\mu)(10, 5)$	$N(e\mu)(10, 5)$	$\Delta$
preselection region	madgraph	$3.4 \pm 0.7$	$4.9 \pm 0.9$	$6.4 \pm 1.0$	$22.9 \pm 1.8$	$18.2 \pm 1.6$	$4.8 \pm 2.8 \text{ (stat)} \pm 1.0 \text{ (syst)}$
	powheg	$2.5 \pm 0.2$	$4.4 \pm 0.3$	$7.0 \pm 0.3$	$19.0 \pm 0.6$	$16.6 \pm 0.5$	$0.6 \pm 0.9 \text{ (stat)} \pm 0.9 \text{ (syst)}$
2010 signal region	madgraph	$0.0 \pm 0.0$	$0.4 \pm 0.3$	$0.6 \pm 0.3$	$1.0 \pm 0.4$	$0.7 \pm 0.3$	$-0.0 \pm 0.6 \text{ (stat)} \pm 0.1 \text{ (syst)}$
	powheg	$0.1 \pm 0.0$	$0.2 \pm 0.1$	$0.4 \pm 0.1$	$1.4 \pm 0.2$	$1.1 \pm 0.1$	$0.1 \pm 0.2 \text{ (stat)} \pm 0.1 \text{ (syst)}$

## 12 Results

### 12.1 Background estimate from the ABCD method

We begin by applying the ABCD method to estimate the background in the 2010 signal region. The data yields in the four regions are summarized in Tables 19 and the  $y$  vs.  $H_T$  distributions are displayed in Fig. 8. The ABCD background prediction is  $N_A \times N_C/N_B = 12.7 \pm 2.4 \text{ (stat)}$ , in agreement with the MC expectation. We also apply the ABCD' method to estimate the background in this region, following the procedure of App. B, and find a predicted background of  $12.8 \pm 2.9 \text{ (stat)}$ , in good agreement with the ABCD prediction.

Next, we apply the ABCD' method to predict the yields in the high  $E_T^{\text{miss}}$  and high  $H_T$  signal regions. The  $y$  vs.  $H_T$  distributions for data are displayed in Fig. 9. The signal regions are indicated, as well as the control regions used to measure the  $f(y)$  and  $g(H_T)$  distributions. For the high  $E_T^{\text{miss}}$  signal region, we find a predicted yield of  $1.0 \pm 0.3 \text{ (stat)}$ , in reasonable agreement with the MC prediction. For the high  $H_T$  signal region, we do not find any events in the control region used to extract  $g(H_T)$  with  $H_T > 600 \text{ GeV}$ , and the ABCD' background estimate is therefore 0. To assess the statistical uncertainty in this prediction, we add a single event “by hand” to the  $g(H_T)$  distribution at  $H_T = 600 \text{ GeV}$ , leading to a predicted yield of 0.6. These results are summarized in Table 18.

Table 18: Summary of results of the ABCD' method, applied to the 3 signal regions. The correction factors are given in Table 15.

Signal Region	ABCD' pred	correction factor	prediction
2010 signal region	$12.8 \pm 2.9$	$1.0 \pm 0.2$	$12.8 \pm 2.9 \text{ (stat)} \pm 2.6 \text{ (syst)}$
high $E_T^{\text{miss}}$ signal region	$1.0 \pm 0.3$	$1.2 \pm 0.5$	$1.2 \pm 0.4 \text{ (stat)} \pm 0.5 \text{ (syst)}$
high $H_T$ signal region	$0.0 \pm 0.6$	$1.0 \pm 0.5$	$0.0 \pm 0.6 \text{ (stat)} \pm 0.3 \text{ (syst)}$

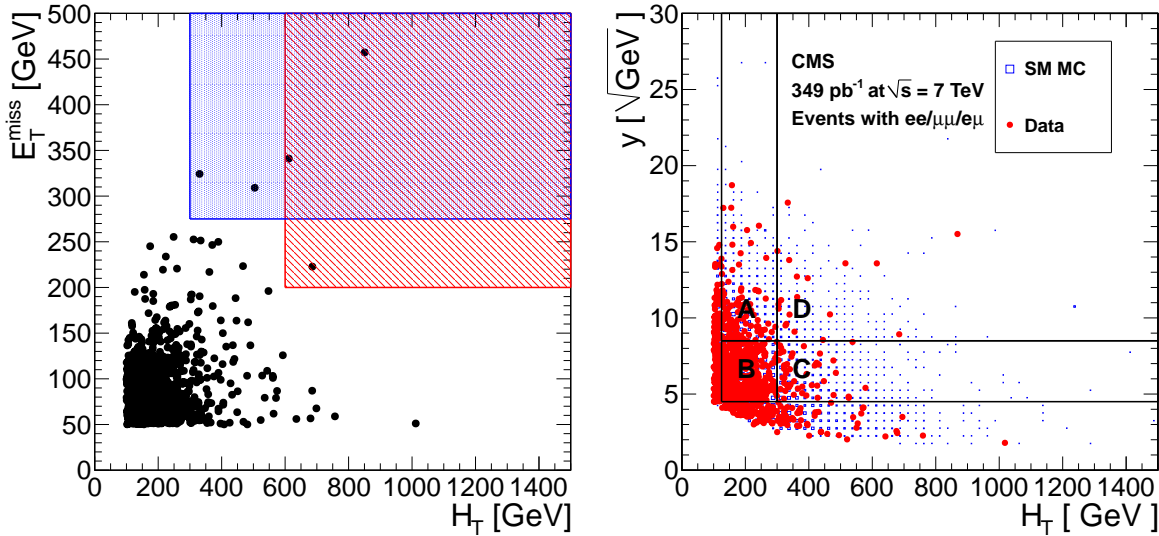


Figure 8: Left: Distribution of  $E_T^{\text{miss}}$  vs.  $H_T$  for SM Monte Carlo and data. The 2011 high  $H_T$  signal region is shown in red. The 2011 high  $E_T^{\text{miss}}$  signal region is shown in blue. Right: Distributions of  $y$  vs.  $H_T$  for SM Monte Carlo and data. The 2010 signal region boundaries are overlaid.

Table 19: Data yields in the four regions of Figure 8 for the 2010 signal region, as well as the predicted yield in region D given by  $N_A \times N_C/N_B$ . The quoted uncertainty on the prediction in data is statistical only, assuming Gaussian errors. We also show the SM Monte Carlo expectations with statistical errors only.

sample	$N_A$	$N_B$	$N_C$	$N_D$	$N_A \times N_C/N_B$
$t\bar{t} \rightarrow \ell^+\ell^-$	$63.9 \pm 2.0$	$252.3 \pm 4.1$	$43.3 \pm 1.7$	$8.5 \pm 0.7$	$11.0 \pm 0.6$
$t\bar{t} \rightarrow \ell^\pm\tau^\mp/\tau^+\tau^-$	$18.5 \pm 1.1$	$55.9 \pm 1.9$	$10.3 \pm 0.8$	$3.4 \pm 0.5$	$3.4 \pm 0.4$
$t\bar{t} \rightarrow \text{fake}$	$1.0 \pm 0.3$	$6.6 \pm 0.7$	$1.1 \pm 0.3$	$0.4 \pm 0.2$	$0.2 \pm 0.1$
DY	$0.9 \pm 0.6$	$13.9 \pm 2.6$	$1.3 \pm 0.8$	$1.7 \pm 1.0$	$0.1 \pm 0.1$
$W^+W^-$	$1.1 \pm 0.1$	$2.7 \pm 0.2$	$0.2 \pm 0.1$	$0.3 \pm 0.1$	$0.1 \pm 0.0$
$W^\pm Z^0$	$0.1 \pm 0.0$	$0.6 \pm 0.0$	$0.1 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
$Z^0 Z^0$	$0.0 \pm 0.0$	$0.2 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
single top	$3.3 \pm 0.2$	$9.6 \pm 0.3$	$0.4 \pm 0.1$	$0.1 \pm 0.0$	$0.1 \pm 0.0$
$W + \text{jets}$	$1.0 \pm 1.0$	$2.2 \pm 1.1$	$0.0 \pm 0.0$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
Total SM MC	$89.9 \pm 2.6$	$344.0 \pm 5.3$	$56.6 \pm 2.1$	$14.5 \pm 1.4$	$14.8 \pm 0.7$
data	110	381	44	19	$12.7 \pm 2.4$

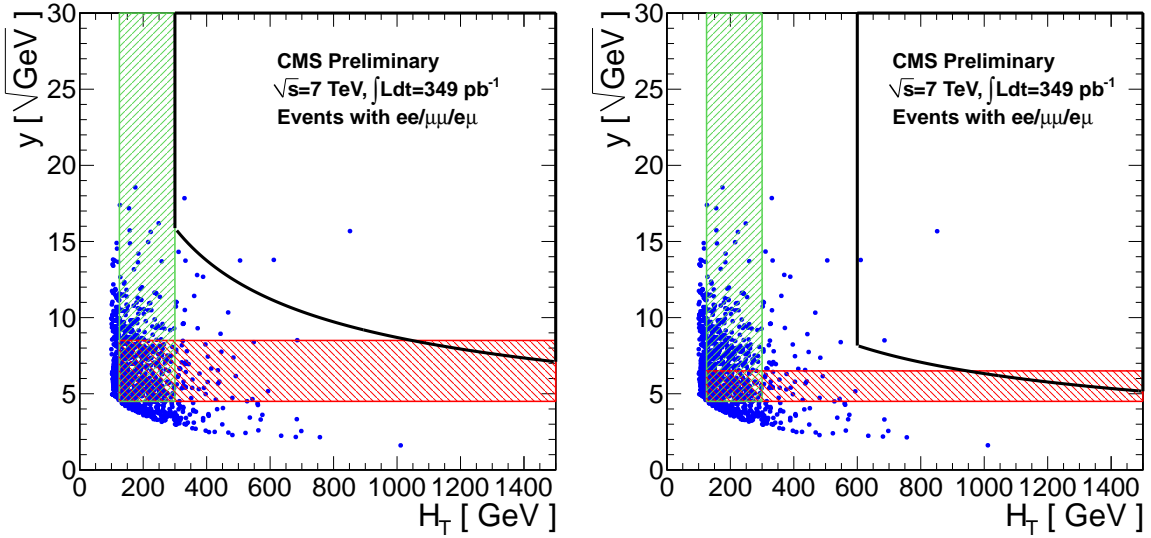


Figure 9: Distributions of  $y$  vs.  $H_T$  in data. The signal regions  $E_T^{\text{miss}} > 275$  GeV,  $H_T > 300$  GeV (left) and  $E_T^{\text{miss}} > 200$  GeV,  $H_T > 600$  GeV (right) are indicated with thick black lines. The  $f(y)$  and  $g(H_T)$  functions are measured using events in the green and red shaded areas, respectively.

## 12.2 Background estimate from the $P_T(\ell\ell)$ method

We begin by extracting the value of the  $E_T^{\text{miss}}$  acceptance scaling factor  $K$  from data, for the  $H_T$  control region 125–300 GeV and for the 2 signal regions  $H_T > 300$  and  $H_T > 600$  GeV. The quantity  $1/K$  is the efficiency for events passing preselection and falling in the given  $H_T$  range to pass the requirement  $p_T(\ell\ell) > 50$  GeV. The values of  $K$  extracted from data and  $t\bar{t}$  MC are given in Table 20. For all 3  $H_T$  regions, the value of  $K$  extracted from data agrees with the  $t\bar{t}$  MC prediction, but for the  $H_T > 600$  GeV region the statistical uncertainty in  $K$  from data is  $\sim 100\%$ . Therefore we use the value of  $K$  extracted from data for the control region 125–300 GeV and for the signal regions  $H_T > 300$ ; for the  $H_T > 600$  GeV region we use  $K$  from  $t\bar{t}$  MC.

For each signal region D, we count the number of events falling in the region D', which is defined using the same requirements as D but switching the  $y$  requirement to a  $p_T(\ell\ell)/\sqrt{H_T}$  requirement (2010 signal region) or switching the  $E_T^{\text{miss}}$  requirement to a  $p_T(\ell\ell)$  requirement (high  $E_T^{\text{miss}}$  and high  $H_T$  signal regions). We subtract off the expected DY contribution using the data-driven  $R_{\text{out/in}}$  technique, using  $R_{\text{out/in}} = 0.13 \pm 0.07$ . We then scale this yield by 2 corrections factors:  $K$ , the  $E_T^{\text{miss}}$  acceptance correction factor, and  $K_C$ , the correction factor determined in Sec. 11. Our final prediction  $N_P$  is given by:

$$N_P = (N(D') - N(DY)) \times K \times K_C,$$

as summarized in Table 21, and displayed in Figs. 11-13. We also perform the  $p_T(\ell\ell)$  method in the  $H_T$  sideband region 125–300 GeV, as a validation of the technique in a high statistics sample which is expected to be dominated by background. The results are summarized in Table 22 and displayed in Fig. 10. The prediction is extracted for the requirement  $y > 8.5 \text{ GeV}^{1/2}$  corresponding to the 2010 signal region, as well as for  $E_T^{\text{miss}} > 200 \text{ GeV}$  corresponding to the high  $H_T$  signal region. In both cases, we observe good agreement between the predicted and observed yields.

Table 20: Summary of the  $E_T^{\text{miss}}$  acceptance scaling factor  $K$ , extracted from data and  $t\bar{t}$  MC.

region	data	$t\bar{t}$ MC
control region: $125 < H_T < 300 \text{ GeV}$	$1.68 \pm 0.14$	$1.67 \pm 0.03$
signal region: $H_T > 300 \text{ GeV}$	$1.45 \pm 0.29$	$1.50 \pm 0.06$
signal region: $H_T > 600 \text{ GeV}$	$1.12 \pm 1.19$	$1.32 \pm 0.20$

Table 21: Summary of results of the dilepton  $p_T$  template method applied to the 3 signal regions. The quantities indicated in the table are discussed in the text. The quoted statistical uncertainty in the prediction  $N_P$  is due to that of  $N(D')$ , the quoted systematic uncertainty includes that of  $N(DY)$ ,  $K$ , and  $K_C$ .

Signal Region	$N(D')$	$N(DY)$	$K$	$K_C$	$N_P$
2010 signal region (UPDATE)	9	$0.8 \pm 0.4$	$1.5 \pm 0.3$	$1.4 \pm 0.4$	$16.7 \pm 6.1 \text{ (stat)} \pm 5.9 \text{ (syst)}$
high $E_T^{\text{miss}}$ signal region	3	$0.5 \pm 0.3$	$1.5 \pm 0.3$	$1.5 \pm 0.5$	$5.4 \pm 3.8 \text{ (stat)} \pm 2.2 \text{ (syst)}$
high $H_T$ signal region	1	$0.0 \pm 0.0$	$1.3 \pm 0.2$	$1.3 \pm 0.4$	$1.7 \pm 1.7 \text{ (stat)} \pm 0.6 \text{ (syst)}$

Table 22: Summary of results of the dilepton  $p_T$  template method applied to the  $H_T$  sideband control region 125–300 GeV. The quantities indicated in the table are discussed in the text. The quoted statistical uncertainty in the prediction  $N_P$  is due to that of  $N(D')$ , the quoted systematic uncertainty includes that of  $N(DY)$  and  $K_C$ . The predictions are compare with the observed yield  $N_O$ .

Control Region	$N(D')$	$N(DY)$	$K$	$K_C$	$N_P$	$N_O$
$125 < H_T < 300 \text{ GeV}, y > 8.5 \text{ GeV}^{1/2}$	54	$2.6 \pm 1.2$	$1.7 \pm 0.1$	$1.4 \pm 0.1$	$120.9 \pm 17.3 \text{ (stat)} \pm 13.6 \text{ (syst)}$	110
$125 < H_T < 300 \text{ GeV}, E_T^{\text{miss}} > 200 \text{ GeV}$	4	$1.0 \pm 0.5$	$1.7 \pm 0.1$	$1.3 \pm 0.2$	$6.5 \pm 4.4 \text{ (stat)} \pm 1.6 \text{ (syst)}$	6

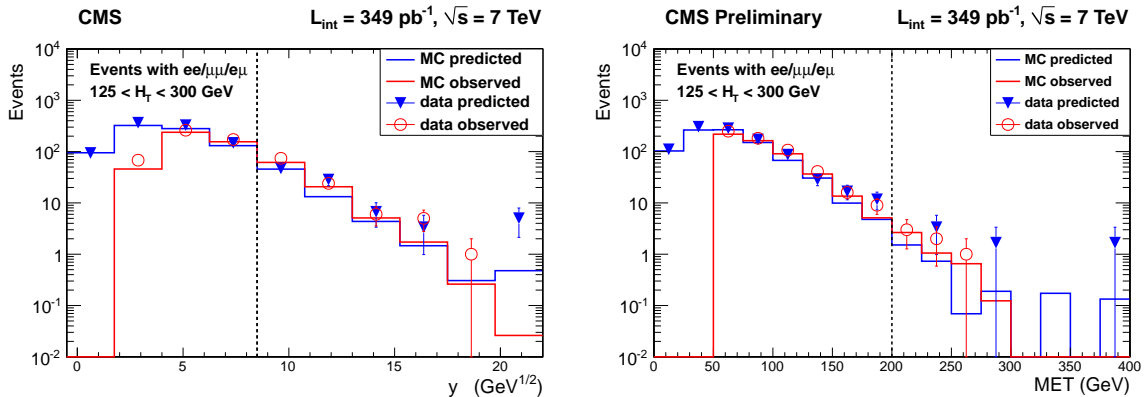


Figure 10: Results of the  $p_T(\ell\ell)$  method in the  $H_T$  sideband region 125-300 GeV. Left: distributions of  $p_T(\ell\ell)/\sqrt{H_T}$  (predicted) and  $y$  (observed) for SM MC and data. The vertical dashed lines indicate the requirement  $y > 8.5 \text{ GeV}^{1/2}$ , corresponding to the 2010 signal region. Right: distributions of  $p_T(\ell\ell)$  (predicted) and  $E_T^{\text{miss}}$  (observed) for SM MC and data. The vertical dashed lines indicate the requirement  $E_T^{\text{miss}} > 200 \text{ GeV}$ , corresponding to the high  $H_T$  signal region.

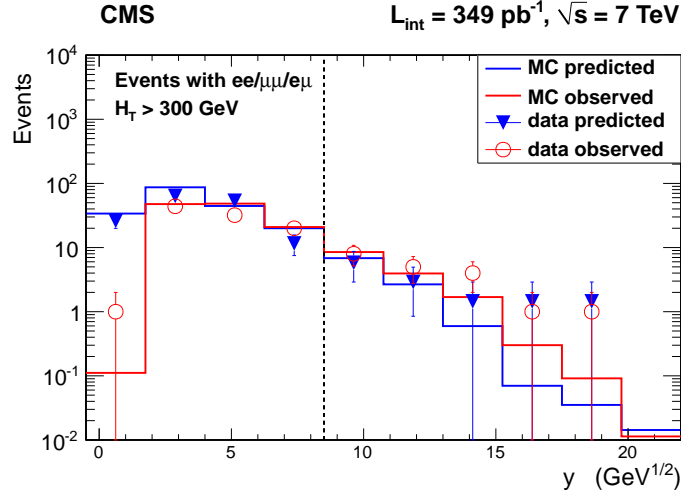


Figure 11: Distributions of  $p_T(\ell\ell)/\sqrt{H_T}$  (predicted) and  $y$  (observed) for SM MC and data, for the  $H_T > 300$  GeV. The vertical dashed lines indicate the requirement  $y > 8.5 \text{ GeV}^{1/2}$  corresponding to the 2010 signal region.

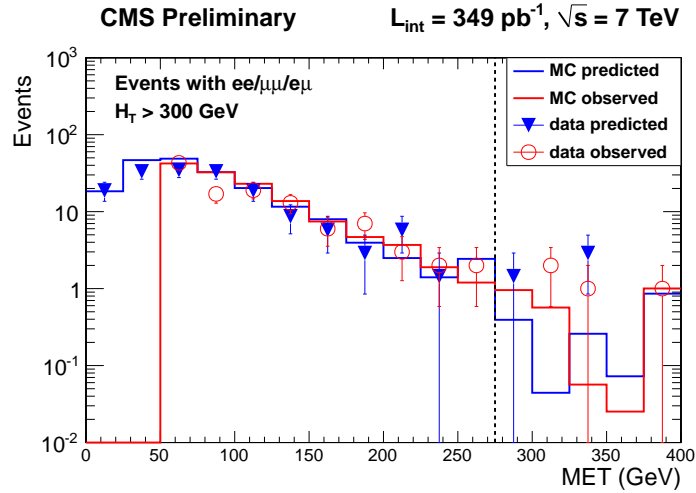


Figure 12: Distributions of  $p_T(\ell\ell)$  (predicted) and  $E_T^{\text{miss}}$  (observed) for SM MC and data, for the region  $H_T > 300$  GeV. The vertical dashed lines indicate the requirement  $E_T^{\text{miss}} > 275 \text{ GeV}$ , corresponding to the high  $E_T^{\text{miss}}$  signal region.



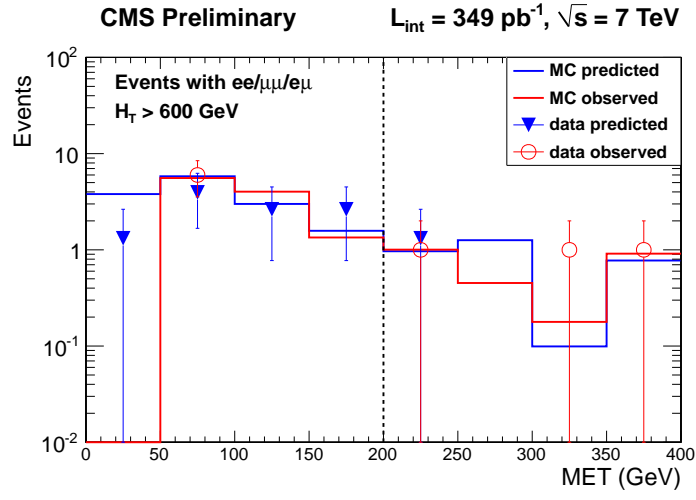


Figure 13: Distributions of  $p_T(\ell\ell)$  (predicted) and  $E_T^{\text{miss}}$  (observed) for SM MC and data, for the region  $H_T > 600$  GeV. The vertical dashed lines indicate the requirement  $E_T^{\text{miss}} > 200$  GeV, corresponding to the high  $H_T$  signal region.

### 12.3 Background estimate from OF subtraction

The results of the OF subtraction technique applied to the high  $p_T$  dilepton trigger sample are summarized in Table 23. We evaluate the quantity  $\Delta = R_{\mu e}N(ee) + \frac{1}{R_{\mu e}}N(\mu\mu) - N(e\mu)$  with  $R_{\mu e} = 1.12 \pm 0.05$  extracted from the ratio of  $Z \rightarrow \mu^+\mu^-$  vs.  $Z \rightarrow e^+e^-$  events in data. We perform the OF subtraction first in the preselection region, and find  $\Delta$  consistent with 0, as expected. We then perform the OF subtraction in all 3 signal regions, and do not observe any excess of same-flavor vs. opposite-flavor events. We do not correct the value of  $\Delta$  for contributions from fake leptons; instead, we assess on uncertainty based on the results of Sec. 10.

Table 23: Summary of results for the OF subtraction technique. The quantity  $\Delta = R_{\mu e}N(ee) + \frac{1}{R_{\mu e}}N(\mu\mu) - N(e\mu)$  is quoted with  $R_{\mu e} = 1.12 \pm 0.05$ . The quoted systematic uncertainty corresponds to that of  $R_{\mu e}$  and the contribution from fake leptons. The  $e\mu$  yields differ from those previously quoted because the  $Z$  mass veto is included here.

region	$N(ee)$	$N(\mu\mu)$	$N(e\mu)$	$\Delta$
preselection region	193	201	394	$2.0 \pm 28$ (stat) $\pm 1.8$ (syst)
2010 signal region	4	4	9	$-0.9 \pm 4.2$ (stat) $\pm 0.6$ (syst)
high $E_T^{\text{miss}}$ signal region	2	0	1	$1.3 \pm 1.9$ (stat) $\pm 0.5$ (syst)
high $H_T$ signal region	1	0	1	$0.1 \pm 1.5$ (stat) $\pm 0.5$ (syst)

For the dilepton- $H_T$  trigger sample, we observe only 1 event in the 2010 signal region, consistent with MC expectations, and no events in either the high  $y$  or high  $H_T$  signal regions. In the case of an excess of events at low lepton  $p_T$ , we will perform the OF subtraction technique of Sec. 11.4.2.

### 12.4 Summary of results

A summary of our results is presented in Table 24. In all 3 signal regions, we observe reasonable agreement between the observed yields and the predictions from MC and data-driven background estimates. We therefore do not observe evidence for an excess of events above SM expectations. After assessing systematic uncertainties in Sec. 13, we proceed to set upper limits on the non-SM contributions to the signal regions in Sec. 14.

Table 24: Summary of the observed and predicted yields in the 3 signal regions. MC errors are statistical only. The systematic uncertainty on the ABCD and  $p_T(\ell\ell)$  method is from the scaling factors from MC closure only. For the OF subtraction, the quantity  $\Delta = R_{\mu e}N(ee) + \frac{1}{R_{\mu e}}N(\mu\mu) - N(e\mu)$  is quoted; the systematic uncertainty here is from the ratio of muon to electron selection efficiencies.

	2010 signal region	high $E_T^{\text{miss}}$ signal region	high $H_T$ signal region
Observed yield	19	4	3
MC prediction	$14.5 \pm 1.4$	$2.6 \pm 0.8$	$2.5 \pm 0.8$
ABCD prediction	$12.7 \pm 2.4$ (stat) $\pm 2.5$ (syst)		
ABCD' prediction	$12.8 \pm 2.9$ (stat) $\pm 2.6$ (syst)	$1.2 \pm 0.4$ (stat) $\pm 0.5$ (syst)	$0.0 \pm 0.6$ (stat) $\pm 0.3$ (syst)
$p_T(\ell\ell)$ prediction	$16.7 \pm 6.1$ (stat) $\pm 5.9$ (syst)	$5.4 \pm 3.8$ (stat) $\pm 2.2$ (syst)	$1.7 \pm 1.7$ (stat) $\pm 0.6$ (syst)
OF subtraction ( $\Delta$ )	$-0.9 \pm 4.2$ (stat) $\pm 0.6$ (syst)	$1.3 \pm 1.9$ (stat) $\pm 0.5$ (syst)	$0.1 \pm 1.5$ (stat) $\pm 0.5$ (syst)

## 13 Acceptance and efficiency systematics

This is a search for new physics contributions to events with high  $E_T^{\text{miss}}$  and lots of jet activity. As seen in Section 12, there is no evidence for a contribution beyond SM expectations.

Strictly speaking it is impossible to talk about “acceptance and efficiency systematics” because these kinds of systematics only apply to a well defined final state. Nevertheless, we can make general statements about the systematic uncertainties, including quantitative estimates of the systematic uncertainties associated with a few specific processes.

The systematic uncertainty on the lepton acceptance consists of two parts: the trigger efficiency uncertainty and the ID and isolation uncertainty. We discuss these in turn.

The trigger efficiency for the high  $p_T$  dilepton triggers has been studied in [7] in detail. The efficiency is found to be approximately 100% for  $ee$ , 95% for  $e\mu$ , and 90% for  $\mu\mu$ . There is a small dependence of the efficiency on the lepton  $p_T$ , which we do not attempt to parameterize. Instead, we assign an uncertainty of 2%, based on the small variation of the efficiency on the lepton  $p_T$ .

To evaluate the uncertainty on the lepton ID and isolation efficiencies, we perform a tag and probe technique on  $Z$  data and MC. We calculate the efficiency for leptons passing isolation criteria to also pass the ID criteria, and the efficiency for leptons passing the ID criteria to also pass the isolation criteria, as summarized in Table. 25. We observe agreement between data and MC within about 2%, and assign a corresponding systematic uncertainty.

Table 25: Tag and probe results on  $Z \rightarrow \ell\ell$  on data and MC. We quote ID efficiency given isolation and the isolation efficiency given ID. **UPDATE TABLE WITH 2011 DATA/MC**

	Data T&P	MC T&P
$\epsilon(id iso)$ electrons	$0.925 \pm 0.007$	$0.934 \pm 0.004$
$\epsilon(iso id)$ electrons	$0.991 \pm 0.002$	$0.987 \pm 0.002$
$\epsilon(id iso)$ muons	$0.962 \pm 0.005$	$0.984 \pm 0.002$
$\epsilon(iso id)$ muons	$0.987 \pm 0.003$	$0.982 \pm 0.002$

Another significant source of systematic uncertainty is associated with the jet and  $E_T^{\text{miss}}$  energy scale. The impact of this uncertainty is final-state dependent. Final states characterized by lots of hadronic activity and  $E_T^{\text{miss}}$  are less sensitive than final states where the  $E_T^{\text{miss}}$  and  $H_T$  are typically close to the requirement. To be more quantitative, we have used the method of Reference [4] to evaluate the systematic uncertainties on the acceptance for  $t\bar{t}$  and two benchmark SUSY points. The uncertainties are calculated assuming a 5% uncertainty to the hadronic energy scale in CMS.

Table 26: Summary of efficiency uncertainties due to the 5% uncertainty in the hadronic energy scale.

Signal Region	$t\bar{t}$	LM1	LM3
2010 signal region	0.28	0.06	0.07
high $E_T^{\text{miss}}$ signal region	0.35	0.14	0.18
high $H_T$ signal region	0.30	0.20	0.21

The uncertainty in the integrated luminosity is 11% [19].

## 14 Derivation of Upper Limits

We proceed to set upper limits on the non-SM contributions to the 3 signal regions. For all 3 regions, we find reasonable agreement between the observed yields and the predictions from MC and from the 2 data-driven methods. We choose here to extract the upper limits using the MC prediction for the background estimate. The 95% CL upper limit is extracted using `cl95cms`, using a log-normal model of nuisance parameter integration. The results are summarized in Table 27. Based on these results, we exclude LM1 but not LM3.

Table 27: Summary of 95% CL upper limits on the non-SM yield. The LM1 and LM3 yields are shown, with uncertainties from the hadronic energy scale, lepton selection and trigger efficiencies, and integrated luminosity.

	2010 signal region	high $E_T^{\text{miss}}$ signal region	high $H_T$ signal region
Observed yield	19	4	3
non-SM yield UL	14	6.9	5.8
LM1 yield	$30.7 \pm 4.0$	$17.4 \pm 2.5$	$14 \pm 2.9$
LM3 yield	$12.4 \pm 1.7$	$6.4 \pm 1.2$	$6.7 \pm 1.5$

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## Appendix A Fakeable Object Definitions

We estimate the contributions from leptons not originating from  $W/Z$  decay (fake leptons) using the data-driven fake rate method [4]. We define the following ‘fakeable object’ selections, by taking the electron and muon requirements listed in Sec. 4 and loosening the following requirements:

- electrons

- $d_0 < 0.2 \text{ cm}$

- $Iso \equiv E_T^{\text{iso}}/p_T < 0.4$ ,  $E_T^{\text{iso}}$  is defined as the sum of transverse energy/momentum deposits in ecal, hcal, and tracker, in a cone of 0.3 A 1 GeV pedestal is subtracted from the ecal energy deposition in the EB, however the ecal energy is never allowed to go negative.

- muons

- $d_0 < 0.2 \text{ cm}$

- $\chi^2/\text{ndof of global fit} < 50$

- $Iso \equiv E_T^{\text{iso}}/p_T < 0.4$ ,  $E_T^{\text{iso}}$  is defined as the sum of transverse energy/momentum deposits in ecal, hcal, and tracker, in a cone of 0.3

## Appendix B The ABCD' Technique

We have developed a novel technique, based on the ABCD technique which we perform in the plane of  $y$  vs.  $H_T$ , which allows us to estimate the background in a signal region defined in the  $E_T^{\text{miss}}$  vs.  $H_T$  plane. We refer to this as the ABCD' technique.

First, we extract the  $y$  and  $H_T$  distributions  $f(y)$  and  $g(H_T)$  from data, using events from control regions which we expect to be dominated by background. Under the assumption that  $y$  and  $H_T$  are weakly-correlated (the same assumption which allows the use of the ABCD technique), we can predict the distribution of events in the  $y$  vs.  $H_T$  plane as:

$$\frac{\partial^2 N}{\partial y \partial H_T} = f(y)g(H_T) \quad (3)$$

Once the distribution of events in the  $y$  vs.  $H_T$  plane is known, the number of events falling in any region of this plane can be deduced. In particular, we can deduce the number of events falling in a region defined by requirements on  $E_T^{\text{miss}}$  and  $H_T$ .

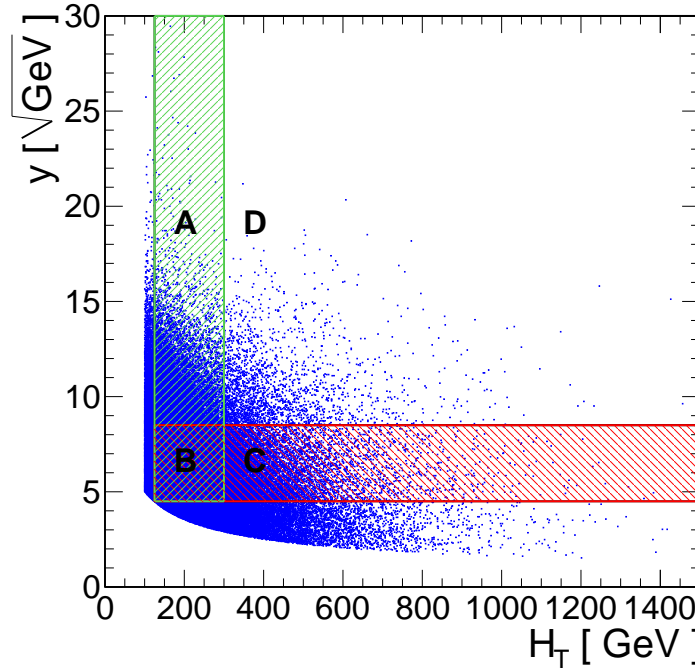


Figure 14: Distributions of  $y$  vs.  $H_T$  for  $t\bar{t}$  MC. The  $f(y)$  and  $g(H_T)$  functions are measured using events in the green and red shaded areas, respectively.

In this section, we study the ABCD' technique by applying it to  $t\bar{t}$  MC (we use the powheg sample which has 10 times the number of dilepton events as the madgraph sample). As a cross-check, we first use the ABCD' technique to estimate the background in the 2010 signal region defined as  $y > 8.5 \text{ GeV}^{1/2}$  and  $H_T > 300 \text{ GeV}$ , which may be compared to the prediction of the standard ABCD technique. We measure the  $f(y)$  and  $g(H_T)$  distributions using events in the regions indicated in Fig. 14, yielding the distributions shown in Fig. 15. Next, we randomly sample values of  $y$  and  $H_T$  from these distributions; each pair of  $y$  and  $H_T$  values is a pseudo-event. We generate 1 million pseudo-events, and find the ratio  $R_{S/C}$ , the ratio of the number of pseudo-events falling in the 2010 signal region (ie. region D) to the number of pseudo-events falling in a control region, defined as the OR of the A, B and C regions. We then multiply this ratio by the number of  $t\bar{t}$  MC events which fall in the control region to get the predicted yield, ie.  $N_{\text{pred}} = R_{S/C} \times N(\text{control})$ . To estimate the statistical uncertainty in the predicted background, we smear the bin contents of  $f(y)$  and  $g(H_T)$  according to their uncertainties. We repeat the prediction 20 times with these smeared distributions, and take the RMS of the deviation from the nominal prediction as the statistical uncertainty. The results are summarized in Table 18, which show that the prediction of the ABCD' method is consistent with that of the ABCD method within the statistical uncertainty.

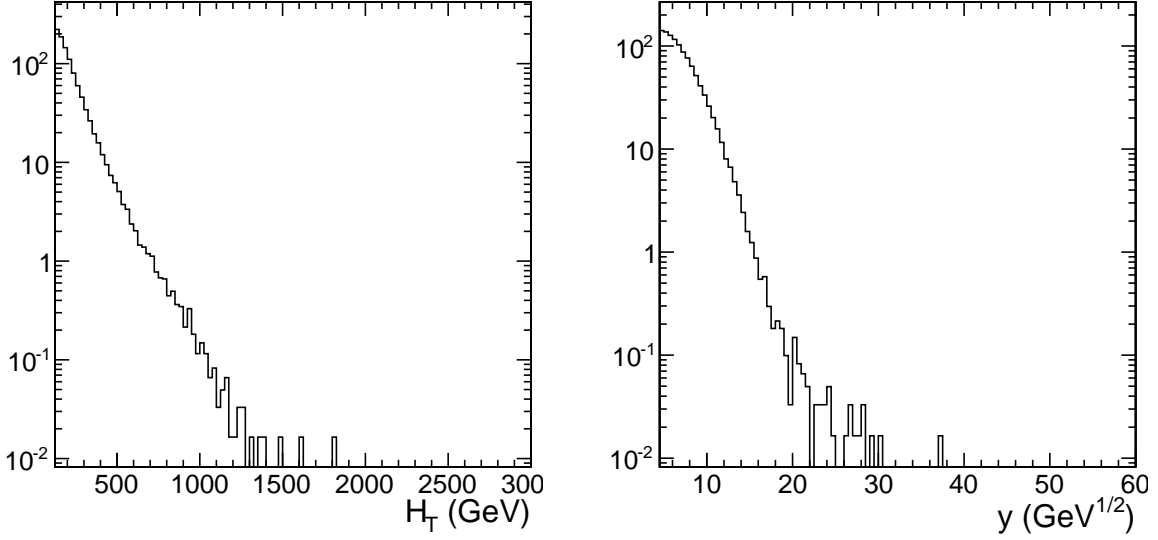


Figure 15: The distributions  $f(y)$  and  $g(H_T)$  extracted from  $t\bar{t}$  MC.

We next apply the ABCD' technique to estimate the background in the regions:

- SR1:  $E_T^{\text{miss}} > 275$  GeV,  $H_T > 300$  GeV
- SR2:  $E_T^{\text{miss}} > 200$  GeV,  $H_T > 600$  GeV.

Note that we are unable to predict the yield in this region using the standard ABCD technique, since  $E_T^{\text{miss}}$  and  $H_T$  are not weakly correlated. The signal regions are shown in Fig. 16. There is a sizable overlap between SR2 and region C, hence when estimating the background for this signal region we restrict the control region used to measure  $g(H_T)$  and to determine  $N(\text{control})$  to  $4.5 < y < 6.5$   $\text{GeV}^{1/2}$ . As summarized in Table 18, we find values of observed / predicted of  $1.30 \pm 0.10$  and  $1.05 \pm 0.07$  for SR1 and SR2, respectively.

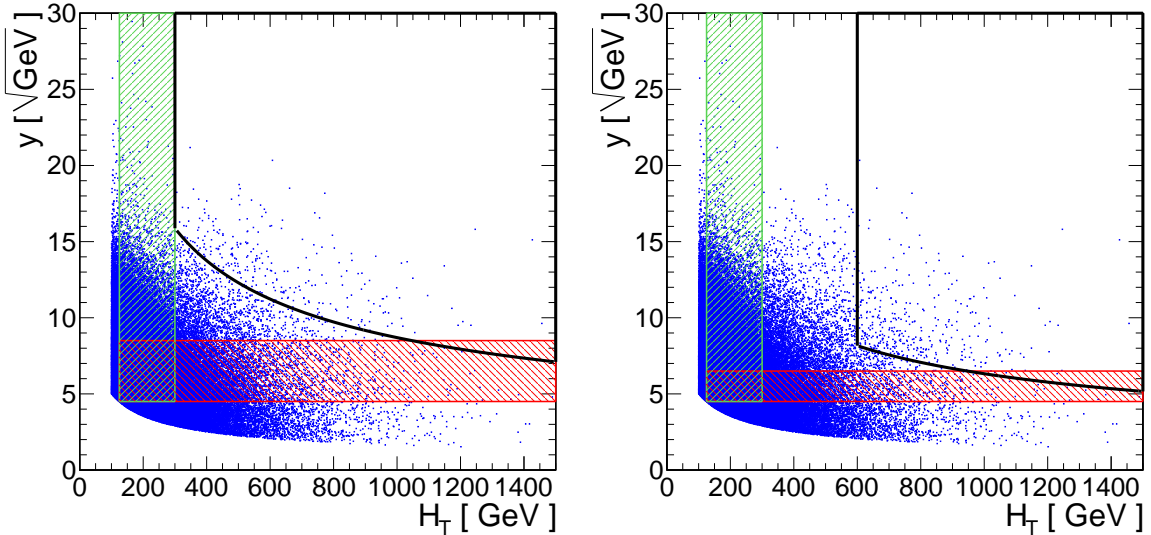


Figure 16: Distributions of  $y$  vs.  $H_T$  for  $t\bar{t}$  MC. The signal regions  $E_T^{\text{miss}} > 275$  GeV,  $H_T > 300$  GeV (left) and  $E_T^{\text{miss}} > 200$  GeV,  $H_T > 600$  GeV (right) are indicated with thick black lines. The  $f(y)$  and  $g(H_T)$  functions are measured using events in the green and red shaded areas, respectively.

Next, we study the ABCD' technique by applying it to samples with size comparable to the expected number of events in  $1 \text{ fb}^{-1}$  of data. We take the full powheg data sample, and split it into subsamples of  $\sim 2500$  events

Table 28: Expected results from  $t\bar{t}$  MC in  $1 \text{ fb}^{-1}$  for the ABCD' method. The quoted uncertainties are statistical only.

signal region	sample	predicted	observed	obs/pred
2010 signal region	madgraph	$44.0 \pm 1.5$	$38.3 \pm 2.4$	$0.87 \pm 0.06$
	powheg	$43.3 \pm 0.5$	$37.0 \pm 0.8$	$0.85 \pm 0.02$
high $E_T^{\text{miss}}$ signal region	madgraph	$3.1 \pm 0.4$	$4.6 \pm 0.8$	$1.47 \pm 0.31$
	powheg	$3.5 \pm 0.1$	$4.5 \pm 0.3$	$1.30 \pm 0.10$
high $H_T$ signal region	madgraph	$5.3 \pm 0.8$	$5.5 \pm 0.9$	$1.03 \pm 0.23$
	powheg	$5.9 \pm 0.3$	$6.2 \pm 0.3$	$1.05 \pm 0.07$

each, which corresponds roughly to the number of expected events in data passing preselection, for an integrated luminosity of  $1 \text{ fb}^{-1}$ . For each sample, we use the ABCD' technique to predict the background in the SR1 and SR2 regions. In Fig. 17, we plot the quantity  $\langle \text{observed} \rangle / \text{predicted}$  for the SR1 and SR2 regions, where  $\langle \text{observed} \rangle$  indicates the observed yield in the signal yield, average over the number of toy MC subsamples. Based on these studies, we apply a correction factor of  $1.2 \pm 0.5$  and  $1.0 \pm 0.5$  for the SR1 and SR2 regions.

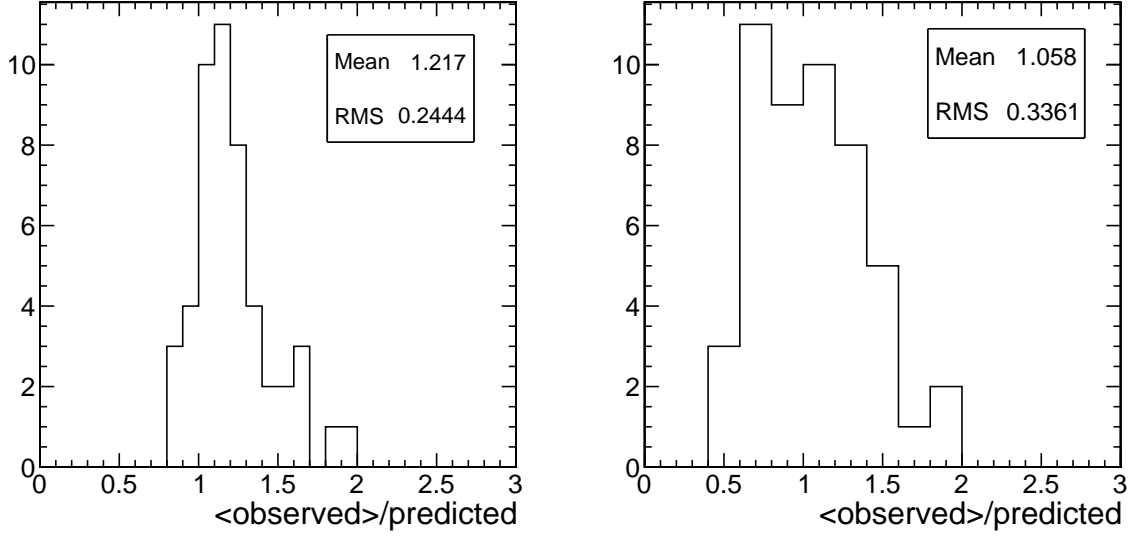


Figure 17: Distributions of  $\langle \text{observed} \rangle / \text{predicted}$  for the toy MC subsamples.



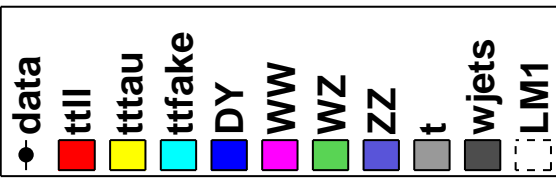
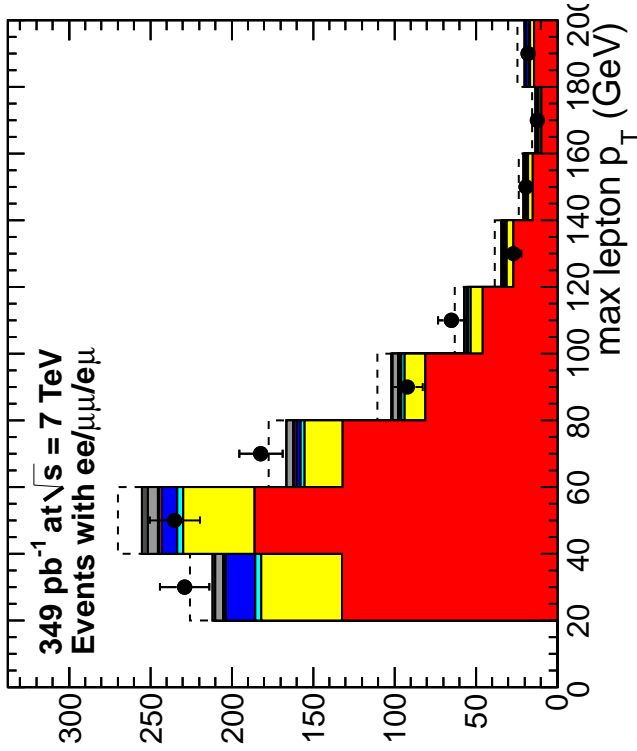
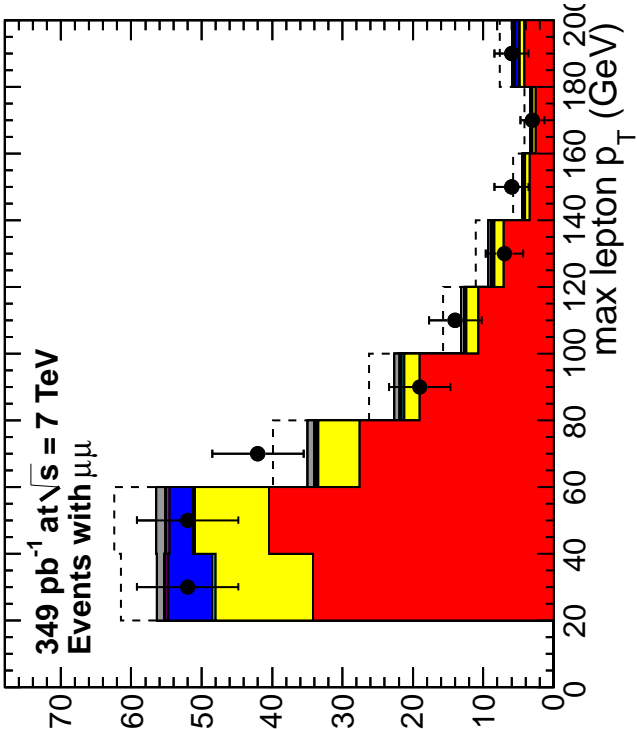
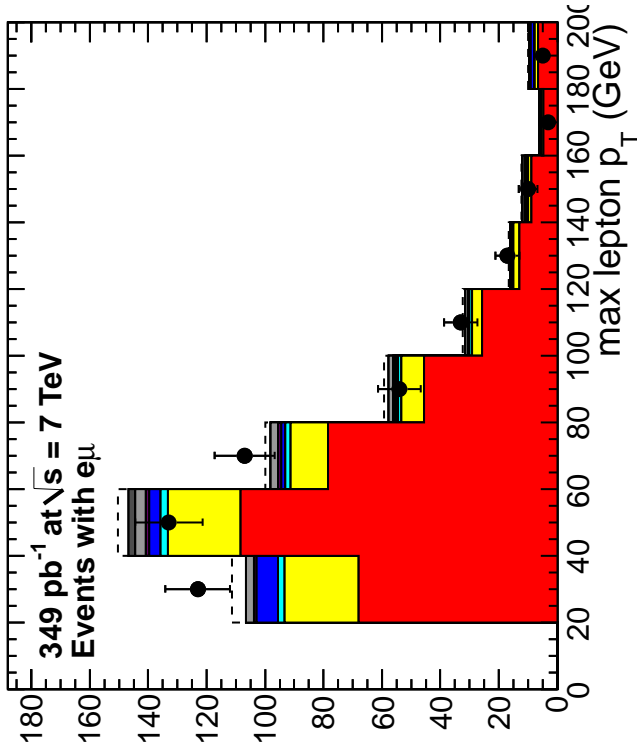
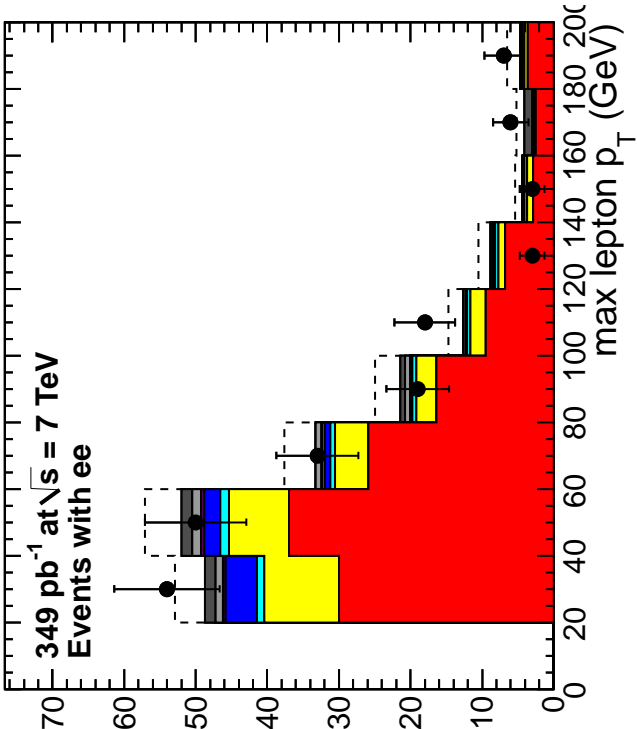
## Appendix C Data/MC Comparison: Preselection Region

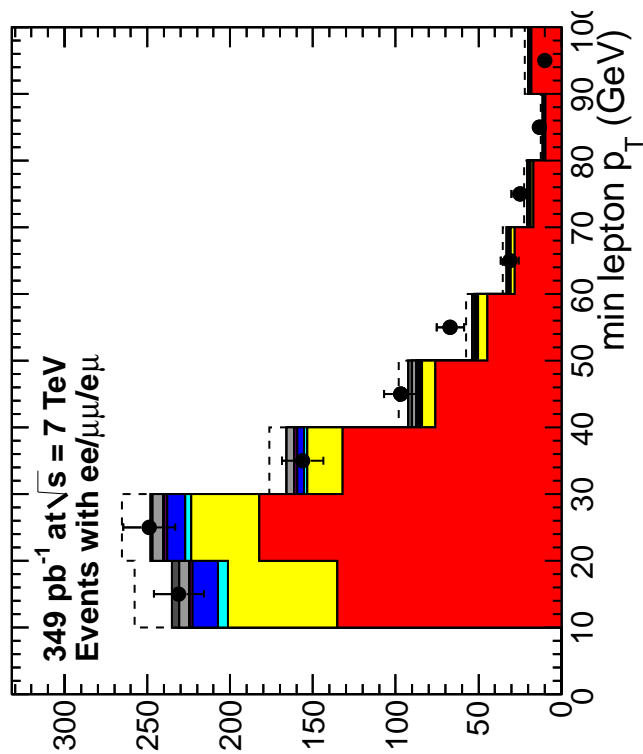
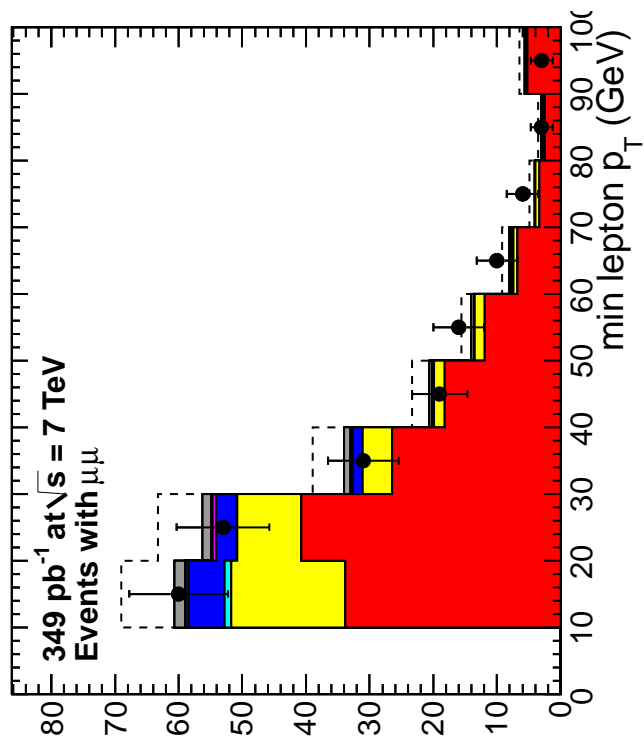
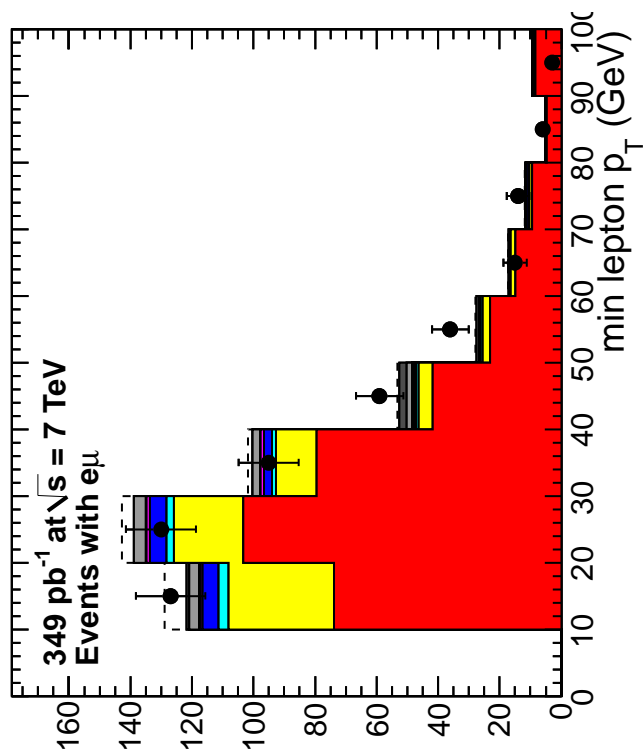
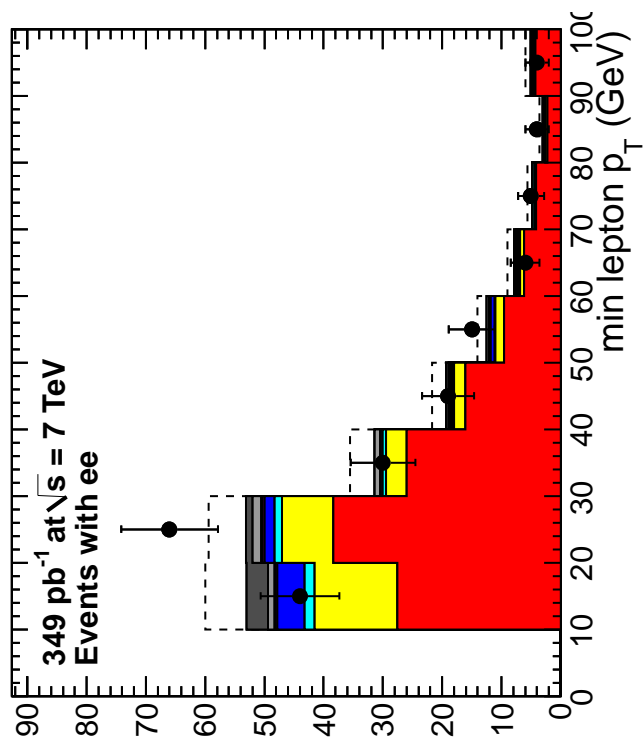
Here we compare data and MC distributions for data passing the preselection requirements. The high  $p_T$  dilepton trigger data is used.

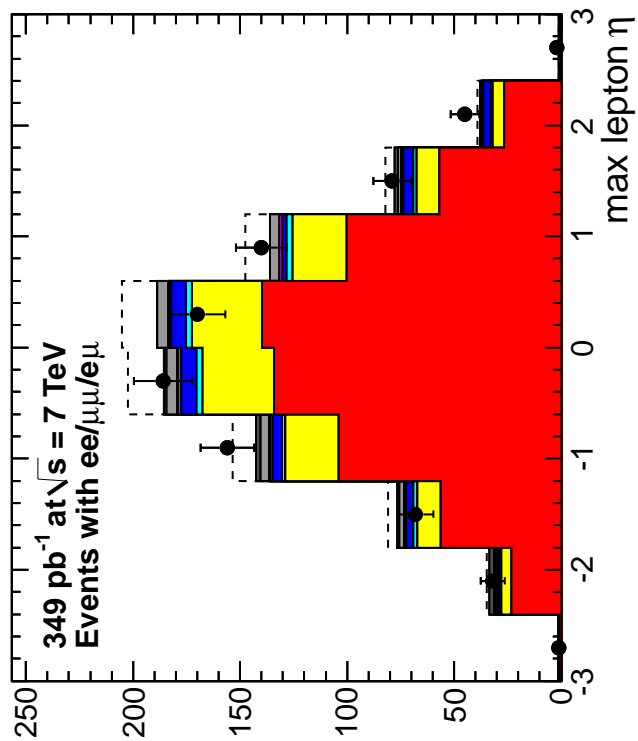
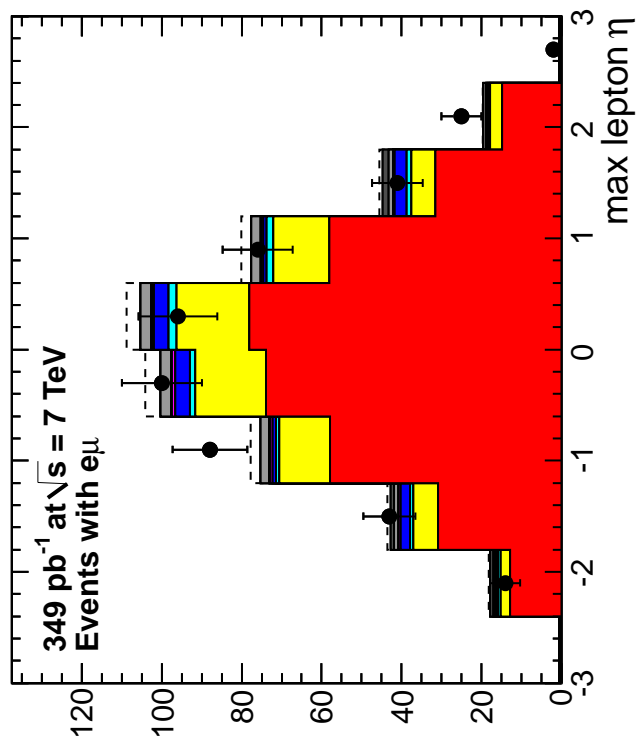
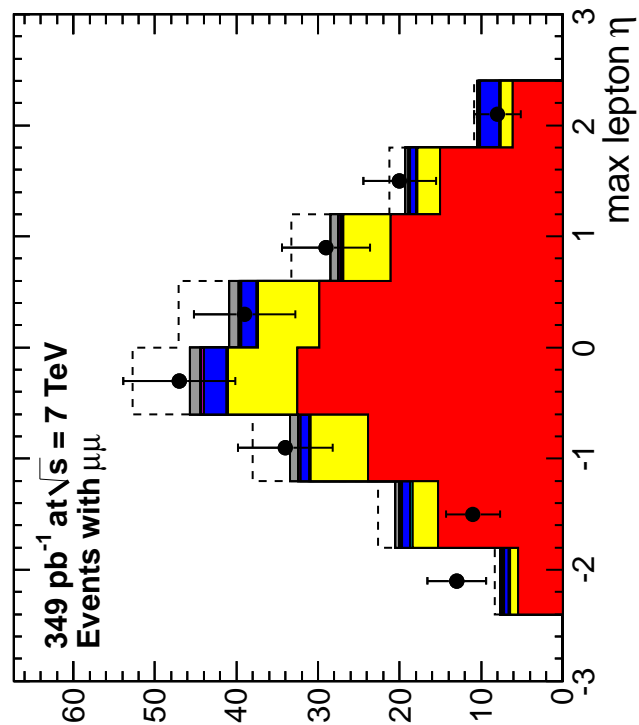
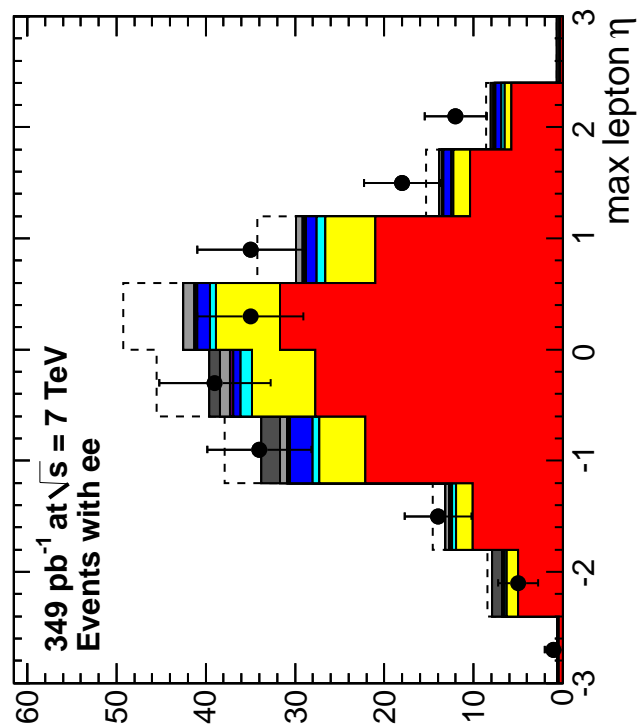
All MC samples are scaled by an overall factor 1.12, the ratio of the observed data yield in the preselection region to the prediction from MC. For illustration purposes, we overlay the distributions from the LM1 SUSY benchmark point.

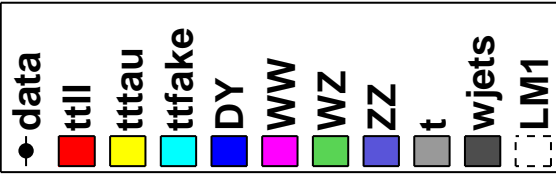
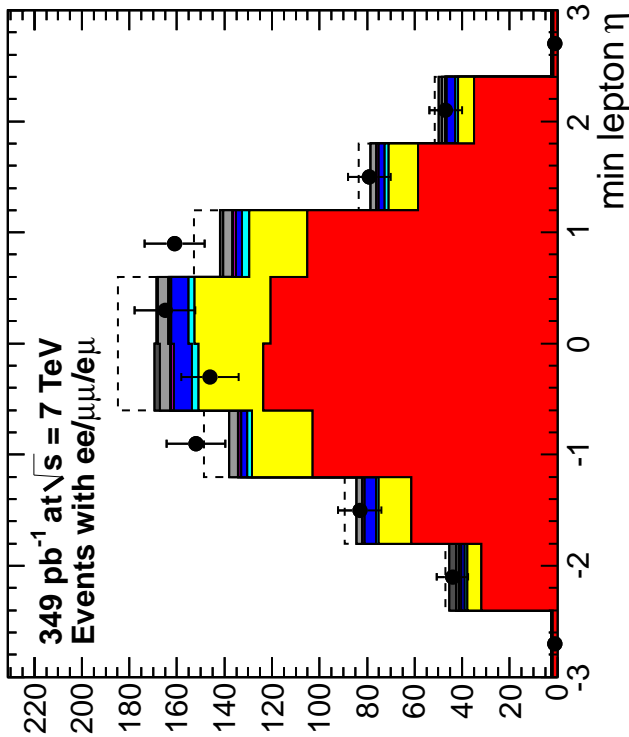
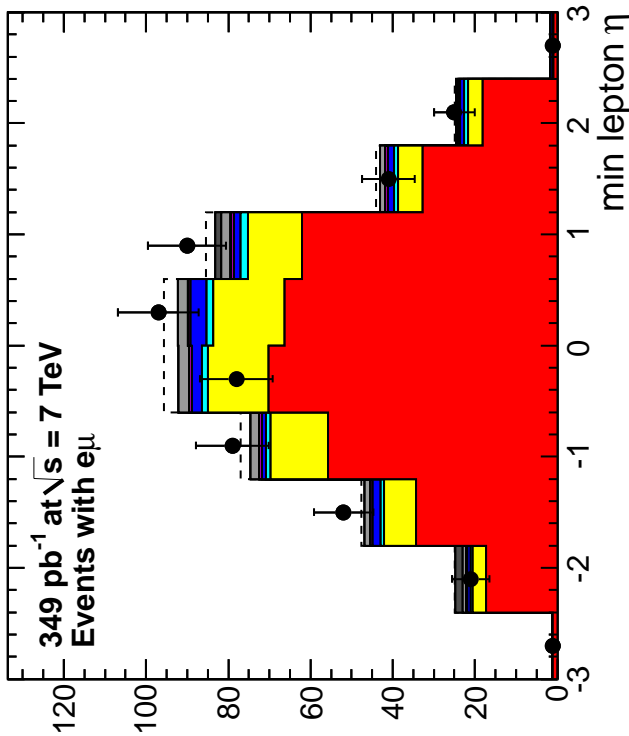
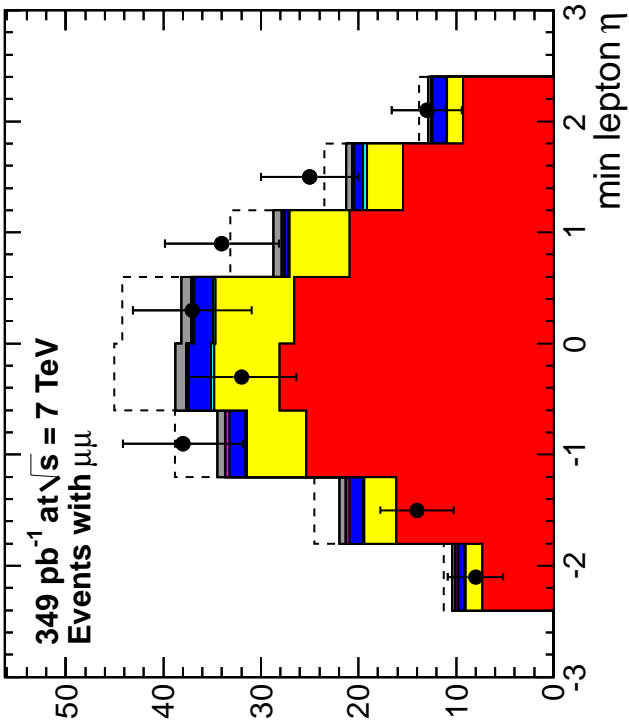
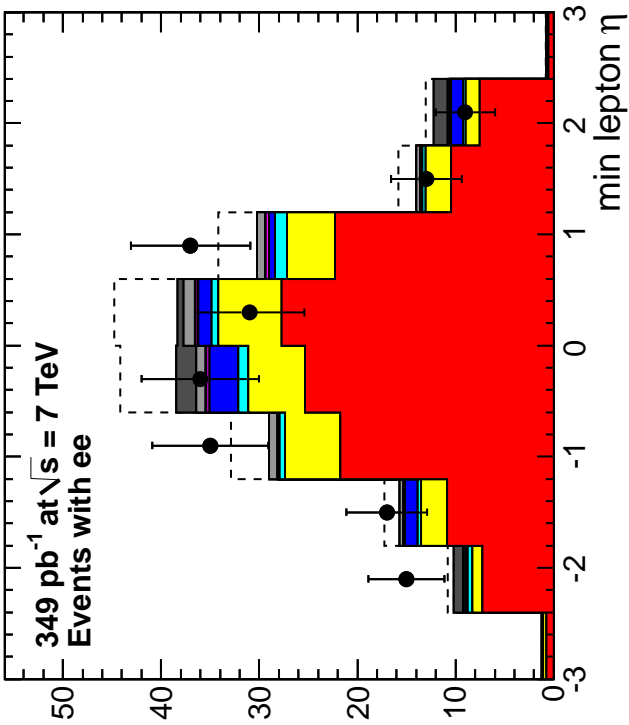
The meaning of most of the variables plotted in the following figures should be obvious. There are some exceptions that we explain below:

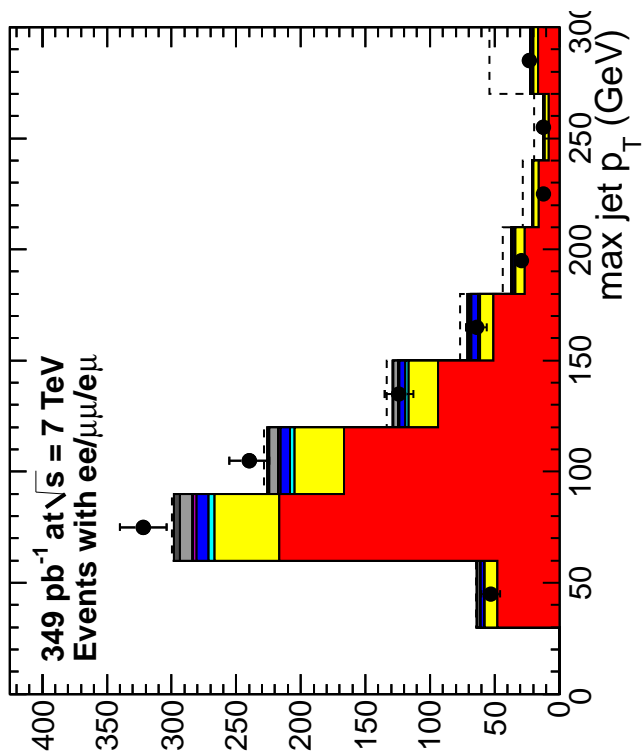
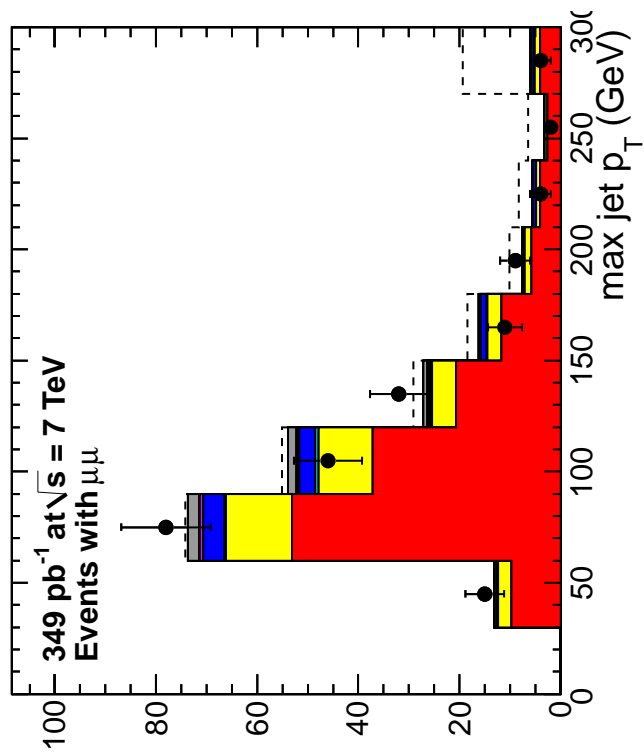
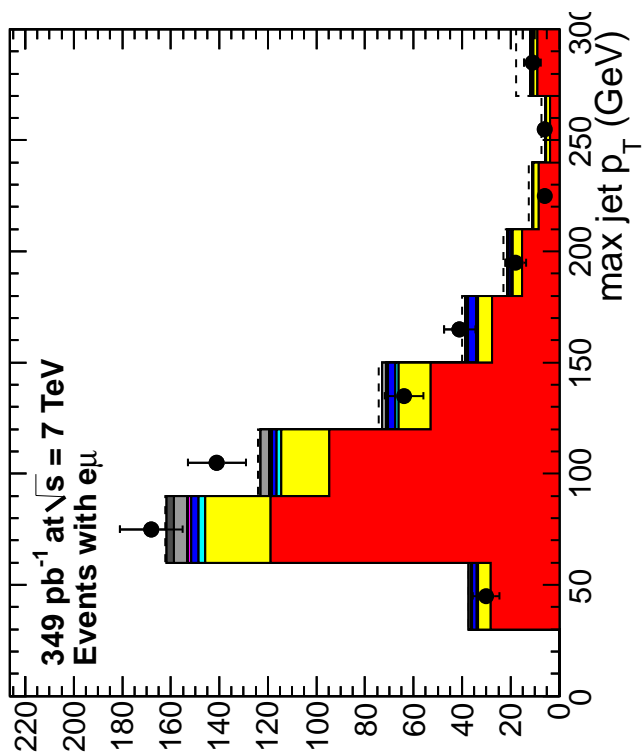
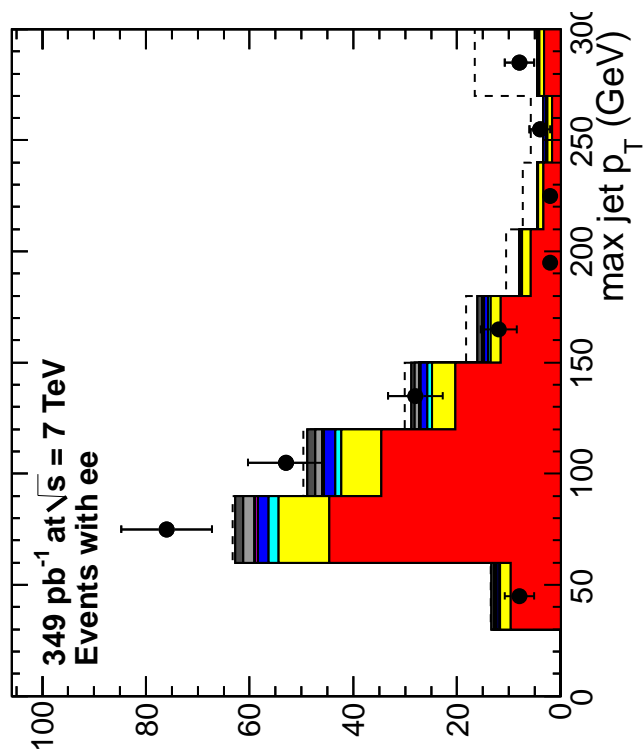
- $MT2$  is a kinematical quantity built from the two leptons and the  $E_T^{\text{miss}}$ . For events with two  $W \rightarrow \ell$  decays it should have a sharp kinematical cutoff at  $W$  mass. For more details, see Reference [23].
- $MT2J$  is very much like  $MT2$  but it is built out of the leptons, the  $E_T^{\text{miss}}$  and the two jets. For  $t\bar{t}$  events it has a kinematical cutoff at  $M_{\text{top}}$ , with tails due to the fact that occasionally one of the  $b$ -jets is not found and is replaced by a gluon jet from ISR or FSR. For more details, see Reference [24].

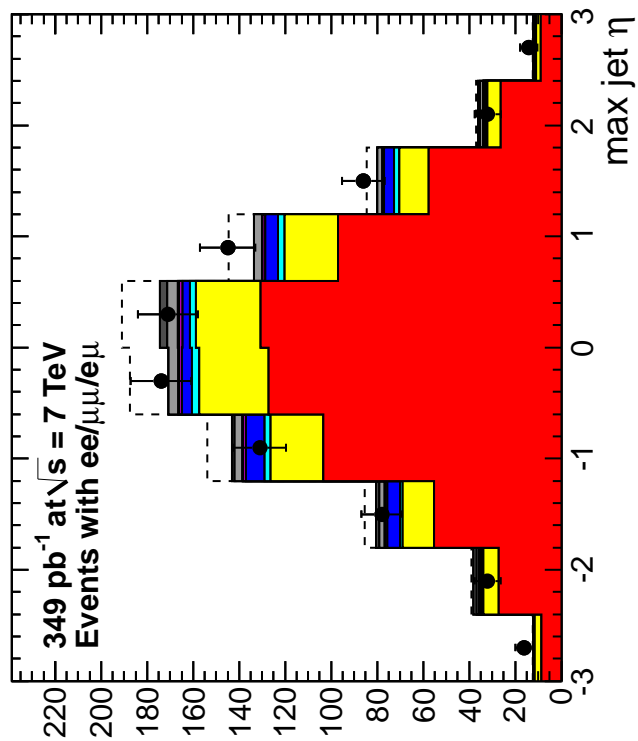
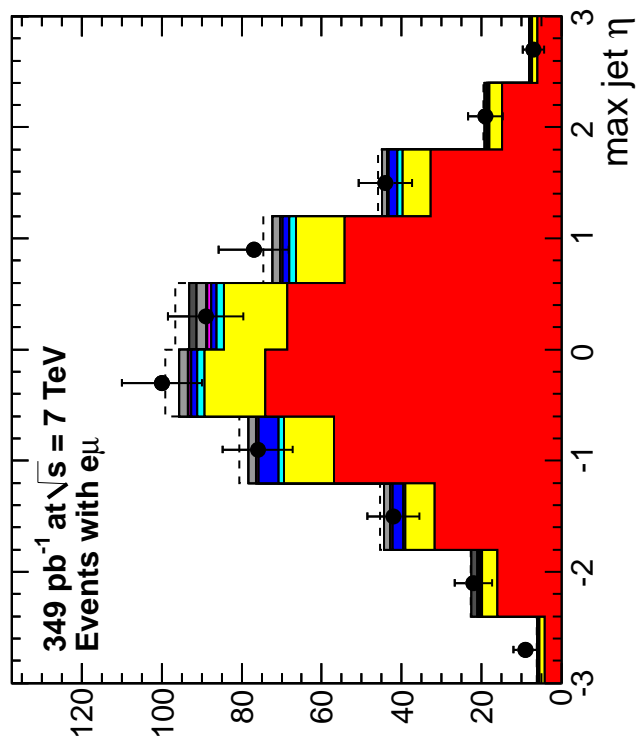
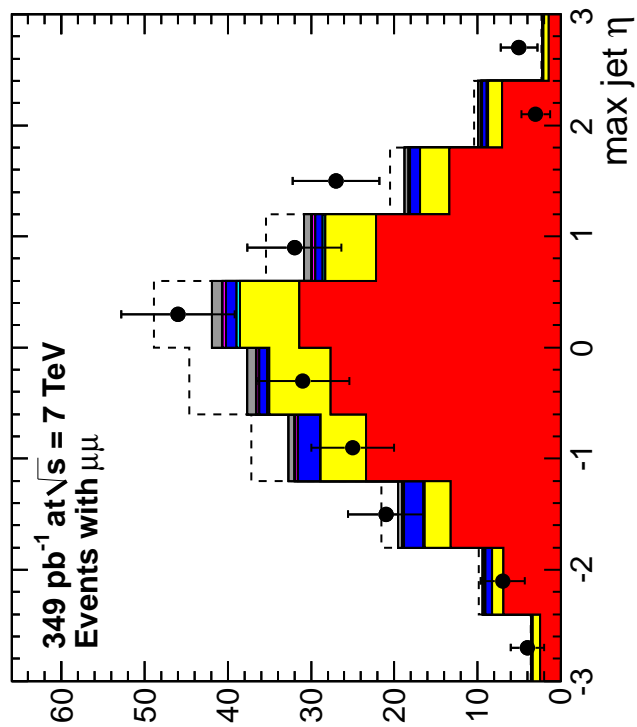
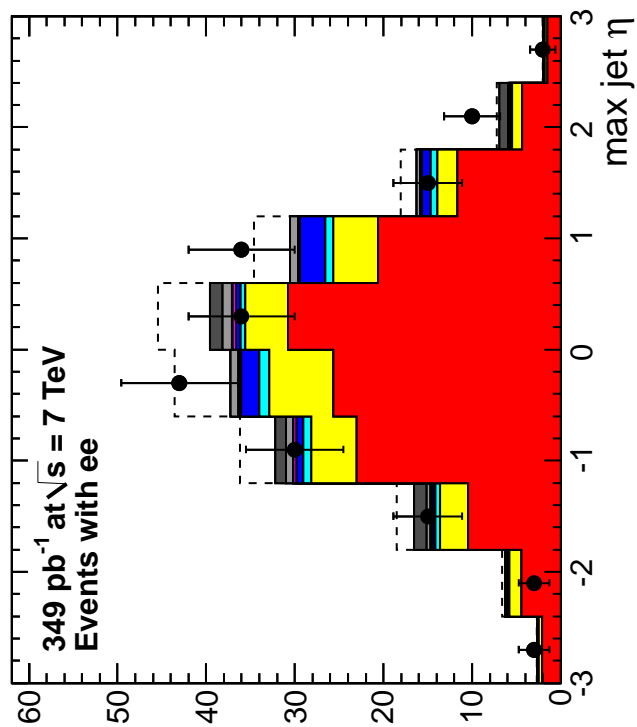


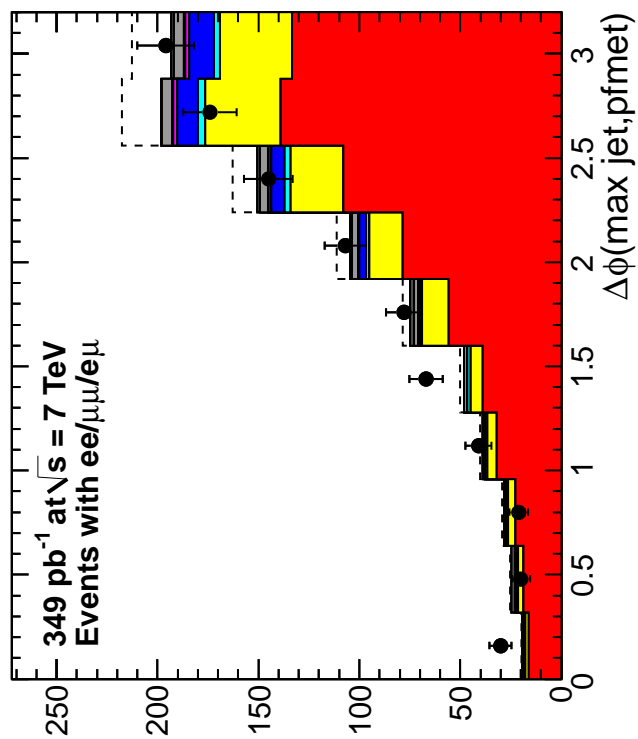
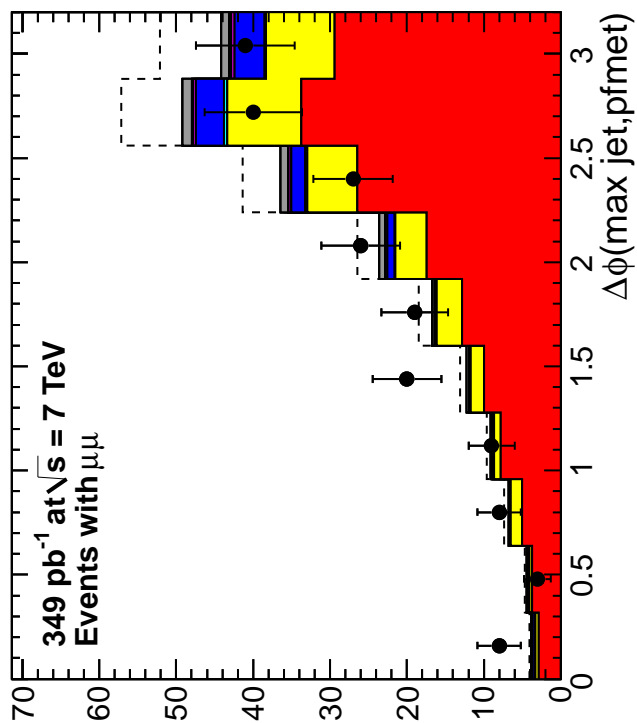
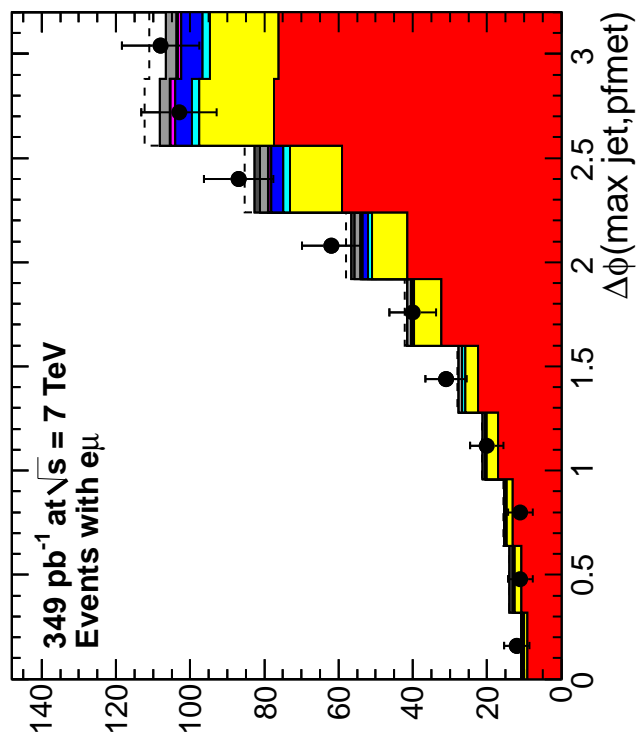
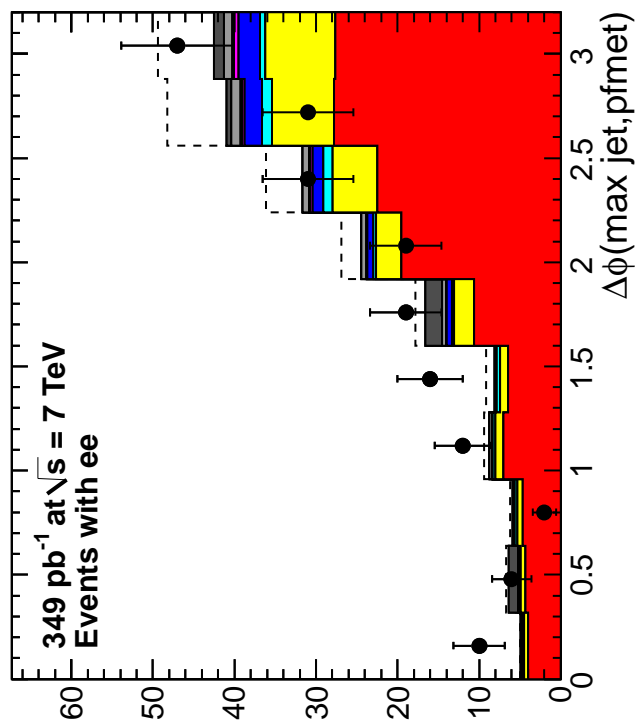




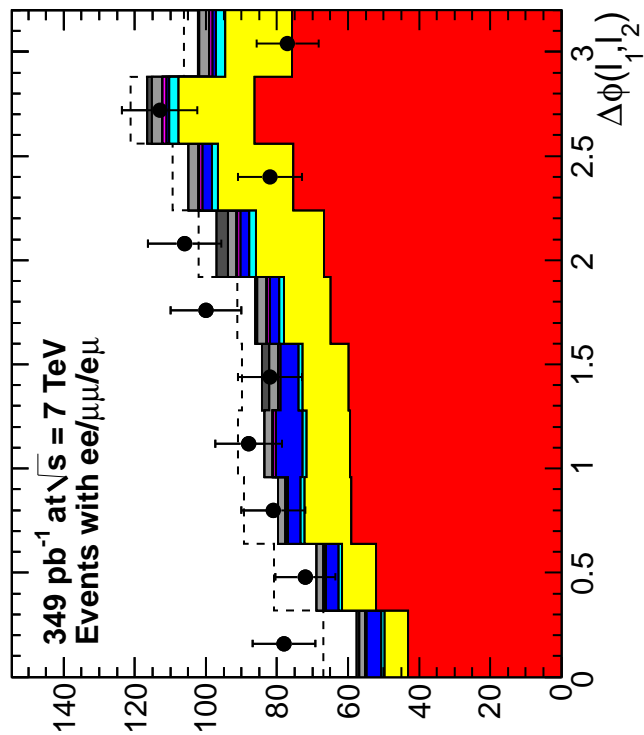
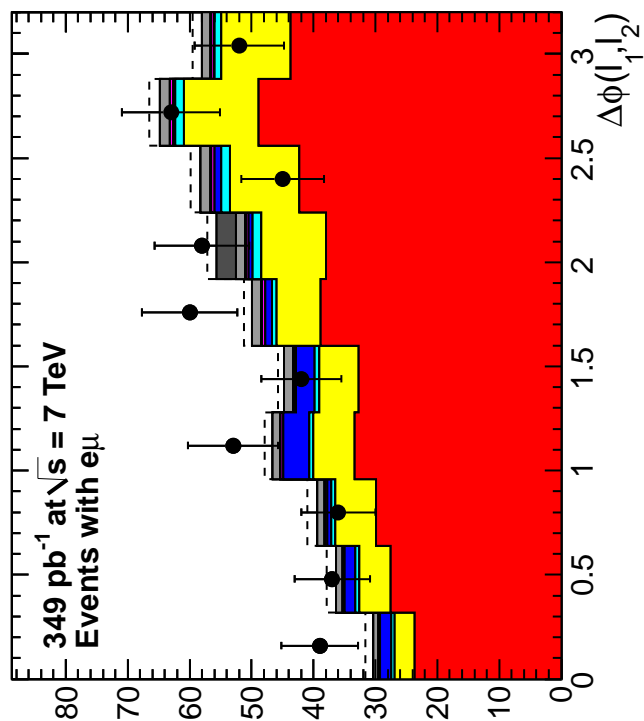
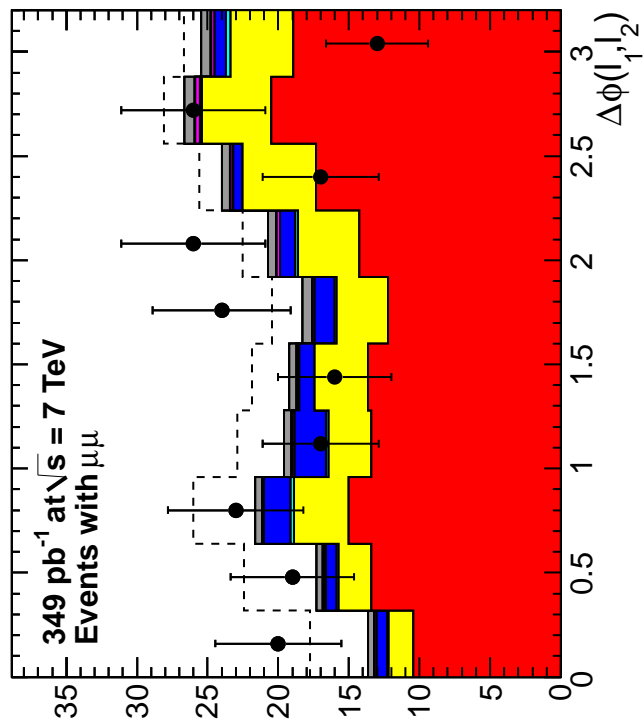
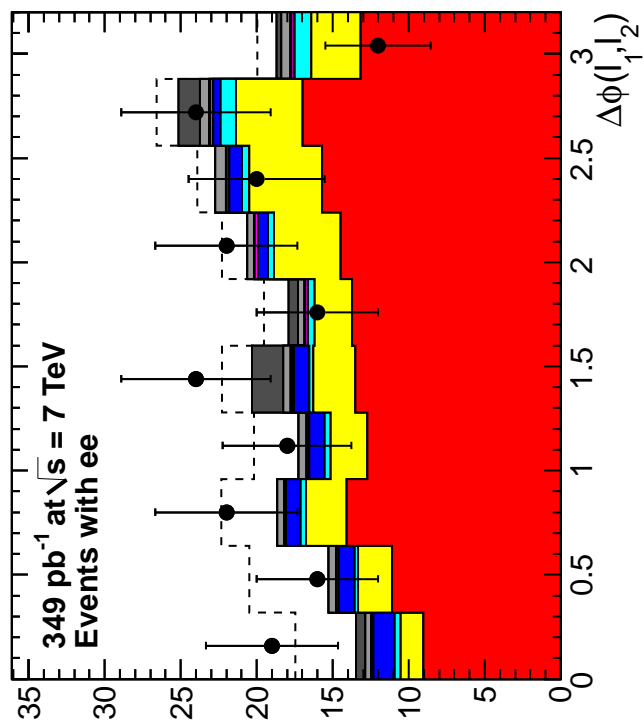


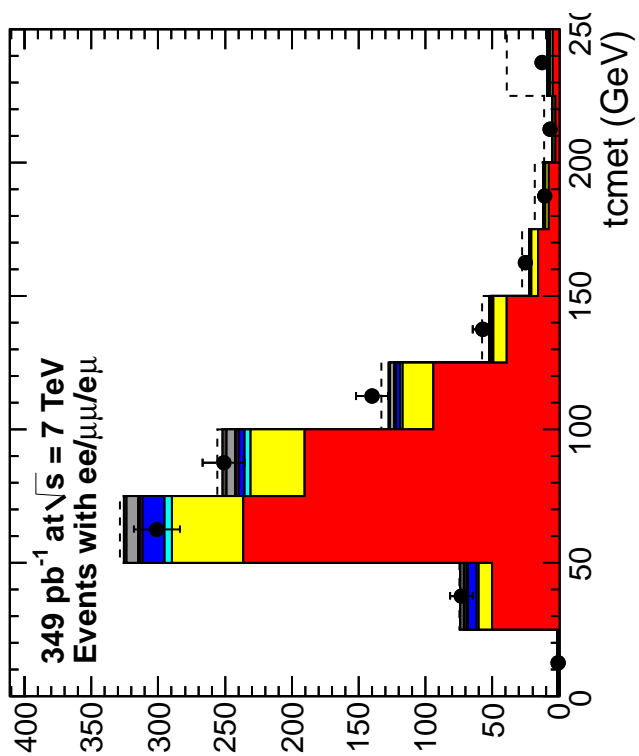
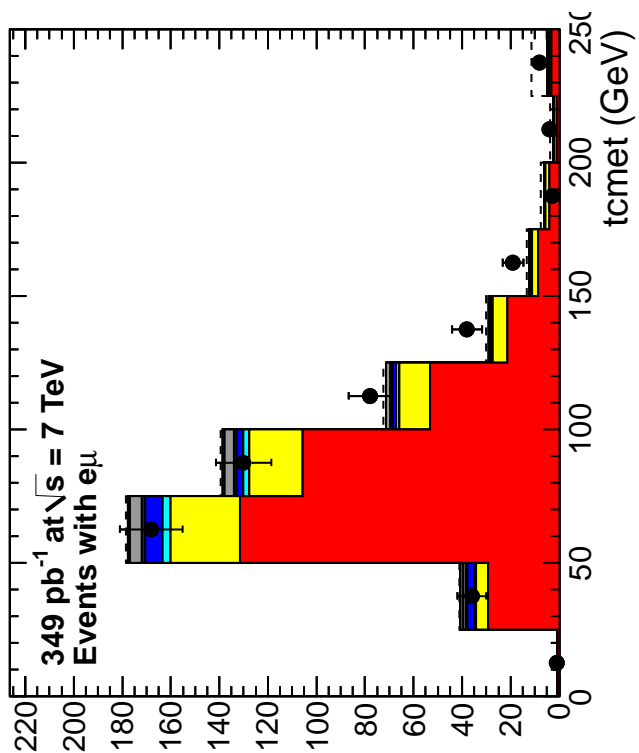
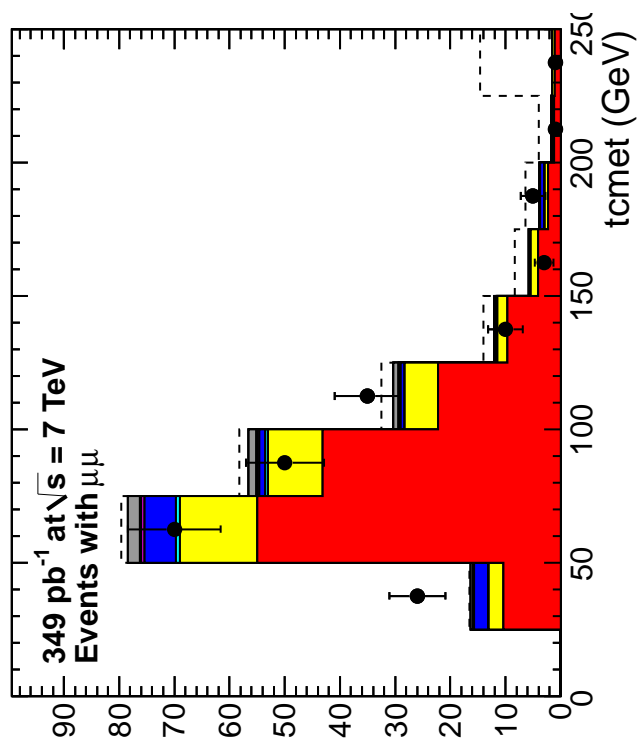
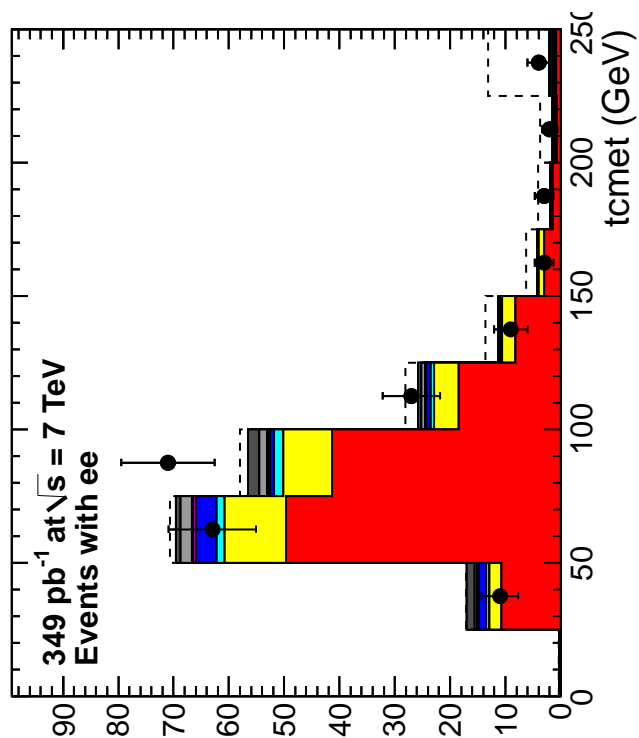


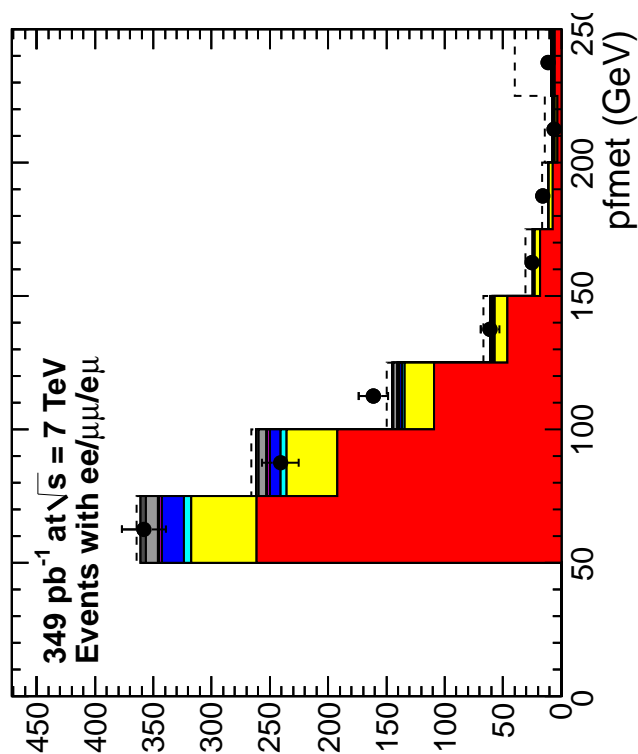
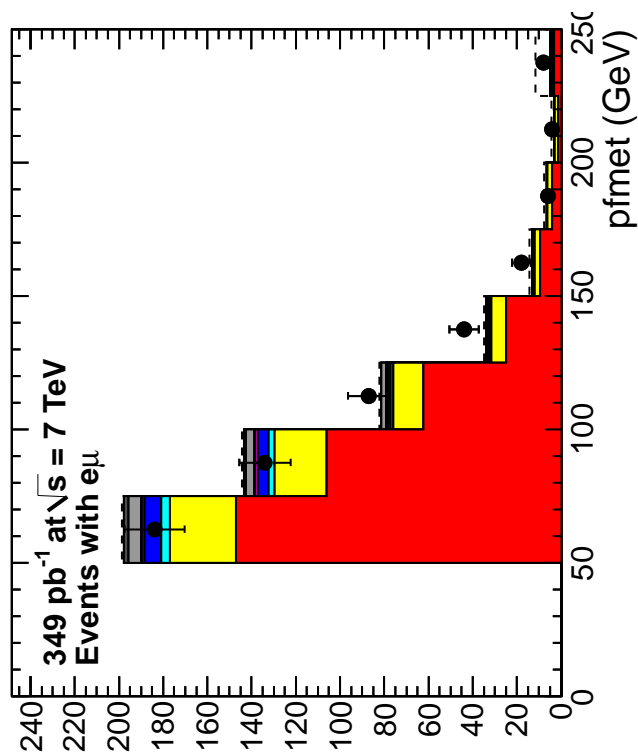
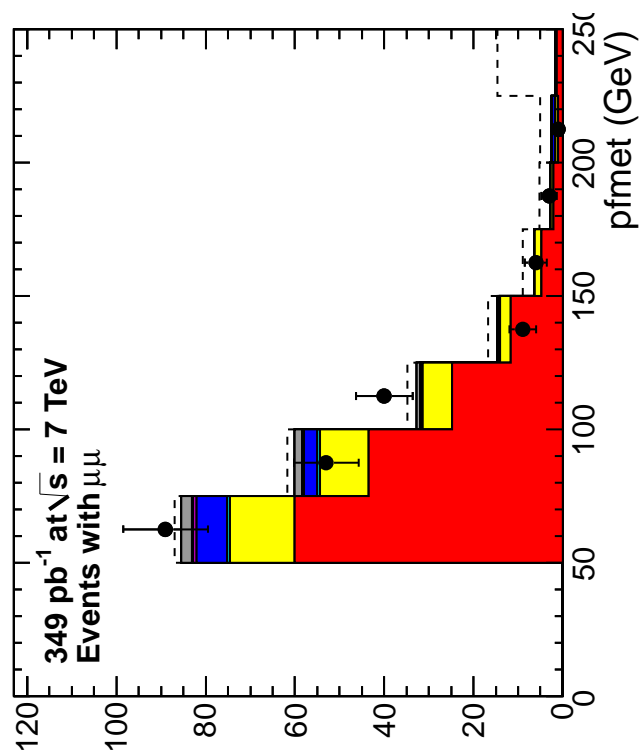
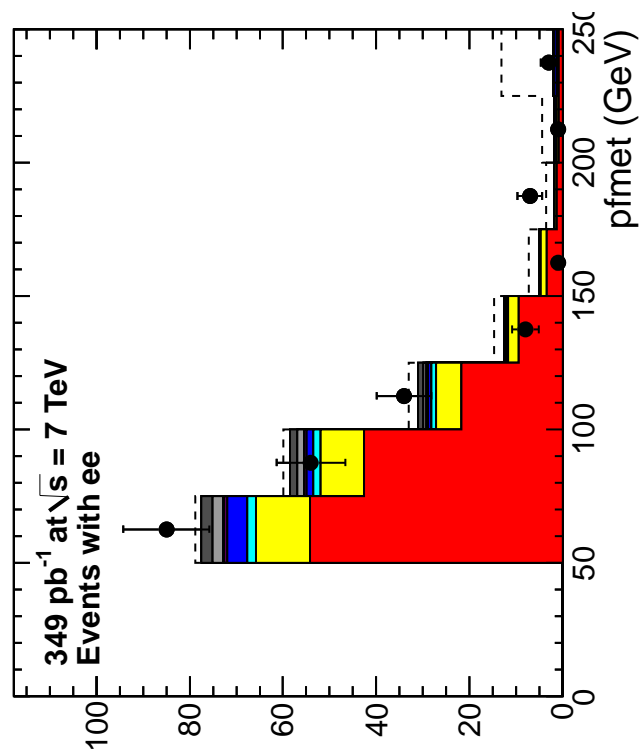


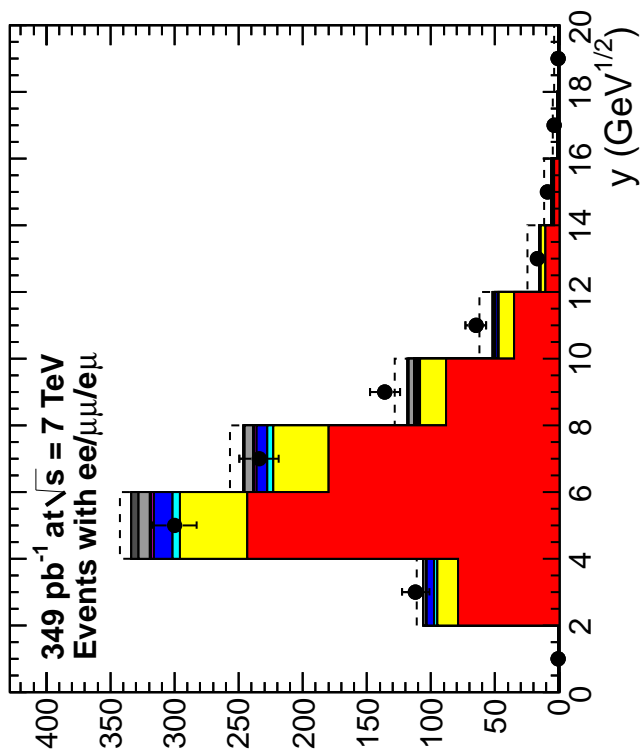
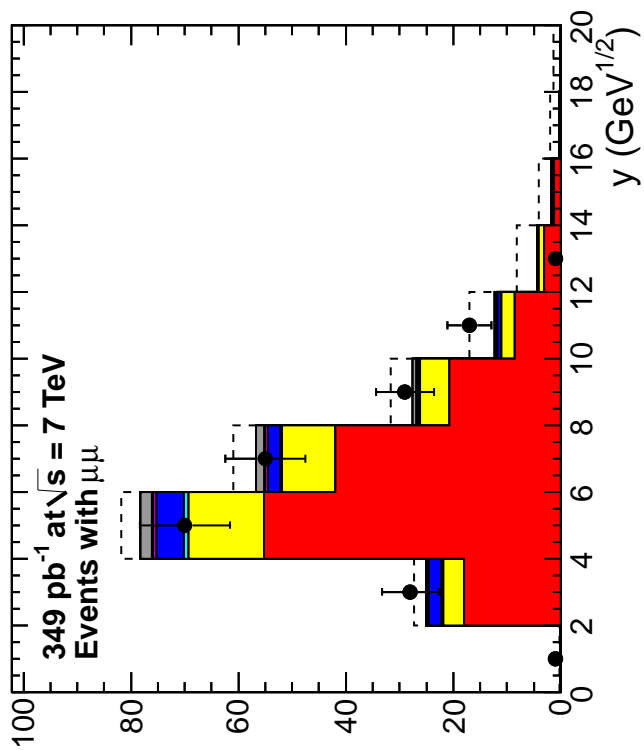
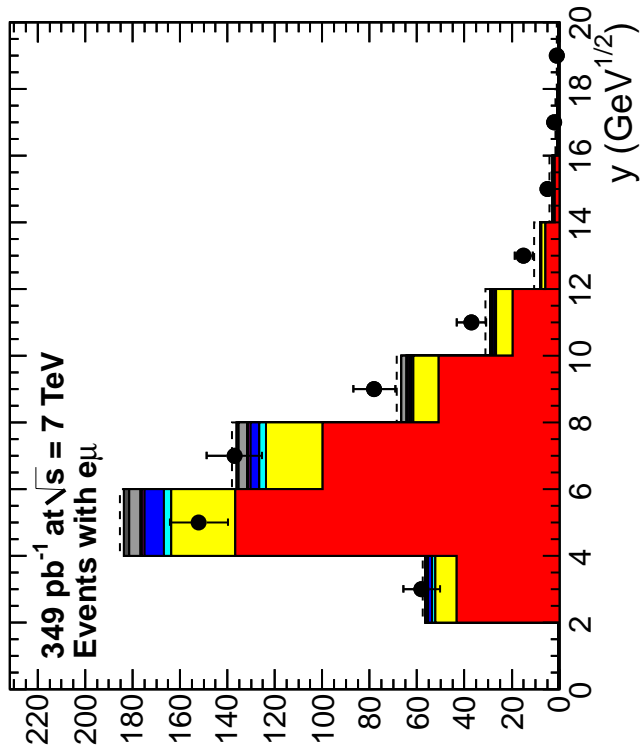
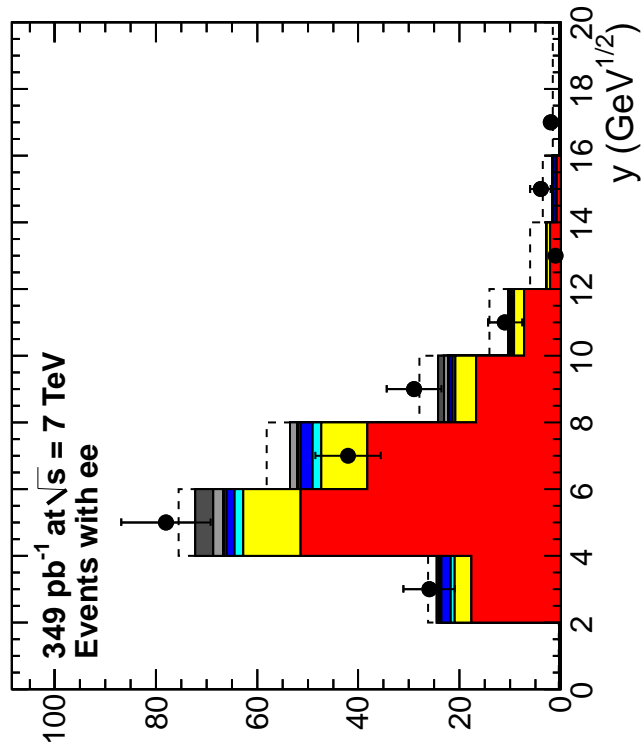


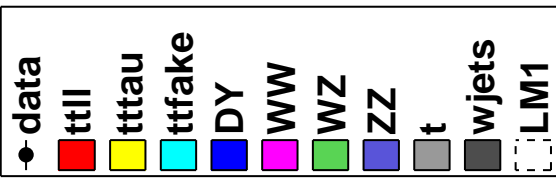
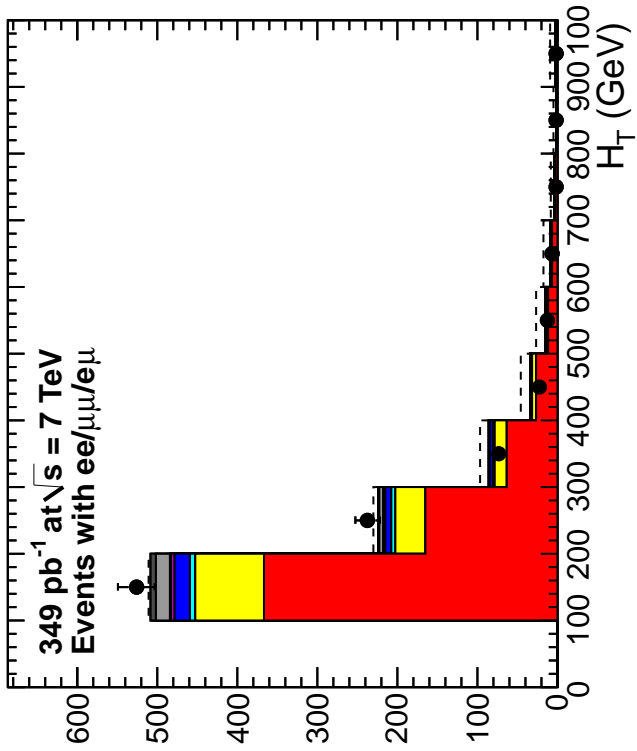
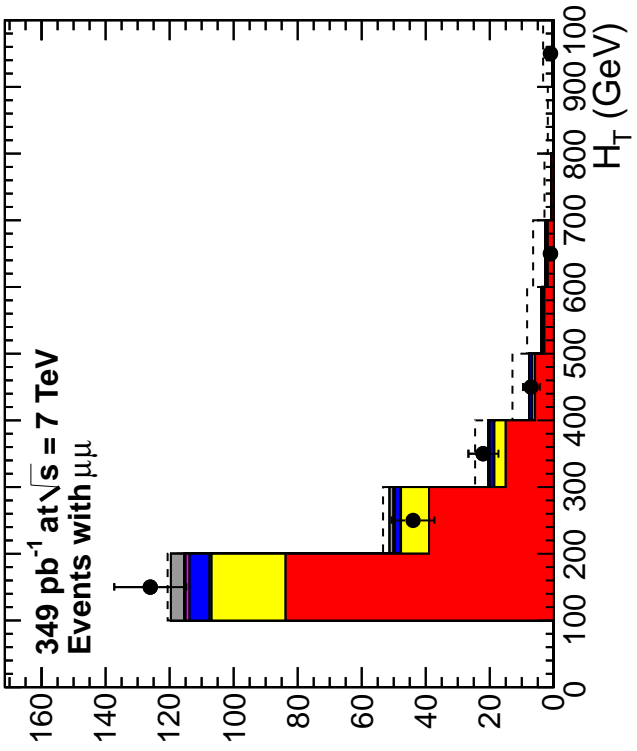
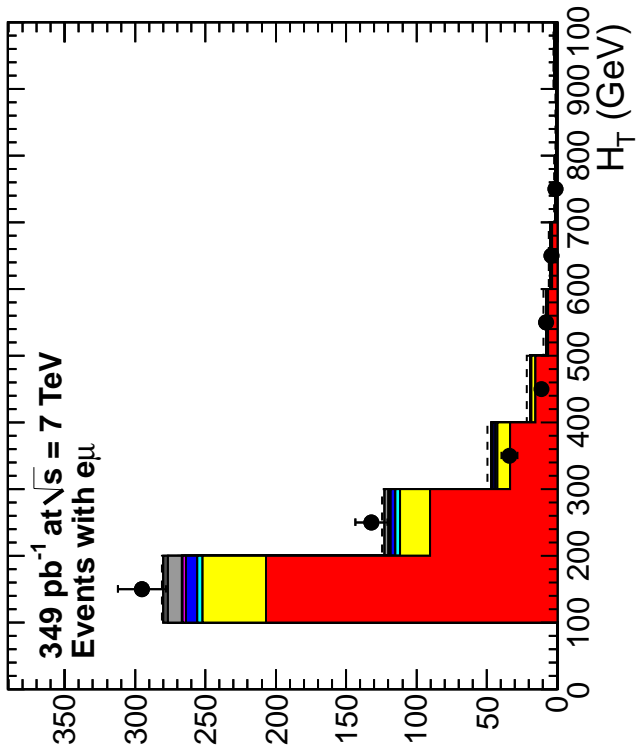
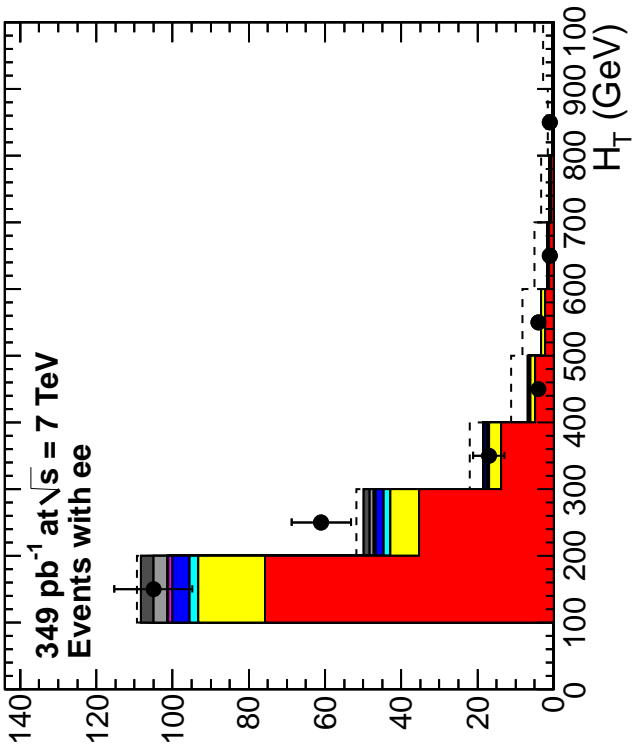


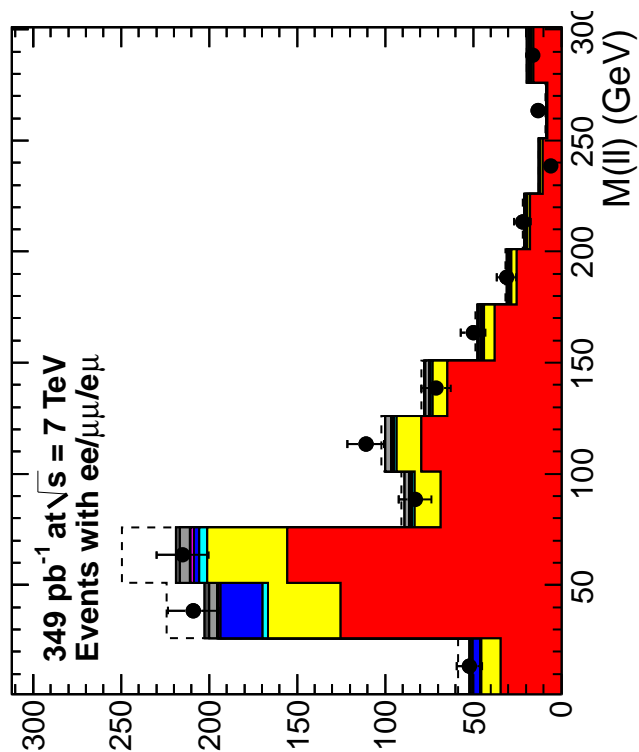
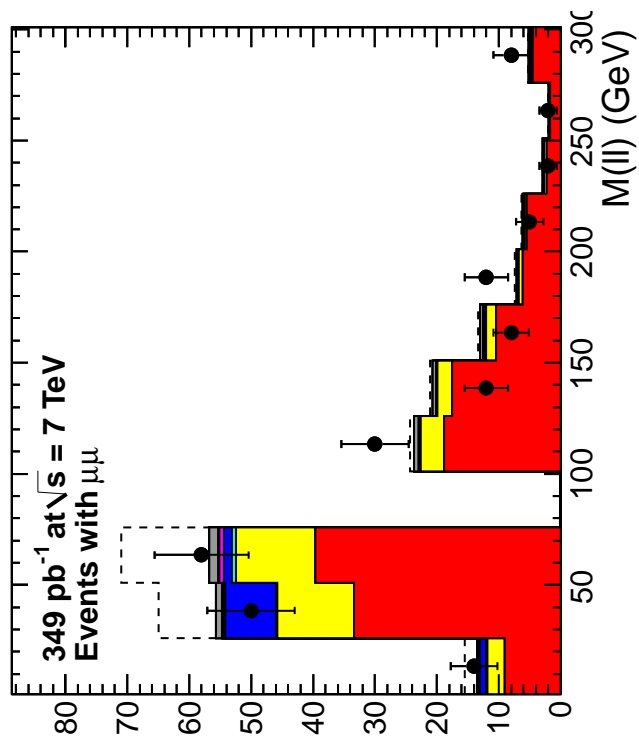
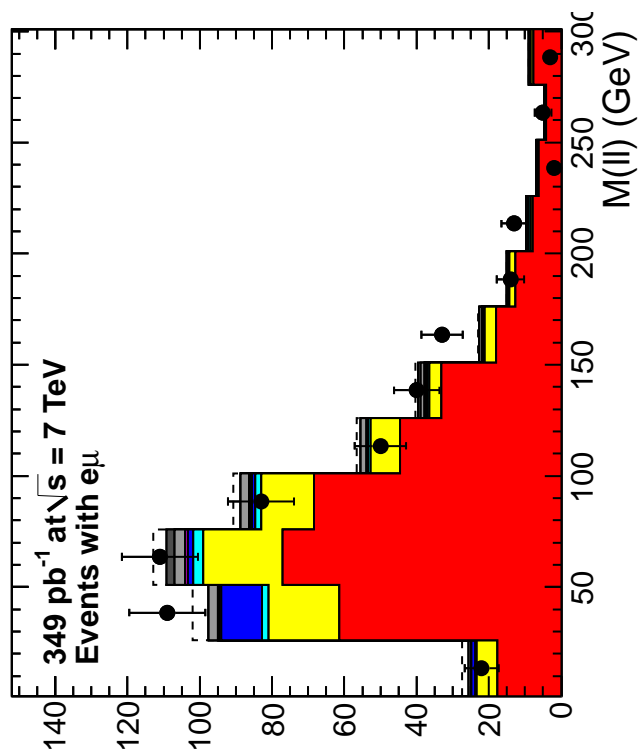
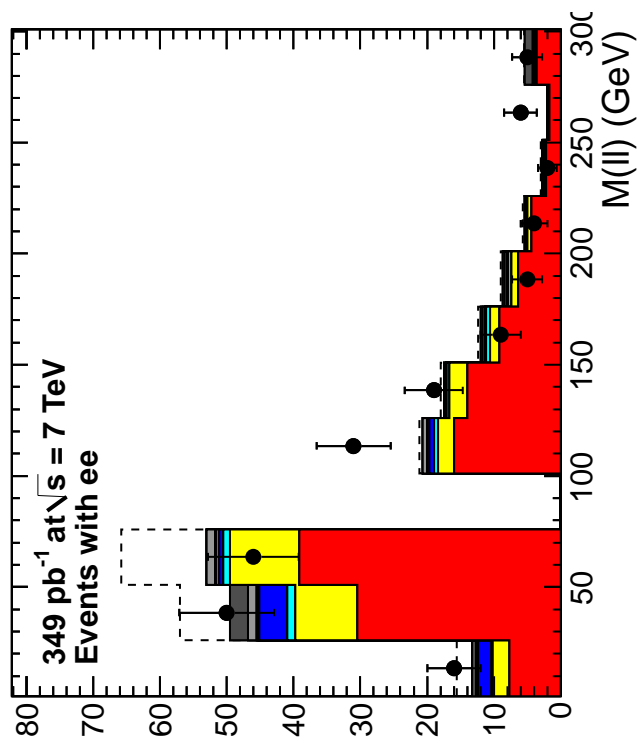


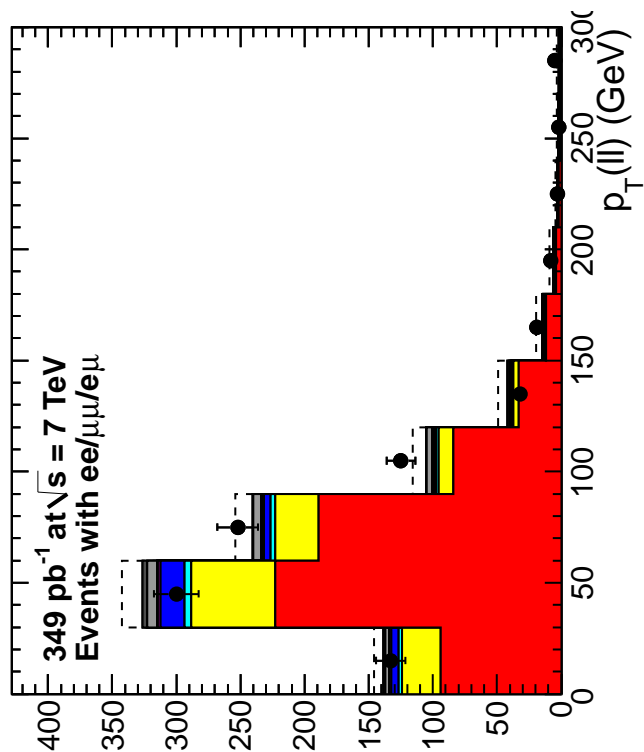
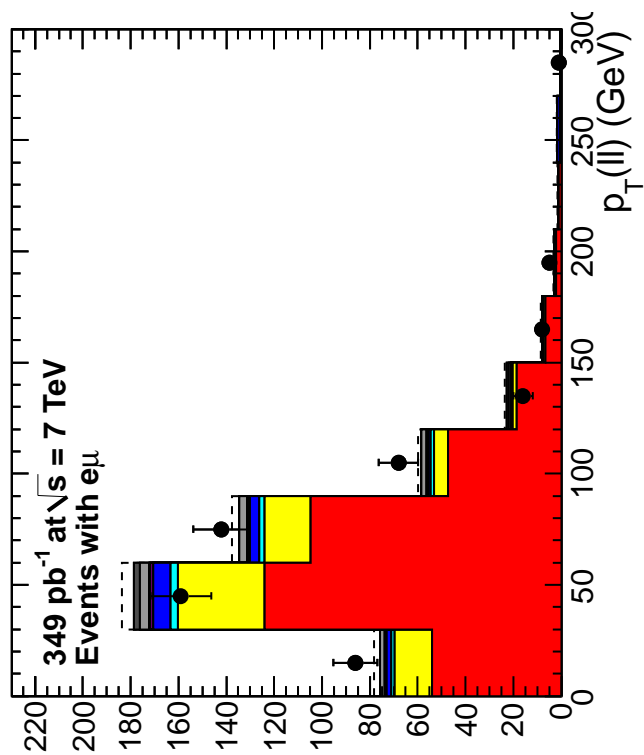
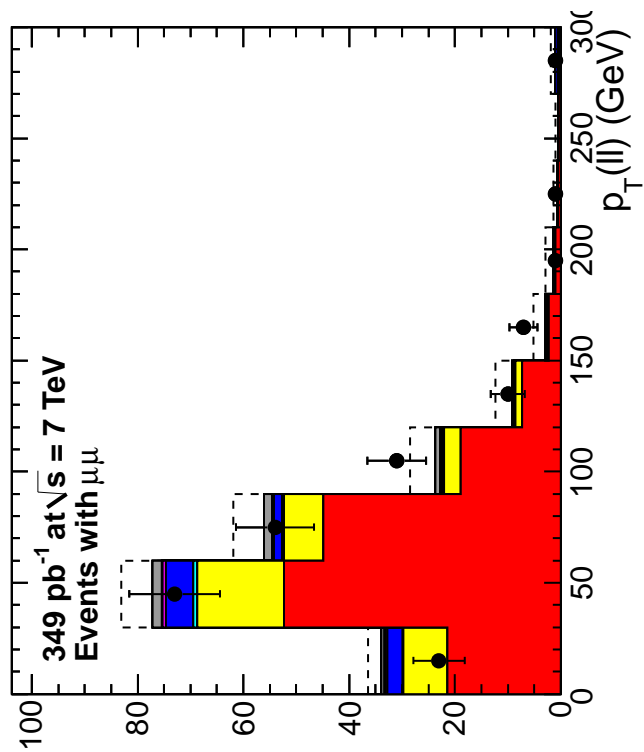
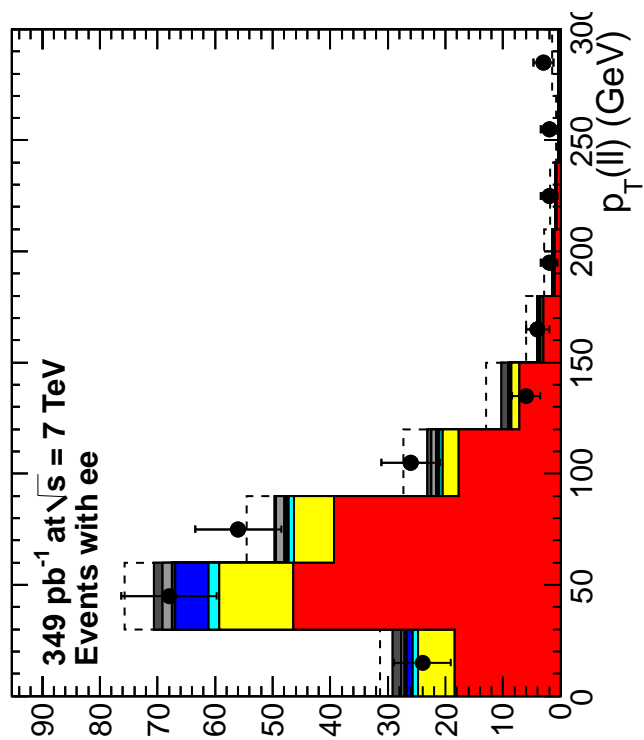


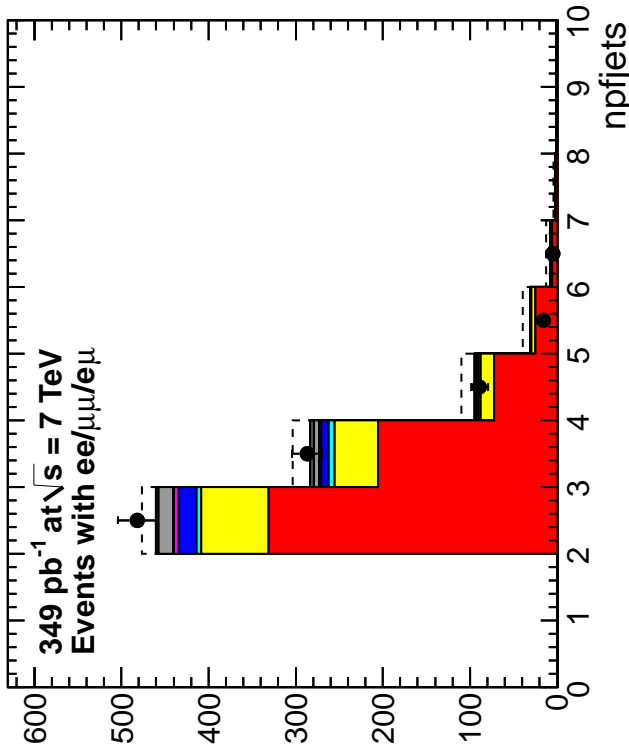
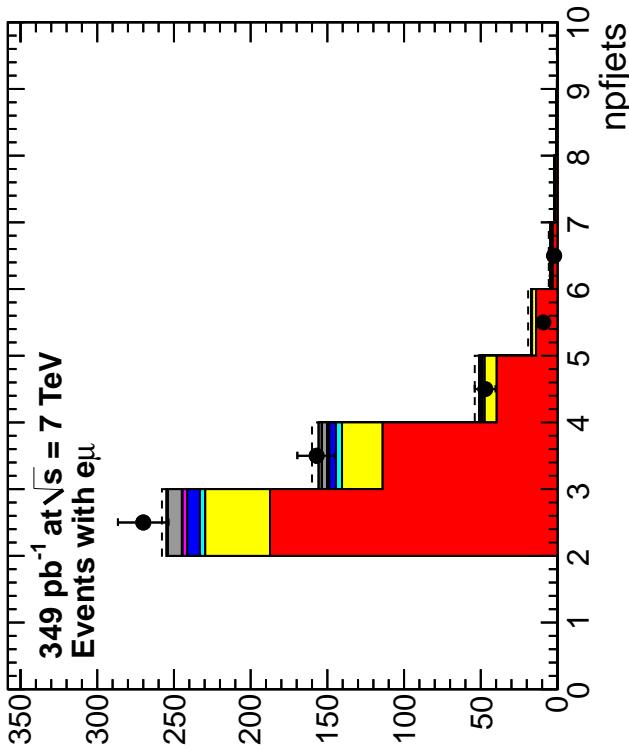
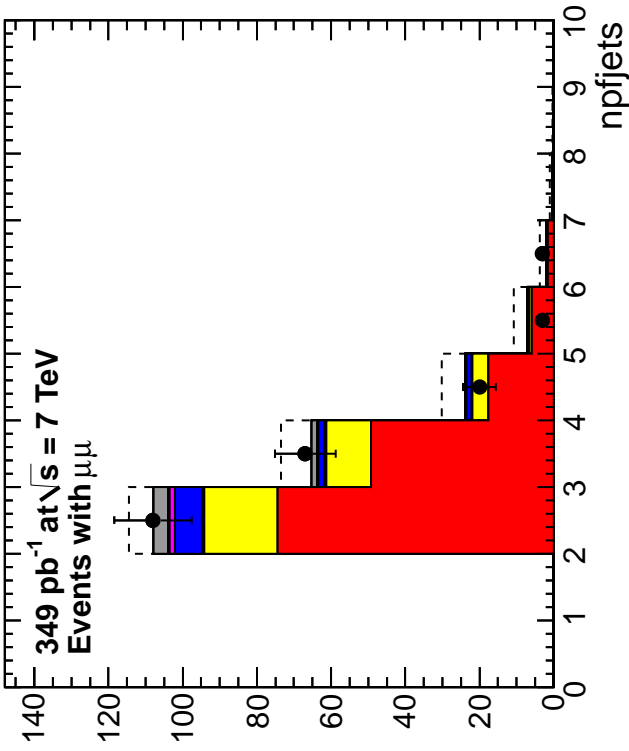
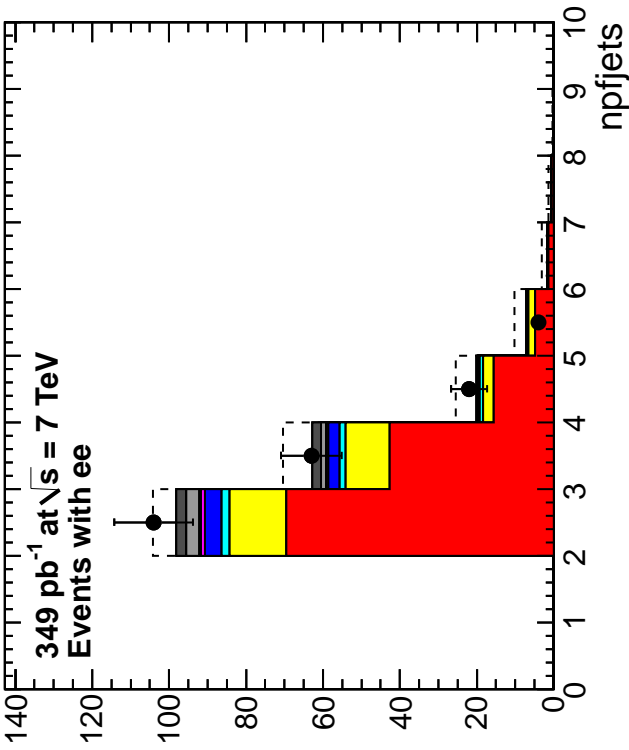




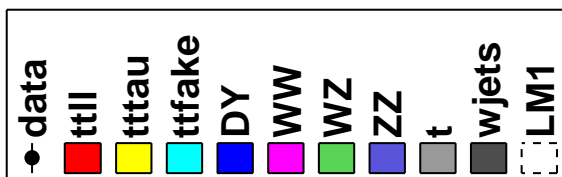
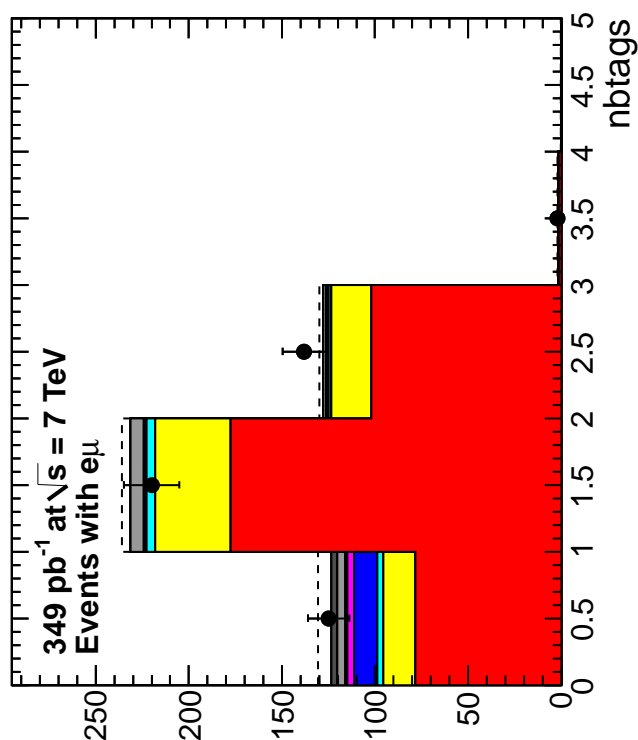
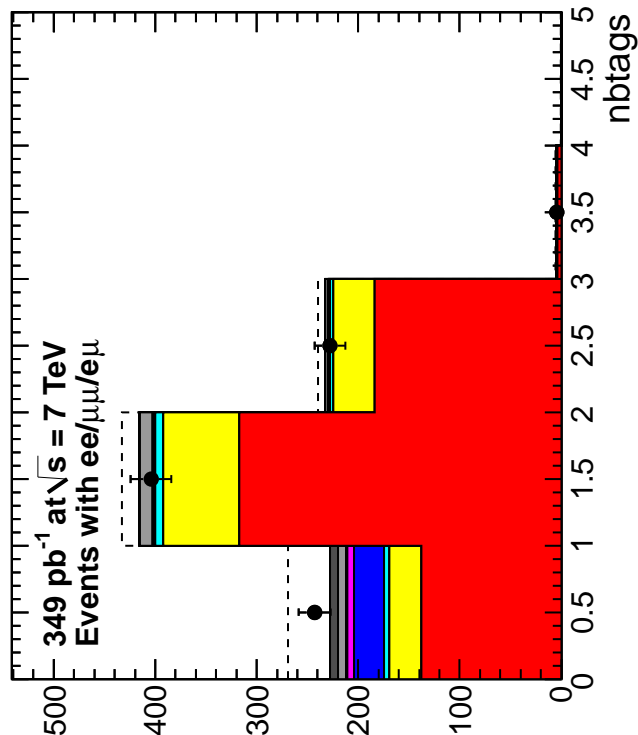
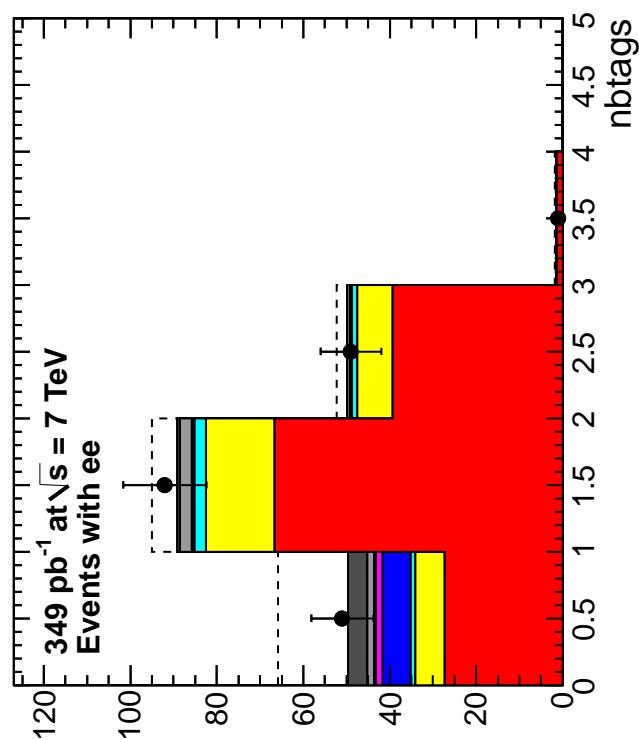


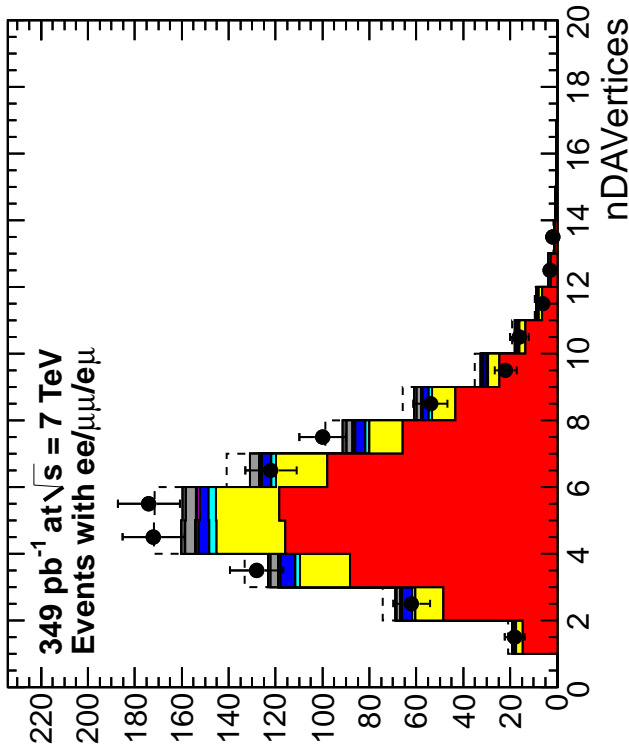
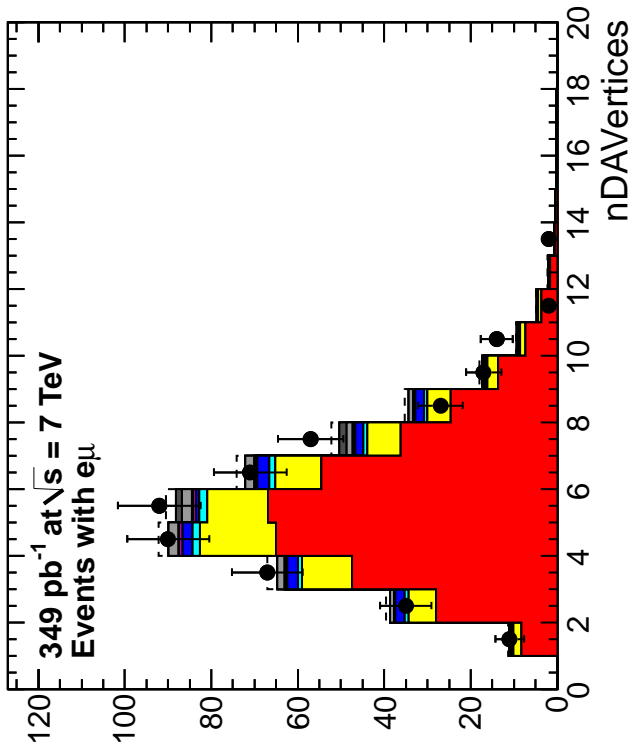
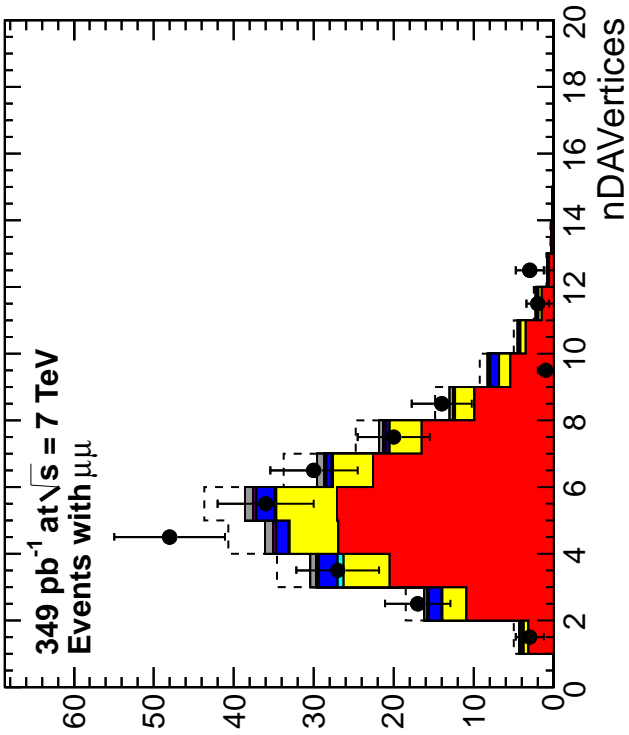
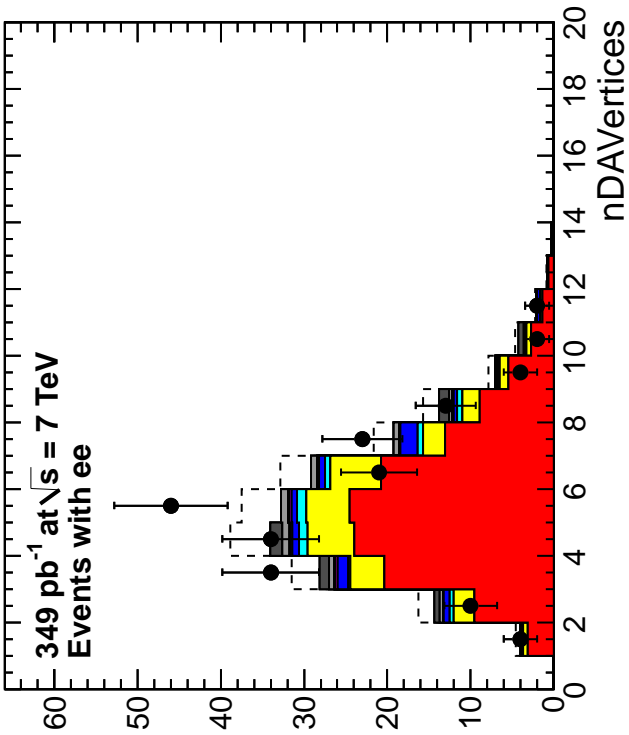


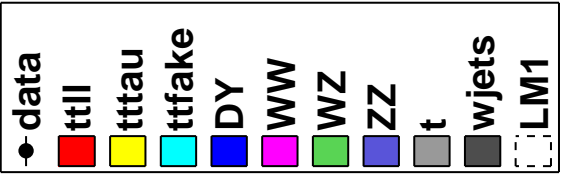
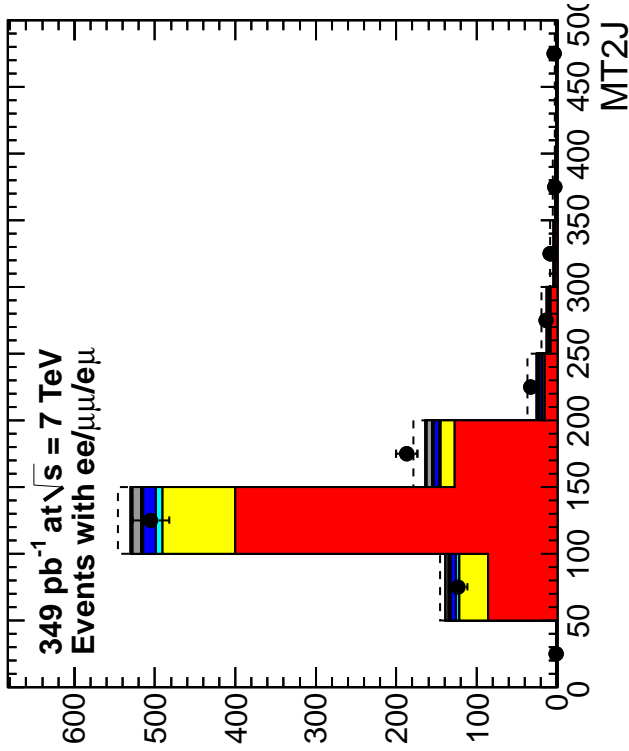
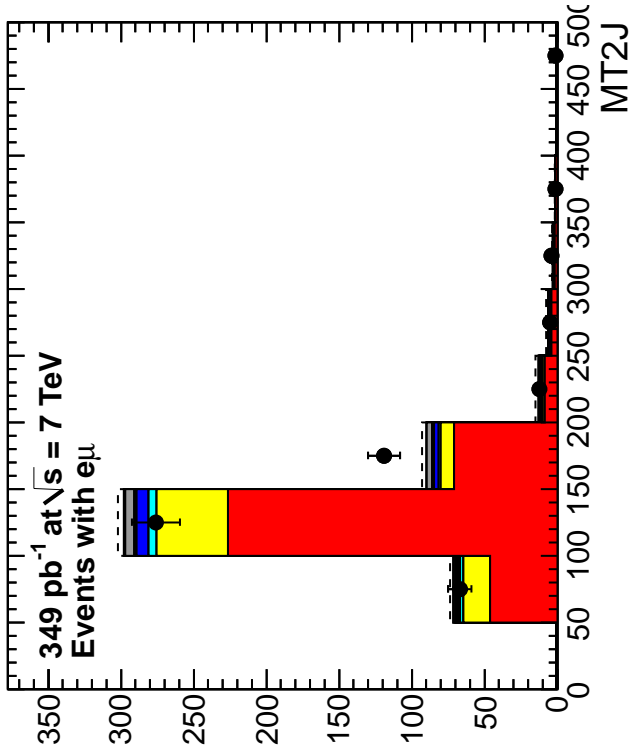
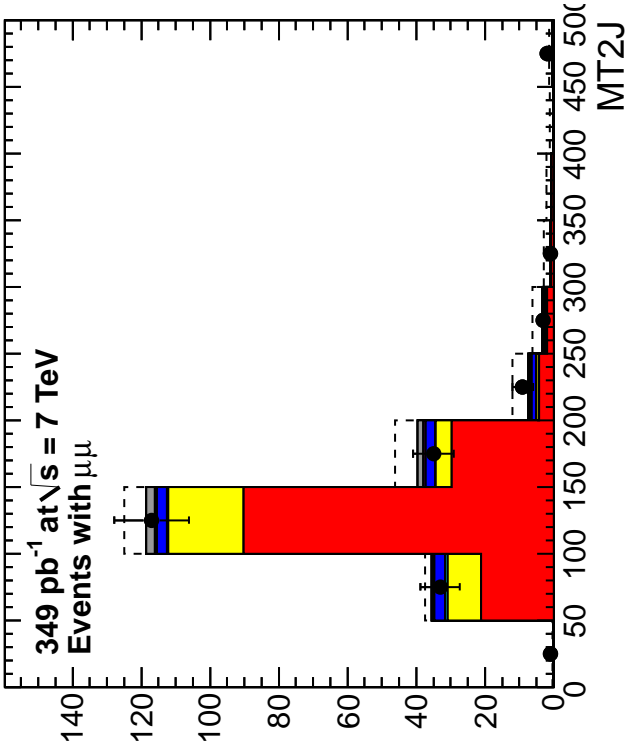
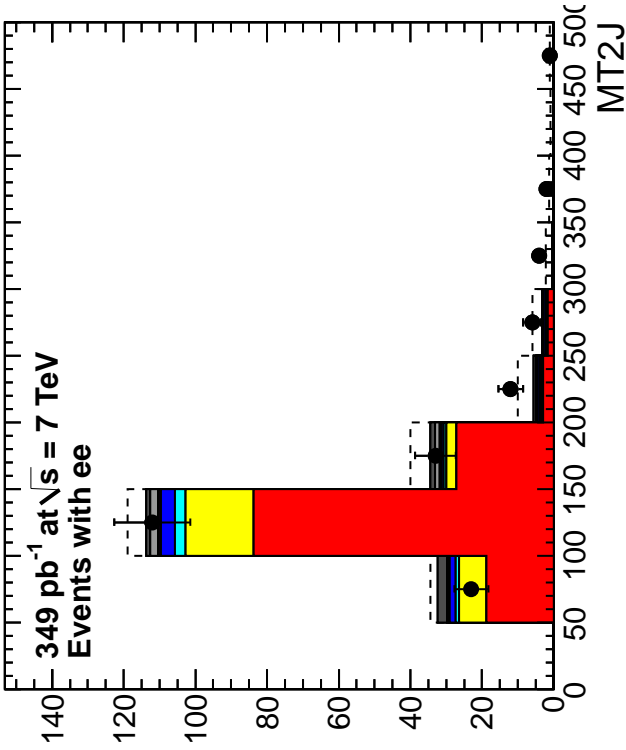


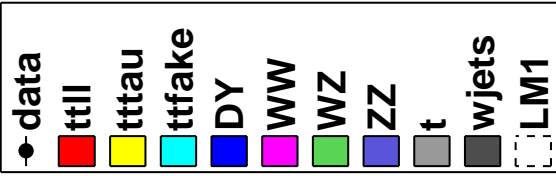
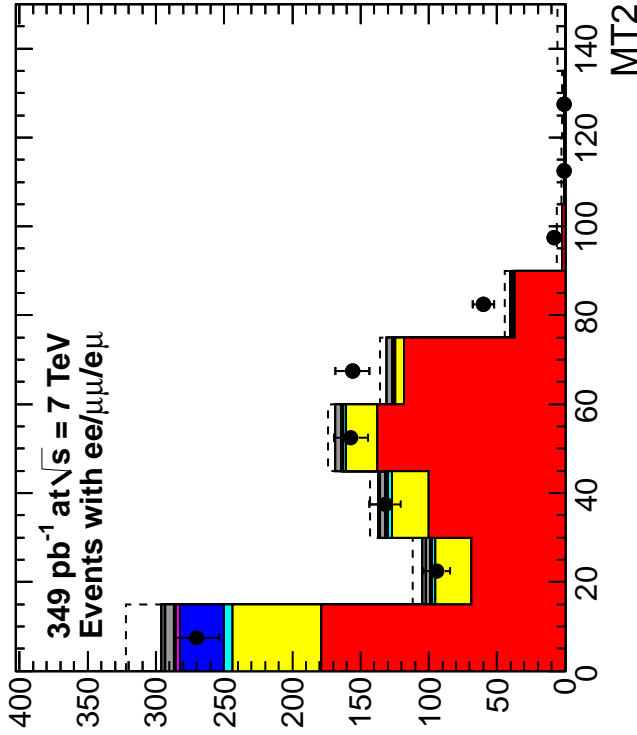
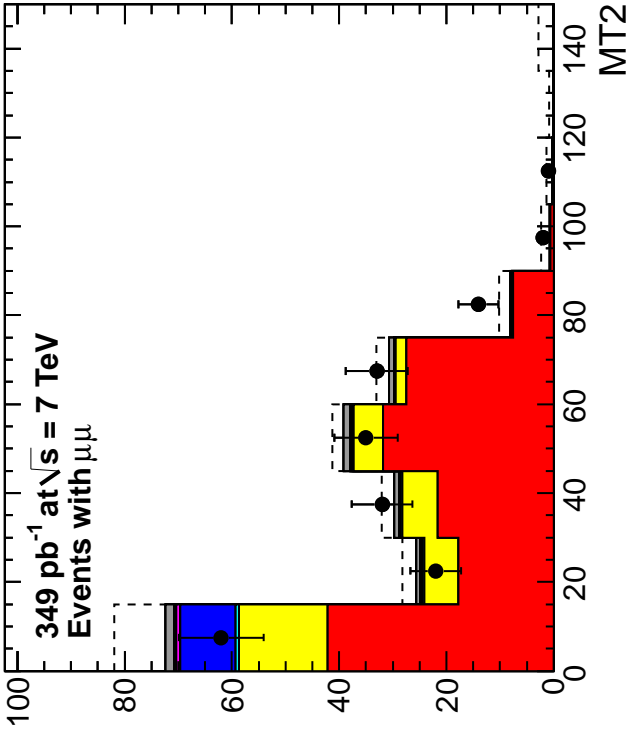
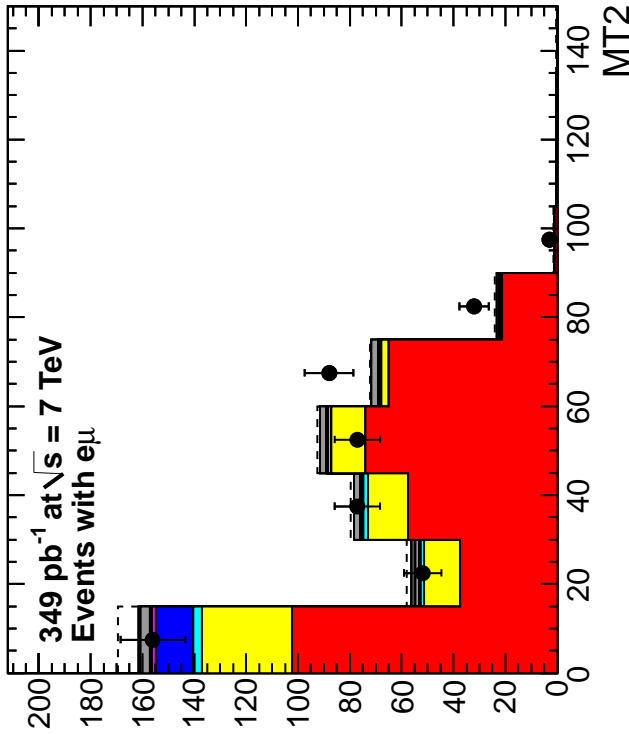
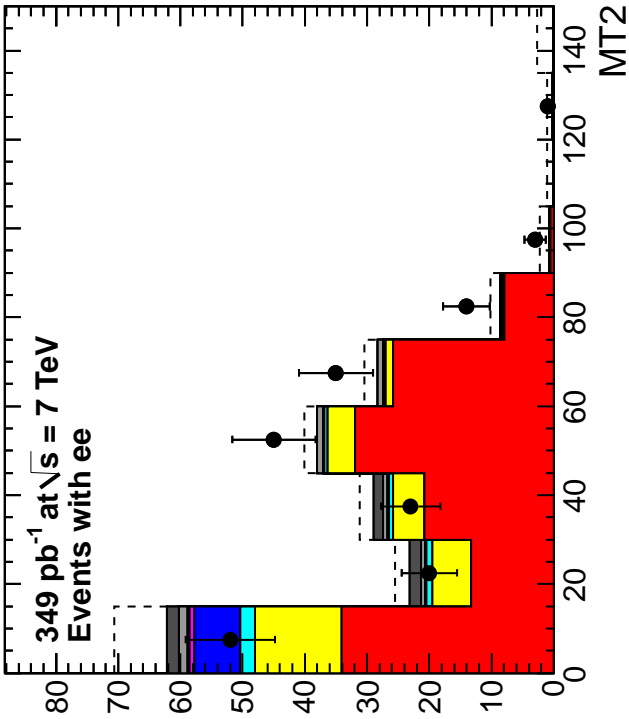


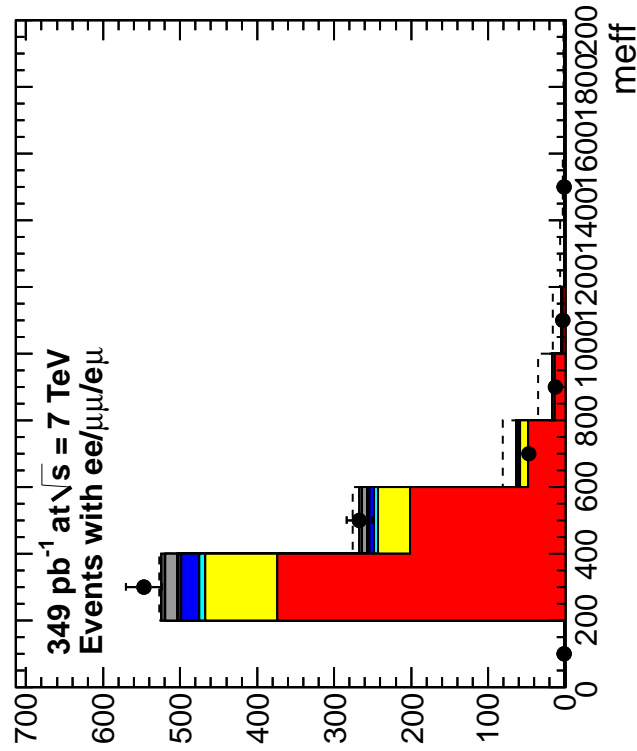
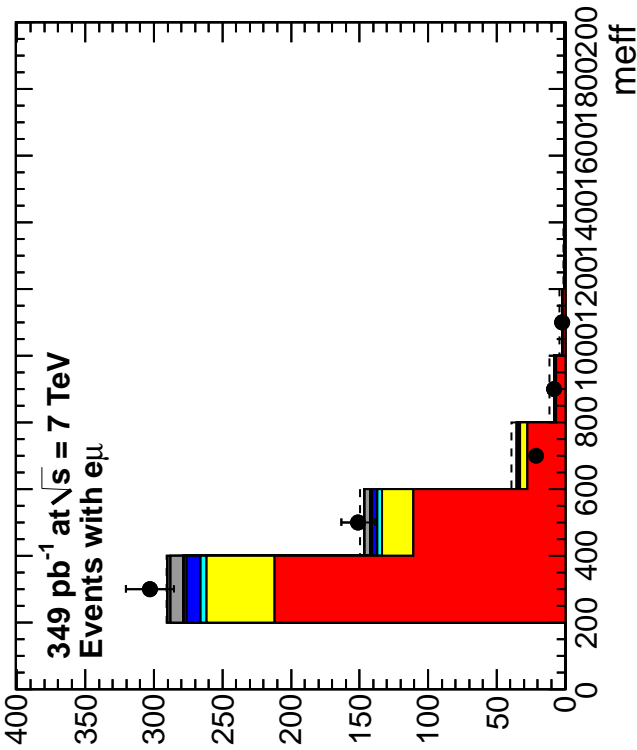
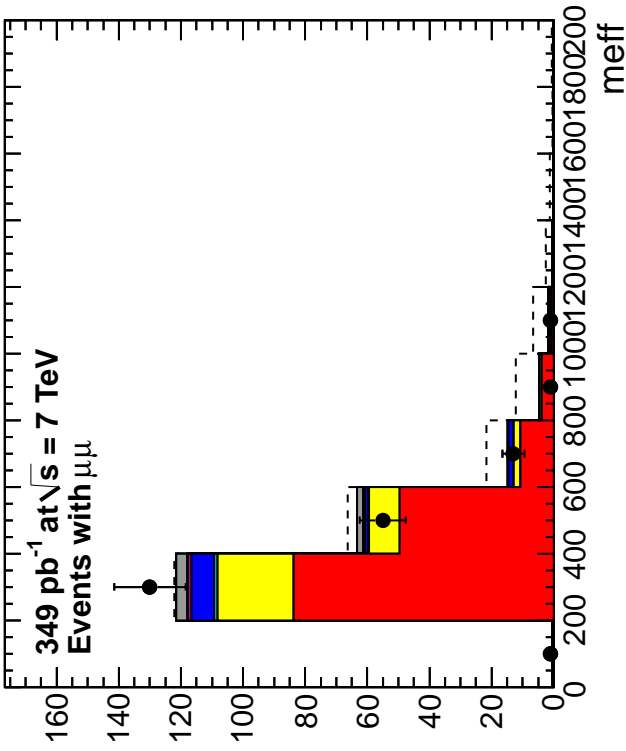
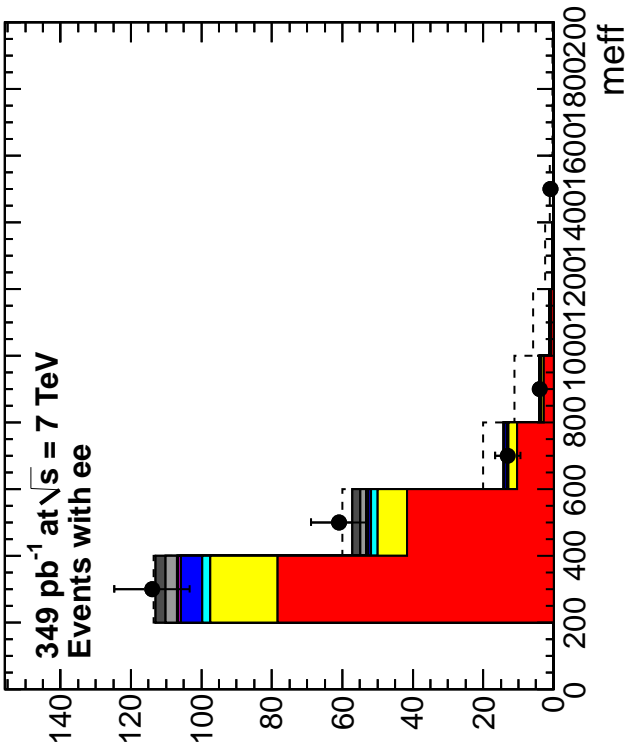












## Appendix D Data/MC Comparison: 2010 Signal Region

Here we compare data and MC distributions for data passing the 2010 signal region requirements (preselection +  $y > 8.5 \text{ GeV}^{1/2} + H_T > 300 \text{ GeV}$ . The high  $p_T$  dilepton trigger data is used. We observe 19 events in this region.

All MC samples are scaled by an overall factor 1.12, the ratio of the observed data yield in the preselection region to the prediction from MC. For illustration purposes, we overlay the distributions from the LM1 SUSY benchmark point.

