

CMS Draft Analysis Note

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Search for VBF Higgs bosons decaying to invisible particles at 13 TeV with 2017 and 2018 data

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Abstract

This note describes the search for invisible decays of Higgs boson produced with vector boson fusion (VBF). The search is performed using a shape-based analysis, using the data collected by CMS at $\sqrt{s} = 13 \text{ TeV}$ in 2017 and 2018, corresponding to integrated luminosities of 41.3 fb^{-1} and 59.7 fb^{-1} , respectively.

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35 1 Introduction

36 This analysis note describes a search for events in which the Higgs boson is produced by vector
 37 boson fusion (VBF), decaying into invisible particles in the final state. The signature of such a
 38 final state will be two separated jets and an imbalance in \vec{p}_T due to the undetected particles.
 39 Two separated jets are the result of the hadronization of two final state quarks emerging from
 40 the VBF process.

41 This analysis makes use of data collected with the CMS detector in proton-proton (pp) colli-
 42 sions in 2017 and 2018 at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 41.3 fb^{-1}
 43 and 59.7 fb^{-1} , respectively.

44 The analysis strategy is similar to that of 2016 VBF analysis, with several improvements. One
 45 of the major improvements in this analysis is the addition of the photon control region as the
 46 fifth control region. The addition of this new control region provides additional constraint and
 47 sensitivity on the final fit. In addition to this, the theory scale factors are re-derived in this
 48 analysis for VBF topology.

49 2 Samples

50 The analysis described in this note is performed using data collected in 2017 by CMS at 13 TeV
 51 and corresponds to an integrated luminosity of 41.5 fb^{-1} . The MC simulation samples for the
 52 background processes have been produced in the Fall17 and Autumn18 campaigns. Further
 53 details are given in the following sub-sections.

54 2.1 Data Samples

55 The datasets listed in Tab. 1 are used to select events in the signal and the control regions, and
 56 to perform measurements on physics objects used in the analysis (e.g. trigger turn-ons).

Table 1: List of datasets used to select events in the signal and control regions. Datasets for both years correspond to the Nano1June2019 campaign, otherwise known as v5. For the 2017 data, the 31Mar2018 reconstruction is used for all periods. For 2018 data, the 17Sep2018 reconstruction is used for runs A to C, and the 22Jan2019 reconstruction is used for run D.

Year	Dataset name	Events selected for
both	/MET/Run201*/NANO AOD	Signal, single muon, double muon control regions
2017	/SingleElectron/Run2017*/NANO AOD	Single electron, double electron control regions
	/SinglePhoton/Run2017*/NANO AOD	Single photon control region
2018	/EGamma/Run2018*/NANO AOD	Single electron, double electron control, single photon control regions

57 2.2 Background Samples

58 Simulation datasets for the background processes are listed in Table 2 and 3. There are several
 59 Standard Model processes that pose as backgrounds to the VBF H_{inv} signal, experimental sig-
 60 nature of the final state being two jets with large rapidity separation and invariant mass, along
 61 with p_T^{miss} . These processes are as follows:

62 **Z($\nu\nu$) + jets** : This process yields the largest irreducible background in the analysis, consist-
 63 ing of a Z boson and 2 or more jets coming from either QCD or EWK vertices. Simulated

samples for this background have been produced at leading order (LO) in QCD using the aMC@NLO generator in several bins of H_T for the QCD case, and in one inclusive sample for the EWK case.

W + jets : This process is the second largest source of background in this analysis, consisting of a W boson and 2 or more jets coming from either QCD or EWK vertices. The contribution of this background can be reduced by rejecting events with charged lepton candidates (electron/muon/tau). However, this process becomes irreducible in the case where the charged leptons are outside of the detector acceptance. Simulation samples for this background have been generated at LO in QCD using the aMC@NLO generator in several bins H_T for the QCD case, and in once inclusive sample for the EWK case.

Z($\ell\ell$) + jets : This process mimics signal-like events in the case where the leptons coming from the Z boson decay are not reconstructed. As in the case of $W \rightarrow \ell\nu$, the contribution of this background is reduced by rejecting events with charged leptons. Simulation samples for this process have been generated at LO in QCD using the aMC@NLO generator in bins of H_T for the QCD case, and in once inclusive sample for the EWK case.

Top: Top-quark decays (both $t\bar{t}$ and single top) also contribute background events to this analysis. In these processes, the W boson produced in a top-quark decay further decays leptonically, which produces genuine p_T^{miss} in the event. Next-to-leading order (NLO) $t\bar{t}$ simulation samples have been produced with the aMC@NLO generator with two additional partons in the matrix element. Single-top events have been generated with the Powheg generator at NLO in QCD with one additional matrix element parton.

Dibosons: Decays of diboson pairs (WW, WZ, ZZ) also constitute background processes. Typically, one of the bosons decays leptonically ($W \rightarrow \ell\nu, Z \rightarrow \nu\nu$) while the other boson decays hadronically, thus producing jets and p_T^{miss} in the final state. Simulated samples for WW, WZ and ZZ production have been generated at LO with Pythia 8.

QCD Multijet: QCD multijet events typically do not have large genuine p_T^{miss} . However, given the large cross section with which these events are produced, even a small fraction of events with jet mismeasurement results in a non-zero contribution of this process as background in the analysis. Simulated QCD samples have been generated at LO in QCD using the MadGraph generator in several bins of H_T .

The MC samples produced using MADGRAPH5_aMC@NLO, and POWHEG generators are interfaced with PYTHIA using the CP5 tune [1] for the fragmentation, hadronization, and underlying event description. In the case of the MADGRAPH5_aMC@NLO samples, jets from the matrix element calculations are matched to the parton shower description following the MLM [2] (FxFx [3]) prescription to match jets from matrix element calculations and parton shower description for LO (NLO) samples. The NNPDF 3.1 NNLO [4] parton distribution functions (PDFs) are used in all generated samples. The propagation of all final-state particles through the CMS detector is simulated with the GEANT 4 software [5]. The simulated events include the effects of pileup, with the multiplicity of reconstructed primary vertices matching that in data. The average number of pileup interactions per proton bunch crossing is found to be 32 for both the 2017 and 2018 data samples used in this analysis (assuming a total inelastic proton-proton cross-section).

Dataset name	Cross section (pb)	Order in QCD
WJetsToLNu_HT-70To100_TuneCP5_13TeV-madgraphMLM-pythia8	1296	LO
WJetsToLNu_HT-100To200_TuneCP5_13TeV-madgraphMLM-pythia8	1392	LO
WJetsToLNu_HT-200To400_TuneCP5_13TeV-madgraphMLM-pythia8	410.2	LO
WJetsToLNu_HT-400To600_TuneCP5_13TeV-madgraphMLM-pythia8	57.95	LO
WJetsToLNu_HT-600To800_TuneCP5_13TeV-madgraphMLM-pythia8	12.98	LO
WJetsToLNu_HT-800To1200_TuneCP5_13TeV-madgraphMLM-pythia8	5.39	LO
WJetsToLNu_HT-1200To2500_TuneCP5_13TeV-madgraphMLM-pythia8	1.08	LO
WJetsToLNu_HT-2500ToInf_TuneCP5_13TeV-madgraphMLM-pythia8	0.008098	LO
ZJetsToNuNu_HT-100To200_13TeV-madgraph	305.3	LO
ZJetsToNuNu_HT-200To400_13TeV-madgraph	91.86	LO
ZJetsToNuNu_HT-400To600_13TeV-madgraph	13.13	LO
ZJetsToNuNu_HT-600To800_13TeV-madgraph	3.242	LO
ZJetsToNuNu_HT-800To1200_13TeV-madgraph	1.501	LO
ZJetsToNuNu_HT-1200To2500_13TeV-madgraph	0.3431	LO
ZJetsToNuNu_HT-2500ToInf_13TeV-madgraph	0.005146	LO
DYJetsToLL_M-50_HT-70to100_TuneCP5_13TeV-madgraphMLM-pythia8	146.9	LO
DYJetsToLL_M-50_HT-100to200_TuneCP5_13TeV-madgraphMLM-pythia8	160.9	LO
DYJetsToLL_M-50_HT-200to400_TuneCP5_13TeV-madgraphMLM-pythia8	48.68	LO
DYJetsToLL_M-50_HT-400to600_TuneCP5_13TeV-madgraphMLM-pythia8	6.998	LO
DYJetsToLL_M-50_HT-600to800_TuneCP5_13TeV-madgraphMLM-pythia8	1.745	LO
DYJetsToLL_M-50_HT-800to1200_TuneCP5_13TeV-madgraphMLM-pythia8	0.8077	LO
DYJetsToLL_M-50_HT-1200to2500_TuneCP5_13TeV-madgraphMLM-pythia8	0.1923	LO
DYJetsToLL_M-50_HT-2500toInf_TuneCP5_13TeV-madgraphMLM-pythia8	0.003477	LO
GJets_HT-40To100_TuneCP5_13TeV-madgraphMLM-pythia8	18640	LO
GJets_HT-100To200_TuneCP5_13TeV-madgraphMLM-pythia8	8641	LO
GJets_HT-200To400_TuneCP5_13TeV-madgraphMLM-pythia8	2196	LO
GJets_HT-400To600_TuneCP5_13TeV-madgraphMLM-pythia8	258.4	LO
GJets_HT-600ToInf_TuneCP5_13TeV-madgraphMLM-pythia8	85.23	LO

Table 2: Simulated datasets for the modelling of single electroweak boson backgrounds. All datasets are accessed at the NanoAOD data tier from the v5 campaign, also known as 1Jun19.

2.3 Signal simulation samples

Simulated signal samples for invisible decays of the Higgs boson are generated using the Powheg generator at NLO in QCD. The samples are normalized to the standard model cross section for Higgs production in the given mode [6]. They are listed in Tab. 4.

3 Trigger

Events for the signal region are collected using a set of dedicated triggers designed to select events with large p_T^{miss} and large H_T^{miss} based on the online particle flow (PF) algorithm. In these dedicated trigger algorithms, identified PF muons are removed from the event before the p_T^{miss} and the H_T^{miss} objects are calculated. With this definition, the signal trigger paths can also be used to select single and double muon events for the W and Z control regions, respectively.

Electron events for the W and Z regions are selected using a single electron trigger. To ensure the trigger efficiency also for high- p_T electrons, the single electron trigger is used in combination with a single photon trigger [7]. The same photon trigger is used to select events for the photon control region.

The full list of triggers used, along with the L1 seeds and the associated primary datasets are

Data set name	Cross section (pb)	Order in QCD
EWKWMINUS2JETS_WTOLNU_M-50_TUNECP5_13TeV-madgraph-pythia8	20.35	LO
EWKWPPLUS2JETS_WTOLNU_M-50_TUNECP5_13TeV-madgraph-pythia8	25.81	LO
EWKZ2JETS_ZTOLL_M-50_TUNECP5_13TeV-madgraph-pythia8	4.321	LO
EWKZ2JETS_ZTONUNU_TUNECP5_13TeV-madgraph-pythia8	10.04	LO
AJJ_EWK_TUNECP5_13TeV_amcatnlo-pythia8	6.096	NLO
GJETS_MJJ-500_SM_5f_TUNECP5_EWK_13TeV-madgraph-pythia8	4.937	LO
GJETS_SM_5f_TUNECP5_EWK_13TeV-madgraph-pythia8	32.91	LO
TTJETS_TUNECP5_13TeV-amcatnloFXFX-pythia8	831.76	NLO
ST_t-channel_top_4f_inclusiveDecays_TUNECP5_13TeV-powhegV2-madspin-pythia8	137.458	NLO
ST_t-channel_antitop_4f_inclusiveDecays_TUNECP5_13TeV-powhegV2-madspin-pythia8	83.0066	NLO
ST_tW_top_5f_inclusiveDecays_TUNECP5_*_13TeV-powheg-pythia8	35.85	NLO
ST_tW_antitop_5f_inclusiveDecays_TUNECP5_*_13TeV-powheg-pythia8	35.85	NLO
WW_TUNECP5_13TeV-pythia8	75.91	LO
WZ_TUNECP5_13TeV-pythia8	27.56	LO
ZZ_TUNECP5_13TeV-pythia8	12.14	LO
QCD_HT1000to1500_TUNECP5_13TeV-madgraph-pythia8	1095	LO
QCD_HT1000to1500_TUNECP5_13TeV-madgraph-pythia8	1095	LO
QCD_HT100to200_TUNECP5_13TeV-madgraph-pythia8	2.369e+07	LO
QCD_HT1500to2000_TUNECP5_13TeV-madgraph-pythia8	99.27	LO
QCD_HT2000toInf_TUNECP5_13TeV-madgraph-pythia8	20.25	LO
QCD_HT200to300_TUNECP5_13TeV-madgraph-pythia8	1.554e+06	LO
QCD_HT300to500_TUNECP5_13TeV-madgraph-pythia8	324300	LO
QCD_HT300to500_TUNECP5_13TeV-madgraph-pythia8	324300	LO
QCD_HT500to700_TUNECP5_13TeV-madgraph-pythia8	29990	LO
QCD_HT50to100_TUNECP5_13TeV-madgraphMLM-pythia8	1.85e+08	LO
QCD_HT700to1000_TUNECP5_13TeV-madgraph-pythia8	6374	LO
QCD_HT700to1000_TUNECP5_13TeV-madgraph-pythia8	6374	LO

Table 3: Simulated datasets for the modelling of EWK V production and other processes. All datasets are accessed at the NanoAOD data tier from the v5 campaign, also known as 1Jun19.

Data set name	Cross section (pb)	Order in QCD
Gluglu_HToInvisible_M125_TUNECP5_13TeV_powheg_pythia8	48.58	NLO
VBF_HToInvisible_M125_13TeV_TUNECP5_powheg_pythia8	3.782	NLO

Table 4: Simulated signal datasets for the modelling of invisible Higgs boson decays. All datasets are accessed at the NanoAOD data tier from the v5 campaign, also known as 1Jun19.

121 shown in Table 5.

122 3.1 Efficiency measurement

123 3.1.1 $p_T^{\text{miss}} + H_T^{\text{miss}}$ triggers

124 The performance of the $p_T^{\text{miss}} + H_T^{\text{miss}}$ triggers is measured using single muon events. The events
 125 are selected from the SingleMuon using the HLT_IsoMu27 (HLT_IsoMu24) trigger for 2017
 126 (2018), and the offline muon is required to be well-identified and have p_T larger than 40 GeV.
 127 The same selection is required as for the single-muon control region used in the final fit (cf. sec.
 128 6.2):

- 129 1. Veto on additional leptons, photons, b jets, τ_{had} candidates.
- 130 2. $\Delta\phi(jet, \vec{p}_T^{\text{miss}}) > 0.5$ for the four leading jets with $p_T > 30$ GeV.

Table 5: HLT paths and the associated L1 seeds used in the analysis for the 2017 and 2018 datasets. The HLT paths ending in “_HT60” are backup triggers introduced to mitigate noise rate problems in 2017. Their inclusion is not strictly necessary for 2018, but is done for consistency.

Year	HLT path	L1 seed	Primary dataset
2017	HLT_PFMETNoMu120_PFMHTNoMu120_IDTight	L1_ETMHF70	MET
	HLT_PFMETNoMu120_PFMHTNoMu120_IDTight_PFHT60	L1_ETMHF80_HTT60er	MET
	HLT_Ele35_WPTight_Gsf	L1_SingleEG24	SingleElectron
		L1_SingleEG30	
2018	HLT_Photon200	L1_SingleJet170	SinglePhoton
		L1_SingleTau100er2p1	
	HLT_PFMETNoMu120_PFMHTNoMu120_IDTight	L1_ETMHF100	
		L1_ETM150	MET
2018	HLT_PFMETNoMu120_PFMHTNoMu120_IDTight_PFHT60	L1_ETMHF90_HTT60er	
		L1_SingleIsoEG24er2p1	
	HLT_Ele32_WPTight_Gsf	L1_SingleEG26er2p5	EGamma
		L1_SingleEG60	
	HLT_Photon200	L1_SingleEG34er2p5	
		L1_SingleJet160er2p5	
		L1_SingleJet180	EGamma
		L1_SingleTau120er2p1	
		L1_SingleEG60	

131 3. $(\text{Calo } p_T^{\text{miss}} - \text{PF } p_T^{\text{miss}}) / \text{recoil} \geq 0.5$

132 4. $M_T(\ell, p_T^{\text{miss}}) < 160 \text{ GeV}$.

133 5. Leading AK4 jet with $p_T > 80 \text{ GeV}$, passing the tight jet ID.

134 6. Subleading AK4 jet with $p_T > 40 \text{ GeV}$.

135 7. $\Delta\eta_{jj} > 1.0$

136 8. $\Delta\phi_{jj} < 1.5$

137 To understand the dependence of the efficiencies on the jet kinematics, we measured the effi-
138 ciency in three different categories:

139 • Two central VBF jets: Leading two jets both satisfying $|\eta| \leq 2.4$

140 • Two forward VBF jets: Leading two jets both satisfying $|\eta| > 2.4$

141 • One central and one forward VBF jet: One of the leading jets is central with $|\eta| \leq 2.4$
142 and the other jet in the pair is forward with $|\eta| > 2.4$

143 In these three categories, efficiencies are measured as a function of M_{jj} and recoil, using both
144 data and MC samples for 2017 and 2018, separately. Figs. 59, 60, 1 and 2 show the results.

145 Fig. 1 shows the efficiencies as a function of recoil in data and MC for the three categories, for
 146 2017 samples, whereas Fig. 2 shows the efficiencies as a function of recoil in data and MC for
 147 the three categories, for 2018 samples.

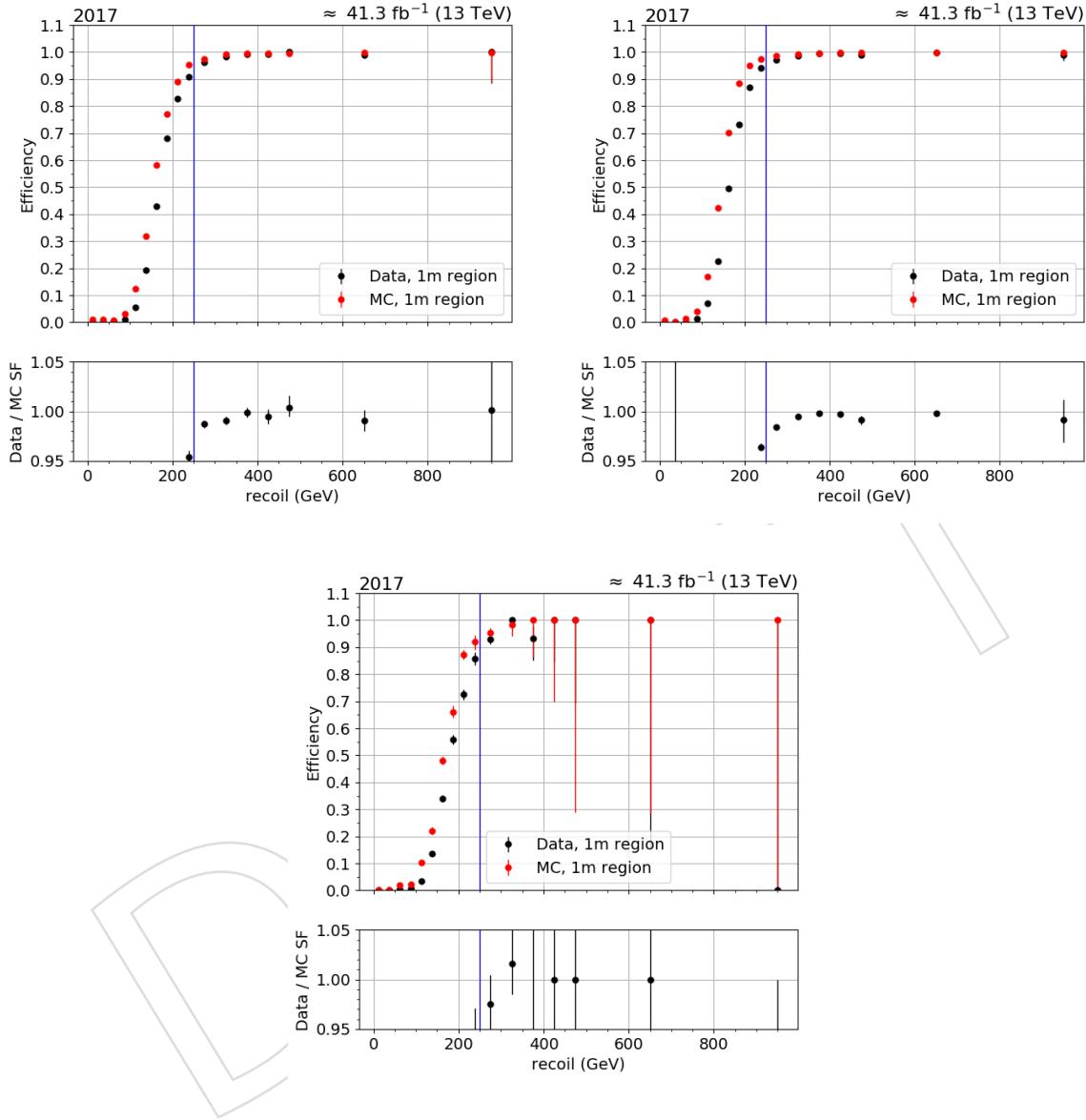


Figure 1: MET trigger efficiency as a function of recoil in three categories: One forward jet and one central jet, two central jets and two forward jets. These results are obtained from 2017 data and MC samples with the selection of single muon events.

148 3.1.2 Photon trigger

149 The photon trigger efficiency is measured using events from the JetHT dataset collected with
 150 the HLT_PFTHT1050 trigger, which was fully unprescaled in 2017 and 2018¹. Events are selected
 151 in the same way as for the photon analysis control region (cf. sec. 6.6), except for the photon
 152 p_T , recoil and trigger requirements. The trigger efficiency ϵ is then determined as:

¹The other, prescaled HLT_PFTHTXXX paths yield lower statistical precision.

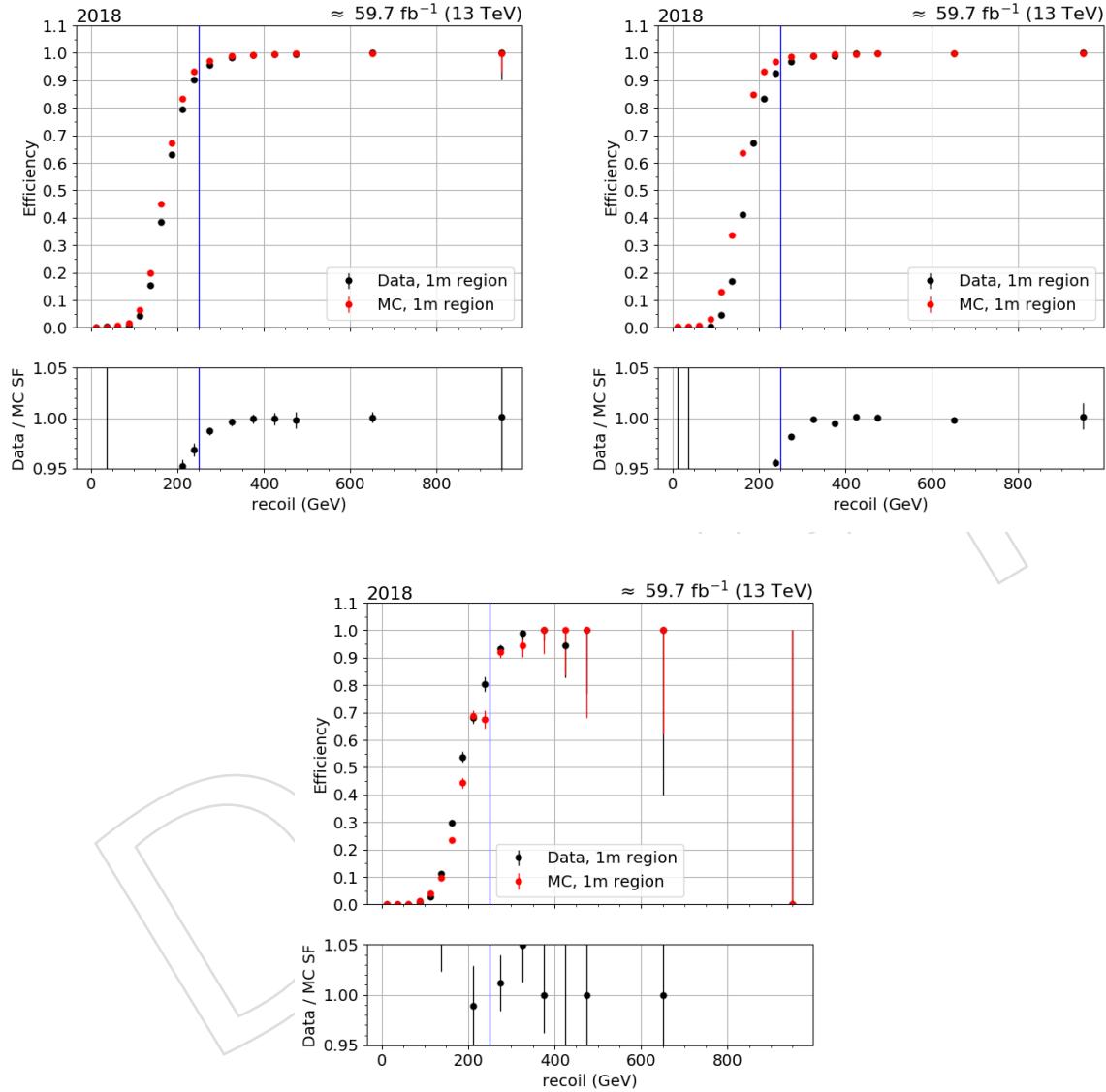


Figure 2: MET trigger efficiency as a function of recoil in three categories: One forward jet and one central jet, two central jets and two forward jets. These results are obtained from 2018 data and MC samples with the selection of single muon events.

$$\epsilon(\text{HLT_Photon200}) = \frac{\text{Offline selection \&& HLT_PFHT1050 \&& HLT_Photon200}}{\text{Offline selection \&& HLT_PFHT1050}}$$

153 The resulting efficiency in data and GJets H_T -binned simulation is shown in Fig. 3. The trigger
 154 efficiency in data is larger than 95% for a photon p_T of larger than 215 GeV, and larger than
 155 99% for photon p_T larger than 400 GeV. Between 250 and 400 GeV, there is a slight inefficiency
 156 amounting to approximately 1% at the most, with a larger amplitude in 2017 than in 2018. In
 157 both years, the turn-on behavior is almost immediate in simulated events, resulting in an MC-
 158 to-data scale factor almost entirely driven by the efficiency in data. The scale factor is within
 159 1% of unity for all bins except the lowest 2017 bin at 215 GeV, where it deviates from unity by
 160 about 4%.

161 Based on these results, the offline p_T cut for the photon in the photon control region is chosen
 162 to be 215 GeV.

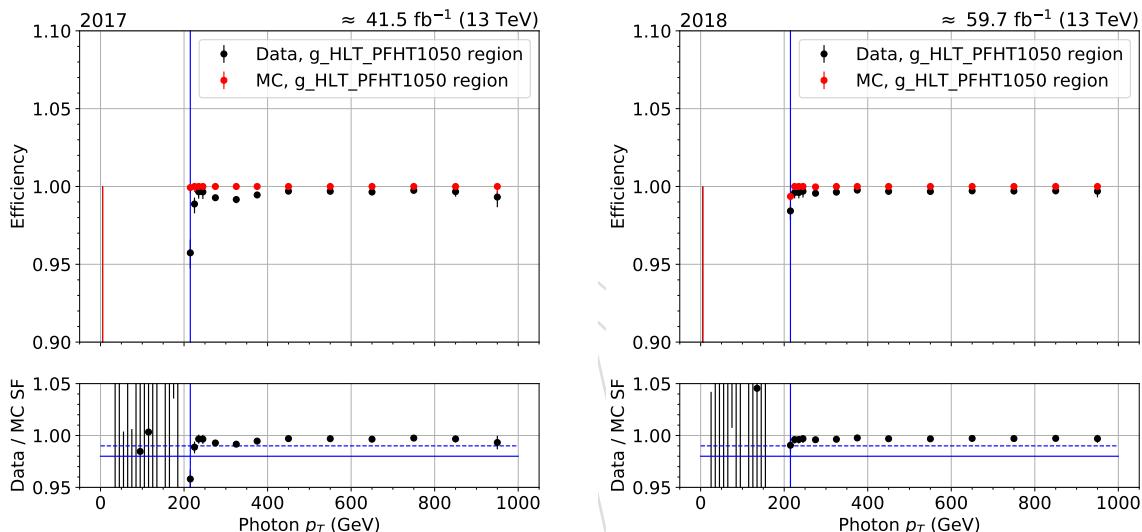


Figure 3: Efficiency of the HLT_Photon200 trigger in data (black) and H_T -binned GJets simulation (red) for 2017 (left) and 2018 (right) as a function of photon p_T . The bottom panel shows the MC-to-data efficiency scale factor. The blue vertical line indicates a photon p_T of 215 GeV, which is the requirement used in the analysis selection.

163 3.1.3 Electron trigger

164 We also need to add information about the single electron trigger efficiencies

165 4 Physics objects

166 All physics objects are used to identify signal-like events, to suppress backgrounds and to de-
 167 fine control regions for background estimation. For the object definitions, we mostly follow the
 168 CMS POG endorsed recommendations. The physics objects and the selection requirements are
 169 described below.

170 **4.1 Jets**

171 In this analysis, jets are reconstructed by clustering PF candidates using the infrared and collinear
 172 safe anti- k_T algorithm [8]. Jets are clustered with a distance parameter of 0.4 and are referred
 173 to as AK4 jets. The reconstructed vertex with the largest value of summed physics-object p_T^2 is
 174 taken to be the primary pp interaction vertex. The physics objects are those returned by a jet
 175 finding algorithm [8, 9] applied to all charged PF candidates associated with the vertex, plus
 176 the corresponding associated missing transverse momentum.

177 Jet momentum is determined as the vector sum of all particle momenta in the jet, and is found
 178 from simulation to be within 5 to 10% of the true momentum over the full p_T spectrum and de-
 179 tector acceptance. An offset correction is applied to jet energies to take into account the contri-
 180 bution from additional proton-proton interactions within the same or nearby bunch crossings
 181 (pileup). Jet energy corrections are derived from simulation, and are confirmed with *in situ*
 182 measurements of the energy balance in dijet, multijet, γ +jet, and leptonic Z+jet events [10]. The
 183 Fall17_17Nov2017_V32 and Autumn18_V8 versions of the jet energy corrections are used for
 184 the 2017 and 2018 data sets, respectively.

185 The AK4 jets used in this analysis are required to pass loose jet identification criteria. In ad-
 186 dition, all the jets with p_T smaller than 50GeV must pass the medium pileup ID criteria. This
 187 additional constraint on all AK4 jets is found to improve the modeling of jet distributions, es-
 188 pecially in the horn regions near $|\eta| = 2.9$. The effect of this requirement is demonstrated in
 189 the sub-leading jet η distribution in Fig. 4.

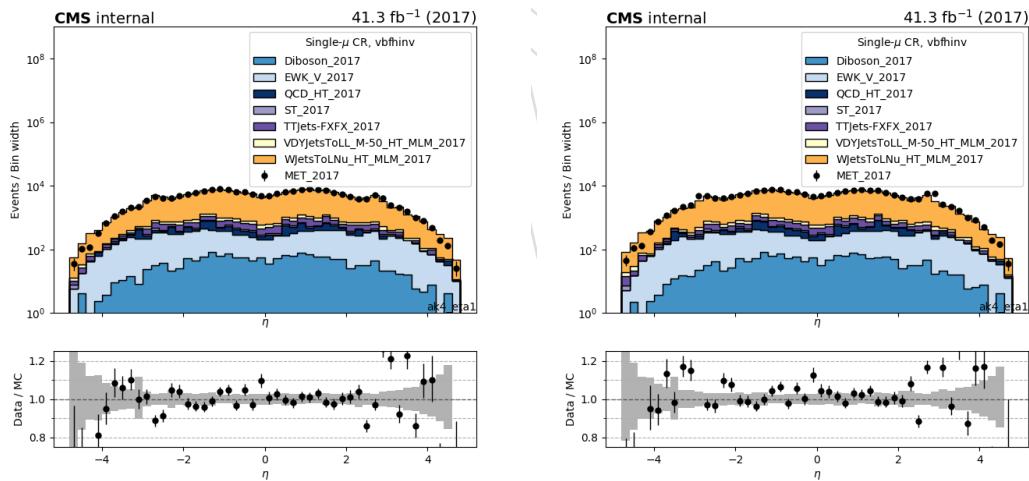


Figure 4: Subleading AK4 jet η distribution in single muon control region with pileup ID re-
 quirement (left) and without pileup ID requirement (right).

190 In addition to the pileup ID requirement, JER corrections are applied to all AK4 jets. Appli-
 191 cation of this correction on all jets is observed to improve the modeling of the jets, especially
 192 near the horn regions near $|\eta| = 2.9$. The effect of JER corrections on the subleading jet eta
 193 distribution is shown in Fig. 5.

194 Lastly, to suppress the contributions due to non-collision backgrounds, the following require-
 195 ments are applied on the leading AK4 jet:

- 196 • Charged hadron energy fraction > 0.1
- 197 • Neutral hadron energy fraction < 0.8

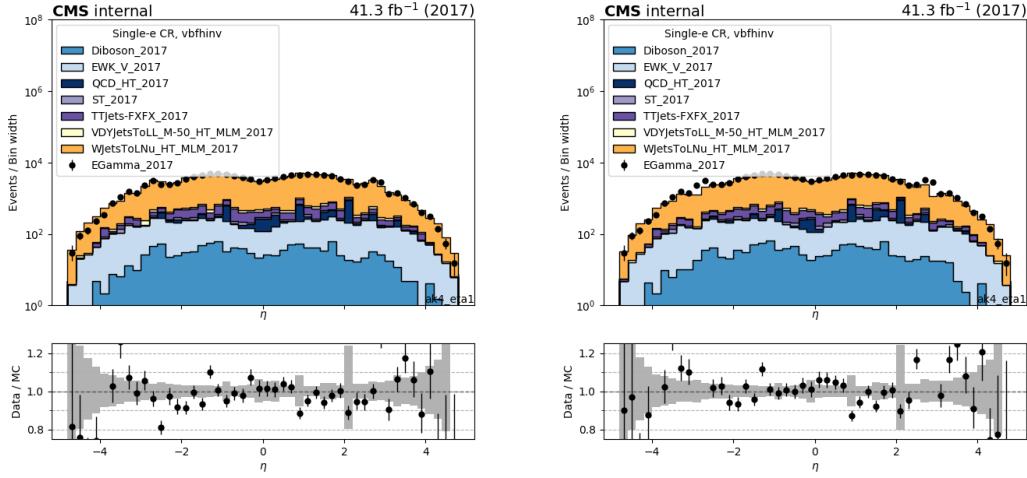


Figure 5: Subleading AK4 jet η distribution in single electron control region with JER corrections applied (left) and without JER corrections applied (right).

4.1.1 b-tagged jets

In this analysis b jets with $p_T > 20$ GeV and $|\eta| < 2.4$ are identified using the “DeepCSV” algorithm [11], adopting a working point (medium) corresponding to correctly identifying a b-jet with a probability of 80%, and misidentifying a light-flavor jet with a probability of 10%. This working point corresponds to the value of DeepCSV tagger to be greater than 0.4941. Events with identified b jets are rejected to reduce the contamination from top quark processes.

4.2 Missing transverse momentum and recoil

The vector \vec{p}_T^{miss} is defined as the imbalance in the transverse momentum of all particles that interact with the detectors. Due to momentum conservation in the plane transverse to the beam axis, \vec{p}_T^{miss} corresponds to the transverse momentum that is carried by undetected particles such as neutrinos. Practically, \vec{p}_T^{miss} is computed as the negative of the vectorial sum of transverse momenta of all PF candidates and is therefore also referred to as PF \vec{p}_T^{miss} . The magnitude of the \vec{p}_T^{miss} is referred to as p_T^{miss} .

Minimum energy thresholds in the calorimeters, inefficiencies in the tracker, nonlinearity of the response of the calorimeter for hadronic particles can lead to an over- or underestimation of p_T^{miss} . The bias on the p_T^{miss} measurement is reduced by propagating the effect of the jet energy corrections introduced in section 4.1 according to

$$\vec{p}_T^{\text{miss}}(\text{corr}) = \vec{p}_T^{\text{miss}} - \sum_{\text{jets}} (\vec{p}_{T,\text{jet}}(\text{corr}) - \vec{p}_{T,\text{jet}}), \quad (1)$$

where the “corr” refers to the scale energy corrected measurements of the related objects.

This “type-I” correction for \vec{p}_T^{miss} uses jet energy scale corrections for all corrected jets with $p_T > 15$ GeV that have less than 0.9 of their energy deposited in the ECAL. Furthermore, if a muon is found in a jet, its 4-momentum is subtracted from the 4-momentum of the jet when performing the correction and is added back to a corrected object.

Since signal events in this analysis contain only jets and no other reconstructed candidates, p_T^{miss} is equivalent to the total hadronic momentum in the event. For the leading backgrounds, this

also corresponds to the transverse momentum of the W or Z boson. To mimic this behavior in the control regions of this analysis, the transverse momentum of the hadronic recoil \vec{U} , defined as the vectorial sum of the transverse momenta of all particles except the vector boson (or its decay products), is used. The variable is computed as

$$\vec{U} = \vec{p}_T^{\text{miss}} + \sum_{i \in \text{leptons, photons}} \vec{p}_T^i \quad (2)$$

where the sum takes into account the leptons and photons used to define the respective control region. The uncertainty of p_T^{miss} has a strong dependence on the event topology. Therefore, the uncertainty on p_T^{miss} is often factorized into its components of jets, leptons and unclustered energy. Each sub-component is then varied within its scale and resolution uncertainty. In this analysis, the largest contribution on the final p_T^{miss} uncertainty comes from the variations of the jet energy scale correction and the magnitude of the uncertainty is estimated to be 4% for the $Z(\nu\nu) + \text{jets}$ events. This uncertainty is not the most recent one and it will be recalculated.

Anomalous high- p_T^{miss} events can appear due to various phenomena. In the ECAL, spurious deposits may appear due to particles striking sensors in the ECAL photodetectors, or from real showers with non-collision origins such as those caused by beam halo particles. ECAL dead cells can cause real energy to be missed, again leading to a spurious imbalance. In the HCAL, spurious energy can arise due to noise in the hybrid photodiode and readout box electronics, as well as direct particle interactions with the light guides and photomultiplier tubes of the forward calorimeter. A number of filters has been developed by the POG/DPG groups to identify and suppress anomalous high p_T^{miss} events [12]. The recommended filters are listed in Tab. 6 and are applied in the analysis.

Table 6: The p_T^{miss} filters recommended by the JME POG [12]. The recommendations apply to both 2017 and 2018. Except for the bad super cluster filter (“ee badSC”), all filters are applied both in data and simulation.

Filter	Name in NanoAOD	Applied in data (MC)
primary vertex filter	Flag_goodVertices	✓(✓)
beam halo filter	Flag_globalSuperTightHalo2016Filter	✓(✓)
HBHE noise filter	Flag_HBHENoiseFilter	✓(✓)
HBHEiso noise filter	Flag_HBHENoiseIsoFilter	✓(✓)
ECAL TP filter	Flag_EcalDeadCellTriggerPrimitiveFilter	✓(✓)
Bad PF Muon Filter	Flag_BadPFMuonFilter	✓(✓)
ee badSC noise filter	Flag_eeBadScFilter	✓(✗)
ECAL bad calibration filter update	Flag_ecalBadCalibFilterV2	✓(✓)

To further minimize the contribution of anomalous high- p_T^{miss} events (specifically due to spurious charged hadrons) in this analysis, a quantity based on the relative ratio of calorimetry based p_T^{miss} and PF based p_T^{miss} is employed. Events satisfying $|E_{\text{T calo}}^{\text{miss}} - E_{\text{T PF}}^{\text{miss}}|/U < 0.5$ are selected in this analysis.

4.3 Leptons

4.3.1 Electrons

Electrons within the geometrical acceptance of $|\eta| < 2.5$ are reconstructed by associating tracks reconstructed in the silicon detector with clusters of energy in the ECAL [13]. Well-identified electron candidates are required to satisfy additional identification criteria based on the shower shape of the energy deposit in the ECAL and the consistency of the electron track with the primary vertex [14]. Electron candidates that are identified as coming from photon conversions in the detector material are removed. An isolation variable is calculated based on the sum of the energies of the PF candidates within a cone of $\Delta R < 0.3$ around the electron. The mean energy deposit in the isolation cone of the electron coming from pileup is estimated following the method described in Ref. [13] and subtracted from the isolation sum. In this note, ‘veto’ [15] electrons with a minimum p_T of 10 GeV are selected with an average efficiency of 95% and their presence is used as a condition to reject events, whereas ‘tight’ [15] electrons with a minimum p_T of 40 GeV and an average efficiency of 70% are used to select the events in the control regions. Full selection criteria are shown in Table 7.

Table 7: Tight and veto electron identification criteria.

Variable	Selection Tight	Selection Veto
	Barrel (Endcaps)	Barrel (Endcap)
Full 5x5 $\sigma_{i\eta i\eta}$	< 0.0104 (< 0.0353)	< 0.0126 (< 0.0457)
$ \Delta\eta_{in} $	< 0.00255 (< 0.00501)	< 0.00463 (< 0.00814)
$ \Delta\phi_{in} $	< 0.022 (< 0.0236)	< 0.148 (< 0.19)
H/E	$< 0.026 + 1.15/E_{SC} + 0.0324\rho/E_{SC}$ ($< 0.0188 + 2.06/E_{SC} + 0.183 * \rho/E_{SC}$)	$< 0.05 + 1.16/E_{SC} + 0.0324\rho/E_{SC}$ ($< 0.05 + 2.54/E_{SC} + 0.183\rho/E_{SC}$)
Relative isolation (ρ correction)	$< 0.0287 + 0.506/p_T$ ($< 0.0445 + 0.963/p_T$)	$< 0.198 + 0.506/p_T$ ($< 0.203 + 0.963/p_T$)
$1/E - 1/p$	< 0.159 (< 0.0197)	< 0.209 (< 0.132)
$ d_{xy}(\text{vtx}) $	< 0.050 (< 0.100)	< 0.050 (< 0.100)
$ d_z(\text{vtx}) $	< 0.100 (< 0.200)	< 0.100 (< 0.200)
Expected Inner Missing Hits	≤ 1 (≤ 1)	≤ 2 (≤ 3)
Pass conversion veto	Yes (Yes)	Yes (Yes)

255 4.3.2 Muons

256 Muons within the geometrical acceptance of $|\eta| < 2.4$ are reconstructed by combining information from the silicon tracker and the muon system [16]. The muons are required to pass set 257 of quality criteria based on the number of spatial points measured in the tracker and in the 258 muon system, the fit quality of the muon track and its consistency with the primary vertex 259 of the event. Similar to electron case, the isolation requirements for muons are also based on 260 the sum of the energies of the PF candidates, but a different cone size of a $\Delta R < 0.4$ is used. 261 The muon isolation variable is corrected for pileup effects by subtracting half of the sum of the 262 transverse momenta of charged particles that are inside the isolation cone and not associated 263 with the primary vertex. In this note, “loose” [17] muons with $p_T > 10$ GeV are selected with 264 an average efficiency of 98% and are used as a condition to reject events, whereas “tight” [18] 265 muons with $p_T > 20$ GeV are selected with an average efficiency of 95% and are used to select 266 events in the control samples. A full list of tight identification criteria is given here: 267

- 268 • Muon reconstructed as a global muon
- 269 • Muon reconstructed as a particle flow muon
- 270 • Normalized χ^2 of the global track less than 10
- 271 • At least one muon chamber hit included in the global track fit
- 272 • Muon segments in at least two muon stations
- 273 • Transverse impact parameter w.r.t. the primary vertex less than 2 mm.
- 274 • Longitudinal impact parameter w.r.t. the primary vertex less than 5 mm.
- 275 • At least one pixel hit
- 276 • Hits on at least 5 tracker layers
- 277 • $\Delta\beta$ relative isolation less than 0.15

278 4.3.3 Taus

279 Hadronically decaying τ leptons are required to pass identification criteria using the hadron- 280 plus-strips algorithm [19]. The algorithm identifies a jet as an hadronically decaying tau lepton 281 candidate if a subset of the particles assigned to the jet is consistent with the decay products 282 of a τ candidate. Candidate τ jets are required to pass both the “DecayModeNewDMs” and 283 “DecayMode” identifiers.

284 In addition, τ candidates are required to be isolated from other activity in the event. The isolation 285 requirement is computed by summing the p_T of the charged PF candidates and PF photon 286 candidates within an isolation cone of $\Delta R = 0.5(0.3)$, around the tau candidate direction. The 287 charged and photon candidates associated with the tau candidate are removed from this sum 288 and further described in Ref. [19]. The “VLoose_IsolationMVArun2v1DBnewDMwLT” isolation 289 working point [20] is employed in this analysis for tau candidates with p_T larger than 290 18 GeV within $|\eta| < 2.3$.

291 4.4 Photons

292 Photon candidates are reconstructed from energy deposits in the ECAL using algorithms that 293 constrain the clusters to the size and shape expected from a photon [21]. The identification of 294 the candidates is based on shower-shape and isolation variables. For isolated photons, scalar 295 sums of the p_T of PF candidates within a cone of $\Delta R < 0.3$ around the photon candidate are 296 required to be below the bounds defined. Only the PF candidates that do not overlap with the 297 EM shower of the candidate photon are included in the isolation sums.

Two candidate definitions are employed. “Loose” photons are used to reject events with unwanted photons. These photons are required to pass the EGamma POG ‘loose’ identification criteria [22], have a transverse momentum of at least 15 GeV and be within $|\eta| < 2.5$. The exact identification criteria are summarized in Table 8. A “tight” photon definition is used for the photon in the dedicated photon control region. These photons are required to be in the barrel ($|\eta| < 1.479$), and have $p_T > 215$ GeV. The POG medium ID is employed, which is summarized in Table 9.

Variable	Selection Barrel (Endcap)
Full 5x5 $\sigma_{i\eta i\eta}$	$< 0.0106 (< 0.0272)$
H/E	$< 0.04596 (< 0.0590)$
charged hadron isolation	$< 1.694 (< 2.089)$
neutral hadron isolation	$< 24.032(19.722) + 0.01512(0.0117) \times p_T + 2.259(2.3) \times 10^{-5} \times p_T^2$
photon isolation	$< 2.876(4.162) + 0.004017(0.0037) \times p_T$
Conversion safe electron veto	Yes (Yes)

Table 8: Loose photon identification criteria.

Variable	Selection Barrel
Full 5x5 $\sigma_{i\eta i\eta}$	< 0.01015
H/E	< 0.02197
charged hadron isolation	< 1.141
neutral hadron isolation	$< 1.189 + 0.01512 \times p_T + 2.259 \times 10^{-5} \times p_T^2$
photon isolation	$< 2.08 + 0.004017 \times p_T$
Conversion safe electron veto	Yes

Table 9: Tight photon identification criteria. The criteria are only given for the barrel region since endcap photons are not taken into account.

4.4.1 Photon purity studies

Photons are reconstructed from ECAL clusters, and can be discriminated from other sources of ECAL deposits due to the properties of the cluster, as well as their lack of other associated signatures such as tracks or HCAL deposits. This discrimination is not perfect, however, and in some cases, non-photon objects will incorrectly be identified as photons (“fakes”). The leading source of fake photons is QCD production of multijet events, where a jet is misidentified. This process is relevant mainly because of its large cross-section, which yields non-negligible contributions to the photon selection even if the per-jet probability of misreconstruction is small.

To estimate the fake contribution to the photon control region, a purity measurement is performed. The photon purity is defined as the fraction of reconstructed photons that is actually due to an isolated photon from the hard scattering event, as opposed to a fake. The purity is obtained from a template fit to the distribution of the $\sigma_{i\eta i\eta}$ variable in data, which $\sigma_{i\eta i\eta}$ variable represents the width of the ECAL shower in the η direction. Due to the different shower behavior of photons and hadrons, the $\sigma_{i\eta i\eta}$ distribution shows characteristically different behavior between these two classes of reconstructed photons: Real photons show a large peak with a cut-off around $\sigma_{i\eta i\eta} \approx 0.01$, while fake photons will have a smaller peak (stemming from actual photons inside jets), and an additional non-peaking bulk region at larger $\sigma_{i\eta i\eta}$ (stemming from hadrons interacting in the ECAL). The inputs to the fit are defined as follows:

- Photons in data are selected by applying the same identification criteria as for the tight selection defined above, with the exception of the $\sigma_{i\eta i\eta}$ requirement. By removing this requirement, the full $\sigma_{i\eta i\eta}$ distribution can be observed.
- A real photon template is obtained from GJETS simulation. The same identification criteria are applied as in data.
- A fake photon template is obtained from data. In this case, the identification criteria are modified by requiring that at least one of the isolation criteria is not passed. Therefore, the photons in this template do not overlap with the 'data' template, and represent reconstructed photons inside jets.

The templates are derived in separate bins of the photon p_T and the measurement is performed separately for 2017 and 2018. Events are selected using the following criteria:

- At least one jet with $p_T > 100$ and $|\eta| < 2.4$, which is not overlapping with a photon of interest.
- The event must pass the HLT_Photon200 trigger, as well as the MET filters.
- The event must have $p_T^{\text{miss}} < 60 \text{ GeV}$.

The fits are shown in Figs. 6 and 7, and the resulting purity as a function of photon p_T is shown in Fig. 8. While the fits are performed in the full range of $\sigma_{i\eta i\eta} < 0.15$, the purity is evaluated only taking into account the contributions with $\sigma_{i\eta i\eta} < 0.01015$, which is the requirement posed in the identification criteria used in the analysis. The resulting purity ranges between 2 and 4%, with a decreasing trend with photon p_T .

5 Reweighting of simulated events

Simulated signal and background samples are corrected for various effects through reweighting procedures outlined in this section.

5.1 Trigger efficiency reweighting

The efficiency is calculated as a function of the recoil and M_{jj} . The trigger is found to be more than 95% efficient for events with a recoil larger than 250 GeV, and more than 99% efficient for events with a recoil larger than 375 GeV. The MC-to-data scale factor is found to be within 1% of unity everywhere except for the lowest recoil bin at 250 GeV, where it is within 2% (c.f. sec. 3.1).

5.2 Pileup reweighting

The pileup (PU) conditions in the simulated samples are not identical to the ones observed measured in data, and a reweighting is applied to remove the difference. The reweighting is performed by matching the true pileup distribution of each simulated sample with the pileup distribution in data, obtained through the pileupCalc tool assuming a minimum bias cross section of $69.2 \pm 4.6\%$ mb, following the recommendations in Ref. [23]. The true pileup distributions in data and simulation are shown in Fig. 9. The distribution of the number of reconstructed vertices for $W \rightarrow \mu\nu$ events before and after PU reweighting is shown in Fig. 10. In this variable, the PU reweighting method leads to a worse overall agreement between data and simulation. To check this behavior, the distribution of the event energy density ρ is shown in Fig. 10, again before and after PU reweighting. Here, the agreement before PU reweighting is worse than in the primary vertex distribution and the PU reweighting clearly improves the agreement.

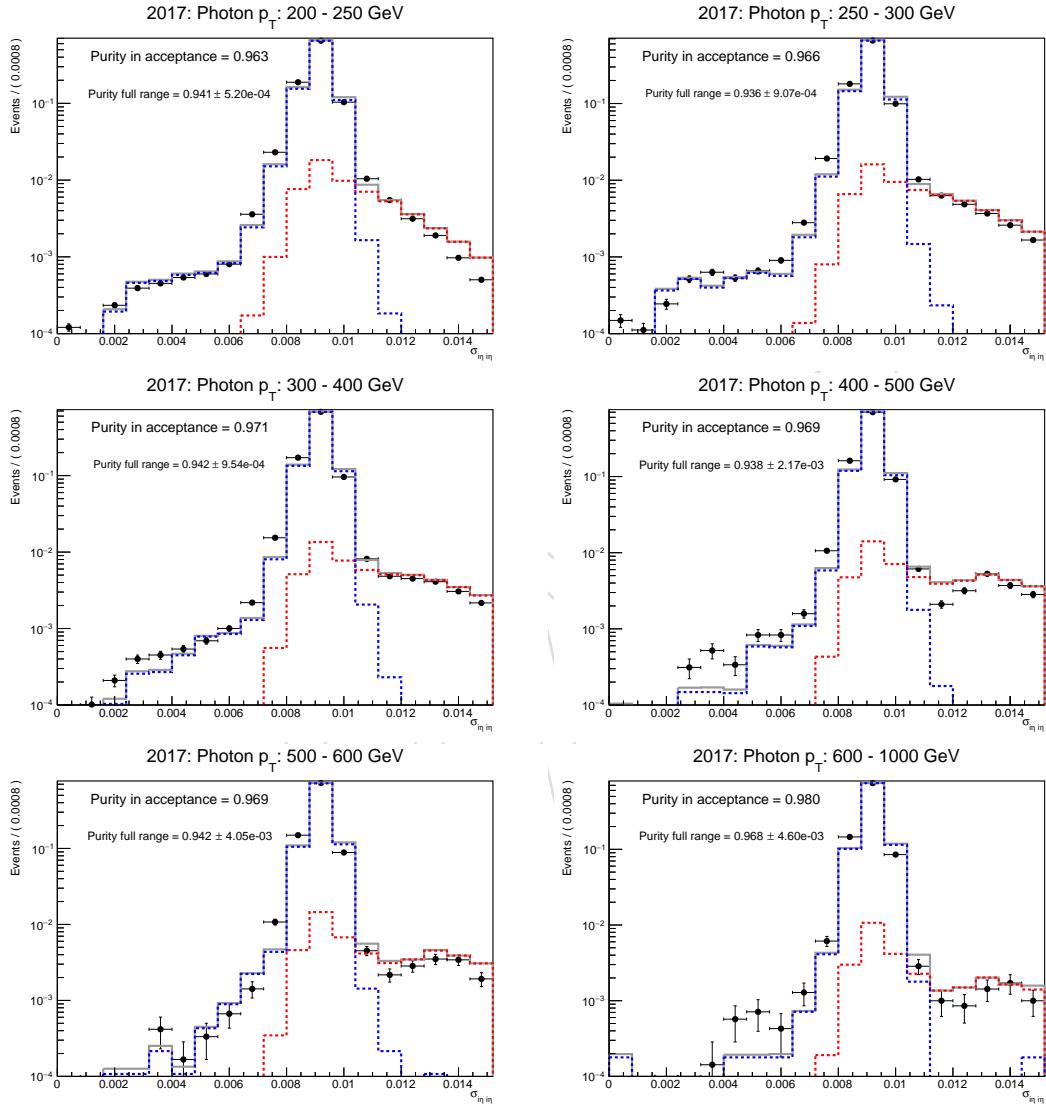


Figure 6: Template fits used to determine the photon purity in the 2017 dataset. The fits are shown in bins of photon p_T , increasing from left to right and top to bottom.

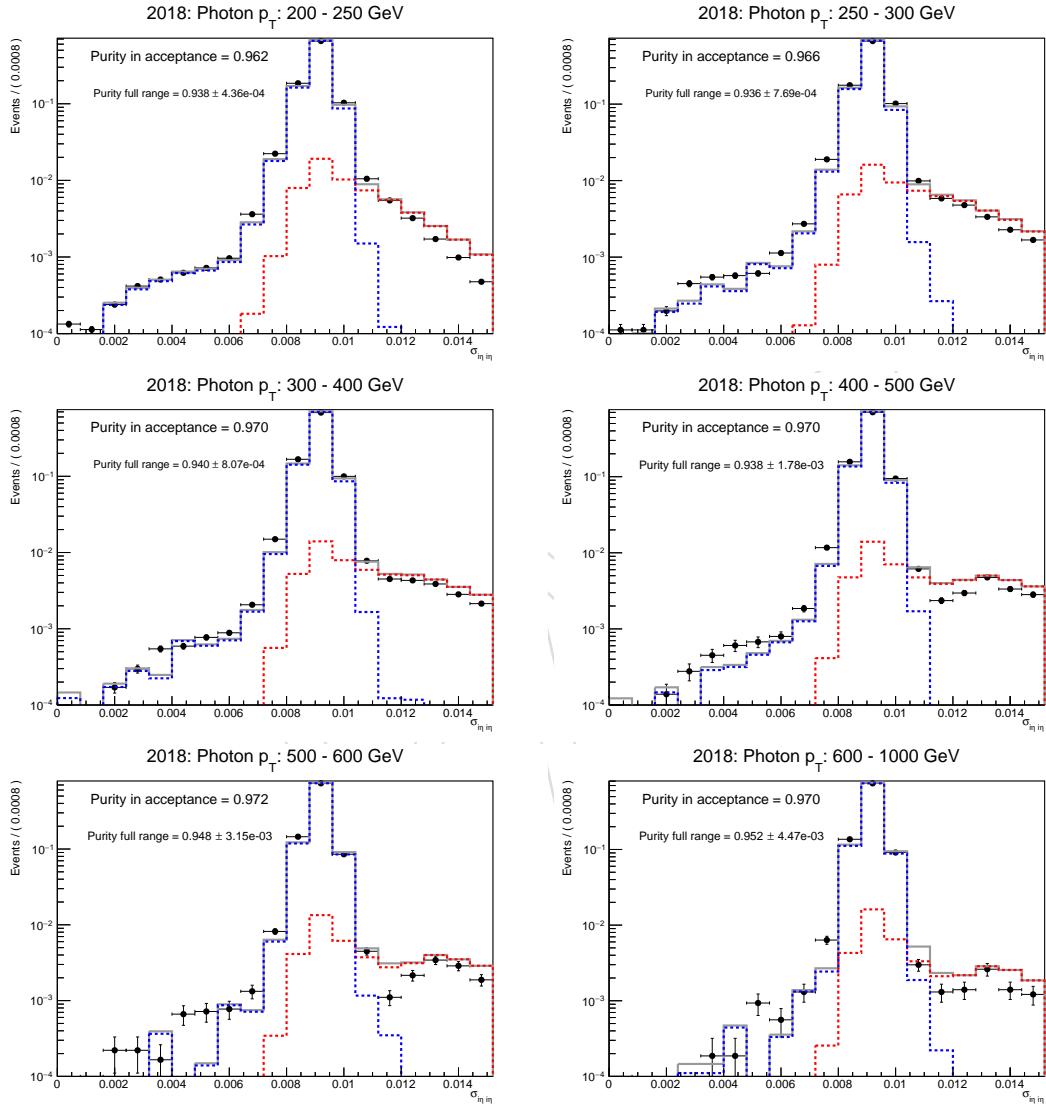


Figure 7: Template fits used to determine the photon purity in the 2018 dataset. The fits are shown in bins of photon p_T , increasing from left to right and top to bottom.

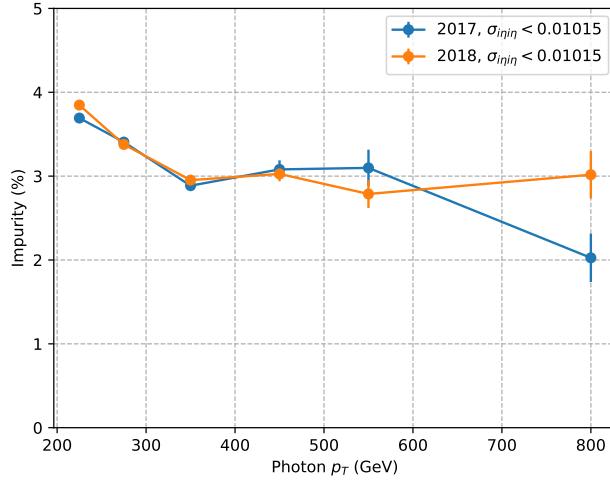


Figure 8: Photon purity as a function of photon p_T . This figure shows the aggregated results obtained from the fits shown in Figs. 6 and 7.

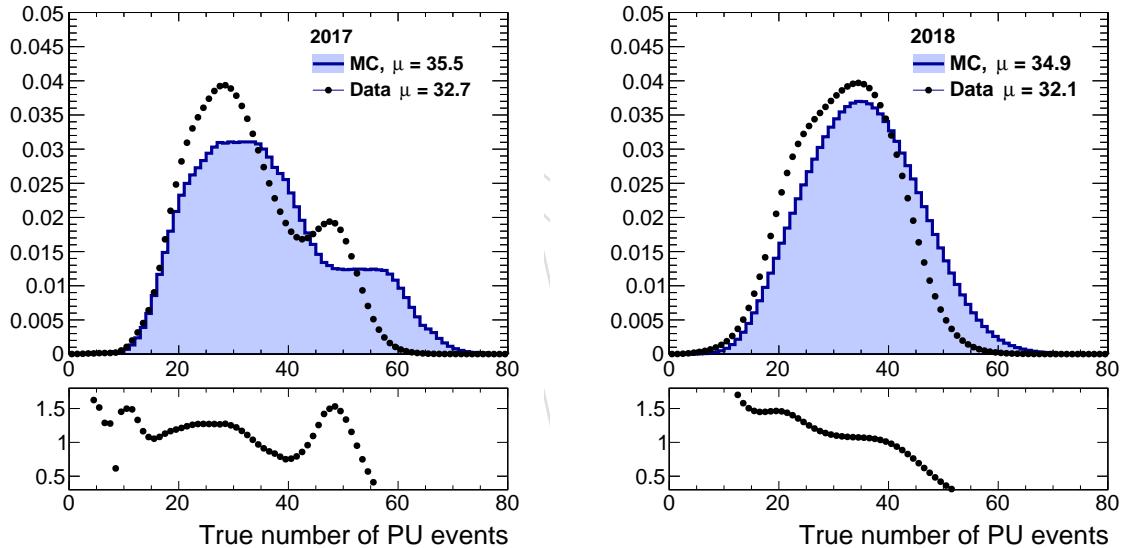


Figure 9: Distribution of the true number of PU events in data and simulation for 2017 (left) and 2018 (right). The distributions for data are extracted assuming a minimum bias cross section of 69.2 mb.

365 5.3 Lepton and photon identification/reconstruction efficiency reweighting

366 Data-to-simulation scale factors are applied to events in the control regions to account for dif-
 367 ferences in the reconstruction, identification and isolation of leptons between data and simu-
 368 lationn. These data-to-MC scale factors are derived from the efficiencies that are measured for
 369 the electron and muon selections in bins of p_T and η in both data and simulation. These scale
 370 factors are provided by the relevant POGs.

371 The reconstruction scale factors for electrons are shown in Fig. 12. The corresponding identifi-
 372 cation scale factors for veto and tight electrons are shown in Fig. 13, and include the effect of
 373 the isolation efficiency.

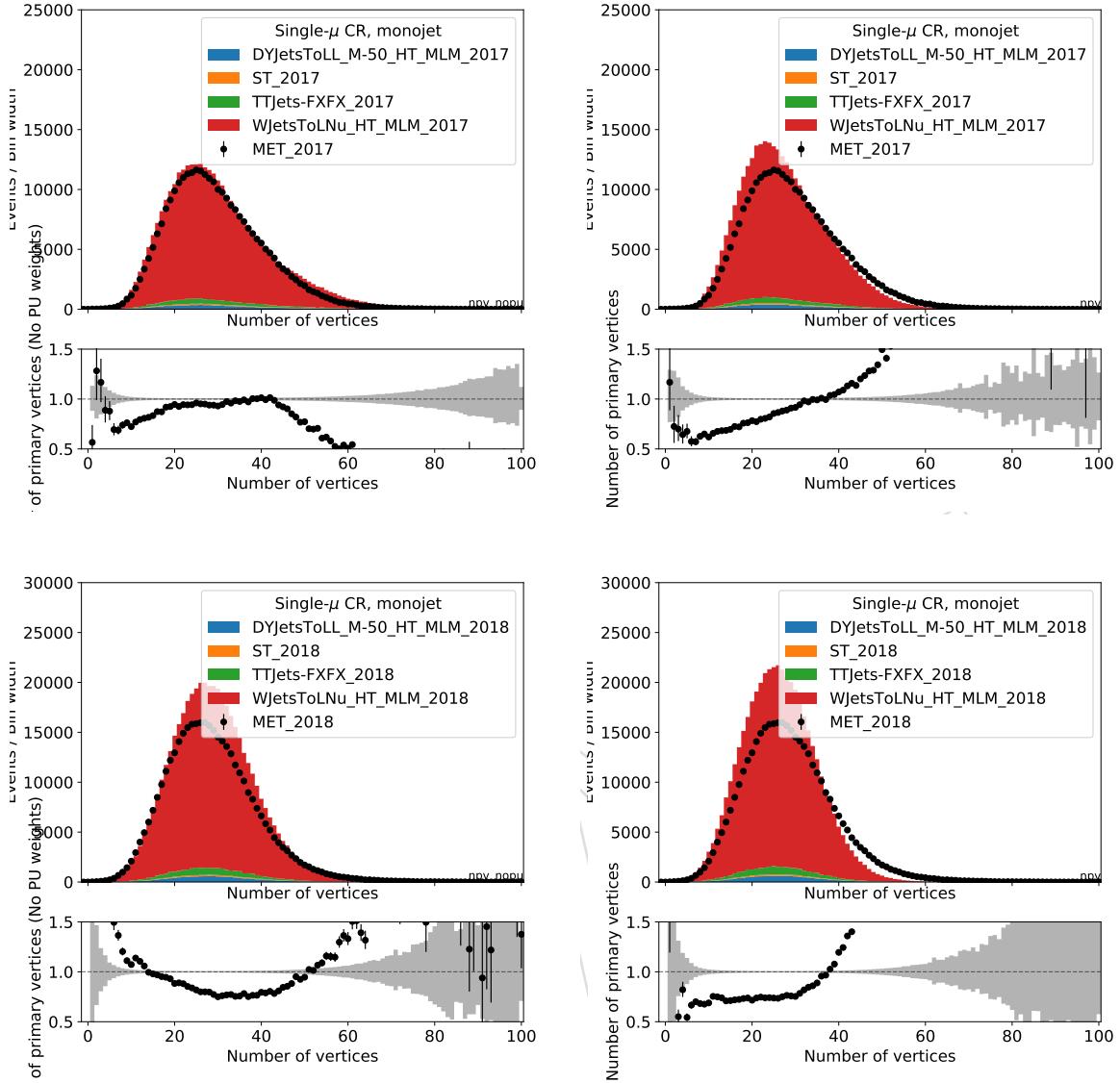


Figure 10: Distribution of the number of vertices in $W \rightarrow \mu\nu$ events in data and simulation before pileup re-weighting (left) and after pileup reweighting (right). The Monte Carlo is normalized to the luminosity of 41.53 and 59.7 fb^{-1} , respectively for 2017 and 2018.

374 The identification scale factors for muons are shown in Fig. 14. Here, isolation scale factors
 375 are applied separately and are shown in Fig. ???. The corresponding corrections for muons are
 376 deemed negligible [24].

377 The scale factors for id and isolation for tight muons are shown in Fig. ??.

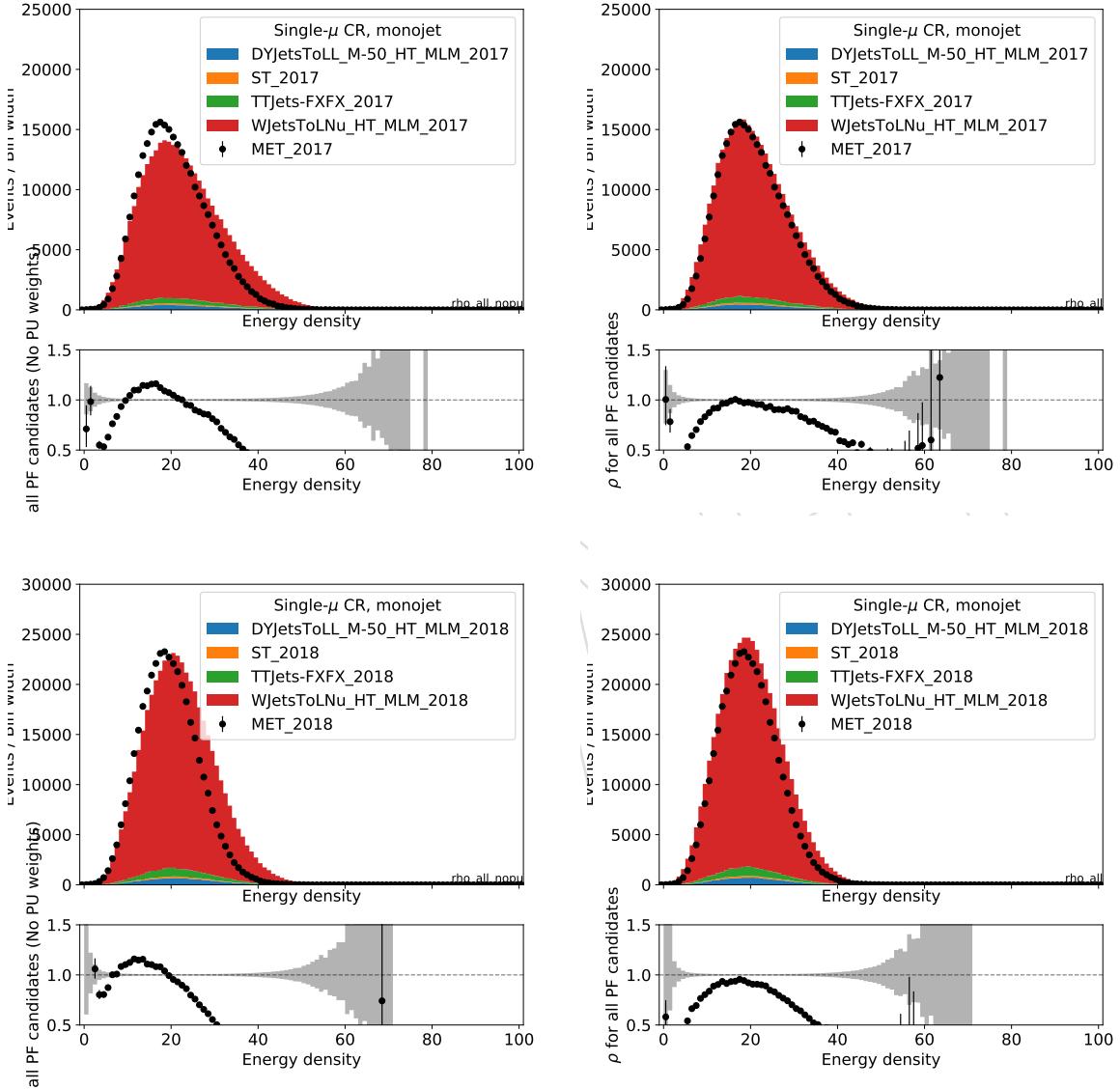


Figure 11: Distribution of the event energy density ρ in $W \rightarrow \mu\nu$ events in data and simulation before pileup re-weighting (left) and after pileup reweighting (right). The Monte Carlo is normalized to the luminosity of 41.53 and 59.7 fb^{-1} , respectively for 2017 and 2018.

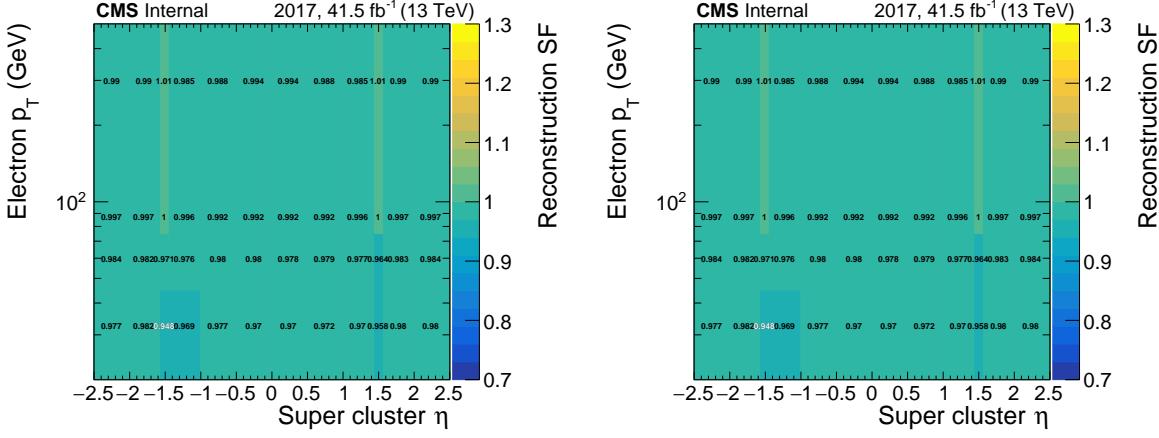


Figure 12: Scale factors for the reconstruction efficiency of electrons starting from a super cluster for 2017 (left) and 2018(right)

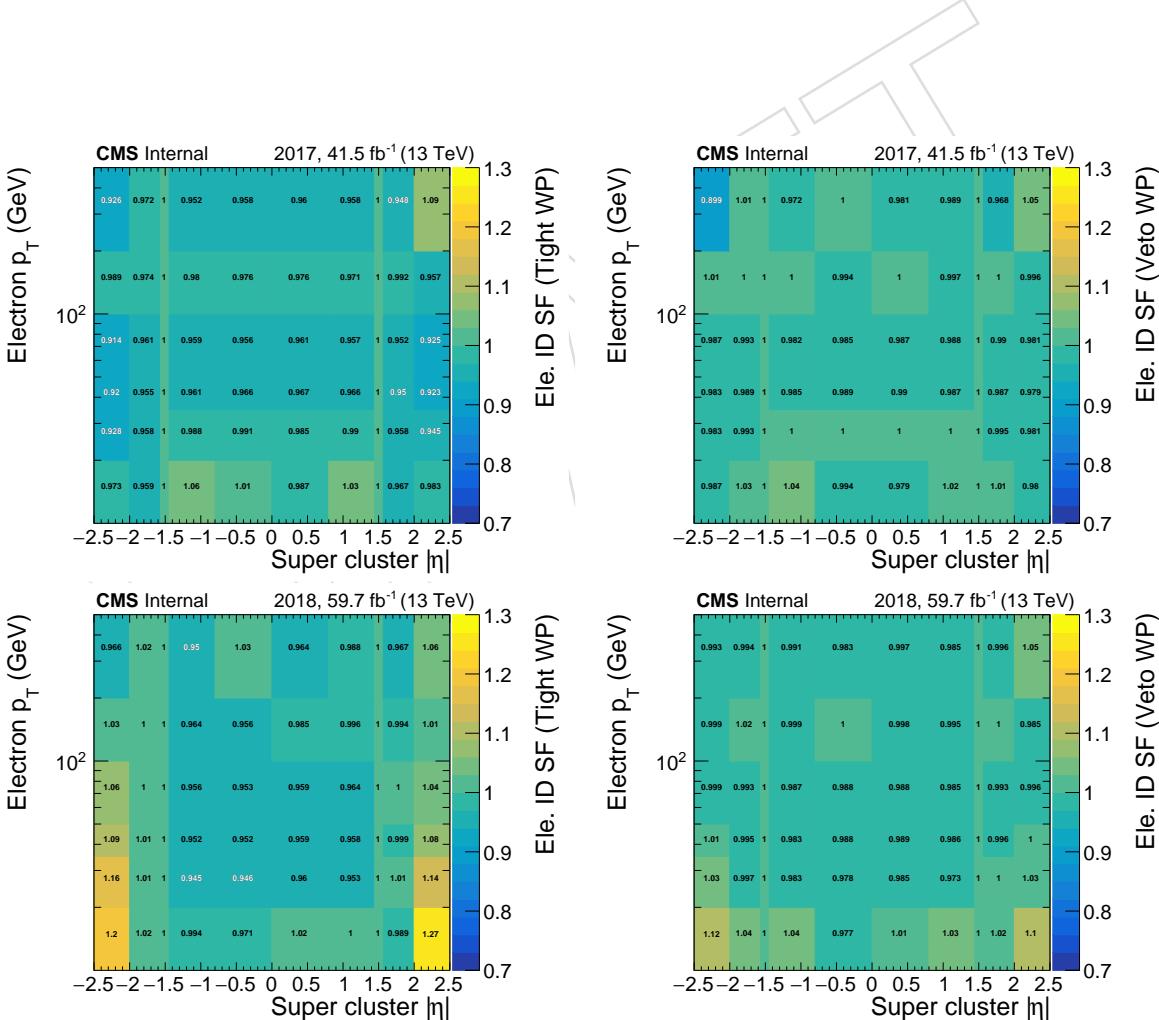


Figure 13: Scale factors for tight (left) and veto (right) electrons are shown for 2017 (top) and 2018 (bottom). The scale factors are provided in bins of electron p_T and η .

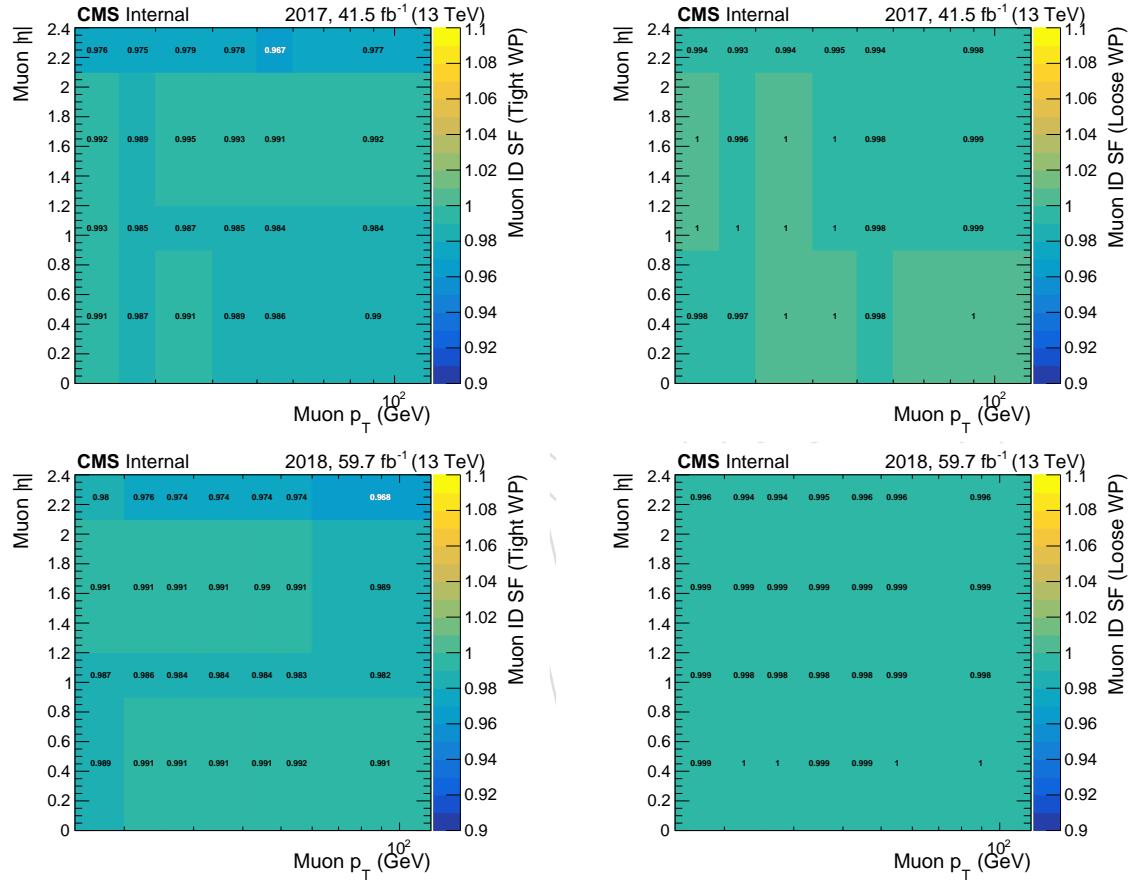


Figure 14: Scale factors for tight (left) and veto (right) muon identification are shown for 2017 (top) and 2018 (bottom). The scale factors are provided in bins of electron p_T and η .

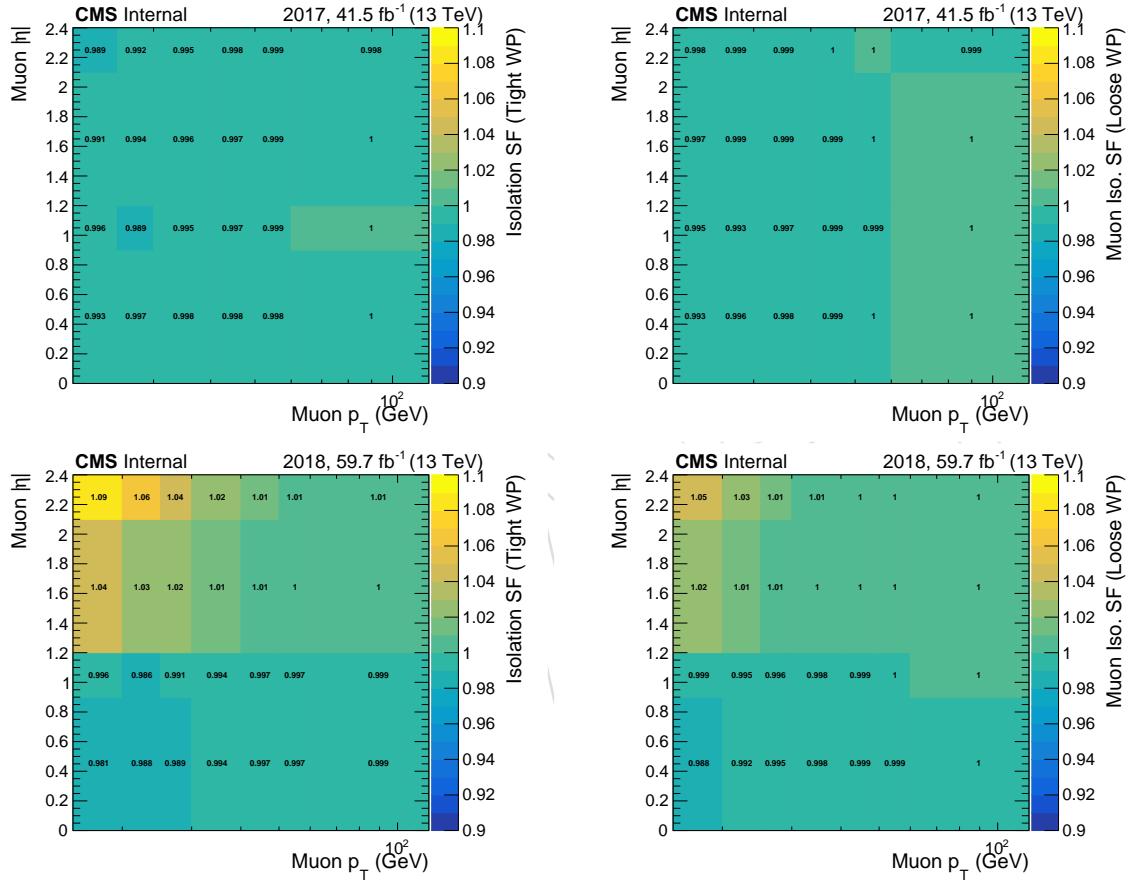


Figure 15: Scale factors for tight (left) and veto (right) muon isolation are shown for 2017 (top) and 2018 (bottom). The scale factors are provided in bins of electron p_T and η .

378 5.4 Higher-order reweighting

379 This analysis uses the ratios of the recoil distributions in signal and control regions to con-
 380 strain the final background estimate in a partially data driven way. As signal and control re-
 381 gions both have large statistical power, precise predictions of these ratios are necessary. To
 382 achieve this goal, the LO simulation samples for the samples W, DY and photon backgrounds
 383 are reweighted using higher-order corrections separately corresponding to NLO QCD, NLO
 384 EW and NNLO QCD terms. The individual corrections are described in more detail in this
 385 section. A concise overview of which corrections are applied to which processes is given in
 386 Tab. 10.

Table 10: Summary of higher-order corrections applied to simulated samples. For each boson production process, separate samples and corrections are available for the EWK and QCD production modes. “MC order” reflects the perturbative order used in the generation of the simulation sample, while the further columns represent corrections applied on a per-event level in the analysis process.

Boson	production mode	MC order	NLO QCD	NNLO QCD	NLO EWK
Z	QCD	LO	✓	✓	✓
	EWK	LO	✓	–	–
W	QCD	LO	✓	✓	✓
	EWK	LO	✓	–	–
γ	QCD	LO	✓	✓	✓
	EWK	LO	–	–	–

387 5.4.1 Generator-level boson construction

388 All theory-based corrections of the W, DY and photon backgrounds are parametrized as a func-
 389 tion of the generator-level p_T of the respective boson $p_{T,V}$. For each simulated event, this quan-
 390 tity is calculated as follows. For DY and W samples, generator-level dilepton candidates are
 391 built from:

- 392 1. “dressed” final-state electrons and muons. Lepton dressing means to collect all photons
 393 radiated off the lepton within a cone of $\Delta R < 0.1$ and adding their four-momenta back
 394 to the lepton four-momentum. This procedure is meant to undo the effect of final state
 395 photon radiation, which would otherwise distort the value of the reconstructed boson
 396 four-momentum. This effect is especially relevant as electrons and muons follow differ-
 397 ent radiation patterns. Lepton dressing is performed in central NanoAOD production
 398 following the procedure used in the RIVET software.
- 399 2. τ leptons with generator status 2. As τ leptons are unstable, they are not present as final
 400 state particles (status 1) in the generator record. The τ lepton before its decay has status
 401 2.
- 402 3. neutrinos with generator status 1.

- 403 The dilepton candidates are checked for flavour consistency with the desired boson candidate.
 404 If multiple candidates are found in an event, the one with the highest invariant mass is used.
 405 For photon events, the generator photon with highest p_T and status 1 is used.

406 **5.4.2 QCD NLO corrections to QCD V processes**

407 Scale factors corresponding to NLO QCD corrections for W and Z production are obtained
 408 from central CMS. For the DY and W processes, samples from “Fall17” campaign, while “Sum-
 409 mer16” samples are used for the γ +jets process. In both cases, all samples are generated using
 410 `MadGraph5_amc@NLO`. The LO samples are binned in HT and are equivalent to the ones used
 411 in the analysis, and are generated with up to four partons in the matrix element. The NLO
 412 samples are generated with up to two additional partons in the matrix element calculation.
 413 Further jet multiplicities are handled by the parton shower, which in both cases is performed
 414 using `Pythia8` with tune CP5.

415 The scale factors are derived by obtaining the distribution of interest at the generator-level in
 416 both samples, normalizing the distributions to their respective cross sections, and then divid-
 417 ing them as $SF = NLO / LO$. Identical selection criteria are applied to both samples based on
 418 the generator-level boson and generator-level AK4 jets, which are clustered using all visible
 419 generator particles with status 1. The requirements are:

- 420 1. At least two generator-level jets, with the leading (trailing) p_T of at least 80 GeV (40 GeV)
 421 and $|\eta| < 4.7$.
- 422 2. The two leading jets must be in opposite hemispheres of the detector, $\eta_1 \times \eta_2 < 0$.
- 423 3. The difference in the azimuthal angle ($\Delta\phi$) between the boson and the four leading jets in
 424 the event is required to be larger than 0.5. Only jets with $p_T > 30$ GeV are considered.

425 Compared to an inclusive derivation of the SF, the inclusion of the selection criteria leads to an
 426 increase in the value of the SF of about 10 – 12%.

427 The scale factors are derived either as a one-dimensional function of the generator-level boson
 428 $p_{T,V}$ (“1D”) or two-dimensionally in $p_{T,V}$ and M_{jj} (“2D”).

The 1D SFs are shown in Fig. 16. To protect the outcome of the reweighting procedure from
 binning effects, the binned scale factor is interpolated using a falling exponential function:

$$SF = a \times \exp(-b \times p_T) + c, \quad (3)$$

429 where p_T is the boson transverse momentum and a , b and c are determined by a fit to the scale
 430 factor histogram. The resulting values of the fit parameters, as well as the resulting interpolated
 431 shape are also shown in Fig. 16.

432 The 2D versions of the SFs are only derived for the W and DY processes, for which the available
 433 simulation samples are bigger and thus allow for finer binning. The scale factors are shown in
 434 Fig. 17.

435 **5.4.3 QCD NNLO corrections to QCD V processes**

436 NNLO corrections are obtained from the fixed-order calculations results in [25]. They are
 437 parametrized as a function of the generator-level boson p_T . The correction is shown in Fig. 18.

438 **5.4.4 EW NLO corrections to QCD V processes**

439 Scale factors corresponding to NLO EW corrections are obtained from Ref. [25] and applied as
 440 a function of the generator-level boson p_T . The scale factors are shown in Fig. 19.

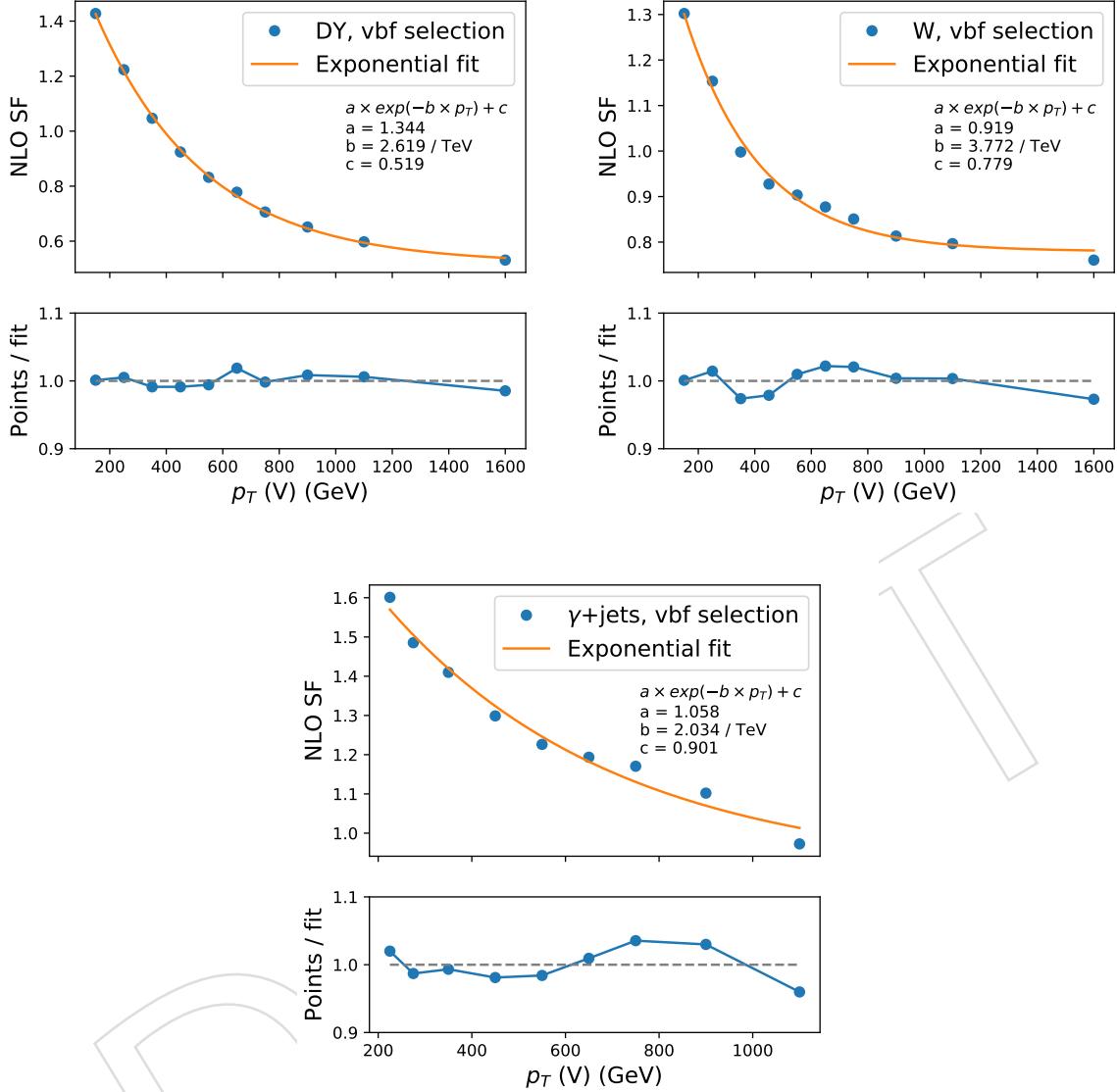


Figure 16: QCD NLO scale factors for the DY (top left), W (top right) and γ +jets processes. The k factors are derived within the generator-level VBF selection described in the text. In the top panel of each plot, the blue markers show the NLO SF derived from the simulated samples. The orange line shows a fit function used to interpolate the SF. The functional form and resulting parameters are given in the figure. In the bottom panel, the blue markers show the ratio of the histogram to the fit result in each bin.

5.4.5 QCD NLO corrections to EWK V processes

The QCD NLO corrections to EWK W and Z production have been calculated in Ref. [26] using the VBF@NLO program. They are parametrized in $p_{T,V}$ and M_{jj} and are shown in Fig. 20.

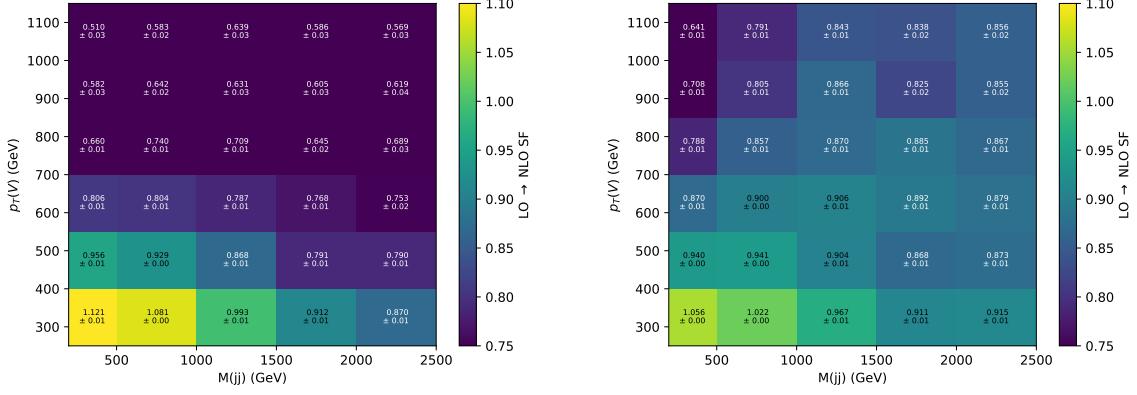


Figure 17: Same as Fig. 16, but now binned in two dimensions of the generator-level boson p_T and M_{jj} . The k factors are derived within the generator-level VBF selection described in the text. The uncertainties quoted in each bin are the statistical uncertainties due to the finite size of simulated samples.

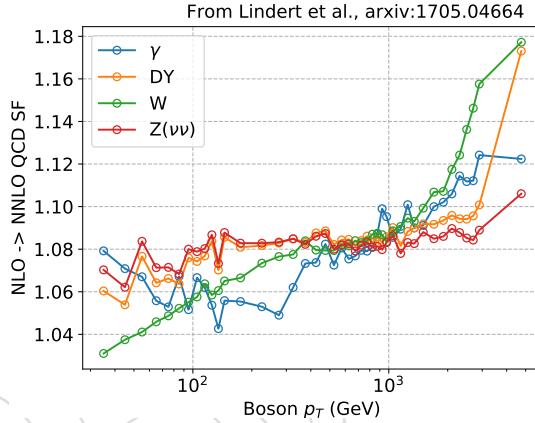


Figure 18: QCD NNLO scale factors for DY , W and photon production as a function of $p_{T,V}$.

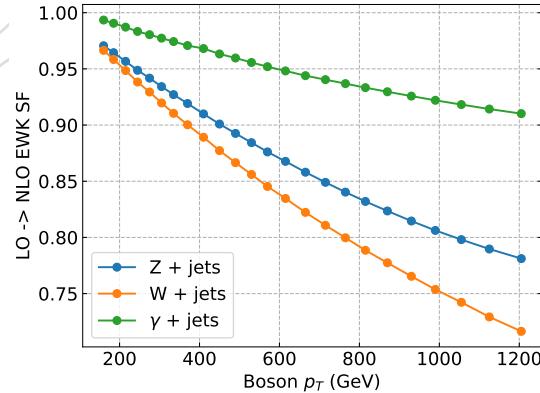


Figure 19: EW NLO scale factors for DY , W and photon production as a function of $p_{T,V}$.

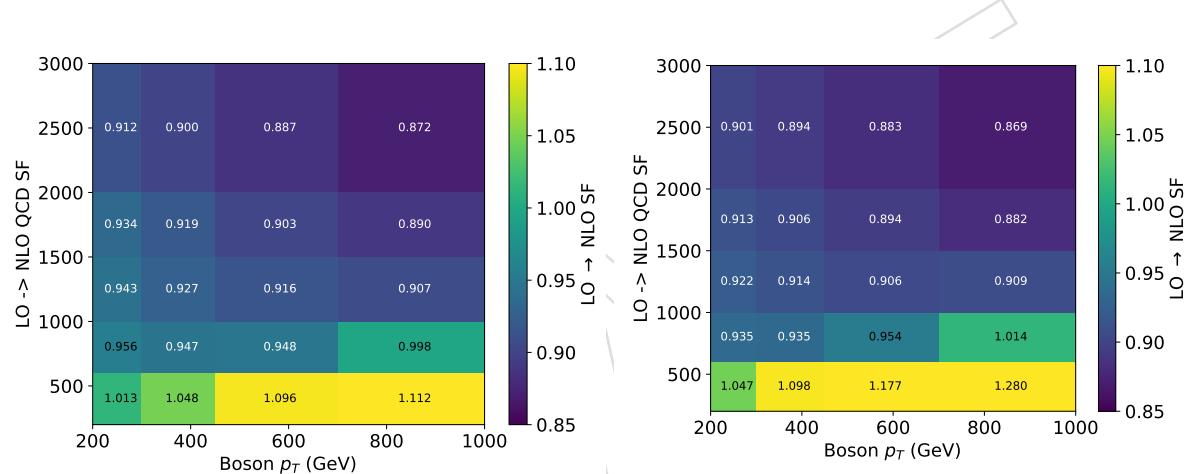


Figure 20: QCD NLO scale factors for EWK DY, W production of $p_{T,V}$ and M_{jj} .

444 6 Event selection

445 6.1 Signal region selection

446 Signal region events are selected using triggers with thresholds of 120 GeV on both $p_{\text{T},\text{trig}}^{\text{miss}}$ and
 447 $H_{\text{T},\text{trig}}^{\text{miss}}$. The $p_{\text{T},\text{trig}}^{\text{miss}}$ corresponds to the magnitude of the vector \vec{p}_{T} sum of all the PF candidates
 448 reconstructed at the trigger level, while the $H_{\text{T},\text{trig}}^{\text{miss}}$ is computed as the magnitude of the vector
 449 \vec{p}_{T} sum of jets with $p_{\text{T}} > 20$ GeV and $|\eta| < 5.0$ reconstructed at the trigger level. The energy
 450 fraction attributed to neutral hadrons in these jets is required to be smaller than 0.9. This re-
 451 quirement suppresses anomalous events with jets originating from detector noise. To be able
 452 to use the same triggers for selecting events in the muon control samples used for background
 453 prediction, muon candidates are not included in the $p_{\text{T},\text{trig}}^{\text{miss}}$ nor $H_{\text{T},\text{trig}}^{\text{miss}}$ computation. The trigger
 454 efficiency is measured to be 96% for events passing the analysis selection for $p_{\text{T}}^{\text{miss}} > 250$ GeV
 455 and becomes more than 99% efficient for events with $p_{\text{T}}^{\text{miss}} > 350$ GeV.

456 Candidate events are required to have $p_{\text{T}}^{\text{miss}} > 250$ GeV. The leading AK4 jet in the signal event
 457 is required to have $p_{\text{T}} > 80$ GeV and $|\eta| < 4.7$, and the subleading AK4 jet is required to have
 458 $p_{\text{T}} > 40$ GeV and $|\eta| < 4.7$. In addition, if the leading jet is within the tracker range, $|\eta| < 2.5$,
 459 it is required to have at least 10% of its energy coming from charged particles and less than 80
 460 % of its energy attributed to neutral hadrons, as discussed in section 4. This selection helps to
 461 remove events originating from beam-induced backgrounds. In addition, the analysis employs
 462 various event filters to reduce events with large misreconstructed $p_{\text{T}}^{\text{miss}}$ [27] originating from
 463 noncollision backgrounds.

464 For the VBF signal events, two leading jets in opposite hemispheres are expected, with large
 465 dijet mass. Furthermore, these jets are expected to have large rapidity separation and small
 466 azimuthal separation. Therefore, this analysis employs several requirements on M_{jj} , $\Delta\eta_{jj}$ and
 467 $\Delta\phi_{jj}$, which can be found in Table 11.

468 The main background processes in this search are the $Z(\nu\nu) + \text{jets}$ and $W(\ell\nu) + \text{jets}$ processes.
 469 The $Z(\nu\nu) + \text{jets}$ process is an irreducible background and constitutes the largest background
 470 in the search. In contrast, the background from $W(\ell\nu) + \text{jets}$ is suppressed by imposing a veto
 471 on events containing one or more loose muons or electrons with $p_{\text{T}} > 10$ GeV, or hadronically
 472 decaying τ leptons with $p_{\text{T}} > 18$ GeV. Events that contain a loose, isolated photon with $p_{\text{T}} >$
 473 15 GeV and $|\eta| < 2.5$ are also rejected. This helps to suppress electroweak (EW) backgrounds in
 474 which a photon is radiated from the initial state. To reduce the contamination from top quark
 475 backgrounds, events are rejected if they contain a b tagged jet with $p_{\text{T}} > 20$ GeV and $|\eta| <$
 476 2.4. These jets are identified using the DeepCSV algorithm [11, 28], adopting the “medium”
 477 working point, which corresponds to correctly identifying a jet originating from a bottom quark
 478 with a probability of 80% and misidentifying a jet originating from a charm quark (light-flavor
 479 jet) with a probability of 12 (2)%. Lastly, QCD multijet background with $E_{\text{T}}^{\text{miss}}$ arising from
 480 mismeasurements of the jet momenta is suppressed by requiring the minimum azimuthal angle
 481 between the $\vec{p}_{\text{T}}^{\text{miss}}$ direction and each of the first four leading jets with p_{T} greater than 30 GeV
 482 and $|\eta| < 2.4$ to be larger than 0.5 radians.

483 The selection requirements for this analysis are summarized in Table 11.

484 Figs. 21, 22 show the distribution of the $E_{\text{T}}^{\text{miss}}$, the number of jets, p_{T} and η distribution of the
 485 leading AK4 jet for events in the VBF signal category respectively for 2017 and 2018 datasets.

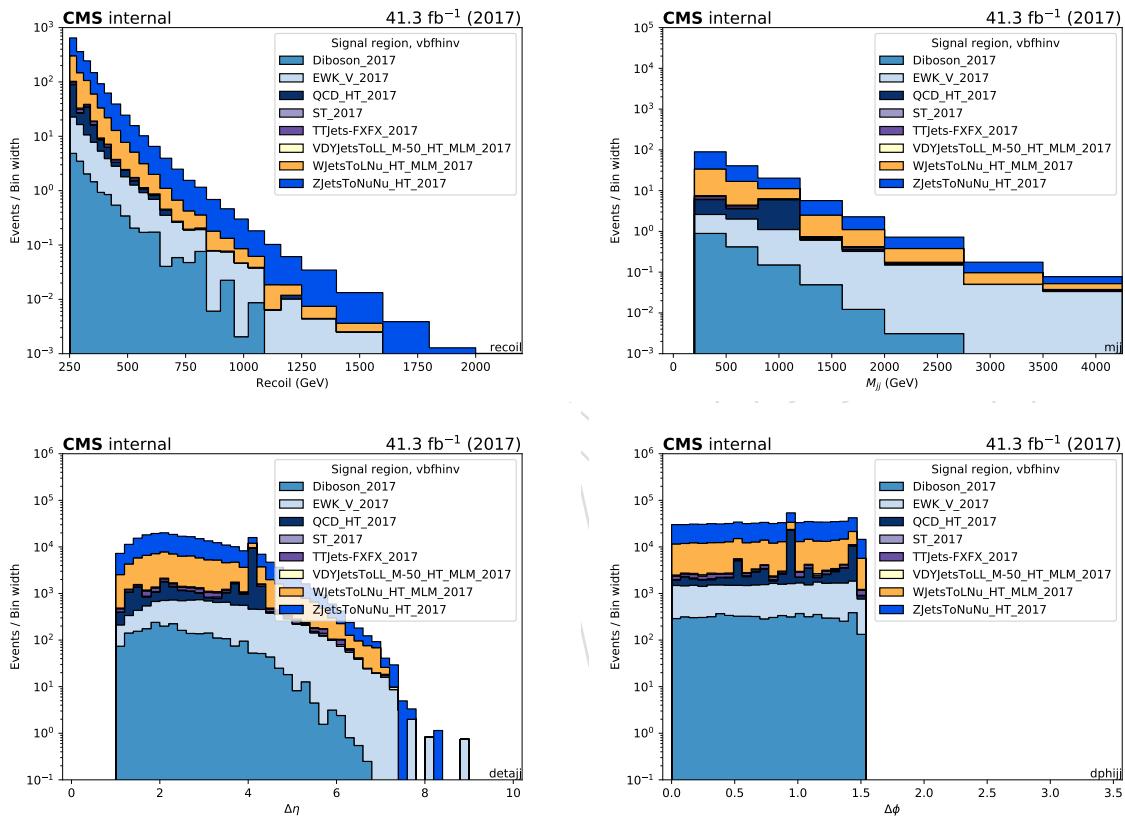


Figure 21: Recoil distribution, M_{jj} distribution, $\Delta\eta_{jj}$ and $\Delta\phi_{jj}$ distribution in the VBF signal region, using 2017 dataset.

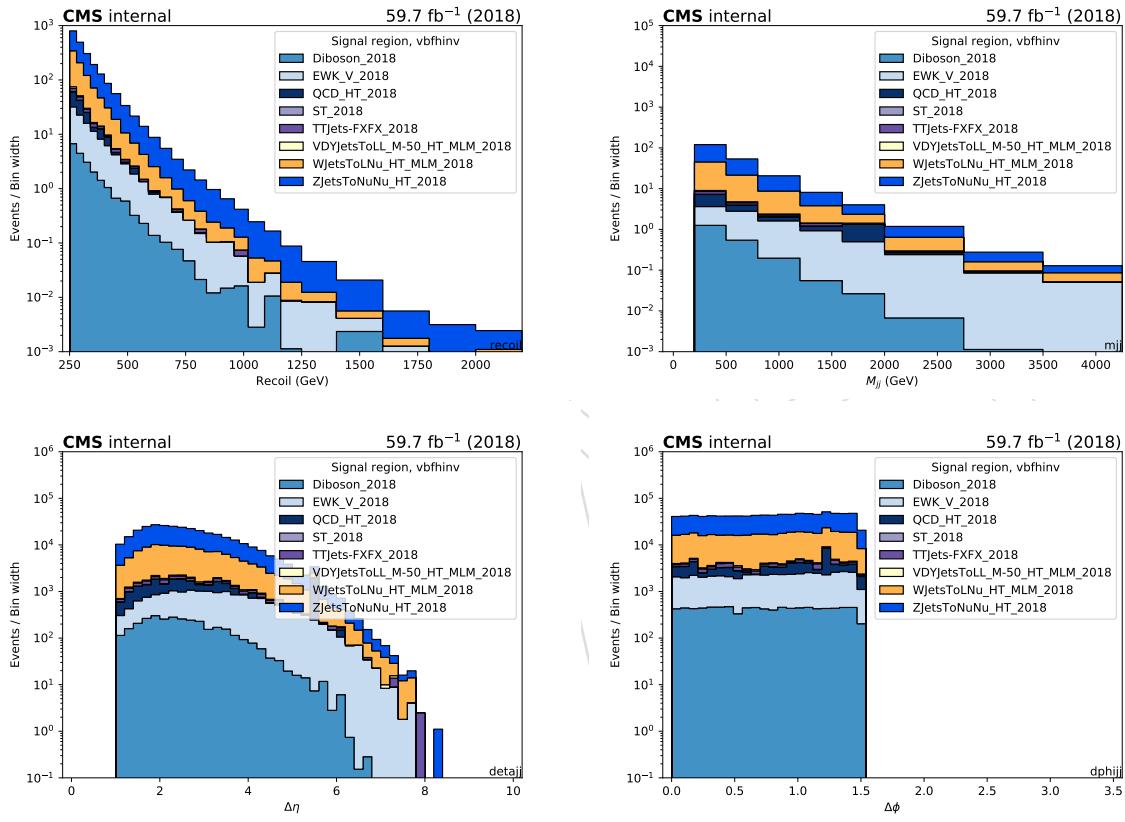


Figure 22: Recoil distribution, M_{jj} distribution, $\Delta\eta_{jj}$ and $\Delta\phi_{jj}$ distribution in the VBF signal region, using 2018 dataset.

Table 11: Summary of the common selection requirements

Variable	Selection	Target background
Muon (electron) veto	$p_T > 10 \text{ GeV}, \eta < 2.4(2.5)$	$Z(\ell\ell) + \text{jets}, W(\ell\nu) + \text{jets}$
τ lepton veto	$p_T > 18 \text{ GeV}, \eta < 2.3$	$Z(\ell\ell) + \text{jets}, W(\ell\nu) + \text{jets}$
Photon veto	$p_T > 15 \text{ GeV}, \eta < 2.5$	$\gamma + \text{jets}$
Bottom jet veto	DeepCSV medium $< 0.4941/0.4184$ (2017 / 2018) for all jets with $p_T > 20 \text{ GeV}, \eta < 2.4$	Top quark
p_T^{miss}	$> 250 \text{ GeV}$	QCD, top quark, $Z(\ell\ell) + \text{jets}$
$\Delta\phi(\vec{p}_T^{\text{jet}}, \vec{p}_T^{\text{miss}})$	$> 0.5 \text{ radians}$	QCD
Leading AK4 jet p_T and η	$> 80 \text{ GeV} \text{ and } \eta < 4.7$	All
Subleading AK4 jet p_T and η	$> 40 \text{ GeV} \text{ and } \eta < 4.7$	All
M_{jj}	$> 200 \text{ GeV}$	
$\Delta\eta_{jj}$	> 1.0	
$\Delta\phi_{jj}$	< 1.5	

486 6.2 Single muon control region selection

487 Single-muon control sample events are selected using full signal region criteria of VBF selec-
 488 tion with the exception of the muon veto. The p_T^{miss} requirement is replaced by an identical
 489 requirement on the hadronic recoil, which is defined as the sum of \vec{p}_T^{miss} and the muon \vec{p}_T , and
 490 thus corresponds to the distribution of the $W p_T$. In the single-muon control sample, exactly
 491 one tightly identified, isolated muon with $p_T > 20 \text{ GeV}$ is required. No additional loose muons
 492 or electrons with $p_T > 10 \text{ GeV}$ are allowed. In addition, the transverse mass of the muon- \vec{p}_T^{miss}
 493 system is required to be smaller than than 160 GeV. The transverse mass (M_T) is computed as
 494
$$M_T = \sqrt{2E_T^{\text{miss}} p_T^\mu (1 - \cos\Delta\phi)}$$
, where p_T^μ is the p_T of the muon, and $\Delta\phi$ is the angle between \vec{p}_T^μ
 495 and \vec{p}_T^{miss} .

496 Figs. 23 and 25 show the distributions of the recoil, M_{jj} , $\Delta\eta_{jj}$ and $\Delta\phi_{jj}$ of the two leading AK4
 497 jets for events in the single-muon control sample for the VBF category in 2017 and 2018 datasets,
 498 respectively. Figs. 24 and 26 show the distributions of the leading muon p_T and η , as well as
 499 the muon- \vec{p}_T^{miss} transverse mass, again for 2017 and 2018, respectively.

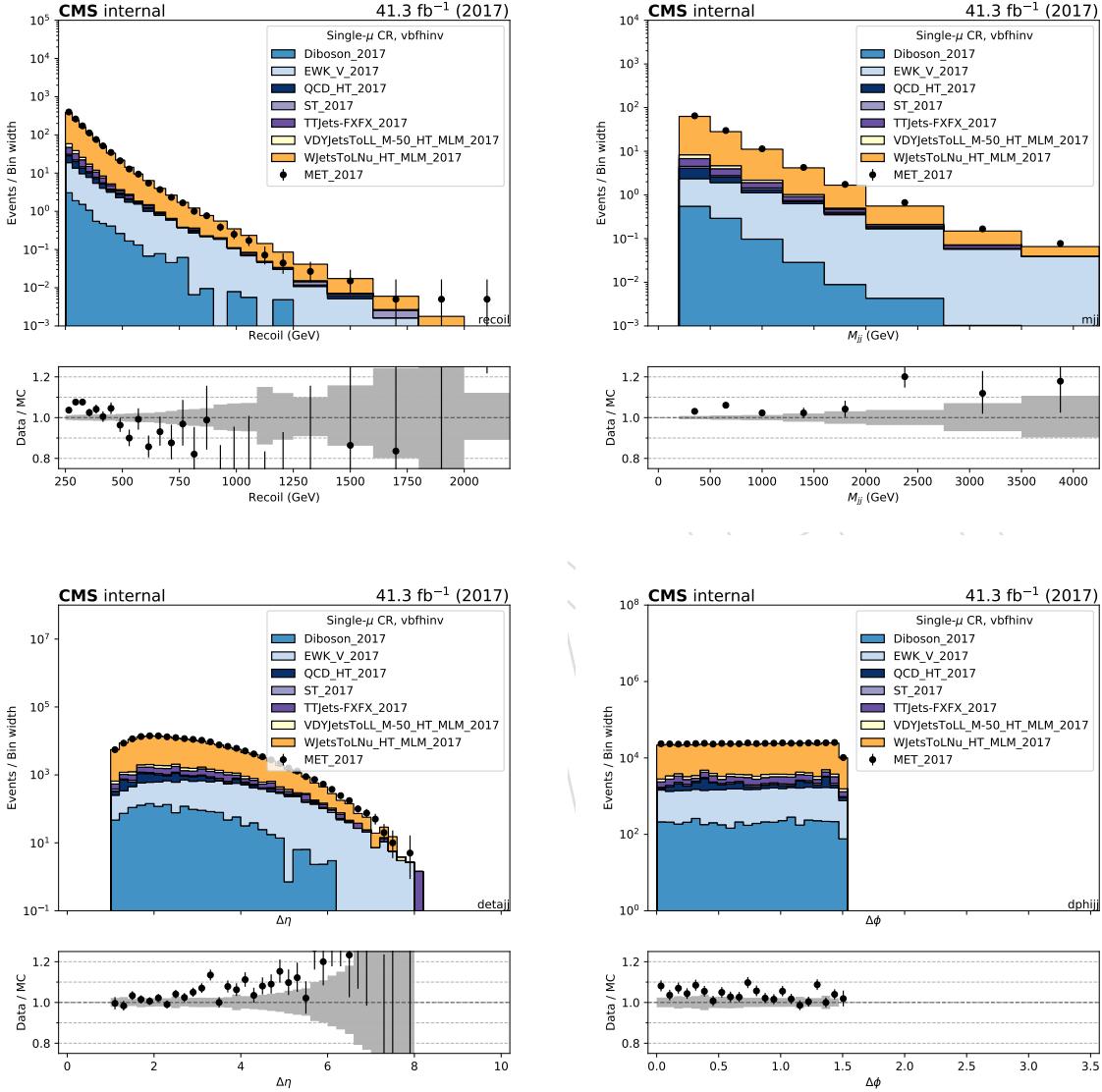


Figure 23: Comparison between 2017 data and Monte Carlo simulation in the single muon control sample for the recoil distribution, the M_{jj} distribution, $\Delta\eta_{jj}$ distribution and $\Delta\phi_{jj}$ distribution for the two leading AK4 jets with the VBF selection.

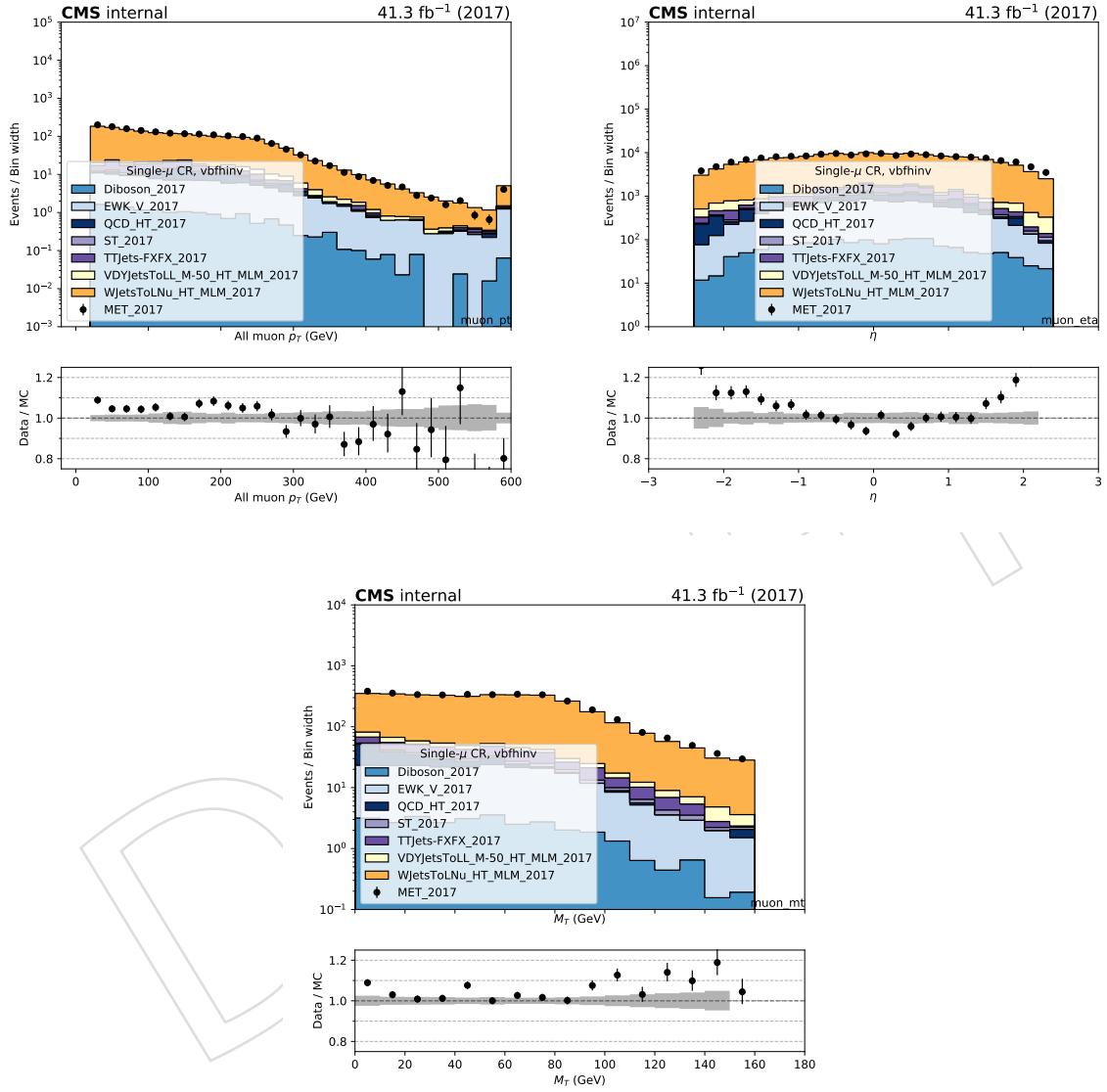


Figure 24: Comparison between 2017 data and Monte Carlo simulation in the single muon control sample for the p_T and η of the leading muon and the transverse mass distribution with the VBF selection.

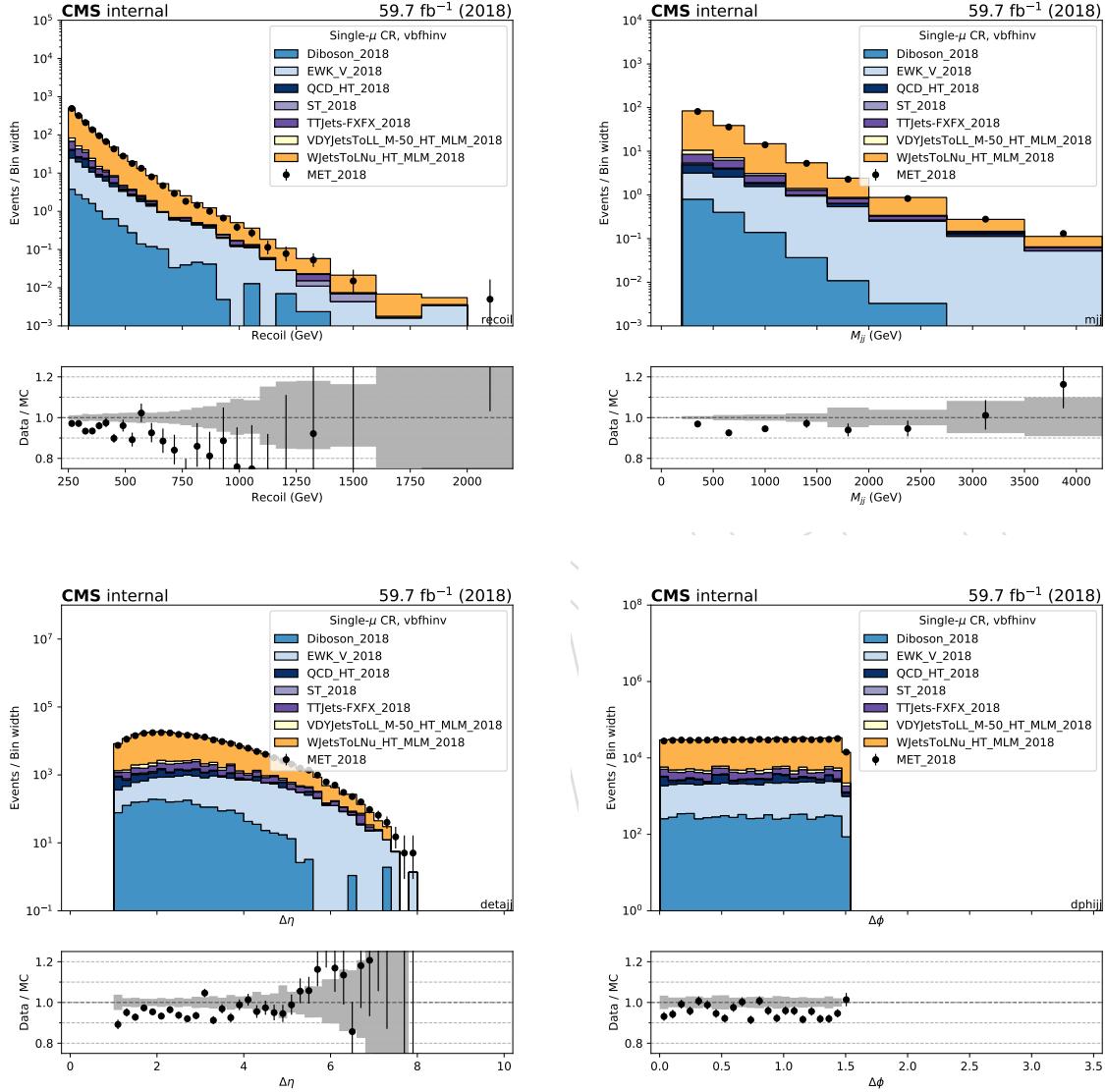


Figure 25: Comparison between 2018 data and Monte Carlo simulation in the single muon control sample for the recoil distribution, the M_{jj} distribution, $\Delta\eta_{jj}$ distribution and $\Delta\phi_{jj}$ distribution for the two leading AK4 jets with the VBF selection.

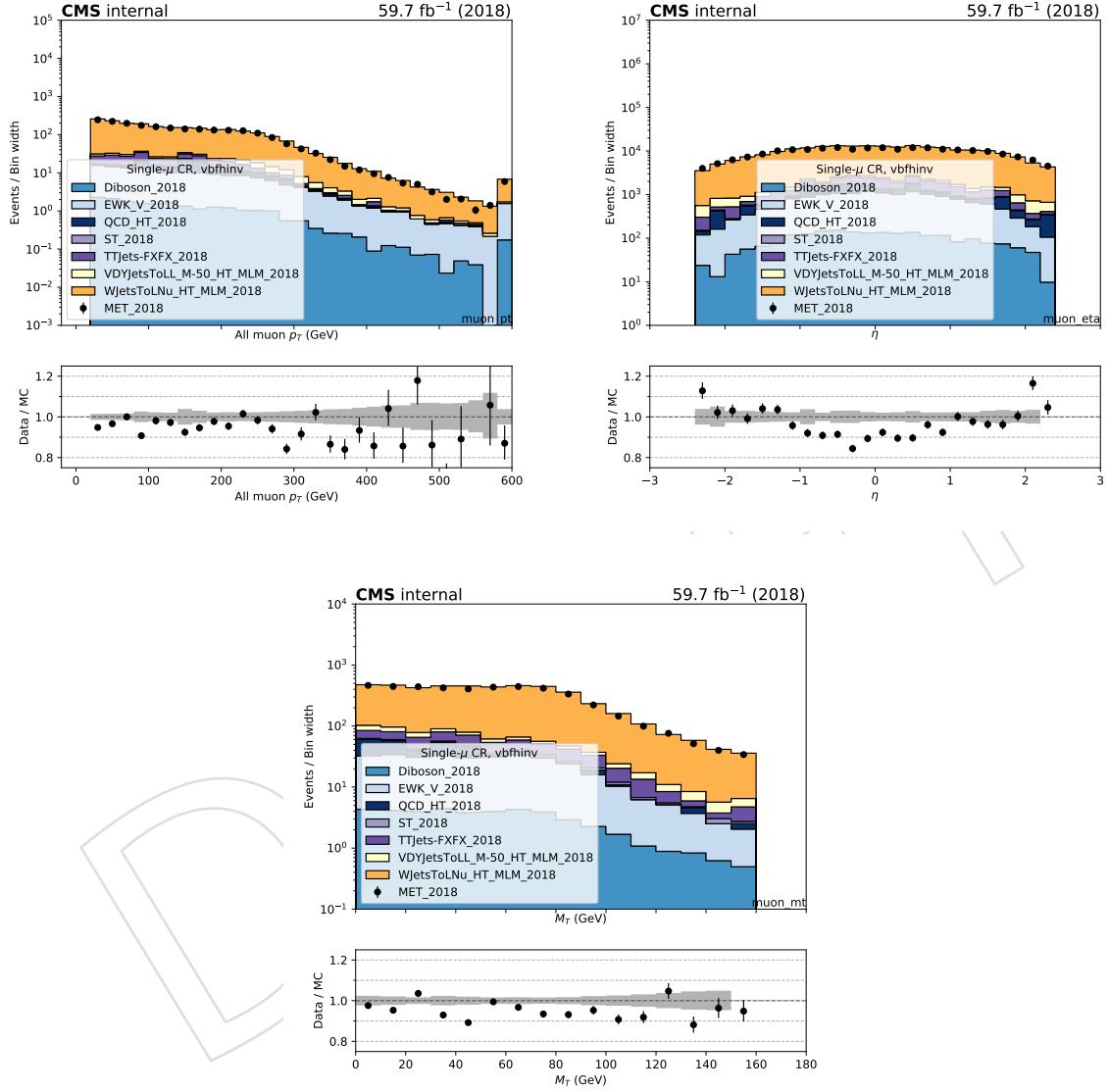


Figure 26: Comparison between 2018 data and Monte Carlo simulation in the single muon control sample for the p_T and η of the leading muon and the transverse mass distribution with the VBF selection.

500 6.3 Single electron control region selection

501 Events for the single-electron control sample are collected with the single-electron and photon
502 triggers described in Sec. 2. The p_T^{miss} requirement is replaced with an identical requirement
503 on the hadronic recoil, which is defined as the sum of \vec{p}_T^{miss} and the electron \vec{p}_T , and thus
504 corresponds to the distribution of the $W p_T$. The events in the single-electron control sample
505 are required to contain exactly one tightly identified and isolated electron with $p_T > 40$ GeV.
506 In addition, the contamination from QCD multijet events in this control sample is suppressed
507 by requiring $E_T^{\text{miss}} > 50$ GeV and $M_T < 160$ GeV.

508 Figs. 27 and 29 show the distributions of the recoil, M_{jj} , $\Delta\eta_{jj}$ and $\Delta\phi_{jj}$ of the two leading AK4
509 jets for events in the single-electron control sample for the VBF category in 2017 and 2018
510 datasets, respectively. Figs. 28 and 30 show the distributions of the leading electron p_T and
511 η , as well as the electron- p_T^{miss} transverse mass, again for 2017 and 2018, respectively.

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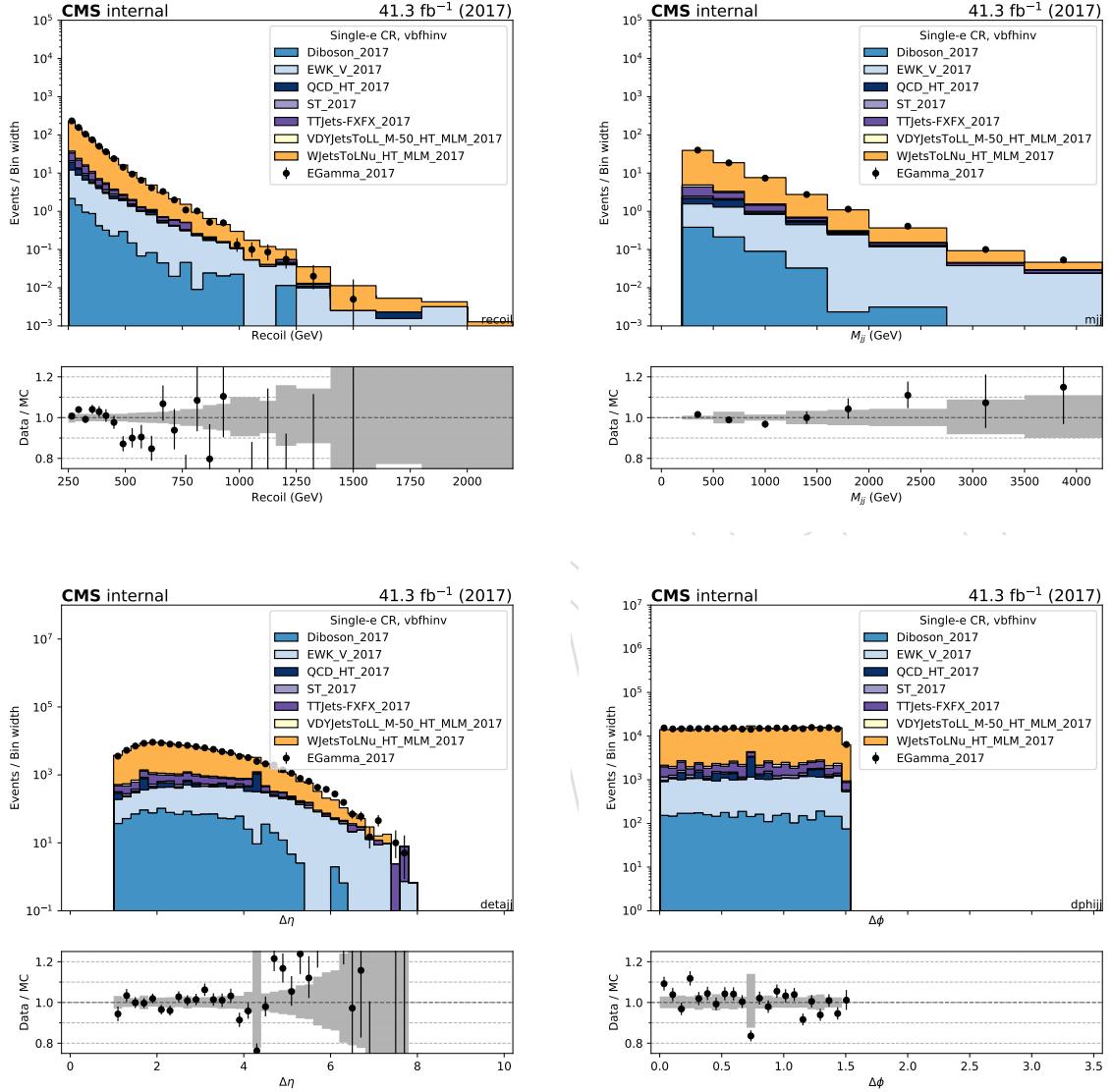


Figure 27: Comparison between 2017 data and Monte Carlo simulation in the single electron control sample for the recoil distribution, the M_{jj} distribution, $\Delta\eta_{jj}$ distribution and $\Delta\phi_{jj}$ distribution for the two leading AK4 jets with the VBF selection.

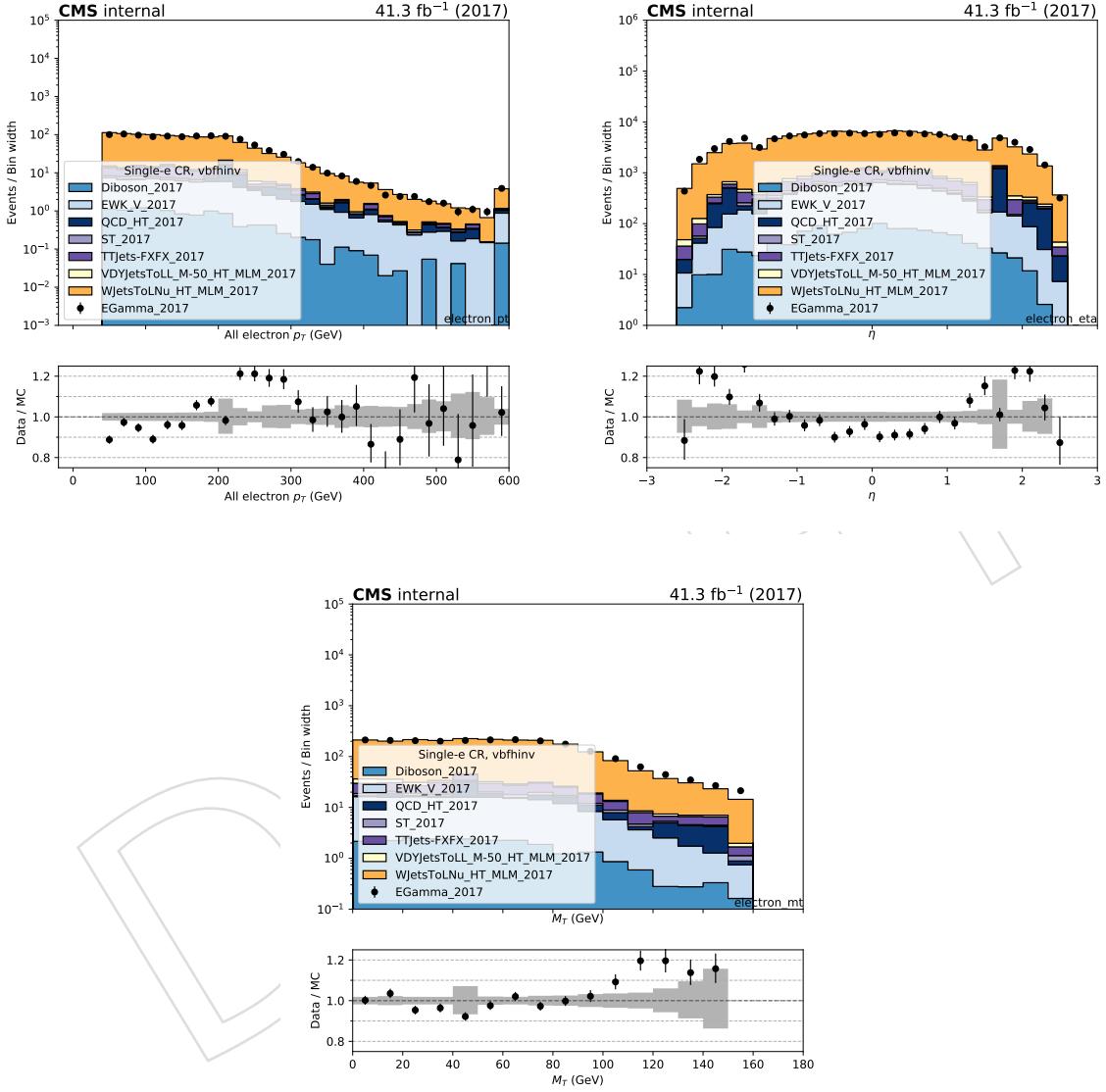


Figure 28: Comparison between 2017 data and Monte Carlo simulation in the single electron control sample for the p_T and η of the leading electron and the transverse mass distribution with the VBF selection.

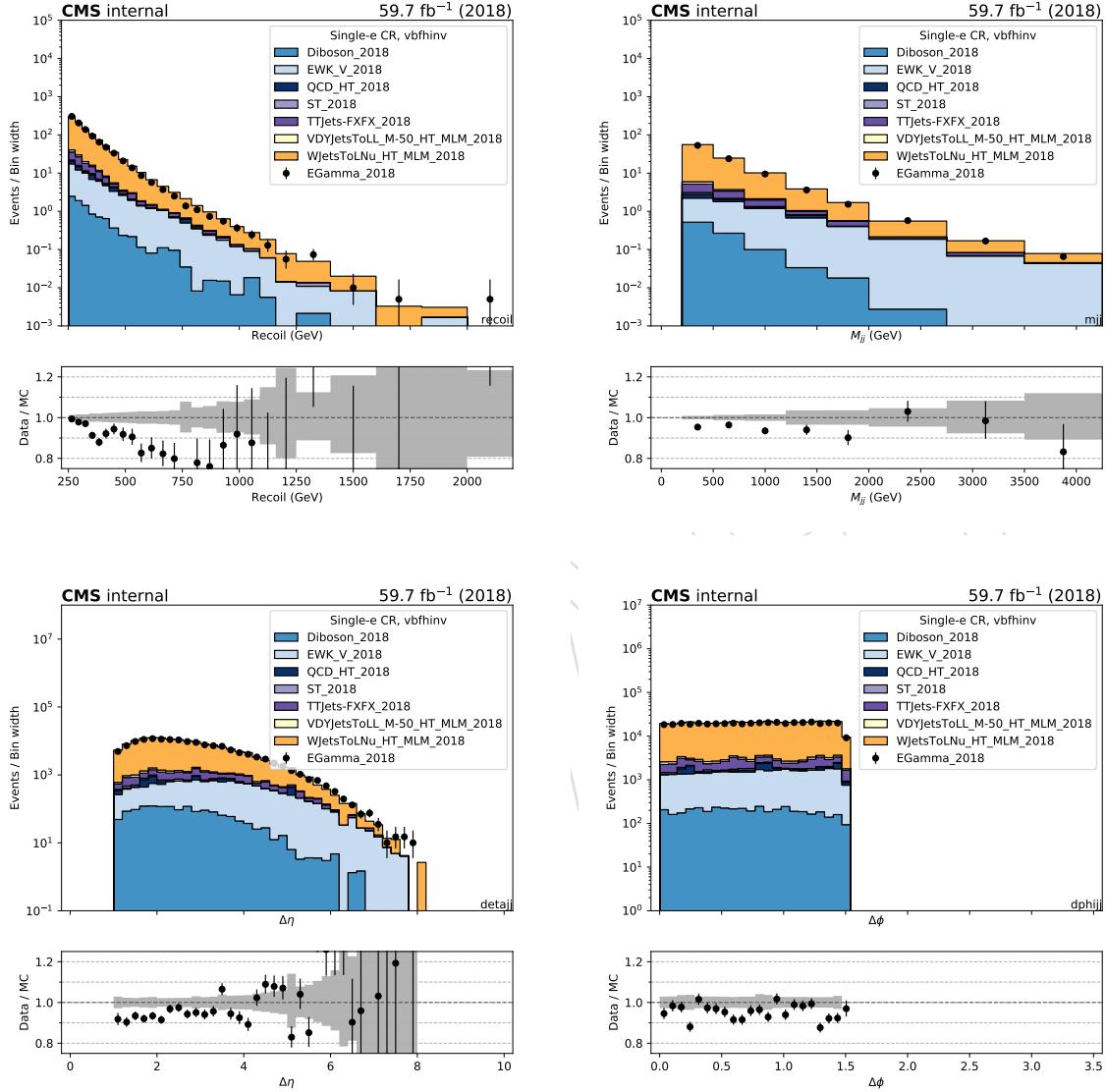


Figure 29: Comparison between 2018 data and Monte Carlo simulation in the single electron control sample for the recoil distribution, the M_{jj} distribution, $\Delta\eta_{jj}$ distribution and $\Delta\phi_{jj}$ distribution for the two leading AK4 jets with the VBF selection.

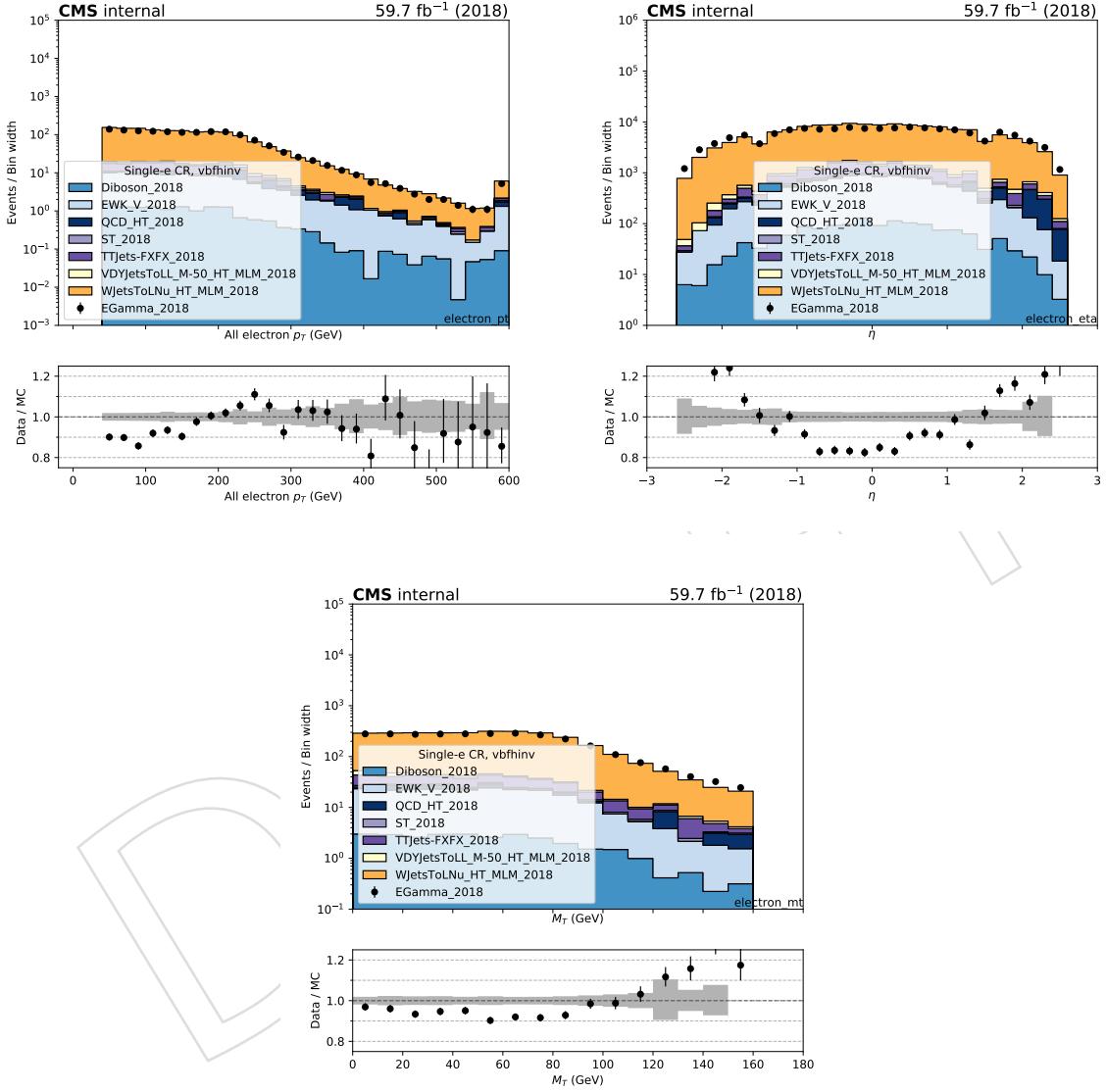


Figure 30: Comparison between 2018 data and Monte Carlo simulation in the single electron control sample for the p_T and η of the leading electron and the dilepton mass distribution with the VBF selection.

512 6.4 Double muon control region selection

513 Double-muon control sample events are selected using full signal region criteria of VBF cate-
514 gory with the exception of the muon veto. In the double-muon control sample, events are se-
515 lected requiring leading (subleading) muon p_T greater than 20 (10) GeV and an invariant mass
516 in the range 60 to 120 GeV, compatible with a Z boson decay. At least one of the two muons
517 is required to pass the tight candidate definition. Events are rejected if there is an additional
518 loose muon or electron with $p_T > 10$ GeV. The SR p_T^{miss} requirement is replacement an identical
519 requirement on the hadronic recoil, which is defined as the sum of \vec{p}_T^{miss} and the muon \vec{p}_T , and
520 thus corresponds to the distribution of the Z p_T smeared with the p_T^{miss} resolution.

521 Figs. 31 and 33 shows the distributions of the recoil, M_{jj} , $\Delta\eta_{jj}$ and $\Delta\phi_{jj}$ of the two leading
522 AK4 jets for events in the double-muon control sample for the VBF category in 2017 and 2018
523 datasets, respectively. Figs. 32 and 34 show the distributions of the leading muon p_T and η , as
524 well as the dimuon mass and p_T , again for 2017 and 2018, respectively.

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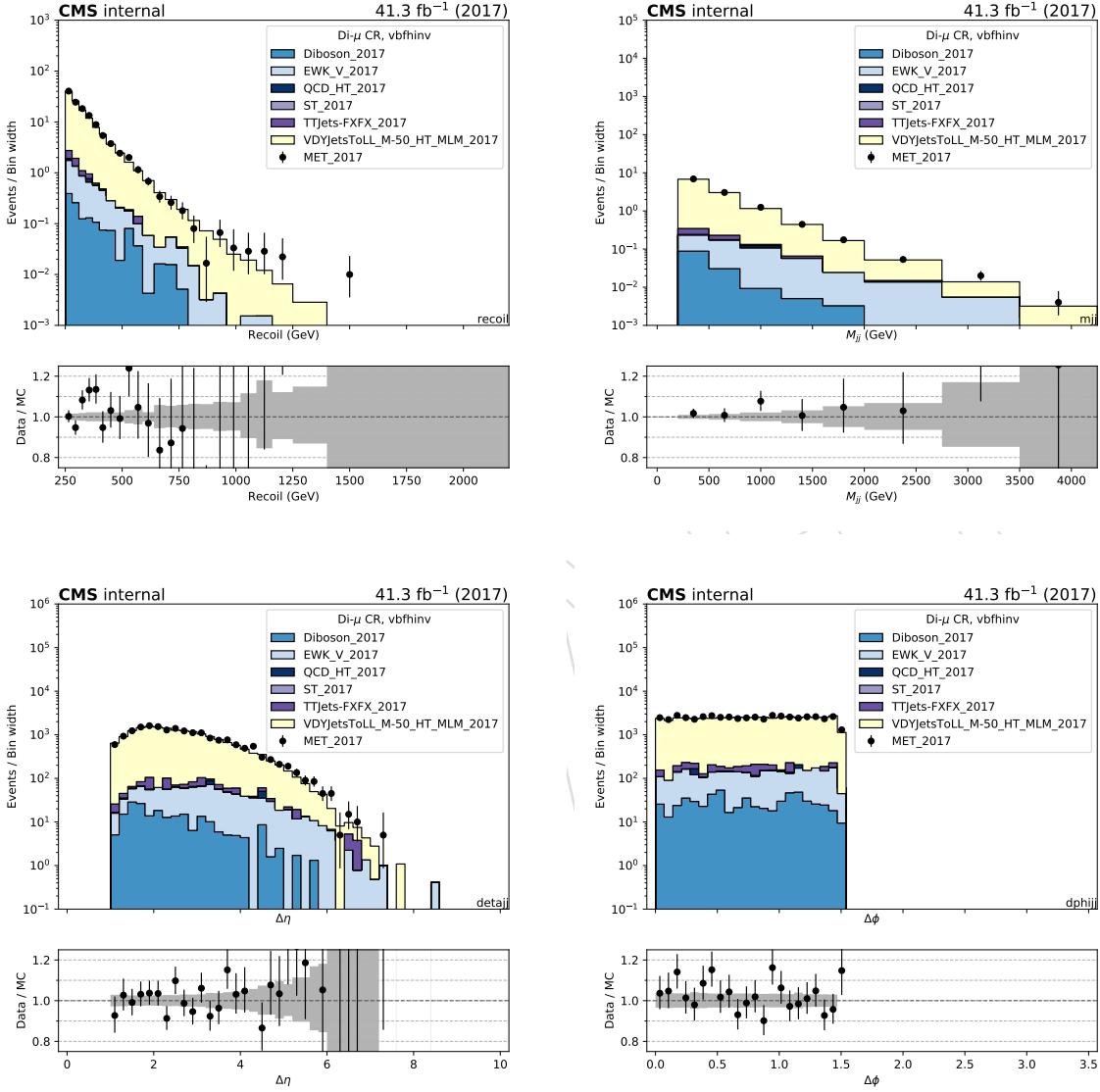


Figure 31: Comparison between 2017 data and Monte Carlo simulation in the double muon control sample for the recoil distribution, the M_{jj} distribution, $\Delta\eta_{jj}$ distribution and $\Delta\phi_{jj}$ distribution for the two leading AK4 jets with the VBF selection.

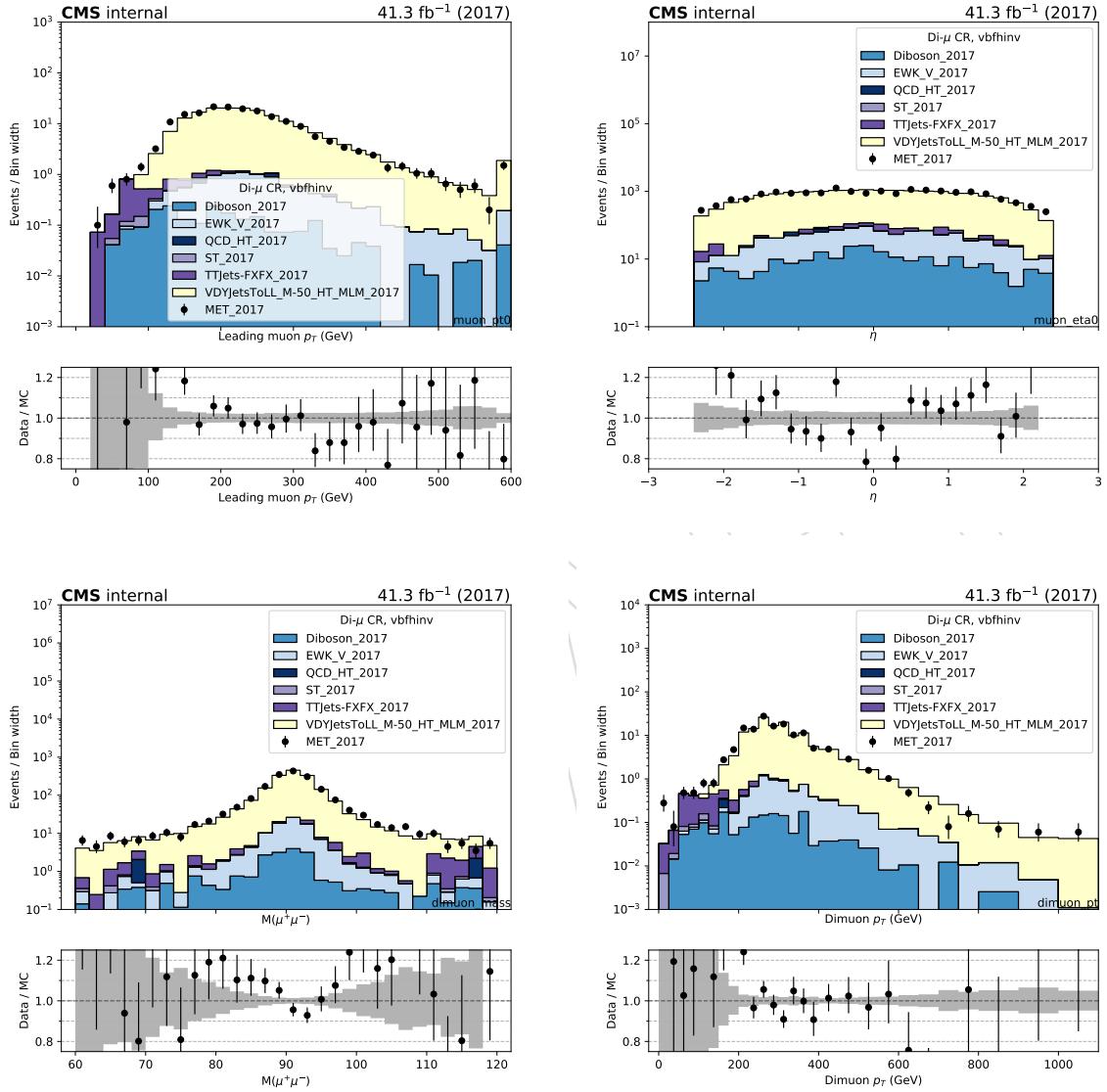


Figure 32: Comparison between 2017 data and Monte Carlo simulation in the double muon control sample for the p_T and η of the leading muon and the transverse mass and p_T of the dimuon candidate with the VBF selection.

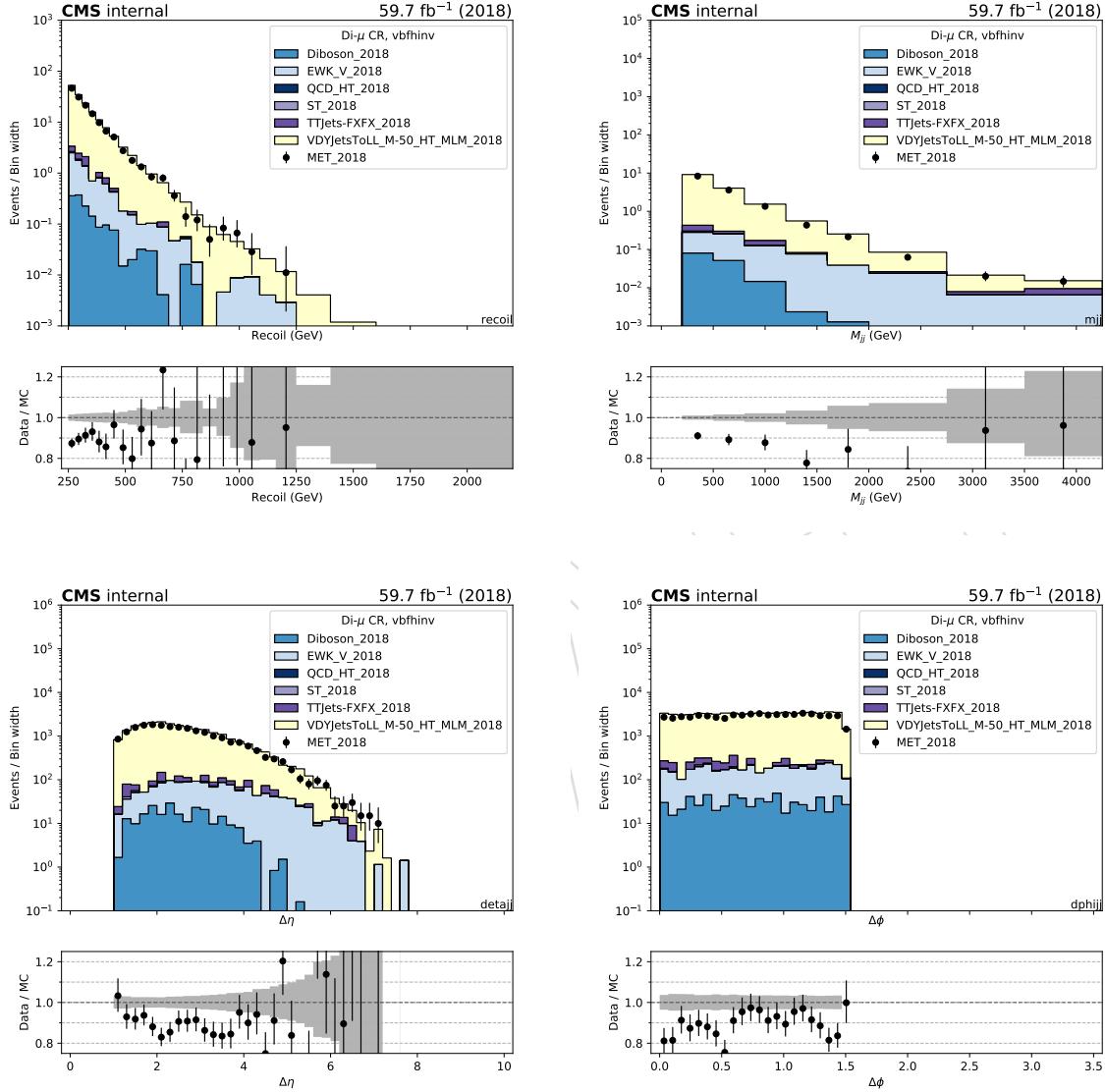


Figure 33: Comparison between 2018 data and Monte Carlo simulation in the double muon control sample for the recoil distribution, the M_{jj} distribution, $\Delta\eta_{jj}$ distribution and $\Delta\phi_{jj}$ distribution for the two leading AK4 jets with the VBF selection.

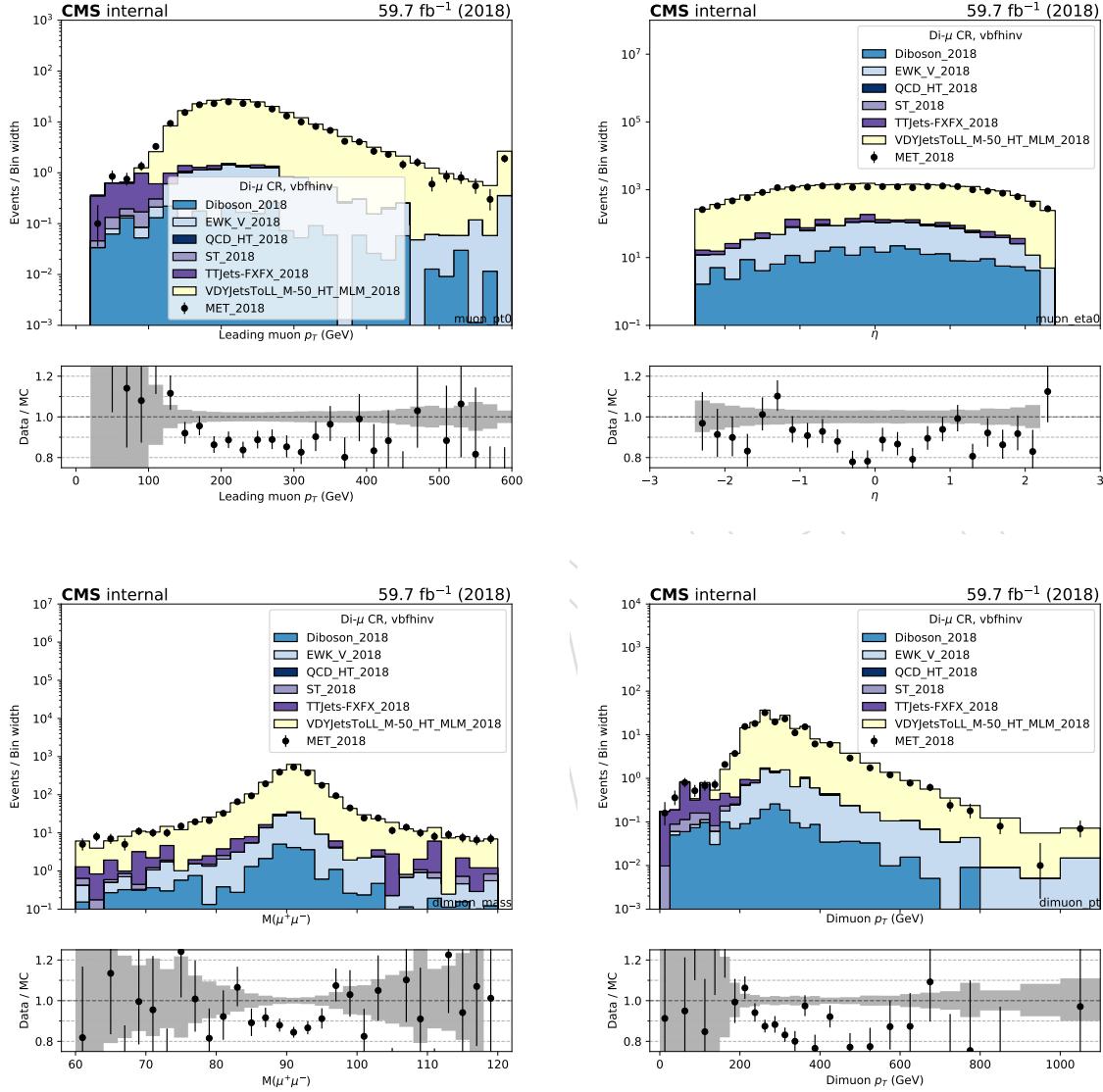


Figure 34: Comparison between 2018 data and monte carlo simulation in the double muon control sample for the p_T and η of the leading muon and the transverse mass and p_T of the dimuon candidate with the VBF selection.

525 **6.5 Double electron control region selection**

526 Events for the double-electron control sample are collected with the single-electron and photon
 527 triggers described in Sec. 2. In the offline analysis, events in the dielectron control sample are
 528 required to contain exactly two oppositely charged electrons with leading (trailing) electron p_T
 529 greater than 40 (10) GeV, with at least one of the two passing the tight candidate definition. The
 530 SR p_T^{miss} requirement is replacement an identical requirement on the hadronic recoil, which is
 531 defined as the sum of \vec{p}_T^{miss} and the muon \vec{p}_T , and thus corresponds to the distribution of the Z
 532 p_T smeared with the p_T^{miss} resolution. Similar to the dimuon control sample case, the invariant
 533 mass of the dielectron system is required to be between 60 and 120 GeV to be consistent with a
 534 Z boson decay.

535 Figs. 35 and 37 shows the distributions of the recoil, M_{jj} , $\Delta\eta_{jj}$ and $\Delta\phi_{jj}$ for the two leading
 536 AK4 jets for events in the double-electron control sample for the VBF category in 2017 and 2018
 537 datasets, respectively. Figs. 36 and 38 show the distributions of the leading electron p_T and η ,
 538 as well as the dielectron mass and p_T , again for 2017 and 2018, respectively.

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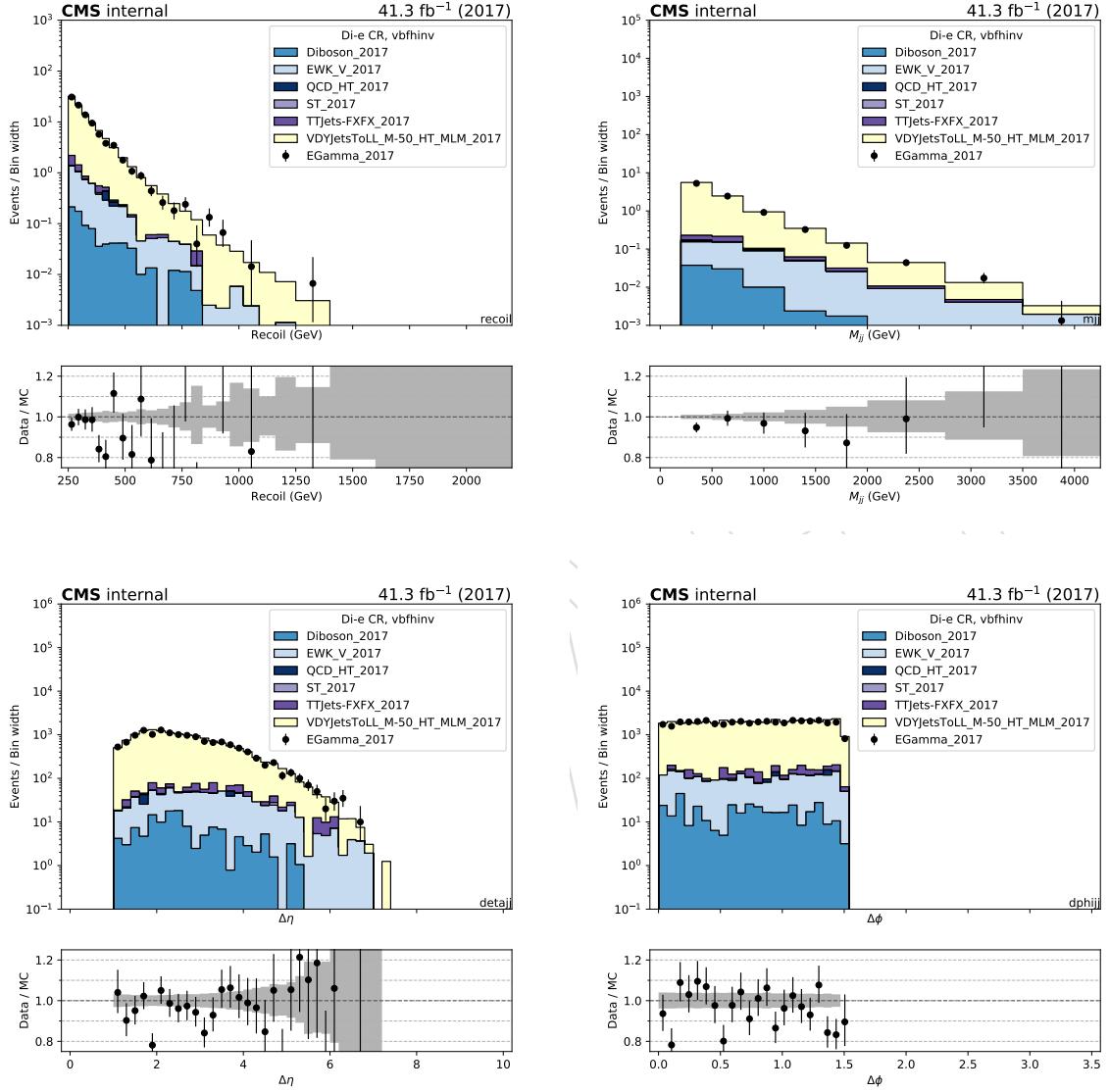


Figure 35: Comparison between 2017 data and Monte Carlo simulation in the double electron control sample for the recoil distribution, the M_{jj} distribution, $\Delta\eta_{jj}$ distribution and $\Delta\phi_{jj}$ distribution for the two leading AK4 jets with the VBF selection.

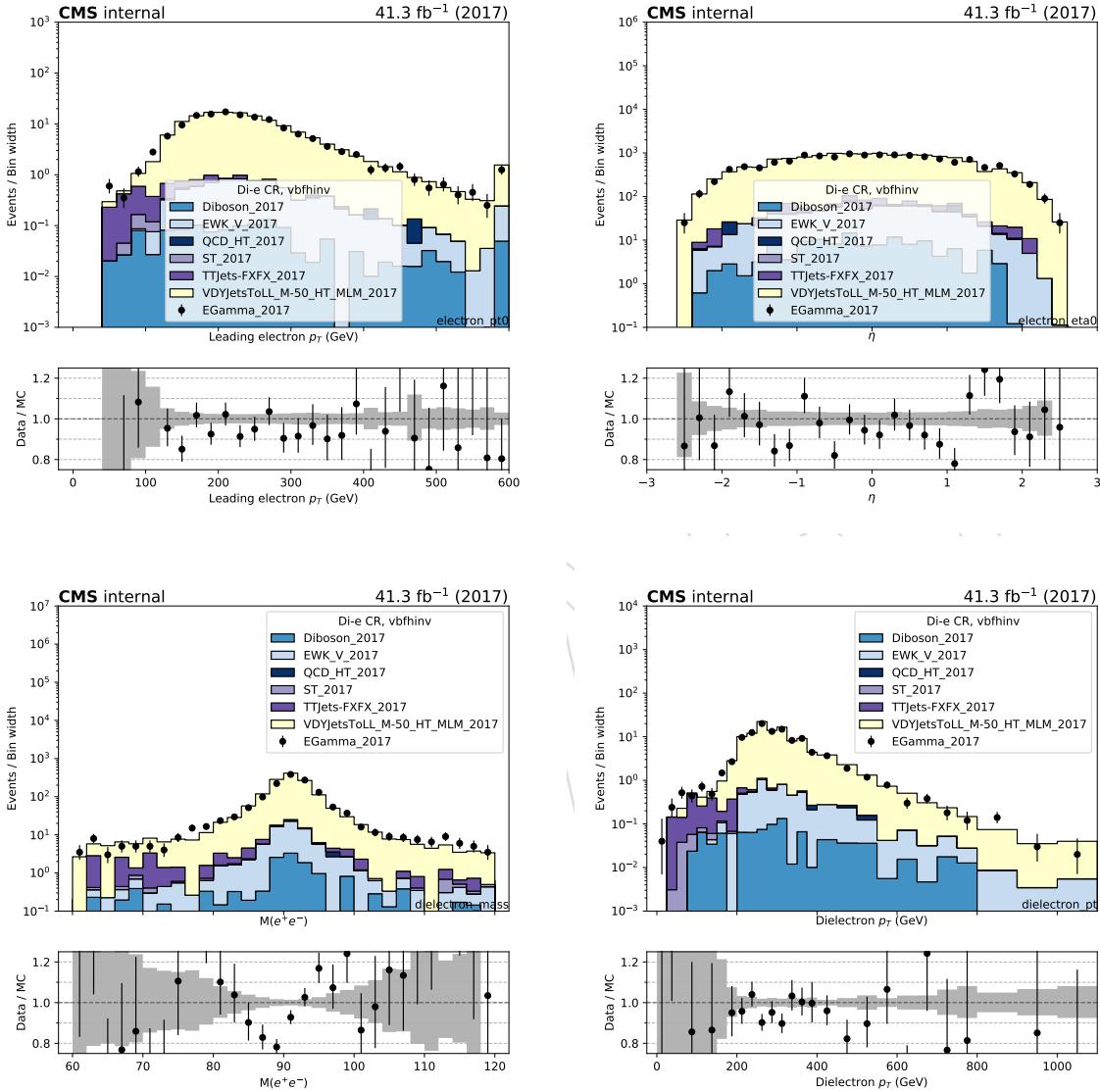


Figure 36: Comparison between 2017 data and Monte Carlo simulation in the double electron control sample for the p_T and η of the leading electron and the transverse mass and p_T of the dielectron candidate with the VBF selection.

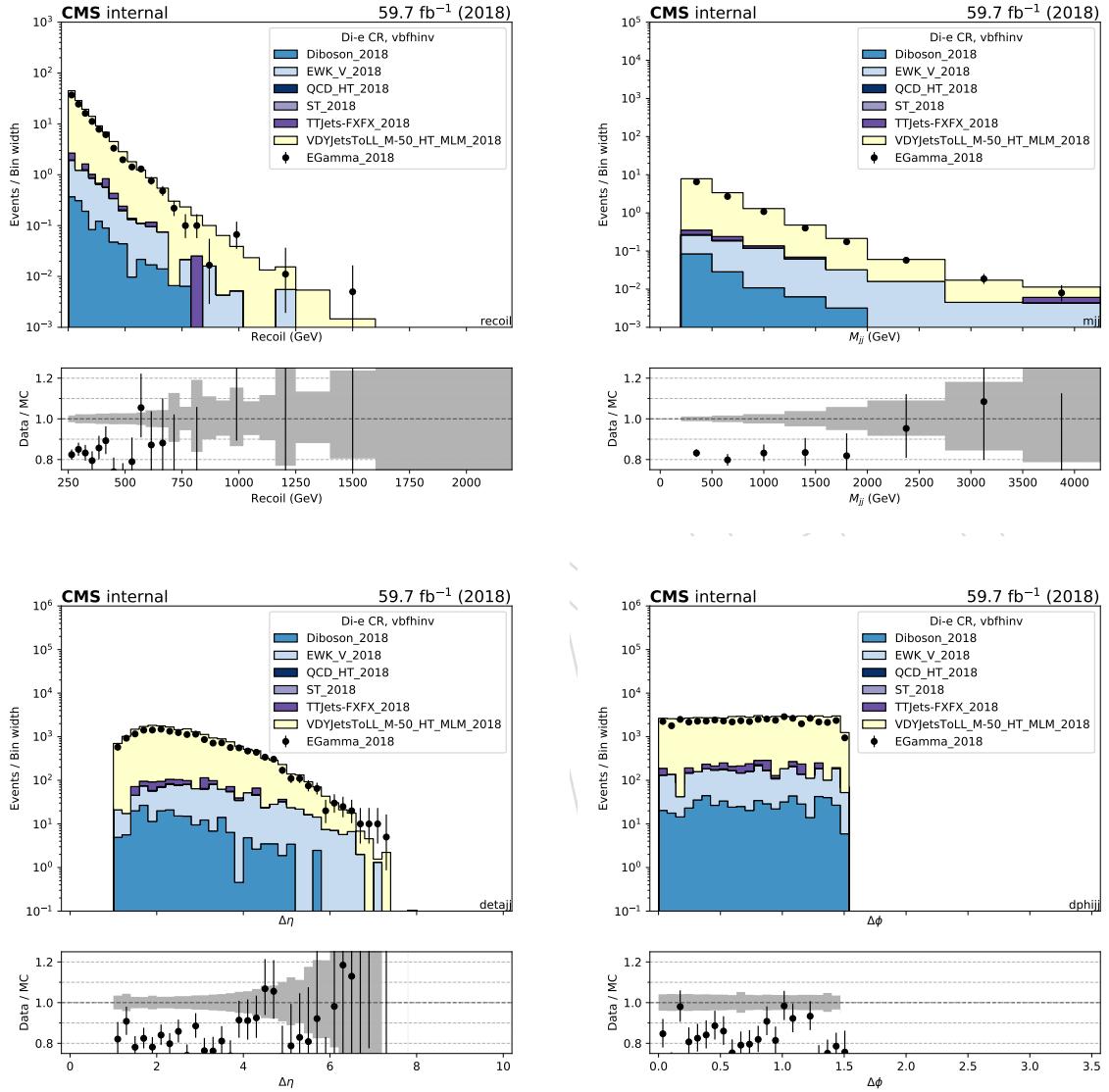


Figure 37: Comparison between 2018 data and Monte Carlo simulation in the double electron control sample for the recoil distribution, the M_{jj} distribution, $\Delta\eta_{jj}$ distribution and $\Delta\phi_{jj}$ distribution for the two leading AK4 jets with the VBF selection.

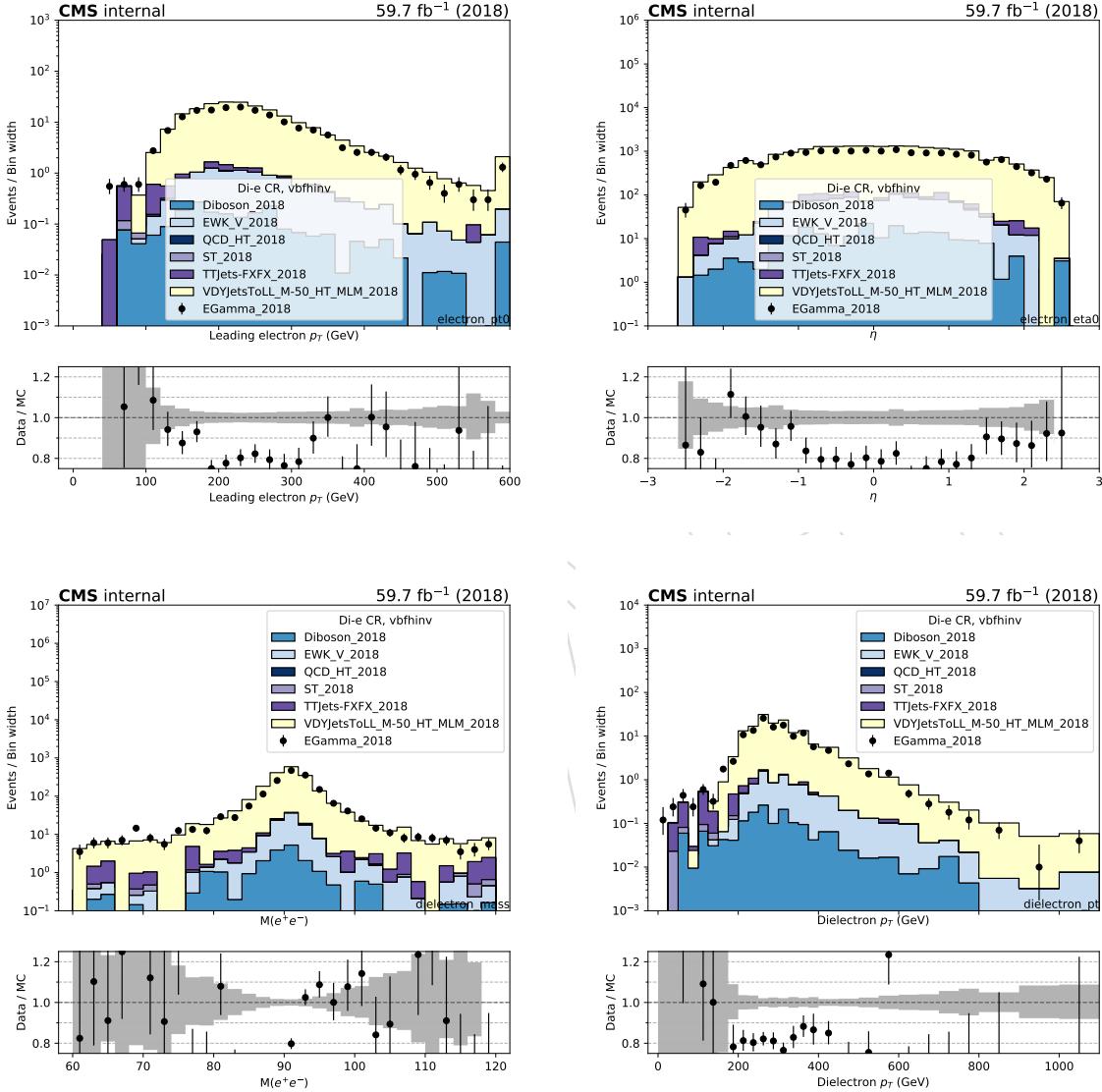


Figure 38: Comparison between 2018 data and Monte Carlo simulation in the double electron control sample for the p_T and η of the leading electron and the transverse mass and p_T of the dielectron candidate with the VBF selection.

539 **6.6 Photon control region**

540 The $\gamma + \text{jets}$ control sample is selected using events with one high- p_T photon collected using
 541 single-photon triggers with p_T thresholds of 165 or 175 GeV, depending on the data taking
 542 conditions. The photon is required to have $p_T > 175$ GeV and to pass tight identification and
 543 isolation criteria, to ensure a high trigger efficiency of 98%.

544 Figs. 39 and 39 show the distributions of the recoil, M_{jj} , $\Delta\eta_{jj}$ and $\Delta\phi_{jj}$ distribution of the two
 545 leading AK4 jets for events in the photon control sample for the VBF category in the 2017 and
 546 2018 datasets, respectively. Similarly, Figs. 40 and 42 show the distributions of the photon p_T
 547 and η .

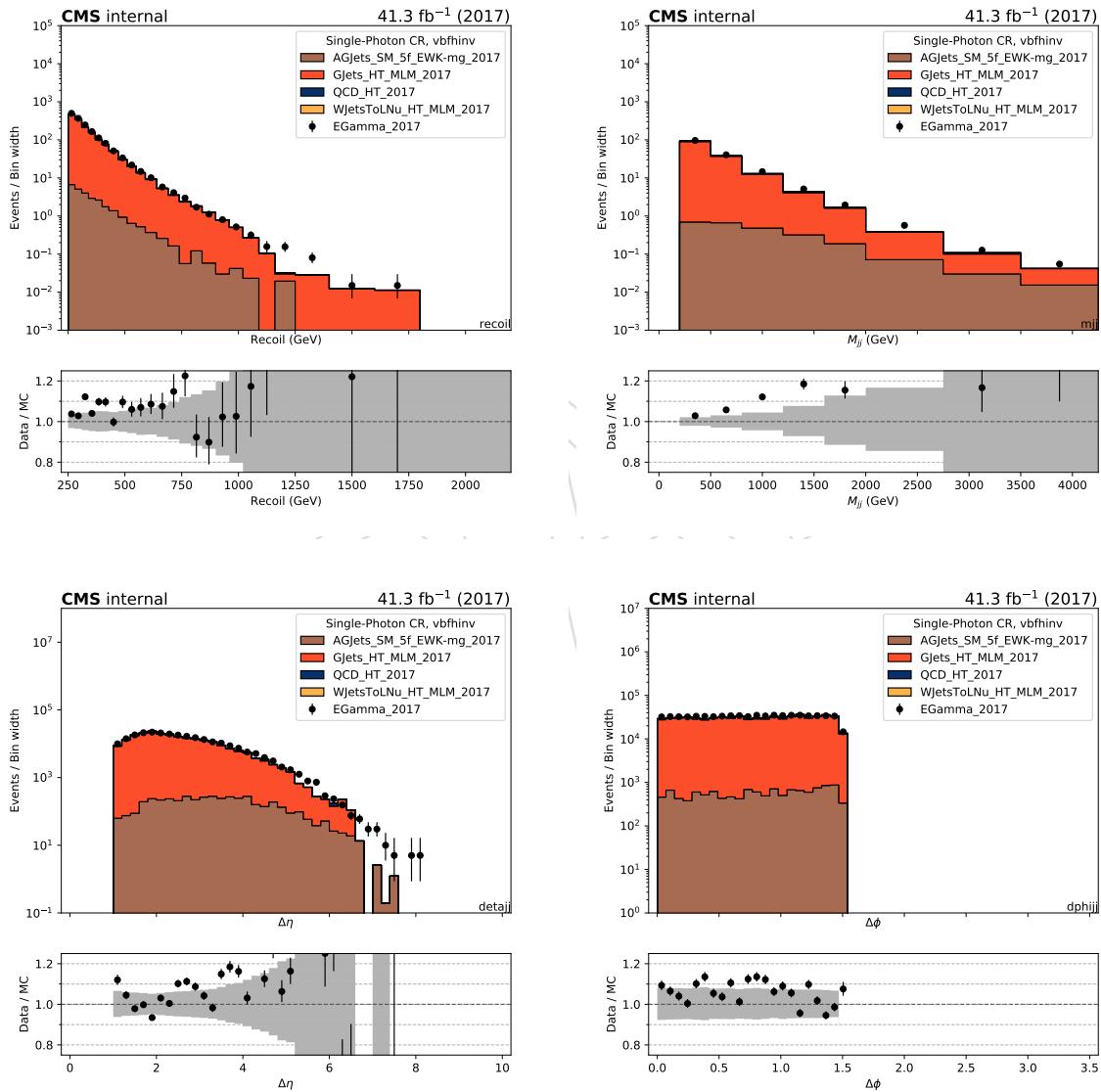


Figure 39: Comparison between 2017 data and Monte Carlo simulation in the photon control sample for the recoil distribution, the M_{jj} distribution, $\Delta\eta_{jj}$ distribution and $\Delta\phi_{jj}$ distribution for the two leading AK4 jets with the VBF selection.

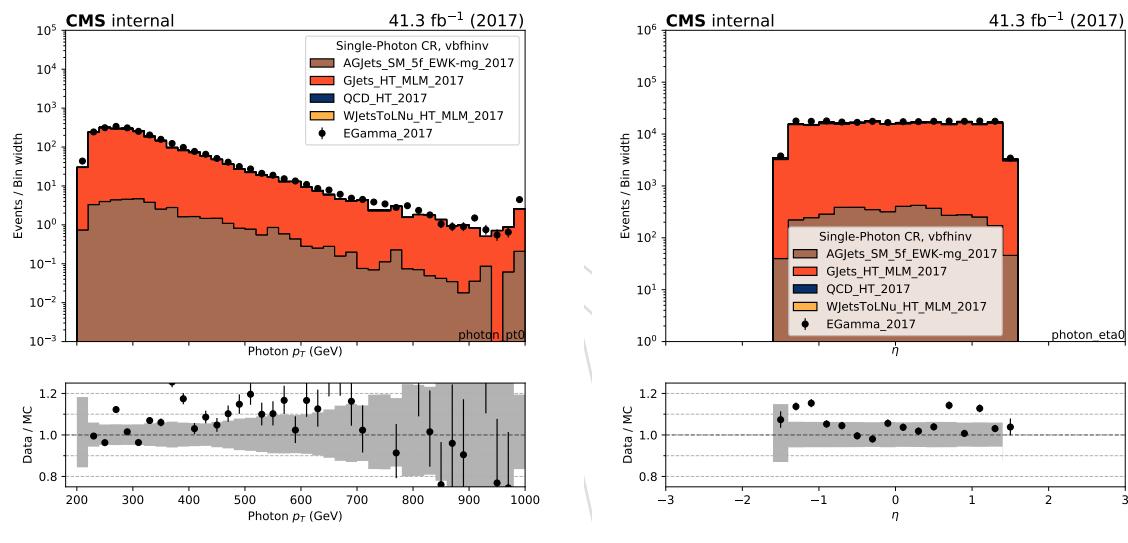


Figure 40: Comparison between 2017 data and Monte Carlo simulation in the photon control sample for the p_T and η of the leading photon with the VBF selection.

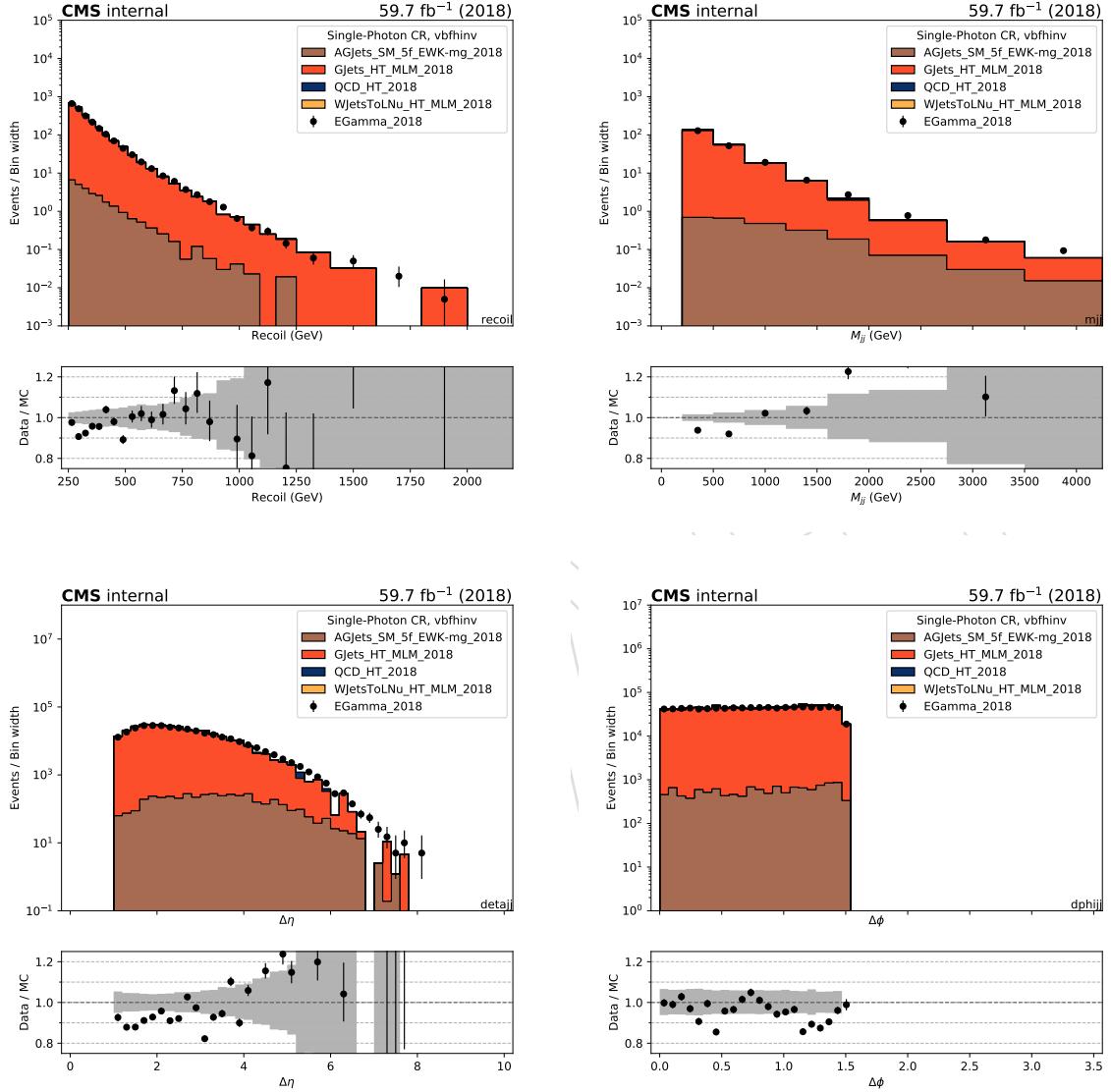


Figure 41: Comparison between 2018 data and Monte Carlo simulation in the photon control sample for the recoil distribution, the M_{jj} distribution, $\Delta\eta_{jj}$ distribution and $\Delta\phi_{jj}$ distribution for the two leading AK4 jets with the VBF selection.

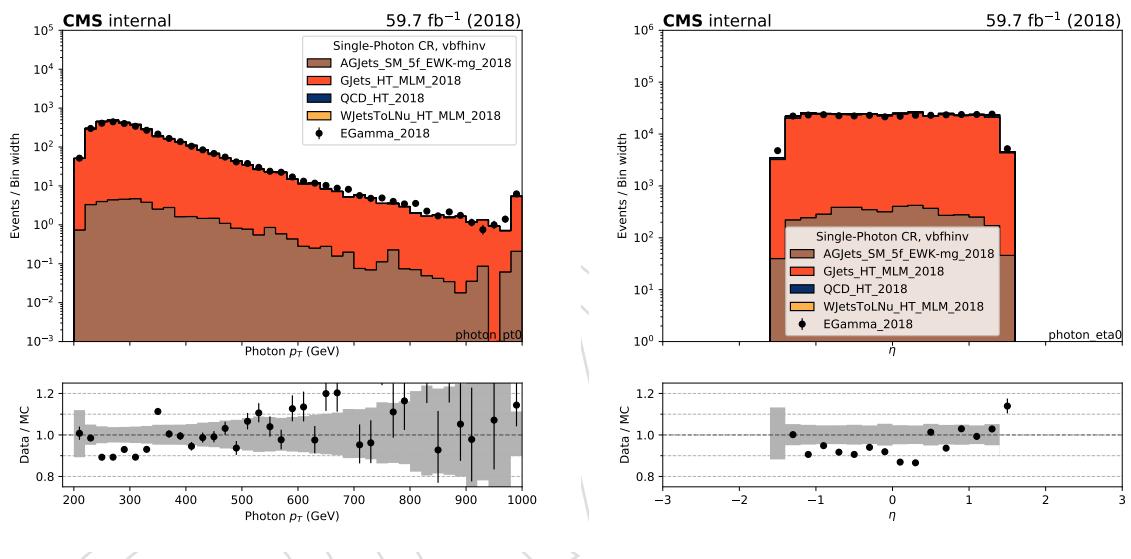


Figure 42: Comparison between 2018 data and Monte Carlo simulation in the photon control sample for the p_T and η of the leading photon with the VBF selection.

548 7 Background estimation

549 The largest background contributions from $Z(\nu\nu) + \text{jets}$ and $W(\ell\nu) + \text{jets}$ processes are esti-
 550 mated using data from four mutually exclusive control samples selected from dimuon, dielec-
 551 tron, single-muon, and single-electron states, as explained below.

552 The remaining backgrounds that contribute to the total event yield in the signal region are
 553 much smaller than those from $Z(\nu\nu) + \text{jets}$ and $W(\ell\nu) + \text{jets}$ processes. These backgrounds in-
 554 clude QCD multijet events which are measured from data using a $\Delta\phi$ extrapolation method [29,
 555 30], and top-quark and diboson processes, which are obtained directly from simulation and are
 556 explained in the previous sections.

557 7.1 Signal extraction strategy

558 A binned likelihood fit to the data (constructed as a product of poisson probabilities) as pre-
 559 sented here:

$$\mathcal{L}(\mu^{Z \rightarrow \nu\nu}, \mu, \theta) = \prod_i \text{Pois}\left(d_i | B_i(\theta) + (1 + f_i(\theta)_{\text{QCD}})\mu_i^{Z \rightarrow \nu\nu} + R_i^{Z \rightarrow \circ \circ} (1 + f_i(\theta)_{\text{EW}})\mu_i^{Z \rightarrow \nu\nu} + \mu S_i(\theta)\right) \times \\ \prod_i \text{Pois}\left(d_i^Z | B_i^Z(\theta) + \frac{\mu_i^{Z \rightarrow \nu\nu}}{R_i^Z(\theta)_{\text{QCD}}} + \frac{\mu_i^{Z \rightarrow \nu\nu}}{R_i^Z(\theta)_{\text{EW}}}\right) \\ \prod_i \text{Pois}\left(d_i^W | B_i^W(\theta) + \frac{f_i(\theta)_{\text{QCD}}\mu_i^{Z \rightarrow \nu\nu}}{R_i^W(\theta)_{\text{QCD}}} + \frac{f_i(\theta)_{\text{EW}}\mu_i^{Z \rightarrow \nu\nu}}{R_i^W(\theta)_{\text{EW}}}\right) \times \quad (4)$$

560 The fit is performed simultaneously in the four different control samples and in the signal re-
 561 gion, for events selected in the vbf category, to estimate the $Z(\nu\nu) + \text{jets}$ and $W(\ell\nu) + \text{jets}$ rate in
 562 each m_{jj} bin. In this likelihood, the expected number of $Z(\nu\nu) + \text{jets}$ events in each bin of m_{jj} are
 563 the free parameters of the fit. The $Z(\nu\nu) + \text{jets}$ and $W(\ell\nu) + \text{jets}$ rates are estimated separately
 564 for the QCD and EW components separately in each m_{jj} bin. However the fit is constrained
 565 using the $R_i^{Z \rightarrow \circ \circ}$ which demonstrates the ratio between the QCD and EW components of the
 566 $Z(\nu\nu) + \text{jets}$ background. This ratio does not have any additional uncertainty. The systematic
 567 uncertainties (θ) enter the likelihood as additive perturbations to the transfer factors $R_i^{Z/W}$,
 568 and are modeled as Gaussians. The parameter $\mu_i^{Z \rightarrow \nu\nu}$ represents the yield of the $Z(\nu\nu) + \text{jets}$
 569 background in the i dijet mass bin into the signal region, and is left freely floating in the fit. The
 570 function $f_i(\theta)$ is the transfer factor between the $Z(\nu\nu) + \text{jets}$ and $W(\ell\nu) + \text{jets}$ backgrounds in
 571 the signal region and represents a constraint between these backgrounds. The likelihood also
 572 includes the signal region with B_i representing all the backgrounds, S representing the nominal
 573 signal prediction, and μ being the signal strength parameter also left floating in the fit.

574 7.2 Transfer factors

Transfer factors, derived from simulation, are used to link the yields of the $Z(\ell\ell) + \text{jets}$ and $W(\ell\nu) + \text{jets}$ processes in the control regions with the $Z(\nu\nu) + \text{jets}$ and $W(\ell\nu) + \text{jets}$ background estimates in the signal region. These transfer factors are defined as the ratio of expected yields of the target process in the signal region and the process being measured in the control sample. As an example:

$$R_i^Z = \frac{N_{i,MC}^{Z \rightarrow \mu^+ \mu^-}}{N_{i,MC}^{Z \rightarrow \nu\nu}} \quad (5)$$

575 where N_i is the number of events in bin i of the dijet mass distribution, R_i is the transfer fac-
 576 tor between the dimuon control region and $Z \rightarrow \nu\nu$ background. Other transfer factors are
 577 constructed in similar manner.

578 To estimate the $W(\ell\nu) + \text{jets}$ background in the signal region, the transfer factors between
 579 the $W(\mu\nu) + \text{jets}$ and $W(e\nu) + \text{jets}$ event yields in the single-lepton control samples and the
 580 $W(\ell\nu) + \text{jets}$ background estimates in the signal region are constructed. These transfer factors
 581 take into account the impact of lepton acceptances and efficiencies, lepton veto efficiencies, and
 582 the difference in the trigger efficiencies in the case of the single-electron control sample. These
 583 transfer factors are shown in Figure 43. The dotted red (blue) line shows the ratio of the pro-
 584 cesses where the V-boson is produced via EW (QCD) production where as the solid lines show
 585 the ratio of the processes where the V-boson is produced both via EW and QCD production.

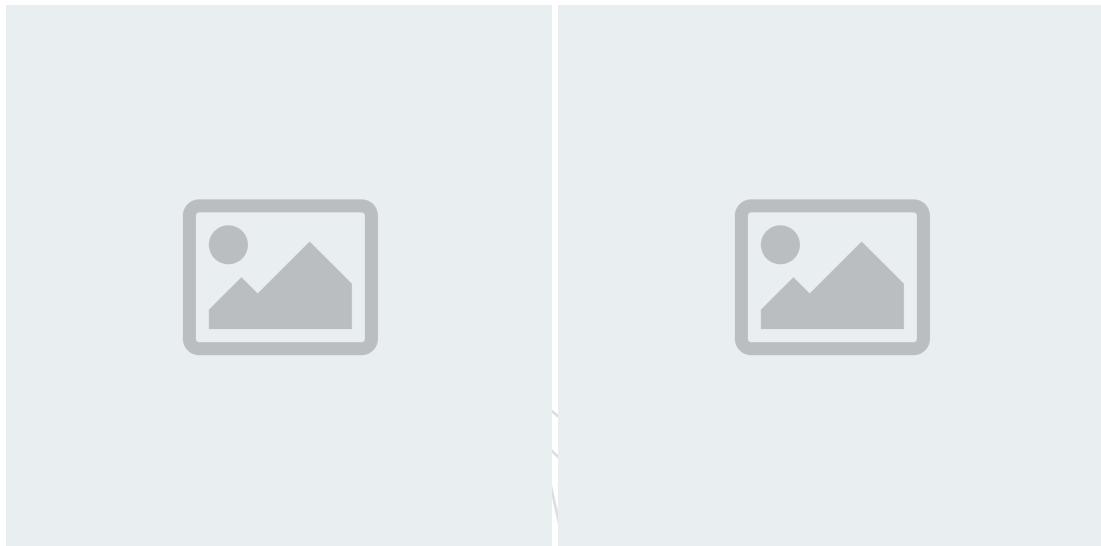


Figure 43: Transfer factors for the $W \rightarrow \ell\nu$ background as a function of the dijet mass using the single muon and single electron control regions for the vbf final state. The grey band shows the statistical and systematic uncertainties on the ratios.

586 The $Z \rightarrow \nu\nu$ background prediction in the signal region is connected to the yields of $Z \rightarrow$
 587 $\mu^+ \mu^-$ and $Z \rightarrow e^+ e^-$ events in the dilepton control samples. The associated transfer factors ac-
 588 count for the differences in the branching ratio of Z bosons to charged leptons relative to neutrinos
 589 and the impact of lepton acceptance and selection efficiencies. In the case of dielectron
 590 events, the transfer factor also takes into account the difference in the trigger efficiencies. The
 591 resulting constraint on the $Z \rightarrow \nu\nu$ background from the dilepton control samples is limited by
 592 the statistical uncertainty in the dilepton control samples due to the large branching fraction
 593 difference of the Z boson decays to muons and electrons compared to that to neutrinos. These
 594 transfer factors are shown in Figure 44. The dotted red (blue) line shows the ratio of the pro-
 595 cesses where the V-boson is produced via EW (QCD) production where as the solid lines show
 596 the ratio of the processes where the V-boson is produced both via EW and QCD production.

597 Finally, a transfer factor is also defined to connect the $Z(\nu\nu) + \text{jets}$ and $W(\ell\nu) + \text{jets}$ background
 598 yields in the signal region to further benefit from larger statistical power that $W(\ell\nu) + \text{jets}$ back-
 599 ground has making it possible to experimentally constrain $Z(\nu\nu) + \text{jets}$ production at high dijet
 600 masses. These transfer factors are shown in Figure 45. The dotted red (blue) line shows the
 601 ratio of the processes where the V-boson is produced via EW (QCD) production where as the
 602 solid lines show the ratio of the processes where the V-boson is produced both via EW and
 603 QCD production.

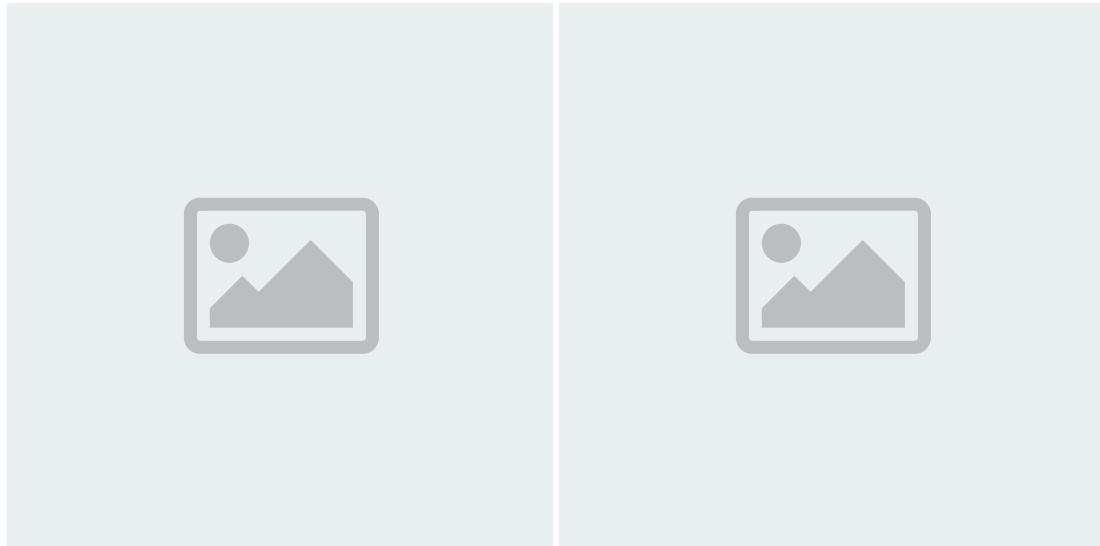


Figure 44: Transfer factors for the $Z(\nu\nu) + \text{jets}$ background as a function of the dijet mass using the dimuon, and dielectron control regions in vbf final state. The grey band shows the statistical and systematic uncertainties on the ratios.

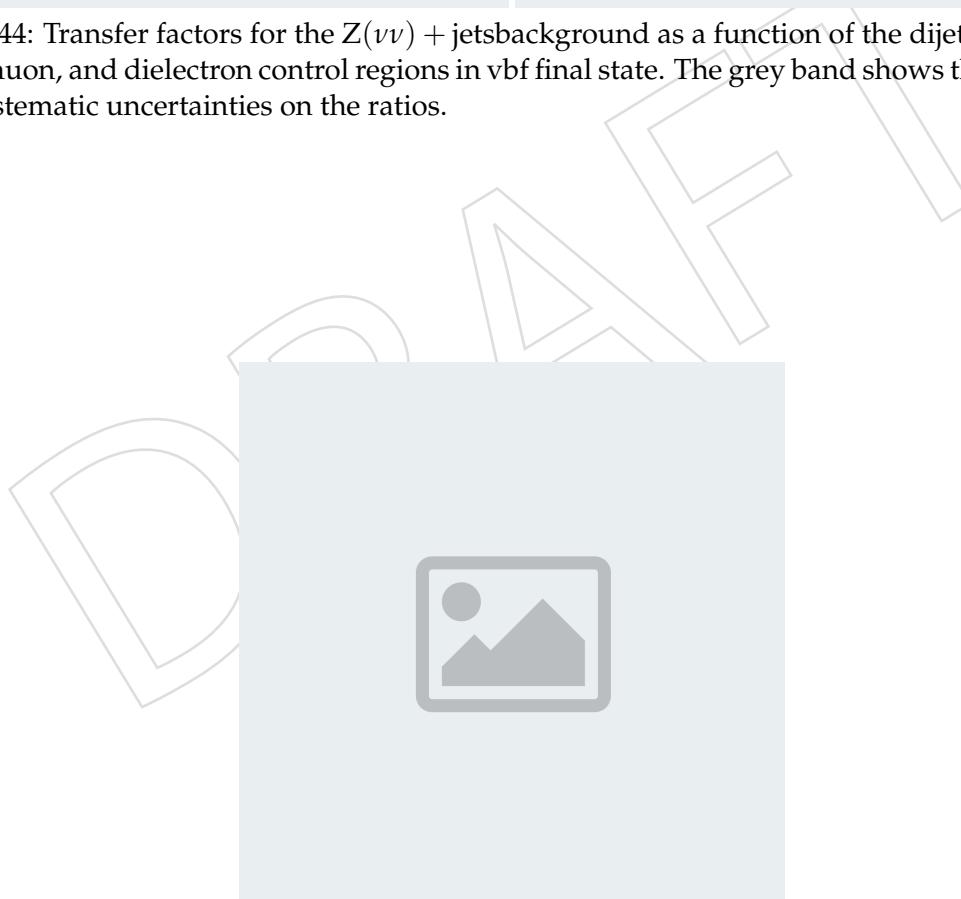


Figure 45: Transfer factors for the to estimate the $Z(\nu\nu)+\text{jets}$ background from $W+\text{jets}$ in the signal region as a function of the dijet mass for the vbf final state. The grey band shows the statistical and systematic uncertainties on the ratios.

604 **7.3 Systematic uncertainties**

605 Systematic uncertainties in the transfer factors are modeled as constrained nuisance parameters
 606 and include both experimental and theoretical uncertainties in the $W + \text{jets}$ to $Z + \text{jets}$ differen-
 607 tial cross section ratios.

608 **7.3.1 Theoretical uncertainties**

609 Theoretical uncertainties in $V + \text{jets}$ processes include effects from QCD and EW higher-order
 610 corrections along with PDF modeling uncertainty. One of the uncertainties considered comes
 611 from the variations around the central renormalization and factorization scale choice. It is eval-
 612 uated by taking the differences in the NLO cross section as a function of boson p_T after chang-
 613 ing the renormalization and factorization scales by a factor of two and a factor of one-half with
 614 respect to the default value. These constant scale variations mainly affect the overall normal-
 615 ization of the boson p_T distributions. This uncertainty is treated to be uncorrelated across the
 616 $Z + \text{jets}$, $W + \text{jets}$ processes, but correlated across the bins of the dijet mass distribution.

617 The PDF uncertainty has been estimated using the standard deviations of weights provided in
 618 the NNPDF3.0 parton distribution set and using the RMS of each bin of the distribution after
 619 varying the full spectra by these weights. This uncertainty is treated to be correlated across the
 620 $Z + \text{jets}$, $W + \text{jets}$ processes, and the bins of the dijet mass distribution.

621 The uncertainty due the EW corrections is assumed to be the full correction itself as a conser-
 622 vative approach. The uncertainty is treated correlated across the processes and across the bins
 623 of the dijet mass spectra.

624 These uncertainties are applied to the QCD and EW $V + \text{jets}$ processes, but are assumed to be
 625 uncorrelated. That is, the QCD $W + \text{jets}$ component has a factorization scale uncertainty that is
 626 the same size as the factorization scale uncertainty on the EW $W + \text{jets}$ component, but the two
 627 are treated as separate nuisances in the signal extraction fit.

628 The summary of the aforementioned theoretical uncertainties including their magnitude per
 629 process and on the ratio are shown in Figure 46

630 **7.3.2 Experimental uncertainties**

631 **Check numbers for 2017/18** Experimental uncertainties including the reconstruction efficiency
 632 (1% per muon or electron), and selection efficiencies of leptons (1% per muon and 2% per
 633 electron), and hadronically decaying τ leptons (5%) are incorporated to the analysis. These
 634 reconstruction and selection efficiencies further translate into an uncertainty in the lepton veto
 635 efficiency of 3%. The lepton veto uncertainties in the transfer factors and are estimated through
 636 propagating the overall uncertainty on the tagging scale factor (loose-muon ID, veto-electron
 637 ID and loose MVA-tau ID) into the vetoed selection based on both the flavour composition
 638 of the $W + \text{jets}$ process the acceptance of the lepton. The overall magnitude of the lepton-
 639 veto uncertainty is found to be around 3 (4)% and is found to be dominated by the τ -veto
 640 uncertainty.

641 The uncertainty in the modeling of E_T^{miss} in simulation [31] is estimated to be 1-2% on the ratios
 642 and is dominated by the uncertainty on the jet energy scale. The jet energy scale uncertainties
 643 found to be not-cancelling in the ratio due to the differences in the jet kinematics between
 644 control and signal regions. The resulting jet energy scale uncertainties in the ratios can be seen
 645 in Figure 47

646 Lastly, uncertainties in the efficiency of the electron (2%), and p_T^{miss} (2%) triggers, are included

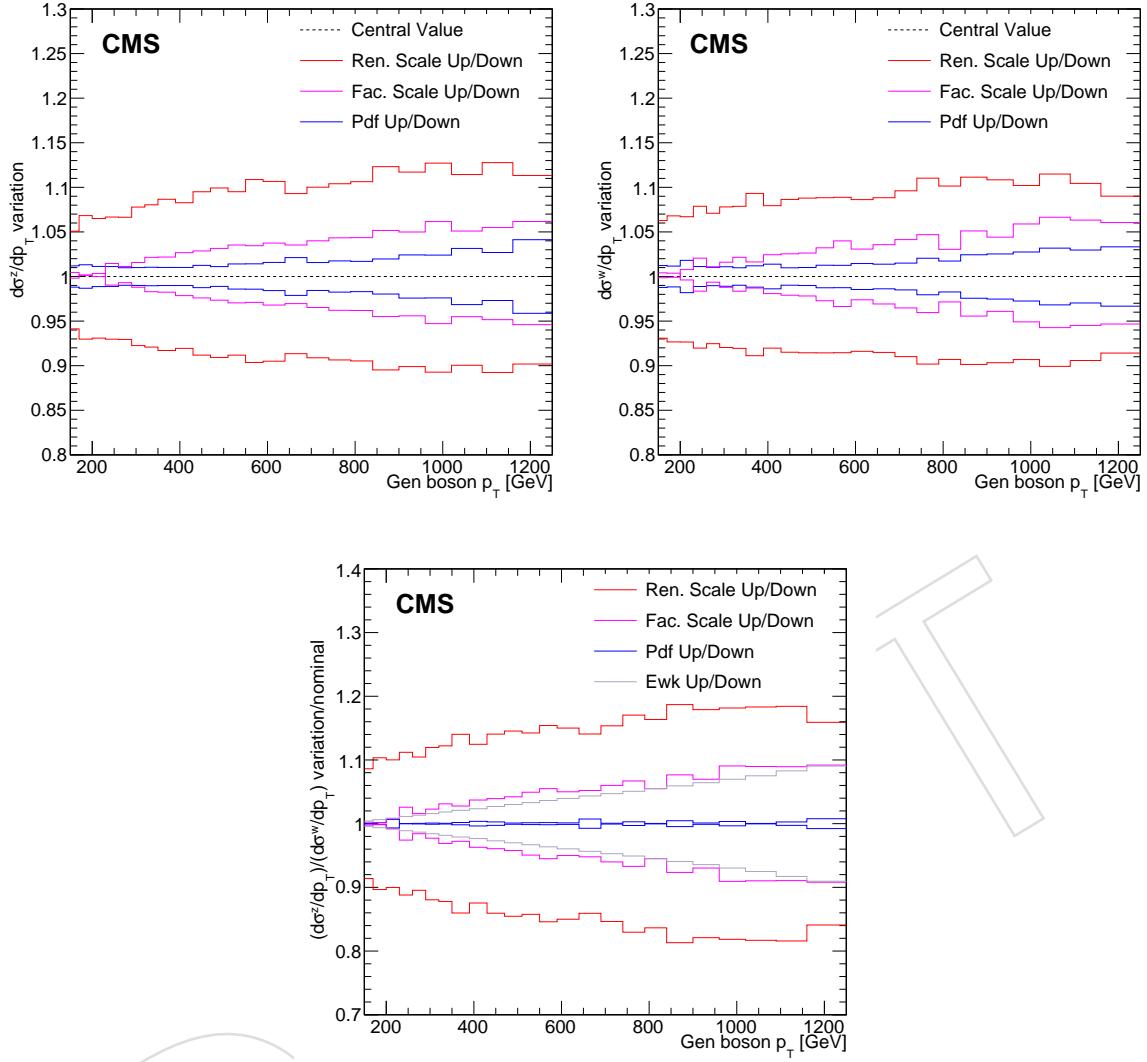


Figure 46: Theoretical uncertainties due to QCD and EW higher-order corrections and the PDF variation is shown for individual processes and for the ratio.

and are fully correlated across all the bins of dijet mass distribution.

The remaining uncertainties are for the monte carlo based backgrounds. A systematic uncertainty of 10% for the top quark background due to the modeling of the top quark p_T distribution in simulation. The uncertainty in the efficiency of the b jet veto is estimated to be 3% (1%) for the top quark (diboson) background. In addition, systematic uncertainties of 10 and 20% are included in the normalizations of the top quark [32] and diboson backgrounds [33, 34], respectively, to account for the uncertainties in their cross sections in the relevant kinematic phase space. Lastly, the uncertainty in the QCD multijet background estimate is found to be between 50–150% due to the variations of the jet response and the statistical uncertainty of the extrapolation factors.

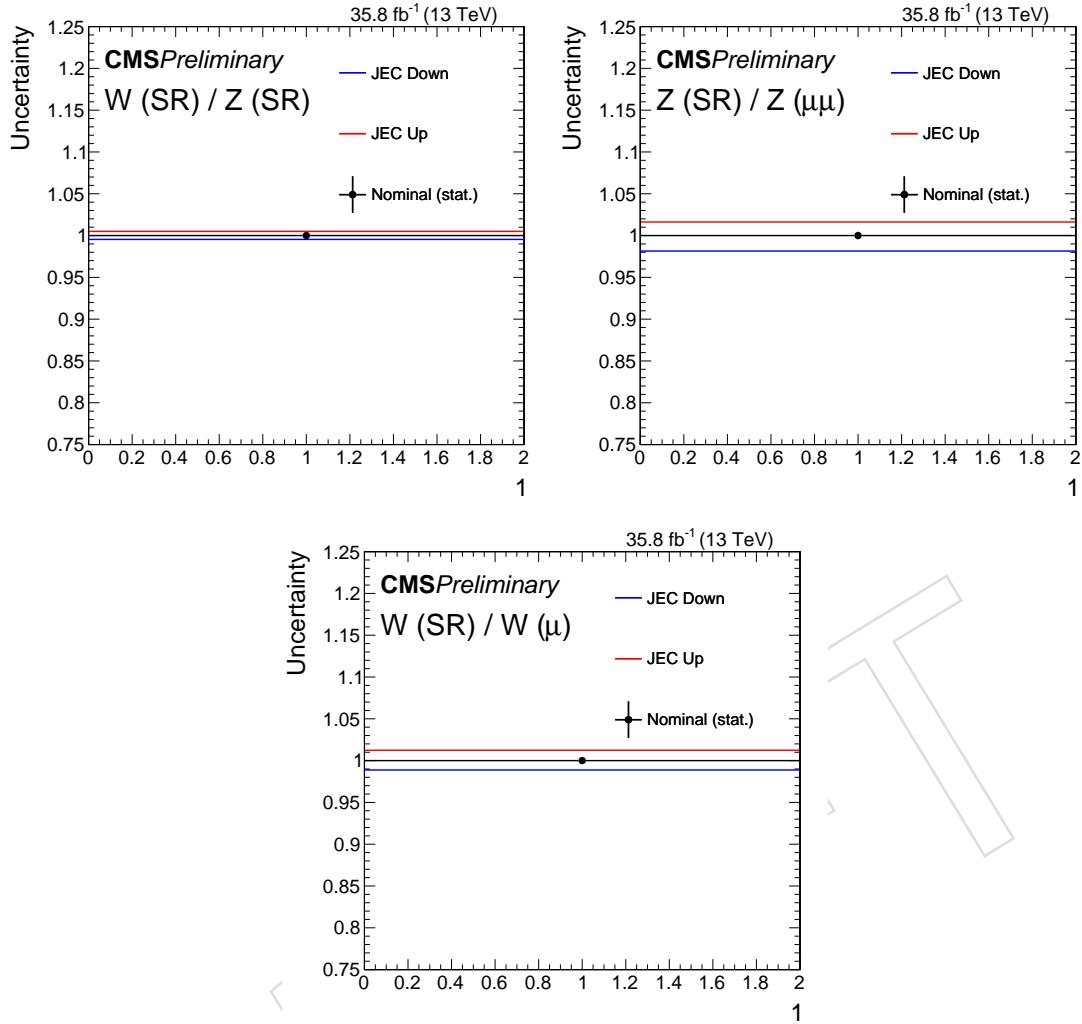


Figure 47: Redo for 2017/18 The resulting jet energy scale uncertainties in the ratios of $W_{\text{SR}}/Z_{\nu\nu}$, $Z_{\nu\nu}/Z_{\mu\mu}$ and $W_{\text{SR}}/W_{\mu\nu}$, respectively.

657 7.4 Control sample validation

658 An important cross-check of the application of p_T -dependent NLO QCD and EW corrections is
 659 represented by the agreement between data and simulation in the ratio of $Z + \text{jets}$ events and
 660 $W + \text{jets}$ events in the control samples as a function of m_{jj} .

661 Figure 48 shows the ratio between $Z(\mu\mu) + \text{jets}$ and $W(\mu\nu) + \text{jets}$ (left), and the one between
 662 $Z(ee) + \text{jets}$ and $W(ev) + \text{jets}$ processes (right) as a function of the dijet mass distribution for
 663 events selected both using 2017 samples (top) and 2018 samples (bottom). Good agreement is
 664 observed between data and simulation after the application of the NLO corrections.

665 7.5 QCD multijet estimation

666 Update for 2017/18

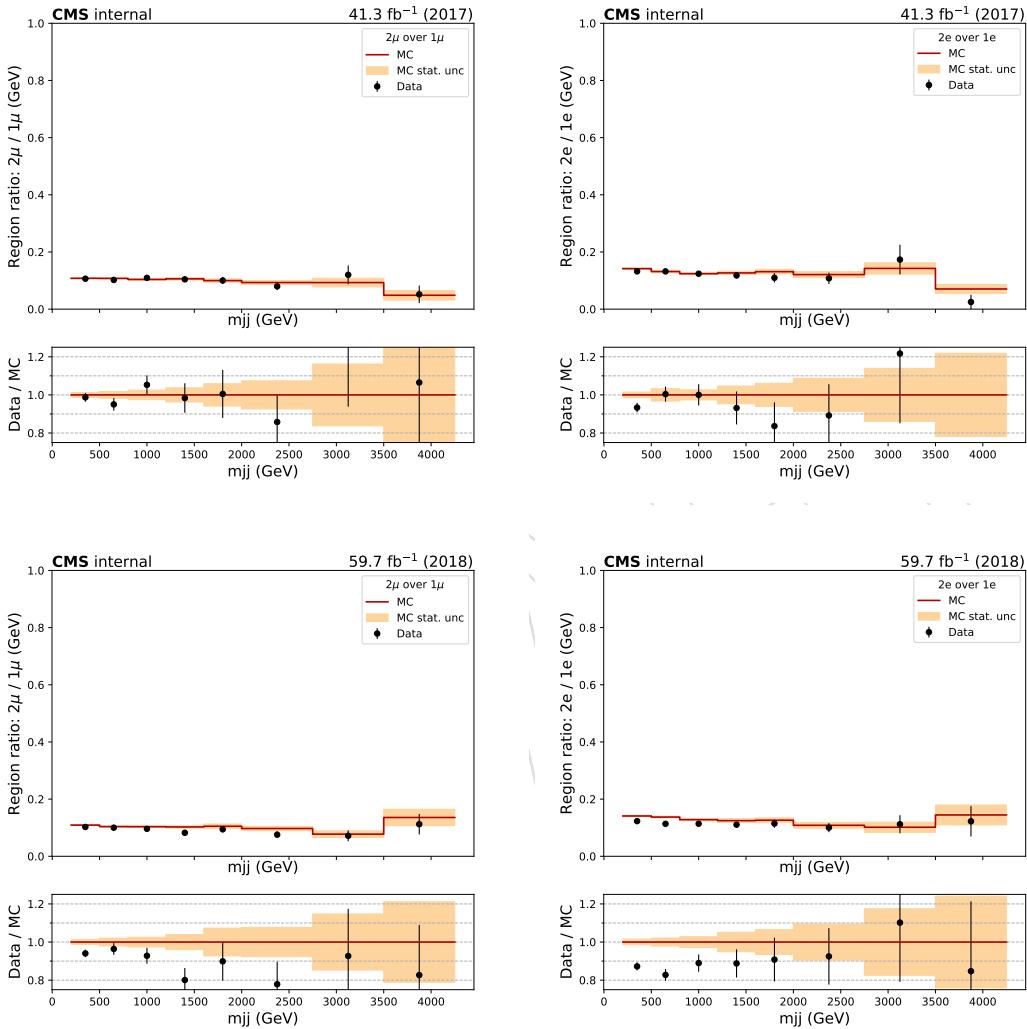


Figure 48: Comparison between data and MC simulation for $Z(\mu\mu) + \text{jets}$ and $W(\mu\nu) + \text{jets}$ (left), $Z(ee) + \text{jets}$ and $W(e\nu) + \text{jets}$ processes (right) ratio as a function of m_{jj} , using 2017 samples (top) and 2018 samples (bottom). The gray bands include both the pre-fit systematic uncertainties and the statistical uncertainty in the simulation.

Source	Process	Uncertainty
Electron trigger	$W_{SR}/W_{ev}, Z_{vv}/Z_{ee}$	1%
E_T^{miss} trigger	$W_{SR}/W_{CR}, Z_{vv}/Z_{CR}, Z/W,$	2%
Muon-reco efficiency	$W_{SR}/W_{\mu\nu}, Z_{vv}/Z_{\mu\mu}$	1% (per leg)
Muon-ID efficiency	$W_{SR}/W_{\mu\nu}, Z_{vv}/Z_{\mu\mu}$	1% (per leg)
Muon-Iso efficiency	$W_{SR}/W_{\mu\nu}, Z_{vv}/Z_{\mu\mu}$	0.5% (per leg)
Electron-reco efficiency	$W_{SR}/W_{ev}, Z_{vv}/Z_{ee}$	1% (per leg)
Electron-IDiso efficiency	$W_{SR}/W_{ev}, Z_{vv}/Z_{ee}$	1.5% (per leg)
Lepton veto	W_{LSR}	3% (QCD), 5.0% (EW)
Jet energy scale	W_{CR}/W_{SR}	2%
Jet energy scale	Z_{CR}/Z_{SR}	1%

Table 12: **Check numbers for 2017/18** Summary of experimental uncertainties affecting used in the analysis.

667 **8 Results**

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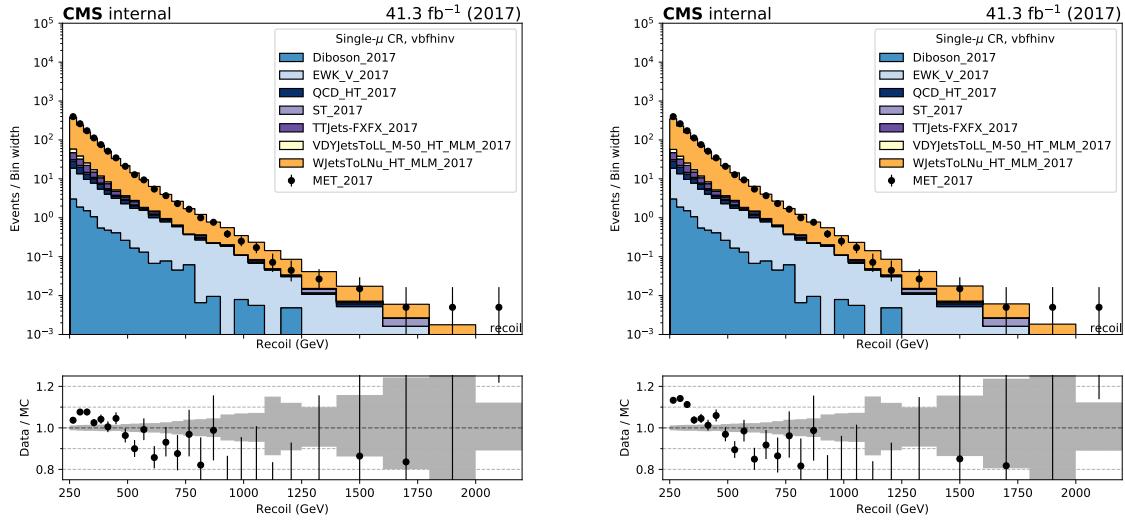


Figure 49: The recoil distribution in the single muon CR for the case in which 1D k-factors are used (left), compared to the case in which 2D k-factors are used (right), using 2017 samples.

668 A Comparison of 1D and 2D QCD k-factors

669 In this appendix, several distributions such as recoil, M_{jj} and $\Delta\eta_{jj}$ are compared for two cases
670 in the single muon control region:

- 671 • Plots with 1D k-factors applied: Function of gen-boson p_T
- 672 • Plots with 2D k-factors applied: Function of gen-boson p_T and M_{jj}

673 Both k-factors are derived from samples in which the VBF selections are applied at the gen level.
674 1D k-factor is a function of generator level vector boson p_T , whereas 2D k-factor is a function
675 of both generator level boson p_T and M_{jj} . The distributions are shown in the following pages.

676 Fig. 49 shows the comparison of the recoil distribution with 2017 samples, while Fig. 50 shows
677 the same comparison with 2018 samples. Fig. 51 shows the comparison of the M_{jj} distribution
678 with 2017 samples, while Fig. 52 shows the same comparison with 2018 samples. Fig. 53 shows
679 the comparison of the $\Delta\eta_{jj}$ distribution with 2017 samples, while Fig. 54 shows the same com-
680 parison with 2018 samples. Fig. 55 shows the comparison of the muon p_T distribution with
681 2017 samples, while Fig. 56 shows the same comparison with 2018 samples. Fig. 57 shows
682 the comparison of the muon η distribution with 2017 samples, while Fig. 58 shows the same
683 comparison with 2018 samples.

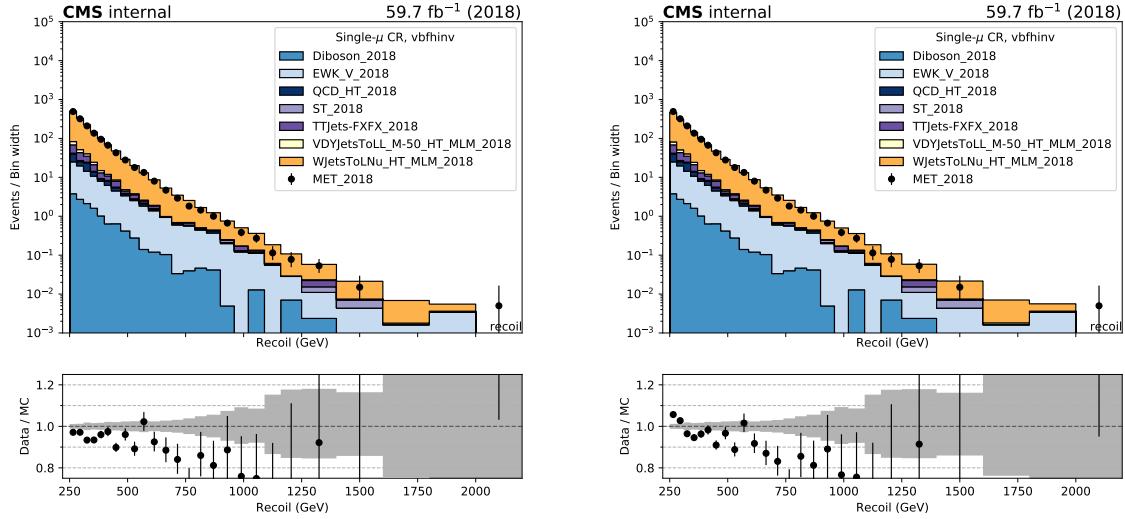


Figure 50: The recoil distribution in the single muon CR for the case in which 1D k-factors are used (left), compared to the case in which 2D k-factors are used (right), using 2018 samples.

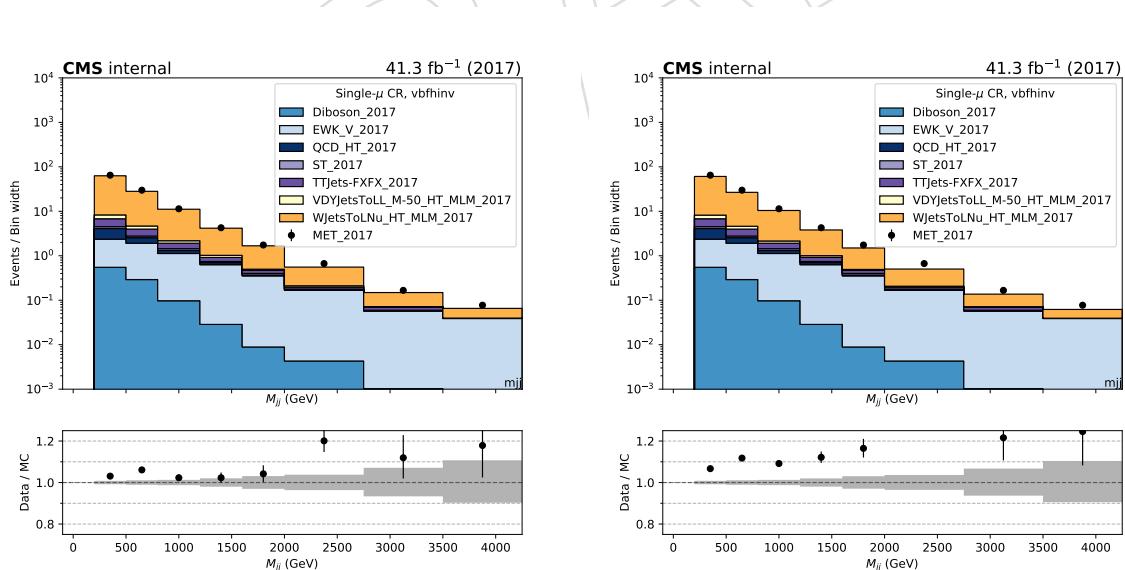


Figure 51: The M_{jj} distribution in the single muon CR for the case in which 1D k-factors are used (left), compared to the case in which 2D k-factors are used (right), using 2017 samples.

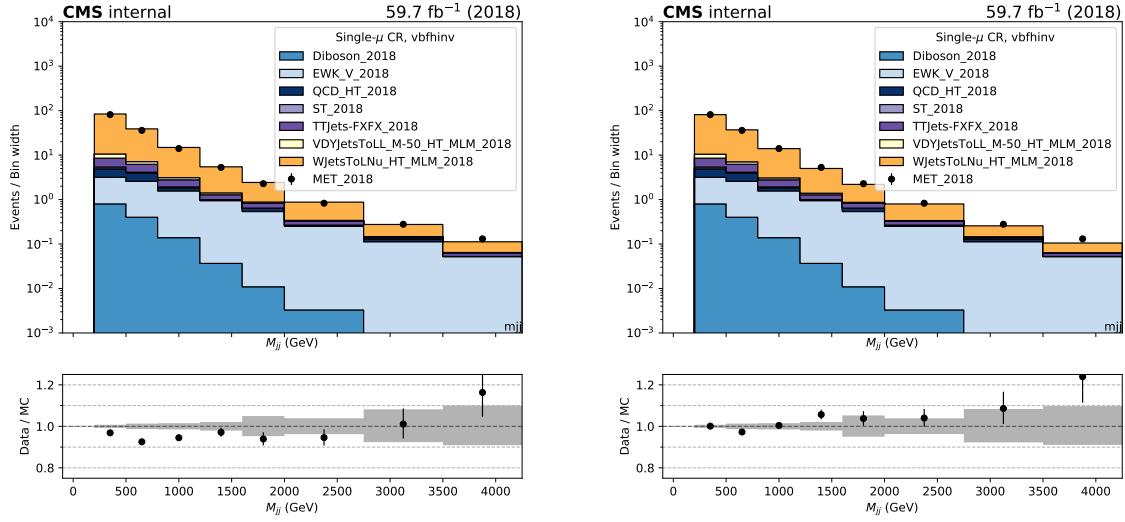


Figure 52: The M_{jj} distribution in the single muon CR for the case in which 1D k-factors are used (left), compared to the case in which 2D k-factors are used (right), using 2018 samples.

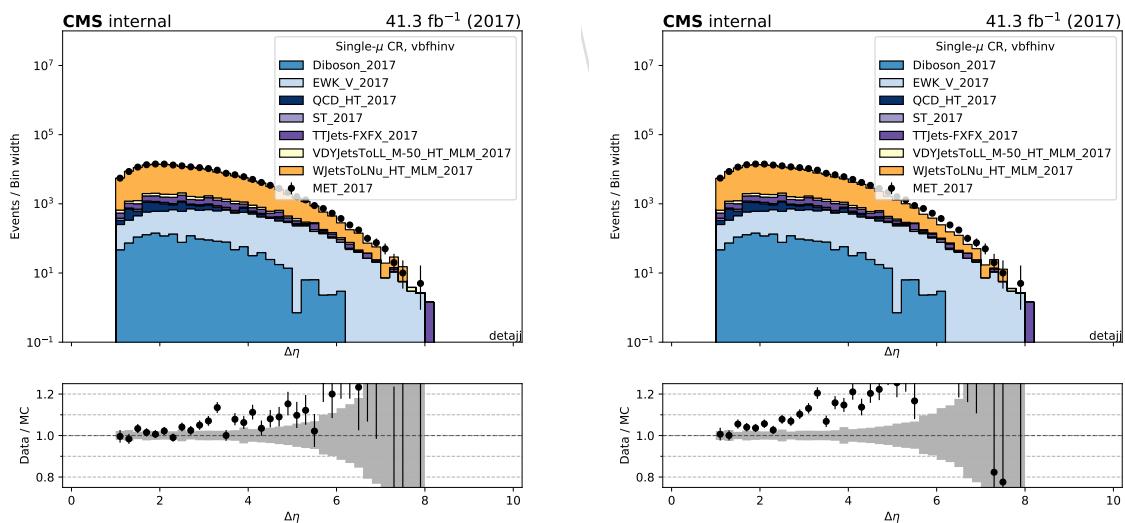


Figure 53: The $\Delta\eta_{jj}$ distribution in the single muon CR for the case in which 1D k-factors are used (left), compared to the case in which 2D k-factors are used (right), using 2017 samples.

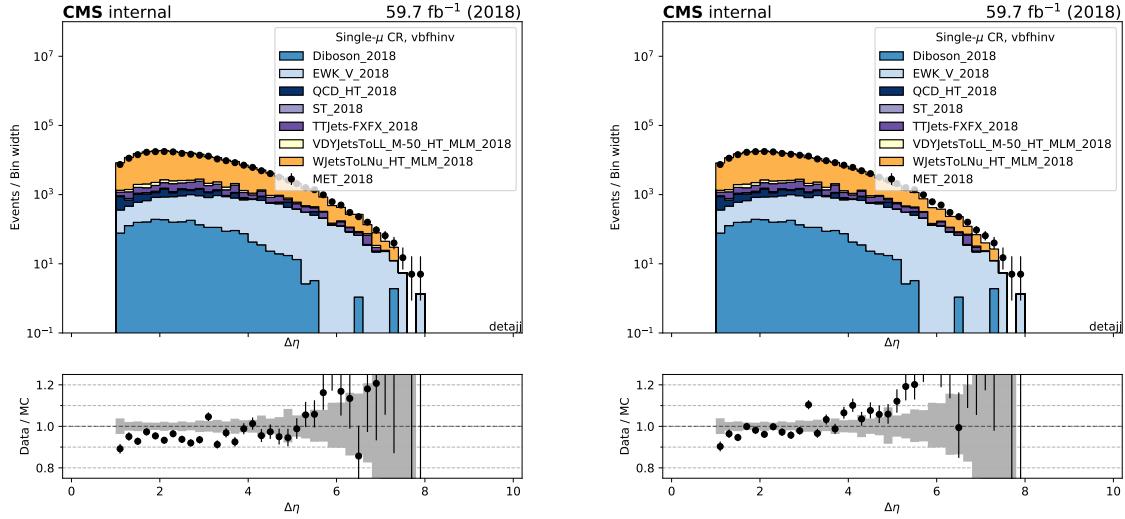


Figure 54: The $\Delta\eta_{jj}$ distribution in the single muon CR for the case in which 1D k-factors are used (left), compared to the case in which 2D k-factors are used (right), using 2018 samples.

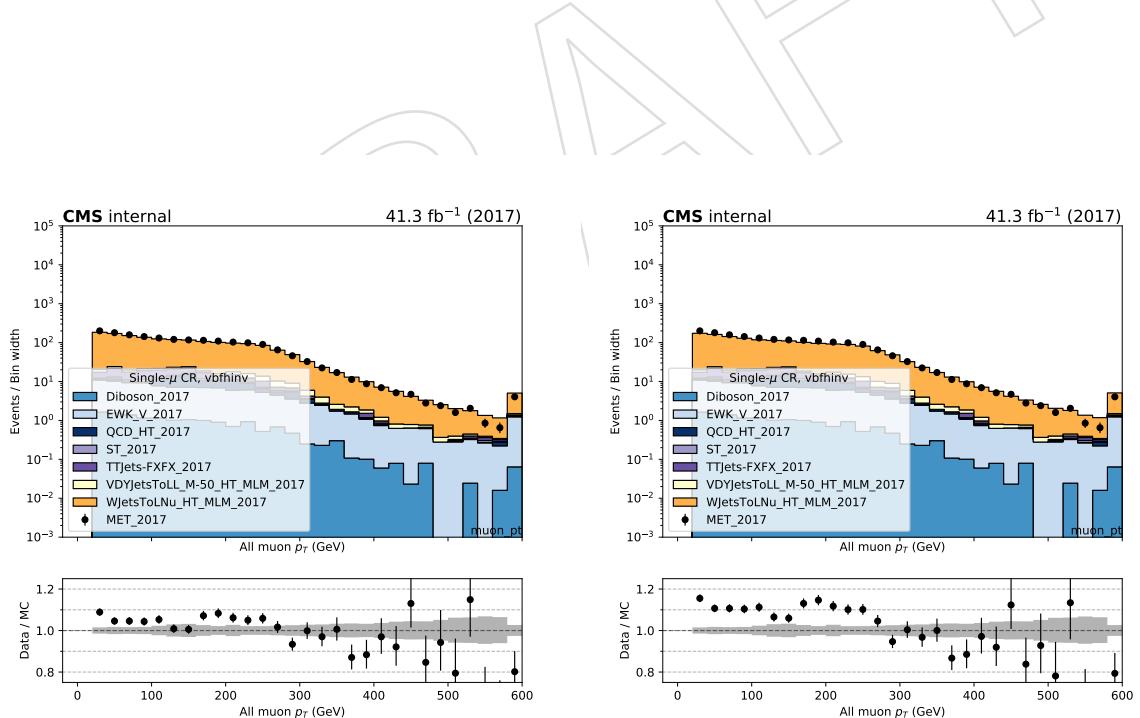


Figure 55: The muon p_T distribution in the single muon CR for the case in which 1D k-factors are used (left), compared to the case in which 2D k-factors are used (right), using 2017 samples.

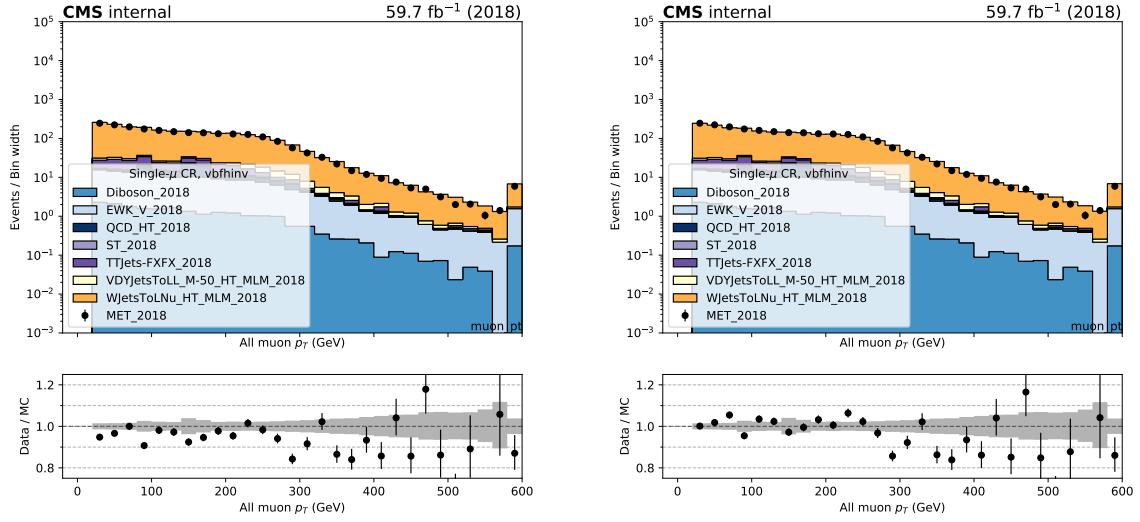


Figure 56: The muon p_T distribution in the single muon CR for the case in which 1D k-factors are used (left), compared to the case in which 2D k-factors are used (right), using 2018 samples.

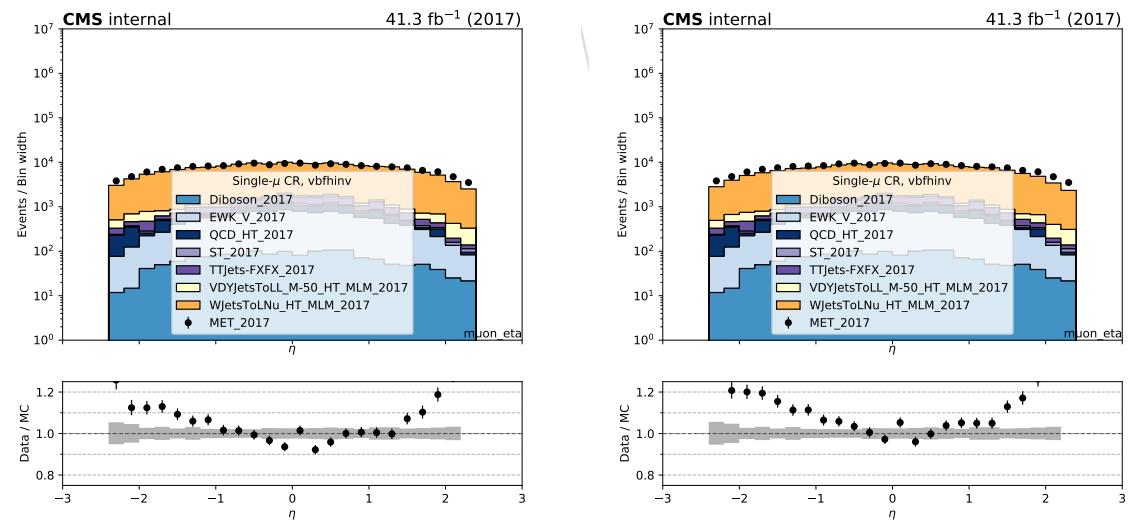


Figure 57: The muon η distribution in the single muon CR for the case in which 1D k-factors are used (left), compared to the case in which 2D k-factors are used (right), using 2017 samples.

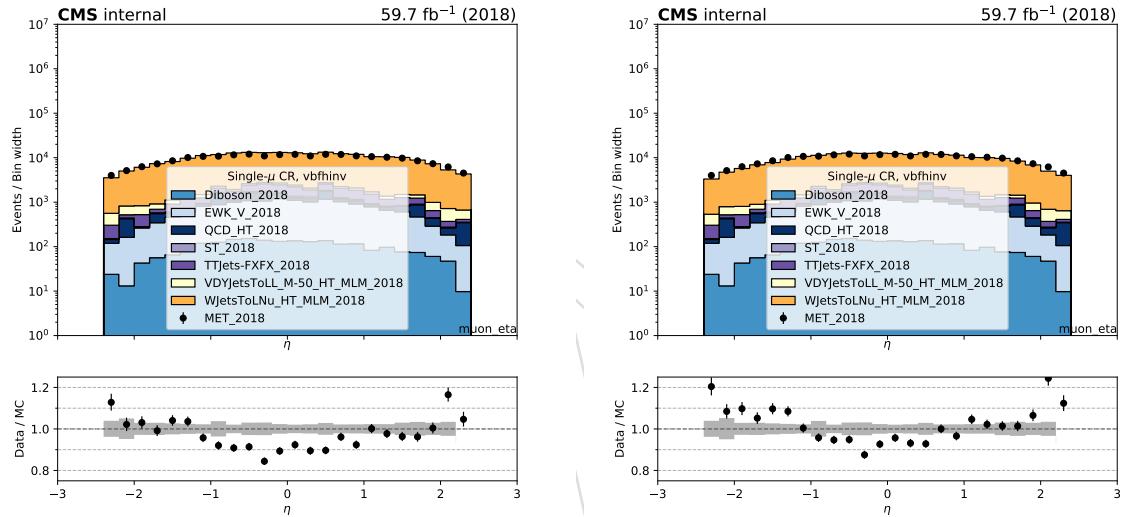


Figure 58: The muon η distribution in the single muon CR for the case in which 1D k-factors are used (left), compared to the case in which 2D k-factors are used (right), using 2018 samples.

684 B Trigger efficiencies in double muon CR

685 In this section, the efficiencies of $p_T^{\text{miss}} + H_T^{\text{miss}}$ triggers measured in double muon control region
 686 are presented. In addition, efficiencies of these triggers as a function of m_{jj} both in single muon
 687 and double muon control region are also presented.

688 Fig. 59 shows the efficiencies as a function of M_{jj} in data and MC for the three categories in
 689 2017, whereas Fig. 60 shows the efficiencies as a function of M_{jj} in data and MC for the three
 690 categories in 2018.

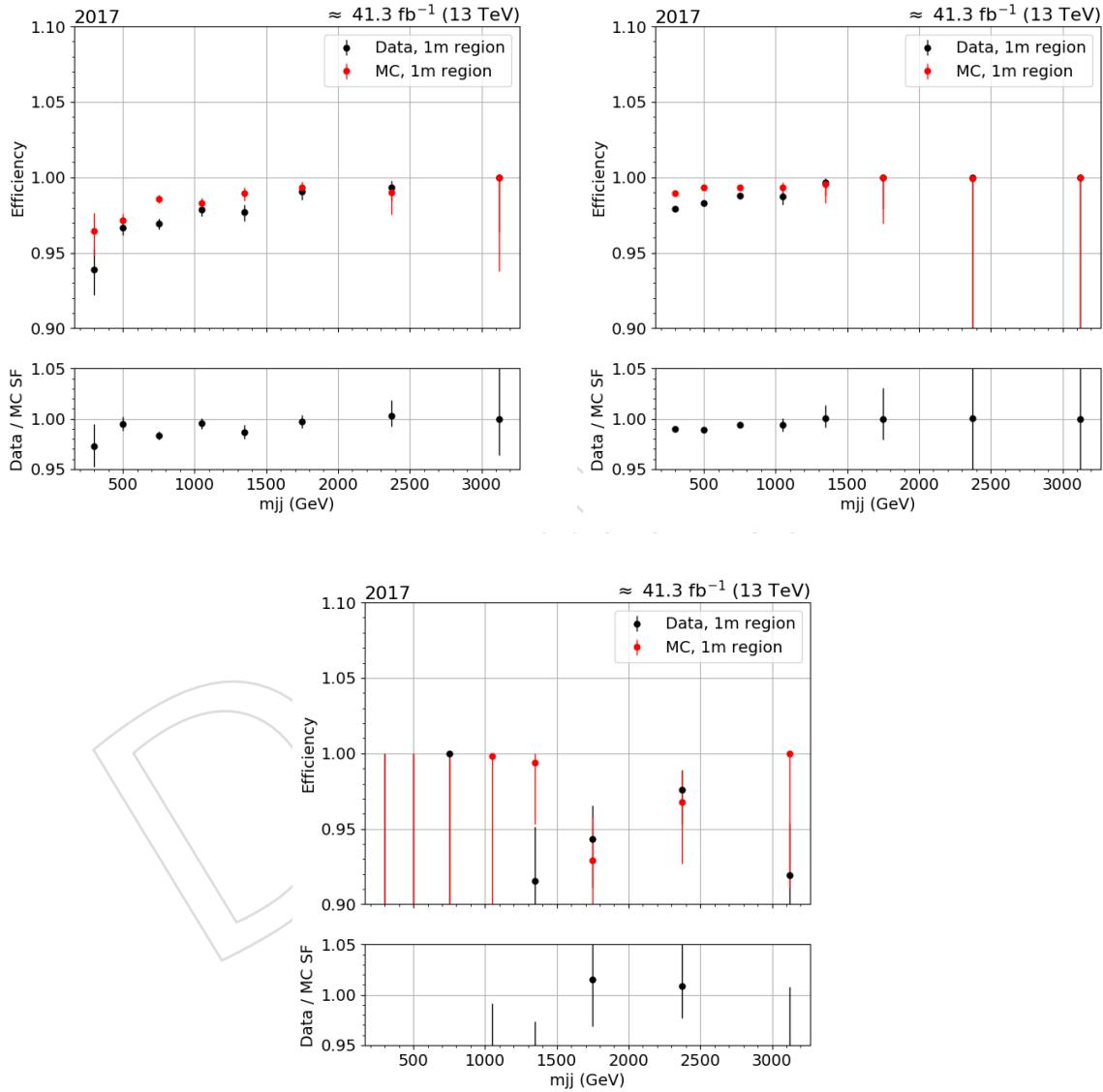


Figure 59: MET trigger efficiency as a function of m_{jj} in three categories: One forward jet and one central jet, two central jets and two forward jets. These results are obtained from 2017 data and MC samples with the selection of single muon events.

691 Figs. 61 and ?? show the efficiencies obtained in double muon CR as a function of recoil in data
 692 and MC for the three jet categories in 2017 and 2018, respectively. Figs. 63 and ?? show the
 693 efficiencies obtained in double muon CR as a function of M_{jj} in data and MC for the three jet

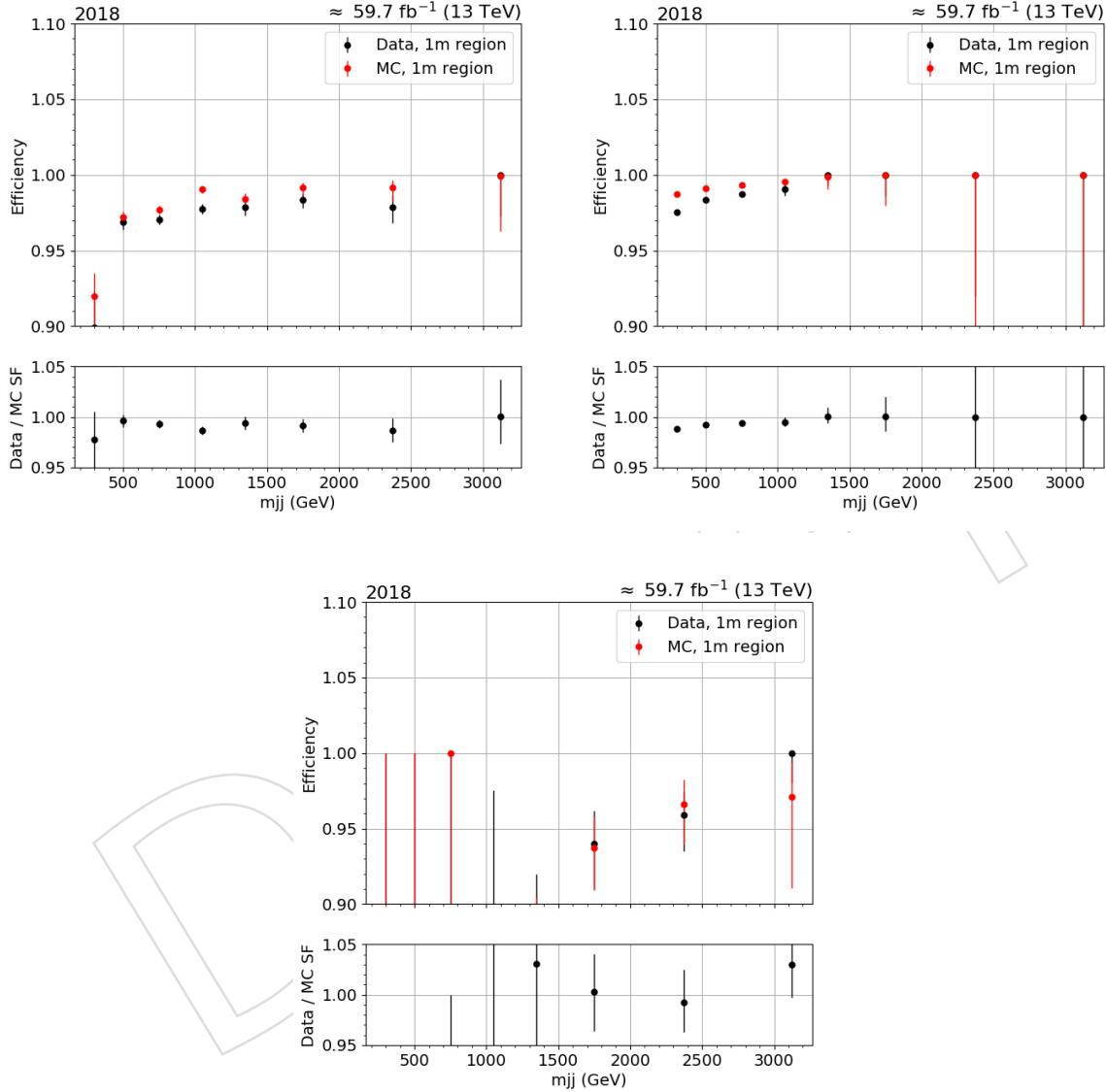


Figure 60: MET trigger efficiency as a function of m_{jj} in three categories: One forward jet and one central jet, two central jets and two forward jets. These results are obtained from 2018 data and MC samples with the selection of single muon events.

categories in 2017 and 2018, respectively.

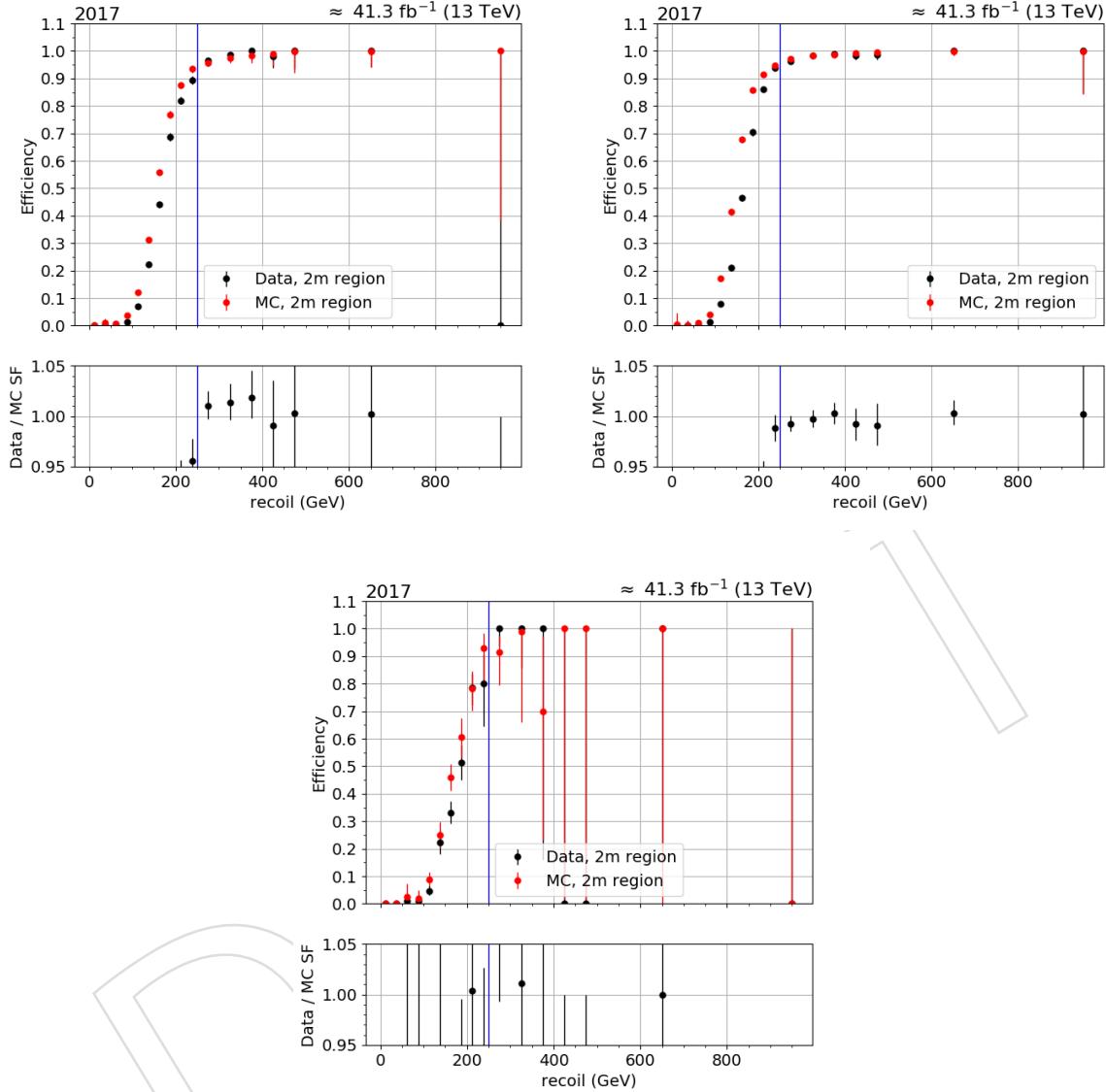


Figure 61: MET trigger efficiency as a function of recoil in three categories: One forward jet and one central jet, two central jets and two forward jets. These results are obtained from 2017 data and MC samples with the selection of double muon events.

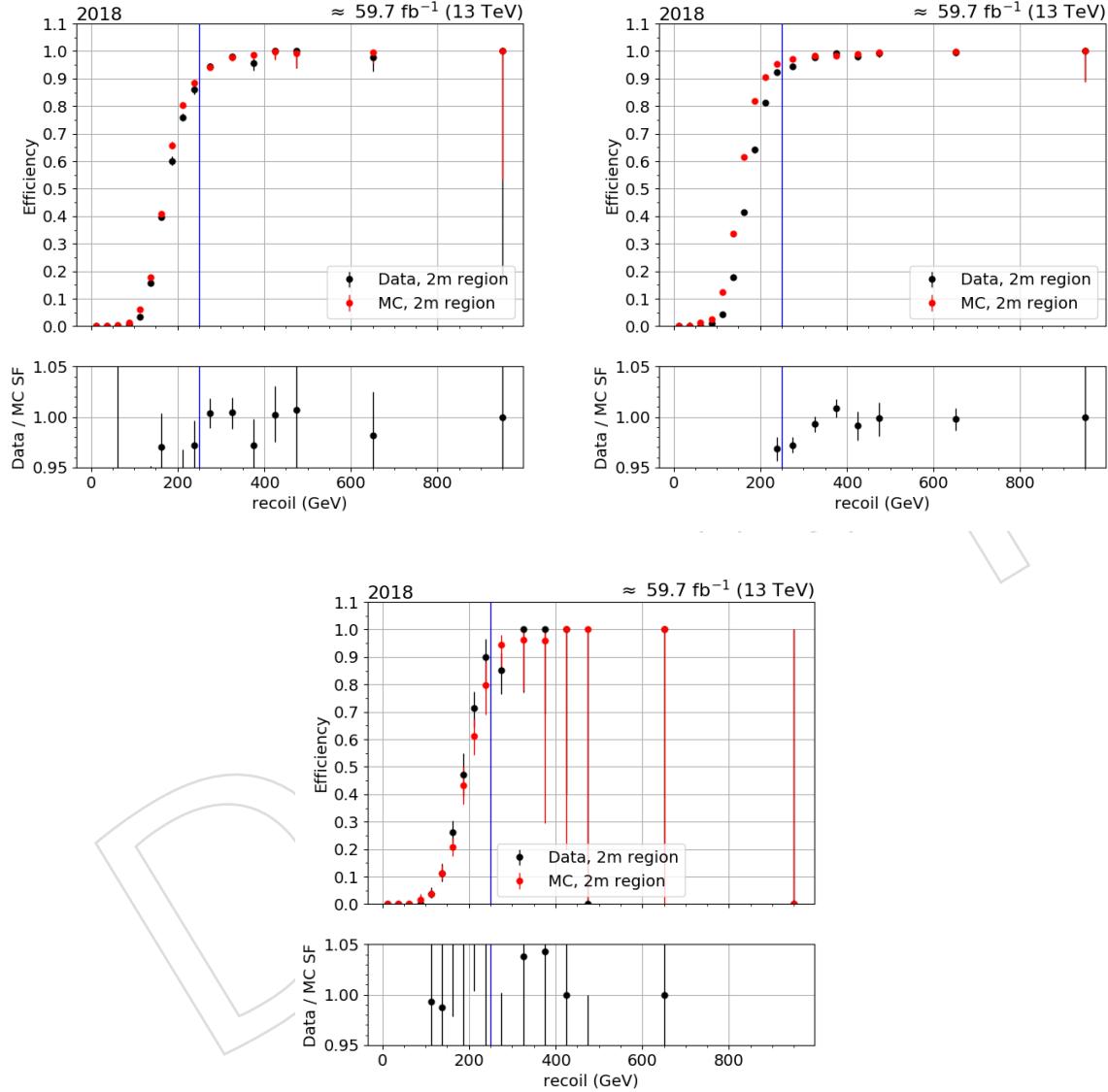


Figure 62: MET trigger efficiency as a function of recoil in three categories: One forward jet and one central jet, two central jets and two forward jets. These results are obtained from 2018 data and MC samples with the selection of double muon events.

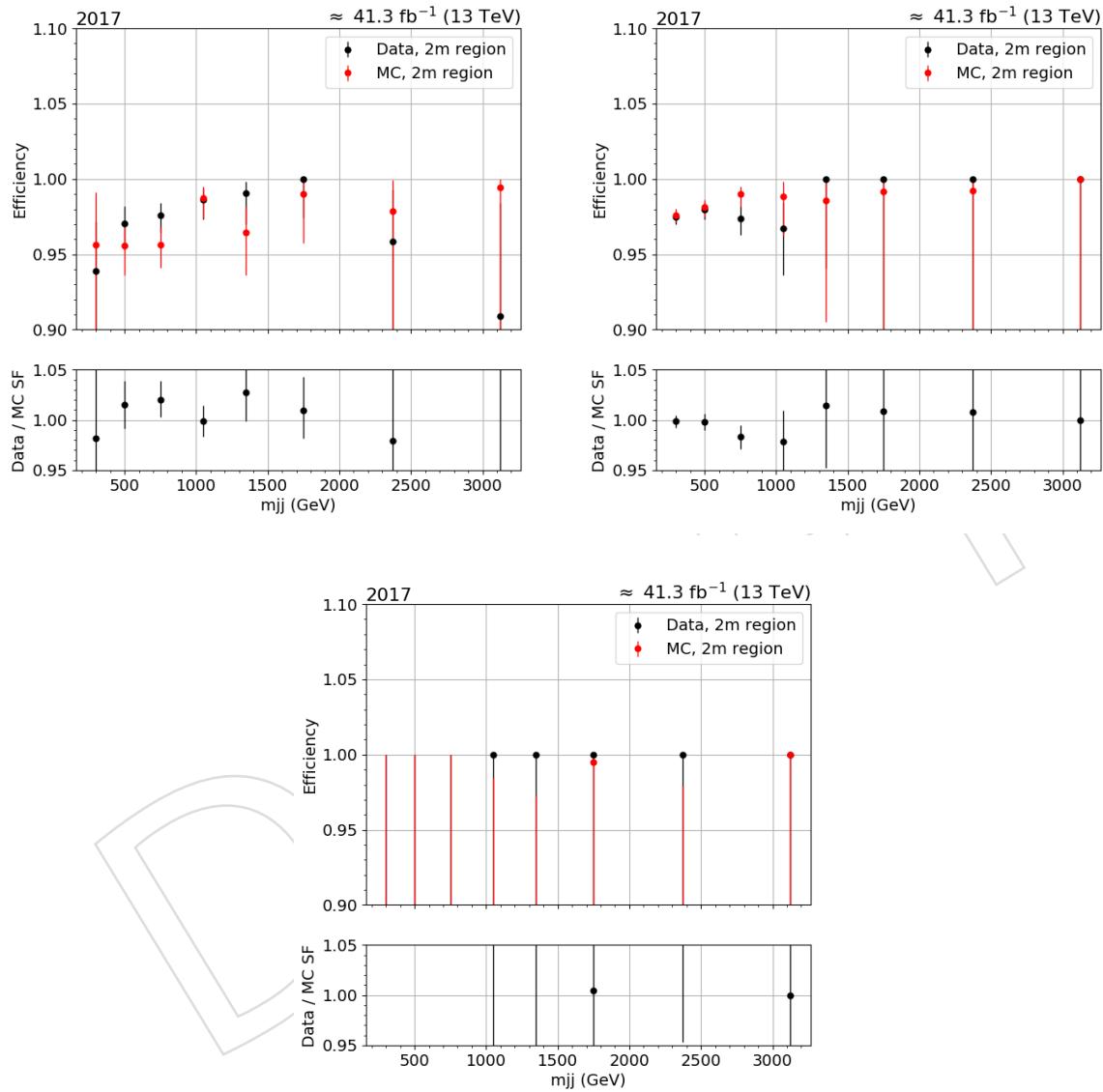


Figure 63: MET trigger efficiency as a function of m_{jj} in three categories: One forward jet and one central jet, two central jets and two forward jets. These results are obtained from 2017 data and MC samples with the selection of double muon events.

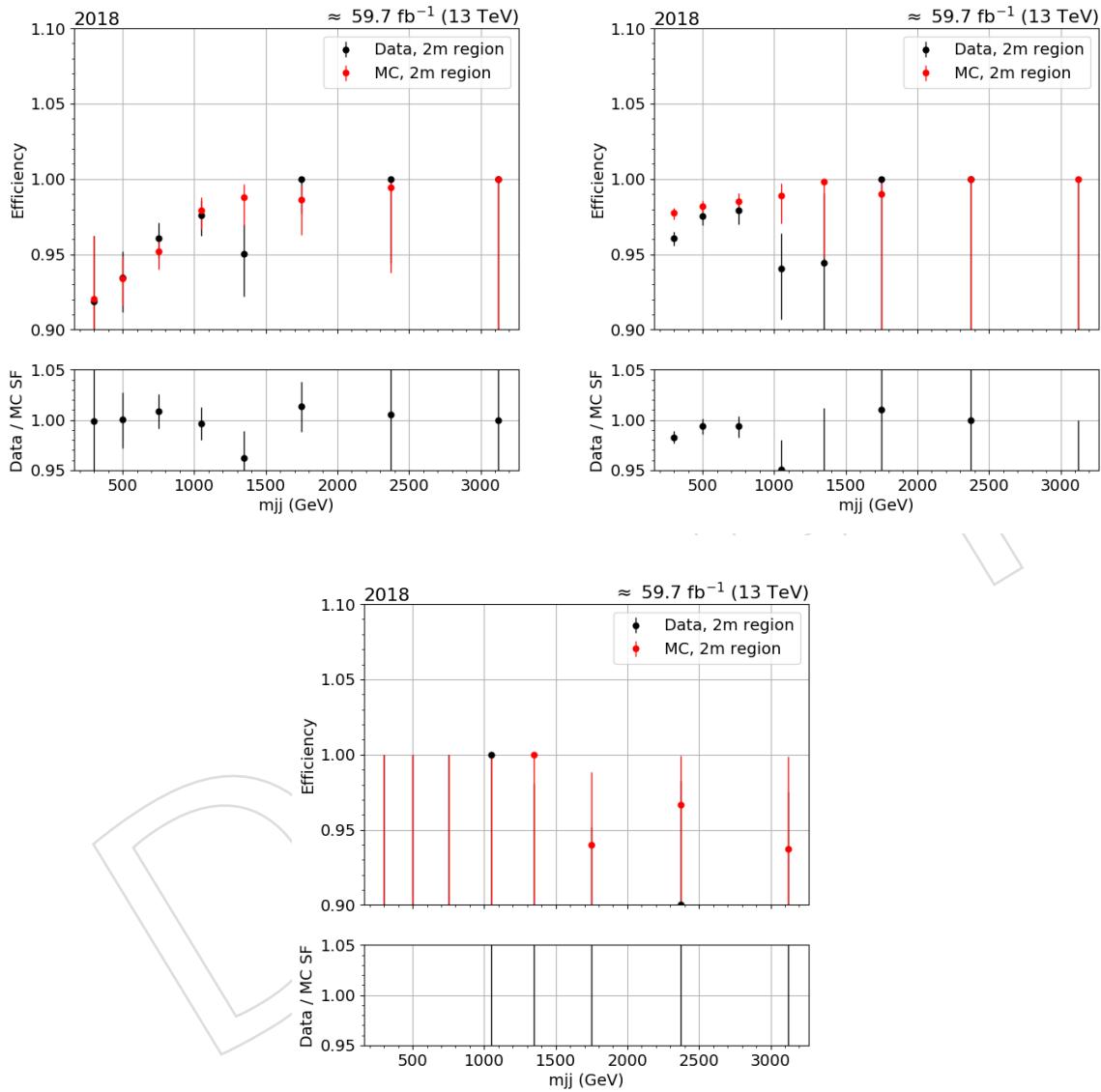


Figure 64: MET trigger efficiency as a function of m_{jj} in three categories: One forward jet and one central jet, two central jets and two forward jets. These results are obtained from 2018 data and MC samples with the selection of double muon events.

695 Acknowledgments

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