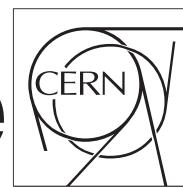


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Measurements of Higgs differential cross section and interpretations in $H \rightarrow ZZ \rightarrow 4\ell$ ($\ell = e, \mu$) channel

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Abstract

Properties of the Higgs boson are measured in the $H \rightarrow ZZ \rightarrow 4\ell$ ($\ell = e, \mu$) decay channel. A data sample of proton-proton collisions at a center-of-mass energy of 13 TeV is used, corresponding to an integrated luminosity of 137 fb^{-1} recorded by the CMS detector at the LHC. The fiducial cross section is measured with respect to several observables sensitive to production and decay of Higgs where the observed results are compared with POWHEG, MADGRAPH5 and NNLOPS theory predictions. The possible interpretations of the results are reported.

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1 Acknowledgments

2 Contents

3	1	Introduction	2
4	2	Datasets, simulation samples and theoretical predictions	3
5	2.1	Triggers and Datasets	3
6	2.2	Simulation samples	6
7	2.3	Simulation samples for interpretations	7
8	3	Objects	8
9	3.1	Electrons	8
10	3.2	Muons	8
11	3.3	Photons for FSR recovery	9
12	3.4	Jets	9
13	4	Signal Modelling	14
14	5	Background Estimation	15
15	5.1	Estimation of ZZ normalization from Data	15
16	6	Analysis Strategy	16
17	6.1	Event Selection	16
18	6.2	Fiducial Volume Significance and Definition	17
19	6.3	Binning strategy for differential observables	18
20	6.4	Unfolding	19
21	6.5	Acceptance and other correction factors	19
22	6.6	Statistical Procedure	20
23	6.7	Extraction of differential $H \rightarrow 4\ell$ cross section	23
24	6.8	Interpretations	27
25	7	Systematic uncertainties	29
26	7.1	Systematic uncertainties treatment when combining the data sets	30
27	8	Results	35
28	8.1	Yields and distributions	35
29	8.2	Differential Cross Sections measurement results	39
30	8.3	Double differential cross section measurements	43
31	8.4	Interpretations	43
32	9	Interpretation	44
33	A	Signal Shapes and Efficiencies	45
34	A.1	Differential bins - Higgs boson transverse momentum	45
35	A.2	Differential bins - rapidity of the Higgs boson	63
36	A.3	Signal fits in differential bins - number of jets	66

37 1 Introduction

38 The ATLAS and CMS collaborations first reported the discovery of a new boson in 2012 [1,
 39 2] consistent with the standard model (SM) Higgs boson [3–8] based on proton-proton (pp)
 40 collisions delivered by the CERN LHC at a center-of-mass energy of $\sqrt{s} = 7\text{ TeV}$ in years 2011
 41 and 8 TeV in 2012. Subsequent studies by CMS using the full LHC Run 1 data set in various
 42 decay channels and production modes and combined measurements from ATLAS and CMS
 43 [9–12] showed that the properties of the new boson are so far consistent with expectations for
 44 the SM Higgs boson.

45 The $H \rightarrow ZZ \rightarrow 4\ell$ decay channel ($\ell = e, \mu$) has a large signal-to-background ratio due to the
 46 complete reconstruction of the final state decay products and excellent lepton momentum res-
 47 olution and is one of the most important channels for studies of the Higgs boson’s properties.
 48 Measurements performed using this decay channel and the Run 1 data set include the deter-
 49 mination of the mass and spin-parity of the new boson [13–15], its width [16, 17] and fiducial
 50 cross sections [18], as well as tests for anomalous HVV couplings [15, 17].

51 In this document we present measurements of the differential fiducial cross sections for the
 52 Higgs boson production in the $H \rightarrow ZZ \rightarrow 4\ell$ decay channel at $\sqrt{s} = 13\text{ TeV}$ using 137 fb^{-1} of
 53 pp collision data collected with the CMS experiment at the LHC in 2016, 2017 and 2018. Differ-
 54 ential measurements for Higgs production variables have already been studied and published
 55 under [19]. In this analysis, in addition, the full available dataset has been fully re-analyzed,
 56 with several improvements:

- 57 • Analysis Ultra Legacy data.
- 58 • Revised measurement of lepton scale factors (Section 3.2.3)
- 59 • several additional (production and as well as decay) observables studied with opti-
 60 mized binning.
- 61 • in addition to POWHEG and NNLOPS, MADGRAPH5_AMC@NLO-FxFx is used as ad-
 62 ditional theory prediction to for comparision of the observed results.
- 63 • Effective Field Theory (EFT) interpretations of differential measurements are also
 64 presented.

65 2 Datasets, simulation samples and theoretical predictions

66 2.1 Triggers and Datasets

67 This analysis uses a ultra legacy data sample recorded by the CMS experiment during 2016,
 68 2017 and 2018, corresponding to 137 fb^{-1} of data.

69 The datasets used for 2016, 2017 and 2018 data taking are listed in Tables 1, 3, and 5, respec-
 70 tively, along with the integrated luminosity. The analysis relies on four different primary
 71 datasets (PDs), *DoubleMuon*, *MuEG*, *EGamma* (or *DoubleEG* and *SingleElectron* for 2016 and
 72 2017), and *SingleMuon*, each of which combines a certain collections of HLT paths. To avoid
 73 duplicate events from different primary datasets, events are taken:

- 74 • from EGamma if they pass the diEle or triEle or singleElectron triggers,
- 75 • from DoubleMuon if they pass the diMuon or triMuon triggers and fail the diEle
 76 and triEle triggers,
- 77 • from MuEG if they pass the MuEle or MuDiEle or DiMuEle triggers and fail the
 78 diEle, triEle, singleElectron, diMuon and triMuon triggers,
- 79 • from SingleMuon if they pass the singleMuon trigger and fail all the above triggers.

80 The HLT paths used for 2016, 2017 and 2018 collision data are listed in Tables 2, 4 and 6, respec-
 81 tively.

Run-range	Dataset	Integrated luminosity
272007-275376	/DoubleMuon/Run2016C-21Feb2020_UL2016_HIPM-v1/MINIAOD /DoubleMuon/Run2016B-21Feb2020_ver1_UL2016_HIPM-v1/MINIAOD /MuonEG/Run2016B-21Feb2020_ver1_UL2016_HIPM-v1/MINIAOD /SingleElectron/Run2016B-21Feb2020_ver1_UL2016_HIPM-v1/MINIAOD /SingleMuon/Run2016B-21Feb2020_ver1_UL2016_HIPM-v1/MINIAOD	5.892 fb^{-1}
275657-276283	/DoubleMuon/Run2016C-17Jul2018-v1/MINIAOD /DoubleEG/Run2016C-21Feb2020_UL2016_HIPM-v1/MINIAOD /MuonEG/Run2016C-21Feb2020_UL2016_HIPM-v1/MINIAOD /SingleElectron/Run2016C-21Feb2020_UL2016_HIPM-v1/MINIAOD /SingleMuon/Run2016C-21Feb2020_UL2016_HIPM-v1/MINIAOD	2.646 fb^{-1}
276315-276811	/DoubleEG/Run2016D-21Feb2020_UL2016_HIPM-v1/MINIAOD /DoubleMuon/Run2016D-21Feb2020_UL2016_HIPM-v1/MINIAOD /MuonEG/Run2016D-21Feb2020_UL2016_HIPM-v1/MINIAOD /SingleElectron/Run2016D-21Feb2020_UL2016_HIPM-v1/MINIAOD /SingleMuon/Run2016D-21Feb2020_UL2016_HIPM-v1/MINIAOD	4.353 fb^{-1}
276831-277420	/DoubleEG/Run2016E-21Feb2020_UL2016_HIPM-v1/MINIAOD /DoubleMuon/Run2016E-21Feb2020_UL2016_HIPM-v1/MINIAOD /MuonEG/Run2016E-21Feb2020_UL2016_HIPM-v1/MINIAOD /SingleElectron/Run2016E-21Feb2020_UL2016_HIPM-v1/MINIAOD /SingleMuon/Run2016E-21Feb2020_UL2016_HIPM-v1/MINIAOD	4.117 fb^{-1}
277772-278808	/DoubleEG/Run2016F-21Feb2020_UL2016_v1/MINIAOD /DoubleMuon/Run2016F-21Feb2020_UL2016_v1/MINIAOD /MuonEG/Run2016F-21Feb2020_UL2016_v1/MINIAOD /SingleElectron/Run2016F-21Feb2020_UL2016_v1/MINIAOD /SingleMuon/Run2016F-21Feb2020_UL2016_v1/MINIAOD	3.186 fb^{-1}
278820-280385	/DoubleEG/Run2016G-21Feb2020_UL2016_v1/MINIAOD /DoubleMuon/Run2016G-21Feb2020_UL2016_v1/MINIAOD /MuonEG/Run2016G-21Feb2020_UL2016_v1/MINIAOD /SingleElectron/Run2016G-21Feb2020_UL2016_v1/MINIAOD /SingleMuon/Run2016G-21Feb2020_UL2016_v1/MINIAOD	7.721 fb^{-1}
280919-284044	/DoubleEG/Run2016H-21Feb2020_UL2016_v1/MINIAOD /DoubleMuon/Run2016H-21Feb2020_UL2016_v1/MINIAOD /MuonEG/Run2016H-21Feb2020_UL2016_v1/MINIAOD /SingleElectron/Run2016H-21Feb2020_UL2016_v2/MINIAOD /SingleMuon/Run2016H-21Feb2020_UL2016_v1/MINIAOD	8.857 fb^{-1}

Table 1: Datasets used in the 2016 analysis.

HLT path	prescale	primary dataset
HLT_Ele17_Ele12_CaloIdL_TrackIdL_IsoVL_DZ	1	DoubleEG
HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_DZ	1	DoubleEG
HLT_DoubleEle33_CaloIdL_GsfTrkIdVL	1	DoubleEG
HLT_Ele16_Ele12_Ele8_CaloIdL_TrackIdL	1	DoubleEG
HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL	1	DoubleMuon
HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL	1	DoubleMuon
HLT_TripleMu_12_10_5	1	DoubleMuon
HLT_Mu8_TrkIsoVVL_Ele17_CaloIdL_TrackIdL_IsoVL	1	MuonEG
HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL	1	MuonEG
HLT_Mu17_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL	1	MuonEG
HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL	1	MuonEG
HLT_Mu23_TrkIsoVVL_Ele8_CaloIdL_TrackIdL_IsoVL	1	MuonEG
HLT_Mu8_DiEle12_CaloIdL_TrackIdL	1	MuonEG
HLT_DiMu9_Ele9_CaloIdL_TrackIdL	1	MuonEG
HLT_Ele25_eta2p1_WPTight	1	SingleElectron
HLT_Ele27_WPtight	1	SingleElectron
HLT_Ele27_eta2p1_WPLoose_Gsf	1	SingleElectron
HLT_IsoMu20 OR HLT_IsoTkMu20	1	SingleMuon
HLT_IsoMu22 OR HLT_IsoTkMu22	1	SingleMuon

Table 2: Trigger paths used in 2016 collision data.

Run-range	Dataset	Integrated luminosity
297046-299329	/DoubleMuon/Run2017B-UL2017_MiniAODv2-v1/MINIAOD /DoubleEG/Run2017B-09Aug2019_UL2017-v1/MINIAOD /MuonEG/Run2017B-UL2017_MiniAODv2-v1/MINIAOD /SingleElectron/Run2017B-UL2017_MiniAODv2-v1/MINIAOD /SingleMuon/Run2017B-09Aug2019_UL2017-v1/MINIAOD	4.792 fb ⁻¹
299368-300676	/DoubleMuon/Run2017C-UL2017_MiniAODv2-v1/MINIAOD /DoubleEG/Run2017C-UL2017_MiniAODv2-v2/MINIAOD /MuonEG/Run2017C-UL2017_MiniAODv2-v1/MINIAOD /SingleElectron/Run2017C-UL2017_MiniAODv2-v1/MINIAOD /SingleMuon/Run2017C-09Aug2019_UL2017-v1/MINIAOD	9.755 fb ⁻¹
302030-303434	/DoubleMuon/Run2017D-UL2017_MiniAODv2-v1/MINIAOD /DoubleEG/Run2017D-UL2017_MiniAODv2-v1/MINIAOD /MuonEG/Run2017D-UL2017_MiniAODv2-v1/MINIAOD /SingleElectron/Run2017D-09Aug2019_UL2017-v1/MINIAOD /SingleMuon/Run2017D-09Aug2019_UL2017-v1/MINIAOD	4.319 fb ⁻¹
303824-304797	/DoubleMuon/Run2017E-09Aug2019_UL2017-v1/MINIAOD /DoubleEG/Run2017E-UL2017_MiniAODv2-v1/MINIAOD /MuonEG/Run2017E-UL2017_MiniAODv2-v1/MINIAOD /SingleElectron/Run2017E-UL2017_MiniAODv2-v1/MINIAOD /SingleMuon/Run2017E-09Aug2019_UL2017-v1/MINIAOD	9.424 fb ⁻¹
305040-306462	/DoubleMuon/Run2017F-UL2017_MiniAODv2-v1/MINIAOD /DoubleEG/Run2017F-09Aug2019_UL2017-v1/MINIAOD /MuonEG/Run2017F-UL2017_MiniAODv2-v1/MINIAOD /SingleElectron/Run2017F-UL2017_MiniAODv2-v1/MINIAOD /SingleMuon/Run2017F-09Aug2019_UL2017-v1/MINIAOD	13.50 fb ⁻¹
278820-280385	/DoubleMuon/Run2017G-09Aug2019_UL2017-v1/MINIAOD /DoubleEG/Run2017G??_MINIAOD /MuonEG/Run2017G??_MINIAOD /SingleElectron/Run2017G??_MINIAOD /SingleMuon/Run2017G?_MINIAOD	7.721 fb ⁻¹
281207-284068	/DoubleMuon/Run2017H-UL2017_MiniAODv2-v1/MINIAOD /DoubleEG/Run2017??_MINIAOD /MuonEG/Run2017H??_MINIAOD /SingleElectron/Run2017H??_MINIAOD /SingleMuon/Run2017H??_MINIAOD	8.857 fb ⁻¹

Table 3: Datasets used in the 2017 analysis.

HLT path	prescale	primary dataset
HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_*	1	DoubleEG
HLT_DoubleEle33_CaloIdL_GsfTrkIdVL	1	DoubleEG
HLT_Ele16_Ele12_Ele8_CaloIdL_TrackIdL	1	DoubleEG
HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass3p8	1	DoubleMuon
HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass8	1	DoubleMuon
HLT_TripleMu_12_10_5	1	DoubleMuon
HLT_TripleMu_10_5_5_D2	1	DoubleMuon
HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL	1	MuonEG
HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ	1	MuonEG
HLT_Mu12_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ	1	MuonEG
HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_DZ	1	MuonEG
HLT_DiMu9_Ele9_CaloIdL_TrackIdL_DZ	1	MuonEG
HLT_Mu8_DiEle12_CaloIdL_TrackIdL	1	MuonEG
HLT_Mu8_DiEle12_CaloIdL_TrackIdL_DZ	1	MuonEG
HLT_Ele35_WPTight_Gsf_v*	1	SingleElectron
HLT_Ele38_WPTight_Gsf_v*	1	SingleElectron
HLT_Ele40_WPTight_Gsf_v*	1	SingleElectron
HLT_IsoMu27	1	SingleMuon

Table 4: Trigger paths used in 2017 collision data.

Run-range	Dataset	Integrated luminosity
315252-316995	/DoubleMuon/Run2018A-UL2018_MiniAODv2-v1/MINIAOD /MuonEG/Run2018A-12Nov2019_UL2018_rsb-v1/MINIAOD /EGamma/Run2018A-12Nov2019_UL2018-v2/MINIAOD /SingleMuon/Run2018A-UL2018_MiniAODv2-v1/MINIAOD	X.XXX fb ⁻¹
317080-319310	/DoubleMuon/Run2018B-UL2018_MiniAODv2-v2/MINIAOD /MuonEG/Run2018B-12Nov2019_UL2018-v1/MINIAOD /EGamma/Run2018B-UL2018_MiniAODv2-v1/MINIAOD /SingleMuon/Run2018B-12Nov2019_UL2018-v2/MINIAOD	X.XXX fb ⁻¹
319337-320065	/DoubleMuon/Run2018C-12Nov2019_UL2018-v2/MINIAOD /MuonEG/Run2018C-12Nov2019_UL2018-v1/MINIAOD /EGamma/Run2018C-UL2018_MiniAODv2-v1/MINIAOD /SingleMuon/Run2018C-12Nov2019_UL2018-v2/MINIAOD	X.XXX fb ⁻¹
320673-325175	/DoubleMuon/Run2018D-UL2018_MiniAODv2-v1/MINIAOD /MuonEG/Run2018D-12Nov2019_UL2018_rsb-v1/MINIAOD /EGamma/Run2018D-UL2018_MiniAODv2-v1/MINIAOD /SingleMuon/Run2018D-12Nov2019_UL2018-v4/MINIAOD	X.XXX fb ⁻¹

Table 5: Datasets used in the 2018 analysis.

HLT path	prescale	primary dataset
HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_v*	1	DoubleEG
HLT_DoubleEle25_CaloIdL_MW_v*	1	DoubleEG
HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass3p8_v*	1	DoubleMuon
HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_v*	1	MuonEG
HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ_v*	1	MuonEG
HLT_Mu12_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ_v*	1	MuonEG
HLT_DiMu9_Ele9_CaloIdL_TrackIdL_DZ_v*	1	MuonEG
HLT_Ele32_WPTight_Gsf_v*	1	SingleElectron
HLT_IsoMu24_v*	1	SingleMuon

Table 6: Trigger paths used in 2018 collision data.

82 2.1.1 Trigger Efficiency

83 The efficiency in data of the combination of triggers used in the analysis with respect to the
 84 offline reconstruction and selection is measured by considering 4ℓ events triggered by single
 85 lepton triggers. Details on the procedures are described in $H \rightarrow ZZ \rightarrow 4\ell$ ($\ell = e, \mu$) analyses
 86 common note [19].

87 A summary of the trigger efficiencies in MC truth, and in MC and data using the tag and probe
 88 method are summarized in table 7. The trigger efficiency in simulation is found to be $> 99\%$ in
 89 each final state.

Final State	$gg \rightarrow H$ MC	$gg \rightarrow H$ MC (matching)	Data (matching)
$4e$	$0.991^{+.002}_{-.002}$	$0.948^{+.004}_{-.004}$	$0.982^{+.005}_{-.007}$
4μ	$0.997^{+.001}_{-.001}$	$0.997^{+.001}_{-.001}$	$1.000^{+.000}_{-.001}$
$2e2\mu$	$0.995^{+.001}_{-.001}$	$0.964^{+.002}_{-.002}$	$0.983^{+.003}_{-.004}$

Table 7: Trigger efficiencies measured using 4ℓ events in 2018 data (TBU).

90 2.2 Simulation samples

91 2.2.1 Signal Samples

92 Descriptions of the SM Higgs boson production are obtained using the POWHEG V2 [20–22]
 93 generator for the five main production modes: gluon fusion ($gg \rightarrow H$) including quark mass
 94 effects [23], vector boson fusion (VBF) [24], and associated production (WH, ZH and $t\bar{t} H$ [25]).
 95 The simulation of Higgs production through gluon fusion i.e. $gg \rightarrow H$ production at next-
 96 to-next-to-leading order (NNLO) is obtained by NNLOPS [26] and is used in the analysis as
 97 reference theory predictions for observed differential cross section results. A dedicated studies
 98 using MADGRAPH5_AMC@NLO-FxFx generators with next-to-leading order (NLO) accuracy
 99 is done for $gg \rightarrow H$ production as additional theoretical predication for fiducial cross section
 100 measurement. Details are described in Section 2.2.1. In the case of WH and ZH the MINLO
 101 HVJ extension of POWHEG is used [27]. The description of the decay of the Higgs boson to
 102 four leptons is obtained using the JHUGEN generator [28]. In the case of WH, ZH and $t\bar{t} H$,
 103 the Higgs boson is allowed to decay to $H \rightarrow ZZ \rightarrow 2\ell^2 X$ such that 4-lepton events where two
 104 leptons originate from the decay of associated Z, W bosons or top quarks are also taken into
 105 account in the simulation. Showering of parton-level events is done using PYTHIA8.209, and in
 106 all cases matching is performed by allowing QCD emissions at all energies in the shower and
 107 vetoing them afterwards according to the POWHEG internal scale. All samples are generated
 108 with the NNPDF 3.1 NLO parton distribution functions (PDFs) [29]. The list of signal samples
 109 and their cross sections are shown in Table 8. For each year, corresponding simulation samples
 110 are reweighted to match the pileup distribution in data for which details are described in [19].

111 Simulation of Higgs production using MADGRAPH5

112 To be updated.

113 2.2.2 Background Samples

114 Production of ZZ via quark-antiquark annihilation is generated at next-to-leading order (NLO)
 115 using POWHEG V2 [30] and PYTHIA8, with the same settings as for the Higgs signal. As this
 116 simulation covers a large range of ZZ invariant masses, dynamical QCD factorization and
 117 renormalization scales have been chosen, equal to m_{ZZ} .

118 The $gg \rightarrow ZZ$ process is simulated at leading order (LO) with MCFM [31, 32]. In order to match
 119 the $gg \rightarrow H \rightarrow ZZ$ transverse momentum spectra predicted by POWHEG at NLO, the showering

Process	Dataset Name	$\sigma \times BR(\times \epsilon_{\text{filter}})$
$gg \rightarrow H(124) \rightarrow ZZ \rightarrow 4\ell$	/GluGluHToZZTo4L_M124_13TeV_powheg2_JHUGenV7011_pythia8/[1]	12.18 fb
$gg \rightarrow H(125) \rightarrow ZZ \rightarrow 4\ell$	/GluGluHToZZTo4L_M125_13TeV_powheg2_JHUGenV7011_pythia8/[1]	12.18 fb
$gg \rightarrow H(126) \rightarrow ZZ \rightarrow 4\ell$	/GluGluHToZZTo4L_M126_13TeV_powheg2_JHUGenV7011_pythia8/[1]	12.18 fb
$qq \rightarrow Hqq \rightarrow ZZqq \rightarrow 4\ell qq$	/VBF_HToZZTo4L_M125_13TeV_powheg2_JHUGenV709_pythia8/[1]	1.044 fb
$qq \rightarrow W^+H \rightarrow W^+ZZ \rightarrow 4\ell + X$	/WplusH_HToZZTo4L_M125_13TeV_powheg2-minlo-HWJ_JHUGenV7011_pythia8/[1]	0.232 fb
$qq \rightarrow W^-H \rightarrow W^-ZZ \rightarrow 4\ell + X$	/WminusH_HToZZTo4L_M125_13TeV_powheg2-minlo-HWJ_JHUGenV7011_pythia8/[1]	0.147 fb
$qq \rightarrow ZH \rightarrow ZZZ \rightarrow 4\ell + X$	/ZH_HToZZ_4LFitter_M125_13TeV_powheg2-minlo-HZJ_JHUGenV7011_pythia8/[1]	0.668 fb
$gg \rightarrow ttH \rightarrow ttZZ \rightarrow 4\ell + X$	/ttH_HToZZ_4LFitter_M125_13TeV_powheg_JHUGenV7011_pythia8/[1]	0.393 fb
$gg \rightarrow bbH \rightarrow bbZZ \rightarrow 4\ell + X$	/bbH_HToZZTo4L_M125_13TeV_JHUGenV7011_pythia8/[1]	0.135 fb
$q\bar{q}/qg \rightarrow tHq \rightarrow tqZZ \rightarrow 4\ell + X$	/tqH_HToZZTo4L_M125_13TeV_JHUGenV7011_pythia8/[1]	0.0213 fb

[1] HIG-RunIISummer20UL18wmLHEGEN-000*

Table 8: Signal Monte Carlo samples and cross sections.

Process	Dataset Name	$\sigma \cdot BR$
$qq \rightarrow ZZ \rightarrow 4\ell$	/ZZTo4L_TuneCP5_13TeV_powheg_pythia8/	1.256 pb
$qq \rightarrow ZZ \rightarrow 4\ell$	/ZZTo4L_TuneCP5_13TeV_amcatnloFXFX_pythia8/	1.212 pb
$gg \rightarrow ZZ \rightarrow 4e$	/GluGluToContinToZZTo4e_13TeV_MCFM701/	0.00159 pb
$gg \rightarrow ZZ \rightarrow 4\tau$	/GluGluToContinToZZTo4mu_13TeV_MCFM701/	0.00159 pb
$gg \rightarrow ZZ \rightarrow 2e2\tau$	/GluGluToContinToZZTo2e2mu_13TeV_MCFM701/	0.00319 pb
$Z \rightarrow \ell\ell + \text{jets}$	/DYJetsToLL_M-50_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8/	6104 pb
$Z \rightarrow \ell\ell + \text{jets}$	/DYJetsToLL_M-10to50_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8/	18610 pb
$WZ \rightarrow 3\ell\nu$	/WZTo3LNu_TuneCUETP8M1_13TeV-powheg_pythia8/	4.430 pb
$t\bar{t}$	/TTJets_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8/	815.96 pb
$t\bar{t} \rightarrow 2\ell 2\nu 2b$	/TTTo2L2Nu_13TeV-powheg/	87.31 pb
ZZZ	/ZZZ_TuneCUETP8M1_13TeV-amcatnlo_pythia8/	0.01398 pb
WZZ	/WZZ_TuneCUETP8M1_13TeV-amcatnlo_pythia8/	0.05565 pb
WWZ	/WWZ_TuneCUETP8M1_13TeV-amcatnlo_pythia8/	0.1651 pb
$t\bar{t}+ZZ$	/TTZZ_TuneCUETP8M2T4_13TeV-madgraph_pythia8/	0.001572 pb
$t\bar{t}+WW$	/TTWW_TuneCUETP8M2T4_3TeV - madgraph - pythia8/	0.007883 pb
$t\bar{t}+Z$	/ttZJets_13TeV_madgraphMLM/	0.259 pb

Table 9: Background Monte Carlo samples and cross sections.

- for MCFM samples is performed with different PYTHIA8 settings, allowing only emissions up to the parton-level scale (“wimpy” shower). Although not directly used to model data observations, additional MC samples of WZ , Drell-Yan+jets, $t\bar{t}$, and tribosons are generated using MADGRAPH5_AMCANTNLO [33] either inclusively or merging several jet multiplicities, as detailed in the table. Table 9 summarizes the MC simulation datasets used for this analysis.

2.3 Simulation samples for interpretations

127 **3 Objects**

128 This analysis follows the same object defintion as in [34] for each year. Detailed description
 129 on objection definitions and scale factors can be found in the corresponding analysis note [19].
 130 Since this analysis is based on Ultra Legacy (UL) full Run 2 data, most of the objects related
 131 ingredients will be reevaluated with respect to [19].

132 The reconstruction of the SM Higgs boson in the decay chain $H \rightarrow ZZ \rightarrow 4\ell$ requires very
 133 efficient lepton reconstruction and identification in order to be sensitive to a low mass Higgs,
 134 for which at least one of the leptons has a p_T within the range 5 - 15 GeV. In this kinematic
 135 region the need is for an optimal efficiency, while retaining the rate of misidentified leptons
 136 low enough. On the same time, to allow a precise measurement of the Higgs boson mass and
 137 together properties, which depend on the lepton kinematics, the analysis needs a precise mo-
 138 mentum measurement. For both reasons, the analysis will make use of high statistics sources
 139 of prompt leptons to measure efficiency, mis-identification rate, and energy scale/resolution.
 140 Muon Efficiency measuremens using UL dataset are described as follows:

141 **3.1 Electrons**

142 **3.1.1 Electron Reconstruction and Identification**

143 Referred to [19].

144 **3.1.2 Electron Energy Calibrations**

145 Referred to [19].

146 **3.1.3 Electron Efficiency Measurements**

147 Referred to [19].

148 **3.2 Muons**

149 **3.2.1 Muon Reconstruction and Identification**

150 Referred to [19].

151 **3.2.2 Muon Energy Calibrations**

152 Referred to [19].

153 **3.2.3 Muon Efficiency Measurements**

154 Muon efficiencies are measured with the Tag and Probe (T&P) method performed on $Z \rightarrow \mu\mu$
 155 and $J/\psi \rightarrow \mu\mu$ events in bins of p_T and η . More details on the methodology can be found
 156 in Ref. [35]. Measurements are extracted using 2016, 2017 and 2018 UL data. The Z sample
 157 is used to measure the muon reconstruction and identification efficiency at high p_T , and the
 158 efficiency of the isolation and impact parameter requirements at all p_T . The J/ψ sample is used
 159 to measure the reconstruction efficiency at low p_T , as it benefits from a better purity in that
 160 kinematic regime.

161 **Reconstruction and identification** Results for the muon reconstruction and identification
 162 efficiency for $p_T > 20$ GeV have been derived by the Muon POG. However, results for low p_T
 163 muons were derived using J/ψ events, with the same definitions of probe and passing probes.
 164 Events are selected using `HLT_Mu8_v*` or `HLT_Mu17_v*` or `HLT_Mu20_v*` triggers. The probe

165 in this measurement are tracks reconstructed in the inner tracker, and the passing probes are
 166 those that are also reconstructed as a global or tracker muon and passing the Muon POG Loose
 167 muon identification.

168 Details on the procedure can be found in Ref. [35]. The efficiency and scale factors used for low
 169 p_T muons are the ones derived using single muon ultra-legacy dataset.

170 The efficiency in data and simulation is shown in Fig. 1.

171 **Impact parameter requirements** The measurement is performed using Z events. Events
 172 are selected with `HLT_IsoMu20_v*` or `HLT_IsoMu22_v*` or `HLT_IsoMu22_eta2p1_v*` for
 173 2016, `HLT_IsoMu27_v*` for 2017 and `HLT_IsoMu24_v*` for 2018 measurements. For this mea-
 174 surement, the probe is a muon passing the POG Loose identification criteria, and it is consid-
 175 ered a passing probe if it satisfies the SIP3D, dxy , dz cuts of this analysis. The results are shown
 176 in Fig. 2.

177 **Isolation requirements** The isolation efficiency is measured using events from the Z decay
 178 for any p_T . The events are selected with the triggers as required for impact parameter require-
 179 ments measurements as explained in previous paragraph. To fit the FSR contribution in the
 180 low mass region, MC template convoluted with the Gaussian is used to better fit the dimuon
 181 invariant mass.

182 The results are shown in Fig. 3.

183 **Tracking** The efficiency to reconstruct a muon track in the inner detector can be measured
 184 using as probes tracks reconstructed in the muon system alone. However, since it comes out to
 185 be 100%, it is no more recommended by muon POG.

186 **Overall results** The product of all the data to simulation scale factors for muon tracking,
 187 reconstruction, identification, impact parameter and isolation requirements is shown in Fig. 4.
 188 The systematic effects on measurements are estimated by ¹:

- 189 1. Varying the analytical signal and background shape models used to fit the dimuon in-
 190 variant mass
- 191 2. Increasing and decreasing the number of bins in dimuon mass distribution
- 192 3. Increasing and decreasing the dimuon mass range
- 193 4. Relaxing and tightening a selection cut on tag muons

194 3.3 Photons for FSR recovery

195 Referred to [19].

196 3.4 Jets

197 Referred to [19].

¹For low p_T measurements of reconstruction and identification only first three systematic sources are used as recommended by muon POG

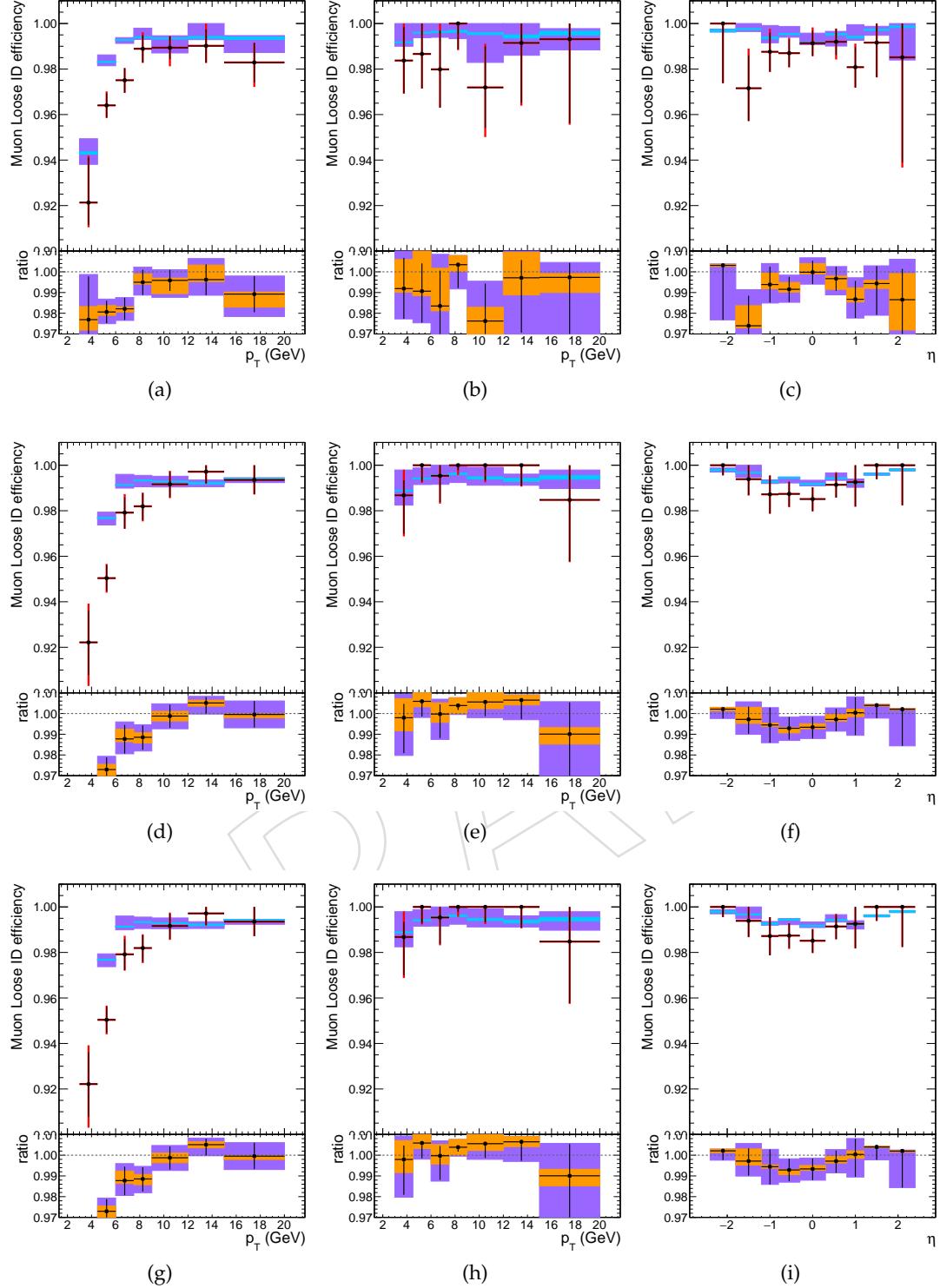


Figure 1: Muon reconstruction and identification efficiency at low p_T , measured with the tag&probe method on J/ψ events, as function of p_T in the barrel (left) and endcaps (center), and as function of η for $p_T > 7\text{ GeV}$ (right), for 2016 (top), 2017 (middle) and 2018 (bottom). In the upper panel, the larger error bars include also the systematical uncertainties, while the smaller ones are purely statistical. In the lower panel showing the ratio of the two efficiencies, the black error bars are for the statistical uncertainty, the orange rectangles for the systematical uncertainty and the violet rectangles include both uncertainties.

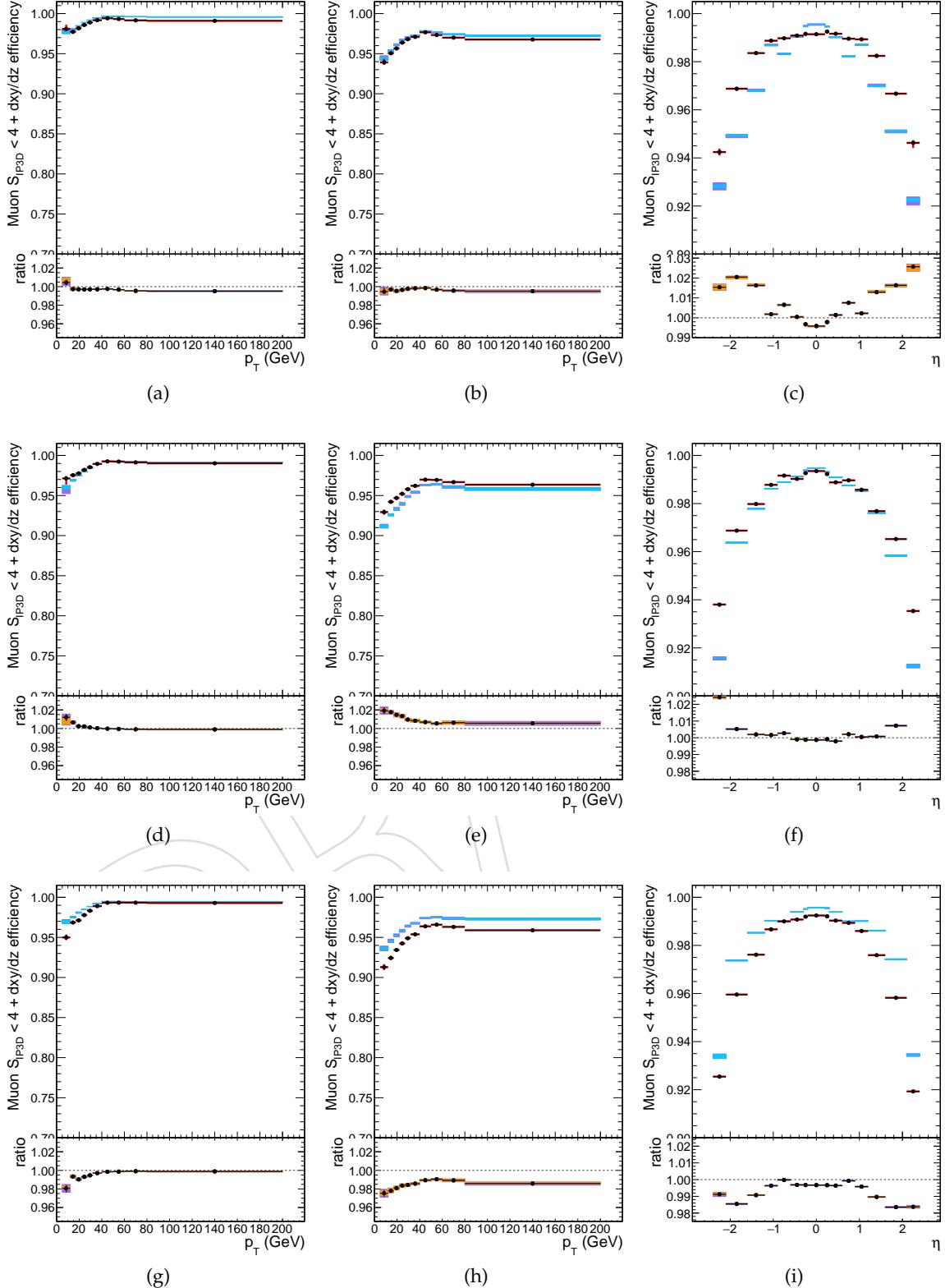


Figure 2: Efficiency of the muon impact parameter requirements, measured with the tag&probe method on Z events, as function of p_T in the barrel (left) and endcaps (center), and as function of η for $p_T > 20$ GeV (right), for 2016 (top), 2017 (middle) and 2018 (bottom). In the upper panel, the larger error bars include also the systematical uncertainties, while the smaller ones are purely statistical. In the lower panel showing the ratio of the two efficiencies, the black error bars are for the statistical uncertainty, the orange rectangles for the systematical uncertainty and the violet rectangles include both uncertainties.

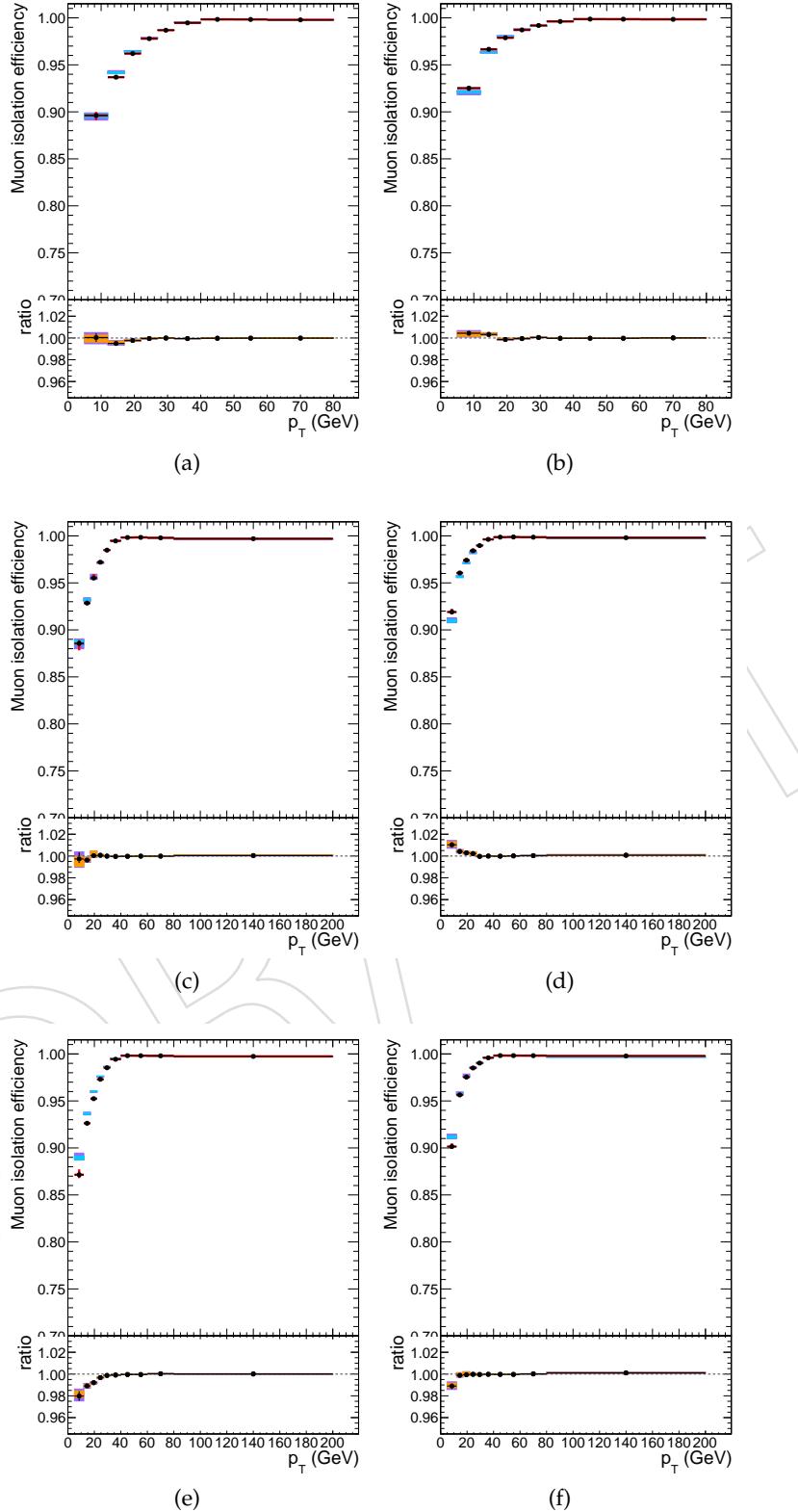


Figure 3: Efficiency of the muon isolation requirement, measured with the tag&probe method on Z events, as function of p_T in the barrel (left) and endcaps (right), for 2016 (top), 2017 (middle) and 2018 (bottom). In the upper panel, the larger error bars include also the systematical uncertainties, while the smaller ones are purely statistical. In the lower panel showing the ratio of the two efficiencies, the black error bars are for the statistical uncertainty, the orange rectangles for the systematical uncertainty and the violet rectangles include both uncertainties.

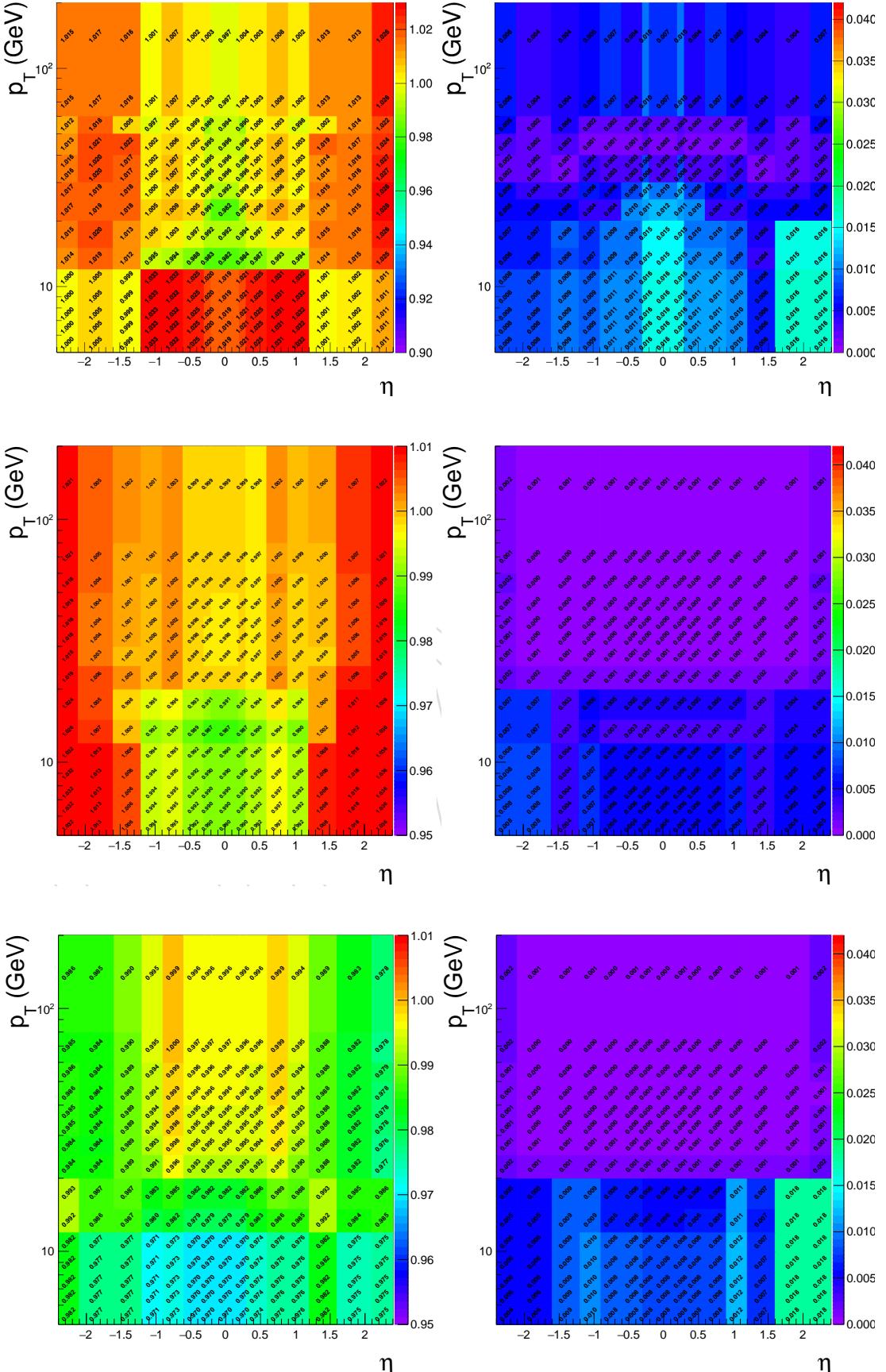


Figure 4: Left: Overall data to simulation scale factors for muons, as function of p_T and η . Right: Uncertainties on data to simulation scale factors for muons, as function of p_T and η . Results are shown for 2016 (top), 2017 (middle) and 2018 (bottom).

¹⁹⁸ **4 Signal Modelling**

¹⁹⁹ Referred to AN [19]

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200 5 Background Estimation

- 201 Details on the background processes and their modeling is discussed in detail in AN [19]. In
 202 order to perform the differential measurements, the background four-lepton mass spectrum
 203 need to be extracted at the reconstruction level for each bin of the considered observable. In
 204 general, the background mass spectrum shape is not the same in every bin of the considered
 205 observable because the background does not have a resonance structure. The mass spectrum
 206 also can have non-negligible correlation with the observables.
- 207 In case of the irreducible backgrounds, the four-lepton mass spectra are extracted as the m_{4l}
 208 template shapes using Monte Carlo simulated events for each bin of the observable considered
 209 for the measurement. Similarly, in case of the reducible backgrounds the templates are built
 210 from the control regions in data.

In each differential bin of $p_T(4\ell)$ fractions of background events are presented in the Table 10.

Table 10: Estimated fraction of background events in each bin of $p_T(4\ell)$, for each final state using 2018 samples.

Background	final state	0 – 15	15 – 30	30 – 45	45 – 80	80 – 120	120 – 200	200 – 13000
qqZZ	2e2μ	0.483668	0.239196	0.130151	0.105276	0.0266332	0.011809	0.00326633
qqZZ	4e	0.459665	0.234399	0.136986	0.114916	0.0388128	0.00989346	0.00532725
qqZZ	4μ	0.492632	0.241203	0.110977	0.109173	0.0297744	0.0129323	0.00330827
ggZZ	2e2μ	0.310446	0.309859	0.191901	0.168134	0.0187793	0.000880282	0.0
ggZZ	4e	0.3085	0.306332	0.19247	0.17433	0.0169994	0.00136908	0.0
ggZZ	4μ	0.321332	0.319311	0.194863	0.150987	0.0128703	0.000638196	0.0
Z+X (CR)	4l	0.0992521	0.211153	0.209307	0.305327	0.120303	0.0483797	0.00627828

211

212 5.1 Estimation of ZZ normalization from Data

- 213 In earlier analyses, both the shape and the normalization for $q\bar{q} \rightarrow ZZ$ background were
 214 measured from simulation. However, with full Run 2 statistics, we can benefit from enough
 215 statistics to extend $m_{4\ell}$ range to fit ZZ normalization from data, still taking shapes from sim-
 216 ulation. This would help to improve the estimation and as well as reduction in uncertainties
 217 because luminosity and other theoretical uncertainties no longer contribute to the normaliza-
 218 tion. (studies in under validation)

219 6 Analysis Strategy

220 6.1 Event Selection

221 6.1.1 Trigger Selection

222 The events are required to have fired the High-Level Trigger paths described in subsection 2.1.
 223 Unlike in the Run I analysis, the trigger requirement does not depend on the selected final state:
 224 it is always the OR of all HLT paths. The reason is in Run II we will be targeting associated
 225 production modes that can come with additional leptons, thus improving trigger efficiency
 226 further.

227 6.1.2 Vertex Selection

228 The events are required to have at least one good primary vertex (PV) fulfilling the following
 229 criteria: high number of degree of freedom ($N_{PV} > 4$), collisions restricted along the z -axis
 230 ($z_{PV} < 24$ cm) and small radius of the PV ($r_{PV} < 2$ cm).

231 6.1.3 Z, ZZ and best ZZ Candidate Selection

232 The four-lepton candidates are built from what we call **selected leptons**, which are the tight
 233 leptons that pass the $SIP_{3D} < 4$ vertex constraint and the isolation cuts, where FSR photons
 234 are subtracted as described in [19]. A lepton cross cleaning is applied by discarding electrons
 235 which are within $\Delta R < 0.05$ of selected muons.

236 The construction and selection of four-lepton candidates proceeds according to the following
 237 sequence:

238 1. **Z candidates** are defined as pairs of selected leptons of opposite charge and matching
 239 flavour (e^+e^- , $\mu^+\mu^-$) that satisfy $12 < m_{\ell\ell(\gamma)} < 120$ GeV/ c^2 , where the Z candidate mass
 240 includes the selected FSR photons if any.

241 2. **ZZ candidates** are defined as pairs of non-overlapping Z candidates. The Z candidate
 242 with reconstructed mass $m_{\ell\ell}$ closest to the nominal Z boson mass is denoted as Z_1 , and
 243 the second one is denoted as Z_2 . ZZ candidates are required to satisfy the following list
 244 of requirements:

- 245 • **Ghost removal** : $\Delta R(\eta, \phi) > 0.02$ between each of the four leptons.
- 246 • **lepton p_T** : Two of the four selected leptons should pass $p_{T,i} > 20$ GeV/ c and
 $p_{T,j} > 10$ GeV/ c . FSR photons are used.
- 247 • **QCD suppression**: all four opposite-sign pairs that can be built with the four
 248 leptons (regardless of lepton flavor) must satisfy $m_{\ell\ell} > 4$ GeV/ c^2 . Here, se-
 249 lected FSR photons are not used in computing $m_{\ell\ell}$, since a QCD-induced low
 250 mass dilepton (eg. J/Ψ) may have photons nearby (e.g. from π_0).
- 251 • **Z_1 mass**: $m_{Z_1} > 40$ GeV/ c^2
- 252 • **'smart cut'**: defining Z_a and Z_b as the mass-sorted alternative pairing Z candi-
 253 dates (Z_a being the one closest to the nominal Z boson mass), require $NOT(|m_{Z_a} -$
 $m_Z| < |m_{Z_1} - m_Z| \text{ AND } m_{Z_b} < 12)$. Selected FSR photons are included in m_Z 's
 254 computations. This cut discards 4μ and $4e$ candidates where the alternative
 255 pairing looks like an on-shell Z + low-mass $\ell^+\ell^-$. (NB. In Run I, such a situa-
 256 tion was avoided by choosing the best ZZ candidate before applying kinematic
 257 cuts to it, most precisely before the $m_{Z_2} > 12$ GeV/ c^2 cut. The present smart
 258 cut allows to choose the best ZZ candidate after all kinematic cuts.)

- 261 • **four-lepton invariant mass:** $m_{4\ell} > 70 \text{ GeV}/c^2$ (selected FSR photons are in-
262 cluded).
- 263 3. Events containing at least one selected ZZ candidate form the **signal region**.
- 264 4. **Best ZZ candidate selection:** If more than one ZZ candidates survive the above selection,
265 we choose the one with Z_1 closest in mass to nominal Z boson mass and Z_2 from the
266 candidates whose lepton give higher p_T sum.

267 **6.2 Fiducial Volume Significance and Definition**

- 268 To minimize the model dependence, results are extracted in the fiducial volume that closely
269 matches with the detector geometry as shown in Figure 5.



Figure 5: Fiducial phase definition among different models.

- 269
- 270 The differential cross subsections are measured in a fiducial region in order to reduce the ef-
271 fects of model dependent acceptances. The fiducial selection mimics the reconstruction level
272 selection, which is optimised to detect a low mass ($m_H 125\text{GeV}$) Higgs boson decaying to 4 lep-
273 tons through two Z bosons. Since in the standard model there are multiple production modes,
274 the fiducial selection and measurement strategy are designed to be independent of how the

275 Higgs boson is produced. For this reason, the inclusion of isolation in the fiducial selection
 276 is necessary in order to make the reconstruction efficiency with respect to the fiducial volume
 277 independent of the number of jets.

278 The fiducial volume is defined to match closely the reconstruction level selection and is very
 279 similar to the definition used in Refs. [18]. With respect to the Run 1 analysis, the leptons are
 280 defined as “dressed” leptons rather than Born level leptons. Leptons are dressed by adding the
 281 four-momenta of leptons within $\Delta R < 0.3$ to the bare leptons. The fiducial lepton isolation cri-
 282 teria is also updated to match the Run 2 reconstruction level isolation. Leptons are considered
 283 isolated at generator level if the sum p_T of particles within a cone $\Delta R < 0.3$ is less than 0.35. The
 284 fiducial volume definition can be seen in Table 11. The fiducial volume acceptance for various
 285 SM production modes can be seen in Table 16.

Table 11: Summary of requirements and selections used in the definition of the fiducial phase space for the $H \rightarrow 4\ell$ cross subsection measurements.

Requirements for the $H \rightarrow 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
leading lepton p_T	$p_T > 20 \text{ GeV}$
next-to-leading lepton p_T	$p_T > 10 \text{ GeV}$
additional electrons (muons) p_T	$p_T > 7(5) \text{ GeV}$
pseudorapidity of electrons (muons)	$ \eta < 2.5(2.4)$
p_T sum of all stable particles within $\Delta R < 0.3$ from lepton	less than $0.35 \cdot p_T$
Event topology	
existence of at least two SFOS lepton pairs, where leptons satisfy criteria above	
inv. mass of the Z_1 candidate	$40 \text{ GeV} < m(Z_1) < 120 \text{ GeV}$
inv. mass of the Z_2 candidate	$12 \text{ GeV} < m(Z_2) < 120 \text{ GeV}$
distance between selected four leptons	$\Delta R(\ell_i \ell_j) > 0.02$ for any $i \neq j$
inv. mass of any opposite sign lepton pair	$m(\ell^+ \ell^-) > 4 \text{ GeV}$
inv. mass of the selected four leptons	$105 \text{ GeV} < m_{4\ell} < 140 \text{ GeV}$
the selected four leptons must originate from the $H \rightarrow 4\ell$ decay	

286 6.3 Binning strategy for differential observables

Choice of bin boundaries and number of bins are two important aspects of differential measurements. With respect to the Run 1 analyses, we are benefitted from more statistic during Run 2 where data is recorded at 137 fb^{-1} with CMS detector. Sufficient statistics has helped to choose more fine binning for the observables than before. Bin boundaries are chosen in such a way that there is similar relative uncertainties on the expected cross section in the respective bins. Relative uncertainty (Δ_{rel}) is defined as:

$$\Delta_{rel}^i = \frac{d\sigma_{fid}^i}{\Delta_{tot}^i} \quad (1)$$

287 where $d\sigma_{fid}^i$ and Δ_{tot}^i are expected cross section and total uncertainty in bin i for a differential
 288 observable.

289 Table 12 shows the current choice of bin boundaries of $p_T(H)$ observables with details of ex-
 290 pected cross section and relative uncertainties in the bins.

Table 12: Differential cross section results for the pT4l observable.

Bin range (GeV)	$d\sigma_{fid}$ (fb)	Δ_{tot} (% fb)	Δ_{rel} (%)	δ_{stat} (% fb)	δ_{syst} (% fb)
0 - 10	0.34	+0.11 -0.096	+33 -28	+0.1 -0.091	+0.048 -0.031
10 - 20	0.53	+0.13 -0.11	+25 -21	+0.12 -0.11	+0.056 -0.037
20 - 30	0.42	+0.11 -0.097	+27 -23	+0.1 -0.093	+0.044 -0.027
30 - 45	0.43	+0.11 -0.094	+25 -22	+0.1 -0.089	+0.044 -0.029
45 - 80	0.52	+0.11 -0.1	+22 -19	+0.1 -0.092	+0.05 -0.038
80 - 120	0.25	+0.073 -0.062	+29 -25	+0.069 -0.06	+0.024 -0.018
120 - 200	0.18	+0.057 -0.048	+31 -26	+0.055 -0.046	+0.016 -0.011
200 - 13000	0.082	+0.036 -0.028	+44 -34	+0.035 -0.028	+0.008 -0.004

291 6.4 Unfolding

292 The effects of imperfect detector resolution can in general have an non-negligible impact on
 293 the shape of the distribution of the measured observables. For this reason, in case of the dif-
 294 ferential cross sections measurements, a procedure to correct for the detection efficiencies and
 295 resolution effects is applied. Throughout this document, this procedure will be referred to as
 296 the unfolding procedure, and the unfolded differential distributions will be referred to as dis-
 297 tributions at the fiducial level. Currently adopted procedure is “bin-by-bin unfolding”. This
 298 procedure for the unfolding of the detector effects from the observed distributions is the same
 299 as in Refs. [18] and [36]. The finite efficiencies and resolution effects are encoded in a detec-
 300 tor response matrix which describes how events migrate from a given observable bin at the
 301 fiducial level to a given bin at the reconstruction level. This matrix is diagonally dominant,
 302 with sizeable off-diagonal elements for observables involving jets. It is aimed we would also
 303 perform matrix inversion method as a validation tool for preceding method.

304 Examples of the efficiency matrices for gluon fusion and VBF production can be seen in Fig. 6.
 305 The matrices for the p_{TH} and N(jets) observables are shown.

306 6.5 Acceptance and other correction factors

307 In this section the acceptance and other correction factors while measuring the cross sections
 308 are discussed in details.

309 6.5.1 Acceptance

310 Ratio of the total number of events passing the fiducial level selectons $N_{fid.}$ to the total number
 311 of the generated events $N_{gen.}$ are is called acceptance as given in Equation 2.

$$A = \frac{N_{fid.}}{N_{gen.}} \quad (2)$$

312 6.5.2 Other correction factors

313 Measurement strategy and definition of the fiducial volume is optimized to:

- 314 • detect a low mass Higgs ($m_H=125.38$ GeV) boson decaying to 4 leptons through a
 315 pair of Z bosons
- 316 • keep the measurements independent of how the Higgs boson is produced.

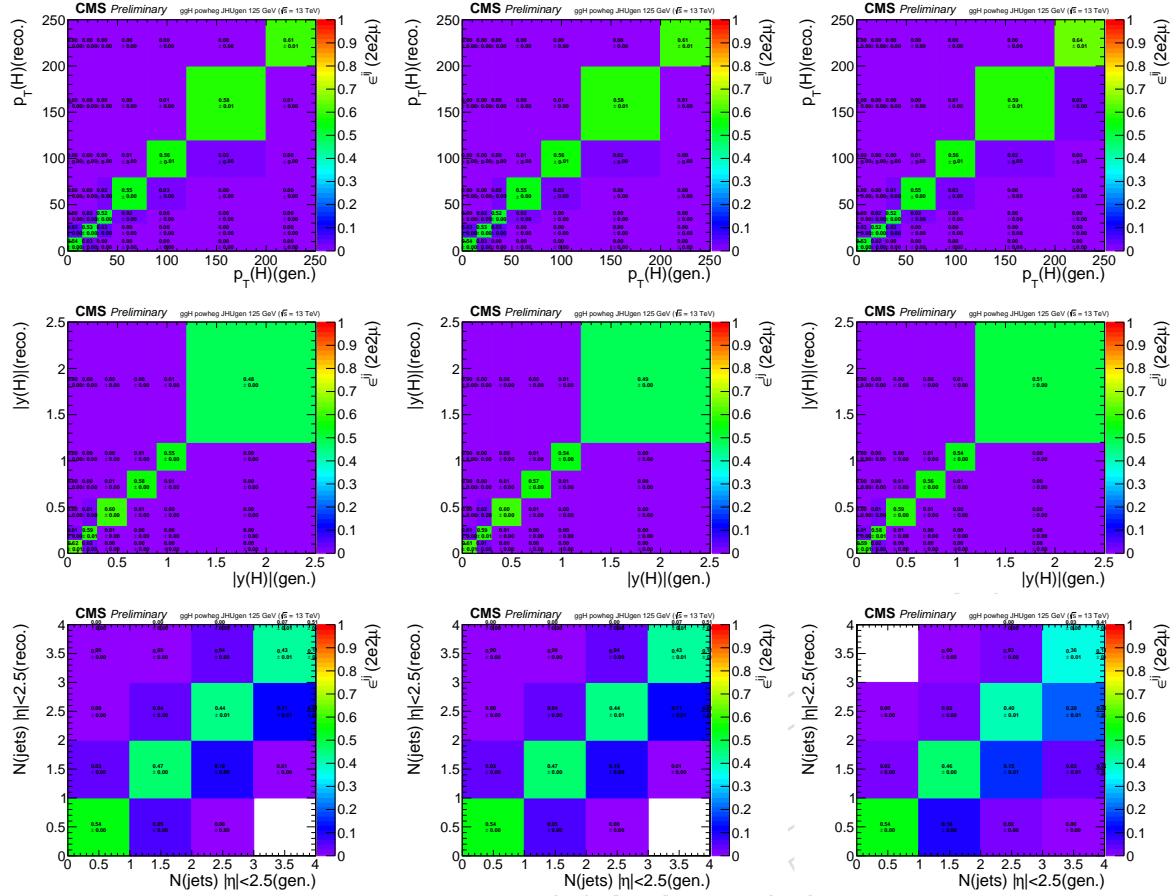


Figure 6: Efficiency matrices for the p_{TH} (top) and yH (middle) and $N(\text{jets})$ (bottom) observables for gluon fusion production modes in the $2e2\mu$ final state in 2016 (left) 2017 (middle) and 2018 (right) (TBU).

For reconstruction efficiency to be independent of fiducial phase space, it is necessary to include isolation in the definition of fiducial phase space.

In case of associated production of Higgs with vector bosons where the bosons can decay leptonically, there is possibility that Higgs is reconstructed from wrong combination of leptons. This makes it necessary to consider such “wrong combination” events as a background in order to keep complete information from unbinned simultaneous fit of signal and background parameterizations to four-lepton invariant mass.

Also, signal events which pass the fiducial level selections but fail the reconstruction are accounted in the fiducial efficiency (ϵ) and the events which pass the reconstruction but fail the fiducial selections are referred to as “nonfiducial signal” events (f_{nonfid}) and are treated as a background as illustrated in Figure 7.

The summary of acceptance and other factors for full Run 2 periods are given Table. 16.

6.6 Statistical Procedure

We measure differential fiducial cross subsection for $pp \rightarrow H \rightarrow 4\ell$ by performing a maximum likelihood fit of the signal and background parameterisations to the observed 4ℓ mass distribution, $N_{\text{obs}}(m_{4\ell})$, and the fiducial cross subsection (σ_{fid}) is directly extracted from the fit. The systematic uncertainties are included in the form of nuisance parameters and are effectively

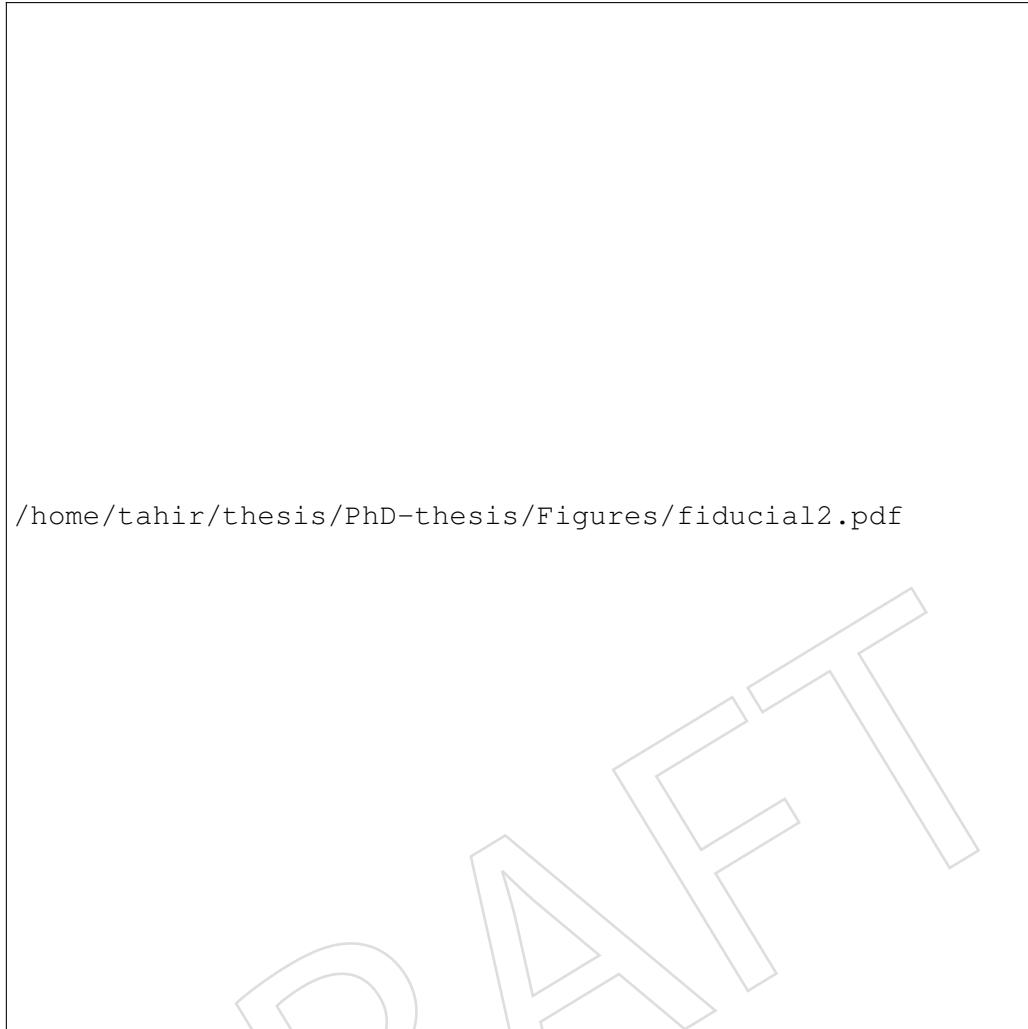


Figure 7: Fiducial efficiency(ϵ) and nonfiducial(f_{nonfid}) signal definition.

Table 13: Summary of different Standard Model signal models (2016).

Signal process	\mathcal{A}_{fid}	ϵ	f_{nonfid}	$(1 + f_{nonfid})\epsilon$
Individual Higgs boson production modes				
gg \rightarrow H (POWHEG) 125 GeV	0.397 ± 0.001	0.604 ± 0.001	0.051 ± 0.001	0.635 ± 0.001
VBF 125 GeV	0.446 ± 0.001	0.618 ± 0.002	0.039 ± 0.001	0.642 ± 0.002
WH 125 GeV	0.328 ± 0.001	0.593 ± 0.002	0.077 ± 0.001	0.638 ± 0.002
ZH 125 GeV	0.340 ± 0.002	0.608 ± 0.003	0.077 ± 0.002	0.655 ± 0.004
ttH 125 GeV	0.312 ± 0.002	0.585 ± 0.003	0.169 ± 0.004	0.684 ± 0.004

³³⁴ integrated out in the fit procedure. The results are obtained using an asymptotic approach [37] with a test statistic based on the profile likelihood ratio [38]. Following the models for signal and background contributions described above, the number of expected events in each final

Table 14: Summary of different Standard Model signal models (2017).

Signal process	\mathcal{A}_{fid}	ϵ	f_{nonfid}	$(1 + f_{\text{nonfid}})\epsilon$
Individual Higgs boson production modes				
gg \rightarrow H (POWHEG) 125 GeV	0.403 ± 0.001	0.593 ± 0.001	0.056 ± 0.001	0.626 ± 0.001
VBF 125 GeV	0.445 ± 0.001	0.609 ± 0.001	0.044 ± 0.001	0.636 ± 0.001
WH 125 GeV	0.329 ± 0.001	0.583 ± 0.002	0.081 ± 0.001	0.631 ± 0.002
ZH 125 GeV	0.341 ± 0.002	0.594 ± 0.003	0.084 ± 0.002	0.644 ± 0.004
ttH 125 GeV	0.318 ± 0.003	0.589 ± 0.006	0.187 ± 0.007	0.699 ± 0.008

Table 15: Summary of different Standard Model signal models (2018).

Signal process	\mathcal{A}_{fid}	ϵ	f_{nonfid}	$(1 + f_{\text{nonfid}})\epsilon$
Individual Higgs boson production modes				
gg \rightarrow H (POWHEG) 125 GeV	0.403 ± 0.001	0.599 ± 0.001	0.055 ± 0.001	0.632 ± 0.001
VBF 125 GeV	0.443 ± 0.001	0.617 ± 0.002	0.043 ± 0.001	0.644 ± 0.002
WH 125 GeV	0.330 ± 0.001	0.625 ± 0.002	0.075 ± 0.001	0.672 ± 0.002
ZH 125 GeV	0.339 ± 0.002	0.629 ± 0.003	0.083 ± 0.002	0.681 ± 0.004
ttH 125 GeV	0.314 ± 0.002	0.589 ± 0.003	0.184 ± 0.004	0.698 ± 0.004

Table 16: Summary of different Standard Model signal models.(Full Run 2)

Signal process	\mathcal{A}_{fid}	ϵ	f_{nonfid}	$(1 + f_{\text{nonfid}})\epsilon$
Individual Higgs boson production modes				
gg \rightarrow H (POWHEG) 125 GeV	0.402 ± 0.001	0.598 ± 0.002	0.054 ± 0.001	0.631 ± 0.002
VBF 125 GeV	0.445 ± 0.002	0.615 ± 0.002	0.043 ± 0.001	0.641 ± 0.003
WH 125 GeV	0.329 ± 0.002	0.604 ± 0.003	0.078 ± 0.002	0.651 ± 0.004
ZH 125 GeV	0.340 ± 0.003	0.613 ± 0.005	0.082 ± 0.004	0.663 ± 0.006
ttH 125 GeV	0.315 ± 0.004	0.588 ± 0.007	0.181 ± 0.009	0.694 ± 0.010

³³⁷ state f and in each bin i of a considered observable is expressed as a function of $m_{4\ell}$ given by:

$$\begin{aligned} N_{\text{obs}}^{f,i}(m_{4\ell}) &= N_{\text{fid}}^{f,i}(m_{4\ell}) + N_{\text{nonfid}}^{f,i}(m_{4\ell}) + N_{\text{nonres}}^{f,i}(m_{4\ell}) + N_{\text{bkg}}^{f,i}(m_{4\ell}) \\ &= \epsilon_{i,j}^f \cdot \left(1 + f_{\text{nonfid}}^{f,i}\right) \cdot \sigma_{\text{fid}}^{f,j} \cdot \mathcal{L} \cdot \mathcal{P}_{\text{res}}(m_{4\ell}) \\ &\quad + N_{\text{nonres}}^{f,i} \cdot \mathcal{P}_{\text{nonres}}(m_{4\ell}) + N_{\text{bkg}}^{f,i} \cdot \mathcal{P}_{\text{bkg}}(m_{4\ell}), \end{aligned} \quad (3)$$

³³⁸ The parameter $\sigma_{\text{fid}}^{f,j}$ is the signal cross subsection in bin j of the fiducial phase space, and it is the
³³⁹ parameter extracted from the measurement.

³⁴⁰ The shape of the resonant signal contribution, $\mathcal{P}_{\text{res}}(m_{4\ell})$, is described by a double-sided Crys-
³⁴¹tal Ball function, as described in previous sections, whose normalisation is proportional to
³⁴² the fiducial cross subsection. The shape of the non-resonant signal contribution, $\mathcal{P}_{\text{nonres}}(m_{4\ell})$,
³⁴³ which arises from WH, ZH, and ttH production where one of the leptons from the Higgs bo-
³⁴⁴son decay is lost or not selected, is empirically modelled by a Landau distribution whose shape
³⁴⁵ parameters are constrained in the fit to be within a range determined from simulation. This
³⁴⁶ contribution is treated as a background and hereafter we will refer to this contribution as the
³⁴⁷ “non-resonant signal” contribution.

³⁴⁸ The $\epsilon_{i,j}^f$ represents the detector response matrix that maps the number of expected events in
³⁴⁹ a given observable bin j at the fiducial level to the number of expected events in the bin i at

350 the reconstruction level. The f_{nonfid}^i fraction describes the ratio of the non-fiducial and fiducial
 351 signal contribution in bin i at the reconstruction level. The efficiency is measured using signal
 352 simulation samples and corrected for residual differences between data and simulation. In the
 353 case of the integrated fiducial cross subsection measurement the efficiencies reduce to a single
 354 values.

355 An additional resonant contribution arises from events which are reconstructed but which do
 356 not originate from the fiducial phase space. These events are due to detector effects which
 357 cause differences between the quantities used for the fiducial phase space definition and the
 358 analogous quantities at the reconstruction level. This contribution is treated as background
 359 and is referred to as the “non-fiducial signal” contribution. The shape of these events is verified
 360 using simulation to be identical to the shape of the fiducial signal and its normalisation is fixed
 361 to be a fraction of the fiducial signal component. The value of this fraction, which we denote
 362 by f_{nonfid} , which has been determined from simulation for each of the studied signal models.

363 The variation between different models of the factor in the final column of Table 16, $(1 +$
 364 $f_{\text{nonfid}})\epsilon$, is directly related to the model dependence of the measurement. The model depen-
 365 dence is defined as the variation of the factor $(1 + f_{\text{nonfid}})\epsilon$ when the relative fraction of each
 366 the production modes are varied within their experimental constraints.

367 **6.7 Extraction of differential $H \rightarrow 4\ell$ cross section**

368 **6.7.1 Considered observables**

369 The differential fiducial cross sections are presented as a function of several kinematic observ-
 370 ables which are sensitive to the Higgs-boson production mechanisms. Examples are rapidity
 371 and transverse momentum of the four-lepton system, associated jet multiplicity and transverse
 372 momentum of the leading jet $p_T(H)$ or $p_T(4\ell)$, $|y(H)|$ or $|y(4\ell)|$, $N(\text{jets})$, and $p_T(\text{jet})$. These
 373 measurements are important to test the Standard Model predictions in the Higgs sector and
 374 can be used to constrain phase spaces of many theories beyond the Standard Model. In addition,
 375 several other observables related to decay of Higgs boson are also studied. These include
 376 m_{Z_1} , m_{Z_2} , ϕ , $\cos\theta^*$ and several other observables which are sensitive to spin and CP or Higgs
 377 bosons.

378 **6.7.2 Choice of bin boundaries**

379 For each kinematic or differential observable, selection procedure of the binning boundaries
 380 has been optimized in order to have a similar expected measured cross-section for every bin.
 381 Relative uncertainties for p_T of Higgs observables are given in Table. 17.

382 **6.7.3 Applying the Statistical Procedure**

383 The fiducial differential cross section is extracted in the bins of kinematic observables at the
 384 fiducial level following the procedure outlined in previous. For signal yields, mass spectrum
 385 of signal is built in each cell of the response matrix using a Double Crystal Ball (DCB) function,
 386 similar to what was done in Ref. [?]. In practice, the same parameters of the CB function are
 387 used in each cell and the systematic uncertainties assigned on the energy scale and resolution
 388 generally cover discrepancy of signal mass spectrum among each cell.

389 Examples of the fitted signal line shapes for differential bins of $p_T(H)$ from gg $\rightarrow H$ (POWHEG
 390 + JHUGEN 125 GeV 2018 sample) in the individual final states are shown in Figure 30, and
 391 examples of the efficiency matrices for $p_T(H)$ for the $2e2\mu$ final state are shown in Fig 9. Many
 392 more examples can be seen in Appendix A.

Table 17: Differential cross section results for the $p_T(H)$ observable.

Bin range (GeV)	$d\sigma_{fid}$ (fb)	Δ_{tot} (% fb)	Δ_{rel} (%)	δ_{stat} (% fb)	δ_{syst} (% fb)
CMS preliminary choice					
0 - 10	0.34	+0.11 −0.096	+33 −28	+0.1 −0.091	+0.048 −0.031
10 - 20	0.53	+0.13 −0.11	+25 −21	+0.12 −0.11	+0.056 −0.037
20 - 30	0.42	+0.11 −0.097	+27 −23	+0.1 −0.093	+0.044 −0.027
30 - 45	0.43	+0.11 −0.094	+25 −22	+0.1 −0.089	+0.044 −0.029
45 - 80	0.52	+0.11 −0.1	+22 −19	+0.1 −0.092	+0.05 −0.038
80 - 120	0.25	+0.073 −0.062	+29 −25	+0.069 −0.06	+0.024 −0.018
120 - 200	0.18	+0.057 −0.048	+31 −26	+0.055 −0.046	+0.016 −0.011
200 - 13000	0.082	+0.036 −0.028	+44 −34	+0.035 −0.028	+0.008 −0.004
Total bins = 8	$\sigma_{fid} = \sum d\sigma_{fid} = 2.8$ (fb)				

393 Figure 10 shows the four lepton mass distributions for an Asimov dataset generated using SM
 394 cross section values and efficiencies from the $gg \rightarrow H$ production mode from POWHEG+JHUGEN,
 395 and resulting fitted values of PDFs of signal and background for different bins of $p_T(H)$ (all fi-
 396 nal states combined).

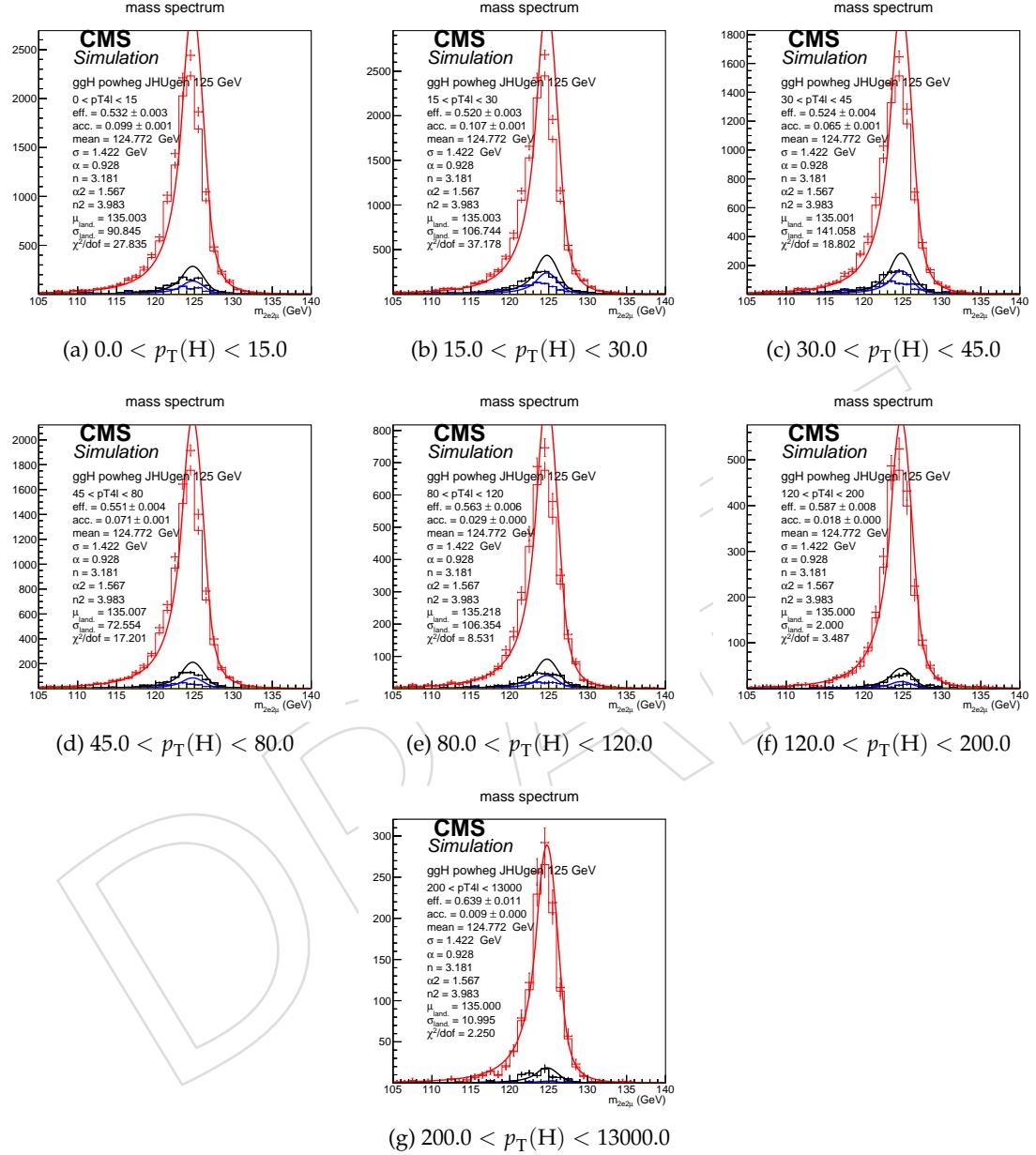


Figure 8: Example signal shapes at reconstruction level for a resonance of $m(4\ell)$ in $2e2\mu$ final state for the $gg \rightarrow H$ production mode from POWHEG+JHUGEN in different bins of $p_T(H)$. The black curve represents events which do not pass the fiducial volume selection. The curve has no effect on the result.

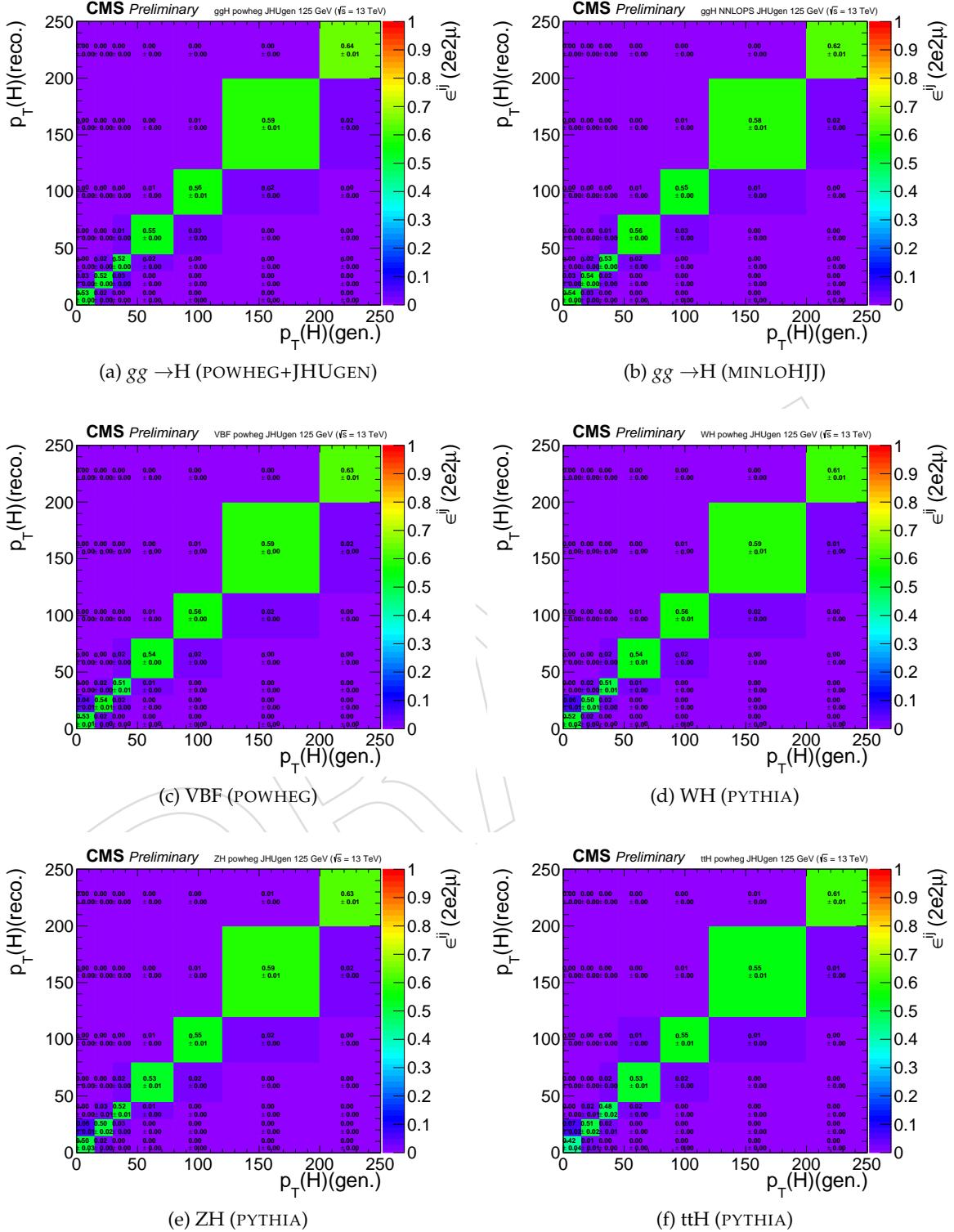


Figure 9: Efficiency response matrices for $p_T(H)$ for different SM production modes in the $2e2\mu$ final state using 2018 samples.

397 6.8 Interpretations

398 To be updated

399 6.8.1 κ -framework

400 To be updated

401 6.8.2 Effective Field Theory

402 To be updated.

403 6.8.3 κ -framework

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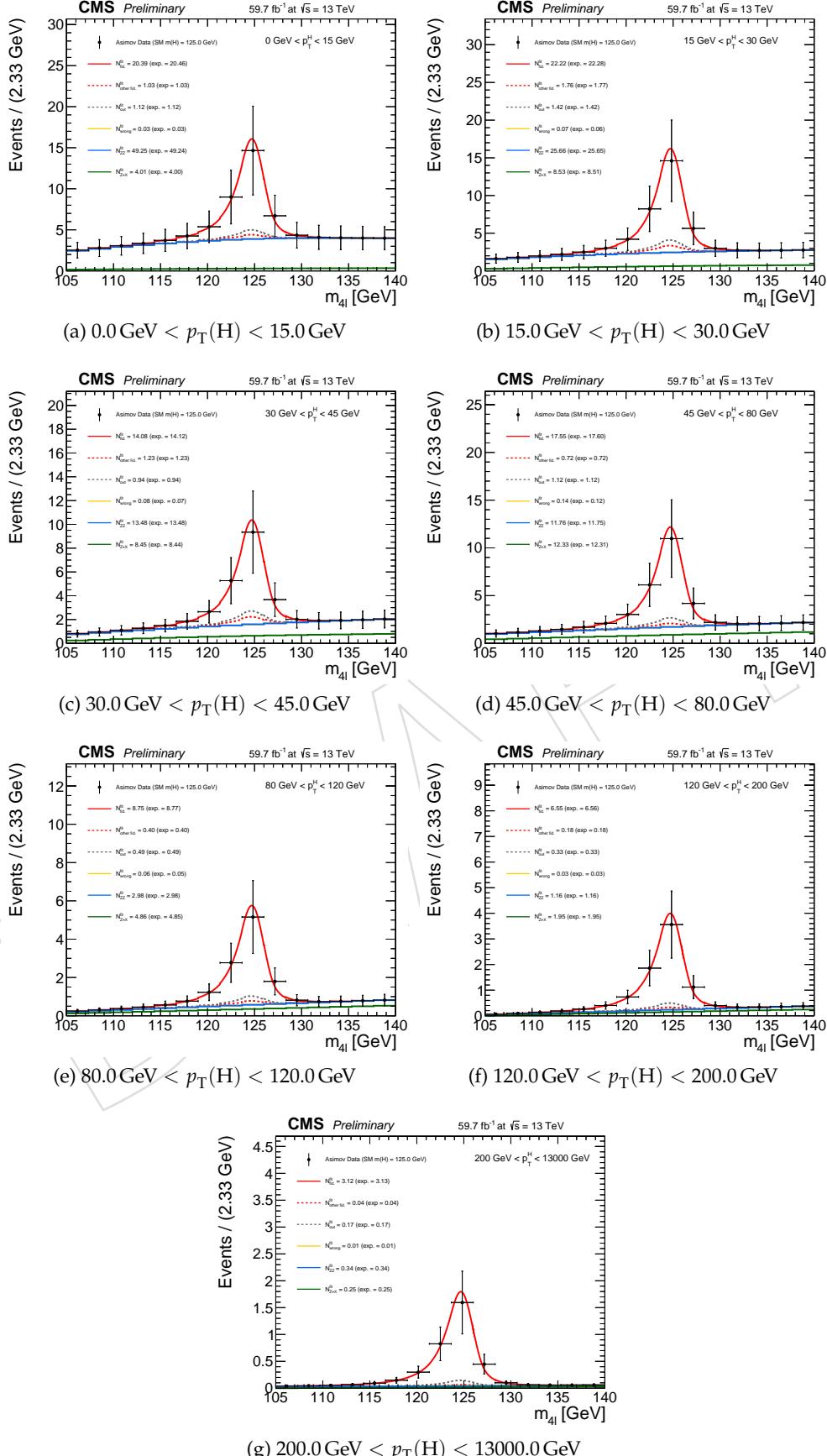


Figure 10: Four lepton mass distributions for an Asimov dataset generated using SM cross section values and SM efficiencies where the $gg \rightarrow H$ prediction is from POWHEG+JHUGEN and resulting fitted values of PDFs of signal and background for different bins of $p_T(\text{H})$ (all final states combined).

404 7 Systematic uncertainties

405 The main experimental uncertainties which affect both signal and background are the uncer-
 406 tainty on the integrated luminosity (from to 2.3% to 2.6%, depending on the data taking period)
 407 and the uncertainty on the lepton identification and reconstruction efficiency (ranging from 1
 408 to 2.5% and from 11 to 15.5% on the overall yields, in the 4μ and $4e$ channels, respectively).
 409 Experimental uncertainties for the reducible background estimation, described in Section ??,
 410 vary between 6% to 32% from the variation of the fake rates. The mismatch in the composition
 411 of backgrounds between the samples where the fake rate is derived and where it is applied
 412 accounts for about 30%.

413 The uncertainty of the lepton energy scale is assessed by propagating down to the four-leptons
 414 invariant mass the uncertainty associated the lepton momentum corrections on each individual
 415 lepton. The uncertainty is treated as uncorrelated (all up or all down). The new four-leptons
 416 invariant mass obtained this way is then fitted with only the mean value floating. The differ-
 417 ence between the new mean value and the default one gives an estimation of the impact of the
 418 lepton energy scale. The values are reported in the Table 18, together with the estimation of the
 419 impact of lepton momentum resolution, following a similar procedure.

Table 18: Difference (in %) between the nominal mean and width of the four-leptons Higgs mass distribution and those where the lepton momentum scale and resolution uncertainties have been propagated.

	4e	4μ	$2e2\mu$
Scale Difference (%)	0.087	0.049	0.069
Resolution Difference (%)	17	12	17

420 The results obtained this way suggest that the uncertainties from 2016 (20% on the resolution,
 421 0.3% for the $4e$ channel for scale) are still valid.

422 Theoretical uncertainties which affect both the signal and background estimation include un-
 423 certainties from the renormalization and factorization scale and choice of PDF set. The uncer-
 424 tainty from the renormalization and factorization scale is determined by varying these scales
 425 between 0.5 and 2 times their nominal value while keeping their ratio between 0.5 and 2. In the
 426 case of ggF production mode, the QCD scale uncertainty is broken down to 9 different sources.
 427 The renormalization and factorization scale affect the overall cross section, the migration of
 428 the stage1.1 bins in different Higgs pT and number of jets, top loop effects are treated as inde-
 429 pendent uncertainties, and correlated among different stage 1.1 bins. The numbers are shown
 430 in Fig ???. The uncertainty from the PDF set is determined by taking the root mean square of
 431 the variation when using different replicas of the default NNPDF set. PDF uncertainty arises
 432 from uncertainty is also taken into account. On the background, an additional uncertainty of
 433 10% on the K factor used for the $gg \rightarrow ZZ$ prediction is applied as described in Section ???. A
 434 systematic uncertainty of 2% on the branching ratio of $H \rightarrow ZZ \rightarrow 4\ell$ only affects the signal
 435 yield. In the case of event categorization, experimental and theoretical uncertainties which ac-
 436 count for possible migration of signal and background events between categories are included.
 437 The main sources of uncertainty on the event categorization include the QCD scale, PDF set,
 438 and the modeling of hadronization and the underlying event. These uncertainties amount to
 439 between 4–20% for the signal and 3–20% for the background depending on the category. The
 440 lower range corresponds to the VBF and VH processes and the upper range corresponds to the
 441 $gg \rightarrow H$ process yield in the VBF-2jet-tagged category. Additional uncertainties come from the
 442 imprecise knowledge of the jet energy scale (from 2% for the $gg \rightarrow H$ yield in the untagged
 443 category to 22% for $gg \rightarrow H$ yield in the VBF-2jet-tagged category) and b-tagging efficiency

⁴⁴⁴ and mistag rate (up to 10% in the $t\bar{t}H$ -tagged category). In the cross section measurement, the
⁴⁴⁵ signal cross section uncertainties arise from theoretical sources are removed.

Table 19: Summary of the experimental systematic uncertainties in the $H \rightarrow 4\ell$ measurements of 2016, 2017 and 2018 data.

Summary of relative systematic uncertainties			
Common experimental uncertainties			
	2016	2017	2018
Luminosity	2.6 %	2.3 %	2.5 %
Lepton identification/reconstruction efficiencies	1.2 – 15.5 %	1.1 – 12 %	0.7 – 11 %
Background related uncertainties			
Reducible background ($Z+X$)	31 – 42 %	31 – 38 %	31 – 37 %
Signal related uncertainties			
Lepton energy scale	0.04 – 0.3 %	0 %	0 %
Lepton energy resolution	20 %	20 %	20 %

Table 20: Summary of the theory systematic uncertainties in the $H \rightarrow 4\ell$ measurements for the inclusive analysis

Summary of inclusive theory uncertainties	
QCD scale (gg)	± 3.9 %
PDF set (gg)	± 3.2 %
Bkg K factor (gg)	± 10 %
QCD scale (VBF)	+0.4/-0.3 %
PDF set (VBF)	± 2.1 %
QCD scale (WH)	+0.5/-0.7 %
PDF set (WH)	± 1.9 %
QCD scale (ZH)	+3.8/-3.1 %
PDF set (ZH)	± 1.6 %
QCD scale ($t\bar{t}H$)	+5.8/-9.2 %
PDF set ($t\bar{t}H$)	± 3.6 %
BR($H \rightarrow ZZ \rightarrow 4\ell$)	2 %
QCD scale ($q\bar{q} \rightarrow ZZ$)	+3.2/-4.2 % %
PDF set ($q\bar{q} \rightarrow ZZ$)	+3.1/-3.4 %
Electroweak corrections ($q\bar{q} \rightarrow ZZ$)	± 0.1 %

⁴⁴⁶ 7.1 Systematic uncertainties treatment when combining the data sets

⁴⁴⁷ In this Section we describe how different systematic uncertainties are treated when combining
⁴⁴⁸ the data sets. The theoretical uncertainties are correlated. All the experimental systematics are
⁴⁴⁹ treated independently.

450 In this subsection we summarize the status of the analysis after selection, showing the inputs to
 451 the final results, namely the event yields and errors in the full signal region and in a restricted
 452 $m_{4\ell}$ range, and the distributions of the main kinematic variables in data and MC.

453 7.1.1 Signal Region Yields

454 The number of candidates observed in data and the expected yields for the backgrounds and
 455 Higgs boson signal after the full event selection are reported in Table 22 for the full range of
 456 $m_{4\ell}$. Table ?? shows the expected and observed yields for each of the 22 event categories, for a
 457 $118 < m_{4\ell} < 130$ GeV mass window around the Higgs boson peak.

Table 21: The number of expected background and signal events and number observed candidates after full analysis selection, for each final state, for the full mass range $m_{4\ell} > 70$ GeV, for an integrated luminosity of 137 fb^{-1} . Signal and ZZ backgrounds are estimated from Monte Carlo simulation, Z+X is estimated from data.

Channel	4μ	$4e$	$2e2\mu$	$4l$
qqZZ	1414.85	748.64	1835.05	3998.54
ggZZ	268.48	163.45	399.78	831.70
ZX	112.84	48.62	151.71	313.18
EW bkg	15.13	12.73	27.83	55.69
Sum of backgrounds	1811.30	973.45	2414.36	5199.11
Signal ($m_H = 125$ GeV)	95.27	46.01	118.53	259.82
Total expected	1906.57	1019.46	2532.90	5458.93
Data	1970	1032	2646	5648

458 7.1.2 Signal Region Distributions

459 The reconstructed four-lepton invariant mass distribution is shown in Figure 13 for the full
 460 dataset, and compared to expectations from the SM backgrounds, first for the full mass range,
 461 and then zooming on the low-mass range and high-mass range. In Figure 14, the same dis-
 462 tributions are shown split by final state ($4e$, 4μ , and $2e2\mu$), for the two same mass ranges. In
 463 Figure ??, they are split by event category, for the low-mass range. The SM background dis-
 464 tributions are obtained combining the rate normalization from data-driven methods and knowl-
 465 edge on shapes taken from the MC samples.

466

467 The reconstructed dilepton invariant masses selected as Z_1 and Z_2 are shown in Figures ??
 468 together with their correlation, both full range of $m_{4\ell}$ and focusing on a $118 < m_{4\ell} < 130$ GeV
 469 mass window around the Higgs boson peak.

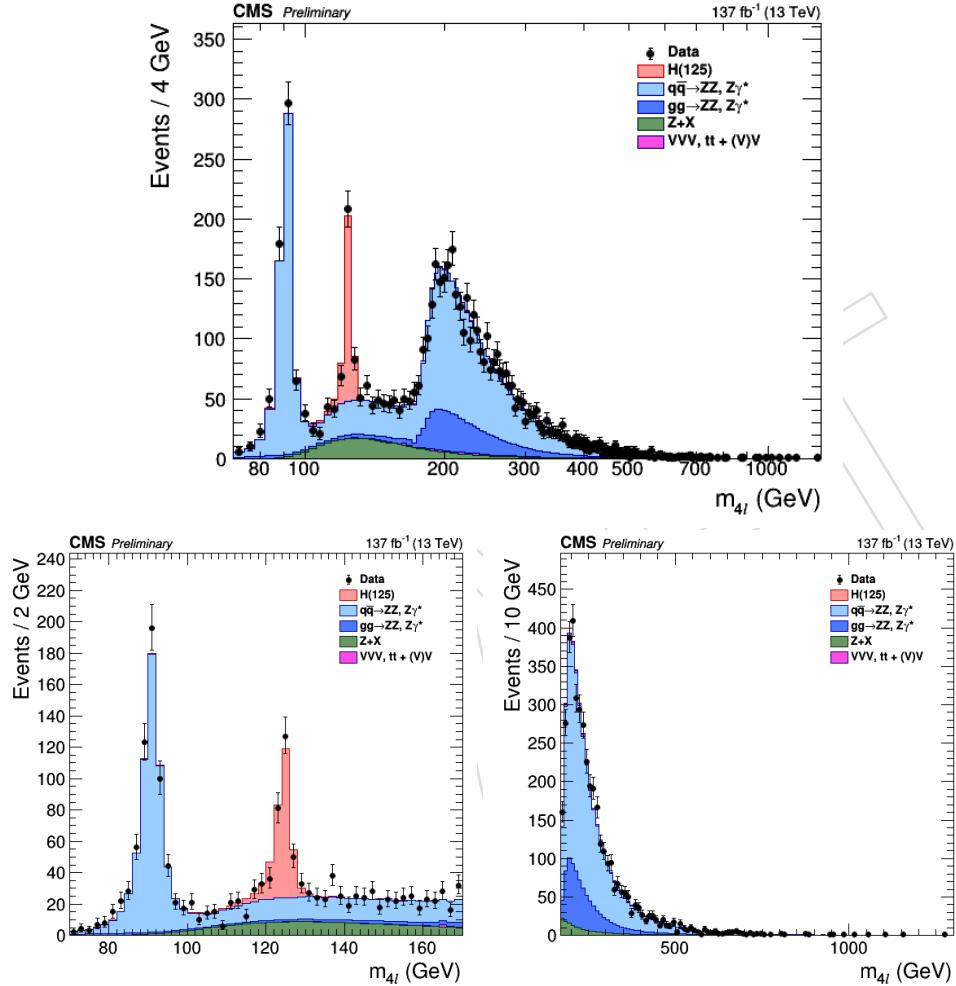


Figure 11: Distribution of the four-lepton reconstructed invariant mass $m_{4\ell}$ in the full mass range (top) and the low-mass range (bottom left) and high-mass range (bottom right). Points with error bars represent the data and stacked histograms represent expected distributions. The 125 GeV Higgs boson signal and the ZZ backgrounds are normalized to the SM expectation, the Z+X background to the estimation from data.

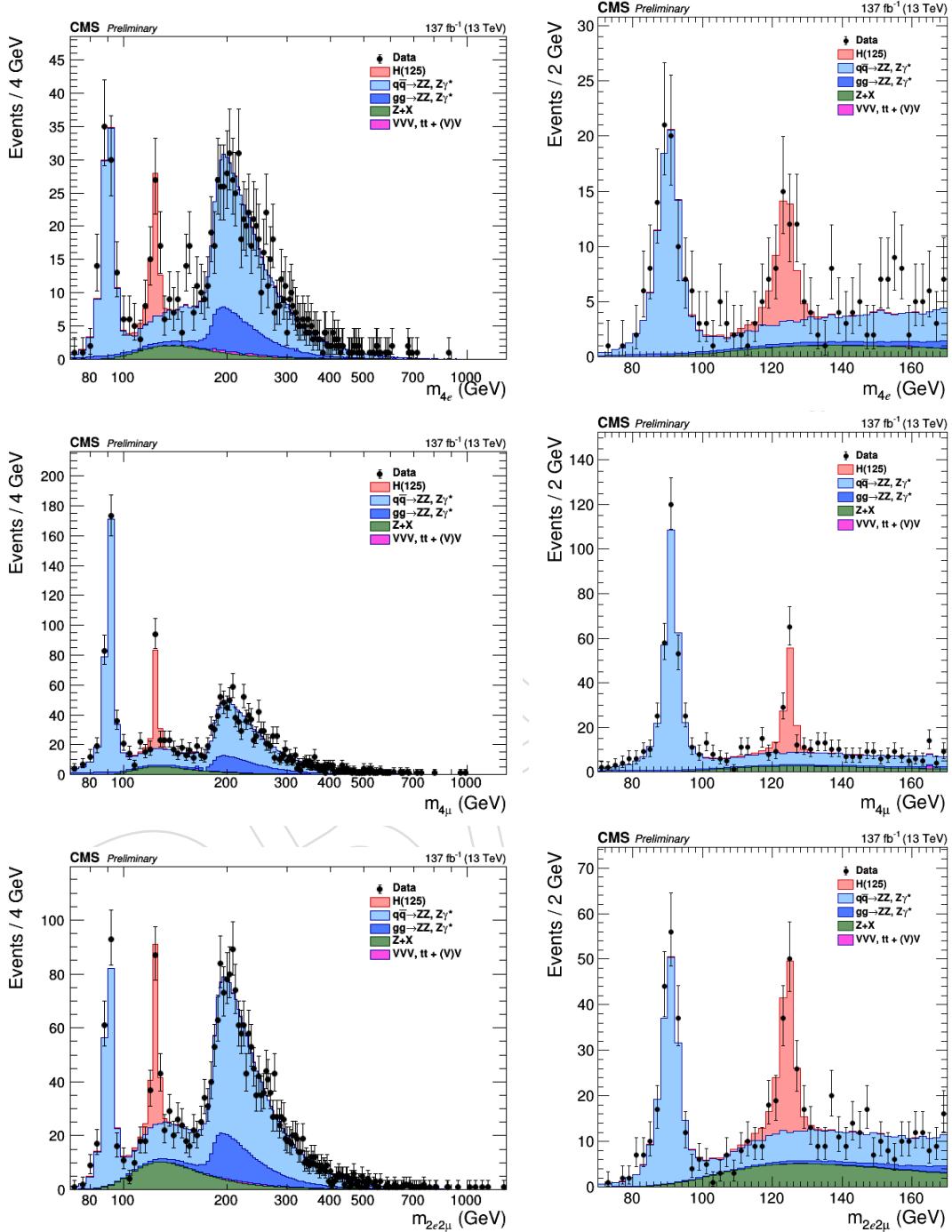
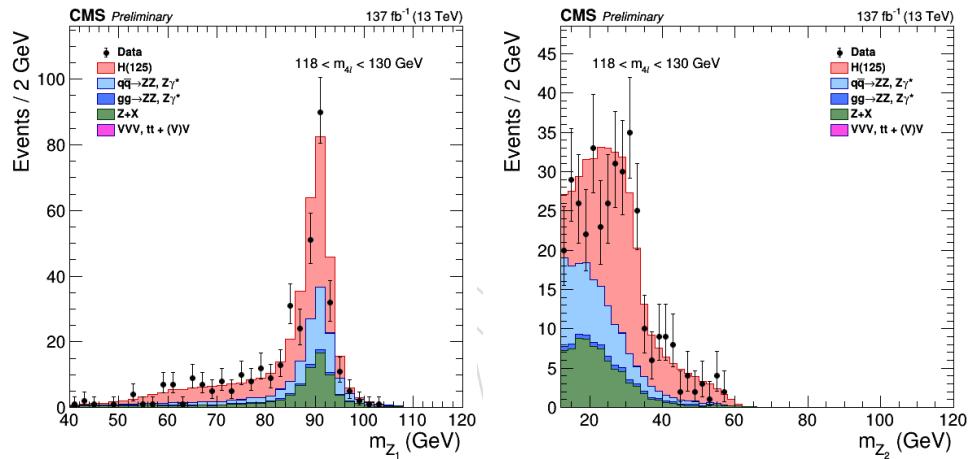


Figure 12: Distribution of the four-lepton reconstructed mass in several sub-channels: $4e$ (top), 4μ (middle), $2e2\mu$ for the low-mass range (bottom) for the full mass range (left) and the low-mass range (right).



Distribution of the Z_1 (left) and Z_2 (right) reconstructed invariant masses for the full mass range (left) and the low mass ($118 < m_{4\ell} < 130$ GeV) range (right). The stacked histograms and the gray scale represent expected distributions, and points represent the data. The 125 GeV Higgs boson signal and the ZZ backgrounds are normalized to the SM expectation, the Z+X background to the estimation from data.

470 8 Results

471 In this section, we describe the methods used for the estimation of the significance of the ex-
 472 cess of events above the SM backgrounds observed in the low-mass region, and of the signal
 473 strength, i.e. its cross section normalized to the one expected for a SM Higgs.

474 To exploit all the properties of the resonance under study or search, a multi-dimensional fit is
 475 implemented. For each of the categories defined in Section ??, the variable used in the maxi-
 476 mum likelihood fit is the four-lepton mass without kinematic refitting $m_{4\ell}$.

477 8.1 Yields and distributions

478 In this subsection we summarize the status of the analysis after selection, showing the inputs to
 479 the final results, namely the event yields and errors in the full signal region and in a restricted
 480 $m_{4\ell}$ range, and the distributions of the main kinematic variables in data and MC.

481 8.1.1 Signal Region Yields

482 The number of candidates observed in data and the expected yields for the backgrounds and
 483 Higgs boson signal after the full event selection are reported in Table 22 for the full range of
 484 $m_{4\ell}$. Table ?? shows the expected and observed yields for each of the 22 event categories, for a
 485 $118 < m_{4\ell} < 130$ GeV mass window around the Higgs boson peak.

Table 22: The number of expected background and signal events and number observed candi-
 dates after full analysis selection, for each final state, for the full mass range $m_{4\ell} > 70$ GeV, for
 an integrated luminosity of 137 fb^{-1} . Signal and ZZ backgrounds are estimated from Monte
 Carlo simulation, Z+X is estimated from data.

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Sum of backgrounds	1811.30	973.45	2414.36	5199.11
Signal ($m_H = 125$ GeV)	95.27	46.01	118.53	259.82
Total expected	1906.57	1019.46	2532.90	5458.93
Data	1970	1032	2646	5648

486 8.1.2 Signal Region Distributions

487 The reconstructed four-lepton invariant mass distribution is shown in Figure 13 for the full
 488 dataset, and compared to expectations from the SM backgrounds, first for the full mass range,
 489 and then zooming on the low-mass range and high-mass range. In Figure 14, the same dis-
 490 tributions are shown split by final state ($4e$, 4μ , and $2e2\mu$), for the two same mass ranges. In
 491 Figure ??, they are split by event category, for the low-mass range. The SM background distri-
 492 butions are obtained combining the rate normalization from data-driven methods and knowl-
 493 edge on shapes taken from the MC samples.

494

495 The reconstructed dilepton invariant masses selected as Z_1 and Z_2 are shown in Figures ??
 496 together with their correlation, both full range of $m_{4\ell}$ and focusing on a $118 < m_{4\ell} < 130$ GeV
 497 mass window around the Higgs boson peak.

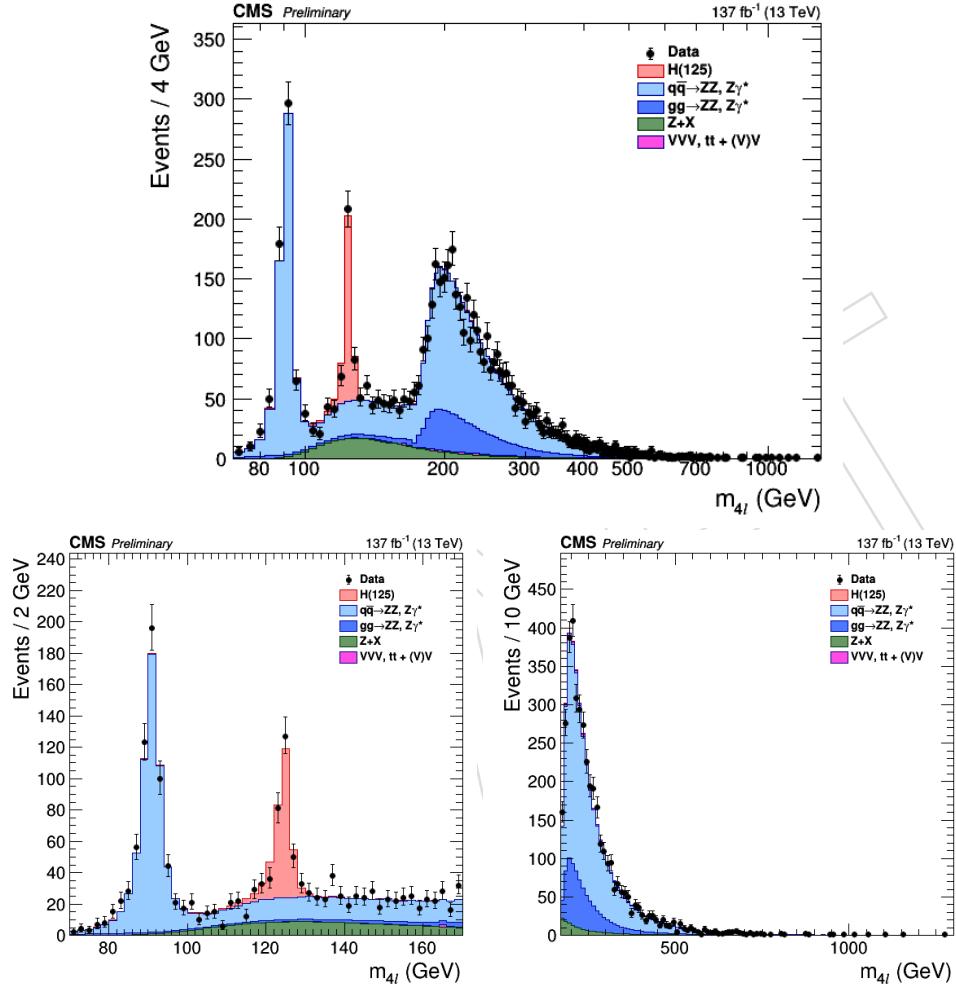


Figure 13: Distribution of the four-lepton reconstructed invariant mass $m_{4\ell}$ in the full mass range (top) and the low-mass range (bottom left) and high-mass range (bottom right). Points with error bars represent the data and stacked histograms represent expected distributions. The 125 GeV Higgs boson signal and the ZZ backgrounds are normalized to the SM expectation, the $Z+X$ background to the estimation from data.

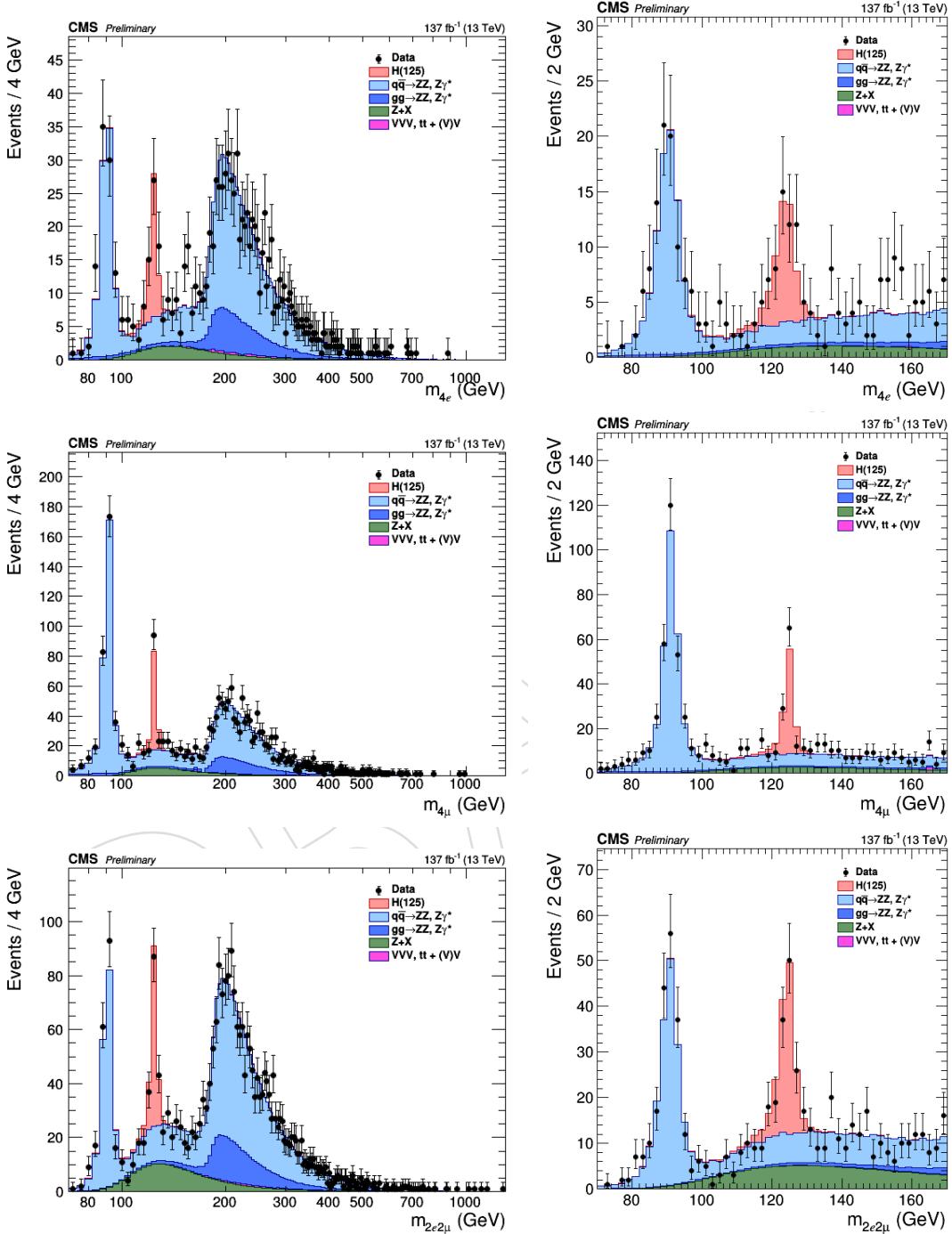
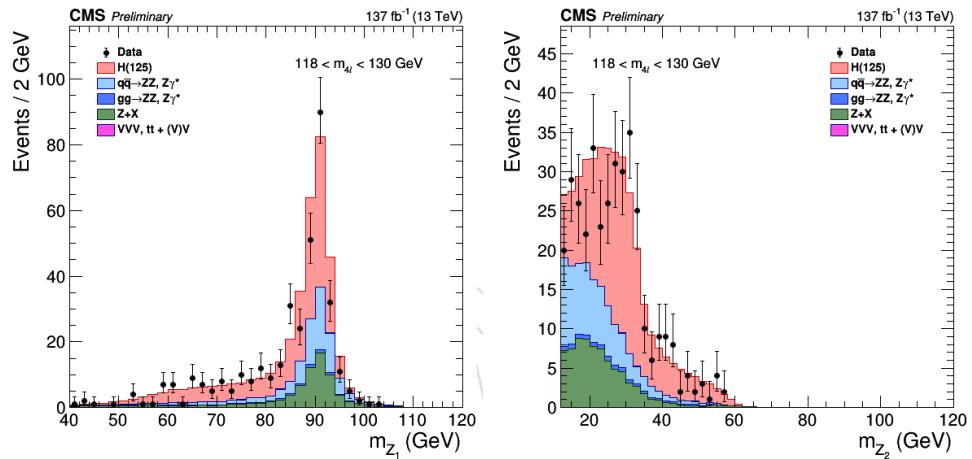


Figure 14: Distribution of the four-lepton reconstructed mass in several sub-channels: $4e$ (top), 4μ (middle), $2e2\mu$ for the low-mass range (bottom) for the full mass range (left) and the low-mass range (right).



Distribution of the Z_1 (left) and Z_2 (right) reconstructed invariant masses for the full mass range (left) and the low mass ($118 < m_{4\ell} < 130$ GeV) range (right). The stacked histograms and the gray scale represent expected distributions, and points represent the data. The 125 GeV Higgs boson signal and the ZZ backgrounds are normalized to the SM expectation, the Z+X background to the estimation from data.

498 8.2 Differential Cross Sections measurement results

499 **FIXME:** Results to be updated with final processing

500 8.2.1 Results for Higgs production observables

501 The expected differential cross section results can be seen in Fig. 15.

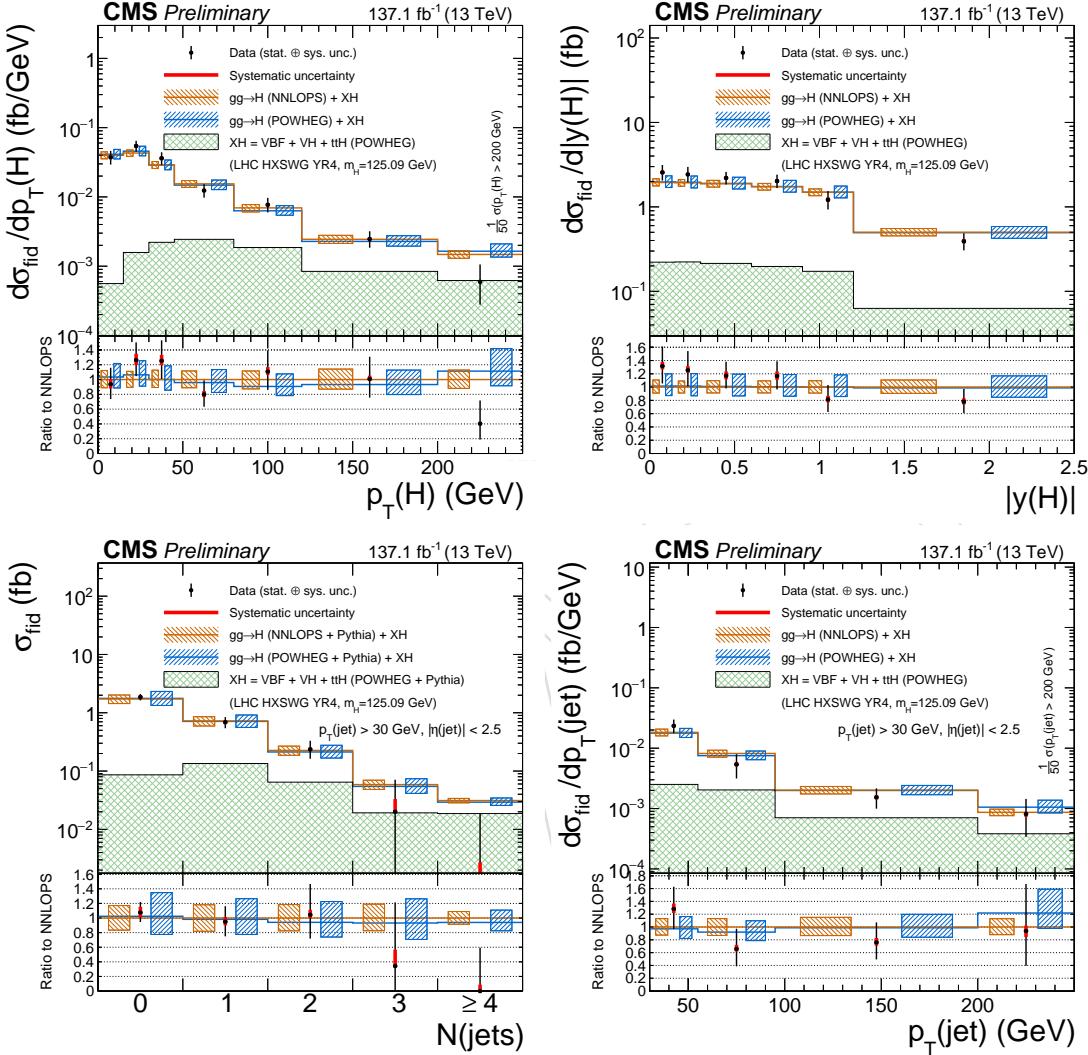


Figure 15: The results of the differential cross section measurement for $p_T(H)$ (middle left), $|y(H)|$ (middle right) and $N(jets)$ (bottom left), p_T of the leading jet (bottom right). The acceptance and theoretical uncertainties in the differential bins are calculated using POWHEG. The sub-dominant component of the signal ($VBF + VH + t\bar{t}H$) is denoted as XH.

502 8.2.2 Results for Higgs decay observables

503 Additional decay observables include Φ , Φ_1 , $m(Z_1)$, $m(Z_2)$, $|\cos\theta^*|$, $|\cos\theta_1|$ and $|\cos\theta_2|$ which
504 are studied in $H \rightarrow 4\ell$ using full Run 2 toy data and compared with the theoretical predictions.

505 In each plot shown below, systematic uncertainty is indicated by red bars and black bars show
506 total statistical and the systematic uncertainties, combined in quadrature. The blue and brown
507 colors show the theoretical predictions. The acceptances and the theoretical uncertainties in
508 differential bins are computed using POWHEG. Sub-dominant production contributions XH

509 = VBF + VH + ttH are shown in green separately. The systematic uncertainties correspond to
510 the generators accuracy are also taken in to account for differential predictions. The fraction of
511 4 μ , 4e and 2e2 μ in each differential bin is allowed to float in fit.

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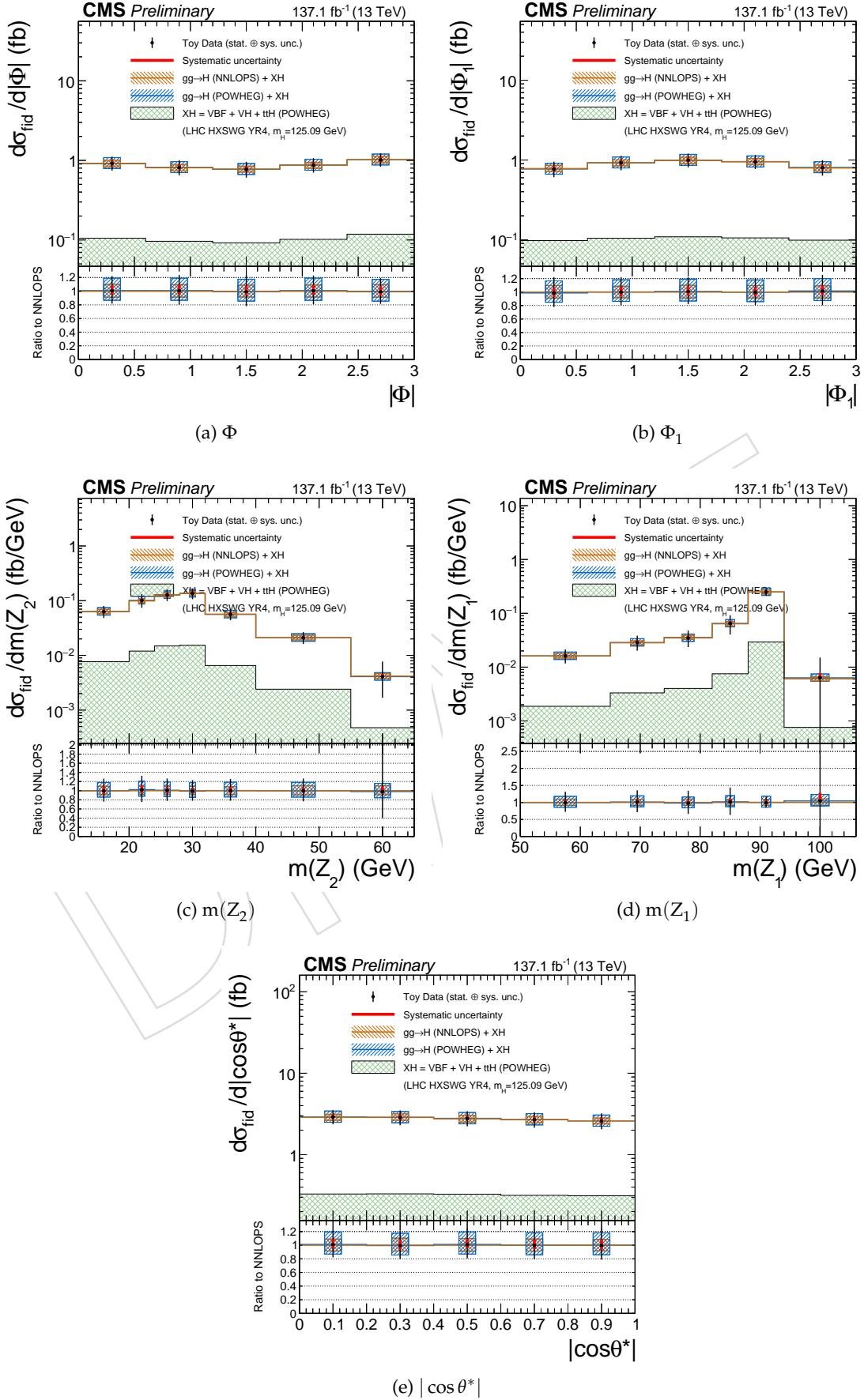


Figure 16: Differential fiducial cross section results using full Run 2 toy data for Φ , Φ_1 , $m(Z_1)$, $m(Z_2)$ and $|\cos\theta^*|$ in $H \rightarrow 4\ell$ and comparison with the theoretical predictions.

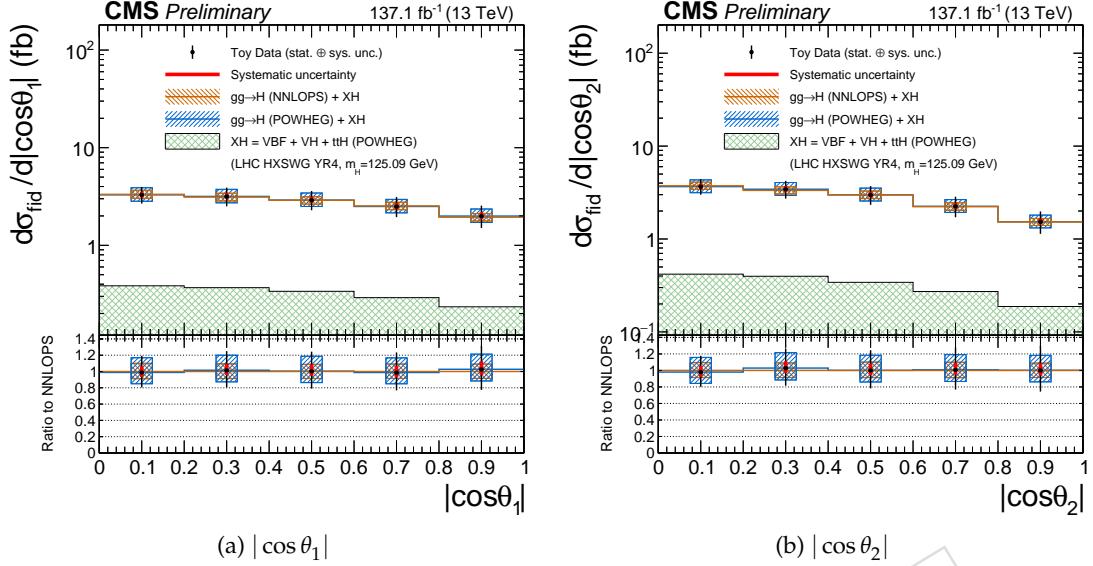


Figure 17: Differential fiducial cross section results using full Run 2 toy data for $|\cos \theta_1|$, $|\cos \theta_2|$ in $H \rightarrow 4\ell$ and comparison with the theoretical predictions. Systematic uncertainty is indicated by red bars and black bars show total statistical and the systematic uncertainties, combined in quadrature. The blue and brown colors show the theoretical predictions. The acceptances and the theoretical uncertainties in differential bins are computed using POWHEG. Sub-dominant production contributions $XH = VBF + VH + t\bar{t}H$ are shown in green separately. The systematic uncertainties correspond to the generators accuracy are also taken in to account for differential predictions. The fraction of 4μ , $4e$ and $2e2\mu$ in each differential bin is allowed to float in fit.

512 8.3 Double differential cross section measurements

513 Differential measurements are extended upto higher dimension upto 2. Several 2D combina-
514 tion are aimed to be measured e.g. $m(Z_1)$ vs $m(Z_2)$ and so forth. To be updated further.

515 8.4 Interpretations

516 To be updated.

517 8.4.1 Constraints on Yukawa Couplings: Fits of coupling modifiers (κ_b vs. κ_c)

518 To be updated.

519 8.4.2 Constraint on Higgs boson trilinear self-coupling (κ_λ)

520 To be updated.

A large, semi-transparent watermark consisting of the word "DRAFT" in a bold, sans-serif font. The letters are oriented diagonally, sloping upwards from the bottom-left towards the top-right. The watermark is rendered in a very light gray color, making it less prominent against the white background.

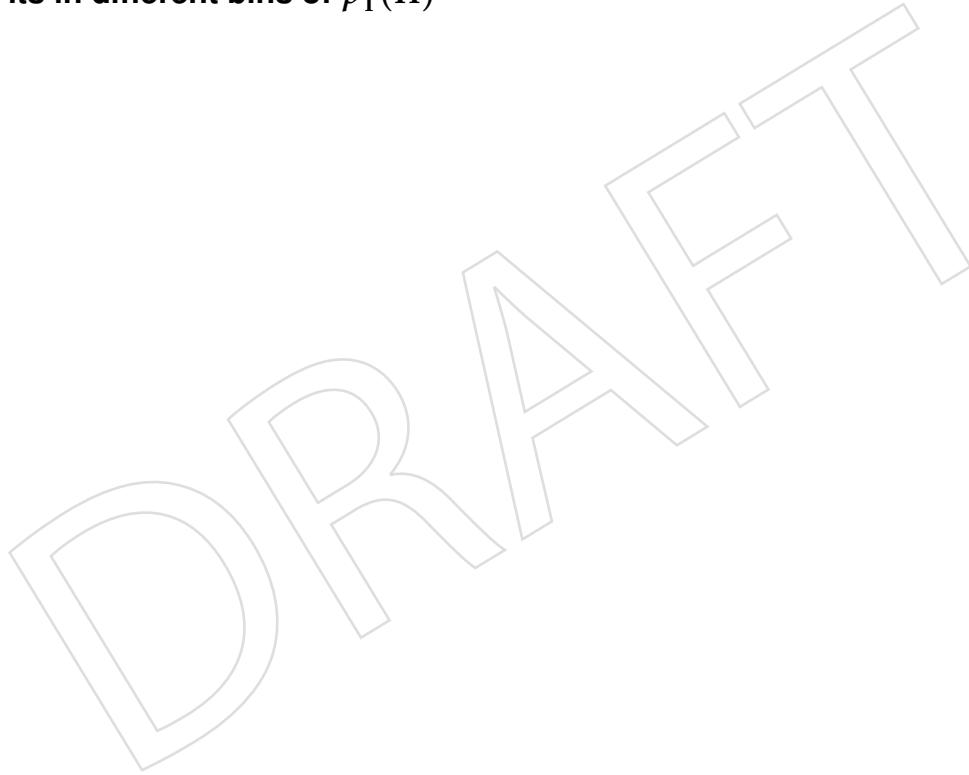
521 **9 Interpretation**

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522 A Signal Shapes and Efficiencies

523 For all plots showing fits to the signal distributions, the red histograms show the distribution of
524 events which pass both the fiducial selection at generator level and pass the full reconstruction
525 level selection, including the selection on $p_T(H)$. The red curve shows a fit to this distribution
526 using a double-sided crystal ball function, and the resulting σ of the fit is also shown on the
527 plot. The blue histograms show events which pass the full reconstruction level selection, and
528 pass the fiducial selection at generator level within a different $p_T(H)$ bin. The blue curves show
529 a fit to this distribution using the same function as the red curve with a different normalization.
530 The black histograms show the distribution of events which pass the full reconstruction level
531 selection but do not pass the fiducial selection at generator level, and the black curve shows a fit
532 to this distribution using the same function as the red curve but with a different normalization.
533 The yellow histogram shows events which pass the full reconstruction level selection but where
534 one of the four selected leptons does not originate from the Higgs boson. The yellow curve
535 shows a fit to this distribution using a Landau function.

536 **A.1 Fits in different bins of $p_T(H)$**



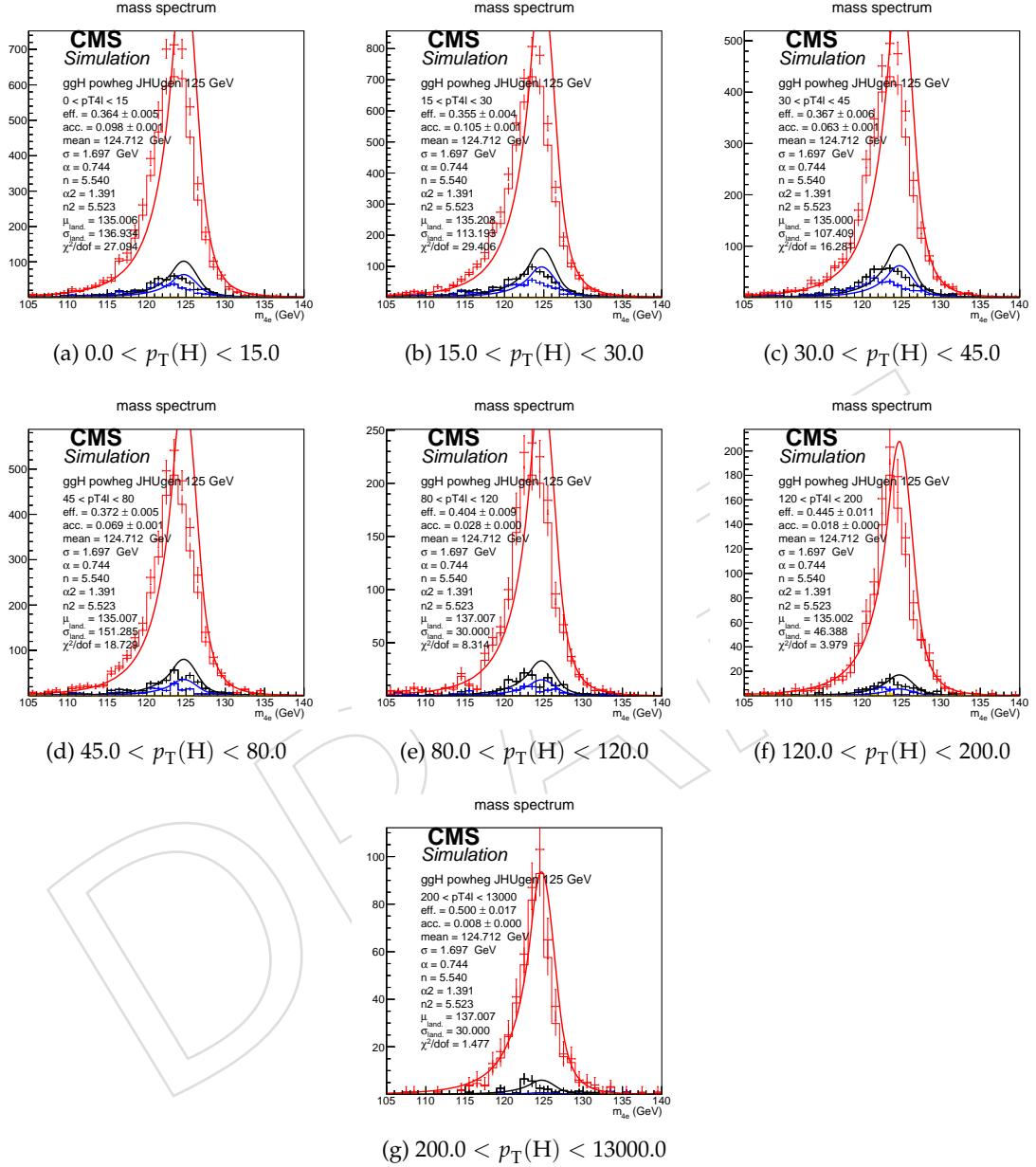


Figure 18: Example signal shapes at reconstruction level for a resonance of $m(4\ell)$ in $4e$ final state for the $gg \rightarrow H$ production mode from POWHEG+JHUGEN in different bins of $p_T(H)$. The black curve represents events which do not pass the fiducial volume selection. The curve has no effect on the result.

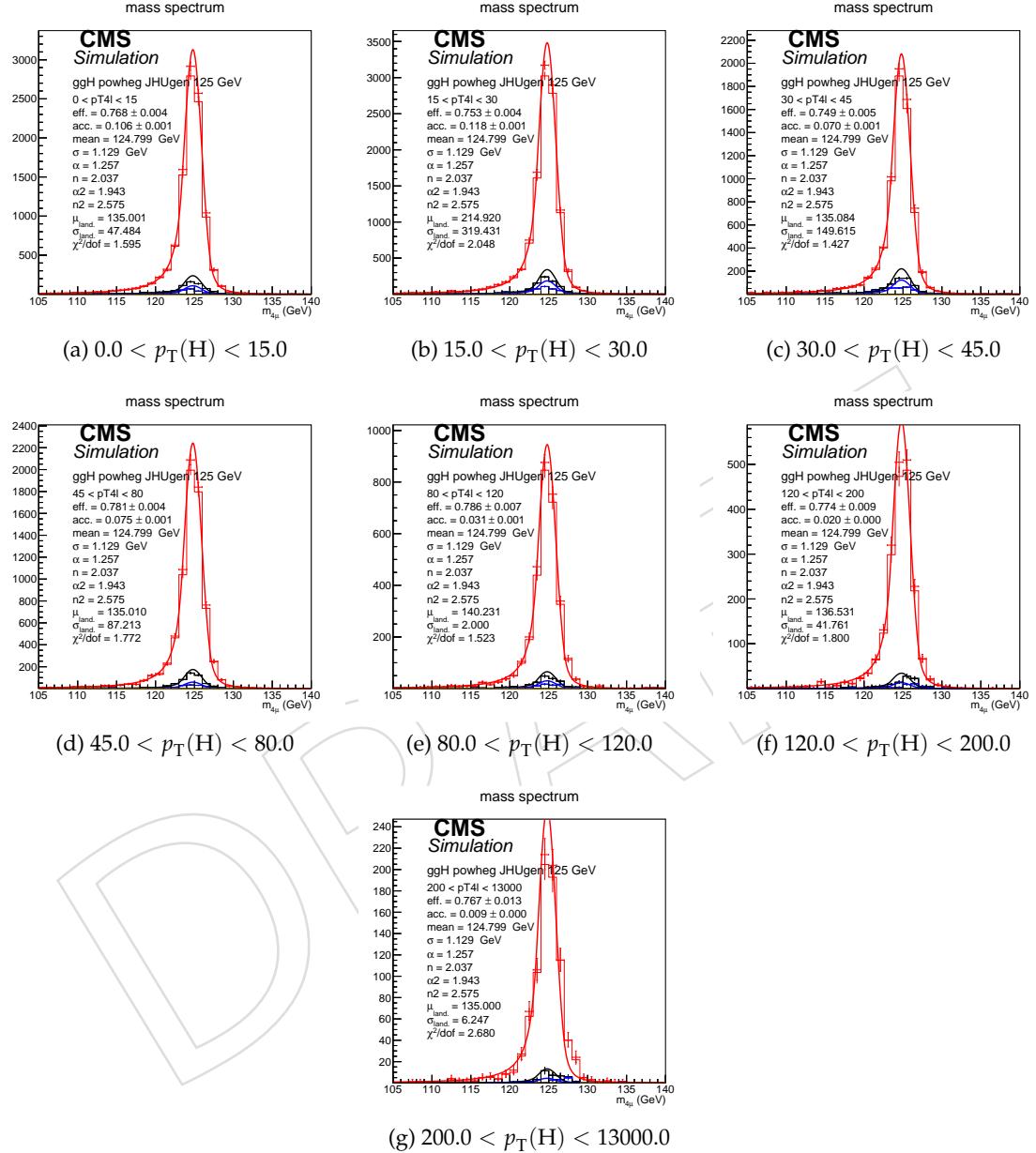


Figure 19: Example signal shapes at reconstruction level for a resonance of $m(4\ell)$ in 4μ final state for the $gg \rightarrow H$ production mode from POWHEG+JHUGEN in different bins of $p_T(H)$. The black curve represents events which do not pass the fiducial volume selection. The curve has no effect on the result.

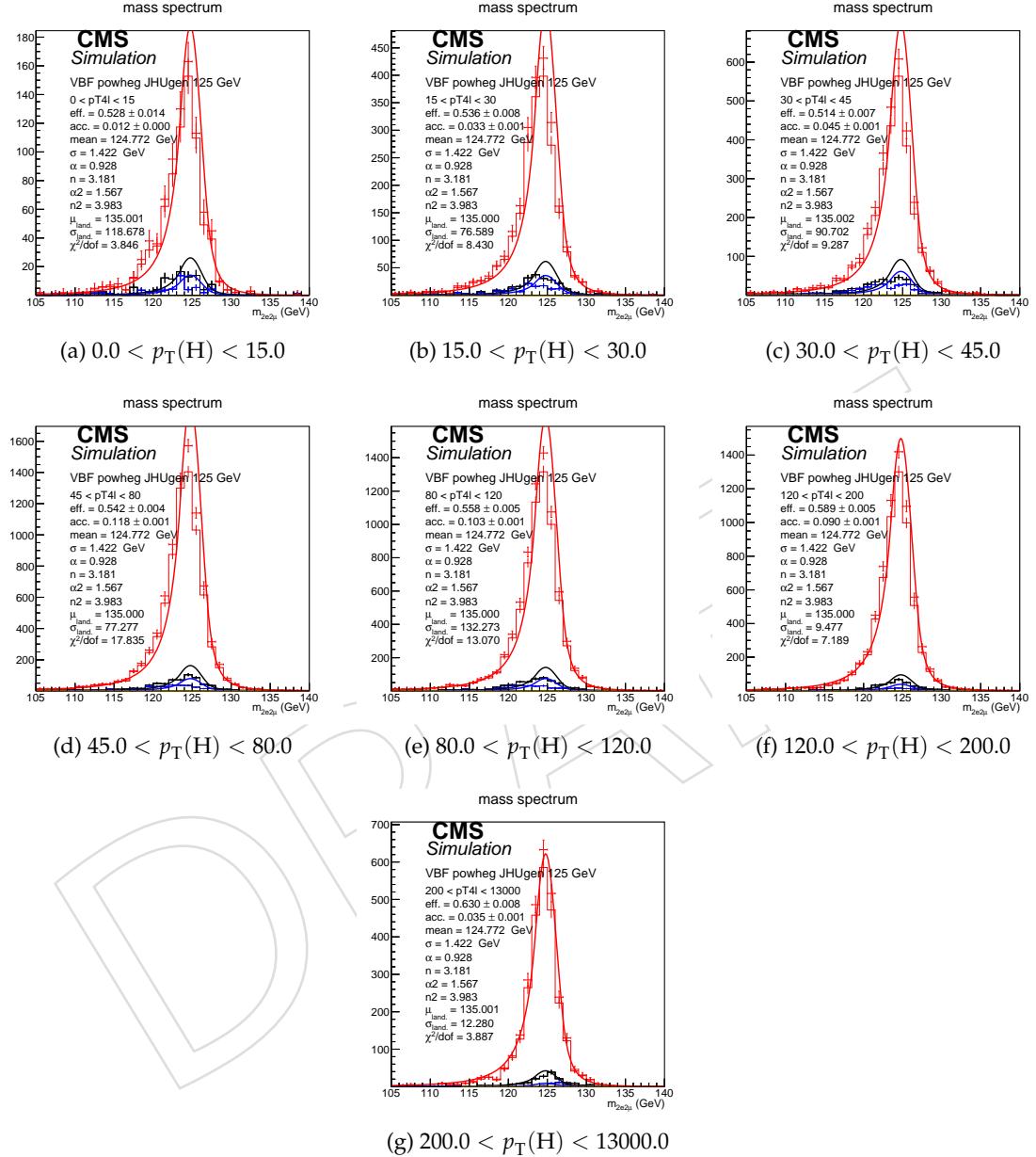


Figure 20: Example signal shapes at reconstruction level for a resonance of $m(4\ell)$ in $2e2\mu$ final state for the VBF production mode from POWHEG+JHUGEN in different bins of $p_T(H)$. The black curve represents events which do not pass the fiducial volume selection. The curve has no effect on the result.

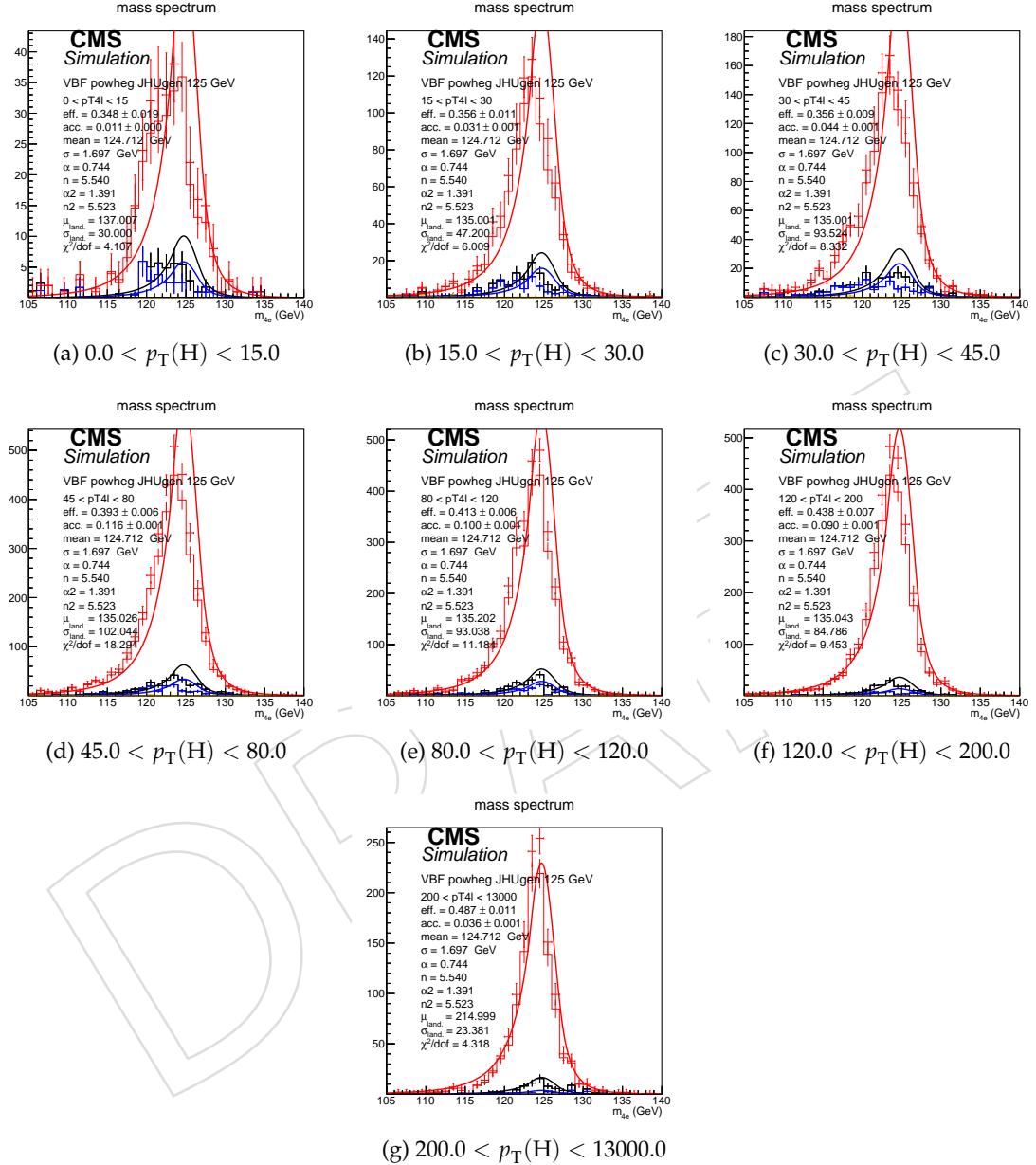


Figure 21: Example signal shapes at reconstruction level for a resonance of $m(4\ell)$ in $4e$ final state for the VBF production mode from POWHEG+JHUGEN in different bins of $p_{\text{T}}(\text{H})$. The black curve represents events which do not pass the fiducial volume selection. The curve has no effect on the result.

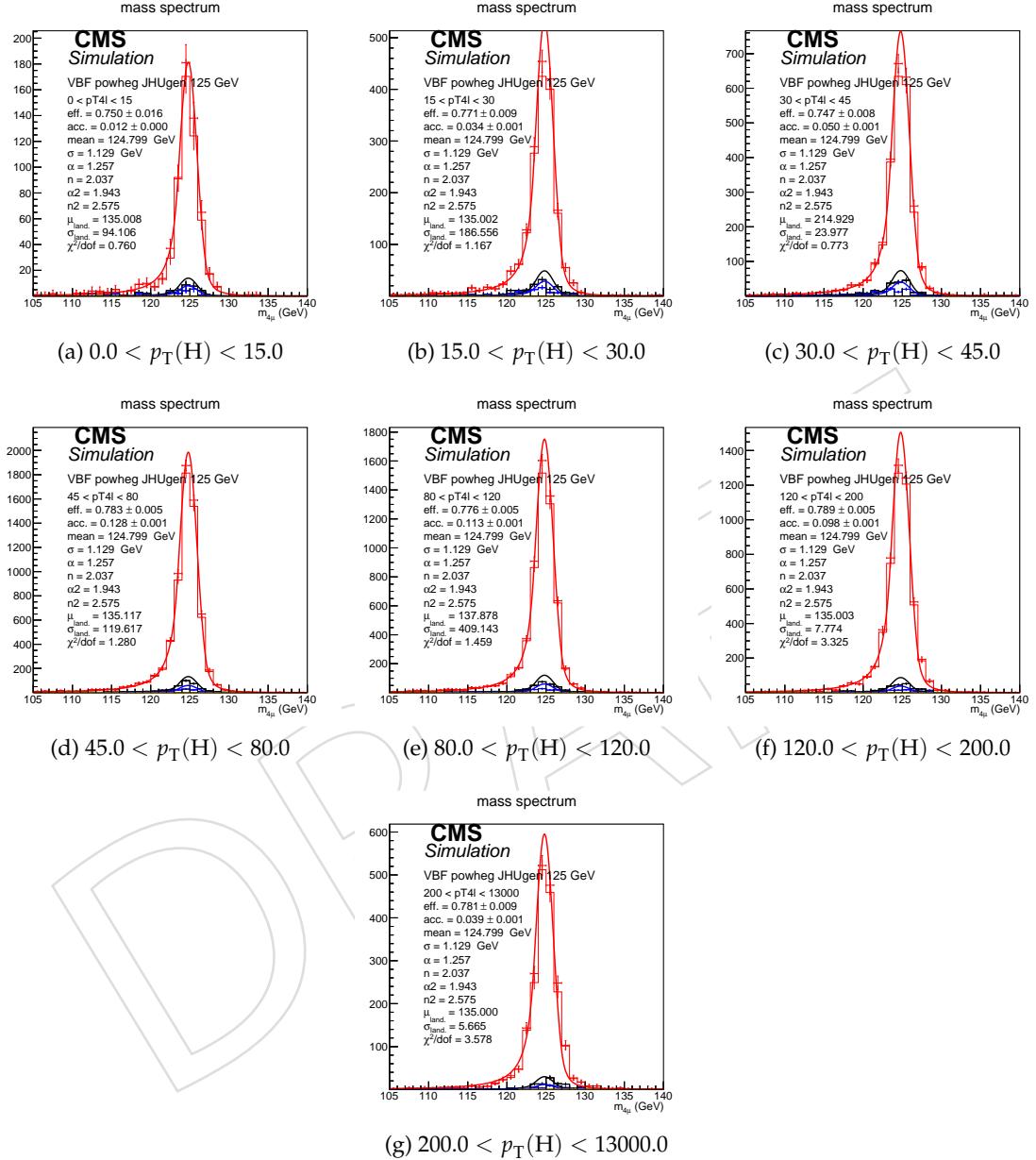


Figure 22: Example signal shapes at reconstruction level for a resonance of $m(4\ell)$ in 4μ final state for the VBF production mode from POWHEG+JHUGEN in different bins of $p_{\text{T}}(\text{H})$. The black curve represents events which do not pass the fiducial volume selection. The curve has no effect on the result.

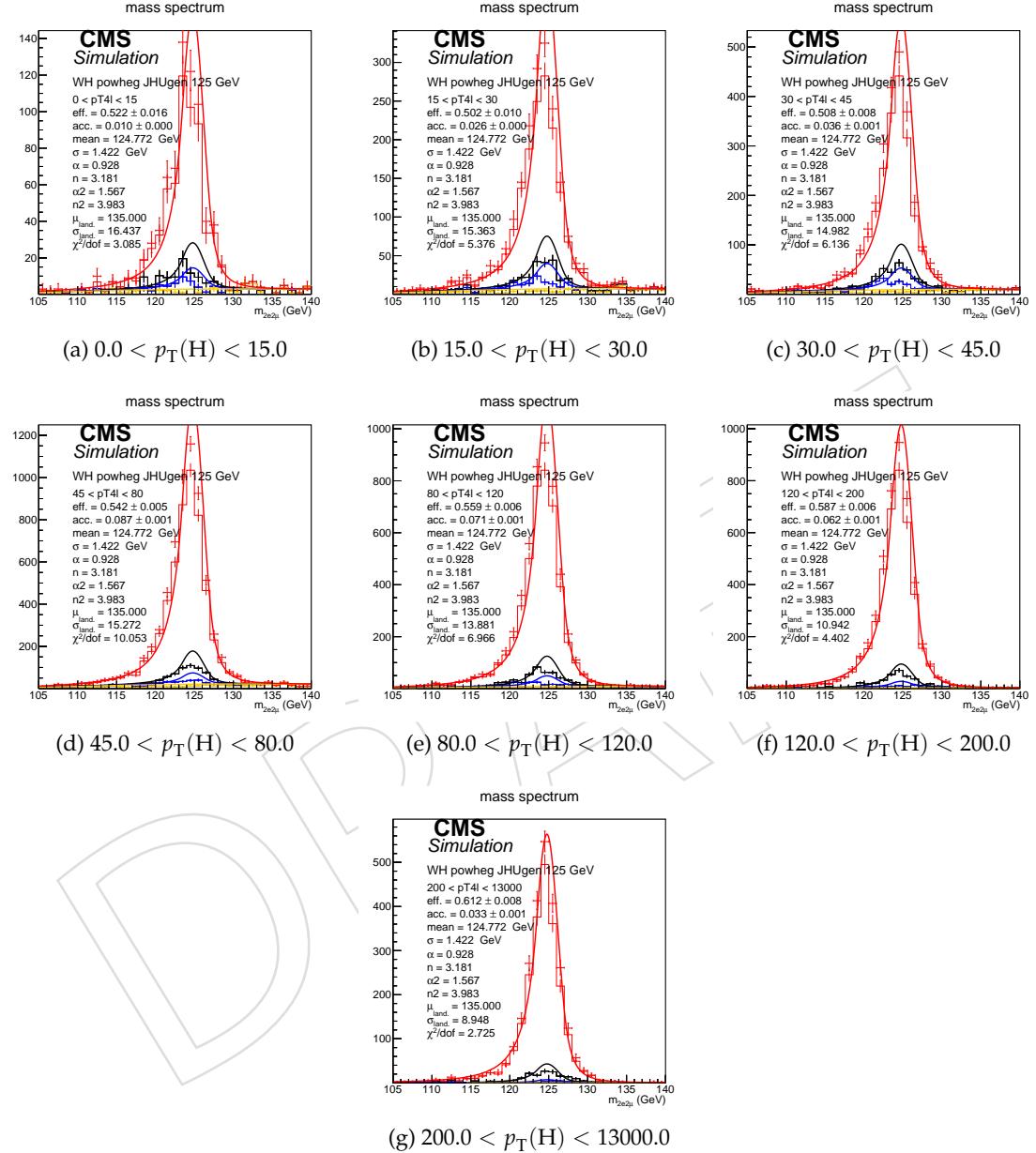


Figure 23: Example signal shapes at reconstruction level for a resonance of $m(4\ell)$ in $2e2\mu$ final state for the WH production mode from POWHEG+JHUGEN in different bins of $p_T(H)$. The black curve represents events which do not pass the fiducial volume selection. The curve has no effect on the result.

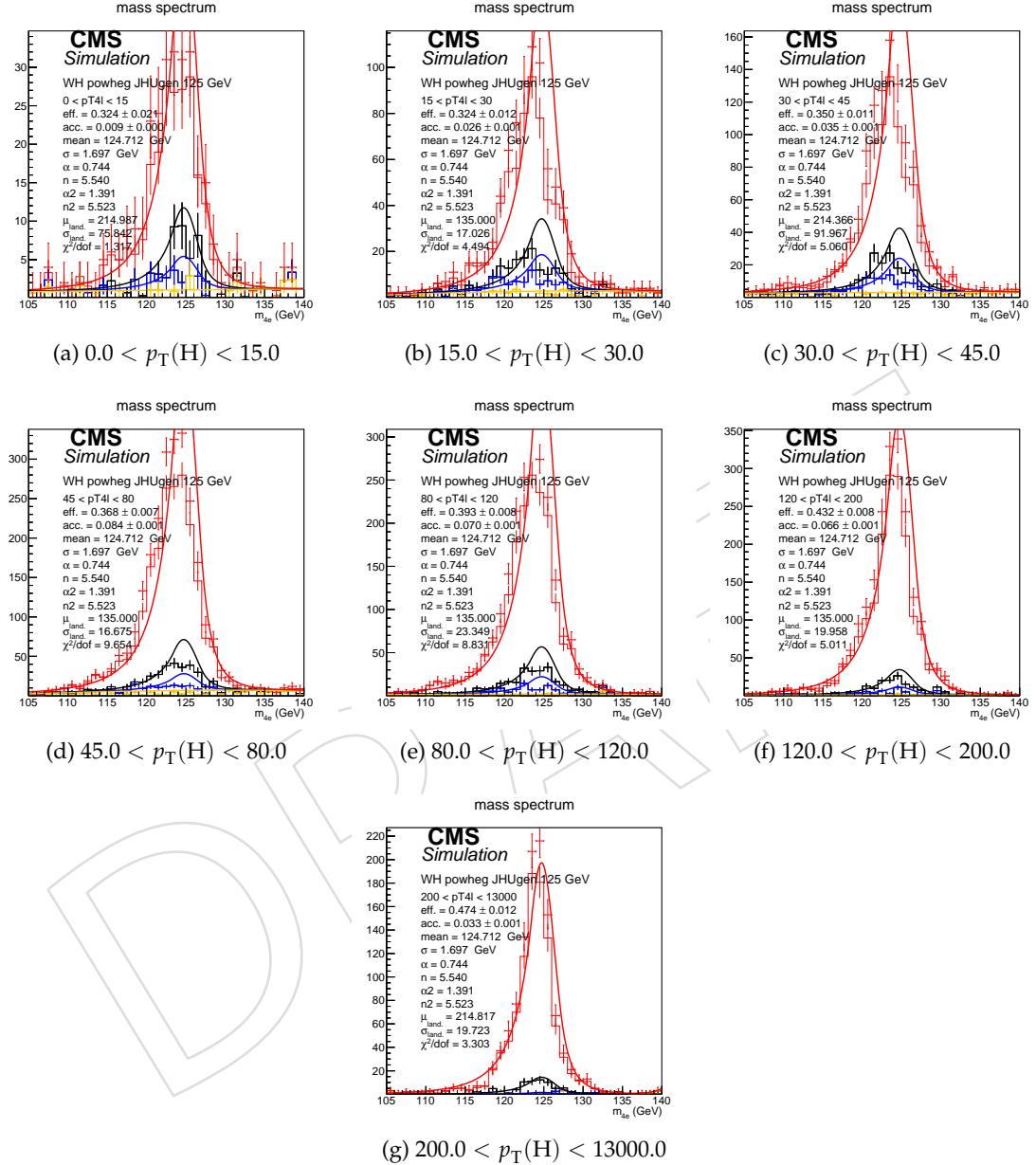


Figure 24: Example signal shapes at reconstruction level for a resonance of $m(4\ell)$ in $4e$ final state for the WH production mode from POWHEG+JHUGEN in different bins of $p_T(H)$. The black curve represents events which do not pass the fiducial volume selection. The curve has no effect on the result.

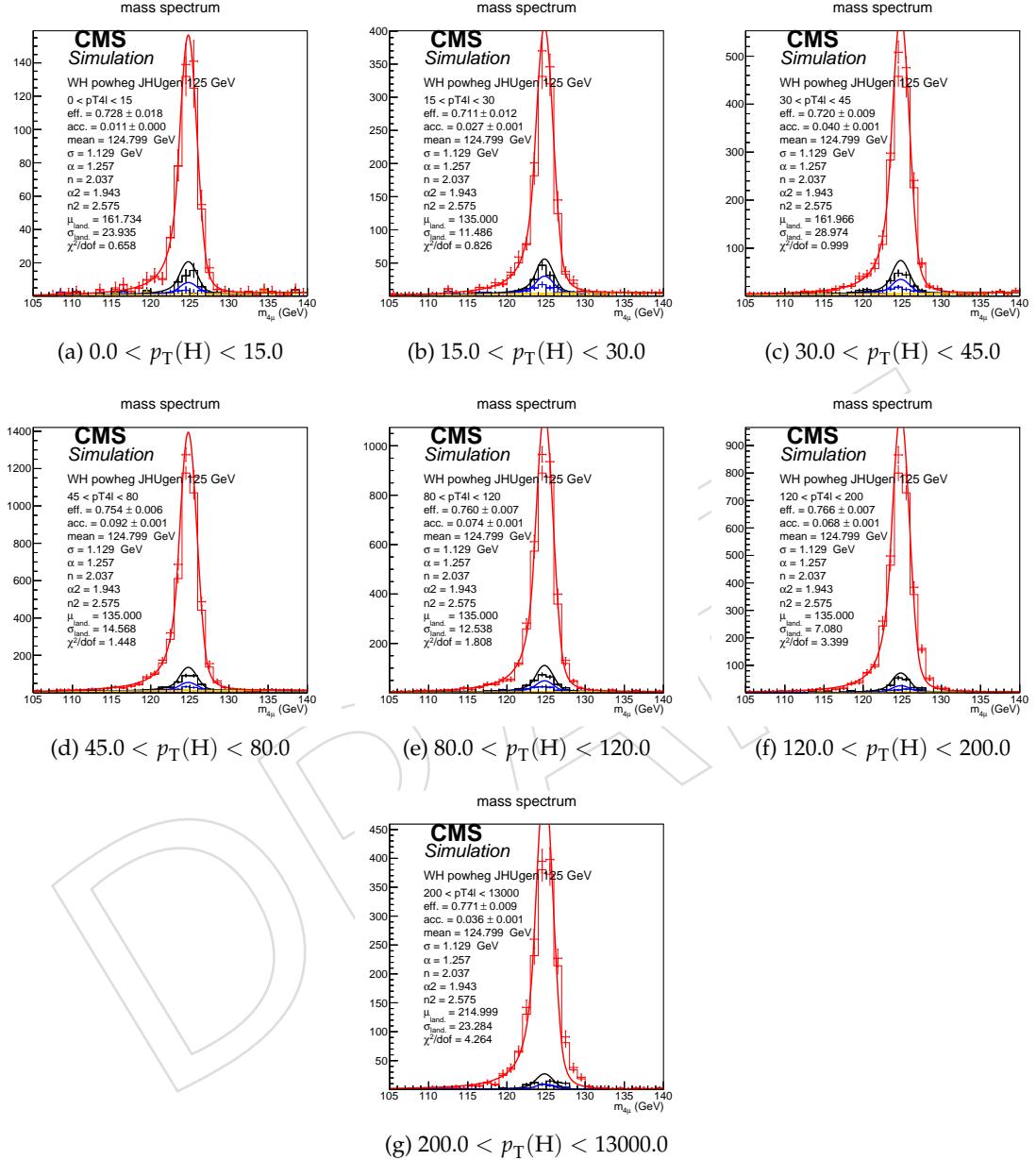


Figure 25: Example signal shapes at reconstruction level for a resonance of $m(4\ell)$ in 4μ final state for the $gg \rightarrow H$ production mode from POWHEG+JHUGEN in different bins of $p_T(H)$. The black curve represents events which do not pass the fiducial volume selection. The curve has no effect on the result.

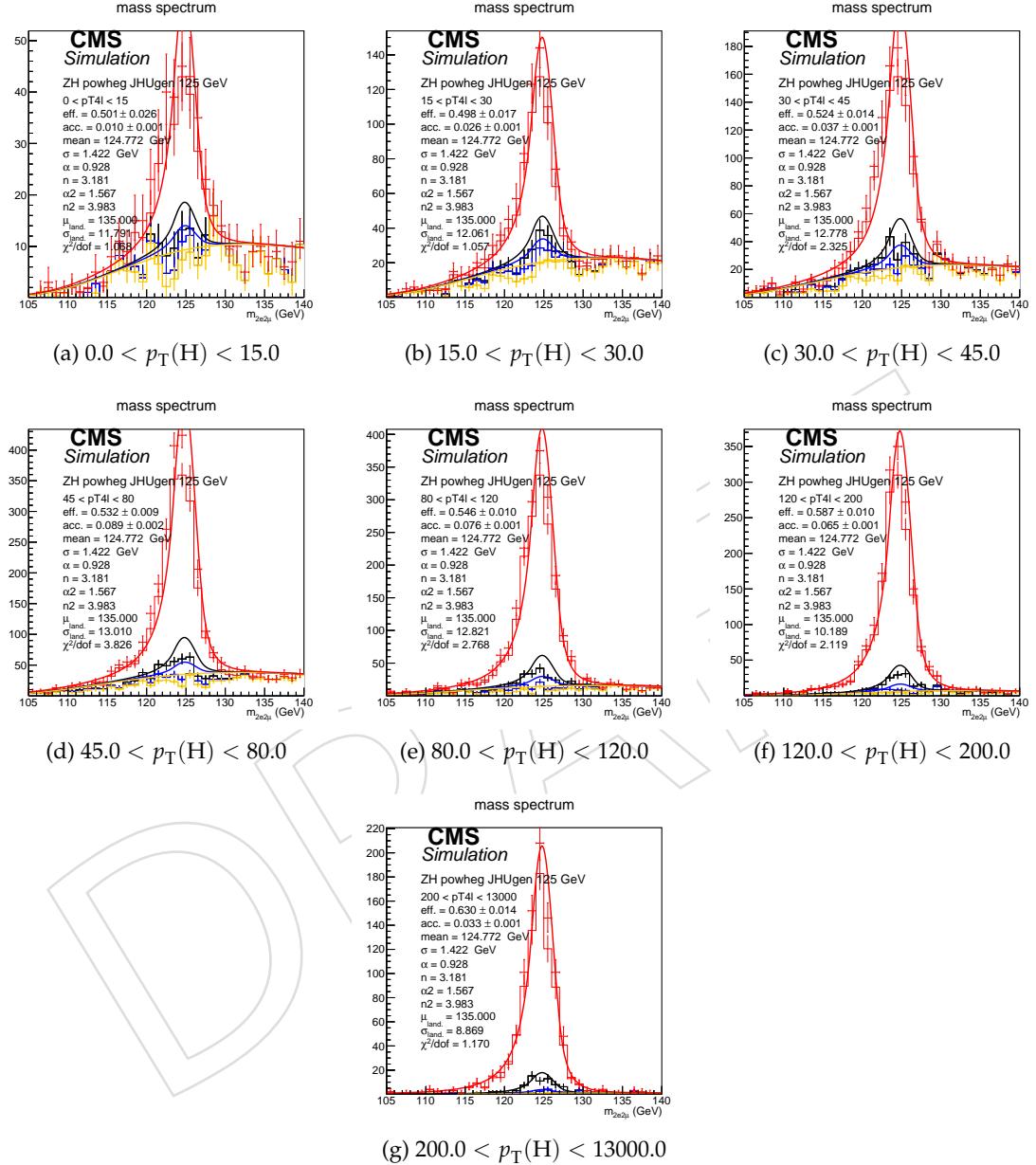


Figure 26: Example signal shapes at reconstruction level for a resonance of $m(4\ell)$ in $2e2\mu$ final state for the ZH production mode from POWHEG+JHUGEN in different bins of $p_T(H)$. The black curve represents events which do not pass the fiducial volume selection. The curve has no effect on the result.

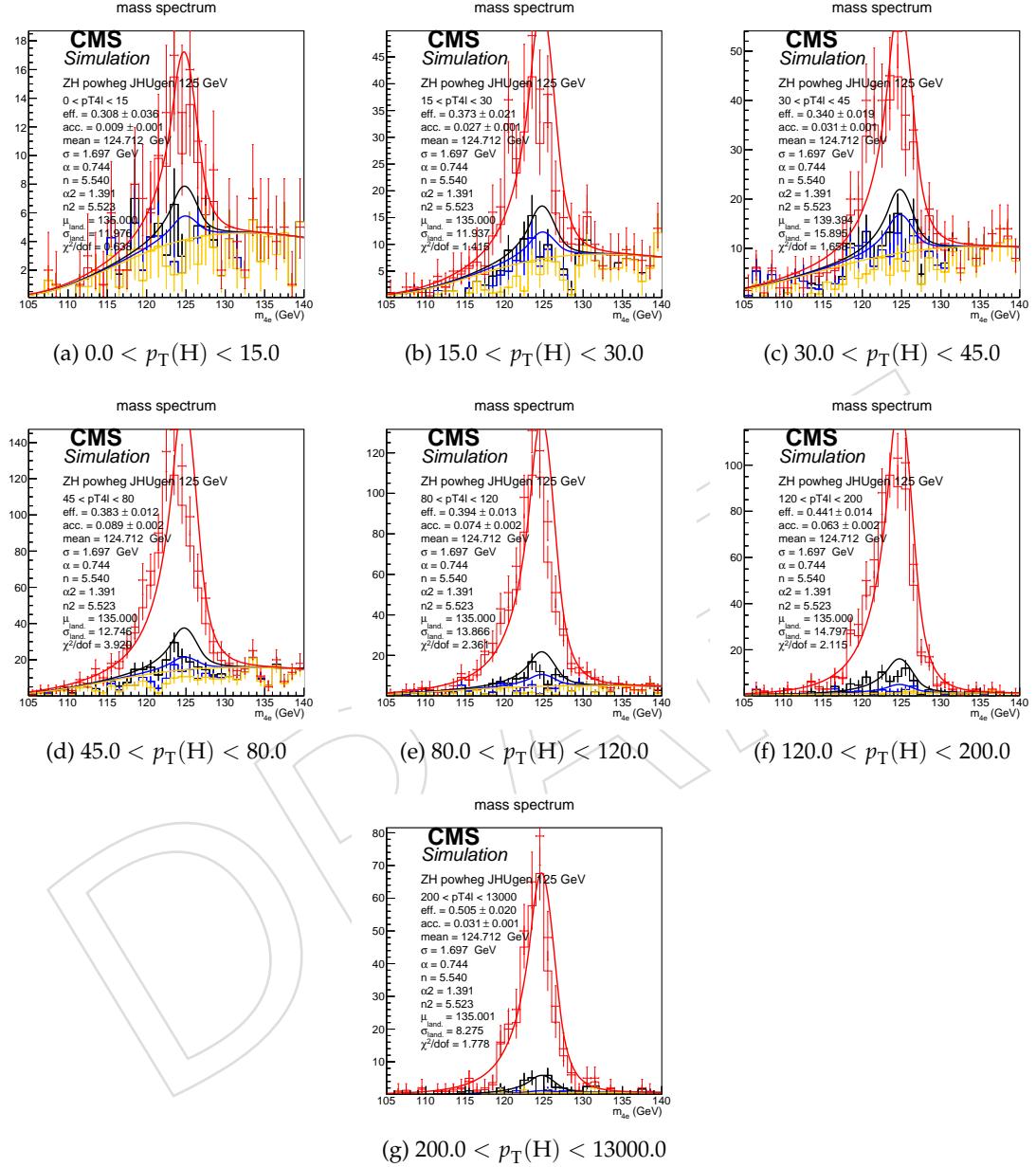


Figure 27: Example signal shapes at reconstruction level for a resonance of $m(4\ell)$ in $4e$ final state for the ZH production mode from POWHEG+JHUGEN in different bins of $p_T(H)$. The black curve represents events which do not pass the fiducial volume selection. The curve has no effect on the result.

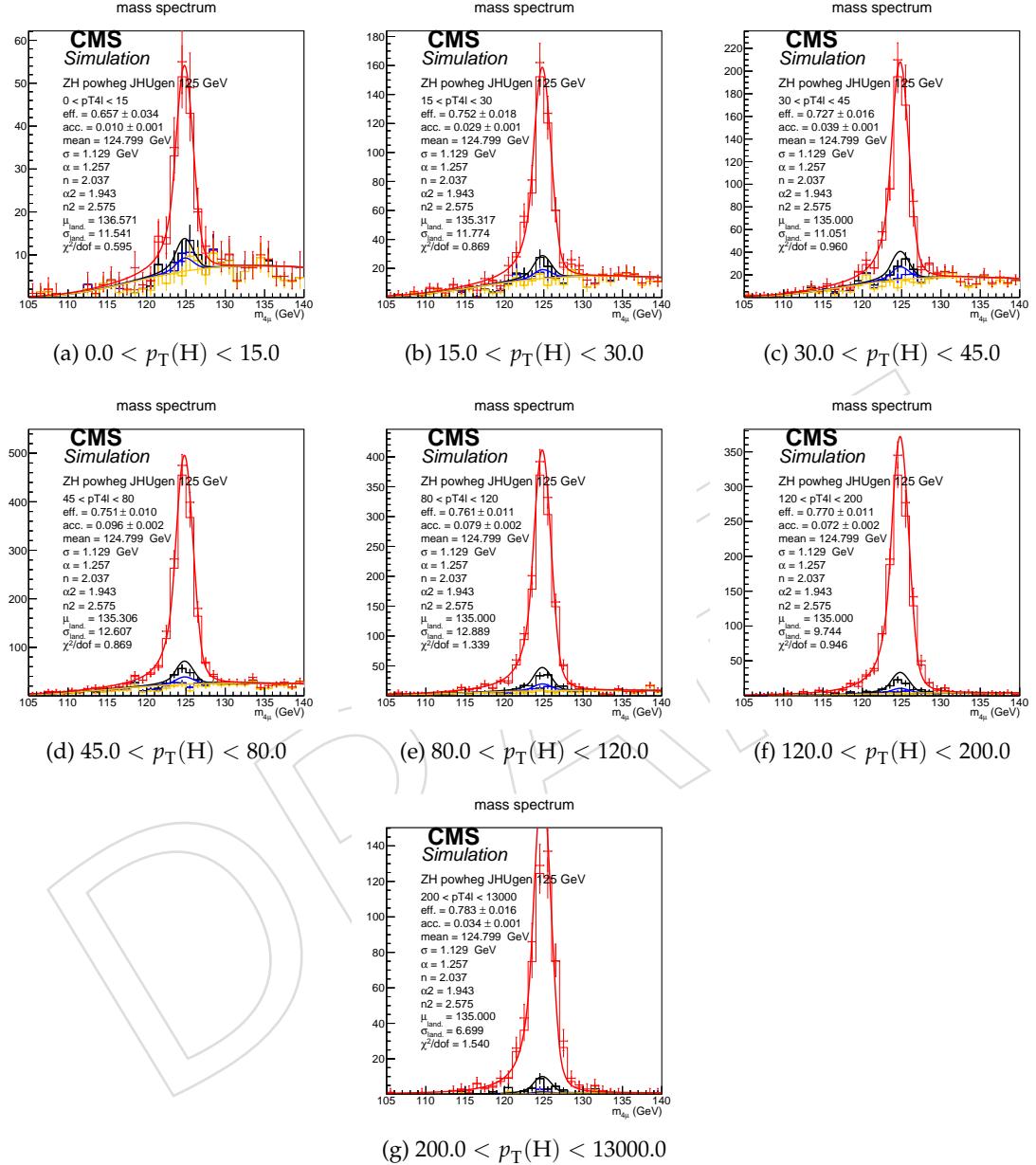


Figure 28: Example signal shapes at reconstruction level for a resonance of $m(4\ell)$ in 4μ final state for the ZH production mode from POWHEG+JHUGEN in different bins of $p_T(H)$. The black curve represents events which do not pass the fiducial volume selection. The curve has no effect on the result.

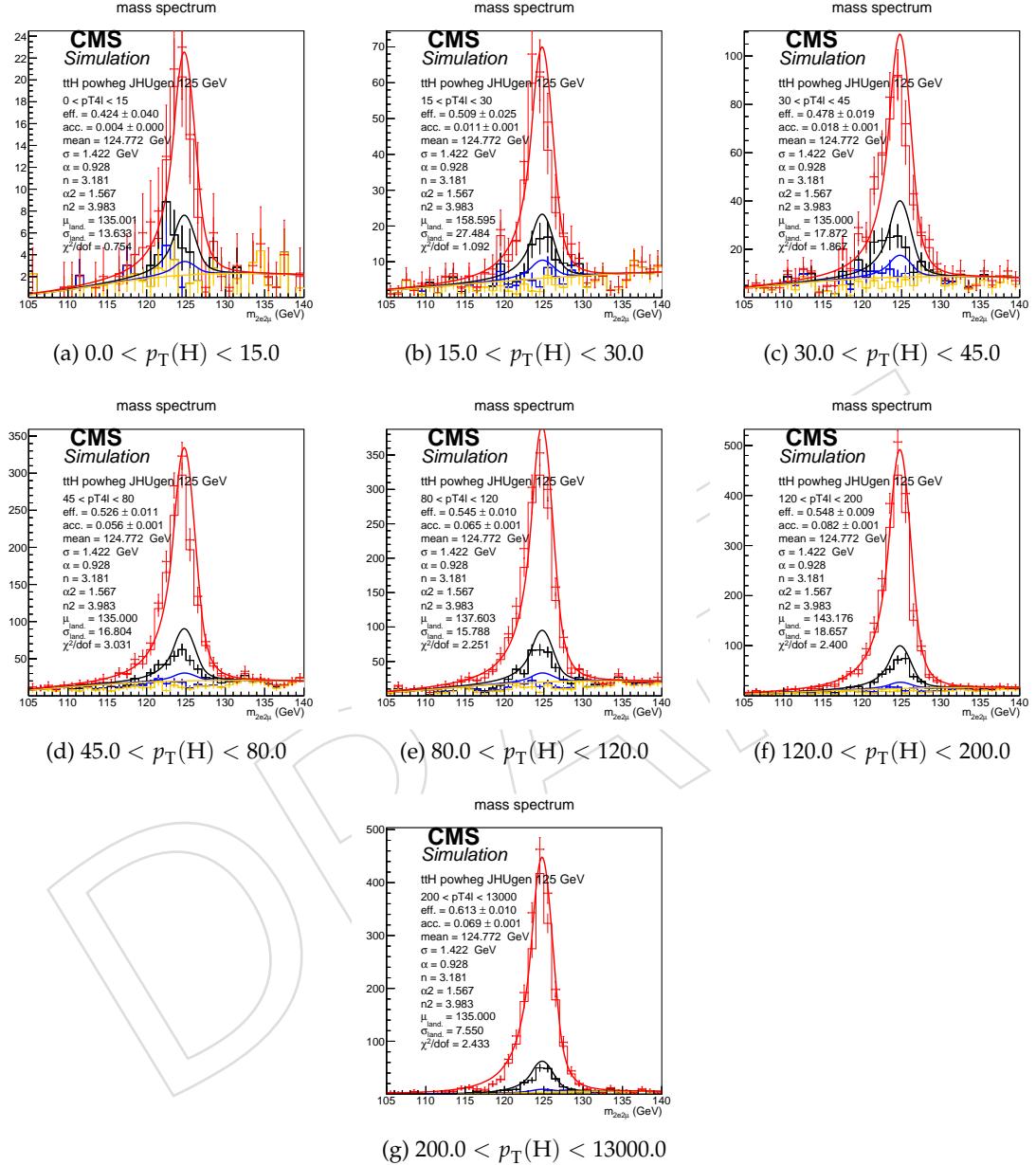


Figure 29: Example signal shapes at reconstruction level for a resonance of $m(4\ell)$ in $2e2\mu$ final state for the $t\bar{t}H$ production mode from POWHEG+JHUGEN in different bins of $p_T(H)$. The black curve represents events which do not pass the fiducial volume selection. The curve has no effect on the result.

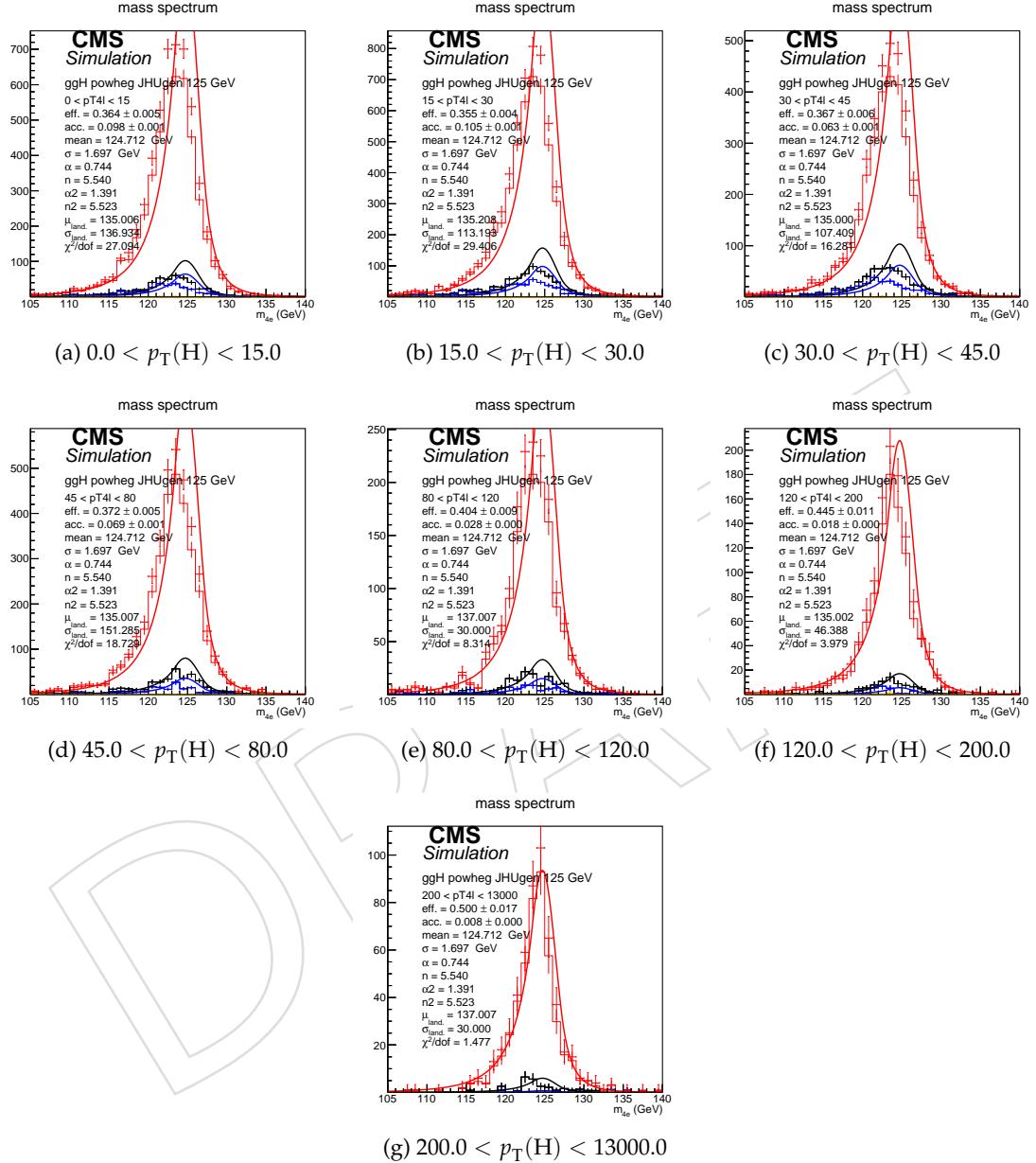


Figure 30: Example signal shapes at reconstruction level for a resonance of $m(4\ell)$ in $4e$ final state for the $t\bar{t}H$ production mode from POWHEG+JHUGEN in different bins of $p_T(H)$. The black curve represents events which do not pass the fiducial volume selection. The curve has no effect on the result.

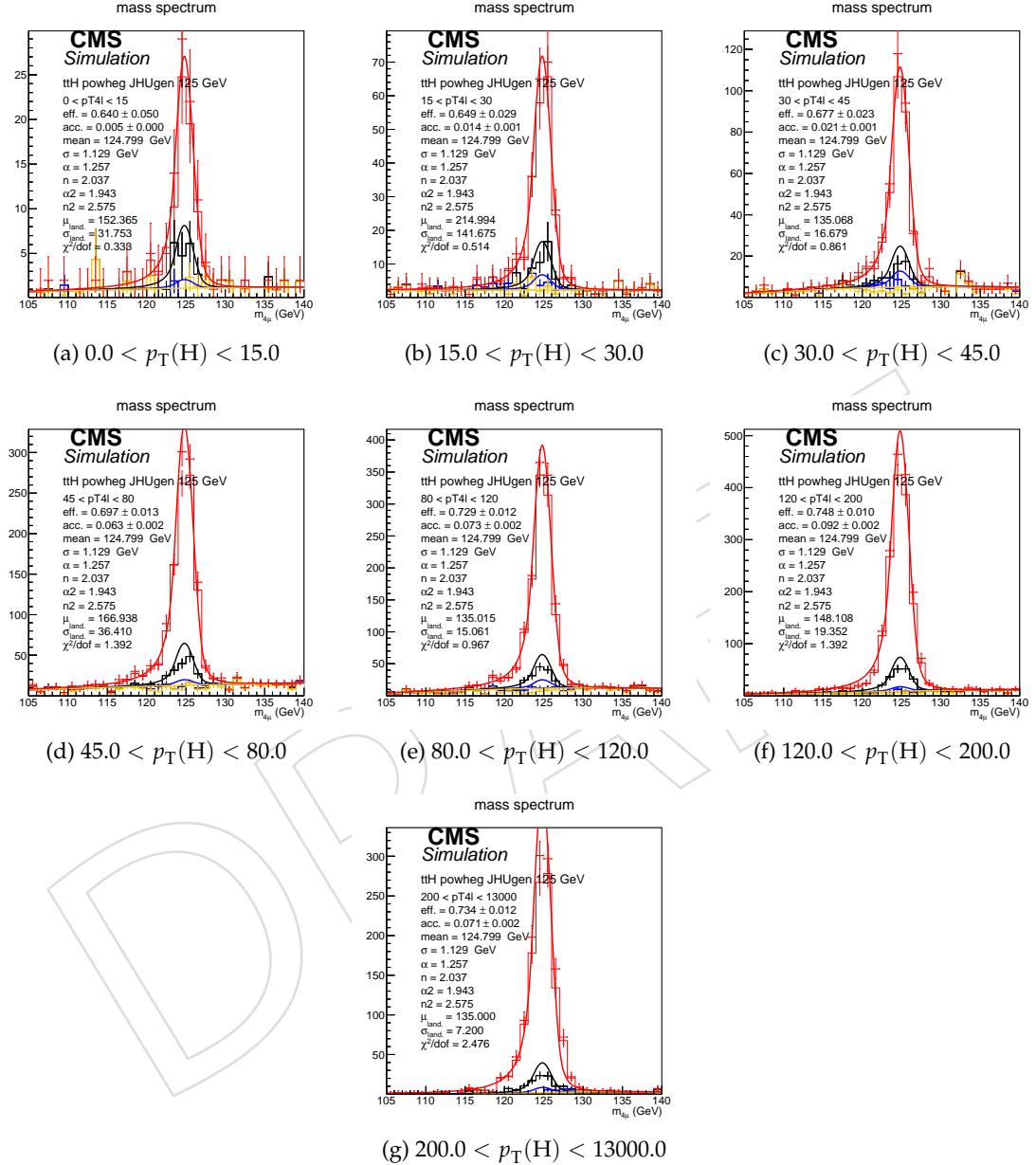


Figure 31: Example signal shapes at reconstruction level for a resonance of $m(4\ell)$ in 4μ final state for the $t\bar{t}H$ production mode from POWHEG+JHUGEN in different bins of $p_{\text{T}}(\text{H})$. The black curve represents events which do not pass the fiducial volume selection. The curve has no effect on the result.

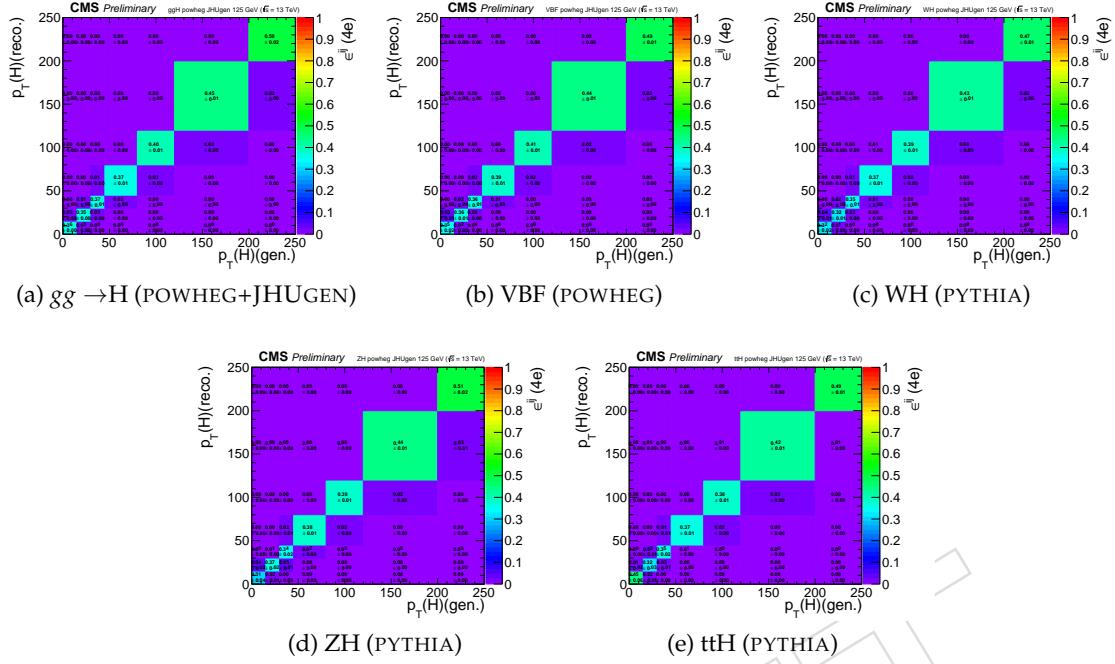


Figure 32: Efficiency matrices for $p_T(H)$ for different SM production modes in the $4e$ final state.

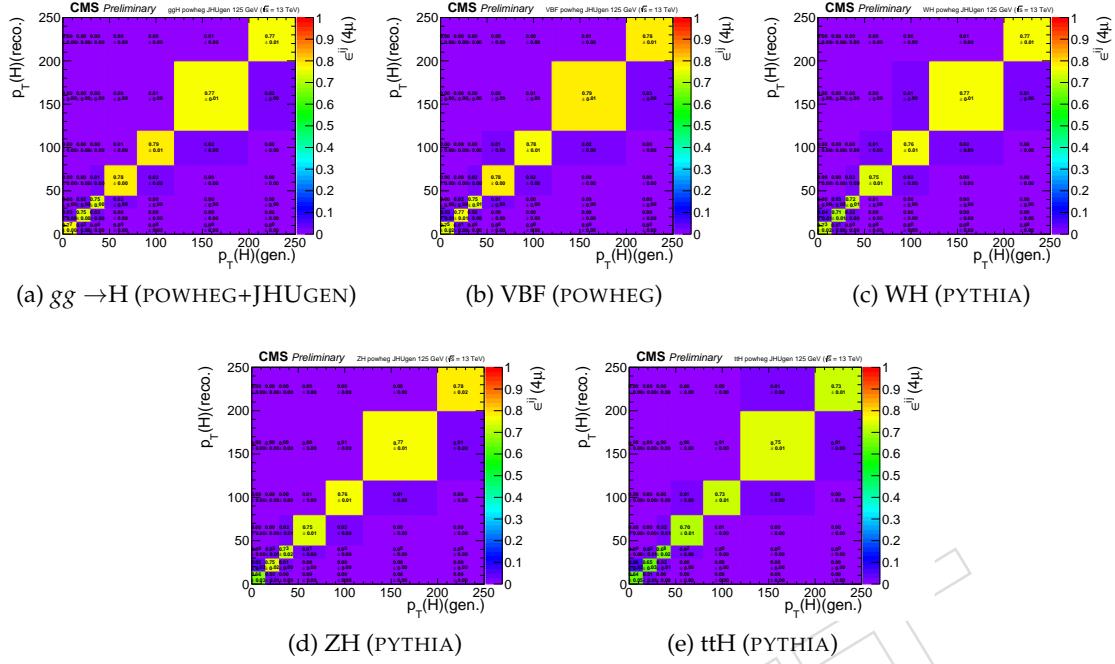


Figure 33: Efficiency matrices for $p_T(H)$ for different SM production modes in the 4μ final state.

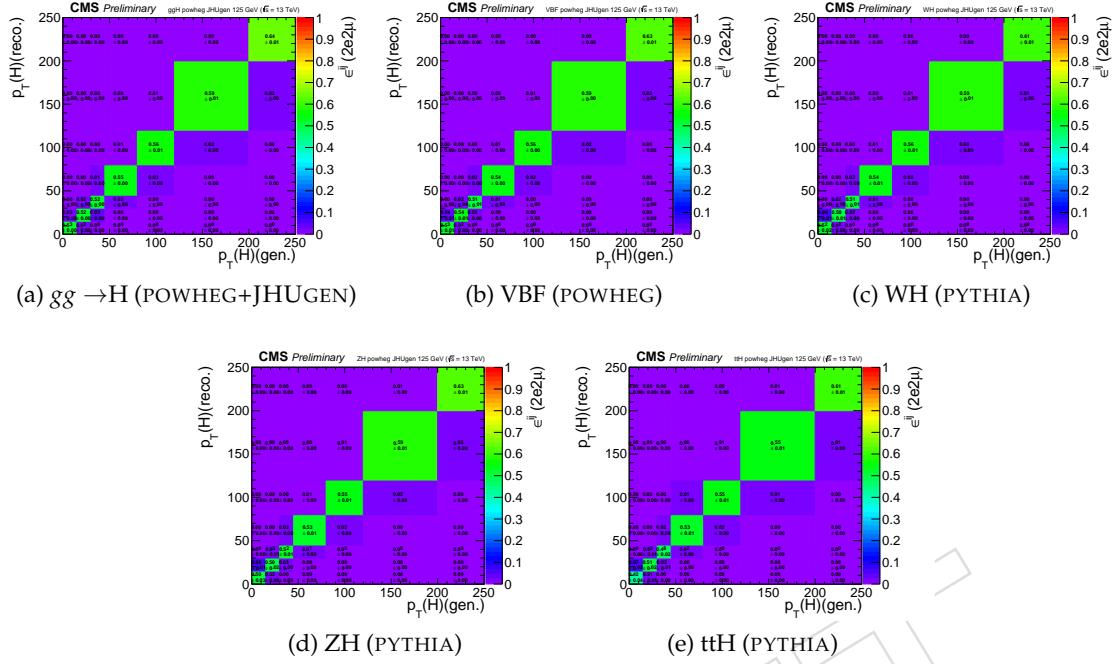


Figure 34: Efficiency matrices for $p_T(H)$ for different SM production modes in the $2e2\mu$ final state.

537 **A.2 Signal inputs in different bins of $|y(H)|$**

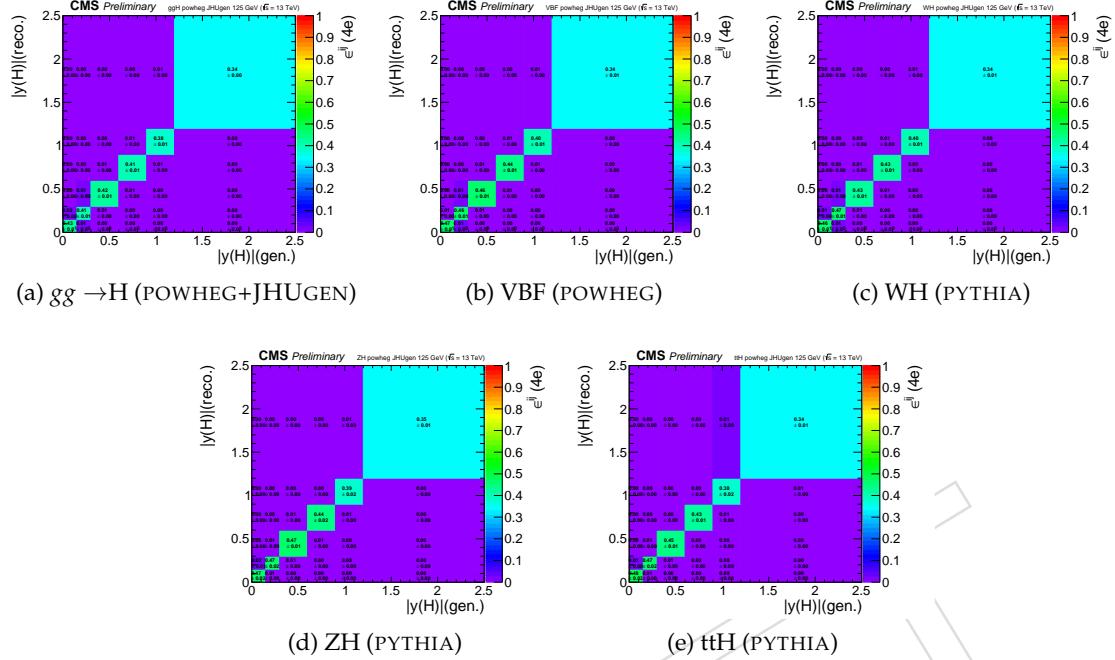


Figure 35: Efficiency matrices for $|y(H)|$ for different SM production modes in the $4e$ final state.

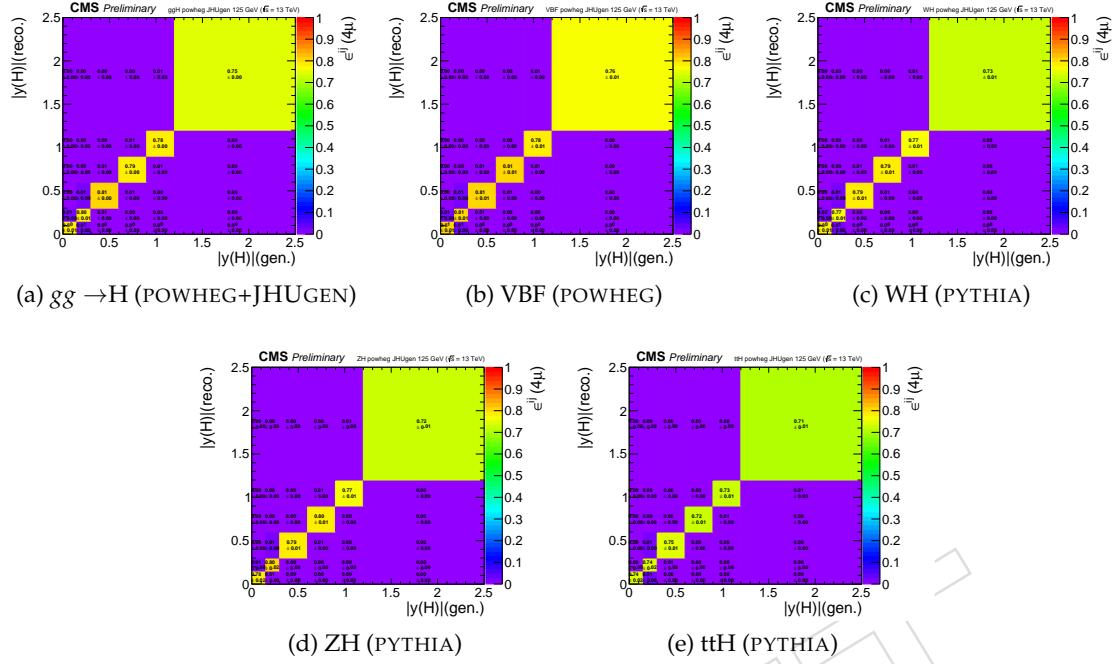


Figure 36: Efficiency matrices for $|y(H)|$ for different SM production modes in the 4μ final state.

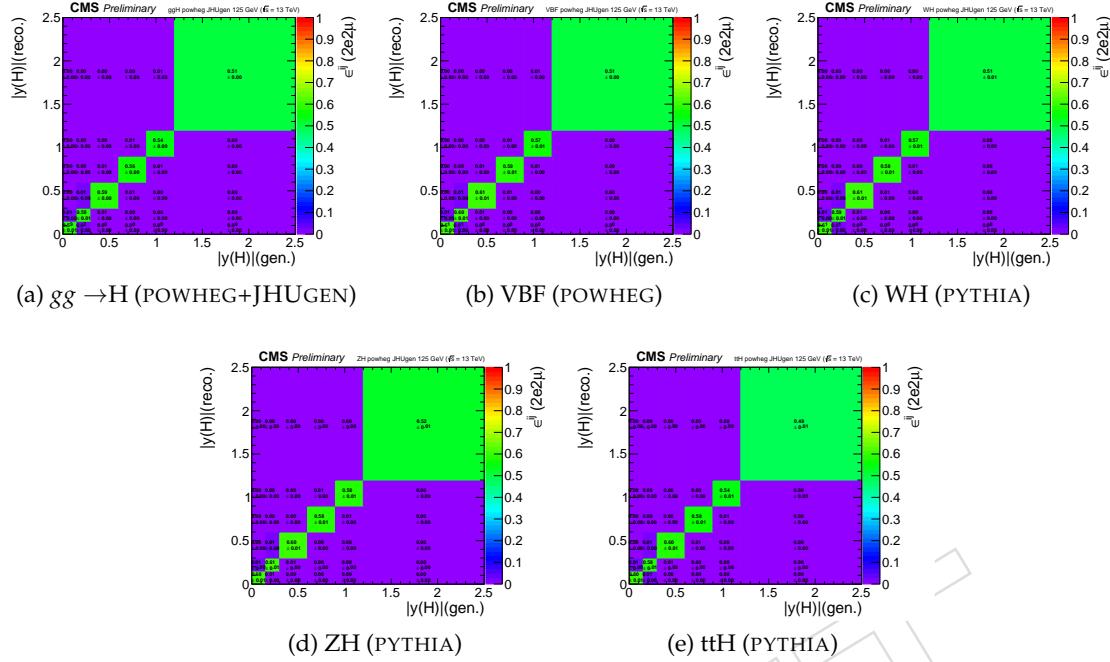


Figure 37: Efficiency matrices for $|y(H)|$ for different SM production modes in the $2e2\mu$ final state.

538 **A.3 Fits in different bins of N(jets)**

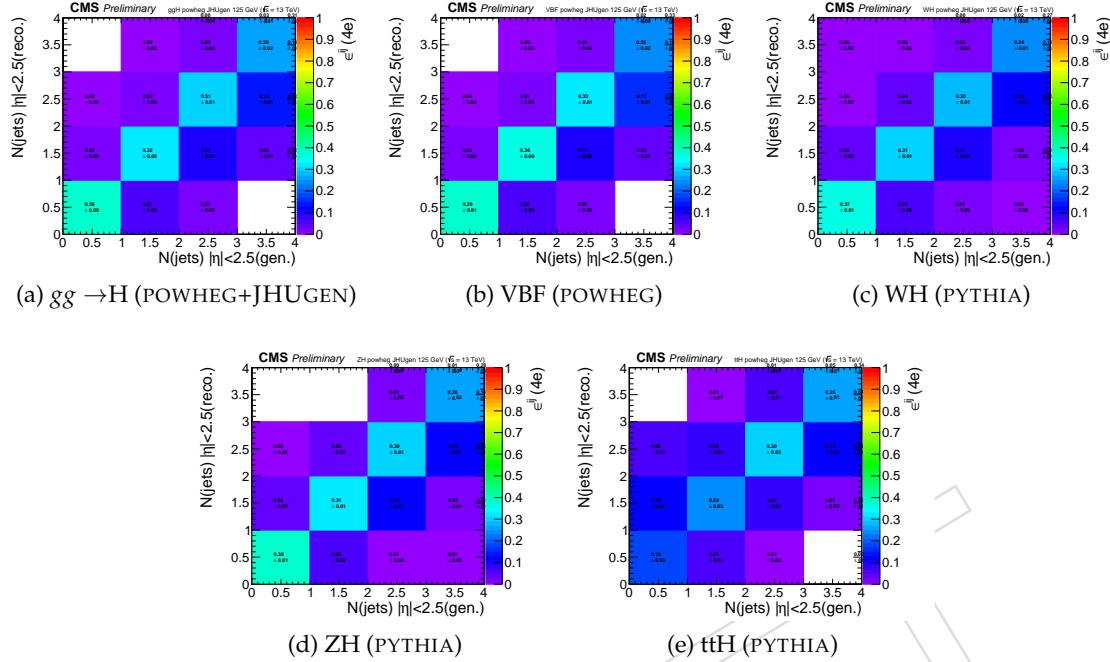


Figure 38: Efficiency matrices for $N(\text{jets})$ for different SM production modes in the $4e$ final state.

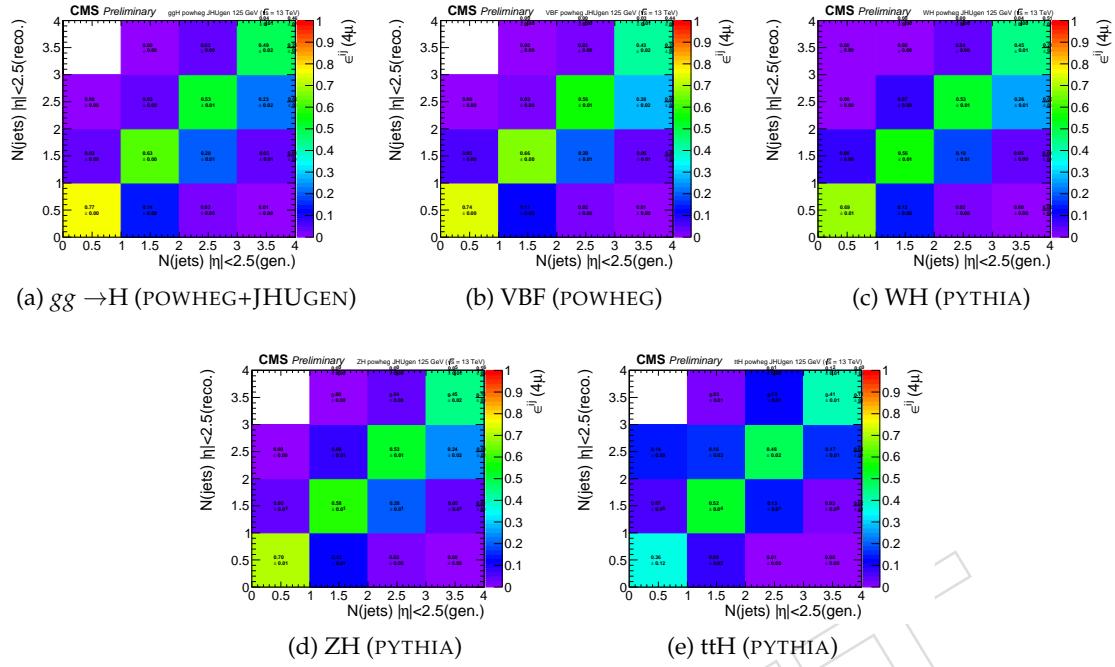


Figure 39: Efficiency matrices for $N(\text{jets})$ for different SM production modes in the 4μ final state.

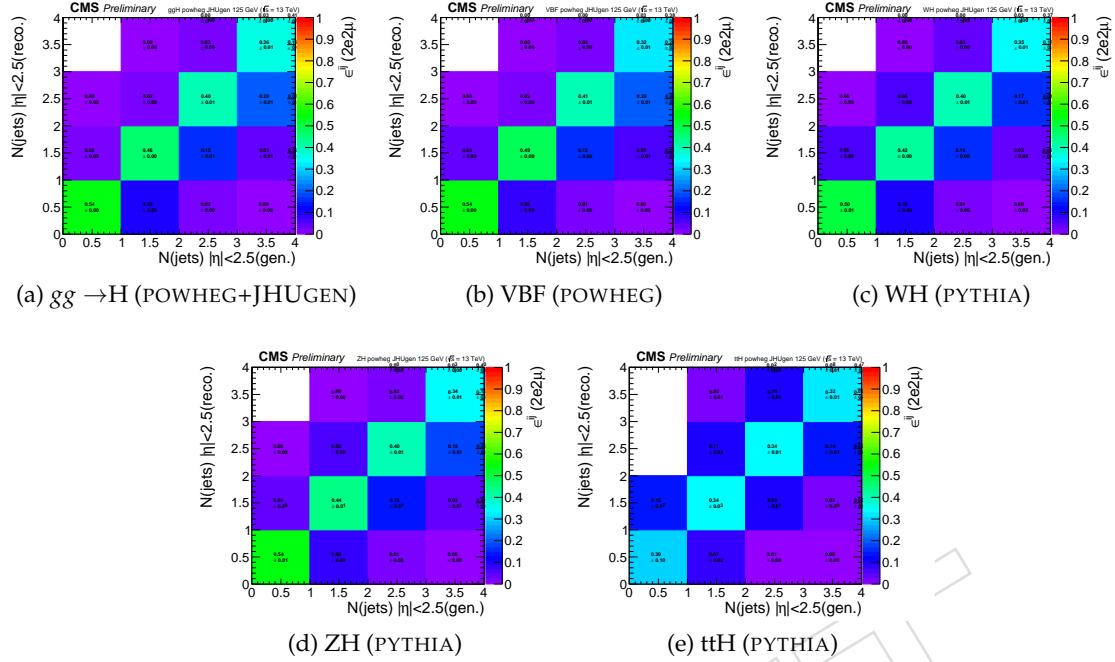


Figure 40: Efficiency matrices for $N(\text{jets})$ for different SM production modes in the $2e2\mu$ final state.

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