

¹ SEARCH FOR EXOTIC HIGGS DECAYS TO LIGHT
² NEUTRAL SCALARS IN FINAL STATES WITH
³ BOTTOM QUARKS AND TAU LEPTONS

⁴ KA YU STEPHANIE KWAN

⁵ A DISSERTATION
⁶ PRESENTED TO THE FACULTY
⁷ OF PRINCETON UNIVERSITY
⁸ IN CANDIDACY FOR THE DEGREE
⁹ OF DOCTOR OF PHILOSOPHY

¹⁰ NOT YET RECOMMENDED FOR ACCEPTANCE
¹¹ BY THE DEPARTMENT OF PHYSICS
¹² ADVISER: ISOBEL OJALVO

¹³ MAY 2024

¹⁴

© Copyright by Ka Yu Stephanie Kwan, 2024.

¹⁵

All Rights Reserved

Abstract

Open questions in particle physics may be addressed by the existence of an extended Higgs sector beyond the Standard Model Higgs boson with mass 125 GeV, which was discovered in 2012 at the Large Hadron Collider (LHC) by the CMS and ATLAS experiments. Many properties of a potential extended Higgs sector remain unconstrained by current measurements, making direct searches of exotic Higgs decays a powerful probe of new physics. The decay of the 125 GeV Higgs boson into two light neutral scalar particles ($h \rightarrow aa$) is allowed in extensions of the Standard Model, such as Two Higgs Doublet Models extended with a scalar singlet (2HDM+S). We present a search at CMS for exotic decays of the 125 GeV Higgs boson to two light neutral scalars, which decay to two bottom quarks and two tau leptons ($h \rightarrow aa \rightarrow bb\tau\tau$). This analysis is combined with a different search where the light scalars decay to two bottom quarks and two muons. The results from the $bb\tau\tau$ analysis and the combined analyses are interpreted in 2HDM+S scenarios. In a different extension of the Standard Model, the Two Real Singlet Model (TRSM), the 125 GeV Higgs boson can decay to two light scalars with unequal mass ($h \rightarrow a_1a_2$). This decay has not been searched for to date at CMS. We present ongoing work on a search for $h \rightarrow a_1a_2$, where the a_2 decays into two a_1 , resulting in four bottom quarks and two tau leptons in the final state, in the $\mu\tau_h$ channel of the $\tau\tau$ decay. Such searches for rare processes will directly benefit from the increased datasets that will be generated by the High-Luminosity LHC (HL-LHC), which is scheduled to increase the LHC’s number of simultaneous proton-proton collisions by a factor of five to seven. To contribute to the performance of the CMS Level-1 Trigger in selecting collisions with interesting physics, this thesis presents an upgraded algorithm for reconstructing electrons and photons in the barrel calorimeter, which will use information with higher spatial granularity to distinguish genuine electrons and photons from background.

⁴²

Acknowledgements

⁴³ Placeholder acknowledgements.

⁴⁵ Contents

⁴⁶	Abstract	iii
⁴⁷	Acknowledgements	iv
⁴⁸	List of Tables	xi
⁴⁹	List of Figures	xiii
⁵⁰	1 Introduction	1
⁵¹	1.1 History of the Standard Model	1
⁵²	1.2 The Standard Model as a gauge theory	3
⁵³	1.3 The Higgs Mechanism	6
⁵⁴	1.4 Two-Higgs Doublet Models	8
⁵⁵	1.5 Two Real Singlet Model	11
⁵⁶	2 The Large Hadron Collider and the CMS Experiment	15
⁵⁷	2.1 The Large Hadron Collider	16
⁵⁸	2.2 Luminosity and pileup	17
⁵⁹	2.3 The High-Luminosity LHC	20
⁶⁰	2.4 The CMS Detector	21
⁶¹	2.5 Sub-detectors of CMS	23
⁶²	2.5.1 Inner tracking system	23
⁶³	2.5.2 ECAL	24
⁶⁴	2.5.3 HCAL	25

65	2.5.4 Muon detectors	27
66	2.5.5 The Level-1 Trigger	28
67	2.5.6 The High-Level Trigger	31
68	2.5.7 Particle reconstruction	32
69	2.5.8 Data storage and computational infrastructure	32
70	3 The Phase-2 Upgrade of CMS	34
71	3.1 The High-Luminosity LHC	34
72	3.2 The Phase-2 Level-1 Trigger	35
73	3.3 Standalone Barrel Calorimeter electron/photon reconstruction	38
74	3.3.1 Phase-2 geometry of the ECAL Barrel trigger	39
75	3.3.2 Phase-2 electron/photon reconstruction algorithm	39
76	4 Datasets and Monte Carlo samples	48
77	4.1 Datasets used	48
78	4.2 Monte Carlo samples	49
79	4.3 Embedded samples	50
80	5 Object reconstruction and corrections applied	53
81	5.1 Object reconstruction	54
82	5.1.1 Taus	54
83	5.1.2 Muons	57
84	5.1.3 Electrons	58
85	5.1.4 Jets	60
86	5.1.5 B-flavored jets	61
87	5.2 Reconstruction of the $\tau\tau$ mass	62
88	5.2.1 Original SVFit “standalone”: maximum likelihood	63
89	5.2.2 “Classic SVFit” with matrix element	64
90	5.2.3 FastMTT: optimized SVFit	64

91	5.3 Corrections applied to simulation	65
92	5.3.1 Tau energy scale	66
93	5.3.2 Muon energy scale	67
94	5.3.3 Electron energy scale	67
95	5.3.4 τ_h identification efficiency	67
96	5.3.5 Trigger efficiencies	68
97	5.3.6 Tau trigger efficiencies	69
98	5.3.7 Single muon trigger efficiencies	70
99	5.3.8 Single electron trigger efficiencies	71
100	5.3.9 $e\mu$ cross-trigger efficiencies	72
101	5.3.10 Electrons and muons faking τ_h : energy scales	73
102	5.3.11 Electrons and muons faking τ_h : misidentification efficiencies .	74
103	5.3.12 Electron ID and tracking efficiency	75
104	5.3.13 Muon ID, isolation, and tracking efficiencies	75
105	5.3.14 Recoil corrections	77
106	5.3.15 Drell-Yan corrections	78
107	5.3.16 Pileup reweighing	78
108	5.3.17 Pre-firing corrections	79
109	5.3.18 Top p_T spectrum reweighing	79
110	5.3.19 B-tagging efficiency	79
111	5.3.20 Jet energy resolution and jet energy smearing	80
112	6 Event selection	81
113	6.1 General procedure for all channels	81
114	6.2 Event selection in the $\mu\tau_h$ channel	83
115	6.3 Event selection in the $e\tau_h$ channel	85
116	6.4 Event selection in the $e\mu$ channel	87
117	6.5 Extra lepton vetoes in all channels	88

¹¹⁸	7 Background estimation	91
¹¹⁹	7.1 Z+jets	91
¹²⁰	7.2 W+jets	92
¹²¹	7.3 $t\bar{t}$ + jets	92
¹²²	7.4 Single top	93
¹²³	7.5 Diboson	93
¹²⁴	7.6 Standard Model Higgs	93
¹²⁵	7.7 Jet faking τ_h	94
¹²⁶	7.8 QCD multijet background	95
¹²⁷	8 Systematic uncertainties	97
¹²⁸	8.1 Uncertainties in the lepton energy scales	98
¹²⁹	8.2 Uncertainties from other lepton corrections	99
¹³⁰	8.3 Uncertainties from jet energy scale and resolution	100
¹³¹	8.4 Uncertainties from b-tagging scale factors	101
¹³²	8.5 Uncertainties from MET	101
¹³³	8.6 Uncertainties associated with samples used	101
¹³⁴	8.7 Other uncertainties	102
¹³⁵	8.8 Pulls and impacts	103
¹³⁶	9 Event categorization and signal extraction	105
¹³⁷	9.1 B-tag jet multiplicity	105
¹³⁸	9.2 DNN-based event categorization	106
¹³⁹	9.3 Methodology for signal extraction	108
¹⁴⁰	9.3.1 Model building and parameter estimation	109
¹⁴¹	9.3.2 Hypothesis testing	111
¹⁴²	9.3.3 Confidence intervals	112
¹⁴³	9.3.4 Profile likelihood ratio	113

¹⁴⁴	9.3.5 Modified frequentist method: CL_S	115
¹⁴⁵	10 Results	116
¹⁴⁶	10.1 Results from $bb\tau\tau$	116
¹⁴⁷	10.2 Combination with $bb\mu\mu$ final state	118
¹⁴⁸	11 Asymmetric exotic Higgs decays	129
¹⁴⁹	11.1 Signal masses	129
¹⁵⁰	11.2 Cascade scenario signal studies	130
¹⁵¹	11.3 Current control plots for $\mu\tau_h$ channel	132
¹⁵²	12 Conclusion and outlook	136

¹⁵³ List of Tables

¹⁵⁴	4.1	Expected event composition after selecting two muons in the embedded technique, before additional cuts (i.e. inclusive), and after adding a requirement on the di-muon mass $m_{\mu\mu} > 70$ GeV, or a requirement on the number of b-tag jets in the event.	52
¹⁵⁵			
¹⁵⁶			
¹⁵⁷			
¹⁵⁸	5.1	Energy scales applied to genuine hadronic tau decays τ_h by data-taking year/era and decay mode, along with systematic errors.	66
¹⁵⁹			
¹⁶⁰	5.2	Energy scales and systematic errors applied to genuine muons.	67
¹⁶¹			
¹⁶²	5.3	Energy scales and systematic errors applied to electrons in embedded samples by data-taking year/era.	67
¹⁶³			
¹⁶⁴	5.4	Tau ID efficiency for the DeepTau vs. jet medium working point, with central, up, and down values for 2018, binned in the tau p_T	68
¹⁶⁵			
¹⁶⁶	5.5	Energy scales and up/down systematic uncertainties applied to electrons misidentified as hadronic taus.	73
¹⁶⁷			
¹⁶⁸	5.6	Tau mis-identification efficiency for the DeepTau Tight and Very Loose (VLoose) working points vs. muons in 2018.	74
¹⁶⁹			
¹⁷⁰	5.7	Tau mis-identification efficiency for the DeepTau Tight and Very Loose (VLoose) working points vs. electrons in 2018.	74

171	6.1	Trigger thresholds used for the leptons in the $bb\mu\mu$ analysis and the 172 $bb\tau\tau$ analysis (the focus of this work). The thresholds for the three $bb\tau\tau$ 173 channels ($e\mu$, $e\tau_h$, and $\mu\tau_h$) are listed separately, with some channels 174 and years taking the logical OR of two triggers with different thresholds.	83
175	6.2	Summary of requirements applied to the leptons in the $bb\mu\mu$ analysis 176 and the $bb\tau\tau$ analysis (the focus of this work). $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ 177 is a measure of spatial separation. Relative isolation is defined in 178 Eqn. 5.2Muonsequation.5.1.2 and Section 5.1.2Muonssubsection.5.1.2. 179 The b-tag jets are required to pass the listed DeepFlavour working 180 points (WP), which are described in Section 5.1.5B-flavored jetssub- 181 section.5.1.5. In the $bb\tau\tau$ analysis, the required $ \eta $ of the hadronic 182 taus are listed for the single and cross triggers respectively. The $bb\mu\mu$ 183 analysis requires two b-tag jets in all events, while the $bb\tau\tau$ analysis 184 only requires one.	84
185	6.3	High-Level Trigger (HLT) paths used to select data and simulation 186 events in 2016 for the three $\tau\tau$ channels.	88
187	6.4	High-Level Trigger (HLT) paths used to select data and simulation 188 events in 2017 for the three $\tau\tau$ channels.	89
189	6.5	High-Level Trigger (HLT) paths used to select data and simulation 190 events in 2018 for the three $\tau\tau$ channels. In 2018 a HLT trigger path 191 using the hadron plus strips (HPS) tau reconstruction algorithm be- 192 came available.	90
193	9.1	Event categorization based on DNN scores for events with exactly 1 194 b-tag jet (1bNN), for the three $\tau\tau$ channels and three eras.	108
195	9.2	Event categorization based on DNN scores for events with 2 b-tag jets 196 (2bNN), for the three $\tau\tau$ channels and three eras.	109

¹⁹⁷ List of Figures

¹⁹⁸ 1.1	Table of Standard Model particles showing the grouping of the fermions into three generations of matter and the bosons, responsible for carrying the three fundamental forces in the Standard Model. The masses, charges, and spins of the particles are shown. The antimatter counter- parts of the fermions are not shown. The possible interactions between the fermions and gauge bosons are highlighted.	3
²⁰⁴ 1.2	An illustration of the Higgs potential.	8
²⁰⁵ 1.3	Branching ratios of a singlet-like pseudoscalar in Type II 2HDM+S for $\tan \beta = 0.5$ (left) and $\tan \beta = 5$ (right).	11
²⁰⁷ 1.4	Benchmark plane BP1 for benchmark scenario 1, for the decay signa- ture $h_{125} \rightarrow h_1 h_2$ with $h_{125} \equiv h_3$, defined in the (M_1, M_2) plane. . . .	14
²⁰⁹ 2.1	Aerial view of the Large Hadron Collider (LHC).	18
²¹⁰ 2.2	Distribution of the mean number of inelastic collisions per bunch cross- ing (pileup) in data, for proton-proton collisions in 2016-2018	20
²¹² 2.3	Sketch of particle trajectories of muons, electrons, charged and neutral hadrons, and photons in a transverse cross-section of the CMS detector.	22
²¹⁴ 2.4	Cross section of the current Phase-1 CMS tracker.	24
²¹⁵ 2.5	Longitudinal view of the CMS detector showing the hadron calorimeter barrel (HB), endcap (HE), outer (HO), and forward (HF) calorimeters.	26

217	2.6	Layout of the CMS barrel muon drift tube (DT) chambers in one of the five wheels.	28
218	2.7	Dataflow for the Phase-1 Level-1 Trigger.	29
219	3.1	Functional diagram of the CMS L1 Phase-2 upgraded trigger design. .	36
220	3.2	Summary of the links between the trigger primitives, the trigger ob- jects, the Level-1 algorithms, and the physics channels in the Phase-2 menu.	38
221	3.3	Schematic of the geometry of the Phase-2 ECAL barrel in the Regional Calorimeter Trigger (RCT), showing the division of the barrel region into 36 Regional Calorimeter Trigger (RCT) cards (<i>red</i>). Each card spans 17×4 towers in $\eta \times \phi$ (<i>green</i>), and each tower is 5×5 in single crystals in $\eta \times \phi$. Towers in the overlap region (<i>shaded yellow</i>) are read out to both the barrel and endcap.	42
222	3.4	Schematic of two example RCT cards in the negative eta (<i>top</i>) and positive eta (<i>center</i>) regions of the ECAL barrel. Each RCT card is divided into five regions: four regions are of size 3×4 towers in $\eta \times \phi$ (<i>bottom left</i>), and a fifth smaller overlap region of size 2×4 towers (<i>bottom right</i>). Each tower is 5×5 ($\eta \times \phi$) in crystals.	43
223	3.5	Schematic of the Phase-2 ECAL barrel in the Global Calorimeter Trig- ger (GCT), which will process the outputs of the Regional Calorimeter Trigger (RCT) in three cards (<i>magenta highlights</i>). Each card in the GCT processes the equivalent of sixteen RCT cards, with the center twelve being unique to that GCT card (<i>shaded pink</i>), and the remain- ing four processed in overlap with the other GCT cards.	44

241	3.6 Illustration of an example electron/photon (e/γ) cluster in the Phase-	
242	2 Level-1 Trigger standalone barrel e/γ reconstruction, in a region of	
243	15×20 crystals (3×4 towers). Each small pink square is one crystal,	
244	the highest-granularity ECAL trigger primitives available to the L1	
245	Trigger in Phase-2. The core cluster consists of the energy sum in a	
246	3×5 window of crystals, (<i>shaded light blue</i>) centered around the seed	
247	crystal (<i>red</i>). Bremsstrahlung corrections are checked in the adjacent	
248	3×5 windows in the ϕ direction (<i>shaded light yellow</i>). The relative	
249	energies in windows of size 2×5 and 5×5 in crystals (<i>dashed dark blue</i>	
250	<i>and dark red</i>) are used to compute shower shape variables to identify	
251	true e/γ objects. Lastly, an isolation sum is computed in a window of	
252	size 7×7 in towers (not shown in figure).	45
253	3.7 Efficiency of the standalone barrel e/γ reconstruction, as a function of	
254	the true electron's transverse momentum p_T	46
255	3.8 Rates of the standalone barrel e/γ reconstruction measured as a func-	
256	tion of the minimum energy (E_T) required of the reconstructed e/γ	
257	object in each event.	47
258	4.1 Cumulative delivered and recorded luminosity versus time for 2015-	
259	2018 at CMS, in proton-proton collision data only, at nominal center-	
260	of-mass energy.	49
261	4.2 Schematic view of the four main steps of the embedding technique for	
262	τ leptons.	51
263	5.1 Distributions of $m_{\tau\tau}$ reconstructed by the classic SVFit algorithm, and	
264	masses of visible tau decay products (before SVFit).	65
265	5.2 Electron/photon energy scale factors and uncertainties for 2018. . . .	68

266	5.3 Hadronic tau leg efficiency of the cross-triggers for $\mu\tau_h$ (<i>left</i>) and $e\tau_h$ 267 (<i>right</i>) triggers as a function of offline tau p_T for 2016, 2017, and 2018.	70
268	5.4 Trigger efficiencies in data (<i>top panels</i>) and ratio of efficiencies af- 269 ter/before a HLT muon reconstruction update (<i>bottom panels</i>) for the 270 muon in the isolated single muon trigger with threshold $p_T > 24$ GeV 271 in the data-taking year 2018, as functions of the muon p_T (<i>left</i>) and 272 muon $ \eta $ (<i>right</i>).	71
273	5.5 Trigger efficiencies in data and the data/MC ratio for the electron in 274 the single electron trigger with threshold $p_T > 32$ GeV in the data- 275 taking year 2018, as functions of the electron p_T (<i>left</i>) and electron $ \eta $ 276 (<i>right</i>).	72
277	5.6 Efficiencies of the electron leg vs. p_T (<i>left</i>) and the muon log vs. η 278 (<i>right</i>), for the HLT path with online thresholds of 12 GeV for the 279 electron and 23 GeV for the muon, with the data-taking years 2016 280 through 2018 overlaid.	73
281	5.7 Efficiencies in data (<i>top panels</i>) and the ratio of efficiencies in data/MC 282 (<i>bottom panels</i>), for the electron multivariate analysis (MVA) identifi- 283 cation (<i>left</i>) and for the Gaussian-sum filter (GSF) tracking (<i>right</i>). . .	75
284	5.8 Muon identification efficiencies in 2015 data and MC as a function of 285 the muon p_T for the loose ID (<i>left</i>) and tight ID (<i>right</i>) working points.	76
286	5.9 Muon isolation efficiencies in Run-2 data as a function of the muon p_T 287 (<i>left</i>) and $ \eta $ (<i>right</i>).	77
288	5.10 Muon tracking efficiencies as a function of $ \eta $ for standalone muons in 289 Run-2 data (<i>black</i>) and Drell-Yan (<i>blue</i>) MC simulation.	78
290	7.1 Leading-order Feynman diagrams of Higgs production.	94

291	8.1 Top sixty pulls and impacts for the combination of all channels and	
292	years.	104
293	9.1 Schematic of the Neyman construction for confidence intervals.	114
294	10.1 Postfit final observed and expected $m_{\tau\tau}$ distributions in the $\mu\tau_h$ chan-	
295	nel, for the 1 b-tag jet and 2 b-tag jet signal and control regions.	120
296	10.2 Postfit final observed and expected $m_{\tau\tau}$ distributions in the $e\tau_h$ chan-	
297	nel, for the 1 b-tag jet and 2 b-tag jet signal and control regions.	121
298	10.3 Postfit final observed and expected $m_{\tau\tau}$ distributions in the $e\mu$ channel.	122
299	10.4 Observed 95% CL exclusion limits (<i>black, solid lines</i>) and expected 95%	
300	CL and 68% CL limits (<i>shaded yellow and green</i>) on the branching	
301	fraction $B(h \rightarrow aa \rightarrow bb\tau\tau)$ in percentages, assuming the Standard	
302	Model production for the 125 GeV Higgs (h). Limits are shown for the	
303	$\mu\tau_h$ channel (<i>top left</i>), the $e\tau_h$ channel (<i>top right</i>), and the $e\mu$ channel	
304	(<i>bottom left</i>), and lastly the combination of all three channels (<i>bottom</i>	
305	<i>right</i>) The dataset corresponds to 138 fb^{-1} of data collected in the	
306	years 2016-2018 at a center-of-mass energy 13 TeV.	123
307	10.5 Observed 95% CL upper limits on $B(h \rightarrow aa)$ in %, for the $bb\tau\tau$ final	
308	state (<i>left</i>) and $bb\mu\mu$ final state (<i>right</i>) using the full Run 2 integrated	
309	luminosity of 138 fb^{-1} in 2HDM+S type I (<i>blue</i>), type II with $\tan\beta =$	
310	2.0 (<i>orange dashed</i>), type III with $\tan\beta = 2.0$ (<i>dotted green</i>), and type	
311	IV with $\tan\beta = 0.6$ (<i>red dashed</i>).	124

312	10.6 Observed 95% CL upper limits on the branching fraction of the 125	
313	GeV Higgs boson to two pseudoscalars, $B(h \rightarrow aa)$, in percentages,	
314	as a function of the pseudoscalar mass m_a , in 2HDM+S type I (<i>blue</i>),	
315	type II with $\tan\beta = 2.0$ (<i>orange dashed</i>), type III with $\tan\beta = 2.0$	
316	(<i>dotted green</i>), and type IV with $\tan\beta = 0.6$ (<i>red dashed</i>), for the	
317	combination of $bb\mu\mu$ and $bb\tau\tau$ channels using the full Run 2 integrated	
318	luminosity of 138 fb^{-1}	125
319	10.7 Observed 95% CL upper limits on $\mathcal{B}(h \rightarrow aa)$ in %, for the combination	
320	of $bb\mu\mu$ and $bb\tau\tau$ channels using the full Run 2 integrated luminosity	
321	of 138 fb^{-1} for Type II (<i>left</i>), Type III (<i>middle</i>), and Type IV (<i>right</i>)	
322	2HDM+S in the $\tan\beta$ vs. m_a phase space.	126
323	10.8 Summary plot of current observed and expected 95% CL limits on the	
324	branching ratio of the 125 GeV Higgs boson to two pseudoscalars, nor-	
325	malized to the Standard Model Higgs production cross-section, $\frac{\sigma(h)}{\sigma_{\text{SM}}} \times$	
326	$B(h \rightarrow aa)$, in the 2HDM+S type I scenario, obtained at CMS with	
327	data collected at 13 TeV.	126
328	10.9 Summary plot of current observed and expected 95% CL limits on the	
329	branching ratio of the 125 GeV Higgs boson to two pseudoscalars, nor-	
330	malized to the Standard Model Higgs production cross-section, $\frac{\sigma(h)}{\sigma_{\text{SM}}} \times$	
331	$B(h \rightarrow aa)$, in the 2HDM+S type II scenario with $\tan\beta = 2.0$, ob-	
332	tained at CMS with data collected at 13 TeV.	127
333	10.10 Summary plot of current observed and expected 95% CL limits on the	
334	branching ratio of the 125 GeV Higgs boson to two pseudoscalars, nor-	
335	malized to the Standard Model Higgs production cross-section, $\frac{\sigma(h)}{\sigma_{\text{SM}}} \times$	
336	$B(h \rightarrow aa)$, in the 2HDM+S type III scenario with $\tan\beta = 2.0$, ob-	
337	tained at CMS with data collected at 13 TeV.	128

338	11.1 Generator-level b-flavor jet transverse momenta p_T , for $h \rightarrow a_1 a_2$ cas-	
339	cade scenario in the $4b2\tau$ final state, for mass hypotheses $(m_{a_1}, m_{a_2}) =$	
340	$(100, 15)$ GeV (<i>left</i>) and $(40, 20)$ GeV (<i>right</i>). In each plot the generator-	
341	level p_T of the leading (<i>black</i>), sub-leading (<i>red</i>), third (<i>blue</i>), and	
342	fourth (<i>light green</i>) are overlaid.	131
343	11.2 Distributions (arbitrary units) of transverse momentum p_T resolution	
344	and ΔR between the two closest generator-level b jets, treated as one	
345	object, and the nearest reconstructed AK4 jet, for two different $h \rightarrow$	
346	$a_1 a_2$ mass hypotheses $(m_{a_1}, m_{a_2}) = (100, 15)$ GeV (<i>top left, top right</i>)	
347	and $(40, 20)$ GeV (<i>bottom left, bottom right</i>) in the ggH production of	
348	the 125 GeV h . In the $(40, 20)$ GeV mass point, the longer p_T resolution	
349	tail (<i>bottom left</i>) indicates that the reconstructed jet underestimates	
350	the generator b-flavor jets' energy, and the significant fraction of events	
351	with larger ΔR values (<i>bottom right</i>) indicate worse matching.	132
352	11.3 Kinematic properties of the leading muon and τ_h in the $\mu\tau_h$ channel: p_T	
353	(<i>top row</i>), η (<i>second row</i>), and ϕ (<i>third row</i>). The visible 4-momenta	
354	of the muon and τ_h are summed, giving the visible di-tau mass m_{vis}	
355	and transverse momentum $p_{T,\text{vis}}$. The errors shown in the figures only	
356	include statistical errors and only several of the full set of systematic	
357	errors (only those associated with the lepton energy scales and τ_h iden-	
358	tification efficiency).	134
359	11.4 Kinematic properties of the leading and sub-leading b-tag jets in the	
360	$\mu\tau_h$ final state: jet p_T (<i>top row</i>), η (<i>second row</i>), ϕ (<i>third row</i>), as well	
361	as the missing transverse energy magnitude and azimuthal direction	
362	(<i>bottom row</i>). The errors shown in the figures only include statistical	
363	errors and only several of the full set of systematic errors (only those	
364	associated with the lepton energy scales and τ_h identification efficiency).	135

³⁶⁵ **Chapter 1**

³⁶⁶ **Introduction**

³⁶⁷ The Standard Model is the current prevailing theoretical framework that encompasses
³⁶⁸ all known elementary particles to date and describes their interactions, yet falls short
³⁶⁹ of describing open problems in physics. Here, we describe the history of the Standard
³⁷⁰ Model and its particle content (Section 1.1), and provide a mathematical motivation of
³⁷¹ the SM as a gauge theory (Section 1.2). We introduce the Higgs mechanism (Section
³⁷² 1.3), and outline two groups of theoretical extensions to the Standard Model that
³⁷³ feature extended Higgs sectors (Sections 1.4 and 1.5).

³⁷⁴ **1.1 History of the Standard Model**

³⁷⁵ The building blocks of our modern-day understanding of particle physics were estab-
³⁷⁶ lished over the course of many decades by experimental discoveries and theoretical
³⁷⁷ advances, culminating in the development of a theoretical framework known as the
³⁷⁸ Standard Model (SM). In the 1880s, the electron was the first subatomic particle to
³⁷⁹ be identified, through measurements of particles produced by ionizing gas. By the
³⁸⁰ 1930s, atoms were known to consist mostly of empty space, with protons and neutrons
³⁸¹ concentrated at the center and orbited by electrons. Spurred by advances in parti-
³⁸² cle accelerator technology, the experimental discoveries of the positron, the muon,

and the pion, painted an increasingly complicated picture of particle physics that could not be described solely with atomic physics [1]. Quantum field theory (QFT) began to be developed in the early 20th century as an extension of the conceptual framework of quantum mechanics to electromagnetic fields [2]. In 1927, Dirac coined the name quantum electrodynamics (QED), which was the first part of QFT that was developed. QED quantized the electromagnetic field and supplied a relativistic theory of the electron, and could be applied to concrete physical processes such as the scattering of high-frequency photons by free electrons (Compton scattering), and the production of electron-positron pairs by photons [2]. In the 1940s the QED-only picture was challenged by the realization that the four-fermion theory of weak interactions had infinities at higher orders of perturbation theory which could not be removed via the technique of renormalization [3], i.e. shifting divergences into parts of the theory that do not influence empirical measurements [2].

In the 1950s and 1960s, QFT was extended to describe not only the electromagnetic force, but also the strong and weak force, with the final picture forming the Standard Model. This took place in the development and maturation of three principles: the quark model, the idea of gauge (or local) symmetry, and spontaneously broken symmetry [3]. In the fully fledged QFT, Lagrangians had to be formed that contained new classes of quantum fields, or particles [2].

The particle content of the Standard Model is summarized in Fig. 1.1. Particles are grouped into fermions, which comprise all known matter, and bosons, which mediate the interactions between particles. Fermions consist of quarks and leptons, and are grouped into three generations. For example, the electron belongs to the first generation of leptons. The second and third generation counterparts of the electron are the muon and the tau lepton, and are over 200 and 30,000 times heavier than the electron respectively. The quarks are also organized into three generations (top and bottom quarks, charm and strange quarks, and up and down quarks), and

410 carry fractional electric charge. Bosons are force carriers; the interaction of fermions
 411 with bosons corresponds to fundamental forces. The Standard Model describes the
 412 electromagnetic force, the strong nuclear force, and the weak nuclear force. Through
 413 the strong force, quarks can form composite particles known as hadrons. Familiar
 414 examples of hadrons are the protons and neutrons in the nucleus of an atom.

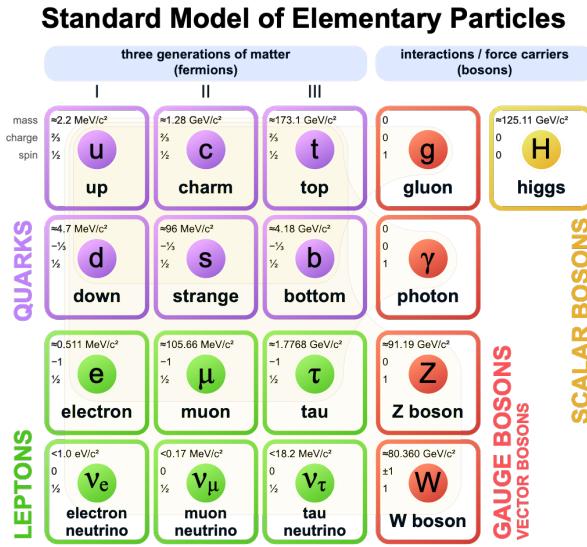


Figure 1.1: Table of Standard Model particles showing the grouping of the fermions into three generations of matter and the bosons, responsible for carrying the three fundamental forces in the Standard Model. The masses, charges, and spins of the particles are shown. The antimatter counterparts of the fermions are not shown. The possible interactions between the fermions and gauge bosons are highlighted.

415 1.2 The Standard Model as a gauge theory

416 In this section we lay the theoretical foundations of the Standard Model as a gauge
 417 theory, starting from the principle of gauge invariance (gauge symmetry), with local
 418 gauge symmetries giving rise to interactions between particles.

419 Gauge theories of elementary particle interactions originate from a freedom of
 420 choice in the mathematical description of particle fields which has no effect on the
 421 particles' physical states [4]. The existence and form of the particles' interactions,

422 can be deduced from the existence of physically indeterminate, gaugable quantities.

423 An example of this gauge invariance is classical physics is the electromagnetic
424 interaction, where the fundamental field is the four-vector potential A^μ [4]. The
425 physical electromagnetic fields and Maxwell's equations arise from the elements of
426 the tensor $F_{\mu\nu}(x) = \partial_\mu A_\nu(x) - \partial_\nu A_\mu(x)$. Any two choices of A^μ that are related by a
427 transformation of the form

$$A_\mu \rightarrow A_\mu + \partial_\mu \alpha \quad (1.1)$$

428 for any real, differentiable function $\alpha(x)$, describe the same physical configuration,
429 and has no effect on Maxwell's equations. This "redundancy" in the choice of gauge
430 in Eqn. 1.1 is called a gauge symmetry.

431 One important consequence of gauge symmetry comes from the application of
432 Noether's theorem, which states that for every global transformation under which the
433 Lagrangian density is invariant, there exists a conserved quantity. If $\mathcal{L}(\Psi(x), \partial_\mu \Psi(x))$
434 is invariant under the transformation of the wave function $\Psi(x) \rightarrow \Psi'(x)$, where
435 $\Psi'(x) = \Psi(x) + \delta\Psi(x)$, then there exists a conserved current

$$\partial_\mu \left(\frac{\partial \mathcal{L}(x)}{\partial (\partial_\mu \Psi(x))} \delta\Psi(x) \right) = 0 \quad (1.2)$$

436 In classical mechanics, the conservation of linear momentum, angular momentum,
437 and energy follows from translational invariance, rotational variance, and invariance
438 under translations in time [4]. Likewise, charge conservation can be shown to arise
439 from the invariance of the Dirac Lagrangian density $\mathcal{L}_{\text{Dirac}} = \bar{\Psi}(i\gamma^\mu \partial_\mu - m)\Psi$ under the
440 particle wavefunction's phase transformation, $\Psi'(x) = \exp(i\epsilon\chi)\Psi(x)$. Thus Noether's
441 theorem establishes a correspondence between a gauge symmetry and a conserved
442 internal property (e.g. charge or momentum).

443 Interactions between particles arise if we modify the wave function with a phase

⁴⁴⁴ transformation $\Psi'(x) = \exp(ie\chi)\Psi(x)$, and allow the phase χ to be a function of
⁴⁴⁵ spacetime [4]. A wave function of the form

$$\Psi'(x) = \exp(ie\chi(x))\Psi(x) \quad (1.3)$$

⁴⁴⁶ can be verified to *not* be a solution to the Dirac equation for free particles: $(i\gamma^\mu\partial_\mu -$
⁴⁴⁷ $m)\Psi(x) = 0$. This necessitates a modified Dirac equation, where the derivative takes
⁴⁴⁸ into account that the vector field $V(x)$ needs to be compared at two displaced space-
⁴⁴⁹ time points in a curvilinear coordinate system:

$$\mathcal{D}_\mu \equiv \lim_{\Delta x^\mu \rightarrow 0} \frac{V_{||}(x + \Delta x) - V(x)}{\Delta x^\mu} \quad (1.4)$$

⁴⁵⁰ We define a covariant derivative,

$$D_\mu = \partial_\mu + ieA_\mu \quad (1.5)$$

⁴⁵¹ where $A_\mu(x)$ is a 4-vector potential. Thus the modified Dirac equation reads:

$$(i\gamma^\mu\mathcal{D}_\mu - m)\Psi(x) = 0 \quad (1.6)$$

⁴⁵² The simultaneous gauge transformation $A'_\mu(x) = A_\mu(x) - \partial_\mu\chi(x)$ and wavefunction
⁴⁵³ transformation $\Psi'(x) = \exp(ie\chi(x))\Psi(x)$ leaves the covariant-derivative form of the
⁴⁵⁴ Dirac equation (Eqn 1.1) invariant.

⁴⁵⁵ The generalization of this result is as follows: if a theory is invariant for unitary
⁴⁵⁶ transformations U of the particle states according to

$$\Psi' = U\Psi \quad (1.7)$$

457 One must define a derivative of the form

$$D^\mu = \partial^\mu + igB^\mu \quad (1.8)$$

458 to keep the theory invariant under Eqn. 1.7. The four-potential B^μ represents the
459 interacting four-potential which must be added to keep the theory invariant.

460 In the case of the Standard Model, the theory is built around the gauge trans-
461 formations $G = SU(3) \times SU(2) \times U(1)$. $SU(3)$ is associated to the strong force
462 (subscripted C); $SU(2)$ is associated to the weak force (subscripted L); and $U(1)$ is
463 hypercharge (subscripted Y). The gauge-covariant derivative is

$$\mathcal{D}_\mu = \partial_\mu - ig'B_\mu \frac{Y}{2} - igW_\mu^\alpha \frac{\tau_a}{2} - ig_s G_\mu^k \frac{\lambda_k}{2} \quad (1.9)$$

464 • In the $U(1)_Y$ term, B_μ is the weak hypercharge field.

465 • In the $SU(2)_L$ term, $W_\mu(x) = (W_\mu^1(x), W_\mu^2(x), W_\mu^3(x))$ are a triplet of four-
466 potentials. $\tau/2$ are the Pauli matrices, generators of the $SU(2)$ transformation.

467 • In the $SU(3)_C$ term, the gluon (color) field is G_μ . λ_k are the Gell-Man matrices,
468 generators of the $SU(3)$ transformation.

469 The invariance of the Standard Model under $SU(3)_C \times SU(2)_L \times U(1)_Y$ requires
470 massless fermions and massless force carriers.

471 1.3 The Higgs Mechanism

472 To introduce mass into the theory, i.e. to change the propagation of the gauge par-
473 ticles and all the fermions, the physical vacuum cannot have all the symmetries of
474 the Standard Model Lagrangian [4]. The symmetries of the physical vacuum must
475 be spontaneously broken, without affecting gauge invariance in the Lagrangian. The

476 Higgs mechanism proposes the existence of a scalar field, or fields, with nonzero vac-
 477 uum expectation values, which reduce the gauge symmetries of the physical vacuum
 478 from $SU(3)_C \times SU(2)_L \times U(1)_Y$ down to $SU(3)_C \times U(1)_{EM}$.

479 The Higgs field interacts with the gauge bosons and fermions throughout space,
 480 impeding their free propagation. The resulting broken symmetry correctly predicts
 481 the mass ratio of the neutral (Z) and charged (W) massive electroweak bosons, and
 482 predicts that at least one physical degree of freedom in the Higgs field is a particle
 483 degree of freedom, called the Higgs boson. The location of the minimum of the Higgs
 484 potential can be constrained from previously measured Standard Model parameters,
 485 but the shape of the mass distribution of the Higgs boson must be experimentally
 486 measured.

487 The minimal choice of Higgs field comes from the breaking of $SU(2)_L \times U(1)_Y$
 488 down to $U(1)_{EM}$. The smallest $SU(2)$ multiplet is the doublet. The existence of three
 489 massive electroweak bosons leads the Higgs sector to have at least three degrees of
 490 freedom. The minimal single-doublet complex scalar Higgs field is

$$\Phi(x) = \begin{pmatrix} \phi^+(x) \\ \phi^0(x) \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1^+(x) + i\phi_2^+(x) \\ \phi_1^0(x) + i\phi_2^0(x) \end{pmatrix} \quad (1.10)$$

491 where ϕ_1^+ , ϕ_2^+ , ϕ_1^0 , and ϕ_2^0 are real (four degrees of freedom). By convention, the
 492 nonzero vacuum expectation value is assigned to ϕ_1^0 .

493 The minimal self-interacting Higgs potential that is invariant under $SU(2)_L \times$
 494 $U(1)_Y$ is given by

$$V(\Phi^\dagger \Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2, \quad \mu^2 > 0, \lambda > 0 \quad (1.11)$$

495 where λ is the coupling strength of the four-point Higgs interaction. The potential

496 energy is minimized at

$$\Phi_{\min} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \text{ where } v = \sqrt{\mu^2/\lambda} \quad (1.12)$$

497 Choosing a fixed orientation of $\langle \Phi \rangle$ out of a continuous set of possible ground states
 498 spontaneously breaks the symmetry of the physical vacuum, as illustrated in Fig 1.2.

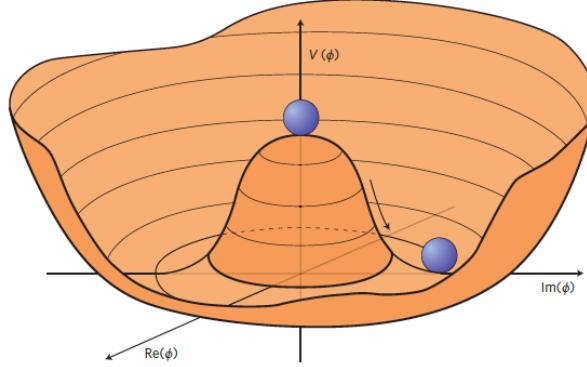


Figure 1.2: An illustration of the Higgs potential [5]. Choosing any of the points at the bottom of the potential breaks spontaneously the rotational $U(1)$ symmetry.

499 The excitations of the Higgs field with respect to the minimum Φ_{\min} are parame-
 500 terized by

$$\Phi(x) = \exp(i\xi(x) \cdot \tau) \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix} \quad (1.13)$$

501 Three degrees of freedom are coupled directly to the electroweak gauge bosons; this
 502 is often referred to as the gauge bosons “eating” the Goldstone bosons to form the
 503 longitudinal polarizations of the massive spin-1 boson states. The $H(x)$ excitation is
 504 in the radial direction and corresponds to the free particle state of the Higgs boson.

505 1.4 Two-Higgs Doublet Models

506 One of the simplest possible extensions to the Standard Model is adding a doublet
 507 to the minimal Higgs sector of the Standard Model, which is a $SU(2)_L$ doublet H

508 with hypercharge $Y = +\frac{1}{2}$, denoted here as $H \sim 2_{+1/2}$. These extensions are found
 509 in several theories such as supersymmetry. A general 2HDM can be extended with a
 510 light scalar (2HDM+S) to obtain a rich set of exotic Higgs decays [6].

The charges of the Higgs fields are chosen to be $H_1 \sim 2_{-1/2}$ and $H_2 \sim 2_{+1/2}$, which acquire vacuum expectation values $v_{1,2}$ which are assumed to be real and aligned [6]. Expanding about the minima yields two complex and four real degrees of freedom:

$$H_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} v_1 + H_{1,R}^0 + iH_{1,I}^0 \\ H_{1,R}^- + iH_{1,I}^- \end{pmatrix} \quad (1.14)$$

$$H_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} H_{2,R}^+ + iH_{2,I}^+ \\ v_2 + H_{2,R}^0 + iH_{2,I}^0 \end{pmatrix} \quad (1.15)$$

511 The charged scalar and pseudoscalar mass matrices are diagonalized by a rotation
 512 angle β , defined as $\tan \beta = v_2/v_1$. One charged (complex) field and one neutral
 513 pseudoscalar combination of $H_{1,2,I}^0$ are eaten by the SM gauge bosons after electroweak
 514 symmetry breaking [6]. The other complex field yields two charged mass eigenstates
 515 H^\pm , which are assumed to be heavy. The remaining three degrees of freedom yield
 516 one neutral pseudoscalar mass eigenstate

$$A = H_{1,I}^0 \sin \beta - H_{2,I}^0 \cos \beta \quad (1.16)$$

517 and two neutral scalar mass eigenstates (where $-\pi/2 \leq \alpha \leq \pi/2$)

$$\begin{pmatrix} h \\ H^0 \end{pmatrix} = \begin{pmatrix} -\sin \alpha & \cos \alpha \\ \cos \alpha & \sin \alpha \end{pmatrix} \begin{pmatrix} H_{1,R}^0 \\ H_{2,R}^0 \end{pmatrix} \quad (1.17)$$

518 We assume that the 2HDM is near or in the decoupling limit: $\alpha \rightarrow \pi/2 - \beta$, where
 519 the lightest state in the 2HDM is h , which we identify as the 125 GeV Higgs particle
 520 [6]. In this limit, the fermion couplings of h become identical to the Standard Model

521 Higgs, while the gauge boson couplings are very close to Standard Model-like for
 522 $\tan \beta \gtrsim 5$. All of the properties of h can be determined by just two parameters: $\tan \beta$
 523 and α , and the fermion couplings to the two Higgs doublets.

524 2HDM can be extended by a scalar singlet (2HDM+S) [6]:

$$S = \frac{1}{\sqrt{2}}(S_R + iS_I) \quad (1.18)$$

525 If this singlet only couples to the Higgs doublets $H_{1,2}$ and has no direct Yukawa
 526 couplings, all of its couplings to SM fermions result from mixing with $H_{1,2}$. Under
 527 these simple assumptions, exotic Higgs decays $h \rightarrow ss \rightarrow X\bar{X}Y\bar{Y}$ or $h \rightarrow aa \rightarrow$
 528 $X\bar{X}Y\bar{Y}$, and $h \rightarrow aZ \rightarrow X\bar{X}Y\bar{Y}$ are permitted, where $s(a)$ is a (pseudo)scalar mass
 529 eigenstate mostly composed of $S_R(S_I)$, and X, Y are Standard Model fermions or
 530 gauge bosons. There are two pseudoscalars in the 2HDM+S, and the mostly singlet-
 531 like pseudoscalar can be chosen to be the one lighter than the SM-like Higgs. For
 532 $m_a < m_h - m_Z \sim 35$ GeV, the exotic Higgs decay $h \rightarrow Za$ is possible, and for
 533 $m_a < m_h/2 \approx 63$ GeV, the exotic Higgs decay $h \rightarrow aa$ is possible.

534 In 2HDM, and by extension 2HDM+S, there are four types of fermion couplings
 535 commonly discussed in the literature that forbid flavor-changing neutral currents at
 536 tree level [6]. These are referred to as Type I (all fermions couple to H_2), Type II
 537 (MSSM-like, d_R and e_R couple to H_1 , u_R to H_2), Type III (lepton-specific, leptons
 538 and quarks couple to H_1 and H_2 respectively) and Type IV (flipped, with u_R , e_R
 539 coupling to H_2 and d_R to H_1). The exact branching ratios of the pseudoscalars to
 540 Standard Model particles vary depending on the 2HDM+S model and the value of
 541 $\tan \beta$ (e.g. Fig. 1.3).

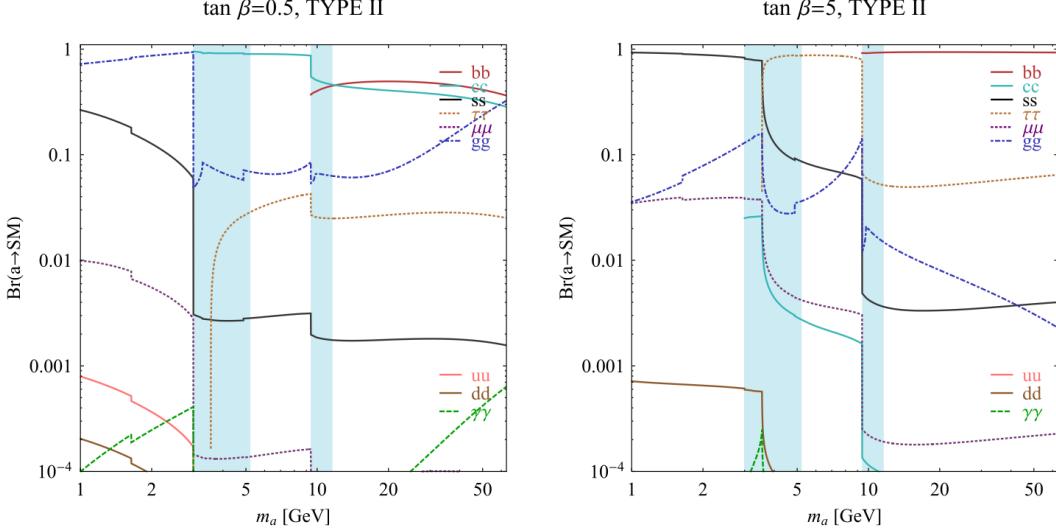


FIG. 7 (color online). Branching ratios of a singletlike pseudoscalar in the 2HDM + S for type-II Yukawa couplings. Decays to quarkonia likely invalidate our simple calculations in the shaded regions.

Figure 1.3: Branching ratios of a singlet-like pseudoscalar in Type II 2HDM+S for $\tan\beta = 0.5$ (left) and $\tan\beta = 5$ (right) from [6], showing the dependence of the branching ratios on $\tan\beta$, as well as the prominence of the branching ratios to bb and $\tau\tau$, the channels searched for in the analysis presented here.

1.5 Two Real Singlet Model

The two real singlet model (TRSM) adds two real singlet degrees of freedom to the Standard Model. These are written as two real singlet fields S and X . Depending on the vacuum expectation values acquired by the scalars, different phases of the model can be realized [7]. To reduce the number of free parameters, two discrete \mathbb{Z}_2 symmetries are introduced. The fields are decomposed as

$$\Phi = \begin{pmatrix} 0 \\ \frac{\phi_h + v}{\sqrt{2}} \end{pmatrix}, S = \frac{\phi_S + v_S}{\sqrt{2}}, X = \frac{\phi_X + v_X}{\sqrt{2}} \quad (1.19)$$

To achieve electroweak-breaking symmetry, $v = v_{SM} \sim 246$ GeV is necessary. If the vacuum expectation values $v_S, v_X \neq 0$ the \mathbb{Z}_2 are spontaneously broken, and the fields $\phi_{h,S,X}$ mix into three physical scalar states. This is called the broken phase and leads to the most interesting collider phenomenology.

552 The mass eigenstates $h_{1,2,3}$ are related to the fields $\phi_{h,S,X}$ through a 3×3 orthogonal
553 mixing matrix denoted R . The mass eigenstates are assumed to be ordered $M_1 \leq$
554 $M_2 \leq M_3$. R is parameterized by the three mixing angles θ_{hS} , θ_{hX} , θ_{SX} . The nine
555 parameters of the scalar potential can be expressed in terms of the three physical
556 Higgs masses, the three mixing angles, and the three vacuum expectation values.

557 After fixing one of the Higgs masses to the mass of the observed Higgs boson, and
558 fixing the Higgs doublet vacuum expectation value to its Standard Model value, there
559 are seven remaining free parameters of the TRSM [7].

560 In one benchmark scenario of TRSM [7], the heaviest scalar state h_3 is identified
561 with the 125 GeV Higgs, h_{125} , and it can decay asymmetrically $h_{125} \rightarrow h_1 h_2$, which
562 we also denote $h \rightarrow a_1 a_2$ to highlight the similarity with the symmetric decay $h \rightarrow aa$
563 typically interpreted in 2HDM+S as discussed. The parameter values in TRSM are
564 chosen such that the coupling of h_3 to Standard Model particles are nearly identical
565 to the Standard Model predictions.

566 In benchmark scenario 1 (benchmark plane 1, or BP1) (Fig. 1.4) [7], the maximal
567 branching ratios for $h_3 \rightarrow h_1 h_2$ reach up to 7 – 8% which translates into a signal
568 rate of around 3 pb. These maximal branching ratios are reached in the intermediate
569 mass state for h_2 , $M_2 \sim 60 – 80$ GeV. For $M_2 < 40$ GeV, although phase space opens
570 up significantly for light decay products, the branching ratio becomes smaller.

571 If the decay channel $h_2 \rightarrow h_1 h_1$ is kinematically open (i.e. $M_2 > 2M_1$), it is the
572 dominant decay mode leading to a significant rate for the $h_1 h_1 h_1$ final state, in a
573 “cascade” decay. In BP1, $BR(h_2 \rightarrow h_1 h_1) \simeq 100\%$ above the red line in Fig. 1.4. If,
574 in addition, $M_1 \gtrsim 10$ GeV, the h_1 decays dominantly to $b\bar{b}$ leading to a sizable rate
575 for the $b\bar{b}b\bar{b}b\bar{b}$ final state as shown in Fig. 1.4 (*bottom right*).

576 If the $h_2 \rightarrow h_1 h_1$ decay is kinematically closed (i.e. $M_2 < 2M_1$), both scalars decay
577 directly to Standard Model particles, with branching ratios identical to a Standard
578 Model-like Higgs boson, i.e. with the $b\bar{b}b\bar{b}$ final state dominating, as shown in Fig. 1.4

579 (*bottom left*), while at smaller masses, combinations with τ leptons and eventually
580 final states with charm quarks and muons become relevant [7].

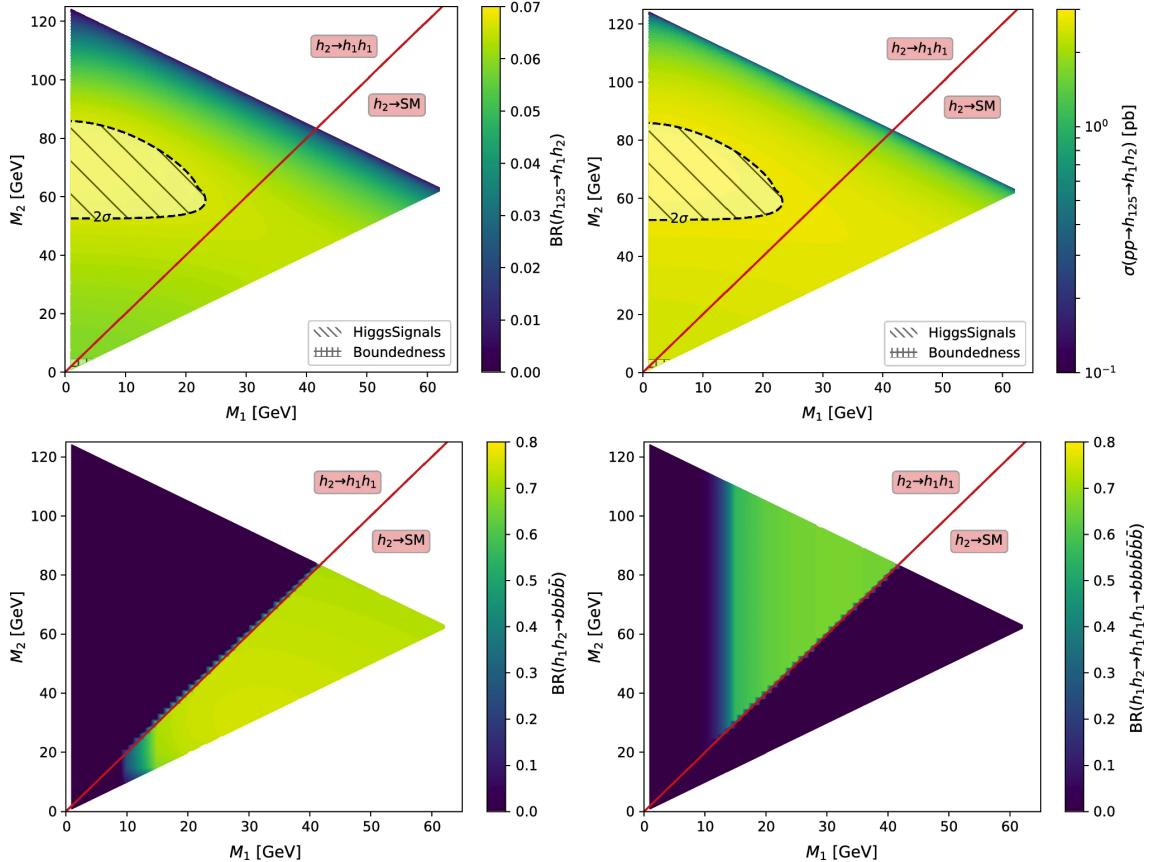


Figure 1.4: Benchmark plane BP1 for benchmark scenario 1 from [7], for the decay signature $h_{125} \rightarrow h_1 h_2$ with $h_{125} \equiv h_3$, defined in the (M_1, M_2) plane. The color code shows $\text{BR}(h_3 \rightarrow h_1 h_2)$ (*top left*) and the 13 TeV LHC signal rate for $pp \rightarrow h_3 \rightarrow h_1 h_2$ (*top right*). The red line separates the region $M_2 > 2M_1$, where $\text{BR}(h_2 \rightarrow h_1 h_1) \sim 100\%$, from the region $M_2 < 2M_1$, where $\text{BR}(h_2 \rightarrow F_{SM}) \sim 100\%$. The *bottom left* and *right* show the branching ratio of the $h_1 h_2$ into (respectively) $b\bar{b}b\bar{b}$, and through a $h_2 \rightarrow h_1 h_1$ cascade to $b\bar{b}b\bar{b}b\bar{b}$. The hatched region indicates where the decay rate slightly exceeds the 2σ upper limit inferred from the LHC Higgs rate measurements, though the region depends on the parameter choices and experimental searches should cover the whole mass range.

⁵⁸¹ **Chapter 2**

⁵⁸² **The Large Hadron Collider and the**
⁵⁸³ **CMS Experiment**

⁵⁸⁴ This chapter introduces the key aspects of the CERN Large Hadron Collider (LHC)
⁵⁸⁵ and the Compact Muon Solenoid (CMS) experiment where the work for this thesis was
⁵⁸⁶ conducted. Section 2.1 describes the history of accelerator developments at CERN
⁵⁸⁷ that led to the construction of the LHC, the current LHC configuration, and the
⁵⁸⁸ largest experiments located at the LHC. The concepts of beam luminosity and pileup,
⁵⁸⁹ which are critical for understanding and measuring high-energy particle collisions,
⁵⁹⁰ are described in Section 2.2 and discussed in the context of the High-Luminosity
⁵⁹¹ LHC (HL-LHC) upgrade in Section 2.3. Lastly, Section 2.4 describes the design
⁵⁹² and function of CMS and its subdetectors, and terminates in a description of data
⁵⁹³ processing at CMS, beginning from online event filtering in the Level-1 Trigger, to
⁵⁹⁴ processing in the High-Level Trigger, to offline particle reconstruction, and finally
⁵⁹⁵ long-term storage and processing of measured events.

596 2.1 The Large Hadron Collider

597 CERN, the European Organization for Nuclear Research, is an international organiza-
598 tion based in Meyrin, Switzerland which operates the world's largest particle physics
599 laboratory, and is the site of the Large Hadron Collider (LHC) [8]. The very first
600 accelerator built at CERN was the 600 MeV Synchrocyclotron (SC), which initially
601 provided beams for CERN's first experiments. The newer and more powerful Proton
602 Synchrotron (PS), which could accelerate particles to an energy of 28 GeV, began op-
603 erations in 1959 and is still in use today. The first hadron collider at CERN was the
604 Intersecting Storage Rings (ISR), which consisted of two interlaced rings each with a
605 diameter of 200. The ISR collided protons at a center-of-mass energy of 62 GeV and
606 began measuring collisions in 1971. In 1968 CERN began to accelerate heavy ions
607 in the Super Proton Synchrotron (SPS), which is 7 kilometers in circumference and
608 was the first of CERN's giant underground rings to be built. The SPS became the
609 forefront of CERN's particle physics program in 1976, and in 1981 was converted into
610 a proton-antiproton collider. The final and largest underground ring constructed at
611 CERN was the Large Electron-Positron (LEP) collider, which was commissioned in
612 July 1989 and hosted 5176 magnets and 128 accelerating cavities located around a
613 27-kilometer circumference. Over 11 years of research, four detectors, ALEPH, DEL-
614 PHI, L3, and OPAL measured the collisions, with collision energies reaching up to
615 209 GeV in the year 2000. In November 2000, LEP was closed down to make way for
616 the construction of the LHC in the same tunnel.

617 In its current configuration, the LHC accelerator complex at CERN is a suc-
618 cession of machines that accelerate particles in stages until they reach their final energy
619 of 6.5 TeV per beam [9] [10]. In Linear accelerator 4 (Linac4), negative hydrogen
620 ions (hydrogen atoms with an additional electron) are accelerated to 160 MeV, and
621 stripped of their two electrons, leaving only protons, before entering the Proton Syn-
622 chrotron Booster (PSB). These protons are accelerated to 2 GeV, then to 26 GeV in

623 the Proton Synchrotron (PS), and 450 GeV in the Super Proton Synchrotron (SPS).
624 The protons are transferred to the two beam pipes of the Large Hadron Collider
625 (LHC). The LHC is a 27-kilometer ring of superconducting magnets, inside which
626 one beam circulates clockwise and the other counterclockwise. Each LHC ring takes
627 4 minutes and 20 seconds to fill, and it takes about 20 minutes for the protons to
628 reach their maximum energy. During normal operating conditions, beams circulate
629 for many hours inside the LHC ring.

630 The beams of particles in the LHC are made to collide at a center-of-mass energy
631 of up to 14 TeV, at four positions at particle detector experiments located around
632 the ring: ATLAS, CMS, ALICE, and LHCb. An aerial view of the four major
633 experiments' locations is shown in Fig. 2.1 [11]. ATLAS and CMS are the two
634 general-purpose detectors with broad physics programmes spanning Standard Model
635 measurements and searches for signatures of new physics [12] [13]. The two experi-
636 ments use different technical solutions and different magnet system designs. ALICE
637 is a general-purpose detector dedicated to measuring LHC heavy-ion collisions, and
638 is designed to address the physics of strongly interacting matter, and the properties
639 of quark-gluon plasma [14]. The LHCb experiment specializes in investigating CP vi-
640 olation through measuring the differences in matter and antimatter, by using a series
641 of subdetectors to detect mainly forward particles close to the beam direction [15].

642 2.2 Luminosity and pileup

643 In order to search for rare processes, such as those resulting from a Higgs, W, or Z
644 boson, a large number of parton interactions per second are required at the LHC.
645 The number of events generated per second by the LHC collisions is given by

$$N_{event} = \mathcal{L} \cdot \sigma_{event} \quad (2.1)$$

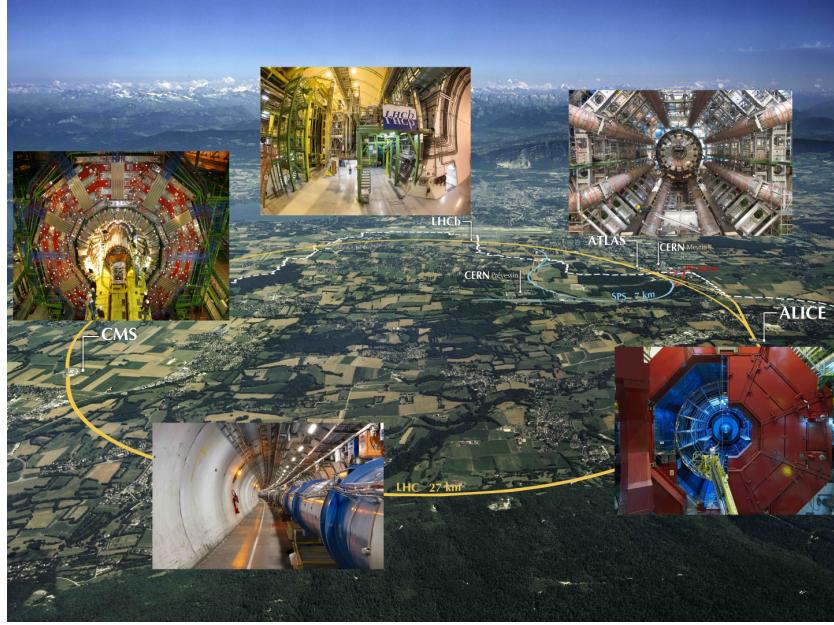


Figure 2.1: Aerial view of the Large Hadron Collider (LHC) spanning the border of France and Switzerland, and the four major experiments located around the ring: CMS (Compact Muon Solenoid), LHCb (LHC beauty), ATLAS (A Toroidal LHC Apparatus), and ALICE (A Large Ion Collider Experiment) [11].

where σ_{event} is the cross-section for the event under study, and \mathcal{L} the instantaneous luminosity. The instantaneous luminosity is measured in units of $\text{cm}^{-2} \text{ s}^{-1}$, and depends only on the beam parameters, and can be written for a Gaussian beam distribution as:

$$\mathcal{L} = \frac{N_b^2 n_b f_{rev} \gamma_r}{4\pi \epsilon_n \beta^*} F \quad (2.2)$$

where the parameters are as defined, along with some example typical nominal values in Phase-1 of the LHC [16] [17]:

- N_b is the number of particles per bunch ($N_b \approx 1.15 \times 10^{11}$ protons per bunch)
- n_b is the number of bunches per beam (maximum 2808),
- f_{rev} is the revolution frequency ($\approx 11 \text{ kHz}$),
- γ_r is the relativistic gamma factor,

- ϵ_n is the normalized transverse beam emittance (area in a transverse plane occupied by the beam particles),
 - β^* is the beta function at the collision point ($\beta^* = 0.55$ m),
 - and F is the geometric luminosity reduction factor due to the crossing angle at the interaction points ($F \approx 0.84$ for Phase-1. Note that complete overlap would give $F = 1$).

Peak luminosity at interaction points 1 and 5 reach values of $\sim 1.0 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$,
with peak luminosity per bunch crossing reaching $\sim 3.56 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$.

Per Eqn. 2.1, the integrated luminosity over time is proportional to the number of events produced, and the size of LHC datasets is commonly presented in terms of integrated luminosity. Collider operation aims to optimize the integrated luminosity. Thus the exploration of rare events in the LHC collisions requires both high beam energies and high beam intensities.

The interaction vertex corresponding to the hard scattering of the protons is called the primary interaction vertex, or primary vertex (PV). The LHC’s nominal beam luminosities are sufficiently large for multiple proton-proton collisions to occur in the same time window of 25 nanoseconds in which proton bunches collide [18]. To measure a proton-proton collision, the primary vertices must be separated from overlapping collisions, called “pileup” collisions.

The pileup is defined as the average number of pp collisions per bunch crossing, and can be estimated from the inelastic pp cross section of $\sigma_{\text{inel}} = 68.6$ millibarns at a center-of-mass energy of $\sqrt{s} = 13$ TeV [19]:

$$\text{Pileup} = \frac{\mathcal{L} \times \sigma_{\text{inel}}}{n_b \cdot f} \sim 22 \quad (2.3)$$

⁶⁷⁸ A distribution of pileup in the data-taking years 2016-2018 is shown in Fig. 2.2.

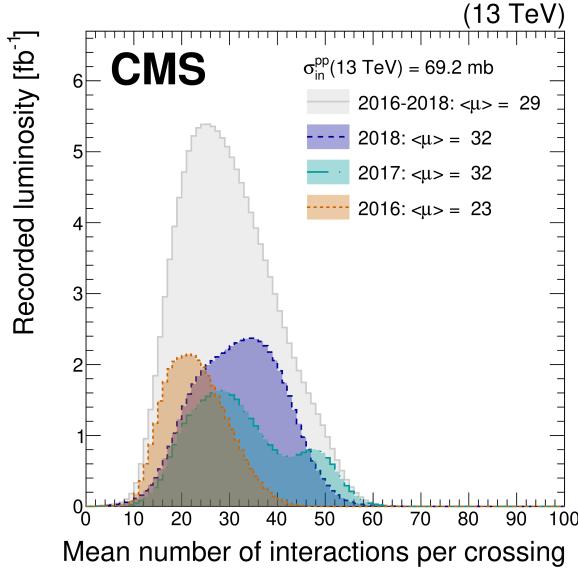


Figure 2.2: Distribution of the mean number of inelastic collisions per bunch crossing (pileup) in data [18], for proton-proton collisions in 2016 (*dotted orange*), 2017 (*dotted light blue*), 2018 (*dotted dark blue*), and integrated over 2016-2018 (*solid grey*). A cross-section of inelastic proton-proton collisions of 69.2 mbarns is assumed. In the running conditions of the High-Luminosity LHC, pileup will reach unprecedented levels of up to 200 per bunch crossing [20].

These multiple collisions will lead to higher occupancies in the detector, and particles originating from the pileup interactions can be confused with those originating from the primary vertex. Thus, higher luminosities create more intense pileup conditions, posing a greater challenge to detector performance and particle reconstruction and identification.

2.3 The High-Luminosity LHC

The High-Luminosity LHC (HL-LHC) is a major upgrade of the LHC scheduled to take place in the late 2020s, that will increase the instantaneous luminosity by a factor of five beyond the original design value, and the integrated luminosity by a factor of ten [20]. This will be accomplished through accelerator technological advances: for instance, reduction of the interaction point β^* from 0.55 m down to 0.15

690 m by installation of new final-focusing magnets, and improvements in the geometric
691 luminosity loss factor $F \approx 1$ through the installation of crab cavities that optimize
692 the orientation of colliding bunches. A further discussion of the HL-LHC upgrades
693 for the CMS detector follows in Chapter 3.

694 2.4 The CMS Detector

695 We give a brief overview of the Compact Muon Solenoid (CMS) experiment here
696 and discuss each of the subdetectors in more detail in the following sections. The
697 CMS experiment was conceived to study proton-proton and lead-lead collisions at
698 a center-of-mass energy of 14 TeV (5.5 TeV nucleon-nucleon) and at luminosities up
699 to $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ ($10^{27} \text{ cm}^{-2} \text{ s}^{-1}$) [21] [22]. Starting from the beam interaction region
700 at the center of the CMS detector, particles first pass through a silicon pixel and
701 strip tracker, in which charged-particle trajectories (tracks) and origins (vertices)
702 are reconstructed from signals (hits) in the sensitive layers. The tracker, electro-
703 magnetic calorimeter (ECAL), and hadronic calorimeter (HCAL) are immersed in a
704 high-magnetic-field superconducting solenoid that bends the trajectories of charged
705 particles. After passing through the tracker, electrons and photons are then absorbed
706 in the electromagnetic calorimeter (ECAL) comprised of lead-tungstate scintillating-
707 crystals. The corresponding electromagnetic showers are detected as clusters of energy
708 recording in neighboring cells, from which the direction and energy of the particles can
709 be determined. Charged and neutral hadrons may initiate a hadronic shower in the
710 ECAL as well, which is then fully absorbed in the hadron calorimeter (HCAL). The
711 resulting clusters are used to estimate their direction and energies. Muons and neu-
712 trinos pass through the calorimeters with little to no interactions. Neutrinos escaped
713 undetected; muons produce hits in additional gas-ionization chamber muon detectors
714 housed in the iron yoke of the flux-return. A sketch of example particle interactions

in a transverse slice of the CMS detector is shown in Fig. 2.3. The collision data is recorded with the use of the Level-1 (L1) trigger (discussed in greater detail in 2.5.5), the High-Level Trigger (HLT), and data acquisition systems ensuring high efficiency in selecting physics events of interest.

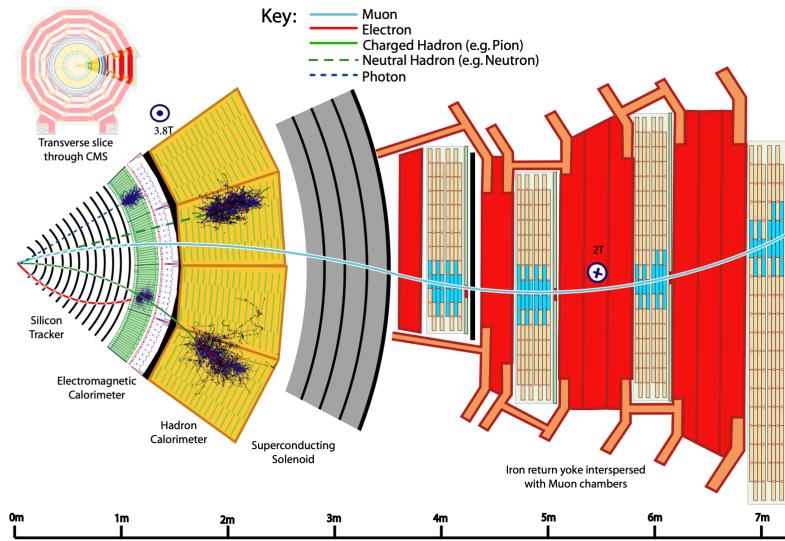


Figure 2.3: Sketch of particle trajectories of muons, electrons, charged and neutral hadrons, and photons in a transverse cross-section of the CMS detector [22].

CMS uses a right-handed coordinate system [21]. The origin is centered at the nominal collision point inside the experiment. The x axis points towards the center of the LHC, and the y axis points vertically upwards. The z axis points along the beam direction. The azimuthal angle, ϕ , is measured from the x axis in the x - y plane, and the radial coordinate in this plane is denoted by r . The polar angle, θ , is measured from the z axis. The pseudorapidity, η , is defined as $\eta = -\ln \tan(\theta/2)$. The momentum and energy transverse to the beam direction, denoted by p_T and E_T respectively, are computed from the x and y components. The momentum imbalance in the transverse plane is called the missing transverse momentum, and its magnitude is denoted by E_T^{miss} .

729 2.5 Sub-detectors of CMS

730 This section details the sub-detectors of CMS that operate to identify and precisely
731 measure muons, electrons, photons, and jets over a large energy range.

732 2.5.1 Inner tracking system

733 The CMS Tracker performs robust tracking and detailed vertex reconstruction in the
734 4 T magnetic field of the superconducting solenoidal magnet. The primary sensors
735 used in the tracker are p^+ on n -bulk devices, which allow high voltage operation and
736 are radiation-resistant [23] [24]. The active envelope of the CMS Tracker extends to a
737 radius of 115 cm, over a length of approximately 270 cm on each side of the interaction
738 point [23]. Charged particles in the region $|\eta| \lesssim 1.6$ benefit from the full momentum
739 measurement precision. In this region, a charged particle with p_T of 1000 GeV has a
740 sagitta of ~ 195 μm . The Tracker acceptance extends further to $|\eta| = 2.5$, with a
741 reduced radius of approximately 50 cm.

742 The high magnetic field of CMS causes low p_T charged particles to travel in helical
743 trajectories with small radii. The majority of events contain particles with a steeply
744 falling p_T spectrum, resulting in a track density which rapidly decreases at higher
745 radii.

746 A schematic view of the current Phase-1 CMS tracker [25], including the pixel
747 detector, is shown in Fig. 2.4. The Phase-1 pixel detector consists of three barrel
748 layers (BPIX) at radii of 4.4 cm, 7.3 cm, and 10.2 cm, and two forward/backward disks
749 (FPIX) at longitudinal positions of ± 34.5 cm and ± 46.5 cm, and extending in radius
750 from about 6 cm to 15 cm. These pixelated detectors produce 3D measurements along
751 the paths of charged particles with single hit resolutions between 10-20 μm .

752 After the pixel and on their way out of the tracker, particles pass through the
753 silicon strip tracker which reaches out to a radius of 130 cm (Fig. 2.4). The sensor el-

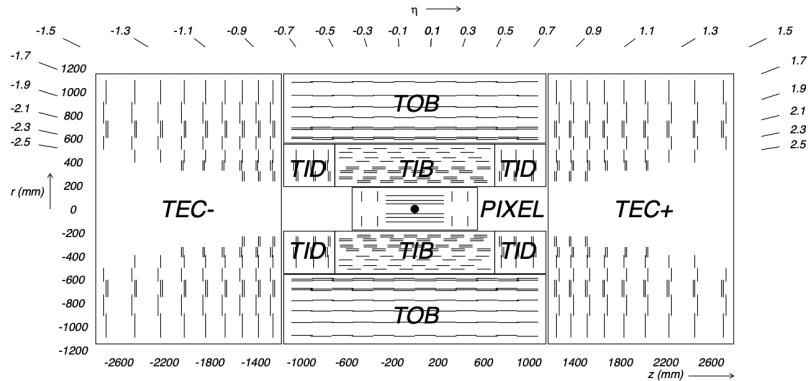


Figure 2.4: Cross section of the current Phase-1 CMS tracker [25]. Each line represents a detector module. Double lines indicate back-to-back modules which deliver two-dimensional (stereo) hits in the strip tracker.

ments in the strip tracker are single-sided p -on- n type silicon micro-strip sensors [21]. The silicon strip detector consists of four inner barrel (TIB) layers assembled in shells, with two inner endcaps (TID), each composed of three small discs. The outer barrel (TOB) consists of six concentric layers. Two endcaps (TEC) close off the tracker on either end.

2.5.2 ECAL

The electromagnetic calorimeter (ECAL) of CMS measures electromagnetic energy deposits with high granularity. One of the driving criteria in the design was the capability of detecting the Standard Model Higgs boson decay to two photons (in fact, the channel in which the 125 GeV Higgs boson was discovered at CMS). ECAL is a hermetic homogeneous calorimeter comprised of 61,200 lead tungstate (PbWO_4) crystals mounted in the central barrel, with 7,324 crystals in each of the two endcaps [21]. A preshower detector is located in front of the endcap crystals. Avalanche photodiodes (APDs) are used as photodetectors in the barrel and vacuum phototriodes (VPTs) in the endcaps.

The design of the ECAL is driven by the behaviour of high-energy electrons, which

770 predominantly lose energy in matter via bremsstrahlung, and high-energy photons
771 by e^+e^- pair production. The characteristic amount of matter traversed for these
772 interactions is the radiation length X^0 , usually measured in units of g cm $^{-2}$. The
773 radiation length is also the mean distance over which a high-energy electron loses all
774 but $1/e$ of its energy via bremsstrahlung [26]. Thus high granularity in η and ϕ , and
775 the length of the ECAL crystals, is designed to capture the shower of e/γ produced
776 by electrons and photons.

777 The barrel part of the ECAL (EB) covers the pseudorapidity range $|\eta| < 1.479$ [21].
778 The barrel granularity is 360-fold in ϕ and (2×85) -fold in η . The crystal cross-section
779 corresponds to approximately 0.0174×0.0174 in $\eta - \phi$ or 22×22 mm 2 at the front
780 face of the crystal, and 26×26 mm 2 at the rear face. The crystal length is 230 mm,
781 corresponding to $25.8 X_0$.

782 The ECAL read-out acquires the signals of the photodetectors [21]. At each bunch
783 crossing, digital sums representing the energy deposit in a trigger tower, comprising
784 5×5 crystals in $\eta \times \phi$, are generated and sent to the Level-1 trigger system (detailed
785 in Section 2.5.5).

786 2.5.3 HCAL

787 The hadronic calorimeter (HCAL) of CMS measures hadronic energy, which is key to
788 characterizing the presence of apparent missing transverse energy which could arise
789 from hadron jets and neutrinos or exotic particles [21]. A schematic of the components
790 of HCAL are shown in Fig. 2.5. The HCAL barrel (HB) and endcaps (HE) are located
791 outside of the tracker and the ECAL, spanning a radius of 1.77 m (outer extent of
792 ECAL) up to 2.95 m (inner extent of the magnet coil). An outer hadron calorimeter
793 (HO) is placed outside the solenoid to complement the barrel calorimeter. Beyond
794 $|\eta| = 3$, the forward hadron calorimeter (HF) at 11.2 m from the interaction point
795 extend the pseudorapidity coverage to $|\eta| = 5.2$.

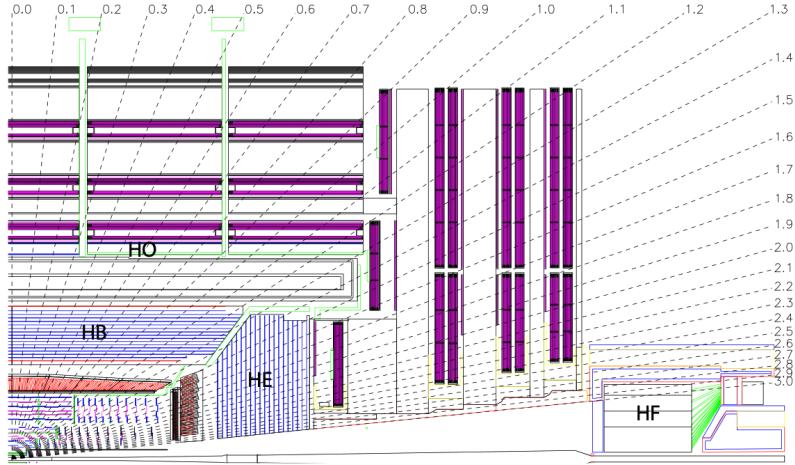


Figure 2.5: Longitudinal view of the CMS detector showing the hadron calorimeter barrel (HB), endcap (HE), outer (HO), and forward (HF) calorimeters from [21].

796 The HB is a sampling calorimeter covering the pseudorapidity range $|\eta| < 1.3$ [21].
 797 It consists of 36 identical azimuthal wedges which form two half-barrels (HB+ and HB-
 798), with a segmentation of $(\Delta\eta, \Delta\phi) = (0.087, 0.087)$. The HE covers pseudorapidity
 799 $1.3 < |\eta| < 3$. The HB and endcap HE calorimeters are sampling calorimeters which
 800 use brass as the absorber and plastic scintillator as the active material. Light from
 801 the plastic scintillator is wavelength-shifted and captured in optic fibers which are
 802 read out by front-end electronics [27].

803 In the central pseudorapidity region, the combined stopping power of EB plus the
 804 HB is insufficient to contain hadron showers [21]. To ensure adequate sampling depth,
 805 the hadron calorimeter is extended with a tail catcher, the HO. The size and position
 806 of the tiles are designed to roughly map the layers of the HB to make towers with
 807 the same granularity of 0.087×0.087 in η and ϕ . HO uses the same active material
 808 as the HB and HE calorimeters, but uses the steel return yoke and magnet material
 809 of CMS as absorbers [27].

810 The HF is a Cherenkov calorimeter based on a steel absorber and quartz fibers
 811 which run longitudinally through the absorber and collect Cherenkov light, primarily
 812 from the electromagnetic component of showers developed in the calorimeter [27].

813 Photomultiplier tubes are used to collect light from the quartz fibers. The HF is
814 designed to survive in the harsh radiation conditions and high particle flux of the for-
815 ward region. On average, 760 GeV per proton-proton interaction is deposited into the
816 two forward calorimeters, compared to only 100 GeV for the rest of the detector [21].
817 Furthermore, this energy has a pronounced maximum at the highest rapidities.

818 2.5.4 Muon detectors

819 The CMS muon system is designed to have the capability of reconstructing the mo-
820 mentum and charge of muons over the kinematic range of the LHC, since muons are a
821 powerful handle on signatures of interesting processes over the high background rate
822 of the LHC [21]. For instance, the decay of the Standard Model Higgs boson into
823 ZZ , which in turn decay to 4 leptons, can be reconstructed with high 4-particle mass
824 resolution if all the leptons are muons, since muons are less affected than electrons
825 by radiative losses in the tracker material.

826 The muon system consists of a cylindrical barrel section and two planar endcap
827 regions [21]. The barrel muon detector consists of drift tube (DT) chambers covering
828 the pseudorapidity region $|\eta| < 1.2$ (Fig. 2.6). The DTs can be used as tracking
829 detectors due to the barrel region’s characteristic low neutron-induced backgrounds,
830 low muon rate, and relatively uniform 4T magnetic field contained in the steel yoke.

831 In the two endcap regions, the muon rates and background levels are high and the
832 magnetic field is large and non-uniform [21]. Here, the muon system uses cathode
833 strip chambers (CSCs) to identify muons between $0.9 < |\eta| < 2.4$. The cathode strips
834 of each chamber run radially outwards and provide a precision measurement in the
835 $r - \phi$ bending plane. The anode wires run approximately perpendicular to the strips
836 and are read out in order to measure η and the beam-crossing time of a muon.

837 In addition to the DT and CSC, a dedicated trigger system consisting of resistive
838 plate chambers (RPCs) in the barrel and endcap regions provide a fast, independent,

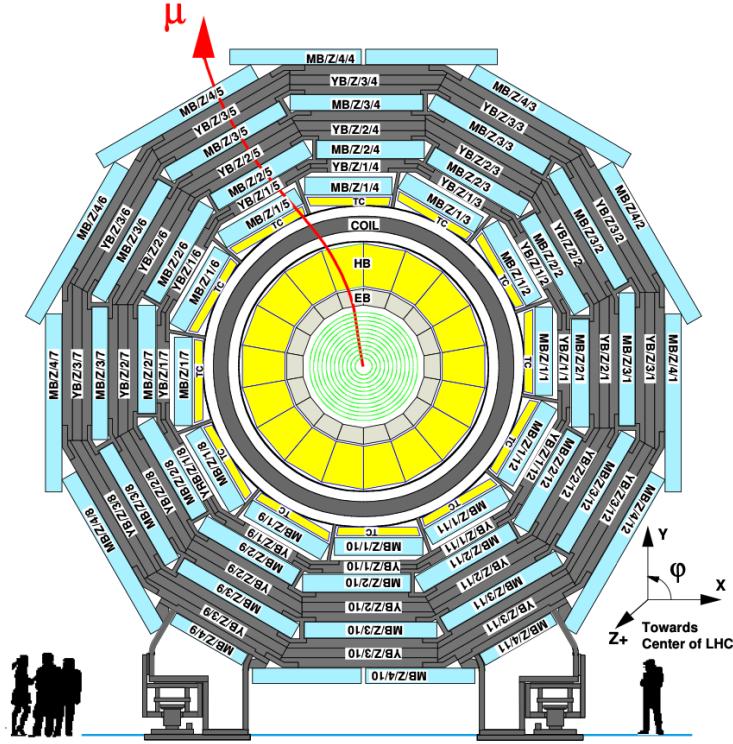


Figure 2.6: Layout of the CMS barrel muon drift tube (DT) chambers in one of the five wheels from [21]. The DTs are organized in 12 sectors of the yoke barrel (YB). In each of the 12 sectors of the yoke, there are 4 muon chambers per wheel (MB1, MB2, MB3, and MB4).

and highly-segmented trigger with a sharp p_T threshold over a large portion of the pseudorapidity range ($|\eta| < 1.6$) of the muon system [21]. RPCs have good time resolution but coarser position resolution compared to the DTs or CSCs. The RPCs also play a role in resolving ambiguities in reconstructing tracks from multiple hits in a chamber.

2.5.5 The Level-1 Trigger

The design performance of the LHC corresponds to an instantaneous luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ with a 25 ns bunch crossing rate, giving an average pile-up (number of simultaneous events) of 25 per bunch crossing [28]. The large number of minimum

848 bias events per bunch crossing, combined with the small cross-sections of possible
 849 physics discovery signatures, necessitates a sophisticated event selection system for
 850 filtering this large event rate, as it is impossible to save all events. This data filtering
 851 system is implemented by CMS in two stages. The first stage is the Level-1 (L1)
 852 Trigger, which is deployed in custom electronic hardware systems and is responsible
 853 for reducing the event rate to around 100 kHz. The second stage is the High-Level
 854 Trigger (HLT) which is described in Section 2.5.6. This section describes the Phase-1
 855 configuration of the Level-1 Trigger.

856 The L1 Trigger data flow of Phase-1 is shown in Fig. 2.7 [28], with organization
 857 into the L1 calorimeter trigger, the L1 muon trigger, and the L1 global trigger.

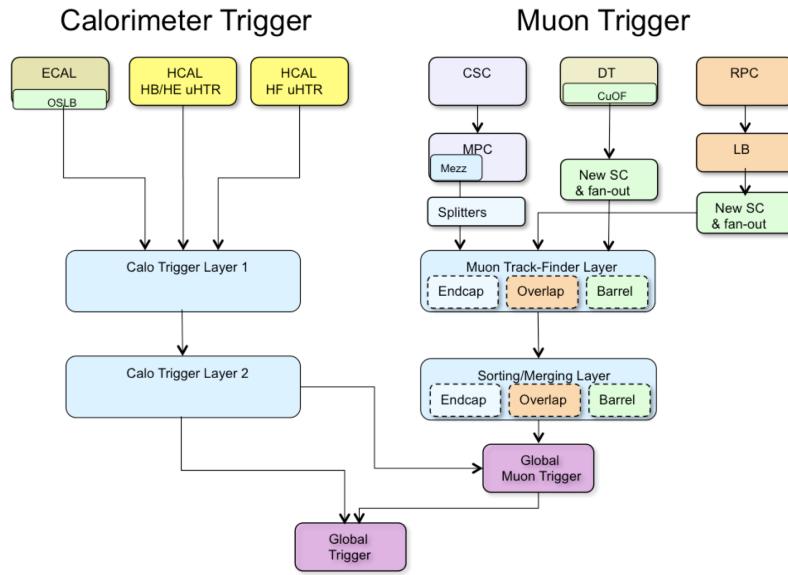


Figure 2.7: Dataflow for the Phase-1 Level-1 Trigger [28], which is implemented in custom hardware and is responsible for reducing the event rate from the LHC bunch crossing frequency of 400 MHz (bunch crossings every 25 ns) to a maximum rate of 100 kHz. In Phase-1, the Level-1 Trigger has access to information from the calorimeter and muon detectors.

858 The L1 calorimeter trigger begins with trigger tower energy sums formed by the
 859 ECAL, HCAL, and HF Trigger Primitive Generator (TPG) circuits from the indi-
 860 vidual calorimeter cell energies. In the original configuration, the ECAL energies

were accompanied by a bit indicating the transverse extent of the electromagnetic energy deposits, and the HCAL energies were accompanied by a bit indicating the presence of minimum ionizing energy [29]. Between Long Shutdowns 1 and 2 (LS1 and LS2), HF was upgraded to provide finer granularity information to the trigger, and the HCAL barrel and endcap front-end electronics were upgraded to provide high-precision timing information and depth segmentation information.

In the original design of the L1 calorimeter trigger, the trigger primitives are processed by the Regional Calorimeter Trigger (RCT, upgraded to Calo Layer 1 after LS2) which finds isolated and non-isolated electron/photon candidates [28]. At this stage, electrons/photon candidates are treated together since they cannot be definitively distinguished at this stage due to lack of tracking information in the L1 trigger. The Global Calorimeter Trigger (GCT, upgraded to Calo Layer 2 after LS2) sorts further the candidate electrons/photon, finds jets (classified as central, forward, and tau) using the E_T sums and performs calibration of the clustered jet energies, and calculates global quantities such as missing E_T . It sends the top four candidates of each type to the global trigger (GT) [28].

Each of the L1 muon triggers has its own trigger logic [29]. The RPC strips are connected to a Pattern Comparator Trigger (PACT), which forms trigger segments that are used to build tracks and calculate p_T . The RPC logic also provides some hit data to the CSC trigger system to resolve ambiguities caused by two muons in the same CSC. The CSCs form local charged tracks (LCTs) from the cathode strips, which are combined with the anode wire information. LCTs are combined into full muon tracks and assigned p_T values.

The Global Muon Trigger (GMT) sorts the RPC, DT, and CSC muon tracks, converts these tracks to the same η , ϕ , and p_T scale, and validates the muon sign [29]. It improves the trigger efficiency by merging muon candidates that were detected in two complementary sub-systems (i.e. DT+RPC, or CSC+RPC). The GMT also

888 contains logic to correlate the found muon tracks with an $\eta-\phi$ grid of quiet calorimeter
889 towers to determine if the muons are isolated, as well as logic to remove duplicate
890 candidates originating in the overlap regions from both DT and CSC systems. The
891 final collection of muons are sorted based on their initial quality, correlation, and p_T ,
892 and the top four muons are sent to the Global Trigger [29].

893 Information from the GCT and GT are sent to the Global Trigger (GT), which
894 makes the Level-1 Accept (L1A) decision to either discard or accept the bunch cross-
895 ing [29]. This is accomplished by sorting ranked trigger objects that are accompanied
896 by positional information in η and ϕ , permitting the trigger to applying criteria with
897 thresholds that can vary based on the location of the trigger objects, and/or to re-
898 quire trigger objects to be close to or opposite from each other. The GT L1A decision
899 arrives at the detector front end with a $3.8\ \mu\text{s}$ latency after the interaction at a rate
900 which is required to be less than 100 kHz, and triggers a full readout of the detector
901 for further processing.

902 **2.5.6 The High-Level Trigger**

903 The HLT is implemented in software running on a large computer farm of fast com-
904 mercial processors [30] [31]. The algorithms in HLT have access to full data from
905 all CMS sub-detectors, including the tracker, with full granularity and resolution.
906 The HLT reconstruction software is similar to what is used offline for full CMS data
907 analysis. As a result, the HLT can calculate quantities with a resolution compara-
908 ble to the final detector resolution, compared to the L1 Trigger. The HLT performs
909 more computationally-intensive algorithms, such as combining tau-jet candidates in
910 the calorimeter with high- p_T stubs in the tracker, to form a hadronic tau trigger. The
911 maximum HLT input rate from the L1 Trigger is 100 kHz, and the HLT output rate
912 is approximately 100 Hz.

913 The HLT contains trigger paths, each corresponding to a dedicated trigger [32].

914 A path consists of several steps implemented as software modules. Each HLT trigger
915 path must be seeded by one or more L1 trigger bits: the first module always looks
916 for a L1 seed, consisting of L1 bit(s) and L1 object(s). Each module performs a well-
917 defined task such as unpacking (raw to digitized quantities), reconstruction of physics
918 objects (electrons, muons, jet, missing transverse energy, etc.), making intermediate
919 decisions that trigger more detailed reconstruction modules, and calculating the final
920 decision for the trigger path. If an intermediate filter decision is negative, the rest of
921 the path is not executed, and the trigger rejects the event.

922 **2.5.7 Particle reconstruction**

923 To build a description of the physics objects present in the particle collision, the
924 basic elements from the detector layers (tracks and clusters of energy) are correlated
925 to identify each particle in the final state. Measurements from different sub-detectors
926 are combined to reconstruct the particle properties. This approach is called particle-
927 flow (PF) reconstruction [22]. Key to the success of the PF reconstruction is the
928 fine spatial granularity of the detector layers. Coarse-grained detectors can cause
929 the signals from different particles to merge, especially within jets. However, if the
930 subdetectors are sufficiently segmented to separate individual particles, it becomes
931 possible to produce a global event description that identifies all physics objects with
932 high efficiencies and resolution.

933 **2.5.8 Data storage and computational infrastructure**

934 The LHC generates over 15 petabytes (15 million gigabytes) of data every year, neces-
935 sitating a flexible computing system that can be accessed by researchers working at
936 the four main LHC experiments: ALICE, ATLAS, CMS, and LHCb. The Worldwide
937 LHC Computing Grid (WLCG) [33] is a global collaboration of computer centers that
938 links thousands of computers and storage systems in over 170 centers across 41 coun-

939 tries. These centers are arranged in “tiers”, and provide near real-time access to users
940 processing, analyzing, and storing LHC data. One of the final stages of data analy-
941 sis at LHC experiments is large-scale data processing taking place over distributing
942 computing, for instance, with the use of Condor [34], a distributed, scalable, flexible
943 batch processing system which accepts a computing job, allocates a resource to it,
944 executes it, and returns the result back to a user transparently.

945 **Chapter 3**

946 **The Phase-2 Upgrade of CMS**

947 This chapter gives an overview of the High-Luminosity LHC upgrade of the LHC in
948 Section 3.1, and the upgrades for the Phase-2 CMS Level-1 (L1) Trigger in Section
949 3.2. One of the major upgrades is the new availability of calorimeter crystal-level
950 information to the L1 calorimeter trigger, compared to the current trigger which only
951 has access to tower-level information (a tower being 5 by 5 in crystals). To capitalize
952 on the increased spatial granularity of this information, an upgraded algorithm is
953 presented which reconstructs and identifies electron and photon candidates in the the
954 Layer-1 Calorimeter Trigger. A description of the algorithm and a validation of its
955 performance in Phase-2 conditions is given in Section 3.3.

956 **3.1 The High-Luminosity LHC**

957 In order to sustain and extend the LHC’s physics discovery program and maintain
958 operability for a decade or more, the LHC is undergoing a major upgrade to the High-
959 Luminosity LHC (HL-LHC). In its final configuration, the HL-LHC will deliver a peak
960 luminosity of $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, potentially leading to total integrated luminosity
961 of 4000 fb^{-1} after ten years of operations, scheduled to begin in 2027 [35]. This
962 integrated luminosity is about ten times the predicted luminosity reach of the LHC

963 in its initial configuration. To enable the CMS experiment to continue operations and
964 data-taking and to maximize the discovery potential of the unprecedented amount
965 of data, the CMS detector is undergoing Phase-2 upgrades in order to perform high-
966 precision measurements and searches for physics beyond the Standard Model in the
967 intense running conditions of the HL-LHC.

968 3.2 The Phase-2 Level-1 Trigger

969 To achieve the goals of the HL-LHC program and to ensure the collection of information-
970 rich datasets in the HL-LHC, the Phase-2 upgrade of the CMS Level-1 Trigger [35]
971 must be upgraded in conjunction with the CMS sub-detectors and their readouts, to
972 maintain physics selectivity. The HL-LHC will produce an intense hadronic environ-
973 ment corresponding to 200 simultaneous collisions per beam crossing, necessitating
974 comprehensive upgrades of the trigger system outlined below.

975 To profit from the extended coverage and increased granularity of the upgraded
976 CMS detector, the latency of the L1 trigger system (time available to produce a L1
977 Accept signal) will be increased significantly from $3.8 \mu\text{s}$ to $12.5 \mu\text{s}$, with an increased
978 maximum output bandwidth of 750 kHz [35]. With the increased latency, in addition
979 to information from calorimeters and muon detectors (as in the Phase-1 system),
980 information from the new tracker and high-granularity endcap calorimeter can also
981 be included at L1 for the first time. This is illustrated in the functional diagram of
982 the architecture of the Phase-2 trigger system in Fig. 3.1.

983 The key feature of the Phase-2 L1 Trigger is the introduction of a correlator layer,
984 where algorithms produce higher-level trigger objects by combining information from
985 sub-detectors, with a selectivity approaching that of offline reconstruction in the
986 HLT [35]. Four independent data processing paths (grouped together in Fig. 3.1) are
987 implemented: tracking, calorimetry, muon systems, and particle-flow techniques:

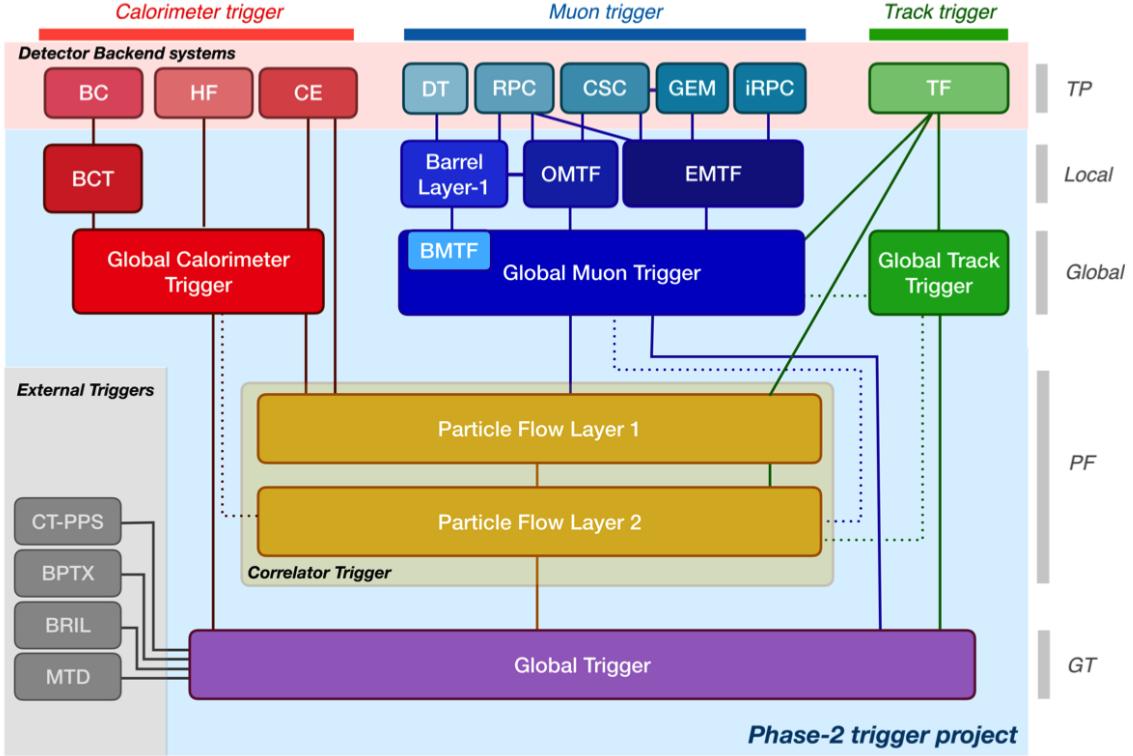


Figure 3.1: Functional diagram of the CMS L1 Phase-2 upgraded trigger design [35], showing the four trigger paths: calorimeter, muon, track, and Particle Flow. For the first time, tracking information will be available as early as the L1 Trigger.

- **Calorimeter Trigger path:** (red, Fig. 3.1) A barrel calorimeter trigger (BCT) and the HGCAL backend are used to produce high-granularity information from the calorimeters to produce high-resolution clusters and identification variables used for later processing. Outputs from the BCT, HGCAL, and the HF are sent to a global calorimeter trigger (GCT), where calorimeter-only objects such as e/γ candidates, hadronically decaying tau lepton candidates, jets, and energy sums are built.
- **Track Trigger path:** (green, Fig. 3.1) Tracks from the Outer Tracker are reconstructed in the track finder (TF) processors as part of the detector backend. A global track trigger (GTT) will reconstruct the primary vertices of the event, along with tracker-only based objects, such as jets and missing transverse momentum.

1000 • **Muon Trigger path:** (*blue*, Fig. 3.1) Trigger primitives are processed by
1001 muon track finder algorithms, again separated into the barrel (barrel muon
1002 track finder, BMTF), overlap (overlap muon track finder, OMTF), and endcap
1003 (endcap muon track finder, EMTF). Standalone muons and stubs containing
1004 information such as position, bend angle, and timing, as well as L1 tracks, are
1005 sent to the global muon trigger (GMT).

1006 • **Particle-Flow Trigger path:** (*yellow*, Fig. 3.1) The correlator trigger (CT)
1007 aims to approach the performance of offline Particle Flow, and is implemented
1008 in two layers. “Layer-1” produces the particle-flow candidates from matching
1009 calorimeter clusters and tracks. “Layer 2” builds and sorts final trigger objects
1010 and applies additional identification and isolation criteria.

1011 The outputs from the above trigger paths are combined in the Global Trigger
1012 (GT) (*purple*, Fig. 3.1), which calculates the final trigger decision (Level-1 Accept),
1013 transmitting it to the Trigger Control and Distribution System (TCDS), which dis-
1014 tributes it to the detector backend systems, initiating the readout to the DAQ. The
1015 GT also provides the interface to external triggers (*grey*, Fig. 3.1), such as trig-
1016 gers for the precision proton spectrometer (PPS), beam position and timing monitors
1017 (BPTX), and luminosity and beam monitoring (BRIL) detectors [35]. The design of
1018 the Phase-2 Level-1 Trigger allows for future inclusion of triggering information, for
1019 instance information about minimum ionizing particles (MIPs) from the MIP Timing
1020 Detector (MTD) [36].

1021 3.3 Standalone Barrel Calorimeter electron/photon

1022 reconstruction

1023 The reconstruction and identification of electrons and photons (e/γ) begin with the
 1024 trigger primitives of the barrel ECAL and HCAL detectors and endcap HGCAL
 1025 calorimeters, covering the pseudorapidity region $|\eta| < 3$. The barrel and endcap re-
 1026 gions of the detector are intrinsically different enough to warrant different approaches
 1027 to e/γ reconstruction. This work focuses on the Standalone Calorimeter e/γ recon-
 1028 struction taking place in the barrel (Fig. 3.2).

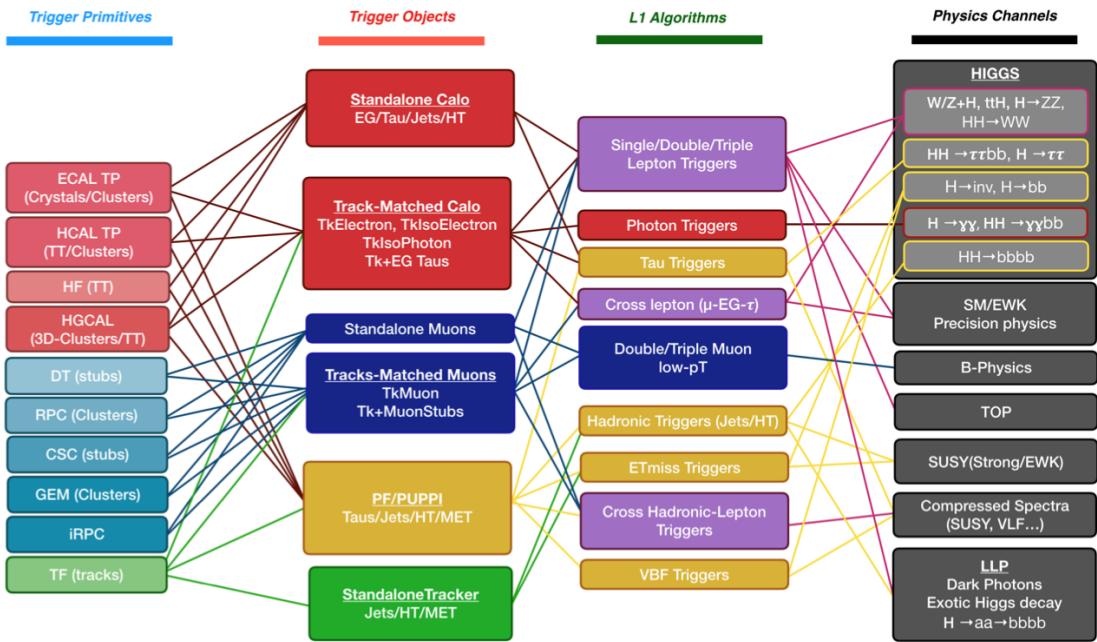


Figure 3.2: Summary of the links between the trigger primitives (*first column*), the trigger objects (*second column*), the Level-1 algorithms used in the menu (*3rd column*), and the physics channels (*4th column*), from [35], where a full description of the Phase-2 L1 algorithms can be found. This work focuses on developments for the Standalone Calorimeter electron and photon ("EG") reconstruction algorithm.

1029 **3.3.1 Phase-2 geometry of the ECAL Barrel trigger**

1030 In Phase-2, the upgrade of both on-detector and off-detector electronics for the barrel
1031 calorimeters trigger primitive generator (TPG) will stream single crystal data from
1032 the on-detector to the backend electronics, in contrast to the lower-granularity output
1033 of the Phase-1 ECAL TPG that is restricted to providing trigger tower sums of 5×5
1034 crystals [35]. A schematic representation of the geometry of the ECAL barrel in the
1035 Regional Calorimeter Trigger (RCT) is shown in Fig. 3.3. The barrel is spanned by
1036 36 RCT cards, each spanning 17×4 towers in $\eta \times \phi$. Each RCT card is subdivided
1037 into five “regions” as shown in Fig. 3.4. After initial clustering and processing, the
1038 outputs of the RCT card are sent to the Global Calorimeter (GCT) trigger, which is
1039 processed in three cards as shown in Fig. 3.5.

1040 **3.3.2 Phase-2 electron/photon reconstruction algorithm**

1041 The standalone barrel algorithm for reconstructing and identifying electrons and pho-
1042 tons in the Phase-2 Level-1 Trigger takes as input the digitized response of each crystal
1043 of the barrel ECAL, with a granularity 0.0175×0.0175 in $\eta \times \phi$, which is 25 times
1044 higher than the input to the Phase-1 trigger, which consisted of trigger towers with
1045 a granularity of 0.0875×0.0875 . In HCAL the tower size of 0.0875×0.0875 is un-
1046 changed. The trigger algorithm is designed to closely reproduce the algorithm used in
1047 the offline reconstruction, with limitations and simplifications due to trigger latency.

1048 In the RCT, an initial requirement of $p_T > 0.5$ GeV is imposed on the input
1049 trigger primitives (i.e. energies from the ECAL crystals and HCAL towers) to reject
1050 contribution from pileup. In one of the regions inside a RCT card (Fig. 3.4), the
1051 crystal containing the highest energy deposit is identified as the seed crystal, as shown
1052 in Fig. 3.6. The energy in the crystals in a window of size 3×5 in $\eta \times \phi$ around
1053 the seed cluster is added into a cluster. The energy is considered “clustered”. The
1054 process is repeated with the remaining “unclustered” energy, until up to four clusters

1055 are produced in the region.

1056 To improve e/γ identification and to reduce background contributions, identifica-
1057 tion and reconstruction algorithms are implemented at this stage:

1058 • Shower shape: The energy deposit sums around the seed crystal is computed in
1059 windows of size 2×5 and 5×5 (Fig. 3.6, *dashed lines*), with true e/γ clusters
1060 tending to produce showers that deposit most of their energy in a 2×5 region.

1061 • Bremsstrahlung recovery: e/γ tend to spread in the ϕ direction due to charged
1062 particles being bent by the magnetic field of the CMS solenoid. If sufficient
1063 energy comparable to the core 3×5 cluster is found in the adjacent 3×5
1064 windows (Fig. 3.6, *shaded yellow*), the energy is added to the core cluster and
1065 no longer considered unclustered energy.

1066 After parallel processing in the regions, the clusters in a RCT card are stitched
1067 together if they are located directly along the borders of a region (Fig. 3.3). The
1068 remaining unclustered ECAL energy is summed into ECAL towers.

1069 From each RCT card, the twelve highest-energy clusters, as well as any remaining
1070 unclustered energy, are sent to the GCT. Since each GCT card has information from
1071 sixteen RCT cards (Fig. 3.5), final stitching across the boundaries of the RCT cards
1072 is performed. One more identification algorithm is performed at this stage:

1073 • Isolation: One handle to reject backgrounds from e.g. pileup, comes from the
1074 tendency for background to be spread more uniformly across a large area in the
1075 detector, whereas genuine e/γ are expected to produce showers concentrated in
1076 the 3×5 crystal window. The energy sum in a large window of 7×7 in towers
1077 is computed and used to reject background.

1078 The performance of the standalone barrel e/γ algorithm in Phase-2 conditions is
1079 summarized in the efficiency and rates. The efficiencies are measured with a simulated
1080 Monte Carlo sample containing electrons. The rates are measured with a simulated

1081 minimum bias sample intended to closely mimic generic proton-proton collisions in
1082 the CMS detector. The performance of the Phase-2 emulator discussed in this work,
1083 which closely mimics the firmware logic and uses fixed-precision integers, is shown to
1084 be comparable to the previous emulator which used floats and idealized logic.

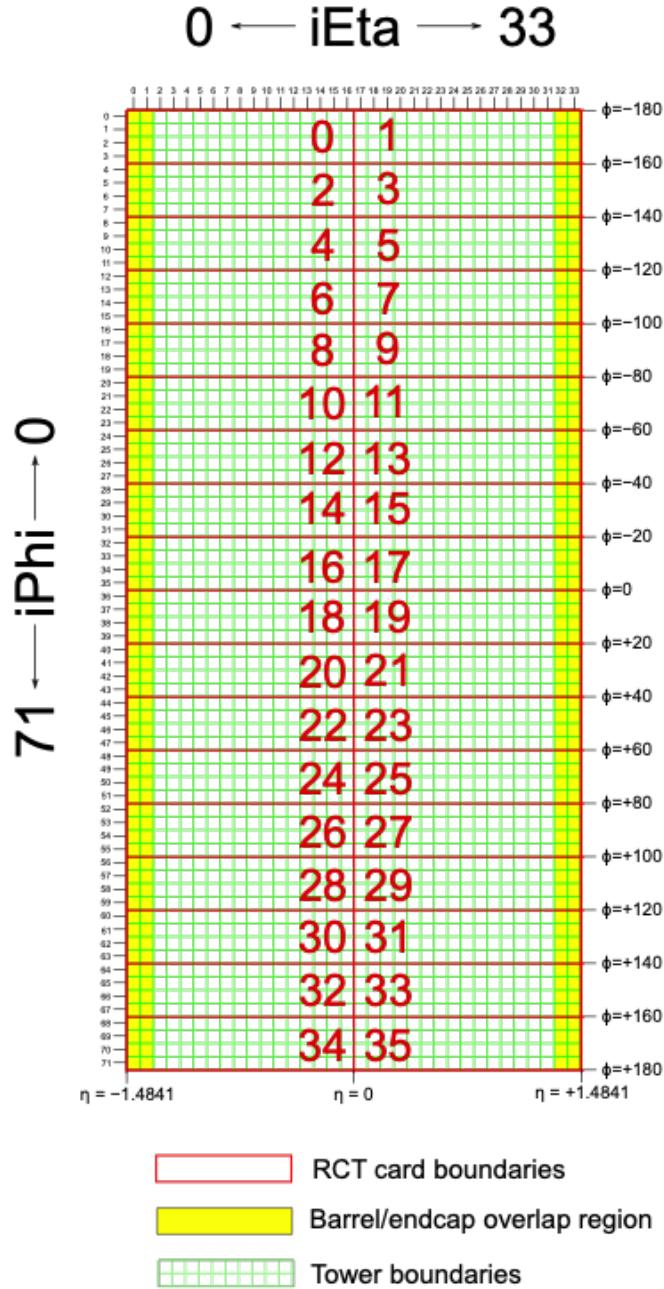


Figure 3.3: Schematic of the geometry of the Phase-2 ECAL barrel in the Regional Calorimeter Trigger (RCT), showing the division of the barrel region into 36 Regional Calorimeter Trigger (RCT) cards (*red*). Each card spans 17×4 towers in $\eta \times \phi$ (*green*), and each tower is 5×5 in single crystals in $\eta \times \phi$. Towers in the overlap region (*shaded yellow*) are read out to both the barrel and endcap.

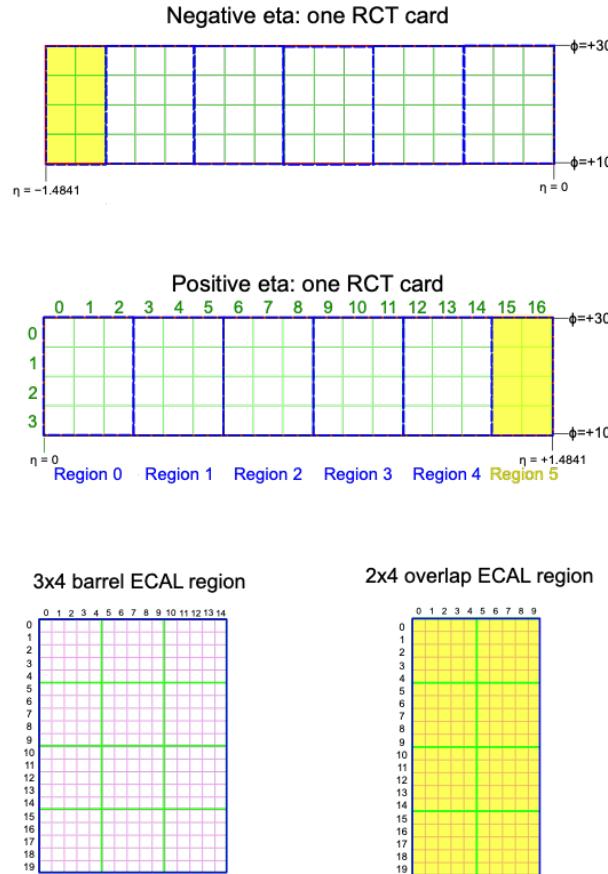


Figure 3.4: Schematic of two example RCT cards in the negative eta (*top*) and positive eta (*center*) regions of the ECAL barrel. Each RCT card is divided into five regions: four regions are of size 3×4 towers in $\eta \times \phi$ (*bottom left*), and a fifth smaller overlap region of size 2×4 towers (*bottom right*). Each tower is 5×5 ($\eta \times \phi$) in crystals.

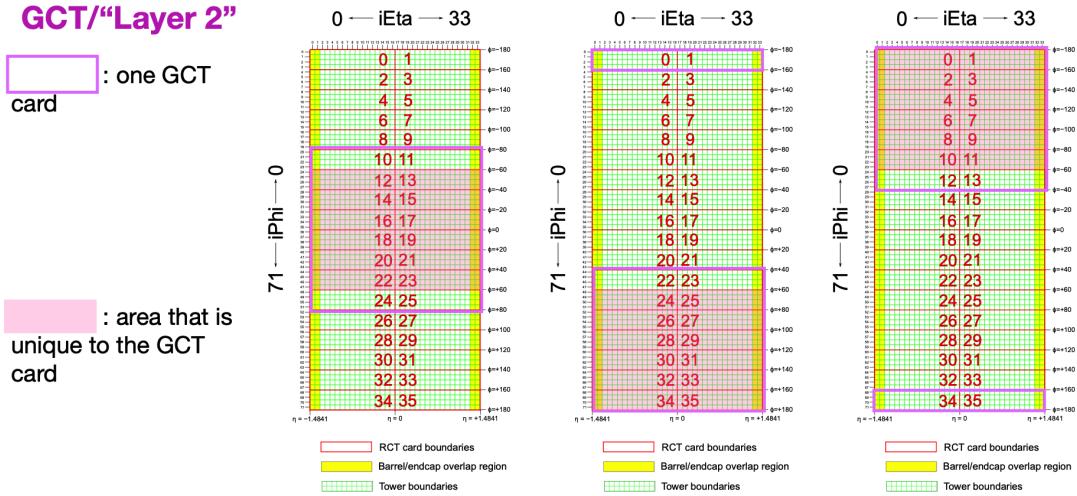


Figure 3.5: Schematic of the Phase-2 ECAL barrel in the Global Calorimeter Trigger (GCT), which will process the outputs of the Regional Calorimeter Trigger (RCT) in three cards (*magenta highlights*). Each card in the GCT processes the equivalent of sixteen RCT cards, with the center twelve being unique to that GCT card (*shaded pink*), and the remaining four processed in overlap with the other GCT cards.

3x4 barrel ECAL region

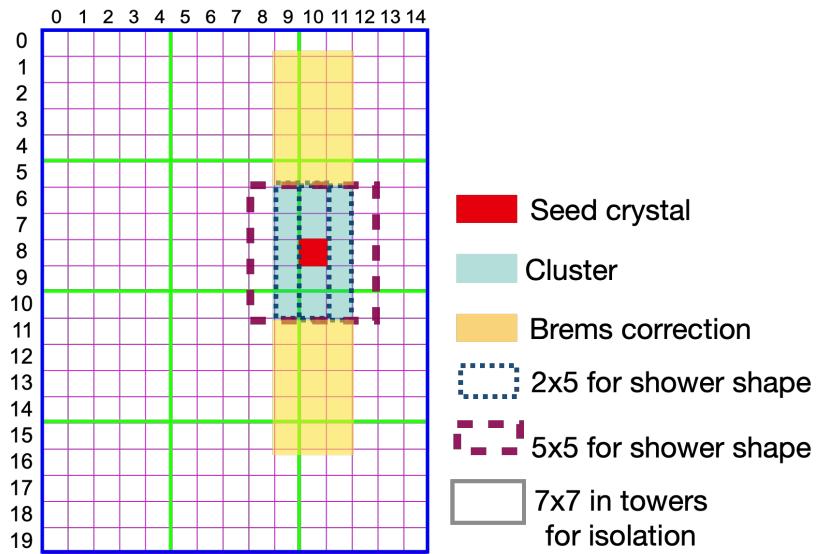


Figure 3.6: Illustration of an example electron/photon (e/γ) cluster in the Phase-2 Level-1 Trigger standalone barrel e/γ reconstruction, in a region of 15×20 crystals (3×4 towers). Each small pink square is one crystal, the highest-granularity ECAL trigger primitives available to the L1 Trigger in Phase-2. The core cluster consists of the energy sum in a 3×5 window of crystals, (*shaded light blue*) centered around the seed crystal (*red*). Bremsstrahlung corrections are checked in the adjacent 3×5 windows in the ϕ direction (*shaded light yellow*). The relative energies in windows of size 2×5 and 5×5 in crystals (*dashed dark blue and dark red*) are used to compute shower shape variables to identify true e/γ objects. Lastly, an isolation sum is computed in a window of size 7×7 in towers (not shown in figure).

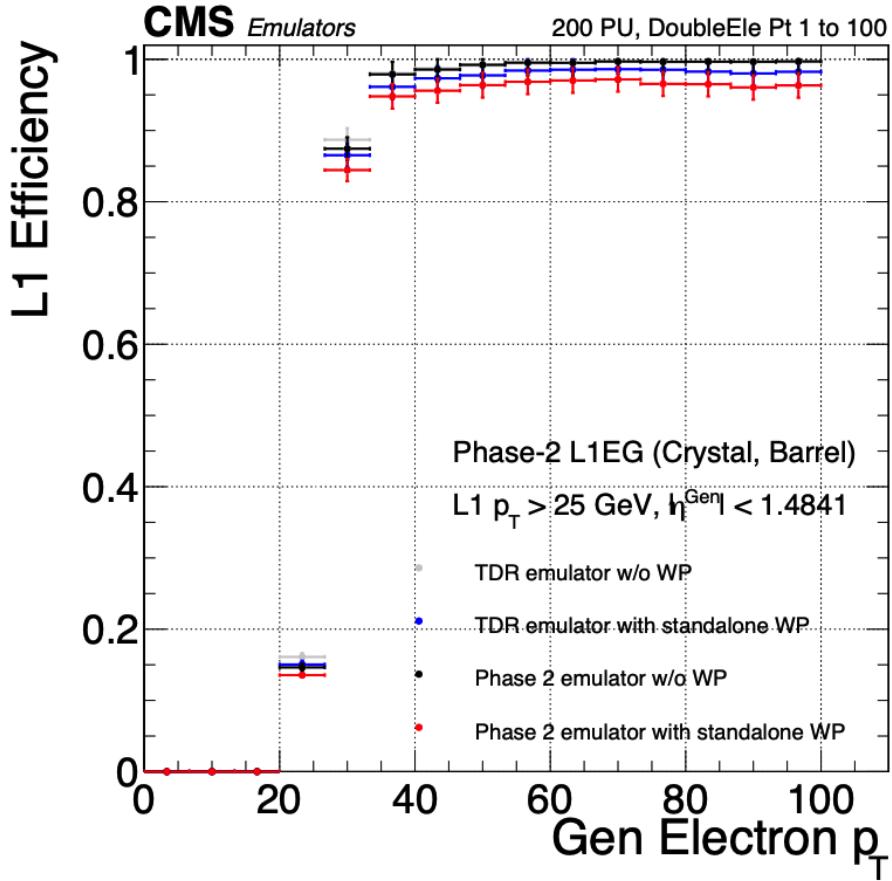


Figure 3.7: Efficiency of the standalone barrel e/γ reconstruction, measured in a simulated sample of electrons, as a function of the true electron’s transverse momentum p_T . The performance of the previous, idealized algorithm as shown in the 2021 Phase-2 TDR [35] with and without the isolation and shower shape discrimination variables (“standalone working point/ WP”) (*dark blue, grey*). The Phase-2 emulator discussed in this work with and without the same working point (*black, red*) is shown to have comparable performance.

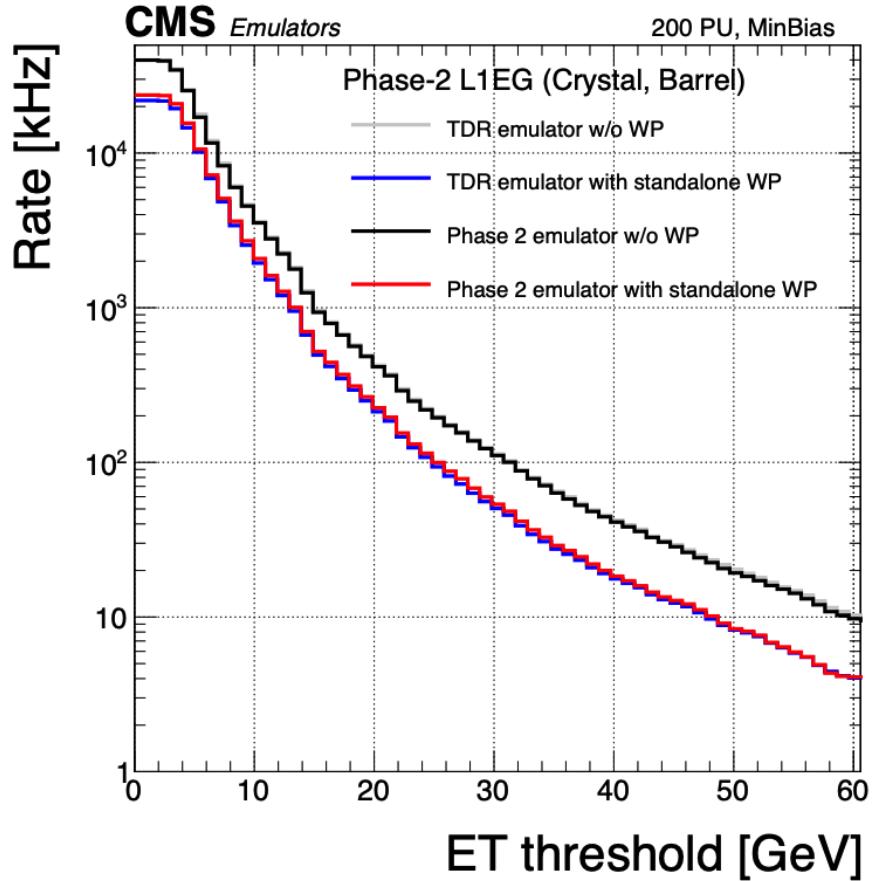


Figure 3.8: Rates of the standalone barrel e/γ reconstruction, evaluated on a minimum bias sample, measured as a function of the minimum energy (E_T) required of the reconstructed e/γ object in each event. The performance of the previous, idealized algorithm as shown in the 2021 Phase-2 TDR [35] with and without the isolation and shower shape discrimination variables (“standalone working point/ WP”) (*dark blue, grey*). The Phase-2 emulator discussed in this work with and without the same working point (*black, red*) is shown to have comparable performance.

1085 **Chapter 4**

1086 **Datasets and Monte Carlo samples**

1087 The search for the exotic decay of the 125 GeV Higgs boson to two light neutral scalars
1088 decaying to a pair of bottom quarks and a pair of tau leptons ($h \rightarrow aa \rightarrow bb\tau\tau$) is
1089 based on proton-proton collision data at a center-of-mass energy 13 TeV collected
1090 in Run-2 of data-taking, spanning the data-taking years 2016, 2017, and 2018. The
1091 datasets used and the triggers used to collect the data are described in Section 4.1.
1092 Section 4.2 describes the Monte Carlo simulated samples that are used to model the
1093 $h \rightarrow aa \rightarrow bb\tau\tau$ signal and background Standard Model processes. Lastly, in order
1094 to obtain a better description of Standard Model backgrounds that contain two tau
1095 leptons, a data-Monte Carlo hybrid technique is used to generate embedded samples
1096 which model processes with genuine $\tau\tau$ in the final state, as detailed in Section 4.3.

1097 **4.1 Datasets used**

1098 The $h \rightarrow aa \rightarrow bb\tau\tau$ analysis [37] is based on proton-proton collision data at a center-
1099 of-mass energy of 13 TeV collected in full Run-2 (2016-18) with the CMS detector.
1100 The data analyzed corresponds to a total integrated luminosity of 138 fb^{-1} (36.33 fb^{-1}
1101 for 2016, 41.53 fb^{-1} for 2017, and 59.74 fb^{-1} for 2018) [38] [39] [40]. The cumulative
1102 delivered and recorded luminosity versus time for 2015-2018 is shown in Fig. 4.1.

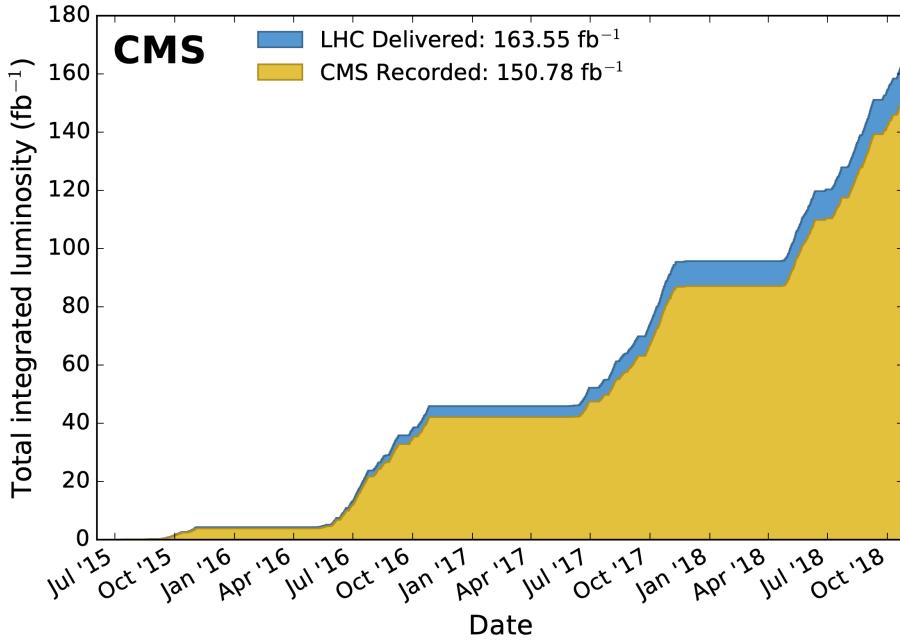


Figure 4.1: Cumulative delivered and recorded luminosity versus time for 2015-2018 at CMS, in proton-proton collision data only, at nominal center-of-mass energy [41].

1103 Data collected with the single muon trigger is used for the $\mu\tau_h$ channel. For the
 1104 $e\tau_h$ channel, data collected with the single electron trigger is used; and for the $e\mu$
 1105 channel, data collected with the electron + muon trigger is used. A more in-depth
 1106 discussion of the triggers used follows in a later section.

1107 A full list of samples used can be found in the full documentation [42] [37].

1108 4.2 Monte Carlo samples

1109 Modeling and computing observables originating from arbitrary physics processes at
 1110 the tree level and at next-to-leading order (NLO) is performed by Monte Carlo (MC)
 1111 event generators, such as Powheg and MadGraph5_amCNLO [43] [44]. The informa-
 1112 tion generated, e.g. the computation of the differential cross sections and kinematics
 1113 of the final state particles, is saved in a compressed file and used to generate MC

1114 samples that are used in physics analyses. The samples are digitized using GEANT4
1115 [45], a platform used at the LHC and other facilities to comprehensively simulate the
1116 passage of particles through matter. The digitized samples are passed through the
1117 same detector reconstruction as real data events collected in the detector.

1118 The samples for modeling the signal ($h \rightarrow aa \rightarrow 2b2\tau$ and $h \rightarrow a_1a_2$) in the
1119 2HDM+S and TRSM are generated at tree-level, for a range of masses of the light
1120 neutral scalar a . For $h \rightarrow aa$, the mass hypotheses for the a range from $m_a =$
1121 (12 GeV, 62.5 GeV). For $h \rightarrow a_1a_2$, the mass hypotheses for the two light scalars span
1122 combinations of m_{a1} , m_{a2} ranging from (12 GeV, 62.5 GeV) for the two scalars.

1123 4.3 Embedded samples

1124 An important background for Higgs boson studies and searches for additional Higgs
1125 bosons is the decay of Z bosons into pairs of τ leptons ($Z \rightarrow \tau\tau$). An embedded tech-
1126 nique was developed in the context of Standard Model Higgs to $\tau\tau$ measurements, to
1127 model $Z \rightarrow \tau\tau$ decays, and was expanded to also model all Standard Model processes
1128 that contain $\tau\tau$ [46]. The embedded technique has since been used successfully at
1129 CMS for the Standard Model $H \rightarrow \tau\tau$ measurement, as well as searches for minimal
1130 supersymmetric extensions to the Standard Model (MSSM) [47] [48].

1131 Fig. 4.2 shows a schematic of how embedded samples are produced. Data events
1132 containing $Z \rightarrow \mu\mu$ decays are selected. In these events, all energy deposits of the
1133 recorded muons are removed, and are replaced with simulated tau leptons with the
1134 same kinematic properties as the removed muons. This results in a hybrid data format
1135 containing information from both observed and simulated events, as illustrated in Fig.
1136 4.2 [46].

1137 In the selection step of the embedded technique, events are selected with at least
1138 one of a set of $\mu\mu$ trigger paths, which require $p_T > 17(8)$ GeV for the leading

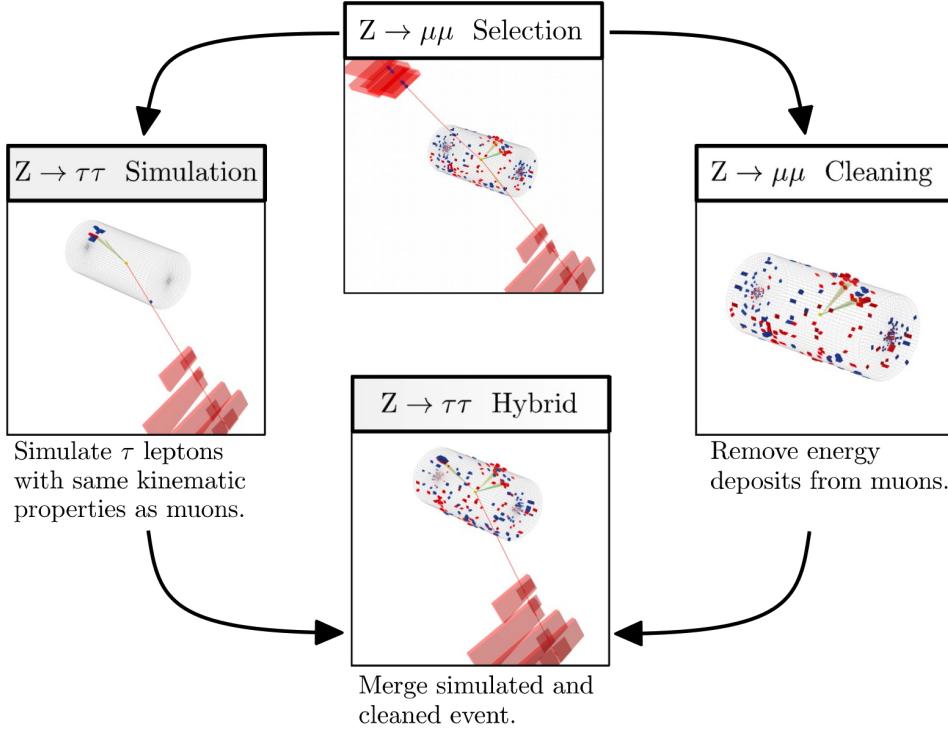


Figure 4.2: Schematic view of the four main steps of the embedding technique for τ leptons, as described in Section 4.3 [46]. A $Z \rightarrow \mu\mu$ event is selected in data ($Z \rightarrow \mu\mu$ selection), all of the energy deposits associated with the muons are removed ($Z \rightarrow \mu\mu$ cleaning), and two τ leptons and their decays are simulated in an empty detector ($Z \rightarrow \tau\tau$ simulation). Lastly, all energy deposits of the simulated τ decays are combined with the data event ($Z \rightarrow \tau\tau$ hybrid).

(sub-leading) muons, and a minimum requirement between 3.8 and 8.0 GeV on the invariant di-muon mass $m_{\mu\mu}$ [46]. The offline reconstructed muons must match the objects at trigger level and also have offline $p_T > 17(8)$ GeV. They must have $|\eta| < 2.4$ and be located at a distance $|d_z| < 0.2$ cm to the primary vertex along the beam axis. To form a Z boson candidate, each muon is required to originate from a global muon track. The muon pairs must have opposite charges with an invariant mass of $m_{\mu\mu} > 20$ GeV. If more than two di-muon pairs are found, the pair with the invariant mass closest to the Z boson mass (91.19 GeV) is chosen.

This selection is designed to be tight enough to ensure a high purity of genuine $\mu\mu$ events, and also loose enough to minimize biases of the embedded event samples. Isolation requirements are avoided, since they would introduce a bias towards less

hadronic activity in the vicinities of the embedded leptons that will appear more isolated than expected in data. The selection results in an expected mixture of events summarized in Table 4.1 from [46]. $Z \rightarrow \mu\mu$ is the dominant process modeled by the embedded technique, with $t\bar{t}$, QCD, and diboson and single top processes becoming more significant when considering events with b-tag jets.

Process	Fraction (%)		
	Inclusive	$m_{\mu\mu} > 70$ GeV	$N(\text{b-tag jets}) > 0$
$Z \rightarrow \mu\mu$	97.36	99.11	69.25
QCD	0.84	0.10	2.08
$t\bar{t}$	0.78	0.55	25.61
$Z \rightarrow \tau\tau$	0.71	0.05	0.57
Diboson, single t	0.17	0.17	2.35
W+jets	0.08	0.02	0.14

Table 4.1: Expected event composition after selecting two muons in the embedded technique [46], before additional cuts (i.e. inclusive, *column 2*), and after adding a requirement on the di-muon mass $m_{\mu\mu} > 70$ GeV (*column 3*), or a requirement on the number of b-tag jets in the event (*column 4*).

The advantage of the embedded technique is that aspects of the event that are difficult to model and describe are directly taken from data, resulting in a better data description than can be achieved with only the $Z \rightarrow \tau\tau$ simulation [46]. The simulation must be tuned extensively to accurately model aspects of the data, such as time-dependent pileup profiles, the production of additional jets, e.g. in multijet and vector boson fusion topologies, the number of reconstructed primary interaction vertices, and the missing transverse momentum p_T^{miss} . Since all events with genuine $\tau\tau$ are estimated with samples made with the embedded technique (referred to as embedded samples from here on), events in Monte Carlo simulation with genuine $\tau\tau$ are not used, in order to avoid double-counting.

¹¹⁶⁵ **Chapter 5**

¹¹⁶⁶ **Object reconstruction and**
¹¹⁶⁷ **corrections applied**

¹¹⁶⁸ In the data processing workflow, data events and simulated events are analyzed to
¹¹⁶⁹ reconstruct physics objects of interest, and algorithms for distinguishing genuine par-
¹¹⁷⁰ ticle candidates from background, are employed. Section 5.1 describes the physical
¹¹⁷¹ properties of the most important objects in the $h \rightarrow aa \rightarrow bb\tau\tau$ analysis: taus,
¹¹⁷² muons, electrons, jets, and jets originating from b-quarks (b-flavor jets), as well as
¹¹⁷³ their reconstruction and identification in CMS. In this analysis, the full energy and
¹¹⁷⁴ momentum of the two tau leptons ($m_{\tau\tau}$) is estimated from the measured (i.e. visible)
¹¹⁷⁵ components of the tau leptons using the SVFit/FastMTT algorithm, which is de-
¹¹⁷⁶ scribed in Section 5.2. Corrections are applied to the simulated samples at the object
¹¹⁷⁷ level and the event level to account for known discrepancies between simulations and
¹¹⁷⁸ the data that the simulations are intended to model. These corrections are listed and
¹¹⁷⁹ detailed in Section 5.3.

₁₁₈₀ **5.1 Object reconstruction**

₁₁₈₁ **5.1.1 Taus**

₁₁₈₂ The tau (τ) is the heaviest known lepton. With a rest mass of 1776.86 MeV, it can
₁₁₈₃ decay to not only electrons and muons, but also hadrons. The mean lifetime of the τ
₁₁₈₄ is $\tau = 290 \times 10^{-15}$ seconds, corresponding to $c\tau = 87.03 \mu\text{m}$, which is short enough
₁₁₈₅ that taus decay in the CMS detector before reaching the detector elements.

₁₁₈₆ In two thirds of the cases, τ leptons decay hadronically, typically into one or three
₁₁₈₇ charged mesons (predominantly π^+ , π^-), often accompanied by neutral pions (that
₁₁₈₈ decay $\pi^0 \rightarrow \gamma\gamma$), and a ν_τ . These hadronic decays are denoted τ_h . In the remainder of
₁₁₈₉ the decays, the tau decays to the lighter leptons (electron or muon), termed leptonic
₁₁₉₀ decays. In all cases, at least one neutrino is produced, resulting in missing transverse
₁₁₉₁ energy in the CMS detector. The tau's largest decay branching ratios (proportional
₁₁₉₂ to probability of decay) are listed below [26]:

- ₁₁₉₃ • 17.8% decay to $e^- \bar{\nu}_e \nu_\tau$
- ₁₁₉₄ • 17.4% decay to $\mu^- \bar{\nu}_\mu \nu_\tau$
- ₁₁₉₅ • 25.5% decay to $\pi^- \pi^0 \nu_\tau$ (ρ^- resonance at 770 MeV)
- ₁₁₉₆ • 10.8% decay to $\pi^- \nu_\tau$
- ₁₁₉₇ • 9.3% decay to $\pi^- \pi^0 \pi^0 \nu_\tau$ (a_1^- resonance at 1200 MeV)
- ₁₁₉₈ • 9.0% decay to $\pi^- \pi^- \pi^+ \nu_\tau$ (a_1^- resonance at 1200 MeV)

₁₁₉₉ The neutrinos escape undetected from the CMS detector and are not considered
₁₂₀₀ in the reconstruction. Charged hadrons leave tracks in the tracking detector before
₁₂₀₁ being absorbed in the hadronic calorimeter; in CMS tau reconstruction terminology,
₁₂₀₂ they are often called “prongs”, i.e. the dominant τ_h decay modes are termed “1 prong”

1203 (π^\pm) , “1 prong + π^0 (s)”, and “3-prong”. Neutral pions decay to two photons which
1204 lose their energy in the electromagnetic calorimeter. Taus that decay to electrons
1205 and muons, are typically triggered on and reconstructed as electrons and muons
1206 respectively.

1207 **Hadron plus strips (HPS) reconstruction of τ_h**

1208 At CMS, hadronically decaying tau leptons are reconstructed with the hadron plus
1209 strips (HPS) algorithm [49] [50]. The HPS algorithm capitalizes on photon conversions
1210 in the CMS tracker material, which originate from the neutral pion (π^0) decaying
1211 to two photons. The bending of electron/positron tracks due to the CMS solenoid
1212 magnetic field leads to a spread of the neutral pions’ calorimeter signatures in the ϕ
1213 direction. This motivates the reconstruction of photons in “strips”: objects that are
1214 built out of PF photons and electrons. The strip reconstruction starts with centering
1215 a strip on the most energetic electromagnetic particle in a PF jet. Among other
1216 electromagnetic particles located in a window of size $\Delta\eta = 0.05$ and $\Delta\phi = 0.20$
1217 around the strip center, the most energetic one is associated with the strip and its
1218 momentum is added to the strip momentum. This is repeated iteratively until no
1219 further particles can be associated. Lastly, strips satisfying a requirement of $p_T^{\text{strip}} > 1$
1220 GeV are combined with charged hadrons to reconstruct individual τ_h decay modes,
1221 where h stands for both π and K :

- 1222 • *Single hadron:* $h^- \nu_\tau$ and $h^- \pi^0 \nu_\tau$ decay modes, in which the neutral pions have
1223 too little energy to be reconstructed as strips.
- 1224 • *One hadron + one strip:* $h^- \pi^0 \nu_\tau$ decay modes, where the photons from the π^0
1225 decay are close together in the calorimeter.
- 1226 • *One hadron + two strips:* $h^- \pi^0 \nu_\tau$ decay modes, where the photons from the π^0
1227 decay are well separated.

- 1228 • *Three hadrons:* $h^-h^+h^-\nu_\tau$ decay modes. The three charged hadrons are re-
1229 quired to originate from the same secondary vertex.

1230 The $h^-\pi^0\pi^0\nu_\tau$ and $h^-h^+h^-\pi^0\nu_\tau$ decay modes do not have their own treatment are
1231 reconstructed with the above topologies.

1232 In the HPS algorithm, the direction of the reconstructed tau momentum \vec{p}^{τ_h}
1233 is required to fall within a distance of $\Delta R = 0.1$ from the original PF jet. All
1234 charged hadrons and strips are required to be contained within a cone of size $\Delta R =$
1235 $(2.8 \text{ GeV})/p_T^{\tau_h}$, from the τ_h as reconstructed by the HPS.

1236 All charged hadrons are assumed to be pions, and they are required to be consis-
1237 tent with the masses of the intermediate meson resonances (if applicable), with the
1238 following allowed windows for candidates: 50-200 MeV for π^0 , 0.3-1.3 GeV for ρ , and
1239 0.8-1.5 GeV for a_1 . If the τ_h decay is compatible with more than one hypothesis, the
1240 one giving the highest $p_T^{\tau_h}$ is chosen. Lastly, an isolation requirement is applied: aside
1241 from the τ_h decay products, no charged hadrons or photons can be present within
1242 an isolation cone of size $\Delta R = 0.5$ around the direction of the τ_h . The outputs of
1243 the HPS algorithm are the reconstructed decay mode and the visible four-momentum
1244 (i.e. the four-momenta of all decay products excluding the neutrinos).

1245 **DeepTau for identifying τ_h**

1246 The identification of τ_h candidates in CMS has historically been divided into separate
1247 discriminators against jets, electrons, and muons. Discriminators versus jets and
1248 electrons use information from derived quantities, such as the p_T sum of particles
1249 near the τ_h axis. Building on the previous multivariate analysis (MVA) classifier [51]
1250 based on a boosted decision tree (BDT), DeepTau is a more recent classifier based on a
1251 deep neural network (DNN) that simultaneously discriminates against jets, electrons,
1252 and muons. The DNN uses a combination of high-level inputs, similar to previous
1253 algorithms, and also uses convolutional layers in η - ϕ space to process information

1254 from all reconstructed particles near the τ_h axis. Convolutional layers are based on
1255 the principle that an image can be processed independently of its position.

1256 The final DeepTau discriminators against jets, muons, and electrons are given by

$$D_\alpha(y) = \frac{y_\tau}{y_\tau + y_\alpha} \quad (5.1)$$

1257 where y_τ (y_α) are estimates of the probabilities for the τ_h candidate to come from
1258 a genuine τ_h (jet, μ , e). Working points for each discriminator with different τ_h
1259 identification efficiencies are defined for D_e , D_μ , and D_{jet} , for usage in physics analyses
1260 and derivation of data-to-simulation corrections [52].

1261 5.1.2 Muons

1262 Muons are the next lightest lepton after taus, with a mass of 105.66 MeV and a
1263 mean lifetime of $\tau = 2.20 \times 10^{-6}$ seconds, or $c\tau = 658.64$ m. At CMS, muons are
1264 identified with requirements on the quality of the track reconstruction and on the
1265 number of measurements in the tracker and the muon systems [53]. In the standard
1266 CMS reconstruction, tracks are first reconstructed independently in the inner tracker
1267 (tracker track) and in the muon system (standalone-muon track). Next, these tracks
1268 are processed in two different methods.

1269 The first is Global Muon reconstruction (outside-in) [53], which fits combined hits
1270 from the tracker track and standalone-muon track, using the Kalman-filter technique.
1271 At large transverse momenta, $p_T \gtrsim 200$ GeV, the global-muon fit can improve the
1272 momentum resolution compared to the tracker-only fit.

1273 The second is Tracker Muon reconstruction (inside-out) [53], which starts with
1274 tracker tracks with $p_T > 0.5$ GeV and total momentum $p_T > 2.5$ GeV. These tracks
1275 are extrapolated outwards to the muon system and matched to detector segments
1276 there, taking into account the magnetic field, expected energy losses, and multiple

1277 Coulomb scattering in the detector material. Tracker Muon reconstruction is more
 1278 efficient than the Global Muon reconstruction at low momenta, $p \lesssim 5$ GeV, because
 1279 it only requires a single muon segment in the muon system, whereas Global Muon
 1280 reconstruction typically requires segments in at least two muon stations.

1281 To further suppress fake muons from decay in flight, isolation cuts are used. A
 1282 relative isolation variable is defined to quantify the energy flow of particles near the
 1283 muon trajectory. A relative isolation is defined similarly for muons and electrons:

$$I^\ell \equiv \frac{\sum_{\text{charged}} p_T + \max(0, \sum_{\text{neutral}} p_T - \frac{1}{2} \sum_{\text{charged, PU}} p_T)}{p_T^\ell} \quad (5.2)$$

1284 where $\sum_{\text{charged}} p_T$ is the scalar sum of the p_T of the charged particles originating from
 1285 the primary vertex and located in a cone of size $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4(0.3)$
 1286 centered on the direction of the muon (electron). The sum $\sum_{\text{neutral}} p_T$ is the equivalent
 1287 for neutral particles. The sum $\sum_{\text{charged, PU}} p_T$ is the scalar sum of the p_T of the
 1288 charged hadrons in the cone originating from pileup vertices. The factor 1/2 comes
 1289 from simulation estimations, which find that the ratio of neutral to charged hadron
 1290 production in the hadronization process of inelastic pp collisions is 1/2. Thus the
 1291 subtracted term is intended to subtract contribution from pileup, from the neutral
 1292 particle contribution to the isolation sum. Finally, this is divided by the lepton
 1293 transverse momentum, p_T^ℓ .

1294 **5.1.3 Electrons**

1295 Electrons are the lightest lepton with a mass of 0.511 MeV. At CMS, electrons are
 1296 reconstructed by associating a track reconstructed in the silicon tracking detector
 1297 with a cluster of energy in the ECAL. Performance is maximized via a combination
 1298 of a stand-alone approach and the complementary global particle-flow approach [54].

1299 In the stand-alone approach, the electron energy, which is typically spread over

1300 several crystals of the ECAL, is clustered with the “hybrid” algorithm in the barrel
1301 and the “multi- 5×5 ” in the endcaps [54]. The hybrid algorithm collects energy in a
1302 small window in η and an extended window in ϕ . It identifies a seed crystal, and adds
1303 arrays of 5×1 crystals in $\eta \times \phi$ in a range of $N = 17$ crystals in both directions of
1304 ϕ , if their energies exceed a minimum threshold, thus forming a supercluster (SC). In
1305 the endcap, crystals are not arranged in an $\eta \times \phi$ geometry; instead clusters are build
1306 around seed crystals in clusters of 5×5 crystals that can partly overlap. Nearby
1307 clusters are grouped into a supercluster, and energy is recovered from associated
1308 deposits in the preshower.

1309 In the PF reconstruction [54], PF clusters are reconstructed by aggregating around
1310 a seed all contiguous crystals with energies two standard deviations above the elec-
1311 tronic noise observed at the beginning of a data-taking run. The energy of a given
1312 crystal can be shared among two or more clusters.

1313 The electron track reconstruction is performed in two ways [54]: the ECAL-based
1314 seeding, which begins with the SC energy and positioning, and the tracker-based
1315 seeding (part of the PF reconstruction algorithm), which uses tracks reconstructed
1316 from the general algorithm for charged particles, extrapolated towards the ECAL and
1317 matched to an SC. Kalman filter (KF) tracks with a small number of hits or that are
1318 not well-fitted, are re-fitted with a dedicated Gaussian sum Filter (GSF).

1319 A global identification variable [54] is defined using a multivariate analysis (MVA)
1320 technique that combines information on track observables (kinematics, quality of the
1321 KF track and GSF track), the electron PF cluster observables (shape and pattern),
1322 and the association between the two (geometric and kinematic observables). For
1323 electrons seeded only through the tracker-based approach, a weak selection is applied
1324 on this MVA variable. For electrons seeded through both approaches, a logical OR is
1325 taken.

1326 Electron isolation, i.e. the presence of energy deposits near the electron trajectory,

1327 is a separate key handle in rejecting significant background. Compared to isolated
 1328 electrons, electrons from misidentified jets or genuine electrons within a jet resulting
 1329 from semileptonic decays of b or c quarks tend to have significant energy deposits
 1330 near the primary trajectory [54]. Offline analyses benefit from the PF technique
 1331 for defining isolation, which sums the PF candidates reconstructed located within a
 1332 specified isolation cone around the electron candidate, as in Eqn. 5.2.

1333 5.1.4 Jets

1334 The vast majority of processes of interest at the LHC contains quarks or gluons in
 1335 the final state, but these particles cannot be observed directly. In a process called
 1336 hadronization, they fragment into spatially-grouped collections of particles called jets,
 1337 which can be detected in the tracking and calorimeter systems. Hadronization and
 1338 the subsequent decays of unstable hadrons can produce hundreds of nearby particles
 1339 in the CMS detector. Jets are reconstructed by the PF algorithm (PF jets), or from
 1340 the sum of the ECAL and HCAL energies deposited in the calorimeter towers (Calo
 1341 jets). In PF jets, typically used in offline analyses, jets are built using the anti- k_T
 1342 (AK) clustering algorithm [55]. The anti- k_T algorithm iterates over particle pairs and
 1343 finds the two that are closest in a distance measure d , and determines whether to
 1344 combine them:

$$d_{ij} = \min(p_{T,i}^{-2}, p_{T,j}^{-2}) \frac{\Delta_{ij}^2}{R^2}, \text{ combine when } d_{ij} < p_{T,i}^{-2}; \text{ stop when } d_{ij} > p_{T,i}^{-2} \quad (5.3)$$

1345 where $\Delta_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$ and $p_{T,i}$, η_i , ϕ_i are the transverse momentum, rapid-
 1346 ity, and azimuthal angle of particle i . The power -2 means that higher-momentum
 1347 particles are clustered first, leading to jets that tend to be centered on the hardest
 1348 (highest p_T) particle.

1349 There are several methods to remove contributions of pileup collisions from jet

1350 clustering [56]:

- 1351 • Charged hadron subtraction (CHS), which removes all charged hadron candi-
1352 dates associated with a track that is not associated with the primary vertex.
- 1353 • PileUp Per Particle Identification (PUPPI), which weighs input particles based
1354 on their likelihood of arising from pileup. QCD particles tend to have a collinear
1355 structure, compared to soft diffuse radiation coming from pileup. The local
1356 shape for charged pileup, used as a proxy for all pileup particles, is used on an
1357 event-by-event basis to calculate a weight for each particle. PUPPI is deployed
1358 in Run-2 and is more performant than CHS in high pileup scenarios.

1359 5.1.5 B-flavored jets

1360 Jets that arise from bottom-quark hadronization (b-flavor jets) have overwhelming
1361 background from processes involving jets from gluons (g) and light-flavor quarks (u, d,
1362 s), and from c-quark fragmentation. The ability to identify b-flavor jets, or b-tagging,
1363 exploits the b hadrons' relatively large masses, long lifetimes, and daughter particles
1364 with hard momentum spectra [55].

1365 The impact parameter (IP) of a track is the 3-dimensional distance between the
1366 track and the primary vertex (PV) at the point of closest approach. The IP is positive
1367 if the track originates from the decay of particles travelling along the jet axis. The
1368 resolution of the IP depends on the p_T and η of the track, motivating the use of the
1369 impact parameter significance S_{IP} (ratio of the IP to its estimated uncertainty) as an
1370 observable [55].

1371 Because of the large but finite lifetimes of the b hadrons, b hadrons tend to
1372 travel a short distance before decaying at a secondary vertex (SV), which can be
1373 measured and reconstructed separately from the primary vertex due to the excellent
1374 position resolution of the pixel detector [55]. Previous b-tagging algorithms (e.g.

1375 CSV, cMVAv2, and DeepCSV) have capitalized on variables such as the presence of
1376 a SV, the flight distance and direction (computed from the vector between the PV
1377 and the SV), and kinematics of the system of associated secondary tracks (e.g. track
1378 multiplicity, mass, and energy).

1379 The DeepJet (formerly known as DeepFlavour) algorithm [57] is a deep-neural-
1380 network multi-classification algorithm, which uses 16 properties of up to 25 charged
1381 and 6 properties of 25 neutral particle-flow jet constituents, as well as 17 properties
1382 from up to 4 secondary vertices associate with the jet. Compared to the previous clas-
1383 sifying algorithm DeepCSV, DeepJet has been demonstrated to have higher efficiency
1384 with lower misidentification probability in Phase-1 data [58].

1385 5.2 Reconstruction of the $\tau\tau$ mass

1386 The final signal extraction is done to the total $\tau\tau$ mass, which is estimated from the
1387 visible $\tau\tau$ mass using the FastMTT algorithm [59]. FastMTT is based on the SVFit
1388 algorithm, originally developed for the Standard Model $H \rightarrow \tau\tau$ analysis [60]. Both
1389 the SVFit algorithms, and the FastMTT algorithm, are described below, to give a
1390 complete picture of how tau decays are parameterized.

1391 To specify a hadronic τ decay, six parameters are needed [60]: the polar and
1392 azimuthal angles of the visible decay product system in the τ rest frame, the three
1393 boost parameters from the τ rest frame to the laboratory frame, and the invariant
1394 mass m_{vis} of the visible decay products. For a leptonic τ decay, two neutrinos are
1395 produced, and a seventh parameter, the invariant mass of the two-neutrino system, is
1396 necessary. The unknown parameters are constrained by four observables that are the
1397 components of the four-momentum of the system formed by the visible decay products
1398 of the τ lepton, measured in the laboratory frame. The remaining unconstrained
1399 parameters for hadronic and leptonic τ decays are thus:

- 1400 • The fraction of the τ energy in the laboratory frame carried by the visible decay
 1401 products,
- 1402 • ϕ , the azimuthal angle of the τ direction in the laboratory frame,
- 1403 • $m_{\nu\nu}$, the invariant mass of the two-neutrino system in leptonic τ decays (for
 1404 hadronic τ decays, $m_{\nu\nu}$ is set to 0).

1405 E_x^{miss} and E_y^{miss} , the x and y components of the missing transverse energy E_T^{miss}
 1406 provide two further constraints.

1407 5.2.1 Original SVFit ‘‘standalone’’: maximum likelihood

1408 In one of the original versions of SVFit, called ‘‘standalone’’ SVFit [60], a maximum
 1409 likelihood fit method is used to reconstruct the mass $m_{\tau\tau}$ by combining the measured
 1410 observables E_x^{miss} and E_y^{miss} with a likelihood model that includes terms for the τ
 1411 decay kinematics and the E_T^{miss} resolution [60]. The likelihood function $f(\vec{z}, \vec{y}, \vec{a}_1 \vec{a}_2)$
 1412 of the parameters $\vec{z} = (E_x^{\text{miss}}, E_y^{\text{miss}})$ in an event is constructed, where the remaining
 1413 parameters are the kinematics of the two τ decays, denoted $\vec{a}_1 = (x_1, \phi_1, m_{\nu\nu,1})$ and
 1414 $\vec{a}_2 = (x_2, \phi_2, m_{\nu\nu,2})$, and the four-momenta of the visible decay products with the
 1415 measured values $\vec{y} = (p_1^{\text{vis}}, p_2^{\text{vis}})$.

1416 The likelihood f is the product of three likelihood functions. The first two likeli-
 1417 hood functions model the decay parameters \vec{a}_1 and \vec{a}_2 of the two τ leptons. For lep-
 1418 tonic decays, the likelihood function is modeled using matrix elements for τ decays,
 1419 and integrated over the allowed phase space $0 \leq x \leq 1$ and $0 \leq m_{\nu\nu} \leq m_\tau \sqrt{1-x}$. For
 1420 hadronic τ decays, a model based on the two-body phase space is used and integrated
 1421 over $m_{\text{vis}}^2/m_{\tau\tau}^2 \leq x \leq 1$. The third likelihood function quantifies the compatibility of
 1422 a τ decay hypothesis with the reconstructed \vec{E}_T^{miss} in an event, assuming the neutrini-
 1423 nos are the only source of missing transverse energy. The expected \vec{E}_T^{miss} resolution

1424 is represented by a covariant matrix, estimated on an event-by-event basis using a
1425 significance algorithm [61].

1426 5.2.2 “Classic SVFit” with matrix element

1427 Classic SVFit is an improved algorithm of the original “standalone” SVFit using the
1428 formalism of the matrix element (ME) method [59]. In the ME method, an estimate
1429 for the unknown model parameter Θ (here, the mass $m_{\tau\tau}$) is obtained by maximizing
1430 the probability density \mathcal{P} . The key ingredients of the probability density are the
1431 squared modulus of the matrix element $|\mathcal{M}(\mathbf{p}, \Theta)|^2$ and the transfer function $W(\mathbf{y}|\mathbf{p})$
1432 (probability density to observe the measured observables \mathbf{y} given the phase space
1433 point \mathbf{p}). The best estimate $m_{\tau\tau}$ is obtained by computing the probability density \mathcal{P}
1434 for a range of mass hypotheses and finding the value of $m_{\tau\tau}$ that maximizes \mathcal{P} .

1435 Distributions illustrating the performance of the classic matrix element SVFit
1436 algorithm are shown in Fig. 5.1 from [59], showing the di-tau mass after and before
1437 application of SVFit to recover energy lost to neutrinos. The SVFit algorithm is
1438 found to improve the sensitivity of the Standard Model $H \rightarrow \tau\tau$ analysis performed
1439 by CMS by about 30%, compared to performing the same analysis using only the
1440 visible mass m_{vis} .

1441 5.2.3 FastMTT: optimized SVFit

1442 FastMTT [62] is a further simplification to the matrix element method of Classic
1443 SVFit which has comparable performance but is about 100 times faster. FastMTT
1444 drops the matrix element component of the computation without significant impact
1445 on the final mass resolution, and simplifies the computation of the transfer functions.
1446 The opening angle of the τ decay products with respect to the initial τ momenta ap-
1447 proaches 0 for τ with high $\gamma = E_\tau/m_\tau$, with typical τ decays from the Z boson decays
1448 already satisfying this condition. In this collinear approximation, the dimensionality

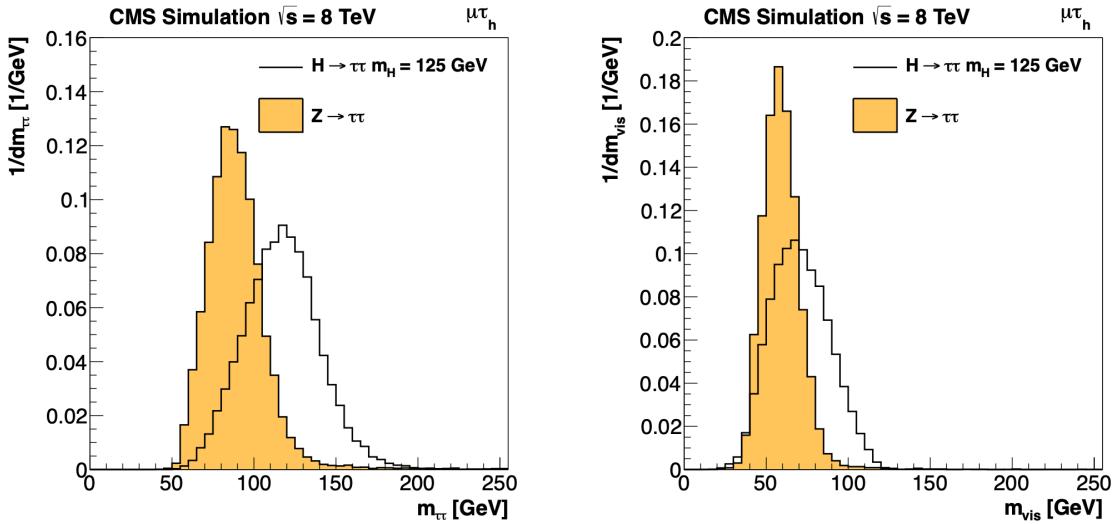


Figure 5.1: Distributions from [59], of $m_{\tau\tau}$ after reconstruction with the original SVFit algorithm (*left*), and before SVFit with only the visible tau decay products (*right*), for $H \rightarrow \tau\tau$ signal events of mass $m_H = 125$ GeV (*black line*) and the $Z/\gamma^* \rightarrow \tau\tau$ background (*orange, solid*), in the decay channel $\tau\tau \rightarrow \mu\tau_h$.

1449 of the transfer function can be reduced in the computation of FastMTT, while still
1450 yielding similar results to Classic SVFit [62].

1451 5.3 Corrections applied to simulation

1452 Corrections are applied to simulated samples to account for known effects in the event
1453 modeling and reconstruction and data-taking, and are intended to bring simulations
1454 in closer agreement with data. Corrections fall into two broad categories: *energy*
1455 *scale corrections* applied to physics objects, and *event-level corrections*. Energy scale
1456 corrections are multiplicative factors applied to the energy and transverse momentum
1457 p_T of simulated objects (e.g. leptons or jets), and bring the average reconstructed en-
1458 ergies of simulated particles into better agreement with those of objects reconstructed
1459 from data. Event-level corrections are applied as a per-event multiplicative weight,
1460 and account for effects such as mis-modeling in simulations of the underlying physics
1461 process, or changing detector operating conditions during data-taking. Event-level

1462 corrections change the shapes of the distributions of all the physical observables.

1463 Uncertainties in scale factors and corrections are also sources of systematic errors
1464 in the analysis, detailed in Chapter 8. Systematic uncertainties in the tau, muon, and
1465 electron energy scales can shift the p_T of the leptons up or down, which can change
1466 whether events pass or fail the offline p_T thresholds for the trigger paths described in
1467 the previous section, i.e. change the number of events in the signal region.

1468 5.3.1 Tau energy scale

1469 An energy scale is applied to the transverse momentum p_T and mass of the hadronic
1470 tau τ_h in the $\mu\tau_h$ and $e\tau_h$ channels, to correct for a deviation of the average recon-
1471 structed τ_h energy from the generator-level energy of the visible τ_h decay products.
1472 These correction factors are derived centrally [51], by fitting to events in $e\tau_h$ and $\mu\tau_h$
1473 final states in Z/γ^* events separately for the h^\pm , $h^\pm\pi^0$, and $h^\pm h^\mp h^\pm$ decays. The
1474 values used are shown in Table 5.1.

1475 When applying the energy scale to the τ_h , the 4-momentum of the missing trans-
1476 verse energy (MET) is adjusted such that the total 4-momenta of the τ_h and the MET
1477 remains unchanged [63].

Tau energy scale factor				
Decay mode	2018	2017	2016 pre-VFP	2016 post-VFP
0	0.991 ± 0.008	0.986 ± 0.009	0.987 ± 0.01	0.993 ± 0.009
1	1.004 ± 0.006	0.999 ± 0.006	0.998 ± 0.006	0.991 ± 0.007
10	0.998 ± 0.007	0.999 ± 0.007	0.984 ± 0.008	1.001 ± 0.007
11	1.004 ± 0.009	0.996 ± 0.01	0.999 ± 0.011	0.997 ± 0.016

Table 5.1: Energy scales applied to genuine hadronic tau decays τ_h by data-taking year/era and decay mode, along with systematic errors.

1478 **5.3.2 Muon energy scale**

1479 An energy scale is applied to the p_T and mass of genuine muons from τ decays in the
1480 $e\mu$ and $\mu\tau_h$ channels [64]. The applied values are the same for MC and embedded
1481 samples and are shown in Table 5.2. Following the SM $H \rightarrow \tau\tau$ analysis, Rochester
1482 corrections are not applied, and instead prescriptions from [65] are followed.

Muon energy scale factor	
Eta range	Value for all years
$ \eta \in [0.0, 1.2)$	1.0 ± 0.004
$ \eta \in [1.2, 2.1)$	1.0 ± 0.009
$ \eta \in [2.1, 2.4)$	1.0 ± 0.027

Table 5.2: Energy scales and systematic errors applied to genuine muons. The values are the same for MC and embedded for all years [66] [65].

1483 **5.3.3 Electron energy scale**

1484 Corrections to the electron energy scale are applied to genuine e from τ decays, and
1485 are binned in two dimensions by electron p_T and η for barrel vs. endcap [67]. The
1486 scale factors are binned in p_T and η for MC samples: e.g. values for 2018 are shown
1487 in Fig. 5.2 from [68]. For embedded samples the electron energy scale is taken as
1488 only binned in η (Table 5.3).

Electron energy scale factor for embedded samples			
Eta range	2018	2017	2016
$ \eta \in [0.0, 1.479)$	0.973 ± 0.005	0.986 ± 0.009	0.9976 ± 0.0050
$ \eta \in [1.479, 2.4)$	0.980 ± 0.0125	0.887 ± 0.0125	0.993 ± 0.0125

Table 5.3: Energy scales and systematic errors applied to electrons in embedded samples, binned in the electron η , by data-taking year [69] [70] [71].

1489 **5.3.4 τ_h identification efficiency**

1490 The τ_h identification efficiency can differ in data and MC [63]. Recommended correc-
1491 tions are provided by the Tau POG, and we use the medium DeepTau vs. jet working

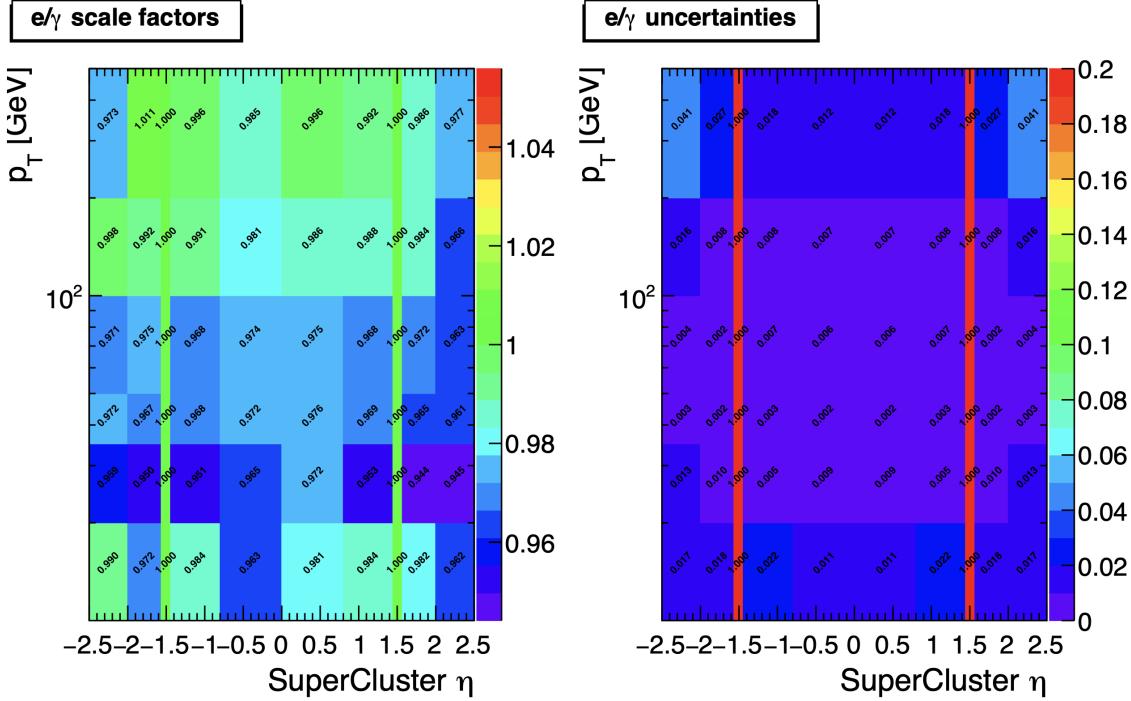


Figure 5.2: Electron/photon energy scale factors (*left*) and corresponding uncertainties (*right*) binned in the electron η and p_T , for the data-taking year 2018 [68].

¹⁴⁹² point values. The identification efficiency is measured in $Z \rightarrow \tau\tau$ events in the $\mu\tau_h$
¹⁴⁹³ final state, and is binned in p_T due to clear p_T dependence of the DeepTau ID.

Tau ID efficiency for DeepTau Medium vs. jet WP in 2018						
p_T (GeV)	< 20	(20, 25]	(25, 30]	(30, 35]	(35, 40]	(40, 500]
Central value	0	0.945	0.946	0.916	0.921	1.005
Up value	0	1.001	0.981	0.946	0.950	1.035
Down value	0	0.888	0.981	0.883	0.893	0.953

Table 5.4: Tau ID efficiency for the DeepTau vs. jet medium working point, with central, up, and down values for 2018, binned in the tau p_T [63].

¹⁴⁹⁴ 5.3.5 Trigger efficiencies

¹⁴⁹⁵ Scale factors are applied to correct for differences in trigger efficiencies between MC
¹⁴⁹⁶ and embedded vs. data, with values taken from tools provided by the Standard Model
¹⁴⁹⁷ $H \rightarrow \tau\tau$ working group which uses the same trigger paths [66]. In the following

1498 sections we review relevant trigger efficiencies in data, which form the basis of the
1499 trigger efficiency corrections applied to MC and embedded.

1500 **5.3.6 Tau trigger efficiencies**

1501 The efficiencies in data of the single- τ_h leg in $\mu\tau_h$, $e\tau_h$, and di- τ_h triggers is computed
1502 centrally per using a Tag and Probe (TnP) method [72] which is outlined here. In
1503 this method, $Z \rightarrow \tau\tau \rightarrow \mu\tau_h$ are selected in data and a Drell-Yan simulated sample
1504 ($Z \rightarrow \ell\ell, \ell = e, \mu, \tau_h$) with high purity. Cuts are applied to reject events not in this
1505 final state, e.g. suppressing $Z \rightarrow \mu\mu$ by vetoing events with a single loose ID muon.
1506 An isolated muon candidate (the tag) with online $p_T > 27$ GeV and $|\eta| < 2.1$ is
1507 identified and matched to an offline μ . An offline τ_h candidate (the probe) is selected,
1508 which is separated from the tag μ , and has $p_T > 20$ GeV and $|\eta| < 2.1$. The probe
1509 τ_h must pass anti-muon and anti-electron discriminators to avoid fakes from muons
1510 and electrons, and must pass the medium MVA tau isolation to suppress fakes from
1511 QCD jets. The trigger efficiency in the TnP method is calculated as

$$\text{Efficiency} = \frac{\text{Number of events passing the TnP selection with fires the HLT path}}{\text{Number of events passing the TnP selection}} \quad (5.4)$$

1512 The efficiencies for the hadronic tau legs in the relevant channels of this analyses
1513 ($\mu\tau_h$ and $e\tau_h$) as a function of the offline tau p_T and η , are shown for data taken in
1514 2016, 2017, and 2018 in Figures 5.3a and 5.3b [72] [73]. In both figures, the different
1515 HLT thresholds and differences in the L1 seed result in higher efficiencies in 2016 and
1516 differences in shapes of the 2016 efficiencies compared to 2017 and 2018. The low
1517 pileup in 2016 also leads to higher efficiencies in that year.

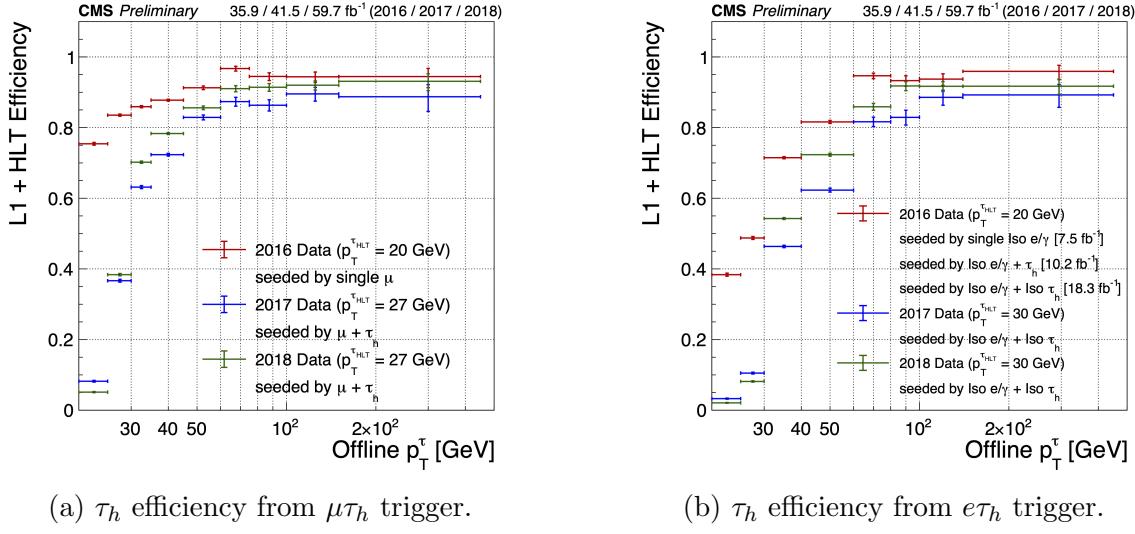


Figure 5.3: Hadronic tau leg efficiency of the cross-triggers for $\mu\tau_h$ (*left*) and $e\tau_h$ (*right*) triggers as a function of offline tau p_T for the years 2016 (red), 2017 (blue) and 2018 (green), from [73]. HLT p_T thresholds and L1 seeds are indicated in the legends.

5.3.7 Single muon trigger efficiencies

The efficiencies for the single isolated muon trigger with $p_T > 24$ GeV used in this analysis, is shown for the data-taking year 2018 in Fig. 5.4a as a function of the muon p_T and as a function of the muon $|\eta|$ in Fig. 5.4b from [74]. The data is split with respect to a HLT muon reconstruction update that was deployed on 15/05/2018. A small asymmetry in efficiencies between negative and positive η in Fig. 5.4b is due to disabled muon chambers (CSCs). The efficiencies shown are estimated using a Tag and Probe method using $Z \rightarrow \mu\mu$ events, with the tag being an offline muon with $p_T > 29$ GeV and $|\eta| < 2.4$ passing a tight ID criteria, and the probe is an online (L1) trigger object with $\Delta R < 0.3$ and passing tight ID and Particle Flow based isolation requirements with $p_T > 26$ GeV.

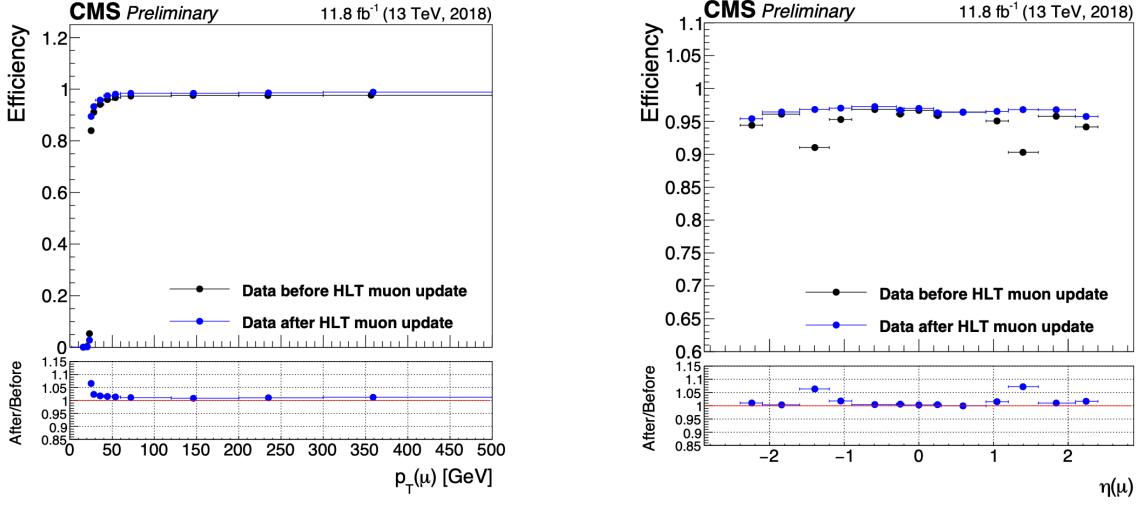
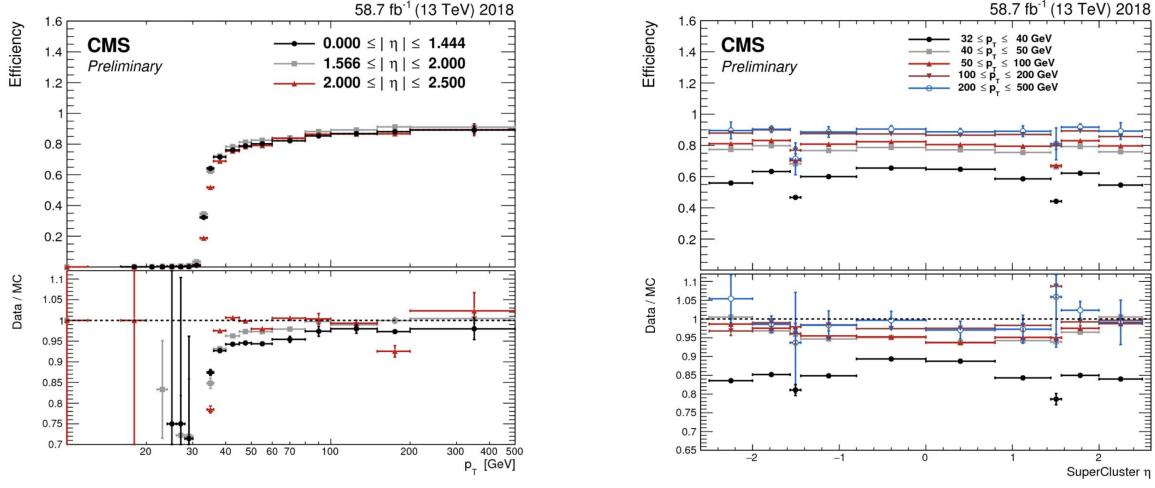
(a) Muon efficiency vs p_T for SingleMuon.(b) Muon efficiency vs $|\eta|$ for SingleMuon.

Figure 5.4: Trigger efficiencies in data (*top panels*) and ratio of efficiencies after/before a HLT muon reconstruction update (*bottom panels*) for the muon in the isolated single muon trigger with threshold $p_T > 24$ GeV in the data-taking year 2018, as functions of the muon p_T (*left*) and muon $|\eta|$ (*right*). Only statistical errors are shown [74].

1529 5.3.8 Single electron trigger efficiencies

1530 The efficiencies in data, and the ratio between data and MC, of the single electron
 1531 HLT trigger with p_T threshold 32 GeV used in this analysis are shown for 2018, as
 1532 a function of the electron p_T in Fig. 5.5a and of the electron $|\eta|$ in Fig. 5.5b, from
 1533 [75]. In the Tag and Probe method used for the 2018 dataset, the tag is an offline
 1534 reconstructed electron with $|\eta| \leq 2.1$ and not in the barrel and endcap overlap region,
 1535 with $p_T > 35$ GeV with tight isolation and shower shape requirements, firing the tag
 1536 trigger. The probe is an offline reconstructed electron with $|\eta| \leq 2.5$ with $E_T^{\text{ECAL}} > 5$
 1537 GeV with no extra identification criteria [75].

1538 The disagreement between data and MC, particularly at low transverse momentum,
 1539 is in part due to detector effects that are difficult to simulate, such as crystal
 1540 transparency losses in the ECAL and the evolution of dead regions in the pixel tracker
 1541 [75].



(a) Electron efficiency vs p_T for single electron.

(b) Electron efficiency vs $|\eta|$ for single electron.

Figure 5.5: Trigger efficiencies in data, and the data/MC ratio for the electron in the single electron trigger with threshold $p_T > 32$ GeV in the data-taking year 2018, as functions of the electron p_T (*left*) and electron $|\eta|$ (*right*) [75]. In the plot vs. p_T , the region $1.442 \leq |\eta| \leq 1.566$ is not included as it corresponds to the transition between barrel and endcap parts of the ECAL.

1542 5.3.9 $e\mu$ cross-trigger efficiencies

1543 The efficiencies of the electron and muons for the cross-trigger with leading muon
 1544 used in the $e\mu$ channel are shown for data in 2016, 2017, and 2018 in Figures 5.6a and
 1545 5.6b [76]. These efficiencies were measured centrally using a Tag and Probe in events
 1546 with Z to dileptons with the same flavor and opposite charge, where the tags are an
 1547 isolated muon or electron, and the probe (offline) candidate is required to satisfy the
 1548 same lepton selection as that of the tag candidate, be matched within $\Delta R < 0.1$ with
 1549 a corresponding online trigger object, and also to pass the cross-trigger. The trigger
 1550 efficiency is then:

$$\text{Efficiency} = \frac{\text{Events passing lepton pair selections and probe passing trigger}}{\text{Events passing lepton pair selections}} \quad (5.5)$$

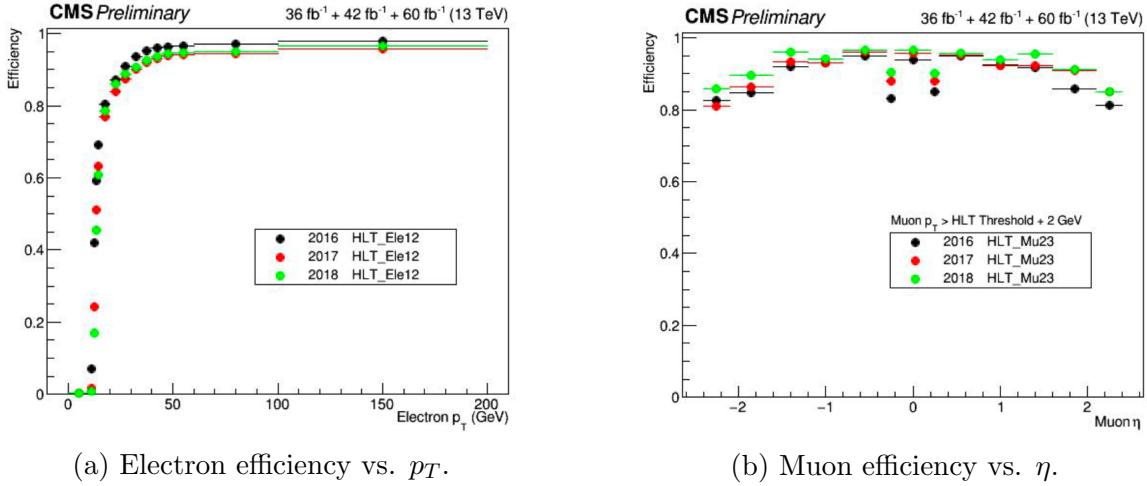


Figure 5.6: Efficiencies of the electron leg vs. p_T (*left*) and the muon leg vs. η (*right*), for the HLT path with online thresholds of 12 GeV for the electron and 23 GeV for the muon, for the data-taking years 2016 (*black*), 2017 (*red*), and 2018 (*green*) [76].

1551 5.3.10 Electrons and muons faking τ_h : energy scales

1552 Energy scales for electrons misidentified as hadronic tau decays (e faking τ_h) are
 1553 provided by the Tau POG, and were measured in the $e\tau_h$ channel with the visible
 1554 invariant mass of the electron and hadronic tau system [66]. This energy scale is
 1555 applied for τ_h with $p_T > 20$ GeV regardless of which DeepTau vs. electron working
 1556 point was used. Values for 2018 are shown in Table 5.5.

Electrons faking τ_h energy scale factor in 2018	
Reconstructed decay mode of the fake τ_h	Central value and (up, down) shifts
0	1.01362 (+0.00474, -0.00904)
1	1.01945 (+0.01598, -0.01226)
10	0.96903 (+0.0125, -0.03404)
11	0.985 (+0.04309, -0.05499)

Table 5.5: Energy scales and up/down systematic uncertainties applied to electrons misidentified as hadronic taus for 2018, binned in decay mode of the fake τ_h [66].

1557 No nominal energy scale is applied for muons mis-reconstructed as τ_h , and the
 1558 uncertainty is treated as $\pm 1\%$ and uncorrelated in the reconstructed decay mode
 1559 [66].

1560 **5.3.11 Electrons and muons faking τ_h : misidentification effi-**
 1561 **ciencies**

1562 Corrections on identification efficiencies are applied to genuine electrons and muons
 1563 misidentified as τ to account for differences in data and MC.

1564 The specific values depend on the vs. electron and vs. muon discriminator working
 1565 points used. For misidentified $\mu \rightarrow \tau_h$, the scale factors are split into different $|\eta|$
 1566 regions, determined by the CMS muon and tracker detector geometries, as shown in
 1567 Table 5.6 for 2018 [63].

Tau ID efficiency for DeepTau vs. muon WPs in 2018		
$ \eta $	Tight working point	VLoose working point
(0.0, 0.2)	0.767 ± 0.127	0.954 ± 0.069
(0.2, 0.6)	1.255 ± 0.258	1.009 ± 0.098
(0.6, 1.0)	0.902 ± 0.203	1.029 ± 0.075
(1.0, 1.45)	0.833 ± 0.415	0.928 ± 0.145
(1.45, 2.0)	4.436 ± 0.814	5.000 ± 0.377
(2.0, 2.53)	1.000 ± 0.000	1.000 ± 0.000

Table 5.6: Tau mis-identification efficiency for the DeepTau Tight and Very Loose (VLoose) working points vs. muons in 2018, binned in the muon $|\eta|$ [63].

1568 For misidentified $e \rightarrow \tau_h$, the scale factors are split into barrel and endcap regions,
 1569 dictated by the ECAL detector geometry, as shown in Table 5.7 for 2018.

Tau ID efficiency for DeepTau vs. electron WPs in 2018		
$ \eta $	Tight working point	VLoose working point
(0.0, 0.73)	1.47 ± 0.27	0.95 ± 0.07
(0.73, 1.509)	1.509 ± 0.0	1.00 ± 0.0
(1.509, 1.929)	1.929 ± 0.2	0.86 ± 0.1
(1.929, 2.683)	2.683 ± 0.9	2.68 ± 0.0

Table 5.7: Tau mis-identification efficiency for the DeepTau Tight and Very Loose (VLoose) working points vs. electrons in 2018, binned in the electron $|\eta|$ [63].

1570 5.3.12 Electron ID and tracking efficiency

1571 Scale factors are applied to MC to correct for differences between MC and data in
 1572 the performance of electron identification (ID) and tracking.

1573 Electron and photon identification, as discussed earlier, use variables with good
 1574 signal vs. background discrimination power such as lateral shower shape and ratio
 1575 of energy deposited in the HCAL to energy deposited in the ECAL at the position
 1576 of the electron. The cut-based electron identification efficiencies in data and ratio of
 1577 efficiencies in data to MC are shown in Fig. 5.7a for the multivariate analysis (MVA)
 1578 identification working point.

1579 The tracking efficiencies in data and the data/MC ratio are shown in Fig. 5.7b
 1580 for the Gaussian-sum filter (GSF) tracking [77].

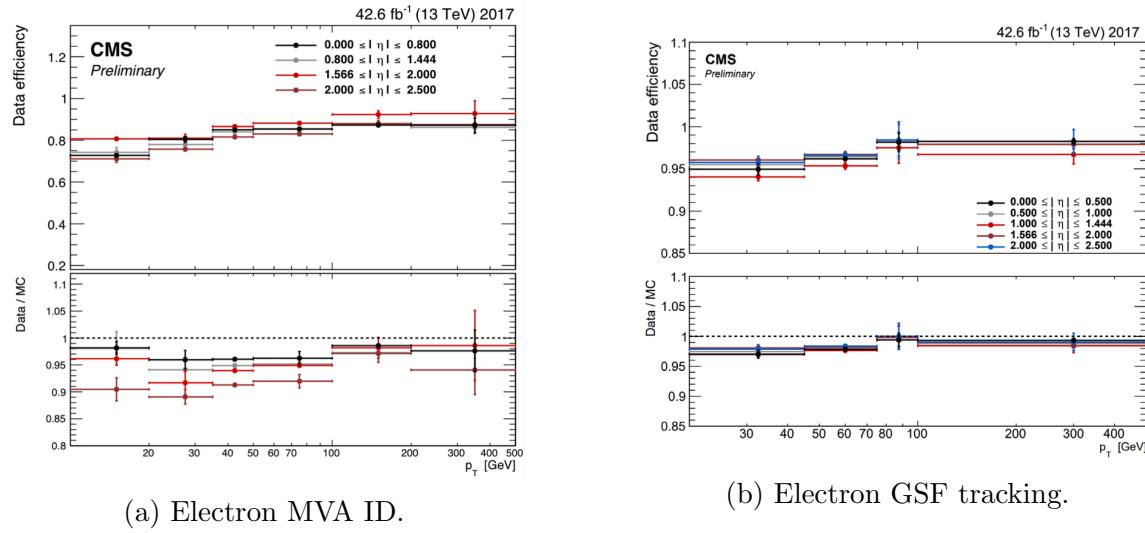


Figure 5.7: Efficiencies in data (*top panels*) and the ratio of efficiencies in data/MC (*bottom panels*), for the electron multivariate analysis (MVA) identification (*left*) and for the Gaussian-sum filter (GSF) tracking (*right*) [77]. Error bars represent statistical and systematic uncertainties.

1581 5.3.13 Muon ID, isolation, and tracking efficiencies

1582 Scale factors are applied to MC to correct for differences between MC and data in
 1583 the performance of muon identification, isolation, and tracking, as detailed below.

1584 The efficiencies for muon identification measured in 2015 data and MC simulation
 1585 are shown in Figures 5.8a and 5.8b for the loose ID and tight ID respectively [78].
 1586 The loose ID is chosen such that efficiency exceeds 99% over the full η range, and the
 1587 data and simulation agree to within 1%. The tight ID is chosen such that efficiency
 1588 varies between 95% and 99% as a function of η , and the data and simulation agree
 1589 to within 1-3%. The muon identification working point used in this analysis is the
 1590 medium ID, which has an efficiency of 98% for all η and an agreement within 1-2%
 1591 [78].

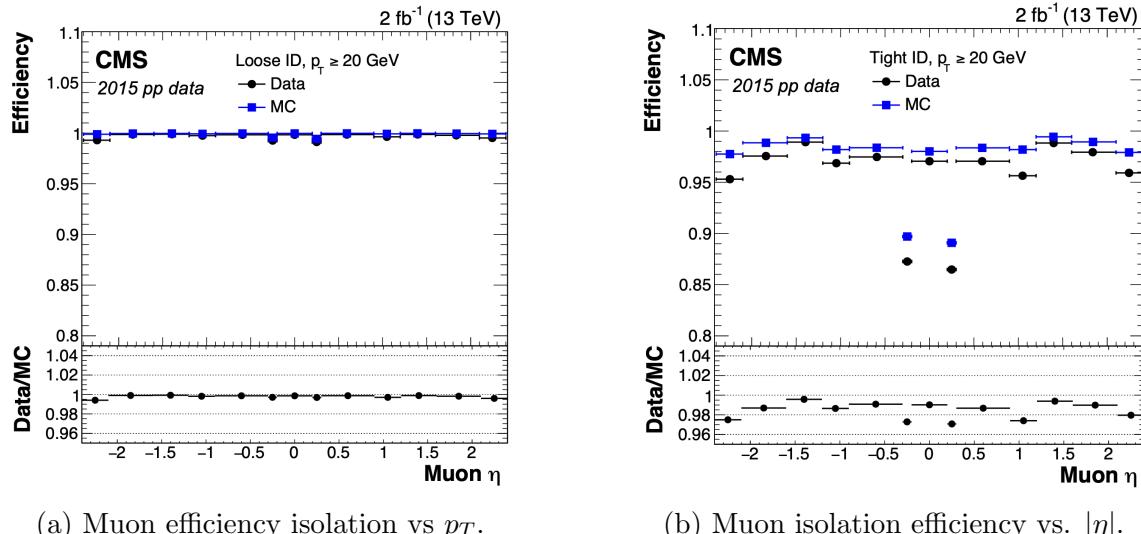
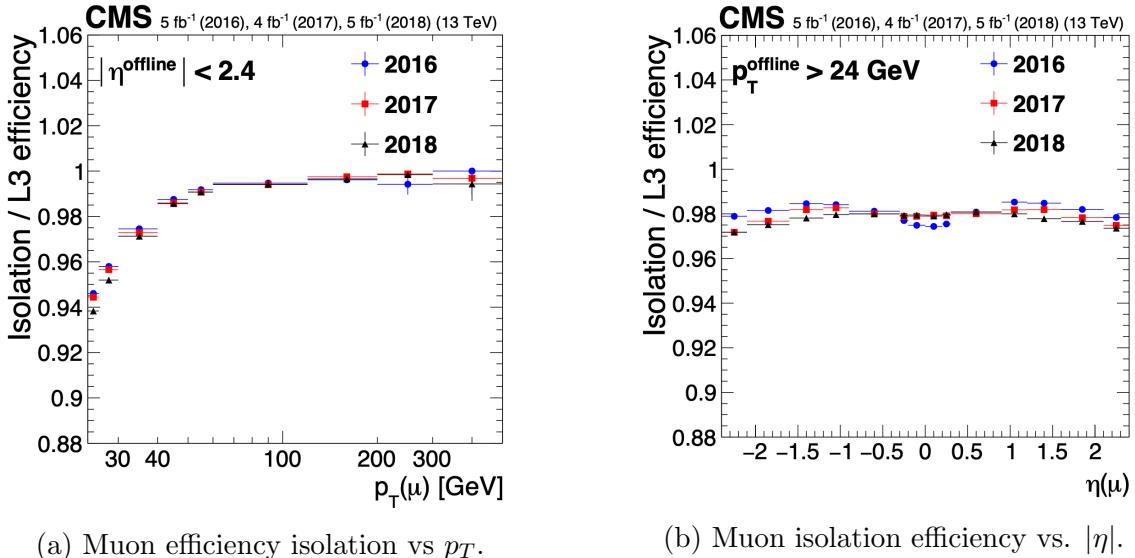


Figure 5.8: Muon identification efficiencies in 2015 data and MC as a function of the muon p_T for the loose ID (*left*) and tight ID (*right*) working points [78].

1592 The efficiencies in data for the muon isolation, as measured in Level-3 muons
 1593 (muons in one of the final stages of reconstruction in the HLT), as a function of the
 1594 muon p_T and $|\eta|$ are shown in Figures 5.9a and 5.9b [78]. The HLT muon reconstruc-
 1595 tion consists of two steps: Level-2 (L2), where the muon is reconstructed in the muon
 1596 subdetectors only, and Level-3 (L3) which is a global fit of tracker and muon hits (i.e.
 1597 the global muon reconstruction as described in Section 5.1.2) [79].

1598 The muon tracking efficiencies as a function of $|\eta|$ for standalone muons (i.e. tracks
 1599 from only the muon system, i.e. DT, CSC, and RPC, as discussed in Section 5.1.2),



(a) Muon efficiency isolation vs p_T .

(b) Muon isolation efficiency vs. $|\eta|$.

Figure 5.9: Muon isolation efficiencies in Run-2 data with respect to Level-3 muons (one of the final stages of HLT muon reconstruction) as a function of the muon p_T (*left*) and $|\eta|$ (*right*) [78].

₁₆₀₀ is shown for data and simulated Drell-Yan samples in Fig. 5.10 [80].

₁₆₀₁ 5.3.14 Recoil corrections

₁₆₀₂ In proton-proton collisions, W and Z bosons are predominantly produced through
₁₆₀₃ quark-antiquark annihilation. Higher-order processes can induce radiated quarks or
₁₆₀₄ gluons that recoil against the boson, imparting a non-zero transverse momentum to
₁₆₀₅ the boson [81]. Recoil corrections accounting for this effect are applied to samples
₁₆₀₆ with W+jets, Z+jets, and Higgs bosons [66]. The corrections are performed on the
₁₆₀₇ vectorial difference between the measured missing transverse momentum and the total
₁₆₀₈ transverse momentum of neutrinos originating from the decay of the W, Z, or Higgs
₁₆₀₉ boson. This vector is projected onto the axes parallel and orthogonal to the boson
₁₆₁₀ p_T . This vector, and the resulting correction to use, is measured in $Z \rightarrow \mu\mu$ events,
₁₆₁₁ since these events have leptonic recoil that do not contain neutrinos, allowing the
₁₆₁₂ 4-vector of the Z boson to be measured precisely. The corrections are binned in
₁₆₁₃ generator-level p_T of the parent boson and also the number of jets in the event.

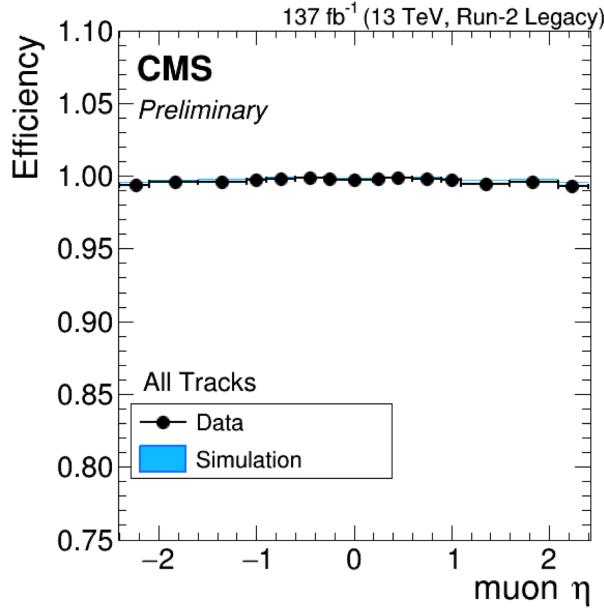


Figure 5.10: Muon tracking efficiencies as a function of $|\eta|$ for standalone muons in Run-2 data (*black*) and Drell-Yan MC simulation (*blue*) [80]. All Tracks refers to tracks which exploit the presence of muon candidates in the muon system to seed the track reconstruction in the inner tracker, in contrast to tracks that use tracker-only hits for seeding. Uncertainties shown are statistical.

5.3.15 Drell-Yan corrections

The Z boson transverse momentum distribution disagrees between leading-order (LO) simulations and data in a $Z \rightarrow \mu\mu$ control region with at least one b-tag jet [82]. Per-event weights derived by the 2016 data-only version of this analysis [82] are applied to $Z \rightarrow \tau\tau/\ell\ell$ events, as a function of the generator-level Z boson p_T to provide better matching of MC to data.

5.3.16 Pileup reweighting

Reweighting is performed to rescale MC events to account for differences between MC and data, in the distribution of the pileup (number of additional proton-proton interactions per bunch crossing). A tool for calculating the pileup reweighting for the MC samples used is provided centrally by the Luminosity POG [83].

1625 **5.3.17 Pre-firing corrections**

1626 In 2016 and 2017 data-taking, a gradual timing shift of ECAL was not properly
1627 propagated to L1 trigger primitives (TPs), resulting in a large fraction of high η
1628 TPs being incorrectly associated with the previous bunch crossing. L1 trigger rules
1629 prevent two consecutive bunch crossings from firing, causing events to be rejected if
1630 significant ECAL energy was deposited in $2.0 < |\eta| < 3.0$. To account for this issue,
1631 MC simulations for 2016 and 2017 are corrected using an event-dependent weight.
1632 Embedded samples are not corrected [48].

1633 **5.3.18 Top p_T spectrum reweighing**

1634 In Run-1 and Run-2 it was observed that the p_T spectra of top quarks in $t\bar{t}$ data
1635 was significantly softer than those predicted by MC simulations [84]. Possible sources
1636 of this discrepancy are higher order QCD and/or electroweak corrections, and non-
1637 resonant production of $t\bar{t}$ -like final states. To account for this, corrections derived
1638 from Run-2 data by the Top Physics Analysis Group (PAG) are applied to the p_T
1639 of the top and anti-top quarks in MC simulations, computed as a function of their
1640 generator-level p_T [84].

1641 **5.3.19 B-tagging efficiency**

1642 In order to predict correct b-tagging discriminant distributions and event yields in
1643 data, the weight of selected MC events is reweighed according to recommendations by
1644 the BTV POG [85]. The reweighing depends on the jet p_T , η , and the b-tagging dis-
1645 criminant. In this method, there is no migration of events from one b-tag multiplicity
1646 bin to another.

1647 5.3.20 Jet energy resolution and jet energy smearing

1648 Calibration of jet energies, i.e. ensuring that the energy and momentum of the recon-
1649 structed jet matches that of the quark/gluon-initiated jet, is a challenging task due
1650 to time-dependent changes in the detector response and calibration and high pileup
1651 [86] [87]. Jet calibration is done via jet energy corrections (JECs) applied to the p_T
1652 of jets in MC samples, accounting successively for the effects of pileup, uniformity of
1653 the detector response, and residual data-simulation jet energy scale differences [88].
1654 Typical jet energy resolutions reported at $\sqrt{s} = 8$ TeV in the central rapidities are
1655 15-20% at 30 GeV and about 10% at 100 GeV [86]. Jet energy corrections are also
1656 propagated to the missing transverse energy.

1657 Measurements show that the jet energy resolution (JER) in data is worse than
1658 in simulation, and so the jets in MC need to be smeared to describe the data. JER
1659 corrections are applied after JEC on MC simulations, and adjust the width of the p_T
1660 distribution based on pileup, jet size, and jet flavor [89]. Tools for applying JEC and
1661 JER are provided centrally by the JER Corrections group.

1662 **Chapter 6**

1663 **Event selection**

1664 This chapter describes how events in data and simulated samples are selected in the
1665 search for $h \rightarrow aa \rightarrow bb\tau\tau$. As described in the previous chapter, the tau lepton can
1666 decay to electrons (e), muons (μ), or hadronic states (τ_h). As a result, several different
1667 final states of the $\tau\tau$ system are possible, and are here referred to as “channels” since
1668 they are mutually exclusive. The three $\tau\tau$ final states studied in this analysis are
1669 muon and hadronic tau ($\mu\tau_h$), electron and hadronic tau ($e\tau_h$), and electron and
1670 muon ($e\mu$). The procedure for dividing events into these three channels begins with
1671 checking the High-Level Trigger paths passed by the events as detailed in Section 6.1.
1672 Events are further accepted or rejected based on criteria applied to the leptons in the
1673 event. These event selections are described for the $\mu\tau_h$ channel in Section 6.2, the $e\tau_h$
1674 channel in Section 6.3, and the $e\mu$ channel in Section 6.4.

1675 **6.1 General procedure for all channels**

1676 For the search for $h \rightarrow aa \rightarrow bb\tau\tau$, three final states of the $\tau\tau$ system are considered:
1677 $\mu\tau_h$, $e\tau_h$, and $e\mu$. The $\tau_h\tau_h$ final state is not considered because signal events in the
1678 $\tau_h\tau_h$ channel would typically produce hadronic taus with momenta below data-taking
1679 trigger thresholds.

1680 In all three final states, events are required to have at least one b-tag jet passing the
1681 medium working point of the DeepFlavour tagger, with $p_T > 20$ GeV, and $|\eta| < 2.4$.
1682 A second b-tag jet is not required because such a requirement would reduce signal
1683 acceptance by 80% compared to only requiring one b-tag jet.

1684 Events in MC samples are sorted into one of the three $\tau\tau$ channels if they pass the
1685 following trigger requirements and requirements on the offline reconstructed objects
1686 in the event, first checking the HLT paths for the $\mu\tau_h$ channel, then $e\tau_h$, and finally $e\mu$.
1687 The two leading leptons (e.g. muon and hadronic tau for the $\mu\tau_h$ channel) that were
1688 determined to have originated from the $\tau\tau$ decay, are called the $\tau\tau$ “legs”. For events
1689 in data and embedded samples, the HLT paths requirements for the corresponding
1690 channel are checked.

1691 After sorting events by HLT paths and identifying the leading tau legs in the offline
1692 reconstructed objects, the p_T of the offline objects is checked against the online trigger
1693 thresholds. Trigger matching is also performed, which checks the correspondence
1694 between each offline reconstructed object used in the analysis (e.g. a muon), and a
1695 trigger object in the HLT (e.g. a HLT muon). An offline object is considered to be
1696 matched, if it corresponds to a trigger object of the same object type, with $\Delta R < 0.5$.
1697 This matched trigger object is also required to pass the filter(s) of the HLT trigger.
1698 The trigger thresholds used for the $bb\mu\mu$ final state and the $bb\tau\tau$ final state (the focus
1699 of this work) are summarized in Tables 6.1.

1700 After checking the HLT paths and trigger objects in each channel, events are
1701 subject to further selection to ensure that they contain leptons and b-tag jet(s) of in-
1702 terest. These requirements are summarized in Table 6.2, and detailed in the following
1703 sections.

Year	Single/dilepton trigger p_T	$bb\mu\mu$	$bb\tau\tau$					
			$e\mu$		$e\tau_h$		$\mu\tau_h$	
		μ	e	μ	e	τ_h	μ	τ_h
2016	Single lepton	24	–	–	25	–	22	–
	p_T -leading lepton	17	23	23	–	–	–	20
	p_T -subleading lepton	8	12	8	–	–	19	–
2017	Single lepton	24	–	–	27, 32	–	24, 27	–
	p_T -leading lepton	17	23	23	–	30	–	27
	p_T -subleading lepton	8	12	8	24	–	20	–
2018	Single lepton	24	–	–	32, 35	–	24, 27	–
	p_T -leading lepton	17	23	23	–	30	–	27
	p_T subleading lepton	8	12	8	24	–	20	–

Table 6.1: Trigger thresholds used for the leptons in the $bb\mu\mu$ analysis and the $bb\tau\tau$ analysis (the focus of this work). The thresholds for the three $bb\tau\tau$ channels ($e\mu$, $e\tau_h$, and $\mu\tau_h$) are listed separately, with some channels and years taking the logical OR of two triggers with different thresholds.

6.2 Event selection in the $\mu\tau_h$ channel

In all three years, a single muon trigger is used if the muon has sufficiently high p_T , otherwise a dilepton $\mu\tau_h$ cross-trigger is used (Tables 6.3, 6.4, and 6.5). For data taken in 2017-2018 (2016), the logical OR of the single muon triggers with online p_T thresholds 24 and 27 (23) GeV is used, with the corresponding offline muon required to have with p_T 1 GeV above the online threshold. For data taken in 2017-2018 (2016), a dilepton $\mu + \tau_h$ cross-trigger with p_T thresholds of 20 (19) and 27 (20) GeV for the muon and tau respectively, is used. The τ_h is required to have $|\eta| < 2.3$ if the single trigger is fired, $|\eta| < 2.1$.

The muon and τ_h are required to have opposite charge and be separated by $\Delta R > 0.4$. The muon is required to have $|\eta| < 2.4$, and the τ_h is required to have $|\eta| < 2.3$ unless a cross-trigger is required, in which case we require $|\eta| < 2.1$ as discussed above.

The muon is required to pass the medium identification (ID) working point [90], which is defined by the Muon POG as a loose muon (i.e. a Particle Flow muon that is either a global or a tracker muon - see Section 5.1.2) with additional requirements on

All years (2016, 2017, 2018) and eras				
Kinematic variable	$bb\mu\mu$		$bb\tau\tau$	
	μ	$e\mu$	$e\tau_h$	$\mu\tau_h$
ΔR between leptons	>0.4	>0.3	>0.4	>0.4
$ \eta $ of electron	-	<2.4	<2.1	-
$ \eta $ of muon	<2.4	<2.4	-	<2.1
$ \eta $ of hadronic tau	-	-	<2.3/< 2.1	<2.3/< 2.1
Relative isolation of electron	-	<0.10	-	<0.15
Relative isolation of muon	<0.25	<0.15	-	<0.15
Leading b-tag jet p_T	>15 GeV		>20 GeV	
Leading b-tag jet $ \eta $	<2.4		<2.4	
Leading b-tag jet WP	Tight		Medium	
Sub-leading b-tag jet p_T	>15 GeV		-	
Sub-leading b-tag jet $ \eta $	<2.4		-	
Sub-leading b-tag jet WP	Loose		-	
ΔR between jet(s) and leptons	>0.4		>0.5	

Table 6.2: Summary of requirements applied to the leptons in the $bb\mu\mu$ analysis and the $bb\tau\tau$ analysis (the focus of this work). $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ is a measure of spatial separation. Relative isolation is defined in Eqn. 5.2 and Section 5.1.2. The b-tag jets are required to pass the listed DeepFlavour working points (WP), which are described in Section 5.1.5. In the $bb\tau\tau$ analysis, the required $|\eta|$ of the hadronic taus are listed for the single and cross triggers respectively. The $bb\mu\mu$ analysis requires two b-tag jets in all events, while the $bb\tau\tau$ analysis only requires one.

1720 track quality and muon quality. This identification criteria is designed to be highly
1721 efficiently for prompt muons and for muons from heavy quark decays. In addition to
1722 the ID, for prompt muons it is recommended to apply cuts on the impact parameter
1723 [90]: we apply $|\Delta(z)| < 0.2$ and $|\Delta(xy)| < 0.045$.

1724 In addition, a cut is applied on the muon relative isolation (defined in Section
1725 5.1.2), to be less than 0.15 in a cone size of $\Delta R = 0.4$, which corresponds to the
1726 Tight Particle Flow isolation requirement [90].

1727 The τ_h is required to pass a cut on its impact parameter of $|\Delta(z)| < 0.2$. The τ_h
1728 is also required to pass the VLoose (Very Loose) DeepTau working point vs. elec-
1729 tron, the Tight DeepTau working point vs. muons, and the VVVLoose and Medium
1730 DeepTau working point vs. jets. Events with taus reconstructed in two of the decay
1731 modes (labeled 5 and 6) are rejected, since these decay modes are meant to recover
1732 3-prong taus, but are only recommended for use in analyses where the benefits in
1733 final significance outweigh the resulting increase in background [63].

1734 For the estimation of the background from jets faking τ_h , which is described in Sec-
1735 tion 7.7, anti-isolated events are selected, by requiring events to pass all the selections
1736 described above, except failing the Medium DeepTau working point vs. jets.

1737 6.3 Event selection in the $e\tau_h$ channel

1738 The HLT trigger paths for the $e\tau_h$ channel are summarized in Tables 6.3, 6.4, and
1739 6.5. Similarly to the $\mu\tau_h$ channel, a single electron trigger is used if the electron has
1740 sufficiently high p_T in 2018 and 2017. For data taken in 2018 (2017), the OR of the
1741 single electron triggers with online p_T thresholds at 32 and 35 (27 and 32) GeV are
1742 used, with the corresponding offline electrons required to have p_T greater than 33
1743 (28) GeV. A $e + \tau_h$ cross-trigger is used for electrons with lower offline p_T between
1744 25 and 33 GeV (25 and 28 GeV). For the 2016 dataset, there is no cross trigger but

1745 only a single electron trigger with online p_T threshold at 25 GeV, which is used if the
1746 offline electron has p_T greater than 26 GeV.

1747 The electron and τ_h are required to have opposite charge and be separated by
1748 $\Delta R > 0.4$. The electron is required to be within $|\eta| < 2.3$ when no cross trigger is
1749 used, and $|\eta| < 2.1$ when the cross trigger is fired. The τ_h is required to have $|\eta| < 2.3$
1750 if no cross trigger is fired, and have $|\eta| < 2.1$ if the cross trigger is fired.

1751 The electron is required to have a relative isolation (same definition as in Section
1752 5.1.2) of less than 0.1 in a cone size of $\Delta R = 0.3$, which is the standard recommended
1753 cone size giving minimal pileup dependence and reduced probability of other objects
1754 overlapping with the cone. The isolation quantity used includes an “effective area”
1755 (EA) correction to remove the effect of pileup in the barrel and endcap parts of the
1756 detector [91].

1757 The electron is also required to pass cuts on its impact parameter of $|\Delta(z)| < 0.2$
1758 and $|\Delta(xy)| < 0.045$. It is also required to pass the non-isolated MVA working point
1759 corresponding to 90% efficiency. The electron’s number of missing hits, which are
1760 gaps in its trajectory through the inner tracker [91], must be less than or equal to
1761 1. The electron must pass a conversion veto, which rejects electrons coming from
1762 photon conversions in the tracker, which should instead be reconstructed as part of
1763 the photon [91].

1764 The impact parameter cut for the τ_h is $|\Delta(z)| < 0.2$. In contrast to the $\mu\tau_h$ event
1765 selection, the vs. electron and vs. muon DeepTau working points are flipped, to
1766 reject muons faking the τ_h leg. The τ_h is required to pass the Tight DeepTau working
1767 point vs. electrons, the VLoose DeepTau working point vs. muons, and the Medium
1768 DeepTau working point vs. jets.

1769 As in the $\mu\tau_h$ channel, for the estimation of the background from jets faking τ_h ,
1770 which is described in Section 7.7, anti-isolated events are selected, by requiring events
1771 to pass all the selections described above, except failing the Medium DeepTau working

1772 point vs. jets.

1773 6.4 Event selection in the $e\mu$ channel

1774 The HLT trigger paths for the $e\mu$ channel are summarized in Tables 6.3, 6.4, and
1775 6.5. Events are selected with the logical OR of two $e + \mu$ cross triggers, where either
1776 the electron or muon can have larger p_T : (1) leading electron, where the electron has
1777 online $p_T > 23$ GeV and muon has online $p_T > 8$ GeV, or (2) leading muon, where
1778 electron has online $p_T > 12$ GeV and muon has online $p_T > 23$ GeV.

1779 The leading and sub-leading leptons are required to have an offline p_T greater
1780 than 1 GeV above the online threshold (i.e. $p_T > 24$ GeV). If the sub-leading lepton
1781 is the electron, the offline p_T threshold is 1 GeV above the online threshold ($p_T > 13$
1782 GeV), but if it is a muon, the offline p_T threshold is required to be at least 5 GeV
1783 greater than the online threshold (i.e. $p_T > 13$ GeV). This is because of poor data
1784 and simulation agreement for low- p_T muons with p_T between 9 GeV and 13 GeV, and
1785 the higher probability of mis-identifying jets as muons at lower p_T . With no effect on
1786 the expected limits, the offline p_T threshold for muons is raised to 13 GeV instead of
1787 9 GeV, even though it may lead to loss in signal acceptance. Both the electron and
1788 muon are required to have $|\eta| < 2.4$.

1789 The electron and muon are required to have opposite charge and be separated
1790 by $\Delta R > 0.3$ (note the decreased separation requirement compared to the other
1791 two channels). The electron is required to pass the non-isolated MVA identification
1792 working point corresponding to 90% efficiency, and to have a relative isolation less
1793 than 0.1 for a cone size of $\Delta R = 0.3$ with the EA pileup subtraction correction.
1794 The electron must have one or fewer missing hits and pass the conversion veto (both
1795 described previously in Section 6.3).

1796 The muon is required to pass the medium identification working point (described

earlier in 6.2), and to have a relative isolation less than 0.15 for a cone size of $\Delta R = 0.4$. The muon impact parameter is required to have $|\Delta(z)| > 0.2$ and $|\Delta(xy)| < 0.045$.

For the QCD multijet background estimation described in Section 7.8, the same-sign region is selected by requiring all the above selections, except the legs are required to have the same electric charge rather than opposite.

2016 $\mu\tau_h$ trigger paths	
Notes	HLT Path
	HLT_IsoMu22_v
	HLT_IsoMu22_eta2p1_v
	HLT_IsoTkMu22_v
	HLT_IsoTkMu22_eta2p1_v
	HLT_IsoMu19_eta2p1_LooseIsoPFTau20_v
	HLT_IsoMu19_eta2p1_LooseIsoPFTau20_SingleL1_v
2016 $e\tau_h$ trigger paths	
Notes	HLT Path
	HLT_Ele25_eta2p1_WPTight_Gsf_v
2016 $e\mu$ trigger paths	
Notes	HLT Path
runs B-F and MC	HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_v
runs B-F and MC	HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_v
runs G-H	HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v
runs G-H	HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ_v

Table 6.3: High-Level Trigger (HLT) paths used to select data and simulation events in 2016 for the three $\tau\tau$ channels.

6.5 Extra lepton vetoes in all channels

Events containing a third lepton (electron or muon) that is neither of the leading $\tau\tau$ legs are rejected, and events with di-muons and di-electrons are vetoed, with criteria taken from the Standard Model $H \rightarrow \tau\tau$ working group [66].

The event is vetoed if a third electron is found with the following properties: $p_T > 10$ GeV, $|\eta| < 2.5$, impact parameter $|\Delta(z)| < 0.2$ and $|\Delta(xy)| < 0.045$, passing non-isolation MVA identification with 90% efficiency, conversion veto, ≤ 1 missing

2017 $\mu\tau_h$ trigger paths	
Notes	HLT Path
	HLT_IsoMu24_v
	HLT_IsoMu27_v
	HLT_IsoMu20_eta2p1_LooseChargedIso_PFTau27_eta2p1_CrossL1_v
2017 $e\tau_h$ trigger paths	
Notes	HLT Path
	HLT_Ele32_WPTight_Gsf_v
	HLT_Ele35_WPTight_Gsf_v
	HLT_Ele24_eta2p1_WPTight_Gsf_Loose_ChargedIsoPFTau30_eta2p1_CrossL1_v
2017 $e\mu$ trigger paths	
Notes	HLT Path
	HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v
	HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ_v

Table 6.4: High-Level Trigger (HLT) paths used to select data and simulation events in 2017 for the three $\tau\tau$ channels.

1809 hits, and relative isolation < 0.3 with cone size $\Delta R = 0.3$. The event is also vetoed if
 1810 a third muon is found with the following properties: $p_T > 10$ GeV, $|\eta| < 2.4$, impact
 1811 parameter $|\Delta(z)| < 0.2$ and $|\Delta(xy)| < 0.045$, medium ID, and isolation < 0.3 with
 1812 cone size $\Delta R = 0.4$.

1813 A di-muon veto is applied, which rejects events containing a pair of muons with
 1814 opposite charge and separation of $\Delta R > 0.15$, that both pass the following selections:
 1815 $p_T > 15$ GeV, $|\eta| < 2.4$, flag for global muons, flag for tracker muon, flag for Particle
 1816 Flow muon, $|\Delta(z)| < 0.2$, $|\Delta(xy)| < 0.045$, and isolation < 0.3 with cone size $\Delta R =$
 1817 0.4. A similar di-electron veto is applied to reject events containing a pair of electrons
 1818 with opposite charge and separation of $\Delta R > 0.15$, that both pass the following
 1819 selections: $p_T > 15$ GeV, $|\eta| < 2.5$, a dedicated electron ID (cut-based) for vetoing
 1820 third leptons, $|\Delta(z)| < 0.2$, $|\Delta(xy)| < 0.045$, with pileup-corrected relative isolation
 1821 < 0.3 with cone size $\Delta R = 0.3$.

1822 These vetoes on extra leptons also ensure orthogonality of events to analyses such
 1823 as the $bb\mu\mu$ final state, whose results are combined with this $bb\tau\tau$ final state as
 1824 described in Section 10.2.

2018 $\mu\tau_h$ trigger paths	
Notes	HLT Path
	HLT_IsoMu24_v
	HLT_IsoMu27_v
only data run < 317509	HLT_IsoMu20_eta2p1_ (contd.)
	LooseChargedIsoPFTauHPS27_eta2p1_CrossL1_v
MC and data run \geq 317509	HLT_IsoMu20_eta2p1_ (contd.)
	LooseChargedIsoPFTauHPS27_eta2p1_TightID_CrossL1_v
2018 $e\tau_h$ trigger paths	
Notes	HLT Path
	HLT_Ele32_WPTight_Gsf_v
	HLT_Ele35_WPTight_Gsf_v
only data run < 317509	HLT_Ele24_eta2p1_WPTight_Gsf_ (contd.)
	LooseChargedIsoPFTauHPS30_eta2p1_CrossL1_v
MC and data run \geq 317509	HLT_Ele24_eta2p1_WPTight_Gsf_ (contd.)
	LooseChargedIsoPFTauHPS30_eta2p1_TightID_CrossL1_v
2018 $e\mu$ trigger paths	
Notes	HLT Path
	HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v
	HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ_v

Table 6.5: High-Level Trigger (HLT) paths used to select data and simulation events in 2018 for the three $\tau\tau$ channels. In 2018 a HLT trigger path using the hadron plus strips (HPS) tau reconstruction algorithm became available.

1825 **Chapter 7**

1826 **Background estimation**

1827 This section describes methods used to estimate sources of background from Standard
1828 Model processes in the search for $h \rightarrow aa \rightarrow bb\tau\tau$. Similar background estimation
1829 methods are being used for the $h \rightarrow a_1a_2$ analysis. The background contributions
1830 directly taken from MC are described in Sections 7.1 to 7.6. Section 7.7 describes
1831 the data-driven method for estimating backgrounds from jets faking hadronic tau
1832 decays ($\text{jet} \rightarrow \tau_h$), which is used in the $\mu\tau_h$ and $e\tau_h$ channels. Section 7.8 describes
1833 the data-driven method for estimating background from quantum chromodynamic
1834 (QCD) processes in the $e\mu$ channel.

1835 **7.1 Z+jets**

1836 A major source of background for $\tau\tau$ analyses is the Drell-Yan (DY) process (Z+jets).
1837 The Z boson decays to $\tau\tau/\mu\mu/ee$ with equal probability of 3.4% each, with the dom-
1838 inant decay modes being to hadrons (around 70%) and neutrinos (invisible) (20%)
1839 [26].

1840 The Drell-Yan contribution with genuine taus, $Z \rightarrow \tau\tau$, is estimated using embed-
1841 ded samples, described in Section 4.3. To avoid double-counting between embedded
1842 and MC samples, in all MC samples, events with legs that originated from genuine τ

1843 are discarded.

1844 The other decays of the Z , $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$, are estimated from MC simulation,
1845 and are hereafter referred to as simply the Drell-Yan background. These MC samples
1846 are generated to leading order (LO) with different numbers of jets (jet multiplicity) in
1847 the matrix element: $Z+1$ jet, $Z+2$ jets, $Z+3$ jets, $Z+4$ jets, and inclusive $Z+jets$. The
1848 cross-sections of the samples with ≥ 1 jets are normalized to next-to-NLO (NNLO)
1849 in QCD.

1850 For the inclusive Drell-Yan sample, two samples are used with different thresholds
1851 for the di-lepton invariant mass ($m_{\ell\ell}$) at the generator level: one with $m_{\ell\ell} > 50$ GeV
1852 and the other with $10 < m_{\ell\ell} < 50$.

1853 7.2 W+jets

1854 The dominant W boson decay modes are to hadrons (67.4%), $e + \nu_e$ (10.7%), $\mu + \nu_\mu$
1855 (10.6%), and $\tau + \nu_\tau$ (11.4%) [26]. The $W+jets$ background is estimated from MC
1856 simulation. Similarly to the $Z+jets$, the $W+jets$ samples are generated with different
1857 jet multiplicities in the matrix element. LO samples are used for greater statistics
1858 and are normalized to NNLO cross sections.

1859 7.3 $t\bar{t} + jets$

1860 In hadron collisions, top quarks are produced singly with the weak interaction, or in
1861 pairs via the strong interaction, with interference between these leading-order pro-
1862 cesses possible in higher orders of the perturbation theory. The top quark is the
1863 heaviest fermion in the Standard Model and has a short lifetime ($\sim 10^{-25}$ s), decay-
1864 ing without hadronization into a bottom quark and a W boson [26], with the decay
1865 modes of the W boson as listed in the previous section. With two top quarks, the
1866 final states of the two resulting W bosons can be described as fully leptonic, semilep-

1867 tonic, and fully hadronic. These three final states are modeled separately with MC
1868 simulation in 2018 and 2017, while for 2016 the sample used is inclusive.

1869 7.4 Single top

1870 There are three main production modes of the single top in pp collisions [92]: the
1871 exchange of a virtual W boson (t channel), the production and decay of a virtual W
1872 boson (s channel), and the associated production of a top quark and W boson (tW ,
1873 or W-associated) channel. As the s channel process is rare and only 3% of the total
1874 production, the dominant production mode of the t -channel and the tW production
1875 are considered and modeled with MC.

1876 7.5 Diboson

1877 In pp collisions, the production of dibosons (pairs of electroweak gauge bosons, i.e.
1878 WW, WZ, and ZZ) is dominated by quark-antiquark annihilation, with a small con-
1879 tribution from gluon-gluon interaction [93]. MC is used to model the pair production
1880 and decays of VV to $2\ell 2\nu$, WZ to $2q 2\ell$ and $3\ell\nu$, and ZZ to 4ℓ and $2q 2\ell$ (q being
1881 quarks and ℓ being leptons).

1882 7.6 Standard Model Higgs

1883 MC is used to simulate backgrounds from major production modes of the Standard
1884 Model 125 GeV Higgs boson: gluon-gluon fusion (ggH), vector boson fusion (VBF),
1885 associated production with a W or Z (WH, ZH), and associated production with a
1886 top pair (ttH) (see Fig. 7.1 for leading-order diagrams). For these production modes,
1887 samples with the Higgs decaying to $\tau\tau$ or to WW are used. Samples made with
1888 higher-order diagrams for WH and ZH that include the production of a jet, with the

1889 Higgs decaying to WW, are also used.

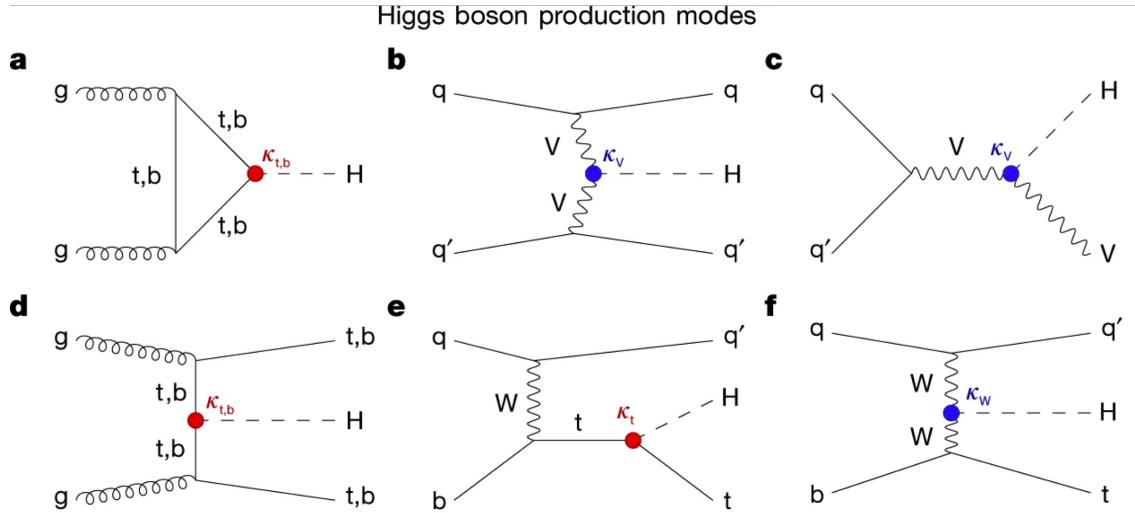


Figure 7.1: Leading-order Feynman diagrams of Higgs production from [94], in ggH (a) and vector boson fusion (VBF; b), associated production with a W or Z (V) boson (VH; c), associated production with a top or bottom quark pair (ttH or bbH); d, and associated production with a single top quark (tH ; e, f).

1890 7.7 Jet faking τ_h

1891 Events with a jet mis-reconstructed as the hadronic tau leg τ_h are a major source of
1892 background in the $\mu\tau_h$ and $e\tau_h$ channels. The main processes contributing to jet $\rightarrow \tau_h$
1893 events are QCD multijet, W+jets, and $t\bar{t}$ production. These events are estimated
1894 using a data-driven method adapted from past analyses [48] [82]. This background
1895 includes contributions from W+jets, QCD multijets, and $t\bar{t}$ +jets. To estimate this
1896 background, a sideband region is constructed, where events are required to pass all
1897 baseline $\mu\tau_h/e\tau_h$ selection criteria, but fail the τ_h isolation criteria. The events in
1898 this sideband region are reweighted with a factor $f/(1 - f)$, where f is the probability
1899 for a jet to be misidentified as a τ_h . The jet $\rightarrow \tau_h$ background is the anti-isolated,
1900 reweighted MC and embedded events subtracted from the anti-isolated, reweighted
1901 data events.

1902 The fake factor is measured in $Z \rightarrow \mu\mu + \text{jets}$ events in data in the $\mu\mu\tau_h$ final
1903 state, as any reconstructed τ_h in these events must originate from a jet. The two
1904 muons are required to be isolated (< 0.15), have opposite electric charge, and have
1905 an invariant mass between 76 and 106 GeV (close to the Z mass). These events are
1906 selected with a double muon trigger, with the leading muon having offline $p_T > 20$
1907 GeV and the subleading muon $p_T > 10$ GeV. Simulated diboson (ZZ and WZ) events
1908 are subtracted to avoid contamination from events with real τ_h . The denominator of
1909 the fake rate corresponds to fake taus passing the VVVLoose working point of the
1910 discriminator vs. jets, while the numerator corresponds to those passing the Medium
1911 working point, i.e. $f = N_{\text{jet passing tight}} / N_{\text{jet passing loose}}$.

1912 f is measured as a function of the τ_h transverse momentum and is 8% - 10% in
1913 each of the data-taking years. f is derived separately for the $\mu\tau_h$ and $e\tau_h$ channels
1914 because the channels use different anti-lepton identification working points.

1915 7.8 QCD multijet background

1916 In the $e\mu$ channel, events with jets faking electrons or muons originating from QCD
1917 multijet, is estimated from data events with the same baseline selection as in the
1918 signal region, except with same-signed (SS) charged $e + \mu$, ensuring orthogonality
1919 with the signal region which requires opposite-sign (OS) $e\mu$ pairs. All same-sign MC
1920 events (both events with real and fake $e + \mu$) are subtracted from same-sign data
1921 events to remove contamination from other backgrounds. i.e. $\text{QCD}_{\text{SS}} = \text{Data}_{\text{SS}} -$
1922 MC_{SS} .

1923 Three scale factors are applied to the QCD_{SS} events to compute the QCD multijet
1924 background [82] [37]:

- 1925 • *OS-to-SS scale factor*: This scales the SS QCD to the OS region, and is mea-
1926 sured from an orthogonal region with an isolated electron and an anti-isolated

1927 muon. Only the muon is chosen to be anti-isolated because this scale factor was
1928 observed to depend more strongly on electron isolation than that of the muon.
1929 This scale factor is treated as a function of the ΔR separation of the trajectories
1930 of the electron and muon, and is measured separately for events with 0 jets, 1,
1931 jet, and greater than 1 jet.

- 1932 • *2D closure correction for the lepton p_T :* This factor accounts for subleading
1933 dependencies of the first scale factor on the p_T of the two leptons. A 2D weight
1934 is derived in a similar fashion, as a ratio of QCD_{OS} events to QCD_{SS} events,
1935 but parameterized by both electron and muon p_T , where the SS events have the
1936 previous scale factor applied.

- 1937 • *Isolation correction for the muon:* The third and final factor is an isolation
1938 correction, which is a bias correction to account for the fact that the fake
1939 factor was determined for less-isolated muons. This factor is obtained as the
1940 ratio of the OS-to-SS scale factors measured in two other control regions: (1)
1941 events where the electron is anti-isolated ($0.15 < \text{iso} < 0.5$) and the muon is
1942 isolated, and (2) events where both leptons are anti-isolated.

¹⁹⁴³ Chapter 8

¹⁹⁴⁴ Systematic uncertainties

¹⁹⁴⁵ The handling of systematic uncertainties is separated into normalization uncertainties
¹⁹⁴⁶ (those that affect the total yield of a variables' distribution) and shape uncertainties
¹⁹⁴⁷ (those that shift the distribution of events). Normalization uncertainties are expressed
¹⁹⁴⁸ as multiplicative factors, while shape uncertainties are represented as up and down
¹⁹⁴⁹ shifts of a variable's distribution.

¹⁹⁵⁰ Up/down shifts of shape uncertainties can change the number of background
¹⁹⁵¹ events in a distribution. For instance, hadronic taus receive corrections from the
¹⁹⁵² nominal tau energy scale, with the nominal, up, and down energy scales provided
¹⁹⁵³ centrally by CMS. For the $\mu\tau_h$ channel, an event could have a τ_h with p_T just below
¹⁹⁵⁴ the offline threshold of 20 GeV (for instance, 19.5 GeV), so in the nominal distribution
¹⁹⁵⁵ of $m_{\tau\tau}$ (or any other variable for this channel), the event is excluded. However, when
¹⁹⁵⁶ we build our distributions with the tau energy scale “up” shift, the energy of this τ_h
¹⁹⁵⁷ may be scaled up to, say, 20.5 GeV, and now the event passes the offline p_T threshold
¹⁹⁵⁸ for the single muon trigger, leading to the event's inclusion in the distributions made
¹⁹⁵⁹ with the tau energy scale “up” shift.

¹⁹⁶⁰ In evaluating the up and down shifts of a specific source of uncertainty, all other
¹⁹⁶¹ corrections and scale factors are held at their nominal values, and the full chain of

1962 object and event selection and event categorization is performed to obtain the observ-
1963 able distributions. Any “downstream” variables that depend on the shifted variable,
1964 e.g. the invariant di-tau mass $m_{\tau\tau}$, must be computed for the nominal case, and then
1965 re-computed separately for each up and down shift of the tau legs’ energy scale. The
1966 objective of this process is to quantify the effect of a single source of uncertainty on
1967 the resulting observable distributions. Each scale factor and correction described in
1968 Section 5.3 has an associated uncertainty. The binning of the uncertainties follows
1969 that of the nominal scale factor value.

1970 Sections 8.1 to 8.5 describe uncertainties associated with physics objects, and
1971 Sections 8.6 and 8.7 describe uncertainties associated with sample-level effects. The
1972 pulls and impacts for the top sixty most important systematics are shown in Section
1973 8.8.

1974 8.1 Uncertainties in the lepton energy scales

1975 The uncertainties in the tau energy scales [63] are binned by the tau decay mode and
1976 are taken as shape uncertainties treated as uncorrelated across the tau decay modes
1977 and years. Same as with the application of the nominal scale factor, when applying
1978 the up or down shifts, the missing transverse energy (p_T^{miss}) of the event is adjusted
1979 so that the 4-vector sum of the tau p_T^{miss} is unchanged.

1980 The uncertainties in the muon energy scale [64] are 0.4% for $|\eta| < 1.2$, 0.9% for
1981 $1.2 < |\eta| < 2.1$, and 2.7% for $2.1 < |\eta| < 2.4$, and are treated as shape uncertainties,
1982 fully uncorrelated between embedded and MC samples.

1983 The uncertainties in the electron energy scale [67] in MC are binned in the electron
1984 $|\eta|$ and p_T , and are shown in Fig. 5.2. The uncertainties range from 0.5% to 2.2% in
1985 the barrel, and 0.3% to 4.1% in the endcap, across the p_T range. The uncertainties
1986 for the embedded sample are binned only in $|\eta|$ and are on the order of 0.5% and

1987 1.25% for the barrel and endcap [71].

1988 There are also uncertainties in the energy scales for electrons and muons misiden-
1989 tified as τ_h . The uncertainty for muons misidentified as τ_h is 1% [63]. For electrons
1990 misidentified as τ_h , the uncertainty is binned in barrel/endcap η and by 1-prong and
1991 1-prong + π_0 decays. The probability for e/μ faking a 3-prong decay mode is much
1992 lower.

1993 8.2 Uncertainties from other lepton corrections

1994 Uncertainties associated with the τ_h identification efficiencies are treated as shapes,
1995 uncorrelated across the seven p_T bins and years. The shape uncertainties in the
1996 embedded samples are taken as 50% correlated with those of the MC samples.

1997 The uncertainties on electron and muon identification efficiencies are taken as
1998 normalization uncertainties of 2% each, with a 50% correlation between embedded
1999 and MC samples.

2000 In the $e\tau_h$ channel, there is an additional uncertainty for the vs. jet discrimination
2001 efficiency [63], because the analysis uses a looser anti-lepton working point (VLoose
2002 WP) than the working points used in the measurement of the efficiency (namely,
2003 VLoose WP vs e, and Tight WP vs mu). For nominal $\tau_h p_T < 100$ GeV, an additional
2004 uncertainty of 3% (5%) is used in MC (embedded), and for high p_T an uncertainty of
2005 15% is used for both.

2006 The uncertainties in trigger efficiencies are taken as shapes [63]. In the $e\tau_h$ and $\mu\tau_h$
2007 channels, there are uncertainties for the single and cross lepton triggers, and in the
2008 $e\mu$ channel there is one uncertainty each for the two $e + \mu$ triggers, and one combined
2009 uncertainty since their trigger phase spaces are not mutually exclusive.

2010 8.3 Uncertainties from jet energy scale and resolution

2011

2012 The jet energy scale uncertainties are taken as shape uncertainties: there are eleven
2013 in total, with seven correlated across years (labeled “Year” below) and the remainder
2014 uncorrelated across years. They affect the b-tag jet p_T and mass, and hence the
2015 missing transverse energy p_T^{miss} . The shifts are propagated through the b-tagging
2016 scale factor calculation and b-tag jet counting.

2017 The uncertainties in the jet energy correction and resolution [86] [95] are as follows:

- 2018 • *Absolute, AbsoluteYear*: flat absolute scale uncertainties.
- 2019 • *BBEC1, BBEC1Year*: for sub-detector regions, with barrel “BB” in $|\eta| < 1.3$
2020 and endcap region 1 “EC1”: $1.3 < |\eta| < 2.5$.
- 2021 • *EC2, EC2 year*: for sub-detector regions, with endcap region 2 “EC2” in $2.5 <$
2022 $|\eta| < 3.0$.
- 2023 • *HF, HF year*: for sub-detector regions, with hadron forward “HF” in $|\eta| > 3$.
- 2024 • *FlavorQCD*: for uncertainty in jet flavor (uds/c/b-quark and gluon) estimates
2025 based on comparing Pythia and Herwig (different MC generator) predictions.
- 2026 • *RelativeBal*: account for difference between log-linear fits of the two methods
2027 used to study the jet energy response: MPF (missing transverse momentum
2028 projection fraction) and p_T balance.
- 2029 • *RelativeSample*: account for η -dependent uncertainty due to a difference be-
2030 tween relative residuals, observed with dijet and Z+jets in Run D of 2018 data.
- 2031 • *JetResolution*: uncertainty in the jet energy resolution.

8.4 Uncertainties from b-tagging scale factors

The b-tagging scale factor has its own set of associated uncertainties (not to be confused with shifts in the b-tagging scale factor due to the propagation of the jet energy scale uncertainties described in the previous section 8.3). They are:

- hf : contamination from heavy flavor ($b+c$) jets in the light flavor region.
 - $hfstats1, hfstats2$: linear and quadratic statistical fluctuations from b -flavor jets.
 - lf : contamination from light flavor ($udsg+c$ jets) in the heavy flavor region.
 - $lfstats1, lfstats2$: linear and quadratic statistical fluctuations from $udsg$ jets.
 - $cferr, cferr2$: uncertainty for charm jets.
- The variations for “ $lf, hf, hfstats1/2, lfstats1/2$ ” are applied to both b and $udsg$ jets.
For c -flavor jets, only “ $cferr1/2$ ” is applied.

8.5 Uncertainties from MET

Samples where recoil corrections were applied ($Z+jets$, $W+jets$, and Standard Model Higgs, as described in Section 5.3) have uncertainties from the response and resolution of the hadronic recoil against the leptonic system. These are each binned in jet multiplicity.

8.6 Uncertainties associated with samples used

Normalization uncertainties related to the samples used are:

- *Cross-section uncertainties*: $\sigma(t\bar{t})$: 4.2%, $\sigma(\text{diboson})$: 5%, $\sigma(\text{single top})$: 5%, $\sigma(\text{ggH})$: 3.2%, $\sigma(\text{qqH})$: 2.1%, $\sigma(\text{WH})$: 1.9%, $\sigma(\text{ZH})$: 1.3%, $\sigma(\text{ttH})$: 3.6%

2052 • *Uncertainties in QCD renormalization scale*: QCD scale(qqH): +0.43%-0.33%,

2053 QCD scale(WH): +0.5%-0.7%, QCD scale(ttH): +5.8%-9.2%

2054 • *Branching ratio uncertainties*: BR($H \rightarrow \tau\tau$): 1.8%, and BR($H \rightarrow WW$): 1.5%.

2055 • *Normalization uncertainties*: 2% for Drell-Yan, 4% for embedded, 20% pre-fit

2056 for the QCD multijet background in the $e\mu$ channel, 20% pre-fit for the jet
2057 faking background.

2058 The $t\bar{t}$ process has additional acceptance uncertainties from QCD scale variation

2059 and parton shower uncertainties [96]. Parton shower uncertainties originate from

2060 the modeling of perturbative and non-perturbative QCD effects handled in parton
2061 shower MC generators. The scale variations are determined from the envelope of the

2062 6 provided shapes due to variations in the factorization scale, renormalization scale,

2063 and their combined variation [96].

2064 The Z p_T reweighing uncertainty in Drell-Yan samples is taken to be 10% of the
2065 nominal value, taken as a shape uncertainty.

2066 The fake rate uncertainties are taken as shape uncertainties. For the weight ap-
2067 plied to scale up anti-isolated events in cross-trigger regions, 20% of the nominal
2068 weight is taken as a shape uncertainty.

2069 8.7 Other uncertainties

2070 A 3.6% yield uncertainty in the signal is used to cover uncertainties in the parton
2071 distribution functions, α_s (fine structure constant), and QCD scale.

2072 Normalization uncertainties from luminosity are applied to all MC samples, di-
2073 vided into those uncorrelated across years, those correlated between 2017 and 2018,
2074 and one for 2018 [83].

2075 8.8 Pulls and impacts

2076 The top impacts and pulls computed for the combination of all channels and years is
2077 shown in Fig. 8.1. The top impacts are related to uncertainty in the signal sample and
2078 cross-section of the $t\bar{t}$ cross-section, and also the yields of the jet faking τ_h background,
2079 which is a major background in all channels and expected to be constrained due to
2080 the yield uncertainty which is taken to be 20% pre-fit.

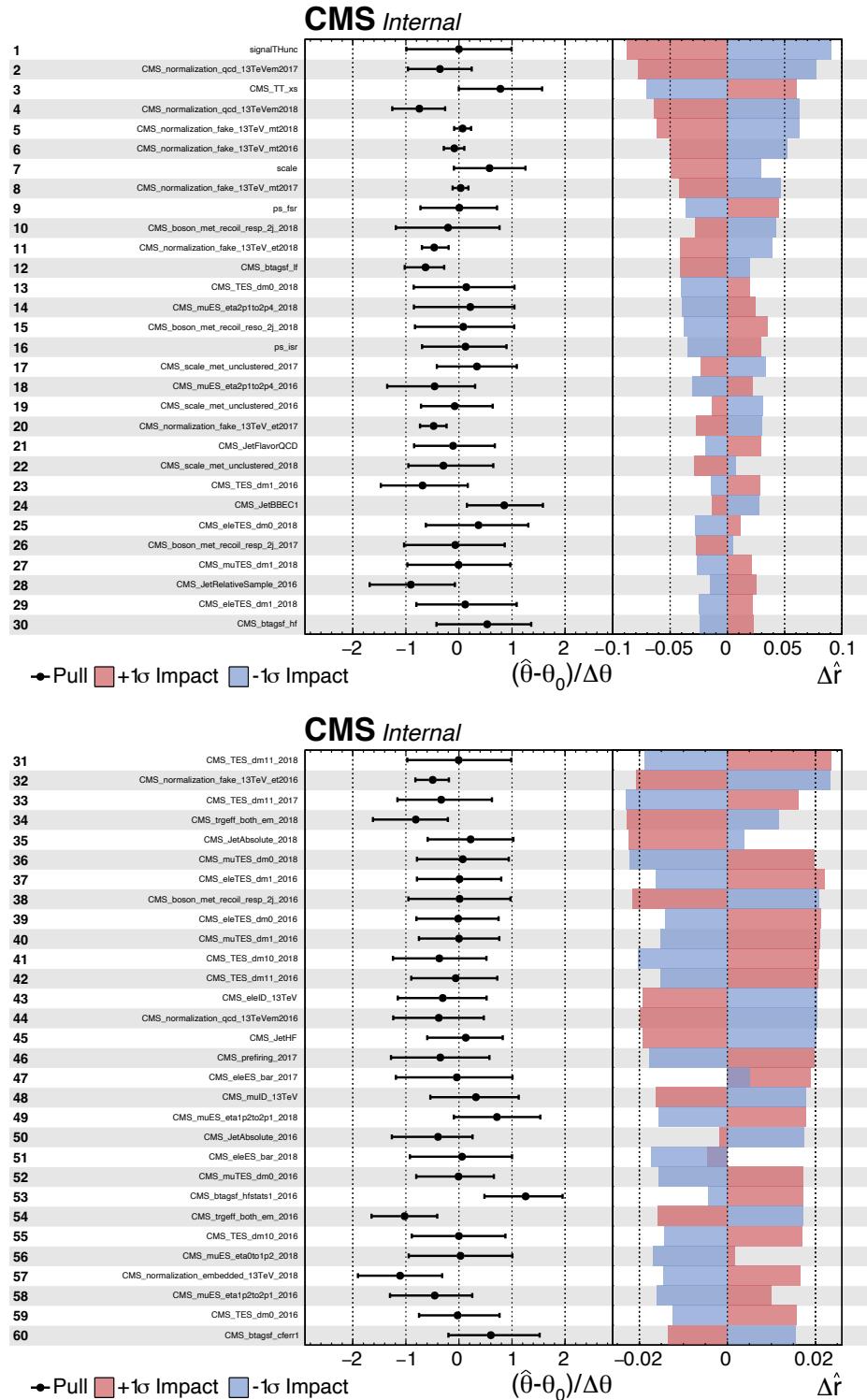


Figure 8.1: Top sixty pulls and impacts for the combination of all channels and years [42].

2081 Chapter 9

2082 Event categorization and signal 2083 extraction

2084 Measured events are divided into categories, based on cuts on values of observables
2085 in the event, or some derived quantity based on the observables in the event. The
2086 objective of event categorization is to divide events into signal regions, where the
2087 signal is enhanced and the background is suppressed, and control regions, which are
2088 signal-poor and used to check that the background estimation methods employed in
2089 the analysis in fact accurately models the data. In this analysis, events in each tau-tau
2090 channel are selected to contain one or more b-tag jets reconstructed in the event as
2091 described in Section 9.1. Events are further divided into signal and control regions
2092 using a deep learning-based approach described in Section 9.2. The signal is extracted
2093 from the di-tau mass distribution in the signal region using the statistical procedure
2094 described in Section 9.3.

2095 9.1 B-tag jet multiplicity

2096 The increased statistics of the full Run-2 dataset enables the separation of events into
2097 events with exactly 1 b-tag jet and events with greater than 1 b-tag jet. Further event

2098 categorization is performed with deep neural networks (DNNs) described below. The
2099 DNNs are used only for separating events into signal and control regions in the 1
2100 b-tag and 2 b-tag jets scenarios. The final results are extracted from the statistical
2101 fitting to the mass of the $\tau\tau$, $m_{\tau\tau}$.

2102 9.2 DNN-based event categorization

2103 Neural networks for event categorization are trained for each of the $\mu\tau_h$, $e\tau_h$, and $e\mu$
2104 channels, for 1 and 2 b-tag jets, giving $3 \times 2 = 6$ networks in total. In the training,
2105 the signal is taken to be all of the possible pseudoscalar mass m_a hypotheses together.
2106 The backgrounds for each DNN are taken to be a representative combination of the
2107 three major backgrounds: $Z \rightarrow \tau\tau$, $t\bar{t} + \text{jets}$, and fake backgrounds. The proportions of
2108 each background for each channel and b-tag jet multiplicity are taken from the yields
2109 in the $m_{\tau\tau}$ distribution. For instance, in the $\mu\tau_h$ 1 b-tag jet category, the composition
2110 of the background for training is 17.4% from $Z \rightarrow \tau\tau$, 42.4% from $t\bar{t} + \text{jets}$, and 40.2%
2111 fakes.

2112 The input variables capture the key differences between the signal and the back-
2113 ground:

- 2114 • Transverse momentum p_T of the electron and muon in the $e\tau_h$ and $\mu\tau_h$ channels,
2115 where the signal tends to have a softer p_T spectrum (lower energy) than the
2116 background.
- 2117 • p_T of the b-tag jet(s). The signal sample b-tag jet(s) tend to have softer p_T .
- 2118 • Invariant masses of the various objects ($\tau\tau$ legs and the b-tag jet(s)), which
2119 tend to be smaller for the signal samples.
- 2120 • The angular separation ΔR between pairs of the objects, where signal samples
2121 peak at smaller ΔR values.

- 2122 • The transverse mass between the missing transverse energy p_T^{miss} and each of
 2123 the four objects [82], defined as

$$m_T(\ell, p_T^{\text{miss}}) \equiv \sqrt{2p_T^\ell \cdot p_T^{\text{miss}}[1 - \cos(\Delta\phi)]} \quad (9.1)$$

2124 where p_T^ℓ is the transverse momentum of the object ℓ , and $\Delta\phi$ is the difference
 2125 in azimuthal angle between the object and the p_T^{miss} . Events from $t\bar{t}$ +jets and
 2126 jets faking τ_h backgrounds have larger p_T^{miss} resulting in larger transverse mass
 2127 values compared to the signal, which tends to have smaller p_T^{miss} that is also
 2128 more aligned with the lepton legs.

- 2129 • The variable D_ζ [82], defined as

$$D_\zeta \equiv p_\zeta - 0.85p_\zeta^{\text{vis}} \quad (9.2)$$

2130 where the ζ axis is the bisector of the transverse directions of the visible τ decay
 2131 products. p_ζ is the component of the p_T^{miss} along the ζ axis, and p_ζ^{vis} is the sum
 2132 of the components of the lepton p_T along the same axis. This variable captures
 2133 the fact that in signal the p_T^{miss} is small and approximately aligned with the $\tau\tau$.
 2134 In contrast, the $Z \rightarrow \tau\tau$ background tends towards large D_ζ values because the
 2135 p_T^{miss} is collinear to the $\tau\tau$, and the $t\bar{t}$ +jets events tend to have small D_ζ due to
 2136 a large p_T^{miss} not aligned with the $\tau\tau$.

- 2137 • For events with 2 b-tag jets, one additional variable is defined to capture the
 2138 difference in the invariant mass of the bb and the $\tau\tau$:

$$\Delta m_{a_1} \equiv (m_{bb} - m_{\tau\tau})/m_{\tau\tau} \quad (9.3)$$

2139 This variable peaks at zero for the $h \rightarrow aa \rightarrow 2b2\tau$ signal.

After training, events in data, MC, and embedded are evaluated with the six DNNs
 and assigned a raw score between 0 and 1 (background-like or signal-like). In order
 to flatten the distribution of the score and define score thresholds for categorizing
 events, the raw output scores are transformed with the function $\tilde{p}(n) = \text{arctanh}(p \times$
 $\tanh(n))/n$ where n is a positive integer. The thresholds of the DNN score used for
 signal/control region definition are determined using scans that optimize the signal
 sensitivity and are shown in Tables 9.1 and 9.2.

	1bNN $\tilde{p}(n = 1.5)$			
	SR1	SR2	SR3	CR
$\mu\tau_h$ 2018	> 0.98	$\in [0.95, 0.98]$	$\in [0.90, 0.95]$	< 0.90
$\mu\tau_h$ 2017	> 0.97	$\in [0.94, 0.97]$	$\in [0.90, 0.94]$	< 0.90
$\mu\tau_h$ 2016	> 0.97	$\in [0.94, 0.97]$	$\in [0.89, 0.94]$	< 0.89
	1bNN $\tilde{p}(n = 1.5)$			
	SR1	SR2	SR3	CR
$e\tau_h$ 2018	> 0.97	$\in [0.945, 0.97]$	$\in [0.90, 0.945]$	< 0.90
$e\tau_h$ 2017	> 0.985	$\in [0.965, 0.985]$	$\in [0.93, 0.965]$	< 0.93
$e\tau_h$ 2016	> 0.985	$\in [0.965, 0.985]$	$\in [0.93, 0.965]$	< 0.93
	1bNN $\tilde{p}(n = 2.5)$			
	SR1	SR2	SR3	CR
$e\mu$ 2018	> 0.99	$\in [0.95, 0.99]$	$\in [0.85, 0.95]$	< 0.85
$e\mu$ 2017	> 0.985	$\in [0.95, 0.985]$	$\in [0.85, 0.95]$	< 0.85
$e\mu$ 2016	> 0.99	$\in [0.95, 0.99]$	$\in [0.85, 0.95]$	< 0.85

Table 9.1: Event categorization based on DNN scores for events with exactly 1 b-tag jet (1bNN), for the three $\tau\tau$ channels and three eras.

9.3 Methodology for signal extraction

After events are divided into categories, the data is compared to the expected backgrounds in the signal region categories. Here, we describe the fundamental concepts behind hypothesis testing in high-energy physics, as well as how exclusion limits can be set on parameters whose true values we cannot measure, culminating in the modified frequentist method CL_S which is used to perform signal extraction in this

	2bNN $\tilde{p}(n = 1.5)$		
	SR1	SR2	CR
$\mu\tau_h$ 2018	> 0.99	$\in [0.96, 0.99]$	< 0.96
$\mu\tau_h$ 2017	> 0.98	$\in [0.94, 0.98]$	< 0.94
$\mu\tau_h$ 2016	> 0.97	$\in [0.93, 0.97]$	< 0.93
	2bNN $\tilde{p}(n = 1.5)$		
	SR1	SR2	CR
$e\tau_h$ 2018	> 0.96	NA	< 0.96
$e\tau_h$ 2017	> 0.985	NA	< 0.985
$e\tau_h$ 2016	> 0.96	NA	< 0.96
	2bNN $\tilde{p}(n = 2.5)$		
	SR1	SR2	CR
$e\mu$ 2018	> 0.98	$\in [0.94, 0.98]$	< 0.94
$e\mu$ 2017	> 0.97	$\in [0.93, 0.97]$	< 0.93
$e\mu$ 2016	> 0.98	$\in [0.94, 0.98]$	< 0.94

Table 9.2: Event categorization based on DNN scores for events with 2 b-tag jets (2bNN), for the three $\tau\tau$ channels and three eras.

2153 analysis.

2154 9.3.1 Model building and parameter estimation

In the frequentist interpretation of probability, an experiment measuring an observable can be repeated, resulting in different values of the observable, e.g. the invariant mass of a candidate Higgs boson in a search for the Higgs [97]. The ensemble of values of the observable x gives rise to the probability density function (PDF) $f(x)$, which has the important property that it is normalized to unity:

$$\int f(x) dx = 1.$$

A parametric family of PDFs

$$f(x|\alpha),$$

2155 read “ f of x given α ”, is referred to as a probability model or model. The parameters α
 2156 typically represent parameters of the theory or an unknown property of the detector’s
 2157 response. The parameters are not frequentist in nature, unlike x . Out of all the
 2158 parameters, typically only a few are of interest, and are called the parameters of
 2159 interest (POI), labeled μ here. The remaining are referred to as nuisance parameters
 2160 (NP) [97] and are labeled $\boldsymbol{\theta}$.

2161 $f(x)$ is the probability density for the observable in one event and we wish to
 2162 describe the probability density for a dataset with many events, $\mathcal{D} = \{x_1, \dots, x_n\}$,
 2163 called the total probability model \mathbf{f} . For instance, if we also have a prediction for
 2164 the total number of events expected, called ν , we also account for the overall Poisson
 2165 probability for observing n events given ν expected:

$$\mathbf{f}(\mathcal{D}|\nu, \alpha) = \text{Poisson}(n|\nu) \prod_{e=1}^n f(x_e|\alpha) \quad (9.4)$$

The likelihood function $L(\alpha)$ is numerically equivalent to $f(x|\alpha)$ for fixed x , or
 $\mathbf{f}(\mathcal{D}|\alpha)$ with \mathcal{D} fixed [97]. The likelihood function is not a probability density for α
 and is not normalized to unity:

$$\int L(\alpha) d(\alpha) \neq 1.$$

2166 i.e. the likelihood function is the value of f as a function of α given a fixed value of
 2167 x .

2168 To estimate the parameter α we use an estimator, which is a function of the
 2169 data. Take for example the measurement of data distributed according to a Gaussian
 2170 probability density $f(x|\mu, \sigma) = \text{Gauss}(x|\mu, \sigma)$. One possible estimator of the mean μ ,
 2171 is the mean of the measured data points $\bar{x} = \sum_{i=1}^n x_i/n$ [97].

2172 A commonly used estimator in physics is the maximum likelihood estimator
 2173 (MLE), defined as the value α which maximizes the likelihood function $L(\alpha)$. This

2174 value, labeled $\hat{\alpha}$, also maximizes $\ln L(\alpha)$ and minimizes $-\ln L(\alpha)$. By convention the
2175 $-\ln L(\alpha)$ is minimized, in a process called “fitting”, and the maximum likelihood
2176 estimate is called the “best fit value”.

2177 9.3.2 Hypothesis testing

2178 In this section we next introduce concepts related to hypothesis testing such as the
2179 test statistic constructed from the ratio of likelihood functions.

2180 The objective of a likelihood analysis is to distinguish different models repre-
2181 senting the various hypotheses, and determine the one that best explains the ex-
2182 perimental outcome. In a search for new physics, a signal is additive on top of the
2183 background. The background-only hypothesis is the null hypothesis, and the signal-
2184 plus-background hypothesis is the alternative.

2185 As a simple example, take the p -value test, for an experiment where we count
2186 events in the signal region, n_{SR} , and expect ν_B background events and ν_S events from
2187 the signal [97]. Then

2188 1. The null hypothesis (H_0), i.e. the background-only hypothesis in this experi-
2189 ment, with the probability modeled by $\text{Poisson}(n_{SR}|\nu_B)$.

2190 2. The alternate hypothesis (H_1), i.e. signal-plus-background hypothesis, with the
2191 probability modeled by $\text{Poisson}(n_{SR}|(\nu_B + \nu_S))$.

2192 The compatibility of the observed data ν_{SR}^0 and the null hypothesis, is quantified as
2193 the probability that the background-only hypothesis would produce at least as many
2194 events as was observed. This probability is the p -value:

$$p = \sum_{n=n_{SR}^0}^{\infty} \text{Poisson}(n|\nu_B). \quad (9.5)$$

2195 If the p -value is very small, we might reject the null hypothesis. The p -value is not the

2196 probability of the null hypothesis given the data; rather, it expresses the probability
2197 that data with a certain property was obtained, assuming the null hypothesis [97].

2198 The p -value is an example of a test statistic T , which maps the data to a single
2199 real number. The Neyman-Pearson lemma states that out of the infinite possibilities
2200 of choices of test statistic, the uniformly most powerful test statistic is the likelihood
2201 ratio T_{NP} [97]:

$$T_{NP}(\mathcal{D}) = \frac{L(\mathcal{D}|H_1)}{L(\mathcal{D}|H_0)} \quad (9.6)$$

To reiterate, the test statistic T is a real-valued function of the data, implying that
a particular probability model $\mathbf{f}(\mathcal{D}|\boldsymbol{\alpha})$ implies a distribution of the test statistic,
 $f(T|\boldsymbol{\alpha})$, which depends on the value of $\boldsymbol{\alpha}$. With this distribution in hand, the p -value
can be evaluated in the following equivalent formulations:

$$p(\boldsymbol{\alpha}) = \int_{T_0}^{\infty} f(T|\boldsymbol{\alpha}) dT \quad (9.7)$$

$$= \int \mathbf{f}(\mathcal{D}|\boldsymbol{\alpha}) \theta(T(\mathcal{D}) - T_0) d\mathcal{D} \quad (9.8)$$

$$= P(T \geq T_0|\boldsymbol{\alpha}) \quad (9.9)$$

2202 where T_0 is the value of T based on the observed data, and $\theta()$ is the Heaviside
2203 function. The size of the test is conventionally chosen to be 10%, 5%, or 1%. As
2204 the p -value depends on $\boldsymbol{\alpha}$ (both the POI and NP), the null hypothesis should not be
2205 rejected if the p -value is larger than the size of the test for any value of the nuisance
2206 parameters.

2207 9.3.3 Confidence intervals

2208 In an example of the measurement of the Standard Model Higgs boson, $\boldsymbol{\alpha}_{\text{POI}} =$
2209 $(\sigma/\sigma_{SM}, M_H)$, with σ/σ_{SM} is the ratio of the production cross-section for Higgs with

respect to its value in the SM, and M_H is the unknown mass of the Higgs, values
 of these parameters outside specific bounds are said to be “excluded at the 95%
 confidence level”. These allowed regions are called confidence levels or confidence
 regions, and the parameter values outside of them are considered excluded [97]. A
 95% confidence interval does not mean that there is a 95% chance that the true value
 of the parameter is inside the interval. Rather, a 95% confidence interval covers the
 true value 95% of the time (even though we do not know the true value).

To construct a confidence interval for a parameter α , the Neyman Construction
 is used to invert a series of hypothesis tests; i.e. for each possible value of α , the null
 hypothesis is treated as α , and we perform a hypothesis test based on a test statistic.
 To construct a 95% confidence interval, we construct a series of hypothesis tests with
 size of 5%. The confidence interval $I(\mathcal{D})$ is constructed by taking the set of parameter
 values $\boldsymbol{\alpha}$ where the null hypothesis is accepted:

$$I(\mathcal{D}) = \{\boldsymbol{\alpha} | P(T(\mathcal{D}) > k_\alpha | \boldsymbol{\alpha}) < \alpha\}, \quad (9.10)$$

where $T(\mathcal{D})$ is the test statistic, and the last α (not bolded) and the subscript k_α
 refer to the size of the test. A schematic of the Neyman construction is shown in Fig.
 9.1. In a more generalized case, the x -axis is the test statistic T .

9.3.4 Profile likelihood ratio

In this section we describe a frequentist statistical procedure based on the profile
 likelihood ratio test statistic, which is implemented using asymptotic distributions.

With a multi-parameter likelihood function $L(\boldsymbol{\alpha})$, the the maximum likelihood of
 one specific parameter α_p with other parameters $\boldsymbol{\alpha}_o$ fixed, is called the conditional
 maximum likelihood estimate and is denoted $\hat{\alpha}_p(\boldsymbol{\alpha}_0)$. The process of choosing specific
 values of the nuisance parameters for a given value of μ , $\mathcal{D}_{\text{simulated}}$, and value of global

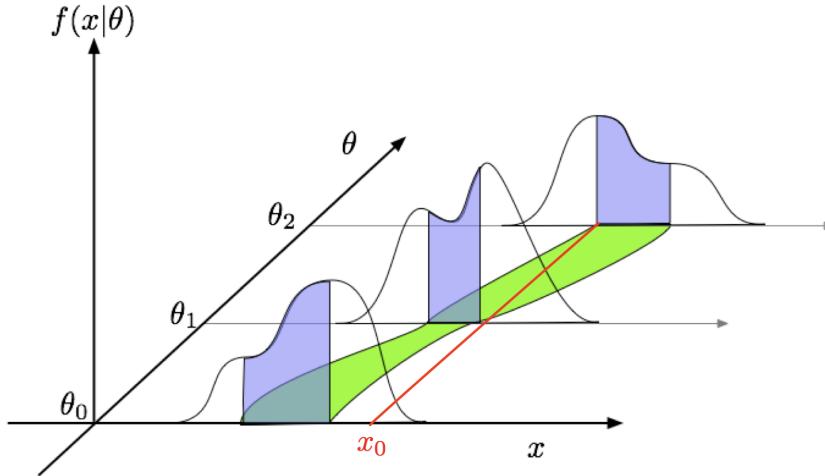


Figure 9.1: Schematic of the Neyman construction for confidence intervals [97]. For each value of θ , we find a region in x where $\int f(x|\theta)dx$ satisfies the size of the test (blue). These regions form a confidence belt (green). The intersection of the observation x_0 (red) with the confidence belt defines the confidence interval $[\theta_1, \theta_2]$ [97].

2233 observables \mathcal{G} is called profiling. From the full list of parameters $\boldsymbol{\alpha}$, we denote the
2234 parameter of interest μ , and the nuisance parameters $\boldsymbol{\theta}$.

2235 We construct the profile likelihood ratio,

$$\lambda(\mu) = \frac{L(\mu, \hat{\boldsymbol{\theta}}(\mu))}{L(\mu, \hat{\boldsymbol{\theta}})} \quad (9.11)$$

2236 which depends explicitly on the parameter of interest μ , implicitly on the data \mathcal{D}_{sim}
2237 and global observables \mathcal{G} , and is independent of the nuisance parameters $\boldsymbol{\theta}$, which
2238 have been eliminated in profiling [97].

2239 The main conceptual reason for constructing the test statistic from the profile
2240 likelihood ratio is that asymptotically (i.e. for measurements with many events) the
2241 distribution of the profile likelihood ratio $\lambda(\mu = \mu_{\text{true}})$ is independent of the values of
2242 the nuisance parameters [97].

2243 The following p -value is used to quantify the consistency with the hypothesis of a
2244 signal strength of μ :

$$p_\mu = \int_{\tilde{q}_{\mu,\text{obs}}}^{\infty} f(\tilde{q}_\mu | \mu, \hat{\boldsymbol{\theta}}(\mu, \text{obs})) d\tilde{q}_\mu \quad (9.12)$$

2245 9.3.5 Modified frequentist method: CL_S

2246 In the modified frequentist method called CL_S , to test a hypothesis with signal, we
 2247 define p'_μ as a ratio of p -values [97]:

$$p'_\mu = \frac{p_\mu}{1 - p_b} \quad (9.13)$$

2248 where p_b is the p -value derived under the background-only hypothesis:

$$p_b = 1 - p_0 \equiv 1 - \int_{\tilde{q}_{\mu,\text{obs}}}^{\infty} f(\tilde{q}_\mu | 0, \hat{\theta}(\mu = 0, \text{obs})) d\tilde{q}_\mu. \quad (9.14)$$

2249 The CL_S upper limit on μ , denoted μ_{up} , is obtained by solving for $p'_{\mu_{up}} = 5\%$.
 2250 If testing the compatibility of the data with the background-only hypothesis, we
 2251 consider the p_b value defined above and conventionally convert it into the quantile
 2252 or “sigma” of a unit Gaussian. z standard deviations (e.g. $z = 5$ in “ 5σ ”) means
 2253 that the probability of falling above these standard deviations, equals p_b (e.g. 3σ
 2254 corresponds to $p_b = 2.7 \times 10^{-3}$ or 95.43%, and 5σ corresponds to $p_b = 5.7 \times 10^{-7}$ or
 2255 99.999943%).

2256 **Chapter 10**

2257 **Results**

2258 In this chapter, Section 10.1 presents the results from the $h \rightarrow aa \rightarrow bb\tau\tau$ analysis
2259 performed on 137 fb^{-1} of data from the full CMS Run-2 dataset in the years 2016 to
2260 2018, with interpretations provided for different 2HDM+S scenarios. This analysis
2261 was combined with a different search in the $h \rightarrow aa \rightarrow bb\mu\mu$ final state, which was
2262 also performed on the full Run-2 dataset. The combination procedure and results
2263 from the combined analyses ($h \rightarrow aa \rightarrow bb\ell\ell$, with $\ell = \mu, \tau$) are detailed in 10.2.
2264 The combined analysis places some of the most stringent limits to date at CMS for
2265 2HDM+S scenarios in the light scalar mass range $m_a = 12 \text{ GeV}$ to 60 GeV .

2266 **10.1 Results from $bb\tau\tau$**

2267 In each of the three $\tau\tau$ channels studied ($\mu\tau_h$, $e\tau_h$, and $e\mu$), events are divided based
2268 on whether they contain exactly 1 or 2 b-tag jets, and further divided into signal
2269 and control regions (SRs and CRs) using the DNN categorization score as described
2270 in Section 9.2. The control regions demonstrate good agreement between observed
2271 events in data, and the sum of the contributions from expected backgrounds that
2272 are modeled in simulated and embedded samples. The signal regions are defined to
2273 be sensitive to the $h \rightarrow aa \rightarrow bb\tau\tau$ signal. The postfit final observed and expected

2274 distributions of the di-tau invariant mass $m_{\tau\tau}$ reconstructed with SVFit (described
2275 in Section 5.2) are shown in Fig. 10.1 for the $\mu\tau_h$ channel, Fig. 10.2 for the $e\tau_h$
2276 channel, and Fig. 10.3 for the $e\mu$ channel. In all figures, the hypothesized yield for
2277 the $h \rightarrow aa \rightarrow bb\tau\tau$ signal is shown for the pseudoscalar mass $m_a = 35$ GeV and
2278 assuming a branching fraction $B(H \rightarrow aa \rightarrow bb\tau\tau) = 10\%$.

2279 The 95% CL expected and observed exclusion limits on the signal strength of the
2280 branching fraction $B(h \rightarrow aa \rightarrow bb\tau\tau)$ as a function of the pseudoscalar mass m_a
2281 ranging from 12 GeV to 60 GeV, are shown for the three $\tau\tau$ channels and all three
2282 channels combined in Fig. 10.4. The limits are shown as percentages and normalized
2283 to the production cross-section of the Standard Model Higgs boson. No excess of
2284 events above the Standard Model expectations is observed. In the limits for the three
2285 $\tau\tau$ channels combined, expected (observed) limits range from 1.4 to 5.6% (1.7 to
2286 7.6%) for pseudoscalar masses between 12 and 60 GeV.

2287 The $e\mu$ channel is the only channel that has signal sensitivity to the $m_a = 12$
2288 GeV pseudoscalar mass hypothesis, because the minimum required spatial separation
2289 $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ between the two τ legs is smaller than the other two channels
2290 ($\Delta R < 0.3$ for $e\mu$, compared to $\Delta R < 0.4$ for the other two channels). This decreased
2291 ΔR requirement results in better signal acceptance for low mass signals for the $e\mu$
2292 channel. The $\mu\tau_h$ and $e\tau_h$ channels are most sensitive to the intermediate mass points
2293 studied, since the analysis targets a resolved signature: at low mass points, the tau
2294 legs are boosted, and at high mass points, the $m_{\tau\tau}$ distributions in signal have larger
2295 overlap with background distributions. In the combination of the three $\tau\tau$ channels,
2296 the limit for $m_a = 12$ GeV comes only from the $e\mu$ channel, and the best sensitivity
2297 is attained at intermediate mass points around $m_a = 20$ GeV to 45 GeV.

2298 To set limits on the branching fraction of the 125 GeV Higgs to the two pseu-
2299 doscalars, $B(h \rightarrow aa)$, we interpret the results in four types of 2HDM+S, which were
2300 introduced in Section 1.4. In 2HDM+S, the theorized branching fraction of the pseu-

2301 doscalars depends on the 2HDM+S model type, the pseudoscalar mass m_a , and the
2302 ratio of the two Higgs doublets' vacuum expectation values $\tan \beta$. In Type I models,
2303 the branching fraction is independent of $\tan \beta$, while in Types II, III, and IV, it is
2304 a function of m_a and $\tan \beta$. Limits for the $bb\tau\tau$ final state as a function of m_a for
2305 2HDM+S Type I (valid for all $\tan \beta$ values), Type II with $\tan \beta = 2.0$, Type III with
2306 $\tan \beta = 2.0$, and Type IV with $\tan \beta = 0.6$ are overlaid and shown in Fig. 10.5a.

2307 **10.2 Combination with $bb\mu\mu$ final state**

2308 Results from this analysis for the $h \rightarrow aa \rightarrow bb\tau\tau$ final state are combined with the
2309 analysis for the $h \rightarrow aa \rightarrow bb\mu\mu$ final state [98]. While the predicted branching ratio
2310 for $aa \rightarrow bb\mu\mu$ is comparatively small, the $bb\mu\mu$ final state has competitive results
2311 due to the excellent di-muon resolution measured by CMS. The $bb\mu\mu$ analysis uses
2312 an unbinned fit to the data using the di-muon mass $m_{\mu\mu}$ distribution. Details can be
2313 found in [98].

2314 Combining the results is possible since the $bb\tau\tau$ analysis explicitly rejects events
2315 with extra leptons, so there is no overlap between the events studied in the $bb\tau\tau$
2316 analysis and the $bb\mu\mu$ analysis. In the statistical combination, several systematic
2317 uncertainties are treated as correlated: the integrated luminosity normalization, the
2318 b-tagging scale factor, the scale factors related to muon reconstruction, identifica-
2319 tion, and trigger efficiencies, the inefficiency in the ECAL trigger readout, and the
2320 theoretical uncertainties related to signal modeling.

2321 Since the results in both final states are statistically limited, the combination ben-
2322 efits from the additional data. For $m_a = 35$ GeV, all systematic uncertainties amount
2323 to around 6% of the total uncertainty, with the dominant systematic uncertainties
2324 coming from jet energy systematics in the $bb\mu\mu$ final state, theoretical uncertainties
2325 in the signal, and uncertainties in the QCD multijet backgrounds in the $e\mu$ channel

2326 of the $bb\tau\tau$ final state.

2327 The mass distributions of the di-muon and di-tau objects ($m_{\mu\mu}$ and $m_{\tau\tau}$) are
2328 compared to the data in a combined maximum likelihood fit to derive upper limits
2329 on $B(h \rightarrow aa)$. The observed limits at 95% CL on $B(h \rightarrow aa)$ for different 2HDM+S
2330 scenarios, are shown for the search for $h \rightarrow aa \rightarrow bb\mu\mu$ in Fig. 10.5b, and the
2331 combined analyses $h \rightarrow aa \rightarrow bb\ell\ell$ in Fig. 10.6.

2332 Exclusion limits in a two-dimensional plane as a function of $\tan\beta$ and m_a are
2333 set for 2HDM+S Types II, III, and IV in Fig. 10.7. The most stringent constraints
2334 are observed for 2HDM+S type III because of large branching fractions predicted in
2335 theory, with predicted branching fractions between 0.47 and 0.42 for $\tan\beta = 2.0$ and
2336 values of m_a between 15 and 60 GeV, compared to the observed 95% CL upper limits
2337 which are between 0.08 and 0.03. For 2HDM+S type IV, the predicted branching
2338 fractions from theory are between 0.26 and 0.20 for $\tan\beta = 0.6$ for values of m_a
2339 between 15 and 60 GeV, and the 95% CL observed upper limits are between 0.12 and
2340 0.05.

2341 The combined results from $h \rightarrow aa \rightarrow bb\ell\ell$ are compared with CMS results in
2342 other final states as a function of the pseudoscalar mass m_a : for 2HDM+S type I in
2343 Fig. 10.8, type II with $\tan\beta = 2.0$ in Fig. 10.9, and type III with $\tan\beta = 2.0$ in Fig.
2344 10.10. In other scenarios, e.g. type III with $\tan\beta = 5.0$, more stringent limits are set
2345 by analyses in other final states, $\mu\mu\tau\tau$ in this case. Other summary plots for other
2346 model types and $\tan\beta$ values can be found at [99].

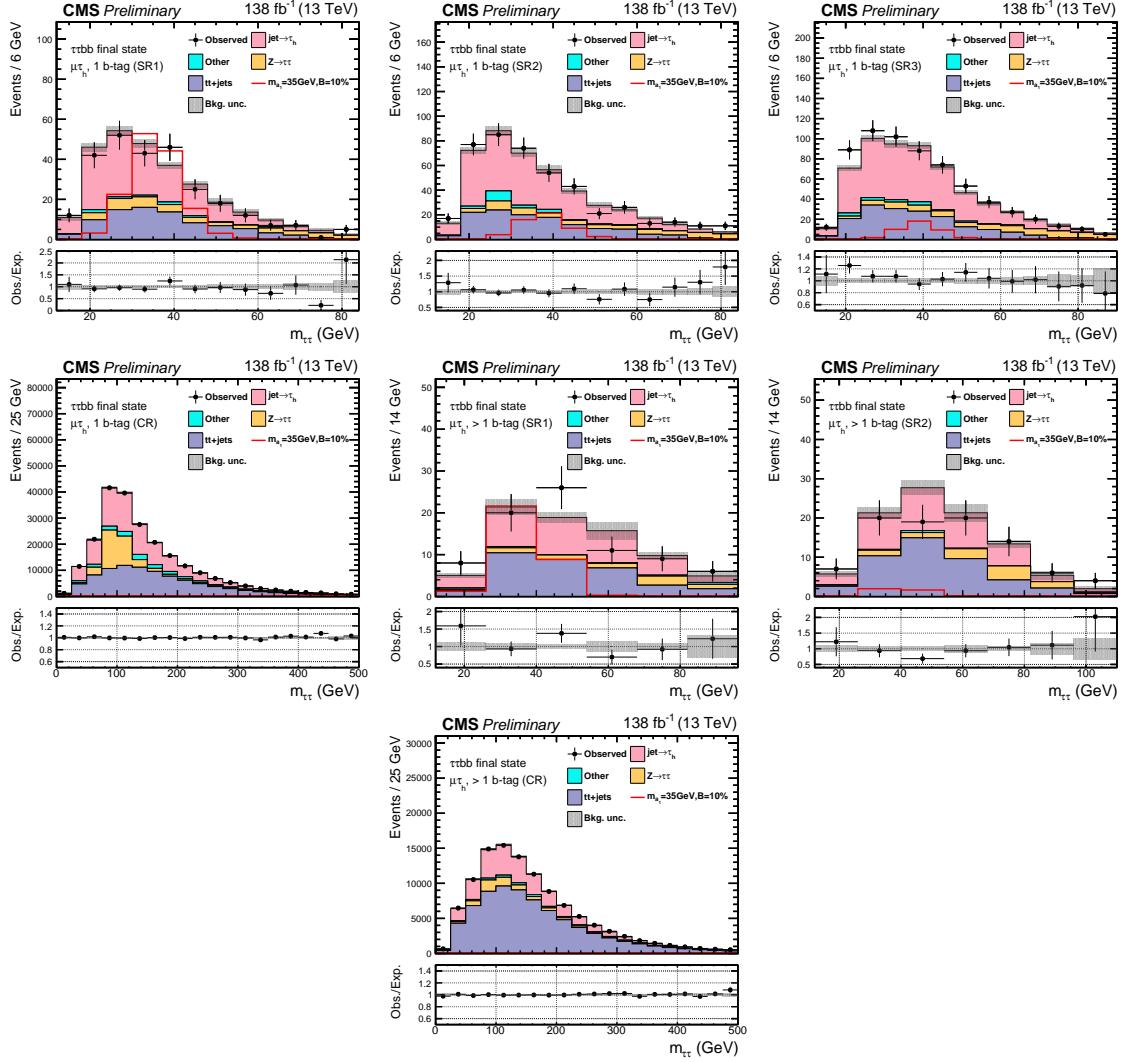


Figure 10.1: Postfit final $m_{\tau\tau}$ observed and expected distributions, and the observed/expected ratios, in the $\mu\tau_h$ channel [42]. Events are divided into the 1 b-tag jet signal regions (SR1, SR2, SR3) (*top row*), 1 b-tag jet control region (*middle row*), 2 b-tag jet signal regions (SR1, SR2) (*middle row*), and lastly the 2 b-tag jet control region (CR) (*bottom*). Statistical and systematic sources of uncertainties in the expected events are added in quadrature and labeled “Bkg. unc” (*shaded gray*). The dominant backgrounds in all categories are jets faking the τ_h leg (*pink*), $Z \rightarrow \tau\tau$ (*orange*), and $t\bar{t}+j$ ets (*purple*). For illustrative purposes, the beyond-Standard Model signal yield from $h \rightarrow aabb\tau\tau$ is shown for the pseudoscalar mass hypothesis $m_a = 35$ GeV, assuming a branching fraction $B(h \rightarrow aa \rightarrow bb\tau\tau) = 10\%$ (*red line*).

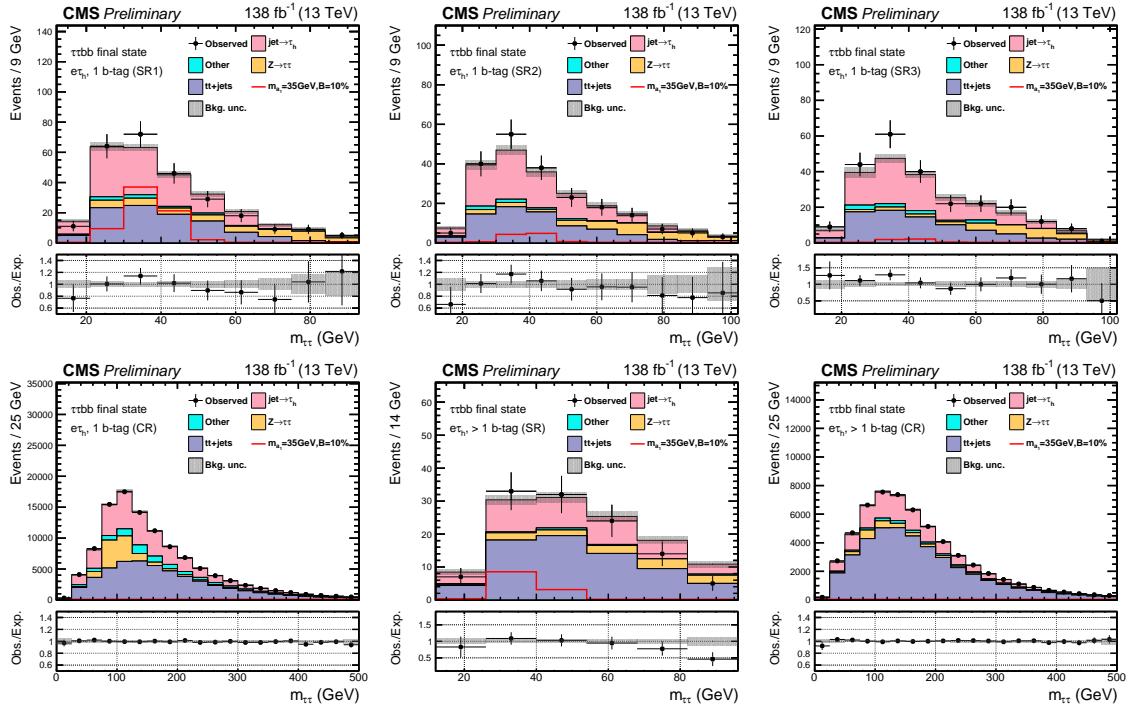


Figure 10.2: Postfit final observed and expected $m_{\tau\tau}$ distributions, and the observed/expected ratios, in the $e\tau_h$ channel [42]. Events are divided into the 1 b-tag jet signal regions (SR1, SR2, SR3) (*top row*), the 1 b-tag jet control region (CR) (*bottom row*), and 2 b-tag jet signal region (SR) and control region (CR) (*bottom row*). Statistical and systematic sources of uncertainties in the expected events are added in quadrature and labeled “Bkg. unc” (*shaded gray*). In this channel, the dominant backgrounds are jets faking the τ_h leg (*pink*), $Z \rightarrow \tau\tau$ (*orange*), and $t\bar{t}+{\rm jets}$ (*purple*). For illustrative purposes, the beyond-Standard Model signal yield from $h \rightarrow aabb\tau\tau$ is shown for the pseudoscalar mass hypothesis $m_a = 35$ GeV, assuming a branching fraction $B(h \rightarrow aa \rightarrow bb\tau\tau) = 10\%$ (*red line*).

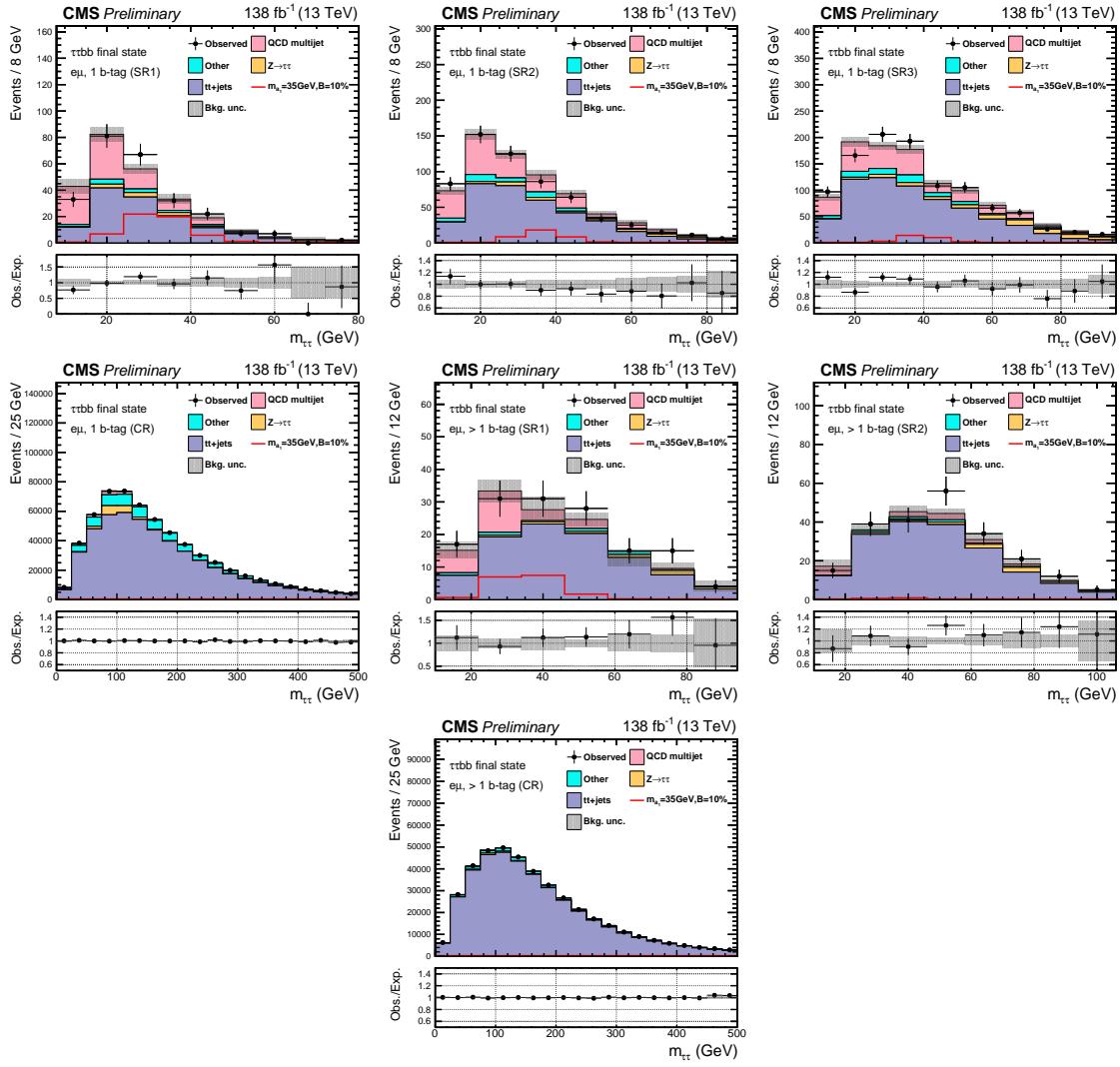


Figure 10.3: Postfit final observed and expected $m_{\tau\tau}$ distributions, and the observed/expected ratios, in the $e\mu$ channel [42]. Events are divided into the 1 b-tag jet signal regions (SR1, SR2, and SR3) (*top row*), 1 b-tag jet control region (CR) (*middle row*), 2 b-tag jet signal regions (SR1 and SR2) (*middle row*), and 2 b-tag jet control region (CR) (*bottom row*). Statistical and systematic sources of uncertainties in the expected events are added in quadrature and labeled “Bkg. unc” (*shaded gray*). The $t\bar{t}+j$ process (*purple*) is a major background, and in the signal regions the QCD multijet (*pink*) is also a major background. TFor illustrative purposes, the beyond-Standard Model signal yield from $h \rightarrow aabb\tau\tau$ is shown for the pseudoscalar mass hypothesis $m_a = 35$ GeV, assuming a branching fraction $B(h \rightarrow aa \rightarrow bb\tau\tau) = 10\%$ (*red line*).

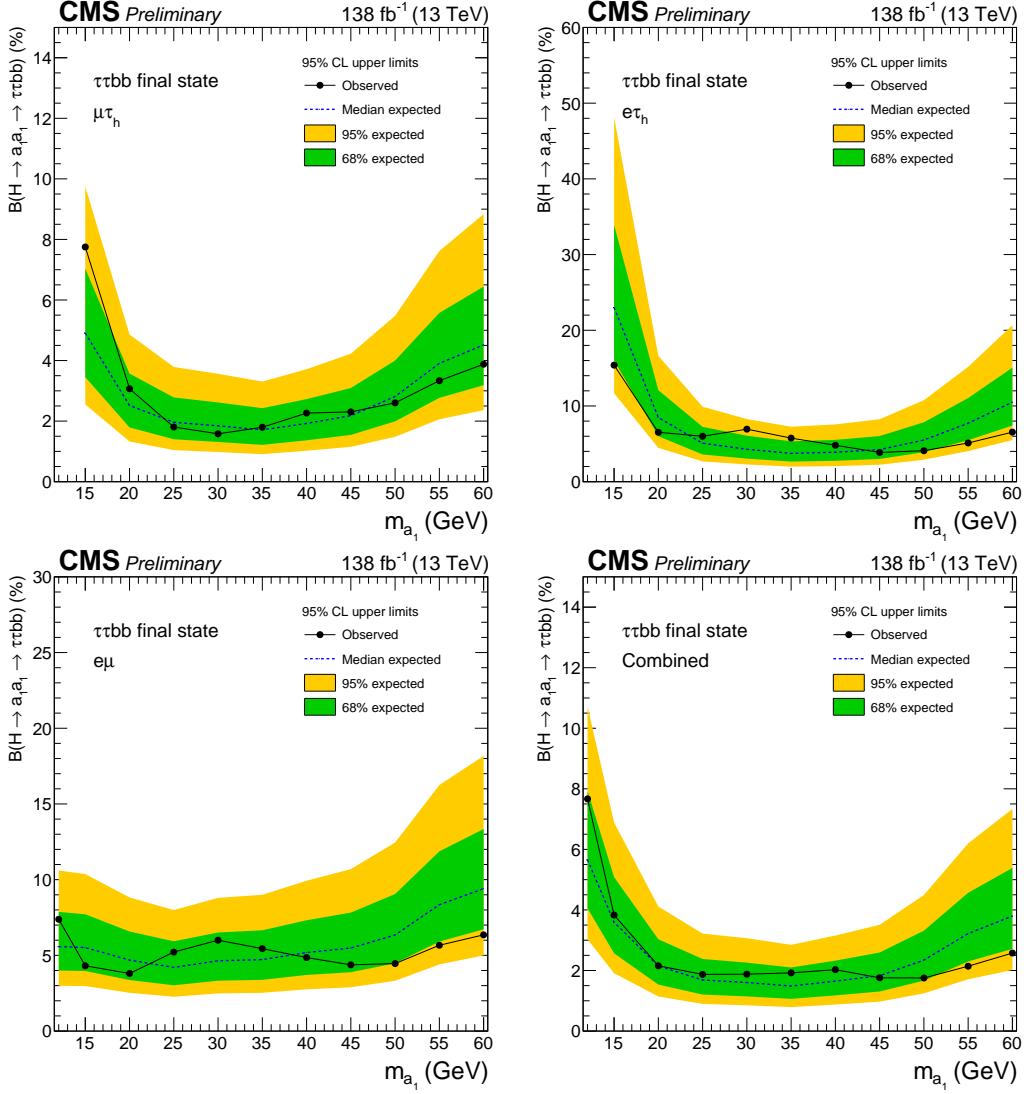
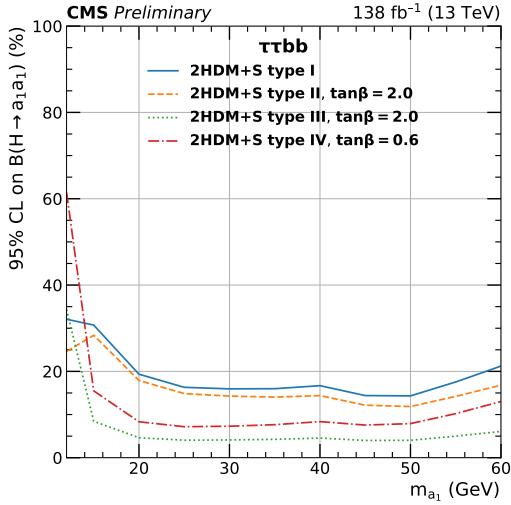
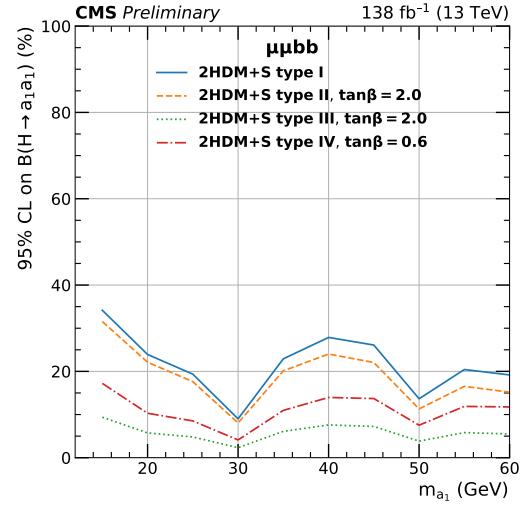


Figure 10.4: Observed 95% CL exclusion limits (*black, solid lines*) and expected 95% CL and 68% CL limits (*shaded yellow and green*) on the branching fraction $B(h \rightarrow aa \rightarrow bb\tau\tau)$ in percentages, assuming the Standard Model production for the 125 GeV Higgs (h). Limits are shown for the $\mu\tau_h$ channel (*top left*), the $e\tau_h$ channel (*top right*), and the $e\mu$ channel (*bottom left*), and lastly the combination of all three channels (*bottom right*) [42]. The dataset corresponds to 138 fb^{-1} of data collected in the years 2016-2018 at a center-of-mass energy 13 TeV. Only the $e\mu$ channel has sensitivity to the mass hypothesis $m_a = 12$ GeV. The best sensitivity is attained at intermediate mass points.



(a) $bb\tau\tau$ final state.



(b) $bb\mu\mu$ final state.

Figure 10.5: Observed 95% CL upper limits on $B(h \rightarrow aa)$ in %, for the $bb\tau\tau$ final state (*left*) and $bb\mu\mu$ final state (*right*) using the full Run 2 integrated luminosity of 138 fb^{-1} in 2HDM+S type I (blue), type II with $\tan\beta = 2.0$ (orange dashed), type III with $\tan\beta = 2.0$ (dotted green), and type IV with $\tan\beta = 0.6$ (red dashed) [42]. Linear interpolation is used between points in the graphs. The $\tan\beta$ values chosen here correspond to the most stringent limits in each model.

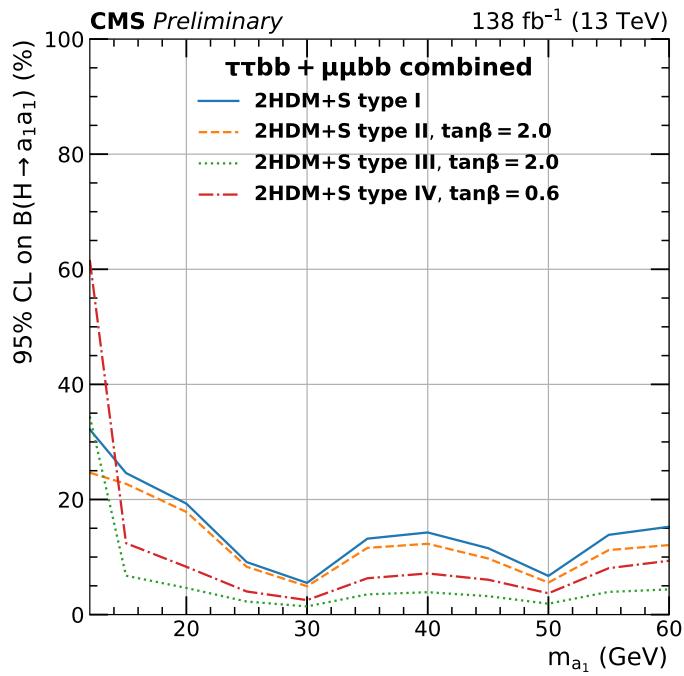


Figure 10.6: Observed 95% CL upper limits on the branching fraction of the 125 GeV Higgs boson to two pseudoscalars, $B(h \rightarrow aa)$, in percentages, as a function of the pseudoscalar mass m_a , in 2HDM+S type I (blue), type II with $\tan\beta = 2.0$ (orange dashed), type III with $\tan\beta = 2.0$ (dotted green), and type IV with $\tan\beta = 0.6$ (red dashed), for the combination of $bb\mu\mu$ and $bb\tau\tau$ channels using the full Run 2 integrated luminosity of 138 fb^{-1} [42].

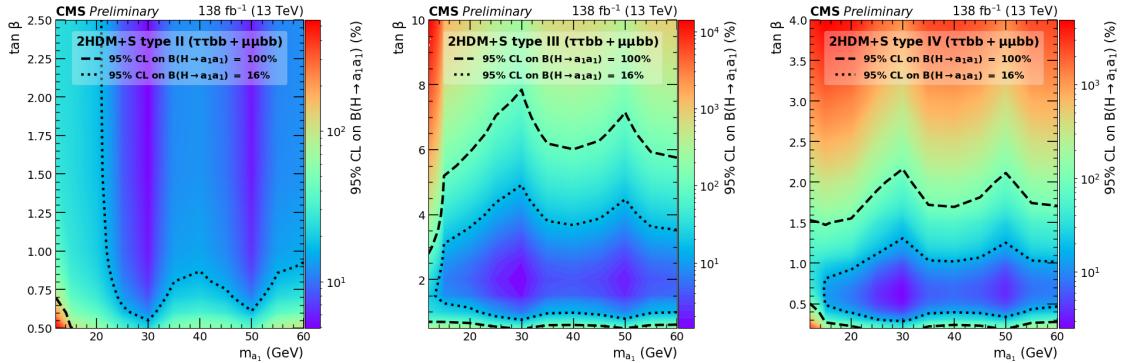


Figure 10.7: Observed 95% CL upper limits on $\mathcal{B}(h \rightarrow aa)$ in %, for the combination of $bb\mu\mu$ and $bb\tau\tau$ channels using the full Run 2 integrated luminosity of 138 fb^{-1} for Type II (*left*), Type III (*middle*), and Type IV (*right*) 2HDM+S in the $\tan \beta$ vs. m_a phase space. The contours (*dashed black*) correspond to branching fractions of 100% and 16%, where 16% is the combined upper limit on Higgs boson to undetected particle decays from previous Run-2 results. All points inside the contour are allowed within that upper limit. Linear extrapolation has been used between different points on the figures [42].

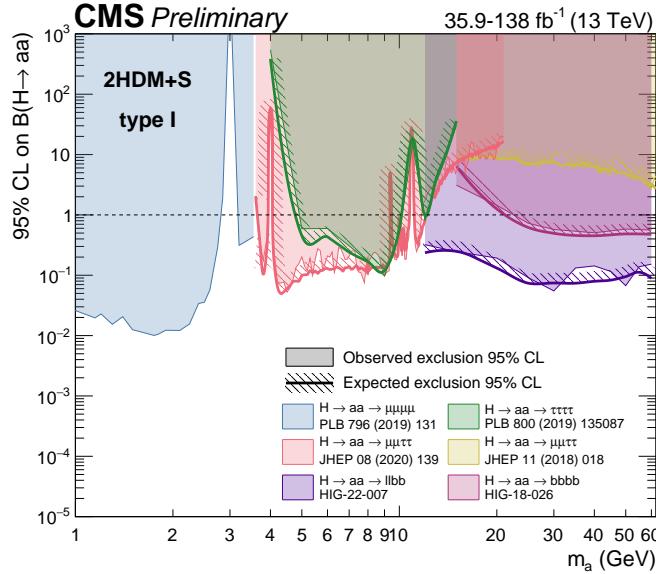


Figure 10.8: Summary plot of current 95% limits on the branching ratio of the 125 GeV Higgs boson to two pseudoscalars, normalized to the Standard Model Higgs production cross-section, $\frac{\sigma(h)}{\sigma_{\text{SM}}} \times B(h \rightarrow aa)$ in the 2HDM+S type I scenario performed with data collected at 13 TeV [99]. Results from different final states studied at CMS are overlaid on this figure: $\mu\mu\mu\mu$ (blue), $\tau\tau\tau\tau$ (green), boosted $2\mu 2\tau$ (red), resolved $2\mu 2\tau$ (yellow), $bbbb$ (magenta), and the combined result for $\ell\ell bb$ ($\ell = \mu, \tau$) (purple).

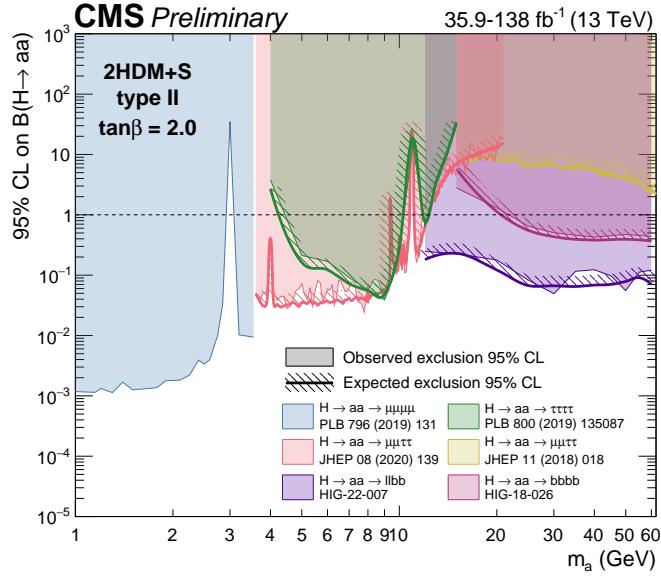


Figure 10.9: Summary plot of current observed and expected 95% CL limits on the branching ratio of the 125 GeV Higgs boson to two pseudoscalars, normalized to the Standard Model Higgs production cross-section, $\frac{\sigma(h)}{\sigma_{\text{SM}}} \times B(h \rightarrow aa)$, in the 2HDM+S type II scenario with $\tan \beta = 2.0$, obtained at CMS with data collected at 13 TeV [99]. Results from different final states studied at CMS are overlaid on this figure: $\mu\mu\mu\mu$ (blue), $\tau\tau\tau\tau$ (green), boosted $2\mu 2\tau$ (red), resolved $2\mu 2\tau$ (yellow), $bbbb$ (magenta), and the combined result for $\ell\ell bb$ ($\ell = \mu, \tau$) (purple).

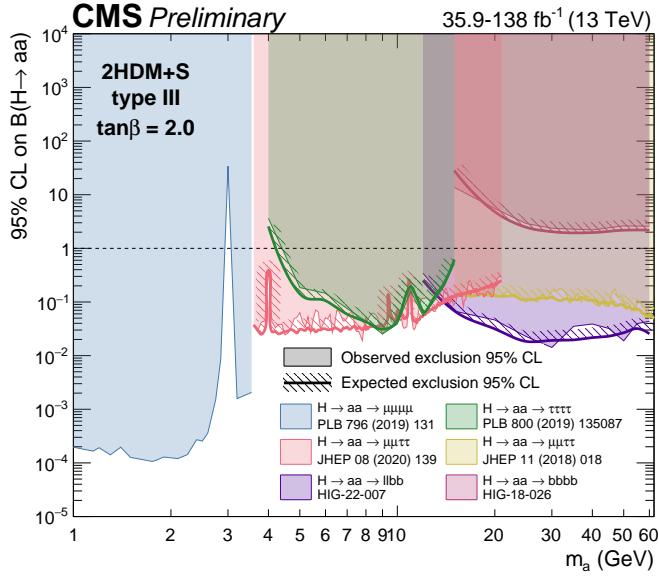


Figure 10.10: Summary plot of current observed and expected 95% CL limits on the branching ratio of the 125 GeV Higgs boson to two pseudoscalars, normalized to the Standard Model Higgs production cross section, $\frac{\sigma(h)}{\sigma_{SM}} \times B(h \rightarrow aa)$ in the 2HDM+S type-III scenario with $\tan \beta = 2.0$, obtained at CMS with data collected at 13 TeV [99]. Results from different final states studied at CMS are overlaid on this figure: $\mu\mu\mu\mu$ (blue), $\tau\tau\tau\tau$ (green), boosted $2\mu 2\tau$ (red), resolved $2\mu 2\tau$ (yellow), $bbbb$ (magenta), and the combined result for $\ell\ell bb$ ($\ell = \mu, \tau$) (purple).

2347 **Chapter 11**

2348 **Asymmetric exotic Higgs decays**

2349 This chapter presents progress towards a search for exotic Higgs decays to two light
2350 scalars with unequal mass ($h \rightarrow a_1 a_2$) final states with bottom quarks and τ leptons,
2351 with plans to interpret the results in the context of Two Real Singlet Models (TRSMs),
2352 described in Section 1.5. Compared to the symmetric decay scenario $h \rightarrow aa$ which
2353 has been studied in multiple final states at CMS with stringent limits set on the
2354 various 2HDM+S scenarios, this asymmetric decay scenario has not been directly
2355 searched for at the CMS experiment. Section 11.1 lists the mass hypotheses of the
2356 new particles a_1 and a_2 that will be studied. Section 11.2 describes the studies on
2357 which channels the analysis will be carried out in. Section 11.3 shows the control
2358 plots produced using the analysis framework that will be used for this analysis.

2359 **11.1 Signal masses**

2360 As discussed in Section 1.5, $h \rightarrow a_1 a_2$ can result in a “cascade” decay if one of the
2361 scalars, a_2 is sufficiently heavy ($m_{a_2} > 2m_{a_1}$). The “non-cascade” case is where the
2362 light scalars decay directly to Standard Model particles.

2363 The mass hypotheses (mass points) (m_{a_1}, m_{a_2}) studied here are:

- 2364 • *Cascade mass points:* (15, 30), (15, 40), (15, 50), (15, 60), (15, 70), (15, 80),
 2365 (15, 90), (15, 100), (15, 110), (20, 40), (20, 50), (20, 60), (20, 70), (20, 80), (20,
 2366 90), (20, 100), (30, 60), (30, 70), (30, 80), and (30, 90) GeV

- 2367 • *Non-cascade mass points:* (15, 20), (15, 30), (20, 30), (20, 40), (30, 40), (30,
 2368 50), (30, 60), (40, 50), (40, 60), (40, 70), (40, 80), (50, 60), and (50, 70) GeV

2369 Samples were produced using the MadGraph5_aMCatNLO event generator, for each
 2370 signal mass point in the gluon-gluon fusion (ggF) and vector boson fusion (VBF)
 2371 production modes of the 125 GeV Higgs boson. In the sample generation, the decays
 2372 of a to Standard Model particles were specified to be decays to bottom quarks or τ
 2373 leptons.

2374 11.2 Cascade scenario signal studies

2375 Studies of the signal phenomenology in the cascade scenario were performed to de-
 2376 termine the viability of the $4b2\tau$ and/or $2b4\tau$ channels.

2377 Cross sections and branching fractions of the $4b2\tau$ and $2b4\tau$ final states were
 2378 compared using cross-section predictions provided by the authors of [7]. For an
 2379 example mass point $m_{a_2} = 80$ GeV, $m_{a_1} = 30$ GeV, the branching fractions to
 2380 $4b2\tau$ is ten times larger than $2b4\tau$: $B(h \rightarrow a_1 a_2 \rightarrow 3a_1 \rightarrow 4b2\tau) = 0.00857$, vs.
 2381 $B(h \rightarrow a_1 a_2 \rightarrow 3a_1 \rightarrow 2b4\tau) = 0.00068$. The $4b2\tau$ final state is chosen for this
 2382 analysis.

2383 In general the four b-flavor jets have low p_T at generator level, as illustrated for
 2384 example mass points (100, 15) GeV and (40, 20) GeV in Fig. 11.1. The p_T distribution
 2385 of the sub-leading jet peaks at an energy below 20 GeV, with the third and fourth
 2386 jets tending to have even softer energies.

2387 An event category with three or more b-tag jets was determined to be infeasible
 2388 due to low statistics in this category, due to the difficulties in reconstructing the third

2389 and fourth b-flavor jets which have very low transverse momenta p_T . Event categories
 2390 with exactly 1 b-tag jet and ≥ 2 b-tag jets will be used.

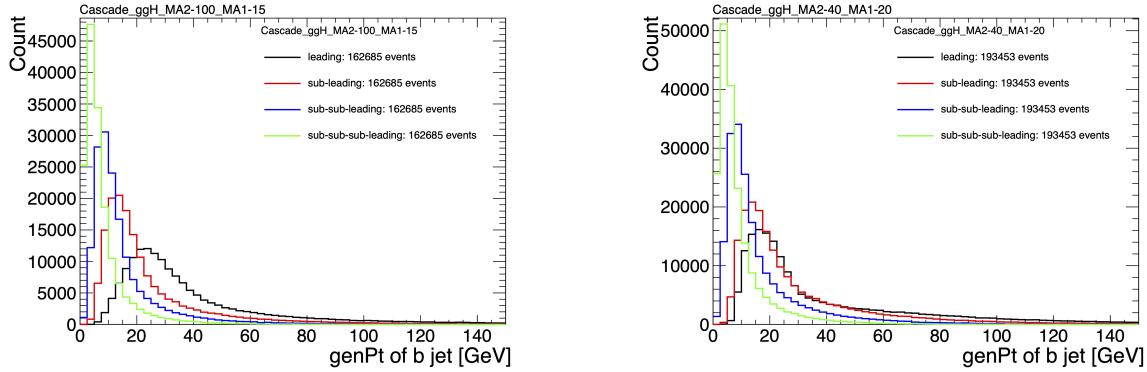


Figure 11.1: Generator-level b-flavor jet transverse momenta p_T , for $h \rightarrow a_1 a_2$ cascade scenario in the $4b2\tau$ final state, for mass hypotheses $(m_{a_1}, m_{a_2}) = (100, 15)$ GeV (*left*) and $(40, 20)$ GeV (*right*). In each plot the generator-level p_T of the leading (*black*), sub-leading (*red*), third (*blue*), and fourth (*light green*) are overlaid.

2391 In the $4b2\tau$ final state, the possibility of the leading and sub-leading b-tag jets
 2392 being sufficiently close in ΔR to require boosted jet reconstruction techniques was
 2393 explored. In the $4b2\tau$ case, the two b-flavor-jets in the generated event that were
 2394 spatially closest in ΔR were considered as one object. This two b-flavor jet object was
 2395 spatially matched in ΔR to the jets reconstructed with the standard AK4 algorithm
 2396 which uses a cone size of $\Delta R = 0.4$. The quality of the p_T resolution (computed as
 2397 $(p_{T,\text{reconstructed}} - p_{T,\text{gen}})/p_{T,\text{gen}}$) and closeness in distance ΔR of the reconstructed jet
 2398 to the nearest generator-level jets, was seen to depend on the absolute and relative
 2399 masses of the light scalars. The best (worst) performance occurred in samples with
 2400 large (small) mass differences between the heavier scalar a_2 and the lighter scalar a_1 ,
 2401 as illustrated for the mass hypotheses (m_{a_1}, m_{a_2}) (100, 15) GeV and (40, 20) GeV in
 2402 Fig. 11.2.

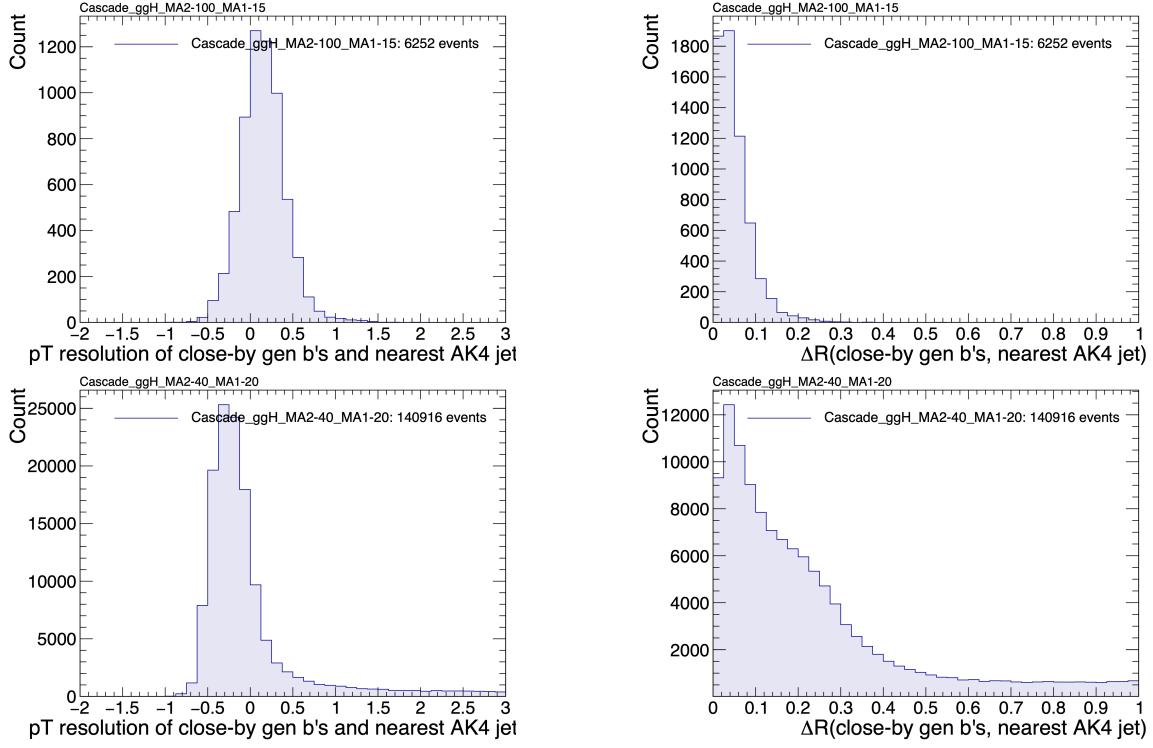


Figure 11.2: Distributions (arbitrary units) of transverse momentum p_T resolution and ΔR between the two closest generator-level b jets, treated as one object, and the nearest reconstructed AK4 jet, for two different $h \rightarrow a_1 a_2$ mass hypotheses (m_{a_1}, m_{a_2}) = (100, 15) GeV (top left, top right) and (40, 20) GeV (bottom left, bottom right) in the ggH production of the 125 GeV h . In the (40, 20) GeV mass point, the longer p_T resolution tail (bottom left) indicates that the reconstructed jet underestimates the generator b -flavor jets' energy, and the significant fraction of events with larger ΔR values (bottom right) indicate worse matching.

11.3 Current control plots for $\mu\tau_h$ channel

The $\tau\tau$ states for the $h \rightarrow a_1 a_2$ to $4b2\tau$ analysis will be similar to those studied in $h \rightarrow aa \rightarrow bb\tau\tau$. For the $\mu\tau_h$ channel, histograms of the key kinematic variables are made for data and the sum of the expected backgrounds, which are estimated from Monte Carlo samples, embedded samples, and the data-driven method for estimating jets faking τ_h as described in Chapter 7. Nominal values of the scale factors and event reweighting are applied, as described in Chapter ???. The errors shown in the figures only include statistical errors and only several of the full set of systematic errors (only those associated with the lepton energy scales and τ_h identification efficiency,

2412 described in Sections 5.3.1, 5.3.2, and 5.3.4).

2413 The p_T , η , and ϕ of the leading muon and hadronic tau τ_h , and the di-tau visible
2414 mass m_{vis} and momentum $p_{T,\text{vis}}$, are shown in Fig. 11.3. The p_T , η , and ϕ of the the
2415 leading and sub-leading b-tag jets, and the missing transverse energy magnitude and
2416 azimuthal direction, are shown in Fig. 11.4.

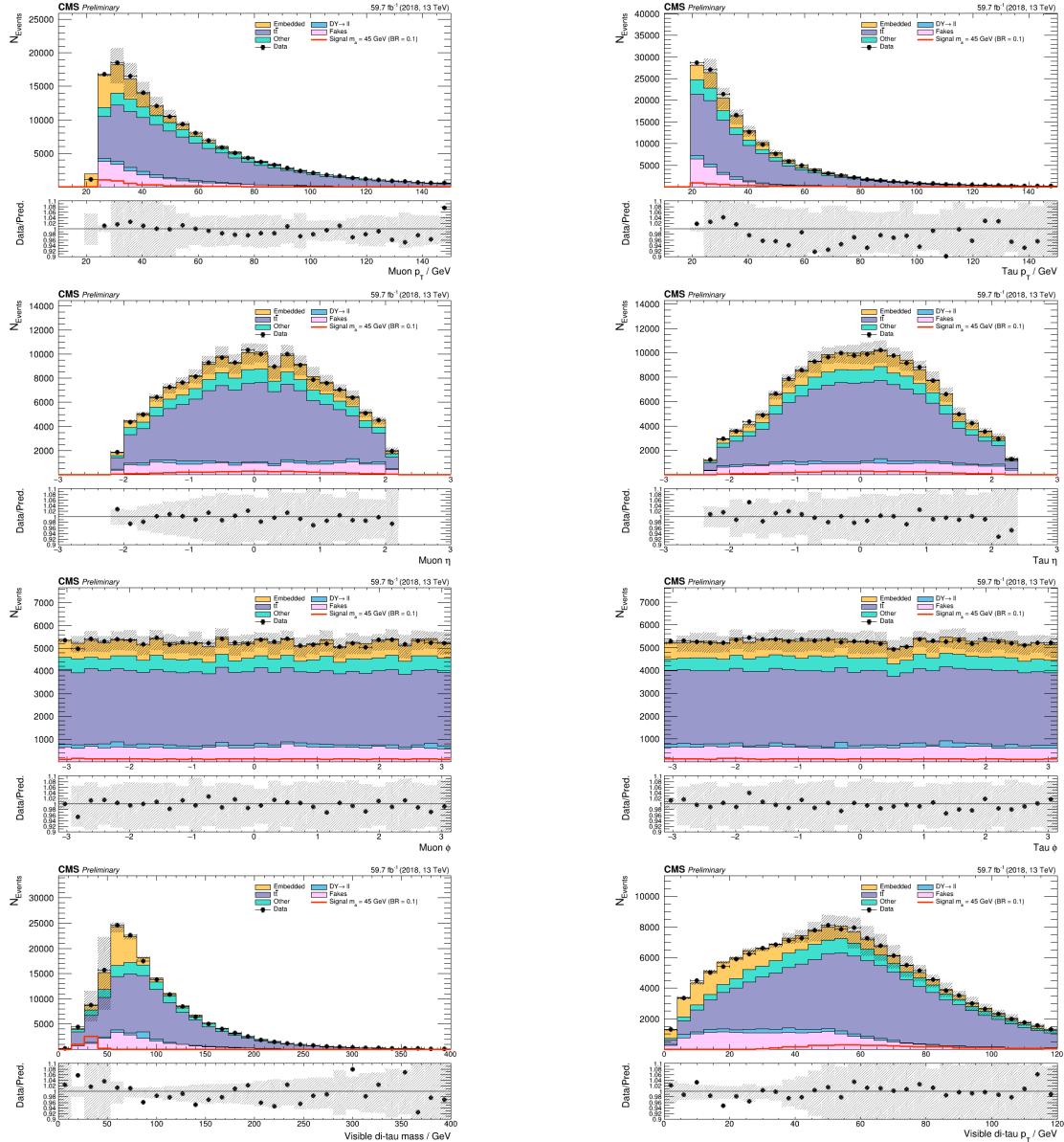


Figure 11.3: Kinematic properties of the leading muon and τ_h in the $\mu\tau_h$ channel: p_T (top row), η (second row), and ϕ (third row). The visible 4-momenta of the muon and τ_h are summed, giving the visible di-tau mass m_{vis} and transverse momentum $p_{T,\text{vis}}$. The errors shown in the figures only include statistical errors and only several of the full set of systematic errors (only those associated with the lepton energy scales and τ_h identification efficiency).

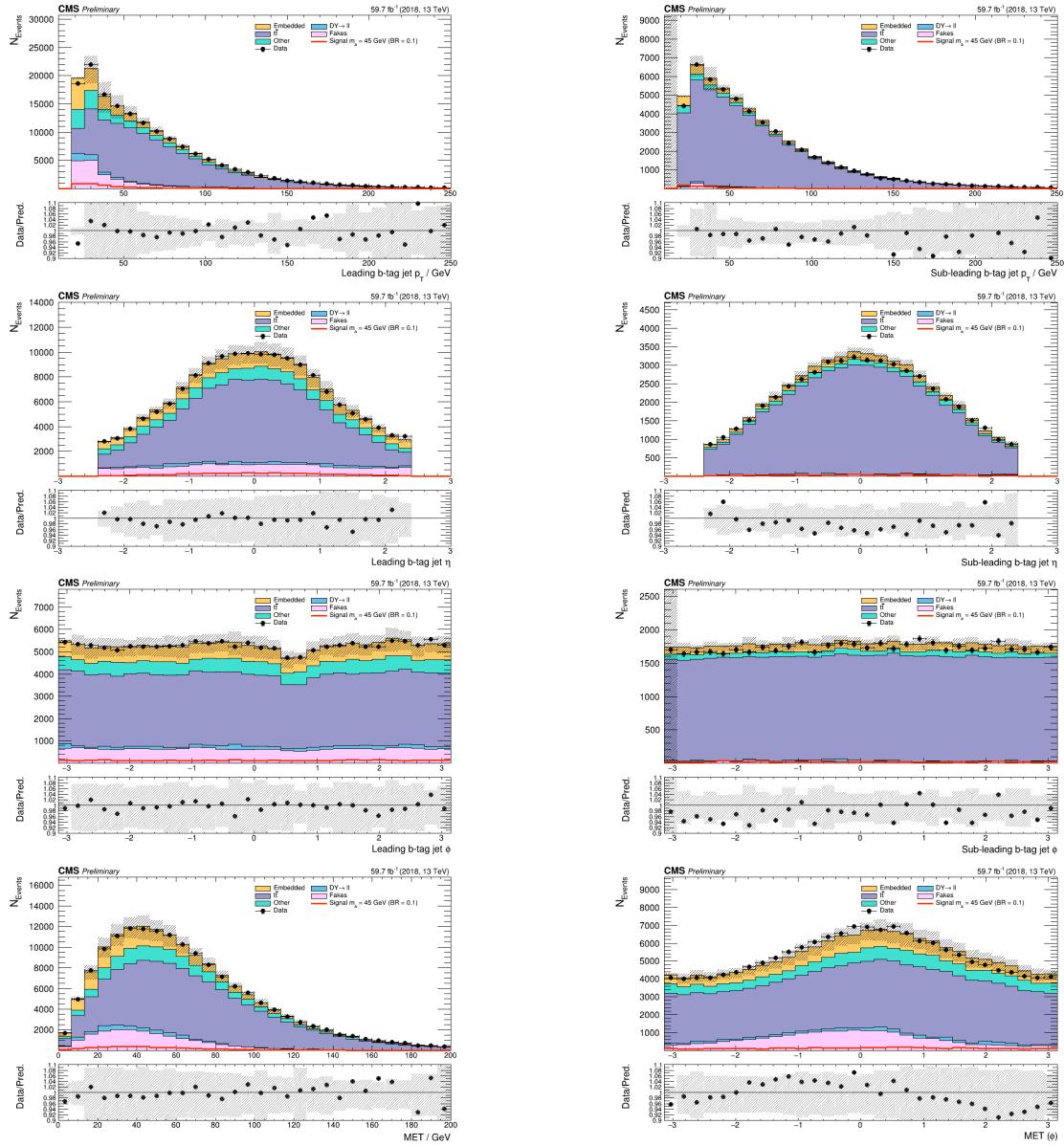


Figure 11.4: Kinematic properties of the leading and sub-leading b-tag jets in the $\mu\tau_h$ final state: jet p_T (*top row*), η (*second row*), ϕ (*third row*), as well as the missing transverse energy magnitude and azimuthal direction (*bottom row*). The errors shown in the figures only include statistical errors and only several of the full set of systematic errors (only those associated with the lepton energy scales and τ_h identification efficiency).

²⁴¹⁷ Chapter 12

²⁴¹⁸ Conclusion and outlook

²⁴¹⁹ With the discovery of a Higgs boson with mass 125 GeV at the LHC in 2012, the LHC
²⁴²⁰ and CMS physics program has evolved to include the precise characterization of the
²⁴²¹ 125 GeV Higgs boson and searching for evidence of additional Higgs particles in an
²⁴²² extended Higgs sector. This thesis presents a direct search at CMS for exotic decays
²⁴²³ of the Higgs boson with mass 125 GeV in data collected in the years 2016-2018 in
²⁴²⁴ proton-proton collisions at center-of-mass energy 13 TeV, to two light neutral scalar
²⁴²⁵ particles that decay to two bottom quarks and two tau leptons ($h \rightarrow aa \rightarrow bb\tau\tau$). The
²⁴²⁶ results are combined with another search that was performed in the $h \rightarrow aa \rightarrow bb\mu\mu$
²⁴²⁷ final state, giving the most stringent limits to date for theories with Two Higgs
²⁴²⁸ Doublet Models extended with a singlet scalar (2HDM+S), for pseudoscalar masses
²⁴²⁹ m_a ranging from 15 GeV to 60 GeV, in a number of 2HDM+S scenarios such as type
²⁴³⁰ II and III with $\tan\beta = 2.0$.

²⁴³¹ As the rich physics program of CMS has set stringent limits on the exotic decay
²⁴³² $h \rightarrow aa$, we turn our attention to direct searches for decays to light neutral scalars
²⁴³³ with potentially unequal mass, $h \rightarrow a_1a_2$, which has not been performed at CMS
²⁴³⁴ to date. Preliminary studies on $h \rightarrow a_1a_2$ signals in the Two Real Singlet Model
²⁴³⁵ (TRSM) are shown, and work is ongoing to develop the analysis for $h \rightarrow a_1a_2$ in final

2436 states with bottom quarks and tau leptons.

2437 To ensure the continued performance of the CMS detector and to enhance its
2438 data-taking capabilities in the intense pileup conditions of the Phase-2 upgrade of
2439 the High-Luminosity LHC, upgrades of the Level-1 Trigger are paramount for filter-
2440 ing the increased data rate of the HL-LHC. This thesis presents work on the stan-
2441 dalone barrel calorimeter algorithm for reconstructing and identifying electron and
2442 photon candidates, using high granularity crystal-level information from the ECAL
2443 subdetector. For Phase-2, the increase in the granularity of information sent from
2444 the electromagnetic calorimeter to the Level-1 trigger, from energy sums over towers
2445 (which are 5×5 in crystals) to crystal-level information, allows for the implementation
2446 of a more sophisticated clustering algorithm that can exploit the fact that genuine
2447 electrons and photons tend to leave energies concentrated a 3×5 window in crystals,
2448 and use shape and isolation information to distinguish genuine electrons and photons
2449 from noise. Electrons and photons are key to characterizing Standard Model pro-
2450 cesses and performing searches for new physics, and this represents one of the many
2451 upgrades of the CMS detector in preparation for Phase-2. With the ongoing Run-3
2452 data collecting period, and wealth of ongoing and scheduled upgrades, there remains
2453 an abundance of directions for detector development and physics at CMS heading
2454 into Phase-2 of the LHC.

- 2455 **Bibliography**
- 2456 [1] Paul H. Frampton. Journeys Beyond the Standard Model. 54(1):52–
2457 52. ISSN 0031-9228. doi: 10.1063/1.1349615. URL <https://doi.org/10.1063/1.1349615>. eprint: https://pubs.aip.org/physicstoday/article-pdf/54/1/52/11109432/52_1_online.pdf.
- 2458 [2] Meinard Kuhlmann. Quantum Field Theory. In Edward N. Zalta and Uri Nodelman, editors, *The Stanford Encyclopedia of Philosophy*. Metaphysics Research
2459 Lab, Stanford University, Summer 2023 edition, 2023.
- 2460 [3] Steven Weinberg. The Making of the Standard Model. *Eur. Phys. J. C*, 34:5–13,
2461 2004. URL <https://cds.cern.ch/record/799984>.
- 2462 [4] Christopher G. Tully. *Elementary Particle Physics in a Nutshell*. Princeton
2463 University Press, Princeton, 2012. ISBN 9781400839353. doi: doi:10.1515/
2464 9781400839353. URL <https://doi.org/10.1515/9781400839353>.
- 2465 [5] John Ellis. Higgs Physics. In *2013 European School of High-Energy Physics*,
2466 pages 117–168, 2015. doi: 10.5170/CERN-2015-004.117.
- 2467 [6] David Curtin, Rouven Essig, Stefania Gori, and Others. Exotic decays of the 125
2468 GeV Higgs boson. *Phys. Rev. D*, 90:075004, Oct 2014. doi: 10.1103/PhysRevD.
2469 90.075004. URL <https://link.aps.org/doi/10.1103/PhysRevD.90.075004>.
- 2470 [7] Tania Robens, Tim Stefański, and Jonas Wittbrodt. Two-real-scalar-singlet

- 2474 extension of the SM: LHC phenomenology and benchmark scenarios. *Eur. Phys.*
2475 *J. C*, 80(2):151, 2020. doi: 10.1140/epjc/s10052-020-7655-x.
- 2476 [8] CERN. The history of CERN, 2024. URL <https://timeline.web.cern.ch/timeline-header/89>.
- 2477
- 2478 [9] R. Schmidt. Accelerator physics and technology of the LHC. In *ROXIE: Routine*
2479 *for the Optimizazation of Magnet X-Sections, Inverse Field Calculation and Coil*
2480 *End Design*, pages 7–17, 1998.
- 2481 [10] J. Vollaire et al. *Linac4 design report*, volume 6/2020 of *CERN Yellow Reports: Monographs*. CERN, Geneva, 9 2020. ISBN 978-92-9083-579-0, 978-92-9083-580-6. doi: 10.23731/CYRM-2020-006.
- 2482
- 2483 [11] Antonella Del Rosso. Aerial view of the LHC and the four major experiments.
2484 2017. URL <https://cds.cern.ch/record/2253966>. General Photo.
- 2485
- 2486 [12] ATLAS Collaboration. ATLAS: Detector and physics performance technical
2487 design report. Volume 1. 5 1999.
- 2488
- 2489 [13] CMS Collaboration. CMS Physics: Technical Design Report Volume 1: Detector
Performance and Software. 2006.
- 2490
- 2491 [14] L Musa. Conceptual Design Report for the Upgrade of the ALICE ITS. Technical
report, CERN, Geneva, 2012. URL <https://cds.cern.ch/record/1431539>.
- 2492
- 2493 [15] S. Amato et al. LHCb technical proposal: A Large Hadron Collider Beauty
Experiment for Precision Measurements of CP Violation and Rare Decays. 2
2494 1998.
- 2495
- 2496 [16] Werner Herr and B Muratori. Concept of luminosity. 2006. doi: 10.5170/
CERN-2006-002.361. URL <https://cds.cern.ch/record/941318>.

- 2497 [17] Olivier S. Brning and Frank Zimmerman. Parameter space for the LHC lumi-
2498 nosity upgrade. ISBN 978-3-95450-115-1. URL <https://accelconf.web.cern.ch/IPAC2012/papers/moppc005.pdf>.
- 2500 [18] CMS Collaboration. Pileup mitigation at CMS in 13 TeV data. *JINST*, 15(09):
2501 P09018, 2020. doi: 10.1088/1748-0221/15/09/P09018.
- 2502 [19] CMS Collaboration. Measurement of the inelastic proton-proton cross section at
2503 $\sqrt{s} = 13$ TeV. *JHEP*, 07:161, 2018. doi: 10.1007/JHEP07(2018)161.
- 2504 [20] CMS Collaboration. High-Luminosity Large Hadron Collider (HL-LHC): Tech-
2505 nical design report. 10/2020, 12 2020. doi: 10.23731/CYRM-2020-0010.
- 2506 [21] CMS Collaboration. The CMS Experiment at the CERN LHC. *JINST*, 3:S08004,
2507 2008. doi: 10.1088/1748-0221/3/08/S08004.
- 2508 [22] CMS Collaboration. Particle-flow reconstruction and global event description
2509 with the CMS detector. *JINST*, 12(10):P10003, 2017. doi: 10.1088/1748-0221/
2510 12/10/P10003.
- 2511 [23] V Karimki, M Mannelli, P Siegrist, H Breuker, A Caner, R Castaldi, K Freudens-
2512 reich, G Hall, R Horisberger, M Huhtinen, and A Cattai. *The CMS tracker*
2513 *system project: Technical Design Report*. Technical design report. CMS. CERN,
2514 Geneva, 1997. URL <https://cds.cern.ch/record/368412>.
- 2515 [24] The Phase-2 Upgrade of the CMS Tracker. Technical report, CERN, Geneva,
2516 2017. URL <https://cds.cern.ch/record/2272264>.
- 2517 [25] CMS Collaboration. CMS Technical Design Report for the Pixel Detector Up-
2518 grade. 9 2012. doi: 10.2172/1151650.
- 2519 [26] R. L. Workman and Others. Review of particle physics. 2022:083C01. doi:
2520 10.1093/ptep/ptac097.

- 2521 [27] CMS Technical Design Report for the Phase 1 Upgrade of the Hadron Calorimeter. 9 2012. doi: 10.2172/1151651.
- 2522
- 2523 [28] CMS Technical Design Report for the Level-1 Trigger Upgrade. 6 2013.
- 2524
- 2525 [29] S. Dasu et al. CMS. The TriDAS project. Technical design report, vol. 1: The trigger systems. 12 2000.
- 2526
- 2527 [30] CMS Collaboration. The Phase-2 Upgrade of the CMS Data Acquisition and High Level Trigger. Technical report, CERN, Geneva, 2021. URL <https://cds.cern.ch/record/2759072>. This is the final version of the document, approved by the LHCC.
- 2528
- 2529
- 2530 [31] C. Foudas. The CMS Level-1 Trigger at LHC and Super-LHC. In *34th International Conference on High Energy Physics*, 10 2008.
- 2531
- 2532 [32] CMS Software Guide. High Level Trigger (TWiki), 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMSPublic/SWGuideHighLevelTrigger>.
- 2533
- 2534 [33] The Worldwide LHC Computing Grid. 2012. URL <https://cds.cern.ch/record/1997398>.
- 2535
- 2536 [34] Douglas Thain, Todd Tannenbaum, and Miron Livny. Distributed computing in practice: the Condor experience. *Concurrency and Computation: Practice and Experience*, 17(2-4):323–356, 2005. doi: <https://doi.org/10.1002/cpe.938>. URL <https://onlinelibrary.wiley.com/doi/abs/10.1002/cpe.938>.
- 2537
- 2538
- 2539
- 2540 [35] Alexandre Zabi, Jeffrey Wayne Berryhill, Emmanuelle Perez, and Alexander D. Tapper. The Phase-2 Upgrade of the CMS Level-1 Trigger. 2020.
- 2541
- 2542 [36] Technical proposal for a MIP timing detector in the CMS experiment Phase 2 upgrade. Technical report, CERN, Geneva, 2017. URL <https://cds.cern.ch/record/2296612>.
- 2543
- 2544

- 2545 [37] CMS Collaboration. Search for exotic decays of the Higgs boson to a pair of
2546 pseudoscalars in the $\mu\mu$ bb and $\tau\tau$ bb final states. *European Physical Journal C*,
2547 2 2024.
- 2548 [38] CMS Collaboration. CMS luminosity measurement for the 2016 data-taking
2549 period. CMS Physics Analysis Summary CMS-PAS-LUM-17-001, 2017. URL
2550 <https://cds.cern.ch/record/2257069>.
- 2551 [39] CMS Collaboration. CMS luminosity measurement for the 2017 data-taking
2552 period at $\sqrt{s} = 13$ TeV. CMS Physics Analysis Summary CMS-PAS-LUM-17-
2553 004, 2018. URL <https://cds.cern.ch/record/2621960>.
- 2554 [40] CMS Collaboration. CMS luminosity measurement for the 2018 data-taking
2555 period at $\sqrt{s} = 13$ TeV. CMS Physics Analysis Summary CMS-PAS-LUM-18-
2556 002, 2019. URL <https://cds.cern.ch/record/2676164>.
- 2557 [41] CMS LUMI Group. CMS Luminosity Public Results (TWiki), 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults>.
- 2559 [42] Cécile Caillol, Pallabi Das, Sridhara Dasu, Pieter Everaerts, Stephanie Kwan,
2560 Isobel Ojalvo, and Ho-Fung Tsoi. CMS AN-20-213 (internal): Search for an
2561 exotic decay of the 125 GeV Higgs boson to light pseudoscalars, with a pair of b
2562 jets and a pair of tau leptons in the final state, 2020.
- 2563 [43] J. Alwall, R. Frederix, S. Frixione, et al. The automated computation of tree-
2564 level and next-to-leading order differential cross sections, and their matching to
2565 parton shower simulations. *Journal of High Energy Physics*, 2014(7), July 2014.
2566 ISSN 1029-8479. doi: 10.1007/jhep07(2014)079. URL [http://dx.doi.org/10.1007/JHEP07\(2014\)079](http://dx.doi.org/10.1007/JHEP07(2014)079).
- 2568 [44] R. Frederix, S. Frixione, V. Hirschi, et al. The automation of next-to-leading
2569 order electroweak calculations. *Journal of High Energy Physics*, 2018(7), July

- 2570 2018. ISSN 1029-8479. doi: 10.1007/jhep07(2018)185. URL [http://dx.doi.org/10.1007/JHEP07\(2018\)185](http://dx.doi.org/10.1007/JHEP07(2018)185).
- 2571
- 2572 [45] S. Agostinelli, J. Allison, K. Amako, et al. Geant4 - a simulation toolkit. 506(3):
2573 250–303. ISSN 0168-9002. doi: 10.1016/S0168-9002(03)01368-8. URL <https://www.sciencedirect.com/science/article/pii/S0168900203013688>.
- 2574
- 2575 [46] CMS Collaboration. An embedding technique to determine $\tau\tau$ backgrounds
2576 in proton-proton collision data. *JINST*, 14(06):P06032, 2019. doi: 10.1088/
2577 1748-0221/14/06/P06032.
- 2578 [47] CMS Collaboration. Search for neutral MSSM Higgs bosons decaying to a pair of
2579 tau leptons in pp collisions. *JHEP*, 10:160, 2014. doi: 10.1007/JHEP10(2014)160.
- 2580 [48] CMS Collaboration. Measurements of Higgs boson production in the decay chan-
2581 nel with a pair of τ leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV. *Eur.*
2582 *Phys. J. C*, 83(7):562, 2023. doi: 10.1140/epjc/s10052-023-11452-8.
- 2583 [49] CMS Collaboration. Reconstruction and identification of tau lepton decays to
2584 hadrons and tau neutrinos at CMS. *Journal of Instrumentation*, 11(01):P01019–
2585 P01019, January 2016. ISSN 1748-0221. doi: 10.1088/1748-0221/11/01/p01019.
2586 URL <http://dx.doi.org/10.1088/1748-0221/11/01/P01019>.
- 2587 [50] CMS Collaboration. Performance of τ -lepton reconstruction and identification
2588 in CMS. *Journal of Instrumentation*, 7(01):P01001, jan 2012. doi: 10.1088/
2589 1748-0221/7/01/P01001. URL <https://dx.doi.org/10.1088/1748-0221/7/01/P01001>.
- 2590
- 2591 [51] CMS Collaboration. Performance of reconstruction and identification of τ leptons
2592 decaying to hadrons and ν_τ in pp collisions at $\sqrt{s} = 13$ TeV. *JINST*, 13(10):
2593 P10005, 2018. doi: 10.1088/1748-0221/13/10/P10005.

- 2594 [52] CMS Collaboration. Identification of hadronic tau lepton decays using a deep
2595 neural network. *JINST*, 17:P07023, 2022. doi: 10.1088/1748-0221/17/07/
2596 P07023.
- 2597 [53] CMS Collaboration. Performance of CMS muon reconstruction in pp collision
2598 events at $\sqrt{s} = 7$ TeV. *Journal of Instrumentation*, 7(10):P10002–P10002,
2599 October 2012. ISSN 1748-0221. doi: 10.1088/1748-0221/7/10/p10002. URL
2600 <http://dx.doi.org/10.1088/1748-0221/7/10/P10002>.
- 2601 [54] CMS Collaboration. Performance of electron reconstruction and selection with
2602 the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV. *Journal of Instru-*
2603 *mentation*, 10(06):P06005, 2015. doi: 10.1088/1748-0221/10/06/P06005. URL
2604 <https://dx.doi.org/10.1088/1748-0221/10/06/P06005>.
- 2605 [55] CMS Collaboration. Identification of b-quark jets with the CMS experiment.
2606 *Journal of Instrumentation*, 8(04):P04013–P04013, April 2013. ISSN 1748-
2607 0221. doi: 10.1088/1748-0221/8/04/p04013. URL <http://dx.doi.org/10.1088/1748-0221/8/04/P04013>.
- 2609 [56] CMS Collaboration. Pileup Removal Algorithms. Technical report, CERN,
2610 Geneva, 2014. URL <https://cds.cern.ch/record/1751454>.
- 2611 [57] CMS Collaboration. CMS Phase 1 heavy flavour identification performance and
2612 developments. 2017. URL <https://cds.cern.ch/record/2263802>.
- 2613 [58] CMS Collaboration. Performance of the DeepJet b tagging algorithm using 41.9
2614 fb^{-1} of data from proton-proton collisions at 13 TeV with Phase 1 CMS detector.
2615 2018. URL <https://cds.cern.ch/record/2646773>.
- 2616 [59] Lorenzo Bianchini, John Conway, Evan Klose Friis, and Christian Veelken. Re-
2617 construction of the Higgs mass in $H \rightarrow \tau\tau$ Events by Dynamical Likelihood

- 2618 techniques. *Journal of Physics: Conference Series*, 513(2):022035, jun 2014.
2619 doi: 10.1088/1742-6596/513/2/022035. URL <https://dx.doi.org/10.1088/1742-6596/513/2/022035>.
- 2621 [60] CMS Collaboration. Evidence for the 125 GeV Higgs boson decaying to a pair
2622 of τ leptons. *JHEP*, 05:104, 2014. doi: 10.1007/JHEP05(2014)104.
- 2623 [61] CMS Collaboration. Missing transverse energy performance of the CMS detector.
2624 *JINST*, 6:P09001, 2011. doi: 10.1088/1748-0221/6/09/P09001.
- 2625 [62] Artur Kalinowski. CMS AN-19-032 (internal): Reconstruction of a τ pair invariant
2626 mass with a simplified likelihood scan, 2019.
- 2627 [63] CMS TAU POG. Tau Physics Object Group: Tau ID Recommendation For Run 2, 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/TauIDRecommendationForRun2>.
- 2630 [64] CMS MUO POG. Muon Physics Object Group: Recommendations, 2024. URL
2631 <https://twiki.cern.ch/twiki/bin/view/CMS/MuonPOG>.
- 2632 [65] CMS MUO POG. Muon Physics Object Group: Reference guidelines and results
2633 for muon momentum scale and resolution in Run II, 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/MuonReferenceScaleResolRun2>.
- 2635 [66] CMS HTT working group. Higgs To Tau Tau Working TWiki for the full Run-
2636 2 legacy analysis, 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/HiggsToTauTauWorkingLegacyRun2>.
- 2638 [67] CMS ELE POG. Electron Physics Object Group: Recommendations,
2639 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/EgammaRunIIRecommendations>.

- 2641 [68] CMS ELE POG. Electron Physics Object Group: Recommendations for
2642 2016 to 2018 UL, 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/EgammaUL2016To2018>.
2643
- 2644 [69] CMS TAU Embedding Group. Tau embedded samples using 2016
2645 data, 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/TauTauEmbeddingSamples2016Legacy>.
2646
- 2647 [70] CMS TAU Embedding Group. Tau embedded samples using 2017
2648 data, 2024. URL <https://twiki.cern.ch/twiki/bin/viewauth/CMS/TauTauEmbeddingSamples2017>.
2649
- 2650 [71] CMS TAU Embedding Group. Tau embedded samples using 2018
2651 data, 2024. URL <https://twiki.cern.ch/twiki/bin/viewauth/CMS/TauTauEmbeddingSamples2018>.
2652
- 2653 [72] Tau Lepton Run 2 Trigger Performance. 2019. URL <https://cds.cern.ch/record/2678958>.
2654
- 2655 [73] CMS Taus High Level Trigger Studies. Tau Lepton Run 2 Trigger Performance
2656 (CMS DP-2019/012), 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMSPublic/HLTTauAllRun2>.
2657
- 2658 [74] Muon HLT Performance with 2018 Data. 2018. URL <https://cds.cern.ch/record/2627469>.
2659
- 2660 [75] Single and Double Electron Trigger Efficiencies using the full Run 2 dataset.
2661 2020. URL <https://cds.cern.ch/record/2888577>.
2662
- 2663 [76] Run II Trigger Performance For $e\mu$ Triggers. 2019. URL <https://cds.cern.ch/record/2687013>.

- 2664 [77] Performance of electron and photon reconstruction in Run 2 with the CMS ex-
2665 periment. 2020. URL <https://cds.cern.ch/record/2725004>.
- 2666 [78] CMS Collaboration. Performance of the CMS muon detector and muon recon-
2667 struction with proton-proton collisions at $\sqrt{s} = 13$ TeV. *JINST*, 13(06):P06015,
2668 2018. doi: 10.1088/1748-0221/13/06/P06015.
- 2669 [79] Piet Verwilligen. Muons in the cms high level trigger system. *Nuclear
2670 and Particle Physics Proceedings*, 273-275:2509–2511, 2016. ISSN 2405-6014.
2671 doi: <https://doi.org/10.1016/j.nuclphysbps.2015.09.441>. URL <https://www.sciencedirect.com/science/article/pii/S240560141500930X>. 37th Inter-
2672 national Conference on High Energy Physics (ICHEP).
- 2673 [80] Muon tracking performance in the CMS Run-2 Legacy data using the tag-and-
2674 probe technique. 2020. URL <https://cds.cern.ch/record/2724492>.
- 2675 [81] V.M. Abazov, B. Abbott, M. Abolins, et al. A novel method for modeling the
2676 recoil in W boson events at hadron colliders. *Nuclear Instruments and Methods
2677 in Physics Research Section A: Accelerators, Spectrometers, Detectors and Asso-
2678 ciated Equipment*, 609(2):250–262, 2009. ISSN 0168-9002. doi: <https://doi.org/10.1016/j.nima.2009.08.056>. URL <https://www.sciencedirect.com/science/article/pii/S0168900209016623>.
- 2679 [82] CMS Collaboration. Search for an exotic decay of the Higgs boson to a pair
2680 of light pseudoscalars in the final state with two b quarks and two τ leptons in
2681 proton-proton collisions at $\sqrt{s} = 13$ TeV. *Phys. Lett. B*, 785:462, 2018. doi:
2682 10.1016/j.physletb.2018.08.057.
- 2683 [83] CMS LUMI POG. Luminosity Physics Object Group: Recommendations, 2024.
2684 URL <https://twiki.cern.ch/twiki/bin/view/CMS/TWikiLUM>.

- 2688 [84] The modeling of the top quark p_T (TWiki), 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/TopPtReweighting>.
- 2689
- 2690 [85] CMS BTV group. Methods to apply b-tagging efficiency scale fac-
- 2691 tors (TWiki), 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/BTagShapeCalibration>.
- 2692
- 2693 [86] CMS Collaboration. Jet energy scale and resolution in the CMS experiment in
- 2694 pp collisions at 8 TeV. *JINST*, 12(02):P02014, 2017. doi: 10.1088/1748-0221/
- 2695 12/02/P02014.
- 2696 [87] Garvita Agarwal. Jet Energy Scale and Resolution Measurements in CMS. *PoS*,
- 2697 ICHEP2022:652, 2022. doi: 10.22323/1.414.0652.
- 2698 [88] CMS JERC group. Jet Energy Corrections (TWiki), 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/JECDataMC>.
- 2699
- 2700 [89] CMS JERC group. Jet Energy Resolution (TWiki), 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/JetResolution>.
- 2701
- 2702 [90] CMS MUO POG. Muon Physics Object Group: Baseline muon selec-
- 2703 tions for Run-II, 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/SWGuideMuonIdRun2>.
- 2704
- 2705 [91] CMS ELE POG. Electron Identification Based on Simple Cuts, 2024. URL
- 2706 <https://twiki.cern.ch/twiki/bin/view/CMSPublic/EgammaPublicData>.
- 2707
- 2708 [92] Jose Enrique Palencia Cortezon. Single top quark production at CMS. Technical report, CERN, Geneva, 2018. URL <https://cds.cern.ch/record/2640578>.
- 2709
- 2710 [93] CMS Collaboration. Measurements of the electroweak diboson production cross
- 2711 sections in proton-proton collisions at $\sqrt{s} = 5.02$ TeV using leptonic decays. *Phys. Rev. Lett.*, 127(19):191801, 2021. doi: 10.1103/PhysRevLett.127.191801.

- 2712 [94] CMS Collaboration. A portrait of the Higgs boson by the CMS experiment
2713 ten years after the discovery. *Nature*, 607(7917):60–68, 2022. doi: 10.1038/
2714 s41586-022-04892-x.
- 2715 [95] CMS JERC group. Jet energy scale uncertainty sources (TWiki), 2024. URL
2716 <https://twiki.cern.ch/twiki/bin/view/CMS/JECUncertaintySources>.
- 2717 [96] TOP Systematic Uncertainties (Run 2) (TWiki), 2024. URL <https://twiki.cern.ch/twiki/bin/viewauth/CMS/TopSystematics>.
- 2719 [97] Kyle Cranmer. Practical Statistics for the LHC. In *2011 European School of
2720 High-Energy Physics*, pages 267–308, 2014. doi: 10.5170/CERN-2014-003.267.
- 2721 [98] Elham Khazaie, Maryam Zeinali, Hamed Bakhshiansohi, and Abideh Jafari.
2722 CMS AN-21-058 (internal): Search for exotic decays of the Higgs boson to a
2723 pair of new light bosons with two muons and two b jets in the final states at
2724 $\sqrt{s} = 13$ TeV, 2021.
- 2725 [99] CMS Higgs Physics Analysis Group. Summary of 2HDM+S searches at 13 TeV
2726 (Run 2), 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMSPublic/Summary2HDMSRun2>.