

1 SEARCH FOR PRODUCTION OF A HIGGS BOSON AND A SINGLE TOP  
2 QUARK IN MULTILEPTON FINAL STATES IN  $pp$  COLLISIONS AT  $\sqrt{s} = 13$   
3 TeV.

4 by

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# **21 Table of Contents**

<b>22 Table of Contents</b>	<b>iii</b>
<b>23 List of Figures</b>	<b>vii</b>
<b>24 List of Tables</b>	<b>x</b>
<b>25 1 INTRODUCTION</b>	<b>1</b>
<b>26 2 Theoretical approach</b>	<b>2</b>
27     2.1 Introduction . . . . .	2
28     2.2 Standard model of particle physics . . . . .	3
29         2.2.1 Fermions . . . . .	5
30             2.2.1.1 Leptons . . . . .	6
31             2.2.1.2 Quarks . . . . .	9
32         2.2.2 Fundamental interactions . . . . .	13
33         2.2.3 Gauge invariance. . . . .	16
34         2.2.4 Gauge bosons . . . . .	18
35     2.3 Electroweak unification and the Higgs mechanism . . . . .	20
36         2.3.1 Spontaneous symmetry breaking (SSB) . . . . .	28
37         2.3.2 Higgs mechanism . . . . .	32

38	2.3.3	Masses of the gauge bosons . . . . .	34
39	2.3.4	Masses of the fermions . . . . .	35
40	2.3.5	The Higgs field . . . . .	36
41	2.3.6	Production of Higgs bosons at LHC . . . . .	37
42	2.3.7	Higgs boson decay channels . . . . .	41
43	2.4	Experimental status of the anomalous Higgs-fermion coupling . . . .	42
44	2.5	Associated production of a Higgs boson and a single top quark . . . .	44
45	2.6	CP-mixing in $tH$ processes . . . . .	49
46	<b>3</b>	<b>The CMS experiment at the LHC</b>	<b>54</b>
47	3.1	Introduction . . . . .	54
48	3.2	The LHC . . . . .	55
49	3.3	The CMS experiment . . . . .	65
50	3.3.1	Coordinate system . . . . .	67
51	3.3.2	Pixels detector . . . . .	68
52	3.3.3	Silicon strip tracker . . . . .	70
53	3.3.4	Electromagnetic calorimeter . . . . .	72
54	3.3.5	Hadronic calorimeter . . . . .	73
55	3.3.6	Superconducting solenoid magnet . . . . .	75
56	3.3.7	Muon system . . . . .	76
57	3.3.8	CMS trigger system . . . . .	77
58	3.3.9	CMS computing . . . . .	79
59	<b>4</b>	<b>Event generation, simulation and reconstruction</b>	<b>83</b>
60	4.1	Event generation . . . . .	84
61	4.2	Monte Carlo Event Generators. . . . .	88
62	4.3	CMS detector simulation. . . . .	89

63	4.4 Event reconstruction . . . . .	91
64	4.4.1 Particle-Flow Algorithm . . . . .	91
65	4.4.1.1 Missing transverse energy . . . . .	103
66	4.4.2 Event reconstruction examples . . . . .	104
67	<b>5 Statistical methods</b>	<b>107</b>
68	5.1 Multivariate analysis . . . . .	107
69	5.1.1 Decision trees . . . . .	110
70	5.1.2 Boosted decision trees (BDT) . . . . .	113
71	5.1.3 Overtraining . . . . .	116
72	5.1.4 Variable ranking . . . . .	116
73	5.1.5 BDT output example . . . . .	117
74	5.2 Statistical inference . . . . .	118
75	5.2.1 Nuisance parameters . . . . .	118
76	5.2.2 Maximum likelihood estimation method . . . . .	119
77	5.2.3 Hypothesis test . . . . .	120
78	5.3 exclusion limits . . . . .	121
79	5.4 asymptotic limits . . . . .	121
80	<b>6 Search for production of a Higgs boson and a single top quark in multilepton final states in pp collisions at <math>\sqrt{s} = 13</math> TeV</b>	<b>122</b>
82	6.1 Introduction . . . . .	122
83	6.2 $tHq$ signature . . . . .	124
84	6.3 Background processes . . . . .	126
85	6.4 Data and MC Samples . . . . .	128
86	6.4.1 Full 2016 dataset and MC samples . . . . .	128
87	6.4.2 Triggers . . . . .	129

88	6.5 Object Identification . . . . .	133
89	6.5.1 Jets and $b$ -jet tagging. . . . .	133
90	6.5.2 Missing Energy MET. . . . .	134
91	6.5.3 Lepton reconstruction and identification . . . . .	135
92	6.5.4 Lepton selection efficiency . . . . .	143
93	6.6 Event selection . . . . .	145
94	6.7 Background predictions . . . . .	146
95	6.8 Signal discrimination . . . . .	148
96	6.8.1 Classifiers response . . . . .	150
97	6.9 Additional discriminating variables . . . . .	154
98	<b>Bibliography</b>	<b>156</b>
99	<b>References</b>	<b>158</b>

# <sup>100</sup> List of Figures

101	2.1 Standard Model of particle physics. . . . .	4
102	2.2 Transformations between quarks . . . . .	12
103	2.3 Fundamental interactions in nature. . . . .	13
104	2.4 SM interactions diagrams . . . . .	14
105	2.5 Neutral current processes . . . . .	21
106	2.6 Spontaneous symmetry breaking mechanism . . . . .	28
107	2.7 SSB Potential form . . . . .	29
108	2.8 Potential for complex scalar field . . . . .	30
109	2.9 SSB mechanism for complex scalar field . . . . .	31
110	2.10 Proton-Proton collision . . . . .	38
111	2.11 Higgs boson production mechanism Feynman diagrams . . . . .	39
112	2.12 Higgs boson production cross section and decay branching ratios . . . . .	40
113	2.13 Two dimensional $\kappa_t$ - $\kappa_V$ plot of the coupling modifiers. ATLAS and CMS combination. . . . .	43
115	2.14 Higgs boson production in association with a top quark mechanism Feyn- man diagrams . . . . .	44
117	2.15 Cross section for $tHq$ process as a function of $\kappa_t$ . . . . .	47
118	2.16 Cross section for $tHW$ process as a function of $\kappa_{Htt}$ . . . . .	48

119	2.17 NLO cross section for $tX_0$ and $t\bar{t}X_0$ .	51
120	2.18 NLO cross section for $tWX_0$ , $t\bar{t}X_0$ .	52
121	3.1 CERN accelerator complex . . . . .	55
122	3.2 LHC protons source. First acceleration stage.	56
123	3.3 The LINAC2 accelerating system at CERN.	57
124	3.4 LHC layout and RF cavities module.	58
125	3.5 LHC dipole magnet. . . . .	60
126	3.6 Integrated luminosity delivered by LHC and recorded by CMS during 2016	62
127	3.7 LHC interaction points . . . . .	63
128	3.8 Multiple $pp$ collision bunch crossing at CMS. . . . .	65
129	3.9 Layout of the CMS detector . . . . .	66
130	3.10 CMS detector coordinate system . . . . .	67
131	3.11 CMS pixel detector schematic view. . . . .	70
132	3.12 SST Schematic view. . . . .	71
133	3.13 CMS ECAL schematic view . . . . .	72
134	3.14 CMS HCAL schematic view . . . . .	74
135	3.15 CMS solenoid magnet . . . . .	75
136	3.16 CMS Muon system schematic view . . . . .	76
137	3.17 CMS Level-1 trigger architecture . . . . .	78
138	3.18 WLCG structure . . . . .	80
139	3.19 Data flow from CMS detector through hardware Tiers . . . . .	82
140	4.1 Event generation process. . . . .	84
141	4.2 Particle flow algorithm. . . . .	92
142	4.3 Jet reconstruction. . . . .	100
143	4.4 Jet energy corrections. . . . .	101

144	4.5	Secondary vertex in a b-hadron decay.	102
145	4.6	HIG-13-004 Event 1 reconstruction.	104
146	4.7	$e\mu$ event reconstruction.	105
147	4.8	Recorded event reconstruction.	106
148	5.1	Scatter plots-MVA event classification.	109
149	5.2	Scalar test statistical.	109
150	5.3	Decision tree.	111
151	5.4	Decision tree output example.	114
152	5.5	BDT output example.	117
153	6.1	$tHq$ event signature.	125
154	6.2	$t\bar{t}$ and $t\bar{t}W$ events signature.	127
155	6.3	Tight vs loose lepton selection efficiencies in the 2lss channel.	143
156	6.4	Tight vs loose lepton selection efficiencies in the 3l channel.	144
157	6.5	Input variables to the BDT for signal discrimination normalized.	149
158	6.6	Input variables to the BDT for signal discrimination not normalized.	151
159	6.7	BDT inputs as seen by TMVA against $t\bar{t}$ .	152
160	6.8	BDT inputs as seen by TMVA against $t\bar{t}V$ .	153
161	6.9	Correlation matrices for the input variables in the TMVA.	154
162	6.10	MVA classifiers performance.	154
163	6.11	Additional discriminating variables distributions.	156

# <sup>164</sup> List of Tables

165	2.1	Fermions of the SM. . . . .	5
166	2.2	Fermion masses. . . . .	6
167	2.3	Lepton properties. . . . .	8
168	2.4	Quark properties. . . . .	9
169	2.5	Fermion weak isospin and weak hypercharge multiplets. . . . .	11
170	2.6	Fundamental interactions features. . . . .	15
171	2.7	SM gauge bosons. . . . .	19
172	2.8	Higgs boson properties. . . . .	37
173	2.9	Predicted branching ratios for a SM Higgs boson with $m_H = 125 \text{ GeV}/c^2$ . . . . .	41
174	2.10	Predicted SM cross sections for $tH$ production at $\sqrt{s} = 13 \text{ TeV}$ . . . . .	46
175	2.11	Predicted enhancement of the $tHq$ and $tHW$ cross sections at LHC . . . . .	49
176	6.1	Signal samples and their cross section and branching fraction. . . . .	129
177	6.2	$\kappa_V$ and $\kappa_t$ combinations. . . . .	130
178	6.3	List of background samples used in this analysis (CMSSW 80X). . . . .	131
179	6.4	Leading-order $t\bar{t}W$ and $t\bar{t}Z$ samples used in the signal BDT training. . . . .	131
180	6.5	Table of high-level triggers that we consider in the analysis. . . . .	132
181	6.6	Trigger efficiency scale factors and associated uncertainties. . . . .	133
182	6.7	Effective areas, for electrons and muons. . . . .	139

183	6.8 Requirements on each of the three muon selections.	142
184	6.9 Criteria for each of the three electron selections.	142
185	6.10 MVA input discriminating variables	150
186	6.11 TMVA input variables ranking for BDTA_GRAD method	155
187	6.12 TMVA configuration used in the BDT training.	155
188	6.13 ROC-integral for all the testing cases.	157

<sup>189</sup> Chapter 1

<sup>190</sup> INTRODUCTION

<sub>191</sub> **Chapter 2**

<sub>192</sub> **Theoretical approach**

<sub>193</sub> **2.1 Introduction**

<sub>194</sub> The physical description of the universe is a challenge that physicists have faced by  
<sub>195</sub> making theories that refine existing principles and proposing new ones in an attempt  
<sub>196</sub> to embrace emerging facts and phenomena.

<sub>197</sub> At the end of 1940s Julian Schwinger [1] and Richard P. Feynman [2], based on  
<sub>198</sub> the work of Sin-Itiro Tomonaga [3], developed an electromagnetic theory consistent  
<sub>199</sub> with special relativity and quantum mechanics that describes how matter and light  
<sub>200</sub> interact; the so-called *quantum electrodynamics* (QED) was born.

<sub>201</sub> QED has become the guide in the development of theories that describe the uni-  
<sub>202</sub> verse. It was the first example of a quantum field theory (QFT), which is the theore-  
<sub>203</sub> tical framework for building quantum mechanical models that describes particles and  
<sub>204</sub> their interactions. QFT is composed of a set of mathematical tools that combines  
<sub>205</sub> classical fields, special relativity and quantum mechanics, while keeping the quantum  
<sub>206</sub> point particles and locality ideas.

<sub>207</sub> This chapter gives an overview of the standard model of particle physics, starting

208 with a description of the particles and interactions that compose it, followed by a  
 209 description of the electroweak interaction, the Higgs boson and the associated pro-  
 210 duction of Higgs boson and a single top quark ( $tH$ ). The description contained in  
 211 this chapter is based on References [4–6].

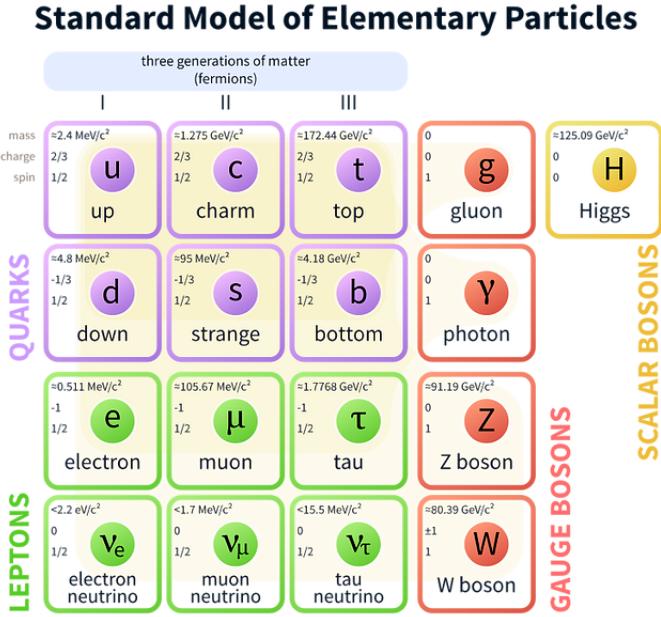
## 212 2.2 Standard model of particle physics

213 Particle physics at the fundamental level is modeled in terms of a collection of inter-  
 214 acting particles and fields in a theory known as the *standard model of particle physics*  
 215 (*SM*). The full picture of the SM is composed of three fields<sup>1</sup> whose excitations are  
 216 interpreted as particles called mediators or force-carriers, a set of fields whose excita-  
 217 tions are interpreted as elementary particles interacting through the exchange of those  
 218 mediators, and a field that gives the mass to elementary particles. Figure 2.1 shows  
 219 the scheme of the SM particles’ organization. In addition, for each of the particles  
 220 in the scheme there exists an antiparticle with the same mass and opposite quantum  
 221 numbers. The existence of antiparticles is a prediction of the relativistic quantum  
 222 mechanics from the solution of the Dirac equation for which a negative energy solu-  
 223 tion is also possible. In some cases a particle is its own anti-particle, like photon or  
 224 Higgs boson.

225 The mathematical formulation of the SM is based on group theory and the use of  
 226 Noether’s theorem [8] which states that for a physical system modeled by a Lagrangian  
 227 that is invariant under a group of transformations a conservation law is expected. For  
 228 instance, a system described by a time-independent Lagrangian is invariant (symmet-  
 229 ric) under time changes (transformations) with the total energy conservation law as

---

<sup>1</sup> The formal and complete treatment of the SM is out of the scope of this document, however a plenty of textbooks describing it at several levels are available in the literature. The treatment in References [5, 6] is quite comprehensive and detailed. Note that gravitational field is not included in the standard model formulation



**Figure 2.1:** Schematic representation of the Standard Model of particle physics. The SM is a theoretical model intended to describe three of the four fundamental forces of the universe in terms of a set of particles and their interactions. [7].

the expected conservation law. In QED, the charge operator ( $Q$ ) is the generator of the  $U(1)$  symmetry which according to the Noether's theorem means that there is a conserved quantity; this conserved quantity is the electric charge and thus the law of conservation of electric charge is established.

In the SM, the symmetry group  $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$  describes three of the four fundamental interactions in nature (see Section 2.2.2): strong interaction (SI), weak interaction (WI) and electromagnetic interactions (EI) in terms of symmetries associated to physical quantities:

- Strong:  $SU(3)_C$  associated to color charge
  - Weak:  $SU(2)_L$  associated to weak isospin and chirality
  - Electromagnetic:  $U(1)_Y$  associated to weak hypercharge and electric charge

241 It will be shown that the electromagnetic and weak interactions are combined in  
 242 the so-called electroweak interaction where chirality, hypercharge, weak isospin and  
 243 electric charge are the central concepts.

244 **2.2.1 Fermions**

245 The basic constituents of the ordinary matter at the lowest level, which form the set  
 246 of elementary particles in the SM formulation, are quarks and leptons. All of them  
 247 have spin 1/2, therefore they are classified as fermions since they obey Fermi-Dirac  
 248 statistics. There are six *flavors* of quarks and three of leptons organized in three  
 249 generations, or families, as shown in Table 2.1.

250

		Generation		
Type		1st	2nd	3rd
Leptons	Charged	Electron (e)	Moun( $\mu$ )	Tau ( $\tau$ )
	Neutral	Electron neutrino ( $\nu_e$ )	Muon neutrino ( $\nu_\mu$ )	Tau neutrino ( $\nu_\tau$ )
Quarks	Up-type	Up (u)	Charm (c)	Top (t)
	Down-type	Down (d)	Strange (s)	Bottom (b)

**Table 2.1:** Fermions of the SM. There are six flavors of quarks and three of leptons, organized in three generations, or families, composed of two pairs of closely related particles. The close relationship is motivated by the fact that each pair of particles is a member of an  $SU(2)_L$  doublet that has an associated invariance under isospin transformations. WI between leptons is limited to the members of the same generation; WI between quarks is not limited but greatly favored, to same generation members.

251

252 There is a mass hierarchy between generations (see Table 2.2), where the higher  
 253 generation particles decays to the lower one, which can explain why the ordinary  
 254 matter is made of particles from the first generation. In the SM, neutrinos are modeled  
 255 as massless particles so they are not subject to this mass hierarchy; however, today it  
 256 is known that neutrinos are massive so the hierarchy could be restated. The reason

257 behind this mass hierarchy is one of the most important open questions in particle  
 258 physics, and it becomes more puzzling when noticing that the mass difference between  
 259 first and second generation fermions is small compared to the mass difference with  
 260 respect to the third generation.

Lepton	Mass (MeV/c <sup>2</sup> )	Quark	Mass (MeV/c <sup>2</sup> )
e	0.51	u	2.2
$\mu$	105.65	c	$1.28 \times 10^3$
$\tau$	1776.86	t	$173.1 \times 10^3$
$\nu_e$	Unknown	d	4.7
$\nu_\mu$	Unknown	s	96
$\nu_\tau$	Unknown	b	$4.18 \times 10^3$

**Table 2.2:** Fermion masses [9]. Generations differ by mass in a way that has been interpreted as a mass hierarchy. Approximate values with no uncertainties are used, for comparison purpose.

261

262 Usually, the second and third generation fermions are produced in high energy  
 263 processes, like the ones recreated in particle accelerators.

### 264 2.2.1.1 Leptons

265 A lepton is an elementary particle that is not subject to the SI. As seen in Table 2.1,  
 266 there are two types of leptons, the charged ones (electron, muon and tau) and the  
 267 neutral ones (the three neutrinos). The electric charge (Q) is the property that gives  
 268 leptons the ability to participate in the EI. From the classical point of view, Q plays  
 269 a central role determining, among others, the strength of the electric field through  
 270 which the electromagnetic force is exerted. It is clear that neutrinos are not affected  
 271 by EI because they don't carry electric charge.

272 Another feature of the leptons that is fundamental in the mathematical description  
 273 of the SM is the chirality, which is closely related to spin and helicity. Helicity

274 defines the handedness of a particle by relating its spin and momentum such that  
 275 if they are parallel then the particle is right-handed; if spin and momentum are  
 276 antiparallel the particle is said to be left-handed. The study of parity conservation  
 277 (or violation) in  $\beta$ -decay has shown that only left-handed electrons/neutrinos or right-  
 278 handed positrons/anti-neutrinos are created [10]; the inclusion of that feature in the  
 279 theory was achieved by using projection operators for helicity, however, helicity is  
 280 frame dependent for massive particles which makes it not Lorentz invariant and then  
 281 another related attribute has to be used: *chirality*.

282 Chirality is a purely quantum attribute which makes it not so easy to describe in  
 283 graphical terms but it defines how the wave function of a particle transforms under  
 284 certain rotations. As with helicity, there are two chiral states, left-handed chiral (L)  
 285 and right-handed chiral (R). In the highly relativistic limit where  $E \approx p \gg m$  helicity  
 286 and chirality converge, becoming exactly the same for massless particles.

287 In the following, when referring to left-handed (right-handed) it will mean left-  
 288 handed chiral (right-handed chiral). The fundamental fact about chirality is that  
 289 while EI and SI are not sensitive to chirality, in WI left-handed and right-handed  
 290 fermions are treated asymmetrically, such that only left-handed fermions and right-  
 291 handed anti-fermions are allowed to couple to WI mediators, which is a violation of  
 292 parity. The way to translate this statement in a formal mathematical formulation is  
 293 based on the isospin symmetry group  $SU(2)_L$ .

294 Each generation of leptons is seen as a weak isospin doublet.<sup>2</sup> The left-handed  
 295 charged lepton and its associated left-handed neutrino are arranged in doublets of  
 296 weak isospin  $T=1/2$  while their right-handed partners are singlets:

---

<sup>2</sup> The weak isospin is an analogy of the isospin symmetry in strong interaction where neutron and proton are affected equally by strong force but differ in their charge.

$$\begin{pmatrix} \nu_l \\ l \end{pmatrix}_L, l_R := \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L, \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L, e_R, \mu_R, \tau_R, \nu_{eR}, \nu_{\mu R}, \nu_{\tau R} \quad (2.1)$$

297     The isospin third component refers to the eigenvalues of the weak isospin operator  
 298    which for doublets is  $T_3 = \pm 1/2$ , while for singlets it is  $T_3 = 0$ . The physical meaning  
 299    of this doublet-singlet arrangement falls in that the WI couples the two particles in  
 300    the doublet by exchanging the interaction mediator while the singlet member is not  
 301    involved in WI. The main properties of the leptons are summarized in Table 2.3.

302       Although all three flavor neutrinos have been observed, their masses remain un-  
 303    known and only some estimations have been made [11]. The main reason is that  
 304    the flavor eigenstates are not the same as the mass eigenstates which implies that  
 305    when a neutrino is created its mass state is a linear combination of the three mass  
 306    eigenstates and experiments can only probe the squared difference of the masses. The  
 307    Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix encodes the relationship  
 308    between flavor and mass eigenstates.

Lepton	Q(e)	$T_3$	$L_e$	$L_\mu$	$L_\tau$	Lifetime (s)
Electron (e)	-1	-1/2	1	0	0	Stable
Electron neutrino( $\nu_e$ )	0	1/2	1	0	0	Unknown
Muon ( $\mu$ )	-1	-1/2	0	1	0	$2.19 \times 10^{-6}$
Muon neutrino ( $\nu_\mu$ )	0	1/2	0	1	0	Unknown
Tau ( $\tau$ )	-1	-1/2	0	0	1	$290.3 \times 10^{-15}$
Tau neutrino ( $\nu_\tau$ )	0	1/2	0	0	1	Unknown

**Table 2.3:** Lepton properties [9]. Q: electric charge,  $T_3$ : weak isospin. Only left-handed leptons and right-handed anti-leptons participate in the WI. Anti-particles with inverted  $T_3$ , Q and lepton number complete the leptons set but are not listed. Right-handed leptons and left-handed anti-leptons, neither listed, form weak isospin singlets with  $T_3 = 0$  and do not take part in the weak interaction.

310 **2.2.1.2 Quarks**

311 Quarks are the basic constituents of protons and neutrons. The way quarks join to  
 312 form bound states, called *hadrons*, is through the SI. Quarks are affected by all the  
 313 fundamental interactions which means that they carry all the four types of charges:  
 314 color, electric charge, weak isospin and mass.

Flavor	$Q(e)$	$I_3$	$T_3$	B	C	S	T	$B'$	Y	Color
Up (u)	2/3	1/2	1/2	1/3	0	0	0	0	1/3	r,b,g
Charm (c)	2/3	0	1/2	1/3	1	0	0	0	4/3	r,b,g
Top(t)	2/3	0	1/2	1/3	0	0	1	0	4/3	r,b,g
Down(d)	-1/3	-1/2	-1/2	1/3	0	0	0	0	1/3	r,b,g
Strange(s)	-1/3	0	-1/2	1/3	0	-1	0	0	-2/3	r,b,g
Bottom(b)	-1/3	0	-1/2	1/3	0	0	0	-1	-2/3	r,b,g

**Table 2.4:** Quark properties [9]. Q: electric charge,  $I_3$ : isospin,  $T_3$ : weak isospin, B: baryon number, C: charmness, S: strangeness, T: topness,  $B'$ : bottomness, Y: hypercharge. Anti-quarks posses the same mass and spin as quarks but all charges (color, flavor numbers) have opposite sign.

315

316 Table 2.4 summarizes the features of quarks, among which the most remarkable  
 317 is their fractional electric charge. Note that fractional charge is not a problem, given  
 318 that quarks are not found isolated, but serves to explain how composed particles are  
 319 formed out of two or more valence quarks<sup>3</sup>.

320 Color charge is responsible for the SI between quarks and is the symmetry ( $SU(3)_C$ )  
 321 that defines the formalism to describe SI. There are three colors: red (r), blue (b)  
 322 and green (g) and their corresponding three anti-colors; thus each quark carries one  
 323 color unit while anti-quarks carries one anti-color unit. As explained in Section 2.2.2,  
 324 quarks are not allowed to be isolated due to the color confinement effect, hence, their  
 325 features have been studied indirectly by observing their bound states created when

---

<sup>3</sup> Hadrons can contain an indefinite number of virtual quarks and gluons, known as the quark and gluon sea, but only the valence quarks determine hadrons' quantum numbers.

326       • one quark with a color charge is attracted by an anti-quark with the correspond-  
 327       ing anti-color charge forming a colorless particle called a *meson*.

328       • three quarks (anti-quarks) with different color (anti-color) charges are attracted  
 329       among them forming a colorless particle called a *baryon (anti-baryon)*.

330       In practice, when a quark is left alone isolated a process called *hadronization* occurs  
 331       where the quark emits gluons (see Section 2.2.4) which eventually will generate new  
 332       quark-antiquark pairs and so on; those quarks will recombine to form hadrons that  
 333       will decay into leptons. This proliferation of particles looks like a *jet* coming from  
 334       the isolated quark. More details about the hadronization process and jet structure  
 335       will be given in chapter4.

336       In the first version of the quark model (1964), M. Gell-Mann [12] and G. Zweig  
 337       [13, 14] developed a consistent way to classify hadrons according to their properties.  
 338       Only three quarks (u, d, s) were involved in a scheme in which all baryons have baryon  
 339       number  $B=1$  and therefore quarks have  $B=1/3$ ; non-baryons have  $B=0$ . Baryon  
 340       number is conserved in SI and EI which means that single quarks cannot be created  
 341       but in pairs  $q - \bar{q}$ .

342       The scheme organizes baryons in a two-dimensional space ( $I_3$  - Y); Y (hyper-  
 343       charge) and  $I_3$  (isospin) are quantum numbers related by the Gell-Mann-Nishijima  
 344       formula [15, 16]:

$$Q = I_3 + \frac{Y}{2} \quad (2.2)$$

345       where  $Y = B + S + C + T + B'$  are the quantum numbers listed in Table 2.4.

346       There are six quark flavors organized in three generations (see Table 2.1) fol-  
 347       lowing a mass hierarchy which, again, implies that higher generations decay to first  
 348       generation quarks.

	Quarks			$T_3$	$Y_W$	Leptons			$T_3$	$Y_W$
Doublets	$(\frac{u}{d'})_L$	$(\frac{c}{s'})_L$	$(\frac{t}{b'})_L$	$(\frac{1/2}{-1/2})$	$1/3$	$(\nu_e)_L$	$(\nu_\mu)_L$	$(\nu_\tau)_L$	$(\frac{1/2}{-1/2})$	-1
Singlets	$u_R$	$c_R$	$t_R$	0	$4/3$	$\nu_{eR}$	$\nu_{\mu R}$	$\nu_{\tau R}$		
	$d'_R$	$s'_R$	$b'_R$	0	$-2/3$	$e_R$	$\mu_R$	$\tau_R$	0	-2

**Table 2.5:** Fermion weak isospin and weak hypercharge multiplets. Weak hypercharge is calculated through the Gell-Mann-Nishijima formula 2.2 but using the weak isospin and charge for quarks.

349

350 Isospin doublets of quarks are also defined (see Table 2.5), and same as for neutrinos, the WI eigenstates are not the same as the mass eigenstates which means that  
 351 members of different quark generations are connected by the WI mediator; thus, up-type quarks are coupled not to down-type quarks (the mass eigenstates) directly but  
 353 to a superposition of down-type quarks ( $q'_d$ ; the weak eigenstates) via WI according  
 354 to:  
 355

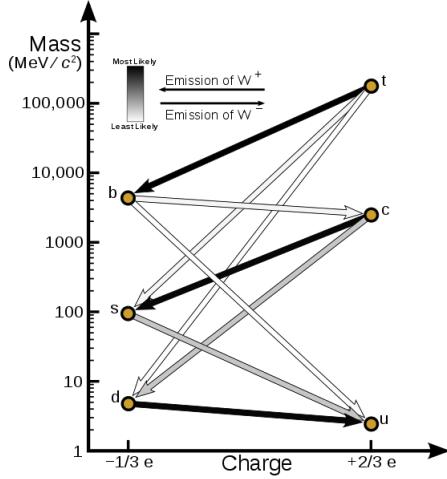
$$q'_d = V_{CKM} q_d$$

356

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \quad (2.3)$$

357 where  $V_{CKM}$  is known as Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix [17,18]  
 358 given by

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & 0.00351^{+0.00015}_{-0.00014} \\ 0.22520 \pm 0.00065 & 0.97344 \pm 0.00016 & 0.0412^{+0.0011}_{-0.0005} \\ 0.00867^{+0.00029}_{-0.00031} & 0.0404^{+0.0011}_{-0.0005} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}. \quad (2.4)$$



**Figure 2.2:** Transformations between quarks through the exchange of a WI. Higher generations quarks decay to first generation quarks by emitting a W boson. The arrow color indicates the likelihood of the transition according to the grey scale in the top left side which represent the CKM matrix parameters [19].

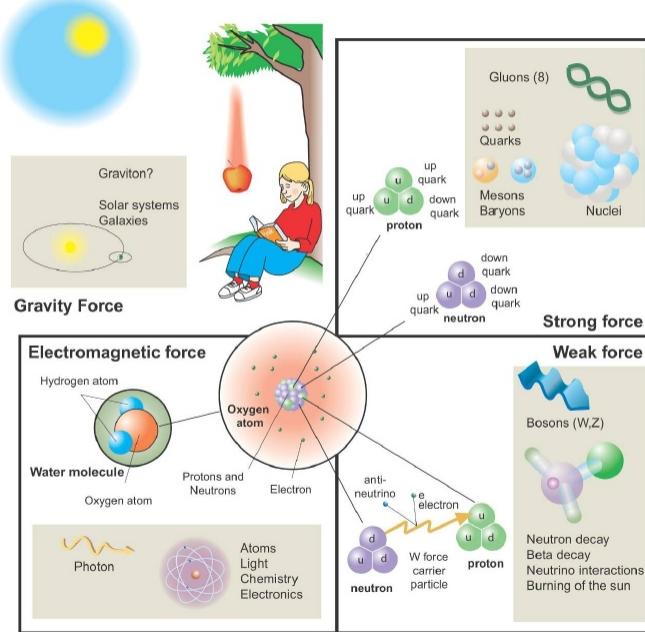
359        The weak decays of quarks are represented in the diagram of Figure 2.2; again  
 360        the CKM matrix plays a central role since it contains the probabilities for the differ-  
 361        ent quark decay channels, in particular, note that quark decays are greatly favored  
 362        between generation members.

363

364        CKM matrix is a  $3 \times 3$  unitary matrix parametrized by three mixing angles and  
 365        the *CP-mixing phase*; the latter is the parameter responsible for the Charge-Parity  
 366        symmetry violation (CP-violation) in the SM. The fact that the top quark decays  
 367        almost all the time to a bottom quark is exploited in this thesis when making the  
 368        selection of the signal events by requiring the presence of a jet tagged as a jet coming  
 369        from a *b* quark in the final state.

## Fundamental interactions.

Illustration: Typoform



Summer School KPI 15 August 2009

**Figure 2.3:** Fundamental interactions in nature. Despite the many manifestations of forces in nature, we can track all of them back to one of the fundamental interactions. The most common forces are gravity and electromagnetic given that all of us are subject and experience them in everyday life.

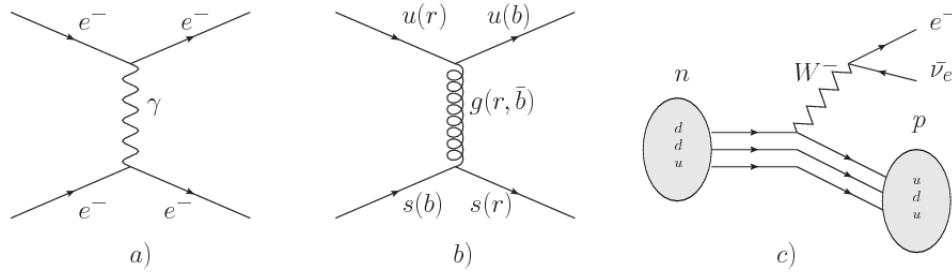
### 370 2.2.2 Fundamental interactions

371 Even though there are many manifestations of force in nature, like the ones represented in Figure 2.3, we can classify all of them in four fundamental interactions:

- 373     • *Electromagnetic interaction (EI)* affects particles that are *electrically charged*,  
374       like electrons and protons. Figure 2.4a. shows a graphical representation, known  
375       as *Feynman diagram*, of electron-electron scattering.
- 376     • *Strong interaction (SI)* described by Quantum Chromodynamics (QCD). Hadrons  
377       like the proton and the neutron have internal structure given that they are composed  
378       of two or more valence quarks<sup>4</sup>. Quarks have fractional electric charge

<sup>4</sup> Particles made of four and five quarks are exotic states not so common.

which means that they are subject to electromagnetic interaction and in the case of the proton they should break apart due to electrostatic repulsion; however, quarks are held together inside the hadrons against their electrostatic repulsion by the *Strong Force* through the exchange of *gluons*. The analog to the electric charge is the *color charge*. Electrons and photons are elementary particles as quarks but they don't carry color charge, therefore they are not subject to SI. A Feynman diagram for gluon exchange between quarks is shown in Figure 2.4b.



**Figure 2.4:** Feynman diagrams representing the interactions in SM; a) EI:  $e$ - $e$  scattering; b) SI: gluon exchange between quarks ; c) WI:  $\beta$ -decay

• *Weak interaction (WI)* described by the weak theory (WT), is responsible, for instance, for the radioactive decay in atoms and the deuterium production within the sun. Quarks and leptons are the particles affected by the weak interaction; they possess a property called *flavor charge* (see 2.2.1) which can be changed by emitting or absorbing one weak force mediator. There are three mediators of the *weak force* known as  $Z$  boson in the case of electrically neutral flavor changes and  $W^\pm$  bosons in the case of electrically charged flavor changes. The *weak isospin* is the WI analog to electric charge in EI, and color charge in SI, and defines how quarks and leptons are affected by the weak force. Figure 2.4c. shows the Feynman diagram of  $\beta$ -decay where a neutron ( $n$ ) is transformed in a proton ( $p$ ) by emitting a  $W^-$  particle.

• *Gravitational interaction (GI)* described by General Theory of Relativity (GR).

398 It is responsible for the structure of galaxies and black holes as well as the  
 399 expansion of the universe. As a classical theory, in the sense that it can be  
 400 formulated without even appeal to the concept of quantization, it implies that  
 401 the space-time is a continuum and predictions can be made without limitation  
 402 to the precision of the measurement tools. The latter represents a direct con-  
 403 tradiction of the quantum mechanics principles. Gravity is deterministic while  
 404 quantum mechanics is probabilistic; despite that, efforts to develop a quantum  
 405 theory of gravity have predicted the *graviton* as mediator of the gravitational  
 406 force<sup>5</sup>.

Interaction	Acts on	Relative strength	Range (m)	Mediators
Electromagnetic (QED)	Electrically charged particles	$10^{-2}$	Infinite	Photon
Strong (QCD)	Quarks and gluons	1	$10^{-15}$	Gluon
Weak (WI)	Leptons and quarks	$10^{-6}$	$10^{-18}$	$W^\pm, Z$
Gravitational (GI)	Massive particles	$10^{-39}$	Infinite	Graviton

**Table 2.6:** Fundamental interactions features [20].

407

408 Table 2.6 summarizes the main features of the fundamental interactions. The  
 409 relative strength of the fundamental forces reveals the meaning of strong and weak;  
 410 in a context where the relative strength of the SI is 1, the EI is about hundred times  
 411 weaker and WI is about million times weaker than the SI. A good description on how  
 412 the relative strength and range of the fundamental interactions are calculated can  
 413 be found in References [20, 21]. In the everyday life, only EI and GI are explicitly  
 414 experienced due to the range of these interactions; i.e., at the human scale distances  
 415 only EI and GI have appreciable effects, in contrast to SI which at distances greater

---

<sup>5</sup> Actually a wide variety of theories have been developed in an attempt to describe gravity; some famous examples are string theory and supergravity.

<sup>416</sup> than  $10^{-15}$  m become negligible.

<sup>417</sup>

<sup>418</sup> **2.2.3 Gauge invariance.**

<sup>419</sup> QED was built successfully on the basis of the classical electrodynamics theory (CED)  
<sup>420</sup> of Maxwell and Lorentz, following theoretical and experimental requirements imposed  
<sup>421</sup> by

- <sup>422</sup>     • Lorentz invariance: independence on the reference frame.
- <sup>423</sup>     • Locality: interacting fields are evaluated at the same space-time point to avoid  
<sup>424</sup>         action at a distance.
- <sup>425</sup>     • Renormalizability: physical predictions are finite and well defined.
- <sup>426</sup>     • Particle spectrum, symmetries and conservation laws already known must emerge  
<sup>427</sup>         from the theory.
- <sup>428</sup>     • Local gauge invariance.

<sup>429</sup> The gauge invariance requirement reflects the fact that the fundamental fields  
<sup>430</sup> cannot be directly measured but associated fields which are the observables. Electric  
<sup>431</sup> (**E**) and magnetic (**B**) fields in CED are associated with the electric scalar potential  
<sup>432</sup>  $V$  and the vector potential **A**. In particular, **E** can be obtained by measuring the  
<sup>433</sup> change in the space of the scalar potential ( $\Delta V$ ); however, two scalar potentials  
<sup>434</sup> differing by a constant  $f$  correspond to the same electric field. The same happens  
<sup>435</sup> in the case of the vector potential **A**; thus, different configurations of the associated  
<sup>436</sup> fields result in the same set of values of the observables. The freedom in choosing one  
<sup>437</sup> particular configuration is known as *gauge freedom*; the transformation law connecting

438 two configurations is known as *gauge transformation* and the fact that the observables  
 439 are not affected by a gauge transformation is called *gauge invariance*.

440 When the gauge transformation:

$$\begin{aligned}\mathbf{A} &\rightarrow \mathbf{A} - \Delta f \\ V &\rightarrow V - \frac{\partial f}{\partial t}\end{aligned}\tag{2.5}$$

441 is applied to Maxwell equations, they are still satisfied and the fields remain invariant.  
 442 Thus, CED is invariant under gauge transformations and is called a *gauge theory*.  
 443 The set of all gauge transformations form the *symmetry group* of the theory, which  
 444 according to the group theory, has a set of *group generators*. The number of group  
 445 generators determine the number of *gauge fields* of the theory.

446 As mentioned in the first lines of Section 2.2, QED has one symmetry group ( $U(1)$ )  
 447 with one group generator (the  $Q$  operator) and one gauge field (the electromagnetic  
 448 field  $A^\mu$ ). In CED there is not a clear definition, beyond the historical convention,  
 449 of which fields are the fundamental and which are the associated, but in QED the  
 450 fundamental field is  $A^\mu$ . When a gauge theory is quantized, the gauge fields are  
 451 quantized and their quanta are called *gauge bosons*. The word boson characterizes  
 452 particles with integer spin which obey Bose-Einstein statistics.

453 As will be detailed in Section 2.3, interactions between particles in a system can  
 454 be obtained by considering first the Lagrangian density of free particles in the sys-  
 455 tem, which of course is incomplete because the interaction terms have been left out,  
 456 and demanding global phase transformation invariance. Global phase transformation  
 457 invariance means that a gauge transformation is performed identically to every point

458 in the space<sup>6</sup> and the Lagrangian remains invariant. Then, the global transformation  
 459 is promoted to a local phase transformation (this time the gauge transformation  
 460 depends on the position in space) and again invariance is required.

461 Due to the space dependence of the local transformation, the Lagrangian density is  
 462 not invariant anymore. In order to reinstate the gauge invariance, the gauge covariant  
 463 derivative is introduced in the Lagrangian and with it the gauge field responsible for  
 464 the interaction between particles in the system. The new Lagrangian density is gauge  
 465 invariant, includes the interaction terms needed to account for the interactions and  
 466 provides a way to explain the interaction between particles through the exchange of  
 467 the gauge boson.

468 This recipe was used to build QED and the theories that aim to explain the  
 469 fundamental interactions.

#### 470 2.2.4 Gauge bosons

471 The importance of the gauge bosons comes from the fact that they are the force  
 472 mediators or force carriers. The features of the gauge bosons reflect those of the fields  
 473 they represent and they are extracted from the Lagrangian density used to describe  
 474 the interactions. In Section 2.3, it will be shown how the gauge bosons of the EI and  
 475 WI emerge from the electroweak Lagrangian. The SI gauge bosons features are also  
 476 extracted from the SI Lagrangian but it is not detailed in this document. The main  
 477 features of the SM gauge bosons will be briefly presented below and summarized in  
 478 Table 2.7.

479 • **Photon.** EI occurs when the photon couples to (is exchanged between) parti-  
 480 cles carrying electric charge; however, The photon itself does not carry electric

---

<sup>6</sup> Here space corresponds to the 4-dimensional space i.e. space-time.

481 charge, therefore, there is no coupling between photons. Given that the photon  
 482 is massless the EI is of infinite range, i.e., electrically charged particles interact  
 483 even if they are located far away one from each other; this also implies that  
 484 photons always move with the speed of light.

485 • **Gluon.** SI is mediated by gluons which just as photons are massless. They  
 486 carry one unit of color charge and one unit of anticolor charge, hence, gluons  
 487 can couple to other gluons. As a result, the range of the SI is not infinite  
 488 but very short due to the attraction between gluons, giving rise to the *color*  
 489 *confinement* which explains why color charged particles cannot be isolated but  
 490 live within composite particles, like quarks inside protons.

491 • **W, Z.**  $W^\pm$  and Z, are massive which explains their short-range. Given that  
 492 the WI is the only interaction that can change the flavor of the interacting  
 493 particles, the W boson is the responsible for the nuclear transmutation where  
 494 a neutron is converted into a proton or vice versa with the involvement of an  
 495 electron and a neutrino (see Figure 2.4c). The Z boson is the responsible for the  
 496 neutral weak processes like neutrino elastic scattering where no electric charge  
 497 but momentum transference is involved. WI gauge bosons carry isospin charge  
 498 which makes interaction between them possible.

Interaction	Mediator	Electric charge (e)	Color charge	Weak Isospin	mass (GeV/c <sup>2</sup> )
Electromagnetic	Photon ( $\gamma$ )	0	No	0	0
Strong	Gluon (g)	0	Yes -octet	No	0
Weak	$W^\pm$	$\pm 1$	No	$\pm 1$	$80.385 \pm 0.015$
	Z	0	No	0	$91.188 \pm 0.002$

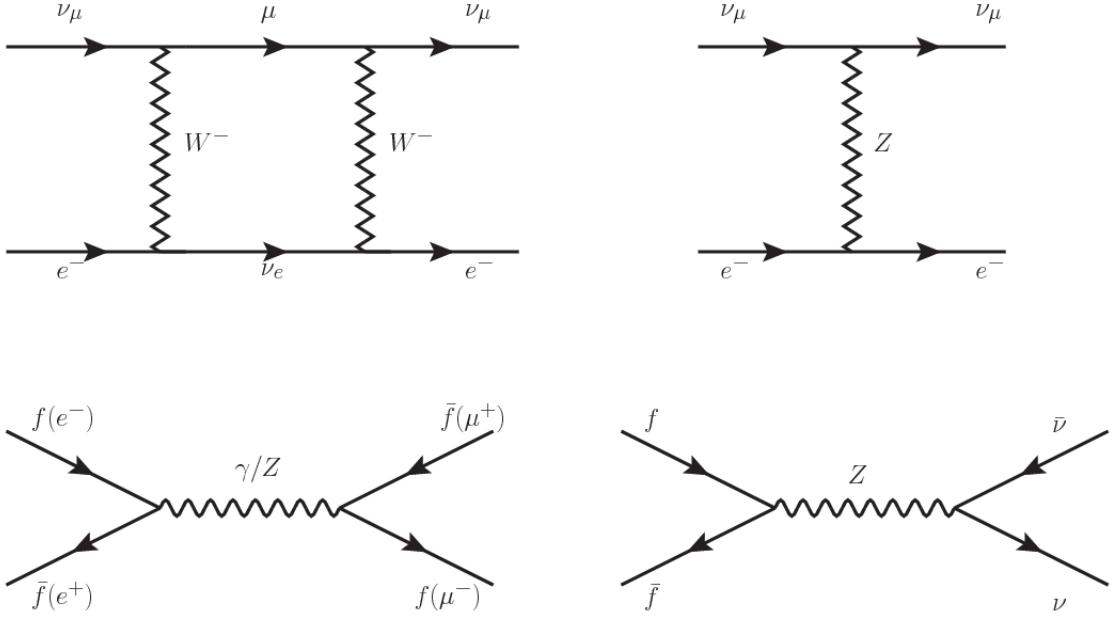
**Table 2.7:** SM gauge bosons main features [9].

500 **2.3 Electroweak unification and the Higgs  
501 mechanism**

502 Physicists dream of building a theory that contains all the interactions in one single  
 503 interaction, i.e., showing that at some scale in energy all the four fundamental inter-  
 504 actions are unified and only one interaction emerges in a *Theory of everything*. The  
 505 first sign of the feasibility of such unification came from success in the construction  
 506 of the CED. Einstein spent years trying to reach that full unification, which by 1920  
 507 only involved electromagnetism and gravity, with no success; however, a new par-  
 508 tial unification was achieved in the 1960's, when S.Glashow [22], A.Salam [23] and  
 509 S.Weinberg [24] independently proposed that electromagnetic and weak interactions  
 510 are two manifestations of a more general interaction called *electroweak interaction*  
 511 (*EWI*). EWI was developed by following the useful prescription provided by QED  
 512 and the gauge invariance principles.

513 The *classic* weak theory developed by Fermi, did not have the concept of the W  
 514 boson but instead it was treated as a point interaction with the dimensionful constant  
 515  $G_F$  associated with it. It works really well at low energies very far off the W mass  
 516 shell. When going up in energy, the theory of weak interactions involving the W  
 517 boson is capable of explaining the  $\beta$ -decay and in general the processes mediated by  
 518  $W^\pm$  bosons. However, there were some processes like the  $\nu_\mu - e$  scattering which  
 519 would require the exchange of two W bosons (see Figure 2.5 top diagrams) giving  
 520 rise to divergent loop integrals and then non-finite predictions. The EWI theory, by  
 521 including neutral currents involving fermions via the exchange of a neutral bosons Z,  
 522 overcomes those divergences and the predictions become realistic.

523 Neutral weak interaction vertices conserve flavor in the same way as the electro-  
 524 magnetic vertices do, but additionally, the Z boson can couple to neutrinos which



**Figure 2.5:** Top:  $\nu_\mu - e^-$  scattering going through charged currents (left) and neutral currents (right). Bottom: neutral current processes for charged fermions (left) and involving neutrinos (right). While neutral current processes involving only charged fermions can proceed through EI or WI, those involving neutrinos can only proceed via WI.

implies that processes involving charged fermions can proceed through EI or WI but processes involving neutrinos can proceed only through WI.

The prescription to build a gauge theory of the WI consists of proposing a free field Lagrangian density that includes the particles involved; next, by requesting invariance under global phase transformations first and generalizing to local phase transformations invariance later, the conserved currents are identified and interactions are generated by introducing gauge fields. Given that the goal is to include the EI and WI in a single theory, the group symmetry considered should be a combination of  $SU(2)_L$  and  $U(1)_{em}$ , however the latter cannot be used directly because the EI treats left and right-handed particles indistinctly in contrast to the former. Fortunately, the weak hypercharge, which is a combination of the weak isospin and the electric charge (Eqn. 2.2) is suitable to be used since it is conserved by the EI and WI. Thus, the

537 symmetry group to be considered is

$$G \equiv SU(2)_L \otimes U(1)_Y \quad (2.6)$$

538 The following treatment applies to any of the fermion generations, but for sim-  
539 plicity the first generation of leptons will be considered [5, 6, 25, 26].

540

541 Given the first generation of leptons

$$\psi_1 = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L, \quad \psi_2 = \nu_{eR}, \quad \psi_3 = e_R^- \quad (2.7)$$

542 the charged fermionic currents are given by

$$J_\mu \equiv J_\mu^+ = \bar{\nu}_{eL} \gamma_\mu e_L, \quad J_\mu^\dagger \equiv J_\mu^- = \bar{e}_L \gamma_\mu \nu_{eL} \quad (2.8)$$

543 and the free Lagrangian is given by

$$\mathcal{L}_0 = \sum_{j=1}^3 i\bar{\psi}_j(x) \gamma^\mu \partial_\mu \psi_j(x). \quad (2.9)$$

544 Mass terms are included directly in the QED free Lagrangians since they preserve  
545 the invariance under the symmetry transformations involved which treat left and right  
546 handed particles similarly, however mass terms of the form

$$m_W^2 W_\mu^\dagger(x) W^\mu(x) + \frac{1}{2} m_Z^2 Z_\mu(x) Z^\mu(x) - m_e \bar{\psi}_e(x) \psi_e(x) \quad (2.10)$$

547 which represent the mass of  $W^\pm$ , Z and electrons, are not invariant under G trans-  
548 formations, therefore the gauge fields described by the EWI are in principle massless.

549 Experiments have shown that the EWI gauge fields are not massless [27–30];

however, they have to acquire mass through a mechanism compatible with the gauge invariance; that mechanism is known as the *Higgs mechanism* and will be considered later in this Section. The global transformations in the combined symmetry group G can be written as

$$\begin{aligned}\psi_1(x) &\xrightarrow{G} \psi'_1(x) \equiv U_Y U_L \psi_1(x), \\ \psi_2(x) &\xrightarrow{G} \psi'_2(x) \equiv U_Y \psi_2(x), \\ \psi_3(x) &\xrightarrow{G} \psi'_3(x) \equiv U_Y \psi_3(x)\end{aligned}\tag{2.11}$$

where  $U_L$  represent the  $SU(2)_L$  transformation acting only on the weak isospin doublet and  $U_Y$  represent the  $U(1)_Y$  transformation acting on all the weak isospin multiplets. Explicitly

$$U_L \equiv \exp\left(i\frac{\sigma_i}{2}\alpha^i\right), \quad U_Y \equiv \exp(iy_i\beta) \quad (i = 1, 2, 3)\tag{2.12}$$

with  $\sigma_i$  the Pauli matrices and  $y_i$  the weak hypercharges. In order to promote the transformations from global to local while keeping the invariance, it is required that  $\alpha^i = \alpha^i(x)$ ,  $\beta = \beta(x)$  and the replacement of the ordinary derivatives by the covariant derivatives

$$\begin{aligned}D_\mu \psi_1(x) &\equiv [\partial_\mu + ig\sigma_i W_\mu^i(x)/2 + ig'y_1 B_\mu(x)] \psi_1(x) \\ D_\mu \psi_2(x) &\equiv [\partial_\mu + ig'y_2 B_\mu(x)] \psi_2(x) \\ D_\mu \psi_3(x) &\equiv [\partial_\mu + ig'y_3 B_\mu(x)] \psi_3(x)\end{aligned}\tag{2.13}$$

561 introducing in this way four gauge fields,  $W_\mu^i(x)$  and  $B_\mu(x)$ , in the process. The  
 562 covariant derivatives (Eqn. 2.13) are required to transform in the same way as fermion  
 563 fields  $\psi_i(x)$  themselves, therefore, the gauge fields transform as:

$$\begin{aligned} B_\mu(x) &\xrightarrow{G} B'_\mu(x) \equiv B_\mu(x) - \frac{1}{g'} \partial_\mu \beta(x) \\ W_\mu^i(x) &\xrightarrow{G} W_\mu^{i\prime}(x) \equiv W_\mu^i(x) - \frac{i}{g} \partial_\mu \alpha_i(x) - \varepsilon_{ijk} \alpha_i(x) W_\mu^j(x). \end{aligned} \quad (2.14)$$

564 The G invariant version of the Lagrangian density 2.9 can be written as

$$\mathcal{L}_0 = \sum_{j=1}^3 i \bar{\psi}_j(x) \gamma^\mu D_\mu \psi_j(x) \quad (2.15)$$

565 where free massless fermion and gauge fields and fermion-gauge boson interactions  
 566 are included. The EWI Lagrangian density must additionally include kinetic terms  
 567 for the gauge fields ( $\mathcal{L}_G$ ) which are built from the field strengths, according to

$$B_{\mu\nu}(x) \equiv \partial_\mu B_\nu - \partial_\nu B_\mu \quad (2.16)$$

$$W_{\mu\nu}^i(x) \equiv \partial_\mu W_\nu^i(x) - \partial_\nu W_\mu^i(x) - g \varepsilon^{ijk} W_\mu^j W_\nu^k \quad (2.17)$$

568 the last term in Eqn. 2.17 is added in order to hold the gauge invariance; therefore,

$$\mathcal{L}_G = -\frac{1}{4} B_{\mu\nu}(x) B^{\mu\nu}(x) - \frac{1}{4} W_{\mu\nu}^i(x) W_i^{\mu\nu}(x) \quad (2.18)$$

569 which contains not only the free gauge fields contributions, but also the gauge fields  
 570 self-interactions and interactions among them.

571 The three weak isospin conserved currents resulting from the  $SU(2)_L$  symmetry

572 are given by

$$J_\mu^i(x) = \frac{1}{2} \bar{\psi}_1(x) \gamma_\mu \sigma^i \psi_1(x) \quad (2.19)$$

573 while the weak hypercharge conserved current resulting from the  $U(1)_Y$  symmetry is  
 574 given by

$$J_\mu^Y = \sum_{j=1}^3 \bar{\psi}_j(x) \gamma_\mu y_j \psi_j(x) \quad (2.20)$$

575 In order to evaluate the electroweak interactions modeled by an isos triplet field  
 576  $W_\mu^i$  that couples to isospin currents  $J_\mu^i$  with strength  $g$  and additionally the singlet  
 577 field  $B_\mu$  which couples to the weak hypercharge current  $J_\mu^Y$  with strength  $g'/2$ . The  
 578 interaction Lagrangian density to be considered is

$$\mathcal{L}_I = -g J^{i\mu}(x) W_\mu^i(x) - \frac{g'}{2} J^{Y\mu}(x) B_\mu(x) \quad (2.21)$$

579 Note that the weak isospin currents are not the same as the charged fermionic cur-  
 580 rents that were used to describe the WI (Eqn. 2.8), since the weak isospin eigenstates  
 581 are not the same as the mass eigenstates, but they are closely related

$$J_\mu = \frac{1}{2}(J_\mu^1 + iJ_\mu^2), \quad J_\mu^\dagger = \frac{1}{2}(J_\mu^1 - iJ_\mu^2). \quad (2.22)$$

582 The same happens with the gauge fields  $W_\mu^i$  which are related to the mass eigen-  
 583 states  $W^\pm$  by

$$W_\mu^+ = \frac{1}{\sqrt{2}}(W_\mu^1 - iW_\mu^2), \quad W_\mu^- = \frac{1}{\sqrt{2}}(W_\mu^1 + iW_\mu^2). \quad (2.23)$$

584 The fact that there are three weak isospin conserved currents is an indication that

585 in addition to the charged fermionic currents, which couple charged to neutral leptons,  
 586 there should be a neutral fermionic current that does not involve electric charge  
 587 exchange; therefore, it couples neutral fermions or fermions of the same electric charge.  
 588 The third weak isospin current contains a term that is similar to the electromagnetic  
 589 current ( $j_\mu^{em}$ ), indicating that there is a relation between them and resembling the  
 590 Gell-Mann-Nishijima formula 2.2 adapted to electroweak interactions

$$Q = T_3 + \frac{Y_W}{2}. \quad (2.24)$$

591 Just as  $Q$  generates the  $U(1)_{em}$  symmetry, the weak hypercharge generates the  
 592  $U(1)_Y$  symmetry as said before. It is possible to write the relationship in terms of  
 593 the currents as

$$j_\mu^{em} = J_\mu^3 + \frac{1}{2} J_\mu^Y. \quad (2.25)$$

594 The neutral gauge fields  $W_\mu^3$  and  $B_\mu$  cannot be directly identified with the  $Z$   
 595 and the photon fields since the photon interacts similarly with left and right-handed  
 596 fermions; however, they are related through a linear combination given by

$$A_\mu = B_\mu \cos \theta_W + W_\mu^3 \sin \theta_W \quad (2.26)$$

$$Z_\mu = -B_\mu \sin \theta_W + W_\mu^3 \cos \theta_W$$

where  $\theta_W$  is known as the *Weinberg angle*. The interaction Lagrangian is now given

by

$$\mathcal{L}_I = -\frac{g}{\sqrt{2}}(J^\mu W_\mu^+ + J^{\mu\dagger} W_\mu^-) - \left(g \sin \theta_W J_\mu^3 + g' \cos \theta_W \frac{J_\mu^Y}{2}\right) A^\mu - \left(g \cos \theta_W J_\mu^3 - g' \sin \theta_W \frac{J_\mu^Y}{2}\right) Z^\mu \quad (2.27)$$

597 the first term is the weak charged current interaction, while the second term is the  
 598 electromagnetic interaction under the condition

$$g \sin \theta_W = g' \cos \theta_W = e, \quad \frac{g'}{g} = \tan \theta_W \quad (2.28)$$

599 contained in the Eqn.2.25; the third term is the neutral weak current.

600

601 Note that the neutral fields transformation given by the Eqn. 2.26 can be written  
 602 in terms of the coupling constants  $g$  and  $g'$  as:

$$A_\mu = \frac{g' W_\mu^3 + g B_\mu}{\sqrt{g^2 + g'^2}}, \quad Z_\mu = \frac{g W_\mu^3 - g' B_\mu}{\sqrt{g^2 + g'^2}}. \quad (2.29)$$

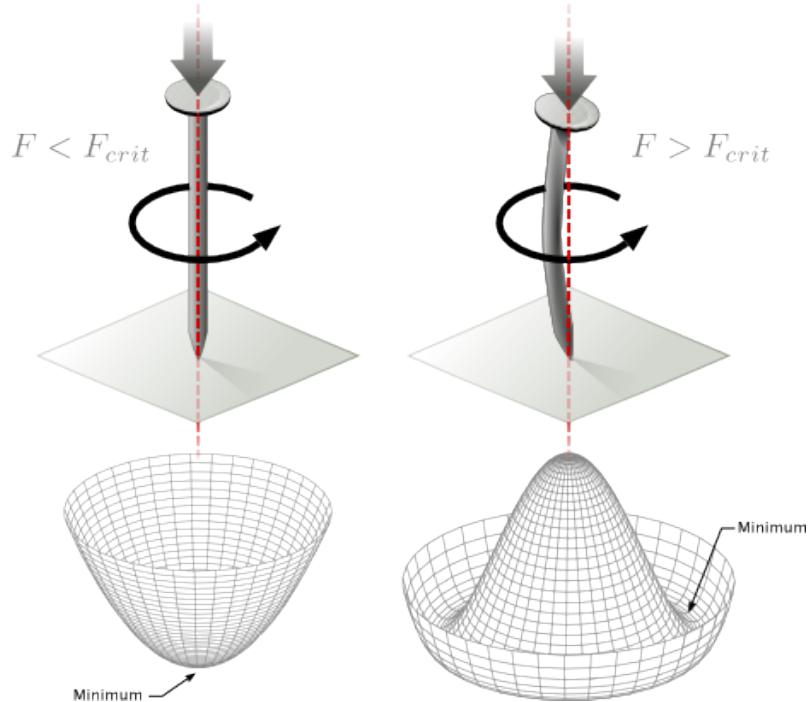
603 So far, the Lagrangian density describing the non-massive EWI is:

$$\mathcal{L}_{nmEWI} = \mathcal{L}_0 + \mathcal{L}_G \quad (2.30)$$

604 where fermion and gauge fields have been considered massless because their regular  
 605 mass terms are manifestly non invariant under G transformations; therefore, masses  
 606 have to be generated in a gauge invariant way. The mechanism by which this goal is  
 607 achieved is known as the *Higgs mechanism* and is closely connected to the concept of  
 608 *spontaneous symmetry breaking*.

### 609 2.3.1 Spontaneous symmetry breaking (SSB)

610 Figure 2.6 left shows a steel nail (top) which is subject to an external force; the form  
 611 of the potential energy is also shown (bottom).



**Figure 2.6:** Spontaneous symmetry breaking mechanism. The steel nail, subject to an external force (top left), has rotational symmetry with respect to its axis. When the external force overcomes a critical value the nail buckles (top right) choosing a minimal energy state (ground state) and thus *breaking spontaneously the rotational symmetry*. The potential energy (bottom) changes but holds the rotational symmetry; however, an infinite number of asymmetric ground states are generated and circularly distributed in the bottom of the potential [31].

612 Before reaching the critical force value, the system has rotational symmetry with  
 613 respect to the nail axis; however, after the critical force value is reached the nail buck-  
 614 les (top right). The form of the potential energy (bottom right) changes appearing a  
 615 set of infinity minima but preserving its rotational symmetry. Right before the nail  
 616 buckles there is no indication of the direction the nail will bend because any of the  
 617 directions are equivalent, but once the nail bends, choosing a direction, an arbitrary

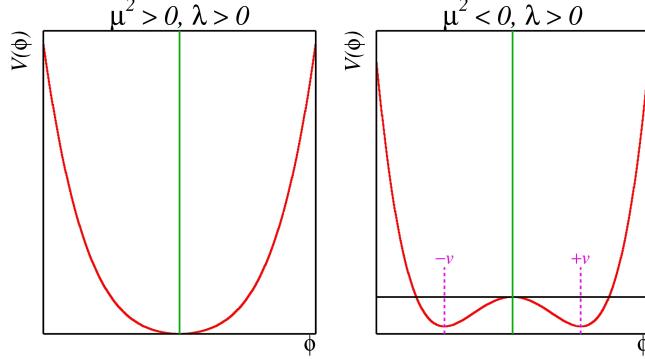
618 minimal energy state (ground state) is selected and it does not share the system's  
 619 rotational symmetry. This mechanism for reaching an asymmetric ground state is  
 620 known as *spontaneous symmetry breaking*.

621 The lesson from this analysis is that the way to introduce the SSB mechanism  
 622 into a system is by adding the appropriate potential to it.

623 Figure 2.7 shows a plot of the potential  $V(\phi)$  in the case of a scalar field  $\phi$

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \quad (2.31)$$

624 If  $\mu^2 > 0$  the potential has only one minimum at  $\phi = 0$  and describes a scalar field  
 625 with mass  $\mu$ . If  $\mu^2 < 0$  the potential has a local maximum at  $\phi = 0$  and two minima  
 626 at  $\phi = \pm\sqrt{-\mu^2/\lambda}$  which enables the SSB mechanism to work.



**Figure 2.7:** Shape of the potential  $V(\phi)$  for  $\lambda > 0$  and:  $\mu^2 > 0$  (left) and  $\mu^2 < 0$  (right). The case  $\mu^2 < 0$  corresponds to the potential suitable for introducing the SSB mechanism by choosing one of the two ground states which are connected via reflection symmetry. [31].

627 In the case of a complex scalar field  $\phi(x)$

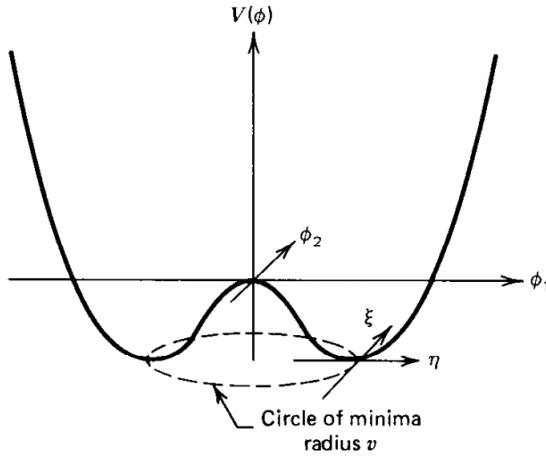
$$\phi(x) = \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2) \quad (2.32)$$

628 the Lagrangian (invariant under global  $U(1)$  transformations) is given by

$$\mathcal{L} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi), \quad V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \quad (2.33)$$

629 where an appropriate potential has been added in order to introduce the SSB.

630 As seen in Figure 2.8, the potential has now an infinite number of minima circularly  
 631 distributed along the  $\xi$ -direction which makes possible the occurrence of the SSB by  
 632 choosing an arbitrary ground state; for instance,  $\xi = 0$ , i.e.  $\phi_1 = v, \phi_2 = 0$



**Figure 2.8:** Potential for complex scalar field. There is a circle of minima of radius  $v$  along the  $\xi$ -direction [6].

$$\phi_0 = \frac{v}{\sqrt{2}} \exp(i\xi) \xrightarrow{SSB} \phi_0 = \frac{v}{\sqrt{2}} \quad (2.34)$$

633 As usual, excitations over the ground state are studied by making an expansion  
 634 about it; thus, the excitations can be parametrized as:

$$\phi(x) = \frac{1}{\sqrt{2}} (v + \eta(x) + i\xi(x)) \quad (2.35)$$

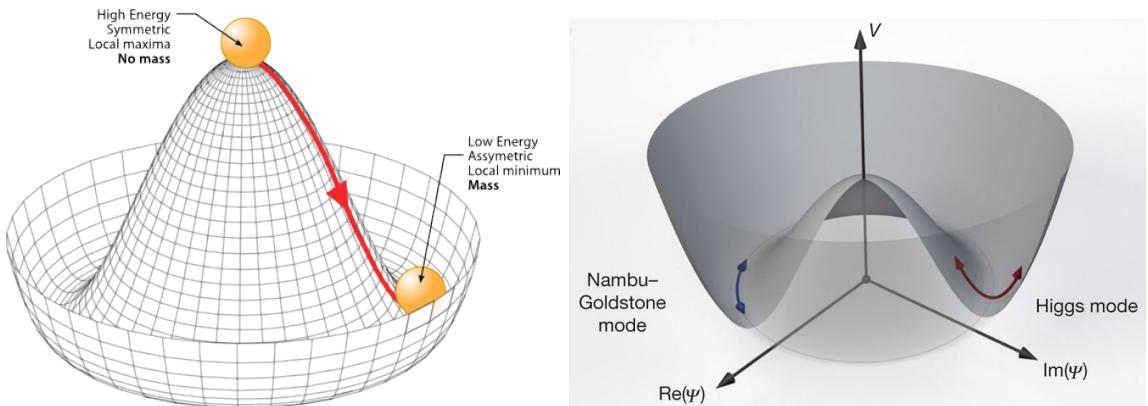
635 which when substituted into Eqn. 2.33 produces a Lagrangian in terms of the new

636 fields  $\eta$  and  $\xi$

$$\mathcal{L}' = \frac{1}{2}(\partial_\mu \xi)^2 + \frac{1}{2}(\partial_\mu \eta)^2 + \mu^2 \eta^2 - V(\phi_0) - \lambda v \eta (\eta^2 + \xi^2) - \frac{\lambda}{4}(\eta^2 + \xi^2)^2 \quad (2.36)$$

637 where the last two terms represent the interactions and self-interaction between the  
 638 two fields  $\eta$  and  $\xi$ . The particular feature of the SSB mechanism is revealed when  
 639 looking to the first three terms of  $\mathcal{L}'$ . Before the SSB, only the massless  $\phi$  field is  
 640 present in the system; after the SSB there are two fields of which the  $\eta$ -field has  
 641 acquired mass  $m_\eta = \sqrt{-2\mu^2}$  while the  $\xi$ -field is still massless (see Figure 2.9).

642



**Figure 2.9:** SSB mechanism for a complex scalar field [31, 32].

643 Thus, the SSB mechanism serves as a method to generate mass but as a side ef-  
 644 fect a massless field is introduced in the system. This fact is known as the Goldstone  
 645 theorem and states that a massless scalar field appears in the system for each con-  
 646 tinuous symmetry spontaneously broken. Another version of the Goldstone theorem  
 647 states that “if a Lagrangian is invariant under a continuous symmetry group  $G$ , but  
 648 the vacuum is only invariant under a subgroup  $H \subset G$ , then there must exist as many  
 649 massless spin-0 particles (Nambu-Goldstone bosons) as broken generators.” [26] The

650 Nambu-Goldstone boson can be understood considering that the potential in the  $\xi$ -  
 651 direction is flat so excitations in that direction are not energy consuming and thus  
 652 represent a massless state.

### 653 2.3.2 Higgs mechanism

654 When the SSB mechanism is introduced in the formulation of the EWI in an attempt  
 655 to generate the mass of the so far massless gauge bosons and fermions, an interesting  
 656 effect is revealed. In order to keep the G symmetry group invariance and generate  
 657 the mass of the EW gauge bosons, a G invariant Lagrangian density ( $\mathcal{L}_S$ ) has to be  
 658 added to the non massive EWI Lagrangian (Eqn. 2.30)

$$\mathcal{L}_S = (D_\mu \phi)^\dagger (D^\mu \phi) - \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2, \quad \lambda > 0, \mu^2 < 0 \quad (2.37)$$

$$D_\mu \phi = \left( i\partial_\mu - g \frac{\sigma_i}{2} W_\mu^i - g' \frac{Y}{2} B_\mu \right) \phi \quad (2.38)$$

659  $\phi$  has to be an isospin doublet of complex scalar fields so it preserves the G invariance;  
 660 thus  $\phi$  can be defined as:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \equiv \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}. \quad (2.39)$$

661 The minima of the potential are defined by

$$\phi^\dagger \phi = \frac{1}{2} (\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2) = -\frac{\mu^2}{2\lambda}. \quad (2.40)$$

662 The choice of the ground state is critical. By choosing a ground state, invariant  
 663 under  $U(1)_{em}$  gauge symmetry, the photon will remain massless and the  $W^\pm$  and  $Z$   
 664 bosons masses will be generated which is exactly what is needed. In that sense, the

665 best choice corresponds to a weak isospin doublet with  $T_3 = -1/2$ ,  $Y_W = 1$  and  $Q = 0$   
 666 which defines a ground state with  $\phi_1 = \phi_2 = \phi_4$  and  $\phi_3 = v$ :

$$\phi_0 \equiv \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad v^2 \equiv -\frac{\mu^2}{\lambda}. \quad (2.41)$$

667 where the vacuum expectation value  $v$  is fixed by the Fermi coupling  $G_F$  according  
 668 to  $v = (\sqrt{2}G_F)^{1/2} \approx 246$  GeV.

669 The G symmetry has been broken and three Nambu-Goldstone bosons will appear.  
 670 The next step is to expand  $\phi$  about the chosen ground state as:

$$\phi(x) = \frac{1}{\sqrt{2}} \exp\left(\frac{i}{v} \sigma_i \theta^i(x)\right) \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix} \approx \frac{1}{\sqrt{2}} \begin{pmatrix} \theta_1(x) + i\theta_2(x) \\ v + H(x) - i\theta_3(x) \end{pmatrix} \quad (2.42)$$

671 to describe fluctuations from the ground state  $\phi_0$ . The fields  $\theta_i(x)$  represent the  
 672 Nambu-Goldstone bosons while  $H(x)$  is known as *Higgs field*. The fundamental fea-  
 673 ture of the parametrization used is that the dependence on the  $\theta_i(x)$  fields is factored  
 674 out in a global phase that can be eliminated by taking the physical *unitary gauge*  
 675  $\theta_i(x) = 0$ . Therefore the expansion about the ground state is given by:

$$\phi(x) \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix} \quad (2.43)$$

676 which when substituted into  $\mathcal{L}_S$  (Eqn. 2.37) results in a Lagrangian containing the  
 677 now massive three gauge bosons  $W^\pm, Z$ , one massless gauge boson (photon) and  
 678 the new Higgs field (H). The three degrees of freedom corresponding to the Nambu-  
 679 Goldstone bosons are now integrated into the massive gauge bosons as their lon-  
 680 gitudinal polarizations which were not available when they were massless particles.  
 681 The effect by which vector boson fields acquire mass after an spontaneous symmetry  
 682 breaking, but without an explicit gauge invariance breaking is known as the *Higgs*

683 mechanism.

684 The mechanism was proposed by three independent groups: F.Englert and R.Brout  
 685 in August 1964 [33], P.Higgs in October 1964 [34] and G.Guralnik, C.Hagen and  
 686 T.Kibble in November 1964 [35]; however, its importance was not realized until  
 687 S.Glashow [22], A.Salam [23] and S.Weinberg [24], independently, proposed that elec-  
 688 tromagnetic and weak interactions are two manifestations of a more general interac-  
 689 tion called *electroweak interaction* in 1967.

### 690 2.3.3 Masses of the gauge bosons

691 The masses of the gauge bosons are extracted by evaluating the kinetic part of La-  
 692 grangian  $\mathcal{L}_S$  in the ground state (known also as the vacuum expectation value), i.e.,

$$\left| \left( \partial_\mu - ig \frac{\sigma_i}{2} W_\mu^i - i \frac{g'}{2} B_\mu \right) \phi_0 \right|^2 = \left( \frac{1}{2} vg \right)^2 W_\mu^+ W^{-\mu} + \frac{1}{8} v^2 (W_\mu^3, B_\mu) \begin{pmatrix} g^2 & -gg' \\ -gg' & g'^2 \end{pmatrix} \begin{pmatrix} W^{3\mu} \\ B^\mu \end{pmatrix} \quad (2.44)$$

693 comparing with the typical mass term for a charged boson  $M_W^2 W^+ W^-$

$$M_W = \frac{1}{2} vg. \quad (2.45)$$

The second term in the right side of the Eqn.2.44 comprises the masses of the neutral bosons, but it needs to be written in terms of the gauge fields  $Z_\mu$  and  $A_\mu$  in order to be compared to the typical mass terms for neutral bosons, therefore using Eqn. 2.29

$$\begin{aligned} \frac{1}{8} v^2 [g^2 (W_\mu^3)^2 - 2gg' W_\mu^3 B^\mu + g'^2 B_\mu^2] &= \frac{1}{8} v^2 [g W_\mu^3 - g' B_\mu]^2 + 0[g' W_\mu^3 + g B_\mu]^2 \quad (2.46) \\ &= \frac{1}{8} v^2 [\sqrt{g^2 + g'^2} Z_\mu]^2 + 0[\sqrt{g^2 + g'^2} A_\mu]^2 \end{aligned}$$

694 and then

$$M_Z = \frac{1}{2}v\sqrt{g^2 + g'^2}, \quad M_A = 0 \quad (2.47)$$

### 695 2.3.4 Masses of the fermions

696 The lepton mass terms can be generated by introducing a gauge invariant Lagrangian  
 697 term describing the Yukawa coupling between the lepton field and the Higgs field

$$\mathcal{L}_{Yl} = -G_l \left[ (\bar{\nu}_l, \bar{l})_L \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} l_R + \bar{l}_R (\phi^-, \bar{\phi}^0) \begin{pmatrix} \nu_l \\ l \end{pmatrix} \right], \quad l = e, \mu, \tau. \quad (2.48)$$

698 After the SSB and replacing the usual field expansion about the ground state  
 699 (Eqn.2.41) into  $\mathcal{L}_{Yl}$ , the mass term arises

$$\mathcal{L}_{Yl} = -m_l(\bar{l}_L l_R + \bar{l}_R l_L) - \frac{m_l}{v}(\bar{l}_L l_R + \bar{l}_R l_L)H = -m_l \bar{l}l \left(1 + \frac{H}{v}\right) \quad (2.49)$$

700  $m_l = \frac{G_l}{\sqrt{2}}v$  (2.50)

701 where the additional term represents the lepton-Higgs interaction. The quark masses  
 702 are generated in a similar way as lepton masses but for the upper member of the  
 703 quark doublet a different Higgs doublet is needed:

$$\phi_c = -i\sigma_2\phi^* = \begin{pmatrix} -\bar{\phi}^0 \\ \phi^- \end{pmatrix}. \quad (2.51)$$

704 Additionally, given that the quark isospin doublets are not constructed in terms  
 705 of the mass eigenstates but in terms of the flavor eigenstates, as shown in Table2.5,  
 706 the coupling parameters will be related to the CKM matrix elements; thus the quark  
 707 Lagrangian is given by:

$$\mathcal{L}_{Yq} = -G_d^{i,j}(\bar{u}_i, \bar{d}'_i)_L \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} d_{jR} - G_u^{i,j}(\bar{u}_i, \bar{d}'_i)_L \begin{pmatrix} -\bar{\phi}^0 \\ \phi^- \end{pmatrix} u_{jR} + h.c. \quad (2.52)$$

708 with  $i,j=1,2,3$ . After SSB and expansion about the ground state, the diagonal form  
 709 of  $\mathcal{L}_{Yq}$  is:

$$\mathcal{L}_{Yq} = -m_d^i \bar{d}_i d_i \left(1 + \frac{H}{v}\right) - m_u^i \bar{u}_i u_i \left(1 + \frac{H}{v}\right) \quad (2.53)$$

710 Fermion masses depend on arbitrary couplings  $G_l$  and  $G_{u,d}$  and are not predicted  
 711 by the theory.

### 712 2.3.5 The Higgs field

713 After the characterization of the fermions and gauge bosons as well as their interac-  
 714 tions, it is necessary to characterize the Higgs field itself. The Lagrangian  $\mathcal{L}_S$  in Eqn.  
 715 2.37 written in terms of the gauge bosons is given by

$$\mathcal{L}_S = \frac{1}{4} \lambda v^4 + \mathcal{L}_H + \mathcal{L}_{HV} \quad (2.54)$$

716

$$\mathcal{L}_H = \frac{1}{2} \partial_\mu H \partial^\mu H - \frac{1}{2} m_H^2 H^2 - \frac{1}{2v} m_H^2 H^3 - \frac{1}{8v^2} m_H^2 H^4 \quad (2.55)$$

717

$$\mathcal{L}_{HV} = m_H^2 W_\mu^+ W^{\mu-} \left(1 + \frac{2}{v} H + \frac{2}{v^2} H^2\right) + \frac{1}{2} m_Z^2 Z_\mu Z^\mu \left(1 + \frac{2}{v} H + \frac{2}{v^2} H^2\right) \quad (2.56)$$

718 The mass of the Higgs boson is deduced as usual from the mass term in the Lagrangian  
 719 resulting in:

$$m_H = \sqrt{-2\mu^2} = \sqrt{2\lambda}v \quad (2.57)$$

720 however, it is not predicted by the theory either. The experimental efforts to find the  
 721 Higgs boson, carried out by the *Compact Muon Solenoid (CMS)* experiment and the *A*  
 722 *Toroidal LHC Appartus (ATLAS)* experiments at the *Large Hadron Collider(LHC)*,  
 723 gave great results by July of 2012 when the discovery of a new particle compatible

724 with the Higgs boson predicted by the electroweak theory [36, 37] was announced.  
 725 Although at the announcement time there were some reservations about calling the  
 726 new particle the *Higgs boson*, today this name is widely accepted. The Higgs mass  
 727 measurement, reported by both experiments [38], is in Table 2.8.

Property	Value
Electric charge	0
Color charge	0
Spin	0
Weak isospin	-1/2
Weak hypercharge	1
Parity	1
Mass (GeV/c <sup>2</sup> )	125.09±0.21 (stat.)±0.11 (syst.)

**Table 2.8:** Higgs boson properties. Higgs mass is not predicted by the theory and the value here corresponds to the experimental measurement.

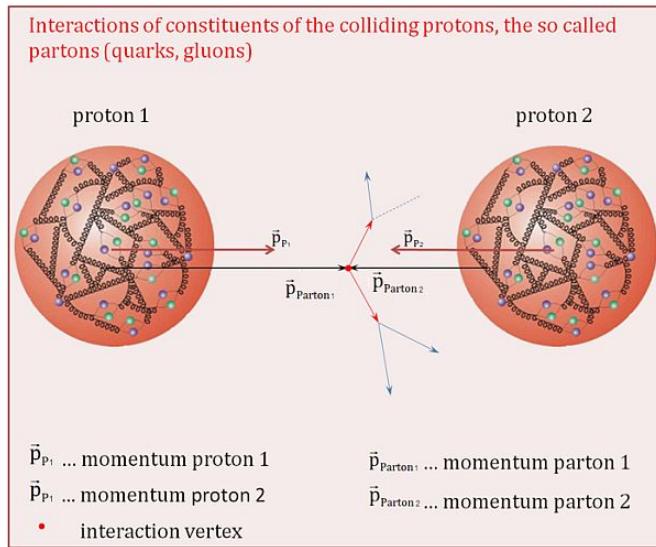
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### 729 2.3.6 Production of Higgs bosons at LHC

730 At the LHC, Higgs bosons are produced as a result of the collision of two counter-  
 731 rotating protons beams. A detailed description of the LHC machine will be presented  
 732 in chapter 3.

733 Protons are composed of quarks and these quarks are bound by gluons; however,  
 734 what is commonly called the quark content of the proton makes reference to the  
 735 valence quarks. In fact, a proton is not just a rigid entity with three balls in it all  
 736 tied up with springs, but the gluons exchanged by the valence quarks tend to split  
 737 spontaneously into quark-antiquark pairs or more gluons, creating *sea of quarks and*  
 738 *gluons* as represented in Figure 2.10.

739 In a proton-proton ( $pp$ ) collision, the proton's constituents, quarks and gluons, are  
 740 those that collide. The  $pp$  cross section depends on the momentum of the colliding  
 741 particles, reason for which it is needed to know how the momentum is distributed

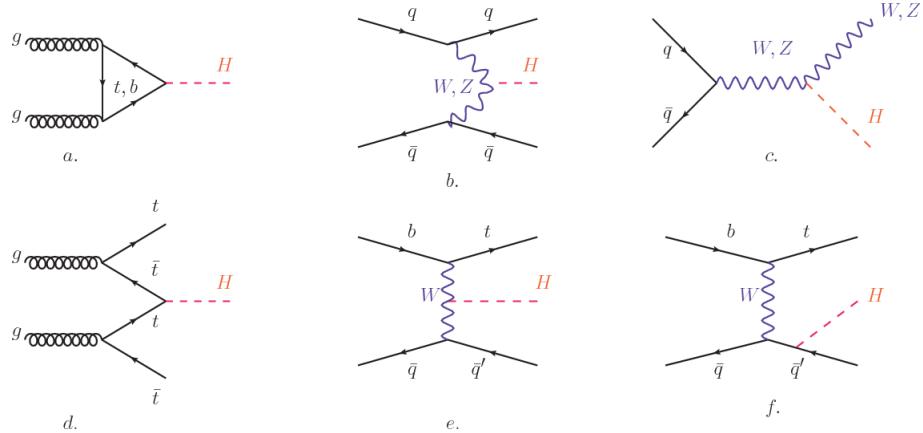


**Figure 2.10:** Proton-proton collision. Protons are composed of 3 valence quarks, a sea of quarks and gluons; therefore in a proton-proton collision, quarks and gluons are those who collide. [39].

inside the proton. Quarks and gluons are known as partons, hence, the functions that describe how the proton momentum is distributed among partons inside it are called *parton distribution functions (PDFs)*; PDFs are determined from experimental data obtained in experiments where the internal structure of hadrons is tested.

In addition, in physics, a common approach to study complex systems consists of starting with a simpler version of them, for which a well known description is available, and adding an additional *perturbation* which represents a small deviation from the known behavior. If the perturbation is small enough, the physical quantities associated with the perturbed system are expressed as a series of corrections to those of the simpler system. The perturbation series corresponds to an expansion in power series of a small parameter, therefore, the more terms are considered in the series (the higher order in the perturbation series), the more precise is the the description of the complex system. If the perturbation does not get progressively smaller, the strategy cannot be applied and new methods have to be employed.

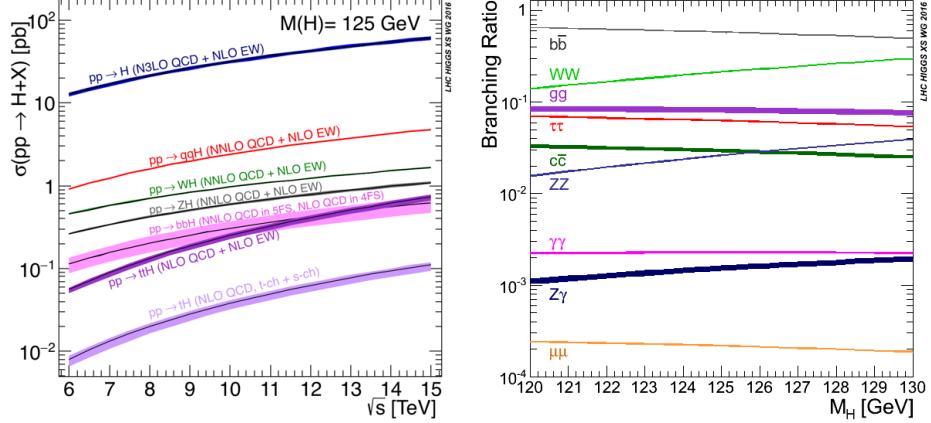
756 High energy systems, like the Higgs production at LHC explored in this thesis,  
 757 usually can be treated perturbatively with the expansion made in terms of the cou-  
 758 pling constants. The overview presented here will be oriented specifically to the Higgs  
 759 boson production mechanisms in  $pp$  collisions at LHC.



**Figure 2.11:** Main Higgs boson production mechanism Feynman diagrams. a. gluon-gluon fusion, b. vector boson fusion (VBF), c. Higgs-strahlung, d. Associated production with a top or bottom quark pair, e-f. associated production with a single top quark.

760 Figure 2.11 shows the Feynman diagrams for the leading order (first order) Higgs  
 761 production processes at LHC, while the cross section for Higgs production as a func-  
 762 tion of the center of mass-energy ( $\sqrt{s}$ ) for  $pp$  collisions is showed in Figure 2.12 left.  
 763 The tags NLO (next to leading order), NNLO (next to next to leading order) and  
 764 N3LO (next to next to next to leading order) make reference to the order at which  
 765 the perturbation series have been considered while the tags QCD and EW correspond  
 766 to the strong and electroweak coupling constants respectively.

767 The main production mechanism is the gluon fusion (Figure 2.11a and  $pp \rightarrow H$  in  
 768 Figure 2.12) given that gluons carry the highest fraction of momentum of the protons  
 769 in  $pp$  colliders. Since the Higgs boson does not couple to gluons, the mechanism  
 770 proceeds through the exchange of a virtual top-quark loop. Note that in this process  
 771 the Higgs boson is produced alone, turning out to be problematic for some Higgs



**Figure 2.12:** Higgs boson production cross sections (left) and decay branching ratios (right) for the main mechanisms. The VBF is indicated as  $qqH$  [40].

772 decays, because such absence of anything produced in association with the Higgs  
 773 represent a trouble for triggering, however, this mechanism is experimentally clean  
 774 when combined with the two-photon or the four-lepton decay channels (see Section  
 775 2.3.7).

776 Vector boson fusion (Figure 2.11b and  $pp \rightarrow qqH$  in Figure 2.12) has the second  
 777 largest production cross section. The scattering of two fermions is mediated by a weak  
 778 gauge boson which later emits a Higgs boson. In the final state, the two fermions tend  
 779 to be located in the central region of the detector; this kind of features are generally  
 780 used as a signature when analyzing the datasets provided by the experiments<sup>7</sup>.

781 The next production mechanism is Higgs-strahlung (Figure 2.11c and  $pp \rightarrow WH, pp \rightarrow$   
 782  $ZH$  in Figure 2.12) where two fermions annihilate to form a weak gauge boson. If the  
 783 initial fermions have enough energy, the emergent boson might emit a Higgs boson.

784 The associated production with a top or bottom quark pair and the associated  
 785 production with a single top quark (Figure 2.11d-f and  $pp \rightarrow bbH, pp \rightarrow t\bar{t}H, pp \rightarrow tH$   
 786 in Figure 2.12) have a smaller cross section than the main three mechanisms above,  
 787 but they provide a good opportunity to test the Higgs-top coupling. The analysis

<sup>7</sup> More details about how to identify events of interest in this analysis will be given in chapter 6.

788 reported in this thesis is developed using these production mechanisms. A detailed  
 789 description of the  $tH$  mechanism will be given in Section 2.5.

790 **2.3.7 Higgs boson decay channels**

791 When a particle can decay through several modes, also known as channels, the prob-  
 792 ability of decaying through a given channel is quantified by the *branching ratio (BR)*  
 793 of the decay channel; thus, the BR is defined as the ratio of number of decays go-  
 794 ing through that given channel to the total number of decays. In regard to the  
 795 Higgs boson decay, the BR can be predicted with accuracy once the Higgs mass is  
 796 known [41, 42]. In Figure 2.12 right, a plot of the BR as a function of the Higgs mass  
 797 is presented; the largest predicted BR corresponds to the  $b\bar{b}$  pair decay channel (see  
 798 Table 2.9) given that it is the heaviest particle pair whose on-shell<sup>8</sup> production is  
 799 kinematically allowed in the decay.

Decay channel	Branching ratio	Rel. uncertainty
$H \rightarrow b\bar{b}$	$5.84 \times 10^{-1}$	$+3.2\% - 3.3\%$
$H \rightarrow W^+W^-$	$2.14 \times 10^{-1}$	$+4.3\% - 4.2\%$
$H \rightarrow \tau^+\tau^-$	$6.27 \times 10^{-2}$	$+5.7\% - 5.7\%$
$H \rightarrow ZZ$	$2.62 \times 10^{-2}$	$+4.3\% - 4.1\%$
$H \rightarrow \gamma\gamma$	$2.27 \times 10^{-3}$	$+5.0\% - 4.9\%$
$H \rightarrow Z\gamma$	$1.53 \times 10^{-3}$	$+9.0\% - 8.9\%$
$H \rightarrow \mu^+\mu^-$	$2.18 \times 10^{-4}$	$+6.0\% - 5.9\%$

**Table 2.9:** Predicted branching ratios and the relative uncertainty for some decay channels of a SM Higgs boson with  $m_H = 125\text{GeV}/c^2$  [9]; the uncertainties are driven by theoretical uncertainties for the different Higgs boson partial widths and by parametric uncertainties associated to the strong coupling and the masses of the quarks which are the input parameters. Further details on these calculations can be found in Reference [43]

800

---

<sup>8</sup> In general, on-shell or real particles are those which satisfy the energy-momentum relation ( $E^2 - |\vec{p}|^2 c^2 = m^2 c^4$ ); off-shell or virtual particles does not satisfy it which is possible under the uncertainty principle of quantum mechanics. Usually, virtual particles correspond to internal propagators in Feynman diagrams.

801 Decays to other lepton and quark pairs, like electron, strange, up, and down  
 802 quark pairs not listed in the table, are also possible but their likelihood is too small  
 803 to measure since they are very lightweight, hence, their interaction with the Higgs  
 804 boson is very weak. On other hand, the decay to top quark pairs is heavily suppressed  
 805 due to the top quark mass ( $\approx 173 \text{ GeV}/c^2$ ).

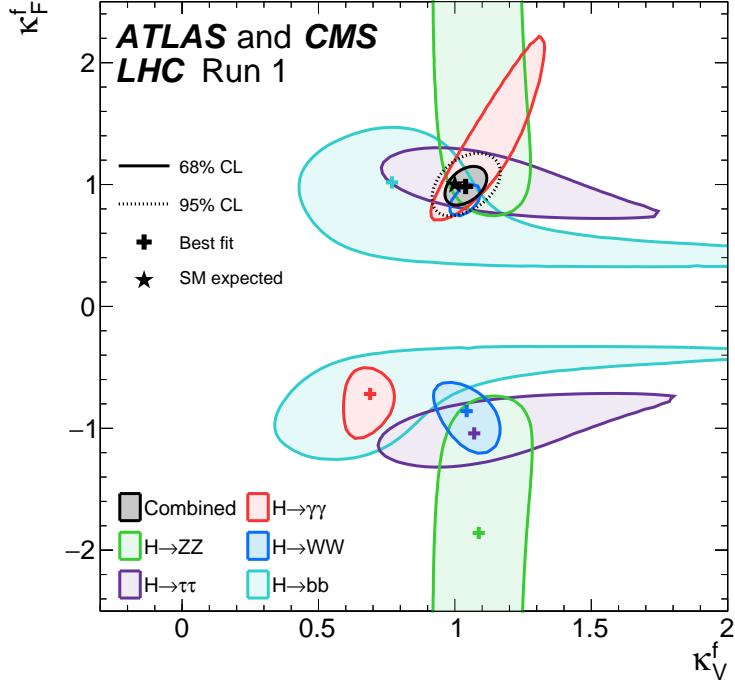
806 Decays to gluons proceed indirectly through a virtual top quark loop while the  
 807 decays to photons proceed through a virtual W boson loop, therefore, their branching  
 808 ratio is smaller compared to direct interaction decays. Same is true for the decay to  
 809 a photon and a Z boson.

810 In the case of decays to pairs of W and Z bosons, the decay proceed with one of  
 811 the bosons being on-shell and the other being off-shell. The likelihood of the process  
 812 diminish depending on how far off-shell are the virtual particles involved, hence, the  
 813 branching ratio for W boson pairs is bigger than for Z boson pairs since Z boson mass  
 814 is bigger than W boson mass.

815 Note that the decay to a pair of virtual top quarks is possible, but the probability  
 816 is way too small.

## 817 **2.4 Experimental status of the anomalous 818 Higgs-fermion coupling**

819 ATLAS and CMS have performed analyses of the anomalous H-f coupling by making  
 820 likelihood scans for the two coupling modifiers,  $\kappa_t$  and  $\kappa_V$ , under the assumption that  
 821  $\kappa_Z = \kappa_W \equiv \kappa_V$  and  $\kappa_t = \kappa_\tau = \kappa_b \equiv \kappa_f$ . Figure 2.13 shows the result of the combination  
 822 of ATLAS and CMS fits; also the individual decay channels combination and the  
 823 global combination results are shown.

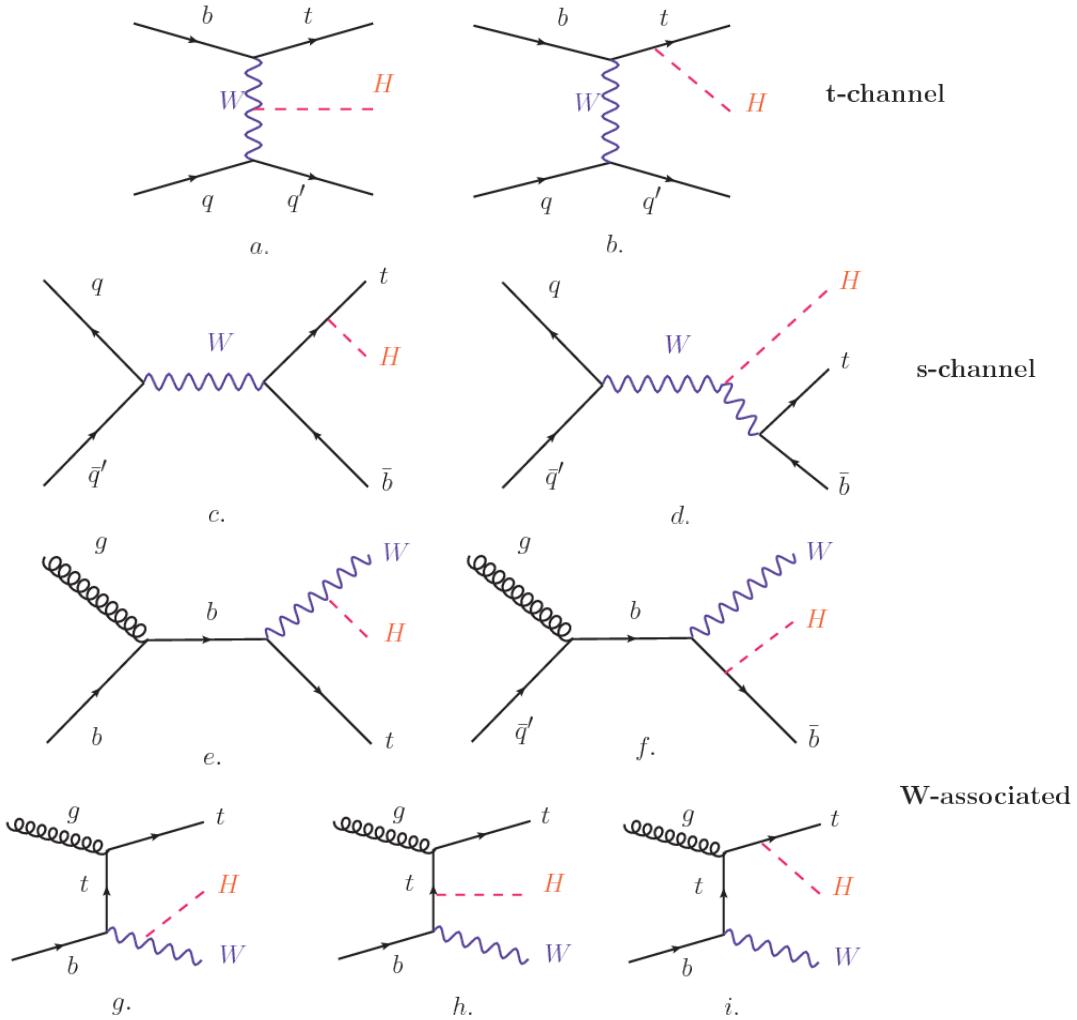


**Figure 2.13:** Combination of the ATLAS and CMS fits for coupling modifiers  $\kappa_t - \kappa_V$ ; also shown the individual decay channels combination and their global combination. No assumptions have been made on the sign of the coupling modifiers [58].

824 Note that from this plot there is limited information on the sign of the coupling  
 825 since most of the regions are sign-symmetric in  $\kappa_F$ ; also, the only information available  
 826 about the sign of the coupling comes from decays rather than production.

827 While all the channels are compatible for positive values of the modifiers, for  
 828 negative values of  $\kappa_t$  there is no compatibility. The best fit for individual channels is  
 829 compatible with negative values of  $\kappa_t$  except for the  $H \rightarrow bb$  channel which is expected  
 830 to be the most sensitive channel; therefore, the best fit for the global fit yields  $\kappa_t \geq 0$ .  
 831 Thus, the anomalous  $H$ - $t$  coupling cannot be excluded completely. That is what  
 832 motivates to look at  $tHq$ , which can help with both of those.

833 **2.5 Associated production of a Higgs boson and a  
834 single top quark**



**Figure 2.14:** Associated Higgs boson production with a top quark mechanism Feynman diagrams. a.,b. t-channel ( $tHq$ ), c.,d. s-channel ( $tHb$ ), e-i. W-associated.

835 The production of Higgs boson in association with a top quark has been extensively  
836 studied [44–48]. While measurements of the main Higgs production mechanisms rates  
837 are sensitive to the strength of the Higgs coupling to W boson or top quark, they are  
838 not sensitive to the relative sign between the two couplings. In this thesis, the Higgs

839 boson production mechanism explored is the associated production with a single top  
 840 quark ( $tH$ ) which offers sensitivity to the relative sign of the Higgs couplings to W  
 841 boson and to top quark. The description given here is based on Reference [46]

A process where two incoming particles interact and produce a final state with two particles can proceed in three called channels (see, for instance, Figure 2.14 omitting the red line). The t-channel represents processes where an intermediate particle is emitted by one of the incoming particles and absorbed by the other. The s-channel represents processes where the two incoming particles merge into an intermediate particle which eventually will split into the particles in the final state. The third channel, u-channel, is similar to the t-channel but the two outgoing particles interchange their roles. These three channels are connected to the so-called Mandelstam variables

$$s = (p_1 + p_2)^2 = (p'_1 + p'_2)^2 \rightarrow \text{square of the center mass-energy.} \quad (2.58)$$

$$t = (p_1 - p'_1)^2 = (p'_2 - p_2)^2 \rightarrow \text{square of the four-momentum transfer.} \quad (2.59)$$

$$u = (p_1 - p'_2)^2 = (p'_1 - p_2)^2 \rightarrow \text{square of the crossed four-momentum transfer.} \quad (2.60)$$

$$s + t + u = m_1^2 + m_2^2 + m'_1^2 + m'_2^2 \quad (2.61)$$

842 which relate the momentum, energy and the angles of the incoming and outgoing  
 843 particles in an scattering process of two particles to two particles. The importance of  
 844 the Mandelstam variables reside in that they form a minimum set of variables needed  
 845 to describe the kinematics of this scattering process; they are Lorentz invariant which  
 846 makes them very useful when doing calculations.

847 The  $tH$  production, where Higgs boson can be radiated either from the top quark or  
 848 from the W boson, is represented by the leading order Feynman diagrams in Figure  
 849 2.14. The cross section for the  $tH$  process is calculated, as usual, summing over  
 850 the contributions from the different Feynman diagrams; therefore it depends on the

interference between the contributions. In the SM, the interference for t-channel ( $tHq$  process) and W-associated ( $tHW$  process) production is destructive [44] resulting in the small cross sections presented in Table 2.10.

tH production channel	Cross section (fb)
t-channel ( $pp \rightarrow tHq$ )	$70.79^{+2.99}_{-4.80}$
W-associated ( $pp \rightarrow tHW$ )	$15.61^{+0.83}_{-1.04}$
s-channel( $pp \rightarrow tHb$ )	$2.87^{+0.09}_{-0.08}$

**Table 2.10:** Predicted SM cross sections for  $tH$  production at  $\sqrt{s} = 13$  TeV [49, 50].

854

855       The s-channel contribution can be neglected. It will be shown that a deviation  
 856 from the SM destructive interference would result in an enhancement of the  $tH$  cross  
 857 section compared to that in SM, which could be used to get information about the  
 858 sign of the Higgs-top coupling [46, 47]. In order to describe  $tH$  production processes,  
 859 Feynman diagram 2.14b will be considered; there, the W boson is radiated by a quark  
 860 in the proton and eventually it will interact with the b quark. In the high energy  
 861 regime, the effective W approximation [51] is used to describe the process as the  
 862 emission of an approximately on-shell W and its hard scattering with the b quark;  
 863 i.e.  $Wb \rightarrow th$ . The scattering amplitude for the process is given by

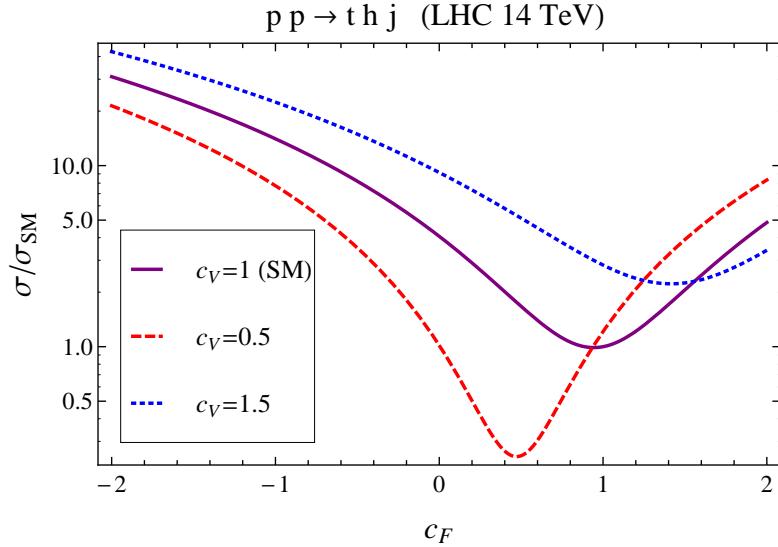
$$\mathcal{A} = \frac{g}{\sqrt{2}} \left[ (\kappa_t - \kappa_V) \frac{m_t \sqrt{s}}{m_W v} A \left( \frac{t}{s}, \varphi; \xi_t, \xi_b \right) + \left( \kappa_V \frac{2m_W}{v} \frac{s}{t} + (2\kappa_t - \kappa_V) \frac{m_t^2}{m_W v} \right) B \left( \frac{t}{s}, \varphi; \xi_t, \xi_b \right) \right], \quad (2.62)$$

864 where  $\kappa_V \equiv g_{HVV}/g_{HVV}^{SM}$  and  $\kappa_t \equiv g_{Ht}/g_{Ht}^{SM} = y_t/y_t^{SM}$  are scaling factors that quan-  
 865 tify possible deviations of the couplings from the SM values, Higgs-Vector boson  
 866 (H-W) and Higgs-top (H-t) respectively, from the SM couplings;  $s = (p_W + p_b)^2$ ,  
 867  $t = (p_W - p_H)^2$ ,  $\varphi$  is the Higgs azimuthal angle around the  $z$  axis taken parallel to the

868 direction of motion of the incoming W; A and B are functions describing the weak in-  
 869 teraction in terms of the chiral states  $(\xi_t, \xi_b)$  of the quarks  $b$  and  $t$ . Terms that vanish  
 870 in the high energy limit have been neglected as well as the Higgs and  $b$  quark masses<sup>9</sup>.

871

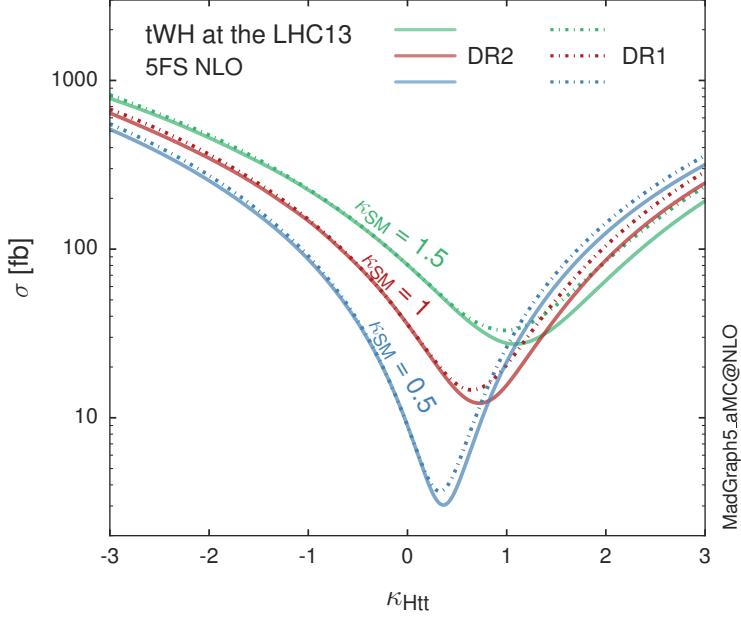
872 The scattering amplitude grows with energy like  $\sqrt{s}$  for  $\kappa_V \neq \kappa_t$ , in contrast to  
 873 the SM ( $\kappa_t = \kappa_V = 1$ ), where the first term in 2.62 cancels out and the amplitude  
 874 is constant for large s; therefore, a deviation from the SM predictions represents an  
 875 enhancement in the  $tHq$  cross section. In particular, for a SM H-W coupling and a  
 876 H-t coupling of inverted sign with respect to the SM ( $\kappa_V = -\kappa_t = 1$ ) the  $tHq$  cross  
 877 section is enhanced by a factor greater 10 as seen in the Figure 2.15 taken from  
 878 Reference [46]; Reference [52] has reported similar enhancement results.



**Figure 2.15:** Cross section for  $tHq$  process as a function of  $\kappa_t$ , normalized to the SM, for three values of  $\kappa_V$ . In the plot  $c_f$  refers to the Higgs-fermion coupling which is dominated by the H-t coupling and represented here by  $\kappa_t$ . Solid, dashed and dotted lines correspond to  $c_V \rightarrow \kappa_V = 1, 0.5, 1.5$  respectively. Note that for the SM ( $\kappa_V = \kappa_t = 1$ ), the destructive effect of the interference is maximal.

---

<sup>9</sup> A detailed explanation of the structure and approximations used to derive  $\mathcal{A}$  can be found in Reference [46]



**Figure 2.16:** Cross section for  $tHW$  process as a function of  $\kappa_{Htt}$ , for three values of  $\kappa_{SM}$  at  $\sqrt{s} = 13$  TeV.  $\kappa_{Htt}^2 = \sigma_{Htt}/\sigma_{Htt}^{SM}$  is a simple re-scaling of the SM Higgs interactions.

879       A similar analysis is valid for the W-associated channel but, in that case, the in-  
 880       terference is more complicated since there are more than two contributions and an ad-  
 881       ditional interference with the production of Higgs boson and a top pair process( $t\bar{t}H$ ).  
 882       The calculations are made using the so-called Diagram Removal (DR) technique where  
 883       interfering diagrams are removed (or added) from the calculations in order to evaluate  
 884       the impact of the removed contributions. DR1 was defined to neglect  $t\bar{t}H$  interference  
 885       while DR2 was defined to take  $t\bar{t}H$  interference into account [53]. As shown in Figure  
 886       2.16, the  $tHW$  cross section is enhanced from about 15 fb (SM:  $\kappa_{Htt} = 1$ ) to about  
 887       150 fb ( $\kappa_{Htt} = -1$ ). Differences between curves for DR1 and DR2 help to gauge the  
 888       impact of the interference with  $t\bar{t}H$ .  
 889       Results of the calculations of the  $tHq$  and  $tHW$  cross sections at  $\sqrt{s} = 13$  TeV can be  
 890       found in Reference [54] and a summary of the results is presented in Table 2.11.

	$\sqrt{s}$ TeV	$\kappa_t = 1$	$\kappa_t = -1$
$\sigma^{LO}(tHq)(\text{fb})$ [46]	8	$\approx 17.4$	$\approx 252.7$
	14	$\approx 80.4$	$\approx 1042$
$\sigma^{NLO}(tHq)(\text{fb})$ [46]	8	$18.28^{+0.42}_{-0.38}$	$233.8^{+4.6}_{-0.0}$
	14	$88.2^{+1.7}_{-0.0}$	$982.8^{+28}_{-0.0}$
$\sigma^{LO}(tHq)(\text{fb})$ [52]	14	$\approx 71.8$	$\approx 893$
$\sigma^{LO}(tHW)(\text{fb})$ [52]	14	$\approx 16.0$	$\approx 139$
$\sigma^{NLO}(tHq)(\text{fb})$ [54]	8	$18.69^{+8.62\%}_{-17.13\%}$	-
	13	$74.25^{+7.48\%}_{-15.35\%}$	$848^{+7.37\%}_{-13.70\%}$
	14	$90.10^{+7.34\%}_{-15.13\%}$	$1011^{+7.24\%}_{-13.39\%}$
$\sigma^{LO}(tHW)(\text{fb})$ [53]	13	$15.77^{+15.91\%}_{-15.76\%}$	-
$\sigma^{NLO}DR1(tHW)(\text{fb})$ [53]	13	$21.72^{+6.52\%}_{-5.24\%}$	$\approx 150$
$\sigma^{NLO}DR2(tHW)(\text{fb})$ [53]	13	$16.28^{+7.34\%}_{-15.13\%}$	$\approx 150$

**Table 2.11:** Predicted enhancement of the  $tHq$  and  $tHW$  cross sections at LHC for  $\kappa_V = 1$  and  $\kappa_t = \pm 1$  at LO and NLO; the cross section enhancement of more than a factor of 10 is due to the flipping in the sign of the H-t coupling with respect to the SM one.

## 892 2.6 CP-mixing in $tH$ processes

893 In addition to the sensitivity to sign of the H-t coupling, the  $tHq$  and  $tHW$ processes  
 894 have been proposed as a tool to investigate the possibility of a H-t coupling that does  
 895 not conserve CP [48, 53, 55].

896 In this thesis, the sensitivity of  $tH$ processes to CP-mixing is also studied on the  
 897 basis of References [48, 53] using the effective field theory framework where a generic  
 898 particle ( $X_0$ ) of spin-0 and a general CP violating interaction with the top quark  
 899 (Htt coupling), can couple to scalar and pseudo-scalar fermionic densities. The H-W  
 900 interaction is assumed to be SM-like. The Lagrangian modeling the H-t interaction  
 901 is given by

$$\mathcal{L}_0^t = -\bar{\psi}_t (c_\alpha \kappa_{Htt} g_{Htt} + i s_\alpha \kappa_{Att} g_{Att} \gamma_5) \psi_t X_0, \quad (2.63)$$

902 where  $\alpha$  is the CP-mixing phase,  $c_\alpha \equiv \cos \alpha$  and  $s_\alpha \equiv \sin \alpha$ ,  $\kappa_{Htt}$  and  $\kappa_{Att}$  are real

903 dimensionless re-scaling parameters<sup>10</sup> used to parametrize the magnitude of the CP-  
 904 violating and CP-conserving parts of the amplitude. The model defines  $g_{Htt} =$   
 905  $g_{Att} = m_t/v = y_t/\sqrt{2}$  with  $v \sim 246$  GeV the Higgs vacuum expectation value. In  
 906 this parametrization, three special cases can be recovered

- 907     • CP-even coupling  $\rightarrow \alpha = 0^\circ$
- 908     • CP-odd coupling  $\rightarrow \alpha = 90^\circ$
- 909     • SM coupling  $\rightarrow \alpha = 0^\circ$  and  $\kappa_{Htt} = 1$

910     The loop induced  $X_0$  coupling to gluons can also be described in terms of the  
 911 parametrization above, according to

$$\mathcal{L}_0^g = -\frac{1}{4} \left( c_\alpha \kappa_{Hgg} g_{Hgg} G_{\mu\nu}^a G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg} G_{\mu\nu}^a \tilde{G}^{a,\mu\nu} \right) X_0. \quad (2.64)$$

912 where  $g_{Hgg} = -\alpha_s/3\pi v$  and  $g_{Agg} = \alpha_s/2\pi v$  and  $G_{\mu\nu}$  is the gluon field strength tensors.  
 913 Under the assumption that the top quark dominates the gluon-fusion process at LHC  
 914 energies,  $\kappa_{Hgg} \rightarrow \kappa_{Htt}$  and  $\kappa_{Agg} \rightarrow \kappa_{Att}$ , so that the ratio between the gluon-gluon  
 915 fusion cross section for  $X_0$  and for the SM Higgs prediction can be written as

$$\frac{\sigma_{NLO}^{gg \rightarrow X_0}}{\sigma_{NLO,SM}^{gg \rightarrow H}} = c_\alpha^2 \kappa_{Htt}^2 + s_\alpha^2 \left( \kappa_{Att} \frac{g_{Agg}}{g_{Hgg}} \right)^2. \quad (2.65)$$

916     If the re-scaling parameters are set to

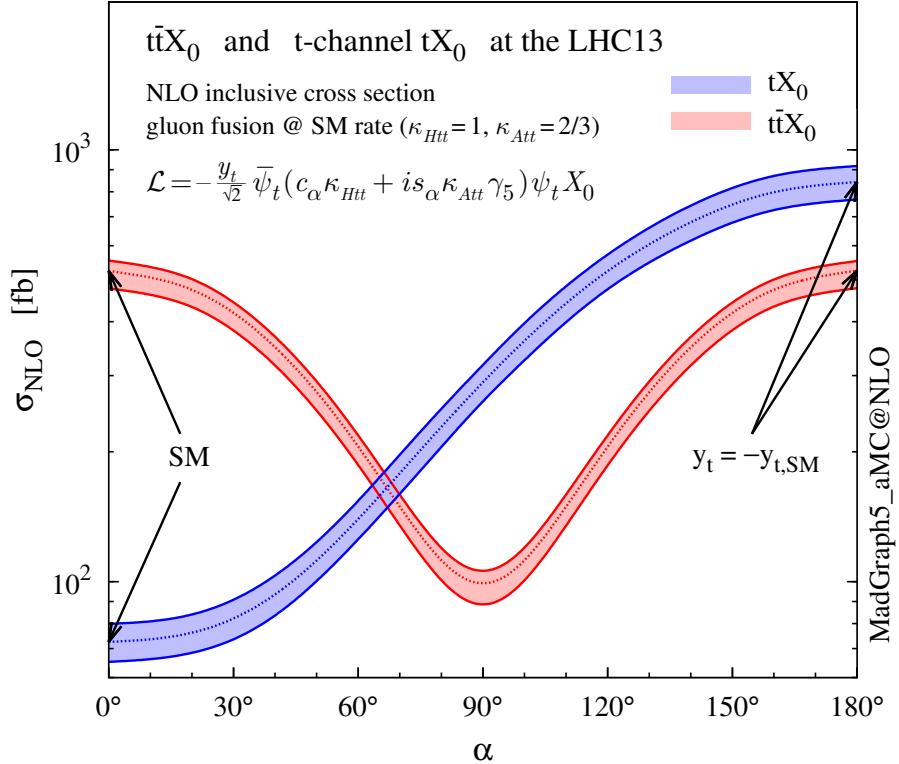
$$\kappa_{Htt} = 1, \quad \kappa_{Att} = \left| \frac{g_{Hgg}}{g_{Agg}} \right| = \frac{2}{3}. \quad (2.66)$$

917 the gluon-fusion SM cross section is reproduced for every value of the CP-mixing  
 918 angle  $\alpha$ ; therefore, by imposing that condition to the Lagrangian density 2.63, the

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<sup>10</sup> analog to  $\kappa_t$  and  $\kappa_V$

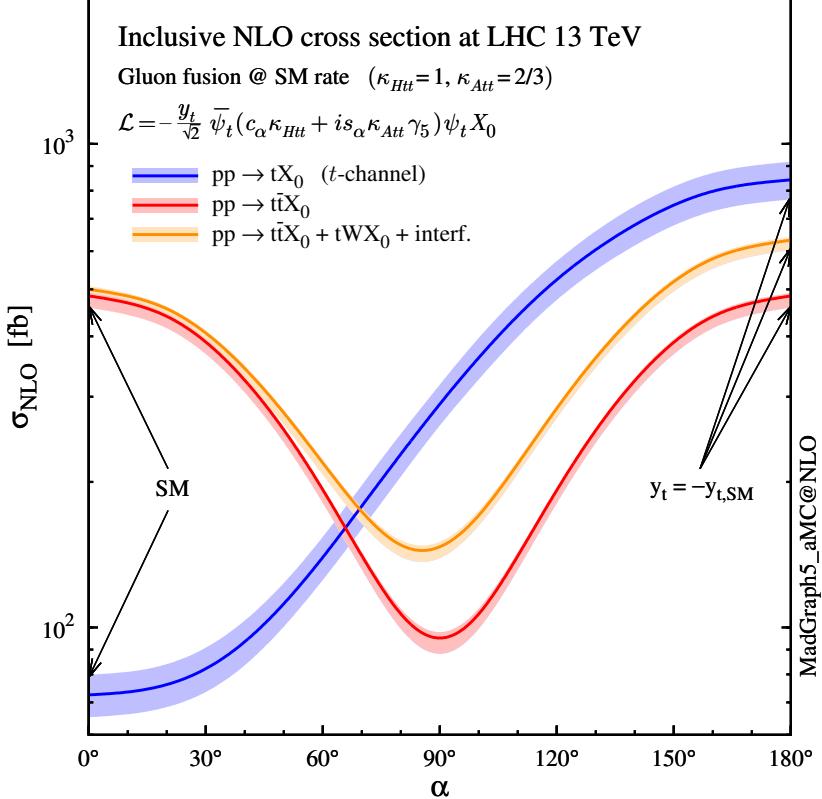
919 CP-mixing angle is not constrained by current data. Figure 2.17 shows the NLO cross  
 920 sections for t-channel  $tX_0$ (blue) and  $t\bar{X}_0$  (red) associated production processes as a  
 921 function of the CP-mixing angle  $\alpha$ .  $X_0$  is a generic spin-0 particle with top quark  
 922 CP-violating coupling. Re-scaling factors  $\kappa_{Htt}$  and  $\kappa_{Att}$  have been set to reproduce  
 923 the SM gluon-fusion cross sections.



**Figure 2.17:** NLO cross sections for t-channel  $tX_0$ (blue) and  $t\bar{X}_0$  (red) associated production processes as a function of the CP-mixing angle  $\alpha$ .  $X_0$  is a generic spin-0 particle with top quark CP-violating coupling [48].

924 It is interesting to notice that the  $tX_0$  cross section is enhanced, by a factor of  
 925 about 10, when a continuous rotation in the scalar-pseudoscalar plane is applied; this  
 926 enhancement is similar to the enhancement produced when the H-t coupling is flipped  
 927 in sign with respect to the SM ( $y_t = -y_{t,SM}$  in the plot), as showed in Section 2.5. In  
 928 contrast, the degeneracy in the  $t\bar{X}_0$  cross section is still present given that it depends

quadratically on the H-t coupling, but more interesting is to notice that  $t\bar{t}X_0$  cross section is exceeded by  $tX_0$  cross section after  $\alpha \sim 60^\circ$ .



**Figure 2.18:** NLO cross sections for t-channel  $tX_0$  (blue),  $t\bar{t}X_0$  (red) associated production processes and combined  $tWX_0 + t\bar{t}X_0$  (including interference) production as a function of the CP-mixing angle  $\alpha$  [48].

930

931     A similar parametrization can be used to investigate the  $tHW$  process sensitivity  
 932 to CP-violating H-t coupling. As said in 2.5, the interference in the W-associated  
 933 channel is more complicated because there are more than two contributions and also  
 934 there is interference with the  $t\bar{t}H$  production process.

935

936     Figure 2.18 shows the NLO cross sections for t-channel  $tX_0$  (blue),  $t\bar{t}X_0$  (red)  
 937 associated production and for the combined  $tWX_0 + t\bar{t}X_0 + interference$  (orange) as  
 938 a function of the CP-mixing angle. It is clear that the effect of the interference in the

939 combined case is the lifting of the degeneracy present in the  $t\bar{t}X_0$  production. The  
940 constructive interference enhances the cross section from about 500 fb at SM ( $\alpha = 0$ )  
941 to about 600 fb ( $\alpha = 180^\circ \rightarrow y_t = -y_{t,SM}$ ).

942 An analysis combining  $tHq$  and  $tHW$  processes will be made in this thesis taking  
943 advantage of the sensitivity improvement.

<sub>944</sub> **Chapter 3**

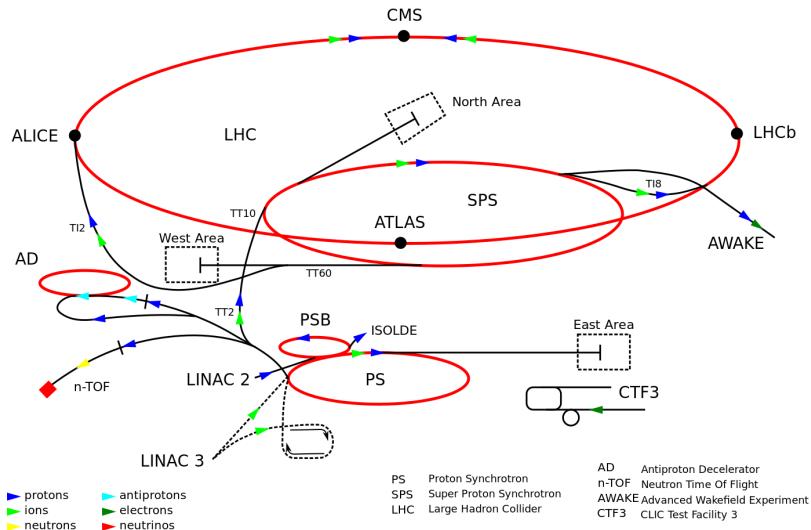
<sub>945</sub> **The CMS experiment at the LHC**

<sub>946</sub> **3.1 Introduction**

<sub>947</sub> Located on the Swiss-French border, the European Council for Nuclear Research  
<sub>948</sub> (CERN) is the largest scientific organization leading the particle physics research.  
<sub>949</sub> About 13000 people in a broad range of fields including users, students, scientists,  
<sub>950</sub> engineers, among others, contribute to the data taking and analysis, with the goal  
<sub>951</sub> of unveiling the secrets of nature and revealing the fundamental structure of the  
<sub>952</sub> universe. CERN is also the home of the Large Hadron Collider (LHC), the largest  
<sub>953</sub> circular particle accelerator around the world, where protons (or heavy ions) traveling  
<sub>954</sub> close to the speed of light, are made to collide. These collisions open a window  
<sub>955</sub> to investigate how particles (and their constituents if they are composite) interact  
<sub>956</sub> with each other, providing clues about the laws of nature. This chapter presents an  
<sub>957</sub> overview of the LHC structure and operation. A detailed description of the CMS  
<sub>958</sub> detector is offered, given that the data used in this thesis have been taken with this  
<sub>959</sub> detector.

## 960 3.2 The LHC

961 With 27 km of circumference, the LHC is currently the largest and most powerful  
 962 circular accelerator in the world. It is installed in the same tunnel where the Large  
 963 Electron-Positron (LEP) collider was located, taking advantage of the existing infras-  
 964 tructure. The LHC is also the larger accelerator in the CERN's accelerator complex  
 965 and is assisted by several successive accelerating stages before the particles are in-  
 966 jected into the LHC ring where they reach their maximum energy (see Figure 3.1).



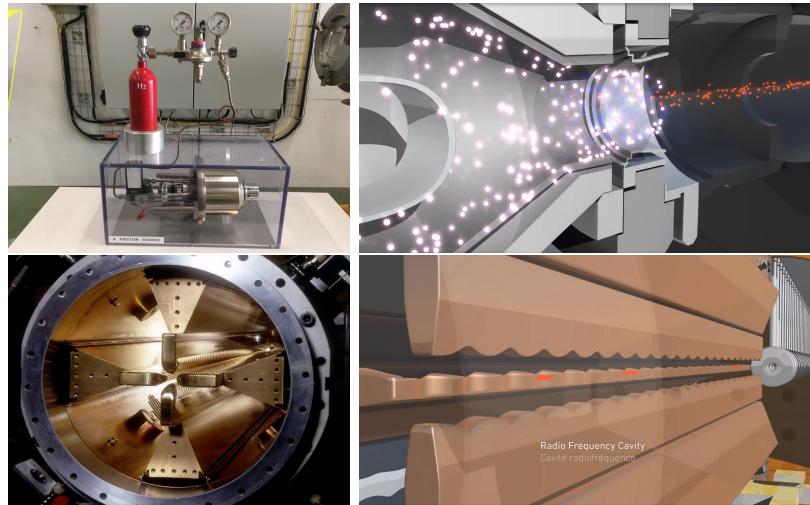
**Figure 3.1:** CERN accelerator complex. Blue arrows show the path followed by protons along the acceleration process [59].

967 LHC runs in three modes depending on the particles being accelerated

- 968     • Proton-Proton collisions ( $pp$ ) for multiple physics experiments.
- 969     • Lead-Lead collisions ( $Pb-Pb$ ) for heavy ion experiments.
- 970     • Proton-Lead collisions ( $p-Pb$ ) for quark-gluon plasma experiments.

971 In this thesis only  $pp$  collisions will be considered.

972



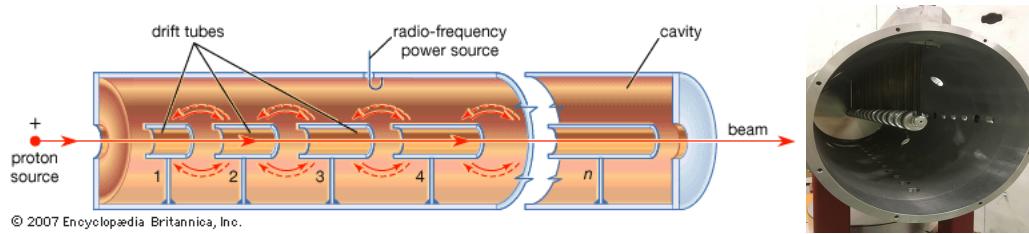
**Figure 3.2:** LHC protons source and the first acceleration stage. Top: the bottle contains hydrogen gas (white dots) which is injected into the metal cylinder to be broken down into electrons (blue dots) and protons (red dots); Bottom: the obtained protons are directed towards the radio frequency quadrupole which perform the first acceleration, focus the beam and create the bunches of protons. [63, 64]

973 Collection of protons starts with hydrogen atoms taken from a bottle, containing hy-  
 974 drogen gas, and injecting them in a metal cylinder; hydrogen atoms are broken down  
 975 into electrons and protons by an intense electric field (see Figure 3.2 top). The re-  
 976 sulting protons leave the metal cylinder towards a radio frequency quadrupole (RFQ)  
 977 that focus the beam, accelerates the protons and creates the packets of protons called  
 978 bunches. In the RFQ, an electric field is generated by a RF wave at a frequency that  
 979 matches the resonance frequency of the cavity where the electrodes are contained.  
 980 The beam of protons traveling on the RFQ axis experiences an alternating electric  
 981 field gradient that generates the focusing forces.

982

983 In order to accelerate the protons, a longitudinal time-varying electric field component  
 984 is added to the system; it is done by giving the electrodes a sinus-like profile as shown  
 985 in Figure 3.2 bottom. By matching the speed and phase of the protons with the  
 986 longitudinal electric field the bunching is performed; protons synchronized with the

987 RFQ (synchronous proton) do not feel an accelerating force, but those protons in the  
 988 beam that have more (or less) energy than the synchronous proton (asynchronous  
 989 protons) will feel a decelerating (accelerating) force; therefore, asynchronous protons  
 990 will oscillate around the synchronous ones forming bunches of protons [61]. From the  
 991 RFQ protons emerge with energy 750 keV in bunches of about  $1.15 \times 10^{11}$  protons [62].

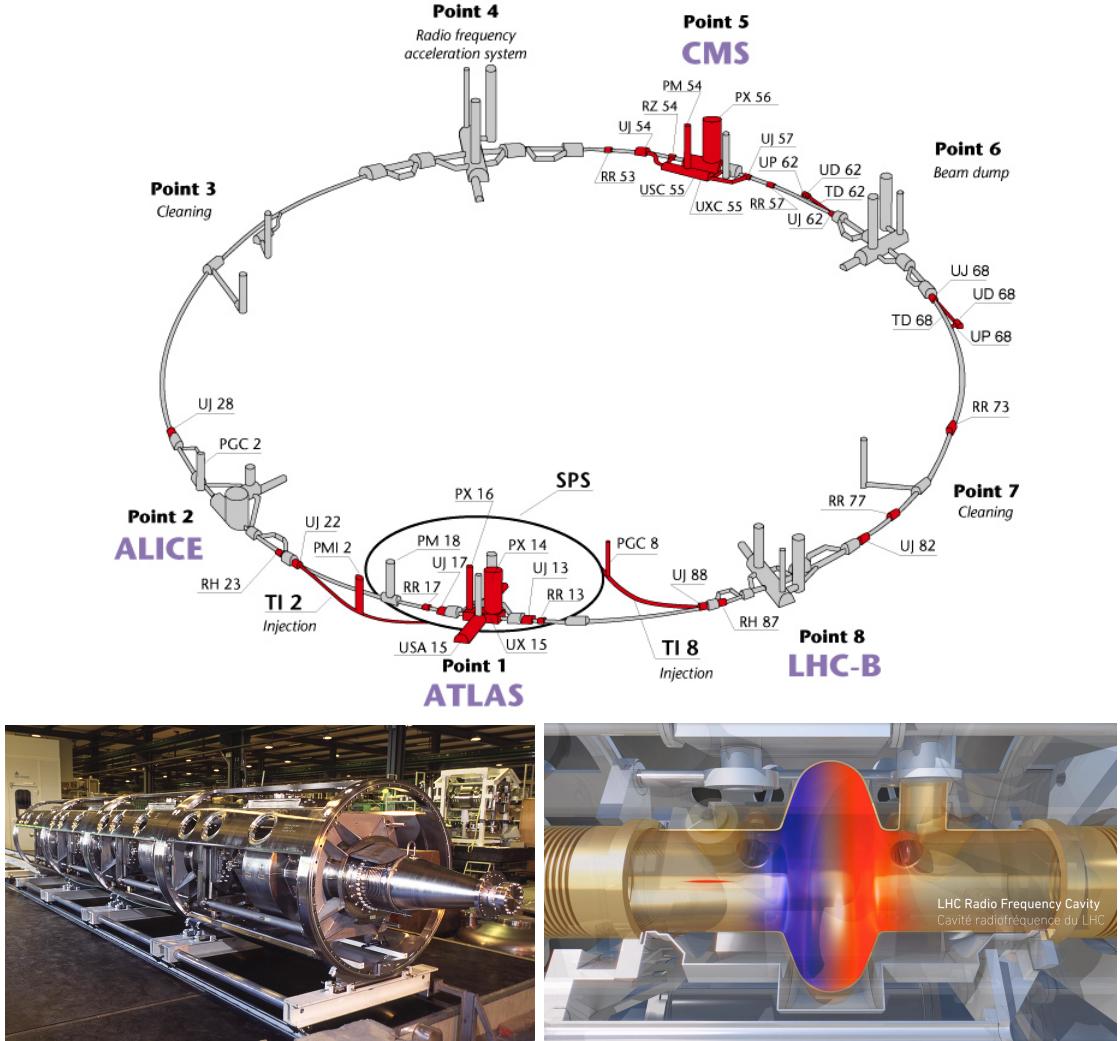


**Figure 3.3:** The LINAC2 accelerating system at CERN. Electric fields generated by radio frequency (RF) create acceleration and deceleration zones inside the cavity; deceleration zones are blocked by drift tubes where quadrupole magnets focus the proton beam. [65]

992 Proton bunches coming from the RFQ go to the linear accelerator 2 (LINAC2) where  
 993 they are accelerated to reach 50 MeV energy. In the LINAC2 stage, acceleration  
 994 is performed using electric fields generated by radio frequency which create zones  
 995 of acceleration and deceleration as shown in Figure 3.3. In the deceleration zones,  
 996 the electric field is blocked using drift tubes where protons are free to drift while  
 997 quadrupole magnets focus the beam.

998

999 The beam coming from LINAC2 is injected into the proton synchrotron booster  
 1000 (PSB) to reach 1.4 GeV in energy. The next acceleration is provided at the pro-  
 1001 ton synchrotron (PS) up to 26 GeV, followed by the injection into the super proton  
 1002 synchrotron (SPS) where protons are accelerated to 450 GeV. Finally, protons are  
 1003 injected into the LHC where they are accelerated to the target energy of 6.5 TeV.  
 1004 PSB, PS, SPS and LHC accelerate protons using the same RF acceleration technique  
 1005 described before.



**Figure 3.4:** Top: LHC layout. The red zones indicate the infrastructure additions to the LEP installations, built to accommodate the ATLAS and CMS experiments which exceed the size of the former experiments located there [60]. Bottom: LHC RF cavities. A module accommodates 4 cavities that accelerate protons and preserve the bunch structure of the beam. [64, 66]

1006 LHC has a system of 16 RF cavities located in the so-called point 4, as shown in  
 1007 Figure 3.4 top, tuned at a frequency of 400 MHz and the protons are carefully timed,  
 1008 so in addition to the acceleration effect the bunch structure of the beam is preserved.  
 1009 Bottom side of Figure 3.4 shows a picture of a RF module composed of 4 RF cavities  
 1010 working in a superconducting state at 4.5 K; also is showed a representation of the

1011 accelerating electric field that accelerates the protons in the bunch.

1012

1013 While protons are accelerated in one section of the LHC ring, where the RF cavities  
 1014 are located, in the rest of their path they have to be kept in the curved trajectory  
 1015 defined by the LHC ring. Technically, LHC is not a perfect circle; RF, injection, beam  
 1016 dumping, beam cleaning and sections before and after the experimental points where  
 1017 protons collide are all straight sections. In total, there are 8 arcs 2.45 Km long each  
 1018 and 8 straight sections 545 m long each. In order to curve the proton's trajectory in  
 1019 the arc sections, superconducting dipole magnets are used.

1020

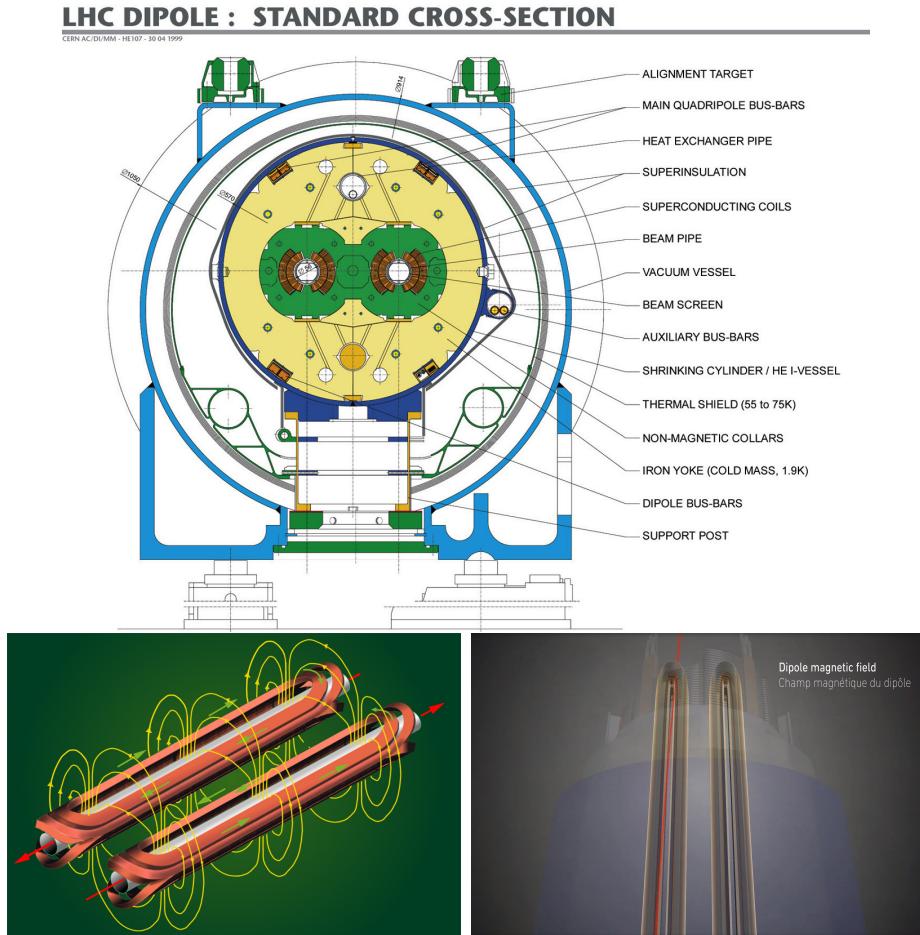
1021 Inside the LHC ring, there are two proton beams traveling in opposite directions in  
 1022 two separated beam pipes; the beam pipes are kept at ultra-high vacuum ( $\sim 10^{-9}$   
 1023 Pa) to ensure that there are no particles that interact with the proton beams. The  
 1024 superconducting dipole magnets used in LHC are made of a NbTi alloy, capable of  
 1025 transporting currents of about 12000 A when cooled at a temperature below 2K using  
 1026 liquid helium (see Figure 3.5).

1027

1028 Protons in the arc sections of LHC feel a centripetal force exerted by the dipole  
 1029 magnets which is perpendicular to the beam trajectory; The magnitude of magnetic  
 1030 field needed can be found assuming that protons travel at  $v \approx c$ , using the standard  
 1031 values for proton mass and charge and the LHC radius, as

$$F_m = \frac{mv^2}{r} = qBv \quad \rightarrow B = 8.33T \quad (3.1)$$

1032 which is about 100000 times the Earth's magnetic field. A representation of the mag-  
 1033 netic field generated by the dipole magnets is shown on the bottom left side of Figure



**Figure 3.5:** Top: LHC dipole magnet transverse view; cooling, shielding and mechanical support are indicated. Bottom left: Magnetic field generated by the dipole magnets; note that the direction of the field inside one beam pipe is opposite with respect to the other beam pipe which guarantee that both proton beams are curved in the same direction towards the center of the ring. The effect of the dipole magnetic field on the proton beam is represented on the bottom right side [64, 67, 68].

1034 3.5. The bending effect of the magnetic field on the proton beam is shown on the  
 1035 bottom right side of Figure 3.5. Note that the dipole magnets are not curved; the  
 1036 arc section of the LHC ring is composed of straight dipole magnets of about 15 m.  
 1037 In total there are 1232 dipole magnets along the LHC ring.

1038

1039 In addition to bending the beam trajectory, the beam has to be focused so it stays

1040 inside the beam pipe. The focusing is performed by quadrupole magnets installed in  
 1041 a different straight section; in total 858 quadrupole magnets are installed along the  
 1042 LHC ring. Other effects like electromagnetic interaction among bunches, interaction  
 1043 with electron clouds from the beam pipe, the gravitational force on the protons, dif-  
 1044 ferences in energy among protons in the same bunch, among others, are corrected  
 1045 using sextupole and other magnetic multipoles.

1046

1047 The two proton beams inside the LHC ring are made of bunches with a cylindrical  
 1048 shape of about 7.5 cm long and about 1 mm in diameter; when bunches are close  
 1049 to the collision point (CP), the beam is focused up to a diameter of about 16  $\mu\text{m}$  in  
 1050 order to maximize the number of collisions per unit area and per second, known as  
 1051 luminosity ( $L$ ). Luminosity can be calculated using

$$L = fn \frac{N_1 N_2}{4\pi\sigma_x\sigma_y} \quad (3.2)$$

1052 where  $f$  is the revolution frequency,  $n$  is the number of bunches per beam,  $N_1$  and  
 1053  $N_2$  are the numbers of protons per bunch ( $1.5 \times 10^{11}$ ),  $\sigma_x$  and  $\sigma_y$  are the gaussian  
 1054 transverse sizes of the bunches. The expected luminosity is about

$$f = \frac{v}{2\pi r_{LHC}} \approx \frac{3 \times 10^8 \text{ m/s}}{27 \text{ km}} \approx 11.1 \text{ kHz},$$

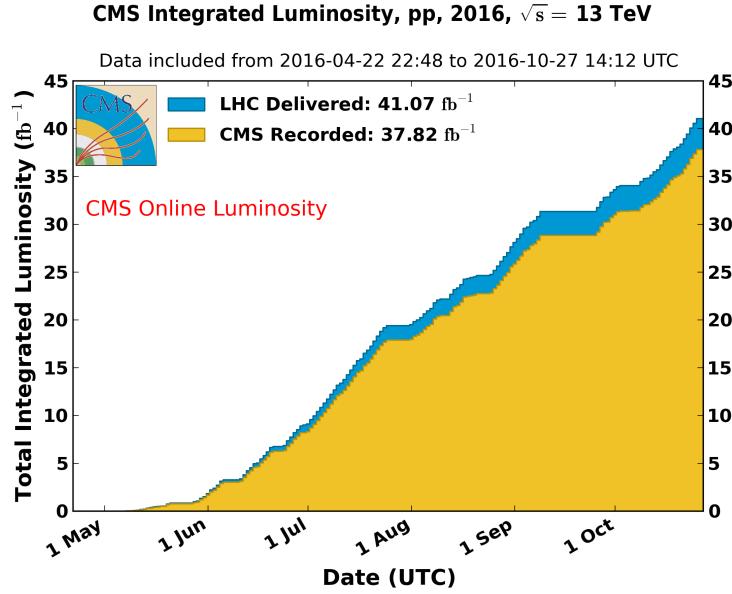
$$n = 2808$$

$$N_1 = N_2 = 1.5 \times 10^{11}$$

$$\sigma_x = \sigma_y = 16 \mu\text{m}$$

1055

$$L = 1.28 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} = 1.28 \times 10^{-5} \text{ fb}^{-1} \text{ s}^{-1} \quad (3.3)$$



**Figure 3.6:** Integrated luminosity delivered by LHC and recorded by CMS during 2016. The difference between the delivered and the recorded luminosity is due to fails and issues occurred during the data taking in the CMS experiment [69].

1056 Luminosity is a fundamental aspect of LHC given that the bigger luminosity the  
 1057 bigger number of collisions, which means that for processes with a very small cross  
 1058 section the number of expected occurrences is increased and so the chances of being  
 1059 detected. The integrated luminosity, i.e., the total luminosity, collected by the CMS  
 1060 experiment during 2016 is shown in Figure 3.6; the data analyzed in this thesis cor-  
 1061 responds to an integrated luminosity of  $35.9 \text{ fb}^{-1}$  at a center of mass-energy  $\sqrt{s} = 13$   
 1062 TeV.

1063

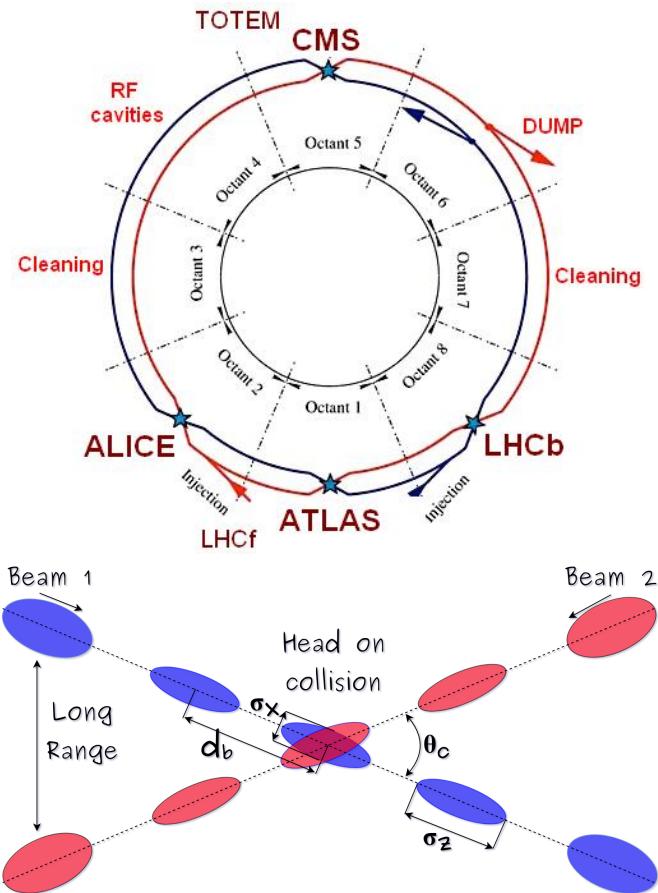
1064 A way to increase  $L$  is increasing the number of bunches in the beam. Currently, the  
 1065 separation between two consecutive bunches in the beam is 7.5 m which corresponds  
 1066 to a time separation of 25 ns. In the full LHC ring the allowed number of bunches is  
 1067  $n = 27\text{km}/7.5\text{m} = 3600$ ; however, there are some gaps in the bunch pattern intended  
 1068 for preparing the dumping and injection of the beam, thus, the proton beams are

1069 composed of 2808 bunches.

1070

1071 Once the proton beams reach the desired energy, they are brought to cross each other  
 1072 producing proton-proton collisions. The bunch crossing happens in precise places  
 1073 where the four LHC experiments are located, as seen in the top of Figure 3.7. In  
 1074 2008, the first set of collisions involved protons with  $\sqrt{s} = 7$  TeV; the energy was  
 1075 increased to 8 TeV in 2012 and to 13 TeV in 2015.

1076



**Figure 3.7:** Top: LHC interaction points. Bunch crossing occurs where the LHC experiments are located [70]. Sections indicated as cleaning are dedicated to collimate the beam in order to protect the LHC ring from collisions with protons in very spreaded bunches. Bottom: bunch crossing scheme. Since the bunch crossing is not perfectly head-on, the luminosity is reduced in a factor of 17%; adapted from Reference [82].

1077 CMS and ATLAS experiments, which are multi-purpose experiments, are enabled  
 1078 to explore physics in any of the collision modes. LHCb experiment is optimized  
 1079 to explore bottom quark physics, while ALICE is optimized for heavy ion collisions  
 1080 searches; TOTEM and LHCf are dedicated to forward physics studies; MoEDAL (not  
 1081 indicated in the Figure) is intended for monopoles or massive pseudo stable particles  
 1082 searches.

1083

1084 At the CP there are two interesting details that need to be addressed. The first one  
 1085 is that the bunch crossing does not occur head-on but at a small crossing angle  $\theta_c$   
 1086 (280  $\mu$ rad in CMS and ATLAS) as shown in the bottom side of Figure 3.7, affecting  
 1087 the overlapping between bunches; the consequence is a reduction of about 17% in  
 1088 the luminosity (represented by a factor not included in eqn. 3.2). The second one  
 1089 is the occurrence of multiple  $pp$  collisions in the same bunch crossing; this effect is  
 1090 called pile-up (PU). A fairly simple estimation of the PU follows from estimating the  
 1091 probability of collision between two protons, one from each of the bunches in course  
 1092 of collision; it depends roughly on the ratio of proton size and the cross section of the  
 1093 bunch in the interaction point, i.e.,

$$P(pp\text{-}collision) \sim \frac{d_{proton}^2}{\sigma_x \sigma_y} = \frac{(1\text{fm})^2}{(16\mu\text{m})^2} \sim 4 \times 10^{-21} \quad (3.4)$$

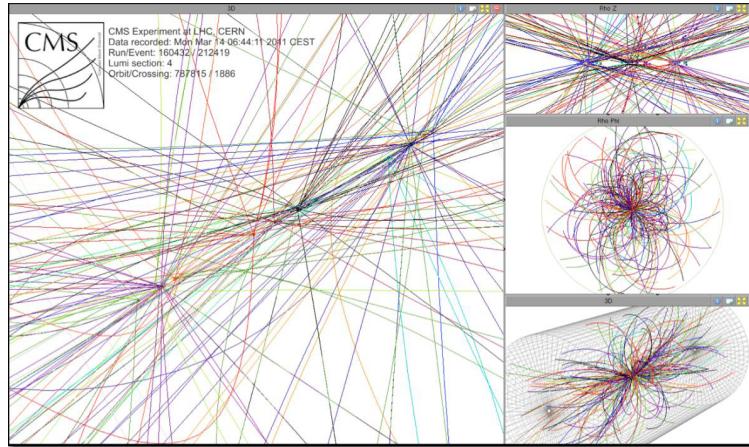
1094 however, there are  $N = 1.15 \times 10^{11}$  protons in a bunch, thus the estimated number of  
 1095 collisions in a bunch crossing is

$$PU = N^2 * P(pp\text{-}collision) \sim 50 \text{ } pp\text{-}collision \text{ per bunch crossing}, \quad (3.5)$$

1096 about 20 of those  $pp$  collisions are inelastic. Each collision generates a vertex, but  
 1097 only the most energetic is considered as a primary vertex; the rest are considered

as PU vertices. A multiple  $pp$  collision event in a bunch crossing at CMS is showed in Figure 3.8. Unstable particles outgoing from the primary vertex will eventually decay; this decay vertex is known as a secondary vertex.

1101



**Figure 3.8:** Multiple  $pp$  collision bunch crossing at CMS. Only the most energetic vertex is considered and the rest are cataloged as PU vertices [71].

1102 Next section presents a description of the CMS detector which it is the detector used  
1103 to collect the data used in this thesis.

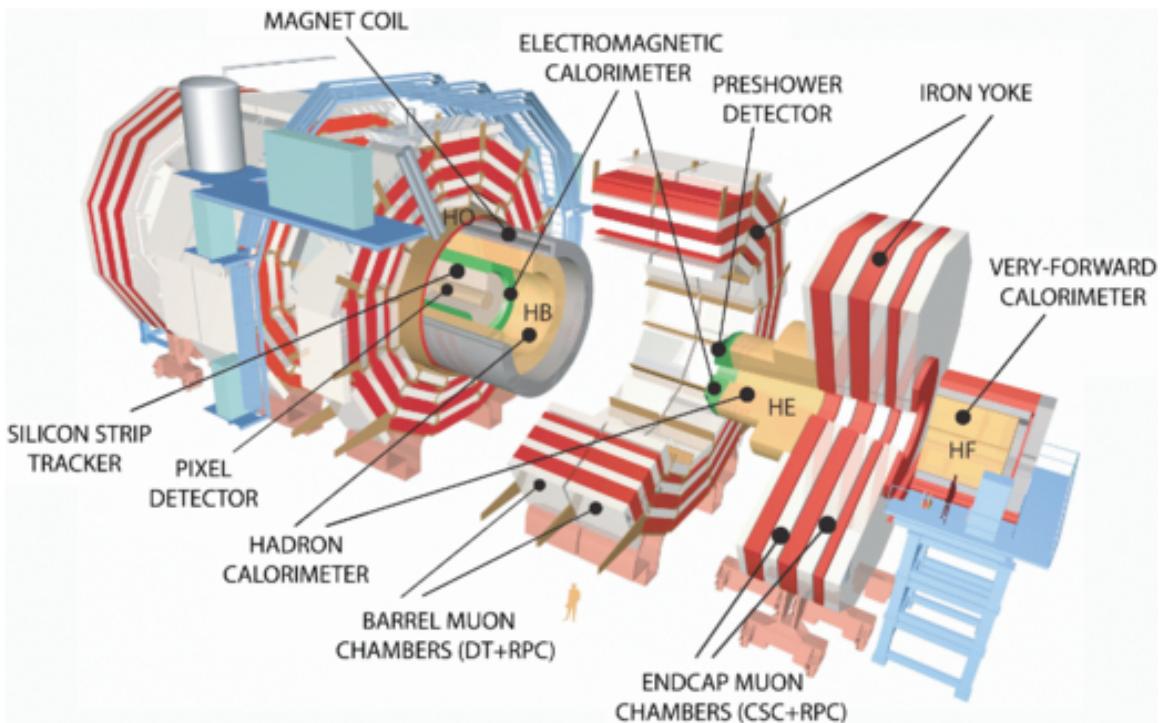
### 1104 3.3 The CMS experiment

1105 CMS is a general-purpose detector designed to conduct research in a wide range  
1106 of physics from the standard model to new physics like extra dimensions and dark  
1107 matter. Located at the point 5 in the LHC layout as shown in Figure 3.4, CMS is  
1108 composed of several detection systems distributed in a cylindrical structure; in total,  
1109 CMS weights about 12500 tons in a very compact 21.6 m long and 14.6 m diameter  
1110 cylinder. It was built in 15 separate sections at the ground level and lowered to the  
1111 cavern individually to be assembled. A complete and detailed description of the CMS  
1112 detector and its components is given in Reference [72] on which this section is based

1113 on.

1114

1115 Figure 3.9 shows the layout of the CMS detector. The design is driven by the require-  
 1116 ments on the identification, momentum resolution and unambiguous charge determi-  
 1117 nation of the muons; therefore, a large bending power is provided by the solenoid  
 1118 magnet made of superconducting cable capable to generate a 3.8 T magnetic field.  
 1119 The detection system is composed of (from the innermost to the outermost)



**Figure 3.9:** Layout of the CMS detector. The several subdetectors are indicated. The central region of the detector is referred as the Barrel section while the endcaps are referred as the forward sections. [73].

1120 • Pixel detector.

1121 • Silicon strip tracker.

1122 • Preshower detector.

1123 • Electromagnetic calorimeter.

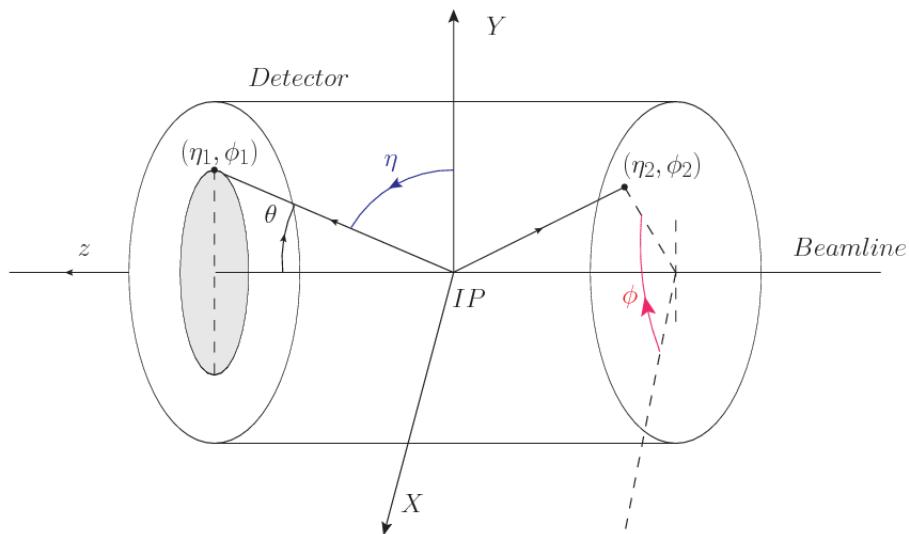
1124 • Hadronic calorimeter.

1125 • Muon chambers (Barrel and endcap)

1126 The central region of the detector is commonly referred as the barrel section while the  
 1127 endcaps are referred as the forward sections of the detector; thus, each subdetector  
 1128 is composed of a barrel section and a forward section.

### 1129 3.3.1 Coordinate system

1130 The coordinate system used by CMS is centered in the geometrical center of the  
 1131 detector which is the same as the CP as shown in Figure 3.10. The  $z$ -axis is parallel  
 1132 to the beam direction, while the  $Y$ -axis pointing vertically upward, and the  $X$ -axis  
 1133 pointing radially inward toward the center of the LHC.



**Figure 3.10:** CMS detector coordinate system.

1134 In addition to the common cartesian and cylindrical coordinate systems, two coor-  
 1135 dinates are of particular utility in particle physics: rapidity ( $y$ ) and pseudorapidity

1136  $(\eta)$ , defined in connection to the polar angle  $\theta$ , energy and longitudinal momentum  
 1137 component (momentum along the  $z$ -axis) according to

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z} \quad \eta = -\ln \left( \tan \frac{\theta}{2} \right) \quad (3.6)$$

1138 Rapidity is related to the angle between the  $XY$ -plane and the direction in which the  
 1139 products of a collision are emitted; it has the nice property that the difference between  
 1140 the rapidities of two particles is invariant with respect to Lorentz boosts along the  $z$ -  
 1141 axis. Thus, data analysis becomes more simple when based on rapidity; however, it is  
 1142 not simple to measure the rapidity of highly relativistic particles, as those produced  
 1143 after  $pp$  collisions. Under the highly relativistic motion approximation,  $y$  can be  
 1144 rewritten in terms of the polar angle, concluding that rapidity is approximately equal  
 1145 to the pseudorapidity defined above, i.e.,  $y \approx \eta$ . Note that  $\eta$  is easier to measure than  $y$   
 1146 given the direct relationship between the former and the polar angle. Angular distance  
 1147 between two objects in the detector ( $\Delta R$ ) is defined in terms of their coordinates  
 1148  $(\eta_1, \phi_1), (\eta_2, \phi_2)$  as

$$\Delta R = \sqrt{(\Delta\eta)^2 - (\Delta\phi)^2} \quad (3.7)$$

### 1149 3.3.2 Pixels detector

1150 The CMS tracking system is designed to provide a precise measurement of the tra-  
 1151 jectory (*track*) followed by the charged particles created after the  $pp$  collisions; also,  
 1152 the precise reconstruction of the primary and secondary origins (*vertices*) is expected  
 1153 in an environment where, each 25 ns, the bunch crossing produce about 20 inelastic  
 1154 collisions and about 1000 particles. An increment in the luminosity is ongoing which  
 1155 implies that the PU will increase accordingly.

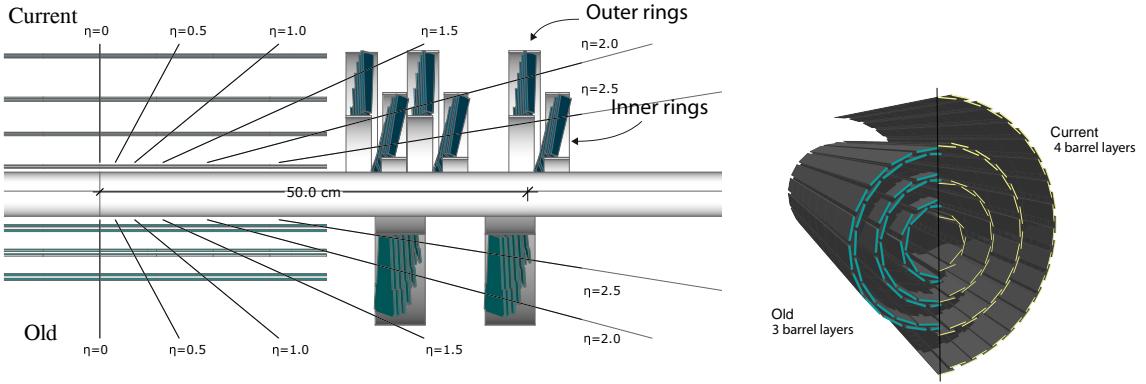
1157 The pixel detector was replaced during the 2016-2017 extended year-end technical  
1158 stop, due to the increasingly challenging operating conditions like the higher particle  
1159 flow and more radiation harsh environment, among others. The new one is responding  
1160 as expected, reinforcing its crucial role in the successful way to fulfill the new LHC  
1161 physics objectives after the discovery of the Higgs boson. The last chapter of this  
1162 thesis is dedicated to describe my contribution to the *Forward Pixel Phase 1 upgrade*.

1163

1164 The current pixel detector is composed of 1856 silicon pixel detector modules orga-  
1165 nized in four-barrel layers in the central region and three disks in the forward region;  
1166 it is designed to record efficiently and with high precision, up to  $10\mu\text{m}$  in the  $XY$ -  
1167 plane and  $20\mu\text{m}$  in the  $z$ -direction, the first four space-points (*hits*) near to the CP  
1168 region (see Figure 3.11 left side) in the range  $|\eta| \leq 2.5$ . The first barrel layer is located  
1169 at a radius of 30 mm from the beamline, while the fourth layer is located at a radius  
1170 of 160 mm closer to the strip tracker inner barrel layer (see Section 3.3.3) in order to  
1171 reduce the rate of fake tracks. The high granularity of the detector is represented in  
1172 its about 123 Mpixels, each of size  $100 \times 150\mu\text{m}^2$ , which is almost twice the channels  
1173 of the old detector. The transverse momentum resolution of tracks can be measured  
1174 with a resolution of 1-2% for muons of  $p_T = 100$  GeV.

1175

1176 Some of the improvements with respect to the previous pixel detector include a higher  
1177 average tracking efficiency and lower average fake rate as well as higher track impact  
1178 parameter resolution which is fundamental in order to increase the efficiency in the  
1179 identification of jets originating from b quarks (b-tagging). A significant source of  
1180 improvement comes from the overall reduction in the material budget of the detector  
1181 which results in fewer photon conversions and less multiple scattering from charged  
1182 particles.



**Figure 3.11:** CMS pixel detector schematic view. Left: layout comparing the layers and disks in the old and current pixel detectors. Right: Transverse-oblique view comparing the pixel barrel layers in the two [75].

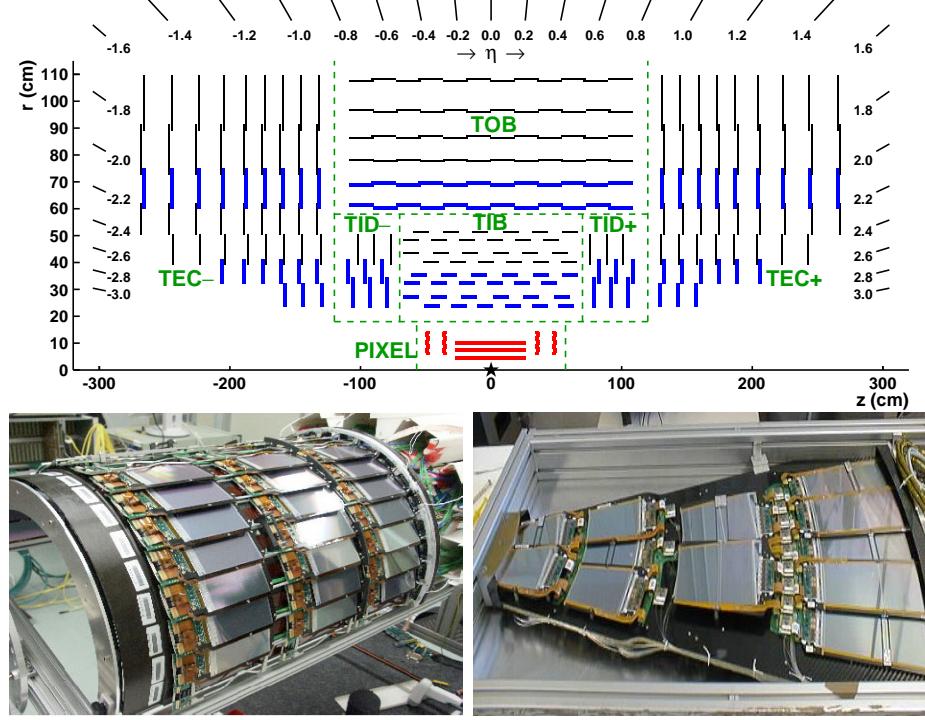
### 1183 3.3.3 Silicon strip tracker

1184 The silicon strip tracker (SST) is the second stage in the CMS tracking system. The  
 1185 top side of Figure 3.12 shows a schematic of the SST. The inner tracker region is com-  
 1186 posed of the tracker inner barrel (TIB) and the tracker inner disks (TID) covering the  
 1187 region  $r < 55$  cm and  $|z| < 118$  cm. The TIB is composed of 4 layers while the TID  
 1188 is composed of 3 disks at each end. The silicon sensors in the inner tracker are 320  
 1189  $\mu\text{m}$  thick, providing a resolution of about 13-38  $\mu\text{m}$  in the  $r\phi$  position measurement.  
 1190

1191 The modules indicated in blue in the schematic view of Figure 3.12 are two modules  
 1192 mounted back-to-back and rotated in the plane of the module by a *stereo* angle of  
 1193 100 mrad; the hits from these two modules, known as *stereo hits*, are combined to  
 1194 provide a measurement of the second coordinate ( $z$  in the barrel and  $r$  on the disks)  
 1195 allowing the reconstruction of hit positions in 3-D.

1196

1197 The outer tracker region is composed of the tracker outer barrel (TOB) and the  
 1198 tracker endcaps (TEC). The six layers of the TOB offer coverage in the region  $r > 55$



**Figure 3.12:** Top: CMS Silicon Strip Tracker (SST) schematic view. The SST is composed of the tracker inner barrel (TIB), the tracker inner disks (TID), the tracker outer barrel (TOB) and the tracker endcaps (TEC). Each part is made of silicon strip modules; the modules in blue represent two modules mounted back-to-back and rotated in the plane of the module by a stereo angle of 120 mrad in order to provide a 3-D reconstruction of the hit positions. Bottom: pictures of the TIB (left) and TEC (right) modules [76–78].

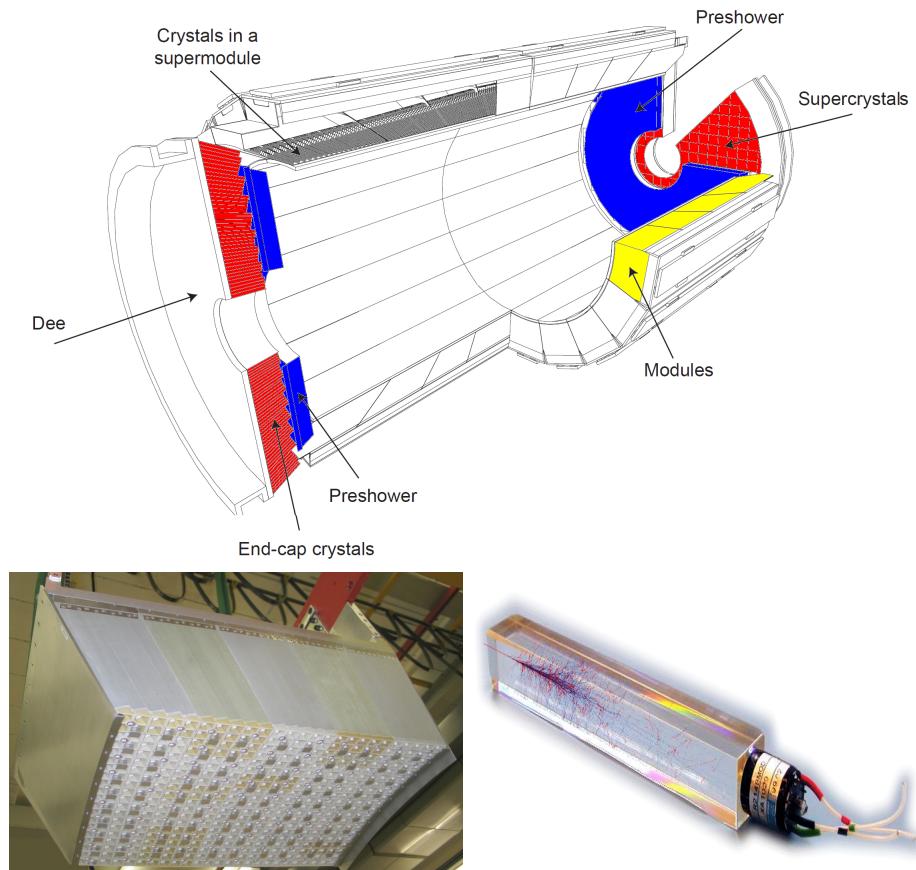
1199 cm and  $|z| < 118$  cm, while the 9 disks of the TEC cover the region  $124 < |z| < 282$   
 1200 cm. The resolution offered by the outer tracker is about  $13\text{--}38 \mu\text{m}$  in the  $r\phi$  position  
 1201 measurement. The inner four TEC disks use silicon sensors  $320 \mu\text{m}$  thick; those in  
 1202 the TOB and the outer three TEC disks use silicon sensors of  $500 \mu\text{m}$  thickness. The  
 1203 silicon strips run parallel to the  $z$ -axis and the distance between strips varies from 80  
 1204  $\mu\text{m}$  in the inner TIB layers to  $183 \mu\text{m}$  in the inner TOB layers; in the endcaps the  
 1205 wedge-shaped sensors with radial strips, whose pitch range between  $81 \mu\text{m}$  at small  
 1206 radii and  $205 \mu\text{m}$  at large radii.

1207

1208 The whole SST has 15148 silicon modules, 9.3 million silicon strips and cover a total

1209 active area of about  $198 \text{ m}^2$ .

1210 **3.3.4 Electromagnetic calorimeter**



**Figure 3.13:** Top: CMS ECAL schematic view. Bottom: Module equipped with the crystals (left); ECAL crystal(right).

1211 The CMS electromagnetic calorimeter (ECAL) is designed to measure the energy of  
 1212 electrons and photons. It is composed of 75848 lead tungstate crystals which have a  
 1213 short radiation length (0.89 cm) and fast response, since 80% of the light is emitted  
 1214 within 25 ns; however, they are combined with Avalanche photodiodes (APDs) as  
 1215 photodetectors given that crystals themselves have a low light yield ( $30\gamma/\text{MeV}$ ). A

1216 schematic view of the ECAL is shown in Figure 3.13.

1217

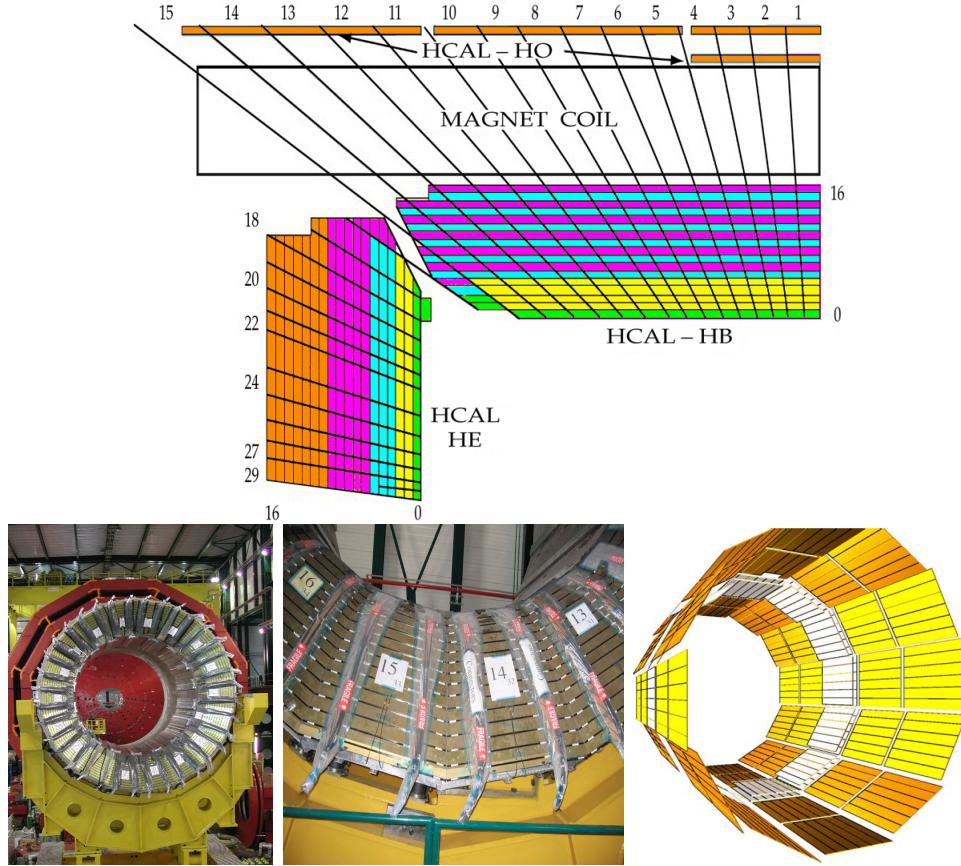
1218 Energy is measured when electrons and photons are absorbed by the crystals which  
 1219 generates an electromagnetic *shower*, as seen in bottom right picture of the Figure  
 1220 3.13; the shower is seen as a *cluster* of energy which depending on the amount of en-  
 1221 ergy deposited can involve several crystals. The ECAL barrel (EB) covers the region  
 1222  $|\eta| < 1.479$ , using crystals of depth of 23 cm and  $2.2 \times 2.2 \text{ cm}^2$  transverse section;  
 1223 the ECAL endcap (EE) covers the region  $1.479 < |\eta| < 3.0$  using crystals of depth  
 1224 22 cm and transverse section of  $2.86 \times 2.86 \text{ cm}^2$ ; the photodetectors used are vacuum  
 1225 phototriodes (VPTs). Each EE is divided in two structures called *Dees*.

1226

1227 In front of the EE, it is installed the preshower detector (ES) which covers the region  
 1228  $1.653 < |\eta| < 2.6$ . The ES provides a precise measurement of the position of electro-  
 1229 magnetic showers, which allows to distinguish electrons and photons signals from  $\pi^0$   
 1230 decay signals. The ES is composed of a layer of lead absorber followed by a layer of  
 1231 plastic scintillators

### 1232 3.3.5 Hadronic calorimeter

1233 Hadrons are not absorbed by the ECAL but by the hadron calorimeter (HCAL),  
 1234 which is made of a combination of alternating brass absorber layers and silicon photo-  
 1235 multiplier(SiPM) layers; therefore, particles passing through the scintillator material  
 1236 produce showers, as in the ECAL, as a result of the inelastic scattering of the hadrons  
 1237 with the detector material. Since the particles are not absorbed in the scintillator,  
 1238 their energy is sampled; therefore the total energy is not measured but estimated from  
 1239 the energy clusters, which reduce the resolution of the detector. Brass was chosen



**Figure 3.14:** Top: CMS HCAL schematic view, the colors indicate the layers that are grouped into the same readout channels. Bottom: picture of a section of the HB; the absorber material is the golden region and scintillators are placed in between the absorber material (left and center). Schematic view of the HO (right). [79, 80]

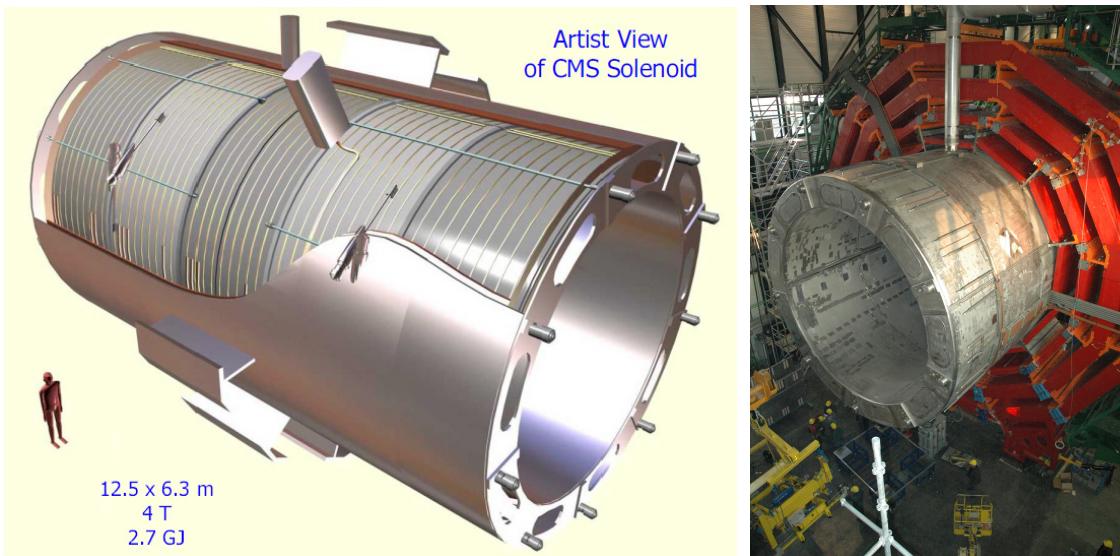
as the absorber material due to its short interaction length ( $\lambda_I = 16.42\text{cm}$ ) and its non-magnetivity. Figure 3.14 shows a schematic view of the CMS HCAL.

1242

1243 The HCAL is divided into four sections; the Hadron Barrel (HB), the Hadron Outer  
 1244 (HO), the Hadron Endcap (HE) and the Hadron Forward (HF) sections. The HB  
 1245 covers the region  $0 < |\eta| < 1.4$ , while the HE covers the region  $1.3 < |\eta| < 3.0$ . The HF,  
 1246 made of quartz fiber scintillator and steel as absorption material, covers the forward  
 1247 region  $3.0 < |\eta| < 5.2$ . Both the HB and HF are located inside the solenoid. The HO

is placed outside the magnet as an additional layer of scintillators with the purpose of measure the energy tails of particles passing through the HB and the magnet (see Figure 3.14 top and bottom right). The upgrades made to the HCAL during the technical stop 2016-2017 consisted in the replacement of the photo transducer, in order to improve the efficiency.

### 3.3.6 Superconducting solenoid magnet



**Figure 3.15:** Artistic representation of the CMS solenoid magnet(left). The magnet is supported on an iron yoke (right) which also serves as the house of the muon detector and as mechanical support for the whole CMS detector [74].

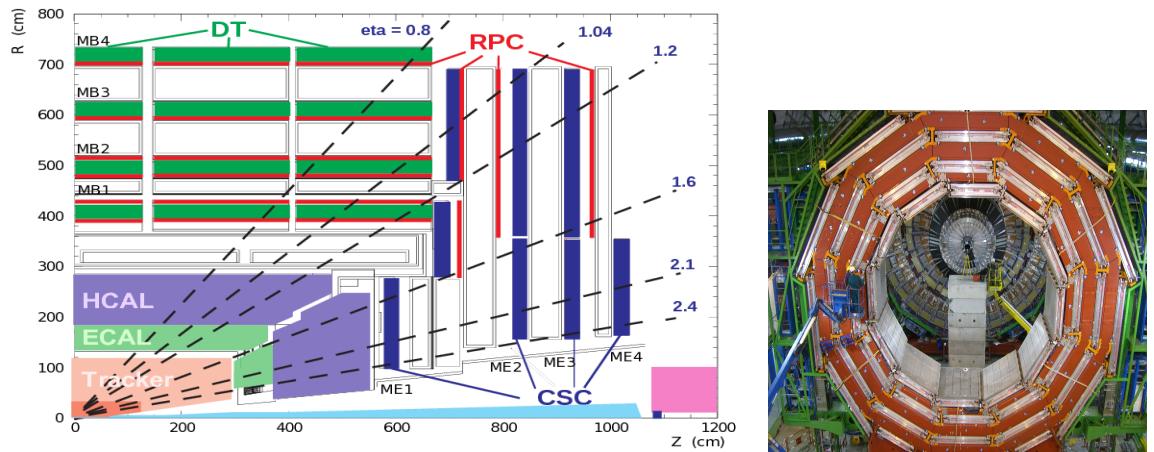
The superconducting magnet installed in the CMS detector is designed to provide an intense and highly uniform magnetic field in the central part of the detector. In fact, the tracking system takes advantage of the bending power of the magnetic field to measure with precision the momentum of the particles that traverse it; the unambiguous determination of the sign for high momentum muons was a driven principle during the design of the magnet. The magnet has a diameter of 6.3 m, a length of 12.5 m and a cold mass of 220 t; the generated magnetic field reaches a strength of 3.8T.

1261 Since it is made of Ni-Tb superconducting cable it has to operate at a temperature  
 1262 of 4.7 K by using a helium cryogenic system; the current circulating in the cables  
 1263 reaches 18800 A under normal running conditions. The left side of Figure 3.15 shows  
 1264 an artistic view of the CMS magnet, while the right side shows a transverse view of  
 1265 the cold mass where the winding structure is visible.

1266

1267 The yoke (see Figure 3.15), composed of 5 barrel wheels and 6 endcap disks made  
 1268 of iron, serves not only as the media for magnetic flux return but also provides the  
 1269 house for the muon detector system and structural stability to the full detector.

### 1270 3.3.7 Muon system



**Figure 3.16:** Left: CMS muon system schematic view; Right: one of the yoke rings with the muon DTs and RPCs installed; in the back it is possible to see the muon endcap [81].

1271 Muons are the only charged particles able to pass through all the CMS detector due  
 1272 to their low ionization energy loss; thus, muons can be separated easily from the  
 1273 high amount of particles produced in a  $pp$  collision. Also, muons are expected to be  
 1274 produced in the decay of several new particles; therefore, a good detection of muons

1275 was on the leading principles when designing the CMS detector.

1276

1277 The CMS muon detection system (muon spectrometer) is embedded in the return  
1278 yoke as seen in Figure 3.16. It is composed of three different detector types, the drift  
1279 tube chambers (DT), Cathode strip chambers (CSC), and resistive plate chambers  
1280 (RPC); DT are located in the central region  $\eta < 1.2$  arranged in four layers of drift  
1281 chambers filled with an Ar/CO<sub>2</sub> gas mixture.

1282

1283 The muon endcaps are made of CSCs covering the region  $\eta < 2.4$  and filled with a  
1284 mixture of Ar/CO<sub>2</sub>/CF<sub>4</sub>. The reason behind using a different detector type lies on  
1285 the different conditions in the forward region like the higher muon rate and higher  
1286 residual magnetic field compared to the central region.

1287

1288 The third type of detector used in the muon system is a set of four disks of RPCs  
1289 working in avalanche mode. The RPCs provide good spatial and time resolutions.  
1290 The track of  $high - p_T$  muon candidates is built combining information from the  
1291 tracking system and the signal from up to six RPCs and four DT chambers.  
1292 The muon tracks are reconstructed from the hits in the several layers of the muon  
1293 system.

### 1294 **3.3.8 CMS trigger system**

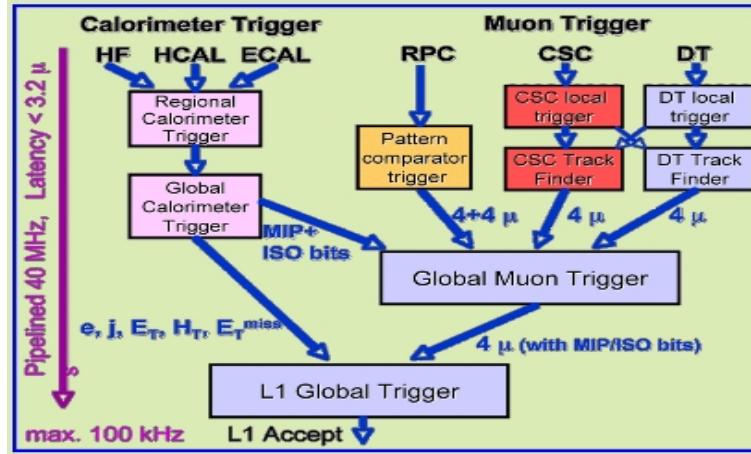
1295 Under normal conditions, CMS expects  $pp$  collisions every 25 ns, i.e., an interaction  
1296 rate of 40 MHz for which it is not possible to store the recorded data in full. In order  
1297 to handle this high event rate data, an online event selection, known as triggering, is  
1298 performed; triggering reduce the event rate to 100 Hz for storage and further offline

1299 analysis.

1300

1301 The trigger system starts with a reduction of the event rate to 100 kHz in the so-  
 1302 called *level 1 trigger (L1)*. L1 is based on dedicated programmable hardware like  
 1303 Field Programmable Gate Arrays (FPGAs) and Application Specific Integrated Cir-  
 1304 cuits (ASICs), partly located in the detector itself; another portion is located in the  
 1305 CMS under-ground cavern. Hit patterns information from the muon chambers and  
 1306 the energy deposits in the calorimeter are used to decide if an event is accepted or  
 1307 rejected, according to selection requirements previously defined, which reflect the in-  
 1308 teresting physics processes. Figure 3.17 shows the L1 trigger architecture.

1309



**Figure 3.17:** CMS Level-1 trigger architecture [82].

1310 The second stage in the trigger system is called *high-level trigger (HLT)*; events ac-  
 1311 cepted by L1 are passed to HLT in order to make an initial reconstruction of them.  
 1312 HLT is software based and runs on a dedicated server farm, using selection algo-  
 1313 rithms and high-level object definitions; the event rate at HLT is reduced to 100 Hz.  
 1314 The first HLT stage takes information from the muon detectors and the calorimeters  
 1315 to make the initial object reconstruction; in the next HLT stage, information from

1316 the pixel and strip detectors is used to do first fast-tracking and then full tracking  
1317 online. This initial object reconstruction is used in further steps of the trigger system.

1318

1319 Events and preliminary reconstructed physics objects from HLT are sent to be fully  
1320 reconstructed at the CERN computing center. Again, the pixel detector information  
1321 provides high-quality seeds for the track reconstruction algorithm offline, primary ver-  
1322 tex reconstruction, electron and photon identification, muon reconstruction,  $\tau$  iden-  
1323 tification, and b-tagging. After full reconstruction, data sets are made available for  
1324 offline analyses.

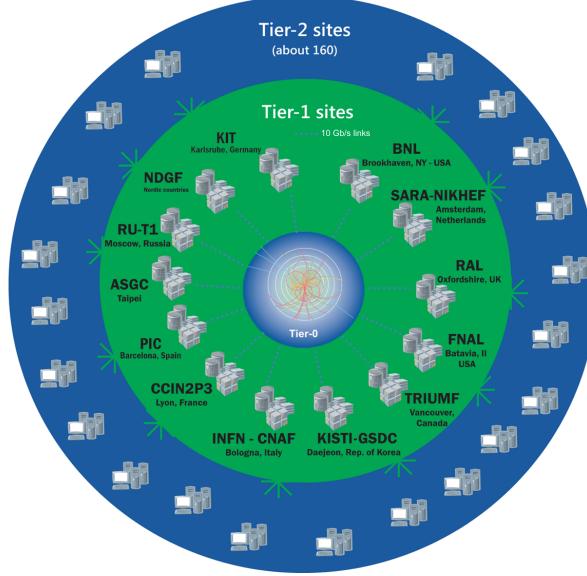
1325

1326 During the 2016-2017 technical stop, the L1 system was updated in order to improve  
1327 the physics object identification by improving the algorithms and accounting for the  
1328 increasing pile-up scenario.

### 1329 **3.3.9 CMS computing**

1330 After the data, coming from the experiment, are processed at several levels, they have  
1331 to be stored and made available for further analysis; in order to cope all the tasks  
1332 implied in the offline data processing, like transfer, simulation, reconstruction and  
1333 reprocessing, among others, a big computing power is required. The CMS computing  
1334 system is based on the distributed architecture concept, where users of the system  
1335 and physical computer centers are distributed worldwide and interconnected by high-  
1336 speed networks.

1337 The worldwide LHC computing grid (WLCG) is the mechanism used to provide that  
1338 distributed environment. WLCG is a tiered structure connecting computing centers  
1339 around the world, which provides the necessary storage and computing facilities. The



**Figure 3.18:** WLCG structure. The primary computer centers (Tier-0) are located at CERN (data center) and at the Wigner datacenter in Budapest. Tier-1 is composed of 13 centers and Tier-2 is composed of about 160 centers. [83].

1340 primary computing centers of the WLCG are located at the CERN and the Wigner  
 1341 datacenter in Budapest and are known as Tier-0 as shown in Figure 3.18. The main  
 1342 responsibilities for each tier level are [83]

- 1343     • **Tier-0:** initial reconstruction of recorded events and storage of the resulting  
       1344 datasets, the distribution of raw data to the Tier-1 centers.
- 1345     • **Tier-1:** provide storage capacity, support for the Grid, safe-keeping of a pro-  
       1346 portional share of raw and reconstructed data, large-scale reprocessing and safe-  
       1347 keeping of corresponding output, generation of simulated events, distribution  
       1348 of data to Tier 2s, safe-keeping of a share of simulated data produced at these  
       1349 Tier 2s.
- 1350     • **Tier-2:** store sufficient data and provide adequate computing power for specific  
       1351 analysis tasks, provide analysis requirements and proportional share of simu-  
       1352 lated event production and reconstruction.

1353 Aside from the general computing strategy to manage the huge amount of data pro-  
1354 duced by experiments, CMS uses a framework to perform a variety of processing,  
1355 selection and analysis tasks. The central concept of the CMS data model referred to  
1356 as *event data model* (EDM) is the *Event*; therefore, an event is the unit that contains  
1357 the information from a single bunch crossing as well as any data derived from that  
1358 information like the reconstructed objects, the details under which additional data  
1359 are derived.

1360

1361 Events are passed as the input to the *physics modules* that obtain information from  
1362 them and create new one; for instance, *event data producers* add new data into the  
1363 events, *analyzers* produce an information summary from an event set, *filters* perform  
1364 selection and triggering.

1365

1366 CMS uses several event formats with different levels of detail and precision

1367 • **Raw format:** events in this format contain the full recorded information from  
1368 the detector as well as trigger decision and other metadata. An extended version  
1369 of raw data is used to store information from the CMS Monte Carlo simulation  
1370 tools. Raw data are stored permanently, occupying about 2MB/event

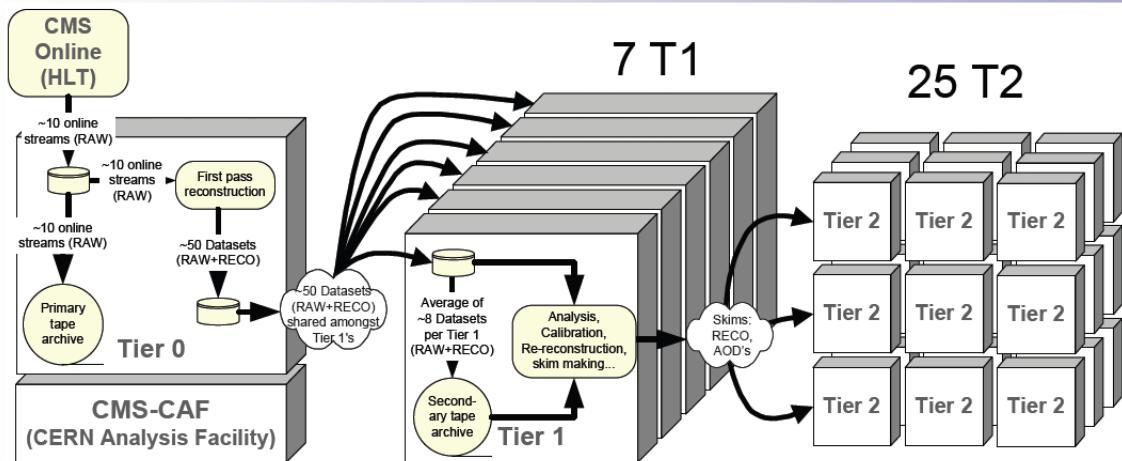
1371 • **RECO format:** events in this format correspond to raw data that have been  
1372 submitted to reconstruction algorithms like primary and secondary vertex re-  
1373 construction, particle ID, track-finding. RECO events contain physical objects  
1374 and all the information used to reconstruct them; average size is about 0.5  
1375 MB/event.

1376 • **AOD format:** Analysis Object Data (AOD) is the data format used in the  
1377 physics analyses given that it contains the parameters describing the high-level

1378        physics objects in addition to enough information to allow a kinematic refitting if  
 1379        needed. AOD events are filtered versions of the RECO events to which skimming  
 1380        or other kind processes have been applied. Requires about 100 kB/event.

1381        • **Non-event data** are data needed to interpret and reconstruct events. Some  
 1382        of the non-event data used by CMS contains information about the detector  
 1383        contraction and condition data like calibrations, alignment, and detector status.

1384        Figure 3.19 shows the data flow scheme between CMS detector and hardware tiers.



**Figure 3.19:** Data flow from CMS detector through hardware Tiers.

1385        The whole collection of software built as a framework is referred to as *CMSSW*. This  
 1386        framework provides the services needed by the simulation, calibration and alignment,  
 1387        and reconstruction modules that process event data, so that physicists can perform  
 1388        analysis. The CMSSW event processing model is composed of one executable, called  
 1389        cmsRun, and several plug-in modules which contains all the tools (calibration, recon-  
 1390        struction algorithms) needed to process an event. The same executable is used for  
 1391        both detector and Monte Carlo data [84].

1392 **Chapter 4**

1393 **Event generation, simulation and  
1394 reconstruction**

1395 The process of analyzing data recorded by the CMS experiment involves several stages  
1396 where the data are processed in order to interpret the information provided by all  
1397 the detection systems; in those stages, the particles produced after the  $pp$  collision  
1398 are identified by reconstructing their trajectories and measuring their features. In  
1399 addition, the SM provides a set of predictions that have to be compared with the  
1400 experimental results; however, in most of the cases, theoretical predictions are not  
1401 directly comparable to experimental results due to the diverse source of uncertainties  
1402 introduced by the experimental setup and theoretical approximations, among others.

1403

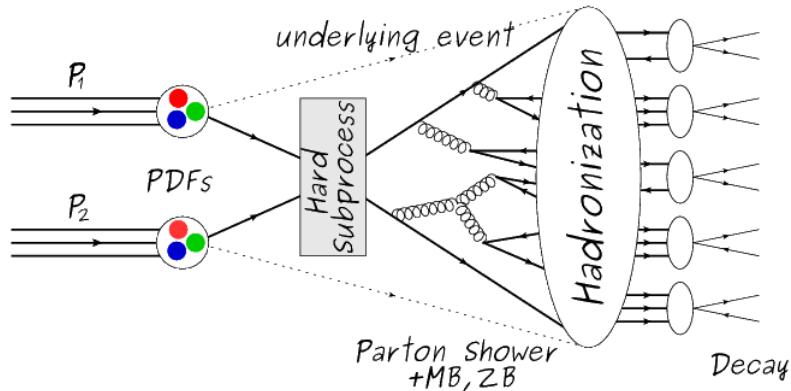
1404 The strategy to face these conditions consists in using statistical methods imple-  
1405 mented in computational algorithms to produce numerical results that can be con-  
1406 trasted with the experimental results. These computational algorithms are commonly  
1407 known as Monte Carlo (MC) methods and, in the case of particle physics, they are  
1408 designed to apply the SM rules and produce predictions about the physical observ-

ables measured in the experiments. Since particle physics is governed by quantum mechanics principles, predictions are not allowed from single events; therefore, a high number of events are *generated* and predictions are produced in the form of statistical distributions for the observables. Effects of the detector presence are included in the predictions by introducing simulations of the detector itself.

1414

1415 This chapter presents a description of the event generation strategy and the tools  
 1416 used to perform the detector simulation and physics objects reconstruction. A com-  
 1417 prehensive review of event generators for LHC physics can be found in Reference [85]  
 1418 on which this chapter is based.

## 1419 4.1 Event generation



**Figure 4.1:** Event generation process. The actual interaction is generated in the hard subprocess. The parton shower describes the evolution of the partons from the hard subprocess. Modified from Reference [86].

1420 The event generation is intended to create events that mimic the behavior of actual  
 1421 events produced in collisions; they obey a sequence of steps from the particles collision  
 1422 hard process to the decay process into the final state. Figure 4.1 shows a schematic  
 1423 view of the event generation process; the fact that the full process can be treated as

1424 several independent steps is motivated by the QCD factorization theorem.

1425

1426 Generation starts by taking into account the PDFs of the incoming particles. Event  
 1427 generators offer the option to chose from several PDF sets depending on the particu-  
 1428 lar process under simulation<sup>1</sup>; in the following,  $pp$  collisions will be considered. The  
 1429 *hard subprocess* describes the actual interaction between partons from the incoming  
 1430 protons; it is represented by the matrix element connecting the initial and final states  
 1431 of the interaction. Normally, the matrix element can be written as a sum over Feyn-  
 1432 man diagrams and consider interferences between terms in the summation. During  
 1433 the generation of the hard subprocess, the production cross section is calculated.

1434

1435 The order to which the cross section is calculated depends on the order of the Feyn-  
 1436 man diagrams involved in the calculation; therefore, radiative corrections are included  
 1437 by considering a higher order Feynman diagrams where QCD radiation dominates.  
 1438 Currently, cross sections calculated to LO do not offer a satisfactory description of the  
 1439 processes, i.e., the results are only reliable for the shape of distributions; therefore,  
 1440 NLO calculations have to be performed with the implication that the computing time  
 1441 needed is highly increased.

1442

1443 The final parton content of the hard subprocess is subjected to the *parton shower*  
 1444 which generates the gluon radiation. Parton shower evolves the partons, i.e., glouns  
 1445 split into quark-antiquark pairs and quarks with enough energy radiate gluons giv-  
 1446 ing rise to further parton multiplication, following the DGLAP (Dokshitzer-Gribov-  
 1447 Lipatov-Altarelli-Parisi) equations. Showering continues until the energy scale is low  
 1448 enough to reach the non-perturbative limit.

---

<sup>1</sup> Tool in Reference [87] allows to plot different PDF sets under customizable conditions.

1449

1450 In the simulation of LHC processes that involve  $b$  quarks, like the single top quark  
 1451 or Higgs associated production, it is needed to consider that the  $b$  quark is heavier  
 1452 than the proton; hence, the QCD interaction description is made in two different  
 1453 schemes [88]

1454 • four-flavor (4F) scheme.  $b$  quarks appear only in the final state because they  
 1455 are heavier than the proton and therefore they can be produced only from the  
 1456 splitting of a gluon into pairs or singly in association with a  $t$  quark in high  
 1457 energy-scale interactions; furthermore, during the simulation, the  $b$ -PDFs are set  
 1458 to zero. Calculations in this scheme are more complicated due to the presence  
 1459 of the second  $b$  quark but the full kinematics is considered already at LO and  
 1460 therefore the accuracy of the description is better.

1461 • five-flavor (5F) scheme.  $b$  quarks are considered massless, therefore they can  
 1462 appear in both initial and final states since they can now be part of the proton;  
 1463 thus, during the simulation  $b$ -PDFs are not set to zero. In this scheme, calcu-  
 1464 lations are simpler than in the 4F scheme and possible logarithmic divergences  
 1465 are absorbed by the PDFs through the DGLAP evolution.

1466 In this thesis, the  $tHq$  events are generated using the 4F scheme in order to reduce  
 1467 uncertainties, while the  $tHW$  events are generated using the 5F scheme to eliminate  
 1468 LO interference with  $t\bar{t}H$  process [53].

1469

1470 Partons involved in the  $pp$  collision are the focus of the simulation, however, the rest  
 1471 of the partons inside the incoming protons are also affected because the remnants are  
 1472 colored objects; also, multiple parton interactions can occur. The hadronization of  
 1473 the remnants and multiple parton interactions are known as *underlying event* and it

1474 has to be included in the simulation. In addition, multiple  $pp$  collisions in the same  
 1475 bunch crossing (pile-up mentioned in 3.2) occurs, actually in two forms

1476 • *in-time PU* which refers to multiple  $pp$  collision in the bunch crossing but that  
 1477 are not considered as primary vertices.

1478 • *Out-of-time PU* which refers to overlapping  $pp$  collisions from consecutive bunch  
 1479 crossings; this can occur due to the time-delays in the detection systems where  
 1480 information from one bunch crossing is assigned to the next or previous one.

1481 While the underlying event effects are included in generation using generator-specific  
 1482 tools, PU effects are added to the generation by overlaying Minimum-bias (MB) and  
 1483 Zero-bias (ZB) events to the generated events. MB events are inelastic events se-  
 1484 lected by using a loose trigger with as little bias as possible, therefore accepting a  
 1485 large fraction of the overall inelastic event; ZB events correspond to random events  
 1486 recorded by the detector when collisions are likely. MB models in-time PU and ZB  
 1487 models out-of-time PU.

1488

1489 The next step in the generation process is called *hadronization*. Since particles with  
 1490 a net color charge are not allowed to exits isolated, they have to recombine to form  
 1491 bound states. This is precisely the process by which the partons resulting from the  
 1492 parton shower arrange themselves as color singlets to form hadrons. At this step, the  
 1493 energy-scale is low and the strong coupling constant is large, therefore hadronization  
 1494 process is non-perturbative and the evolution of the partons is described using phe-  
 1495 nomenological models. Most of the baryons and mesons produced in the hadronization  
 1496 are unstable and hence they will decay in the detector.

1497

1498 The last step in the generation process corresponds to the decay of the unstable  
 1499 particles generated during hadronization; it is also simulated in the hadronization  
 1500 step, based on the known branching ratios.

1501 **4.2 Monte Carlo Event Generators.**

1502 The event generation described in the previous section has been implemented in  
 1503 several software packages for which a brief description is given.

1504 • **PYTHIA 8.** It is a program designed to perform the generation of high energy  
 1505 physics events which describes the collisions between particles such as electrons  
 1506 and protons. Several theories and models are implemented in it, in order to  
 1507 describe physical aspects like hard and soft interaction, parton distributions,  
 1508 initial and final-state parton showers, multiple parton interactions, beam rem-  
 1509 nants, hadronization<sup>2</sup> and particle decay. Thanks to extensive testing, several  
 1510 optimized parametrizations, known as *tunings*, have been defined in order to  
 1511 improve the description of actual collisions to a high degree of precision; for  
 1512 analysis at  $\sqrt{s} = 13$  TeV, the underline event CUETP8M1 tune is employed [90].  
 1513 The calculation of the matrix element is performed at LO which is not enough  
 1514 for the current required level of precision; therefore, pythia is often used for  
 1515 parton shower, hadronization and decays, while other event generators are used  
 1516 to generate the matrix element at NLO.

1517 • **MadGraph5\_aMC@NLO.** MadGraph is a matrix element generator which  
 1518 calculates the amplitudes for all contributing Feynman diagrams of a given pro-  
 1519 cess but does not provide a parton shower while MC@NLO incorporates NLO

---

<sup>2</sup> based in the Lund string model [89]

1520 QCD matrix elements consistently into a parton shower framework; thus, Mad-  
 1521 Graph5\_aMC@NLO, as a merger of the two event generators MadGraph5 and  
 1522 aMC@NLO, is an event generator capable to calculate tree-level and NLO cross  
 1523 sections and perform the matching of those with the parton shower. It is one of  
 1524 the most frequently used matrix element generators; however, it has the partic-  
 1525 ular feature of the presence of negative event weights which reduce the number  
 1526 of events used to reproduce the properties of the objects generated [91].

1527

1528 • **POWHEG.** It is an NLO matrix element generator where the hardest emis-  
 1529 sion of color charged particles is generated in such a way that the negative event  
 1530 weights issue of MadGraph5\_aMC@NLO is overcome; however, the method re-  
 1531 quires an interface with  $p_T$ -ordered parton shower or a parton shower generator  
 1532 where this highest emission can be vetoed in order to avoid double counting of  
 1533 this highest-energetic emission. PYTHIA is a commonly matched to POWHEG  
 1534 event generator [92].

1535 Events resulting from the whole generation process are known as MC events.

### 1536 4.3 CMS detector simulation.

1537 After generation, MC events contain the physics of the collisions but they are not  
 1538 ready to be compared to the events recorded by the experiment since these recorded  
 1539 events correspond to the response of the detection systems to the interaction with  
 1540 the particles traversing them. The simulation of the CMS detector has to be applied  
 1541 on top of the event generation; it is simulated with a MC toolkit for the simulation  
 1542 of particles passing through matter called Geant4 which is also able to simulate the

1543 electronic signals that would be measured by all detectors inside CMS.

1544

1545 The simulation takes the generated particles contained in the MC events as input,  
1546 makes them pass through the simulated geometry, and models physics processes that  
1547 particles experience during their passage through matter. The full set of results from  
1548 particle-matter interactions corresponds to the simulated hit which contains informa-  
1549 tion about the energy loss, momentum and position. Particles of the input event are  
1550 called *primary*, while the particles originating from GEANT4-modeled interactions of  
1551 a primary particle with matter are called a *secondary*. Simulated hits are the input  
1552 of subsequent modules that emulate the response of the detector readout system and  
1553 triggers. The output from the emulated detection systems and triggers is known as  
1554 digitization [93, 94].

1555

1556 The modeling of the CMS detector corresponds to the accurate modeling of the  
1557 interaction among particles, the detector material, and the magnetic field. This  
1558 simulation procedure includes the following standard steps

- 1559     • Modeling of the Interaction Region.
- 1560     • Modeling of the particle passage through the hierarchy of volumes that compose  
1561        CMS detector and of the accompanying physics processes.
- 1562     • Modeling of the effect of multiple interactions per beam crossing and/or the  
1563        effect of events overlay ( Pile-Up simulation).
- 1564     • Modeling of the detector's electronics response, signal shape, noise, calibration  
1565        constants (digitization).

1566 In addition to the full simulation, i.e., a detailed detector simulation, a faster simu-  
 1567 lation (FastSim) have been developed, that may be used where much larger statistics  
 1568 are required. In FastSim, detector material effects are parametrized and included in  
 1569 the hits; those hits are used as input of the same higher-level algorithms<sup>3</sup> used to an-  
 1570 alyze the recorded events. In this way, comparisons between fast and full simulations  
 1571 can be performed [96].

1572  
 1573 After the full detector simulation, the output events can be directly compared to  
 1574 events actually recorded in the CMS detector. The collection of MC events that  
 1575 reproduces the expected physics for a given process is known as MC sample.

## 1576 **4.4 Event reconstruction.**

1577 The CMS experiment use the *particle-flow event reconstruction algorithm (PF)* to do  
 1578 the reconstruction of particles produced in  $pp$  collisions. Next sections will present  
 1579 a basic description of the *Elements* used by PF (tracker tracks, energy clusters, and  
 1580 muon tracks), based in the References [97, 98] where more detailed descriptions can  
 1581 be found.

### 1582 **4.4.1 Particle-Flow Algorithm.**

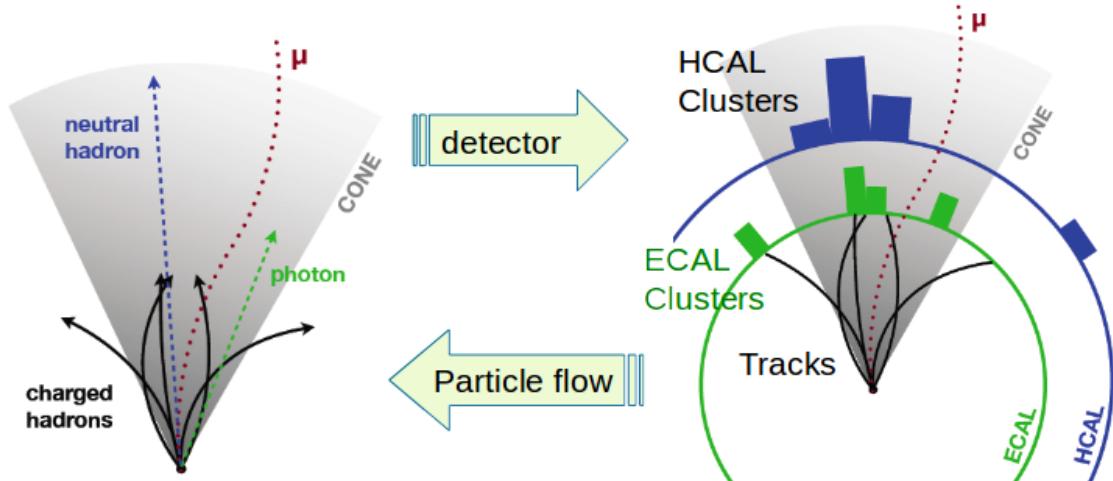
1583 Each of the several sub detection systems of the CMS detector is dedicated to identify  
 1584 a specific type of particles, i.e., photons and electrons are absorbed by the ECAL  
 1585 and their reconstruction is based on ECAL information; hadrons are reconstructed  
 1586 from clusters in the HCAL while muons are reconstructed from hits in the muon

---

<sup>3</sup> track fitting, calorimeter clustering, b tagging, electron identification, jet reconstruction and calibration, trigger algorithms which will be considered in the next sections

1587 chambers. PF is designed to correlate signals from all the detector layers (tracks and  
 1588 energy clusters) in order to reconstruct and identify each final state particle and its  
 1589 properties as sketched in Figure 4.2.

1590



**Figure 4.2:** Particle flow algorithm. Information from the several CMS detection systems is provided as input to the algorithm which then combine it to identify and reconstruct all the particles in the final state and their properties. Reconstruction of simulated events is also performed by providing information from MC samples, detector and trigger simulation [99].

1591 For instance, a charged hadron is identified by a geometrical connection, known as  
 1592 *link*, between one or more calorimeter clusters and a track in the tracker, provided  
 1593 there are no hits in the muon system; combining several measurements allows a better  
 1594 determination of the energy and charge sign of the charged hadron.

### 1595 Charged-particle track reconstruction.

1596 The strategy used by PF in order to reconstruct tracks is called *Iterative Tracking*  
 1597 which occurs in four steps

- 1598 • Seed generation where initial track candidates are found by looking for a combi-  
 1599 nation of hits in the pixel detector, strip tracker, and muon chambers. In total

1600        ten iterations are performed, each one with a different seeding requirement.  
 1601        Seeds are used to estimate the trajectory parameters and uncertainties at the  
 1602        time of the full track reconstruction. Seeds are also considered track candidates.

- 1603        • Track finding using a tracking software known as Combinatorial Track Finder  
               (CTF) [100]. The seed trajectories are extrapolated along the expected flight  
               path of a charged particle, in agreement to the trajectory parameters obtained  
               in the first step, in an attempt to find additional hits that can be assigned to  
               the track candidates.
- 1608        • Track-fitting where the found tracks are passed as input to a module which  
               provides the best estimate of the parameters of each trajectory.
- 1610        • Track selection where track candidates are submitted to a selection which dis-  
               cards those that fail a set of defined quality criteria.

1612        Iterations differ in the seeding configuration and the final track selection as elaborated  
 1613        in References [97, 98]. In the first iteration, high  $p_T$  tracks and tracks produced near  
 1614        to the interaction region are identified and those hits are masked thereby reducing  
 1615        the combinatorial complexity. Next, iterations search for more complicated tracks,  
 1616        like low  $p_T$  tracks and tracks from b hadron decays, which tend to be displaced from  
 1617        the interaction region.

1618        **Vertex reconstruction.**

1619        During the track reconstruction, an extrapolation toward to the calorimeters is per-  
 1620        formed in order to match energy deposits; that extrapolation is performed also toward  
 1621        the beamline in order to find the origin of the track known as *vertex*. The vertex re-  
 1622        construction is performed by selecting from the available reconstructed tracks, those

1623 that are consistent with being originated in the interaction region where  $pp$  collisions  
 1624 are produced. The selection involves a requirement on the number of tracker (pixel  
 1625 and strip) hits and the goodness of the track fit.

1626

1627 Selected tracks are clustered using a *deterministic annealing algorithm* (DA)<sup>4</sup>. A set  
 1628 of candidate vertices and their associated tracks, resulting from the DA, are then fit-  
 1629 ted with an *adaptive vertex fitter* (AVF) to produce the best estimate of the vertices  
 1630 locations.

1631

1632 The  $p_T$  of the tracks associated to a reconstructed vertex is added, squared and used  
 1633 to organize the vertices; the vertex with the highest squared sum is designated as the  
 1634 *primary vertex* (PV) while the rest are designated as PU vertices.

### 1635 Calorimeter clustering.

1636 After traversing the CMS tracker system, electrons, photons and hadrons deposit their  
 1637 energy in the ECAL and HCAL cells. The PF clustering algorithm aims to provide  
 1638 a high detection efficiency even for low-energy particles and an efficient distinction  
 1639 between close energy deposits. The clustering runs independently in the ECAL barrel  
 1640 and endcaps, HCAL barrel and endcaps, and the two preshower layers, following two  
 1641 steps

- 1642     • cells with an energy larger than a given seed threshold and larger than the energy  
   1643       of the neighboring cells are identified as cluster seeds. The neighbor cells are  
   1644       those that either share a side with the cluster seed candidate, or the eight closest  
   1645       cells including cells that only share a corner with the seed candidate.

---

<sup>4</sup> DA algorithm and AVF are described in detail in References [102, 103]

1646       • cells with at least a corner in common with a cell already in the cluster seed  
 1647           and with an energy above a cell threshold are grouped into topological clusters.

1648 Clusters formed in this way are known as *particle-flow clusters*. With this clustering  
 1649 strategy, it is possible to detect and measure the energy and direction of photons and  
 1650 neutral hadrons as well as differentiate these neutral particles from the charged hadron  
 1651 energy deposits. In cases involving charged hadrons for which the track parameters  
 1652 are not determined accurately, for instance, low-quality and high- $p_T$  tracks, clustering  
 1653 helps in the energy measurements.

1654 **Electron track reconstruction.**

1655 Although the charged-particle track reconstruction described above works for elec-  
 1656 trons, they lose a significant fraction of their energy via bremsstrahlung photon radi-  
 1657 ation before reaching the ECAL; thus, the reconstruction performance depends on the  
 1658 ability to measure also the radiated energy. The reconstruction strategy, in this case,  
 1659 requires information from the tracking system and from the ECAL. Bremsstrahlung  
 1660 photons are emitted at similar  $\eta$  values to that of the electron but at different values  
 1661 of  $\phi$ ; therefore, the radiated energy can be recovered by grouping ECAL clusters in a  
 1662  $\eta$  window over a range of  $\phi$  around the electron direction. The group is called ECAL  
 1663 supercluster.

1664

1665 Electron candidates from the track-seeding and ECAL super clustering are merged  
 1666 into a single collection which is submitted to a full electron tracking fit with a  
 1667 Gaussian-sum filter (GSF) [101]. The electron track and its associated ECAL su-  
 1668 percluster form a *particle-flow electron*.

1669 **Muon track reconstruction.**

1670 Given that the CMS detector is equipped with a muon spectrometer capable to iden-  
 1671 tify and measure the momentum of the muons traversing it, the muon reconstruction  
 1672 is not specific to PF; therefore, three different muon types are defined

- 1673     • *Standalone muon.* A clustering on the DTs or CSCs hits is performed to form  
   1674       track segments; those segments are used as seeds for the reconstruction in the  
   1675       muon spectrometer. All DTs, CSCs, and RPCs hits along the muon trajectory  
   1676       are combined and fitted to form the full track. The fitting output is called a  
   1677       *standalone-muon track*.
- 1678     • *Tracker muon.* Each track in the inner tracker with  $p_T$  larger than 0.5 GeV and  
   1679       a total momentum  $p$  larger than 2.5 GeV is extrapolated to the muon system.  
   1680       A *tracker muon track* corresponds to a extrapolated track that matches at least  
   1681       one muon segment.
- 1682     • *Global muon.* When tracks in the inner tracker (inner tracks) and standalone-  
   1683       muon tracks are matched and turn out being compatibles, their hits are com-  
   1684       bined and fitted to form a *global-muon track*.

1685 Global muons sharing the same inner track with tracker muons are merged into a  
 1686 single candidate. PF muon identification uses the muon energy deposits in ECAL,  
 1687 HCAL, and HO associated with the muon track to improve the muon identification.

1688 **Particle identification and reconstruction.**

1689 PF elements are connected by a linker algorithm that tests the connection between any  
 1690 pair of elements; if they are found to be linked, a geometrical distance that quantifies  
 1691 the quality of the link is assigned. Two elements may be linked indirectly through

1692 common elements. Linked elements form *PF blocks* and each PF block may contain  
 1693 elements originating in one or more particles. Links can be established between  
 1694 tracks, between calorimeter clusters, and between tracks and calorimeter clusters.  
 1695 The identification and reconstruction start with a PF block and proceed as follows

1696 • Muons. An *isolated global muon* is identified by evaluating the presence of  
 1697 inner track and energy deposits close to the global muon track in the  $(\eta, \phi)$   
 1698 plane, i.e., in a particular point of the global muon track, inner tracks and  
 1699 energy deposits are sought within a radius of  $\Delta R = 0.3$  (see eqn. 3.7) from the  
 1700 muon track; if they exit and the  $p_T$  of the found track added to the  $E_T$  of the  
 1701 found energy deposit does not exceed 10% of the muon  $p_T$  then the global muon  
 1702 is an isolated global muon. This isolation condition is stringent enough to reject  
 1703 hadrons misidentified as muons.

1704 *Non-isolated global muons* are identified using additional selection requirements  
 1705 on the number of track segments in the muon system and energy deposits along  
 1706 the muon track. Muons inside jets are identified with more stringent criteria  
 1707 in isolation and momentum as described in Reference [104]. The PF elements  
 1708 associated with an identified muon are masked from the PF block.

1709 • Electrons are identified and reconstructed as described above plus some addi-  
 1710 tional requirements on fourteen variables like the amount of energy radiated,  
 1711 the distance between the extrapolated track position at the ECAL and the po-  
 1712 sition of the associated ECAL supercluster, among others, which are combined  
 1713 in an specialized multivariate analysis strategy that improves the electron iden-  
 1714 tification. Tracks and clusters used to identify and reconstruct electrons are  
 1715 masked in the PF block.

- 1716     • Isolated photons are identified from ECAL superclusters with  $E_T$  larger than 10  
 1717       GeV, for which the energy deposited at a distance of 0.15, from the supercluster  
 1718       position on the  $(\eta, \phi)$  plane, does not exceed 10% of the supercluster energy;  
 1719       note that this is an isolation requirement. In addition, there must not be links  
 1720       to tracks. Clusters involved in the identification and reconstruction are masked  
 1721       in the PF block.
- 1722     • Bremsstrahlung photons and prompt photons tend to convert to electron-positron  
 1723       pairs inside the tracker, therefore, a dedicated finder algorithm is used to link  
 1724       tracks that seem to originate from a photon conversion; in case those two tracks  
 1725       are compatible with the direction of a bremsstrahlung photon, they are also  
 1726       linked to the original electron track. Photon conversion tracks are also masked  
 1727       in the PF block.
- 1728     • The remaining elements in the PF block are used to identify hadrons. In the  
 1729       region  $|\eta| \leq 2.5$ , neutral hadrons are identified with HCAL clusters not linked  
 1730       to any track while photons from neutral pion decays are identified with ECAL  
 1731       clusters without links to tracks. In the region  $|\eta| > 2.5$  ECAL clusters linked to  
 1732       HCAL clusters are identified with a charged or neutral hadron shower; ECAL  
 1733       clusters with no links are identified with photons. HCAL clusters not used yet,  
 1734       are linked to one or more unlinked tracks and to an unlinked ECAL in order to  
 1735       reconstruct charged-hadrons or a combination of photons and neutral hadrons  
 1736       according to certain conditions on the calibrated calorimetric energy.
- 1737     • Charged-particle tracks may be liked together when they converge to a *sec-  
 1738       ondary vertex (SV)* displaced from the interaction point where the PV and PU  
 1739       vertices are reconstructed; at least three tracks are needed in that case, of which  
 1740       at most one has to be an incoming track with hits in tracker region between a

1741 PV and the SV.

1742

1743 The linker algorithm, as well as the whole PF algorithm, has been validated and  
 1744 commissioned; results from that validation are presented in the Reference [97].

1745 **Jet reconstruction.**

1746 Quarks and gluons may be produced in the  $pp$  collisions, therefore, their hadronization  
 1747 will be seen in the detector as a shower of hadrons and their decay products in the  
 1748 form of a *jet*. The anti- $k_t$  algorithm [105] is used to perform the jet reconstruction  
 1749 by clustering those PF particles within a cone (see Figure 4.3); previously, isolated  
 1750 electrons, isolated muons, and charged particles associated with other interaction  
 1751 vertices are excluded from the clustering.

1752 The anti- $k_t$  algorithm proceeds in a sequential recombination of PF particles; the  
 1753 distance between particles  $i$  and  $j$  ( $d_{ij}$ ) and the distance between particles and the  
 1754 beam are defined as

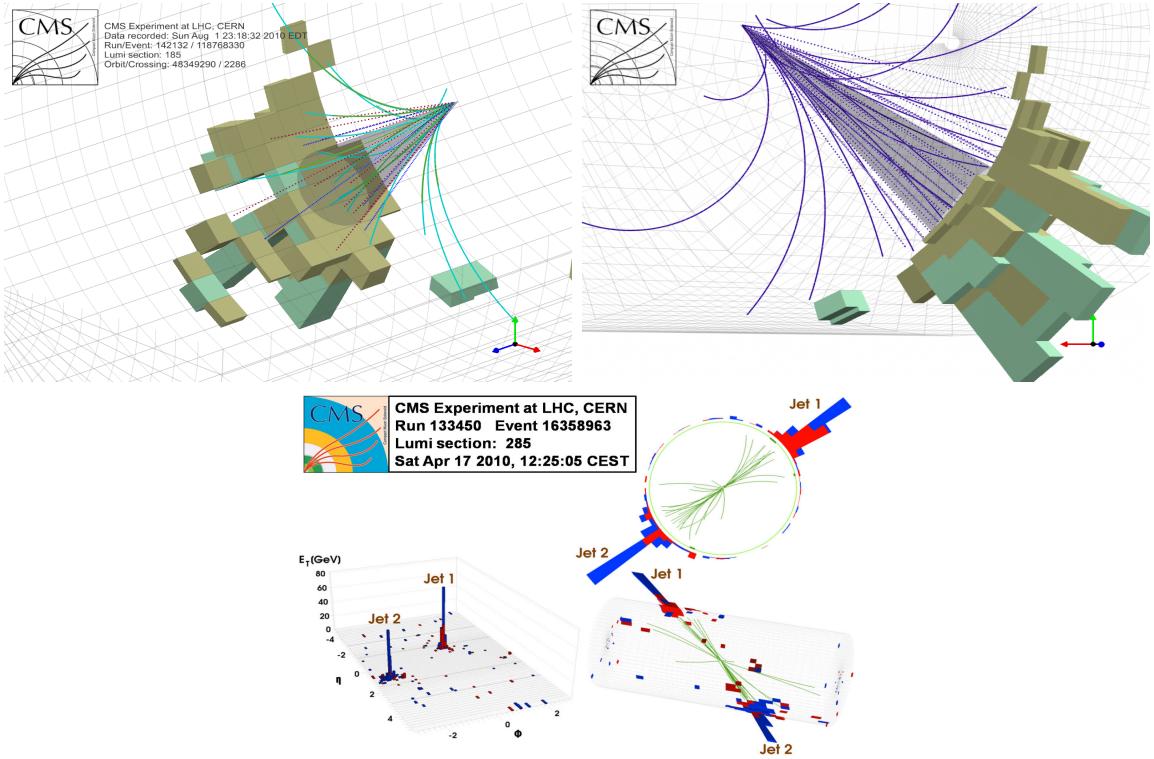
$$d_{ij} = \min\left(\frac{1}{k_{ti}^2}, \frac{1}{k_{tj}^2}\right) \frac{\Delta_{ij}^2}{R^2}$$

$$d_{iB} = \frac{1}{k_{ti}^2} \quad (4.1)$$

1755 where  $\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$ ,  $k_{ti}, y_i$  and  $\phi_i$  are the transverse momentum, ra-  
 1756 pidity and azimuth of particle  $i$  respectively and  $R$  is the called jet radius. For all  
 1757 the remaining PF particles, after removing the isolated ones,  $d_{ij}$  and  $d_{iB}$  are calcu-  
 1758 lated<sup>5</sup> and the smallest is identified; if it is a  $d_{ij}$ , particles  $i$  and  $j$  are replaced with

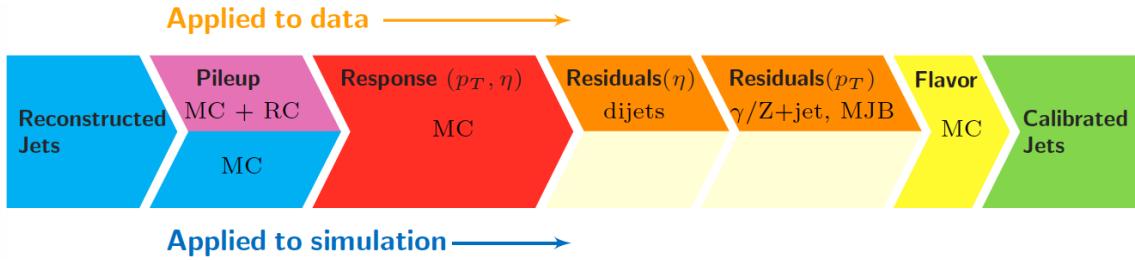
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<sup>5</sup> Notice that this is a combinatorial calculation.



**Figure 4.3:** Jet reconstruction performed by the anti- $k_t$  algorithm. Top: Two different views of a CMS recorded event are presented. Continuous lines correspond to tracks left by charged particles in the tracker while dotted lines are the imaginary paths followed by neutral particles. The green cubes represent the ECAL cells while the blue ones represent the HCAL cells; in both cases, the height of the cube represent the amount of energy deposited in the cells [106]. Bottom: Reconstruction of a recorded event with two jets [107].

1759 a new object whose momentum is the vectorial sum of the combined particles. If the  
 1760 smallest distance is a  $d_{iB}$  the clustering process ends, the object  $i$  (which at this stage  
 1761 should be a combination of several PF particles) is declared as a *Particle-flow-jet* (PF  
 1762 jet) and all the associated PF particles are removed from the detector. The clustering  
 1763 process is repeated until no PF particles remain.  
 1764 Even though jets can be reconstructed efficiently, there are some effects that are not in-  
 1765 cluded in the reconstruction and that lead to discrepancies between the reconstructed  
 1766 results and the predicted results; in order to overcome these discrepancies, a factor-  
 1767 ized model has been designed in the form of jet energy corrections (JEC) [108, 109]



**Figure 4.4:** Jet energy correction diagram. Correction levels are applied sequentially in the indicated fixed order [109].

1768 applied sequentially as shown in the diagram of Figure 4.4.

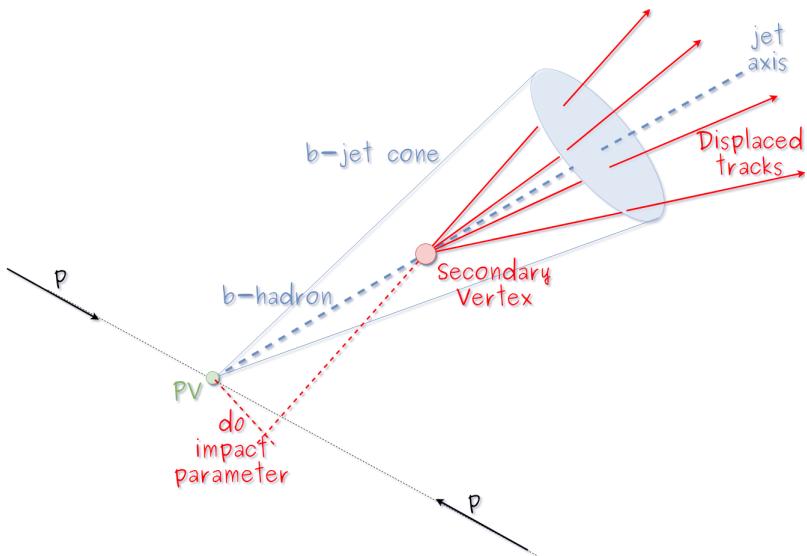
1769 At each level, the jet four-momentum is multiplied by a scaling factor based on jet  
1770 properties, i.e.,  $\eta$ , flavor, etc.

- Level 1 correction removes the energy coming from pile-up. The scale factor is determined using a MC sample of QCD dijet (2 jets) events with and without pileup overlay; it is parametrized in terms of the offset energy density  $\rho$ , jet area A, jet  $\eta$  and jet  $p_T$ . Different corrections are applied to data and MC due to the detector simulation.
  - MC-truth correction accounts for differences between the reconstructed jet energy and the MC particle-level energy. The correction is determined on a QCD dijet MC sample and is parametrized in terms of the jet  $p_T$  and  $\eta$ .
  - Residuals correct remaining small differences within jet response in data and MC. The Residuals  $\eta$ -dependent correction compares jets of similar  $p_T$  in the barrel reference region. The Residuals  $p_T$ -dependent correct the jet absolute scale (JES vs  $p_T$ ).
  - Jet-flavor corrections are derived in the same way as MC-truth corrections but using QCD pure flavor samples.

1785 ***b*-tagging of jets.**

1786 A particular feature of the hadrons containing bottom quarks (*b*-hadrons) is that  
 1787 their lifetime is long enough to travel some distance before decaying, but it is not as  
 1788 long as those of light quark hadrons; therefore, when looking at the hadrons produced  
 1789 in  $pp$  collisions, *b*-hadrons decay typically inside the tracker rather than reaching the  
 1790 calorimeters as some light-hadrons do. As a result, a *b*-hadron decay gives rise to a  
 1791 displaced vertex (secondary vertex) with respect to the primary vertex as shown in  
 1792 Figure 4.5; the SV displacement is in the order of a few millimeters. A jet resulting  
 1793 from the decay of a *b*-hadron is called *b* jet; other jets are called light jets.

1794



**Figure 4.5:** Secondary vertex in a *b*-hadron decay.

1795 Several methods to identify *b*-jets (*b*-tagging) have been developed; the method used  
 1796 in this thesis is known as *Combined Secondary Vertex* algorithm in its second version  
 1797 (CSVv2) [110]. By using information of the impact parameter, the reconstructed  
 1798 secondary vertices, and the jet kinematics as input in a multivariate analysis that  
 1799 combines the discrimination power of each variable in one global discriminator vari-

able, three working points (references): loose, medium and tight, are defined which quantify the probabilities of mistag jets from light quarks as jets from  $b$  quarks; 10, 1 and 0.1 % respectively. Although the mistagging probability decreases with the working point strength, the efficiency to correctly tag  $b$ -jets also decreases as 83, 69 and 49 % for the respective working point; therefore, a balance needs to be achieved according to the specific requirements of the analysis.

#### 4.4.1.1 Missing transverse energy.

The fact that proton bunches carry momentum along the  $z$ -axis implies that for each event it is expected that the momentum in the transverse plane is balanced. Imbalances are quantified by the missing transverse energy (MET) and are attributed to several sources including particles escaping undetected through the beam pipe, neutrinos produced in weak interactions processes which do not interact with the detector and thus escaping without leaving a sign, or even undiscovered particles predicted by models beyond the SM.

1814

1815 The PF algorithm assigns the negative sum of the momenta of all reconstructed PF  
1816 particles to the *particle-flow MET* according to

$$\vec{E}_T = - \sum_i \vec{p}_{T,i} \quad (4.2)$$

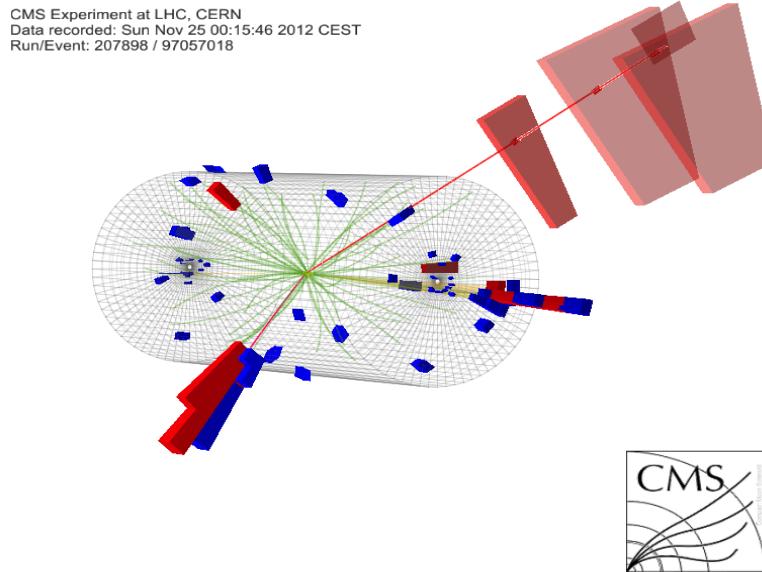
1817 JEC are propagated to the calculation of the  $\vec{E}_T$  as described in the Reference [111].

1818

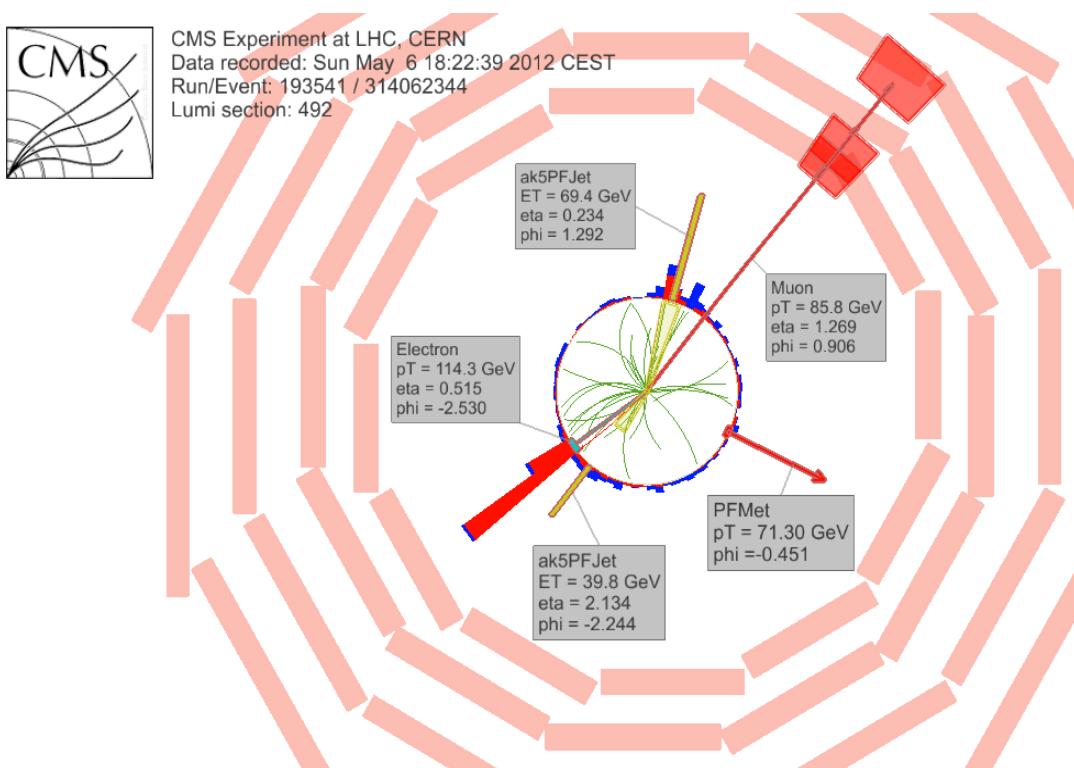
1819 **4.4.2 Event reconstruction examples**

1820 Figures 4.6-4.8 show the results of the reconstruction performed on 3 recorded events.

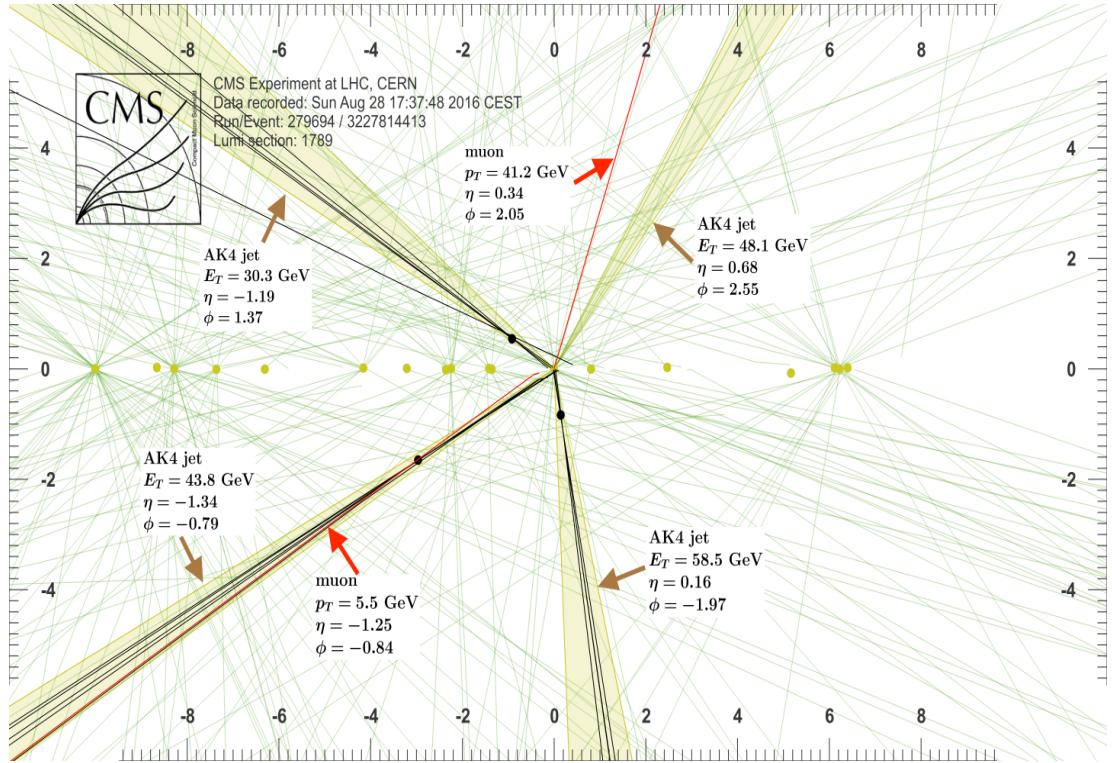
1821 Descriptions are taken directly from the source.



**Figure 4.6:** HIG-13-004 Event 1 reconstruction results; “HIG-13-004 Event 1: Event recorded with the CMS detector in 2012 at a proton-proton center-of-mass energy of 8 TeV. The event shows characteristics expected from the decay of the SM Higgs boson to a pair of  $\tau$  leptons. Such an event is characterized by the production of two forward-going jets, seen here in opposite endcaps. One of the  $\tau$  decays to a muon (red lines on the right) and neutrinos, while the other  $\tau$  decays into a charged hadron and a neutrino.” [112].



**Figure 4.7:**  $e\mu$  event reconstruction results; “An  $e\mu$  event candidate selected in 8 TeV data, as seen from the direction of the proton beams. The kinematics of the main objects used in the event selection are highlighted: two isolated leptons and two particle-flow jets. The reconstructed missing transverse energy is also displayed for reference” [113].



**Figure 4.8:** Recorded event reconstruction results;“Recorded event ( $\rho$ - $z$  projection) with three jets with  $p_T > 30$  GeV with one displaced muon track in 2016 data collected at 13 TeV. Each of the three jets has a displaced reconstructed vertex. The jet with  $p_T(j) = 43.8$  GeV,  $\eta(j) = -1.34$ ,  $\phi(j) = -0.79$  contains muon with  $p_T(\mu) = 5.5$  GeV,  $\eta(\mu) = -1.25$ ,  $\phi(\mu) = -0.84$ . Event contains reconstructed isolated muon with  $p_T(\mu) = 41.2$  GeV,  $\eta(\mu) = 0.34$ ,  $\phi(\mu) = 2.05$  and MET with  $p_T = 72.5$  GeV,  $\phi = -0.32$ . Jet candidates for a  $b$ -jet from top quark leptonic and hadronic decays are tagged by CSVv2T algorithm. One of the other two jets is tagged by CharmT algorithm. Tracks with  $p_T > 0.5$  GeV are shown. The number of reconstructed primary vertices is 18. Reconstructed  $m_T(W)$  is 101.8 GeV. Beam spot position correction is applied. Reconstructed primary vertices are shown in yellow color, while reconstructed displaced vertices and associated tracks are presented in black color. Dimensions are given in cm” [114].

1822 **Chapter 5**

1823 **Statistical methods**

1824 In the course of analyzing the data sets provided by the CMS experiment and used in  
1825 this thesis, several statistical tools have been employed; in this chapter, a description  
1826 of these tools will be presented, starting with the general statement of the multivariate  
1827 analysis method, followed by the particularities of the Boosted Decision Trees (BDT)  
1828 method and its application to the classification problem. Statistical inference methods  
1829 used will also be presented. This chapter is based mainly on the references [115–117].

1830 **5.1 Multivariate analysis**

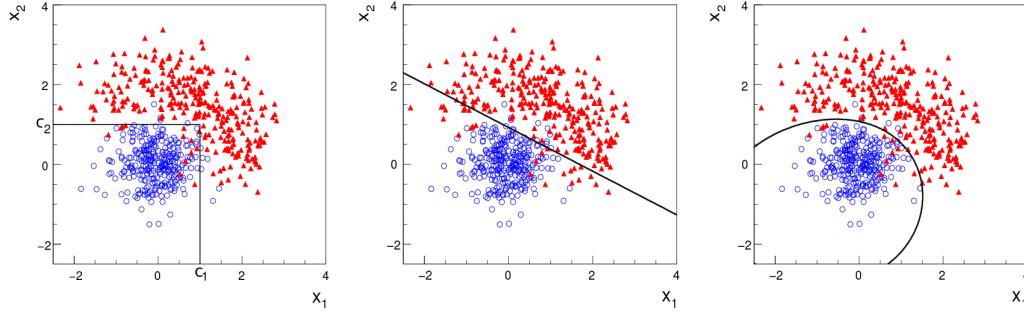
1831 Multivariate data analysis (MVA) makes reference to statistical techniques that an-  
1832 alyze data containing information of more than one variable, commonly taking into  
1833 account the effects of all variables on the response of the particular variable under  
1834 investigation, i.e., considering all the correlations between variables. MVA is em-  
1835 ployed in a variety of fields like consumer and market research, quality control and  
1836 process optimization. From a MVA it is possible to identify the dominant patterns  
1837 in the data, like groups, outliers and trends, and determine to which group a set of

1838 values belong; in the particle physics context, MVA methods are used to perform the  
 1839 selection of certain type of events, from a large data set, using a potentially large  
 1840 number of measurable properties for each event.

1841 Processes with small cross section, as the  $tHq$  process, normally are hidden behind  
 1842 more common processes; therefore, the data set results in a subset of events with  
 1843 characteristic features of interest (signal) mixed in randomly with a much larger  
 1844 number of SM events that can mimic these features of interest (background) which  
 1845 implies that it is not possible to say with certainty that a given event is signal or  
 1846 background. In that sense, the problem can be formulated as one where a set of  
 1847 events have to be classified according to some features; these features correspond to  
 1848 the measurements of several parameters like energy or momentum, organized in a  
 1849 set of *input variables*. The measurements for each event can be written in a vector  
 1850  $\mathbf{x} = (x_1, \dots, x_n)$  for which

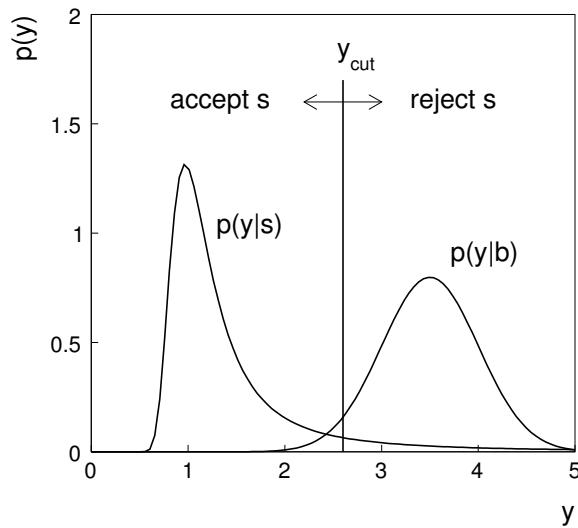
- 1851     • Signal hypotheses  $\rightarrow f(\mathbf{x}|s)$  is the probability density (*likelihood function*) that  
   1852        $\mathbf{x}$  is the set of measured values given that the events is a signal event.
- 1853     • Background hypotheses  $\rightarrow f(\mathbf{x}|b)$  is the probability density (*likelihood function*)  
   1854       that  $\mathbf{x}$  is the set of measured values given that the event is a background event.

1855     Figure 5.1 shows three ways to perform a classification of events for which mea-  
 1856       surements of two properties, two input variables, have been performed; blue circles  
 1857       represent signal events while red triangles represent background events. The classi-  
 1858       fication on (a) is *cut-based* requiring  $x_1 < c_1$  and  $x_2 < c_2$ ; usually the cut values are  
 1859       chosen according to some knowledge about the event process. In (b), the classification  
 1860       is performed by stating a cut involving a linear function of the input variables and  
 1861       so the boundary, while in (c) the the relationship between the input variables is not  
 1862       linear thus the boundary is not linear either.



**Figure 5.1:** Scatter plots-MVA event classification. Distribution of two input variables  $x_1$  and  $x_2$  measured for a set of events; blue circles represent signal events and red triangles represent background events. The classification is based on (a) cuts, (b) linear boundary, and (c) nonlinear boundary [115]

1863        The boundary can be parametrized in terms of the input variables such that the  
 1864      cut is set on the parametrization instead of on the variables, i.e.,  $y(\mathbf{x}) = y_{cut}$  with  
 1865       $y_{cut}$  a constant; thus, the acceptance or rejection of an event is based on what side  
 1866      of the boundary is the event located. If  $y(\mathbf{x})$  has functional form, it can be used to  
 1867      determine the probability distribution functions  $p(y|s)$  and  $p(y|b)$  and then perform  
 1868      a scalar test statistic with a single cut on the scalar variable  $y$ .



**Figure 5.2:** Distributions of the scalar test statistic  $y(\mathbf{x})$  under the signal and background hypotheses. [115]

1869       Figure 5.2 illustrates what would be the probability distribution functions under  
 1870   the signal and background hypotheses for a scalar test statistic with a cut on the  
 1871   classifier  $y$ . Notice that the tails of the distributions indicate that some signal events  
 1872   fall on the rejection region and some background events fall on the acceptance region;  
 1873   therefore, it is convenient to define the *efficiency* with which events of a given type  
 1874   are accepted, thus, the signal and background efficiencies are given by

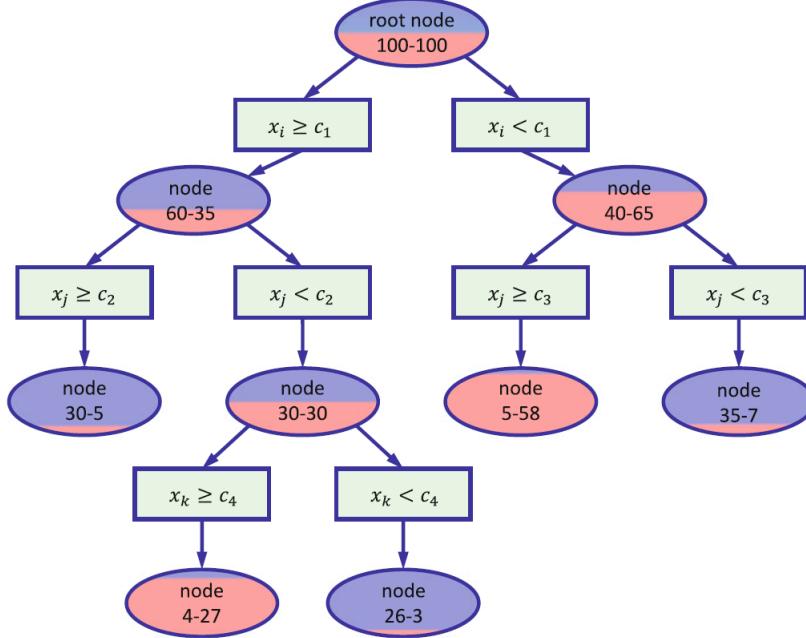
$$\varepsilon_s = P(\text{accept event}|s) = \int_A f(\mathbf{x}|s) d\mathbf{x} = \int_{-\infty}^{y_{\text{cut}}} p(y|s) dy , \quad (5.1)$$

$$\varepsilon_b = P(\text{accept event}|b) = \int_A f(\mathbf{x}|b) d\mathbf{x} = \int_{-\infty}^{y_{\text{cut}}} p(y|b) dy , \quad (5.2)$$

1875   where  $A$  is the acceptance region. Under these conditions, the background hypothesis  
 1876   corresponds to the *null hypothesis* ( $H_0$ ), the signal hypothesis corresponds to the  
 1877   *alternative hypothesis* ( $H_1$ ), the background efficiency is the significance level of the  
 1878   test, and signal efficiency is the power of the test; what is sought in an analysis is to  
 1879   maximize the power of the test relative to the significance level.

### 1880 5.1.1 Decision trees

1881   For this thesis, the implementation of the MVA strategy, described above, is per-  
 1882   formed through decision trees by using the TMVA software package [116] included in  
 1883   the the ROOT analysis framework [118]. In a simple picture, a decision tree classifies  
 1884   events according to their input variables values by setting a cut on each input variable  
 1885   and checking which events are on which side of the cut, just as proposed in the MVA  
 1886   strategy, but in addition, as a machine learning algorithm, decision trees offer the  
 1887   possibility to be trained and then perform the classification efficiently.



**Figure 5.3:** Example of a decision tree. Each node is fed with a MC sample mixing signal and background events (left-right numbers); nodes colors represent the relative amount of signal/background events [117].

1888        The training or growing of a decision tree is the process that defines the rules for  
 1889        classifying events; this process is represented in figure5.3 and consist of several steps

1890        • take MC samples of signal and background events and split them into two parts  
 1891        each; first parts form the training sample which will be used in the decision tree  
 1892        training, while the second parts form the test sample which will be used for  
 1893        testing the final classifier obtained from the training. Each event has associated  
 1894        a set of input variables  $\mathbf{x} = (x_1, \dots, x_n)$  which serve to distinguish between signal  
 1895        and background events. The training sample is taken in at the root *node*.

1896        • pick one variable, say  $x_i$   
 1897        • pick one value of  $x_i$ , each event has its own value of  $x_i$ , and split the training  
 1898        sample into two subsamples  $B_1$  and  $B_2$ ;  $B_1$  contains events for which  $x_i < c_1$

1899 while  $B_2$  contains the rest of the training events;

1900 • scan all possible values of  $x_i$  and find the splitting value that provides the *best*  
 1901 classification<sup>1</sup>, i.e.,  $B_1$  is mostly made of signal events while  $B_2$  is mostly made  
 1902 of background events.

1903 • It is possible that variables other than the picked one produce a better classi-  
 1904 fication, hence, all the variables have to be evaluated. Pick the next variable,  
 1905 say  $x_j$ , and repeat the scan over its possible values.

1906 • At the end, all the variables and their values will have been scanned, the *best*  
 1907 variable and splitting value will have been identified, say  $x_1, c_1$ , and there will  
 1908 be two nodes fed with the subsamples  $B_1$  and  $B_2$ .

1909 Nodes are further split by repeating the decision process until: a given number of  
 1910 final nodes is obtained, nodes are largely dominated by either signal or background  
 1911 events, or nodes has too few events to continue. Final nodes are called *leaves* and they  
 1912 are classified as signal or background leaves according to the class of the majority of  
 1913 events in them. Each *branch* in the tree corresponds to a sequence of cuts.

1914 The quality of the classification at each node is evaluated through a separation  
 1915 criteria; there are several of them but the *Gini Index* ( $G$ ) is the one used in the  
 1916 decision trees trained for the analysis in this thesis.  $G$  is written in terms of the  
 1917 purity ( $P$ ), i.e. the fraction of signal events, of the samples after the separation is  
 1918 made; it is given by

$$G = P(1 - P) \quad (5.3)$$

---

<sup>1</sup> Quality of the classification will be treated in the next paragraph.

1919 notice that  $P=0.5$  at the root node while  $G=0$  for pure leaves. For a node  $A$  split  
 1920 into two nodes  $B_1$  and  $B_2$  the G gain is

$$\Delta G = G(A) - G(B_1) - G(B_2) \quad (5.4)$$

1921 the *best* classification corresponds to that for which the gain of G is maximized; hence,  
 1922 the scanning over all event's variables and their values is of capital importance.

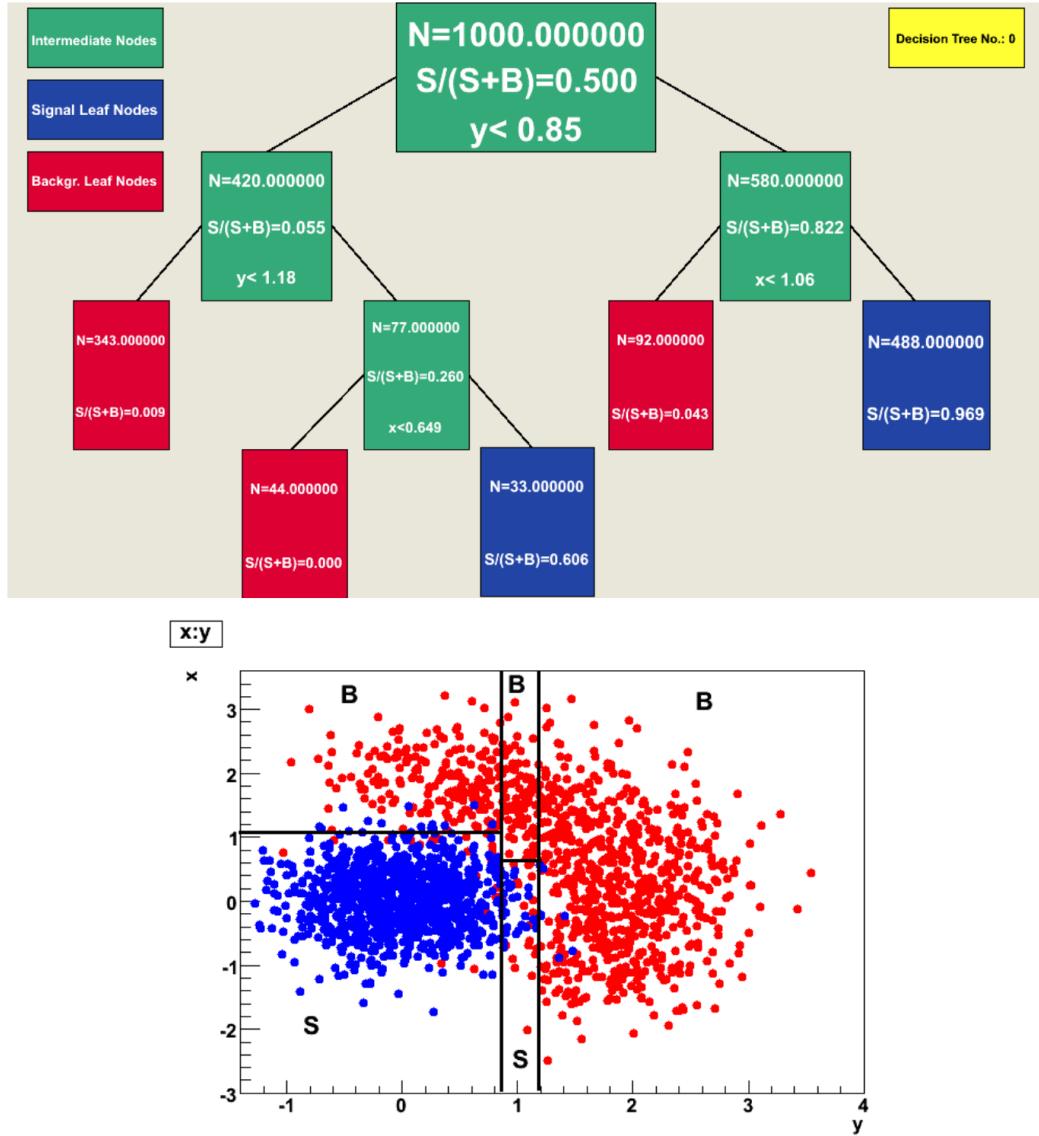
1923 In order to provide a numerical output for the classification, events in a sig-  
 1924 nal(background) leaf are assigned an score of 1(-1) each, defining in this way the  
 1925 decision tree *classifier or weak learner* as

$$f(\mathbf{x}) = \begin{cases} 1 & \mathbf{x} \text{ in signal region,} \\ -1 & \mathbf{x} \text{ in background region.} \end{cases}$$

1926 Figure 5.4 shows an example of the classification of a sample of events, containing  
 1927 two variables, performed by a decision tree.

### 1928 5.1.2 Boosted decision trees (BDT).

1929 Event misclassification occurs when a training event ends up in the wrong leaf, i.e., a  
 1930 signal event ends up in a background leaf or a background event ends up in a signal  
 1931 leaf. A way to correct it is to assign a weight to the misclassified events and train  
 1932 a second tree using the reweighted events; the event reweighting is performed by a  
 1933 boosting algorithm, events with increased weight are known as *boosted* events, in such  
 1934 a way that when used in the training of a new decision tree they get correctly classified.  
 1935 The process is repeated iteratively adding a new tree to a forest and creating a set  
 1936 of classifiers which are combined to create the next classifier; the final classifier offers



**Figure 5.4:** Example of a decision tree output. Each leaf, blue for signal events and red for background events, represent a region in the variables phase space [119].

1937 more stability<sup>2</sup> and has a smaller misclassification rate than any individual ones. The  
 1938 resulting tree collection is known as a *boosted decision tree (BDT)*.  
 1939 Thus, purity of the sample is generalized to

<sup>2</sup> Decision trees suffer from sensitivity to statistical fluctuations in the training sample which may leads to very different results with an small change in the training samples.

$$P = \frac{\sum_s w_s}{\sum_s w_s + \sum_b w_b} \quad (5.5)$$

1940 where  $w_s$  and  $w_b$  are the weights of the events; the Gini index is also generalized

$$G = \left( \sum_i^n w_i \right) P(1 - P) \quad (5.6)$$

1941 with  $n$  the number of events in the node. The final score of an event, after pass-  
 1942 ing through the forest, is calculated as the renormalized sum of all the individual  
 1943 (possibly weighted) scores; thus, high(low) score implies that the event is most likely  
 1944 signal(background).

1945 The boosting procedure, implemented in the *Gradient boosting* algorithm used  
 1946 in this thesis, produce a classifier  $F(\mathbf{x})$  which is the weighted sum of the individual  
 1947 classifiers obtained after each iteration,i.e.,

$$F(\mathbf{x}) = \sum_{m=1}^M \beta_m f(\mathbf{x}; a_m) \quad (5.7)$$

1948 where M is the number of trees in the forest. The *loss function*  $L(F, y)$  represent the  
 1949 deviation between the classifier  $F(\mathbf{x})$  response and the true value  $y$  obtained from the  
 1950 training sample (1 for signal events and -1 for background event), according to

$$L(F, y) = \ln(1 + e^{-2F(\mathbf{x})y}) \quad (5.8)$$

1951 thus, the reweighting is employed to ensure the minimization of the loss function;  
 1952 a more detailed description of the minimization procedure can be found in reference  
 1953 [120]. The final classifier output is later used as a final discrimination variable, labeled  
 1954 as *BDT output/response*.

1955 **5.1.3 Overtraining.**

1956 Decision trees offer the possibility to have as many nodes as wished in order to  
 1957 reduce the misclassification to zero (in theory); however, when a classifier is too much  
 1958 adjusted to a particular training sample, the classifier response to a slightly different  
 1959 sample may leads to a completely different classification results; this effect is know  
 1960 as *overtraining*.

1961 An alternative to reduce the overtraining in BDTs consist in pruning the tree by  
 1962 removing statistically insignificant nodes after the tree growing is completed but this  
 1963 option is not available for BDTs with gradient boosting in the TMVA-toolkit, there-  
 1964 fore, the overtraining has to be reduced by tuning the algorithm, number of nodes,  
 1965 minimum number of events in the leaves, etc. The overtraining can be evaluated  
 1966 by comparing the responses of the classifier when running over the training and test  
 1967 samples.

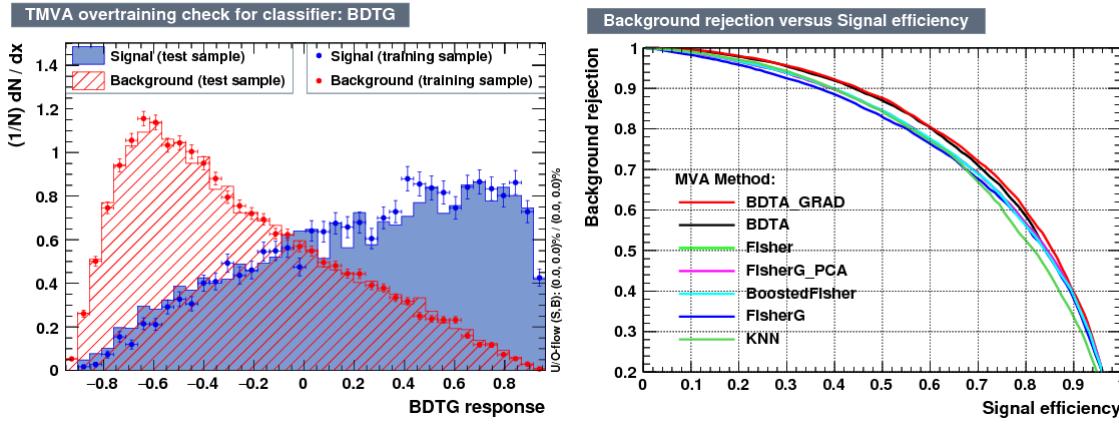
1968 **5.1.4 Variable ranking.**

1969 BDTs have the couple of particular advantages related to the input variables; on one  
 1970 side, they are relatively insensitive to the number of input variables used in the vector  
 1971  $\mathbf{x}$ . The ranking of the BDT input variables is determined by counting the number of  
 1972 times a variable is used to split decision tree nodes; in addition, the separation gain-  
 1973 squared achieved in the splitting and the number of events in the node are accounted  
 1974 by applying a weighting to that number. Thus, those variables with small or no power  
 1975 to separate signal and background events are rarely chosen to split the nodes,i.e., are  
 1976 effectively ignored.

1977 On the other side, variables correlations play an important role for some MVA  
 1978 methods like the Fisher discriminant algorithm in which the first step consist of

1979 performing a linear transformation to a phase space where the correlations between  
 1980 variables are removed; in case of BDT algorithm, correlations do not affect the per-  
 1981 formance.

1982 **5.1.5 BDT output example.**



**Figure 5.5:** Left: Output distributions for the gradient boosted decision tree (BDTG) classifier using a sample of signal( $pp \rightarrow tHq$ ) and background( $pp \rightarrow t\bar{t}$ ) events. Right: Background rejection vs signal efficiency (ROC curves) for various MVA classifiers running over the same sample used to produce the plot on the left.

1983 Left side of figure 5.5 shows the BDT output distributions for signal( $pp \rightarrow tHq$ )  
 1984 and background( $pp \rightarrow t\bar{t}$ ) events; this plot is the equivalent to the one showed in  
 1985 figure 5.2. A forest with 800 trees, maximum depth per tree = 3, and gradient  
 1986 boosting have been used as training parameters. The BDTG classifier offers a good  
 1987 separation power; while there is a small overtraining in the signal distribution, the  
 1988 background distribution seems to be well predicted which might indicate that the  
 1989 sample is composed of more background than signal events.

1990 Right side of figure 5.5 shows the background rejection vs signal efficiency curves  
 1991 for several combinations of MVA classifiers-boosting algorithms; these curves are  
 1992 known as ROC curves and give an indication of the performance of the classifier. The

1993 best performance is achieved with the BDTG classifier (BDTA\_GRAD).

## 1994 5.2 Statistical inference.

1995 Once events are classified, the next step consists in finding the parameters that define  
 1996 the likelihood functions  $f(\mathbf{x}|s), f(\mathbf{x}|b)$  for signal and background events respectively.  
 1997 In general, likelihood functions depend not only on the measurements but also on  
 1998 parameters ( $\theta_m$ ) that define their shapes; the process of estimating these *unknown*  
 1999 *parameters* and their uncertainties from the experimental data is called *inference*.  
 2000 The likelihood function for  $N$  the events the in a sample is the combination of all the  
 2001 likelihoods functions

$$L(\boldsymbol{\theta}) = \prod_{i=1}^N f(\mathbf{x}^i|\boldsymbol{\theta}) = \prod_{i=1}^N f(x_1^i, \dots, x_n^i; \theta_1, \dots, \theta_m) \quad (5.9)$$

2002 Thus, the estimation of the unknown parameters from experimental data samples  
 2003 is written in terms of a central value using the notation

$$\theta = \hat{\theta} \pm \delta\theta \quad (5.10)$$

2004 where the interval  $[\hat{\theta} + \delta\theta, \hat{\theta} - \delta\theta]$  is called *confidence interval*; it is usually inter-  
 2005 preted, in the limit of infinite number of experiments, as the interval where the true  
 2006 value of the unknown parameter  $\theta$  is contained with a probability of 0.6827 (if no  
 2007 other convention is stated).

### 2008 5.2.1 Nuisance parameters.

2009 The unknown parameter vector  $\boldsymbol{\theta}$  is made of two types of parameters: on one side,  
 2010 those parameters that provide information about the physical observables of interest

2011 for the experiment (*parameters of interest*); on the other side, the *nuisance parameters*  
 2012 that are not of direct interest for the experiment but that needs to be included in  
 2013 the analysis in order to achieve a satisfactory description of the data. They represent  
 2014 effects of the detector response like the finite resolutions of the detection systems,  
 2015 miscalibrations, and in general any source of uncertainty introduced in the analysis.

2016 In some cases the nuisance parameters are estimated using dedicated data samples,  
 2017 for instance data from test beams for calibration purposes, when MC samples are  
 2018 not suitable. The nuisance parameter uncertainties produce *systematic uncertainties*  
 2019 while the uncertainties associated to fluctuations in data and related to the estimation  
 2020 of the parameters of interest produce *statistical uncertainties*.

### 2021 5.2.2 Maximum likelihood estimation method

2022 The function that produce the estimate of a parameter is called *estimator*, there-  
 2023 fore, estimators are usually constructed using mathematical procedures encoded in  
 2024 algorithms. The estimation method used in this thesis is the *Maximum Likelihood*  
 2025 *Estimation* method (MLE); it is based on the combined likelihood function defined  
 2026 by eqn. 5.9 and the procedure seeks for the parameter set that corresponds to the  
 2027 maximum value of the combined likelihood function, i.e., the *maximum likelihood*  
 2028 *estimator* of the unknown parameter vector  $\boldsymbol{\theta}$  is the function that produce the vec-  
 2029 tor  $\hat{\boldsymbol{\theta}}$  for which the likelihood function  $L(\boldsymbol{\theta})$  evaluated at the measured sample  $\mathbf{x}$  is  
 2030 maximum.

2031 Usually, the logarithm of the likelihood function is used in the numerical algo-  
 2032 rithms implementations in order to avoid underflow the numerical precision of the  
 2033 computers due to the product of low likelihoods. In addition, it is usual minimize the  
 2034 negative logarithm of the likelihood function instead of maximizing the logarithm of

2035 it because in this way the procedure consist of differentiate a sum of therms and set  
 2036 the sum to zero; therefore

$$F(\boldsymbol{\theta}) = -\ln L(\boldsymbol{\theta}) = -\sum_{i=1}^N f(\mathbf{x}^i | \boldsymbol{\theta}). \quad (5.11)$$

2037 The minimization process is performed by the software MINUIT [121] imple-  
 2038 mented in the ROOT analysis framework. In case of large data samples the compu-  
 2039 tational resources needed to calculate the likelihood function are too big; therefore,  
 2040 the parameter estimation is performed using binned distributions of the variables of  
 2041 interest for which the *binned likelihood function* is given by

$$L(data|\mu, \theta) = \prod_{i=1} \frac{(\mu s_i(\theta) + b_i(\theta))^{n_i}}{n_i!} e^{-\mu s_i(\theta) - b_i(\theta)}, \quad (5.12)$$

2042 with  $s_i$  and  $b_i$  the expected number of signal and background yields for bin  $i$  respec-  
 2043 tively,  $n_i$  is the observed number of events in the bin  $i$  and  $\mu = \sigma/\sigma_{SM}$  is the signal  
 2044 strength. Notice that the number of entries per bin follows a Poisson distribution.  
 2045 The analysis presented in this thesis is based on the binned distribution of the ratio  
 2046 signal/background obtained from the BDT outputs.

### 2047 5.2.3 Hypothesis test

2048 The test statistic mentioned in section 5.1 involving  
 2049 ; it is achieved, according to the Neyman-Pearson lemma [122],  
 2050 by defining the acceptance region such that, for  $\mathbf{x}$  inside the region, the likelihood  
 2051 ratio, i.e., the ratio of probability distribution functions for signal and background,

2052 **5.3 exclusion limits**

2053 **5.4 asymptotic limits**

2054 **Chapter 6**

2055 **Search for production of a Higgs  
2056 boson and a single top quark in  
2057 multilepton final states in pp  
2058 collisions at  $\sqrt{s} = 13$  TeV**

2059 **6.1 Introduction**

2060 The Higgs boson discovery, supported on experimental observations and theoretical  
2061 predictions made about the SM, gives the clue of the way in that elementary particles  
2062 acquire mass through the Higgs mechanism; therefore, knowing the Higgs mass, the  
2063 Higgs-boson and Higgs-fermion couplings can be tested. In order to test the Higgs-top  
2064 coupling, several measurements have been performed, as stated in the chapter 2, but  
2065 they are limited to measure the square of the coupling; however, the production of a  
2066 Higgs boson in association with a single top quark ( $tH$ ) not only offers access to the  
2067 sign of the coupling, but also, to the CP phase of the Higgs couplings.

2068 This chapter presents the search for the associated production of a Higgs boson  
 2069 and a single top quark events, focusing on leptonic signatures provided by the Higgs  
 2070 decay modes to  $WW$ ,  $ZZ$ , and  $\tau\tau$ ; the 13 TeV dataset produced in 2016, which  
 2071 corresponds to an integrated luminosity of  $35.9\text{fb}^{-1}$ , is used. Constraints on the sign  
 2072 of the Higgs-top coupling ( $y_t$ ) have been derived from the decay rate of Higgs boson  
 2073 to photon pairs [45] and from the cross section for associated production of Higgs and  
 2074 Z bosons via gluon fusion [123], with recent results disfavoring negative signs of the  
 2075 coupling [56, 58, 124]. It expands previous analyses performed at 8 TeV [125, 126] and  
 2076 searches for associated production of  $t\bar{t}$  pair and a Higgs boson in the multilepton final  
 2077 state channel [127]; it also complements searches in other decay channels targeting  
 2078  $H \rightarrow b\bar{b}$  [128].

2079 As shown in section 2.5, the SM cross section of the associated production of a  
 2080 Higgs boson and a single top quark ( $tHq$ ) process is driven by a destructive interfer-  
 2081 ence between two contributions (see Figure 2.14), where the Higgs couples to either  
 2082 the W boson or the top quark; however, if the sign of the Higgs-top coupling is flipped  
 2083 with respect to the SM prediction, a large enhancement of the cross section occurs,  
 2084 making this analysis sensitive to such deviation. A second process, where the Higgs  
 2085 boson and top quark are accompanied by a W boson ( $tHW$ ) has similar behavior,  
 2086 albeit with a weaker interference pattern and lower contribution to the  $tH$  cross sec-  
 2087 tion, therefore, a combination of both processes would increase the sensitivity; in  
 2088 this analysis both contributions are combined and referred as  $tH$ channel. A third  
 2089 contribution comes from  $t\bar{t}H$  process. The purpose of this analysis is to investigate  
 2090 the exclusion of the presence of the  $tH + t\bar{t}H$  processes under the assumption of the  
 2091 anomalous Higgs-top coupling modifier ( $\kappa_t = -1$ ). The analysis exploits signatures  
 2092 with two leptons of the same sign (*2lss channel*) and three leptons (*3l channel*) in  
 2093 the final state.

2094        The first sections present the characteristic  $tHq$  signature as well as the expected  
 2095        backgrounds. The MC samples, data sets, and the physics object definitions are  
 2096        then defined. Following, the background predictions, the signal extraction, and the  
 2097        statistical treatment of the selected events as well as the systematic uncertainties are  
 2098        described. The final section present the results for the exclusion limits as a function  
 2099        of the ratio of  $\kappa_t$  and the dimensionless modifier of the Higgs-vector boson  $\kappa_V$ .

2100        **6.2  $tHq$  signature**

2101        In order to select events of  $tHq$  process, its features are translated into a set of  
 2102        selection rules; figure 6.1 shows the Feynman diagram and an schematic view of the  
 2103         $tHq$  process from the  $pp$  collision to the final state configuration. A single top quark  
 2104        is produced accompanied by a light quark, denoted as  $q$ ; this light quark is produced  
 2105        predominantly in the forward region of the detector. The Higgs boson which can  
 2106        be either emitted by the exchanged  $W$  boson or directly by the singly produced top  
 2107        quark.

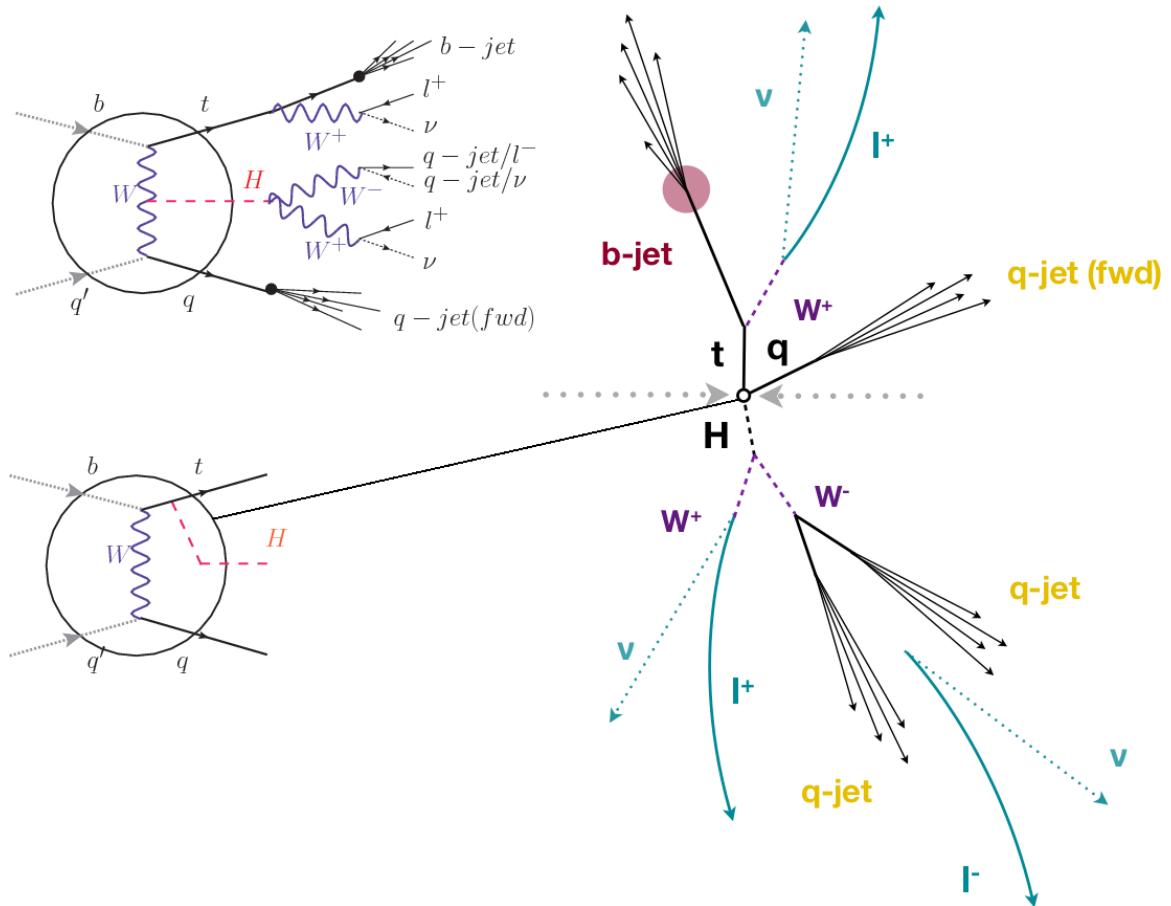
2108        The top quark and Higgs boson decay after their production in the detector due to  
 2109        their high masses/low lifetimes. The Higgs boson is required to decay into a  $W$  boson  
 2110        pair<sup>1</sup>. The top quark almost always decays into a bottom quark and a  $W$  boson, as  
 2111        encoded in the CMK matrix. The  $W$  bosons are required to decay hadronically in  
 2112        the 2lss channel case and leptonically in the 3l channel case, while  $\tau$  leptons are not  
 2113        reconstructed separately and only their leptonic decays into either electrons or muons  
 2114        are considered in this analysis.

2115        In summary, the signal process is characterized by a the final state with

- 2116        • one light-flavored forward jet,

---

<sup>1</sup> ZZ and  $\tau\tau$  decays are also include in the analysis but they are not separately reconstructed



**Figure 6.1:**  $tHq$  event signature. Left: Feynman diagram including the whole evolution up to the final state for the case of the Higgs boson emitted by the  $W$  boson (top); Feynman diagram for the case where the Higgs boson is emitted by the top quark. Right: Schematic view as it would be seen in the detector; the circle in the Feynman diagrams on the left corresponds to the circle in the center of the schematic view as indicated by the line connecting them. In the 2lss channel, one of the  $W$  bosons from the Higgs boson decays to two light-quark jets while in the 3l channel both  $W$  bosons decays to leptons.

- 2117     • one central b-jet,
  - 2118     • 2lss channel  $\rightarrow$  two leptons of the same sign, two neutrinos and two light (often  
2119        soft) jets,
  - 2120     • 3l channel  $\rightarrow$  three leptons, three neutrinos and no central light-flavored jets,
- 2121     The presence of neutrinos is inferred from the presence of MET. The analysis has

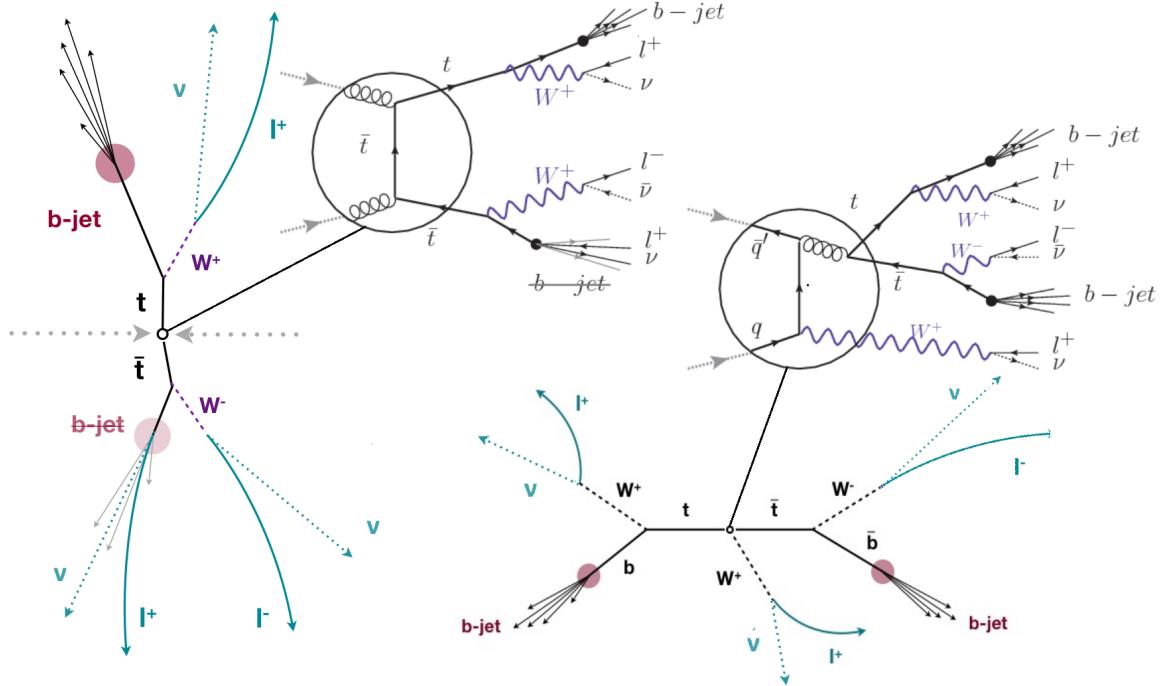
2122 been made public by CMS as a Physics Analysis Summary [129] combining the result  
 2123 for the three lepton and two lepton same-sign channels. Currently, an effort to turn  
 2124 the analysis into a paper is ongoing.

2125 **6.3 Background processes**

2126 The background processes are those that can mimic the signal signature or at least  
 2127 can be reconstructed as that as a result of certain circumstances. The backgrounds  
 2128 can be classified as

- 2129     • Irreducible backgrounds where genuine prompt leptons are produced in on-  
 2130         shell W and Z boson decays; they can be reliably estimated directly from MC  
 2131         simulated events, using higher-order cross sections or data control regions for  
 2132         the overall normalization.
- 2133     • Reducible backgrounds where at least one of the leptons is *non-prompt*, i.e., pro-  
 2134         duced within a hadronic jet, either a genuine lepton from heavy flavor decays.  
 2135         misreconstructed jets, also known as *mis-ID leptons* or *fake leptons*, are consid-  
 2136         ered non-prompt leptons as well. These non-prompt leptons leave tracks and  
 2137         hits in the detection systems as would a prompt lepton, but correlating those  
 2138         hits with nearby jets could be a way of removing them. Reducible backgrounds  
 2139         are not well predicted by simulation, and are estimated using data-driven meth-  
 2140         ods.

2141 The main sources of background events in the case of  $tHq$  process are  $t\bar{t}$  process  
 2142 and  $t\bar{t} + X(X = W, Z, \gamma)$  processes, here represented together as  $t\bar{t}V$  process. Figure  
 2143 6.2 shows the signature for  $t\bar{t}$  and  $t\bar{t}W$  processes;



**Figure 6.2:**  $t\bar{t}$  (left) and  $t\bar{t}W$ (right) events signature as they would be seen in the detector; the Feynman diagrams including the whole evolution up to the final state are also showed. The  $t\bar{t}$  process signature is very similar to that of the signal process with one fake lepton and non forward activity. The  $t\bar{t}W$ process present a higher b-jet multiplicity compared to the signal process, a prompt lepton and no forward activity.

2144     The largest contribution to irreducible backgrounds involving prompt leptons  
 2145   comes from  $t\bar{t}W$ ,  $t\bar{t}Z$ , processes for which the number of ( $b-$ )jets (( $b-$ )jet multiplicity)  
 2146   is higher than that of the signal events, while for other contributing background  
 2147   events,  $WZ$ ,  $ZZ$ , and rare SM processes like  $W^\pm W^\pm qq$ ,  $t\bar{t}t\bar{t}$ ,  $tZq$ ,  $tZW$ ,  $WWW$ ,  
 2148    $WWZ$ ,  $WZZ$ ,  $ZZZ$ , the ( $b-$ )jet multiplicity is lower compared to that of the signal  
 2149   events. None of the irreducible backgrounds present activity in the forward region of  
 2150   the detector.

2151     On the side of the reducible backgrounds, the largest contribution comes from the  
 2152    $t\bar{t}$  events which have a very similar signature to the signal events but does no present  
 2153   activity in the forward region of the detector either; A particular feature of the  $t\bar{t}$   
 2154   events is their charge-symmetry which is also a difference with the signal events.

2155        The charge misidentification plays an important role in the the 2lss channel since  
 2156      leptons in processes like  $t\bar{t}$  + jets or  $Z$  + jets can be charge misidentified, leading to  
 2157      backgrounds increments. An identification variable have been designed in order to  
 2158      reject this type of background events.

## 2159     **6.4 Data and MC Samples**

2160    Technical developments on the event generator side allow for an event-wise reweight-  
 2161    ing that can change the event kinematics based on specific generation parameters.  
 2162    This way not only the case of  $C_t = \sqrt{2}$ , but a whole range of  $\kappa_t$  and  $\kappa_V$  values can  
 2163    be investigated.

2164        The data considered in this analysis were collected by the CMS experiment dur-  
 2165        ing 2016 and correspond to a total integrated luminosity of  $35.9 fb^{-1}$ . Only periods  
 2166        when the CMS magnet was on were considered when selecting the data samples, that  
 2167        corresponds to the 23 Sep 2016 (Run B to G) and PromptReco (Run H) versions  
 2168        of the datasets. The MC samples used in this analysis correspond to the RunI-  
 2169        ISummer16MiniAODv2 campaign produced with CMSSW 80X. The two signal sam-  
 2170        ples (for  $tHq$  and  $tHW$ ) were produced with MG5\_aMC@NLO (version 5.222), in  
 2171        leading-order order mode, and are normalized to next-to-leading-order cross sections,  
 2172        see Tab. 6.1. Each sample is generated with a set of event weights corresponding to  
 2173        different values of  $\kappa_t$  and  $\kappa_V$  couplings as shown in Tab. 6.2.

### 2174     **6.4.1 Full 2016 dataset and MC samples**

2175    Different MC generators were used to generate the background processes. The dom-  
 2176    inant sources ( $t\bar{t}$ ,  $t\bar{t}W$ ,  $t\bar{t}Z$ ,  $t\bar{t}H$ ) were produced using AMC@NLO interfaced to  
 2177    PYTHIA8, and are scaled to NLO cross sections. Other processes are simulated us-

Sample	$\sigma$ [pb]	BF
/THQ_Hincl_13TeV-madgraph-pythia8_TuneCUETP8M1/	0.7927	0.324
/THW_Hincl_13TeV-madgraph-pythia8_TuneCUETP8M1/	0.1472	1.0

**Table 6.1:** Signal samples and their cross section and branching fraction used in this analysis. See Ref. [138] for more details.

ing POWHEG interfaced to PYTHIA, or bare PYTHIA (see table 6.3 and [127] for more details).

## 6.4.2 Triggers

We consider online-reconstructed events triggered by one, two, or three leptons. Single-lepton triggers are included to boost the acceptance of events where the  $p_T$  of the sub-leading lepton falls below the threshold of the double-lepton triggers. Additionally, by including double-lepton triggers in the  $\geq 3$  lepton category, as well as single-lepton triggers in all categories, we increase the efficiency, considering the logical “or” of the trigger decisions of all the individual triggers in a given category. Tab. 6.5 shows the lowest-threshold non-prescaled triggers present in the High-Level Trigger (HLT) menus for both Monte-Carlo and data in 2016.

### Trigger efficiency scale factors

The efficiency of events to pass the trigger is measured in simulation (trivially using generator information) and in the data (using event collected by an uncorrelated MET trigger). Small differences between the data and MC efficiencies are corrected by applying scale factors as shown in Tab. 6.6. The exact procedure and control plots are documented in [132] for the current analysis.

		<i>tHq</i>		<i>tHW</i>		
$\kappa_V$	$\kappa_t$	sum of weights	cross section [pb]	sum of weights	cross section [pb]	LHE weights
1.0	-3.0	35.700022	2.991	11.030445	0.6409	LHEweight_wgt[446]
1.0	-2.0	20.124298	1.706	5.967205	0.3458	LHEweight_wgt[447]
1.0	-1.5	14.043198	1.205	4.029093	0.2353	LHEweight_wgt[448]
1.0	-1.25	11.429338	0.9869	3.208415	0.1876	LHEweight_wgt[449]
1.0	-1.0		0.7927		0.1472	
1.0	-0.75	7.054998	0.6212	1.863811	0.1102	LHEweight_wgt[450]
1.0	-0.5	5.294518	0.4723	1.339886	0.07979	LHEweight_wgt[451]
1.0	-0.25	3.818499	0.3505	0.914880	0.05518	LHEweight_wgt[452]
1.0	0.0	2.627360	0.2482	0.588902	0.03881	LHEweight_wgt[453]
1.0	0.25	1.719841	0.1694	0.361621	0.02226	LHEweight_wgt[454]
1.0	0.5	1.097202	0.1133	0.233368	0.01444	LHEweight_wgt[455]
1.0	0.75	0.759024	0.08059	0.204034	0.01222	LHEweight_wgt[456]
1.0	1.0	0.705305	0.07096	0.273617	0.01561	LHEweight_wgt[457]
1.0	1.25	0.936047	0.0839	0.442119	0.02481	LHEweight_wgt[458]
1.0	1.5	1.451249	0.1199	0.709538	0.03935	LHEweight_wgt[459]
1.0	2.0	3.335034	0.2602	1.541132	0.08605	LHEweight_wgt[460]
1.0	3.0	10.516125	0.8210	4.391335	0.2465	LHEweight_wgt[461]
1.5	-3.0	45.281492	3.845	13.426212	0.7825	LHEweight_wgt[462]
1.5	-2.0	27.606715	2.371	7.809713	0.4574	LHEweight_wgt[463]
1.5	-1.5	20.476088	1.784	5.594971	0.3290	LHEweight_wgt[464]
1.5	-1.25	17.337465	1.518	4.635978	0.2749	LHEweight_wgt[465]
1.5	-1.0	14.483302	1.287	3.775902	0.2244	LHEweight_wgt[466]
1.5	-0.75	11.913599	1.067	3.014744	0.1799	LHEweight_wgt[467]
1.5	-0.5	9.628357	0.874	2.352505	0.1410	LHEweight_wgt[468]
1.5	-0.25	7.627574	0.702	1.789184	0.1081	LHEweight_wgt[469]
1.5	0.0	5.911882	0.5577	1.324946	0.08056	LHEweight_wgt[470]
1.5	0.25	4.479390	0.4365	0.959295	0.05893	LHEweight_wgt[471]
1.5	0.5	3.331988	0.3343	0.692727	0.04277	LHEweight_wgt[472]
1.5	0.75	2.469046	0.2558	0.525078	0.03263	LHEweight_wgt[473]
1.5	1.0	1.890565	0.2003	0.456347	0.02768	LHEweight_wgt[474]
1.5	1.25	1.596544	0.1689	0.486534	0.02864	LHEweight_wgt[475]
1.5	1.5	1.586983	0.1594	0.615638	0.03509	LHEweight_wgt[476]
1.5	2.0	2.421241	0.2105	1.170602	0.06515	LHEweight_wgt[477]
1.5	3.0	7.503280	0.5889	3.467546	0.1930	LHEweight_wgt[478]
0.5	-3.0	27.432685	2.260	8.929074	0.5136	LHEweight_wgt[479]
0.5	-2.0	13.956013	1.160	4.419093	0.2547	LHEweight_wgt[480]
0.5	-1.5	8.924438	0.7478	2.757611	0.1591	LHEweight_wgt[481]
0.5	-1.25	6.835341	0.5726	2.075247	0.1204	LHEweight_wgt[482]
0.5	-1.0	5.030704	0.4273	1.491801	0.08696	LHEweight_wgt[483]
0.5	-0.75	3.510528	0.2999	1.007273	0.05885	LHEweight_wgt[484]
0.5	-0.5	2.274811	0.1982	0.621663	0.03658	LHEweight_wgt[485]
0.5	-0.25	1.323555	0.1189	0.334972	0.01996	LHEweight_wgt[486]
0.5	0.0	0.656969	0.06223	0.147253	0.008986	LHEweight_wgt[487]
0.5	0.25	0.274423	0.02830	0.058342	0.003608	LHEweight_wgt[488]
0.5	0.5	0.176548	0.01778	0.068404	0.003902	LHEweight_wgt[489]
0.5	0.75	0.363132	0.03008	0.177385	0.009854	LHEweight_wgt[490]
0.5	1.0	0.834177	0.06550	0.385283	0.02145	LHEweight_wgt[491]
0.5	1.25	1.589682	0.1241	0.692099	0.03848	LHEweight_wgt[492]
0.5	1.5	2.629647	0.2047	1.097834	0.06136	LHEweight_wgt[493]
0.5	2.0	5.562958	0.4358	2.206057	0.1246	LHEweight_wgt[494]
0.5	3.0	14.843102	1.177	5.609519	0.3172	LHEweight_wgt[495]

**Table 6.2:**  $\kappa_V$  and  $\kappa_t$  combinations generated for the two signal samples and their NLO cross sections. The *tHq* cross section is multiplied by the branching fraction of the enforced leptonic decay of the top quark (0.324). See also Ref. [138].

Sample	$\sigma$ [pb]
TTWJetsToLNu_TuneCUETP8M1_13TeV-amcatnloFXFX-madspin-pythia8	0.2043
TTZToLLNuNu_M-10_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.2529
ttHJetToNonbb_M125_13TeV_amcatnloFXFX_madspin_pythia8_mWCutfix /store/cmst3/group/susy/gpetrucc/13TeV/u/TTLL_m1to10_LO_NoMS_for76X/	0.2151 0.0283
WGToLNuG_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	585.8
ZGTo2LG_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	131.3
TGJets_TuneCUETP8M1_13TeV_amcatnlo_madspin_pythia8	2.967
TGJets_TuneCUETP8M1_13TeV_amcatnlo_madspin_pythia8	2.967
TTGJets_TuneCUETP8M1_13TeV-amcatnloFXFX-madspin-pythia8	3.697
WpWpJJ_EWK-QCD_TuneCUETP8M1_13TeV-madgraph-pythia8	0.03711
ZZZ_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.01398
WWZ_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.1651
WZZ_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.05565
WW_DoubleScattering_13TeV-pythia8	1.64
tZq_ll_4f_13TeV-amcatnlo-pythia8_TuneCUETP8M1	0.0758
ST_tWll_5f_LO_13TeV-MadGraph-pythia8	0.01123
TTTT_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.009103
WZTo3LNu_TuneCUETP8M1_13TeV-powheg-pythia8	4.4296
ZZTo4L_13TeV_powheg_pythia8	1.256
TTJets_SingleLeptFromTbar_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	182.1754
TTJets_SingleLeptFromT_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	182.1754
TTJets_DiLept_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	87.3
DYJetsToLL_M-10to50_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	18610
DYJetsToLL_M-50_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	6024
WJetsToLNu_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	61526.7
ST_tW_top_5f_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M1	35.6
ST_tW_antitop_5f_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M1	35.6
ST_t-channel_4f_leptonDecays_13TeV-amcatnlo-pythia8_TuneCUETP8M1	70.3144
ST_t-channel_antitop_4f_leptonDecays_13TeV-powheg-pythia8_TuneCUETP8M1	26.2278
ST_s-channel_4f_leptonDecays_13TeV-amcatnlo-pythia8_TuneCUETP8M1	3.68064
WWTo2L2Nu_13TeV-powheg	10.481

**Table 6.3:** List of background samples used in this analysis (CMSSW 80X). In the first section of the table are listed the samples of the processes for which we use the simulation to extract the final yields and shapes, in the second section the samples of the processes we will estimate from data. The MC simulation is used to design the data driven methods and derive the associated systematics.

Sample	$\sigma$ [pb]
ttWJets_13TeV_madgraphMLM	0.6105
ttZJets_13TeV_madgraphMLM	0.5297/0.692

**Table 6.4:** Leading-order  $t\bar{t}W$  and  $t\bar{t}Z$  samples used in the signal BDT training.

Same-sign dilepton (==2 muons)
HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_v*
HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_DZ_v*
HLT_IsoMu22_v*
HLT_IsoTkMu22_v*
HLT_IsoMu22_eta2p1_v*
HLT_IsoTkMu22_eta2p1_v*
HLT_IsoMu24_v*
HLT_IsoTkMu24_v*
Same-sign dilepton (==2 electrons)
HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v*
HLT_Ele27_eta2p1_WP Loose_Gsf_v*
HLT_Ele27_WPTight_Gsf_v*
HLT_Ele25_eta2p1_WPTight_Gsf_v*
Same-sign dilepton (==1 muon, ==1 electron)
HLT_Mu23_TrkIsoVVL_Ele8_CaloIdL_TrackIdL_IsoVL_v*
HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_v*
HLT_Mu23_TrkIsoVVL_Ele8_CaloIdL_TrackIdL_IsoVL_DZ_v*
HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ_v*
HLT_IsoMu22_v*
HLT_IsoTkMu22_v*
HLT_IsoMu22_eta2p1_v*
HLT_IsoTkMu22_eta2p1_v*
HLT_IsoMu24_v*
HLT_IsoTkMu24_v*
HLT_Ele27_WPTight_Gsf_v*
HLT_Ele25_eta2p1_WPTight_Gsf_v*
HLT_Ele27_eta2p1_WP Loose_Gsf_v*
Three lepton and Four lepton
HLT_DiMu9_Ele9_CaloIdL_TrackIdL_v*
HLT_Mu8_DiEle12_CaloIdL_TrackIdL_v*
HLT_TripleMu_12_10_5_v*
HLT_Ele16_Ele12_Ele8_CaloIdL_TrackIdL_v*
HLT_Mu23_TrkIsoVVL_Ele8_CaloIdL_TrackIdL_IsoVL_v*
HLT_Mu23_TrkIsoVVL_Ele8_CaloIdL_TrackIdL_IsoVL_DZ_v*
HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_v*
HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ_v*
HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v*
HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_v*
HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_DZ_v*
HLT_IsoMu22_v*
HLT_IsoTkMu22_v*
HLT_IsoMu22_eta2p1_v*
HLT_IsoTkMu22_eta2p1_v*
HLT_IsoMu24_v*
HLT_IsoTkMu24_v*
HLT_Ele27_WPTight_Gsf_v*
HLT_Ele25_eta2p1_WPTight_Gsf_v*
HLT_Ele27_eta2p1_WP Loose_Gsf_v*

**Table 6.5:** Table of high-level triggers that we consider in the analysis.

Category	Scale Factor
ee	$1.01 \pm 0.02$
e $\mu$	$1.01 \pm 0.01$
$\mu\mu$	$1.00 \pm 0.01$
3l	$1.00 \pm 0.03$

**Table 6.6:** Trigger efficiency scale factors and associated uncertainties, shown here rounded to the nearest percent.

## 2195 6.5 Object Identification

2196 In this section, the specific definitions of the physical objects in terms of the numerical  
 2197 values assigned to the reconstruction parameters are presented; thus, the provided  
 2198 details summarize and complement the descriptions presented in previous chapters.  
 2199 The object reconstruction and selection strategy used in this thesis is inherited from  
 2200 the analyses in references [127, 132], thus, the information provided in this section is  
 2201 extracted from those documents unless other references are stated.

### 2202 6.5.1 Jets and $b$ -jet tagging.

2203 In this analysis, jets are reconstructed by clustering PF candidates using the anti- $k_t$   
 2204 algorithm with parameter distance  $\Delta R = 0.4$ ; those charged hadrons that are not  
 2205 consistent with the selected primary vertex are discarded from the clustering. The  
 2206 jet energy is then corrected for the varying response of the detector as a function  
 2207 of transverse momentum  $p_T$  and pseudorapidity  $\eta$ . Jets are selected for use in the  
 2208 analysis only if they have  $p_T > 25$  GeV and are separated from any selected leptons  
 2209 by  $\Delta R > 0.4$ .

2210 Jets coming from the primary vertex and jets coming from pile-up vertices are  
 2211 distinguished using a MVA discriminator based on the differences in the jet shapes,  
 2212 in the relative multiplicity of charged and neutral components, and in the different  
 2213 fraction of transverse momentum which is carried by the hardest components. Jet

2214 tracks are also required to be compatible with the primary vertex.

2215 Jets originated from the hadronization of a  $b$  quark are selected using a MVA  
 2216 likelihood discriminant which uses track-based lifetime information and reconstructed  
 2217 secondary vertices (CSV algorithm). Only jets within the CMS tracker acceptance  
 2218 ( $\eta < 2.4$ ) are identified with this tool. Data samples are used to measure the efficiency  
 2219 of the  $b$ -jet tagging and the probability to misidentify jets from light quarks or gluons;  
 2220 in both cases the measurements are parametrized as a function of the jet  $p_T$  and  $\eta$   
 2221 and later used to correct differences between the data and MC simulation in the  $b$   
 2222 tagging performance, by applying per-jet weights to the simulation, dependent on  
 2223 the jet  $p_T$ ,  $\eta$ ,  $b$  tagging discriminator, and flavor (from simulation truth) [130]. The  
 2224 per-event weight is taken as the product of the per-jet weights, including those of the  
 2225 jets associated to the leptons. The weights are derived on  $t\bar{t}$  and Z+jets events.

2226 Two working points are defined, based on the CSV algorithm output: *loose*' work-  
 2227 ing point (CSV>0.46) with a  $b$  signal tagging efficiency of about 83% and a mistagging  
 2228 rate of about 8%; and *medium* working point (CSV>0.80) with  $b$ -tagging efficiency of  
 2229 about 69% and mistagging rate of order 1% [131]. Tagging of jets from charm quarks  
 2230 have efficiencies of about 40% and 18% for loose and medium working points re-  
 2231 spectively. Separate scale factors are applied to jets originating from bottom/charm  
 2232 quarks and from light quarks in simulated events to match the tagging efficiencies  
 2233 measured in the data.

## 2234 6.5.2 Missing Energy MET.

2235 As stated in section 4.4.1.1, the MET vector is calculated as the negative of the vector  
 2236 sum of transverse momenta of all PF candidates in the event and its magnitude is  
 2237 referred to as  $E_T^{miss}$ . Due to pile-up interactions, the performance in determining

2238 MET is degraded; in order to correct for that, the energy from the selected jets and  
 2239 leptons that compose the event is assigned to the variable  $H_T^{miss}$ . It is calculated in  
 2240 the same way as  $E_T^{miss}$  and although it has worse resolution than  $E_T^{miss}$ , it is more  
 2241 robust in the sense that it does not rely on the soft part of the event. The event  
 2242 selection uses a linear discriminator based on the two variables given by

$$E_T^{miss} LD = 0.00397 * E_T^{miss} + 0.00265 * H_T^{miss} \quad (6.1)$$

2243 taking advantage of the fact that the correlation between  $E_T^{miss}$  and  $H_T^{miss}$  is less  
 2244 for events with instrumental missing energy than for events with real missing energy.  
 2245 The working point  $E_T^{miss} LD > 0.2$  was chosen to ensure a good signal efficiency while  
 2246 keeping a good background rejection.

### 2247 6.5.3 Lepton reconstruction and identification

2248 Two types of leptons are defined in this analysis: *signal leptons* are those coming from  
 2249  $W, Z$  and  $\tau$  decays which usually are isolated from other particles; *background leptons*  
 2250 are defined as leptons produced in  $b$ -jet hadron decays, light-jets misidentification,  
 2251 and photon conversions.

2252 The process of reconstruction and identification of electron and muon candidates  
 2253 was described in chapter4, hence, the identification variables used in order to retain  
 2254 the highest possible efficiency for signal leptons while maximizing the rejection of  
 2255 background leptons are listed and described in the following sections <sup>2</sup>.

2256 The identification variables include not only observables related directly to the re-  
 2257 constructed leptons themselves, but also to the clustered energy deposits and charged  
 2258 particles in a cone around the lepton direction (jet-related variables); an initial loose

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<sup>2</sup> the studies performed to optimize the identification are far from the scope of this thesis, therefore, only general descriptions are provided

2259 preselection of leptons candidates is performed and then an MVA discriminator, re-  
 2260 ferred to as *lepton MVA* discriminator, is used to distinguish signal leptons from  
 2261 background leptons.

2262 **Muons.**

2263 The Physics Objects Groups (POG) at CMS, are in charge of studying and defining  
 2264 the set of selection criteria applied on the course of reconstruction and identification  
 2265 of particles. These selection criteria are implemented in the CMS framework in the  
 2266 form of several object identification working points according to the strength of the  
 2267 requirements.

2268 The muon candidates are reconstructed by combining information from the tracker  
 2269 system and the muon detection system of CMS detector and the POG defined three  
 2270 working points for muon identification *MuonID* [133];

- 2271     • *POG Loose Muon ID* is a particle identified as a muon by the PF event re-  
 2272         construction and also reconstructed either as a global-muon or as an arbitrated  
 2273         tracker-muon. This identification criteria is designed to be highly efficient for  
 2274         prompt muons and for muons from heavy and light quark decays; it can be com-  
 2275         plemented by applying impact parameter cuts in analyses with prompt muon  
 2276         signals.
- 2277     • *POG Medium Muon ID* is a Loose muon with additional track-quality and  
 2278         muon-quality (spatial matching between the individual measurements in the  
 2279         tracker and the muon system) requirements. This identification criteria is de-  
 2280         signed to be highly efficient in the separation of the muons coming from decay  
 2281         in flight of heavy quarks and muons coming from B meson decays as well as  
 2282         prompt muons. An additional category *MVA Prompt ID* is defined in this iden-

2283 tification criteria directed to discriminated muons from B mesons and prompt  
 2284 muons (from W,Z and  $\tau$  decays). The Medium ID provides the same fake rate as  
 2285 the Tight Muon ID but a higher efficiency on prompt and B-decays muons. [134]

- 2286 • *POG Tight Muon ID* is a global muon with additional muon-quality require-  
 2287 ments Tight Muon ID selects a subset of the PF muons.

2288 Only muons within the muon system acceptance  $|\eta| < 2.4$  and minimum  $p_T$  of 5  
 2289 GeV are considered.

2290 **Electrons.**

2291 Electrons are reconstructed using information from the tracker and from the electro-  
 2292 magnetic calorimeter and identified by an MVA algorithm (*MVA eID* discriminant)  
 2293 using the shape of the calorimetric shower variables like the shape in  $\eta$  and  $\phi$ , the clus-  
 2294 ter circularity, widths along  $\eta$  and  $\phi$ ; track-cluster matching variables like  $E_{tot}/p_{in}$ ,  
 2295  $E_{Ele}/p_{out}$ ,  $\Delta\eta_{in}$ ,  $\Delta\eta_{out}$ ,  $\Delta\phi_{in}$ ,  $1/E - 1/p$ ; and track quality variables like  $\xi^2$  of the  
 2296 GSF tracks, the number of hits used by the GSF filter [135].

2297 A loose selection based on  $\eta$ -dependent cuts on this discriminant is used to prese-  
 2298 lect electron candidates, the full shape of the discriminant is used in the lepton MVA  
 2299 selection to separate signal leptons from background leptons (described in section  
 2300 6.5.3).

2301 In order to reject electrons from photon conversions, electron candidates with  
 2302 missing hits in the pixel tracker layers or matched to a conversion secondary vertex  
 2303 are discarded. Electrons are selected for the analysis if they have  $p_T > 7$  GeV and  
 2304 are located within the tracker system acceptance region ( $|\eta| < 2.5$ ).

2305 **Lepton vertexing and pile-up rejection.**

2306 The impact parameter in the transverse plane  $d_0$ , impact parameter along the z  
 2307 axis  $d_z$ , and the impact parameter significance in the detector space  $SIP_{3D}$ , are  
 2308 considered to perform the identification and rejection of pile-up, misreconstructed  
 2309 tracks, and background leptons from b-hadron decays; pile-up and misreconstructed  
 2310 track mitigation is achieved by imposing loose cuts on the impact parameter variables.  
 2311 The full shape of the those variables is used in a lepton MVA classifier to achieve the  
 2312 best separation between the signal and the background leptons.

2313 **Lepton isolation.**

2314 PF is able to recognize leptons from two different sources: on one side, leptons from  
 2315 the decays of heavy particles, such as W and Z bosons, which are normally isolated  
 2316 in space from the hadronic activity in the event; on the other side, leptons from the  
 2317 decays of hadrons and jets misidentified as leptons, which are not isolated as the  
 2318 former. For highly boosted systems, like the lepton and the  $b$ -jet generated in the  
 2319 semileptonic decay of a boosted top, the decay products tend to be more closer and  
 2320 sometimes they even overlap; thus, the PF standard definition of isolation in terms of  
 2321 the separation between the lepton candidates and other PF objects in the  $\eta$ - $\phi$  plane,

$$\Delta R = \sqrt{(\eta^l - \eta^i)^2 + (\phi^l - \phi^i)^2} < 0.3 \quad (6.2)$$

2322 which considers all the neutral, charged hadrons and photons in a cone around the  
 2323 leptons, is refocused to the local isolation of the leptons through the mini-isolation  
 2324  $I_{mini}$  [136] defined as the sum of particle flow candidates  $p_T$  within a cone around

2325 the lepton, corrected for the effects of pileup and divided by the lepton  $p_T$

$$I_{mini} = \frac{\sum_R p_T(h^\pm) - \max\left(0, \sum_R p_T(h^0) + p_T(\gamma) - \rho \mathcal{A} \left(\frac{R}{0.3}\right)^2\right)}{p_T(l)} \quad (6.3)$$

2326 where  $\rho$  is the pileup energy density,  $h^\pm, h^0, \gamma, l$ , represent the charged hadron, neutral  
 2327 hadrons, photons, and the lepton, respectively. The radius  $R$  of the cone depends on  
 2328 the  $p_T$  of the lepton according to

$$R = \frac{10\text{GeV}}{\min(\max(p_T(l), 50\text{GeV}), 200\text{GeV})}, \quad (6.4)$$

2329 The  $p_T$  dependence of the cone size allows for greater signal efficiency. Setting a  
 2330 cut on  $I_{mini}$  below a given threshold ensures that the lepton is locally isolated, even  
 2331 in boosted systems. The effect of pileup is mitigated using the so-called effective area  
 2332 correction  $\mathcal{A}$  listed in Table 6.7.

$ \eta $ range	$\mathcal{A}(e)$ neutral/charged	$\mathcal{A}(\mu)$ neutral/charged
0.0 - 0.8	0.1607 / 0.0188	0.1322 / 0.0191
0.8 - 1.3	0.1579 / 0.0188	0.1137 / 0.0170
1.3 - 2.0	0.1120 / 0.0135	0.0883 / 0.0146
2.0 - 2.2	0.1228 / 0.0135	0.0865 / 0.0111
2.2 - 2.5	0.2156 / 0.0105	0.1214 / 0.0091

**Table 6.7:** Effective areas, for electrons and muons used to mitigate the effect of pileup by using the so-called effective area correction.

2333 A loose cut on  $I_{mini}$  is applied to pre-select the muon and electron candidates;  
 2334 however, the full shape is used in the lepton MVA discriminator when performing the  
 2335 signal lepton selection.

2336 **Jet-related variables.**

2337 In order to reject misidentified leptons from  $b$ -jets, mostly coming from  $t\bar{t}$ +jets,  
 2338 Drell-Yan+jets, and W+jets events, the vertexing and isolation described in previous  
 2339 sections are complemented with additional variables related to the closest recon-  
 2340 structed jet to the lepton, i.e., the PF jets reconstructed<sup>3</sup> around the leptons with  
 2341  $\Delta R = \sqrt{(\eta^l - \eta^{jet})^2 + (\phi^l - \phi^{jet})^2} < 0.5$ . The identification variables used in the lep-  
 2342 ton MVA discriminator are the ratio  $p_T^l/p_T^{jet}$ , the CSV b-tagging discriminator value  
 2343 of the jet, the number of charged tracks of the jet, and the relative  $p_T$  given by

$$p_T^{rel} = \frac{(\vec{p}_{jet} - \vec{p}_l) \cdot \vec{p}_l}{\|\vec{p}_{jet} - \vec{p}_l\|}. \quad (6.5)$$

2344 **LeptonMVA discriminator.**

2345 Electrons and muons passing the basic selection process described above are referred  
 2346 to as *loose leptons*. Additional discrimination between signal leptons and background  
 2347 leptons is crucial considering that the rate of  $t\bar{t}$  production is much larger than the  
 2348 signal, hence, an overwhelming background from  $t\bar{t}$  production. To maximally ex-  
 2349 ploit the available information in each event to that end, the dedicated lepton MVA  
 2350 discriminator, based on a boosted decision tree (BDT) algorithm, has been built so  
 2351 that all the identification variables can be used together.

2352 The lepton MVA discriminator training is performed using simulated signal Loose  
 2353 leptons from the  $t\bar{t}H$  MC sample and fake leptons from the  $t\bar{t}$  +jets MC sample,  
 2354 separately for muons and electrons. The input variables used include vertexing, iso-  
 2355 lation and jet-related variables, the  $p_T$  and  $\eta$  of the lepton, the electron MVA eID  
 2356 discriminator and the muon segment-compatibility variables. An additional require-  
 2357 ment known as *tight-charge* requirement, is imposed by comparing two independent

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<sup>3</sup> charged hadrons from PU vertices are not removed prior to the jet clustering.

2358 measurement of the charge, one from the ECAL supercluster and the other from the  
 2359 tracker; thus, the consistency in the measurements of the electron charge is ensured  
 2360 so that events with a wrong electron charge assignment are rejected; this variable is  
 2361 particularly used in the 2lss channel to suppress opposite-sign events for which the  
 2362 charge of one of the leptons has been mismeasured. The tight-charge requirement for  
 2363 muons is represented by the requirement of a consistently well measured track trans-  
 2364 verse momentum given by  $\Delta p_T/p_T < 0.2$ . Leptons are selected for the final analysis  
 2365 if they pass a given threshold of the BDT output, and are referred to as *tight leptons*  
 2366 in the following.

2367 The validation of the lepton MVA algorithm and the lepton identification variables  
 2368 is performed using data in various control regions; the details about that validation  
 2369 are not discussed here but can be found in Reference [132].

## 2370 Selection definitions

2371 Electron and muon object identification is defined in three different sets of selections  
 2372 criteria; the *Loose*, *Fakeable Object*, and *Tight* selection. These three levels of selection  
 2373 are designed to serve for event level vetoes, the fake rate estimation application region,  
 2374 and the final signal selection, respectively. The  $p_T$  of fakeable objects is defined as  
 2375  $0.85 \times p_T(\text{jet})$ , where the jet is the one associated to the lepton object. This mitigates  
 2376 the dependence of the fake rate on the momentum of the fakeable object and thereby  
 2377 improves the precision of the method.

2378 Tables 6.8 and 6.9 list the full criteria for the different selections of muons and  
 2379 electrons.

2380 In addition to the previously defined requirements for jets, they are required to  
 2381 be separated from any lepton candidates passing the fakeable object selections by  
 2382  $\Delta R > 0.4$ .

Cut	Loose	Fakeable object	Tight
$ \eta  < 2.4$	✓	✓	✓
$p_T$	$> 5\text{GeV}$	$> 15\text{GeV}$	$> 15\text{GeV}$
$ d_{xy}  < 0.05$ (cm)	✓	✓	✓
$ d_z  < 0.1$ (cm)	✓	✓	✓
$\text{SIP}_{3D} < 8$	✓	✓	✓
$I_{\text{mini}} < 0.4$	✓	✓	✓
is Loose Muon	✓	✓	✓
jet CSV	—	$< 0.8484$	$< 0.8484$
is Medium Muon	—	—	✓
tight-charge	—	—	✓
lepMVA $> 0.90$	—	—	✓

**Table 6.8:** Requirements on each of the three muon selections. In the cases where the cut values change between the selections, those values are listed in the table. Otherwise, whether the cut is applied is indicated.

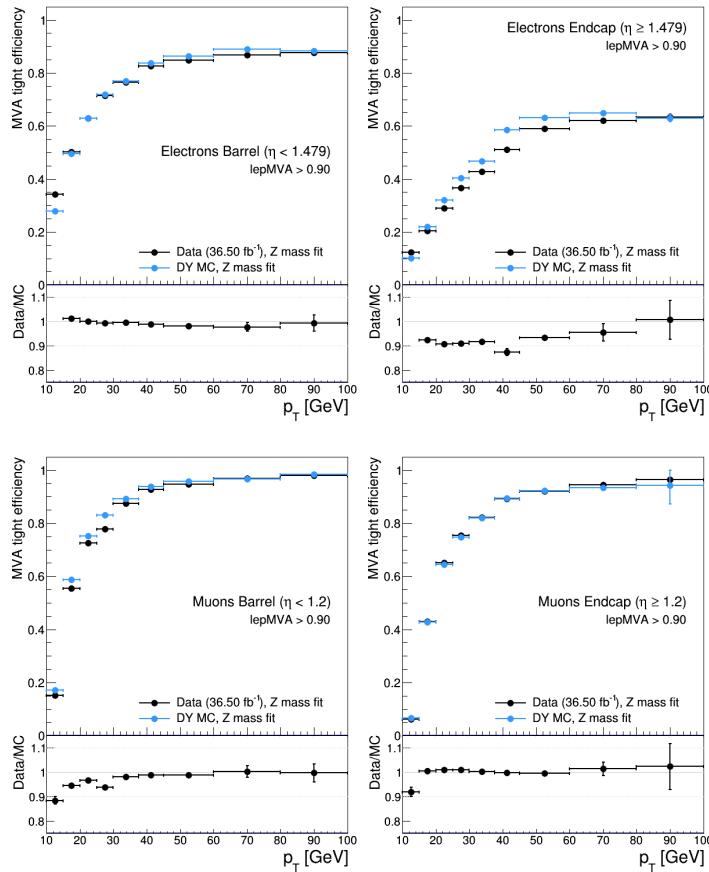
Cut	Loose	Fakeable Object	Tight
$ \eta  < 2.5$	✓	✓	✓
$p_T$	$> 7\text{GeV}$	$> 15\text{GeV}$	$> 15\text{GeV}$
$ d_{xy}  < 0.05$ (cm)	✓	✓	✓
$ d_z  < 0.1$ (cm)	✓	✓	✓
$\text{SIP}_{3D} < 8$	✓	✓	✓
$I_{\text{mini}} < 0.4$	✓	✓	✓
MVA eID $> (0.0, 0.0, 0.7)$	✓	✓	✓
$\sigma_{in\eta} < (0.011, 0.011, 0.030)$	—	✓	✓
H/E $< (0.10, 0.10, 0.07)$	—	✓	✓
$\Delta\eta_{in} < (0.01, 0.01, 0.008)$	—	✓	✓
$\Delta\phi_{in} < (0.04, 0.04, 0.07)$	—	✓	✓
$-0.05 < 1/E - 1/p < (0.010, 0.010, 0.005)$	—	✓	✓
$p_T^{\text{ratio}}$	—	$> 0.5^\dagger / -$	—
jet CSV	—	$< 0.3^\dagger / < 0.8484$	$< 0.8484$
tight-charge	—	—	✓
conversion rejection	—	—	✓
Number of missing hits	$< 2$	$= 0$	$= 0$
lepton MVA $> 0.90$	—	—	✓

**Table 6.9:** Criteria for each of the three electron selections. In cases where the cut values change between selections, those values are listed in the table. Otherwise, whether the cut is applied is indicated. In some cases, the cut values change for different  $\eta$  ranges. These ranges are  $0 < |\eta| < 0.8$ ,  $0.8 < |\eta| < 1.479$ , and  $1.479 < |\eta| < 2.5$  and the respective cut values are given in the form (value<sub>1</sub>, value<sub>2</sub>, value<sub>3</sub>). For the two  $p_T^{\text{ratio}}$  and CSV rows, the cuts marked with a  $\dagger$  are applied to leptons that fail the lepton MVA cut, while the loose cut value is applied to those that pass the lepton MVA cut.

### 2383 6.5.4 Lepton selection efficiency

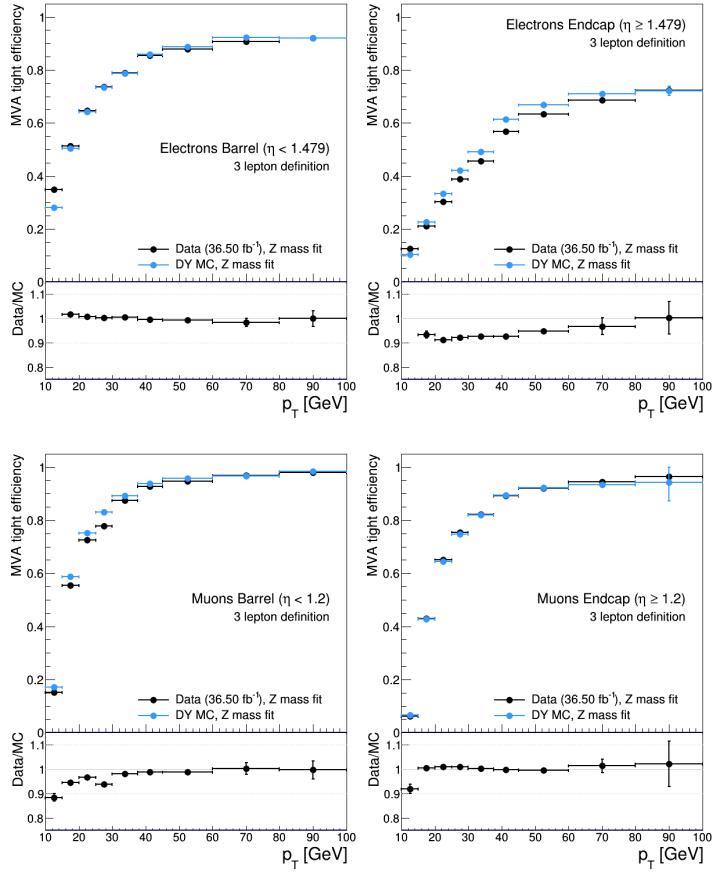
2384 Efficiencies of reconstruction and selecting loose leptons are measured both for muons  
 2385 and electrons using a tag and probe method on both data and MC, using  $Z \rightarrow \ell^+ \ell^-$   
 2386 [137]. The scale factors are derived from the ratio of efficiencies  $\varepsilon_i(p_T, \eta)$  measured  
 2387 for a given lepton in data/MC, according to

$$\rho(p_T, \eta) = \frac{\varepsilon_{\text{data}}(p_T, \eta)}{\varepsilon_{\text{MC}}(p_T, \eta)}. \quad (6.6)$$



**Figure 6.3:** Tight vs loose selection efficiencies for electrons (top), and muons (bottom), for the 2lss definition, i.e., including the tight-charge requirement.

2388 The scale factor for each event is used to correct the weight of the event in the



**Figure 6.4:** Tight vs loose selection efficiencies for electrons (top), and muons (bottom), for the 3l channel not including the tight-charge requirement.

2389 full sample; therefore, the full simulation correction is given by the product of all  
 2390 the individual scale factors. The scale factors used in this thesis are inherited from  
 2391 the reference [132] which in turns inherited them from leptonic SUSY analyses using  
 2392 equivalent lepton selections.

2393 The efficiency of applying the tight selection as defined in Tables 6.8 and 6.9, on the  
 2394 loose leptons are determined by using a tag and probe method on a sample of Drell-  
 2395 Yan enriched events. Figures 6.3 and 6.4 show the efficiencies for the 2lss channel and  
 2396 3l channel respectively. Efficiencies in the 2lss channel have been produced including  
 2397 the tight-charge requirement, while for the 3l channel it is not included. Number

2398 of passed and failed probes are determined from a fit to the invariant mass of the  
 2399 dilepton system.

2400 Simulation is corrected using these scale factors; note that they depends on  $\eta$  and  
 2401  $p_T$ .

2402 **6.6 Event selection**

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2413 The analysis is designed to efficiently identify and select prompt leptons from  
 2414 on-shell W and

2415 Z boson decays and to reject non-prompt leptons from b quark decays and spurious  
 2416 lepton

2417 signatures from hadronic jets. Events are then selected in the various lepton  
 2418 channels, and are

2419 required to contain hadronic jets, some of which must be consistent with b quark  
 2420 hadronization. Finally, the signal yield is extracted by simultaneously fitting the  
 2421 output of two dedicated

2422 multivariate discriminants (trained to separate the  $tHq$  signal from the two dom-  
 2423 inant backgrounds) in all categories

2424 . Multivariate techniques are used to discriminate the signal from the dominant  
 2425 backgrounds. The analysis yields a 95% confidence level (C.L.) upper limit on the  
 2426 combined  $tH + ttH$  production cross section times branching ratio of 0.64 pb, with  
 2427 an expected limit of 0.32 pb, for a scenario with  $kt = \sqrt{1.0}$  and  $kV = 1.0$ . Values  
 2428 of  $kt$  outside the range of  $\sqrt{1.25}$  to  $\sqrt{1.60}$  are excluded at 95% C.L., assuming  $kV$   
 2429  $= 1.0$ .

2430 Dont forget to mention previous constrains to ct check reference ?? and references  
 2431 <https://link.springer.com/content/pdf/10.1007%2FJHEP01%282013%29088.pdf> (para-  
 2432 graph after eq 2)

2433 We selects events with three leptons and a  $b$ -jet tagged jet in the final state. The  $tHq$   
 2434 signal contribution is then determined in a fit of the observed data to two multivariate  
 2435 classifier outputs, each trained to discriminate against one of the two dominant back-  
 2436 grounds of events with non-prompt leptons from  $t\bar{t}$  and of associated production of  $t\bar{t}$   
 2437 and vector bosons ( $t\bar{t}W$ ,  $t\bar{t}Z$ ). The fit result is then used to set an upper limit on the  
 2438 combined  $t\bar{t}H$ ,  $tHq$  and  $tHW$  production cross section, as a function of the relative  
 2439 coupling strengths of Higgs and top quark and Higgs and W boson, respectively.

## 2440 6.7 Background predictions

2441 The modeling of reducible and irreducible backgrounds in this analysis uses the exact  
 2442 methods, analysis code, and ROOT trees used for the  $t\bar{t}H$  multilepton analysis. We  
 2443 give a brief description of the methods and refer to the documentation of that analysis  
 2444 in Refs. [127, 132] for any details.

2445 The backgrounds in three-lepton final states can be split in two broad categories:

irreducible backgrounds with genuine prompt leptons (i.e. from on-shell W and Z boson decays); and reducible backgrounds where at least one of the leptons is “non-prompt”, i.e. produced within a hadronic jet, either a genuine lepton from heavy flavor decays, or simply mis-reconstructed jets.

Irreducible backgrounds can be reliably estimated directly from Monte-Carlo simulated events, using higher-order cross sections or data control regions for the overall normalization. This is done in this analysis for all backgrounds involving prompt leptons:  $t\bar{t}W$ ,  $t\bar{t}Z$ ,  $t\bar{t}H$ ,  $WZ$ ,  $ZZ$ ,  $W^\pm W^\pm qq$ ,  $t\bar{t}t\bar{t}$ ,  $tZq$ ,  $tZW$ ,  $WWW$ ,  $WWZ$ ,  $WZZ$ ,  $ZZZ$ .

Reducible backgrounds, on the other hand, are not well predicted by simulation, and are estimated using data-driven methods. In the case of non-prompt leptons, a fake rate method is used,

Additional identification criteria are applied for electrons with  $p_T$  greater than 30 GeV to mimic the identification applied at trigger level in order to ensure consistency between the measurement region and application region of the fake-rate.

where the contribution to the final selection is estimated by extrapolating from a sideband (or “application region”) with a looser lepton definition (the fakeable object definitions in Tabs. 6.8 and 6.9) to the signal selection. The tight-to-loose ratios (or “fake rates”) are measured in several background dominated data events with dedicated triggers, subtracting the residual prompt lepton contribution using MC. Non-prompt leptons in our signal regions are predominantly produced in  $t\bar{t}$  events, with a much smaller contribution, from Drell–Yan production. The systematic uncertainty on the normalization of the non-prompt background estimation is on the order of 50%, and thereby one of the dominant limitations on the performance of multilepton analyses in general and this analysis in particular. It consists of several individual sources, such as the result of closure tests of the method using simulated

2472 events, limited statistics in the data control regions due to necessary prescaling of  
 2473 lepton triggers, and the uncertainty in the subtraction of residual prompt leptons  
 2474 from the control region.

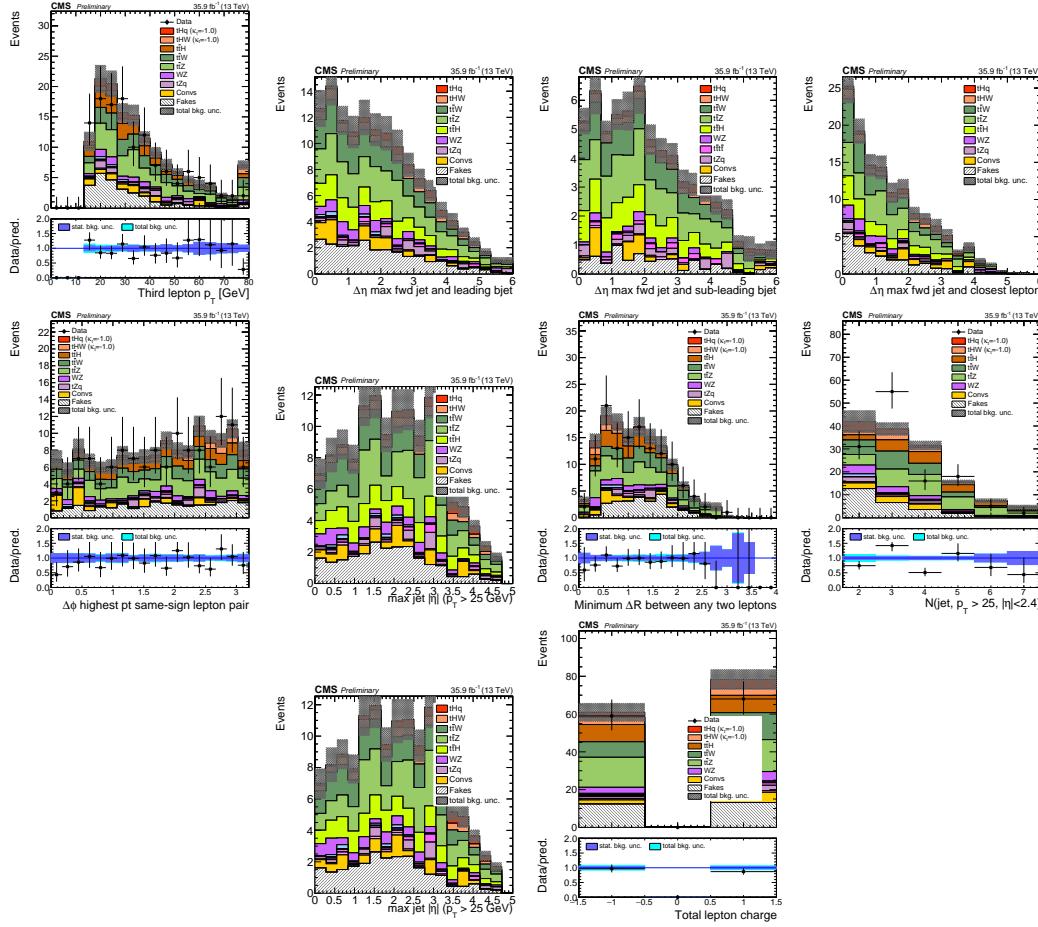
2475 The fake background where the leptons pass the looser selection are weighted  
 2476 according to how many of them fail the tight criteria. Events with a single failing  
 2477 lepton are weighted with the factor  $f/(1-f)$  for the estimate to the tight selection  
 2478 region, where  $f$  is the fake rate. Events with two failing leptons are given the negative  
 2479 weight  $-f_i f_j / (1-f_i)(1-f_j)$ , and for three leptons the weight is positive and equal  
 2480 to the product of  $f/(1-f)$  factor evaluated for each failing lepton.

2481 Figures 6.5 show the distributions of some relevant kinematic variables, normalized  
 2482 to the cross section of the respective processes and to the integrated luminosity.

## 2483 6.8 Signal discrimination

2484 The  $tHq$  signal is separated from the main backgrounds using a boosted decision  
 2485 tree (BDT) classifier, trained on simulated signal and background events. A set  
 2486 of discriminating variables are given as input to the BDT which produces a output  
 2487 distribution maximizing the discrimination power. Table 6.10 lists the input variables  
 2488 used while Figures 6.6 show their distributions for the relevant signal and background  
 2489 samples, for the three lepton channel. Two BDT classifiers are trained for the two  
 2490 main backgrounds expected in the analysis: events with prompt leptons from  $t\bar{t}W$  and  
 2491  $t\bar{t}Z$  (also referred to as  $t\bar{t}V$ ), and events with non-prompt leptons from  $t\bar{t}$ . The datasets  
 2492 used in the training are the  $tHq$  signal (see Tab. 6.1), and LO MADGRAPH samples  
 2493 of  $t\bar{t}W$  and  $t\bar{t}Z$ , in an admixture proportional to their respective cross sections (see  
 2494 Tab. 6.4).

2495 The MVA analysis consist of two stages: first a “training” where the MVA method



**Figure 6.5:** Distributions of input variables to the BDT for signal discrimination, three lepton channel, normalized to their cross section and to  $35.9\text{fb}^{-1}$ .

is trained to discriminate between simulated signal and background events, then a “test” stage where the trained algorithm is used to classify different events from the samples. The sample is obtained from a pre-selection (see Tab. ?? with pre-selection cuts). Figures 6.7 show the input variables distributions as seen by the MVA algorithm. Note that in contrast to the distributions in Fig. 6.6 only the main backgrounds ( $t\bar{t}$  from simulation,  $t\bar{t}V$ ) are included.

Note that splitting the training in two groups reveals that some variables show opposite behavior for the two background sources; potentially screening the discrimination power if they were to be used in a single discriminant. For some other variables

Variable name	Description
nJet25	Number of jets with $p_T > 25$ GeV, $ \eta  < 2.4$
MaxEtaJet25	Maximum $ \eta $ of any (non-CSV-loose) jet with $p_T > 25$ GeV
totCharge	Sum of lepton charges
nJetEta1	Number of jets with $ \eta  > 1.0$ , non-CSV-loose
detaFwdJetBJet	$\Delta\eta$ between forward light jet and hardest CSV loose jet
detaFwdJet2BJet	$\Delta\eta$ between forward light jet and second hardest CSV loose jet (defaults to -1 in events with only one CSV loose jet)
detaFwdJetClosestLep	$\Delta\eta$ between forward light jet and closest lepton
dphiHighestPtSSPair	$\Delta\phi$ of highest $p_T$ same-sign lepton pair
minDRll	minimum $\Delta R$ between any two leptons
Lep3Pt/Lep2Pt	$p_T$ of the 3 <sup>rd</sup> lepton (2 <sup>nd</sup> for ss2l)

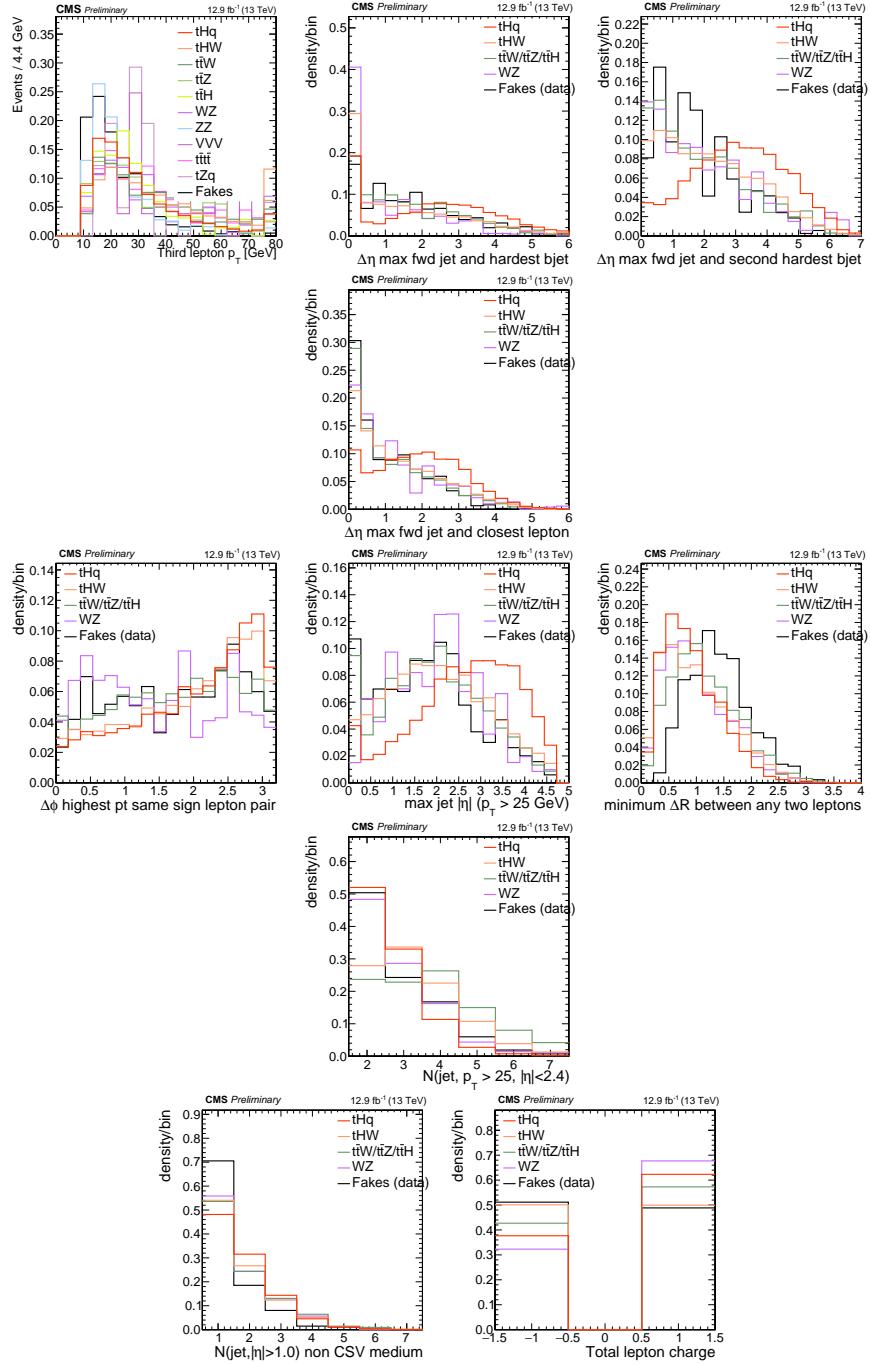
**Table 6.10:** MVA input discriminating variables

2505 the distributions are similar in both background cases.

2506 From table 6.10, it is clear that the input variables are correlated to some extend.  
 2507 These correlations play an important role for some MVA methods like the Fisher  
 2508 discriminant method in which the first step consist of performing a linear transfor-  
 2509 mation to an phase space where the correlations between variables are removed. In  
 2510 case a boosted decision tree (BDT) method however, correlations do not affect the  
 2511 performance. Figure 6.9 show the linear correlation coefficients for signal and back-  
 2512 ground for the two training cases (the signal values are identical by construction). As  
 2513 expected, strong correlations appears for variables related to the forward jet activity.  
 2514 Same trend is seen in case of the same sign dilepton channel in Figure ??.

### 2515 6.8.1 Classifiers response

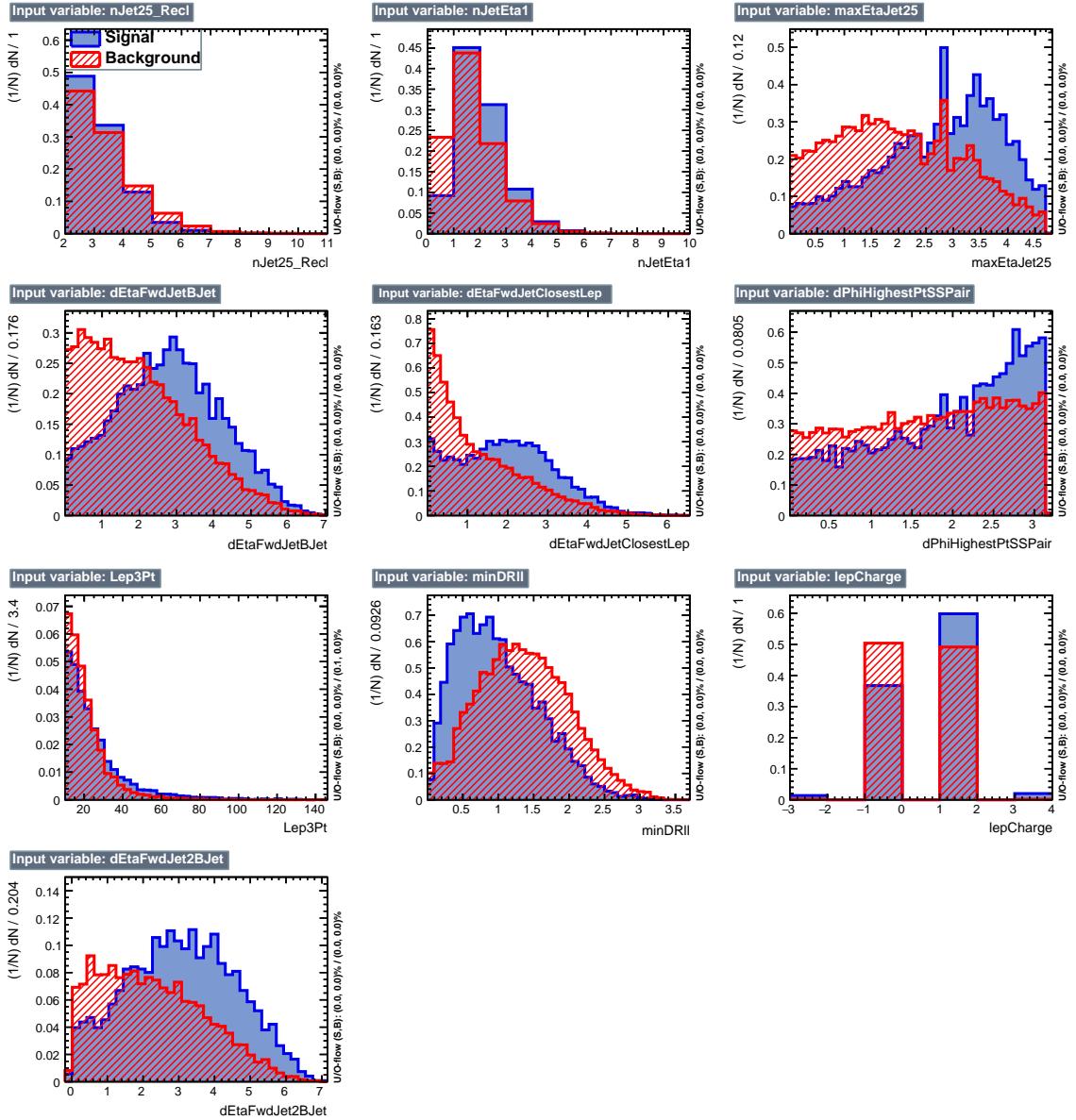
2516 Several MVA algorithms were evaluated to determine the most appropriate method  
 2517 for this analysis. The plots in Fig. 6.10 (top) show the background rejection as a  
 2518 function of the signal efficiency for  $t\bar{t}$  and  $t\bar{t}V$  trainings (ROC curves) for the different



**Figure 6.6:** Distributions of input variables to the BDT for signal discrimination, three lepton channel.

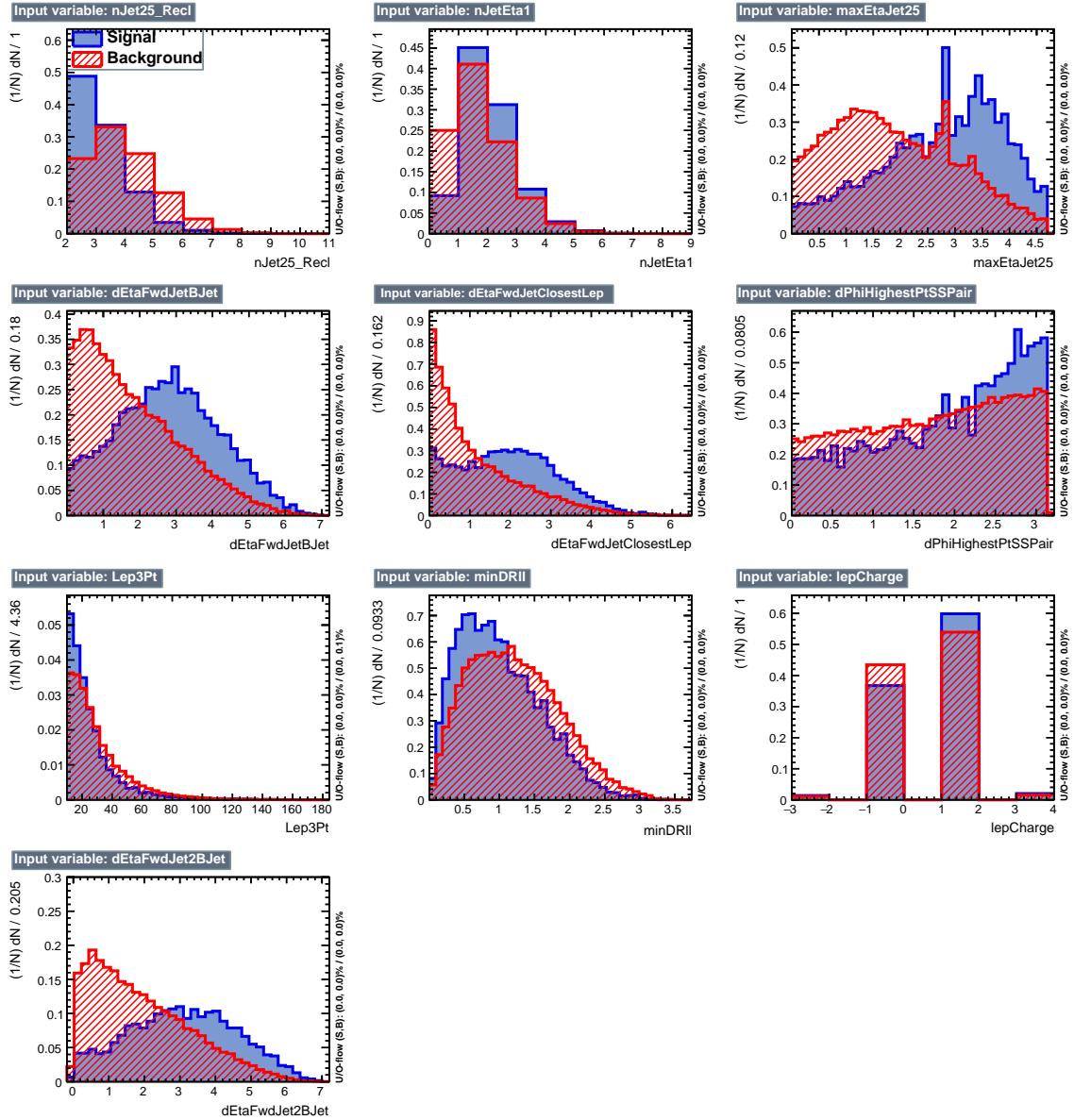
2519 algorithms that were evaluated.

2520 In both cases the gradient boosted decision tree (“BDTA\_GRAD”) classifier offers

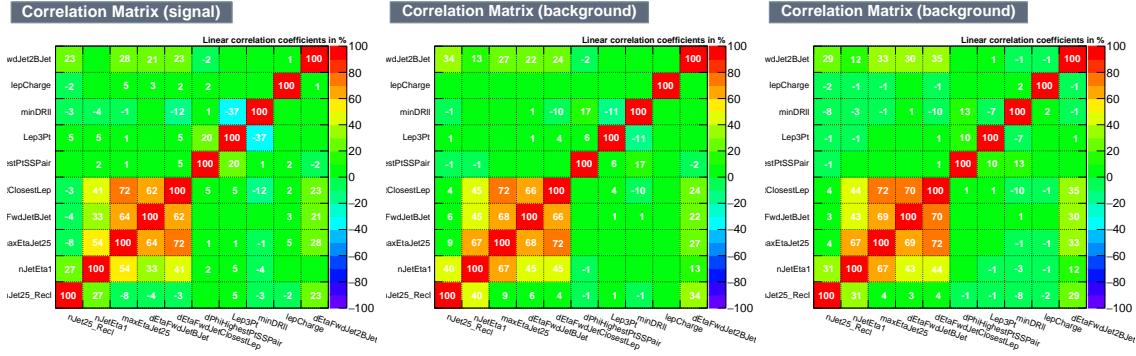


**Figure 6.7:** BDT inputs as seen by TMVA (signal, in blue, is  $tHq$ , background, in red, is  $t\bar{t}$ ) for the three lepton channel, discriminated against  $t\bar{t}$  (fakes) background.

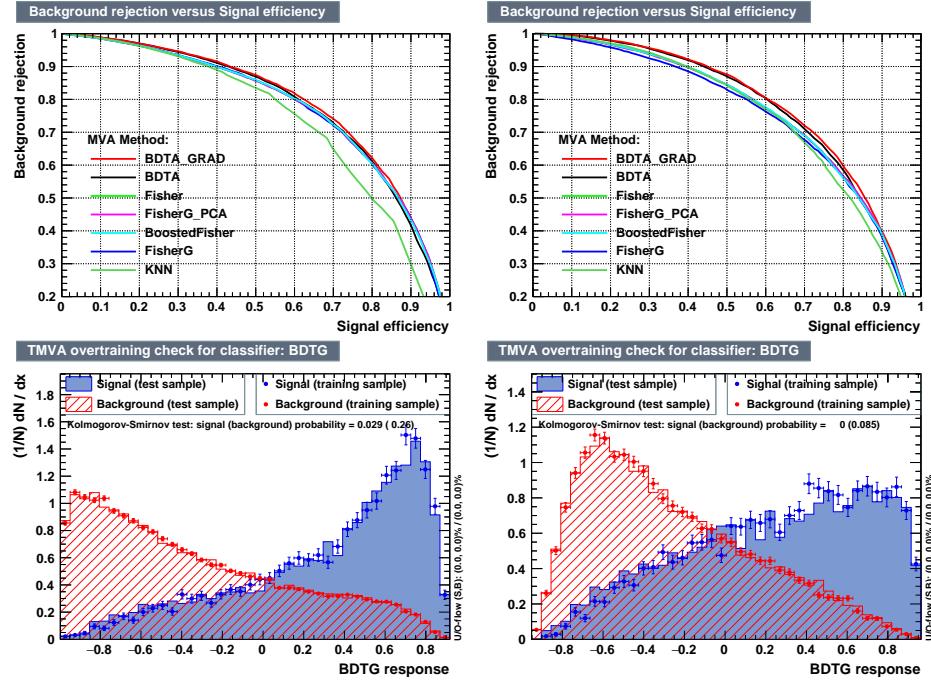
the best results, followed by an adaptive BDT classifier (“BDTA”). The BDTA\_GRAD classifier output distributions for signal and backgrounds are shown on the bottom of Fig. 6.10. As expected, a good discrimination power is obtained using default discriminator parameter values, with minimal overtraining. TMVA provides a ranking of the input variables by their importance in the classification process, shown in Tab. 6.11.



**Figure 6.8:** BDT inputs as seen by TMVA (signal, in blue, is  $tHq$ , background, in red, is  $t\bar{t}W+t\bar{t}Z$ ) for the three lepton channel, discriminated against  $t\bar{t}V$  background.



**Figure 6.9:** Signal (left),  $t\bar{t}$  background (middle), and  $t\bar{t}V$  background (right.) correlation matrices for the input variables in the TMVA analysis for the three lepton channel.



**Figure 6.10:** Top: background rejection vs signal efficiency (ROC curves) for various MVA classifiers (top) in the three lepton channel against  $t\bar{t}V$  (left) and  $t\bar{t}$  (right). Bottom: classifier output distributions for the gradient boosted decision trees, for training against  $t\bar{t}V$  (left) and against  $t\bar{t}$  (right).

## 2527 6.9 Additional discriminating variables

2528 Two additional discriminating variables were tested considering the fact that the  
 2529 forward jet in the background could come from the pileup; since we have a real forward

ttbar training			ttV training		
Rank	Variable	Importance	Variable	Importance	
1	minDRll	1.329e-01	dEtaFwdJetBJet	1.264e-01	
2	dEtaFwdJetClosestLep	1.294e-01	Lep3Pt	1.224e-01	
3	dEtaFwdJetBJet	1.209e-01	maxEtaJet25	1.221e-01	
4	dPhiHighestPtSSPair	1.192e-01	dEtaFwdJet2BJet	1.204e-01	
5	Lep3Pt	1.158e-01	dEtaFwdJetClosestLep	1.177e-01	
6	maxEtaJet25	1.121e-01	minDRll	1.143e-01	
7	dEtaFwdJet2BJet	9.363e-02	dPhiHighestPtSSPair	9.777e-02	
8	nJetEta1	6.730e-02	nJet25_Recl	9.034e-02	
9	nJet25_Recl	6.178e-02	nJetEta1	4.749e-02	
10	lepCharge	4.701e-02	lepCharge	4.116e-02	

**Table 6.11:** TMVA input variables ranking for BDTA\_GRAD method for the trainings in the three lepton channel. For both trainings the rankings show almost the same 5 variables in the first places.

---

```

TMVA.Types.kBDT
NTrees=800
BoostType=Grad
Shrinkage=0.10
!UseBaggedGrad
nCuts=50
MaxDepth=3
NegWeightTreatment=PairNegWeightsGlobal
CreateMVAPdfs

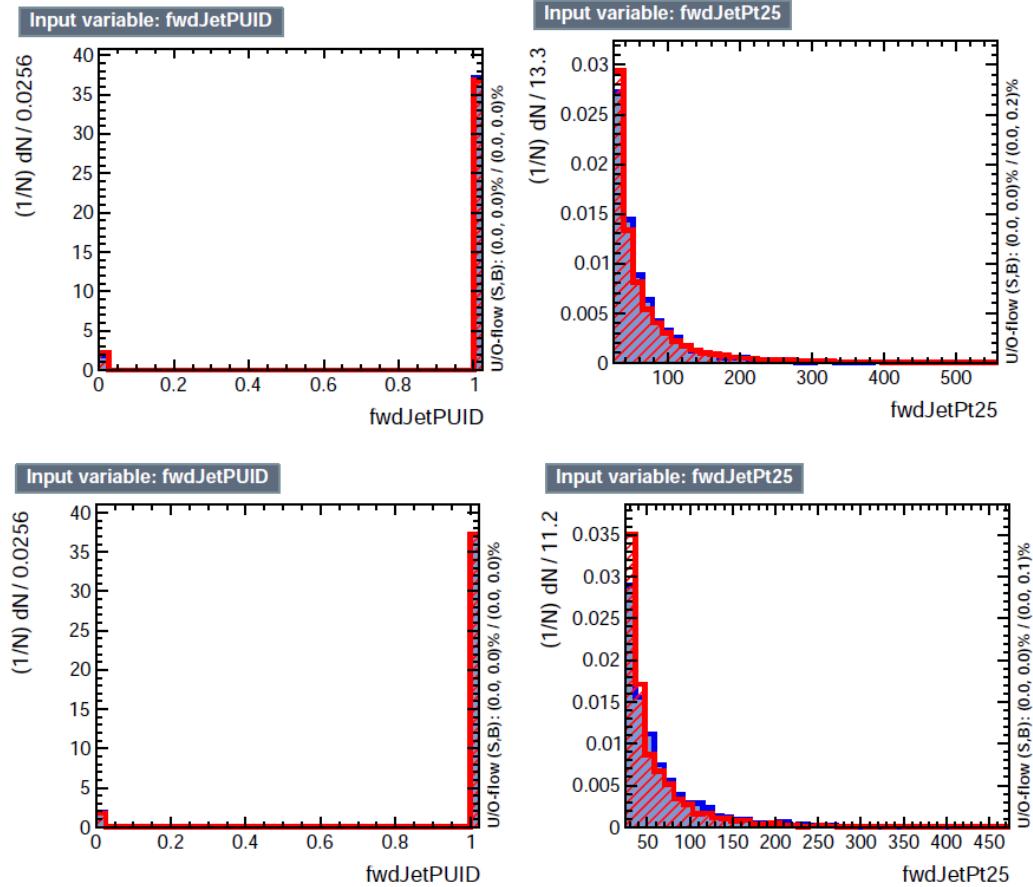
```

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**Table 6.12:** TMVA configuration used in the BDT training.

jet in the signal, it could give some improvement in the discriminating power. The additional variables describe the forward jet momentum (fwdJetPt25) and the forward jet identification(fwdJetPUID). Distributions for these variables in the three lepton channel are shown in the figure 6.11. The forward jet identification distribution show that for both, signal and background, jets are mostly real jets.

The testing was made including in the MVA input one variable at a time, so we can evaluate the dicrimination power of each variable, and then both simultaneously. fwdJetPUID was ranked in the last place in importance (11) in both training (ttV and tt) while fwdJetPt25 was ranked 3 in the ttV training and 7 in the tt training. When training using 12 variables, fwdJetPt25 was ranked 5 and 7 in the ttV and tt



**Figure 6.11:** Additional discriminating variables distributions for ttv training (Top row) and tt training (bottom row) in the three lepton channel. The origin of the jets in the forward jet identification distribution is tagged as 0 for “pileup jets” while “real jets” are tagged as 1.

2540 trainings respectively, while `fwdJetPUID` was ranked 12 in both cases.

2541 The improvement in the discrimination performance provided by the additional  
 2542 variables is about 1%, so it was decided not to include them in the procedure. Table  
 2543 6.13 show the ROC-integral for all the testing cases we made.

ROC-integral	
base 10 var ttv	0.848
+ fwdJetPUID ttv	0.849
+ fwdJetPt25 ttv	0.856
12 var ttv	0.856
<hr/>	
base 10 var tt	0.777
+ fwdJetPUID tt	0.777
+ fwdJetPt25 tt	0.787
12 var	0.787

**Table 6.13:** ROC-integral for all the testing cases we made in the evaluation of the additional variables discriminating power. The improvement in the discrimination performance provided by the additional variables is about 1%

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