

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

²²	Table of Contents	iii
²³	List of Figures	vii
²⁴	List of Tables	ix
²⁵	1 INTRODUCTION	1
²⁶	2 Theoretical approach	2
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 Bosons	18
³⁴	2.3 Electroweak unification and the Higgs mechanism	20
³⁵	2.3.1 Spontaneous symmetry breaking (SSB)	28
³⁶	2.3.2 Higgs mechanism	32
³⁷	2.3.3 Masses of the gauge bosons	34

38	2.3.4	Masses of the fermions	35
39	2.3.5	The Higgs field	36
40	2.3.6	Higgs boson production mechanisms at LHC.	37
41	2.3.7	Higgs decay channels	41
42	2.4	Associated Production of Higgs Boson and Single Top Quark.	42
43	2.5	The CP-mixing in tH processes	47
44	2.6	Experimental status of anomalous Higg-fermion coupling.	51
45	3	The CMS experiment at the LHC	53
46	3.1	Introduction	53
47	3.2	The LHC	54
48	3.3	The CMS experiment	64
49	3.3.1	Coordinate system	66
50	3.3.2	Pixels detector	67
51	3.3.3	Silicon strip tracker	69
52	3.3.4	Electromagnetic calorimeter	71
53	3.3.5	Hadronic calorimeter	72
54	3.3.6	Superconducting solenoid magnet	72
55	3.3.7	muon system	73
56	3.3.8	trigger system - HLT- L1	73
57	3.3.9	computing model	75
58	3.4	Event generation simulation and reconstruction	75
59	3.4.1	event generation	75
60	3.4.2	Hard scattering	75
61	3.4.3	parton shower	75
62	3.4.4	hadronization and decays	75

63	3.4.5	underlying events and pileup	75
64	3.4.6	MC - MadEvent, MadGraph and madgraphNLO, powheg, pythia, tauola	75
65	3.4.7	detector simulation	75
66	3.4.8	event reconstruction- particle flow algorithm, vertexing , muon reco, electron reco, photon and hadron reco, jets reco, anti-kt algoritm, jet energy corrections, btagging, MET	75
67	3.4.9	MVA methods, NN, BDT, boosting, overtraining, variable ranking	75
68	3.4.10	statistical inference, likelihood parametrization	75
69	3.4.11	nuisance paraeters	75
70	3.4.12	exclusion limits	75
71	3.4.13	asymptotic limits	75
72	4	Search for production of a Higgs boson and a single top quark in multilepton final states in pp collisions at $\sqrt{s} = 13$ TeV	76
73	4.1	Introduction	76
74	4.2	Data and MC Samples	78
75	4.2.1	Full 2016 dataset and MC samples	78
76	4.2.2	Triggers	81
77	4.2.2.1	Trigger efficiency scale factors	81
78	4.3	Object Identification and event selection	82
79	4.3.1	Jets and b tagging	82
80	4.3.2	Lepton selection	83
81	4.3.3	Lepton selection efficiency	84
82	4.4	Background predictions	85

88	4.5 Signal discrimination	86
89	4.5.1 Classifiers response	90
90	4.6 Additional discriminating variables	93
91	5 The CMS forward pixel detector	96
92	5.0.1 The phase 1 FPix upgrade	96
93	5.0.2 FPix module production line	96
94	5.0.3 The Gluing stage	96
95	5.0.4 The Encapsulation stage	96
96	5.0.5 The FPix module production yields	96
97	Bibliography	96
98	References	97

⁹⁹ List of Figures

100	1.1	^{14}N neutron capture in a PECVD polymerized pyridine film. The Q-value of this reaction is 626 keV. Taken from [22]	1
102	2.1	Standard model of particle physics.	4
103	2.2	WI transformations between quarks	12
104	2.3	Fundamental interactions in nature.	13
105	2.4	SM interactions diagrams	14
106	2.5	Neutral current processes	21
107	2.6	Spontaneous symmetry breaking mechanism	28
108	2.7	SSB Potential form	30
109	2.8	Potential for complex scalar field	30
110	2.9	SSB mechanism for complex scalar field	31
111	2.10	Proton-Proton collision	38
112	2.11	Higgs production mechanism Feynman diagrams	39
113	2.12	Higgs production cross section and decay branching ratios	40
114	2.13	Associated Higgs production mechanism Feynman diagrams	43
115	2.14	Cross section for tHq process as a function of κ_t	45
116	2.15	Cross section for tHW process as a function of κ_{Htt}	46
117	2.16	NLO cross section for tX_0 and $t\bar{t}X_0$	49

118	2.17 NLO cross section for $tWX_0, t\bar{t}X_0$	50
119	2.18 Combined coupling modifiers κ_t - κ_V fits of ATLAS and CMS.	51
120	3.1 CERN accelerator complex	54
121	3.2 LHC protons source and first acceleration stage.	55
122	3.3 The LINAC2 accelerating system at CERN.	56
123	3.4 LHC layout and RF cavities module.	57
124	3.5 LHC dipole magnet.	59
125	3.6 2016 CMS Integrated luminosity	61
126	3.7 LHC interaction points	62
127	3.8 Multiple pp collision bunch crossing at CMS.	64
128	3.9 CMS detector drawing	65
129	3.10 CMS coordinate system	66
130	3.11 CMS pixel detector schematic view.	68
131	3.12 SST Schematic view.	69
132	3.13 CMS ECAL schematic view	71
133	3.14 CMS solenoid magnet	73
134	4.1 The two leading-order diagrams of tHq production.	77
135	4.2 Input variables to the BDT for signal discrimination normalized.	87
136	4.3 Input variables to the BDT for signal discrimination not normalized.	89
137	4.4 BDT inputs as seen by TMVA against $t\bar{t}$	90
138	4.5 BDT inputs as seen by TMVA against $t\bar{t}V$	91
139	4.6 Correlation matrices for the input variables in the TMVA.	92
140	4.7 MVA classifiers performance.	92
141	4.8 Additional discriminating variables distributions.	94

¹⁴² List of Tables

143	2.1	Fermions of the SM.	5
144	2.2	Fermion masses.	6
145	2.3	Leptons properties.	9
146	2.4	Quarks properties.	9
147	2.5	Fermion weak isospin and weak hypercharge multiplets.	11
148	2.6	Fundamental interactions features.	15
149	2.7	SM gauge bosons.	20
150	2.8	Higgs boson properties.	37
151	2.9	Predicted branching ratios for a SM Higgs boson with $m_H = 125 \text{ GeV}/c^2$	42
152	2.10	Predicted SM cross sections for tH production at $\sqrt{s} = 13 \text{ TeV}$	44
153	2.11	Predicted enhancement of the tHq and tHW cross sections at LHC	47
154	4.1	Signal samples and their cross section and branching fraction.	78
155	4.2	κ_V and κ_t combinations.	79
156	4.3	List of background samples used in this analysis (CMSSW 80X).	80
157	4.4	Leading-order $t\bar{t}W$ and $t\bar{t}Z$ samples used in the signal BDT training. . . .	80
158	4.5	Table of high-level triggers that we consider in the analysis.	81
159	4.6	Trigger efficiency scale factors and associated uncertainties.	82
160	4.7	Requirements on each of the three muon selections.	83

161	4.8	Criteria for each of the three electron selections.	84
162	4.9	MVA input discriminating variables	88
163	4.10	TMVA input variables ranking for BDTA_GRAD method	93
164	4.11	TMVA configuration used in the BDT training.	93
165	4.12	ROC-integral for all the testing cases.	95

¹⁶⁶ Chapter 1

¹⁶⁷ INTRODUCTION

Figure 1.1: ^{14}N neutron capture in a PECVD polymerized pyridine film. The Q-value of this reaction is 626 keV. Taken from [22]

¹⁶⁸ **Chapter 2**

¹⁶⁹ **Theoretical approach**

¹⁷⁰ **2.1 Introduction**

¹⁷¹ The physical description of the universe is a challenge that physicists have faced by
¹⁷² making theories that refine existing principles and proposing new ones in an attempt
¹⁷³ to embrace emerging facts and phenomena.

¹⁷⁴

¹⁷⁵ At the end of 1940s Julian Schwinger [11] and Richard P. Feynman [12], based in
¹⁷⁶ the work of Sin-Itiro Tomonaga [13], developed an electromagnetic theory consistent
¹⁷⁷ with special relativity and quantum mechanics that describes how matter and light
¹⁷⁸ interact; the so-called “quantum eletrodynamics” (QED) had born.

¹⁷⁹

¹⁸⁰ QED has become the guide in the development of theories that describe the universe.
¹⁸¹ It was the first example of a quantum field theory (QFT), which is the theoretical
¹⁸² framework for building quantum mechanical models that describes particles and their
¹⁸³ interactions. QFT is composed of a set of mathematical tools that combines classical
¹⁸⁴ fields, special relativity and quantum mechanics, while keeping the quantum point

185 particles and locality ideas.

186 This chapter gives an overview of the standard model of particle physics, starting
 187 with a description of the particles and interactions that compose it, followed by a
 188 description of the electroweak interaction, the Higgs boson and the associated pro-
 189 duction of Higgs boson and a single top quark (tH). The description contained in
 190 this chapter is based on references [1–3].

191 2.2 Standard model of particle physics

192 Particle physics at the fundamental level is modeled in terms of a collection of in-
 193 teracting particles and fields in a theory known as the “standard model of particle
 194 physics (SM)”¹.

195

196 The full picture of the SM is composed of three fields², whose excitations are inter-
 197 preted as particles called mediators or force-carriers; a set of fields, whose excitations
 198 are interpreted as elementary particles, interacting through the exchange of those
 199 mediators and a field that gives the mass to elementary particles. Figure 2.1 shows
 200 an scheme of the SM particles organization. In addition to the particles in the scheme
 201 (but not listed in it), their corresponding anti-particles, with opposite quantum num-
 202 bers, are also part of the picture; some particles are their own anti-particles, like
 203 photon or Higgs, or anti-particle is already listed like in the W^+ and W^- case.

204

205 The mathematical formulation of the SM is based on group theory and the use of

¹ 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 “An Introduction To Quantum Field Theory (Frontiers in Physics)” by Michael E. Peskin and Dan V. Schroeder is quite comprehensive and detailed.

² Note that gravitational field is not included in the standard model formulation

Standard Model of Elementary Particles

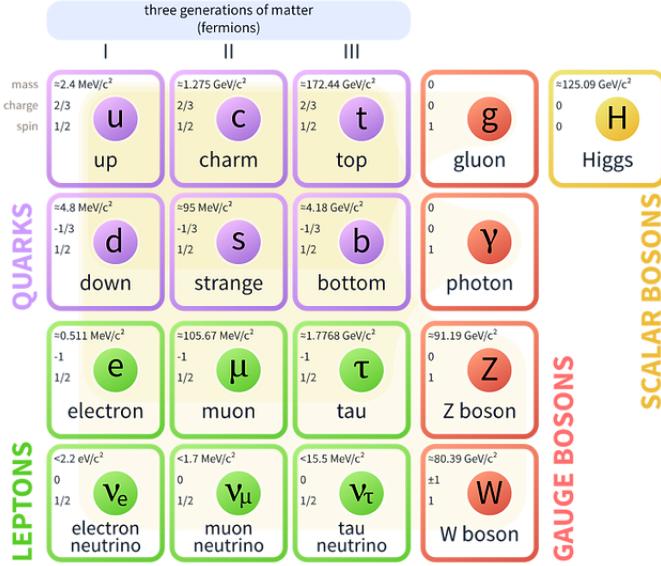


Figure 2.1: Schematic representation of the Standard model of particle physics. SM is a theoretical model intended to describe three of the four fundamental forces of the universe in terms of a set of particles and their interactions. [18].

206 Noether's theorem [17] which states that for a physical system modeled by a La-
 207 grangian that is invariant under a group of transformations a conservation law is
 208 expected. For instance, a system described by a time-independent Lagrangian is
 209 invariant (symmetric) under time changes (transformations) with the total energy
 210 conservation law as the expected conservation law. In QED, the charge operator
 211 (Q) is the generator of the $U(1)$ symmetry which according to the Noether's theorem
 212 means that there is a conserved quantity; this conserved quantity is the electric charge
 213 and thus the law conservation of electric charge is established.

214

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

218 associated to physical quantities:

219 • Strong: $SU(3)_C$ associated to color charge

220 • Weak: $SU(2)_L$ associated to weak isospin and chirality

221 • Electromagnetic: $U(1)_Y$ associated to weak hypercharge and electric charge

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

225 **2.2.1 Fermions**

226 The basic constituents of the ordinary matter at the lowest level, which form the set
 227 of elementary particles in the SM formulation, are quarks and leptons. All of them
 228 have spin 1/2, therefore they are classified as fermions since they obey Fermi-Dirac
 229 statistics. There are six “flavors” of quarks and three of leptons organized in three
 230 generations, or families, as shown in table 2.1.

231

Generation				
	Type	1st	2nd	3rd
Leptons	Charged	Electron (e)	Moun(μ)	Tau (τ)
	Neutral	Electron neutrino (ν_e)	Muon neutrino (ν_μ)	Tau neutrino (ν_τ)
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 WI between leptons is limited to the members of the same generation; WI between quarks is not limited but greatly favoured, to same generation members.

232

233 There is a mass hierarchy between generations (see table 2.2), where the higher gener-
 234 ation particles decays to the lower one, which can explain why the ordinary matter is
 235 made of particles in the first generation. In the SM, neutrinos are modeled as massless
 236 particles so they are not subject to this mass hierarchy; however, today it is known
 237 that neutrinos are massive so the hierarchy could be restated. The reason behind this
 238 mass hierarchy is one of the most important open questions in particle physics, and
 239 it becomes more puzzling when noticing that the mass difference between first and
 240 second generation fermions is small compared to the mass difference with respect to
 241 the third generation.

Lepton	Mass (MeV/c ²)	Quark	Mass (MeV/c ²)
e	0.51	u	2.2
μ	105.65	c	1.28×10^3
τ	1776.86	t	173.1×10^3
ν_e	Unknown	d	4.7
ν_μ	Unknown	s	96
τ_μ	Unknown	b	4.18×10^3

Table 2.2: Fermion masses [21]. Generations differ by mass in a way that have been interpreted as a masss hierarchy. Approximate values with no uncertainties are used, for comparison purpose.

242
 243 Usually, the second and third generation fermions are produced in high energy pro-
 244 cesses, like the ones recreated in particle accelerators.

245 2.2.1.1 Leptons

246 A lepton is an elementary particle that is not subject to the SI. As seen in table 2.1,
 247 there are two types of leptons, the charged ones (electron, muon and tau) and the
 248 neutral ones (the three neutrinos). The electric charge (Q) is the property that gives
 249 leptons the ability to participate in the EI. From the classical point of view, Q plays

250 a central role determining, among others, the strength of the electric field through
251 which the electromagnetic force is exerted. It is clear that neutrinos are not affected
252 by EI because they don't carry electric charge.

253

254 Another feature of the leptons that is fundamental in the mathematical description
255 of the SM is the chirality, which is closely related to spin and helicity. Helicity defines
256 the handedness of a particle by relating its spin and momentum such that if they
257 are parallel then the particle is right-handed; if spin and momentum are antiparallel
258 the particle is said to be left-handed. The study of parity conservation (or viola-
259 tion) in β -decay has shown that only left-handed electrons/neutrinos or right-handed
260 positrons/anti-neutrinos are created [19]; the inclusion of that feature in the theory
261 was achieved by using projection operators for helicity, however, helicity is frame de-
262 pendent for massive particles which makes it not Lorentz invariant and then another
263 related attribute has to be used: *chirality*.

264

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

270

271 In the following, when referring to left-handed (right-handed) it will mean left-handed
272 chiral (right-handed chiral). The fundamental fact about chirality is that while EI
273 and SI are not sensitive to chirality, in WI left-handed and right-handed fermions are
274 treated asymmetrically, such that only left handed fermions and right-handed anti-
275 fermions are allowed to couple to WI mediators, which is a violation of parity. The

276 way to translate this statement in a formal mathematical formulation is based on the
 277 isospin symmetry group $SU(2)_L$.

278

279 Each generation of leptons is seen as a weak isospin doublet.³ The left-handed charged
 280 lepton and its associated left-handed neutrino are arranged in doublets of weak isospin
 281 $T=1/2$ while their right-handed partners are singlets:

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

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

287

288 Altough all three flavor neutrinos have been observed, their masses remain unknown
 289 and only some estimations have been made [20]. The main reason is that the fla-
 290 vor eigenstates are not the same as the mass eigenstates which implies that when
 291 a neutrino is created its mass state is a linear combination of the three mass eigen-
 292 states and experiments can only probe the squared difference of the masses. The
 293 Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix encode the relationship
 294 between flavor and mass eigenstates.

295

³ 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.

Lepton	Q(e)	T_3	L_e	L_μ	L_τ	Lifetime (s)
Electron (e)	-1	-1/2	1	0	0	Stable
Electron neutrino(ν_e)	0	1/2	1	0	0	Unknown
Muon (μ)	-1	-1/2	0	1	0	2.19×10^{-6}
Muon neutrino (ν_μ)	0	1/2	0	1	0	Unknown
Tau (τ)	-1	-1/2	0	0	1	290.3×10^{-15}
Tau neutrino (τ_μ)	0	1/2	0	0	1	Unknown

Table 2.3: Leptons properties [21]. 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.

296 2.2.1.2 Quarks

297 Quarks are the basic constituents of protons and neutrons. The way quarks join to
 298 form bound states, called “hadrons”, is through the SI. Quarks are affected by all the
 299 fundamental interactions which means that they carry all the four types of charges:
 300 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: Quarks properties [21]. 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.

301

302 Table 2.4 summarizes the features of quarks, among which the most particular is
 303 their fractional electric charge. Note that fractional charge is not a problem, given
 304 that quarks are not found isolated, but serves to explain how composed particles are

305 formed out of two or more valence quarks⁴.

306

307 Color charge is the responsible for the SI between quarks and is the symmetry
 308 ($SU(3)_C$) that defines the formalism to describe SI. There are three colors: red (r),
 309 blue(b) and green(g) and their corresponding three anti-colors; thus each quark carries
 310 one color unit while anti-quarks carries one anti-color unit. As said above, quarks are
 311 not allowed to be isolated due to the color confinement effect, therefore their features
 312 have been studied indirectly by observing their bound states created when:

- 313 • one quark with a color charge is attracted by an anti-quark with the correspond-
 314 ing anti-color charge forming a colorless particle called a “meson.”
- 315 • three quarks (anti-quarks) with different color (anti-color) charges are attracted
 316 among them forming a colorless particle called a “baryon(anti-baryon).”

317 In the first version of the quark model (1964), M. Gell-Mann [22] and G. Zweig
 318 [23,24] developed a consistent way to classify hadrons according to their properties.
 319 Only three quarks (u, d, s) were involved in a scheme in which all baryons have
 320 baryon number B=1 and therefore quarks have B=1/3; non-baryons have B=0. The
 321 scheme organizes baryons in a two-dimensional space (I_3 - Y); Y (hypercharge) and I_3
 322 (isospin) are quantum numbers related by the Gell-Mann-Nishijima formula [25, 26]:

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

323 where $Y = B + S + C + T + B'$ are the quantum numbers listed in table 2.4. Baryon
 324 number is conserved in SI and EI which means that single quarks cannot be created

⁴ 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.

325 but in pairs $q - \bar{q}$.

326

327 There are six quark flavors organized in three generations (see table 2.1) following a
 328 mass hierarchy which, again, implies that higher generations decay to first generation
 329 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	ν_{eR}	$\nu_{\mu R}$	$\nu_{\tau R}$	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.

330

331 Isospin doublets of quarks are also defined (see table 2.5) and as for neutrinos, the
 332 mass eigenstates are not the same as the WI eigenstates which means that members of
 333 different quark generations are connected by the WI mediator; thus, up-type quarks
 334 are coupled not to down-type quarks directly but to a superposition of down-type
 335 quarks (q'_d) via WI according to:

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

336

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

337 where V_{CKM} is known as Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix [27,28].
 338 The weak decays of quarks are represented in the diagram of figure 2.2; again the
 339 CKM matrix plays a central role since it contains the probabilities for the different

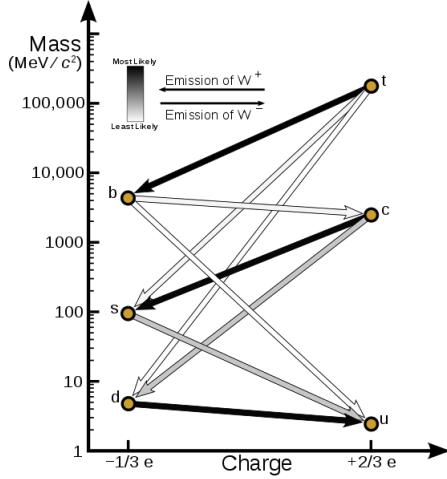


Figure 2.2: Transformations between quarks through WI. Higher generations quarks decay to first generation quarks by emitting a W boson. The arrow color indicates the likelihood of the transition according to the grey scale in the top left side which represent the CKM matrix parameters [29].

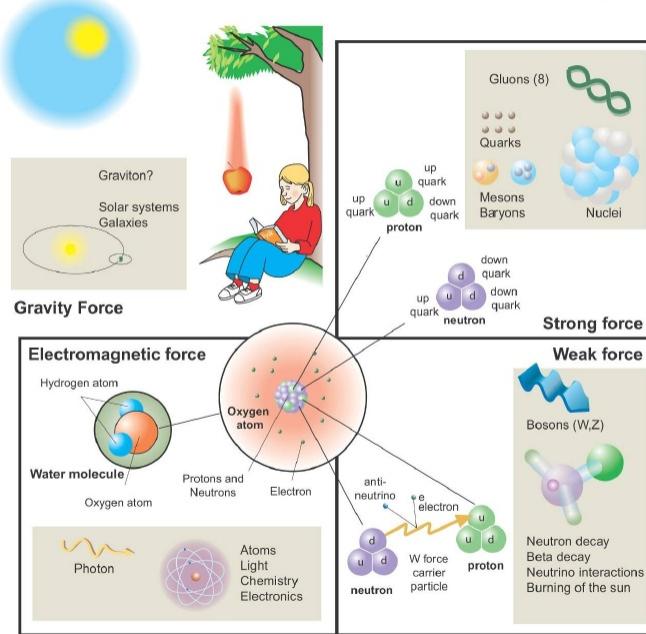
340 quark decay channels, in particular, note that quark decays are greatly favored be-
341 tween generation members.

342

343 CKM matrix is a 3×3 unitary matrix parametrized by three mixing angles and
344 the *CP-mixing phase*; the latter is the parameter responsible for the Charge-Parity
345 symmetry violation (CP-violation) in the SM. The fact that the b quark decays almost
346 all the times to a top quark is exploited in this thesis when making the selection of
347 the signal events by requiring the presence of a jet tagged as a jet coming from a
348 b quark in the final state. The effect of the *CP-mixing phase* on the cross section of
349 associated production of Higgs boson and a single top process is also explored in this
350 thesis.

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.

351 2.2.2 Fundamental interactions

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

- 355 • *Electromagnetic interaction (EI)* affects particles that are “electrically charged,” 356 like electrons and protons. It is described by QED combining quantum mechanics, 357 special relativity and electromagnetism in order to explain how particles 358 with electric charge interact through the exchange of photons, therefore, one 359 says that “Electromagnetic Force” is mediated by “photons”. Figure 2.4a. shows 360 a graphical representation, known as “feynman diagram”, of electron-electron

361 scattering.

- 362 • *Strong interaction (SI)* described by Quantum Chromodynamics (QCD). Hadrons
 363 like proton and neutron have internal structure given that they are composed
 364 of two or more valence quarks⁵. Quarks have fractional electric charge which
 365 means that they are subject to electromagnetic interaction and in the case of the
 366 proton they should break apart due to electrostatic repulsion; however, quarks
 367 are held together inside the hadrons against their electrostatic repulsion by the
 368 “Strong Force” through the exchange of “gluons.” The analog to the electric
 369 charge is the “color charge”. Electrons and photons are elementary particles
 370 as quarks but they don’t carry color charge, therefore they are not subject to
 371 SI. The feynman diagram for gluon exchange between quarks is shown in figure
 372 2.4b.

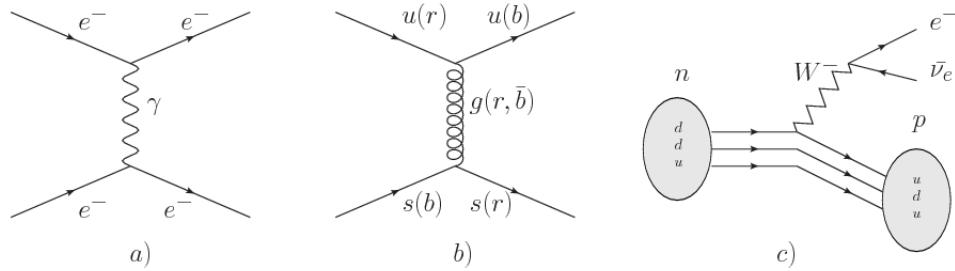


Figure 2.4: Feynman diagrams representing the interactions in SM; a) EI: e - e scattering; b) SI: gluon exchange between quarks ; c) WI: β -decay

- 373 • *Weak interaction (WI)* described by the weak theory (WT), is responsible, for
 374 instance, for the radioactive decay in atoms and proton-proton (pp) fusion
 375 within the sun. Quarks and leptons are the particles affected by the weak
 376 interaction; they possess a property called “flavor charge” (see 2.2.1) which can
 377 be changed by emitting or absorbing one weak force mediator. There are three
 378 mediators of the “weak force” known as “Z” boson in the case of electrically

⁵ particles made of four and five quarks are exotic states not so common.

379 neutral changes and “ W^\pm ” bosons in the case of electrically charged changes.
 380 The “weak isospin” is the WI analog to electric charge in EI, and color charge
 381 in SI, and defines how quarks and leptons are affected by the weak force. Figure
 382 2.4c. shows the feynman diagram of β -decay where a newtron (n) is transformed
 383 in a proton (p) by emmiting a W^- particle. Since this thesis is in the frame
 384 of the electroweak interaction, a more detailed description of it will be given in
 385 section 2.3

386 • *Gravitational interaction (GI)* described by General Theory of Relativity (GR).
 387 It is responsible for the structure of galaxies and black holes as well as the
 388 expansion of the universe. As a classical theory, in the sense that it can be for-
 389 mulated without even appeal to the concept of quantization, it implies that the
 390 spacetime is a continuum and predictions can be made without limitation to the
 391 precision of the measurement tools. The latter represent a direct contradiction
 392 of the quantum mechanics principles. Gravity is deterministic while quantum
 393 mechanics is probabilistic; despite that, efforts to develop a quantum theory of
 394 gravity have predicted the “graviton” as mediator of the Gravitational force⁶.

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 [30].

395

396 Table 2.6 sumarizes the main features of the fundamental interactions. The rela-
 397 tive strength of the fundamental forces reveals the meaning of strong and weak; in

⁶ Actually a wide variety of theories have been developed in an attempt to describe gravity; some famous examples are string theory and supergravity.

398 a context where the relative strength of the SI is 1, the EI is about hundred times
 399 weaker and WI is about million times weaker than the SI. A good description on
 400 how the relative strength and range of the fundamental interactions are calculated
 401 can be found in references [30, 31]. In the everyday life, only EI and GI are explicitly
 402 experienced due to the range of these interactions; i.e., at the human scale distances
 403 only EI and GI have appreciable effects, in contrast to SI which at distances greater
 404 than 10^{-15} m become negligible.

405

406 QED was built successfully on the basis of the classical electrodynamics theory (CED)
 407 of Maxwell and Lorentz, following theoretical and experimental requirements imposed
 408 by

- 409 • lorentz invariance: independence on the reference frame.
- 410 • locallity: interacting fields are evaluated at the same space-time point to avoid
 action at a distance.
- 412 • renormalizability: physical predictions are finite and well defined
- 413 • particle spectrum, symmetries and conservation laws already known must emerge
 from the theory.
- 415 • gauge invariance.

416 The gauge invariance requirement reflects the fact that the fundamental fields cannot
 417 be directly measured but associated fields which are the observables. Electric (“**E**”)
 418 and magnetic (“**B**”) fields in CED are associated with the electric scalar potential
 419 “**V**” and the vector potential “**A**”. In particular, **E** can be obtained by measuring
 420 the change in the space of the scalar potential (ΔV); however, two scalar potentials

421 differing by a constant “f” correspond to the same electric field. The same happens in
 422 the case of the vector potential “ \mathbf{A} ”; thus, different configurations of the associated
 423 fields result in the same set of values of the observables. The freedom in choosing
 424 one particular configuration is known as “gauge freedom”; the transformation law con-
 425 necting two configurations is known as “gauge transformation” and the fact that the
 426 observables are not affected by a gauge transformation is called “gauge invariance”.

427

428 When the gauge transformation:

$$\begin{aligned} \mathbf{A} &\rightarrow \mathbf{A} - \Delta f \\ V &\rightarrow V - \frac{\partial f}{\partial t} \end{aligned} \tag{2.4}$$

429 is applied to Maxwell equations, they are still satisfied and the fields remain invariant.
 430 Thus, CED is invariant under gauge transformations and is called a “gauge theory”.
 431 The set of all gauge transformations form the “symmetry group” of the theory, which
 432 according to the group theory, has a set of “group generators”. The number of group
 433 generators determine the number of “gauge fields” of the theory.

434

435 As mentioned in the first lines of section 2.2, QED has one symmetry group ($U(1)$)
 436 with one group generator (the Q operator) and one gauge field (the electromagnetic
 437 field A^μ). In CED there is not a clear definition, beyond the historical convention, of
 438 which fields are the fundamental and which are the associated, but in QED it is clear
 439 that the fundamental field is A^μ . When a gauge theory is quantized, the gauge field
 440 is quantized and its quanta is called “gauge boson”. The word boson characterizes
 441 particles with integer spin which obey Bose-Einstein statistics.

442

443 As will be detailed in section 2.3, interactions between particles in a system can be
 444 obtained by considering first the Lagrangian density of free particles in the system,
 445 which of course is incomplete because the interaction terms have been left out, and
 446 demanding global phase transformation invariance. Global phase transformation in-
 447 variance means that a gauge transformation is performed identically to every point
 448 in the space⁷ and the Lagrangian remains invariant. Then, the global transformation
 449 is promoted to a local phase transformation (this time the gauge transformation de-
 450 pends on the position in space) and again invariance is required.

451

452 Due to the space dependence of the local transformation, the Lagrangian density is
 453 not invariant anymore. In order to restate the gauge invariance, the gauge covariant
 454 derivative is introduced in the Lagrangian and with it the gauge field responsible for
 455 the interaction between particles in the system. The new Lagrangian density is gauge
 456 invariant, includes the interaction terms needed to account for the interactions and
 457 provides a way to explain the interaction between particles through the exchange of
 458 the gauge boson.

459 This recipe was used to build QED and the theories that aim to explain the funda-
 460 mental interactions.

461 **2.2.3 Gauge Bosons**

462 The importance of the gauge bosons comes from the fact that they are the force
 463 mediators or force carriers. The features of the gauge bosons reflect those of the
 464 fields they represent and they are extracted from the Lagrangian density used to
 465 describe the interactions. In section 2.3, it will be shown how the gauge bosons of the

⁷ Here space corresponds to the 4-dimensional space i.e. space-time.

466 EI and WI emerge from the electroweak Lagrangian. The SI gauge bosons features
467 are also extracted from the SI Lagrangian but it is not detailed in this document. The
468 main features of the SM gauge bosons will be briefly presented below and summarized
469 in table 2.7.

470 • **Photon.** EI occurs when the photon couples to (is exchanged between) particles
471 carrying electric charge; however, the photon itself does not carry electric charge,
472 therefore, there is no coupling between photons. Given that the photon is
473 massless the EI is of infinite range, i.e., electrically charged particles interact
474 even if they are located far away one from each other; this also implies that
475 photons always move with the speed of light.

476 • **Gluon.** SI is mediated by gluons which, same as photons, are massless. They
477 carry one unit of color charge and one unit of anticolor charge which means that
478 gluons couple to other gluons. As a result, the range of the SI is not infinite
479 but very short due to the attraction between gluons, giving rise to the “color
480 confinement” which explains why color charged particles cannot be isolated but
481 live within composited particles, like quarks inside protons.

482 • **W, Z.** The WI mediators, W^\pm and Z, are massive which explains their short-
483 range. Given that the WI is the only interaction that can change the flavor
484 of the interacting particles, the W boson is the responsible for the nuclear
485 transmutation where a neutron is converted in a proton or vice versa with the
486 involvement of an electron and a neutrino (see figure 2.4c). The Z boson is the
487 responsible of the neutral weak processes like neutrino elastic scattering where
488 no electric charge but momentum transference is involved. WI gauge bosons
489 carry isospin charge which makes possible the interaction between them.

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

Table 2.7: SM gauge bosons main features [21].

490

491 **2.3 Electroweak unification and the Higgs
492 mechanism**

493 Physicists dream of building a theory that contains all the interactions in one single
494 interaction, i.e., showing that at some scale in energy all the four fundamental in-
495 teractions are unified and only one interaction emerges in a “Theory of everything”.
496 The first sign of the feasibility of such unification comes from success in the con-
497 struction of the CED. Einstein spent years trying to reach that dream, which by
498 1920 only involved electromagnetism and gravity, with no success; however, a new
499 partial unification was achieved in the 1960’s, when S.Glashow [14], A.Salam [15] and
500 S.Weinberg [16] independently proposed that electromagnetic and weak interactions
501 are two manifestations of a more general interaction called “electroweak interaction
502 (EWT)”. Both, QCD and EWT, were developed in parallel and following the useful
503 prescription provided by QED and the gauge invariance principles.

504

505 The theory of weak interactions was capable of explaining the β -decay and in general
506 the processes mediated by W^\pm bosons. However, there were some processes like the
507 “ $\nu_\mu - e$ scattering” which would require the exchange of two W bosons (see figure 2.5
508 top diagrams) giving rise to divergent loop integrals and then non finite predictions.

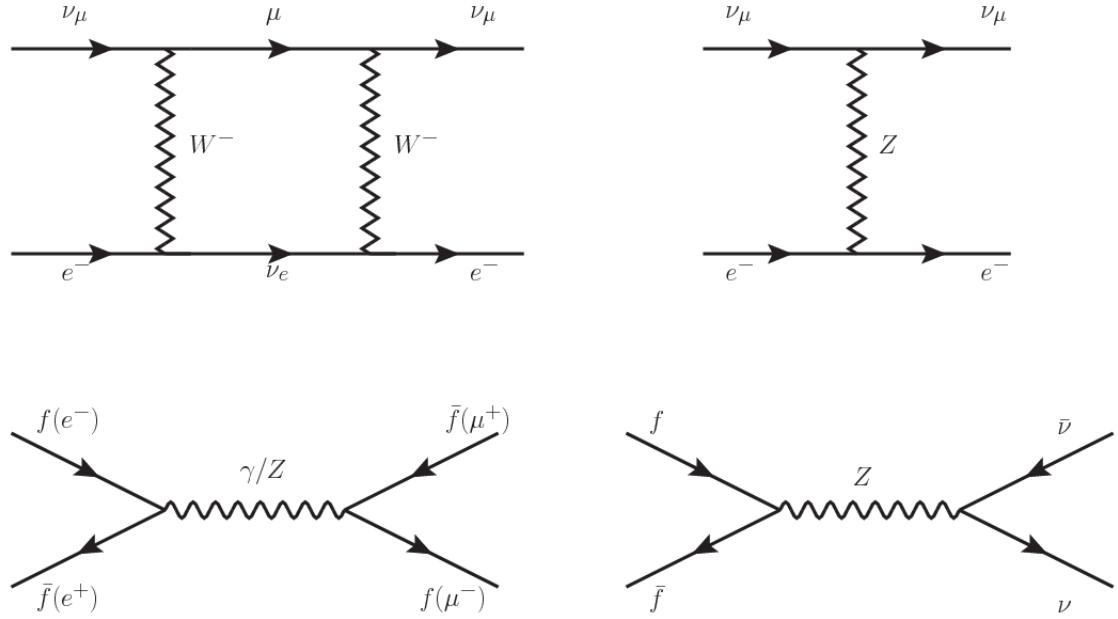


Figure 2.5: Top: $\nu_\mu - e^-$ scattering going through charged currents (left) and neutral currents (right). Bottom: neutral current processes for charged fermions (left) and involving neutrinos (right). While neutral current processes involving only charged fermions can proceed through EI or WI,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

509 By including neutral currents involving fermions via the exchange of neutral bosons
 510 Z , those divergences are compensated and the predictions become realistic.

511

512 Neutral weak interaction vertices conserve flavor in the same way as the electromag-
 513 netic vertices do, but additionally, the Z boson can couple to neutrinos which implies
 514 that processes involving charged fermions can proceed through EI or WI but processes
 515 involving neutrinos can proceed only through WI.

516

517 The prescription to build a gauge theory of the WI consists of proposing a free field
 518 Lagrangian density that includes the particles involved; next, by requesting invari-
 519 ance under global phase transformations first and generalizing to local phase trans-
 520 formations invariance later, the conserved currents are identified and interactions are

521 generated by introducing gauge fields. Given that the goal is to include the EI and
 522 WI in a single theory, the group symmetry considered should be a combination of
 523 $SU(2)_L$ and $U(1)_{em}$, however the latter cannot be used directly because the EI treats
 524 left and right-handed particles indistinctly in contrast to the former. Fortunately, the
 525 weak hypercharge, which is a combination of the weak isospin and the electric charge
 526 (eqn 2.2) is suitable to be used since it is conserved by the EI and WI. Thus, the
 527 symmetry group to be considered is

$$G \equiv SU(2)_L \otimes U(1)_Y \quad (2.5)$$

528 The following treatment applies to any of the fermion generations, but for simplicity
 529 the first generation of leptons will be considered [2, 3, 32, 33].

530

531 Given the first generation of leptons

$$\psi_1 = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L, \quad \psi_2 = \nu_{eR}, \quad \psi_3 = e_R^- \quad (2.6)$$

532 the charged fermionic currents are given by

$$J_\mu \equiv J_\mu^+ = \bar{\nu}_{eL} \gamma_\mu e_L, \quad J_\mu^\dagger \equiv J_\mu^- = \bar{e}_L \gamma_\mu \nu_{eL} \quad (2.7)$$

533 and the free Lagrangian is given by

$$\mathcal{L}_0 = \sum_{j=1}^3 i\bar{\psi}_j(x) \gamma^\mu \partial_\mu \psi_j(x). \quad (2.8)$$

534 Mass terms are included directly in the QED and QCD free Lagrangians since they
 535 preserve the invariance under the symmetry transformations involved which treat
 536 left-handed and right-handed similarly, however mass terms of the form

$$m_W^2 W_\mu^\dagger(x) W^\mu(x) + \frac{1}{2} m_Z^2 Z_\mu(x) Z^\mu(x) - m_e \bar{\psi}_e(x) \psi_e(x) \quad (2.9)$$

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

539

540 Experiments have shown that the gauge fields are not massless; however, they have
 541 to acquire mass through a mechanism compatible with the gauge invariance; that
 542 mechanism is known as the “Higgs mechanism” and will be considered later in this
 543 section. The global transformations in the combined symmetry group G can be
 544 written as

$$\begin{aligned} \psi_1(x) &\xrightarrow{G} \psi'_1(x) \equiv U_Y U_L \psi_1(x), \\ \psi_2(x) &\xrightarrow{G} \psi'_2(x) \equiv U_Y \psi_2(x), \\ \psi_3(x) &\xrightarrow{G} \psi'_3(x) \equiv U_Y \psi_3(x) \end{aligned} \quad (2.10)$$

545 where U_L represent the $SU(2)_L$ transformation acting only on the weak isospin dou-
 546 blet and U_Y represent the $U(1)_Y$ transformation acting on all the weak isospin mul-
 547 tiplets. Explicitly

$$U_L \equiv \exp\left(i \frac{\sigma_i}{2} \alpha^i\right), \quad U_Y \equiv \exp(i y_i \beta) \quad (i = 1, 2, 3) \quad (2.11)$$

548 with σ_i the Pauli matrices and y_i the weak hypercharges. In order to promote the
 549 transformations from global to local while keeping the invariance, it is required that
 550 $\alpha^i = \alpha^i(x)$, $\beta = \beta(x)$ and the replacement of the ordinary derivatives by the covariant
 551 derivatives

$$\begin{aligned}
D_\mu \psi_1(x) &\equiv \left[\partial_\mu + ig\sigma_i W_\mu^i(x)/2 + ig'y_1 B_\mu(x) \right] \psi_1(x) \\
D_\mu \psi_2(x) &\equiv \left[\partial_\mu + ig'y_2 B_\mu(x) \right] \psi_2(x) \\
D_\mu \psi_3(x) &\equiv \left[\partial_\mu + ig'y_3 B_\mu(x) \right] \psi_3(x)
\end{aligned} \tag{2.12}$$

552 introducing in this way four gauge fields, $W_\mu^i(x)$ and $B_\mu(x)$, in the process. The
553 covariant derivatives (eqn 2.12) are required to transform in the same way as fermion
554 fields $\psi_i(x)$ themselves, therefore, the gauge fields transform as:

$$\begin{aligned}
B_\mu(x) &\xrightarrow{G} B'_\mu(x) \equiv B_\mu(x) - \frac{1}{g'} \partial_\mu \beta(x) \\
W_\mu^i(x) &\xrightarrow{G} W_\mu^{i\prime}(x) \equiv W_\mu^i(x) - \frac{i}{g} \partial_\mu \alpha_i(x) - \varepsilon_{ijk} \alpha_i(x) W_\mu^j(x).
\end{aligned} \tag{2.13}$$

555 The G invariant version of the Lagrangian density 2.8 can be written as

$$\mathcal{L}_0 = \sum_{j=1}^3 i\bar{\psi}_j(x) \gamma^\mu D_\mu \psi_j(x) \tag{2.14}$$

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

$$B_{\mu\nu}(x) \equiv \partial_\mu B_\nu - \partial_\nu B_\mu \tag{2.15}$$

$$W_{\mu\nu}^i(x) \equiv \partial_\mu W_\nu^i(x) - \partial_\nu W_\mu^i(x) - g\varepsilon^{ijk} W_\mu^j W_\nu^k \tag{2.16}$$

559 the last term in eqn. 2.16 is added in order to hold the gauge invariance; therefore,

$$\mathcal{L}_G = -\frac{1}{4}B_{\mu\nu}(x)B^{\mu\nu}(x) - \frac{1}{4}W_{\mu\nu}^i(x)W_i^{\mu\nu}(x) \quad (2.17)$$

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

562

563 The three weak isospin conserved currents resulting from the $SU(2)_L$ symmetry are
 564 given by

$$J_\mu^i(x) = \frac{1}{2}\bar{\psi}_1(x)\gamma_\mu\sigma^i\psi_1(x) \quad (2.18)$$

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

$$J_\mu^Y = \sum_{j=1}^3 \bar{\psi}_j(x)\gamma_\mu y_j \psi_j(x) \quad (2.19)$$

567 In order to evaluate the electroweak interactions modeled by an isotriplet field W_μ^i
 568 which couples to isospin currents J_μ^i with strength g and additionally the singlet
 569 field B_μ which couples to the weak hypercharge current J_μ^Y with strength $g'/2$. The
 570 interaction Lagrangian density to be considered is

$$\mathcal{L}_I = -g J^{i\mu}(x) W_\mu^i(x) - \frac{g'}{2} J^{Y\mu}(x) B_\mu(x) \quad (2.20)$$

571 Note that the weak isospin currents are not the same as the charged fermionic currents
 572 that were used to describe the WI (eqn 2.7), since the weak isospin eigenstates are
 573 not the same as the mass eigenstates, but they are closely related

$$J_\mu = \frac{1}{2}(J_\mu^1 + iJ_\mu^2), \quad J_\mu^\dagger = \frac{1}{2}(J_\mu^1 - iJ_\mu^2). \quad (2.21)$$

574 The same happens with the gauge fields W_μ^i which are related to the mass eigenstates
 575 W^\pm by

$$W_\mu^+ = \frac{1}{\sqrt{2}}(W_\mu^1 - iW_\mu^2), \quad W_\mu^- = \frac{1}{\sqrt{2}}(W_\mu^1 + iW_\mu^2). \quad (2.22)$$

576 The fact that there are three weak isospin conserved currents is an indication that in
 577 addition to the charged fermionic currents, which couple charged to neutral leptons,
 578 there should be a neutral fermionic current that does not involve electric charge
 579 exchange; therefore, it couples neutral fermions or fermions of the same electric charge.
 580 The third weak isospin current contains a term that is similar to the electromagnetic
 581 current (j_μ^{em}), indicating that there is a relation between them and resembling the
 582 Gell-Mann-Nishijima formula 2.2 adapted to electroweak interactions

$$Q = T_3 + \frac{Y_W}{2}. \quad (2.23)$$

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

$$j_\mu^{em} = J_\mu^3 + \frac{1}{2}J_\mu^Y. \quad (2.24)$$

586 The neutral gauge fields W_μ^3 and B_μ cannot be directly identified with the Z and the
 587 photon fields since the photon interacts similarly with left and right-handed fermions;
 588 however, they are related through a linear combination given by

$$A_\mu = B_\mu \cos \theta_W + W_\mu^3 \sin \theta_W \quad (2.25)$$

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

589 where θ_W is known as the “Weinberg angle.” The interaction Lagrangian is now given

590 by

$$\mathcal{L}_I = -\frac{g}{\sqrt{2}}(J^\mu W_\mu^+ + J^{\mu\dagger} W_\mu^-) - \left(g \sin \theta_W J_\mu^3 + g' \cos \theta_W \frac{J_\mu^Y}{2}\right) A^\mu - \left(g \cos \theta_W J_\mu^3 - g' \sin \theta_W \frac{J_\mu^Y}{2}\right) Z^\mu \quad (2.26)$$

591 the first term is the weak charged current interaction, while the second term is the

592 electromagnetic interaction under the condition

$$g \sin \theta_W = g' \cos \theta_W = e, \quad \frac{g'}{g} = \tan \theta_W \quad (2.27)$$

593 contained in the eqn.2.24; the third term is the neutral weak current.

594

595 Note that the neutral fields transformation given by the eqn. 2.25 can be written in

596 terms of the coupling constants g and g' as:

$$A_\mu = \frac{g' W_\mu^3 + g B_\mu}{\sqrt{g^2 + g'^2}}, \quad Z_\mu = \frac{g W_\mu^3 - g' B_\mu}{\sqrt{g^2 + g'^2}} \quad (2.28)$$

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

$$\mathcal{L}_{nmEWI} = \mathcal{L}_0 + \mathcal{L}_G \quad (2.29)$$

598 where fermion and gauge fields have been considered massless because their regular

599 mass terms are manifestly non invariant under G transformations; therefore, masses

600 have to be generated in a gauge invariant way. The mechanism by which this goal is
 601 achieved is known as the “Higgs mechanism” and is closely connected to the concept
 602 of “spontaneous symmetry breaking.”

603 2.3.1 Spontaneous symmetry breaking (SSB)

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

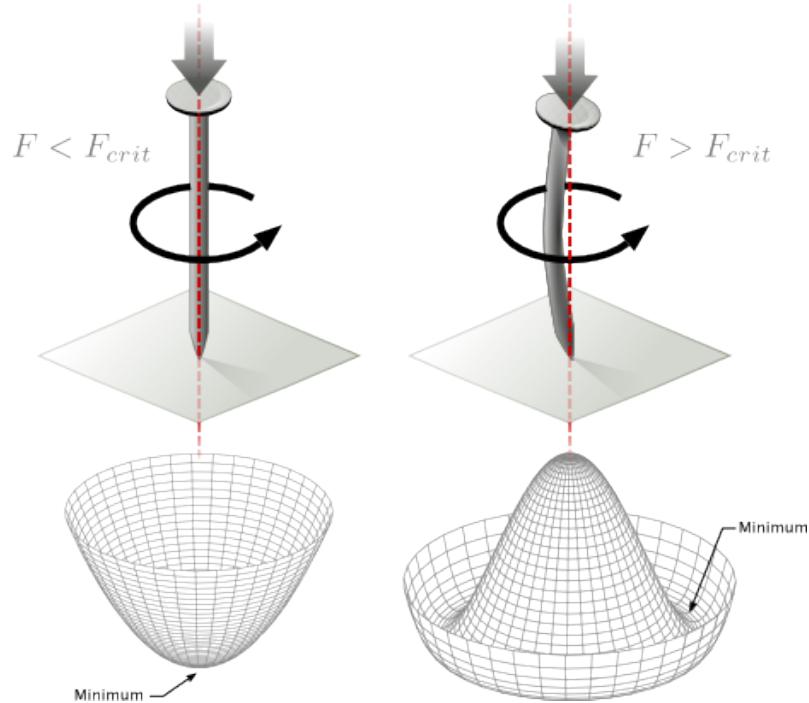


Figure 2.6: Spontaneous symmetry breaking mechanism. The steel nail, subject to an external force (top left), has rotational symmetry with respect to its axis. When the external force overcomes a critical value the nail buckles (top right) choosing a minimal energy state (ground state) and thus “*breaking 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 [34].

607 Before reaching the critical force value, the system has rotational symmetry with re-
 608 spect to the nail axis; however, after the critical force value is reached the nail buckles
 609 (top right). The form of the potential energy (bottom right) changes, preserving its
 610 rotational symmetry although its minima does not exhibit that rotational symmetry
 611 any longer. Right before the nail buckles there is no indication of the direction the
 612 nail will bend because any of the directions are equivalent, but once the nail bends,
 613 choosing a direction, an arbitrary minimal energy state (ground state) is selected and
 614 it does not share the system's rotational symmetry. This mechanism for reaching an
 615 asymmetric ground state is known as "*spontaneous symmetry breaking*".
 616 The lesson from this analysis is that the way to introduce the SSB mechanism into a
 617 system is by adding the appropriate potential to it.

618

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

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \quad (2.30)$$

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

623

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

$$\phi(x) = \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2) \quad (2.31)$$

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

$$\mathcal{L} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi), \quad V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \quad (2.32)$$

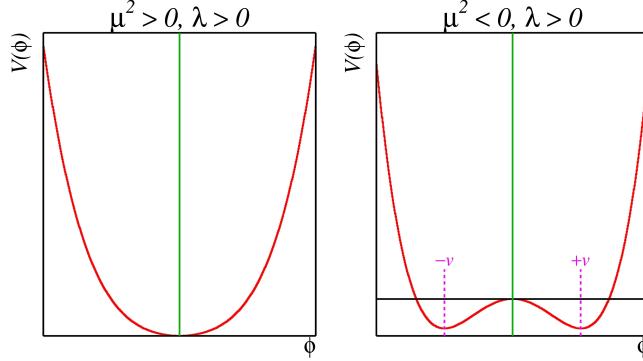


Figure 2.7: Shape of the potential $V(\phi)$ for $\lambda > 0$ and: $\mu^2 > 0$ (left) and $\mu^2 < 0$ (right). The case $\mu^2 < 0$ corresponds to the potential suitable for introducing the SSB mechanism by choosing one of the two ground states which are connected via reflection symmetry. [34].

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

627

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

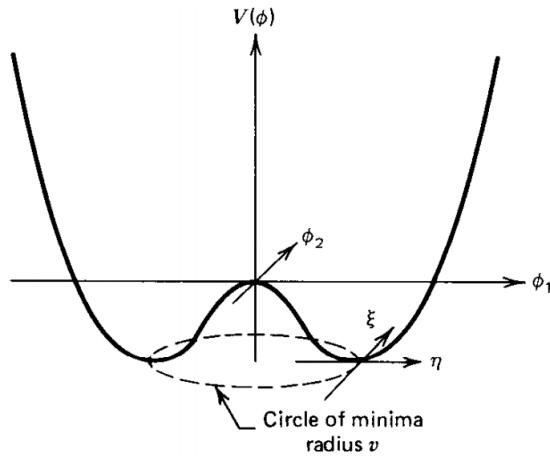


Figure 2.8: Potential for complex scalar field. There is a circle of minima of radius v along the ξ -direction [3].

$$\phi_0 = \frac{v}{\sqrt{2}} \exp(i\xi) \xrightarrow{\text{SSB}} \phi_0 = \frac{v}{\sqrt{2}} \quad (2.33)$$

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

$$\phi(x) = \frac{1}{\sqrt{2}}(v + \eta(x) + i\xi(x)) \quad (2.34)$$

633 which when substituted into eqn. 2.32 produces a Lagrangian in terms of the new
 634 fields η and ξ

$$\mathcal{L}' = \frac{1}{2}(\partial_\mu \xi)^2 + \frac{1}{2}(\partial_\mu \eta)^2 + \mu^2 \eta^2 - V(\phi_0) - \lambda v \eta (\eta^2 + \xi^2) - \frac{\lambda}{4}(\eta^2 + \xi^2)^2 \quad (2.35)$$

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

640

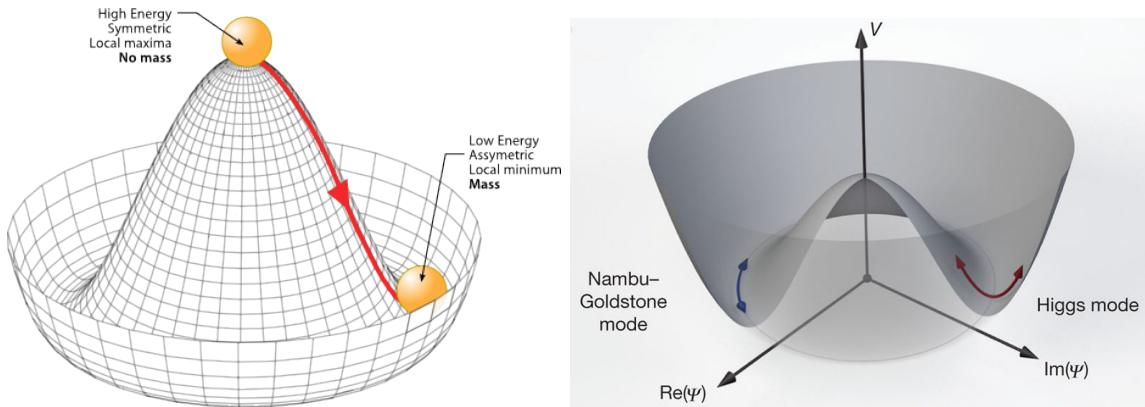


Figure 2.9: SSB mechanism for a complex scalar field [34, 35].

641 Thus, the SSB mechanism serves as a method to generate mass but as a side effect a

642 massless field is introduced in the system. This fact is known as the Goldstone theorem
 643 and states that a massless scalar field appears in the system for each continuous
 644 symmetry spontaneously broken. Another version of the Goldstone theorem states
 645 that “*if a Lagrangian is invariant under a continuous symmetry group G , but the*
 646 *vacuum is only invariant under a subgroup $H \subset G$, then there must exist as many*
 647 *massless spin-0 particles (Nambu-Goldstone bosons) as broken generators.*” [33] The
 648 Nambu-Goldstone boson can be understood considering that the potential in the ξ -
 649 direction is flat so excitations in that direction are not energy consuming and thus
 650 represent a massless state.

651 2.3.2 Higgs mechanism

652 When the SSB mechanism is introduced in the formulation of the EWI in an attempt
 653 to generate the mass of the so far massless gauge bosons and fermions, an interesting
 654 effect is revealed. In order to keep the G symmetry group invariance and generate
 655 the mass of the EW gauge bosons, a G invariant Lagrangian density (\mathcal{L}_S) has to be
 656 added to the non massive EWI Lagrangian (eqn. 2.29)

$$\mathcal{L}_S = (D_\mu \phi)^\dagger (D^\mu \phi) - \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2, \quad \lambda > 0, \mu^2 < 0 \quad (2.36)$$

$$D_\mu \phi = \left(i\partial_\mu - g \frac{\sigma_i}{2} W_\mu^i - g' \frac{Y}{2} B_\mu \right) \phi \quad (2.37)$$

657 ϕ has to be an isospin doublet of complex scalar fields so it preserves the G invariance;
 658 thus ϕ can be defined as:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \equiv \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}. \quad (2.38)$$

659 The minima of the potential are defined by

$$\phi^\dagger \phi = \frac{1}{2}(\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2) = -\frac{\mu^2}{2\lambda}. \quad (2.39)$$

660 The choice of the ground state is critical. By choosing a ground state, invariant under
 661 $U(1)_{em}$ gauge symmetry, the photon will remain massless and the W^\pm and Z bosons
 662 masses will be generated which is exactly what is needed. In that sense, the best
 663 choice corresponds to a weak isospin doublet with $T_3 = -1/2$, $Y_W = 1$ and $Q = 0$
 664 which defines a ground state with $\phi_1 = \phi_2 = \phi_4$ and $\phi_3 = v$:

$$\phi_0 \equiv \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad v^2 \equiv -\frac{\mu^2}{\lambda}. \quad (2.40)$$

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

667

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

$$\phi(x) = \frac{1}{\sqrt{2}} \exp\left(\frac{i}{v} \sigma_i \theta^i(x)\right) \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix} \approx \frac{1}{\sqrt{2}} \begin{pmatrix} \theta_1(x) + i\theta_2(x) \\ v + H(x) - i\theta_3(x) \end{pmatrix} \quad (2.41)$$

670 to describe fluctuations from the ground state ϕ_0 . The fields $\theta_i(x)$ represent the
 671 Nambu-Goldstone bosons while $H(x)$ is known as “higgs field.” The fundamental
 672 feature of the parametrization used is that the dependence on the $\theta_i(x)$ fields is
 673 factored out in a global phase that can be eliminated by taking the physical “unitary
 674 gauge” $\theta_i(x) = 0$. Therefore the expansion about the ground state is given by:

$$\phi(x) \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix} \quad (2.42)$$

675 which when substituted into \mathcal{L}_S (eqn. 2.36) results in a Lagrangian containing the now
 676 massive three gauge bosons W^\pm, Z , one massless gauge boson (photon) and the new
 677 Higgs field (H). The three degrees of freedom corresponding to the Nambu-Goldstone
 678 bosons are now integrated into the massive gauge bosons as their longitudinal po-
 679 larizations which were not available when they were massless particles. The effect
 680 by which vector boson fields acquire mass after an spontaneous symmetry breaking,
 681 but without an explicit gauge invariance breaking is known as the “*Higgs mechanism*”.

682

683 The mechanism was proposed by three independent groups: F.Englert and R.Brout
 684 in August 1964 [36], P.Higgs in October 1964 [37] and G.Guralnik, C.Hagen and
 685 T.Kibble in November 1964 [38]; however, its importance was not realized until
 686 S.Glashow [14], A.Salam [15] and S.Weinberg [16], independently, proposed that elec-
 687 tromagnetic and weak interactions are two manifestations of a more general interac-
 688 tion called “electroweak interaction” in 1967.

689 2.3.3 Masses of the gauge bosons

690 The mass of the gauge bosons is extracted by evaluating the kinetic part of Lagrangian
 691 \mathcal{L}_S in the ground state (known also as the vacuum expectation value), i.e.,

$$\left| \left(\partial_\mu - ig \frac{\sigma_i}{2} W_\mu^i - i \frac{g'}{2} B_\mu \right) \phi_0 \right|^2 = \left(\frac{1}{2} v g \right)^2 W_\mu^+ W^{-\mu} + \frac{1}{8} v^2 (W_\mu^3, B_\mu) \begin{pmatrix} g^2 & -gg' \\ -gg' & g'^2 \end{pmatrix} \begin{pmatrix} W^{3\mu} \\ B^\mu \end{pmatrix} \quad (2.43)$$

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

$$M_W = \frac{1}{2} v g. \quad (2.44)$$

The second term in the right side of the eqn.2.43 comprises the masses of the neutral

bosons, but it needs to be written in terms of the gauge fields Z_μ and A_μ in order to be compared to the typical mass terms for neutral bosons, therefore using eqn. 2.28

$$\begin{aligned} \frac{1}{8}v^2[g^2(W_\mu^3)^2 - 2gg'W_\mu^3B^\mu + g'^2B_\mu^2] &= \frac{1}{8}v^2[gW_\mu^3 - g'B_\mu]^2 + 0[g'W_\mu^3 + gB_\mu]^2 \\ &= \frac{1}{8}v^2[\sqrt{g^2 + g'^2}Z_\mu]^2 + 0[\sqrt{g^2 + g'^2}A_\mu]^2 \end{aligned} \quad (2.45)$$

693 and then

$$M_Z = \frac{1}{2}v\sqrt{g^2 + g'^2}, \quad M_A = 0 \quad (2.46)$$

694 2.3.4 Masses of the fermions

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

$$\mathcal{L}_{Yl} = -G_l \left[(\bar{\nu}_l, \bar{l})_L \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} l_R + \bar{l}_R (\phi^-, \bar{\phi}^0) \begin{pmatrix} \nu_l \\ l \end{pmatrix}_L \right], \quad l = e, \mu, \tau. \quad (2.47)$$

697 After the SSB and replacing the usual field expansion about the ground state (eqn.2.40)
698 into \mathcal{L}_{Yl} , the mass term arises

$$\mathcal{L}_{Yl} = -m_l(\bar{l}_L l_R + \bar{l}_R l_L) - \frac{m_l}{v}(\bar{l}_L l_R + \bar{l}_R l_L)H = -m_l \bar{l} \left(1 + \frac{H}{v} \right) \quad (2.48)$$

699

$$m_l = \frac{G_l}{\sqrt{2}}v \quad (2.49)$$

700 where the additional term represents the lepton-Higgs interaction. The quark masses
701 are generated in a similar way as lepton masses but for the upper member of the

702 quark doublet a different Higgs doublet is needed:

$$\phi_c = -i\sigma_2\phi^* = \begin{pmatrix} -\bar{\phi}^0 \\ \phi^- \end{pmatrix}. \quad (2.50)$$

703 Additionally, given that the quark isospin doublets are not constructed in terms of
 704 the mass eigenstates but in terms of the flavor eigenstates, as shown in table 2.5, the
 705 coupling parameters will be related to the CKM matrix elements; thus the quark
 706 Lagrangian is given by:

$$\mathcal{L}_{Yq} = -G_d^{i,j}(\bar{u}_i, \bar{d}_i)_L \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} d_{jR} - G_u^{i,j}(\bar{u}_i, \bar{d}_i)_L \begin{pmatrix} -\bar{\phi}^0 \\ \phi^- \end{pmatrix} u_{jR} + h.c. \quad (2.51)$$

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

$$\mathcal{L}_{Yq} = -m_d^i \bar{d}_i d_i \left(1 + \frac{H}{v} \right) - m_u^i \bar{u}_i u_i \left(1 + \frac{H}{v} \right) \quad (2.52)$$

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

711 2.3.5 The Higgs field

712 After the characterization of the fermions and gauge bosons as well as their interac-
 713 tions, it is necessary to characterize the Higgs field itself. The Lagrangian \mathcal{L}_S in eqn.
 714 2.36 written in terms of the gauge bosons is given by

$$\mathcal{L}_S = \frac{1}{4}\lambda v^4 + \mathcal{L}_H + \mathcal{L}_{HV} \quad (2.53)$$

715

$$\mathcal{L}_H = \frac{1}{2}\partial_\mu H \partial^\mu H - \frac{1}{2}m_H^2 H^2 - \frac{1}{2v}m_H^2 H^3 - \frac{1}{8v^2}m_H^2 H^4 \quad (2.54)$$

716

$$\mathcal{L}_{HV} = m_H^2 W_\mu^+ W^{\mu-} \left(1 + \frac{2}{v}H + \frac{2}{v^2}H^2 \right) + \frac{1}{2}m_Z^2 Z_\mu Z^\mu \left(1 + \frac{2}{v}H + \frac{2}{v^2}H^2 \right) \quad (2.55)$$

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

$$m_H = \sqrt{-2\mu^2} = \sqrt{2\lambda}v \quad (2.56)$$

719 however, it is not predicted by the theory either. The experimental efforts to find
 720 the Higgs boson, carried out by the “Compact Muon Solenoid (CMS)” experiment
 721 and the “A Toroidal LHC AppartuS (ATLAS)” experiments at the “Large Hadron
 722 Collider(LHC)”, gave great results by July of 2012 when the discovery of a new
 723 particle compatible with the Higgs boson predicted by the electroweak theory [39, 40]
 724 was announced. Although at the announcement time there were some reservations
 725 about calling the new particle the “Higgs boson”, today this name is widely accepted.
 726 The Higgs mass measurement, reported by both experiments [41], is in table 2.8.

Property	Value
Electric charge	0
Colour charge	0
Spin	0
Weak isospin	-1/2
Weak hypercharge	1
Parity	1
Mass (GeV/c ²)	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.

727

728 2.3.6 Higgs boson production mechanisms at LHC.

729 At LHC, Higgs boson is produced as a result of the collision of two counter-rotating
 730 protons beams. A detailed description of the LHC machine will be presented in
 731 chapter 3. “The total cross section” is a parameter that quantifies the number of pp
 732 collisions that happen when a number of protons are fired at each other. Different
 733 results can be obtained after a pp collision and for each one the “cross section” is

734 defined as the number of pp collisions that conclude in that particular result with
 respect to the number of protons fired at each other.

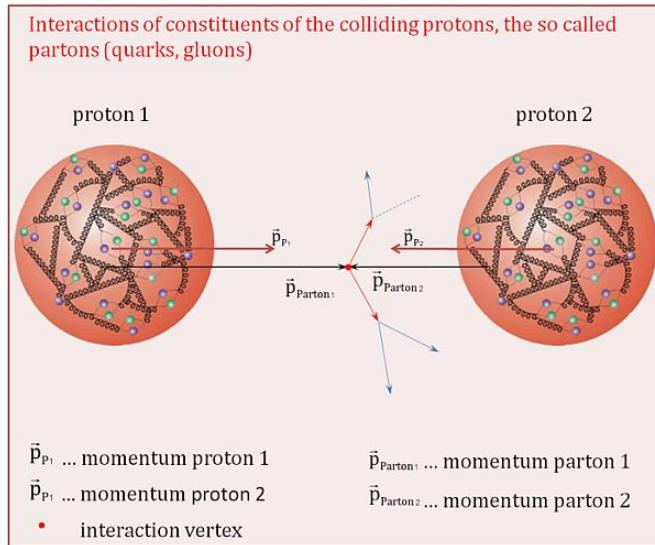


Figure 2.10: Proton-proton collision. Protons are composed of 3 valence quarks, a sea of quarks and gluons; therefore in a proton-proton collision, quarks and gluons are those who collide. [45].

735

736 Protons are composed of quarks and these quarks are bound by gluons; however,
737 what is commonly called the quark content of the proton makes reference to the
738 valence quarks. A sea of quarks and gluons is also present inside the proton as repre-
739 sented in figure 2.10. In a proton-proton (pp) collision, the constituents (quarks and
740 gluons) are those who collide. The pp cross section depends on the momentum of
741 the colliding particles, reason for which it is needed to know how the momentum is
742 distributed inside the proton. Quarks and gluons are known as partons and the func-
743 tions that describe how the proton momentum is distributed among partons inside it
744 are called “parton distribution functions (PDFs)”; PDFs are determined from experi-
745 mental data obtained in experiments where the internal structure of hadrons is tested.

746

⁷⁴⁷ In addition, in physics, a common approach to study complex systems consists in

748 starting with a simpler version of them, for which a well known description is avail-
 749 able, and add an additional “perturbation” which represents a small deviation from
 750 the known behavior. If the perturbation is small enough, the physical quantities as-
 751 sociated with the perturbed system are expressed as a series of corrections to those
 752 of the simpler system; therefore, the more terms are considered in the series (the
 753 higher order in the perturbation series), the more precise is the the description of the
 754 complex system.

755

756 This thesis explores the Higgs production at LHC; therefore the overview presented
 757 here will be oriented specifically to the production mechanisms after pp collisions at
 758 LHC.

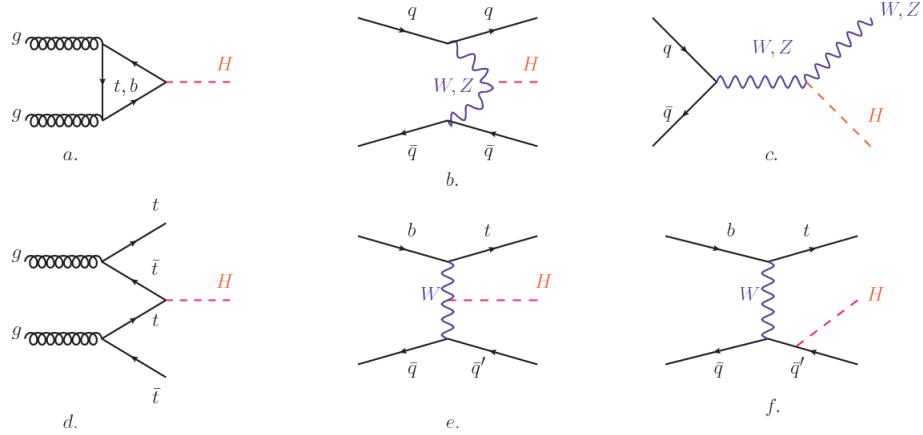


Figure 2.11: Main Higgs production mechanism Feynman diagrams. a. gluon-gluon fusion, b. vector boson fusion (VBF), c. Higgs-strahlung, d. Associated production with a top or bottom quark pair, e-f. associated production with a single top quark.

759 Figure 2.11 shows the Feynman diagrams for the leading order (first order) Higgs
 760 production processes at LHC, while the cross section for Higgs production as a func-
 761 tion of the center of mass-energy (\sqrt{s}) for pp collisions is showed in figure 2.12 left.
 762 The tags NLO (next to leading order), NNLO (next to next to leading order) and
 763 N3LO (next to next to next to leading order) make reference to the order at which

the perturbation series have been considered.

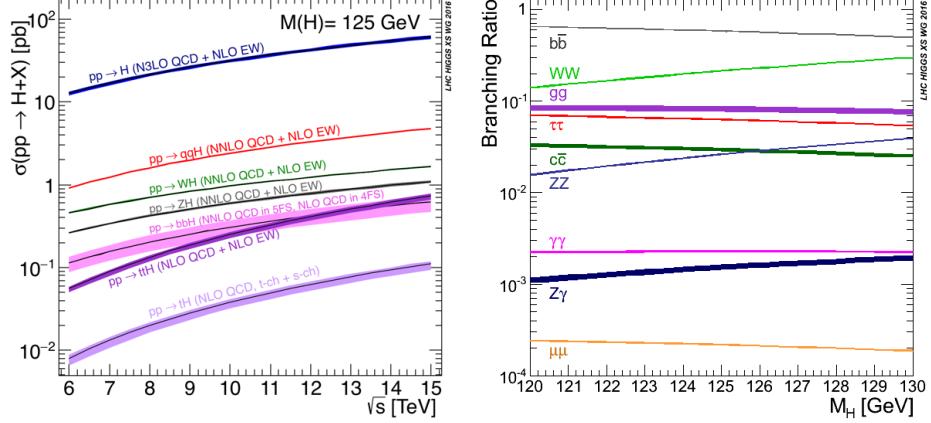


Figure 2.12: Higgs production cross sections (left) and decay branching ratios (right) for the main mechanisms. The VBF is indicated as $q\bar{q}H$ [42].

As shown in eqns 2.47, 2.51 and 2.55, the strength of the Higgs-fermion interaction is proportional to the fermion mass while the strength of the Higgs-gauge boson interaction is proportional to the square of the gauge boson mass, which implies that the Higgs production and decay mechanisms are dominated by couplings $H - (W, Z, t, b, \tau)$.

The main production mechanism is the gluon fusion (figure 2.11a and $pp \rightarrow H$ in figure 2.12) given that gluons carry the highest fraction of momentum of the protons in pp colliders. Since the Higgs boson does not couple to gluons, the mechanism proceeds through the exchange of a virtual top-quark loop given that for it the coupling is the biggest. Note that in this process, the Higgs boson is produced alone, which makes this mechanism experimentally clean when combined with the two-photon or the four-lepton decay channels (see section 2.3.7).

Vector boson fusion (figure 2.11b and $pp \rightarrow q\bar{q}H$ in figure 2.12) has the second largest production cross section. The scattering of two fermions is mediated by a weak gauge boson which later emits a Higgs boson. In the final state, the two fermions

780 tend to be located in a particular region of the detector which is used as a signature
 781 when analyzing the datasets provided by the experiments. More details about how
 782 to identify events of interest in an analysis will be given in chapter 4.

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

787 The associated production with a top or bottom quark pair and the associated pro-
 788 duction with a single top quark (figure 2.11d-f and $pp \rightarrow bbH, pp \rightarrow t\bar{t}H, pp \rightarrow tH$
 789 in figure 2.12) have a smaller cross section than the main three mechanisms above,
 790 but they provide a good opportunity to test the Higgs-top coupling. The analysis
 791 reported in this thesis is developed using these production mechanisms. A detailed
 792 description of the tH mechanism will be given in section 2.4.

793 2.3.7 Higgs decay channels

794 When a particle can decay through several modes, also known as channels, the
 795 probability of decaying through a given channel is quantified by the “branching ratio
 796 (BR)” of the decay channel; thus, the BR is defined as the ratio of number of decays
 797 going through that given channel to the total number of decays. In regard to the
 798 Higgs boson decay, the BR can be predicted with accuracy once the Higgs mass is
 799 known [43, 44]. In figure 2.12 right, a plot of the BR as a function of the Higgs mass
 800 is presented. The largest predicted BR corresponds to the $b\bar{b}$ pair decay channel (see
 801 table 2.9).

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

Table 2.9: Predicted branching ratios and the relative uncertainty for a SM Higgs boson with $m_H = 125\text{GeV}/c^2$. [21]

803 2.4 Associated Production of Higgs Boson and 804 Single Top Quark.

Associated production of Higgs boson has been extensively studied [46–50]. While measurements of the main Higgs production mechanisms rates are sensitive to the strength of the Higgs coupling to W boson or top quark, they are not sensitive to the relative sign between the two couplings. In this thesis, the Higgs boson production mechanism explored is the associated production with a single top quark ($t\bar{h}$) which offers sensitiveness to the relative sign of the Higgs couplings to W boson and to top quark. The description given here is based on the reference [48]

812
813 A process where two incoming particles interact and produce a final state with two
814 particles can proceed in three ways also called channels (see, for instance, figure 2.13
815 omitting the red line). The t-channel represents processes where an intermediate
816 particle is emitted by one of the incoming particles and absorbed by the other. The
817 s-channel represents processes where the two incoming particles merge into an inter-
818 mediate particle which eventually will split into the particles in the final state. The
819 third channel, u-channel, is similar to the t-channel but the two outgoing particles

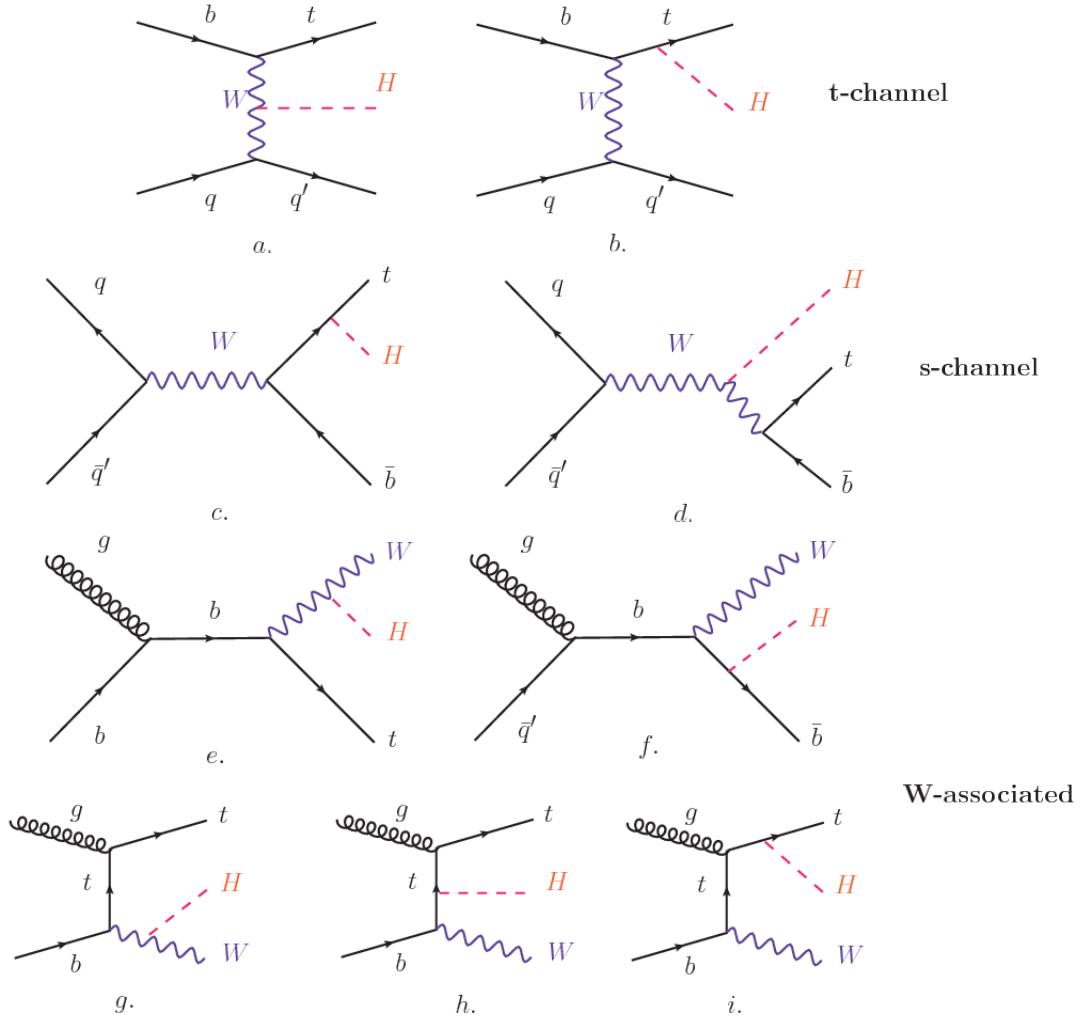


Figure 2.13: Associated higgs production mechanism Feynman diagrams. a.,b. t-channel (tHq), c.,d. s-channel (tHb), e.-i. W-associated.

820 interchange their roles.

821

822 The th production, where Higgs boson can be radiated either from the top quark or
 823 from the W boson, is represented by the leading order Feynman diagrams in figure
 824 2.13. The cross section for the th process is calculated, as usual, summing over
 825 the contributions from the different feynman diagrams; therefore it depends on the
 826 interference between the contributions. In the SM, the interference for t-channel (tHq

process) and W-associated (tHW process) production is destructive [46] 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 [51, 52].

829

830 While the s-channel contribution can be neglected, it will be shown that a deviation
 831 from the SM destructive interference would result in an enhancement of the th cross
 832 section compared to that in SM, which could be used to get information about the
 833 sign of the Higgs-top coupling [48, 49]. In order to describe th production processes,
 834 Feynman diagram 2.13b will be considered; there, the W boson is radiated by a
 835 quark in the proton and eventually it will interact with the b quark. In the high
 836 energy regime, the effective W approximation [53] allows to describe the process as
 837 the emmision of an approximately on-shell W and its hard scattering with the b
 838 quark; i.e. $Wb \rightarrow th$. The scattering amplitude for the process is given by

$$\mathcal{A} = \frac{g}{\sqrt{2}} \left[(\kappa_t - \kappa_V) \frac{m_t \sqrt{s}}{m_W v} A \left(\frac{t}{s}, \varphi; \xi_t, \xi_b \right) + \left(\kappa_V \frac{2m_W s}{v} \frac{1}{t} + (2\kappa_t - \kappa_V) \frac{m_t^2}{m_W v} \right) B \left(\frac{t}{s}, \varphi; \xi_t, \xi_b \right) \right], \quad (2.57)$$

839 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-
 840 tify possible deviations of the couplings, Higgs-Vector boson (H-W) and Higgs-top
 841 (H-t) respectively, from the SM couplings; $s = (p_W + p_b)^2$, $t = (p_W - p_H)^2$, φ is the
 842 Higgs azimuthal angle around the z axis taken parallel to the direction of motion of
 843 the incoming W; A and B are funtions describing the weak interaction in terms of

844 the chiral states of the quarks b and t. Terms that vanish in the high energy limit
 845 have been neglected as well as the Higgs and b quark masses⁸.

846

847 The scattering amplitude grows with energy like \sqrt{s} for $\kappa_V \neq \kappa_t$, in contrast to
 848 the SM ($\kappa_t = \kappa_V = 1$), where the first term in 2.57 cancels out and the amplitude
 849 is constant for large s; therefore, a deviation from the SM predictions represents an
 850 enhancement in the tHq cross section. In particular, for a SM H-W coupling and a H-t
 851 coupling of inverted sign with respect to the SM ($\kappa_V = -\kappa_t = 1$) the tHq cross section
 852 is enhanced by a factor greater 10 as seen in the figure 2.14 taken from reference [48];
 853 reference [54] has reported similar enhancement results.

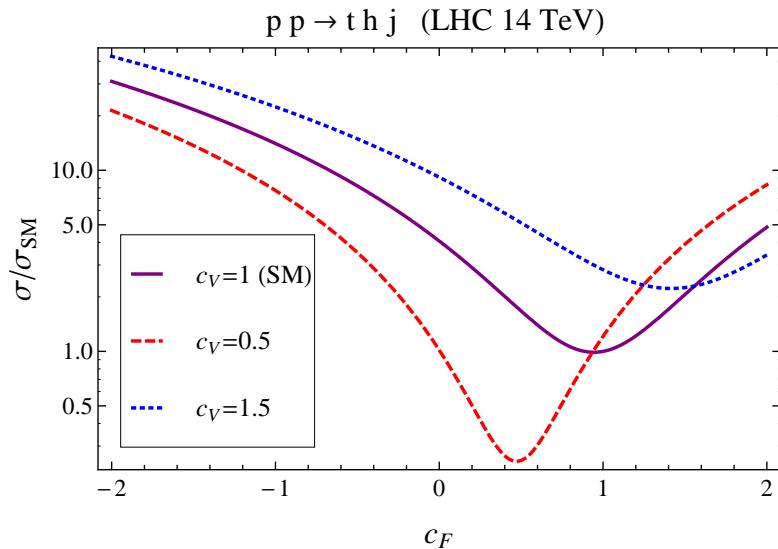


Figure 2.14: Cross section for tHq process as a function of κ_t , normalized to the SM, for three values of κ_V . In the plot c_f refers to the Higgs-fermion coupling which is dominated by the H-t coupling and represented here by κ_t . Solid, dashed and dotted lines correspond to $c_V \rightarrow \kappa_V = 1, 0.5, 1.5$ respectively. Note that for the SM ($\kappa_V = \kappa_t = 1$), the destructive effect of the interference is maximal.

854 A similar analysis is valid for the W-associated channel but, in that case, the inter-
 855 ference is more complicated since there are more than two contributions and an ad-

⁸ A detailed explanation of the structure and approximations used to derive \mathcal{A} can be found in reference [48]

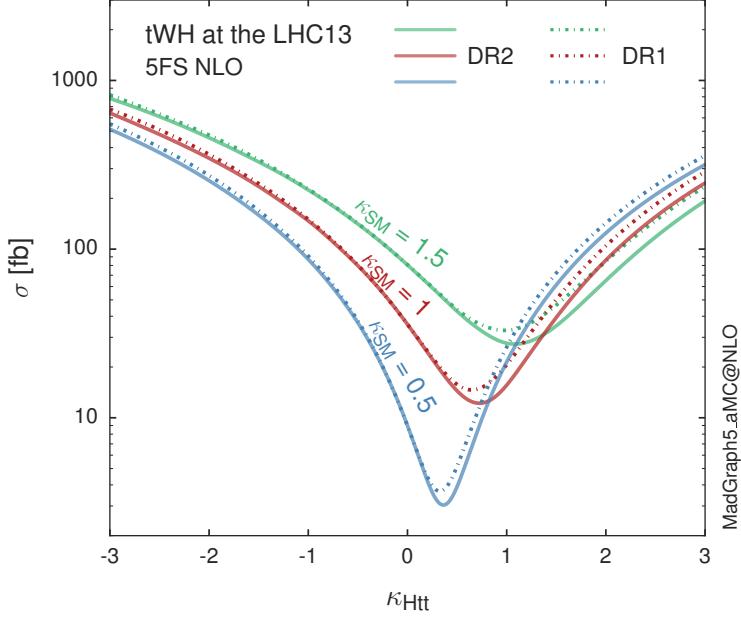


Figure 2.15: Cross section for tHW process as a function of κ_{Htt} , for three values of κ_{SM} at $\sqrt{s} = 13$ TeV. $\kappa_{Htt}^2 = \sigma_{Htt}/\sigma_{Htt}^{SM}$ is a simple rescaling of the SM Higgs interactions.

ditional interference with the production of Higgs boson and a top pair process($t\bar{t}H$).
The calculations are made using the so-called Diagram Removal (DR) technique where
interfering diagrams are removed (or added) from the calculations in order to evaluate
the impact of the removed contributions. DR1 was defined to neglect $t\bar{t}H$ interference
while DR2 was defined to take $t\bar{t}H$ interference into account [55]. As shown in figure
2.15, the tHW cross section is enhanced from about 15 fb (SM: $\kappa_{Htt} = 1$) to about
150 fb ($\kappa_{Htt} = -1$). Differences between curves for DR1 and DR2 help to gauge the
impact of the interference with $t\bar{t}H$.
Results of the calculations of the tHq and tHW cross sections at $\sqrt{s} = 13$ TeV can be
found in reference [56] and a summary of the results is presented in table 2.11.

	\sqrt{s} TeV	$\kappa_t = 1$	$\kappa_t = -1$
$\sigma^{LO}(tHq)(\text{fb})$ [48]	8	≈ 17.4	≈ 252.7
	14	≈ 80.4	≈ 1042
$\sigma^{NLO}(tHq)(\text{fb})$ [48]	8	$18.28^{+0.42}_{-0.38}$	$233.8^{+4.6}_{-0.0}$
	14	$88.2^{+1.7}_{-0.0}$	$982.8^{+28}_{-0.0}$
$\sigma^{LO}(tHq)(\text{fb})$ [54]	14	≈ 71.8	≈ 893
$\sigma^{LO}(tHW)(\text{fb})$ [54]	14	≈ 16.0	≈ 139
$\sigma^{NLO}(tHq)(\text{fb})$ [56]	8	$18.69^{+8.62\%}_{-17.13\%}$	-
	13	$74.25^{+7.48\%}_{-15.35\%}$	$848^{+7.37\%}_{-13.70\%}$
	14	$90.10^{+7.34\%}_{-15.13\%}$	$1011^{+7.24\%}_{-13.39\%}$
$\sigma^{LO}(tHW)(\text{fb})$ [55]	13	$15.77^{+15.91\%}_{-15.76\%}$	-
$\sigma^{NLO}DR1(tHW)(\text{fb})$ [55]	13	$21.72^{+6.52\%}_{-5.24\%}$	≈ 150
$\sigma^{NLO}DR2(tHW)(\text{fb})$ [55]	13	$16.28^{+7.34\%}_{-15.13\%}$	≈ 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 flippling in the sign of the H-t coupling with respect to the SM one.

867 2.5 The CP-mixing in tH processes

868 In addition to the sensitivity to sign of the H-t coupling, tHq and tHW processes have
 869 been proposed as a tool to investigate the possibility of a H-t coupling that does not
 870 conserve CP [50, 55, 57]. Current experimental results are consistent with SM H-V
 871 and H-t couplings; however, negative H-t coupling is not excluded completely [59].

872

873 In this thesis, the sensitivity of th processes to CP-mixing is also studied in the
 874 effective field theory framework and based in references [50, 55]; a generic particle
 875 (X_0) of spin-0 and a general CP violating interaction with the top quark, can couple
 876 to scalar and pseudoscalar fermionic densities. The H-W interaction is assumed to
 877 be SM-like. The Lagrangian modeling the H-t interaction is given by

$$878 \quad \mathcal{L}_0^t = -\bar{\psi}_t (c_\alpha \kappa_{Htt} g_{Htt} + i s_\alpha \kappa_{Att} g_{Att} \gamma_5) \psi_t X_0, \quad (2.58)$$

878 where α is the CP-mixing phase, $c_\alpha \equiv \cos \alpha$ and $s_\alpha \equiv \sin \alpha$, κ_{Htt} and κ_{Att} are real
 879 dimensionless rescaling parameters⁹, $g_{Htt} = g_{Att} = m_t/v = y_t/\sqrt{2}$ and $v \sim 246$ GeV is
 880 the Higgs vacuum expectation value. In this parametrization, it is easy to recover
 881 three special cases

- 882 • CP-even coupling $\rightarrow \alpha = 0^\circ$
- 883 • CP-odd coupling $\rightarrow \alpha = 90^\circ$
- 884 • SM coupling $\rightarrow \alpha = 0^\circ$ and $\kappa_{Htt} = 1$

885 The loop induced X_0 coupling to gluons can also be described in terms of the
 886 parametrization above, according to

$$\mathcal{L}_0^g = -\frac{1}{4} \left(c_\alpha \kappa_{Hgg} g_{Hgg} G_{\mu\nu}^a G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg} G_{\mu\nu}^a \tilde{G}^{a,\mu\nu} \right) X_0. \quad (2.59)$$

887 where $g_{Hgg} = -\alpha_s/3\pi v$ and $g_{Agg} = \alpha_s/2\pi v$. Under the assumption that the top quark
 888 dominates the gluon-fusion process at LHC energies, $\kappa_{Hgg} \rightarrow \kappa_{Htt}$ and $\kappa_{Agg} \rightarrow \kappa_{Att}$,
 889 so that the ratio between the gluon-gluon fusion cross section for X_0 and for the SM
 890 Higgs prediction can be written as

$$\frac{\sigma_{NLO}^{gg \rightarrow X_0}}{\sigma_{NLO,SM}^{gg \rightarrow H}} = c_\alpha^2 \kappa_{Htt}^2 + s_\alpha^2 \left(\kappa_{Att} \frac{g_{Agg}}{g_{Hgg}} \right)^2. \quad (2.60)$$

891 If the rescaling parameters are set to

$$\kappa_{Htt} = 1, \quad \kappa_{Att} = \left| \frac{g_{Hgg}}{g_{Agg}} \right| = \frac{2}{3}. \quad (2.61)$$

892 the gluon-fusion SM cross section is reproduced for every value of the CP-mixing
 893 angle α ; therefore, by imposing that condition to the Lagrangian density 2.58, the

⁹ analog to κ_t and κ_V

CP-mixing angle is not constrained by current data. Figure 2.16 shows the NLO cross sections for t-channel tX_0 (blue) and $t\bar{t}X_0$ (red) associated production processes as a function of the CP-mixing angle α . X_0 is a generic spin-0 particle with top quark CP-violating coupling. Rescaling factors κ_{Htt} and κ_{Att} have been set to reproduce the SM gluon-fusion cross sections.

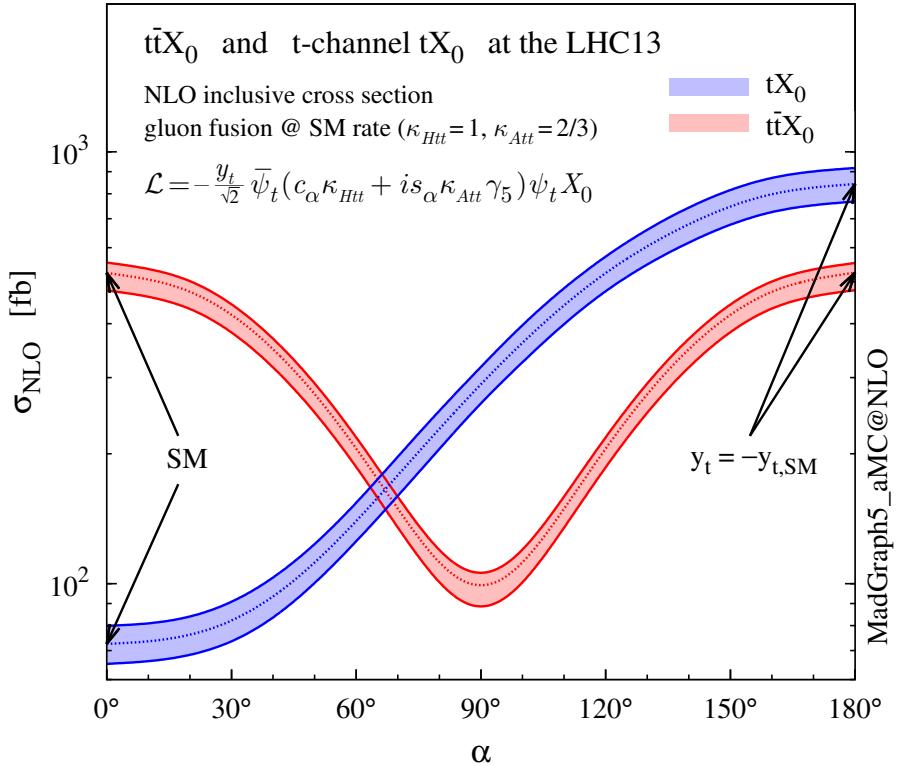


Figure 2.16: NLO cross sections for t-channel tX_0 (blue) and $t\bar{t}X_0$ (red) associated production processes as a function of the CP-mixing angle α . X_0 is a generic spin-0 particle with top quark CP-violating coupling [50].

It is interesting to notice that the tX_0 cross section is enhanced, by a factor of about 10, when a continuous rotation in the scalar-pseudoscalar plane is applied; this enhancement is similar to the enhancement produced when the H-t coupling is flipped in sign with respect to the SM ($y_t = -y_{t,SM}$ in the plot), as showed in section 2.4. In contrast, the degeneracy in the $t\bar{t}X_0$ 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 $\alpha \sim 60^\circ$.

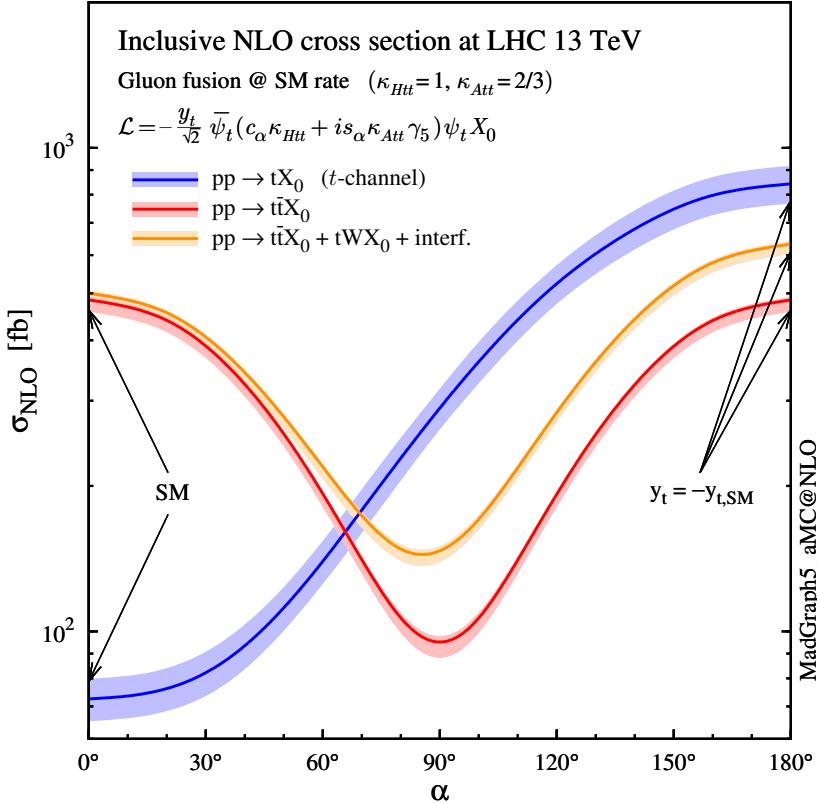


Figure 2.17: NLO cross sections for t-channel tX_0 (blue), $t\bar{t}X_0$ (red) associated production processes and combined $tWX_0 + t\bar{t}X_0$ (including interference) production as a function of the CP-mixing angle α [50].

905

906 A similar parametrization can be used to investigate the tHW process sensitivity to
 907 CP-violating H-t coupling. As said in 2.4, the interference in the W-associated chan-
 908 nel is more complicated because there are more than two contributions and also there
 909 is interference with the $t\bar{t}H$ production process.

910

911 Figure 2.17 shows the NLO cross sections for t-channel tX_0 (blue), $t\bar{t}X_0$ (red) asso-
 912 ciated production and for the combined $tWX_0 + t\bar{t}X_0 +$ interference (orange) as a
 913 function of the CP-mixing angle. It is clear that the effect of the interference in the

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

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

919 **2.6 Experimantal status of anomalous**
 920 **Higg-fermion coupling.**

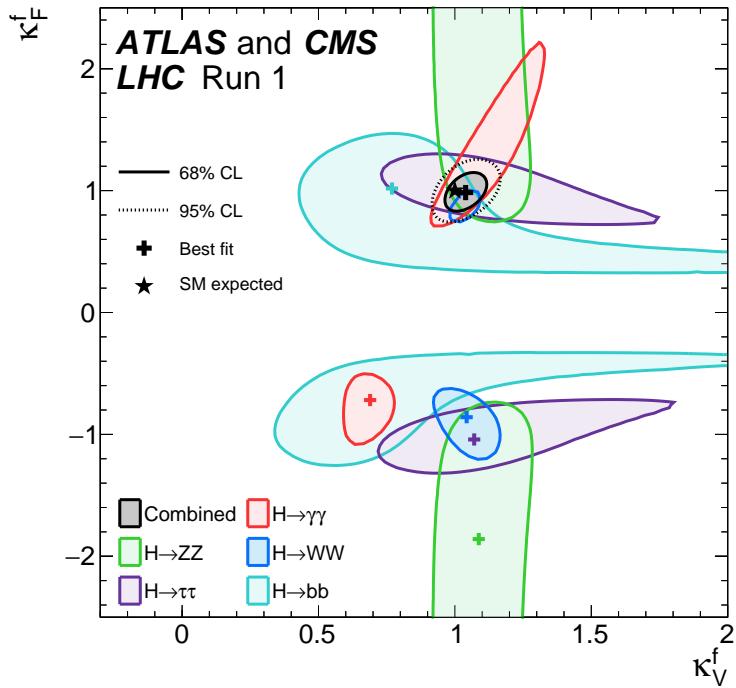


Figure 2.18: Combination of coupling modifiers κ_t - κ_V fits of ATLAS and CMS; also shown the individual decay channels combination and their global combination. No assumptions have been made on the sign of the coupling modifiers [59].

921 ATLAS and CMS have performed analysis of the anomalous H-f coupling by making
 922 likelihood scans for the two coupling modifiers, κ_t and κ_V , under the assumption that

923 $\kappa_Z = \kappa_W = \kappa_V$ and $\kappa_t = \kappa_\tau = \kappa_b = \kappa_f$. Figure 2.18 shows the result of the combination
924 of ATLAS and CMS fits; also the individual decay channels combination and the
925 global combination result are shown.

926 While all the channels are compatible for positive values of the modifiers, for negative
927 values of κ_t there is no compatibility. The best fit for individual channels is compatible
928 with negative values of κ_t except for the $H \rightarrow bb$ channel which is expected to be the
929 most sensitive channel; therefore, the best fit for the global fit yields $\kappa_t \geq 0$. Thus,
930 the anomalous H-t coupling cannot be excluded completely.

931 Chapter 3

932 The CMS experiment at the LHC

933 3.1 Introduction

934 Located in the Swiss-French border, the European Council for Nuclear Research
935 (CERN) is the largest scientific organization leading the particle physics research.
936 About 13000 people in a broad range of fields including users, students, scientists,
937 engineers among others, contribute to the data taking and analysis, with the goal
938 of unveiling the secrets of the nature and revealing the fundamental structure of the
939 universe. CERN is also the home of the Large Hadron Collider (LHC), the largest
940 circular particle accelerator around the world, where protons (or heavy ions) travel-
941 ing close to the speed of light, are made to collide. These collisions open a window
942 to investigate how particles (and their constituents if they are composite) interact
943 with each other, providing clues about the laws of the nature. This chapter present
944 an overview of the LHC structure and operation. A detailed description of the CMS
945 detector is offered, given that the data used in this thesis have been taken with this
946 detector.

947 3.2 The LHC

948 With 27 km of circumference, the LHC is currently the largest and most powerful
 949 accelerator in the world. It is installed in the same tunnel where the large Electron-
 950 Positron (LEP) collider was located, taking advantage of the existing infraestructure.
 951 The LHC is also the larger accelerator in the CERN's accelerator complex and is
 952 assisted by several successive accelerating stages before the particles are injected into
 953 the LHC ring where they reach their maximum eneregy (see figure 3.1).

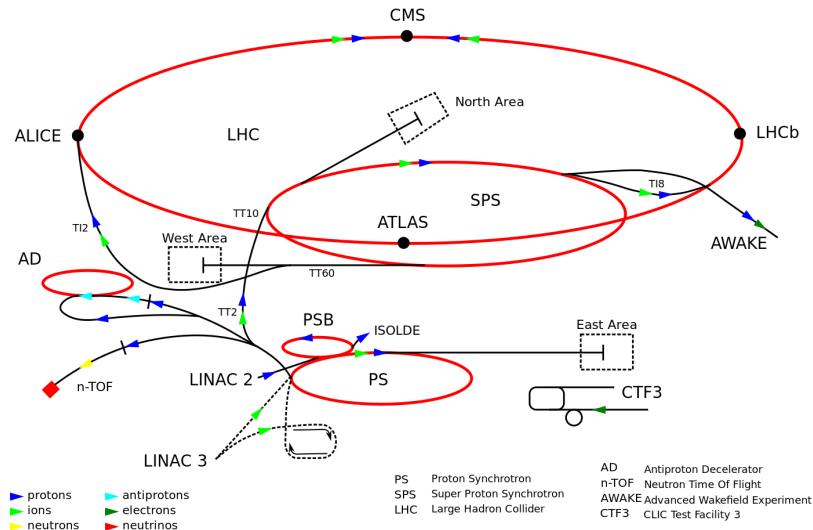


Figure 3.1: CERN accelerator complex. Blue arrows show the path followed by protons along the acceleration process [60].

954 LHC run in three modes depending on the particles being accelerated

- 955 ● Proton-Proton collisions (pp) for multiple physics experiments.
- 956 ● Lead-Lead collisions (Pb-Pb) for heavy ion experiments.
- 957 ● Proton-Lead collisions (p-Pb) for quark-gluon plasma experiments.

958 In this thesis pp collisions will be considered.

959

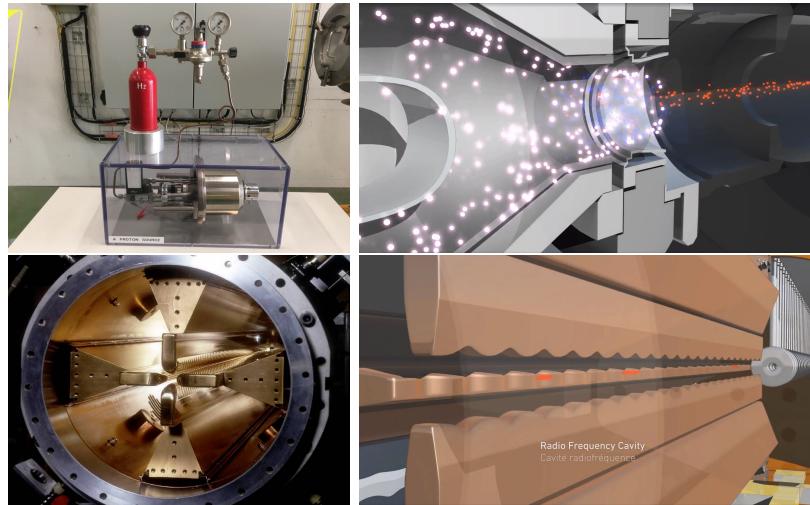


Figure 3.2: LHC protons source and first acceleration stage. Top: the bottle contains hydrogen gas (white dots) which is injected into the metal cylinder to be broken down into electrons(blue dots) and protons(red dots); Bottom: the obtained protons are directed towards the radio frequency quadrupole which perform the first acceleration, focus the beam and create the bunches of protons. [64, 65]

960 Collection of protons starts with hydrogen atoms taken from a bottle, containing hy-
 961 drogen gas, and injecting them in a metal cillinder; hydrogen atoms are broken down
 962 into electrons and protons by an intense electric field (see figure3.2 top). The result-
 963 ing protons leave the metal cylinder towards a radio frecuency quadrupole (RFQ)
 964 that focus the beam, accelerate the protons and create the packets of protons called
 965 bunches. In the RFQ, an electric field is generated by a RF wave at a frecuency that
 966 matches the resonance frecuency of the cavity where the electrodes are contained.
 967 The beam of protons traveling on the RFQ axis experience an alternating electric
 968 field gradient that generates the focusing forces.

969

970 In order to accelerate the protons, a longitudinal time-varying electric field compo-
 971 nent is added to the system; it is done by giving the electrodes a sinus-like profile as
 972 shown in figure 3.2 bottom. By matching the speed and phase of the protons with the
 973 longitudinal electric field the bunching is performed; protons synchronized with the

974 RFQ (synchronous proton) does not feel an accelerating force, but those protons in
 975 the beam that have more (or less) energy than the synchronous proton (asynchronous
 976 protons) will feel a decelerating (accelerating) force; therefore, asynchronous protons
 977 will oscillate around the synchronous ones forming bunches of protons [62]. From
 978 the RFQ emerges protons with energy 750 keV in bunches of about 1.15×10^{11} pro-
 979 tons [63].

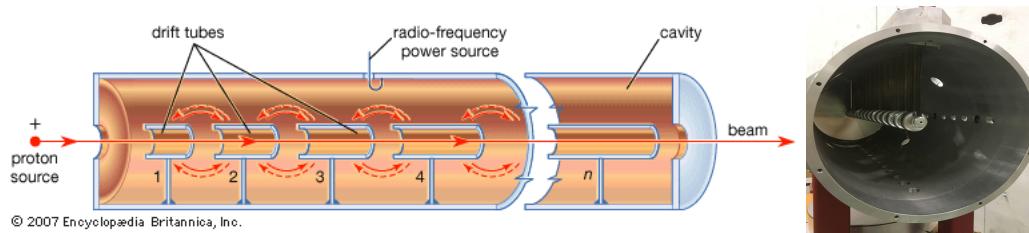


Figure 3.3: The LINAC2 accelerating system at CERN. Radio frequency (RF) generated electric fields create acceleration and deceleration zones inside the cavity; deceleration zones are blocked by drift tubes where quadrupole magnets focus the proton beam. [66]

980 Proton bunches coming from the RFQ goes to the linear accelerator 2 (LINAC2)
 981 where they are accelerated to reach 50 MeV energy. In the LINAC2 stage, acceler-
 982 ation is performed using radio frequency generated electric fields which create zones
 983 of acceleration and deceleration as shown in figure 3.3. In the decelerations zones
 984 the electric field is blocked using drift tubes where protons are free to drift while
 985 quadrupole magnets focus the beam.

986

987 The beam coming from LINAC2 is injected into the proton synchrotron booster
 988 (PSB) to reach 1.4 GeV in energy. The next acceleration is provided at the pro-
 989 ton synchrotron (PS) up to 26 GeV, followed by the injection into the super proton
 990 synchrotron (SPS) where protons are accelerated to 450 GeV. Finally, protons are
 991 injected into the LHC where they are accelerated to the target energy of 6.5 TeV.
 992 PSB, PS, SPS and LHC accelerate protons using the same RF acceleration technic

described before.

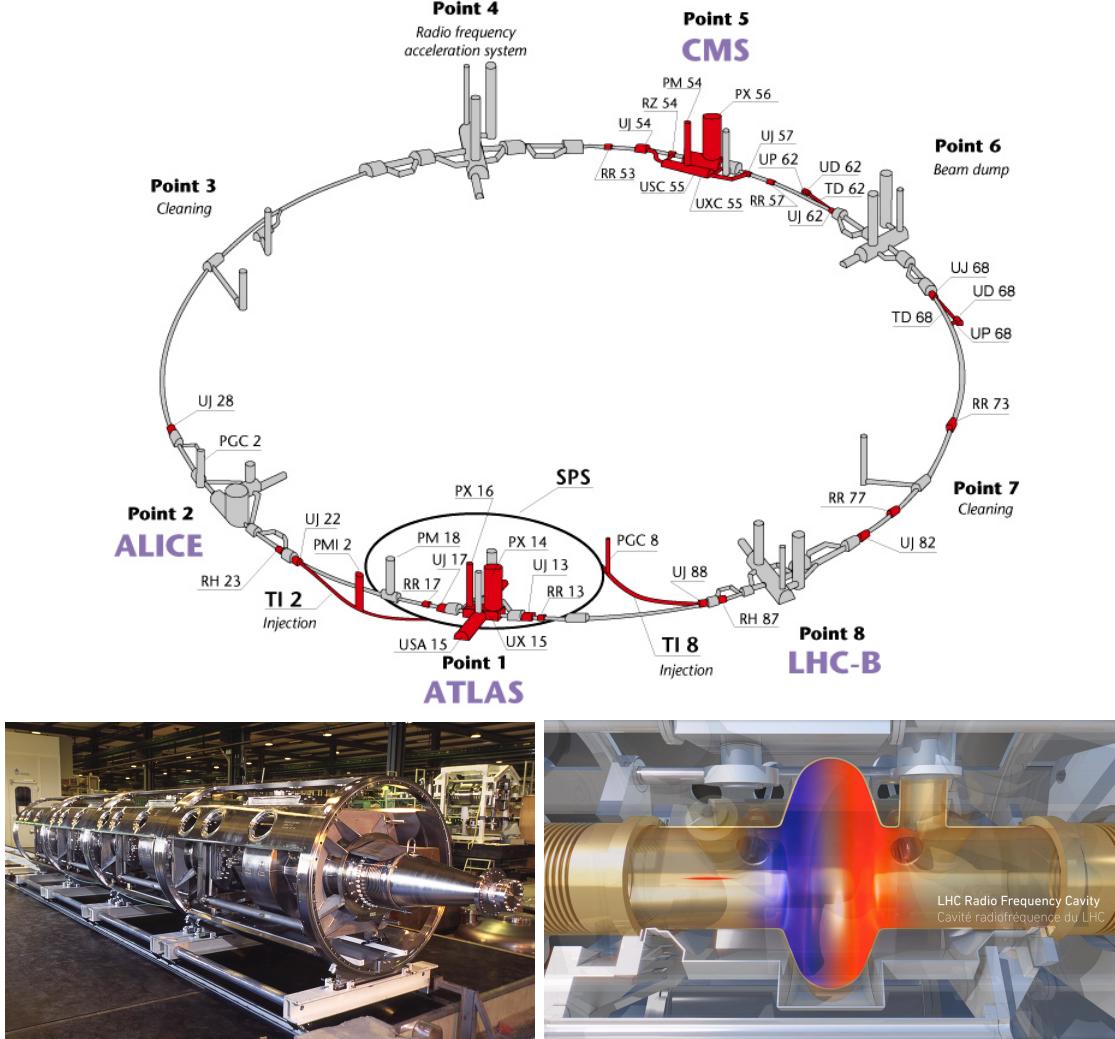


Figure 3.4: Top: LHC layout. The red zones indicate the infrastructure additions to the LEP installations, built to accommodate the ATLAS and CMS experiments which exceed the size of the former experiments located there [61]. Bottom: LHC RF cavities. A module accommodates 4 cavities that accelerate protons and preserve the bunch structure of the beam. [65, 67]

LHC have a system of 16 RF cavities located in the so-called point 4, as shown in figure 3.4 top, tuned at a frequency of 400 MHz and the protons are carefully timed so additionally to the acceleration effect the bunch structure of the beam is preserved. Bottom side of figure 3.4 shows a picture of a Rf module composed of 4 RF cavities

998 working in a superconducting state at 4.5 K; also is showed a representation of the
 999 accelerating electric field that accelerates the protons in the bunch.

1000

1001 While protons are accelerated in one section of the LHC ring, where the RF cavities
 1002 are located, in the rest of their path they have to be kept in the curved trajectory
 1003 defined by the LHC ring. Technically, LHC is not a perfect circle; RF, injection, beam
 1004 dumping, beam cleaning and sections before and after the experimental points where
 1005 protons collide are all straight sections. In total, there are 8 arcs 2.45 Km long each
 1006 and 8 straight sections 545 m long each. In order to curve the proton's trajectory in
 1007 the the arc sections, superconducting dipole magnets are used.

1008

1009 Inside the LHC ring, there are two proton beams traveling in opposite directions in
 1010 two separated beam pipes; the beam pipes are kept at ultra high vacuum ($\sim 10^{-9}$
 1011 Pa) to ensure that there are no particles that interact with the proton beams. The
 1012 superconducting dipole magnets used in LHC are made of a NbTi alloy, capable of
 1013 transporting currents of about 12000 A when cooled at a temperature below 2K using
 1014 liquid helium (see figure 3.5).

1015 Protons in the arc sections of LHC feel a centripetal force exerted by the dipole
 1016 magnets which is perpendicular to the beam trajectory; The magnitude of magnetic
 1017 field needed can be found assuming that protons travel at $v \approx c$, using the standard
 1018 values for proton mass and charge and the LHC radius, as

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

1019 wich is about 100000 times the Earth's magnetic field. A representation of the mag-
 1020 netic field generated by the dipole magnets is shown in the bottom left side of figure

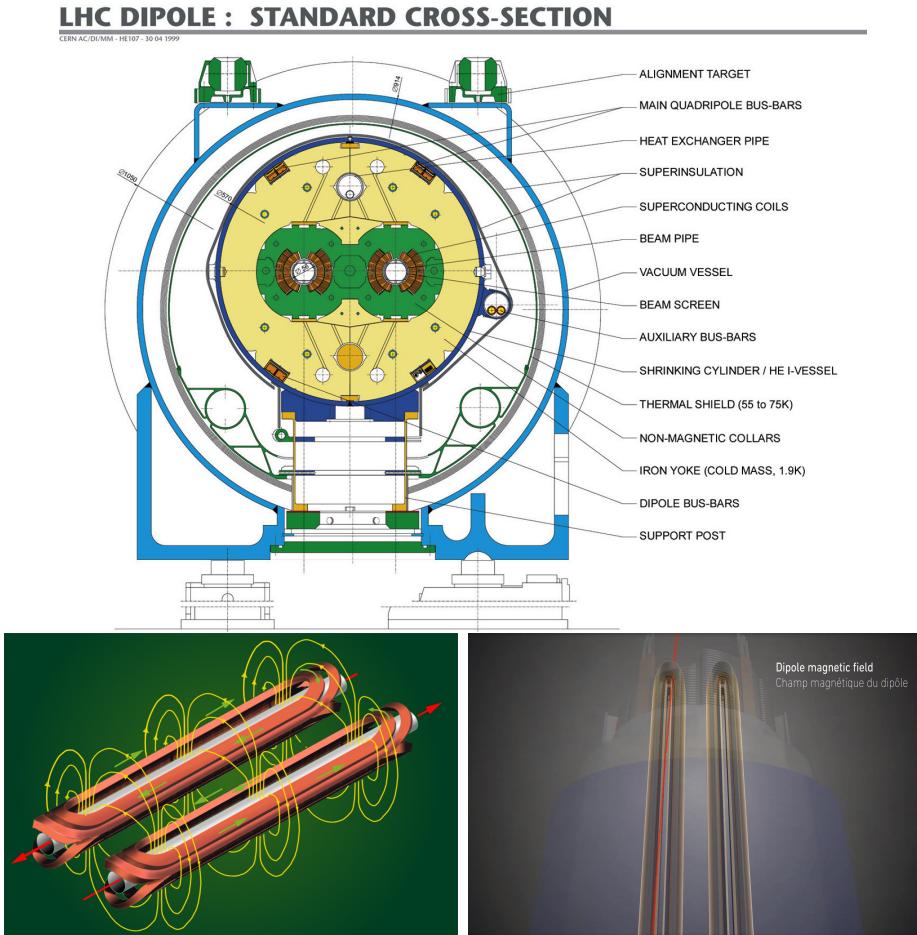


Figure 3.5: Top: LHC dipole magnet transversal view; cooling, shielding and mechanical support are indicated. Bottom left: Magnetic field generated by the dipole magnets; note that the direction of the field inside one beam pipe is opposite with respect to the other beam pipe which guarantee that both 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 in the bottom right side [65, 68, 69].

1021 3.5. The bending effect of the magnetic field on the proton beam is shown in the
 1022 bottom right side of figure 3.5. Note that the dipole magnets are not curved; the arc
 1023 section of the LHC ring is composed of straight dipole magnets of about 15 m. In
 1024 total there are 1232 dipole magnets along the LHC ring.
 1025 In addition to bending the beam trajectory, the beam has to be focused so it stays in
 1026 side the beam pipe. The focusing is performed by quadrupole magnets installed in

1027 another straight section; in total 858 quadrupole magnets are installed along the LHC
 1028 ring. Other effects like electromagnetic interaction among bunches, interaction with
 1029 electron clouds from the beam pipe, gravitational force on the protons, differences in
 1030 energy among protons in the same bunch, among others, are corrected using sextupole
 1031 and other magnetic multipoles.

1032 The two proton beams inside the LHC ring are made of bunches with a cylindrical
 1033 shape of about 7.5 cm long and about 1 mm in diameter; when bunches are close
 1034 to the collision point (CP), the beam is focused up to a diameter of about 16 μm
 1035 in order to maximize the luminosity (L) defined as the number of collisions per unit
 1036 area and per second. Luminosity can be calculated using

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

1037 where f is the revolution frequency, n is the number of bunches per beam, N_1 and N_2
 1038 are the number of protons per bunch, σ_x and σ_y are the gaussian transverse sizes of
 1039 the bunches. Using

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

$$n = 2808$$

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

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

1040

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

1041 Luminosity is a fundamental aspect for LHC given that the bigger luminosity, the
 1042 bigger number of collisions, which means that for processes with a very small cross

section the number of expected occurrences is increased and so the chances of being detected. The integrated luminosity collected by the CMS experiment during 2016 is shown in figure 3.6; the data analyzed in this thesis corresponds to an integrated luminosity of 35.9 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$.

A way to increase L is increasing the number of bunches in the beam. Currently, the separation between two consecutive bunches in the beam is 7.5 m which corresponds to a time separation of 25 ns. In the full LHC ring the allowed number of bunches is $n = 27\text{km}/7.5\text{m} = 3600$; however, there are some gaps in the bunch pattern intended for preparing the dumping and injection of the beam, thus, the proton beams are composed of 2808 bunches.

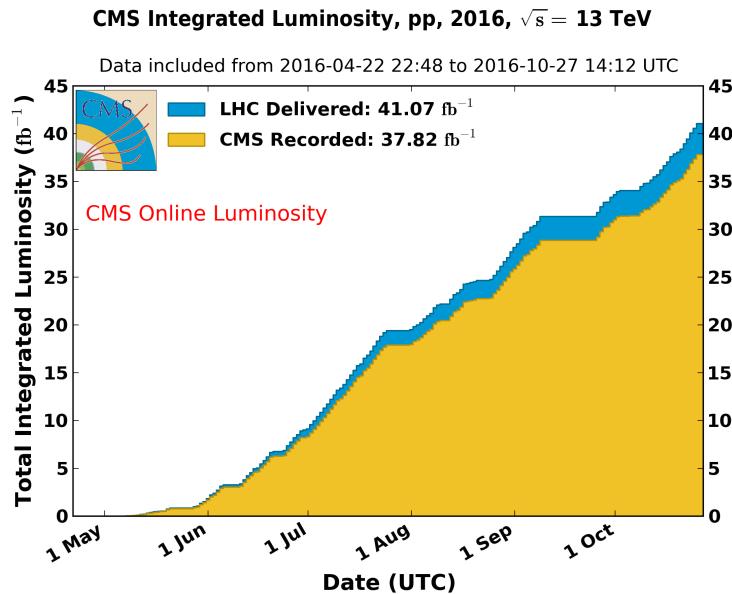


Figure 3.6: Integrated luminosity delivered by LHC and recorded by CMS during 2016. The difference between the delivered and the recorded luminosities is due to fails and issues occurred during the data taking in the CMS experiment [70].

Once the proton beams reach the desired energy, they are brought to cross each other producing proton-proton collisions. The bunch crossing happens in precise places where the four LHC experiments are located, as seen in figure 3.7 left. In 2008, the

1056 first set of collisions involved protons with $\sqrt{s} = 7$ TeV; the energy was increased to
 1057 8 TeV in 2012 and to 13 TeV in 2015.

1058 CMS and ATLAS experiments, which are multi-purpose experiments, are enabled
 1059 to explore physics in any of the collision modes. LHCb experiment is optimized
 1060 to explore bottom quark physics, while ALICE is optimized for heavy ion collisions
 1061 searches; TOTEM and LHCf are dedicated to forward physics studies; MoEDAL (not
 1062 indicated in the figure) is intended for monopoles or massive pseudo stable particles
 1063 searches.

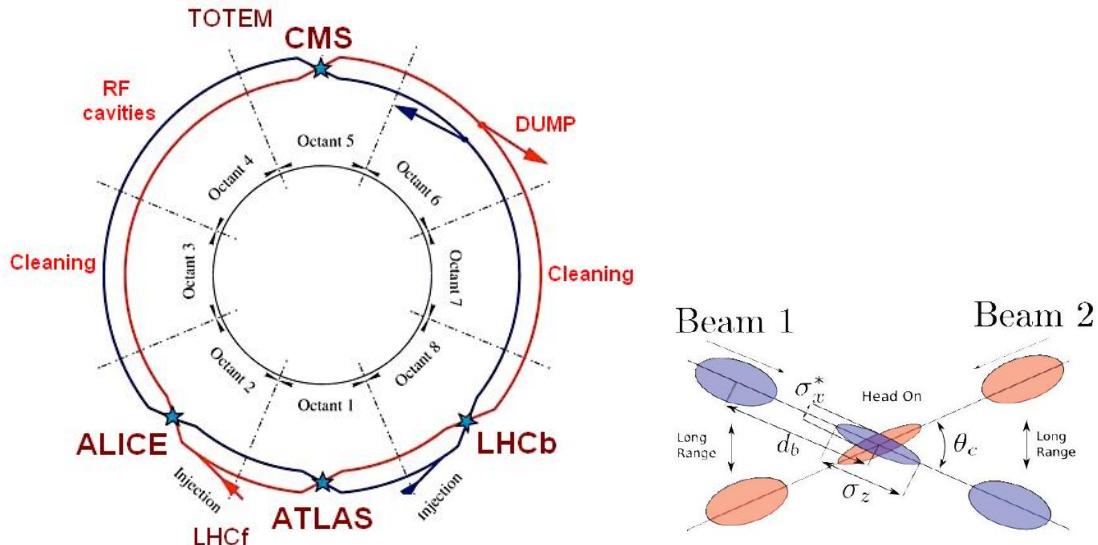


Figure 3.7: Left: LHC interaction points. Bunch crossing occurs where the LHC experiments are located [71]. Sections indicated as cleaning are dedicated to collimate the beam in order to protect the LHC ring from collisions with protons in very spreaded bunches. Right: bunch crossing scheme. Since the bunch crossing is not perfectly head-on, the luminosity is reduced in a factor of 17%.

1064 At the CP there are two interesting details that need to be addressed. The first
 1065 one is that the bunch crossing does not occur head-on but at a small crossing angle
 1066 (280 μ rad in CMS and ATLAS) as shown in the right side of figure 3.7, affecting the
 1067 overlapping between bunches; the consequence is a reduction of about 17% in the
 1068 luminosity. The second one is occurrence of multiple pp collisions in the same bunch

1069 crossing; this effect is called pile-up (PU). A fairly simple estimation of the PU follows
 1070 from estimating the probability of collision between two protons, one from each of
 1071 the bunches in course of collision; it depends roughly on the ratio of proton size and
 1072 the cross section of the bunch in the interaction point, i.e.,

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

1073 however, there are $N = 1.15 \times 10^{11}$ protons in a bunch, thus the estimated number of
 1074 collisions in a bunch crossing is

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

1075 about 20 of those pp collisions are inelastic. Each collision generates a vertex, but
 1076 only the most energetic is considered as a primary vertex; the rest are considered
 1077 as PU vertices. A simulation of a multiple pp collision event in a bunch crossing at
 1078 CMS is showed in figure3.8. Unstable particles outgoing from the primary vertex will
 1079 eventually decay; this decay vertex is known as a secondary vertex.

1080 When the beams are exhausted, i.e. the number of protons in the bunches is reduced
 1081 beyond a limit, or in case of emergency, the beams have to be extracted from the
 1082 beam pipes; the dumping system, in the dump section, perform the extraction safely
 1083 by directing the beams towards graphite blocks that absorb the beam energy.

1084

1085 Next section present a description of the CMS detector, since it is the detector used
 1086 to collect the data used in this thesis.

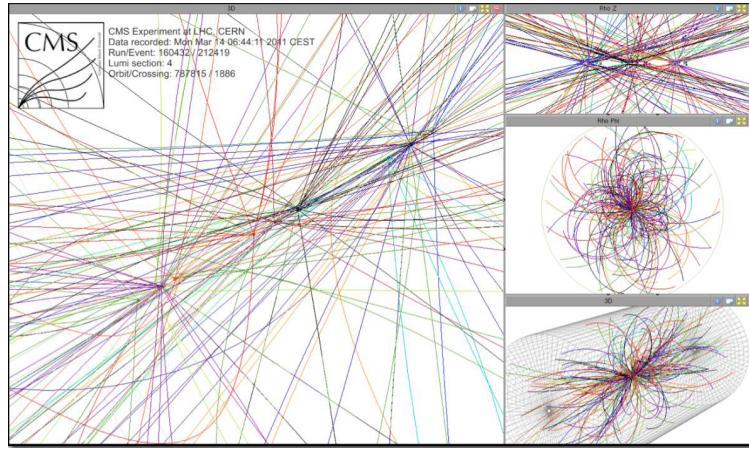


Figure 3.8: Multiple pp collision bunch crossing at CMS. Only the most energetic vertex is considered and the rets are cataloged as PU vertices [].

1087 3.3 The CMS experiment

1088 CMS is a general purpose detector designed to conduct research in a wide range of
 1089 physics from standard model to new physics like extra dimensions and dark matter.
 1090 Located at the point 5 in the LHC layout as shown in figure 3.4, CMS is composed
 1091 of several detection systems distributed in a cylindrical structure,. In total, CMS
 1092 weights about 12500 tons in a very compact 21.6 m long and 14.6 m diameter cylin-
 1093 der. It was built in 15 separate sections at the ground level and lowered to the
 1094 cavern individually to be assembled. A complete and detailed description of the CMS
 1095 detector and its components is given in reference [72] on which this section is based in.
 1096

1097 Figure 3.9 shows the layout of the CMS detector. The design is driven by the require-
 1098 ments on the identification, momentum resolution and unambiguous charge determi-
 1099 nation of the muons; therefore, a large bending power is provided by the solenoid
 1100 magnet made of superconducting cable capable to generate a 3.8 T magnetic field.
 1101 The detection system is composed of (from the innermost to the outermost)

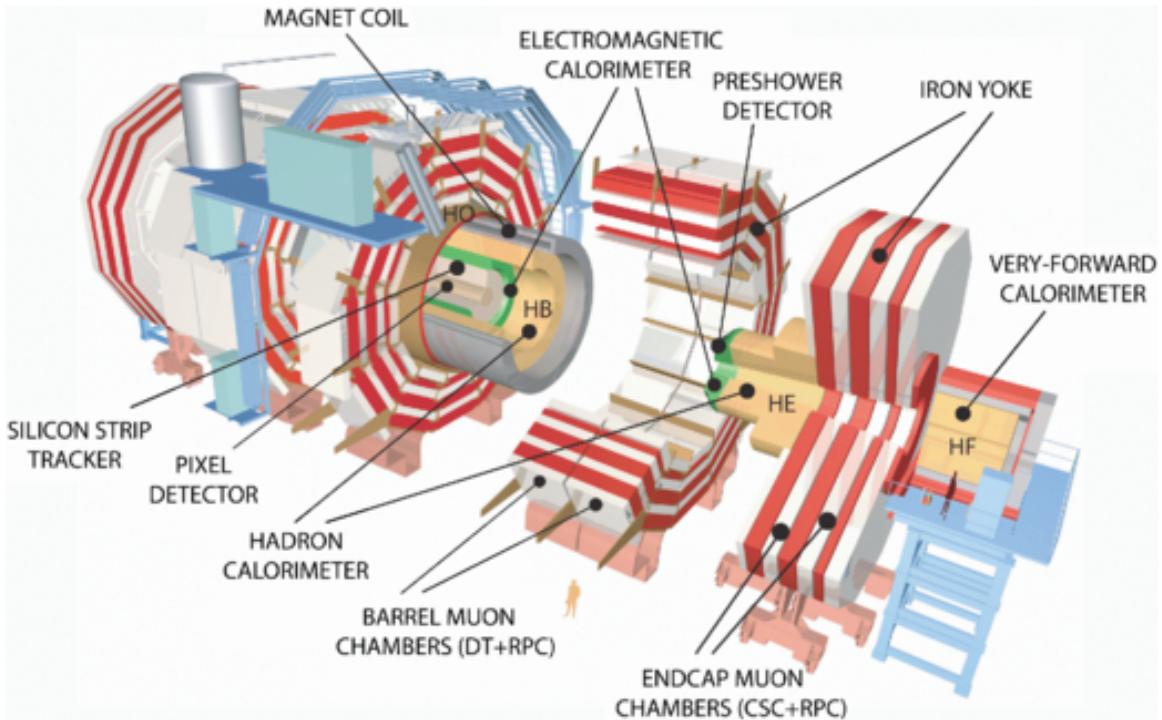


Figure 3.9: CMS detector drawing. The several subdetectors are indicated. The central region of the detector is referred as the Barrel section while the endcaps are referred as the forward sections. [73].

1102 • Pixel detector.

1103 • Silicon strip tracker.

1104 • Preshwoer detector.

1105 • Electromagnetic calorimeter.

1106 • Hadronic calorimeter.

1107 • Muon chambers (Barrel and endcap)

1108 The central region of the detector is commonly referred as the barrel section while the
 1109 endcaps are referred as the forward sections of the detector; thus, each subdetector
 1110 is composed of a barrel section and a forward section.

3.3.1 Coordinate system

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

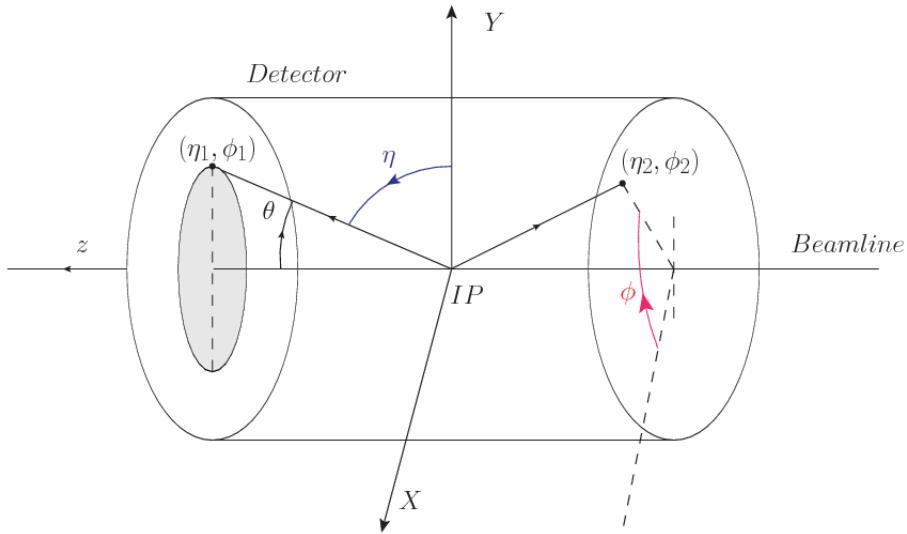


Figure 3.10: CMS coordinate system.

In addition to the common cartesian and cylindrical coordinate systems, two coordinates are of particular utility in particle physics: rapidity(y) and pseudorapidity(η), defined in connection to the polar angle θ , energy and longitudinal momentum component (momentum along the z -axis) according to

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

Rapidity is related to the angle between the XY -plane and the direction in which the products of a collision are emitted; it has the nice property that the difference between the rapidities of two particles is invariant with respect to Lorentz boosts along the z -axis. Thus, data analysis becomes more simple when based in rapidity;

however, it is not simple to measure the rapidity of highly relativistic particles, as those produced after pp collisions. Under the highly relativistic motion approximation y can be rewritten in terms of the polar angle, arriving to the conclusion that rapidity is approximately equal to the pseudorapidity defined above, i.e. $y \approx \eta$. Note that η is easier to measure than y given the direct relationship between the former and the polar angle. Angular distance between two objects in the detector (ΔR) is defined in terms of their coordinates $(\eta_1, \phi_1), (\eta_2, \phi_2)$ as

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

3.3.2 Pixels detector

The CMS tracking system is designed to provide a precise measurement of the trajectory followed by the charged particles created after the pp collisions as; also, the precise reconstruction of the primary and secondary vertices is expected in an environment where, each 25 ns, the bunch crossing produce about 20 inelastic collisions and about 1000 particles. An increment in the luminosity is ongoing which implies that the PU will increase accordingly.

1138

The pixel detector was replaced during the 2016-2017 year end shut down, due to the increasingly challenging operation conditions like the higher particle flow and more radiation harsh environment among others. The new one is responding as expected, reinforcing its crucial role in the successful way to fulfil the new LHC physics objectives after the discovery of the Higgs boson. The last chapter of this thesis is dedicated to describe my contribution to the “Forward Pixel Phase 1 upgrade”.

1145

1146 The current pixel detector is composed of 1856 silicon pixel detector modules orga-
 1147 nized in four barrel layers in the central region and three disks in the forward region;
 1148 it is designed to record efficiently and with high precision, up to $10\mu\text{m}$ in the XY -
 1149 plane and $20\mu\text{m}$ in the z -direction, the first four space-points near to the CP region
 1150 (see figure 3.11 left side) in the range $|\eta| \leq 2.5$. The first barrel layer is located at a
 1151 radius of 30 mm from the beamline, while the fourth layer is located at a radius of
 1152 160 mm closer to the strip tracker inner barrel layer (see section 3.3.3) in order to
 1153 reduce the rate of fake tracks. The high granularity of the detector is represented in
 1154 its about 123 Mpixels, each of size $100 \times 150\mu\text{m}^2$, which is almost twice the channels
 1155 of the old detector. The transverse momentum resolution of tracks can be measured
 1156 with a resolution of 1-2% for muons of $p_T = 100$ GeV.

1157

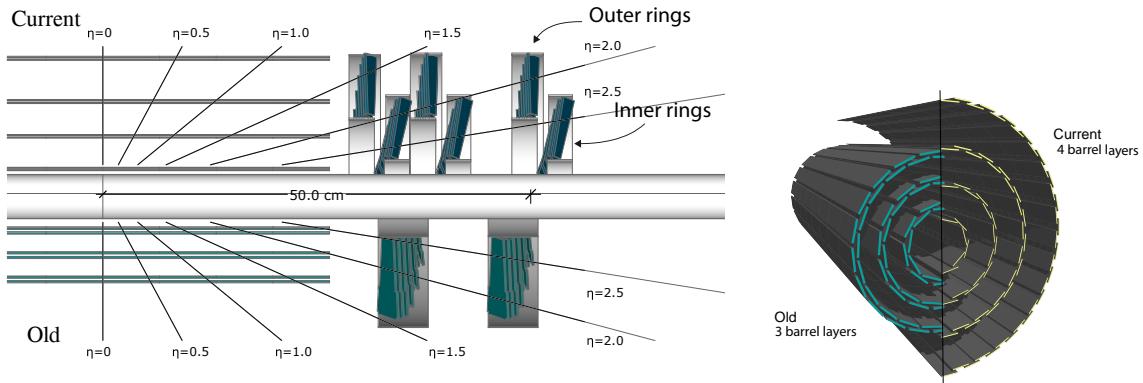


Figure 3.11: CMS pixel detector schematic view. Left: layout comparing the layers and disks in the old and current pixel detectors. Right: Transverse-oblique view comparing the pixel barrel layers in the two [75].

1158 Some of the improvements with respect to the previous pixel detector include a higher
 1159 average tracking efficiency and lower average fake rate as well as higher track impact
 1160 parameter resolution which is fundamental in order to increase the efficiency in the
 1161 identification of jets originating from b quarks (b-tagging). A significant source of

improvement comes from the overall reduction in the material budget of the detector which results in less photon conversions and less multiple scattering from charged particles.

3.3.3 Silicon strip tracker

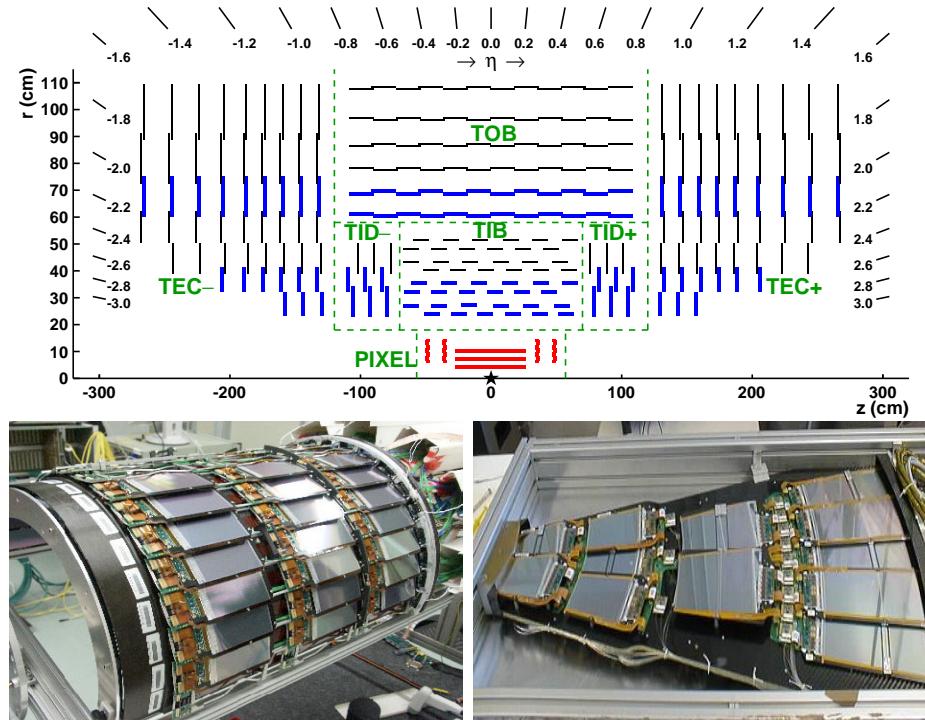


Figure 3.12: Top: CMS Silicon Strip Tracker (SST) schematic view. The SST is composed of the tracker inner barrel (TIB), the tracker inner disks (TID), the tracker outer barrel (TOB) and the tracker endcaps (TEC). Each part is made of silicon strip modules; the modules in blue represent two modules mounted 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].

The silicon strip tracker (SST) is the second stage in the CMS tracking system . The top side of figure 3.12 shows a schematic of the SST. The inner tracker region is composed of the tracker inner barrel (TIB) and the tracker inner disks (TID) covering the region $r < 55$ cm and $|z| < 118$ cm. The TIB is composed of 4 layers while the TID

1170 is composed of 3 disks at each end. The silicon sensors in the inner tracker are 320
1171 μm thick, providing a resolution of about 13-38 μm in the $r\phi$ position measurement.

1172

1173 The modules indicated in blue in the schematic view of figure 3.12 are two modules
1174 mounted back-to-back and rotated in the plane of the module by a “stereo” angle of
1175 100 mrad; the hits from these two modules, known as “stereo hits”, are combined to
1176 provide a measurement of the second coordinate (z in the barrel and r on the disks)
1177 allowing the reconstruction of hit positions in 3-D.

1178

1179 The outer tracker region is composed of the tracker outer barrel (TOB) and the
1180 tracker endcaps (TEC). The 6 layers of the TOB offers coverage in the region $r > 55$
1181 cm and $|z| < 118$ cm, while the 9 disks of the TEC cover the region $124 < |z| < 282$
1182 cm. The resolution offered by the outer tracker is about 13-38 μm in the $r\phi$ position
1183 measurement. The inner four TEC disks use silicon sensors 320 μm thick; those in
1184 the TOB and the outer three TEC disks use silicon sensors of 500 μm thickness. The
1185 silicon strips run parallel to the z -axis and the distance between strips varies from 80
1186 μm in the inner TIB layers to 183 μm in the inner TOB layers; in the endcaps the
1187 wedge-shaped sensors with radial strips, whose pitch range between 81 μm at small
1188 radii and 205 μm at large radii.

1189

1190 The whole SST has 15148 silicon modules, 9.3 million silicon strips and cover a total
1191 active area of about 198 m^2

1192 3.3.4 Electromagnetic calorimeter

1193 The CMS electromagnetic calorimeter (ECAL) is designed to measure the energy of
1194 electrons and photons. It is composed of 75848 lead tungstate crystals which has
1195 a short radiation length (0.89 cm) and fast response given that 80% of the light
1196 is emitted within 25 ns; however, they are combined with Avalanche photodiodes
1197 (APDs) as photodetectors given that crystals itself has a low light yield ($30\gamma/\text{MeV}$).
1198 An schematic view of the ECAL is shown in figure 3.13. The ECAL barrel (EB) cover
1199 the region $|\eta| < 1.479$, using crystals of depth of 23 cm and $2.2 \times 2.2 \text{ cm}^2$ transverse
 section.

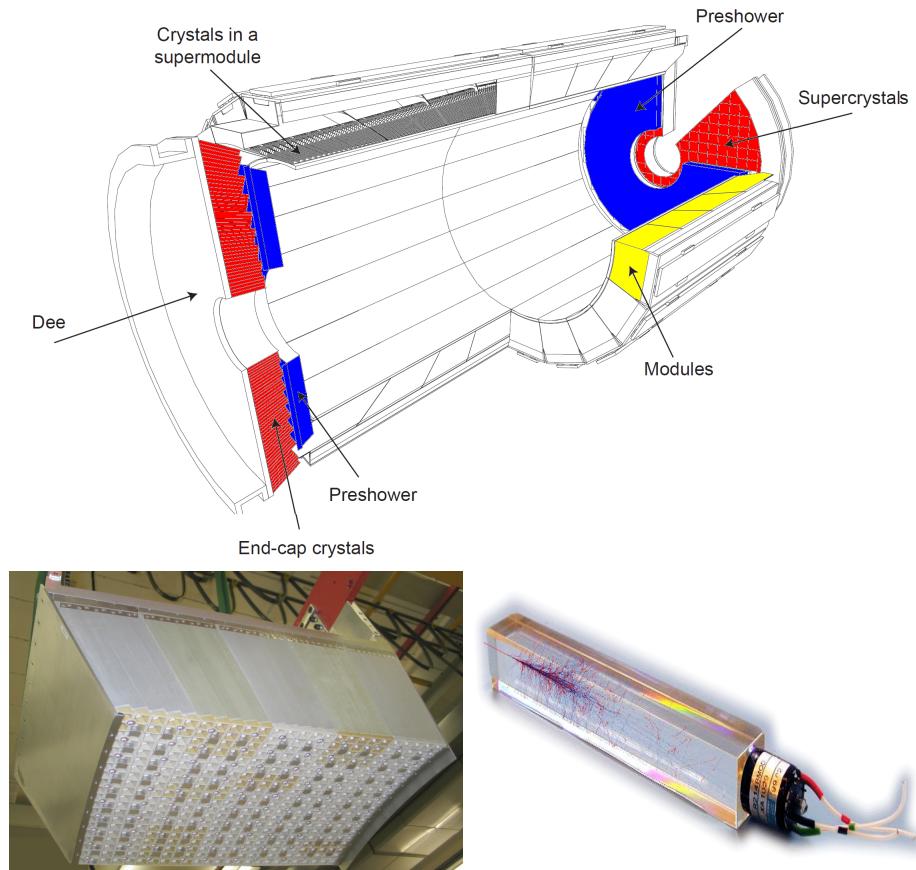


Figure 3.13: Top: CMS ECAL schematic view. Bottom: Module equipped with the crystals (left); ECAL crystal(right).

1201 The ECAL endcap (EE) cover the region $1.479 < |\eta| < 3.0$ using crystals of depth
 1202 22 cm and transverse section of $2.86 \times 2.86 \text{ cm}^2$; the photodetectors used are vacuum
 1203 phototriodes (VPTs). Each EE is divided in two structures called “Dees”.

1204

1205 In front of the EE, it is installed the preshower detector (ES) which covers the region
 1206 $1.653 < |\eta| < 2.6$. The ES provides a precise measurement of the position of electro-
 1207 magnetic showers, which allows to distinguish electrons and photons signals from π^0
 1208 decay signals. The ES is composed of a layer of lead absorber followed by a layer of
 1209 plastic scintillators

1210 **3.3.5 Hadronic calorimeter**

1211 **3.3.6 Superconducting solenoid magnet**

1212 The superconducting magnet installed in the CMS detector is designed to provide
 1213 an intense and highly uniform magnetic field in the central part of the detector. In
 1214 fact, the tracking system take advantage of the bending power of the magnetic field
 1215 to measure with precision the momentum of the particles that traverse it; the unan-
 1216 biguous determination of the sign for high momentum muons was a driven principle
 1217 during the desing of the magnet. The magnet has a diameter of 6.3 m, a lenght of
 1218 12.5 m in a cold mass of 220 t; the generated a magnetic fiels reach a strength of 3.8T.
 1219 Since it is made of Ni-Tb superconducting cable it has to operate at a temperature
 1220 of 4.7 K by using a heluim cryogenic system; the current circulating in the cables
 1221 reach 18800 A under normal running conditions. The left side of figure 3.14 shows
 1222 an artistic view of the CMS magnet, while the right side shows a transverse view of
 1223 the cold mass where the winding structure is visible.

1224

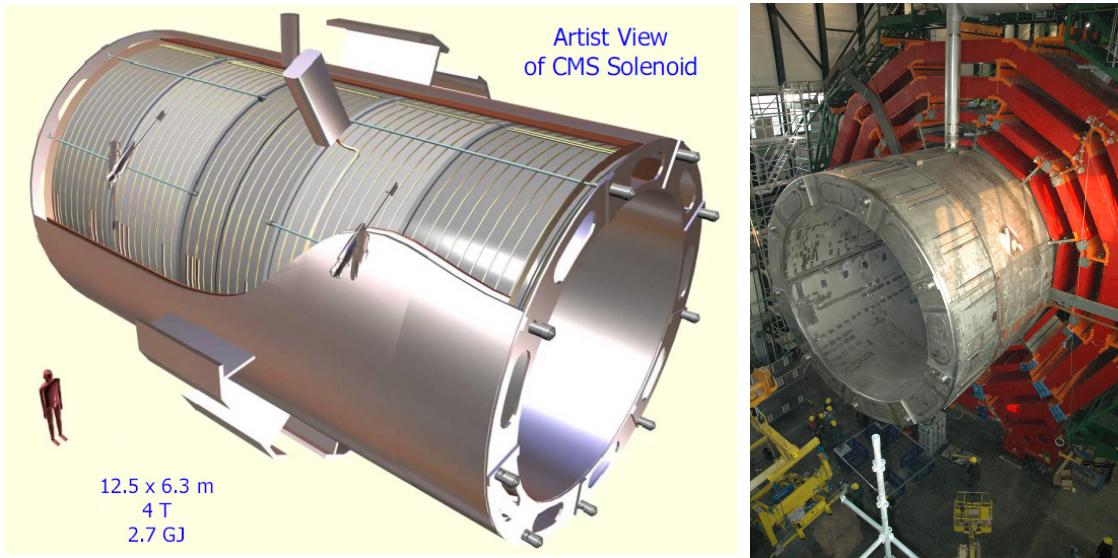


Figure 3.14: Artistic representation of the CMS solenoid magnet(left). The magnet is supported on an iron yoke (right) which also serves as the house of the muon detector and as mechanical support for the whole CMS detector [74].

1225 The yoke (see figure 3.14), composed of 5 barrel wheels and 6 endcap disks made
 1226 of iron, serves not only as the media for magnetic flux return, but also provides the
 1227 house for the muon detector sytem and structural stability to the full detector.

1228 **3.3.7 muon system**

1229 **3.3.8 trigger system - HLT- L1**

1230 The online event selection process (trigger) must reduce the huge rate to about 100
 1231 events/s for storage and subsequent analysis. The short time between bunch crossings,
 1232 25 ns, has major implications for the design of the read-out and trigger systems.

1233 Due to its high segmentation, the pixel detector not only forms high quality seeds
 1234 for the track reconstruction algorithm offline, but is also used to do fast tracking online
 1235 in the high level trigger (HLT) for primary vertex reconstruction, electron/photon
 1236 identification, muon reconstruction, tau identification and b-tagging.

1237 **3.3.9 computing model**

1238 **3.4 Event generation simulation and**
1239 **reconstruction**

1240 **3.4.1 event generation**

1241 **3.4.2 Hard scattering**

1242 **3.4.3 parton shower**

1243 **3.4.4 hadronization and decays**

1244 **3.4.5 underlying events and pileup**

1245 **3.4.6 MC - MadEvent, MadGraph and madgraphNLO,**
1246 **powheg, pythia, tauola**

1247 **3.4.7 detector simulation**

1248 **3.4.8 event reconstruction- particle flow algorithm,**
1249 **vertexing , muon reco, electron reco, photon and**
1250 **hadron reco, jets reco, anti-kt algoritm, jet energy**
1251 **corrections, btagging, MET**

1252 **3.4.9 MVA methods, NN, BDT, boosting, overtraining,**
1253 **variable ranking**

1254 **3.4.10 statistical inference, likelihood parametrization**

1255 **3.4.11 nuisance paraeters**

¹²⁵⁸ **Chapter 4**

¹²⁵⁹ **Search for production of a Higgs**

¹²⁶⁰ **boson and a single top quark in**

¹²⁶¹ **multilepton final states in pp**

¹²⁶² **collisions at $\sqrt{s} = 13$ TeV**

¹²⁶³ **4.1 Introduction**

¹²⁶⁴ Dont forget to mention previous constrains to ct check reference ?? and references

¹²⁶⁵ <https://link.springer.com/content/pdf/10.1007%2FJHEP01>

¹²⁶⁶ A. Azatov, R. Contino and J. Galloway, "Model-Independent Bounds on a

¹²⁶⁷ Light Higgs," JHEP 1204 (2012) 127 [arXiv:1202.3415 [hep-ph]].

¹²⁶⁸ J. R. Espinosa, C. Grojean, M. Muhlleitner and M. Trott, "Fingerprinting

¹²⁶⁹ Higgs Suspects at the LHC," JHEP 1205 (2012) 097 [arXiv:1202.3697 [hep-ph]].

¹²⁷⁰ This chapter present the search for the associated production of a Higgs boson and

¹²⁷¹ a single top quark events with three leptons in the final state, targeting Higgs decay

1272 modes to WW , ZZ , and $\tau\tau$. The analysis uses the 13 TeV dataset produced in 2016,
 1273 corresponding to an integrated luminosity of 35.9fb^{-1} . It is based on and expands
 1274 previous analyses at 8 TeV [79, 80] and searches for associated production of $t\bar{t}$ and
 1275 Higgs in the same channel [81], and complements searches in other decay channels
 1276 targeting $H \rightarrow b\bar{b}$ [82].

1277 As showed in section 2.4, the cross section of the associated production of a Higgs
 1278 boson and a single top quark (tHq) process is driven by a destructive interference of
 1279 two contributions (see Figure 4.1), where the Higgs couples to either the W boson or
 1280 the top quark. Any deviation from the standard model (SM) in the Higgs coupling
 1281 structure could therefore lead to a large enhancement of the cross section, making
 1282 this analysis sensitive to such deviations. A second process, where the Higgs and
 1283 top quark are accompanied by a W boson (tHW) has similar behavior, albeit with a
 1284 weaker interference pattern.

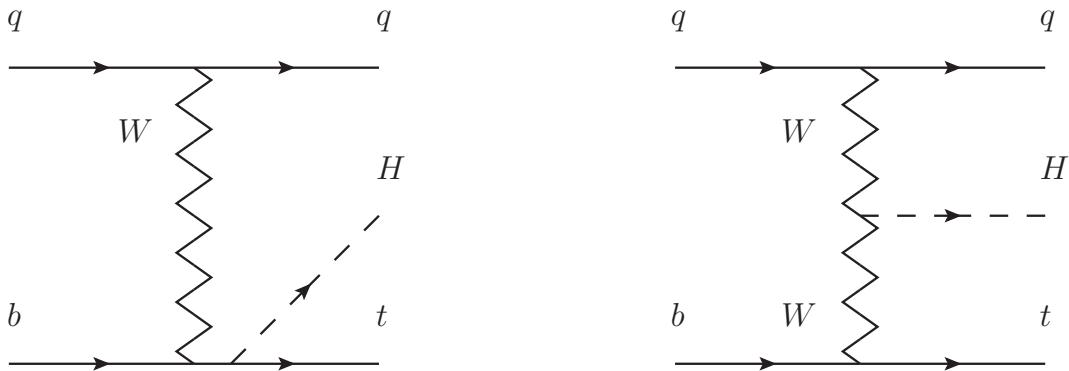


Figure 4.1: The two leading-order diagrams of tHq production.

1285 We selects events with three leptons and a b tagged jet in the final state. The tHq
 1286 signal contribution is then determined in a fit of the observed data to two multivariate
 1287 classifier outputs, each trained to discriminate against one of the two dominant back-
 1288 grounds of events with non-prompt leptons from $t\bar{t}$ and of associated production of $t\bar{t}$

1289 and vector bosons ($t\bar{t}W$, $t\bar{t}Z$). The fit result is then used to set an upper limit on the
 1290 combined $t\bar{t}H$, tHq and tHW production cross section, as a function of the relative
 1291 coupling strengths of Higgs and top quark and Higgs and W boson, respectively.

1292 4.2 Data and MC Samples

1293 The data considered in this analysis were collected by the CMS experiment dur-
 1294 ing 2016 and correspond to a total integrated luminosity of 35.9fb^{-1} . Only periods
 1295 when the CMS magnet was on were considered when selecting the data samples, that
 1296 corresponds to the 23 Sep 2016 (Run B to G) and PromptReco (Run H) versions
 1297 of the datasets. The MC samples used in this analysis correspond to the RunI-
 1298 ISummer16MiniAODv2 campaign produced with CMSSW 80X. The two signal sam-
 1299 ples (for tHq and tHW) were produced with MG5_aMC@NLO (version 5.222), in
 1300 leading-order mode, and are normalized to next-to-leading-order cross sections,
 1301 see Tab. 4.1. Each sample is generated with a set of event weights corresponding to
 1302 different values of κ_t and κ_V couplings as shown in Tab. 4.2.

1303 4.2.1 Full 2016 dataset and MC samples

Sample	σ [pb]	BF
/THQ_Hincl_13TeV-madgraph-pythia8_TuneCUETP8M1/	0.7927	0.324
/THW_Hincl_13TeV-madgraph-pythia8_TuneCUETP8M1/	0.1472	1.0

Table 4.1: Signal samples and their cross section and branching fraction used in this analysis. See Ref. [83] for more details.

1304 Different MC generators were used to generate the background processes. The
 1305 dominant sources ($t\bar{t}$, $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}H$) were produced using AMC@NLO interfaced
 1306 to PYTHIA8, and are scaled to NLO cross sections. Other processes are simulated

		<i>tHq</i>		<i>tHW</i>		
κ_V	κ_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 4.2: κ_V and κ_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. [83].

Sample	σ [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_L0_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 4.3: 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	σ [pb]
ttWJets_13TeV_madgraphMLM	0.6105
ttZJets_13TeV_madgraphMLM	0.5297/0.692

Table 4.4: Leading-order $t\bar{t}W$ and $t\bar{t}Z$ samples used in the signal BDT training.

1307 using POWHEG interfaced to PYTHIA, or bare PYTHIA (see table 4.3 and [81]
1308 for more details).

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_WPLoose_Gsf_v*

Table 4.5: Table of high-level triggers that we consider in the analysis.

1309 4.2.2 Triggers

1310 We consider online-reconstructed events triggered by one, two, or three leptons.
 1311 Single-lepton triggers are included to boost the acceptance of events where the p_T of
 1312 the sub-leading lepton falls below the threshold of the double-lepton triggers. Ad-
 1313 ditionally, by including double-lepton triggers in the ≥ 3 lepton category, as well
 1314 as single-lepton triggers in all categories, we increase the efficiency, considering the
 1315 logical “or” of the trigger decisions of all the individual triggers in a given category.
 1316 Tab. 4.5 shows the lowest-threshold non-prescaled triggers present in the High-Level
 1317 Trigger (HLT) menus for both Monte-Carlo and data in 2016.

1318 4.2.2.1 Trigger efficiency scale factors

1319 The efficiency of events to pass the trigger is measured in simulation (trivially using
 1320 generator information) and in the data (using event collected by an uncorrelated

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

Table 4.6: Trigger efficiency scale factors and associated uncertainties, shown here rounded to the nearest percent.

1321 MET trigger). Small differences between the data and MC efficiencies are corrected
 1322 by applying scale factors as shown in Tab. 4.6. The exact procedure and control plots
 1323 are documented in [84] for the current analysis.

1324 4.3 Object Identification and event selection

1325 4.3.1 Jets and b tagging

1326 The analysis uses anti- k_t (0.4) particle-flow (PF) jets, corrected for charged hadrons
 1327 not coming from the primary vertex (charged hadron subtraction), and having jet
 1328 energy corrections (`Summer16_23Sep2016V3`) applied as a function of the jet E_T and
 1329 η . Jets are only considered if they have a transverse energy above 25GeV.

1330 In addition, they are required to be separated from any lepton candidates passing
 1331 the fakeable object selections (see Tables 4.7 and 4.8) by $\Delta R > 0.4$.

1332 The loose and medium working points of the CSV b-tagging algorithm are used to
 1333 identify b jets. Data/simulation differences in the b tagging performance are corrected
 1334 by applying per-jet weights to the simulation, dependent on the jet p_T , eta, b tagging
 1335 discriminator, and flavor (from simulation truth) [85]. The per-event weight is taken
 1336 as the product of the per-jet weights, including those of the jets associated to the
 1337 leptons. More details can be found in the corresponding $t\bar{t}H$ documentation [81, 84].

1338 **4.3.2 Lepton selection**

Cut	Loose	Fakeable object	Tight
$ \eta < 2.4$	✓	✓	✓
p_T	$> 5\text{GeV}$	$> 15\text{GeV}$	$> 15\text{GeV}$
$ d_{xy} < 0.05 \text{ (cm)}$	✓	✓	✓
$ d_z < 0.1 \text{ (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 4.7: 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. For the two p_T^{ratio} and CSV rows, the cuts marked with a † 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.

1339 The lepton reconstruction and selection is identical to that used in the $t\bar{t}H$ mul-
 1340 tilepton analysis, as documented in Refs. [81, 84]. For details on the reconstruction
 1341 algorithms, isolation, pileup mitigation, and a description of the lepton MVA discrim-
 1342 inator and validation plots thereof, we refer to that document since they are out of
 1343 the scope of this thesis. Three different selections are defined both for the electron
 1344 and muon object identification: the *Loose*, *Fakeable Object*, and *Tight* selection. As
 1345 described in more detail later, these are used for event level vetoes, the fake rate
 1346 estimation application region, and the final signal selection, respectively. The p_T of
 1347 fakeable objects is defined as $0.85 \times p_T(\text{jet})$, where the jet is the one associated to the
 1348 lepton object. This mitigates the dependence of the fake rate on the momentum of
 1349 the fakeable object and thereby improves the precision of the method.

1350 Tables 4.7 and 4.8 list the full criteria for the different selections of muons and
 1351 electrons.

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

Table 4.8: 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 η 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 (value₁, value₂, value₃).

1352 4.3.3 Lepton selection efficiency

1353 Efficiencies of reconstruction and selecting loose leptons are measured both for muons
 1354 and electrons using a tag and probe method on both data and MC, using $Z \rightarrow \ell^+ \ell^-$.
 1355 Corresponding scale factors are derived from the ratio of efficiencies and applied to the
 1356 selected These. Events are produced for the leptonic SUSY analyses using equivalent
 1357 lepton selections and recycled for the $t\bar{t}H$ analysis as well as for this analysis. The
 1358 efficiencies of applying the tight selection as defined in Tables 4.7 and 4.8, on the
 1359 loose leptons are determined again by using a tag and probe method on a sample of
 1360 DY-enriched events. They are documented for the $t\bar{t}H$ analysis in Ref. [84] and are
 1361 exactly equivalent for this analysis.

1362 4.4 Background predictions

1363 The modeling of reducible and irreducible backgrounds in this analysis uses the exact
 1364 methods, analysis code, and ROOT trees used for the $t\bar{t}H$ multilepton analysis. We
 1365 give a brief description of the methods and refer to the documentation of that analysis
 1366 in Refs. [81, 84] for any details.

1367 The backgrounds in three-lepton final states can be split in two broad categories:
 1368 irreducible backgrounds with genuine prompt leptons (i.e. from on-shell W and Z
 1369 boson decays); and reducible backgrounds where at least one of the leptons is “non-
 1370 prompt”, i.e. produced within a hadronic jet, either a genuine lepton from heavy
 1371 flavor decays, or simply mis-reconstructed jets.

1372 Irreducible backgrounds can be reliably estimated directly from Monte-Carlo sim-
 1373 ulated events, using higher-order cross sections or data control regions for the overall
 1374 normalization. This is done in this analysis for all backgrounds involving prompt lep-
 1375 tons: $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}H$, WZ , ZZ , $W^\pm W^\pm qq$, $t\bar{t}t\bar{t}$, tZq , tZW , WWW , WWZ , WZZ ,
 1376 ZZZ .

1377 Reducible backgrounds, on the other hand, are not well predicted by simulation,
 1378 and are estimated using data-driven methods. In the case of non-prompt leptons, a
 1379 fake rate method is used, where the contribution to the final selection is estimated by
 1380 extrapolating from a sideband (or “application region”) with a looser lepton definition
 1381 (the fakeable object definitions in Tabs. 4.7 and 4.8) to the signal selection. The tight-
 1382 to-loose ratios (or “fake rates”) are measured in several background dominated data
 1383 events with dedicated triggers, subtracting the residual prompt lepton contribution
 1384 using MC. Non-prompt leptons in our signal regions are predominantly produced in $t\bar{t}$
 1385 events, with a much smaller contribution, from Drell–Yan production. The systematic
 1386 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 events, limited statistics in the data control regions due to necessary prescaling of lepton triggers, and the uncertainty in the subtraction of residual prompt leptons from the control region.

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

Figures 4.2 show the distributions of some relevant kinematic variables, normalized to the cross section of the respective processes and to the integrated luminosity.

4.5 Signal discrimination

The tHq signal is separated from the main backgrounds using a boosted decision tree (BDT) classifier, trained on simulated signal and background events. A set of discriminating variables are given as input to the BDT which produces a output distribution maximizing the discrimination power. Table 4.9 lists the input variables used while Figures 4.3 show their distributions for the relevant signal and background samples, for the three lepton channel. Two BDT classifiers are trained for the two main backgrounds expected in the analysis: events with prompt leptons from $t\bar{t}W$ and $t\bar{t}Z$ (also referred to as $t\bar{t}V$), and events with non-prompt leptons from $t\bar{t}$. The datasets used in the training are the tHq signal (see Tab. 4.1), and LO MADGRAPH samples

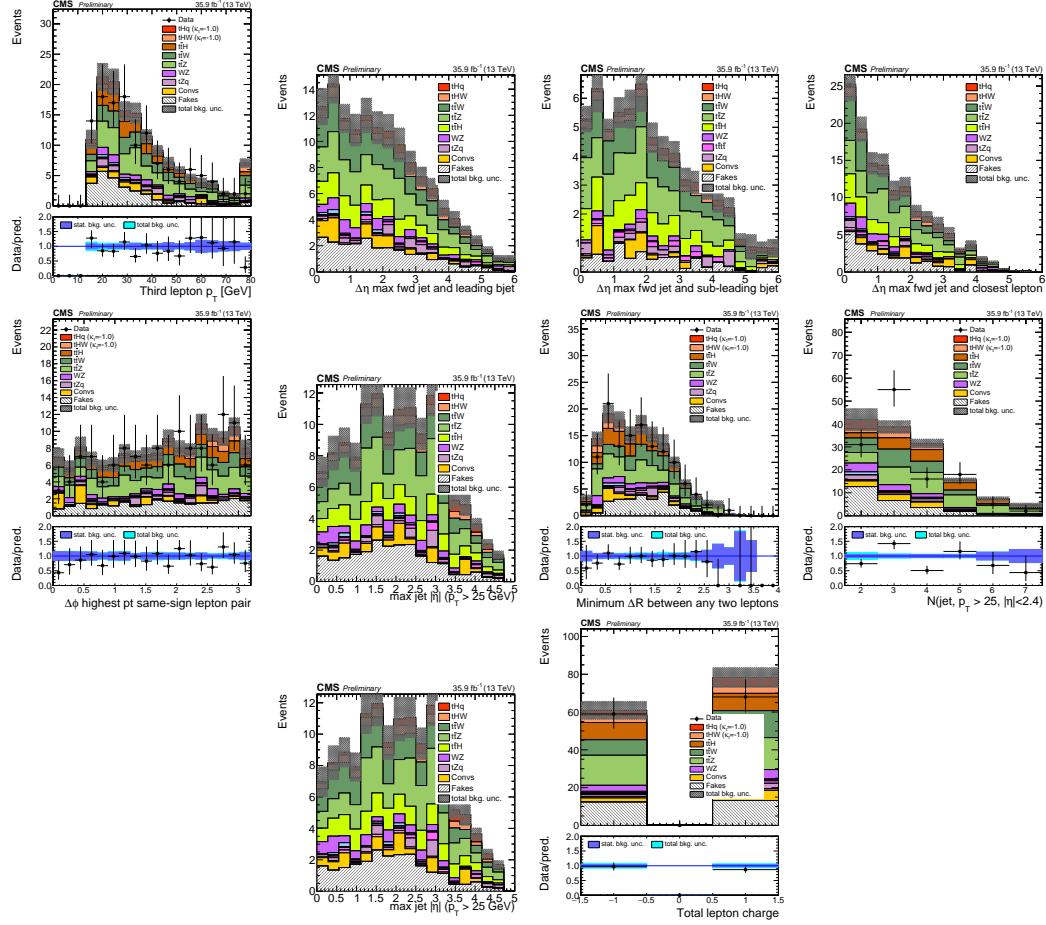


Figure 4.2: Distributions of input variables to the BDT for signal discrimination, three lepton channel, normalized to their cross section and to 35.9fb^{-1} .

of $t\bar{t}W$ and $t\bar{t}Z$, in an admixture proportional to their respective cross sections (see Tab. 4.4).

The MVA analysis consist of two stages: first a “training” where the MVA method 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 4.4 show the input variables distributions as seen by the MVA algorithm. Note that in contrast to the distributions in Fig. 4.3 only the main backgrounds ($t\bar{t}$ from simulation, $t\bar{t}V$) are included.

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 ΔR between any two leptons
Lep3Pt/Lep2Pt	p_T of the 3 rd lepton (2 nd for ss2l)

Table 4.9: MVA input discriminating variables

1420 Note that splitting the training in two groups reveals that some variables show
 1421 opposite behavior for the two background sources; potentially screening the discrimi-
 1422 nation power if they were to be used in a single discriminant. For some other variables
 1423 the distributions are similar in both background cases.

1424 From table 4.9, it is clear that the input variables are correlated to some extend.
 1425 These correlations play an important role for some MVA methods like the Fisher
 1426 discriminant method in which the first step consist of performing a linear transfor-
 1427 mation to an phase space where the correlations between variables are removed. In
 1428 case a boosted decision tree (BDT) method however, correlations do not affect the
 1429 performance. Figure 4.6 show the linear correlation coefficients for signal and back-
 1430 ground for the two training cases (the signal values are identical by construction). As
 1431 expected, strong correlations appears for variables related to the forward jet activity.
 1432 Same trend is seen in case of the same sign dilepton channel in Figure ??.

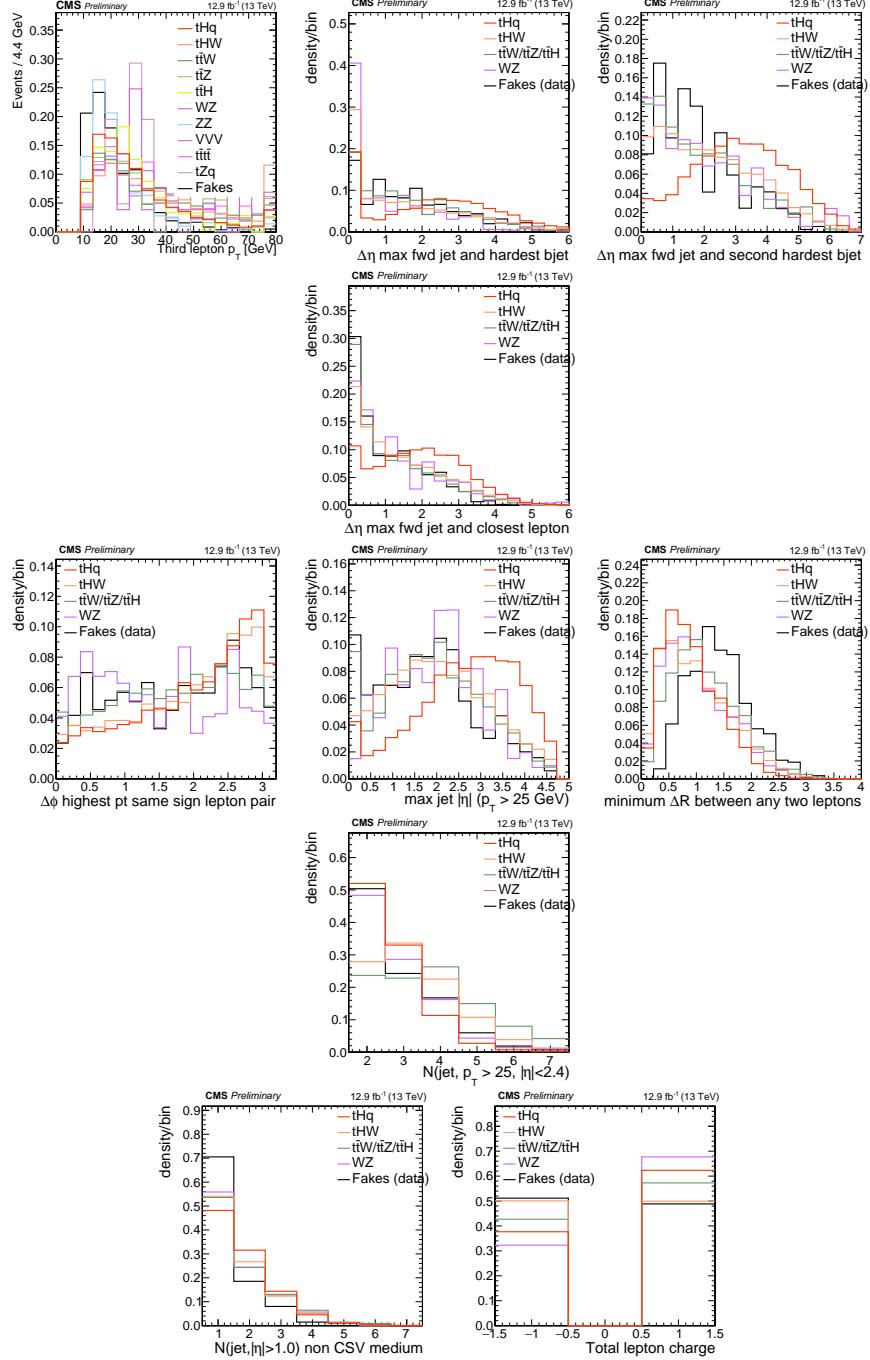


Figure 4.3: Distributions of input variables to the BDT for signal discrimination, three lepton channel.

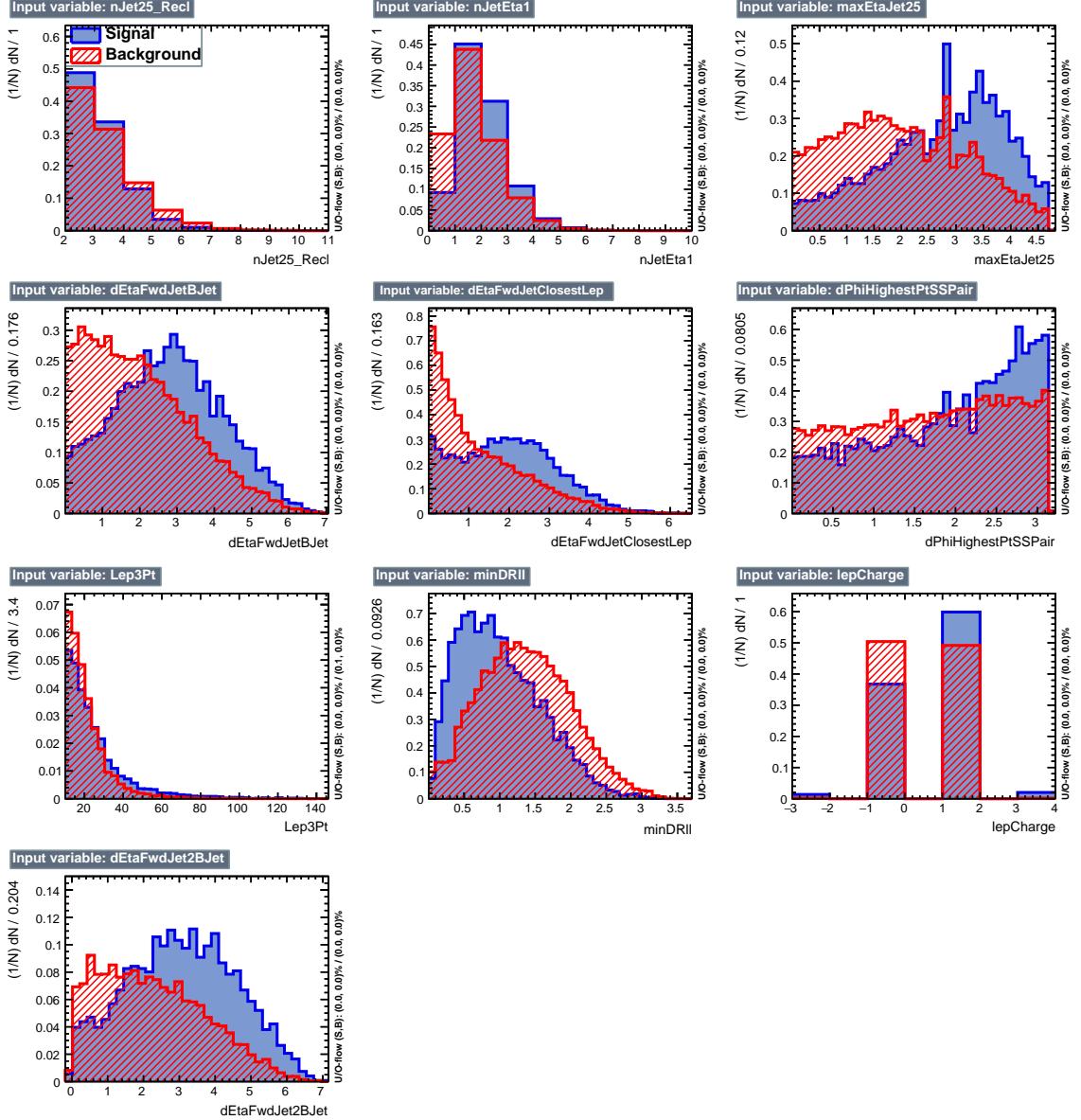


Figure 4.4: BDT inputs as seen by TMVA (signal, in blue, is tHq , background, in red, is $t\bar{t}$) for the three lepton channel, discriminated against $t\bar{t}$ (fakes) background.

1433 4.5.1 Classifiers response

1434 Several MVA algorithms were evaluated to determine the most appropriate method
 1435 for this analysis. The plots in Fig. 4.7 (top) show the background rejection as a
 1436 function of the signal efficiency for $t\bar{t}$ and $t\bar{t}V$ trainings (ROC curves) for the different

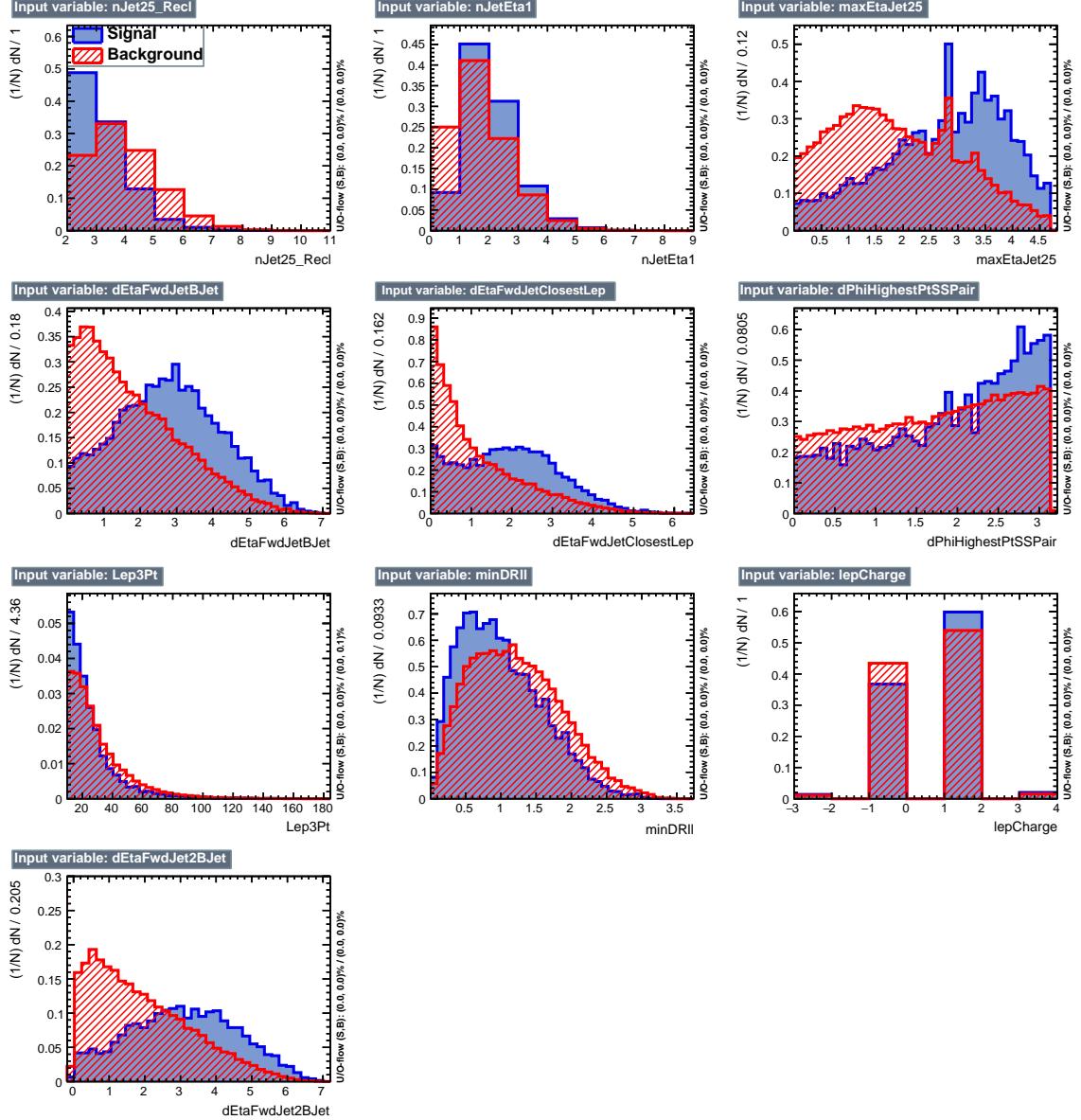


Figure 4.5: BDT inputs as seen by TMVA (signal, in blue, is tHq , background, in red, is $t\bar{t}W+t\bar{t}Z$) for the three lepton channel, discriminated against $t\bar{t}V$ background.

algorithms that were evaluated.

In both cases the gradient boosted decision tree (“BDTA_GRAD”) classifier offers 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. 4.7. As expected, a good discrimination power is obtained using default discrim-

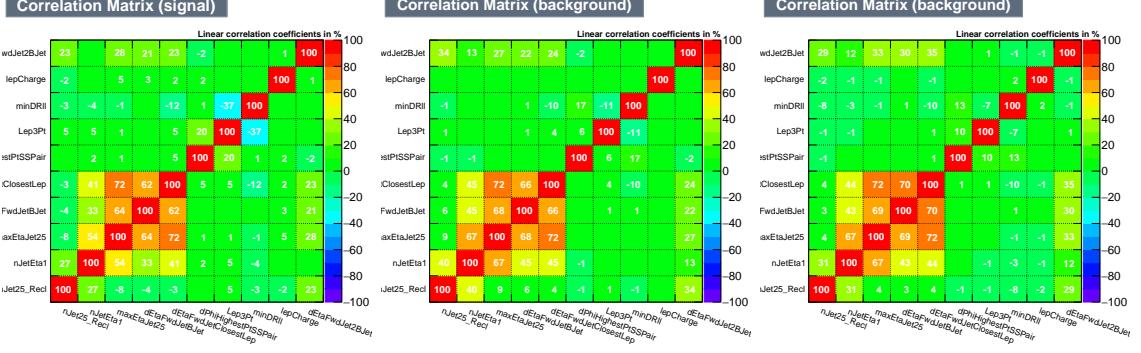


Figure 4.6: Signal (left), $t\bar{t}$ background (middle), and $t\bar{t}V$ background (right.) correlation matrices for the input variables in the TMVA analysis for the three lepton channel.

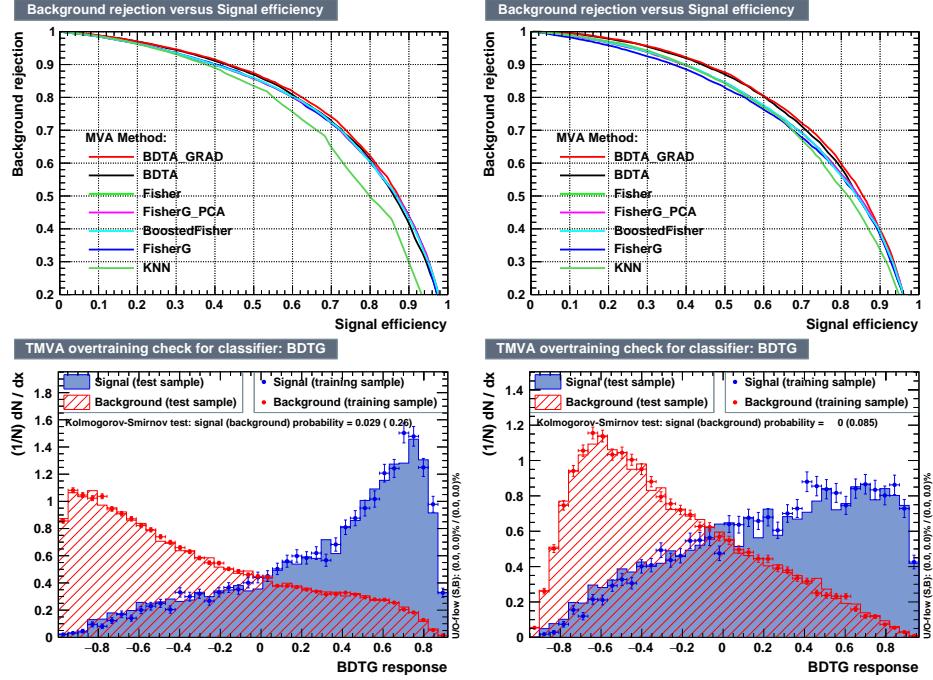


Figure 4.7: Top: background rejection vs signal efficiency (ROC curves) for various MVA classifiers (top) in the three lepton channel against $t\bar{t}V$ (left) and $t\bar{t}$ (right). Bottom: classifier output distributions for the gradient boosted decision trees, for training against $t\bar{t}V$ (left) and against $t\bar{t}$ (right).

inator parameter values, with minimal overtraining. TMVA provides a ranking of the
1442 input variables by their importance in the classification process, shown in Tab. 4.10.
1443
1444 The TMVA settings used in the BDT training are shown in Tab. 4.11.

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 4.10: 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

```

Table 4.11: TMVA configuration used in the BDT training.

1445 4.6 Additional discriminating variables

1446 Two additional discriminating variables were tested considering the fact that the
 1447 forward jet in the background could come from the pileup; since we have a real
 1448 forward jet in the signal, it could give some improvement in the discriminating power.
 1449 The additional variables describe the forward jet momentum (fwdJetPt25) and the
 1450 forward jet identification(fwdJetPUID). Distributions for these variables in the three
 1451 lepton channel are shown in the figure 4.8. The forward jet identification distribution
 1452 show that for both, signal and background, jets are mostly real jets.

1453 The testing was made including in the MVA input one variable at a time, so we

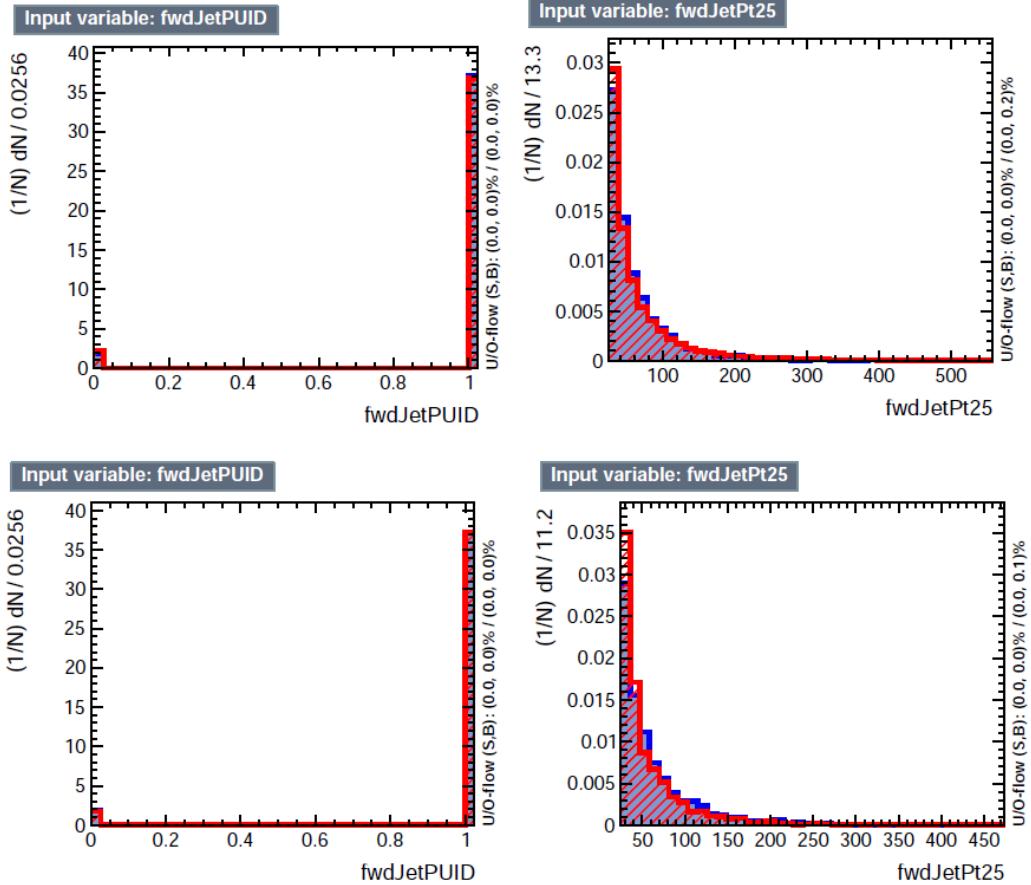


Figure 4.8: Additional discriminating variables distributions for ttV training (Top row) and tt training (bottom row) in the three lepton channel. The origin of the jets in the forward jet identification distribution is tagged as 0 for “pileup jets” while “real jets” are tagged as 1.

1454 can evaluate the discrimination power of each variable, and then both simultaneously.
 1455 fwdJetPUID was ranked in the last place in importance (11) in both training (ttV
 1456 and tt) while fwdJetPt25 was ranked 3 in the ttV training and 7 in the tt training.
 1457 When training using 12 variables, fwdJetPt25 was ranked 5 and 7 in the ttV and tt
 1458 trainings respectively, while fwdJetPUID was ranked 12 in both cases.

1459 The improvement in the discrimination performance provided by the additional
 1460 variables is about 1%, so it was decided not to include them in the procedure. Table
 1461 4.12 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 4.12: 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%

¹⁴⁶² **Chapter 5**

¹⁴⁶³ **The CMS forward pixel detector**

¹⁴⁶⁴ **5.0.1 The phase 1 FPix upgrade**

¹⁴⁶⁵ **5.0.2 FPix module production line**

¹⁴⁶⁶ **5.0.3 The Gluing stage**

¹⁴⁶⁷ **5.0.4 The Encapsulation stage**

¹⁴⁶⁸ **5.0.5 The FPix module production yields**

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