

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

5 Jose Andres Monroy Montañez

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18 Jose Andres Monroy Montañez, Ph.D.

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¹⁸² Chapter 1

¹⁸³ INTRODUCTION

¹⁸⁴ **Chapter 2**

¹⁸⁵ **Theoretical approach**

¹⁸⁶ **2.1 Introduction**

¹⁸⁷ The physical description of the universe is a challenge that physicists have faced by
¹⁸⁸ making theories that refine existing principles and proposing new ones in an attempt
¹⁸⁹ to embrace emerging facts and phenomena.

¹⁹⁰

¹⁹¹ At the end of 1940s Julian Schwinger [1] and Richard P. Feynman [2], based in the
¹⁹² work of Sin-Itiro Tomonaga [3], developed an electromagnetic theory consistent with
¹⁹³ special relativity and quantum mechanics that describes how matter and light inter-
¹⁹⁴ act; the so-called “quantum eletrodynamics” (QED) had born.

¹⁹⁵

¹⁹⁶ QED has become the guide in the development of theories that describe the universe.
¹⁹⁷ It was the first example of a quantum field theory (QFT), which is the theoretical
¹⁹⁸ framework for building quantum mechanical models that describes particles and their
¹⁹⁹ interactions. QFT is composed of a set of mathematical tools that combines classical
²⁰⁰ fields, special relativity and quantum mechanics, while keeping the quantum point

201 particles and locality ideas.

202 This chapter gives an overview of the standard model of particle physics, starting
 203 with a description of the particles and interactions that compose it, followed by a
 204 description of the electroweak interaction, the Higgs boson and the associated pro-
 205 duction of Higgs boson and a single top quark (tH). The description contained in
 206 this chapter is based on references [4–6].

207 2.2 Standard model of particle physics

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

211

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

220

221 The mathematical formulation of the SM is based on group theory and the use of
 222 Noether’s theorem [8] which states that for a physical system modeled by a Lagrangian

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 references [?] is quite comprehensive and detailed.

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

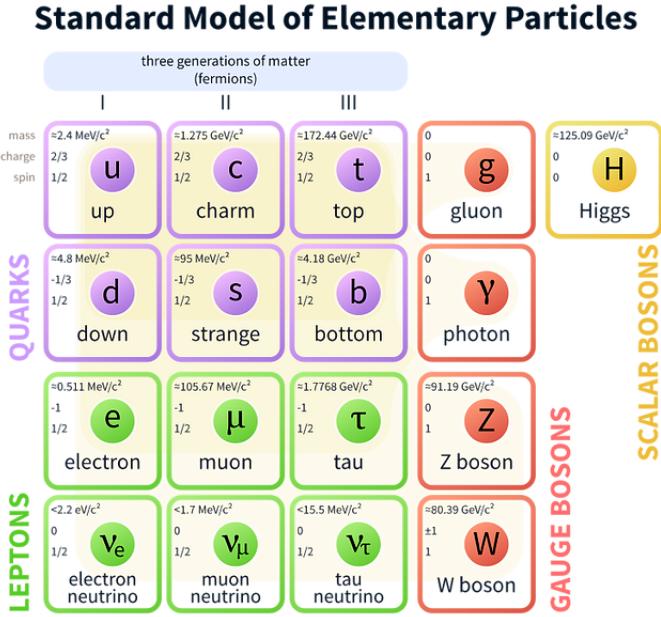


Figure 2.1: Schematic representation of the Standard model of particle physics. SM is a theoretical model intended to describe three of the four fundamental forces of the universe in terms of a set of particles and their interactions. [7].

223 that is invariant under a group of transformations a conservation law is expected. For
 224 instance, a system described by a time-independent Lagrangian is invariant (symmet-
 225 ric) under time changes (transformations) with the total energy conservation law as
 226 the expected conservation law. In QED, the charge operator (Q) is the generator of
 227 the $U(1)$ symmetry which according to the Noether's theorem means that there is a
 228 conserved quantity; this conserved quantity is the electric charge and thus the law
 229 conservation of electric charge is established.

230

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

- 235 • Strong: $SU(3)_C$ associated to color charge
- 236 • Weak: $SU(2)_L$ associated to weak isospin and chirality
- 237 • Electromagnetic: $U(1)_Y$ associated to weak hypercharge and electric charge
- 238 It will be shown that the electromagnetic and weak interactions are combined in
 239 the so-called electroweak interaction where chirality, hypercharge, weak isospin and
 240 electric charge are the central concepts.

241 **2.2.1 Fermions**

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

247

		Generation		
		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.

248

249 There is a mass hierarchy between generations (see table 2.2), where the higher gener-
 250 ation particles decays to the lower one, which can explain why the ordinary matter is

made of particles in the first generation. In the SM, neutrinos are modeled as massless particles so they are not subject to this mass hierarchy; however, today it is known that neutrinos are massive so the hierarchy could be restated. The reason behind this mass hierarchy is one of the most important open questions in particle physics, and it becomes more puzzling when noticing that the mass difference between first and second generation fermions is small compared to the mass difference with respect to 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 [9]. 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.

258

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

261 2.2.1.1 Leptons

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

268 by EI because they don't carry electric charge.

269

270 Another feature of the leptons that is fundamental in the mathematical description
271 of the SM is the chirality, which is closely related to spin and helicity. Helicity defines
272 the handedness of a particle by relating its spin and momentum such that if they
273 are parallel then the particle is right-handed; if spin and momentum are antiparallel
274 the particle is said to be left-handed. The study of parity conservation (or viola-
275 tion) in β -decay has shown that only left-handed electrons/neutrinos or right-handed
276 positrons/anti-neutrinos are created [10]; the inclusion of that feature in the theory
277 was achieved by using projection operators for helicity, however, helicity is frame de-
278 pendent for massive particles which makes it not Lorentz invariant and then another
279 related attribute has to be used: *chirality*.

280

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

286

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

294

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

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

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

303

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

311

312 2.2.1.2 Quarks

313 Quarks are the basic constituents of protons and neutrons. The way quarks join to
 314 form bound states, called “hadrons”, is through the SI. Quarks are affected by all the

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

315 fundamental interactions which means that they carry all the four types of charges:
 316 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 [9]. Q: electric charge, I_3 : isospin, T_3 : weak isospin, B: baryon number, C: charmness, S: strangeness, T: topness, B' : bottomness, Y: hypercharge. Anti-quarks posses the same mass and spin as quarks but all charges (color, flavor numbers) have opposite sign.

317
 318 Table 2.4 summarizes the features of quarks, among which the most particular is
 319 their fractional electric charge. Note that fractional charge is not a problem, given
 320 that quarks are not found isolated, but serves to explain how composed particles are
 321 formed out of two or more valence quarks⁴.

322

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.

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

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

333 In practice, when a quark is left alone isolated a process called “hadronization” occurs
 334 where the quark emits gluons (see section 2.2.3) which eventually will generate new
 335 quark-antiquark pairs and so on; those quarks will recombine to form hadrons that
 336 will decay into leptons. This proliferation of particles looks like a “jet” coming from
 337 the isolated quark. More details about the hadronization process and jet structure
 338 will be given in chapter4.

339 In the first version of the quark model (1964), M. Gell-Mann [12] and G. Zweig
 340 [13, 14] developed a consistent way to classify hadrons according to their properties.
 341 Only three quarks (u, d, s) were involved in a scheme in which all baryons have
 342 baryon number $B=1$ and therefore quarks have $B=1/3$; non-baryons have $B=0$. The
 343 scheme organizes baryons in a two-dimensional space ($I_3 - Y$); Y (hypercharge) and I_3
 344 (isospin) are quantum numbers related by the Gell-Mann-Nishijima formula [15, 16]:

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

345 where $Y = B + S + C + T + B'$ are the quantum numbers listed in table 2.4. Baryon
 346 number is conserved in SI and EI which means that single quarks cannot be created
 347 but in pairs $q - \bar{q}$.

348

349 There are six quark flavors organized in three generations (see table 2.1) following a
 350 mass hierarchy which, again, implies that higher generations decay to first generation
 351 quarks.

	Quarks			T_3	Y_W	Leptons			T_3	Y_W
Doublets	$(\begin{smallmatrix} u \\ d' \end{smallmatrix})_L$	$(\begin{smallmatrix} c \\ s' \end{smallmatrix})_L$	$(\begin{smallmatrix} t \\ b' \end{smallmatrix})_L$	$(\begin{smallmatrix} 1/2 \\ -1/2 \end{smallmatrix})$	1/3	$(\begin{smallmatrix} \nu_e \\ e \end{smallmatrix})_L$	$(\begin{smallmatrix} \nu_\mu \\ \mu \end{smallmatrix})_L$	$(\begin{smallmatrix} \nu_\tau \\ \tau \end{smallmatrix})_L$	$(\begin{smallmatrix} 1/2 \\ -1/2 \end{smallmatrix})$	-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.

352

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

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

358

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

359 where V_{CKM} is known as Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix [17,18].

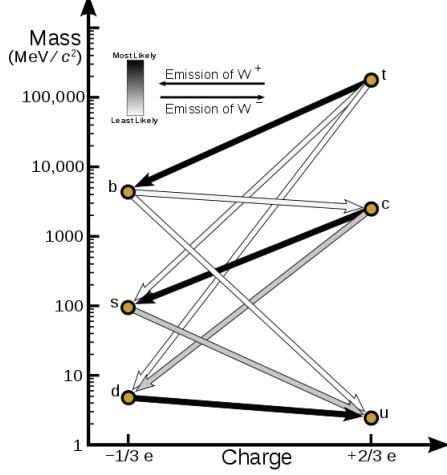


Figure 2.2: Transformations between quarks through the exchange of a WI. Higher generations quarks decay to first generation quarks by emitting a W boson. The arrow color indicates the likelihood of the transition according to the grey scale in the top left side which represent the CKM matrix parameters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

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

364

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

373 **2.2.2 Fundamental interactions**

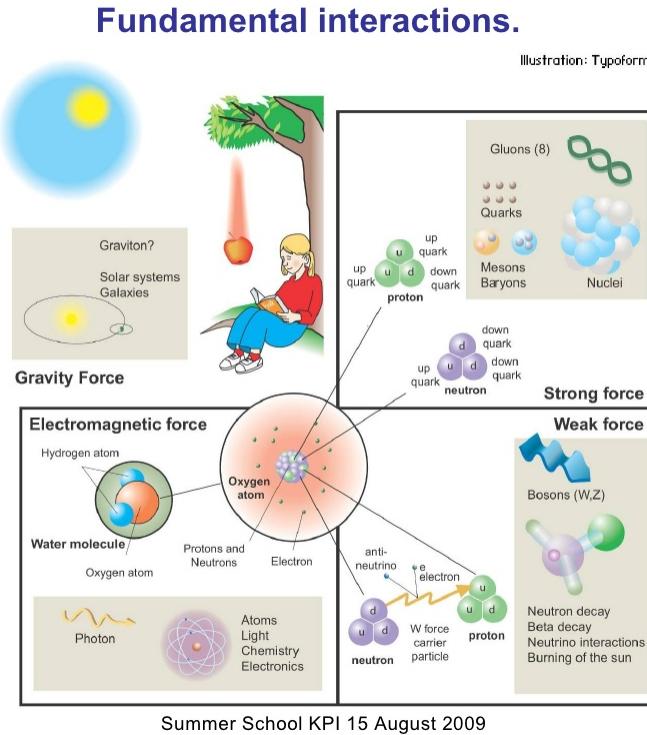


Figure 2.3: Fundamental interactions in nature. Despite the many manifestations of forces in nature, we can track all of them back to one of the fundamental interactions. The most common forces are gravity and electromagnetic given that all of us are subject and experience them in everyday life.

374 Even though there are many manifestations of force in nature, like the ones repre-

375 sented in figure 2.3, we can classify all of them into one of four fundamental interac-

376 tions:

- 377 ● *Electromagnetic interaction (EI)* affects particles that are “electrically charged,”
- 378 like electrons and protons. It is described by QED combining quantum mechan-
- 379 ics, special relativity and electromagnetism in order to explain how particles
- 380 with electric charge interact through the exchange of photons, therefore, one
- 381 says that “Electromagnetic Force” is mediated by “photons”. Figure 2.4a. shows

382 a graphical representation, known as “feynman diagram”, of electron-electron
 383 scattering.

- 384 • *Strong interaction (SI)* described by Quantum Chromodynamics (QCD). Hadrons
 385 like proton and neutron have internal structure given that they are composed
 386 of two or more valence quarks⁵. Quarks have fractional electric charge which
 387 means that they are subject to electromagnetic interaction and in the case of the
 388 proton they should break apart due to electrostatic repulsion; however, quarks
 389 are held together inside the hadrons against their electrostatic repulsion by the
 390 “Strong Force” through the exchange of “gluons.” The analog to the electric
 391 charge is the “color charge”. Electrons and photons are elementary particles
 392 as quarks but they don’t carry color charge, therefore they are not subject to
 393 SI. The feynman diagram for gluon exchange between quarks is shown in figure
 394 2.4b.

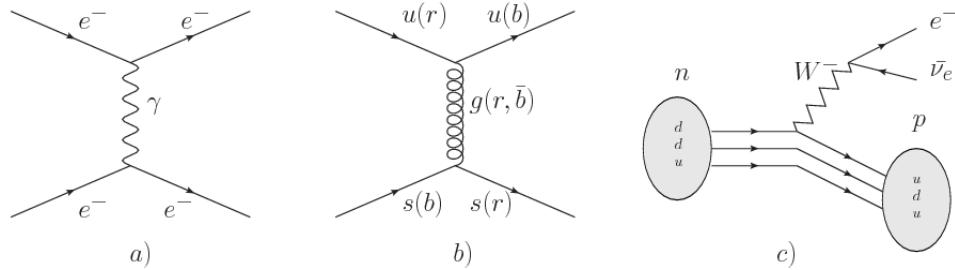


Figure 2.4: Feynman diagrams representing the interactions in SM; a) EI: e-e scattering; b) SI: gluon exchange between quarks ; c) WI: β -decay

- 395 • *Weak interaction (WI)* described by the weak theory (WT), is responsible, for
 396 instance, for the radioactive decay in atoms and proton-proton (pp) fusion
 397 within the sun. Quarks and leptons are the particles affected by the weak
 398 interaction; they possess a property called “flavor charge” (see 2.2.1) which can
 399 be changed by emitting or absorbing one weak force mediator. There are three

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

400 mediators of the “weak force” known as “Z” boson in the case of electrically
 401 neutral changes and “ W^\pm ” bosons in the case of electrically charged changes.
 402 The “weak isospin” is the WI analog to electric charge in EI, and color charge
 403 in SI, and defines how quarks and leptons are affected by the weak force. Figure
 404 2.4c. shows the feynman diagram of β -decay where a newtron (n) is transformed
 405 in a proton (p) by emmiting a W^- particle. Since this thesis is in the frame
 406 of the electroweak interaction, a more detailed description of it will be given in
 407 section 2.3

408 • *Gravitational interaction (GI)* described by General Theory of Relativity (GR).
 409 It is responsible for the structure of galaxies and black holes as well as the
 410 expansion of the universe. As a classical theory, in the sense that it can be for-
 411 mulated without even appeal to the concept of quantization, it implies that the
 412 spacetime is a continuum and predictions can be made without limitation to the
 413 precision of the measurement tools. The latter represent a direct contradiction
 414 of the quantum mechanics principles. Gravity is deterministic while quantum
 415 mechanics is probabilistic; despite that, efforts to develop a quantum theory of
 416 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 [20].

417

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

418 Table 2.6 summarizes the main features of the fundamental interactions. The rela-
 419 tive strength of the fundamental forces reveals the meaning of strong and weak; in
 420 a context where the relative strength of the SI is 1, the EI is about hundred times
 421 weaker and WI is about million times weaker than the SI. A good description on
 422 how the relative strength and range of the fundamental interactions are calculated
 423 can be found in references [20, 21]. In the everyday life, only EI and GI are explicitly
 424 experienced due to the range of these interactions; i.e., at the human scale distances
 425 only EI and GI have appreciable effects, in contrast to SI which at distances greater
 426 than 10^{-15} m become negligible.

427

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

- 431 • lorentz invariance: independence on the reference frame.
- 432 • locality: interacting fields are evaluated at the same space-time point to avoid
 433 action at a distance.
- 434 • renormalizability: physical predictions are finite and well defined
- 435 • particle spectrum, symmetries and conservation laws already known must emerge
 436 from the theory.
- 437 • gauge invariance.

438 The gauge invariance requirement reflects the fact that the fundamental fields cannot
 439 be directly measured but associated fields which are the observables. Electric (“E”)
 440 and magnetic (“B”) fields in CED are associated with the electric scalar potential

441 “V” and the vector potential “A”. In particular, \mathbf{E} can be obtained by measuring
 442 the change in the space of the scalar potential (ΔV); however, two scalar potentials
 443 differing by a constant “f” correspond to the same electric field. The same happens in
 444 the case of the vector potential “A”; thus, different configurations of the associated
 445 fields result in the same set of values of the observables. The freedom in choosing
 446 one particular configuration is known as “gauge freedom”; the transformation law con-
 447 necting two configurations is known as “gauge transformation” and the fact that the
 448 observables are not affected by a gauge transformation is called “gauge invariance”.

449

450 When the gauge transformation:

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

451 is applied to Maxwell equations, they are still satisfied and the fields remain invariant.
 452 Thus, CED is invariant under gauge transformations and is called a “gauge theory”.
 453 The set of all gauge transformations form the “symmetry group” of the theory, which
 454 according to the group theory, has a set of “group generators”. The number of group
 455 generators determine the number of “gauge fields” of the theory.

456

457 As mentioned in the first lines of section 2.2, QED has one symmetry group ($U(1)$)
 458 with one group generator (the Q operator) and one gauge field (the electromagnetic
 459 field A^μ). In CED there is not a clear definition, beyond the historical convention, of
 460 which fields are the fundamental and which are the associated, but in QED it is clear
 461 that the fundamental field is A^μ . When a gauge theory is quantized, the gauge field

462 is quantized and its quanta is called “gauge boson”. The word boson characterizes
 463 particles with integer spin which obvey Bose-einstein statistics.

464

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

473

474 Due to the space dependence of the local tranformation, the Lagrangian density is
 475 not invariant anymore. In order to restate the gauge invariance, the gauge covariant
 476 derivative is introduced in the Lagrangian and with it the gauge field responsible for
 477 the interaction between particles in the system. The new Lagrangian density is gauge
 478 invariant, includes the interaction terms needed to account for the interactions and
 479 provides a way to explain the interaction between particles through the exchange of
 480 the gauge boson.

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

483 **2.2.3 Gauge bosons**

484 The importance of the gauge bosons comes from the fact that they are the force
 485 mediators or force carriers. The features of the gauge bosons reflect those of the

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

486 fields they represent and they are extracted from the Lagrangian density used to
 487 describe the interactions. In section 2.3, it will be shown how the gauge bosons of the
 488 EI and WI emerge from the electroweak Lagrangian. The SI gauge bosons features
 489 are also extracted from the SI Lagrangian but it is not detailed in this document. The
 490 main features of the SM gauge bosons will be briefly presented below and summarized
 491 in table 2.7.

- 492 • **Photon.** EI occurs when the photon couples to (is exchanged between) particles
 493 carrying electric charge; however, the photon itself does not carry electric charge,
 494 therefore, there is no coupling between photons. Given that the photon is
 495 massless the EI is of infinite range, i.e., electrically charged particles interact
 496 even if they are located far away one from each other; this also implies that
 497 photons always move with the speed of light.
- 498 • **Gluon.** SI is mediated by gluons which, same as photons, are massless. They
 499 carry one unit of color charge and one unit of anticolor charge which means that
 500 gluons couple to other gluons. As a result, the range of the SI is not infinite
 501 but very short due to the attraction between gluons, giving rise to the “color
 502 confinement” which explains why color charged particles cannot be isolated but
 503 live within composited particles, like quarks inside protons.
- 504 • **W, Z.** The WI mediators, W^\pm and Z, are massive which explains their short-
 505 range. Given that the WI is the only interaction that can change the flavor
 506 of the interacting particles, the W boson is the responsible for the nuclear
 507 transmutation where a neutron is converted in a proton or vice versa with the
 508 involvement of an electron and a neutrino (see figure 2.4c). The Z boson is the
 509 responsible of the neutral weak processes like neutrino elastic scattering where

510 no electric charge but momentum transference is involved. WI gauge bosons
 511 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 Z	± 1 0	No No	± 1 0	80.385 ± 0.015 91.188 ± 0.002

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

512

513 **2.3 Electroweak unification and the Higgs 514 mechanism**

515 Physicists dream of building a theory that contains all the interactions in one single
 516 interaction, i.e., showing that at some scale in energy all the four fundamental in-
 517 teractions are unified and only one interaction emerges in a “Theory of everything”.
 518 The first sign of the feasibility of such unification comes from success in the con-
 519 struction of the CED. Einstein spent years trying to reach that dream, which by
 520 1920 only involved electromagnetism and gravity, with no success; however, a new
 521 partial unification was achieved in the 1960’s, when S.Glashow [22], A.Salam [23] and
 522 S.Weinberg [24] independently proposed that electromagnetic and weak interactions
 523 are two manifestations of a more general interaction called “electroweak interaction
 524 (EWT)”. Both, QCD and EWT, were developed in parallel and following the useful
 525 prescription provided by QED and the gauge invariance principles.

526

527 The theory of weak interactions was capable of explaining the β -decay and in general
 528 the processes mediated by W^\pm bosons. However, there were some processes like the

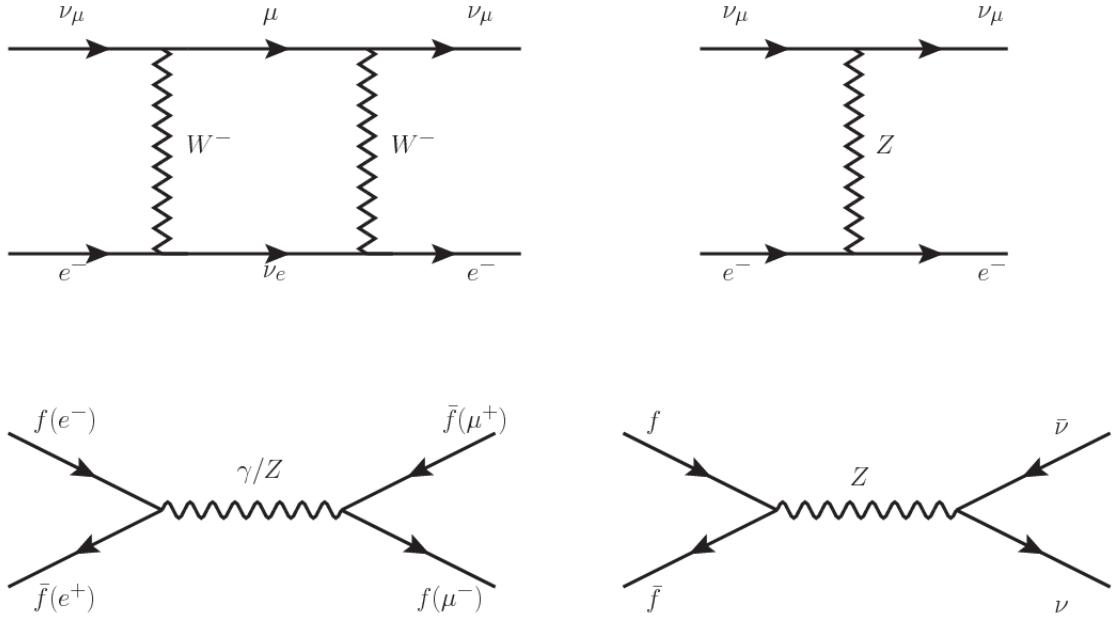


Figure 2.5: Top: $\nu_\mu - e^-$ scattering going through charged currents (left) and neutral currents (right). Bottom: neutral current processes for charged fermions (left) and involving neutrinos (right). While neutral current processes involving only charged fermions can proceed through EI or WI,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

529 “ $\nu_\mu - e$ scattering” which would require the exchange of two W bosons (see figure 2.5
 530 top diagrams) giving rise to divergent loop integrals and then non finite predictions.
 531 By including neutral currents involving fermions via the exchange of neutral bosons
 532 Z, those divergences are compensated and the predictions become realistic.

533

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

538

539 The prescription to build a gauge theory of the WI consists of proposing a free field
 540 Lagrangian density that includes the particles involved; next, by requesting invari-

541 ance under global phase transformations first and generalizing to local phase trans-
 542 formations invariance later, the conserved currents are identified and interactions are
 543 generated by introducing gauge fields. Given that the goal is to include the EI and
 544 WI in a single theory, the group symmetry considered should be a combination of
 545 $SU(2)_L$ and $U(1)_{em}$, however the latter cannot be used directly because the EI treats
 546 left and right-handed particles indistinctly in contrast to the former. Fortunately, the
 547 weak hypercharge, which is a combination of the weak isospin and the electric charge
 548 (eqn 2.2) is suitable to be used since it is conserved by the EI and WI. Thus, the
 549 symmetry group to be considered is

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

550 The following treatment applies to any of the fermion generations, but for simplicity
 551 the first generation of leptons will be considered [5, 6, 25, 26].

552

553 Given the first generation of leptons

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

554 the charged fermionic currents are given by

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

555 and the free Lagrangian is given by

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

556 Mass terms are included directly in the QED and QCD free Lagrangians since they

557 preserve the invariance under the symmetry transformations involved which treat
 558 left-handed and right-handed similarly, however mass terms of the form

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

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

561

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

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

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

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

570 with σ_i the Pauli matrices and y_i the weak hypercharges. In order to promote the
 571 transformations from global to local while keeping the invariance, it is required that

572 $\alpha^i = \alpha^i(x)$, $\beta = \beta(x)$ and the replacement of the ordinary derivatives by the covariant
 573 derivatives

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

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

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

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

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

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

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

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

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

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

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

584

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

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

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

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

589 In order to evaluate the electroweak interactions modeled by an isos triplet field W_μ^i
590 which couples to isospin currents J_μ^i with strength g and additionally the singlet
591 field B_μ which couples to the weak hypercharge current J_μ^Y with strength $g'/2$. The
592 interaction Lagrangian density to be considered is

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

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

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

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

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

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

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

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

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

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

$$\begin{aligned} A_\mu &= B_\mu \cos \theta_W + W_\mu^3 \sin \theta_W \\ Z_\mu &= -B_\mu \sin \theta_W + W_\mu^3 \cos \theta_W \end{aligned} \quad (2.25)$$

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

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

613 the first term is the weak charged current interaction, while the second term is the
 614 electromagnetic interaction under the condition

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

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

616

617 Note that the neutral fields transformation given by the eqn. 2.25 can be written in
 618 terms of the coupling constants g and g' as:

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

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

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

620 where fermion and gauge fields have been considered massless because their regular
 621 mass terms are manifestly non invariant under G transformations; therefore, masses
 622 have to be generated in a gauge invariant way. The mechanism by which this goal is
 623 achieved is known as the “Higgs mechanism” and is closely connected to the concept
 624 of “spontaneous symmetry breaking.”

625 2.3.1 Spontaneous symmetry breaking (SSB)

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

628

629 Before reaching the critical force value, the system has rotational symmetry with re-
 630 spect to the nail axis; however, after the critical force value is reached the nail buckles
 631 (top right). The form of the potential energy (bottom right) changes, preserving its
 632 rotational symmetry although its minima does not exhibit that rotational symmetry
 633 any longer. Right before the nail buckles there is no indication of the direction the
 634 nail will bend because any of the directions are equivalent, but once the nail bends,
 635 choosing a direction, an arbitrary minimal energy state (ground state) is selected and
 636 it does not share the system’s rotational symmetry. This mechanism for reaching an
 637 asymmetric ground state is known as “*spontaneous symmetry breaking*”.

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

640

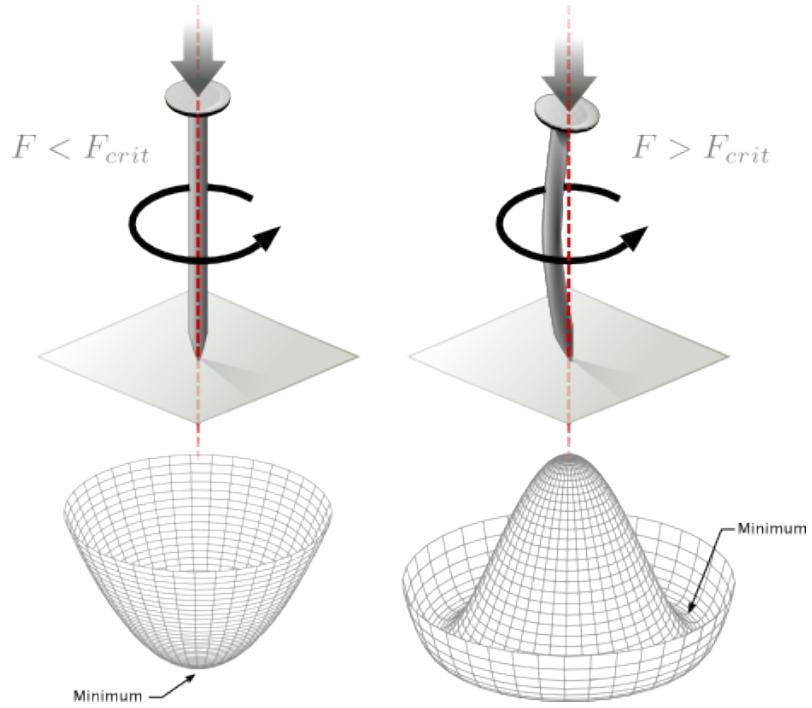


Figure 2.6: Spontaneous symmetry breaking mechanism. The steel nail, subject to an external force (top left), has rotational symmetry with respect to its axis. When the external force overcomes a critical value the nail buckles (top right) choosing a minimal energy state (ground state) and thus “*breaking 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 [27].

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

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

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

645

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

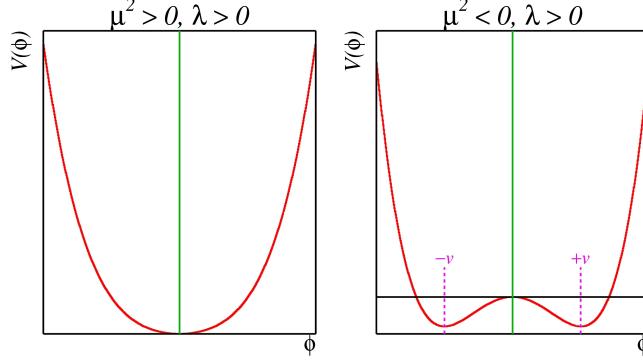


Figure 2.7: Shape of the potential $V(\phi)$ for $\lambda > 0$ and: $\mu^2 > 0$ (left) and $\mu^2 < 0$ (right). The case $\mu^2 < 0$ corresponds to the potential suitable for introducing the SSB mechanism by choosing one of the two ground states which are connected via reflection symmetry. [27].

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

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

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

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

649

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

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

653 As usual, excitations over the ground state are studied by making an expansion about

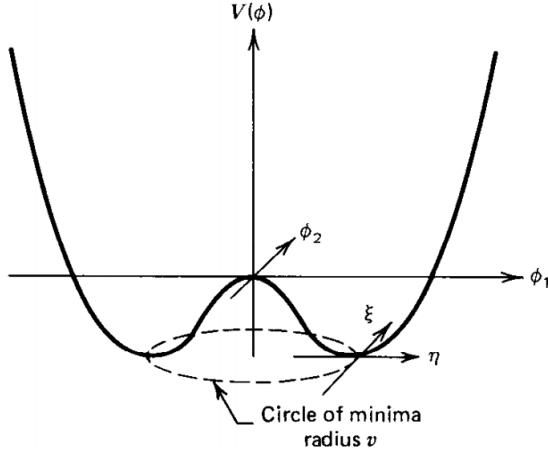


Figure 2.8: Potential for complex scalar field. There is a circle of minima of radius v along the ξ -direction [6].

654 it; thus, the excitation can be parametrized as:

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

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

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

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

662

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

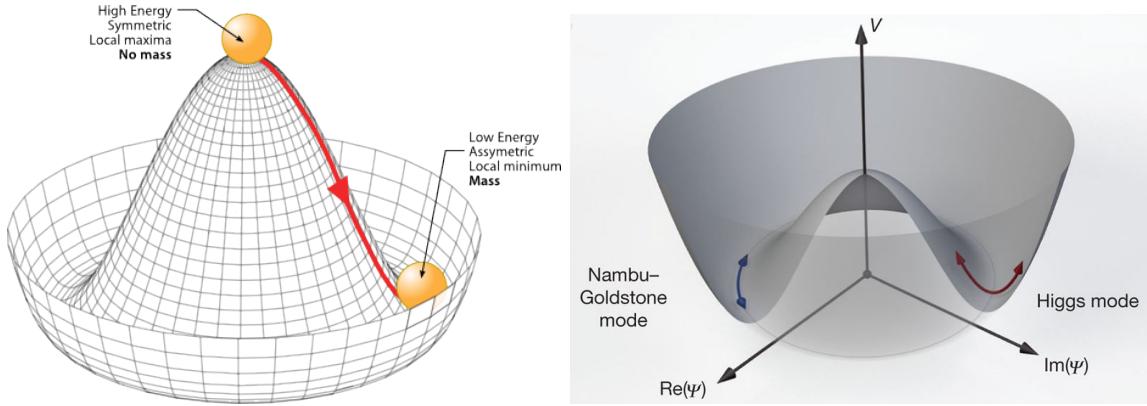


Figure 2.9: SSB mechanism for a complex scalar field [27, 28].

664 *massless field is introduced in the system.* This fact is known as the Goldstone theorem
 665 and states that a massless scalar field appears in the system for each continuous
 666 symmetry spontaneously broken. Another version of the Goldstone theorem states
 667 that “*if a Lagrangian is invariant under a continuous symmetry group G , but the*
 668 *vacuum is only invariant under a subgroup $H \subset G$, then there must exist as many*
 669 *massless spin-0 particles (Nambu-Goldstone bosons) as broken generators.*” [26] The
 670 Nambu-Goldstone boson can be understood considering that the potential in the ξ -
 671 direction is flat so excitations in that direction are not energy consuming and thus
 672 represent a massless state.

673 2.3.2 Higgs mechanism

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

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

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

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

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

681 The minima of the potential are defined by

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

682 The choice of the ground state is critical. By choosing a ground state, invariant under
 683 $U(1)_{em}$ gauge symmetry, the photon will remain massless and the W^\pm and Z bosons
 684 masses will be generated which is exactly what is needed. In that sense, the best
 685 choice corresponds to a weak isospin doublet with $T_3 = -1/2$, $Y_W = 1$ and $Q = 0$
 686 which defines a ground state with $\phi_1 = \phi_2 = \phi_4$ and $\phi_3 = v$:

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

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

689

690 The G symmetry has been broken and three Nambu-Goldstone bosons will appear.

691 The next step is to expand ϕ about the chosen ground state as:

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

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

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

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

704

705 The mechanism was proposed by three independent groups: F.Englert and R.Brout
 706 in August 1964 [29], P.Higgs in October 1964 [30] and G.Guralnik, C.Hagen and
 707 T.Kibble in November 1964 [31]; however, its importance was not realized until
 708 S.Glashow [22], A.Salam [23] and S.Weinberg [24], independently, proposed that elec-
 709 tromagnetic and weak interactions are two manifestations of a more general interac-
 710 tion called “electroweak interaction” in 1967.

711 2.3.3 Masses of the gauge bosons

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

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

- 714 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

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

- 715 and then

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

716 **2.3.4 Masses of the fermions**

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

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

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

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

721

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

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

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

725 Additionally, given that the quark isospin doublets are not constructed in terms of
 726 the mass eigenstates but in terms of the flavor eigenstates, as shown in table2.5, the
 727 coupling parameters will be related to the CKM matrix elements; thus the quark
 728 Lagrangian is given by:

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

729 with $i,j=1,2,3$. After SSB and expansion about the ground state, the diagonal form

730 of \mathcal{L}_{Yq} is:

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

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

733 2.3.5 The Higgs field

734 After the characterization of the fermions and gauge bosons as well as their interac-
735 tions, it is necessary to characterize the Higgs field itself. The Lagrangian \mathcal{L}_S in eqn.
736 2.36 written in terms of the gauge bosons is given by

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

737

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

738

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

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

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

741 however, it is not predicted by the theory either. The experimental efforts to find
742 the Higgs boson, carried out by the “Compact Muon Solenoid (CMS)” experiment
743 and the “A Toroidal LHC AppartuS (ATLAS)” experiments at the “Large Hadron
744 Collider(LHC)”, gave great results by July of 2012 when the discovery of a new
745 particle compatible with the Higgs boson predicted by the electroweak theory [32, 33]
746 was announced. Although at the announcement time there were some reservations
747 about calling the new particle the “Higgs boson”, today this name is widely accepted.

748 The Higgs mass measurement, reported by both experiments [34], 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)	$125.09 \pm 0.21 \text{ (stat.)} \pm 0.11 \text{ (syst.)}$

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

749

750 2.3.6 Production of Higgs bosons at LHC

751 At LHC, Higgs boson is produced as a result of the collision of two counter-rotating
 752 protons beams. A detailed description of the LHC machine will be presented in
 753 chapter 3. “The total cross section” is a parameter that quantifies the number of pp
 754 collisions that happen when a number of protons are fired at each other. Different
 755 results can be obtained after a pp collision and for each one the “cross section” is
 756 defined as the number of pp collisions that conclude in that particular result with
 757 respect to the number of protons fired at each other.

758 Protons are composed of quarks and these quarks are bound by gluons; however,
 759 what is commonly called the quark content of the proton makes reference to the
 760 valence quarks. A sea of quarks and gluons is also present inside the proton as repre-
 761 sented in figure 2.10. In a proton-proton (pp) collision, the constituents (quarks and
 762 gluons) are those who collide. The pp cross section depends on the momentum of
 763 the colliding particles, reason for which it is needed to know how the momentum is
 764 distributed inside the proton. Quarks and gluons are known as partons and the func-
 765 tions that describe how the proton momentum is distributed among partons inside it

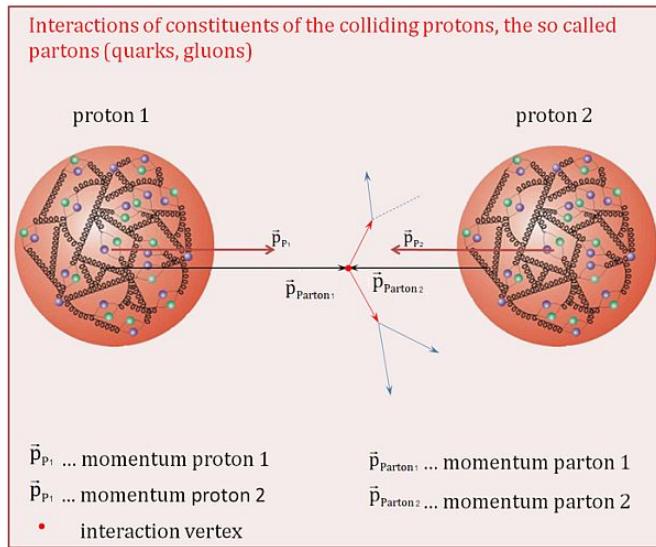


Figure 2.10: Proton-proton collision. Protons are composed of 3 valence quarks, a sea of quarks and gluons; therefore in a proton-proton collision, quarks and gluons are those who collide. [35].

766 are called “parton distribution functions (PDFs)”; PDFs are determined from experi-

767 mental data obtained in experiments where the internal structure of hadrons is tested.

768

In addition, in physics, a common approach to study complex systems consists in starting with a simpler version of them, for which a well known description is available, and add an additional “perturbation” which represents a small deviation from the known behavior. If the perturbation is small enough, the physical quantities associated with the perturbed system are expressed as a series of corrections to those of the simpler system; therefore, the more terms are considered in the series (the higher order in the perturbation series), the more precise is the description of the complex system.

777

778 This thesis explores the Higgs production at LHC; therefore the overview presented
779 here will be oriented specifically to the production mechanisms after pp collisions at

780 LHC.

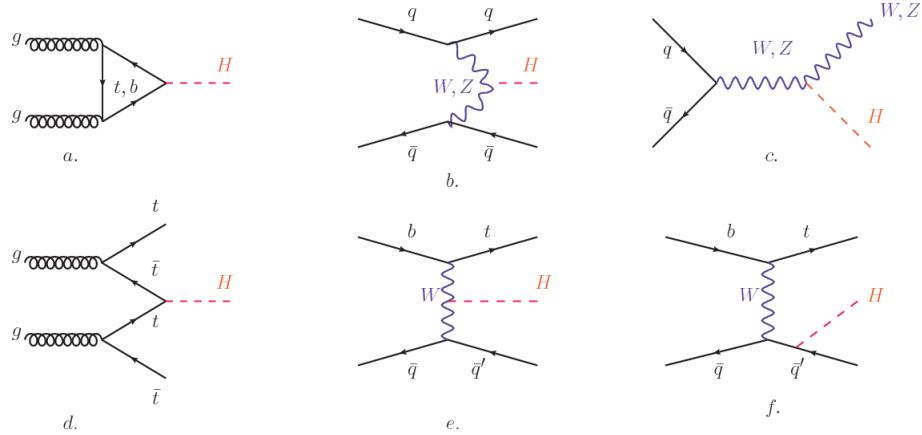


Figure 2.11: Main Higgs boson production mechanism Feynman diagrams. a. gluon-gluon fusion, b. vector boson fusion (VBF), c. Higgs-strahlung, d. Associated production with a top or bottom quark pair, e-f. associated production with a single top quark.

781 Figure 2.11 shows the Feynman diagrams for the leading order (first order) Higgs
 782 production processes at LHC, while the cross section for Higgs production as a func-
 783 tion of the center of mass-energy (\sqrt{s}) for pp collisions is showed in figure 2.12 left.
 784 The tags NLO (next to leading order), NNLO (next to next to leading order) and
 785 N3LO (next to next to next to leading order) make reference to the order at which
 786 the perturbation series have been considered.

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

792 The main production mechanism is the gluon fusion (figure 2.11a and $pp \rightarrow H$ in figure
 793 2.12) given that gluons carry the highest fraction of momentum of the protons in pp
 794 colliders. Since the Higgs boson does not couple to gluons, the mechanism proceeds
 795 through the exchange of a virtual top-quark loop given that for it the coupling is

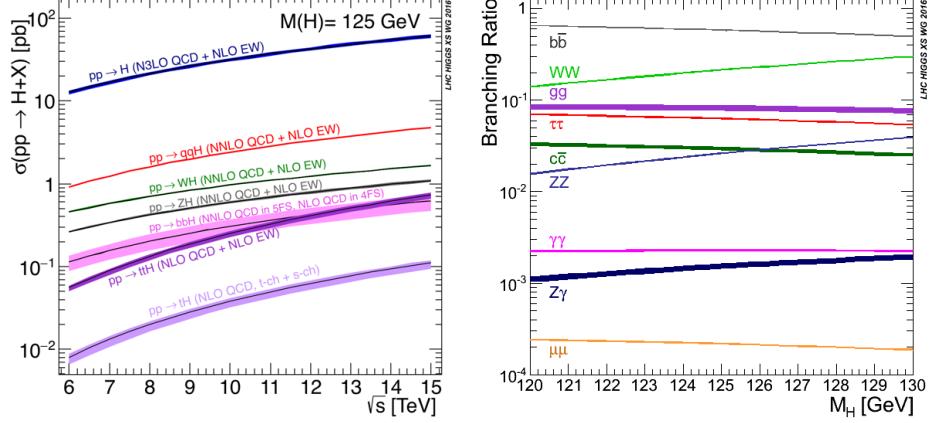


Figure 2.12: Higgs boson production cross sections (left) and decay branching ratios (right) for the main mechanisms. The VBF is indicated as qqH [36].

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 $pp \rightarrow qqH$ 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 tend to be located in a particular region of the detector which is used as a signature when analyzing the datasets provided by the experiments. More details about how to identify events of interest in an analysis will be given in chapter 6.

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

The associated production with a top or bottom quark pair and the associated production with a single top quark (figure 2.11d-f and $pp \rightarrow bbH, pp \rightarrow t\bar{t}H, pp \rightarrow tH$ in figure 2.12) have a smaller cross section than the main three mechanisms above,

812 but they provide a good opportunity to test the Higgs-top coupling. The analysis
 813 reported in this thesis is developed using these production mechanisms. A detailed
 814 description of the tH mechanism will be given in section 2.4.

815 **2.3.7 Higgs boson decay channels**

816 When a particle can decay through several modes, also known as channels, the
 817 probability of decaying through a given channel is quantified by the “branching ratio
 818 (BR)” of the decay channel; thus, the BR is defined as the ratio of number of decays
 819 going through that given channel to the total number of decays. In regard to the
 820 Higgs boson decay, the BR can be predicted with accuracy once the Higgs mass is
 821 known [37, 38]. In figure 2.12 right, a plot of the BR as a function of the Higgs mass
 822 is presented. The largest predicted BR corresponds to the $b\bar{b}$ pair decay channel (see
 823 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 $m_H = 125 GeV/c^2$. [9]

825 **2.4 Associated production of a Higgs boson and a
826 single Top quark.**

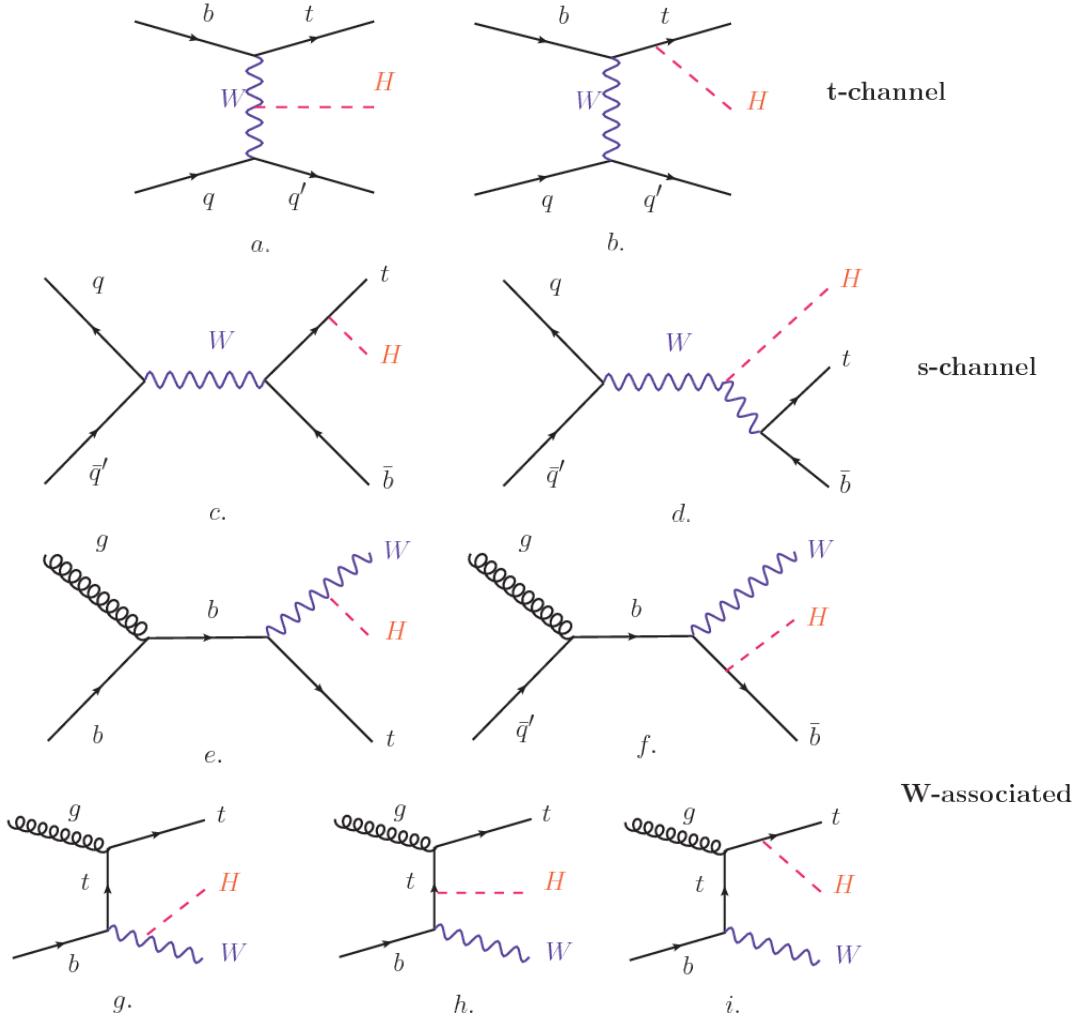


Figure 2.13: Associated Higgs boson production mechanism Feynman diagrams. a.,b. t-channel (tHq), c.,d. s-channel (tHb), e-i. W-associated.

827 Associated production of Higgs boson has been extensively studied [39–43]. While
828 measurements of the main Higgs production mechanisms rates are sensitive to the
829 strength of the Higgs coupling to W boson or top quark, they are not sensitive to the
830 relative sign between the two couplings. In this thesis, the Higgs boson production

mechanism explored is the associated production with a single top quark (tH) 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 [41]

834

835 A process where two incoming particles interact and produce a final state with two
 836 particles can proceed in three ways also called channels (see, for instance, figure 2.13
 837 ommiting the red line). The t-channel represents processes where an intermediate
 838 particle is emitted by one of the incoming particles and absorbed by the other. The
 839 s-channel represents processes where the two incoming particles merge into an inter-
 840 mediate particle which eventually will split into the particles in the final state. The
 841 third channel, u-channel, is similar to the t-channel but the two outgoing particles
 842 interchange their roles.

843

844 The tH production, where Higgs boson can be radiated either from the top quark
 845 or from the W boson, is represented by the leading order Feynman diagrams in
 846 figure ???. The cross section for the tH process is calculated, as usual, summing over
 847 the contributions from the different feynman diagrams; therefore it depends on the
 848 interference between the contributions. In the SM, the interference for t-channel (tHq
 849 process) and W-associated (tHW process) production is destructive [39] resulting in
 850 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 [44, 45].

851

852 While the s-channel contribution can be neglected, it will be shown that a deviation
 853 from the SM destructive interference would result in an enhancement of the tH cross
 854 section compared to that in SM, which could be used to get information about the
 855 sign of the Higgs-top coupling [41, 42]. In order to describe tH production processes,
 856 Feynman diagram 2.13b will be considered; there, the W boson is radiated by a
 857 quark in the proton and eventually it will interact with the b quark. In the high
 858 energy regime, the effective W approximation [46] allows to describe the process as
 859 the emmision of an approximately on-shell W and its hard scattering with the b
 860 quark; i.e. $Wb \rightarrow th$. The scattering amplitude for the process is given by

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

861 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-
 862 tify possible deviations of the couplings, Higgs-Vector boson (H-W) and Higgs-top
 863 (H-t) respectively, from the SM couplings; $s = (p_W + p_b)^2$, $t = (p_W - p_H)^2$, φ is the
 864 Higgs azimuthal angle around the z axis taken parallel to the direction of motion of
 865 the incoming W; A and B are funtions describing the weak interaction in terms of
 866 the chiral states of the quarks b and t . Terms that vanish in the high energy limit
 867 have been neglected as well as the Higgs and b quark masses⁸.

868

869 The scattering amplitude grows with energy like \sqrt{s} for $\kappa_V \neq \kappa_t$, in contrast to
 870 the SM ($\kappa_t = \kappa_V = 1$), where the first term in 2.57 cancels out and the amplitude
 871 is constant for large s ; therefore, a deviation from the SM predictions represents an
 872 enhancement in the tHq cross section. In particular, for a SM H-W coupling and a H-t

⁸ A detailed explanation of the structure and approximations used to derive \mathcal{A} can be found in reference [41]

873 coupling of inverted sign with respect to the SM ($\kappa_V = -\kappa_t = 1$) the tHq cross section
 874 is enhanced by a factor greater 10 as seen in the figure 2.14 taken from reference [41];
 875 reference [47] has reported similar enhancement results.

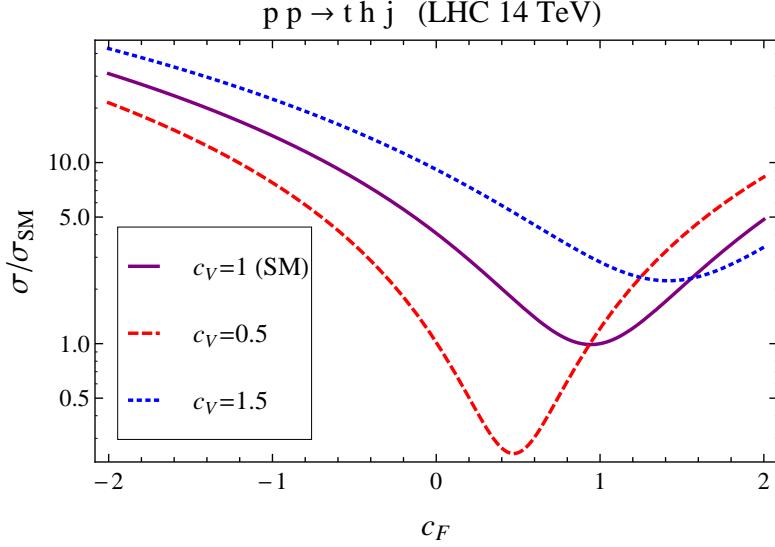


Figure 2.14: Cross section for tHq process as a function of κ_t , normalized to the SM, for three values of κ_V . In the plot c_f refers to the Higgs-fermion coupling which is dominated by the H-t coupling and represented here by κ_t . Solid, dashed and dotted lines correspond to $c_V \rightarrow \kappa_V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

876 A similar analysis is valid for the W-associated channel but, in that case, the inter-
 877 ference is more complicated since there are more than two contributions and an ad-
 878 ditional interference with the production of Higgs boson and a top pair process($t\bar{t}H$).
 879 The calculations are made using the so-called Diagram Removal (DR) technique where
 880 interfering diagrams are removed (or added) from the calculations in order to evaluate
 881 the impact of the removed contributions. DR1 was defined to neglect $t\bar{t}H$ interference
 882 while DR2 was defined to take $t\bar{t}H$ interference into account [48]. As shown in figure
 883 2.15, the tHW cross section is enhanced from about 15 fb (SM: $\kappa_{Htt} = 1$) to about
 884 150 fb ($\kappa_{Htt} = -1$). Differences between curves for DR1 and DR2 help to gauge the
 885 impact of the interference with $t\bar{t}H$.

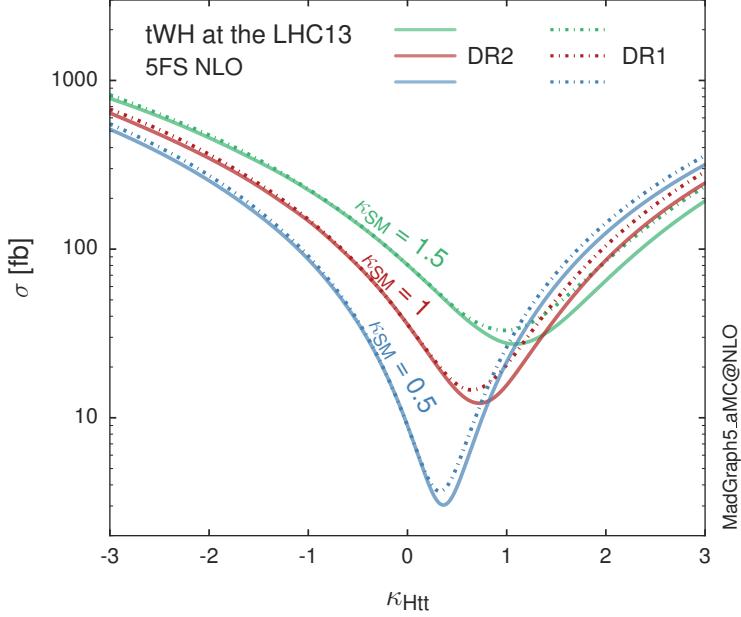


Figure 2.15: Cross section for tHW process as a function of κ_{Htt} , for three values of κ_{SM} at $\sqrt{s} = 13$ TeV. $\kappa_{Htt}^2 = \sigma_{Htt}/\sigma_{Htt}^{SM}$ is a simple rescaling of the SM Higgs interactions.

886 Results of the calculations of the tHq and tHW cross sections at $\sqrt{s} = 13$ TeV can be
 887 found in reference [49] and a summary of the results is presented in table 2.11.

888

889 2.5 The CP-mixing in tH processes

890 In addition to the sensitivity to sign of the H-t coupling, tHq and tHW processes have
 891 been proposed as a tool to investigate the possibility of a H-t coupling that does not
 892 conserve CP [43, 48, 50]. Current experimental results are consistent with SM H-V
 893 and H-t couplings; however, negative H-t coupling is not excluded completely [53].

894

895 In this thesis, the sensitivity of tH processes to CP-mixing is also studied in the
 896 effective field theory framework and based in references [43, 48]; a generic particle

	\sqrt{s} TeV	$\kappa_t = 1$	$\kappa_t = -1$
$\sigma^{LO}(tHq)(fb)$ [41]	8	≈ 17.4	≈ 252.7
	14	≈ 80.4	≈ 1042
$\sigma^{NLO}(tHq)(fb)$ [41]	8	$18.28^{+0.42}_{-0.38}$	$233.8^{+4.6}_{-0.0}$
	14	$88.2^{+1.7}_{-0.0}$	$982.8^{+28}_{-0.0}$
$\sigma^{LO}(tHq)(fb)$ [47]	14	≈ 71.8	≈ 893
$\sigma^{LO}(tHW)(fb)$ [47]	14	≈ 16.0	≈ 139
$\sigma^{NLO}(tHq)(fb)$ [49]	8	$18.69^{+8.62\%}_{-17.13\%}$	-
	13	$74.25^{+7.48\%}_{-15.35\%}$	$848^{+7.37\%}_{-13.70\%}$
	14	$90.10^{+7.34\%}_{-15.13\%}$	$1011^{+7.24\%}_{-13.39\%}$
$\sigma^{LO}(tHW)(fb)$ [48]	13	$15.77^{+15.91\%}_{-15.76\%}$	-
$\sigma^{NLO}DR1(tHW)(fb)$ [48]	13	$21.72^{+6.52\%}_{-5.24\%}$	≈ 150
$\sigma^{NLO}DR2(tHW)(fb)$ [48]	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.

897 (X_0) of spin-0 and a general CP violating interaction with the top quark, can couple
 898 to scalar and pseudoscalar fermionic densities. The H-W interaction is assumed to
 899 be SM-like. The Lagrangian modeling the H-t interaction is given by

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

900 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
 901 dimensionless rescaling parameters⁹, $g_{Htt} = g_{Att} = m_t/v = y_t/\sqrt{2}$ and $v \sim 246$ GeV is
 902 the Higgs vacuum expectation value. In this parametrization, it is easy to recover
 903 three special cases

904 • CP-even coupling $\rightarrow \alpha = 0^\circ$

905 • CP-odd coupling $\rightarrow \alpha = 90^\circ$

906 • SM coupling $\rightarrow \alpha = 0^\circ$ and $\kappa_{Htt} = 1$

⁹ analog to κ_t and κ_V

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

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

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

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

913 If the rescaling parameters are set to

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

914 the gluon-fusion SM cross section is reproduced for every value of the CP-mixing
 915 angle α ; therefore, by imposing that condition to the Lagrangian density 2.58, the
 916 CP-mixing angle is not constrained by current data. Figure 2.16 shows the NLO cross
 917 sections for t-channel tX_0 (blue) and $t\bar{t}X_0$ (red) associated production processes as
 918 a function of the CP-mixing angle α . X_0 is a generic spin-0 particle with top quark
 919 CP-violating coupling. Rescaling factors κ_{Htt} and κ_{Att} have been set to reproduce
 920 the SM gluon-fusion cross sections.

921 It is interesting to notice that the tX_0 cross section is enhanced, by a factor of
 922 about 10, when a continuous rotation in the scalar-pseudoscalar plane is applied; this
 923 enhancement is similar to the enhancement produced when the H-t coupling is flipped
 924 in sign with respect to the SM ($y_t = -y_{t,SM}$ in the plot), as showed in section 2.4. In

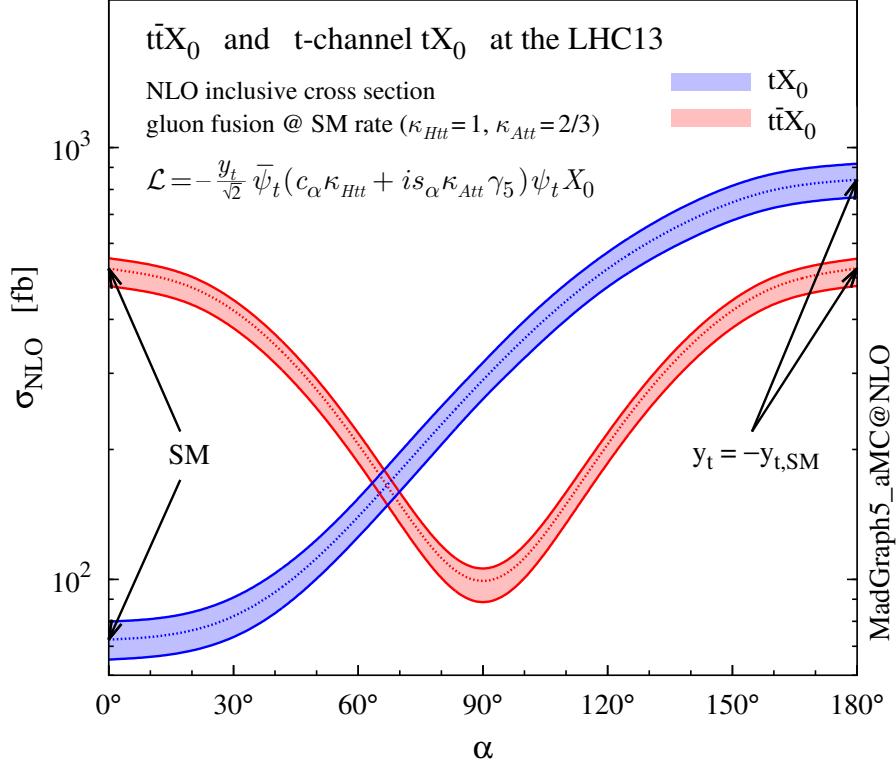


Figure 2.16: NLO cross sections for t-channel tX_0 (blue) and $t\bar{t}X_0$ (red) associated production processes as a function of the CP-mixing angle α . X_0 is a generic spin-0 particle with top quark CP-violating coupling [43].

925 contrast, the degeneracy in the $t\bar{t}X_0$ cross section is still present given that it depends
 926 quadratically on the H-t coupling, but more interesting is to notice that $t\bar{t}X_0$ cross
 927 section is exceeded by tX_0 cross section after $\alpha \sim 60^\circ$.

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

932

933 Figure 2.17 shows the NLO cross sections for t-channel tX_0 (blue), $t\bar{t}X_0$ (red) asso-
 934 ciated production and for the combined $tWX_0 + t\bar{t}X_0 +$ interference (orange) as a

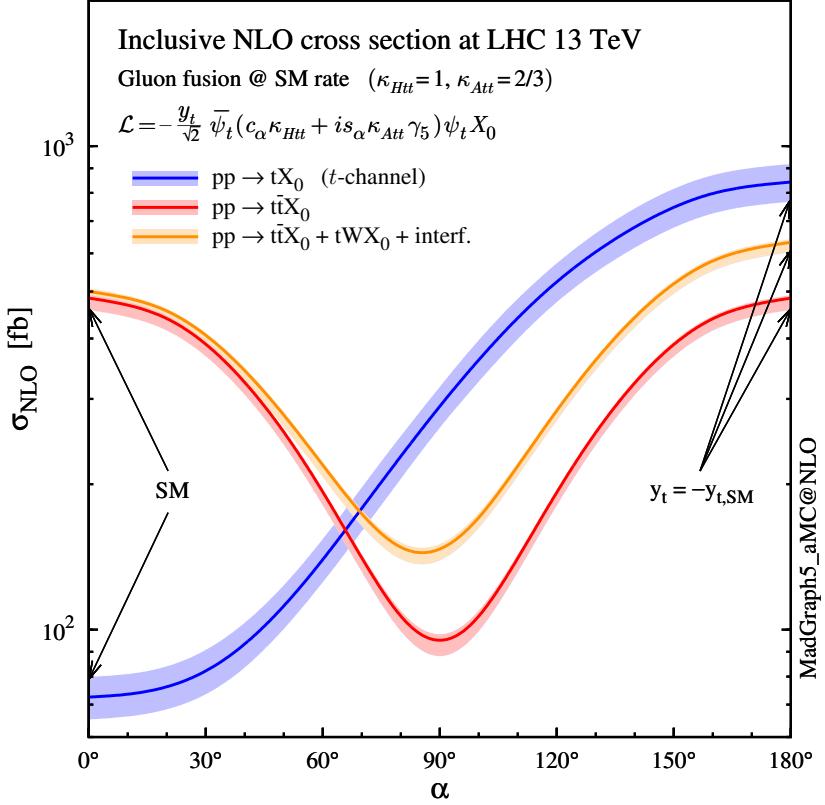


Figure 2.17: NLO cross sections for t-channel tX_0 (blue), $t\bar{t}X_0$ (red) associated production processes and combined $tWX_0 + t\bar{t}X_0$ (including interference) production as a function of the CP-mixing angle α [43].

function of the CP-mixing angle. It is clear that the effect of the interference in the combined case is the lifting of the degeneracy present in the $t\bar{t}X_0$ production. The constructive interference enhances the cross section from about 500 fb at SM ($\alpha = 0$) to about 600 fb ($\alpha = 180^\circ \rightarrow y_t = -y_{t,SM}$).
 An analysis combining tHq and tHW processes will be made in this thesis taking advantage of the sensitivity improvement.

941 **2.6 Experimantal status of the anomalous**
 942 **Higg-fermion coupling.**

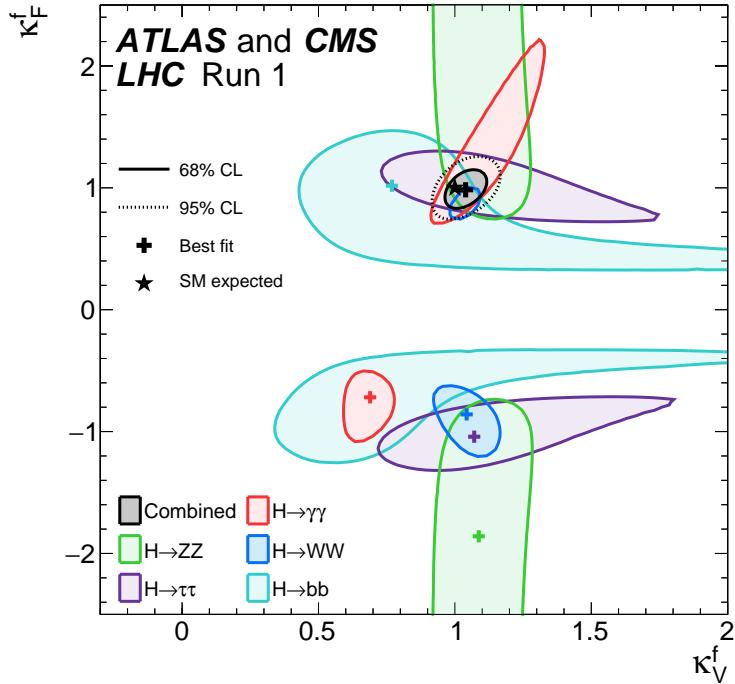


Figure 2.18: Combination of the ATLAS and CMS fits for coupling modifiers κ_t - κ_V ; also shown the individual decay channels combination and their global combination. No assumptions have been made on the sign of the coupling modifiers [53].

943 ATLAS and CMS have performed analysis of the anomalous H-f coupling by making
 944 likelihood scans for the two coupling modifiers, κ_t and κ_V , under the assumption that
 945 $\kappa_Z = \kappa_W = \kappa_V$ and $\kappa_t = \kappa_\tau = \kappa_b = \kappa_f$. Figure 2.18 shows the result of the combination
 946 of ATLAS and CMS fits; also the individual decay channels combination and the
 947 global combination results are shown.
 948 While all the channels are compatible for positive values of the modifiers, for negative
 949 values of κ_t there is no compatibility. The best fit for individual channels is compatible
 950 with negative values of κ_t except for the $H \rightarrow bb$ channel which is expected to be the

951 most sensitive channel; therefore, the best fit for the global fit yields $\kappa_t \geq 0$. Thus,
952 the anomalous H-t coupling cannot be excluded completely.

953 **Chapter 3**

954 **The CMS experiment at the LHC**

955 **3.1 Introduction**

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

969 3.2 The LHC

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

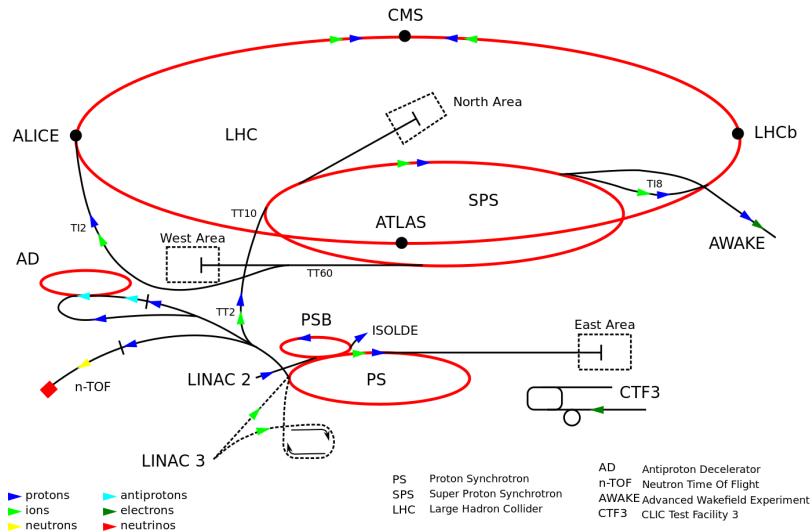


Figure 3.1: CERN accelerator complex. Blue arrows show the path followed by protons along the acceleration process [54].

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

- 977 • Proton-Proton collisions (pp) for multiple physics experiments.
- 978 • Lead-Lead collisions ($Pb-Pb$) for heavy ion experiments.
- 979 • Proton-Lead collisions ($p-Pb$) for quark-gluon plasma experiments.

980 In this thesis only pp collisions will be considered.

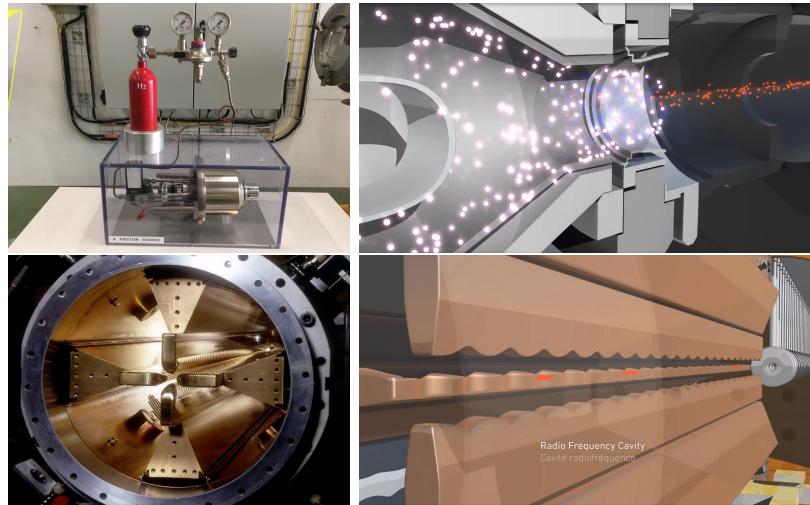


Figure 3.2: LHC protons source and the first acceleration stage. Top: the bottle contains hydrogen gas (white dots) which is injected into the metal cylinder to be broken down into electrons(blue dots) and protons(red dots); Bottom: the obtained protons are directed towards the radio frequency quadrupole which perform the first acceleration, focus the beam and create the bunches of protons. [58, 59]

982 Collection of protons starts with hydrogen atoms taken from a bottle, containing hy-
 983 drogen gas, and injecting them in a metal cylinder; hydrogen atoms are broken down
 984 into electrons and protons by an intense electric field (see figure3.2 top). The result-
 985 ing protons leave the metal cylinder towards a radio frequency quadrupole (RFQ)
 986 that focus the beam, accelerates the protons and creates the packets of protons called
 987 bunches. In the RFQ, an electric field is generated by a RF wave at a frequency that
 988 matches the resonance frequency of the cavity where the electrodes are contained.
 989 The beam of protons traveling on the RFQ axis experiences an alternating electric
 990 field gradient that generates the focusing forces.

991

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

996 RFQ (synchronous proton) do not feel an accelerating force, but those protons in the
 997 beam that have more (or less) energy than the synchronous proton (asynchronous
 998 protons) will feel a decelerating (accelerating) force; therefore, asynchronous protons
 999 will oscillate around the synchronous ones forming bunches of protons [56]. From the
 1000 RFQ protons emerge with energy 750 keV in bunches of about 1.15×10^{11} protons [57].

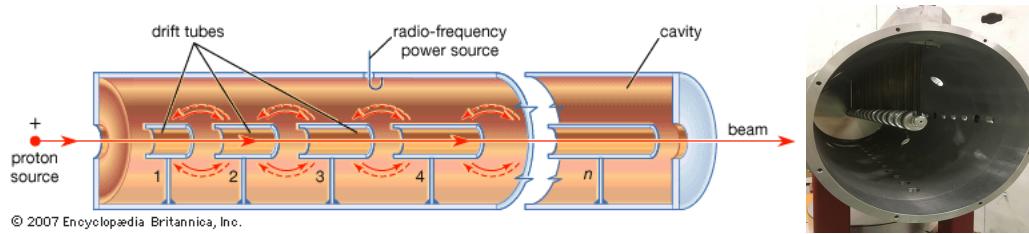


Figure 3.3: The LINAC2 accelerating system at CERN. Electric fields generated by radio frequency (RF) create acceleration and deceleration zones inside the cavity; deceleration zones are blocked by drift tubes where quadrupole magnets focus the proton beam. [60]

1001 Proton bunches coming from the RFQ go to the linear accelerator 2 (LINAC2) where
 1002 they are accelerated to reach 50 MeV energy. In the LINAC2 stage, acceleration
 1003 is performed using electric fields generated by radio frequency which create zones
 1004 of acceleration and deceleration as shown in figure 3.3. In the deceleration zones,
 1005 the electric field is blocked using drift tubes where protons are free to drift while
 1006 quadrupole magnets focus the beam.

1007

1008 The beam coming from LINAC2 is injected into the proton synchrotron booster
 1009 (PSB) to reach 1.4 GeV in energy. The next acceleration is provided at the pro-
 1010 ton synchrotron (PS) up to 26 GeV, followed by the injection into the super proton
 1011 synchrotron (SPS) where protons are accelerated to 450 GeV. Finally, protons are
 1012 injected into the LHC where they are accelerated to the target energy of 6.5 TeV.
 1013 PSB, PS, SPS and LHC accelerate protons using the same RF acceleration technique
 1014 described before.

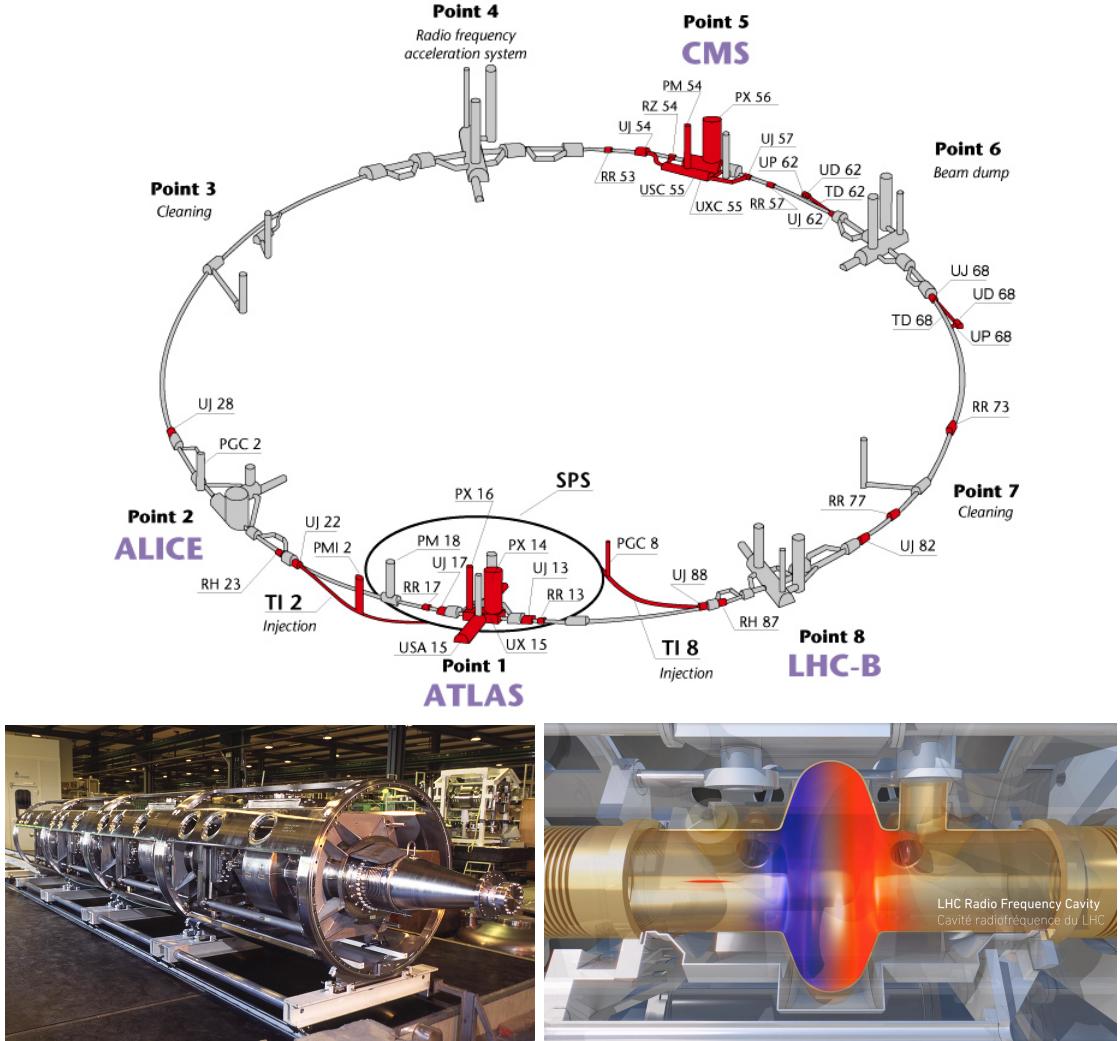


Figure 3.4: Top: LHC layout. The red zones indicate the infrastructure additions to the LEP installations, built to accommodate the ATLAS and CMS experiments which exceed the size of the former experiments located there [55]. Bottom: LHC RF cavities. A module accommodates 4 cavities that accelerate protons and preserve the bunch structure of the beam. [59, 61]

1015 LHC has a system of 16 RF cavities located in the so-called point 4, as shown in
 1016 figure 3.4 top, tuned at a frequency of 400 MHz and the protons are carefully timed,
 1017 so in addition to the acceleration effect the bunch structure of the beam is preserved.
 1018 Bottom side of figure 3.4 shows a picture of a RF module composed of 4 RF cavities
 1019 working in a superconducting state at 4.5 K; also is showed a representation of the

1020 accelerating electric field that accelerates the protons in the bunch.

1021

1022 While protons are accelerated in one section of the LHC ring, where the RF cavities
 1023 are located, in the rest of their path they have to be kept in the curved trajectory
 1024 defined by the LHC ring. Technically, LHC is not a perfect circle; RF, injection, beam
 1025 dumping, beam cleaning and sections before and after the experimental points where
 1026 protons collide are all straight sections. In total, there are 8 arcs 2.45 Km long each
 1027 and 8 straight sections 545 m long each. In order to curve the proton's trajectory in
 1028 the arc sections, superconducting dipole magnets are used.

1029

1030 Inside the LHC ring, there are two proton beams traveling in opposite directions in
 1031 two separated beam pipes; the beam pipes are kept at ultra-high vacuum ($\sim 10^{-9}$
 1032 Pa) to ensure that there are no particles that interact with the proton beams. The
 1033 superconducting dipole magnets used in LHC are made of a NbTi alloy, capable of
 1034 transporting currents of about 12000 A when cooled at a temperature below 2K using
 1035 liquid helium (see figure 3.5).

1036

1037 Protons in the arc sections of LHC feel a centripetal force exerted by the dipole
 1038 magnets which is perpendicular to the beam trajectory; The magnitude of magnetic
 1039 field needed can be found assuming that protons travel at $v \approx c$, using the standard
 1040 values for proton mass and charge and the LHC radius, as

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

1041 which is about 100000 times the Earth's magnetic field. A representation of the mag-
 1042 netic field generated by the dipole magnets is shown on the bottom left side of figure

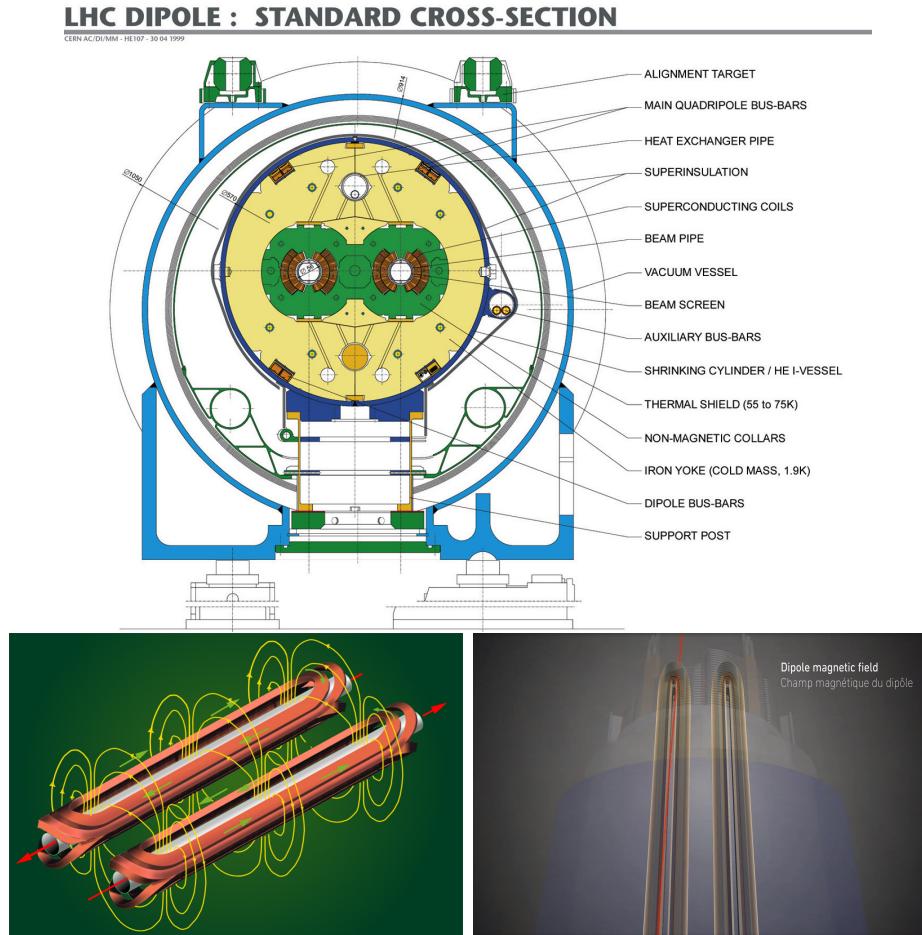


Figure 3.5: Top: LHC dipole magnet transverse view; cooling, shielding and mechanical support are indicated. Bottom left: Magnetic field generated by the dipole magnets; note that the direction of the field inside one beam pipe is opposite with respect to the other beam pipe which guarantee that both proton beams are curved in the same direction towards the center of the ring. The effect of the dipole magnetic field on the proton beam is represented on the bottom right side [59, 62, 63].

1043 3.5. The bending effect of the magnetic field on the proton beam is shown on the
 1044 bottom right side of figure 3.5. Note that the dipole magnets are not curved; the arc
 1045 section of the LHC ring is composed of straight dipole magnets of about 15 m. In
 1046 total there are 1232 dipole magnets along the LHC ring.

1047

1048 In addition to bending the beam trajectory, the beam has to be focused so it stays

1049 inside the beam pipe. The focusing is performed by quadrupole magnets installed in
 1050 a different straight section; in total 858 quadrupole magnets are installed along the
 1051 LHC ring. Other effects like electromagnetic interaction among bunches, interaction
 1052 with electron clouds from the beam pipe, the gravitational force on the protons, dif-
 1053 ferences in energy among protons in the same bunch, among others, are corrected
 1054 using sextupole and other magnetic multipoles.

1055

1056 The two proton beams inside the LHC ring are made of bunches with a cylindrical
 1057 shape of about 7.5 cm long and about 1 mm in diameter; when bunches are close
 1058 to the collision point (CP), the beam is focused up to a diameter of about 16 μm in
 1059 order to maximize the number of collisions per unit area and per second, known as
 1060 luminosity (L). Luminosity can be calculated using

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

1061 where f is the revolution frequency, n is the number of bunches per beam, N_1 and
 1062 N_2 are the numbers of protons per bunch (1.5×10^{11}), σ_x and σ_y are the gaussian
 1063 transverse sizes of the bunches. The expected luminosity is about

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

$$n = 2808$$

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

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

1064

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

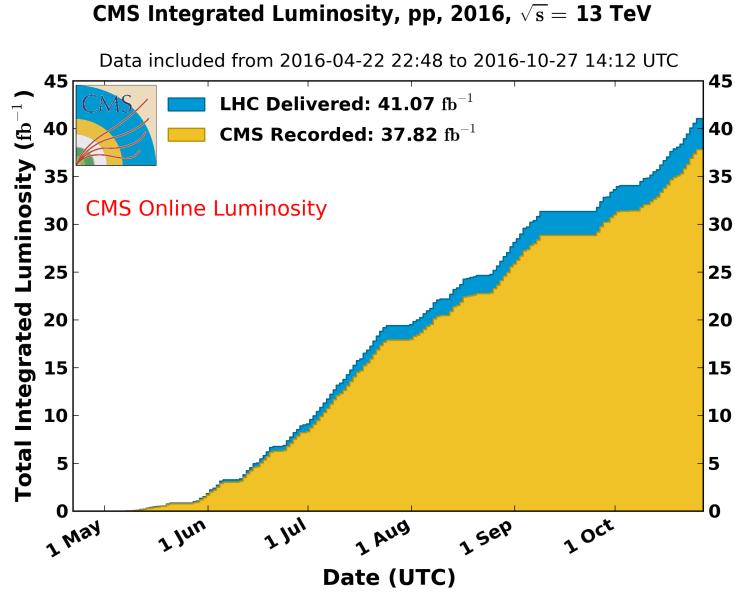


Figure 3.6: Integrated luminosity delivered by LHC and recorded by CMS during 2016. The difference between the delivered and the recorded luminosity is due to fails and issues occurred during the data taking in the CMS experiment [64].

1065 Luminosity is a fundamental aspect of LHC given that the bigger luminosity the
 1066 bigger number of collisions, which means that for processes with a very small cross
 1067 section the number of expected occurrences is increased and so the chances of being
 1068 detected. The integrated luminosity, i.e., the total luminosity, collected by the CMS
 1069 experiment during 2016 is shown in figure 3.6; the data analyzed in this thesis corre-
 1070 sponds to an integrated luminosity of 35.9 fb^{-1} at a center of mass-energy $\sqrt{s} = 13$
 1071 TeV.

1072

1073 A way to increase L is increasing the number of bunches in the beam. Currently, the
 1074 separation between two consecutive bunches in the beam is 7.5 m which corresponds
 1075 to a time separation of 25 ns. In the full LHC ring the allowed number of bunches is
 1076 $n = 27\text{km}/7.5\text{m} = 3600$; however, there are some gaps in the bunch pattern intended
 1077 for preparing the dumping and injection of the beam, thus, the proton beams are

1078 composed of 2808 bunches.

1079

1080 Once the proton beams reach the desired energy, they are brought to cross each other
 1081 producing proton-proton collisions. The bunch crossing happens in precise places
 1082 where the four LHC experiments are located, as seen in the top of figure 3.7. In 2008,
 1083 the first set of collisions involved protons with $\sqrt{s} = 7$ TeV; the energy was increased
 1084 to 8 TeV in 2012 and to 13 TeV in 2015.

1085

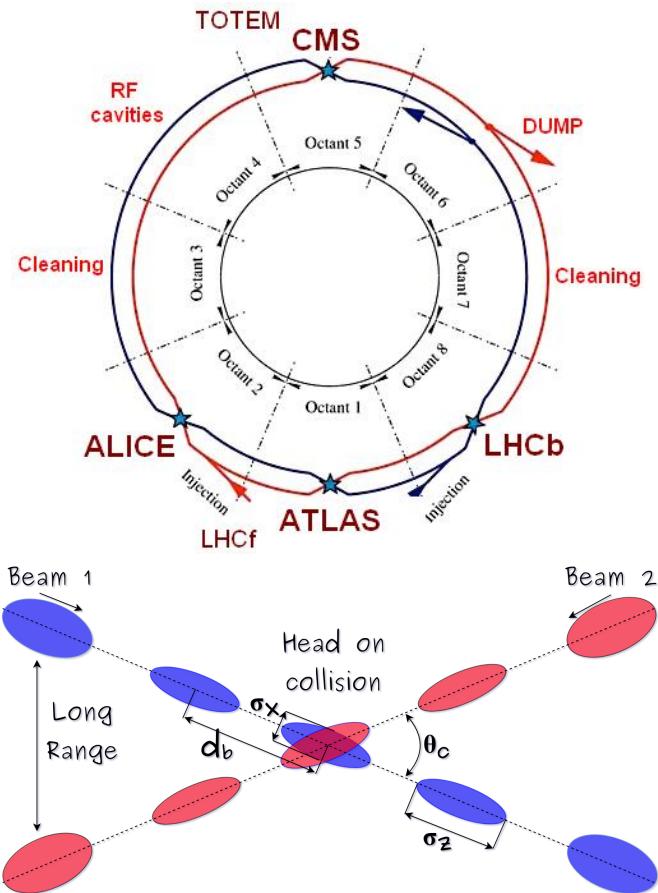


Figure 3.7: Top: LHC interaction points. Bunch crossing occurs where the LHC experiments are located [65]. Sections indicated as cleaning are dedicated to collimate the beam in order to protect the LHC ring from collisions with protons in very spreaded bunches. Bottom: bunch crossing scheme. Since the bunch crossing is not perfectly head-on, the luminosity is reduced in a factor of 17%; adapted from reference [77].

1086 CMS and ATLAS experiments, which are multi-purpose experiments, are enabled
 1087 to explore physics in any of the collision modes. LHCb experiment is optimized
 1088 to explore bottom quark physics, while ALICE is optimized for heavy ion collisions
 1089 searches; TOTEM and LHCf are dedicated to forward physics studies; MoEDAL (not
 1090 indicated in the figure) is intended for monopoles or massive pseudo stable particles
 1091 searches.

1092

1093 At the CP there are two interesting details that need to be addressed. The first one
 1094 is that the bunch crossing does not occur head-on but at a small crossing angle “ θ_c ”
 1095 (280 μ rad in CMS and ATLAS) as shown in the bottom side of figure 3.7, affecting
 1096 the overlapping between bunches; the consequence is a reduction of about 17% in
 1097 the luminosity (represented by a factor not included in eqn: 3.2). The second one
 1098 is the occurrence of multiple pp collisions in the same bunch crossing; this effect is
 1099 called pile-up (PU). A fairly simple estimation of the PU follows from estimating the
 1100 probability of collision between two protons, one from each of the bunches in course
 1101 of collision; it depends roughly on the ratio of proton size and the cross section of the
 1102 bunch in the interaction point, i.e.,

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

1103 however, there are $N = 1.15 \times 10^{11}$ protons in a bunch, thus the estimated number of
 1104 collisions in a bunch crossing is

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

1105 about 20 of those pp collisions are inelastic. Each collision generates a vertex, but
 1106 only the most energetic is considered as a primary vertex; the rest are considered as

1107 PU vertices. A multiple pp collision event in a bunch crossing at CMS is showed in
 1108 figure3.8. Unstable particles outgoing from the primary vertex will eventually decay;
 1109 this decay vertex is known as a secondary vertex.

1110

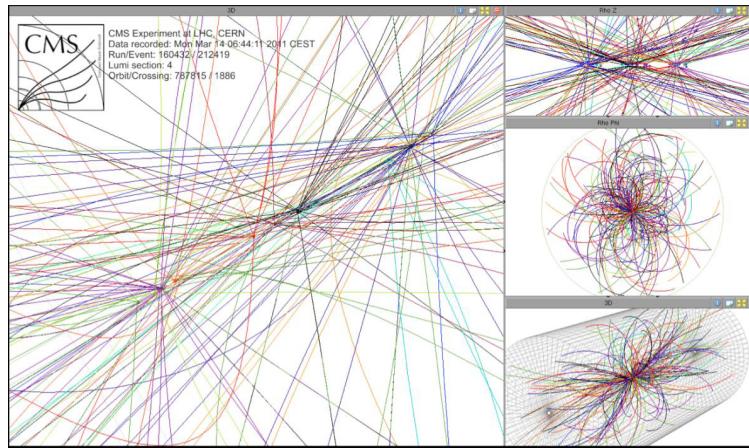


Figure 3.8: Multiple pp collision bunch crossing at CMS. Only the most energetic vertex is considered and the rest are catalogued as PU vertices [66].

1111 Next section presents a description of the CMS detector which it is the detector used
 1112 to collect the data used in this thesis.

1113 3.3 The CMS experiment

1114 CMS is a general-purpose detector designed to conduct research in a wide range
 1115 of physics from the standard model to new physics like extra dimensions and dark
 1116 matter. Located at the point 5 in the LHC layout as shown in figure 3.4, CMS is
 1117 composed of several detection systems distributed in a cylindrical structure; in total,
 1118 CMS weights about 12500 tons in a very compact 21.6 m long and 14.6 m diameter
 1119 cylinder. It was built in 15 separate sections at the ground level and lowered to the
 1120 cavern individually to be assembled. A complete and detailed description of the CMS

1121 detector and its components is given in reference [67] on which this section is based on.

1122

1123 Figure 3.9 shows the layout of the CMS detector. The design is driven by the require-
 1124 ments on the identification, momentum resolution and unambiguous charge determi-
 1125 nation of the muons; therefore, a large bending power is provided by the solenoid
 1126 magnet made of superconducting cable capable to generate a 3.8 T magnetic field.
 1127 The detection system is composed of (from the innermost to the outermost)

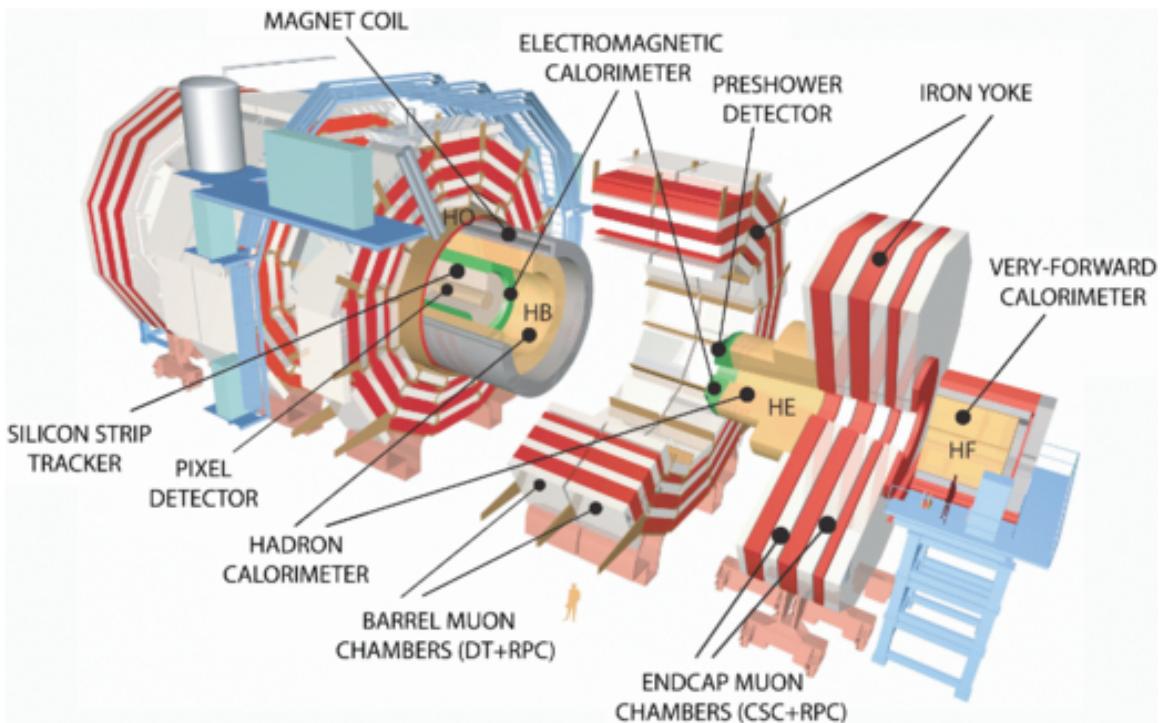


Figure 3.9: Layout of the CMS detector. The several subdetectors are indicated. The central region of the detector is referred as the Barrel section while the endcaps are referred as the forward sections. [68].

1128 • Pixel detector.

1129 • Silicon strip tracker.

1130 • Preshower detector.

1131 • Electromagnetic calorimeter.

1132 • Hadronic calorimeter.

1133 • Muon chambers (Barrel and endcap)

1134 The central region of the detector is commonly referred as the barrel section while the
 1135 endcaps are referred as the forward sections of the detector; thus, each subdetector
 1136 is composed of a barrel section and a forward section.

1137 3.3.1 Coordinate system

1138 The coordinate system used by CMS is centered in the geometrical center of the
 1139 detector which is the same as the CP as shown in figure 3.10. The z -axis is parallel
 1140 to the beam direction, while the Y -axis pointing vertically upward, and the X -axis
 1141 pointing radially inward toward the center of the LHC.

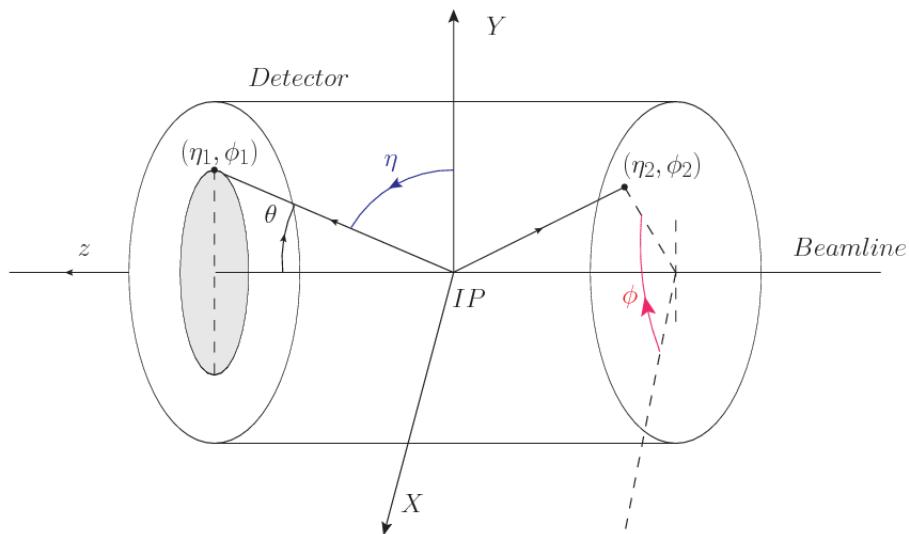


Figure 3.10: CMS detector coordinate system.

1142 In addition to the common cartesian and cylindrical coordinate systems, two coordi-
 1143 nates are of particular utility in particle physics: rapidity(y) and pseudorapidity(η),

1144 defined in connection to the polar angle θ , energy and longitudinal momentum com-
 1145 ponent (momentum along the z -axis) according to

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

1146 Rapidity is related to the angle between the XY -plane and the direction in which the
 1147 products of a collision are emitted; it has the nice property that the difference between
 1148 the rapidities of two particles is invariant with respect to Lorentz boosts along the z -
 1149 axis. Thus, data analysis becomes more simple when based on rapidity; however, it is
 1150 not simple to measure the rapidity of highly relativistic particles, as those produced
 1151 after pp collisions. Under the highly relativistic motion approximation, y can be
 1152 rewritten in terms of the polar angle, concluding that rapidity is approximately equal
 1153 to the pseudorapidity defined above, i.e., $y \approx \eta$. Note that η is easier to measure than y
 1154 given the direct relationship between the former and the polar angle. Angular distance
 1155 between two objects in the detector (ΔR) is defined in terms of their coordinates
 1156 $(\eta_1, \phi_1), (\eta_2, \phi_2)$ as

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

1157 3.3.2 Pixels detector

1158 The CMS tracking system is designed to provide a precise measurement of the tra-
 1159 jectory (*track*) followed by the charged particles created after the pp collisions; also,
 1160 the precise reconstruction of the primary and secondary origins (*vertices*) is expected
 1161 in an environment where, each 25 ns, the bunch crossing produce about 20 inelastic
 1162 collisions and about 1000 particles. An increment in the luminosity is ongoing which
 1163 implies that the PU will increase accordingly.

1165 The pixel detector was replaced during the 2016-2017 extended year-end technical
1166 stop, due to the increasingly challenging operating conditions like the higher particle
1167 flow and more radiation harsh environment, among others. The new one is respond-
1168 ing as expected, reinforcing its crucial role in the successful way to fulfill the new
1169 LHC physics objectives after the discovery of the Higgs boson. The last chapter of
1170 this thesis is dedicated to describe my contribution to the “Forward Pixel Phase 1
1171 upgrade”.

1172

1173 The current pixel detector is composed of 1856 silicon pixel detector modules orga-
1174 nized in four-barrel layers in the central region and three disks in the forward region;
1175 it is designed to record efficiently and with high precision, up to $10\mu\text{m}$ in the XY -
1176 plane and $20\mu\text{m}$ in the z -direction, the first four space-points (*hits*) near to the CP
1177 region (see figure 3.11 left side) in the range $|\eta| \leq 2.5$. The first barrel layer is located
1178 at a radius of 30 mm from the beamline, while the fourth layer is located at a radius
1179 of 160 mm closer to the strip tracker inner barrel layer (see section 3.3.3) in order to
1180 reduce the rate of fake tracks. The high granularity of the detector is represented in
1181 its about 123 Mpixels, each of size $100 \times 150\mu\text{m}^2$, which is almost twice the channels
1182 of the old detector. The transverse momentum resolution of tracks can be measured
1183 with a resolution of 1-2% for muons of $p_T = 100$ GeV.

1184

1185 Some of the improvements with respect to the previous pixel detector include a higher
1186 average tracking efficiency and lower average fake rate as well as higher track impact
1187 parameter resolution which is fundamental in order to increase the efficiency in the
1188 identification of jets originating from b quarks (b-tagging). A significant source of
1189 improvement comes from the overall reduction in the material budget of the detector
1190 which results in fewer photon conversions and less multiple scattering from charged

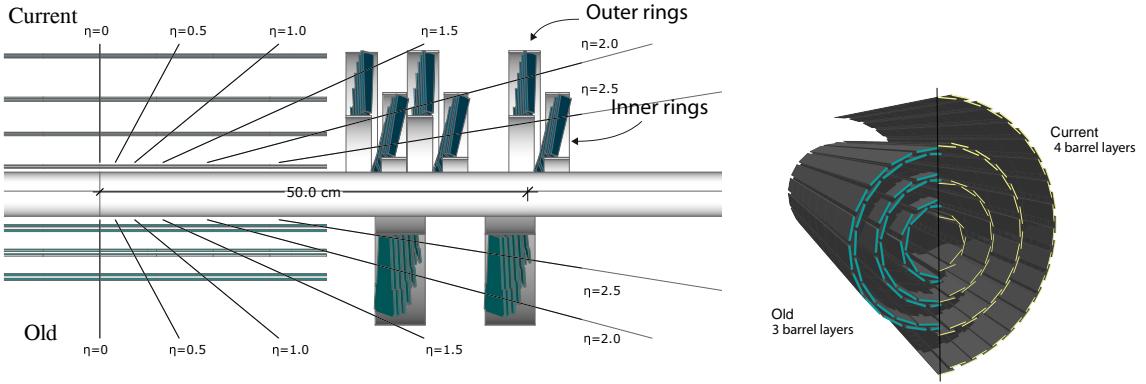


Figure 3.11: CMS pixel detector schematic view. Left: layout comparing the layers and disks in the old and current pixel detectors. Right: Transverse-oblique view comparing the pixel barrel layers in the two [70].

1191 particles.

1192 3.3.3 Silicon strip tracker

1193 The silicon strip tracker (SST) is the second stage in the CMS tracking system. The
 1194 top side of figure 3.12 shows a schematic of the SST. The inner tracker region is com-
 1195 posed of the tracker inner barrel (TIB) and the tracker inner disks (TID) covering the
 1196 region $r < 55$ cm and $|z| < 118$ cm. The TIB is composed of 4 layers while the TID
 1197 is composed of 3 disks at each end. The silicon sensors in the inner tracker are 320
 1198 μm thick, providing a resolution of about 13-38 μm in the $r\phi$ position measurement.

1199

1200 The modules indicated in blue in the schematic view of figure 3.12 are two modules
 1201 mounted back-to-back and rotated in the plane of the module by a “stereo” angle of
 1202 100 mrad; the hits from these two modules, known as “stereo hits”, are combined to
 1203 provide a measurement of the second coordinate (z in the barrel and r on the disks)
 1204 allowing the reconstruction of hit positions in 3-D.

1205

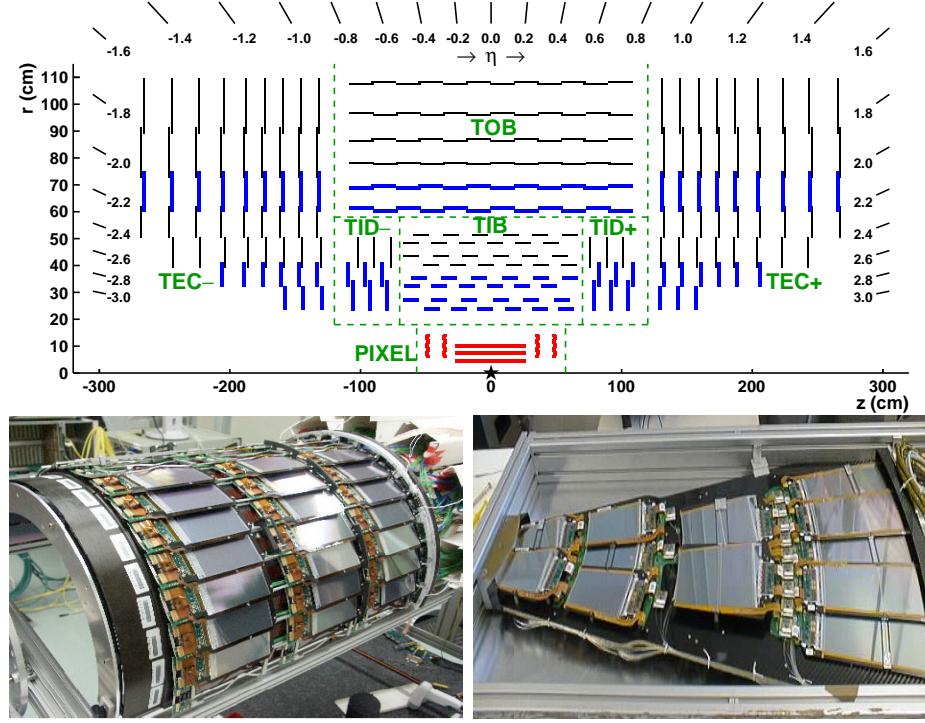


Figure 3.12: Top: CMS Silicon Strip Tracker (SST) schematic view. The SST is composed of the tracker inner barrel (TIB), the tracker inner disks (TID), the tracker outer barrel (TOB) and the tracker endcaps (TEC). Each part is made of silicon strip modules; the modules in blue represent two modules mounted 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 [71–73].

1206 The outer tracker region is composed of the tracker outer barrel (TOB) and the
 1207 tracker endcaps (TEC). The six layers of the TOB offer coverage in the region $r > 55$
 1208 cm and $|z| < 118$ cm, while the 9 disks of the TEC cover the region $124 < |z| < 282$
 1209 cm. The resolution offered by the outer tracker is about $13\text{--}38 \mu\text{m}$ in the $r\phi$ position
 1210 measurement. The inner four TEC disks use silicon sensors $320 \mu\text{m}$ thick; those in
 1211 the TOB and the outer three TEC disks use silicon sensors of $500 \mu\text{m}$ thickness. The
 1212 silicon strips run parallel to the z -axis and the distance between strips varies from 80
 1213 μm in the inner TIB layers to $183 \mu\text{m}$ in the inner TOB layers; in the endcaps the
 1214 wedge-shaped sensors with radial strips, whose pitch range between $81 \mu\text{m}$ at small
 1215 radii and $205 \mu\text{m}$ at large radii.

1216

1217 The whole SST has 15148 silicon modules, 9.3 million silicon strips and cover a total
 1218 active area of about 198 m^2 .

1219 **3.3.4 Electromagnetic calorimeter**

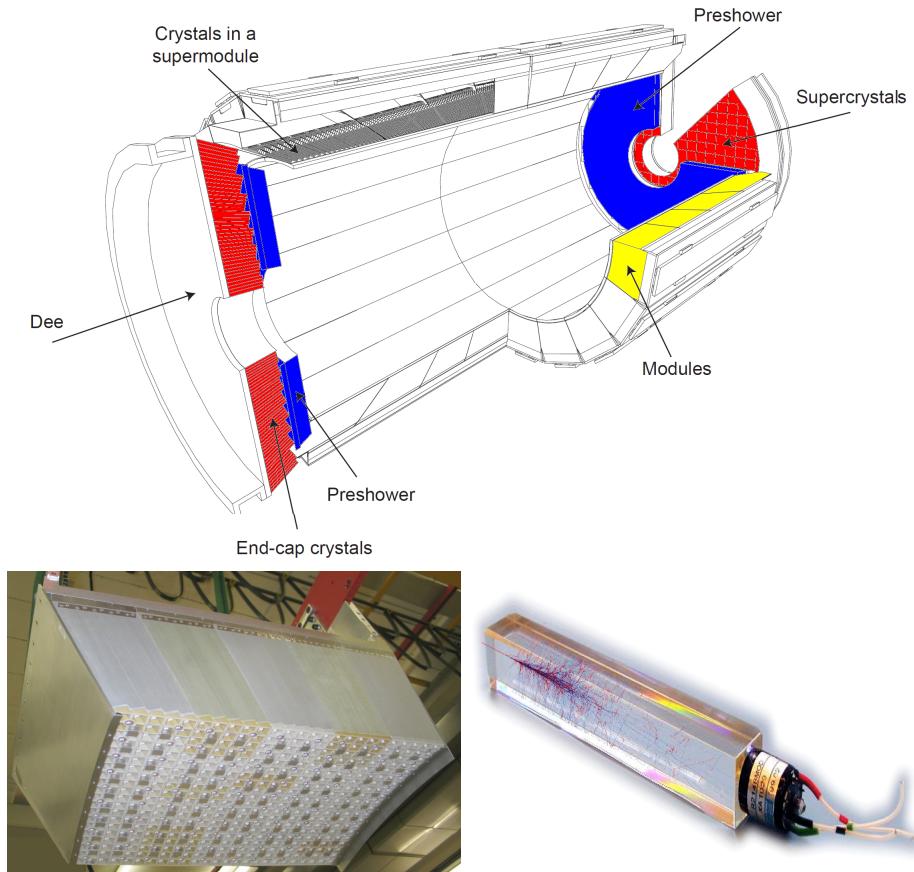


Figure 3.13: Top: CMS ECAL schematic view. Bottom: Module equipped with the crystals (left); ECAL crystal(right).

1220 The CMS electromagnetic calorimeter (ECAL) is designed to measure the energy of
 1221 electrons and photons. It is composed of 75848 lead tungstate crystals which have a
 1222 short radiation length (0.89 cm) and fast response, since 80% of the light is emitted
 1223 within 25 ns; however, they are combined with Avalanche photodiodes (APDs) as

1224 photodetectors given that crystals themselves have a low light yield ($30\gamma/\text{MeV}$). A
 1225 schematic view of the ECAL is shown in figure 3.13.

1226

1227 Energy is measured when electrons and photons are absorbed by the crystals which
 1228 generates an electromagnetic “shower”, as seen in bottom right picture of the fig-
 1229 ure3.13; the shower is seen as a *cluster* of energy which depending on the amount
 1230 of energy deposited can involve several crystals. The ECAL barrel (EB) covers the
 1231 region $|\eta| < 1.479$, using crystals of depth of 23 cm and $2.2 \times 2.2 \text{ cm}^2$ transverse
 1232 section; the ECAL endcap (EE) covers the region $1.479 < |\eta| < 3.0$ using crystals
 1233 of depth 22 cm and transverse section of $2.86 \times 2.86 \text{ cm}^2$; the photodetectors used
 1234 are vacuum phototriodes (VPTs). Each EE is divided in two structures called “Dees”.

1235

1236 In front of the EE, it is installed the preshower detector (ES) which covers the region
 1237 $1.653 < |\eta| < 2.6$. The ES provides a precise measurement of the position of electro-
 1238 magnetic showers, which allows to distinguish electrons and photons signals from π^0
 1239 decay signals. The ES is composed of a layer of lead absorber followed by a layer of
 1240 plastic scintillators

1241 3.3.5 Hadronic calorimeter

1242 Hadrons are not absorbed by the ECAL but by the hadron calorimeter (HCAL),
 1243 which is made of a combination of alternating brass absorber layers and silicon photo-
 1244 multiplier(SiPM) layers; therefore, particles passing through the scintillator material
 1245 produce showers, as in the ECAL, as a result of the inelastic scattering of the hadrons
 1246 with the detector material. Since the particles are not absorbed in the scintillator,
 1247 their energy is sampled; therefore the total energy is not measured but estimated from

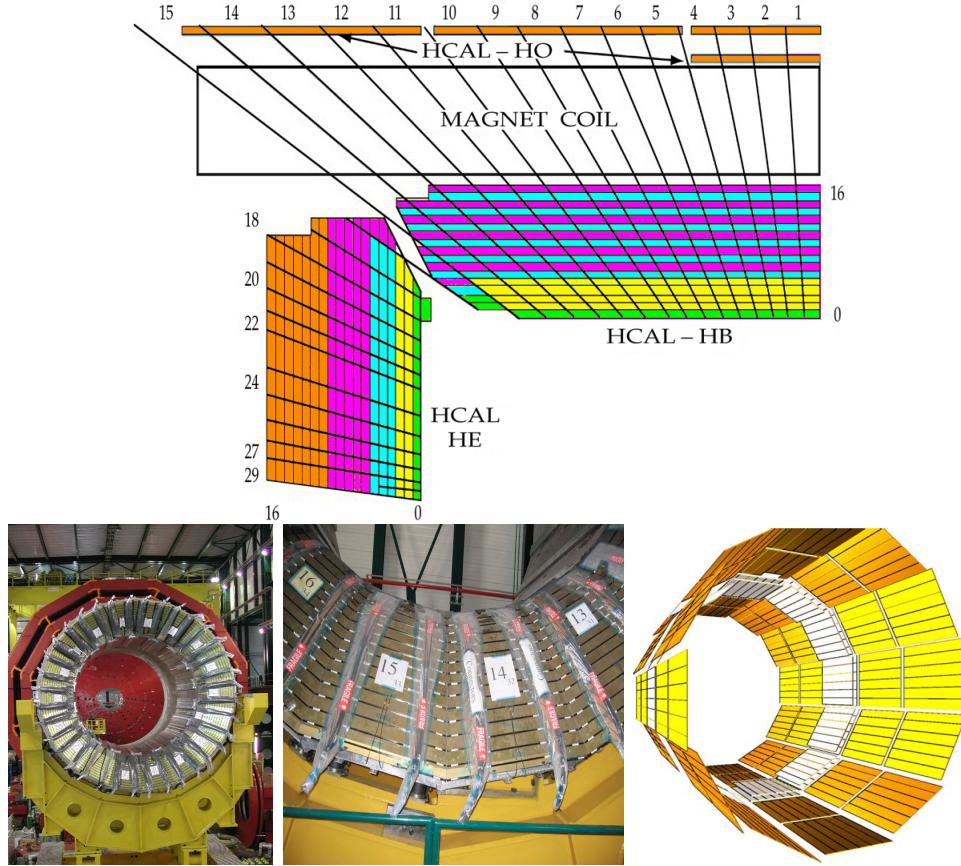


Figure 3.14: Top: CMS HCAL schematic view, the colors indicate the layers that are grouped into the same readout channels. Bottom: picture of a section of the HB; the absorber material is the golden region and scintillators are placed in between the absorber material (left and center). Schematic view of the HO (right). [74,75]

1248 the energy clusters, which reduce the resolution of the detector. Brass was chosen
 1249 as the absorber material due to its short interaction length ($\lambda_I = 16.42\text{cm}$) and its
 1250 non-magnetivity. Figure 3.14 shows a schematic view of the CMS HCAL.

1251

1252 The HCAL is divided into four sections; the Hadron Barrel (HB), the Hadron Outer
 1253 (HO), the Hadron Endcap (HE) and the Hadron Forward (HF) sections. The HB
 1254 covers the region $0 < |\eta| < 1.4$, while the HE covers the region $1.3 < |\eta| < 3.0$. The HF,
 1255 made of quartz fiber scintillator and steel as absorption material, covers the forward

region $3.0 < |\eta| < 5.2$. Both the HB and HF are located inside the solenoid. The HO is placed outside the magnet as an additional layer of scintillators with the purpose of measure the energy tails of particles passing through the HB and the magnet (see figure 3.14 top and bottom right). The upgrades made to the HCAL during the technical stop 2016-2017 consisted in the replacement of the photo transducer, in order to improve the efficiency.

3.3.6 Superconducting solenoid magnet

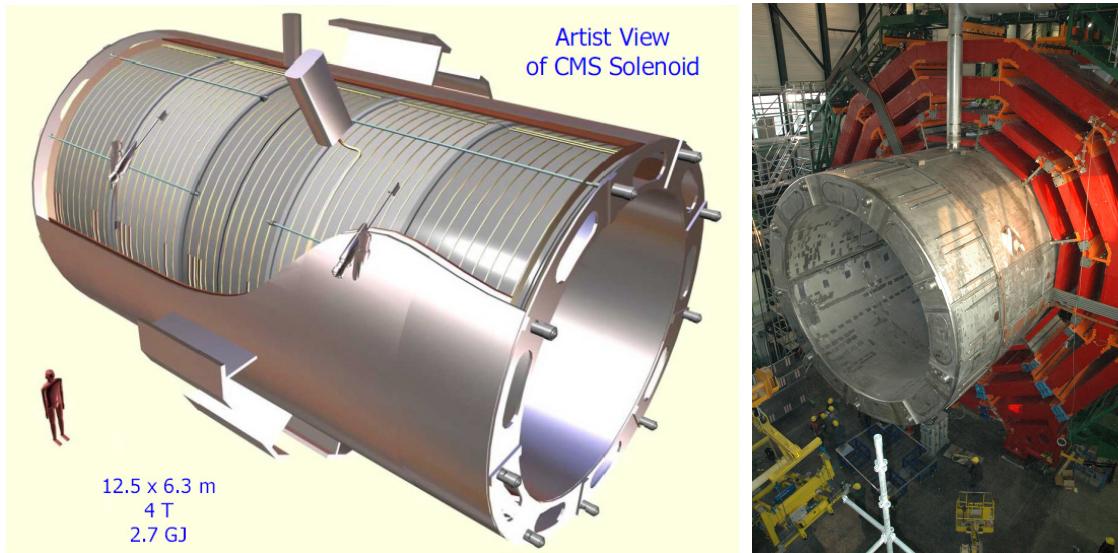


Figure 3.15: Artistic representation of the CMS solenoid magnet(left). The magnet is supported on an iron yoke (right) which also serves as the house of the muon detector and as mechanical support for the whole CMS detector [69].

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

1269 m and a cold mass of 220 t; the generated magnetic field reaches a strength of 3.8T.
 1270 Since it is made of Ni-Tb superconducting cable it has to operate at a temperature
 1271 of 4.7 K by using a helium cryogenic system; the current circulating in the cables
 1272 reaches 18800 A under normal running conditions. The left side of figure 3.15 shows
 1273 an artistic view of the CMS magnet, while the right side shows a transverse view of
 1274 the cold mass where the winding structure is visible.

1275

1276 The yoke (see figure 3.15), composed of 5 barrel wheels and 6 endcap disks made
 1277 of iron, serves not only as the media for magnetic flux return but also provides the
 1278 house for the muon detector system and structural stability to the full detector.

1279 3.3.7 Muon system

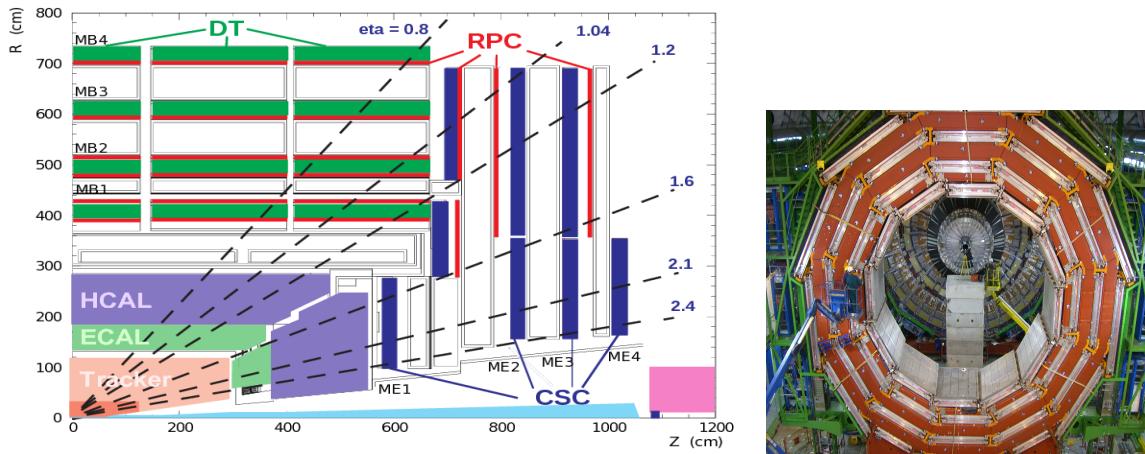


Figure 3.16: Left: CMS muon system schematic view; Right: one of the yoke rings with the muon DTs and RPCs installed; in the back it is possible to see the muon endcap [76].

1280 Muons are the only charged particles able to pass through all the CMS detector due
 1281 to their low ionization energy loss; thus, muons can be separated easily from the
 1282 high amount of particles produced in a pp collision. Also, muons are expected to be
 1283 produced in the decay of several new particles; therefore, a good detection of muons

1284 was on the leading principles when designing the CMS detector.

1285

1286 The CMS muon detection system (muon spectrometer) is embedded in the return
1287 yoke as seen in figure 3.16. It is composed of three different detector types, the drift
1288 tube chambers (DT), Cathode strip chambers (CSC), and resistive plate chambers
1289 (RPC); DT are located in the central region $\eta < 1.2$ arranged in four layers of drift
1290 chambers filled with an Ar/CO₂ gas mixture.

1291

1292 The muon endcaps are made of CSCs covering the region $\eta < 2.4$ and filled with a
1293 mixture of Ar/CO₂/CF₄. The reason behind using a different detector type lies on
1294 the different conditions in the forward region like the higher muon rate and higher
1295 residual magnetic field compared to the central region.

1296

1297 The third type of detector used in the muon system is a set of four disks of RPCs
1298 working in avalanche mode. The RPCs provide good spatial and time resolutions.
1299 The track of $high - p_T$ muon candidates is built combining information from the
1300 tracking system and the signal from up to six RPCs and four DT chambers.
1301 The muon tracks are reconstructed from the hits in the several layers of the muon
1302 system.

1303 3.3.8 CMS trigger system

1304 Under normal conditions, CMS expects pp collisions every 25 ns, i.e., an interaction
1305 rate of 40 MHz for which it is not possible to store the recorded data in full. In order
1306 to handle this high event rate data, an online event selection, known as triggering, is
1307 performed; triggering reduce the event rate to 100 Hz for storage and further offline

1308 analysis.

1309

1310 The trigger system starts with a reduction of the event rate to 100 kHz in the so-called
 1311 “level 1 trigger (L1)”. L1 is based on dedicated programmable hardware like Field
 1312 Programmable Gate Arrays (FPGAs) and Application Specific Integrated Circuits
 1313 (ASICs), partly located in the detector itself; another portion is located in the CMS
 1314 under-ground cavern. Hit patterns information from the muon chambers and the en-
 1315 ergy deposits in the calorimeter are used to decide if an event is accepted or rejected,
 1316 according to selection requirements previously defined, which reflect the interesting
 1317 physics processes. Figure 3.17 shows the L1 trigger architecture.

1318

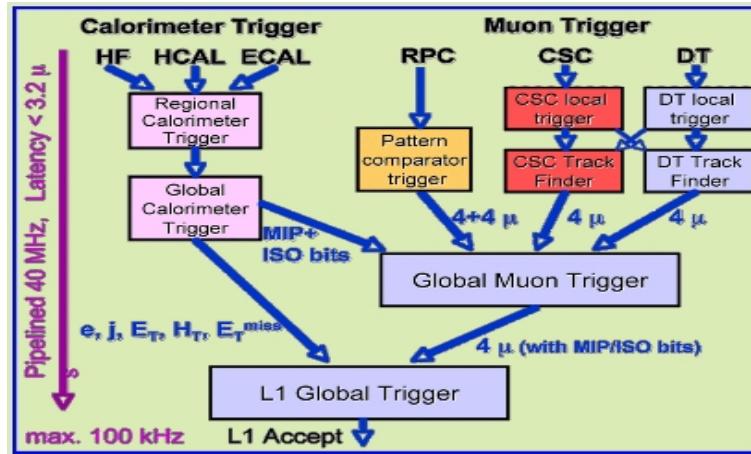


Figure 3.17: CMS Level-1 trigger architecture [77].

1319 The second stage in the trigger system is called “high-level trigger (HLT)”; events
 1320 accepted by L1 are passed to HLT in order to make an initial reconstruction of them.
 1321 HLT is software based and runs on a dedicated server farm, using selection algo-
 1322 rithms and high-level object definitions; the event rate at HLT is reduced to 100 Hz.
 1323 The first HLT stage takes information from the muon detectors and the calorimeters
 1324 to make the initial object reconstruction; in the next HLT stage, information from

1325 the pixel and strip detectors is used to do first fast-tracking and then full tracking
1326 online. This initial object reconstruction is used in further steps of the trigger system.

1327

1328 Events and preliminary reconstructed physics objects from HLT are sent to be fully
1329 reconstructed at the CERN computing center. Again, the pixel detector information
1330 provides high-quality seeds for the track reconstruction algorithm offline, primary ver-
1331 tex reconstruction, electron and photon identification, muon reconstruction, τ iden-
1332 tification, and b-tagging. After full reconstruction, data sets are made available for
1333 offline analyses.

1334

1335 During the 2016-2017 technical stop, the L1 system was updated in order to improve
1336 the physics object identification by improving the algorithms and accounting for the
1337 increasing pile-up scenario.

1338 **3.3.9 CMS computing**

1339 After the data, coming from the experiment, are processed at several levels, they have
1340 to be stored and made available for further analysis; in order to cope all the tasks
1341 implied in the offline data processing, like transfer, simulation, reconstruction and
1342 reprocessing, among others, a big computing power is required. The CMS computing
1343 system is based on the distributed architecture concept, where users of the system
1344 and physical computer centers are distributed worldwide and interconnected by high-
1345 speed networks.

1346 The worldwide LHC computing grid (WLCG) is the mechanism used to provide that
1347 distributed environment. WLCG is a tiered structure connecting computing centers
1348 around the world, which provides the necessary storage and computing facilities. The

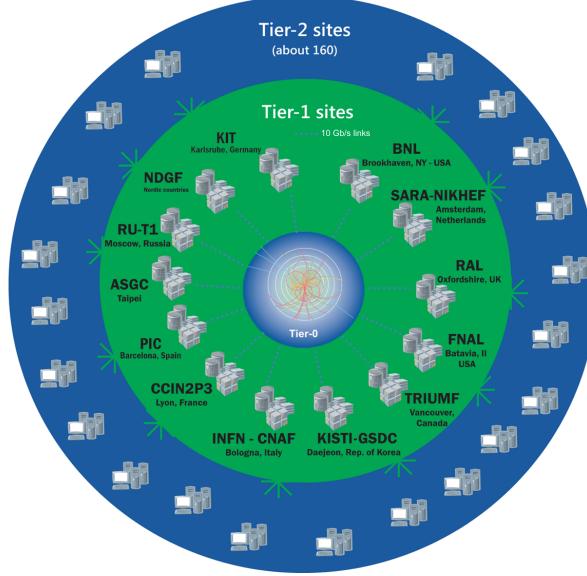


Figure 3.18: WLCG structure. The primary computer centers (Tier-0) are located at CERN (data center) and at the Wigner datacenter in Budapest. Tier-1 is composed of 13 centers and Tier-2 is composed of about 160 centers. [78].

1349 primary computing centers of the WLCG are located at the CERN and the Wigner
 1350 datacenter in Budapest and are known as Tier-0 as shown in figure 3.18. The main
 1351 responsibilities for each tier level are [78]

- 1352 • **Tier-0:** initial reconstruction of recorded events and storage of the resulting
 1353 datasets, the distribution of raw data to the Tier-1 centers.
- 1354 • **Tier-1:** provide storage capacity, support for the Grid, safe-keeping of a pro-
 1355 portional share of raw and reconstructed data, large-scale reprocessing and safe-
 1356 keeping of corresponding output, generation of simulated events, distribution
 1357 of data to Tier 2s, safe-keeping of a share of simulated data produced at these
 1358 Tier 2s.
- 1359 • **Tier-2:** store sufficient data and provide adequate computing power for specific
 1360 analysis tasks, provide analysis requirements and proportional share of simu-
 1361 lated event production and reconstruction.

1362 Aside from the general computing strategy to manage the huge amount of data pro-
1363 duced by experiments, CMS uses a framework to perform a variety of processing,
1364 selection and analysis tasks. The central concept of the CMS data model referred to
1365 as “event data model” (EDM) is the “Event”; therefore, an event is the unit that con-
1366 tains the information from a single bunch crossing as well as any data derived from
1367 that information like the reconstructed objects, the details under which additional
1368 data are derived.

1369

1370 Events are passed as the input to the “physics modules” that obtain information from
1371 them and create new one; for instance, “event data producers” add new data into the
1372 events, “analyzers” produce an information summary from an event set, “filters” per-
1373 form selection and triggering.

1374

1375 CMS uses several event formats with different levels of detail and precision

1376 • **Raw format:** events in this format contain the full recorded information from
1377 the detector as well as trigger decision and other metadata. An extended version
1378 of raw data is used to store information from the CMS Monte Carlo simulation
1379 tools. Raw data are stored permanently, occupying about 2MB/event

1380 • **RECO format:** events in this format correspond to raw data that have been
1381 submitted to reconstruction algorithms like primary and secondary vertex re-
1382 construction, particle ID, track-finding. RECO events contain physical objects
1383 and all the information used to reconstruct them; average size is about 0.5
1384 MB/event.

1385 • **AOD format:** Analysis Object Data (AOD) is the data format used in the
1386 physics analyses given that it contains the parameters describing the high-level

1387 physics objects in addition to enough information to allow a kinematic refitting if
 1388 needed. AOD events are filtered versions of the RECO events to which skimming
 1389 or other kind processes have been applied. Requires about 100 kB/event.

1390 • **Non-event data** are data needed to interpret and reconstruct events. Some
 1391 of the non-event data used by CMS contains information about the detector
 1392 contraction and condition data like calibrations, alignment, and detector status.

1393 Figure 3.19 shows the data flow scheme between CMS detector and hardware tiers.

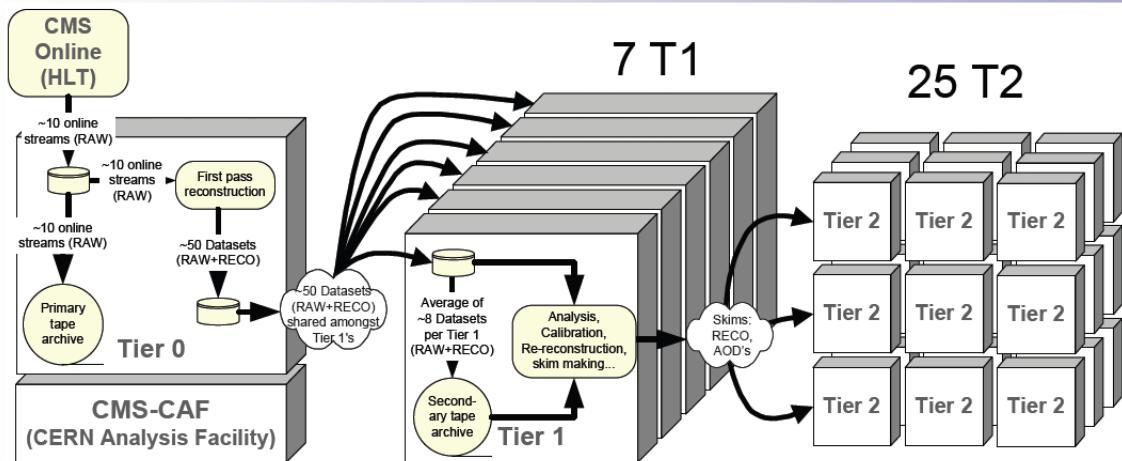


Figure 3.19: Data flow from CMS detector through hardware Tiers.

1394 The whole collection of software built as a framework is referred to as “CMSSW”. This
 1395 framework provides the services needed by the simulation, calibration and alignment,
 1396 and reconstruction modules that process event data, so that physicists can perform
 1397 analysis. The CMSSW event processing model is composed of one executable, called
 1398 cmsRun, and several plug-in modules which contains all the tools (calibration, recon-
 1399 struction algorithms) needed to process an event. The same executable is used for
 1400 both detector and Monte Carlo data [79].

1401 **Chapter 4**

1402 **Event generation, simulation and
1403 reconstruction**

1404 The process of analyzing the data recorded by the CMS experiment involves several
1405 stages where the data are processed in order to interpret the information provided by
1406 all the detection systems; in those stages, the particles produced after the pp collision
1407 are identified by reconstructing their trajectories and measuring their features. In
1408 addition, the SM provides a set of predictions that have to be compared with the
1409 experimental results; however, in most of the cases, theoretical predictions are not
1410 directly comparable to experimental results due to the diverse source of uncertainties
1411 introduced by the experimental setup and theoretical approximations among others.

1412

1413 The strategy to face these conditions consist in using statistical methods implemented
1414 in computational algorithms to produce numerical results that can be contrasted with
1415 the experimental results. These computational algorithms are commonly known as
1416 Monte Carlo (MC) methods and, in the case of particle physics, they are designed to
1417 apply the SM rules and produce predictions about the physical observables measured

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

1423

1424 This chapter presents a description of the event generation strategy and the tools
 1425 used to perform the detector simulation and physics objects reconstruction. A com-
 1426 prehensive review of event generators for LHC physics can be found in reference [80]
 1427 on which this chapter is based.

1428 4.1 Event generation

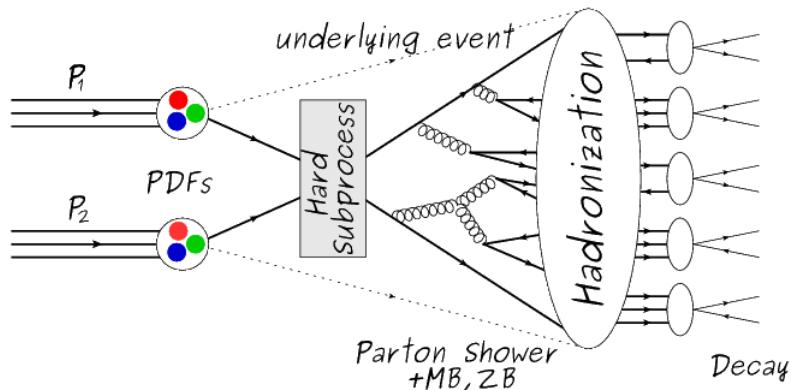


Figure 4.1: Event generation process. In the first step, the PDF of the colliding particles is considered so the specific interaction is described. The actual interaction is generated in the hard subprocess; the cross-section of the process is calculated from the matrix element connecting the initial and final states. The parton shower describes the evolution of the partons from the hard subprocess according to the DGLAP equations. At this step, the underlying event and PU effects are included in the generation. The resulting partons from the parton shower are recombined to form hadrons in the hadronization step; most of them are unstable, therefore, their decays are also generated in agreement to the known branching ratios. Modified from reference [81].

1429 The event generation is intended to create events that mimic the behavior of actual
 1430 events produced in the collisions; they obey a sequence of steps from the particles colli-
 1431 sion hard process to the decay process into the final state particles. Figure 4.1 shows
 1432 a schematic view of the event generation process; the fact that the full process can
 1433 be treated as several independent steps is based on the QCD factorization theorem.

1434

1435 Generation starts by taking into account the PDFs of the incoming particles. Event
 1436 generators offer the option to choose from several PDF sets depending on the partic-
 1437 ular process under simulation¹; in the following pp collisions will be considered. The
 1438 *hard subprocess* describes the actual interaction between partons from the incoming
 1439 protons; it is represented by the matrix element connecting the initial and final states
 1440 of the interaction. Normally, the matrix element can be written as a sum over Feyn-
 1441 man diagrams and consider interferences between terms in the summation. During
 1442 the generation of the hard subprocess, the production cross section is calculated.

1443

1444 The order to which the cross section is calculated depends on the order of the Feyn-
 1445 man diagrams involved in the calculation; therefore, radiative corrections are included
 1446 by considering a higher order Feynman diagrams where QCD radiation dominates.
 1447 Currently, cross sections calculated to LO do not offer a satisfactory description of the
 1448 processes, i.e., the results are only reliable for the shape of distributions; therefore,
 1449 NLO calculations have to be performed with the implication that the computing time
 1450 needed is highly increased.

1451

1452 The final parton content of the hard subprocess is subjected to the *parton shower*
 1453 which generates the gluon radiation. Parton shower evolves the partons; i.e., gluons

¹ Tool in Reference [82] allows to plot different PDF sets under customizable conditions.

1454 split into quark-antiquark pairs and quarks of enough energy radiate gluons giving rise
 1455 to further parton multiplication, following the DGLAP (Dokshitzer-Gribov-Lipatov-
 1456 Altarelli-Parisi) equations. Showering continues until the energy scale is low enough
 1457 to reach the non-perturbative limit.

1458

1459 In the simulation of LHC processes that involve b quarks like the single top quark or
 1460 Higgs associated production, it is needed to consider that the b quark is heavier than
 1461 the proton; in this sense, the QCD interaction description is made in two different
 1462 schemes [83]

1463 • four-flavor (4F) scheme. b quarks appear only in the final state because they
 1464 are heavier than the proton and therefore they can be produced only from the
 1465 splitting of a gluon into pairs or singly in association with a t quark in high
 1466 energy-scale interactions. During the simulation, the b -PDFs are set to zero
 1467 because it cannot be part of the proton. Calculations in this scheme are more
 1468 complicated due to the presence of the second b quark but the full kinematics is
 1469 considered already at LO and therefore the accuracy of the description is better.

1470 • five-flavor (5F) scheme. b quarks are considered massless, therefore they can
 1471 appear in both initial and final states since it can now be part of the proton; thus,
 1472 during the simulation b -PDFs are not set to zero. In this scheme, calculations
 1473 are simpler than in the 4F scheme and possible logarithmic divergences are
 1474 absorbed by the PDFs through the DGLAP evolution.

1475 In this thesis, the tHq events are generated using the 4F scheme in order to reduce
 1476 uncertainties, while the tHW events are generated using the 5F scheme to eliminate
 1477 LO interference with the $t\bar{t}H$ process [48].

1478

1479 Partons involved in the pp collision are the focus of the simulation, however, the rest
 1480 of the partons inside the incoming protons are also affected because the remnants are
 1481 colored objects; also, multiple parton interactions can occur. The hadronization of
 1482 the remnants and multiple parton interactions are known as “underlying event” and
 1483 it has to be included in the simulation. In addition, multiple pp collisions in the same
 1484 bunch crossing (pile-up mentioned in 3.2) occurs, actually in two forms

- 1485 • *in-time PU* which refers to multiple pp collision in the bunch crossing but that
 1486 are not considered as primary vertices.
- 1487 • *Out-of-time PU* which refers to overlapping pp collisions from consecutive bunch
 1488 crossings; this can occurs due to the time-delays in the detection systems where
 1489 information from one bunch crossing is assigned to the next or previous one.

1490 While the underlying event effects are included in generation using generator-specific
 1491 tools, PU effects are added to the generation by overlaying Minimum-bias (MB) and
 1492 Zero-bias (ZB) events to the generated events. MB events are inelastic events selected
 1493 by using a loose (minimum bias) trigger with as little bias as possible, therefore ac-
 1494 cepting a large fraction of the overall inelastic event; ZB events correspond to random
 1495 events recorded by the detector when collisions are likely. MB model in-time PU and
 1496 ZB model out-of-time PU.

1497

1498 The next step in the generation process is called “hadronization”. Since particles
 1499 with a net color charge are not allowed to exits isolated, they have to recombine
 1500 to form bound states. This is precisely the process by which the partons resulting
 1501 from the parton shower arrange themselves as color singlets to form hadrons. At
 1502 this step, the energy-scale is low and the strong coupling constant is large, there-
 1503 fore hadronization process is non-perturbative and the evolution of the partons is

1504 described using phenomenological models. Most of the baryons and mesons produced
 1505 in the hadronization are unstable and hence they will decay in the detector.

1506

1507 The last step in the generation process corresponds to the decay of the unstable
 1508 particles generated during hadronization; it is also simulated in the hadronization
 1509 step, based on the known branching ratios.

1510 4.2 Monte Carlo Event Generators.

1511 The event generation described in the previous section has been implemented in
 1512 several software packages for which a brief description is given.

- 1513 • **PYTHIA 8.** It is a program designed to perform the generation of high en-
 1514 ergy physics events which describe the collisions between particles such as elec-
 1515 trons, protons. Several theories and models are implemented in it, in order to
 1516 describe physical aspects like hard and soft interaction, parton distributions,
 1517 initial and final-state parton showers, multiple parton interactions, beam rem-
 1518 nants, hadronization² and particle decay. Thanks to extensive testing, several
 1519 optimized parametrizations, known as “tunings”, have been defined in order
 1520 to improve the description of actual collisions to a high degree of precision; for
 1521 analysis at $\sqrt{s} = 13$ TeV, the underline event CUETP8M1 tune is employed [85].
 1522 The calculation of the matrix element is performed at LO which is not enough
 1523 for the current required level of precision; therefore, pythia is often used for
 1524 parton shower, hadronization and decays, while other event generators are used
 1525 to generate the matrix element at NLO.

² based in the Lund string model [84]

1526 • **MadGraph5_aMC@NLO.** MadGraph is a matrix element generator which
 1527 calculates the amplitudes for all contributing Feynman diagrams of a given pro-
 1528 cess but does not provide a parton shower while MC@NLO incorporate NLO
 1529 QCD matrix elements consistently into a parton shower framework; thus, Mad-
 1530 Graph5_aMC@NLO, as a merger of the two event generators MadGraph5 and
 1531 aMC@NLO, is an event generator capable to calculate tree-level and NLO cross
 1532 sections and perform the matching of those with the parton shower. It is one of
 1533 the most frequently used matrix element generators; however, it has the partic-
 1534 ular feature of the presence of negative event weights which reduce the number
 1535 of events used to reproduce the properties of the objects generated [86].

1536

1537 • **POWHEG.** It is an NLO matrix element generator where the hardest emis-
 1538 sion of color charged particles is generated in such a way that the negative event
 1539 weights issue of MadGraph5_aMC@NLO is overcome; however, the method re-
 1540 quires an interface with p_T -ordered parton shower or a parton shower generator
 1541 where this highest emission can be vetoed in order to avoid double counting of
 1542 this highest-energetic emission. PYTHIA is a commonly matched to POWHEG
 1543 event generator [87].

1544 Events resulting from the whole generation process are known as MC events.

1545 4.3 CMS detector simulation.

1546 After generation, MC events contain the physics of the collisions but they are not
 1547 ready to be compared to the events recorded by the experiment since these recorded
 1548 events correspond to the response of the detection systems to the interaction with

1549 the particles traversing them. The simulation of the CMS detector has to be applied
1550 on top of the event generation; it is simulated with a MC toolkit for the simulation
1551 of particles passing through matter called Geant4 which is also able to simulate the
1552 electronic signals that would be measured by all detectors inside CMS.

1553

1554 The simulation takes the generated particles contained in the MC events as input,
1555 makes them pass through the simulated geometry, and models physics processes that
1556 particles experience during their passage through matter. The full set of results from
1557 particle-matter interactions correspond to the simulated hit which contains informa-
1558 tion about the energy loss, momentum, position. Particles of the input event are
1559 called “primary”, while the particles originating from GEANT4-modeled interactions
1560 of a primary particle with matter are called a “secondary”. Simulated hits are the in-
1561 put of subsequent modules that emulate the response of the detector readout system
1562 and triggers. The output from the emulated detection systems and triggers is known
1563 as digitization [88, 89].

1564

1565 The modeling of the CMS detector corresponds to the accurate modeling of the
1566 interaction among particles, the detector material, and the magnetic field. This
1567 simulation procedure includes the following standard steps

1568 • Modeling of the Interaction Region.

1569 • Modeling of the particle passage through the hierarchy of volumes that compose
1570 CMS detector and of the accompanying physics processes.

1571 • Modeling of the effect of multiple interactions per beam crossing and/or the
1572 effect of events overlay (Pile-Up simulation).

1573 • Modeling of the detector’s electronics response, signal shape, noise, calibration
 1574 constants (digitization).

1575 In addition to the full simulation, i.e. a detailed detector simulation, a faster simula-
 1576 tion (FastSim) have been developed, that may be used where much larger statistics
 1577 are required. In FastSim, detector material effects are parametrized and included in
 1578 the hits; those hits are used as input of the same higher-level algorithms³ used to an-
 1579 alyze the recorded events. In this way, comparisons between fast and full simulations
 1580 can be performed [91].

1581

1582 After the full detector simulation, the output events can be directly compared with
 1583 events actually recorded in the CMS detector. The collection of MC events that
 1584 reproduce the expected physics for a given process are known as MC samples.

1585 **4.4 Event reconstruction.**

1586 In contrast to MC samples for which all the particles’ information is available from
 1587 it’s identity to its mass and energy, recorded events contain the electronic signals,
 1588 provided by the CMS detection systems, encoding the interaction of physical parti-
 1589 cles with the detector matter; these electronic signals have to be combined in order
 1590 to identify these particles and measure their features i.e., particles have to be “recon-
 1591 structed” using the signals provided by the detection systems. The CMS experiment
 1592 use the “particle-flow event reconstruction algorithm (PF)” to do the reconstruction
 1593 of particles produced in pp collisions. Next sections will present a basic description

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

1594 of the *Elements* used by PF (tracker tracks, energy clusters, and muon tracks), based
 1595 in the references [92, 93] where more detailed descriptions can be found.

1596 **4.4.1 Particle-Flow Algorithm.**

1597 Each of the several sub detection systems of the CMS detector is dedicated to identi-
 1598 fying a specific type of particles, i.e., photons and electrons are absorbed by the ECAL
 1599 and their reconstruction is based on ECAL information; hadrons are reconstructed
 1600 from clusters in the HCAL while muons are reconstructed from hits in the muon
 1601 chambers. PF is designed to correlate signals from all the detector layers (tracks and
 1602 energy clusters) in order to reconstruct and identify each final state particle and its
 1603 properties as sketched in figure 4.2.

1604

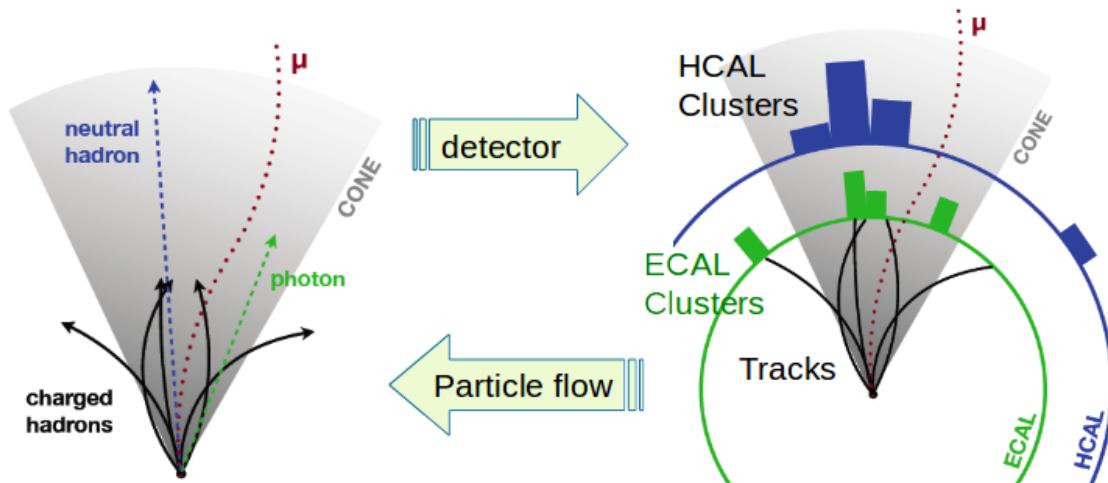


Figure 4.2: Particle flow algorithm. Information from the several CMS detection systems if provided as input to the algorithm which then combine it to identify and reconstruct all the particles in the final state and their properties. Reconstruction of simulated events is also performed by providing information from MC samples, detector and trigger simulation [94].

1605 For instance, a charged hadron is identified by a geometrical connection, know as *link*
 1606 between one or more calorimeter clusters and a track in the tracker provided there

1607 are no hits in the muon system; combining several measurements allows a better
 1608 determination of the energy and charge sign of the charged hadron.

1609 **Charged-particle track reconstruction.**

1610 The strategy used by PF in order to reconstruct tracks is called “Iterative Tracking”
 1611 which occurs in four steps

- 1612 • Seed generation where initial track candidates are found by looking for a combi-
 1613 nation of hits in the pixel detector, strip tracker, and muon chambers. In total
 1614 ten iterations are performed, each one with a different seeding requirement.
 1615 Seeds are used to estimate the trajectory parameters and uncertainties at the
 1616 time of the full track reconstruction. Seeds are also considered track candidates.

- 1617 • Track finding using a tracking software known as Combinatorial Track Finder
 1618 (CTF) [95]. The seed trajectories are extrapolated along the expected flight
 1619 path of a charged particle, in agreement to the trajectory parameters obtained
 1620 in the first step, in an attempt to find additional hits that can be assigned to
 1621 the track candidates.

- 1622 • Track-fitting where the found tracks are passed as input to a module which
 1623 provides the best estimate of the parameters of each trajectory.

- 1624 • Track selection where track candidates are submitted to a selection which dis-
 1625 cards those that fail a set of defined quality criteria.

1626 Iterations differ in the seeding configuration and the final track selection as elaborated
 1627 in references [92, 93]. In the first iteration, high p_T tracks and tracks produced near
 1628 to the interaction region are identified and those hits are masked thereby reducing
 1629 the combinatorial complexity. Next iterations search for more complicated tracks,

1630 like low p_T tracks and tracks from b hadron decays, which tend to be displaced from
 1631 the interaction region.

1632 **Vertex reconstruction.**

1633 During the track reconstruction, an extrapolation toward to the calorimeters is per-
 1634 formed in order to match energy deposits; that extrapolation is performed also toward
 1635 the beamline in order to find the origin of the track known as *vertex*. The vertex re-
 1636 construction is performed by selecting from the available reconstructed tracks, those
 1637 that are consistent with being originated in the interaction region where pp collisions
 1638 are produced. The selection involves a requirement on the number of tracker (pixel
 1639 and strip) hits and the goodness of the track fit.

1640

1641 Selected tracks are clustered using a “deterministic annealing algorithm (DA)”⁴. A
 1642 set of candidate vertices and their associated tracks, resulting from the DA, are then
 1643 fitted with an “adaptive vertex fitter (AVF)” to produce the best estimate of the
 1644 vertices locations.

1645

1646 The p_T of the several tracks associated to a reconstructed vertex is added, squared and
 1647 used to organize the vertices; the vertex with the highest squared sum is designated
 1648 as the *primary vertex (PV)* while the rest are designated as PU vertices.

1649 **Calorimeter clustering.**

1650 After traversing the CMS tracker system, electrons, photons and hadrons deposit their
 1651 energy in the ECAL and HCAL cells. The PF clustering algorithm aims to provide
 1652 a high detection efficiency even for low-energy particles and an efficient distinction

⁴ DA algorithm and AVF are described in detail in references [97,98]

1653 between close energy deposits. The clustering runs independently in the ECAL barrel
 1654 and endcaps, HCAL barrel and endcaps, and the two preshower layers, following two
 1655 steps

- 1656 • cells with an energy larger than a given seed threshold and larger than the energy
 1657 of the neighboring cells are identified as cluster seeds. The neighbor cells are
 1658 those that either share a side with the cluster seed candidate, or the eight closest
 1659 cells including cells that only share a corner with the seed candidate.
- 1660 • cells with at least a corner in common with a cell already in the cluster seed
 1661 and with an energy above a cell threshold are grouped into topological clusters.

1662 Clusters formed in this way are known as *particle-flow clusters*. With this clustering
 1663 strategy, it is possible to detect and measure the energy and direction of photons and
 1664 neutral hadrons as well as differentiate these neutral particles from the charged hadron
 1665 energy deposits. In cases involving charged hadrons for which the track parameters
 1666 are not determined accurately, for instance, low-quality and high- p_T tracks, clustering
 1667 helps in the energy measurements.

1668 Electron track reconstruction.

1669 Although the charged-particle track reconstruction described above works for elec-
 1670 trons, they lose a significant fraction of their energy via bremsstrahlung photon radi-
 1671 ation before reaching the ECAL; thus, the reconstruction performance depends on the
 1672 ability to measure also the radiated energy. The reconstruction strategy, in this case,
 1673 requires information from the tracking system and from the ECAL. Bremsstrahlung
 1674 photons are emitted at similar η values to that of the electron but at different values
 1675 of ϕ ; therefore, the radiated energy can be recovered by grouping ECAL clusters in a
 1676 η window over a range of ϕ around the electron direction. The group is called ECAL

1677 supercluster.

1678

1679 Electron candidates from the track-seeding and ECAL super clustering are merged
 1680 into a single collection which is submitted to a full electron tracking fit with a
 1681 Gaussian-sum filter (GSF) [96]. The electron track and its associated ECAL su-
 1682 percluster form a *particle-flow electron*.

1683 **Muon track reconstruction.**

1684 Given that the CMS detector is equipped with a muon spectrometer capable to iden-
 1685 tify and measure the momentum of the muons traversing it, the muon reconstruction
 1686 is not specific to PF; therefore, three different muon types are defined

- 1687 • *Standalone muon.* A clustering on the DTs or CSCs hits is performed to form
 1688 track segments; those segments are used as seeds for the reconstruction in the
 1689 muon spectrometer. All DTs, CSCs, and RPCs hits along the muon trajectory
 1690 are combined and fitted to form the full track. The fitting output is called a
 1691 *standalone-muon track*.
- 1692 • *tracker muon.* Each track in the inner tracker with p_T larger than 0.5 GeV and
 1693 a total momentum p larger than 2.5 GeV is extrapolated to the muon system. A
 1694 *tracker muon track* corresponds to the extrapolated tracks that match at least
 1695 one muon segment.
- 1696 • *Global muon.* When tracks in the inner tracker (inner tracks) and standalone-
 1697 muon tracks are matched and turn out being compatibles, their hits are com-
 1698 bined and fitted to form a *global-muon track*.

1699 Global muons sharing the same inner track with tracker muons are merged into a
 1700 single candidate. PF muon identification uses the muon energy deposits in ECAL,
 1701 HCAL, and HO associated with the muon track to improve the muon identification.

1702 **Particle identification and reconstruction.**

1703 PF elements are connected by a linker algorithm that tests the connection between any
 1704 pair of elements; if they are found to be linked, a geometrical distance that quantifies
 1705 the quality of the link is assigned. Two elements may be linked indirectly through
 1706 common elements. Linked elements form *PF blocks* and a PF block may contain
 1707 elements originating in one or more particles. Links can be established between
 1708 tracks, between calorimeter clusters, and between tracks and calorimeter clusters.
 1709 The identification and reconstruction start with a PF block and proceeds as follows

1710 • Muons. An “isolated global muon” is identified by evaluating the presence of
 1711 inner track and energy deposits close to the global muon track in the (η, ϕ)
 1712 plane, i.e., in a particular point of the global muon track, inner tracks and
 1713 energy deposits are sought within a radius of $\Delta R = 0.3$ (see eqn. 3.7) from the
 1714 muon track; if they exist and the p_T of the found track added to the E_T of the
 1715 found energy deposit does not exceed 10% of the muon p_T then the global muon
 1716 is an isolated global muon. This isolation condition is stringent enough to reject
 1717 hadrons misidentified as muons.

1718 “Non-isolated global muons” are identified using additional selection require-
 1719 ments on the number of track segments in the muon system and energy deposits
 1720 along the muon track. Muons inside jets are identified with more stringent crite-
 1721 ria in isolation and momentum as described in reference [99]. The PF elements
 1722 associated with an identified muon are masked from the PF block.

- 1723 ● Electrons are identified and reconstructed as described above plus some addi-
 1724 tional requirements on fourteen variables like the amount of energy radiated,
 1725 the distance between the extrapolated track position at the ECAL and the po-
 1726 sition of the associated ECAL supercluster among others, which are combined
 1727 in a specialized multivariate analysis strategy that improves the electron iden-
 1728 tification. Tracks and clusters used to identify and reconstruct electrons are
 1729 masked in the PF block.
- 1730 ● Isolated photons are identified from ECAL superclusters with E_T larger than 10
 1731 GeV, for which the energy deposited at a distance of 0.15, from the supercluster
 1732 position on the (η, ϕ) plane, does not exceed 10% of the supercluster energy;
 1733 note that this is an isolation requirement. In addition, there must not be links
 1734 to tracks. Clusters involved in the identification and reconstruction are masked
 1735 in the PF block.
- 1736 ● Bremsstrahlung photons and prompt photons tend to convert to electron-positron
 1737 pairs inside the tracker, therefore, a dedicated finder algorithm is used to link
 1738 tracks that seem to originate from a photon conversion; in case those two tracks
 1739 are compatible with the direction of a bremsstrahlung photon, they are also
 1740 linked to the original electron track. Photon conversion tracks are also masked
 1741 in the PF block.
- 1742 ● The remaining elements in the PF block are used to identify hadrons. In the
 1743 region $|\eta| \leq 2.5$, neutral hadrons are identified with HCAL clusters not linked
 1744 to any track while photons from neutral pion decays are identified with ECAL
 1745 clusters without links to tracks. In the region $|\eta| > 2.5$ ECAL clusters linked to
 1746 HCAL clusters are identified with a charged or neutral hadron shower; ECAL
 1747 clusters with no links are identified with photons. HCAL clusters not used yet,

1748 are linked to one or more unlinked tracks and to an unlinked ECAL in order to
 1749 reconstruct charged-hadrons or a combination of photons and neutral hadrons
 1750 according to certain conditions on the calibrated calorimetric energy.

- 1751 • Charged-particle tracks may be liked together when they converge to a “sec-
 1752 ondary vertex (SV) ” displaced from the interaction point where the PV and
 1753 PU vertices are reconstructed; at least three tracks are needed in that case,
 1754 of which at most one has to be an incoming track with hits in tracker region
 1755 between a PV and the SV.

1756

1757 The linker algorithm, as well as the whole PF algorithm, has been validated and
 1758 commissioned; results from that validation are presented in the references [92].

1759 **Jet reconstruction.**

1760 Quarks and gluons may be produced in the pp collisions, therefore, their hadronization
 1761 will be seen in the detector as a shower of hadrons and their decay products in the
 1762 form of a “jet”. The anti- k_t algorithm [100] is used to perform the jet reconstruction
 1763 by clustering those PF particles within a cone (see figure 4.3); previously, isolated
 1764 electrons, isolated muons, and charged particles associated with other interaction
 1765 vertices are excluded from the clustering.

1766 The anti- k_t algorithm proceeds in a sequential recombination of PF particles; the
 1767 distance between particles i and j (d_{ij}) and the distance between particles and the
 1768 beam are defined as

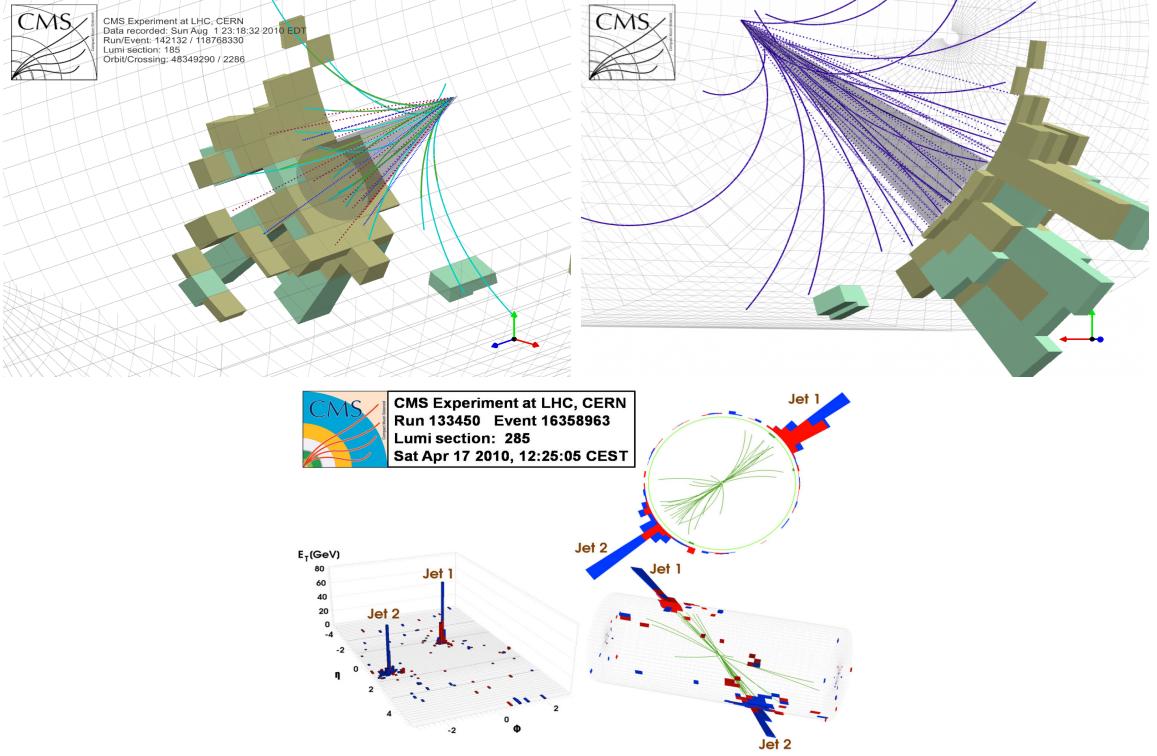


Figure 4.3: Jet reconstruction performed by the anti- k_t algorithm. Top: Two different views of a CMS recorded event are presented. Continuous lines correspond to the tracks left by charged particles in the tracker while dotted lines are the imaginary paths followed by neutral particles. The green cubes represent the ECAL cells while the blue ones represent the HCAL cells; in both cases, the height of the cube represent the amount of energy deposited in the cells [101]. Bottom: Reconstruction of a recorded event with two jets [102].

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

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

1769 where $\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$, k_{ti} , y_i and ϕ_i are the transverse momentum, ra-
1770 pidity and azimuth of particle i respectively and R is the called jet radius. For all
1771 the remaining PF particles, after removing the isolated ones, d_{ij} and d_{iB} are calcu-

lated⁵ and the smallest is identified; if it is a d_{ij} , particles i and j are replaced with a new object whose momentum is the vectorial sum of the combined particles. If the smallest distance is a d_{iB} the clustering process ends, the object i (which at this stage should be a combination of several PF particles) is declared as a *Particle-flow-jet* (PF jet) and all the associated PF particles are removed from the detector. The clustering process is repeated until no PF particles remain.

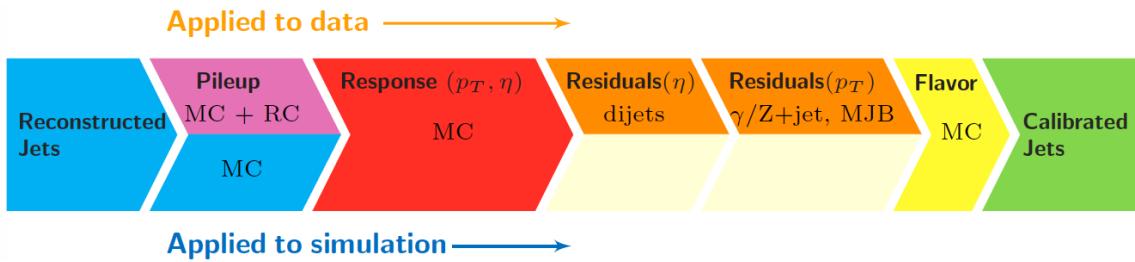


Figure 4.4: Jet energy correction diagram. Correction levels are applied sequentially in the indicated fixed order [104].

Even though jets can be reconstructed efficiently, there are some effects that are not included in the reconstruction and that lead to discrepancies between the reconstructed results and the predicted results; in order to overcome these discrepancies, a factorized model has been designed in the form of jet energy corrections (JEC) [103, 104] applied sequentially as shown in the diagram of figure 4.4.

At each level, the jet four-momentum is multiplied by a scaling factor based on jet properties, i.e., η , flavor, etc.

- Level 1 correction removes the energy coming from pile-up. The scale factor is determined using a MC sample of QCD dijet events with and without pileup overlay; it is parametrized in terms of the offset energy density ρ , jet area A , jet η and jet p_T . Different corrections are applied to data and MC due to the detector simulation.

⁵ Notice that this is a combinatorial calculation.

- 1790 • MC-truth correction accounts for differences between the reconstructed jet en-
- 1791 ergy and the MC particle-level energy. The correction is determined on a QCD
- 1792 dijet MC sample and is parametrized in terms of the jet p_T and η .
- 1793 • Residuals correct remaining small differences within jet response in data and
- 1794 MC. The Residuals η -dependent correction compares jets of similar p_T in the
- 1795 barrel reference region. The Residuals p_T -dependent correct the jet absolute
- 1796 scale (JES vs p_T).
- 1797 • Jet-flavor corrections are derived in the same way as MC-truth corrections but
- 1798 using QCD pure flavor samples.

1799 ***b*-tagging of jets.**

1800 A particular feature of the hadrons containing bottom quarks (b-hadrons) is that
 1801 they have a lifetime long enough to travel some distance before decaying, but it is
 1802 not as long as those of light quark hadrons; therefore, when looking at the hadrons
 1803 produced in pp collisions, b-hadrons decay typically inside the tracker rather than
 1804 reach the calorimeters as some light-hadrons do. As a result, a b-hadron decay gives
 1805 rise to a displaced vertex (secondary vertex) with respect to the primary vertex as
 1806 shown in figure 4.5; the SV displacement is in the order of a few millimeters. A jet
 1807 resulting from the decay of a b-hadron is called *b* jet; other jets are called light jets.

1808

1809 Several methods to identify *b*-jets (*b*-tagging) have been developed; the method used in
 1810 this thesis is known as “Combined Secondary Vertex” algorithm in its second version
 1811 (CSVv2) [105]. By using information of the impact parameter, the reconstructed
 1812 secondary vertices and the jet kinematics in a multivariate analysis that combines
 1813 the discrimination power of each variable in one global discriminator variable, three

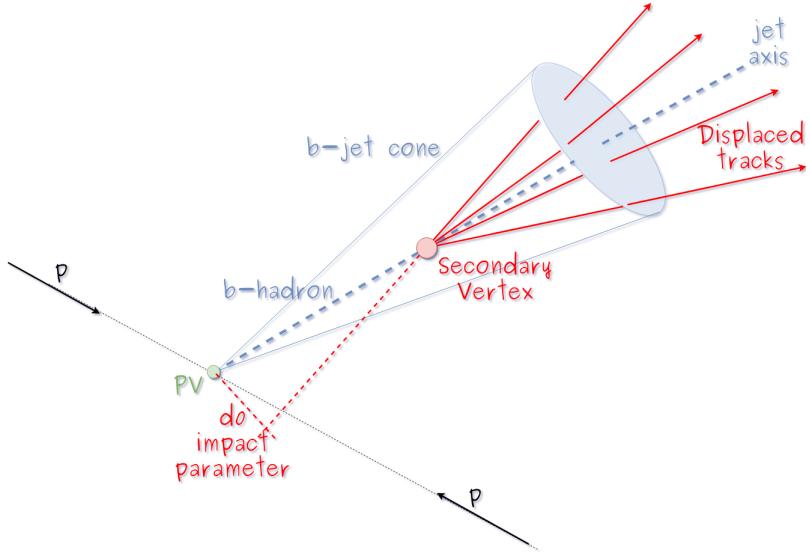


Figure 4.5: Secondary vertex in a b-hadron decay.

1814 working points (references): loose, medium and tight, are defined which quantify the
 1815 probabilities of mistag jets from light quarks as jets from b quarks; 10, 1 and 0.1 %
 1816 respectively. Although the mistagging probability decrease with the working point
 1817 strength, the efficiency to correctly tag b -jets also decrease as 83, 69 and 49 % for the
 1818 respective working point; therefore, a balance needs to be achieved according to the
 1819 specific requirements of the analysis.

1820 Missing transverse energy.

1821 The fact that proton bunches carry momentum along the z axis implies that for each
 1822 event, momentum balance in the transverse plane is expected. Imbalances are quan-
 1823 tified by the missing transverse energy (MET) and are attributed to several sources
 1824 including particles escaping undetected through the beam pipe, neutrinos produced in
 1825 weak interactions processes which do not interact with the detector and thus escaping
 1826 without leaving a sign, or even undiscovered particles predicted by models beyond
 1827 the SM.

1828

1829 The PF algorithm assign the negative sum of the momenta of all reconstructed PF
 1830 particles to the *particle-flow MET* according to

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

1831 JEC are propagated to the calculation of the \vec{E}_T as described in the reference [106].

1832

1833 4.4.2 Event reconstruction examples

1834 Figures 4.6-4.8 show the results of the reconstruction performed on 3 recorded events.
 1835 Descriptions are taken directly from the source.

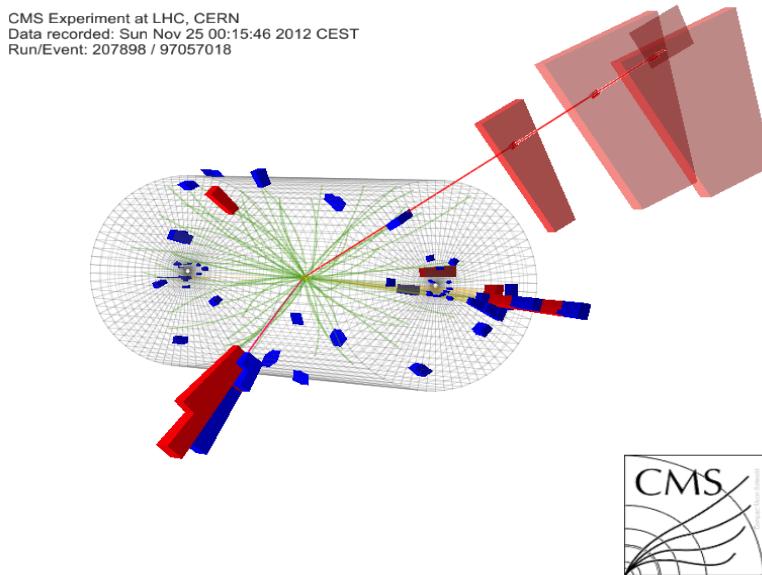


Figure 4.6: HIG-13-004 Event 1 reconstruction results; “HIG-13-004 Event 1: Event recorded with the CMS detector in 2012 at a proton-proton center-of-mass energy of 8 TeV. The event shows characteristics expected from the decay of the SM Higgs boson to a pair of τ leptons. Such an event is characterized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

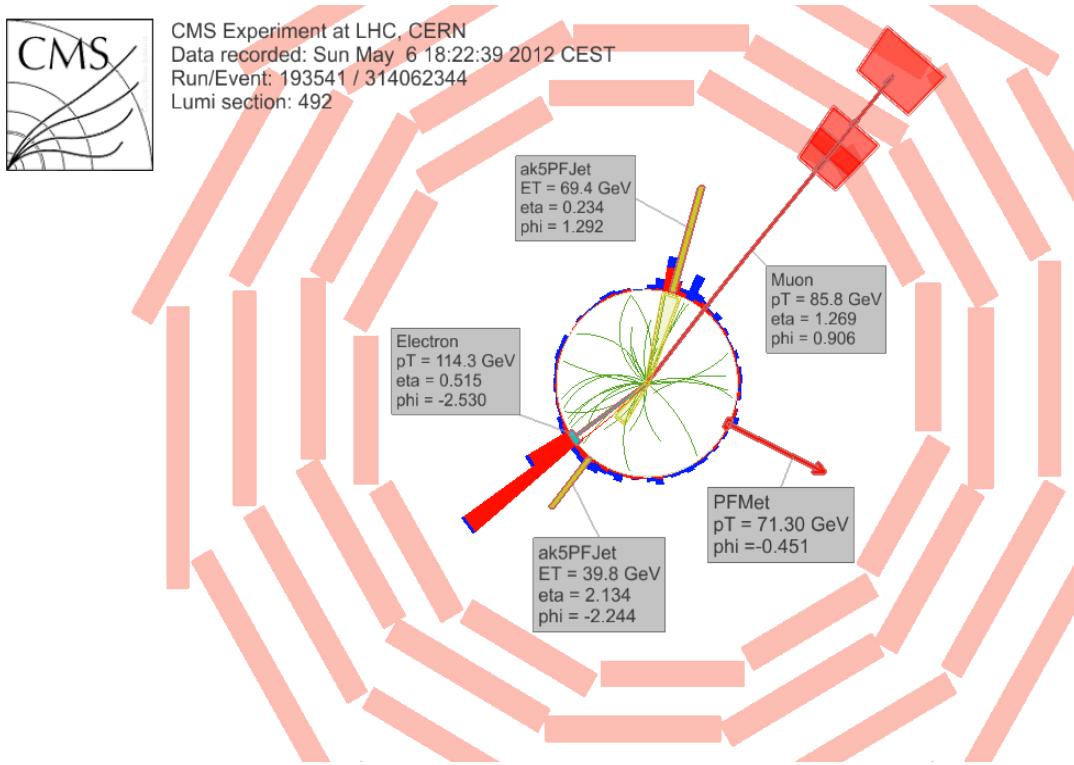


Figure 4.7: $e\mu$ event reconstruction results; “An $e\mu$ event candidate selected in 8 TeV data, as seen from the direction of the proton beams. The kinematics of the main objects used in the event selection are highlighted: two isolated leptons and two particle-flow jets. The reconstructed missing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

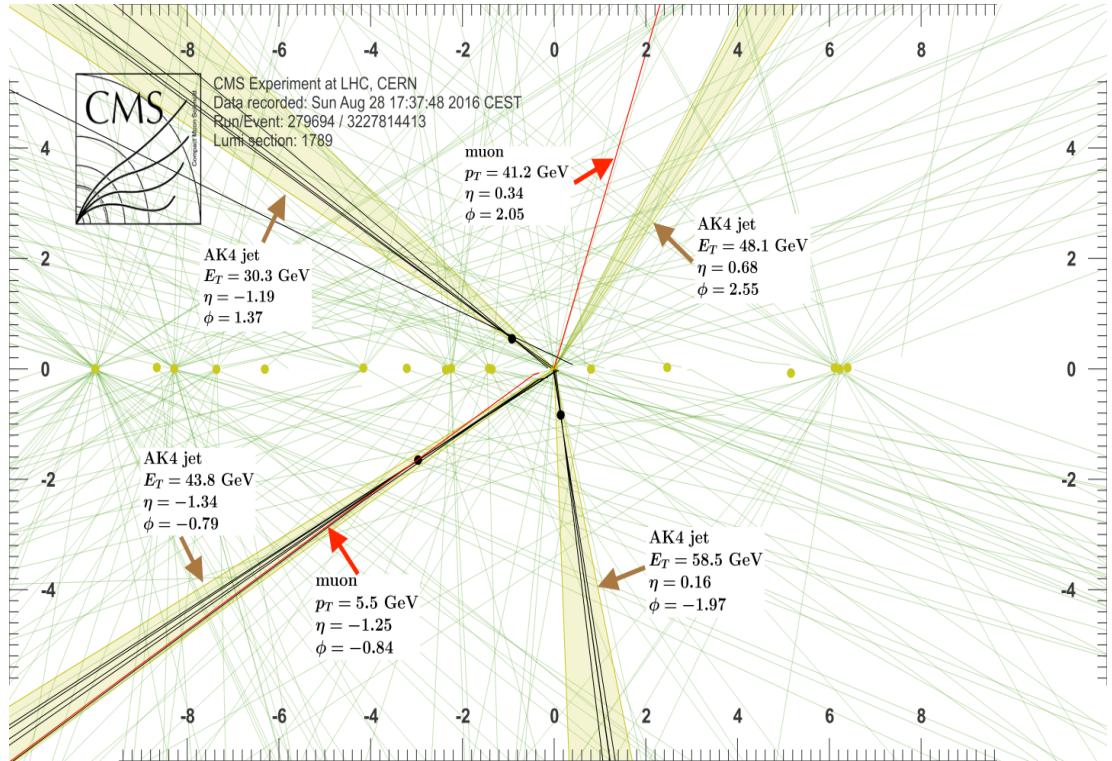


Figure 4.8: Recorded event reconstruction results;“Recorded event (ρ -z projection) with three jets with $p_T > 30$ GeV with one displaced muon track in 2016 data collected at 13 TeV. Each of the three jets has a displaced reconstructed vertex. The jet with $p_T(j) = 43.8$ GeV, $\eta(j) = -1.34$, $\phi(j) = -0.79$ contains muon with $p_T(\mu) = 5.5$ GeV, $\eta(\mu) = -1.25$, $\phi(\mu) = -0.84$. Event contains reconstructed isolated muon with $p_T(\mu) = 41.2$ GeV, $\eta(\mu) = 0.34$, $\phi(\mu) = 2.05$ and MET with $p_T = 72.5$ GeV, $\phi = -0.32$. Jet candidates for a b -jet from top quark leptonic and hadronic decays are tagged by CSVv2T algorithm. One of the other two jets is tagged by CharmT algorithm. Tracks with $p_T > 0.5$ GeV are shown. The number of reconstructed primary vertices is 18. Reconstructed $m_T(W)$ is 101.8 GeV. Beam spot position correction is applied. Reconstructed primary vertices are shown in yellow color, while reconstructed displaced vertices and associated tracks are presented in black color. Dimensions are given in cm” [107].

1836 **Chapter 5**

1837 **Statistical methods**

1838 In the course of analyzing the data sets provided by the CMS experiment and used in
1839 this thesis, several statistical tools have been employed; in this chapter, a description
1840 of these tools will be presented, starting with the general statement of the multivariate
1841 analysis method, followed by the particularities of the Boosted Decision Trees (BDT)
1842 method and its application to the classification problem. Statistical inference methods
1843 used will also be presented. This chapter is based mainly on the references [108–110].

1844 **5.1 Multivariate analysis**

1845 Multivariate data analysis (MVA) makes reference to statistical techniques that an-
1846 alyze data containing information of more than one variable, commonly taking into
1847 account the effects of all variables on the response of the particular variable under
1848 investigation, i.e., considering all the correlations between variables. MVA is em-
1849 ployed in a variety of fields like consumer and market research, quality control and
1850 process optimization. From a MVA it is possible to identify the dominant patterns
1851 in the data, like groups, outliers and trends, and determine to which group a set of

1852 values belong; in the particle physics context, MVA methods are used to perform the
 1853 selection of certain type of events, from a large data set, using a potentially large
 1854 number of measurable properties for each event.

1855 Processes with small cross section, as the tHq process, normally are hidden behind
 1856 more common processes; therefore, the data set results in a subset of events with
 1857 characteristic features of interest (signal) mixed in randomly with a much larger
 1858 number of SM events that can mimic these features of interest (background) which
 1859 implies that it is not possible to say with certainty that a given event is signal or
 1860 background. In that sense, the problem can be formulated as one where a set of
 1861 events have to be classified according to some features; these features correspond to
 1862 the measurements of several parameters like energy or momentum, organized in a
 1863 set of *input variables*. The measurements for each event can be written in a vector
 1864 $\mathbf{x} = (x_1, \dots, x_n)$ for which

- 1865 • Signal hypotheses $\rightarrow f(\mathbf{x}|s)$ is the probability density (*likelihood function*) that
 1866 \mathbf{x} is the set of measured values given that the events is a signal event.
- 1867 • Background hypotheses $\rightarrow f(\mathbf{x}|b)$ is the probability density (*likelihood function*)
 1868 that \mathbf{x} is the set of measured values given that the event is a background event.

1869 Figure 5.1 shows three ways to perform a classification of events for which mea-
 1870 surements of two properties, two input variables, have been performed; blue circles
 1871 represent signal events while red triangles represent background events. The classi-
 1872 fication on (a) is *cut-based* requiring $x_1 < c_1$ and $x_2 < c_2$; usually the cut values are
 1873 chosen according to some knowledge about the event process. In (b), the classification
 1874 is performed by stating a cut involving a linear function of the input variables and
 1875 so the boundary, while in (c) the the relationship between the input variables is not
 1876 linear thus the boundary is not linear either.

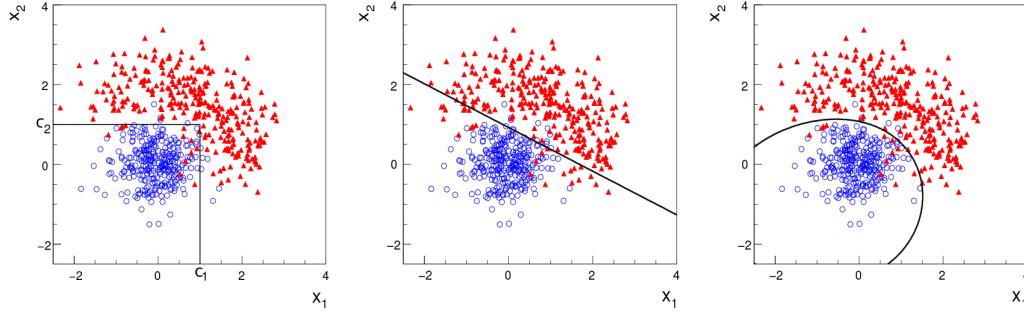


Figure 5.1: Scatter plots-MVA event classification. Distribution of two input variables x_1 and x_2 measured for a set of events; blue circles represent signal events and red triangles represent background events. The classification is based on (a) cuts, (b) linear boundary, and (c) nonlinear boundary [108]

1877 The boundary can be parametrized in terms of the input variables such that the
 1878 cut is set on the parametrization instead of on the variables, i.e., $y(\mathbf{x}) = y_{cut}$ with
 1879 y_{cut} a constant; thus, the acceptance or rejection of an event is based on what side
 1880 of the boundary is the event located. If $y(\mathbf{x})$ has functional form, it can be used to
 1881 determine the probability distribution functions $p(y|s)$ and $p(y|b)$ and then perform
 1882 a scalar test statistic with a single cut on the scalar variable y .

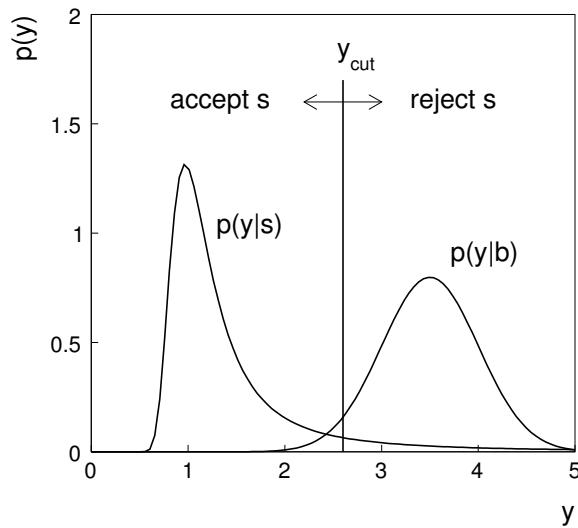


Figure 5.2: Distributions of the scalar test statistic $y(\mathbf{x})$ under the signal and background hypotheses. [108]

1883 Figure 5.2 illustrates what would be the probability distribution functions under
 1884 the signal and background hypotheses for a scalar test statistic with a cut on the
 1885 classifier y . Notice that the tails of the distributions indicate that some signal events
 1886 fall on the rejection region and some background events fall on the acceptance region;
 1887 therefore, it is convenient to define the *efficiency* with which events of a given type
 1888 are accepted, thus, the signal and background efficiencies are given by

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

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

1889 where A is the acceptance region. Under these conditions, the background hypothesis
 1890 corresponds to the *null hypothesis* (H_0), the signal hypothesis corresponds to the
 1891 *alternative hypothesis* (H_1), the background efficiency is the significance level of the
 1892 test, and signal efficiency is the power of the test; what is sought in an analysis is to
 1893 maximize the power of the test relative to the significance level.

1894 5.1.1 Decision trees

1895 For this thesis, the implementation of the MVA strategy, described above, is per-
 1896 formed through decision trees by using the TMVA software package [109] included in
 1897 the the ROOT analysis framework [111]. In a simple picture, a decision tree classifies
 1898 events according to their input variables values by setting a cut on each input variable
 1899 and checking which events are on which side of the cut, just as proposed in the MVA
 1900 strategy, but in addition, as a machine learning algorithm, decision trees offer the
 1901 possibility to be trained and then perform the classification efficiently.

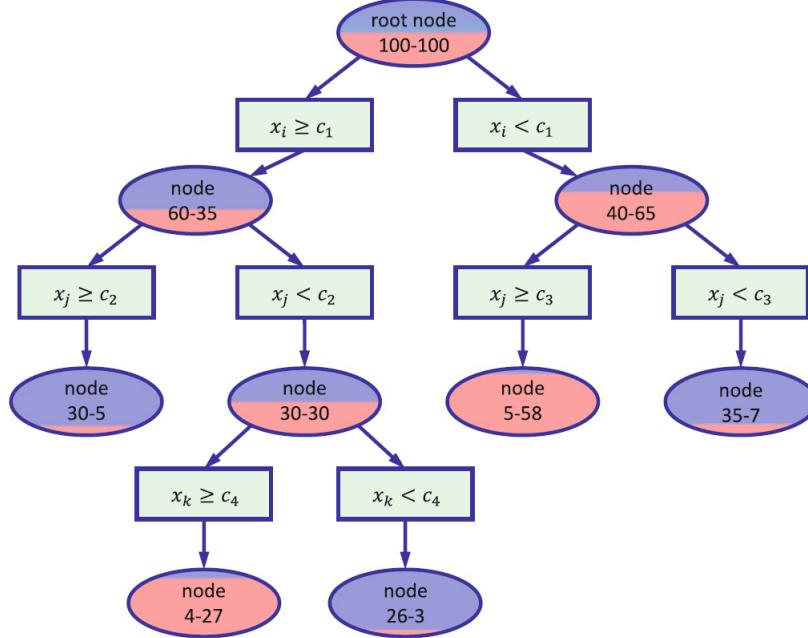


Figure 5.3: Example of a decision tree. Each node is fed with a MC sample mixing signal and background events (left-right numbers); nodes colors represent the relative amount of signal/background events [110].

1902 The training or growing of a decision tree is the process that defines the rules for
 1903 classifying events; this process is represented in figure 5.3 and consist of several steps

1904 • take MC samples of signal and background events and split them into two parts
 1905 each; first parts form the training sample which will be used in the decision tree
 1906 training, while the second parts form the test sample which will be used for
 1907 testing the final classifier obtained from the training. Each event has associated
 1908 a set of input variables $\mathbf{x} = (x_1, \dots, x_n)$ which serve to distinguish between signal
 1909 and background events. The training sample is taken in at the root *node*.

1910 • pick one variable, say x_i
 1911 • pick one value of x_i , each event has its own value of x_i , and split the training
 1912 sample into two subsamples B_1 and B_2 ; B_1 contains events for which $x_i < c_1$

1913 while B_2 contains the rest of the training events;

1914 • scan all possible values of x_i and find the splitting value that provides the *best*
 1915 classification¹, i.e., B_1 is mostly made of signal events while B_2 is mostly made
 1916 of background events.

1917 • It is possible that variables other than the picked one produce a better classi-
 1918 fication, hence, all the variables have to be evaluated. Pick the next variable,
 1919 say x_j , and repeat the scan over its possible values.

1920 • At the end, all the variables and their values will have been scanned, the *best*
 1921 variable and splitting value will have been identified, say x_1, c_1 , and there will
 1922 be two nodes fed with the subsamples B_1 and B_2 .

1923 Nodes are further split by repeating the decision process until: a given number of
 1924 final nodes is obtained, nodes are largely dominated by either signal or background
 1925 events, or nodes has too few events to continue. Final nodes are called *leaves* and they
 1926 are classified as signal or background leaves according to the class of the majority of
 1927 events in them. Each *branch* in the tree corresponds to a sequence of cuts.

1928 The quality of the classification at each node is evaluated through a separation
 1929 criteria; there are several of them but the *Gini Index* (G) is the one used in the
 1930 decision trees trained for the analysis in this thesis. G is written in terms of the
 1931 purity (P), i.e. the fraction of signal events, of the samples after the separation is
 1932 made; it is given by

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

¹ Quality of the classification will be treated in the next paragraph.

1933 notice that $P=0.5$ at the root node while $G=0$ for pure leaves. For a node A split
 1934 into two nodes B_1 and B_2 the G gain is

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

1935 the *best* classification corresponds to that for which the gain of G is maximized; hence,
 1936 the scanning over all event's variables and their values is of capital importance.

1937 In order to provide a numerical output for the classification, events in a sig-
 1938 nal(background) leaf are assigned an score of 1(-1) each, defining in this way the
 1939 decision tree *classifier or weak learner* as

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

1940 Figure 5.4 shows an example of the classification of a sample of events, containing
 1941 two variables, performed by a decision tree.

1942 5.1.2 Boosted decision trees (BDT).

1943 Event misclassification occurs when a training event ends up in the wrong leaf, i.e., a
 1944 signal event ends up in a background leaf or a background event ends up in a signal
 1945 leaf. A way to correct it is to assign a weight to the misclassified events and train
 1946 a second tree using the reweighted events; the event reweighting is performed by a
 1947 boosting algorithm, events with increased weight are known as *boosted* events, in such
 1948 a way that when used in the training of a new decision tree they get correctly classified.
 1949 The process is repeated iteratively adding a new tree to a forest and creating a set
 1950 of classifiers which are combined to create the next classifier; the final classifier offers

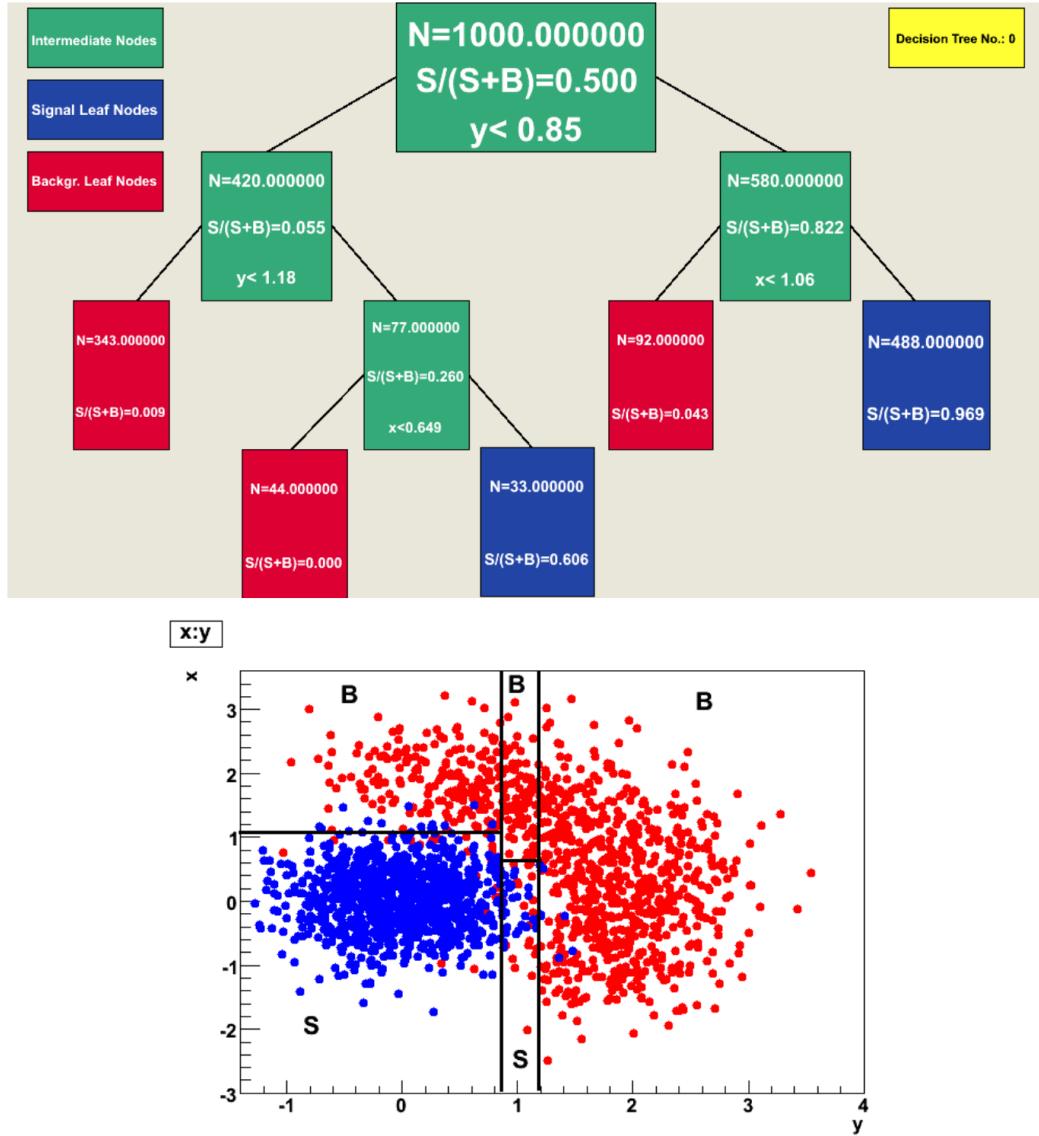


Figure 5.4: Example of a decision tree output. Each leaf, blue for signal events and red for background events, represent a region in the variables phase space [112].

1951 more stability² and has a smaller misclassification rate than any individual ones. The
 1952 resulting tree collection is known as a *boosted decision tree (BDT)*.
 1953 Thus, purity of the sample is generalized to

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

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

1954 where w_s and w_b are the weights of the events; the Gini index is also generalized

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

1955 with n the number of events in the node. The final score of an event, after pass-
 1956 ing through the forest, is calculated as the renormalized sum of all the individual
 1957 (possibly weighted) scores; thus, high(low) score implies that the event is most likely
 1958 signal(background).

1959 The boosting procedure, implemented in the *Gradient boosting* algorithm used
 1960 in this thesis, produce a classifier $F(\mathbf{x})$ which is the weighted sum of the individual
 1961 classifiers obtained after each iteration,i.e.,

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

1962 where M is the number of trees in the forest. The *loss function* $L(F, y)$ represent the
 1963 deviation between the classifier $F(\mathbf{x})$ response and the true value y obtained from the
 1964 training sample (1 for signal events and -1 for background event), according to

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

1965 thus, the reweighting is employed to ensure the minimization of the loss function;
 1966 a more detailed description of the minimization procedure can be found in reference
 1967 [113]. The final classifier output is later used as a final discrimination variable, labeled
 1968 as *BDT output/response*.

1969 **5.1.3 Overtraining.**

1970 Decision trees offer the possibility to have as many nodes as wished in order to
 1971 reduce the misclassification to zero (in theory); however, when a classifier is too much
 1972 adjusted to a particular training sample, the classifier response to a slightly different
 1973 sample may leads to a completely different classification results; this effect is know
 1974 as *overtraining*.

1975 An alternative to reduce the overtraining in BDTs consist in pruning the tree by
 1976 removing statistically insignificant nodes after the tree growing is completed but this
 1977 option is not available for BDTs with gradient boosting in the TMVA-toolkit, there-
 1978 fore, the overtraining has to be reduced by tuning the algorithm, number of nodes,
 1979 minimum number of events in the leaves, etc. The overtraining can be evaluated
 1980 by comparing the responses of the classifier when running over the training and test
 1981 samples.

1982 **5.1.4 Variable ranking.**

1983 BDTs have the couple of particular advantages related to the input variables; on one
 1984 side, they are relatively insensitive to the number of input variables used in the vector
 1985 \mathbf{x} . The ranking of the BDT input variables is determined by counting the number of
 1986 times a variable is used to split decision tree nodes; in addition, the separation gain-
 1987 squared achieved in the splitting and the number of events in the node are accounted
 1988 by applying a weighting to that number. Thus, those variables with small or no power
 1989 to separate signal and background events are rarely chosen to split the nodes,i.e., are
 1990 effectively ignored.

1991 On the other side, variables correlations play an important role for some MVA
 1992 methods like the Fisher discriminant algorithm in which the first step consist of

1993 performing a linear transformation to a phase space where the correlations between
 1994 variables are removed; in case of BDT algorithm, correlations do not affect the per-
 1995 formance.

1996 **5.1.5 BDT output example.**

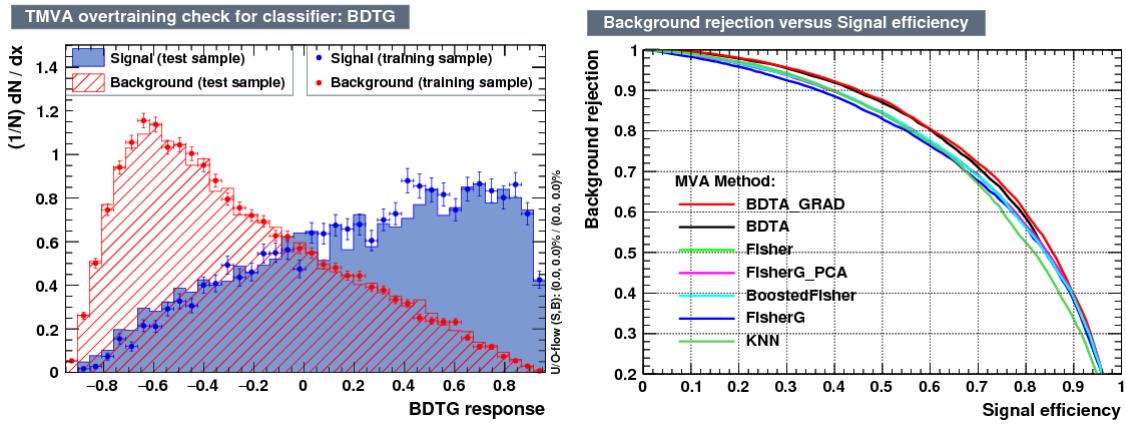


Figure 5.5: Left: Output distributions for the gradient boosted decision tree (BDTG) classifier using a sample of signal($pp \rightarrow tHq$) and background($pp \rightarrow t\bar{t}$) events. Right: Background rejection vs signal efficiency (ROC curves) for various MVA classifiers running over the same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

1997 Left side of figure 5.5 shows the BDT output distributions for signal($pp \rightarrow tHq$)
 1998 and background($pp \rightarrow t\bar{t}$) events; this plot is the equivalent to the one showed in
 1999 figure 5.2. A forest with 800 trees, maximum depth per tree = 3, and gradient
 2000 boosting have been used as training parameters. The BDTG classifier offers a good
 2001 separation power; while there is a small overtraining in the signal distribution, the
 2002 background distribution seems to be well predicted which might indicate that the
 2003 sample is composed of more background than signal events.

2004 Right side of figure 5.5 shows the background rejection vs signal efficiency curves
 2005 for several combinations of MVA classifiers-boosting algorithms; these curves are
 2006 known as ROC curves and give an indication of the performance of the classifier. The

2007 best performance is achieved with the BDTG classifier (BDTA_GRAD).

2008 5.2 Statistical inference.

2009 Once events are classified, the next step consists in finding the parameters that define
 2010 the likelihood functions $f(\mathbf{x}|s), f(\mathbf{x}|b)$ for signal and background events respectively.
 2011 In general, likelihood functions depend not only on the measurements but also on
 2012 parameters (θ_m) that define their shapes; the process of estimating these *unknown*
 2013 *parameters* and their uncertainties from the experimental data is called *inference*.
 2014 The likelihood function for N the events the in a sample is the combination of all the
 2015 likelihoods functions

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

2016 Thus, the estimation of the unknown parameters from experimental data samples
 2017 is written in terms of a central value using the notation

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

2018 where the interval $[\hat{\theta} + \delta\theta, \hat{\theta} - \delta\theta]$ is called *confidence interval*; it is usually inter-
 2019 preted, in the limit of infinite number of experiments, as the interval where the true
 2020 value of the unknown parameter θ is contained with a probability of 0.6827 (if no
 2021 other convention is stated).

2022 5.2.1 Nuisance parameters.

2023 The unknown parameter vector $\boldsymbol{\theta}$ is made of two types of parameters: on one side,
 2024 those parameters that provide information about the physical observables of interest

2025 for the experiment (*parameters of interest*); on the other side, the *nuisance parameters*
 2026 that are not of direct interest for the experiment but that needs to be included in
 2027 the analysis in order to achieve a satisfactory description of the data. They represent
 2028 effects of the detector response like the finite resolutions of the detection systems,
 2029 miscalibrations, and in general any source of uncertainty introduced in the analysis.

2030 In some cases the nuisance parameters are estimated using dedicated data samples,
 2031 for instance data from test beams for calibration purposes, when MC samples are
 2032 not suitable. The nuisance parameter uncertainties produce *systematic uncertainties*
 2033 while the uncertainties associated to fluctuations in data and related to the estimation
 2034 of the parameters of interest produce *statistical uncertainties*.

2035 5.2.2 Maximum likelihood estimation method

2036 The function that produce the estimate of a parameter is called *estimator*, there-
 2037 fore, estimators are usually constructed using mathematical procedures encoded in
 2038 algorithms. The estimation method used in this thesis is the *Maximum Likelihood*
 2039 *Estimation* method (MLE); it is based on the combined likelihood function defined
 2040 by eqn. 5.9 and the procedure seeks for the parameter set that corresponds to the
 2041 maximum value of the combined likelihood function, i.e., the *maximum likelihood*
 2042 *estimator* of the unknown parameter vector $\boldsymbol{\theta}$ is the function that produce the vec-
 2043 tor $\hat{\boldsymbol{\theta}}$ for which the likelihood function $L(\boldsymbol{\theta})$ evaluated at the measured sample \mathbf{x} is
 2044 maximum.

2045 Usually, the logarithm of the likelihood function is used in the numerical algo-
 2046 rithms implementations in order to avoid underflow the numerical precision of the
 2047 computers due to the product of low likelihoods. In addition, it is usual minimize the
 2048 negative logarithm of the likelihood function instead of maximizing the logarithm of

2049 it because in this way the procedure consist of differentiate a sum of therms and set
 2050 the sum to zero; therefore

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

2051 The minimization process is performed by the software MINUIT [114] imple-
 2052 mented in the ROOT analysis framework. In case of large data samples the compu-
 2053 tational resources needed to calculate the likelihood function are too big; therefore,
 2054 the parameter estimation is performed using binned distributions of the variables of
 2055 interest for which the *binned likelihood function* is given by

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

2056 with s_i and b_i the expected number of signal and background yields for bin i respec-
 2057 tively, n_i is the observed number of events in the bin i and $\mu = \sigma/\sigma_{SM}$ is the signal
 2058 strength. Notice that the number of entries per bin follows a Poisson distribution.
 2059 The analysis presented in this thesis is based on the binned distribution of the ratio
 2060 signal/background obtained from the BDT outputs.

2061 5.2.3 Hypothesis test

2062 The test statistic mentioned in section 5.1 involving
 2063 ; it is achieved, according to the Neyman-Pearson lemma [115],
 2064 by defining the acceptance region such that, for \mathbf{x} inside the region, the likelihood
 2065 ratio, i.e., the ratio of probability distribution functions for signal and background,

2066 **5.3 exclusion limits**

2067 **5.4 asymptotic limits**

2068 **Chapter 6**

2069 **Search for production of a Higgs**
2070 **boson and a single top quark in**
2071 **multilepton final states in pp**
2072 **collisions at $\sqrt{s} = 13$ TeV**

2073 **6.1 Introduction**

2074 The Higgs boson discovery, supported on experimental observations and theoretical
2075 predictions made about the SM, gives the clue of the way in that elementary particles
2076 acquire mass through the Higgs mechanism; therefore, knowing the Higgs mass, the
2077 Higgs-boson and Higgs-fermions couplings can be tested. In order to test the Higgs-
2078 top coupling, several measurements have been performed, as stated in the chapter 2,
2079 but they are limited to measure the square of the coupling; however, the production
2080 of a Higgs boson in association with a single top quark (tH) not only offers access to
2081 the sign of the coupling, but also, to the CP phase of the Higgs couplings.

2082 This chapter presents the search for the associated production of a Higgs boson
 2083 and a single top quark events, focusing on leptonic signatures provided by the Higgs
 2084 decay modes to WW , ZZ , and $\tau\tau$; the 13 TeV dataset produced in 2016, which
 2085 corresponds to an integrated luminosity of 35.9fb^{-1} , is used. Constraints on the sign
 2086 of the Higgs- top coupling (y_t) have been derived from the decay rate of Higgs bosons
 2087 to photon pairs [40] and from the cross section for associated production of Higgs and
 2088 Z bosons via gluon fusion [116], with recent results disfavoring negative signs of the
 2089 coupling [51,53,117]. It expands previous analyses performed at 8 TeV [118,119] and
 2090 searches for associated production of $t\bar{t}$ pair and a Higgs boson in the multilepton final
 2091 state channel [120]; it also complements searches in other decay channels targeting
 2092 $H \rightarrow b\bar{b}$ [121].

2093 As shown in section 2.4, the SM cross section of the associated production of a
 2094 Higgs boson and a single top quark (tHq) process is driven by a destructive interfer-
 2095 ence between two contributions (see Figure 2.13), where the Higgs couples to either
 2096 the W boson or the top quark; however, if the sign of the Higgs-top coupling is flipped
 2097 with respect to the SM prediction, a large enhancement of the cross section occurs,
 2098 making this analysis sensitive to such deviation. A second process, where the Higgs
 2099 boson and top quark are accompanied by a W boson (tHW) has similar behavior,
 2100 albeit with a weaker interference pattern and lower contribution to the tH cross sec-
 2101 tion, therefore, a combination of both processes would increase the sensitivity; in
 2102 this analysis both contributions are combined and referred as tH channel. A third
 2103 contribution comes from $t\bar{t}H$ process. The purpose of this analysis is to investigate
 2104 the exclusion of the presence of the $tH + t\bar{t}H$ processes under the assumption of the
 2105 anomalous Higgs-top coupling modifier ($\kappa_t = -1$). The analysis exploits signatures with
 2106 three leptons in the final state.

2107 The first sections present the characteristic tHq signature as well as the expected

backgrounds. The MC samples, data sets, and the physics object definitions are then defined. Following, the background predictions, the signal extraction, and the statistical treatment of the selected events as well as the systematic uncertainties are described. The final section present the results for the exclusion limits as a function of the ratio of κ_t and the dimensionless modifier of the Higgs-vector boson κ_V .

6.2 tHq signature

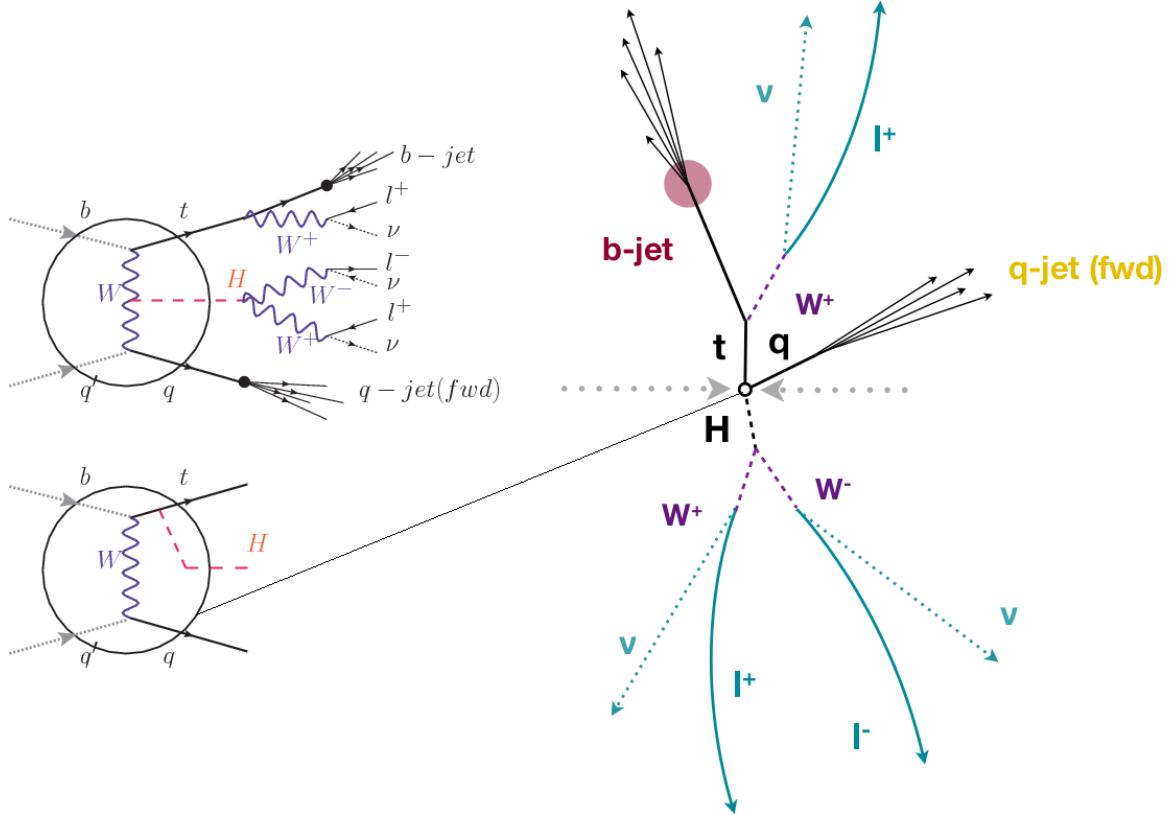


Figure 6.1: tHq event signature. Left: Feynman diagram including the whole evolution up to the final state for the case of the Higgs boson emitted by the W boson (top); feynman diagram for the case where the Higgs boson is emitted by the top quark. Right: Schematic view as it would be seen in the detector; The circle in the feynman diagrams on the left corresponds to the circle in the center of the schematic view as indicated by the line connecting them.

2114 In order to select events of tHq process, its features are translated into a set of
 2115 selection rules; figure 6.1 shows the Feynman diagram and an schematic view of the
 2116 tHq process from the pp collision to the final state configuration. A single top quark
 2117 is produced accompanied by a light quark, denoted as q ; this light quark is produced
 2118 predominantly in the forward region of the detector. The Higgs boson which can
 2119 be either emitted by the exchanged W boson or directly by the singly produced top
 2120 quark.

2121 The top quark and Higgs boson decay after their production in the detector due to
 2122 their high masses/low lifetimes. The Higgs boson is required to decay into a W boson
 2123 pair¹. The top quark almost always decays into a bottom quark and a W boson, as
 2124 encoded in the CMK matrix. The W bosons are required to decay leptonically while
 2125 τ leptons are not reconstructed separately and only their leptonic decays into either
 2126 electrons or muons are considered in this analysis.

2127 In summary, the signal process is characterized by a the final state with one
 2128 light-flavored forward jet, one central b-jet, three leptons (muons, electrons or a
 2129 combination of them), three neutrinos and no central light-flavored jets. The presence
 2130 of neutrinos is inferred from the presence of MET.

2131 6.3 Background processes

2132 The background processes are those that can mimic the signal signature or at least
 2133 can be reconstructed as that as a result of certain circumstances. The backgrounds
 2134 can be classified as

- 2135 • Irreducible backgrounds where genuine prompt leptons are produced in on-
 2136 shell W and Z boson decays; they can be reliably estimated directly from MC

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

2137 simulated events, using higher-order cross sections or data control regions for
 2138 the overall normalization.

- 2139 • Reducible backgrounds where at least one of the leptons is *non-prompt*, i.e., pro-
 2140 duced within a hadronic jet, either a genuine lepton from heavy flavor decays.
 2141 Mis-reconstructed jets, also known as *mis-ID leptons* or *fake leptons*, are con-
 2142 sidered non-prompt leptons as well. These non-prompt leptons leave tracks and
 2143 hits in the detection systems as would a prompt lepton, but correlating those
 2144 hits with nearby jets could be a way of removing them. Reducible backgrounds
 2145 are not well predicted by simulation, and are estimated using data-driven meth-
 2146 ods.

2147 The main sources of background events in the case of tHq process are $t\bar{t}$ process
 2148 and $t\bar{t} + X (X = W, Z, \gamma)$ processes, here represented together as $t\bar{t}V$ process. Figure
 2149 6.2 shows the signature for $t\bar{t}$ and $t\bar{t}W$ processes;

2150 The largest contribution to irreducible backgrounds involving prompt leptons
 2151 comes from $t\bar{t}W$, $t\bar{t}Z$, processes for which the number of ($b-$)jets (($b-$)jet multiplicity)
 2152 is higher than that of the signal events, while for other contributing background
 2153 events, WZ , ZZ , and rare SM processes like $W^\pm W^\pm qq$, $t\bar{t}t\bar{t}$, tZq , tZW , WWW ,
 2154 WWZ , WZZ , ZZZ , the ($b-$)jet multiplicity is lower compared to that of the signal
 2155 events. None of the irreducible backgrounds present activity in the forward region of
 2156 the detector.

2157 On the side of the reducible backgrounds, the largest contribution comes from the
 2158 $t\bar{t}$ events which have a very similar signature to the signal events but does no present
 2159 activity in the forward region of the detector either; A particular feature of the $t\bar{t}$
 2160 events is their charge-symmetry which is also a difference with the signal events.

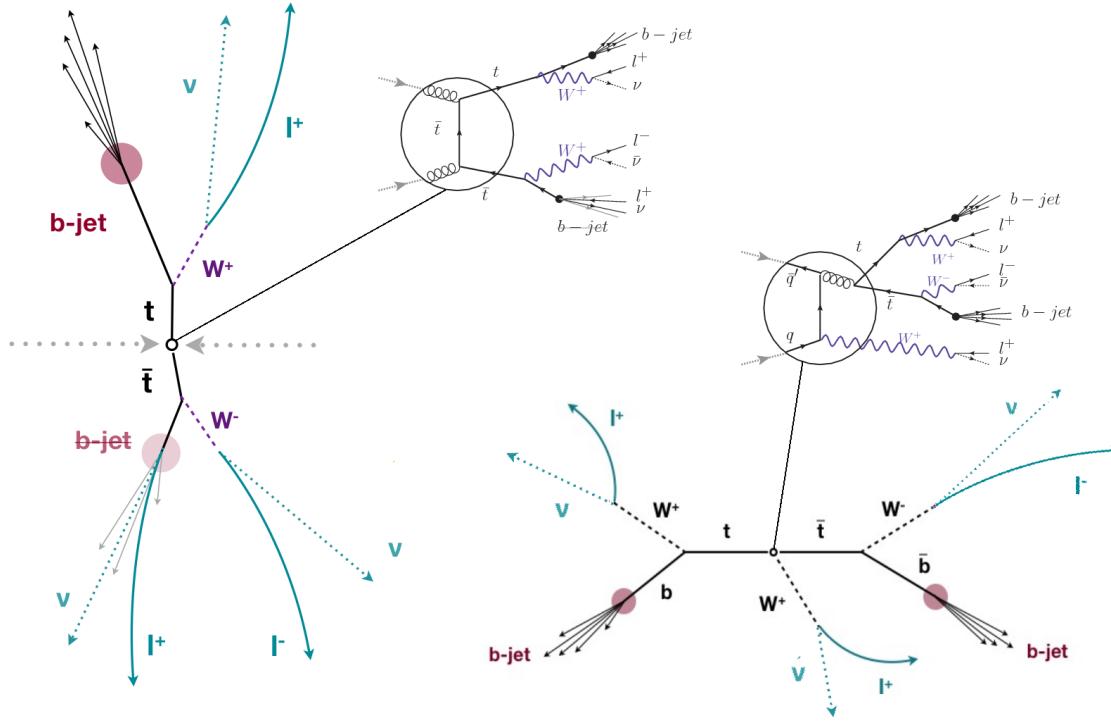


Figure 6.2: $t\bar{t}$ (left) and $t\bar{t}W$ (right) events signature as they would be seen in the detector; the feynman diagrams including the whole evolution up to the final state are also showed. The $t\bar{t}$ process signature is very similar to that of the signal process with one fake lepton and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

2161 6.4 Object Identification and event selection

2162 In this section, the specific definitions of the physical objects in terms of the numerical
 2163 values assigned to the reconstruction parameters are presented; thus, the provided
 2164 details complement the descriptions presented in previous chapter.

2165 6.4.1 Jets and b tagging

2166 In this analysis, jets are reconstructed by clustering PF candidates using the anti- k_t
 2167 algorithm with parameter distance $\Delta R = 0.4$; those charged hadrons that are not
 2168 consistent with the selected primary vertex are discarded from the clustering. The

jet energy is then corrected for the varying response of the detector as a function of transverse momentum p_T and pseudorapidity η . Jets are selected for use in the analysis only if they have $p_T > 25$ GeV and are separated from any selected leptons by $\Delta R > 0.4$.

Jets that are likely to have originated from the hadronization of a b quark, are selected through a multivariate likelihood discriminant that uses track-based lifetime information and reconstructed secondary vertices (CSV algorithm). Only jets within the CMS tracker acceptance ($\eta < 2.4$) are identified with this technique. The efficiency to correctly tag b -jets and the probability to misidentify jets from light quarks or gluons are measured in data as a function of the jet p_T and η , and are used to correct for differences in the performance of the algorithm in simulated events. Two working points based on the algorithm output are used: *loose*', with a b signal tagging efficiency of about 83% and a mistagging rate of about 8%; and *medium*, with b efficiency of about 69% and mistagging rate of order 1% cite. Tagging efficiencies for jets from charm quarks are about 40

the loose (medium) working point. Separate scale factors are applied to jets originating from

bottom/charm quarks and from light quarks in simulated events to match the tagging efficiencies measured in the data.

The primary vertex is chosen as the vertex with the highest sum of p_T of its constituent tracks. The prescribed jet energy corrections are applied as a function of the jet ET and \hat{E}_T [17]. In addition, a multivariate discriminator is applied to distinguish between jets coming from the primary vertex and jets coming from pile-up vertices. The discrimination is based on the differences in the jet shapes, in the relative multiplicity of charged and neutral components, and in the different fraction of transverse momentum which is carried by the hardest

2195 components. 187 Within the tracker acceptance the jet tracks are also required to
 2196 be compatible with the primary 188 vertex. Jets are only considered if they have
 2197 a transverse energy above 25 GeV and $|\hat{p}_T| < 2.4$. 189 In addition, they have to be
 2198 separated from any lepton candidates passing the Fakeable Object selection, described
 2199 below, by requiring $\Delta R =$

2200 The primary vertex is chosen as the vertex with the highest sum of p_T 181
 2201 of its constituent 182 tracks. The prescribed jet energy corrections are applied as
 2202 a function of the jet ET and \hat{p}_T [17]. In 183 addition, a multivariate discriminator
 2203 is applied to distinguish between jets coming from the 184 primary vertex and jets
 2204 coming from pile-up vertices. The discrimination is based on the differences in
 2205 the jet shapes, in the relative multiplicity of charged and neutral components, and
 2206 in the different fraction of transverse momentum which is carried by the hardest
 2207 components. 187 Within the tracker acceptance the jet tracks are also required to
 2208 be compatible with the primary 188 vertex. Jets are only considered if they have
 2209 a transverse energy above 25 GeV and $|\hat{p}_T| < 2.4$. 189 In addition, they have to be
 2210 separated from any lepton candidates passing the Fakeable Object selection, described
 2211 below, by requiring $\Delta R = p_T(\hat{p}_T \cdot \hat{p}_T^{\text{jet}}) / (\hat{p}_T + \hat{p}_T^{\text{jet}}) > 0.4$.

2212 corrected for charged hadrons not coming from the primary vertex (charged hadron
 2213 subtraction), and having jet energy corrections (`Summer16_23Sep2016V3`) applied as
 2214 a function of the jet E_T and η . Jets are only considered if they have a transverse
 2215 energy above 25 GeV.

2216 In addition, they are required to be separated from any lepton candidates passing
 2217 the fakeable object selections (see Tables 6.1 and 6.2) by $\Delta R > 0.4$.

2218 The loose and medium working points of the CSV b-tagging algorithm are used to
 2219 identify b jets. Data/simulation differences in the b tagging performance are corrected
 2220 by applying per-jet weights to the simulation, dependent on the jet p_T , eta, b tagging

discriminator, and flavor (from simulation truth) [?]. The per-event weight is taken as the product of the per-jet weights, including those of the jets associated to the leptons. More details can be found in the corresponding $t\bar{t}H$ documentation [120, 123].

6.4.2 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$ (cm)	✓	✓	✓
$ d_z < 0.1$ (cm)	✓	✓	✓
$\text{SIP}_{3D} < 8$	✓	✓	✓
$I_{\text{mini}} < 0.4$	✓	✓	✓
is Loose Muon	✓	✓	✓
jet CSV	—	< 0.8484	< 0.8484
is Medium Muon	—	—	✓
tight-charge	—	—	✓
lepMVA > 0.90	—	—	✓

Table 6.1: 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.

The lepton reconstruction and selection is identical to that used in the $t\bar{t}H$ multilepton analysis, as documented in Refs. [120, 123]. For details on the reconstruction algorithms, isolation, pileup mitigation, and a description of the lepton MVA discriminator and validation plots thereof, we refer to that document since they are out of the scope of this thesis. Three different selections are defined both for the electron and muon object identification: the *Loose*, *Fakeable Object*, and *Tight* selection. As described in more detail later, these are used for event level vetoes, the fake rate estimation application region, and the final signal selection, respectively. The p_T of fakeable objects is defined as $0.85 \times p_T(\text{jet})$, where the jet is the one associated to the

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 6.2: 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).

lepton object. This mitigates the dependence of the fake rate on the momentum of the fakeable object and thereby improves the precision of the method.

Tables 6.1 and 6.2 list the full criteria for the different selections of muons and electrons.

6.4.3 Lepton selection efficiency

Efficiencies of reconstruction and selecting loose leptons are measured both for muons and electrons using a tag and probe method on both data and MC, using $Z \rightarrow \ell^+\ell^-$. Corresponding scale factors are derived from the ratio of efficiencies and applied to the selected These. Events are produced for the leptonic SUSY analyses using equivalent

2243 lepton selections and recycled for the $t\bar{t}H$ analysis as well as for this analysis. The
 2244 efficiencies of applying the tight selection as defined in Tables 6.1 and 6.2, on the
 2245 loose leptons are determined again by using a tag and probe method on a sample of
 2246 DY-enriched events. They are documented for the $t\bar{t}H$ analysis in Ref. [123] and are
 2247 exactly equivalent for this analysis.

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2258 The analysis is designed to efficiently identify and select prompt leptons from
 2259 on-shell W and

2260 Z boson decays and to reject non-prompt leptons from b quark decays and spurious
 2261 lepton

2262 signatures from hadronic jets. Events are then selected in the various lepton
 2263 channels, and are

2264 required to contain hadronic jets, some of which must be consistent with b quark
 2265 hadronization. Finally, the signal yield is extracted by simultaneously fitting the
 2266 output of two dedicated

2267 multivariate discriminants (trained to separate the tHq signal from the two dom-
 2268 inant backgrounds) in all categories

2269 . Multivariate techniques are used to discriminate the signal from the dominant
 2270 backgrounds. The analysis yields a 95% confidence level (C.L.) upper limit on the
 2271 combined $tH + ttH$ production cross section times branching ratio of 0.64 pb, with
 2272 an expected limit of 0.32 pb, for a scenario with $kt = \sqrt{1.0}$ and $kV = 1.0$. Values
 2273 of kt outside the range of $\sqrt{1.25}$ to $\sqrt{1.60}$ are excluded at 95% C.L., assuming kV
 2274 $= 1.0$.

2275 Dont forget to mention previous constrains to ct check reference ?? and references
 2276 <https://link.springer.com/content/pdf/10.1007%2FJHEP01%282013%29088.pdf> (para-
 2277 graph after eq 2)

2278 We selects events with three leptons and a b tagged jet in the final state. The tHq
 2279 signal contribution is then determined in a fit of the observed data to two multivariate
 2280 classifier outputs, each trained to discriminate against one of the two dominant back-
 2281 grounds of events with non-prompt leptons from $t\bar{t}$ and of associated production of $t\bar{t}$
 2282 and vector bosons ($t\bar{t}W$, $t\bar{t}Z$). The fit result is then used to set an upper limit on the
 2283 combined $t\bar{t}H$, tHq and tHW production cross section, as a function of the relative
 2284 coupling strengths of Higgs and top quark and Higgs and W boson, respectively.

2285 6.5 Data and MC Samples

2286 The data considered in this analysis were collected by the CMS experiment dur-
 2287 ing 2016 and correspond to a total integrated luminosity of $35.9 fb^{-1}$. Only periods
 2288 when the CMS magnet was on were considered when selecting the data samples, that
 2289 corresponds to the 23 Sep 2016 (Run B to G) and PromptReco (Run H) versions
 2290 of the datasets. The MC samples used in this analysis correspond to the RunI-
 2291 ISummer16MiniAODv2 campaign produced with CMSSW 80X. The two signal sam-
 2292 ples (for tHq and tHW) were produced with MG5_aMC@NLO (version 5.222), in

2293 leading-order order mode, and are normalized to next-to-leading-order cross sections,
 2294 see Tab. 6.3. Each sample is generated with a set of event weights corresponding to
 2295 different values of κ_t and κ_V couplings as shown in Tab. 6.4.

2296 **6.5.1 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 6.3: Signal samples and their cross section and branching fraction used in this analysis. See Ref. [122] for more details.

2297 Different MC generators were used to generate the background processes. The
 2298 dominant sources ($t\bar{t}$, $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}H$) were produced using AMC@NLO interfaced
 2299 to PYTHIA8, and are scaled to NLO cross sections. Other processes are simulated
 2300 using POWHEG interfaced to PYTHIA, or bare PYTHIA (see table 6.5 and [120]
 2301 for more details).

2302 **6.5.2 Triggers**

2303 We consider online-reconstructed events triggered by one, two, or three leptons.
 2304 Single-lepton triggers are included to boost the acceptance of events where the p_T of
 2305 the sub-leading lepton falls below the threshold of the double-lepton triggers. Ad-
 2306 ditionally, by including double-lepton triggers in the ≥ 3 lepton category, as well
 2307 as single-lepton triggers in all categories, we increase the efficiency, considering the
 2308 logical “or” of the trigger decisions of all the individual triggers in a given category.
 2309 Tab. 6.7 shows the lowest-threshold non-prescaled triggers present in the High-Level
 2310 Trigger (HLT) menus for both Monte-Carlo and data in 2016.

		<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 6.4: 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. [122].

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_LO_NoMS_for76X/	0.2151 0.0283
WGToLNuG_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	585.8
ZGTo2LG_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	131.3
TGJets_TuneCUETP8M1_13TeV_amcatnlo_madspin_pythia8	2.967
TGJets_TuneCUETP8M1_13TeV_amcatnlo_madspin_pythia8	2.967
TTGJets_TuneCUETP8M1_13TeV-amcatnloFXFX-madspin-pythia8	3.697
WpWpJJ_EWK-QCD_TuneCUETP8M1_13TeV-madgraph-pythia8	0.03711
ZZZ_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.01398
WWZ_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.1651
WZZ_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.05565
WW_DoubleScattering_13TeV-pythia8	1.64
tZq_ll_4f_13TeV-amcatnlo-pythia8_TuneCUETP8M1	0.0758
ST_tWll_5f_LO_13TeV-MadGraph-pythia8	0.01123
TTTT_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.009103
WZTo3LNu_TuneCUETP8M1_13TeV-powheg-pythia8	4.4296
ZZTo4L_13TeV_powheg_pythia8	1.256
TTJets_SingleLeptFromTbar_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	182.1754
TTJets_SingleLeptFromT_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	182.1754
TTJets_DiLept_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	87.3
DYJetsToLL_M-10to50_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	18610
DYJetsToLL_M-50_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	6024
WJetsToLNu_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	61526.7
ST_tW_top_5f_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M1	35.6
ST_tW_antitop_5f_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M1	35.6
ST_t-channel_4f_leptonDecays_13TeV-amcatnlo-pythia8_TuneCUETP8M1	70.3144
ST_t-channel_antitop_4f_leptonDecays_13TeV-powheg-pythia8_TuneCUETP8M1	26.2278
ST_s-channel_4f_leptonDecays_13TeV-amcatnlo-pythia8_TuneCUETP8M1	3.68064
WWTo2L2Nu_13TeV-powheg	10.481

Table 6.5: 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 6.6: Leading-order $t\bar{t}W$ and $t\bar{t}Z$ samples used in the signal BDT training.

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

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

2311 6.5.2.1 Trigger efficiency scale factors

2312 The efficiency of events to pass the trigger is measured in simulation (trivially using
 2313 generator information) and in the data (using event collected by an uncorrelated
 2314 MET trigger). Small differences between the data and MC efficiencies are corrected
 2315 by applying scale factors as shown in Tab. 6.8. The exact procedure and control plots
 2316 are documented in [123] for the current analysis.

2317 6.6 Background predictions

2318 The modeling of reducible and irreducible backgrounds in this analysis uses the exact
2319 methods, analysis code, and ROOT trees used for the $t\bar{t}H$ multilepton analysis. We
2320 give a brief description of the methods and refer to the documentation of that analysis
2321 in Refs. [120, 123] for any details.

2322 The backgrounds in three-lepton final states can be split in two broad categories:
2323 irreducible backgrounds with genuine prompt leptons (i.e. from on-shell W and Z
2324 boson decays); and reducible backgrounds where at least one of the leptons is “non-
2325 prompt”, i.e. produced within a hadronic jet, either a genuine lepton from heavy
2326 flavor decays, or simply mis-reconstructed jets.

2327 Irreducible backgrounds can be reliably estimated directly from Monte-Carlo sim-
2328 ulated events, using higher-order cross sections or data control regions for the overall
2329 normalization. This is done in this analysis for all backgrounds involving prompt lep-
2330 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 ,
2331 ZZZ .

2332 Reducible backgrounds, on the other hand, are not well predicted by simulation,
2333 and are estimated using data-driven methods. In the case of non-prompt leptons, a
2334 fake rate method is used, where the contribution to the final selection is estimated by
2335 extrapolating from a sideband (or “application region”) with a looser lepton definition
2336 (the fakeable object definitions in Tabs. 6.1 and 6.2) to the signal selection. The tight-
2337 to-loose ratios (or “fake rates”) are measured in several background dominated data
2338 events with dedicated triggers, subtracting the residual prompt lepton contribution
2339 using MC. Non-prompt leptons in our signal regions are predominantly produced in $t\bar{t}$
2340 events, with a much smaller contribution, from Drell–Yan production. The systematic
2341 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 6.3 show the distributions of some relevant kinematic variables, normalized to the cross section of the respective processes and to the integrated luminosity.

6.7 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 6.9 lists the input variables used while Figures 6.4 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. 6.3), and LO MADGRAPH samples

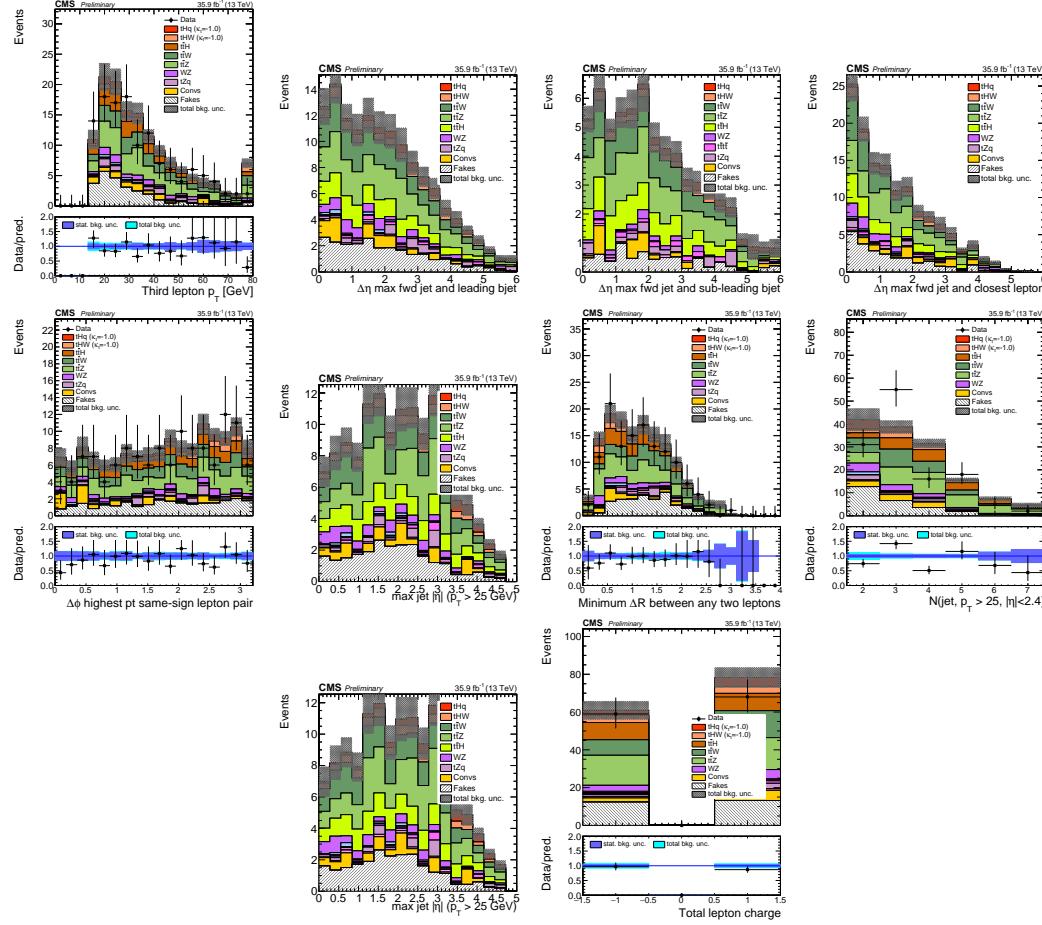


Figure 6.3: Distributions of input variables to the BDT for signal discrimination, three lepton channel, normalized to their cross section and to 35.9 fb^{-1} .

of $t\bar{t}W$ and $t\bar{t}Z$, in an admixture proportional to their respective cross sections (see Tab. 6.6).

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 6.5 show the input variables distributions as seen by the MVA algorithm. Note that in contrast to the distributions in Fig. 6.4 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 6.9: MVA input discriminating variables

2375 Note that splitting the training in two groups reveals that some variables show
 2376 opposite behavior for the two background sources; potentially screening the discrimi-
 2377 nation power if they were to be used in a single discriminant. For some other variables
 2378 the distributions are similar in both background cases.

2379 From table 6.9, it is clear that the input variables are correlated to some extend.
 2380 These correlations play an important role for some MVA methods like the Fisher
 2381 discriminant method in which the first step consist of performing a linear transfor-
 2382 mation to an phase space where the correlations between variables are removed. In
 2383 case a boosted decision tree (BDT) method however, correlations do not affect the
 2384 performance. Figure 6.7 show the linear correlation coefficients for signal and back-
 2385 ground for the two training cases (the signal values are identical by construction). As
 2386 expected, strong correlations appears for variables related to the forward jet activity.
 2387 Same trend is seen in case of the same sign dilepton channel in Figure ??.

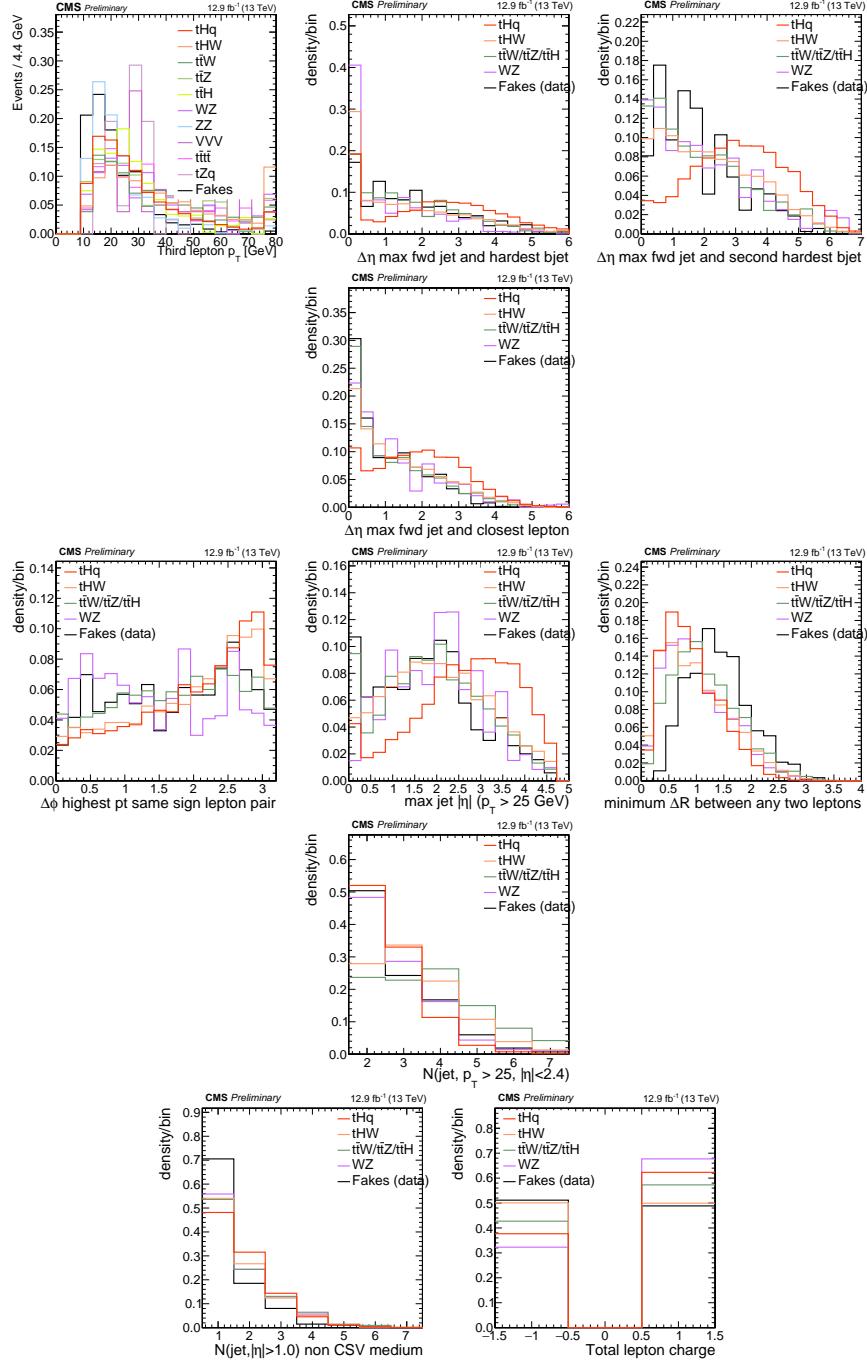


Figure 6.4: Distributions of input variables to the BDT for signal discrimination, three lepton channel.

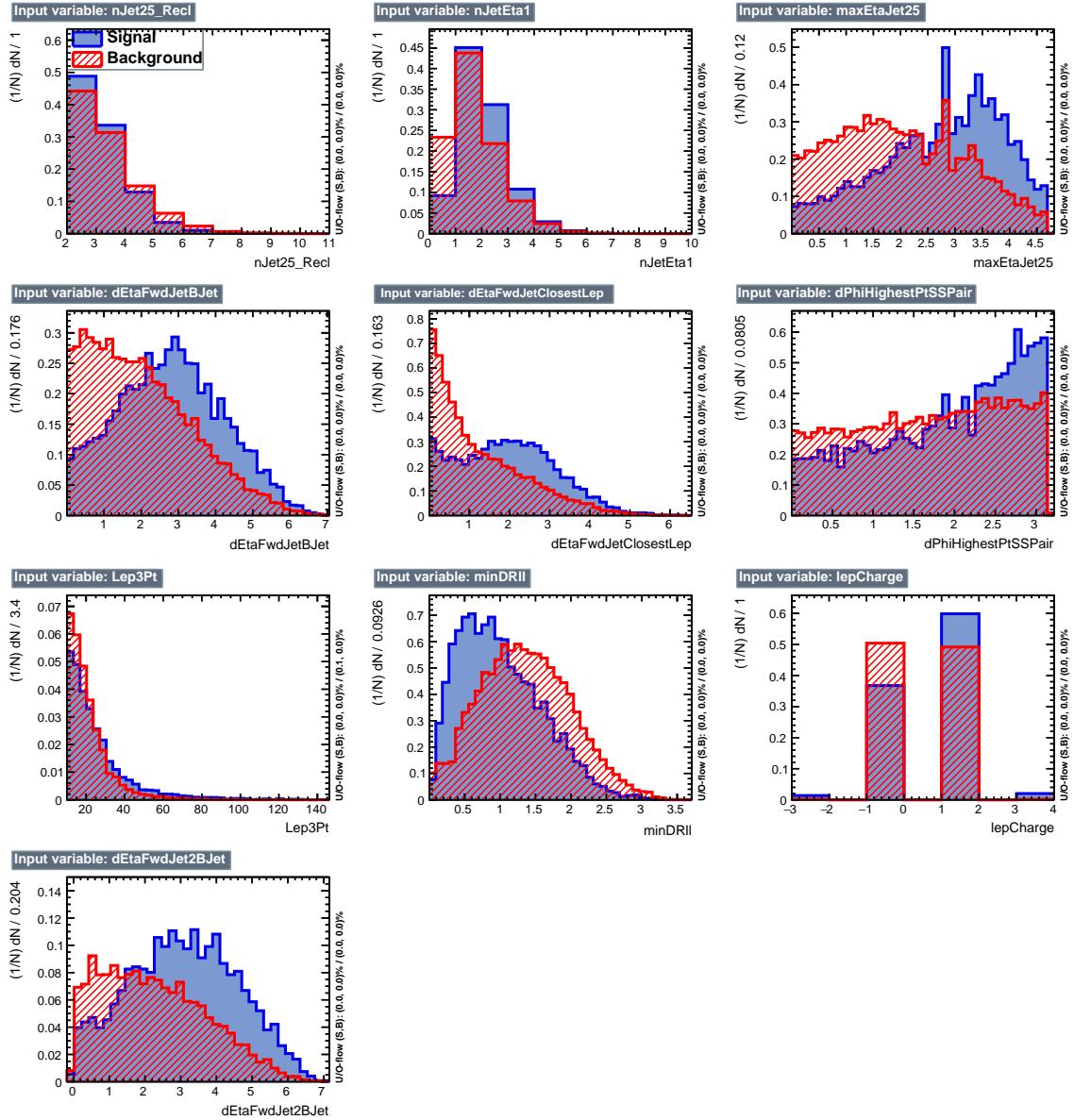


Figure 6.5: BDT inputs as seen by TMVA (signal, in blue, is tHq , background, in red, is $t\bar{t}$) for the three lepton channel, discriminated against $t\bar{t}$ (fakes) background.

2388 6.7.1 Classifiers response

2389 Several MVA algorithms were evaluated to determine the most appropriate method
 2390 for this analysis. The plots in Fig. 6.8 (top) show the background rejection as a
 2391 function of the signal efficiency for $t\bar{t}$ and $t\bar{t}V$ trainings (ROC curves) for the different

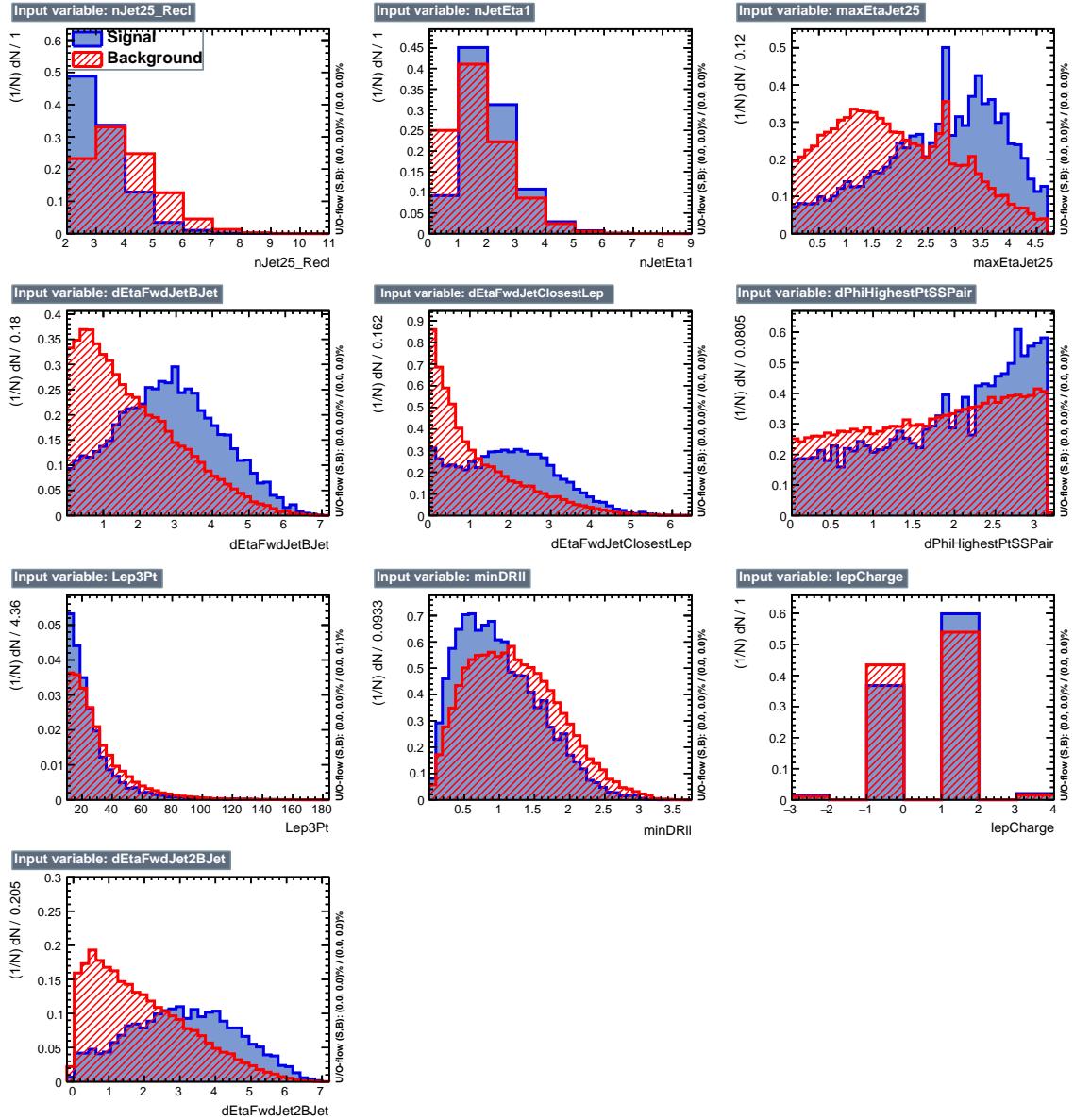


Figure 6.6: BDT inputs as seen by TMVA (signal, in blue, is tHq , background, in red, is $t\bar{t}W+t\bar{t}Z$) for the three lepton channel, discriminated against $t\bar{t}V$ background.

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. 6.8. As expected, a good discrimination power is obtained using default discrim-

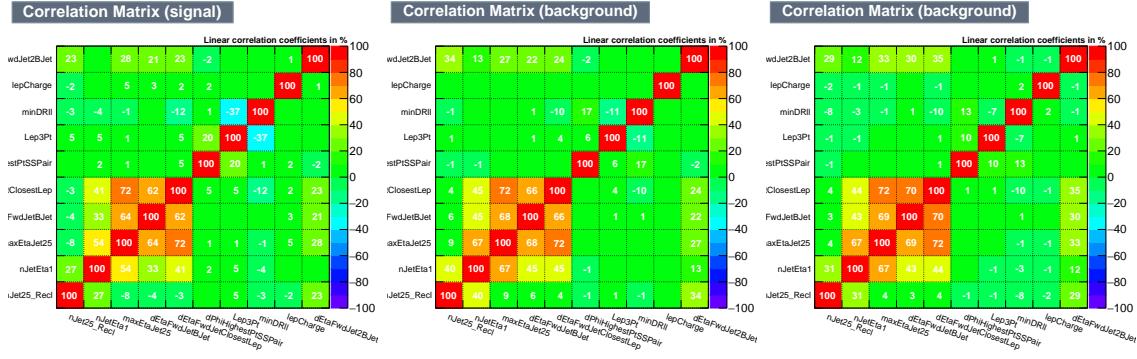


Figure 6.7: Signal (left), $t\bar{t}$ background (middle), and $t\bar{t}V$ background (right.) correlation matrices for the input variables in the TMVA analysis for the three lepton channel.

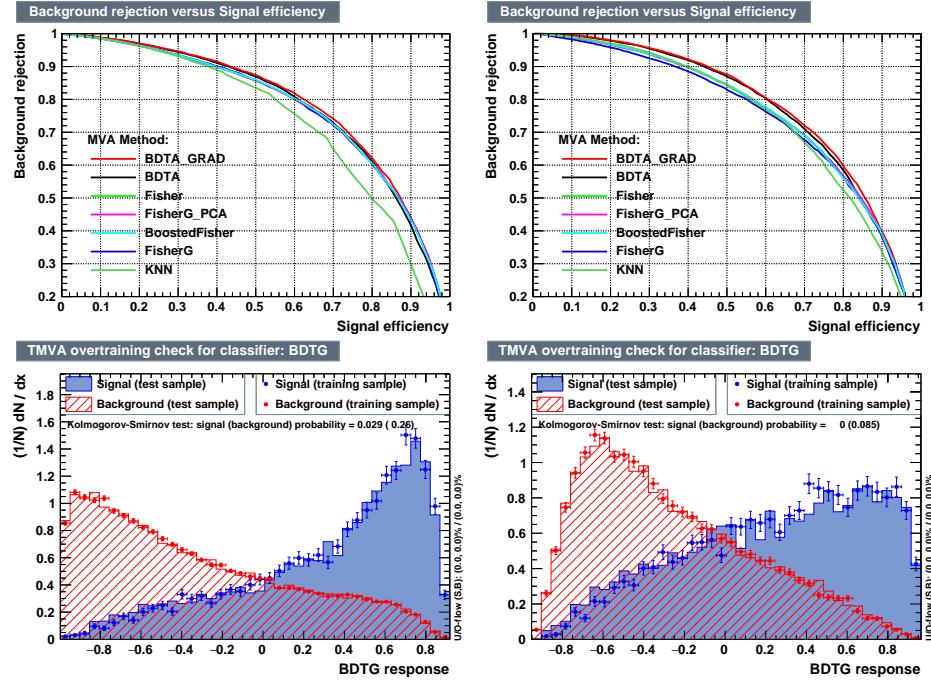


Figure 6.8: Top: background rejection vs signal efficiency (ROC curves) for various MVA classifiers (top) in the three lepton channel against $t\bar{t}V$ (left) and $t\bar{t}$ (right). Bottom: classifier output distributions for the gradient boosted decision trees, for training against $t\bar{t}V$ (left) and against $t\bar{t}$ (right).

2397 inator parameter values, with minimal overtraining. TMVA provides a ranking of the
 2398 input variables by their importance in the classification process, shown in Tab. 6.10.
 2399 The TMVA settings used in the BDT training are shown in Tab. 6.11.

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

Table 6.10: 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 6.11: TMVA configuration used in the BDT training.

2400 6.8 Additional discriminating variables

2401 Two additional discriminating variables were tested considering the fact that the
 2402 forward jet in the background could come from the pileup; since we have a real
 2403 forward jet in the signal, it could give some improvement in the discriminating power.
 2404 The additional variables describe the forward jet momentum (fwdJetPt25) and the
 2405 forward jet identification(fwdJetPUID). Distributions for these variables in the three
 2406 lepton channel are shown in the figure 6.9. The forward jet identification distribution
 2407 show that for both, signal and background, jets are mostly real jets.

2408 The testing was made including in the MVA input one variable at a time, so we

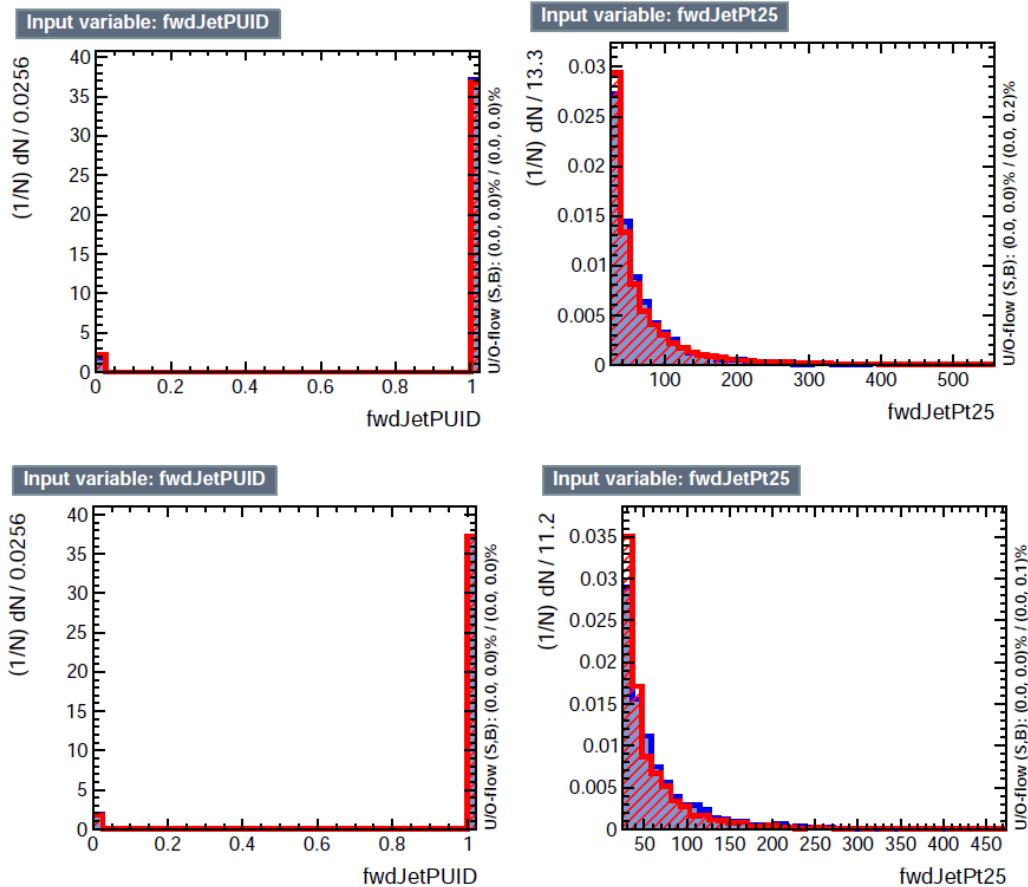


Figure 6.9: Additional discriminating variables distributions for ttV training (Top row) and tt training (bottom row) in the three lepton channel. The origin of the jets in the forward jet identification distribution is tagged as 0 for “pileup jets” while “real jets” are tagged as 1.

2409 can evaluate the discrimination power of each variable, and then both simultaneously.
 2410 fwdJetPUID was ranked in the last place in importance (11) in both training (ttV
 2411 and tt) while fwdJetPt25 was ranked 3 in the ttV training and 7 in the tt training.
 2412 When training using 12 variables, fwdJetPt25 was ranked 5 and 7 in the ttV and tt
 2413 trainings respectively, while fwdJetPUID was ranked 12 in both cases.

2414 The improvement in the discrimination performance provided by the additional
 2415 variables is about 1%, so it was decided not to include them in the procedure. Table
 2416 6.12 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 6.12: 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%

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