

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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20 Adviser: Kenneth Bloom and Aaron Dominguez

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¹⁹⁰ Chapter 1

¹⁹¹ INTRODUCTION

¹⁹² **Chapter 2**

¹⁹³ **Theoretical approach**

¹⁹⁴ **2.1 Introduction**

¹⁹⁵ The physical description of the universe is a challenge that physicists have faced by
¹⁹⁶ making theories that refine existing principles and proposing new ones in an attempt
¹⁹⁷ to embrace emerging facts and phenomena.

¹⁹⁸ At the end of 1940s Julian Schwinger [1] and Richard P. Feynman [2], based on
¹⁹⁹ the work of Sin-Itiro Tomonaga [3], developed an electromagnetic theory consistent
²⁰⁰ with special relativity and quantum mechanics that describes how matter and light
²⁰¹ interact; the so-called *quantum electrodynamics* (QED) was born.

²⁰² QED has become the guide in the development of theories that describe the uni-
²⁰³ verse. It was the first example of a quantum field theory (QFT), which is the theore-
²⁰⁴ tical framework for building quantum mechanical models that describes particles and
²⁰⁵ their interactions. QFT is composed of a set of mathematical tools that combines
²⁰⁶ classical fields, special relativity and quantum mechanics, while keeping the quantum
²⁰⁷ point particles and locality ideas.

²⁰⁸ This chapter gives an overview of the standard model of particle physics, starting

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

213 2.2 Standard model of particle physics

214 Particle physics at the fundamental level is modeled in terms of a collection of inter-
 215 acting particles and fields in a theory known as the *standard model of particle physics*
 216 (*SM*). The full picture of the SM is composed of three fields¹ whose excitations are
 217 interpreted as particles called mediators or force-carriers, a set of fields whose excita-
 218 tions are interpreted as elementary particles interacting through the exchange of those
 219 mediators, and a field that gives the mass to elementary particles. Figure 2.1 shows
 220 the scheme of the SM particles’ organization. In addition, for each of the particles
 221 in the scheme there exists an antiparticle with the same mass and opposite quantum
 222 numbers. The existence of antiparticles is a prediction of the relativistic quantum
 223 mechanics from the solution of the Dirac equation for which a negative energy solu-
 224 tion is also possible. In some cases a particle is its own anti-particle, like photon or
 225 Higgs boson.

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

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 [5, 6] is quite comprehensive and detailed. Note that gravitational field is not included in the standard model formulation

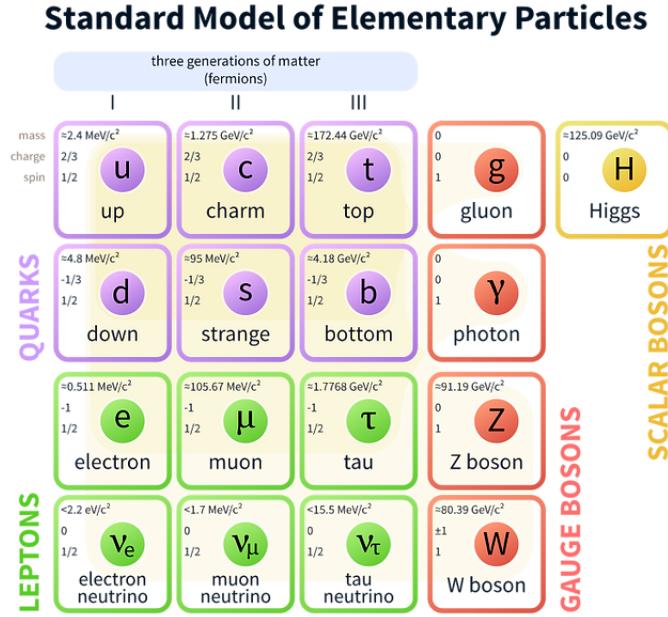


Figure 2.1: Schematic representation of the Standard Model of particle physics. The SM is a theoretical model intended to describe three of the four fundamental forces of the universe in terms of a set of particles and their interactions. [7].

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

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

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

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

245 **2.2.1 Fermions**

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

		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 each pair of particles is a member of an $SU(2)_L$ doublet that has an associated invariance under isospin transformations. WI between leptons is limited to the members of the same generation; WI between quarks is not limited but greatly favored, to same generation members.

251

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

258 physics, and it becomes more puzzling when noticing that the mass difference between
 259 first and second generation fermions is small compared to the mass difference with
 260 respect to the third generation.

Lepton	Mass (MeV/c 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 has been interpreted as a mass hierarchy. Approximate values with no uncertainties are used, for comparison purpose.

261

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

264 2.2.1.1 Leptons

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

272 Another feature of the leptons that is fundamental in the mathematical description
 273 of the SM is the chirality, which is closely related to spin and helicity. Helicity
 274 defines the handedness of a particle by relating its spin and momentum such that

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

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

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

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

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

² 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.

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

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

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

309

310 2.2.1.2 Quarks

311 Quarks are the basic constituents of protons and neutrons. The way quarks join to
 312 form bound states, called *hadrons*, is through the SI. Quarks are affected by all the

313 fundamental interactions which means that they carry all the four types of charges:
 314 color, electric charge, weak isospin and mass.

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

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

315

316 Table 2.4 summarizes the features of quarks, among which the most remarkable
 317 is their fractional electric charge. Note that fractional charge is not a problem, given
 318 that quarks are not found isolated, but serves to explain how composed particles are
 319 formed out of two or more valence quarks³.

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

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

³ 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.

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

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

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

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

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

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

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

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

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

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

356

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

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

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

359 The weak decays of quarks are represented in the diagram of Figure 2.2; again
360 the CKM matrix plays a central role since it contains the probabilities for the differ-

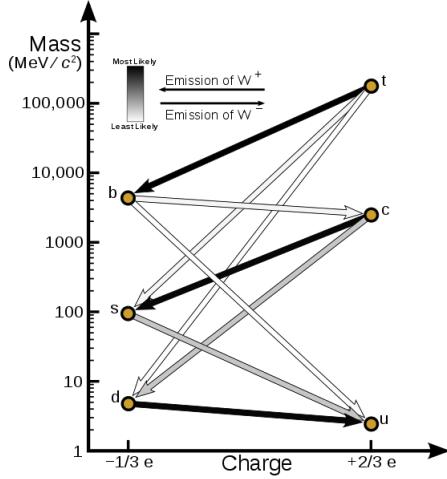


Figure 2.2: Transformations between quarks through the exchange of a WI. Higher generations quarks decay to first generation quarks by emitting a W boson. The arrow color indicates the likelihood of the transition according to the grey scale in the top left side which represent the CKM matrix parameters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

361 ent quark decay channels, in particular, note that quark decays are greatly favored
 362 between generation members.

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

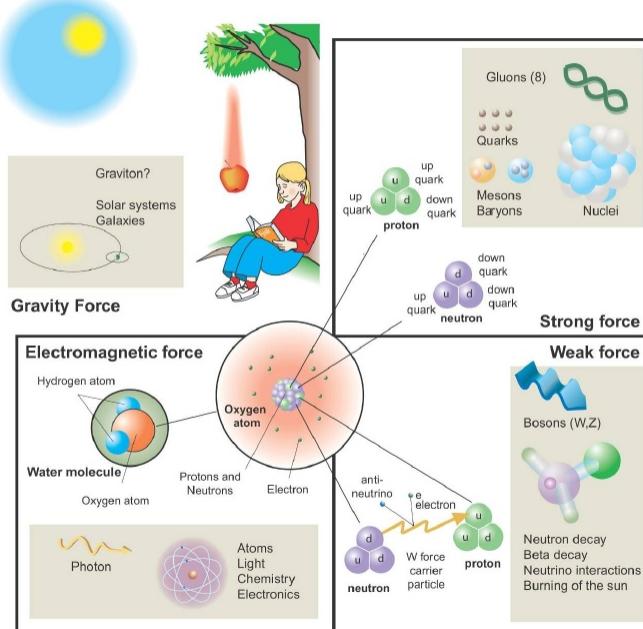
369 2.2.2 Fundamental interactions

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

372 • *Electromagnetic interaction (EI)* affects particles that are *electrically charged*,
 373 like electrons and protons. Figure 2.4a. shows a graphical representation, known

Fundamental interactions.

Illustration: Typoform



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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 as *Feynman diagram*, of electron-electron scattering.

- 375 • *Strong interaction (SI)* described by Quantum Chromodynamics (QCD). Hadrons
 376 like the proton and the neutron have internal structure given that they are com-
 377 posed of two or more valence quarks⁴. Quarks have fractional electric charge
 378 which means that they are subject to electromagnetic interaction and in the case
 379 of the proton they should break apart due to electrostatic repulsion; however,
 380 quarks are held together inside the hadrons against their electrostatic repulsion
 381 by the *Strong Force* through the exchange of *gluons*. The analog to the electric
 382 charge is the *color charge*. Electrons and photons are elementary particles as

⁴ Particles made of four and five quarks are exotic states not so common.

383 quarks but they don't carry color charge, therefore they are not subject to SI. A
 384 Feynman diagram for gluon exchange between quarks is shown in Figure 2.4b.

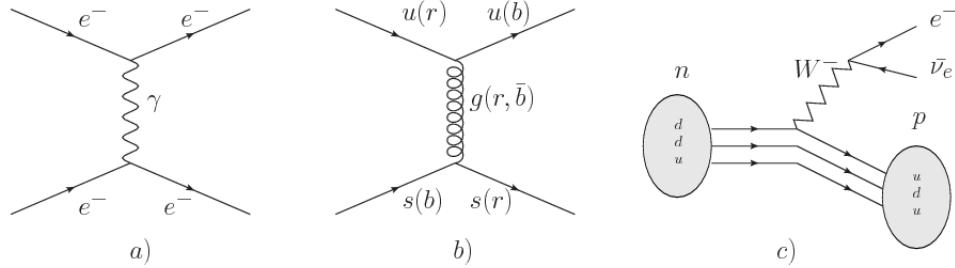


Figure 2.4: Feynman diagrams representing the interactions in SM; a) EI: e - e scattering; b) SI: gluon exchange between quarks ; c) WI: β -decay

385 • *Weak interaction (WI)* described by the weak theory (WT), is responsible, for
 386 instance, for the radioactive decay in atoms and the deuterium production
 387 within the sun. Quarks and leptons are the particles affected by the weak
 388 interaction; they possess a property called *flavor charge* (see 2.2.1) which can
 389 be changed by emitting or absorbing one weak force mediator. There are three
 390 mediators of the *weak force* known as Z boson in the case of electrically neutral
 391 flavor changes and W^\pm bosons in the case of electrically charged flavor changes.
 392 The *weak isospin* is the WI analog to electric charge in EI, and color charge in
 393 SI, and defines how quarks and leptons are affected by the weak force. Figure
 394 2.4c. shows the Feynman diagram of β -decay where a neutron (n) is transformed
 395 in a proton (p) by emitting a W^- particle.

396 • *Gravitational interaction (GI)* described by General Theory of Relativity (GR).
 397 It is responsible for the structure of galaxies and black holes as well as the
 398 expansion of the universe. As a classical theory, in the sense that it can be
 399 formulated without even appeal to the concept of quantization, it implies that
 400 the space-time is a continuum and predictions can be made without limitation

401 to the precision of the measurement tools. The latter represents a direct con-
 402 tradiction of the quantum mechanics principles. Gravity is deterministic while
 403 quantum mechanics is probabilistic; despite that, efforts to develop a quantum
 404 theory of gravity have predicted the *graviton* as mediator of the gravitational
 405 force⁵.

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].

406

407 Table 2.6 summarizes the main features of the fundamental interactions. The
 408 relative strength of the fundamental forces reveals the meaning of strong and weak;
 409 in a context where the relative strength of the SI is 1, the EI is about hundred times
 410 weaker and WI is about million times weaker than the SI. A good description on how
 411 the relative strength and range of the fundamental interactions are calculated can
 412 be found in References [20, 21]. In the everyday life, only EI and GI are explicitly
 413 experienced due to the range of these interactions; i.e., at the human scale distances
 414 only EI and GI have appreciable effects, in contrast to SI which at distances greater
 415 than 10^{-15} m become negligible.

416 2.2.3 Gauge invariance.

417 QED was built successfully on the basis of the classical electrodynamics theory (CED)
 418 of Maxwell and Lorentz, following theoretical and experimental requirements imposed

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

419 by

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

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

438 When the gauge transformation:

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

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

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

451 As will be detailed in Section 2.3, interactions between particles in a system can
 452 be obtained by considering first the Lagrangian density of free particles in the sys-
 453 tem, which of course is incomplete because the interaction terms have been left out,
 454 and demanding global phase transformation invariance. Global phase transforma-
 455 tion means that a gauge transformation is performed identically to every point
 456 in the space⁶ and the Lagrangian remains invariant. Then, the global transforma-
 457 tion is promoted to a local phase transformation (this time the gauge transformation
 458 depends on the position in space) and again invariance is required.

⁶ Here space corresponds to the 4-dimensional space i.e. space-time.

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

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

468 2.2.4 Gauge bosons

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

- 477 • **Photon.** EI occurs when the photon couples to (is exchanged between) parti-
 478 cles carrying electric charge; however, The photon itself does not carry electric
 479 charge, therefore, there is no coupling between photons. Given that the photon
 480 is massless the EI is of infinite range, i.e., electrically charged particles interact
 481 even if they are located far away one from each other; this also implies that
 482 photons always move with the speed of light.

- 483 • **Gluon.** SI is mediated by gluons which just as photons are massless. They
 484 carry one unit of color charge and one unit of anticolor charge, hence, gluons
 485 can couple to other gluons. As a result, the range of the SI is not infinite
 486 but very short due to the attraction between gluons, giving rise to the *color*
 487 *confinement* which explains why color charged particles cannot be isolated but
 488 live within composite particles, like quarks inside protons.
- 489 • **W, Z.** W^\pm and Z, are massive which explains their short-range. Given that
 490 the WI is the only interaction that can change the flavor of the interacting
 491 particles, the W boson is the responsible for the nuclear transmutation where
 492 a neutron is converted into a proton or vice versa with the involvement of an
 493 electron and a neutrino (see Figure 2.4c). The Z boson is the responsible for the
 494 neutral weak processes like neutrino elastic scattering where no electric charge
 495 but momentum transference is involved. WI gauge bosons carry isospin charge
 496 which makes interaction between them possible.

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

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

497

498 **2.3 Electroweak unification and the Higgs 499 mechanism**

500 Physicists dream of building a theory that contains all the interactions in one single
 501 interaction, i.e., showing that at some scale in energy all the four fundamental inter-

actions are unified and only one interaction emerges in a *Theory of everything*. The first sign of the feasibility of such unification came from success in the construction of the CED. Einstein spent years trying to reach that full unification, which by 1920 only involved electromagnetism and gravity, with no success; however, a new partial unification was achieved in the 1960's, when S.Glashow [22], A.Salam [23] and S.Weinberg [24] independently proposed that electromagnetic and weak interactions are two manifestations of a more general interaction called *electroweak interaction* (EWI). EWI was developed by following the useful prescription provided by QED and the gauge invariance principles.

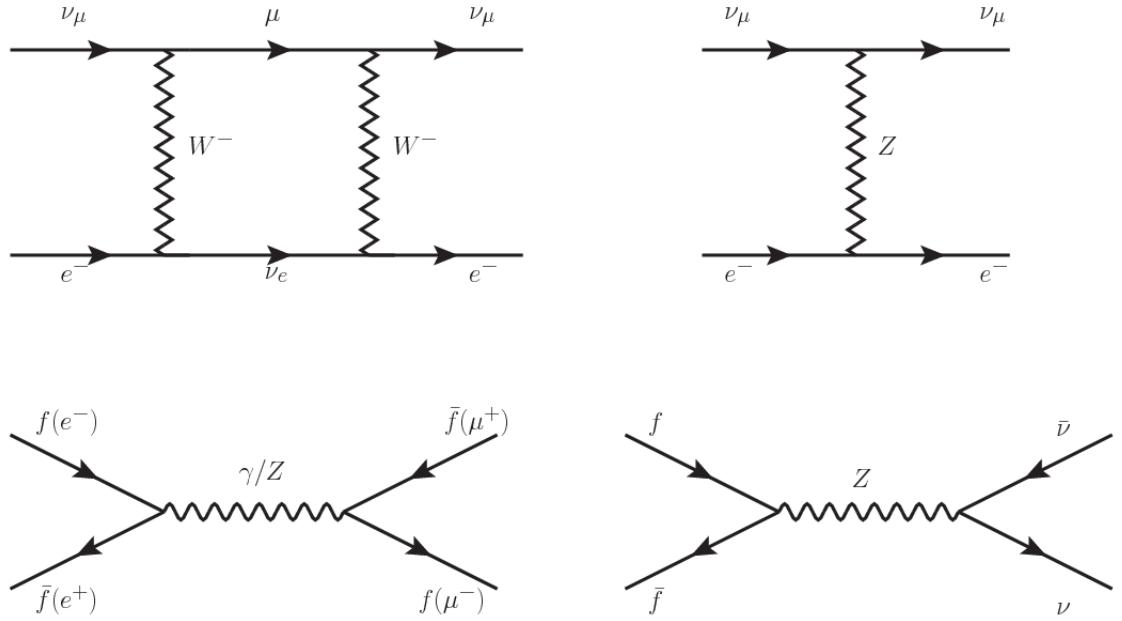


Figure 2.5: Top: $\nu_\mu - e^-$ scattering going through charged currents (left) and neutral currents (right). Bottom: neutral current processes for charged fermions (left) and involving neutrinos (right). While neutral current processes involving only charged fermions can proceed through EI or WI,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

The *classic* weak theory developed by Fermi, did not have the concept of the W boson but instead it was treated as a point interaction with the dimensionful constant G_F associated with it. It works really well at low energies very far off the W mass

shell. When going up in energy, the theory of weak interactions involving the W boson is capable of explaining the β -decay and in general the processes mediated by W^\pm bosons. However, there were some processes like the $\nu_\mu - e$ scattering which would require the exchange of two W bosons (see Figure 2.5 top diagrams) giving rise to divergent loop integrals and then non-finite predictions. The EWI theory, by including neutral currents involving fermions via the exchange of a neutral bosons Z, overcomes those divergences and the predictions become realistic.

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

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

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

The following treatment applies to any of the fermion generations, but for sim-

537 plicity the first generation of leptons will be considered [5, 6, 25, 26].

538 Given the first generation of leptons

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

539 the charged fermionic currents are given by

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

540 and the free Lagrangian is given by

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

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

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

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

546 Experiments have shown that the EWI gauge fields are not massless [27–30];
 547 however, they have to acquire mass through a mechanism compatible with the gauge
 548 invariance; that mechanism is known as the *Higgs mechanism* and will be considered
 549 later in this Section. The global transformations in the combined symmetry group G
 550 can be written as

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

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

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

554 with σ_i the Pauli matrices and y_i the weak hypercharges. In order to promote the
 555 transformations from global to local while keeping the invariance, it is required that
 556 $\alpha^i = \alpha^i(x)$, $\beta = \beta(x)$ and the replacement of the ordinary derivatives by the covariant
 557 derivatives

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

579 The same happens with the gauge fields W_μ^i which are related to the mass eigen-
 580 states W^\pm by

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

581 The fact that there are three weak isospin conserved currents is an indication that
 582 in addition to the charged fermionic currents, which couple charged to neutral leptons,
 583 there should be a neutral fermionic current that does not involve electric charge
 584 exchange; therefore, it couples neutral fermions or fermions of the same electric charge.
 585 The third weak isospin current contains a term that is similar to the electromagnetic

586 current (j_μ^{em}), indicating that there is a relation between them and resembling the
 587 Gell-Mann-Nishijima formula 2.2 adapted to electroweak interactions

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

588 Just as Q generates the $U(1)_{em}$ symmetry, the weak hypercharge generates the
 589 $U(1)_Y$ symmetry as said before. It is possible to write the relationship in terms of
 590 the currents as

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

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

$$\begin{aligned} A_\mu &= B_\mu \cos \theta_W + W_\mu^3 \sin \theta_W \\ Z_\mu &= -B_\mu \sin \theta_W + W_\mu^3 \cos \theta_W \end{aligned} \quad (2.26)$$

where θ_W is known as the *Weinberg angle*. The interaction Lagrangian is now given by

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

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

595 electromagnetic interaction under the condition

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

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

597

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

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

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

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

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

606 2.3.1 Spontaneous symmetry breaking (SSB)

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

609 Before reaching the critical force value, the system has rotational symmetry with
 610 respect to the nail axis; however, after the critical force value is reached the nail buck-

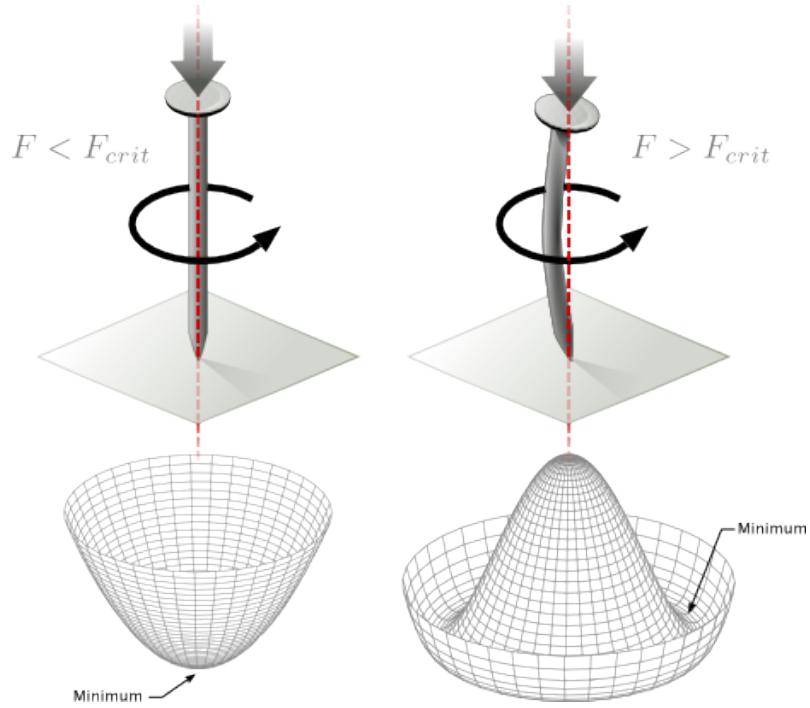


Figure 2.6: Spontaneous symmetry breaking mechanism. The steel nail, subject to an external force (top left), has rotational symmetry with respect to its axis. When the external force overcomes a critical value the nail buckles (top right) choosing a minimal energy state (ground state) and thus *breaking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

611 les (top right). The form of the potential energy (bottom right) changes appearing a
 612 set of infinity minima but preserving its rotational symmetry. Right before the nail
 613 buckles there is no indication of the direction the nail will bend because any of the
 614 directions are equivalent, but once the nail bends, choosing a direction, an arbitrary
 615 minimal energy state (ground state) is selected and it does not share the system's
 616 rotational symmetry. This mechanism for reaching an asymmetric ground state is
 617 known as *spontaneous symmetry breaking*.

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

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

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

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

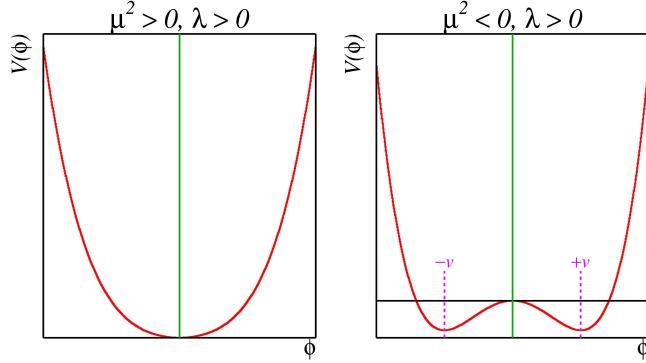


Figure 2.7: Shape of the potential $V(\phi)$ for $\lambda > 0$ and: $\mu^2 > 0$ (left) and $\mu^2 < 0$ (right). The case $\mu^2 < 0$ corresponds to the potential suitable for introducing the SSB mechanism by choosing one of the two ground states which are connected via reflection symmetry. [31].

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

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

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

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

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

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

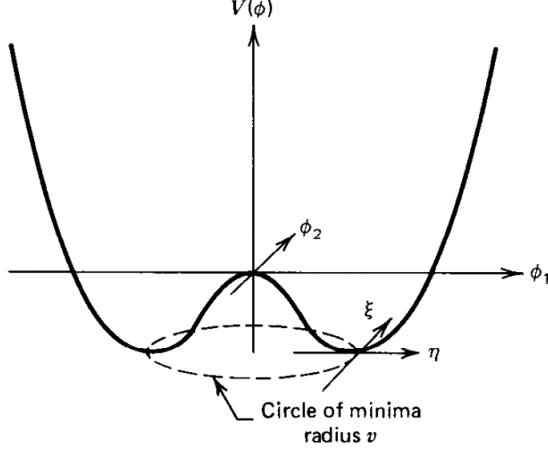


Figure 2.8: Potential for complex scalar field. There is a circle of minima of radius v along the ξ -direction [6].

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

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

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

632 which when substituted into Eqn. 2.33 produces a Lagrangian in terms of the new
633 fields η and ξ

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

634 where the last two terms represent the interactions and self-interaction between the
635 two fields η and ξ . The particular feature of the SSB mechanism is revealed when
636 looking to the first three terms of \mathcal{L}' . Before the SSB, only the massless ϕ field is

637 present in the system; after the SSB there are two fields of which the η -field has
 638 acquired mass $m_\eta = \sqrt{-2\mu^2}$ while the ξ -field is still massless (see Figure 2.9).

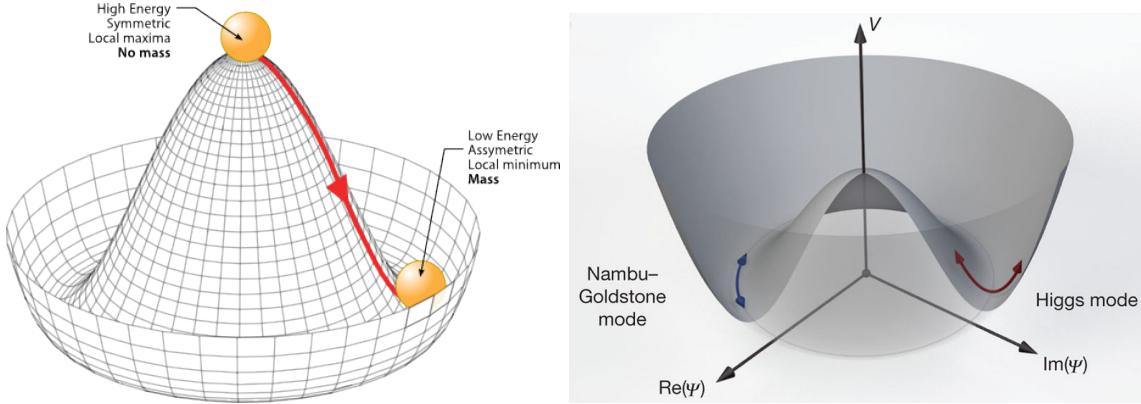


Figure 2.9: SSB mechanism for a complex scalar field [31, 32].

639 Thus, the SSB mechanism serves as a method to generate mass but as a side ef-
 640 fect a massless field is introduced in the system. This fact is known as the Goldstone
 641 theorem and states that a massless scalar field appears in the system for each con-
 642 tinuous symmetry spontaneously broken. Another version of the Goldstone theorem
 643 states that “if a Lagrangian is invariant under a continuous symmetry group G , but
 644 the vacuum is only invariant under a subgroup $H \subset G$, then there must exist as many
 645 massless spin-0 particles (Nambu-Goldstone bosons) as broken generators.” [26] The
 646 Nambu-Goldstone boson can be understood considering that the potential in the ξ -
 647 direction is flat so excitations in that direction are not energy consuming and thus
 648 represent a massless state.

649 2.3.2 Higgs mechanism

650 When the SSB mechanism is introduced in the formulation of the EWI in an attempt
 651 to generate the mass of the so far massless gauge bosons and fermions, an interesting
 652 effect is revealed. In order to keep the G symmetry group invariance and generate

653 the mass of the EW gauge bosons, a G invariant Lagrangian density (\mathcal{L}_S) has to be
 654 added to the non massive EWI Lagrangian (Eqn. 2.30)

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

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

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

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

657 The minima of the potential are defined by

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

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

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

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

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

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

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

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

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

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

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

686 **2.3.3 Masses of the gauge bosons**

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

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

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

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

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

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

690 and then

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

691 **2.3.4 Masses of the fermions**

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

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

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

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

696

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

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

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

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

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

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

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

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

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

708 2.3.5 The Higgs field

709 After the characterization of the fermions and gauge bosons as well as their interac-
710 tions, it is necessary to characterize the Higgs field itself. The Lagrangian \mathcal{L}_S in Eqn.
711 2.37 written in terms of the gauge bosons is given by

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

712

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

713

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

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

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

716 however, it is not predicted by the theory either. The experimental efforts to find the
717 Higgs boson, carried out by the *Compact Muon Solenoid (CMS)* experiment and the *A*
718 *Toroidal LHC Appartus (ATLAS)* experiments at the *Large Hadron Collider (LHC)*,
719 gave great results by July of 2012 when the discovery of a new particle compatible
720 with the Higgs boson predicted by the electroweak theory [36, 37] was announced.
721 Although at the announcement time there were some reservations about calling the
722 new particle the *Higgs boson*, today this name is widely accepted. The Higgs mass

723 measurement, reported by both experiments [38], is in Table 2.8.

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

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

724

725 2.3.6 Production of Higgs bosons at LHC

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

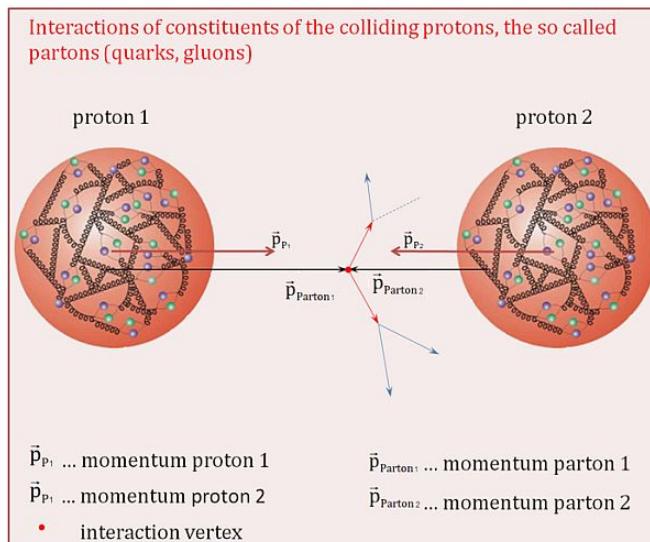


Figure 2.10: Proton-proton collision. Protons are composed of 3 valence quarks, a sea of quarks and gluons; therefore in a proton-proton collision, quarks and gluons are those who collide. [39].

728

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

735 In a proton-proton (pp) collision, the proton's constituents, quarks and gluons, are
736 those that collide. The pp cross section depends on the momentum of the colliding
737 particles, reason for which it is needed to know how the momentum is distributed
738 inside the proton. Quarks and gluons are known as partons, hence, the functions that
739 describe how the proton momentum is distributed among partons inside it are called
740 *parton distribution functions (PDFs)*; PDFs are determined from experimental data
741 obtained in experiments where the internal structure of hadrons is tested.

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

752 High energy systems, like the Higgs production at LHC explored in this thesis,
753 usually can be treated perturbatively with the expansion made in terms of the cou-
754 pling constants. The overview presented here will be oriented specifically to the Higgs

755 boson production mechanisms in pp collisions at LHC.

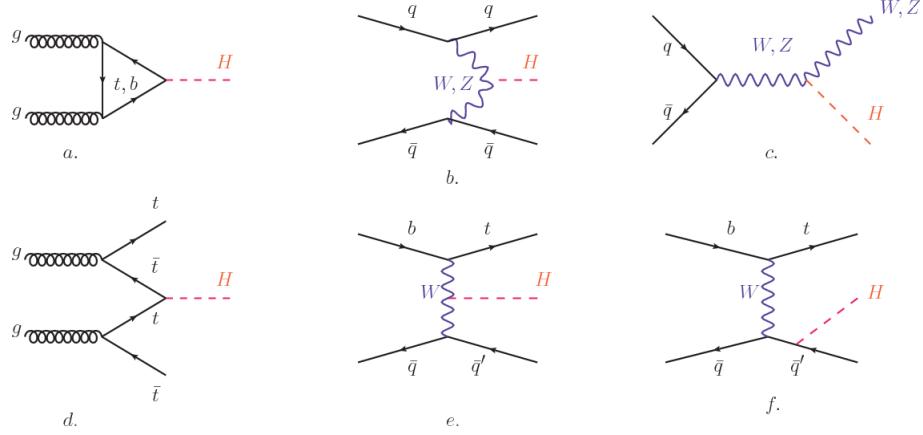


Figure 2.11: Main Higgs boson production mechanism Feynman diagrams. a. gluon-gluon fusion, b. vector boson fusion (VBF), c. Higgs-strahlung, d. Associated production with a top or bottom quark pair, e-f. associated production with a single top quark.

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

763 The main production mechanism is the gluon fusion (Figure 2.11a and $pp \rightarrow H$ in
 764 Figure 2.12) given that gluons carry the highest fraction of momentum of the protons
 765 in pp colliders. Since the Higgs boson does not couple to gluons, the mechanism
 766 proceeds through the exchange of a virtual top-quark loop. Note that in this process
 767 the Higgs boson is produced alone, turning out to be problematic for some Higgs
 768 decays, because such absence of anything produced in association with the Higgs
 769 represent a trouble for triggering, however, this mechanism is experimentally clean
 770 when combined with the two-photon or the four-lepton decay channels (see Section

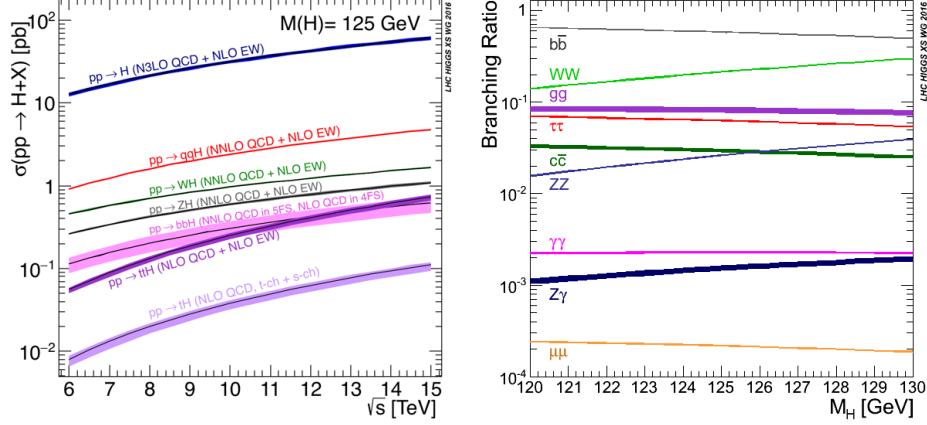


Figure 2.12: Higgs boson production cross sections (left) and decay branching ratios (right) for the main mechanisms. The VBF is indicated as qqH [40].

771 2.3.7).

772 Vector boson fusion (Figure 2.11b and $pp \rightarrow qqH$ in Figure 2.12) has the second
 773 largest production cross section. The scattering of two fermions is mediated by a weak
 774 gauge boson which later emits a Higgs boson. In the final state, the two fermions tend
 775 to be located in the central region of the detector; this kind of features are generally
 776 used as a signature when analyzing the datasets provided by the experiments⁷.

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

780 The associated production with a top or bottom quark pair and the associated
 781 production with a single top quark (Figure 2.11d-f and $pp \rightarrow bbH, pp \rightarrow t\bar{t}H, pp \rightarrow tH$
 782 in Figure 2.12) have a smaller cross section than the main three mechanisms above,
 783 but they provide a good opportunity to test the Higgs-top coupling. The analysis
 784 reported in this thesis is developed using these production mechanisms. A detailed
 785 description of the tH mechanism will be given in Section 2.5.

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

786 **2.3.7 Higgs boson decay channels**

787 When a particle can decay through several modes, also known as channels, the prob-
 788 ability of decaying through a given channel is quantified by the *branching ratio (BR)*
 789 of the decay channel; thus, the BR is defined as the ratio of number of decays go-
 790 ing through that given channel to the total number of decays. In regard to the
 791 Higgs boson decay, the BR can be predicted with accuracy once the Higgs mass is
 792 known [41,42]. In Figure 2.12 right, a plot of the BR as a function of the Higgs mass
 793 is presented; the largest predicted BR corresponds to the $b\bar{b}$ pair decay channel (see
 794 Table 2.9) given that it is the heaviest particle pair whose on-shell⁸ production is
 795 kinematically allowed in the decay.

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

796

797 Decays to other lepton and quark pairs, like electron, strange, up, and down
 798 quark pairs not listed in the table, are also possible but their likelihood is too small

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

799 to measure since they are very lightweight, hence, their interaction with the Higgs
 800 boson is very weak. On other hand, the decay to top quark pairs is heavily suppressed
 801 due to the top quark mass ($\approx 173 \text{ GeV}/c^2$).

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

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

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

813 **2.4 Experimental status of the anomalous**

814 **Higgs-fermion coupling**

815 ATLAS and CMS have performed analyses of the anomalous H-f coupling by making
 816 likelihood scans for the two coupling modifiers, κ_t and κ_V , under the assumption
 817 that $\kappa_Z = \kappa_W \equiv \kappa_V$ and $\kappa_t = \kappa_\tau = \kappa_b \equiv \kappa_f$. Figure 2.13 shows the result of the
 818 combination of ATLAS and CMS fits; also the individual decay channels combination
 819 and the global combination results are shown. Note that from this plot there is limited
 820 information on the sign of the coupling since the only information available about the
 821 sign of the coupling comes from decays rather than production.

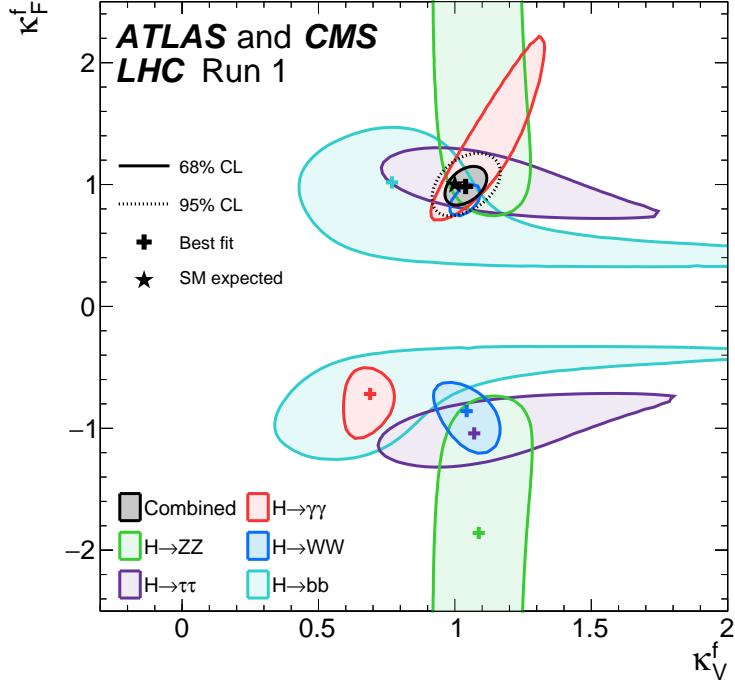


Figure 2.13: Combination of the ATLAS and CMS fits for coupling modifiers $\kappa_t - \kappa_V$; also shown the individual decay channels combination and their global combination. No assumptions have been made on the sign of the coupling modifiers [58].

822 While all the channels are compatible for positive values of the modifiers, for neg-
 823 ative values of κ_t there is no compatibility. The best fit for individual channels is
 824 compatible with negative values of κ_t except for the $H \rightarrow bb$ channel. The best fit
 825 for the global fit yields $\kappa_t \geq 0$ in contrast to the yields from the individual channels;
 826 the reason of this resides in the $H \rightarrow \gamma\gamma$ coupling parameter. $H \rightarrow \gamma\gamma$ decay proceeds
 827 through a loop of either top quarks or W bosons, hence, this channel is sensitive to κ_t
 828 due to the interference of these two amplitude contributions. Under the assumption
 829 that no beyond SM particles take part in the loops, a flipped sign of κ_t will increase
 830 the $H \rightarrow \gamma\gamma$ branching fraction by a factor of ~ 2.4 which is not supported by mea-
 831 surements; thus, this large asymmetry between the positive and negative coupling
 832 ratios in the $H \rightarrow \gamma\gamma$ channel drives the yield of the global fit. Nevertheless, since the

833 $H \rightarrow bb$ channel is expected to be the most sensitive channel and its best fit value of
 834 κ_t is positive, the global fit is well supported as shown in Reference [58].

835 Although the contributions from all the other decay channels are small compared
 836 to the $H \rightarrow bb$ the anomalous H-t coupling cannot be excluded completely, thus, that
 837 motivates to look at tH processes, which can help with both, the limited information
 838 on the sign of the H-t coupling and the access to information from the Higgs boson
 839 production rather than from its decays.

840 **2.5 Associated production of a Higgs boson and a 841 single top quark**

842 The production of Higgs boson in association with a top quark has been extensively
 843 studied [44–48]. While measurements of the main Higgs production mechanisms rates
 844 are sensitive to the strength of the Higgs coupling to W boson or top quark, they are
 845 not sensitive to the relative sign between the two couplings. In this thesis, the Higgs
 846 boson production mechanism explored is the associated production with a single top
 847 quark (tH) which offers sensitivity to the relative sign of the Higgs couplings to W
 848 boson and to top quark. The description given here is based on Reference [46]

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

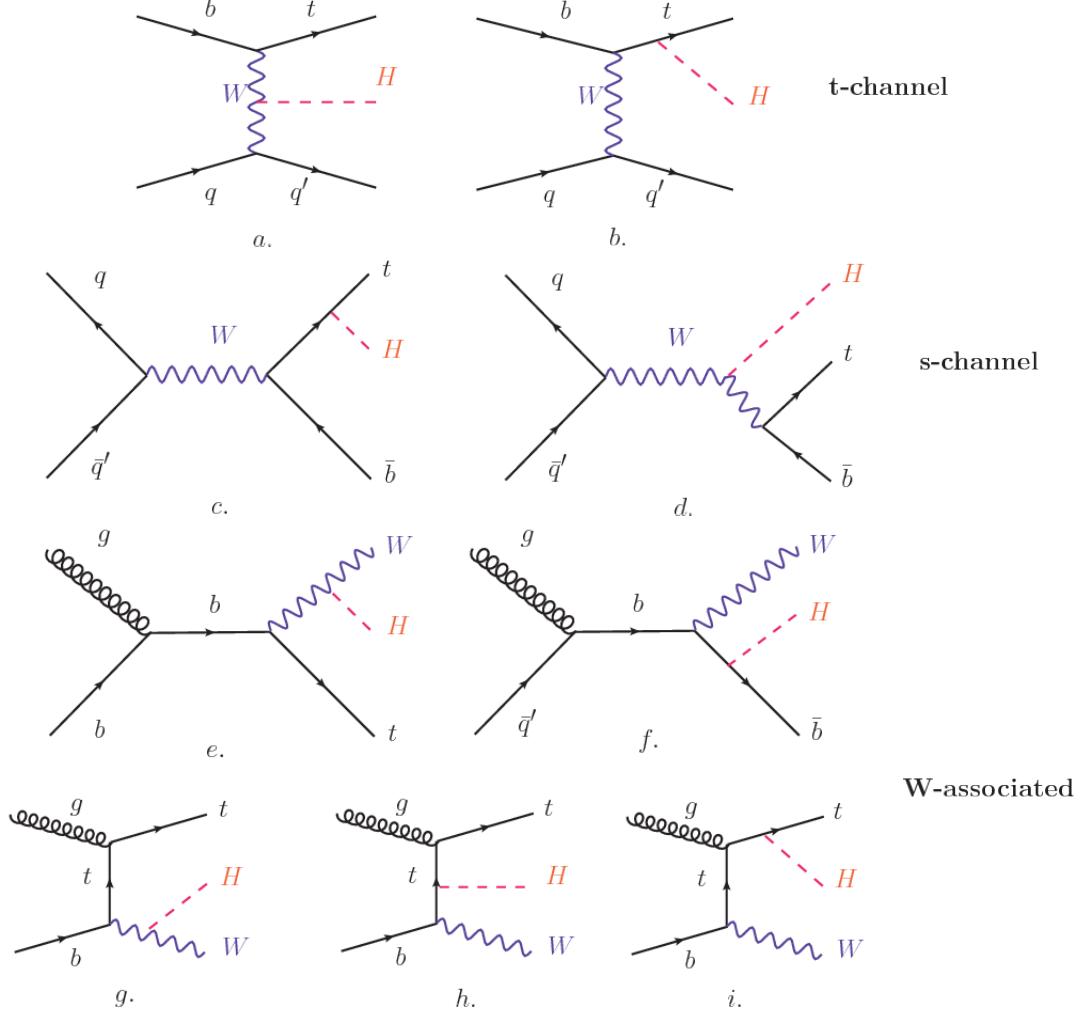


Figure 2.14: Associated Higgs boson production with a top quark mechanism Feynman diagrams. a.,b. t-channel (tHq), c.,d. s-channel (tHb), e-i. W-associated.

roles. These three channels are connected to the so-called Mandelstam variables

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

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

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

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

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

854 The tH production, where Higgs boson can be radiated either from the top quark or
 855 from the W boson, is represented by the leading order Feynman diagrams in Figure
 856 2.14. The cross section for the tH process is calculated, as usual, summing over
 857 the contributions from the different Feynman diagrams; therefore it depends on the
 858 interference between the contributions. In the SM, the interference for t-channel (tHq
 859 process) and W-associated (tHW process) production is destructive [44] resulting in
 860 the small cross sections presented in Table 2.10.

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

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

861

862 The s-channel contribution can be neglected. It will be shown that a deviation
 863 from the SM destructive interference would result in an enhancement of the tH cross
 864 section compared to that in SM, which could be used to get information about the
 865 sign of the Higgs-top coupling [46, 47]. In order to describe tH production processes,
 866 Feynman diagram 2.14b will be considered; there, the W boson is radiated by a quark
 867 in the proton and eventually it will interact with the b quark. In the high energy
 868 regime, the effective W approximation [51] is used to describe the process as the

869 emission of an approximately on-shell W and its hard scattering with the b quark;
 870 i.e. $Wb \rightarrow th$. The scattering amplitude for the process is given by

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

871 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 quantify
 872 possible deviations of the couplings from the SM values, Higgs-Vector boson (H-
 873 W) and Higgs-top (H-t) respectively, from the SM couplings; $s = (p_W + p_b)^2$, $t =$
 874 $(p_W - p_H)^2$, φ is the Higgs azimuthal angle around the z axis taken parallel to the
 875 direction of motion of the incoming W; A and B are functions describing the weak
 876 interaction in terms of the chiral states (ξ_t, ξ_b) of the quarks b and t . Terms that
 877 vanish in the high energy limit have been neglected as well as the Higgs and b quark
 878 masses⁹.

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

886 A similar analysis is valid for the W-associated channel but, in that case, the in-
 887 terference is more complicated since there are more than two contributions and an ad-
 888 ditional interference with the production of Higgs boson and a top pair process($t\bar{t}H$).
 889 The calculations are made using the so-called Diagram Removal (DR) technique where

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

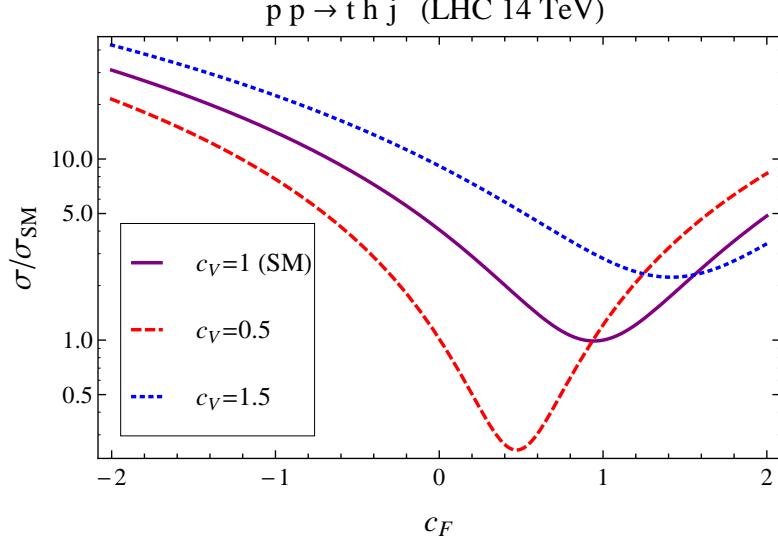


Figure 2.15: Cross section for tHq process as a function of κ_t , normalized to the SM, for three values of κ_V . In the plot c_f refers to the Higgs-fermion coupling which is dominated by the H-t coupling and represented here by κ_t . Solid, dashed and dotted lines correspond to $c_V \rightarrow \kappa_V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

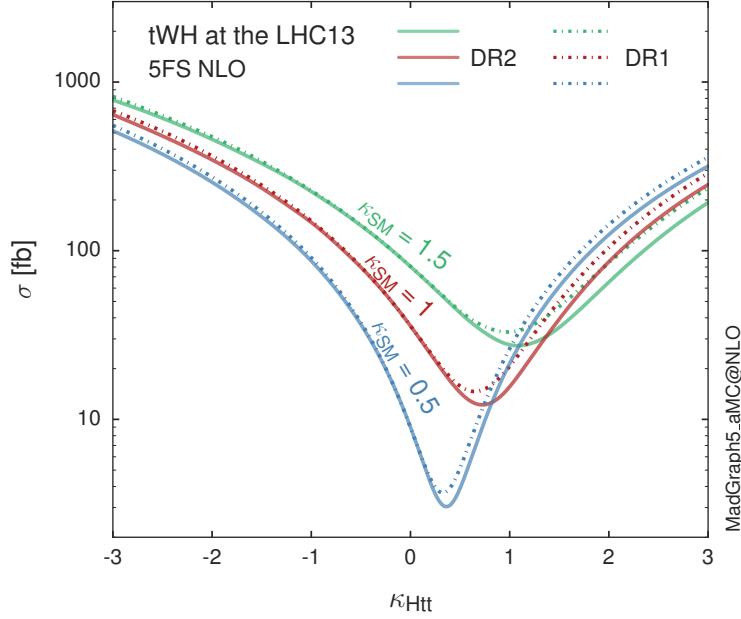


Figure 2.16: Cross section for tHW process as a function of κ_{Htt} , for three values of κ_{SM} at $\sqrt{s} = 13$ TeV. $\kappa_{Htt}^2 = \sigma_{Htt}/\sigma_{Htt}^{SM}$ is a simple re-scaling of the SM Higgs interactions.

interfering diagrams are removed (or added) from the calculations in order to evaluate the impact of the removed contributions. DR1 was defined to neglect $t\bar{t}H$ interference while DR2 was defined to take $t\bar{t}H$ interference into account [53]. As shown in Figure 2.16, the tHW cross section is enhanced from about 15 fb (SM: $\kappa_{Htt} = 1$) to about 150 fb ($\kappa_{Htt} = -1$). Differences between curves for DR1 and DR2 help to gauge the impact of the interference with $t\bar{t}H$. Results of the calculations of the tHq and tHW cross sections at $\sqrt{s} = 13$ TeV can be found in Reference [54] and a summary of the results is presented in Table 2.11.

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

898

2.6 CP-mixing in tH processes

In addition to the sensitivity to sign of the H-t coupling, the tHq and tHW processes have been proposed as a tool to investigate the possibility of a H-t coupling that does

902 not conserve CP [48, 53, 55].

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

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

909 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
 910 dimensionless re-scaling parameters¹⁰ used to parametrize the magnitude of the CP-
 911 violating and CP-conserving parts of the amplitude. The model defines $g_{Htt} =$
 912 $g_{Att} = m_t/v = y_t/\sqrt{2}$ with $v \sim 246$ GeV the Higgs vacuum expectation value. In
 913 this parametrization, three special cases can be recovered

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

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

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

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

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

919 where $g_{Hgg} = -\alpha_s/3\pi v$ and $g_{Agg} = \alpha_s/2\pi v$ and $G_{\mu\nu}$ is the gluon field strength tensors.

920 Under the assumption that the top quark dominates the gluon-fusion process at LHC

¹⁰ analog to κ_t and κ_V

energies, $\kappa_{Hgg} \rightarrow \kappa_{Htt}$ and $\kappa_{Agg} \rightarrow \kappa_{Att}$, so that the ratio between the gluon-gluon fusion cross section for X_0 and for the SM Higgs prediction can be written as

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

If the re-scaling parameters are set to

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

the gluon-fusion SM cross section is reproduced for every value of the CP-mixing angle α ; therefore, by imposing that condition to the Lagrangian density 2.63, the CP-mixing angle is not constrained by current data. Figure 2.17 shows the NLO cross sections for t-channel tX_0 (blue) and $t\bar{t}X_0$ (red) associated production processes as a function of the CP-mixing angle α . X_0 is a generic spin-0 particle with top quark CP-violating coupling. Re-scaling factors κ_{Htt} and κ_{Att} have been set to reproduce the SM gluon-fusion cross sections.

It is interesting to notice that the tX_0 cross section is enhanced, by a factor of about 10, when a continuous rotation in the scalar-pseudoscalar plane is applied; this enhancement is similar to the enhancement produced when the H-t coupling is flipped in sign with respect to the SM ($y_t = -y_{t,SM}$ in the plot), as showed in Section 2.5. In contrast, the degeneracy in the $t\bar{t}X_0$ cross section is still present given that it depends quadratically on the H-t coupling, but more interesting is to notice that $t\bar{t}X_0$ cross section is exceeded by tX_0 cross section after $\alpha \sim 60^\circ$.

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

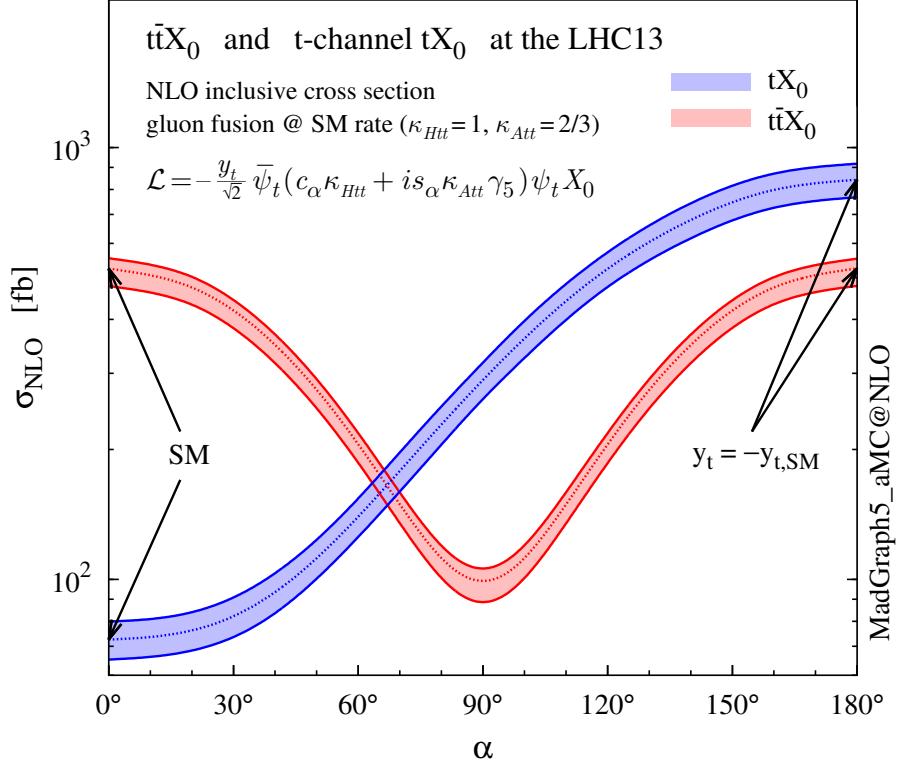


Figure 2.17: NLO cross sections for t-channel tX_0 (blue) and $t\bar{t}X_0$ (red) associated production processes as a function of the CP-mixing angle α . X_0 is a generic spin-0 particle with top quark CP-violating coupling [48].

942 Figure 2.18 shows the NLO cross sections for t-channel tX_0 (blue), $t\bar{t}X_0$ (red)
943 associated production and for the combined $tWX_0 + t\bar{t}X_0 + \text{interference}$ (orange) as
944 a function of the CP-mixing angle. It is clear that the effect of the interference in the
945 combined case is the lifting of the degeneracy present in the $t\bar{t}X_0$ production. The
946 constructive interference enhances the cross section from about 500 fb at SM ($\alpha = 0$)
947 to about 600 fb ($\alpha = 180^\circ \rightarrow y_t = -y_{t,SM}$).

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

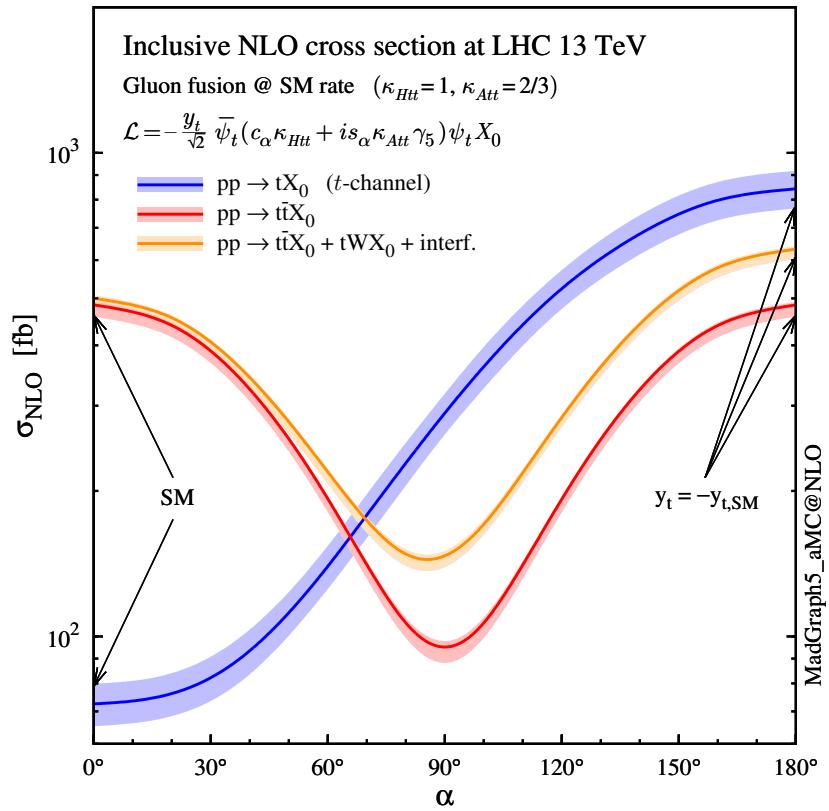


Figure 2.18: NLO cross sections for t-channel tX_0 (blue), $t\bar{t}X_0$ (red) associated production processes and combined $tWX_0 + t\bar{t}X_0$ (including interference) production as a function of the CP-mixing angle α [48].

950 **Chapter 3**

951 **The CMS experiment at the LHC**

952 **3.1 Introduction**

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

965 3.2 The LHC

966 With 27 km of circumference, the LHC is currently the most powerful circular accelerator
 967 in the world. It is installed in the same tunnel where the Large Electron-Positron
 968 (LEP) collider was located, taking advantage of the existing infrastructure. The LHC
 969 is part of the CERN's accelerator complex composed of several successive accelerat-
 970 ing stages before the particles are injected into the LHC ring where they reach their
 971 maximum energy (see Figure 3.1).

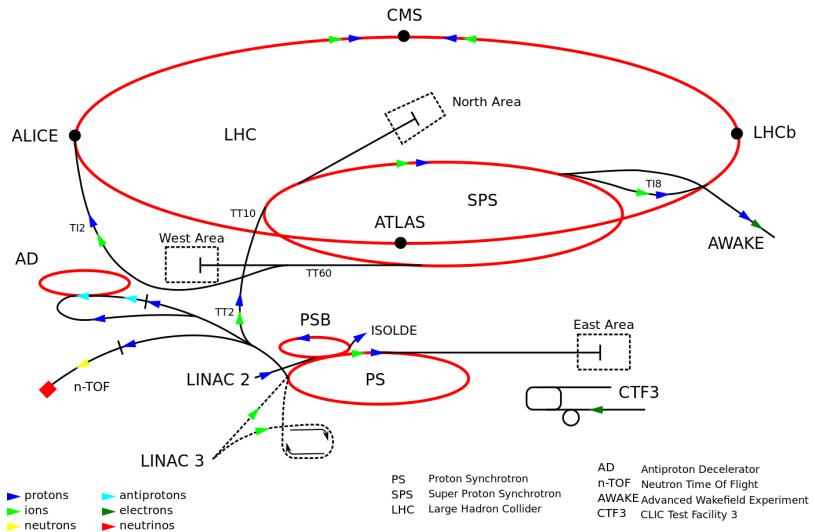


Figure 3.1: CERN accelerator complex. Blue arrows show the path followed by protons along the acceleration process [59].

972 The LHC runs in three collision modes depending on the particles being acceler-
 973 ated

- 974 • Proton-Proton collisions (pp) for multiple physics experiments.
- 975 • Lead-Lead collisions ($Pb-Pb$) for heavy ion experiments.
- 976 • Proton-Lead collisions ($p-Pb$) for quark-gluon plasma experiments.

977 In this thesis only pp collisions will be considered.

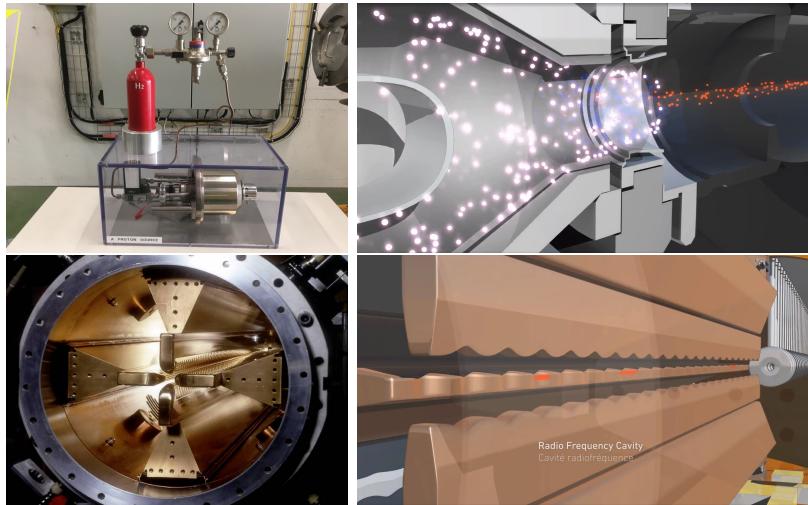


Figure 3.2: LHC protons source and the first acceleration stage. Top: the bottle contains hydrogen gas which is injected into the metal cylinder (white dots) to be broken down into electrons (blue dots) and protons (red dots); Bottom: the obtained protons are directed towards the radio frequency quadrupole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

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

987 In order to accelerate the protons, a longitudinal time-varying electric field com-
 988 ponent is added to the system; it is done by giving the electrodes a sine-like profile as
 989 shown in Figure 3.2 bottom. By matching the speed and phase of the protons with
 990 the longitudinal electric field the bunching is performed; protons synchronized with

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

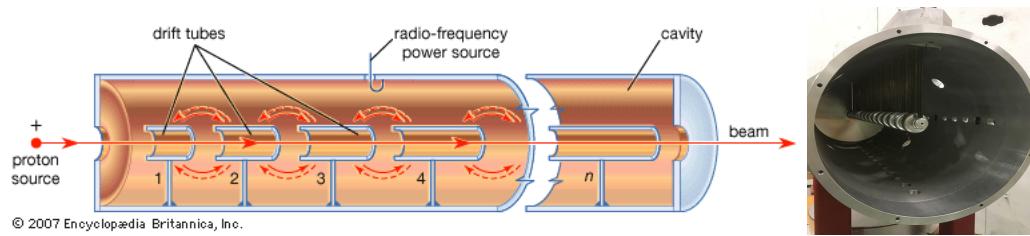


Figure 3.3: Left: drawing of the LINAC2 accelerating system at CERN. Electric fields generated by radio frequency (RF) create acceleration and deceleration zones inside the cavity; deceleration zones are blocked by drift tubes where quadrupole magnets focus the proton beam. Right: picture of a real RF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

996 Proton bunches coming from the RFQ go to the linear accelerator 2 (LINAC2)
 997 where they are accelerated to reach 50 MeV energy. In the LINAC2 stage, acceleration
 998 is performed using electric fields generated by radio frequency which create zones
 999 of acceleration and deceleration as shown in Figure 3.3. In the deceleration zones,
 1000 the electric field is blocked using drift tubes where protons are free to drift while
 1001 quadrupole magnets focus the beam.

1002 The beam coming from LINAC2 is injected into the proton synchrotron booster
 1003 (PSB) to reach 1.4 GeV in energy. The next acceleration is provided at the proton
 1004 synchrotron (PS) up to 26 GeV, followed by the injection into the super proton
 1005 synchrotron (SPS) where protons are accelerated to 450 GeV. Finally, protons are
 1006 injected into the LHC where they are accelerated to the target energy of 6.5 TeV.

1007 PSB, PS, SPS and LHC accelerate protons using the same RF acceleration tech-
 1008 nique described before.

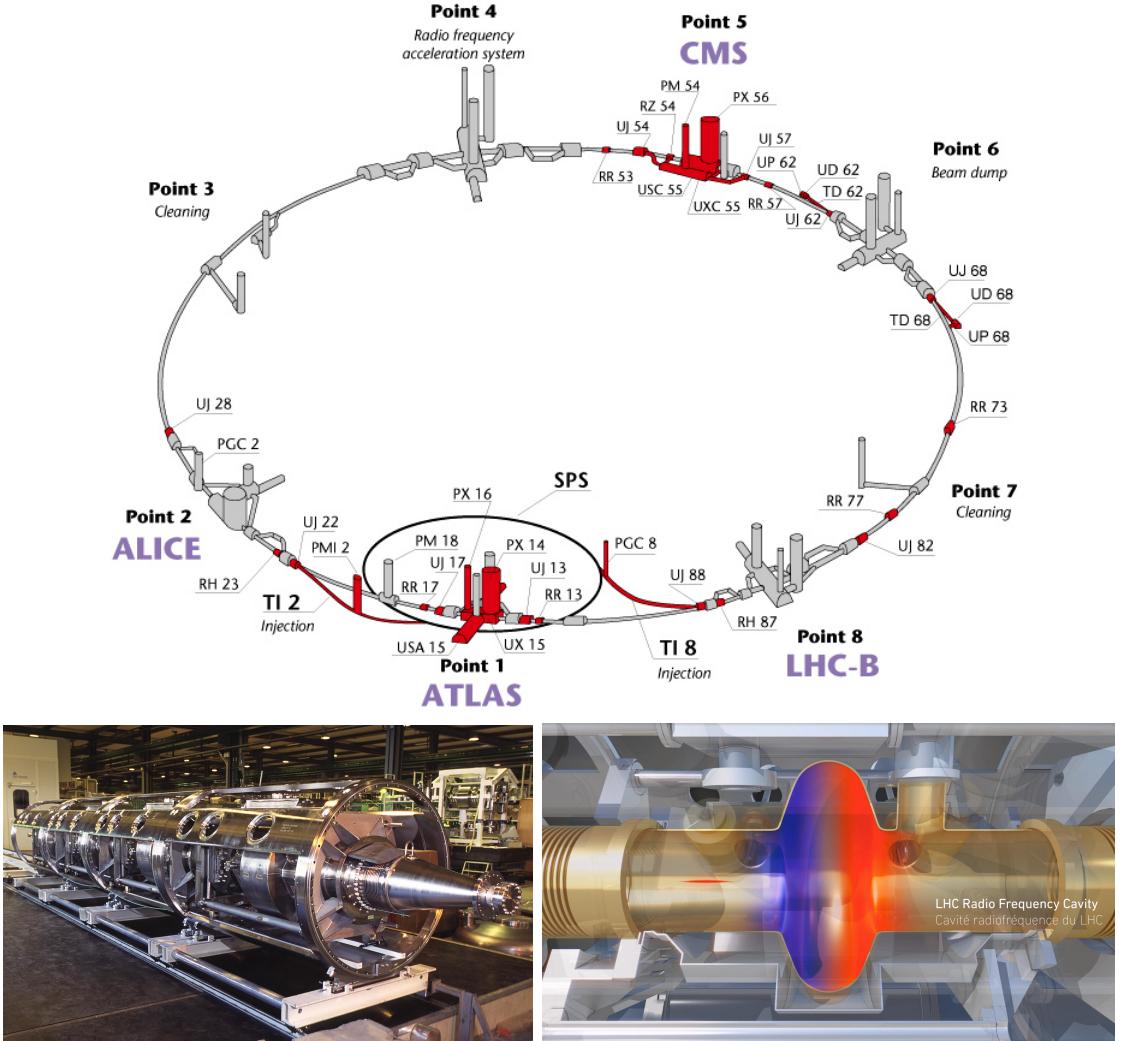


Figure 3.4: Top: LHC layout. The red zones indicate the infrastructure additions to the LEP installations, built to accommodate the ATLAS and CMS experiments which exceed the size of the former experiments located there [60]. Bottom: LHC RF cavities. A module (left picture) accommodates 4 cavities, each like the one in the right drawing, that accelerate protons and preserve the bunch structure of the beam. The color gradient pattern represents the strength of the electric field inside the cavity; red zone corresponds to the maximum of the oscillation electric field while the blue zone corresponds to the minimum. [64, 66]

1009 The LHC has a system of 16 RF cavities located in the so-called point 4, as
 1010 shown in Figure 3.4 top, tuned at a frequency of 400 MHz. The bottom side of
 1011 Figure 3.4 shows a picture of a RF module composed of 4 RF cavities working in a
 1012 superconducting state at 4.5 K; also, a representation of the accelerating electric field

1013 that accelerates the protons in the bunch is shown. The maximum of the oscillating
 1014 electric field (red region) picks the proton bunches at the entrance of the cavity
 1015 and keeps accelerating them through the whole cavity. The protons are carefully
 1016 timed so that in addition to the acceleration effect the bunch structure of the beam
 1017 is preserved.

1018 While protons are accelerated in one section of the LHC ring, where the RF cavities
 1019 are located, in the rest of their path they have to be kept in the curved trajectory
 1020 defined by the LHC ring. Technically, LHC is not a perfect circle; RF, injection, beam
 1021 dumping, beam cleaning and sections before and after the experimental points where
 1022 protons collide are all straight sections. In total, there are 8 arcs 2.45 km long each
 1023 and 8 straight sections 545 m long each. In order to curve the proton's trajectory in
 1024 the arc sections, superconducting dipole magnets are used.

1025 Inside the LHC ring, there are two proton beams traveling in opposite directions
 1026 in two separated beam pipes; the beam pipes are kept at ultra-high vacuum ($\sim 10^{-9}$
 1027 Pa) to ensure that there are no particles that interact with the proton beams. The
 1028 superconducting dipole magnets used in LHC are made of a NbTi alloy, capable of
 1029 transporting currents of about 12000 A when cooled at a temperature below 2K using
 1030 liquid helium (see Figure 3.5).

1031 Protons in the arc sections of LHC feel a centripetal force exerted by the dipole
 1032 magnets; the magnitude of magnetic field needed to keep the protons in the LHC
 1033 curved trayectomy can be found assuming that protons travel at $v \approx c$, using the
 1034 standard values for proton mass and charge and the LHC radius, as

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

1035 which is about 100000 times the Earth's magnetic field. A representation of the

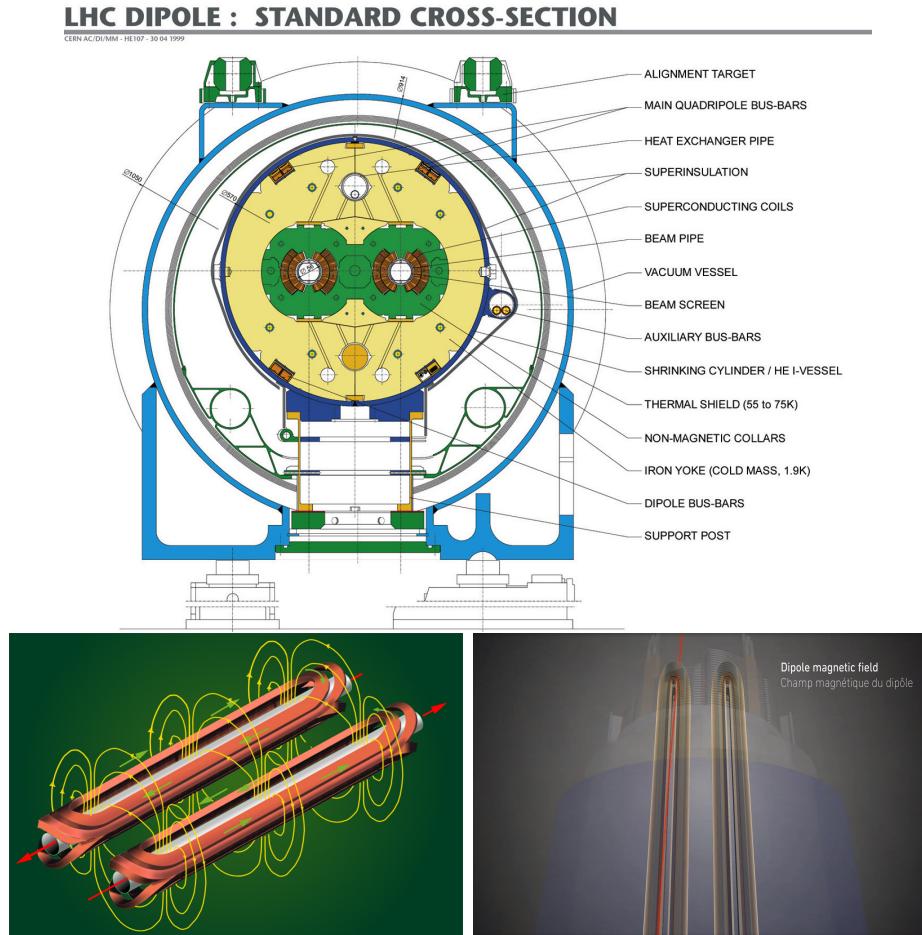


Figure 3.5: Top: LHC dipole magnet transverse view; cooling, shielding and mechanical support are indicated. Bottom left: Magnetic field generated by the dipole magnets; note that the direction of the field inside one beam pipe is opposite with respect to the other beam pipe which guarantee that both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

1036 magnetic field generated by the dipole magnets is shown on the bottom left side of
 1037 Figure 3.5. The bending effect of the magnetic field on the proton beam is shown on
 1038 the bottom right side of Figure 3.5. Note that the dipole magnets are not curved;
 1039 the arc section of the LHC ring is composed of straight dipole magnets of about 15
 1040 m. In total there are 1232 dipole magnets along the LHC ring.

1041 In addition to the bending of the beam trajectory, the beam has to be focused. The

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

The two proton beams inside the LHC ring are made of bunches with a cylindrical shape of about 7.5 cm long and about 1 mm in diameter; when bunches are close to the interaction point (IP), the beam is focused up to a diameter of about 16 μm in order to maximize the probability of collisions between protons. The number of collisions per second is proportional to the cross section of the bunches with the *luminosity* (L) as the proportionality factor, thus, the luminosity can be calculated using

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

where f is the revolution frequency, n is the number of bunches per beam, N_1 and N_2 are the numbers of protons per bunch, σ_x and σ_y are the gaussian transverse sizes of the bunches. With the expected parameters, the LHC expected luminosity is about

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

$$n = 2808$$

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

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

1057

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

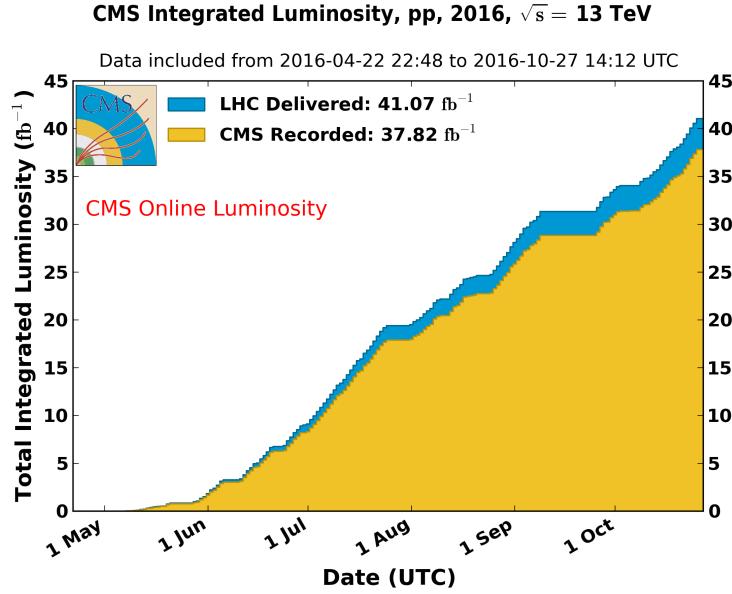


Figure 3.6: Integrated luminosity delivered by LHC and recorded by CMS during 2016. The difference between the delivered and the recorded luminosity is due to fails and issues occurred during the data taking in the CMS experiment [69].

1058 Luminosity is a fundamental aspect of LHC given that the bigger luminosity the
 1059 bigger number of collisions, which means that for processes with a very small cross
 1060 section the number of expected occurrences is increased and so the chances of being
 1061 detected. The integrated luminosity, collected by the CMS experiment during 2016
 1062 is shown in Figure 3.6; the data analyzed in this thesis corresponds to an integrated
 1063 luminosity of 35.9 fb^{-1} at a center of mass-energy $\sqrt{s} = 13 \text{ TeV}$.

1064 One way to increase L is increasing the number of bunches in the beam. Cur-
 1065 rently, the separation between two consecutive bunches in the beam is 7.5 m which
 1066 corresponds to a time separation of 25 ns. In the full LHC ring the allowed number
 1067 of bunches is $n = 27\text{km}/7.5\text{m} = 3600$; however, there are some gaps in the bunch pat-
 1068 tern intended for preparing the dumping and injection of the beam, thus, the proton
 1069 beams are composed of 2808 bunches.

1070 Once the proton beams reach the desired energy, they are brought to cross each

1071 other producing pp collisions. The bunch crossing happens in precise places where
 1072 the four LHC experiments are located, as seen in the top of Figure 3.7. In 2008 pp
 1073 collisions of $\sqrt{s} = 7$ TeV were performed; the energy was increased to 8 TeV in 2012
 1074 and to 13 TeV in 2015.

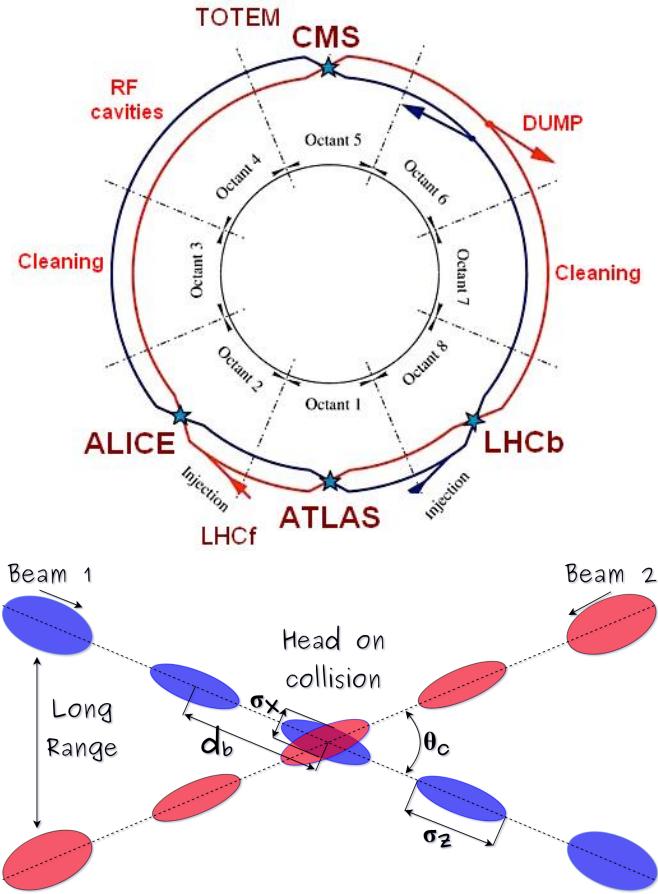


Figure 3.7: Top: LHC interaction points. Bunch crossing occurs where the LHC experiments are located [70]. Sections indicated as cleaning are dedicated to collimate the beam in order to protect the LHC ring from collisions with protons in very spreaded bunches. Bottom: bunch crossing scheme. Since the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

1075 The CMS and ATLAS experiments are multi-purpose experiments, hence, they
 1076 are enabled to explore physics in any of the LHC collision modes. LHCb experiment
 1077 is optimized to explore bottom quark physics, while ALICE is optimized for heavy

1078 ion collisions searches; TOTEM and LHCf are dedicated to forward physics studies;
 1079 MoEDAL (not indicated in the Figure) is intended for monopole or massive pseudo
 1080 stable particles searches.

1081 At the IP there are two interesting details that need to be addressed. The first
 1082 one is that the bunch crossing does not occur head-on but at a small crossing angle θ_c
 1083 (280 μ rad in CMS and ATLAS) as shown in the bottom side of Figure 3.7, affecting
 1084 the overlapping between bunches; the consequence is a reduction of about 17% in
 1085 the luminosity (represented by a factor not included in eqn. 3.2). The second one
 1086 is the occurrence of multiple pp collisions in the same bunch crossing; this effect is
 1087 called *pileup* (PU). A fairly simple estimation of the PU follows from estimating the
 1088 probability of collision between two protons, one from each of the bunches in the
 1089 course of collision; it depends roughly on the ratio of proton size and the cross section
 1090 of the bunch in the IP, i.e.,

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

1091 however, there are $N = 1.15 \times 10^{11}$ protons in a bunch, thus the estimated number of
 1092 collisions in a bunch crossing is

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

1093 about 20 of which are inelastic. A multiple pp collision event in a bunch crossing at
 1094 CMS is shown in Figure 3.8.

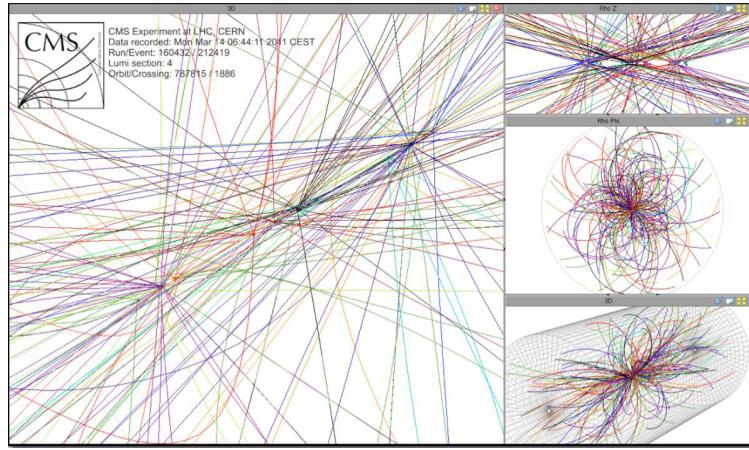


Figure 3.8: Multiple pp collision bunch crossing at CMS. [71].

1095 3.3 The CMS experiment

1096 CMS is a general-purpose detector designed to conduct research in a wide range
 1097 of physics from the standard model to new physics like extra dimensions and dark
 1098 matter. Located at Point 5 in the LHC layout as shown in Figure 3.4, CMS is
 1099 composed of several detection systems distributed in a cylindrical structure; in total,
 1100 CMS weights about 12500 tons in a very compact 21.6 m long and 14.6 m diameter
 1101 cylinder. It was built in 15 separate sections at the ground level and lowered to the
 1102 cavern individually to be assembled. A complete and detailed description of the CMS
 1103 detector and its components is given in Reference [72] on which this section is based.
 1104 Figure 3.9 shows the layout of the CMS detector. The detection system is composed
 1105 of (from the innermost to the outermost)

- 1106 • Pixel detector.
- 1107 • Silicon strip tracker.
- 1108 • Preshower detector.
- 1109 • Electromagnetic calorimeter.

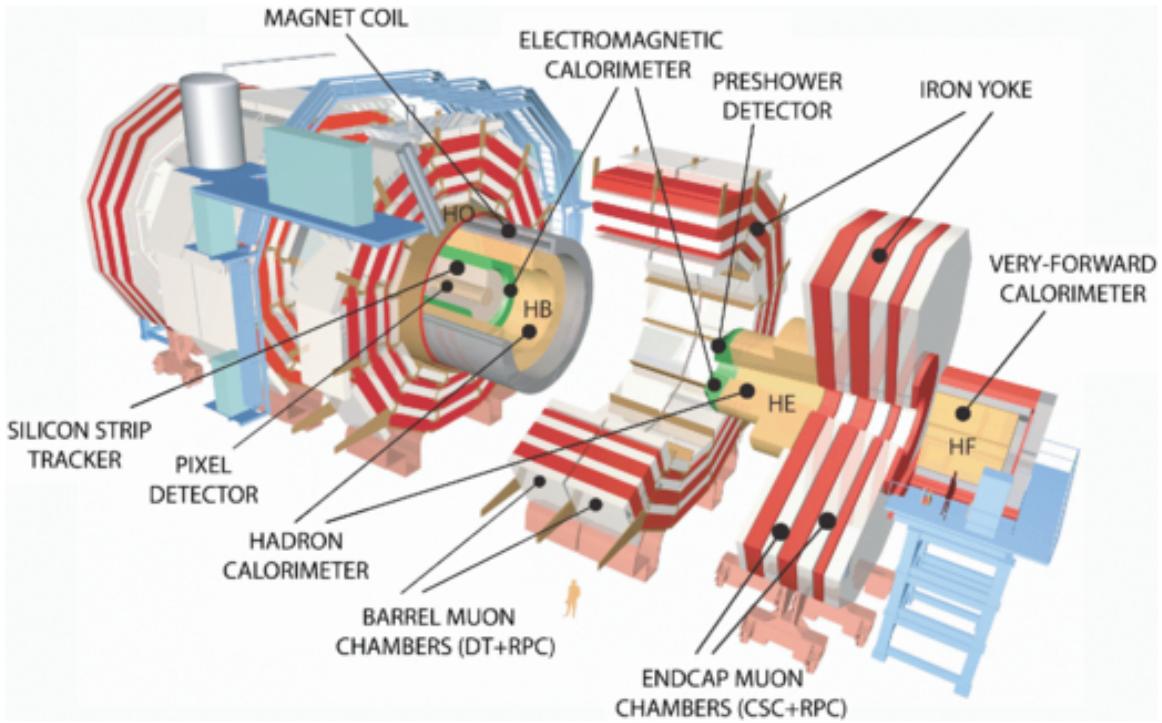


Figure 3.9: Layout of the CMS detector. The several subdetectors are indicated. The central region of the detector is referred as the barrel section while the endcaps are referred as the forward sections. [73].

1110 • Hadronic calorimeter.

1111 • Muon chambers (barrel and endcap)

1112 The central region of the detector is commonly referred as the barrel section while
 1113 the endcaps are referred as the forward sections of the detector; thus, each subdetector
 1114 is composed of a barrel section and a forward section.

1115 When a pp collision happens inside the CMS detector, many different particles are
 1116 produced, but only some of them live long enough to be detected; they are electrons,
 1117 photons, pions, kaons, protons, neutrons and muons. Thus, the CMS detector was
 1118 designed to detect those particles and measure their properties. Figure 3.10 shows
 1119 a transverse slice of the CMS detector. The silicon tracker (pixel detector + strip
 1120 tracker) is capable to register the track of the charged particles traversing it, while

1121 calorimeters (electromagnetic and hadronic) measure the energy of the particles that
 1122 are absorbed by their materials. Considering the detectable particles, mentioned
 1123 above, emerging from the IP, a basic description of the detection process is as follows.

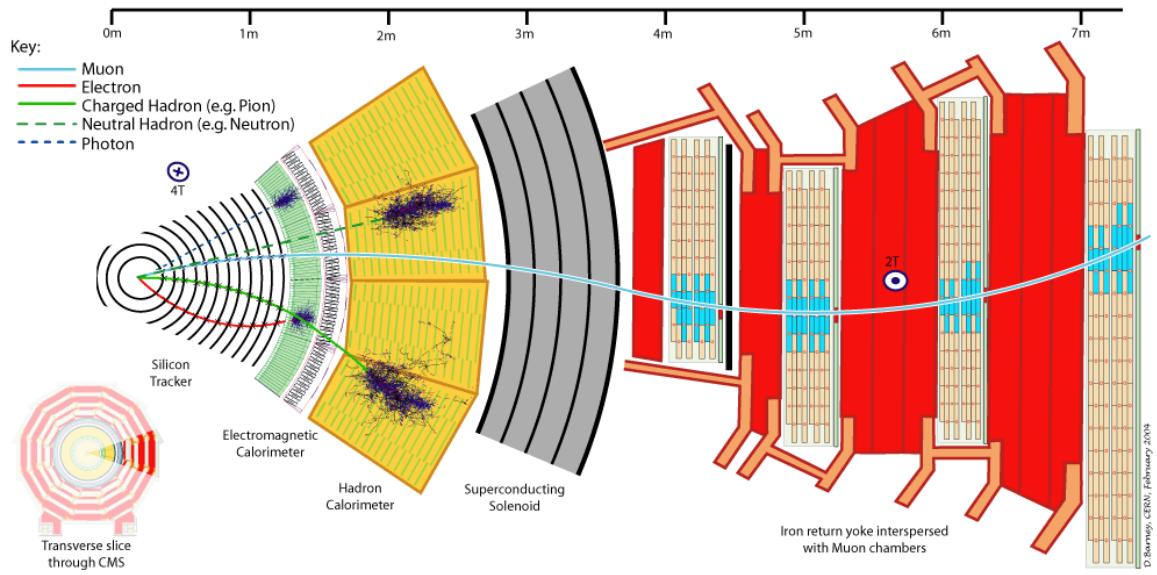


Figure 3.10: CMS detector transverse slice.

1124 A muon emerging from the IP, will create a track on the silicon tracker and on
 1125 the muon chambers. The design of the CMS detector is driven by the requirements
 1126 on the identification, momentum resolution and unambiguous charge determination
 1127 of the muons; therefore, a large bending power is provided by the solenoid magnet
 1128 made of superconducting cable capable of generating a 3.8 T magnetic field. The
 1129 muon track is bent twice since the magnetic field inside the solenoid is directed along
 1130 the z -direction but outside its direction is reversed. Muons interact very weakly with
 1131 the calorimeters, therefore, it is not absorbed but escape away from the detector.

1132 An electron emerging from the IP will create a track along the tracker which will
 1133 be bent due to the presence of the magnetic field, later, it will be absorbed in the
 1134 electromagnetic calorimeter where its energy is measured.

1135 A photon will not leave a track because it is neutral, but it will be absorbed in
 1136 the electromagnetic calorimeter.

1137 A neutral hadron, like the neutron, will not leave a track either but it will lose a
 1138 small amount of its energy during its passage through the electromagnetic calorimeter
 1139 and then it will be absorbed in the hadron calorimeter depositing the rest of its energy.

1140 A charged hadron, like the proton or π^\pm , will leave a curved track on the silicon
 1141 tracker, some of its energy in the electromagnetic calorimeter and finally will be
 1142 absorbed in the hadronic calorimeter.

1143 A more detailed description of each detection system will be presented in the
 1144 following sections.

1145 3.3.1 Coordinate system

1146 The coordinate system used by CMS is centered on the geometrical center of the
 1147 detector which is the nominal IP as shown in Figure 3.11¹. The z -axis is parallel
 1148 to the beam direction, while the Y -axis pointing vertically upward, and the X -axis
 1149 pointing radially inward toward the center of the LHC.

1150 In addition to the common cartesian and cylindrical coordinate systems, two co-
 1151 ordinates are of particular utility in particle physics: rapidity (y) and pseudorapidity
 1152 (η), defined in connection to the polar angle θ , energy and longitudinal momentum
 1153 component (momentum along the z -axis) according to

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

1154 Rapidity is related to the angle between the XY -plane and the direction in which
 1155 the products of a collision are emitted; it has the nice property that the difference

¹ Not all the pp interaction occur at the nominal IP because of the bunch lenght, therefore, each pp collision has its own IP location

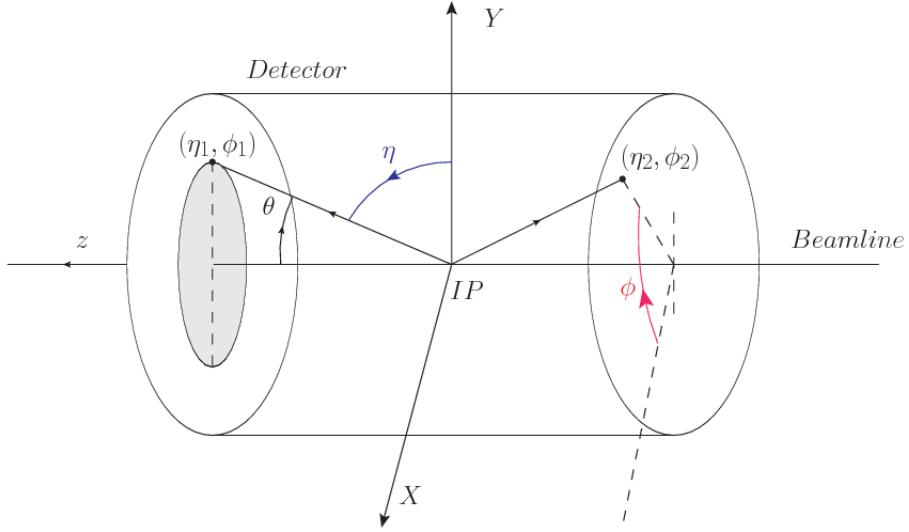


Figure 3.11: CMS detector coordinate system.

1156 between the rapidities of two particles is invariant with respect to Lorentz boosts
 1157 along the z -axis, hence, data analysis becomes more simple when based on rapid-
 1158 ity; however, it is not simple to measure the rapidity of highly relativistic particles,
 1159 as those produced after pp collisions. Under the highly relativistic motion approxi-
 1160 mation, y can be rewritten in terms of the polar angle, concluding that rapidity is
 1161 approximately equal to the pseudorapidity defined above, i.e., $y \approx \eta$. Note that η
 1162 is easier to measure than y given the direct relationship between the former and the
 1163 polar angle.

1164 The angular distance between two objects in the detector (ΔR) is commonly used
 1165 to judge the isolation of those object; it is defined in terms of their coordinates (η_1, ϕ_1) ,
 1166 (η_2, ϕ_2) as

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

1167 **3.3.2 Pixels detector**

1168 The CMS tracking system is designed to provide a precise measurement of the tra-
 1169 jectory (*track*) followed by the charged particles created after the pp collisions; also,
 1170 the precise reconstruction of the primary and secondary origins (*vertices*) is expected
 1171 in an environment where, each 25 ns, the bunch crossing produce about 20 inelastic
 1172 collisions and about 1000 particles. An increment in the luminosity is ongoing which
 1173 implies that the PU will increase accordingly.

1174

1175 The pixel detector was replaced during the 2016-2017 extended year-end technical
 1176 stop, due to the increasingly challenging operating conditions like the higher particle
 1177 flow and more radiation harsh environment, among others. The new one is responding
 1178 as expected, reinforcing its crucial role in the successful way to fulfill the new LHC
 1179 physics objectives after the discovery of the Higgs boson. The last chapter of this
 1180 thesis is dedicated to describe my contribution to the *Forward Pixel Phase 1 upgrade*.

1181

1182 The current pixel detector is composed of 1856 silicon pixel detector modules orga-
 1183 nized in four-barrel layers in the central region and three disks in the forward region;
 1184 it is designed to record efficiently and with high precision, up to $10\mu\text{m}$ in the XY -
 1185 plane and $20\mu\text{m}$ in the z -direction, the first four space-points (*hits*) near to the IP
 1186 region (see Figure 3.12 left side) in the range $|\eta| \leq 2.5$. The first barrel layer is located
 1187 at a radius of 30 mm from the beamline, while the fourth layer is located at a radius
 1188 of 160 mm closer to the strip tracker inner barrel layer (see Section 3.3.3) in order to
 1189 reduce the rate of fake tracks. The high granularity of the detector is represented in
 1190 its about 123 Mpixels, each of size $100 \times 150\mu\text{m}^2$, which is almost twice the channels
 1191 of the old detector. The transverse momentum resolution of tracks can be measured

1192 with a resolution of 1-2% for muons of $p_T = 100$ GeV.

1193

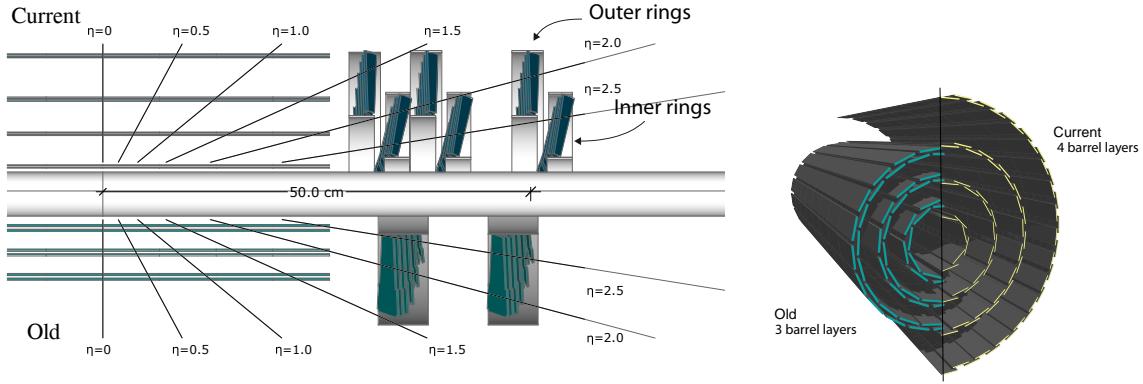


Figure 3.12: CMS pixel detector schematic view. Left: layout comparing the layers and disks in the old and current pixel detectors. Right: Transverse-oblique view comparing the pixel barrel layers in the two [75].

1194 Some of the improvements with respect to the previous pixel detector include a higher
 1195 average tracking efficiency and lower average fake rate as well as higher track impact
 1196 parameter resolution which is fundamental in order to increase the efficiency in the
 1197 identification of jets originating from b quarks (b-tagging). A significant source of
 1198 improvement comes from the overall reduction in the material budget of the detector
 1199 which results in fewer photon conversions and less multiple scattering from charged
 1200 particles.

1201 3.3.3 Silicon strip tracker

1202 The silicon strip tracker (SST) is the second stage in the CMS tracking system. The
 1203 top side of Figure 3.13 shows a schematic of the SST. The inner tracker region is com-
 1204 posed of the tracker inner barrel (TIB) and the tracker inner disks (TID) covering the
 1205 region $r < 55$ cm and $|z| < 118$ cm. The TIB is composed of 4 layers while the TID
 1206 is composed of 3 disks at each end. The silicon sensors in the inner tracker are 320

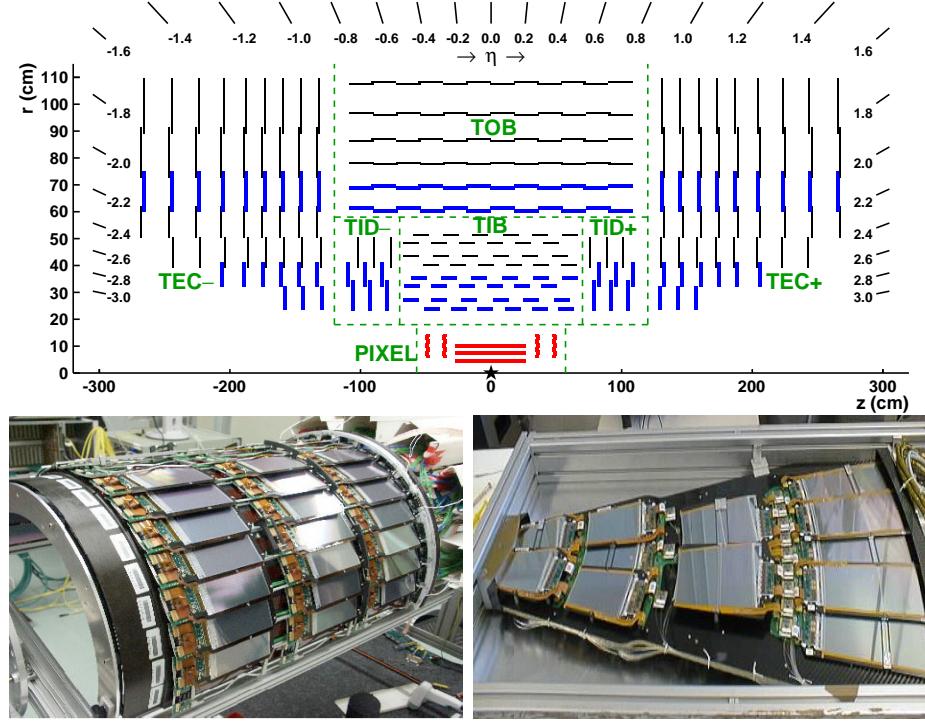


Figure 3.13: Top: CMS Silicon Strip Tracker (SST) schematic view. The SST is composed of the tracker inner barrel (TIB), the tracker inner disks (TID), the tracker outer barrel (TOB) and the tracker endcaps (TEC). Each part is made of silicon strip modules; the modules in blue represent two modules mounted back-to-back and rotated in the plane of the module by a stereo angle of 120 mrad in order to provide a 3-D reconstruction of the hit positions. Bottom: pictures of the TIB (left) and TEC (right) modules [76–78].

1207 μm thick, providing a resolution of about 13–38 μm in the $r\phi$ position measurement.

1208

1209 The modules indicated in blue in the schematic view of Figure 3.13 are two modules
 1210 mounted back-to-back and rotated in the plane of the module by a *stereo* angle of
 1211 100 mrad; the hits from these two modules, known as *stereo hits*, are combined to
 1212 provide a measurement of the second coordinate (z in the barrel and r on the disks)
 1213 allowing the reconstruction of hit positions in 3-D.

1214

1215 The outer tracker region is composed of the tracker outer barrel (TOB) and the
 1216 tracker endcaps (TEC). The six layers of the TOB offer coverage in the region $r > 55$

1217 cm and $|z| < 118$ cm, while the 9 disks of the TEC cover the region $124 < |z| < 282$
 1218 cm. The resolution offered by the outer tracker is about $13\text{-}38 \mu\text{m}$ in the $r\phi$ position
 1219 measurement. The inner four TEC disks use silicon sensors $320 \mu\text{m}$ thick; those in
 1220 the TOB and the outer three TEC disks use silicon sensors of $500 \mu\text{m}$ thickness. The
 1221 silicon strips run parallel to the z -axis and the distance between strips varies from 80
 1222 μm in the inner TIB layers to $183 \mu\text{m}$ in the inner TOB layers; in the endcaps the
 1223 wedge-shaped sensors with radial strips, whose pitch range between $81 \mu\text{m}$ at small
 1224 radii and $205 \mu\text{m}$ at large radii.

1225

1226 The whole SST has 15148 silicon modules, 9.3 million silicon strips and cover a total
 1227 active area of about 198 m^2 .

1228 3.3.4 Electromagnetic calorimeter

1229 The CMS electromagnetic calorimeter (ECAL) is designed to measure the energy of
 1230 electrons and photons. It is composed of 75848 lead tungstate crystals which have a
 1231 short radiation length (0.89 cm) and fast response, since 80% of the light is emitted
 1232 within 25 ns; however, they are combined with Avalanche photodiodes (APDs) as
 1233 photodetectors given that crystals themselves have a low light yield ($30\gamma/\text{MeV}$). A
 1234 schematic view of the ECAL is shown in Figure 3.14.

1235

1236 Energy is measured when electrons and photons are absorbed by the crystals which
 1237 generates an electromagnetic *shower*, as seen in bottom right picture of the Figure
 1238 3.14; the shower is seen as a *cluster* of energy which depending on the amount of en-
 1239 ergy deposited can involve several crystals. The ECAL barrel (EB) covers the region
 1240 $|\eta| < 1.479$, using crystals of depth of 23 cm and $2.2 \times 2.2 \text{ cm}^2$ transverse section;

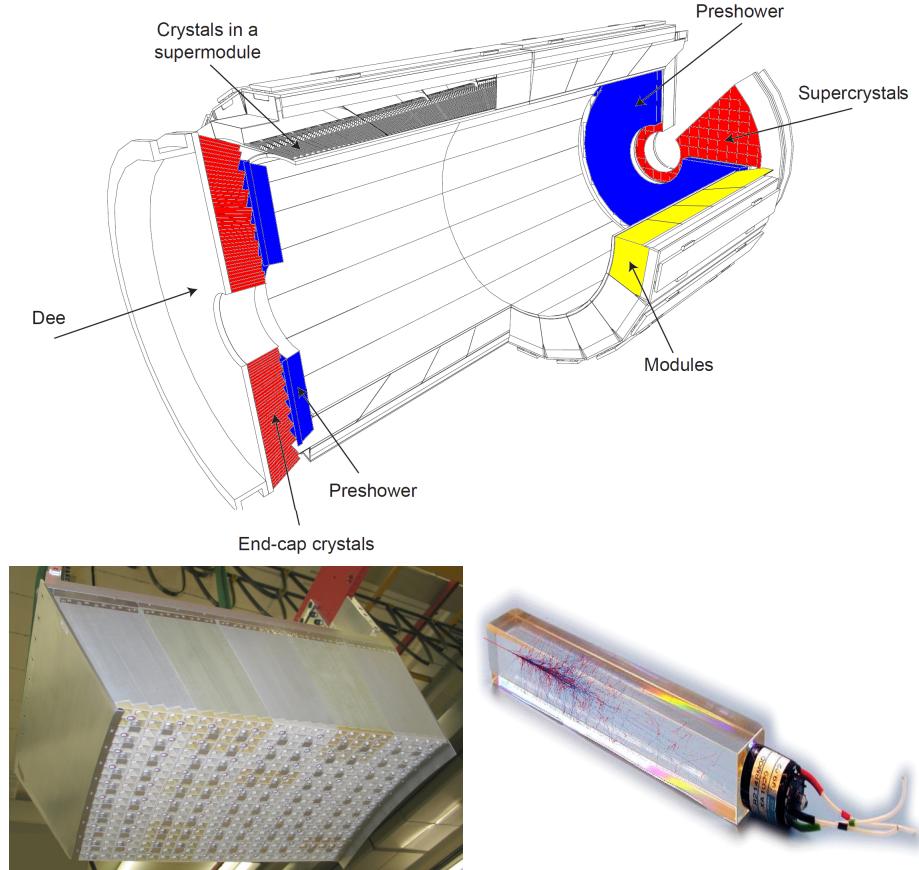


Figure 3.14: Top: CMS ECAL schematic view. Bottom: Module equipped with the crystals (left); ECAL crystal(right).

1241 the ECAL endcap (EE) covers the region $1.479 < |\eta| < 3.0$ using crystals of depth

1242 22 cm and transverse section of $2.86 \times 2.86 \text{ cm}^2$; the photodetectors used are vacuum

1243 phototriodes (VPTs). Each EE is divided in two structures called *Dees*.

1244

1245 In front of the EE, it is installed the preshower detector (ES) which covers the region

1246 $1.653 < |\eta| < 2.6$. The ES provides a precise measurement of the position of electro-

1247 magnetic showers, which allows to distinguish electrons and photons signals from π^0

1248 decay signals. The ES is composed of a layer of lead absorber followed by a layer of

1249 plastic scintillators

1250 **3.3.5 Hadronic calorimeter**

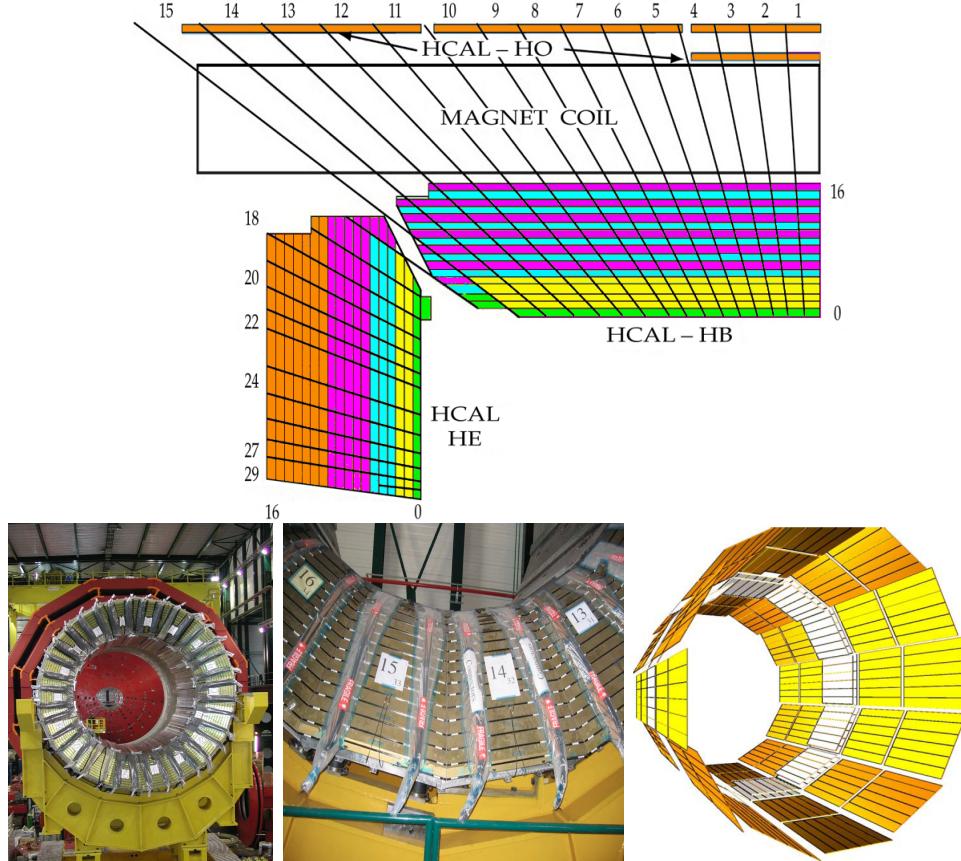


Figure 3.15: Top: CMS HCAL schematic view, the colors indicate the layers that are grouped into the same readout channels. Bottom: picture of a section of the HB; the absorber material is the golden region and scintillators are placed in between the absorber material (left and center). Schematic view of the HO (right). [79, 80]

1251 Hadrons are not absorbed by the ECAL but by the hadron calorimeter (HCAL),
 1252 which is made of a combination of alternating brass absorber layers and silicon photo-
 1253 multiplier(SiPM) layers; therefore, particles passing through the scintillator material
 1254 produce showers, as in the ECAL, as a result of the inelastic scattering of the hadrons
 1255 with the detector material. Since the particles are not absorbed in the scintillator,
 1256 their energy is sampled; therefore the total energy is not measured but estimated from
 1257 the energy clusters, which reduce the resolution of the detector. Brass was chosen

1258 as the absorber material due to its short interaction length ($\lambda_I = 16.42\text{cm}$) and its
 1259 non-magnetivity. Figure 3.15 shows a schematic view of the CMS HCAL.

1260

1261 The HCAL is divided into four sections; the Hadron Barrel (HB), the Hadron Outer
 1262 (HO), the Hadron Endcap (HE) and the Hadron Forward (HF) sections. The HB
 1263 covers the region $0 < |\eta| < 1.4$, while the HE covers the region $1.3 < |\eta| < 3.0$. The HF,
 1264 made of quartz fiber scintillator and steel as absorption material, covers the forward
 1265 region $3.0 < |\eta| < 5.2$. Both the HB and HF are located inside the solenoid. The HO
 1266 is placed outside the magnet as an additional layer of scintillators with the purpose
 1267 of measure the energy tails of particles passing through the HB and the magnet (see
 1268 Figure 3.15 top and bottom right). The upgrades made to the HCAL during the
 1269 technical stop 2016-2017 consisted in the replacement of the photo transducer, in
 1270 order to improve the efficiency.

1271 **3.3.6 Superconducting solenoid magnet**

1272 The superconducting magnet installed in the CMS detector is designed to provide
 1273 an intense and highly uniform magnetic field in the central part of the detector. In
 1274 fact, the tracking system takes advantage of the bending power of the magnetic field
 1275 to measure with precision the momentum of the particles that traverse it; the unam-
 1276 biguous determination of the sign for high momentum muons was a driven principle
 1277 during the design of the magnet. The magnet has a diameter of 6.3 m, a length of 12.5
 1278 m and a cold mass of 220 t; the generated magnetic field reaches a strength of 3.8T.
 1279 Since it is made of Ni-Tb superconducting cable it has to operate at a temperature
 1280 of 4.7 K by using a helium cryogenic system; the current circulating in the cables
 1281 reaches 18800 A under normal running conditions. The left side of Figure 3.16 shows

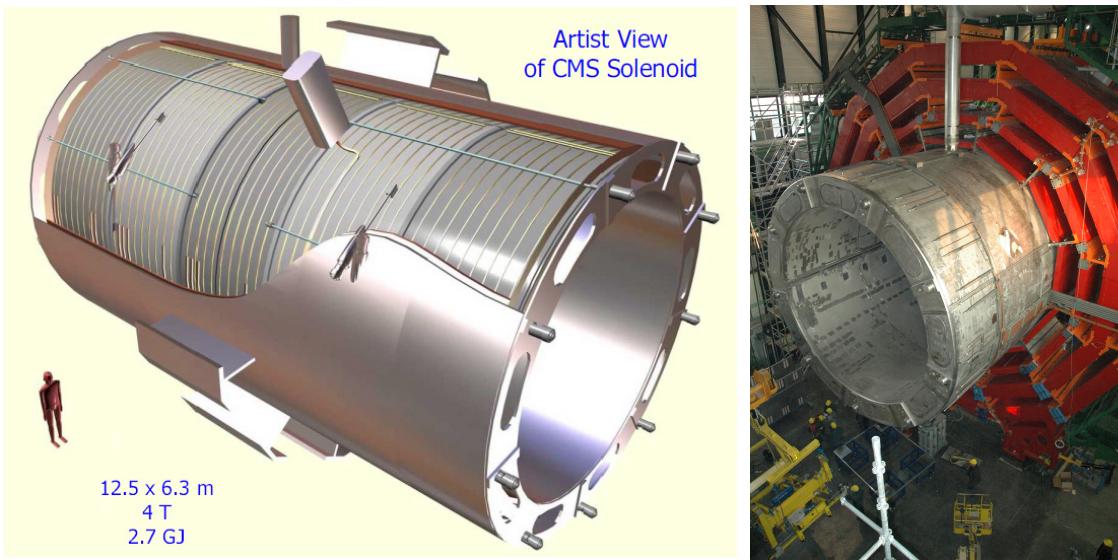


Figure 3.16: Artistic representation of the CMS solenoid magnet(left). The magnet is supported on an iron yoke (right) which also serves as the house of the muon detector and as mechanical support for the whole CMS detector [74].

1282 an artistic view of the CMS magnet, while the right side shows a transverse view of
 1283 the cold mass where the winding structure is visible.

1284

1285 The yoke (see Figure 3.16), composed of 5 barrel wheels and 6 endcap disks made
 1286 of iron, serves not only as the media for magnetic flux return but also provides the
 1287 house for the muon detector system and structural stability to the full detector.

1288 **3.3.7 Muon system**

1289 Muons are the only charged particles able to pass through all the CMS detector due
 1290 to their low ionization energy loss; thus, muons can be separated easily from the
 1291 high amount of particles produced in a pp collision. Also, muons are expected to be
 1292 produced in the decay of several new particles; therefore, a good detection of muons
 1293 was on the leading principles when designing the CMS detector.

1294

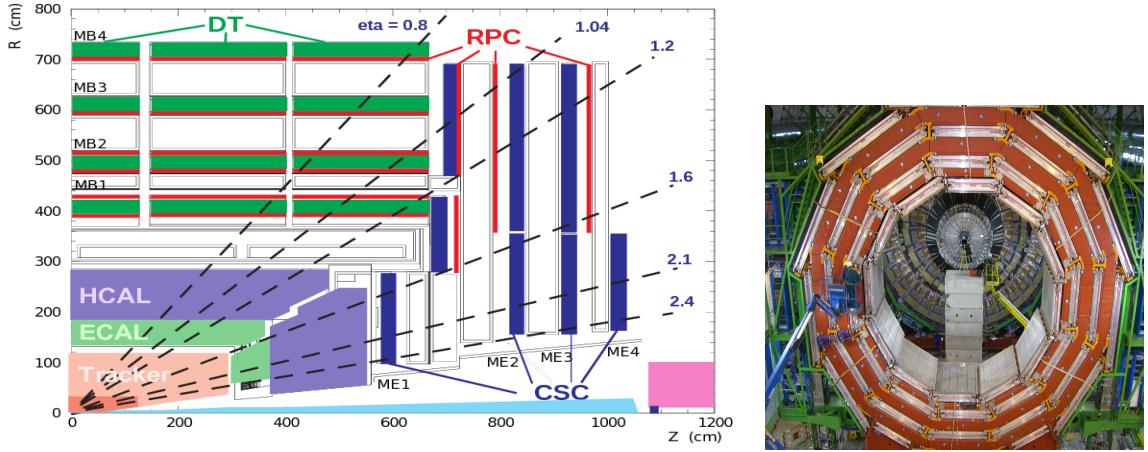


Figure 3.17: Left: CMS muon system schematic view; Right: one of the yoke rings with the muon DTs and RPCs installed; in the back it is possible to see the muon endcap [81].

1295 The CMS muon detection system (muon spectrometer) is embedded in the return
 1296 yoke as seen in Figure 3.17. It is composed of three different detector types, the drift
 1297 tube chambers (DT), Cathode strip chambers (CSC), and resistive plate chambers
 1298 (RPC); DT are located in the central region $\eta < 1.2$ arranged in four layers of drift
 1299 chambers filled with an Ar/CO₂ gas mixture.

1300

1301 The muon endcaps are made of CSCs covering the region $\eta < 2.4$ and filled with a
 1302 mixture of Ar/CO₂/CF₄. The reason behind using a different detector type lies on
 1303 the different conditions in the forward region like the higher muon rate and higher
 1304 residual magnetic field compared to the central region.

1305

1306 The third type of detector used in the muon system is a set of four disks of RPCs
 1307 working in avalanche mode. The RPCs provide good spatial and time resolutions.
 1308 The track of $high - p_T$ muon candidates is built combining information from the
 1309 tracking system and the signal from up to six RPCs and four DT chambers.
 1310 The muon tracks are reconstructed from the hits in the several layers of the muon

1311 system.

1312 3.3.8 CMS trigger system

1313 Under normal conditions, CMS expects pp collisions every 25 ns, i.e., an interaction
1314 rate of 40 MHz for which it is not possible to store the recorded data in full. In order
1315 to handle this high event rate data, an online event selection, known as triggering, is
1316 performed; triggering reduce the event rate to 100 Hz for storage and further offline
1317 analysis.

1318

1319 The trigger system starts with a reduction of the event rate to 100 kHz in the so-
1320 called *level 1 trigger (L1)*. L1 is based on dedicated programmable hardware like
1321 Field Programmable Gate Arrays (FPGAs) and Application Specific Integrated Cir-
1322 cuits (ASICs), partly located in the detector itself; another portion is located in the
1323 CMS under-ground cavern. Hit patterns information from the muon chambers and
1324 the energy deposits in the calorimeter are used to decide if an event is accepted or
1325 rejected, according to selection requirements previously defined, which reflect the in-
1326 teresting physics processes. Figure 3.18 shows the L1 trigger architecture.

1327

1328 The second stage in the trigger system is called *high-level trigger (HLT)*; events ac-
1329 cepted by L1 are passed to HLT in order to make an initial reconstruction of them.
1330 HLT is software based and runs on a dedicated server farm, using selection algo-
1331 rithms and high-level object definitions; the event rate at HLT is reduced to 100 Hz.
1332 The first HLT stage takes information from the muon detectors and the calorimeters
1333 to make the initial object reconstruction; in the next HLT stage, information from
1334 the pixel and strip detectors is used to do first fast-tracking and then full tracking

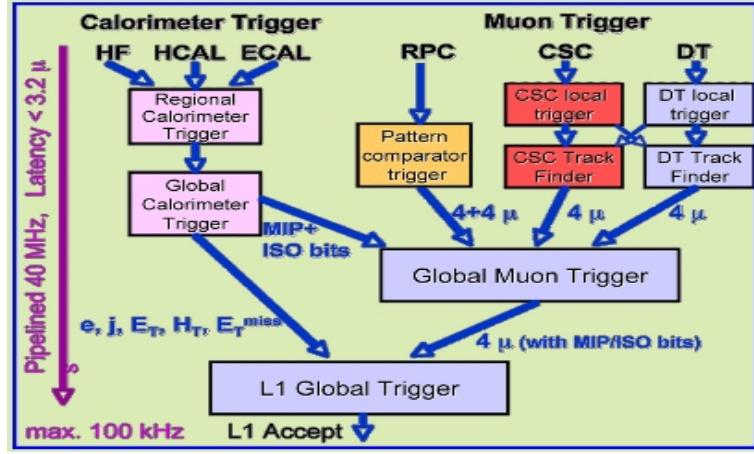


Figure 3.18: CMS Level-1 trigger architecture [82].

1335 online. This initial object reconstruction is used in further steps of the trigger system.

1336

1337 Events and preliminary reconstructed physics objects from HLT are sent to be fully
 1338 reconstructed at the CERN computing center. Again, the pixel detector information
 1339 provides high-quality seeds for the track reconstruction algorithm offline, primary ver-
 1340 tex reconstruction, electron and photon identification, muon reconstruction, τ iden-
 1341 tification, and b-tagging. After full reconstruction, data sets are made available for
 1342 offline analyses.

1343

1344 During the 2016-2017 technical stop, the L1 system was updated in order to improve
 1345 the physics object identification by improving the algorithms and accounting for the
 1346 increasing pile-up scenario.

1347 **3.3.9 CMS computing**

1348 After the data, coming from the experiment, are processed at several levels, they have
 1349 to be stored and made available for further analysis; in order to cope all the tasks
 1350 implied in the offline data processing, like transfer, simulation, reconstruction and

1351 reprocessing, among others, a big computing power is required. The CMS computing
 1352 system is based on the distributed architecture concept, where users of the system
 1353 and physical computer centers are distributed worldwide and interconnected by high-
 1354 speed networks.

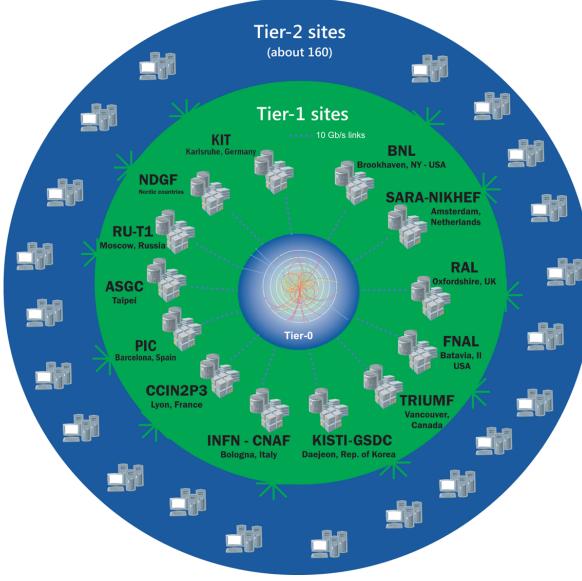


Figure 3.19: WLCG structure. The primary computer centers (Tier-0) are located at CERN (data center) and at the Wigner datacenter in Budapest. Tier-1 is composed of 13 centers and Tier-2 is composed of about 160 centers. [83].

1355 The worldwide LHC computing grid (WLCG) is the mechanism used to provide that
 1356 distributed environment. WLCG is a tiered structure connecting computing centers
 1357 around the world, which provides the necessary storage and computing facilities. The
 1358 primary computing centers of the WLCG are located at the CERN and the Wigner
 1359 datacenter in Budapest and are known as Tier-0 as shown in Figure 3.19. The main
 1360 responsibilities for each tier level are [83]

- 1361 • **Tier-0:** initial reconstruction of recorded events and storage of the resulting
 1362 datasets, the distribution of raw data to the Tier-1 centers.

1363 • **Tier-1:** provide storage capacity, support for the Grid, safe-keeping of a pro-
 1364 portional share of raw and reconstructed data, large-scale reprocessing and safe-
 1365 keeping of corresponding output, generation of simulated events, distribution
 1366 of data to Tier 2s, safe-keeping of a share of simulated data produced at these
 1367 Tier 2s.

1368 • **Tier-2:** store sufficient data and provide adequate computing power for specific
 1369 analysis tasks, provide analysis requirements and proportional share of simu-
 1370 lated event production and reconstruction.

1371 Aside from the general computing strategy to manage the huge amount of data pro-
 1372 duced by experiments, CMS uses a framework to perform a variety of processing,
 1373 selection and analysis tasks. The central concept of the CMS data model referred to
 1374 as *event data model* (EDM) is the *Event*; therefore, an event is the unit that contains
 1375 the information from a single bunch crossing as well as any data derived from that
 1376 information like the reconstructed objects, the details under which additional data
 1377 are derived.

1378

1379 Events are passed as the input to the *physics modules* that obtain information from
 1380 them and create new one; for instance, *event data producers* add new data into the
 1381 events, *analyzers* produce an information summary from an event set, *filters* perform
 1382 selection and triggering.

1383

1384 CMS uses several event formats with different levels of detail and precision

1385 • **Raw format:** events in this format contain the full recorded information from
 1386 the detector as well as trigger decision and other metadata. An extended version

1387 of raw data is used to store information from the CMS Monte Carlo simulation
1388 tools. Raw data are stored permanently, occupying about 2MB/event

1389 • **RECO format:** events in this format correspond to raw data that have been
1390 submitted to reconstruction algorithms like primary and secondary vertex re-
1391 construction, particle ID, track-finding. RECO events contain physical objects
1392 and all the information used to reconstruct them; average size is about 0.5
1393 MB/event.

1394 • **AOD format:** Analysis Object Data (AOD) is the data format used in the
1395 physics analyses given that it contains the parameters describing the high-level
1396 physics objects in addition to enough information to allow a kinematic refitting if
1397 needed. AOD events are filtered versions of the RECO events to which skimming
1398 or other kind processes have been applied. Requires about 100 kB/event.

1399 • **Non-event data** are data needed to interpret and reconstruct events. Some
1400 of the non-event data used by CMS contains information about the detector
1401 contraction and condition data like calibrations, alignment, and detector status.

1402 Figure 3.20 shows the data flow scheme between CMS detector and hardware tiers.
1403 The whole collection of software built as a framework is referred to as *CMSSW*. This
1404 framework provides the services needed by the simulation, calibration and alignment,
1405 and reconstruction modules that process event data, so that physicists can perform
1406 analysis. The CMSSW event processing model is composed of one executable, called
1407 cmsRun, and several plug-in modules which contains all the tools (calibration, recon-
1408 struction algorithms) needed to process an event. The same executable is used for
1409 both detector and Monte Carlo data [84].

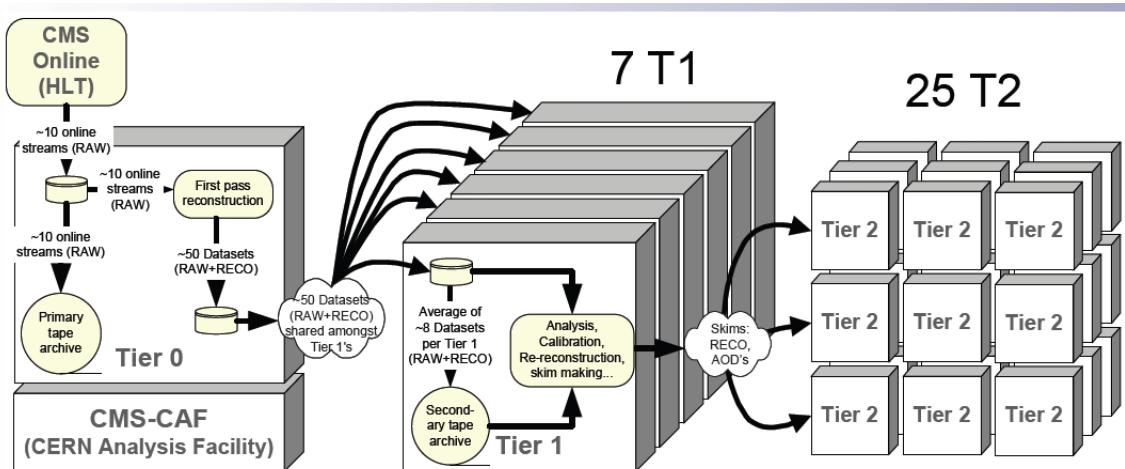


Figure 3.20: Data flow from CMS detector through hardware Tiers.

1410 **Chapter 4**

1411 **Event generation, simulation and
1412 reconstruction**

1413 The process of analyzing data recorded by the CMS experiment involves several stages
1414 where the data are processed in order to interpret the information provided by all
1415 the detection systems; in those stages, the particles produced after the pp collision
1416 are identified by reconstructing their trajectories and measuring their features. In
1417 addition, the SM provides a set of predictions that have to be compared with the
1418 experimental results; however, in most of the cases, theoretical predictions are not
1419 directly comparable to experimental results due to the diverse source of uncertainties
1420 introduced by the experimental setup and theoretical approximations, among others.

1421

1422 The strategy to face these conditions consists in using statistical methods imple-
1423 mented in computational algorithms to produce numerical results that can be con-
1424 trasted with the experimental results. These computational algorithms are commonly
1425 known as Monte Carlo (MC) methods and, in the case of particle physics, they are
1426 designed to apply the SM rules and produce predictions about the physical observ-

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

1432

1433 This chapter presents a description of the event generation strategy and the tools
 1434 used to perform the detector simulation and physics objects reconstruction. A com-
 1435 prehensive review of event generators for LHC physics can be found in Reference [85]
 1436 on which this chapter is based.

1437 4.1 Event generation

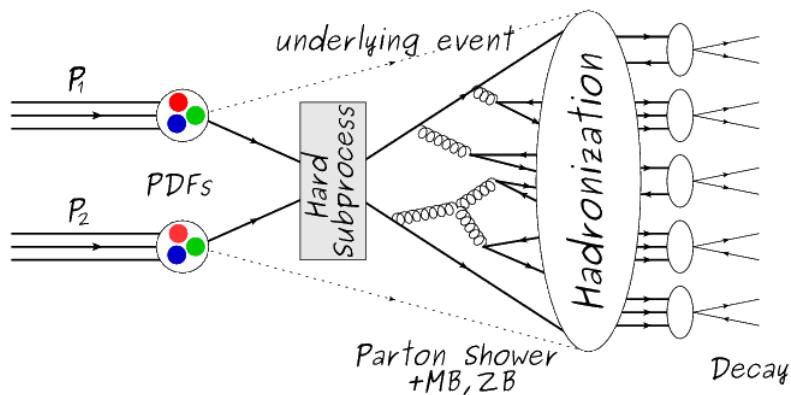


Figure 4.1: Event generation process. The actual interaction is generated in the hard subprocess. The parton shower describes the evolution of the partons from the hard subprocess. Modified from Reference [86].

1438 The event generation is intended to create events that mimic the behavior of actual
 1439 events produced in collisions; they obey a sequence of steps from the particles collision
 1440 hard process to the decay process into the final state. Figure 4.1 shows a schematic
 1441 view of the event generation process; the fact that the full process can be treated as

1442 several independent steps is motivated by the QCD factorization theorem.

1443

1444 Generation starts by taking into account the PDFs of the incoming particles. Event
 1445 generators offer the option to chose from several PDF sets depending on the particu-
 1446 lar process under simulation¹; in the following, pp collisions will be considered. The
 1447 *hard subprocess* describes the actual interaction between partons from the incoming
 1448 protons; it is represented by the matrix element connecting the initial and final states
 1449 of the interaction. Normally, the matrix element can be written as a sum over Feyn-
 1450 man diagrams and consider interferences between terms in the summation. During
 1451 the generation of the hard subprocess, the production cross section is calculated.

1452

1453 The order to which the cross section is calculated depends on the order of the Feyn-
 1454 man diagrams involved in the calculation; therefore, radiative corrections are included
 1455 by considering a higher order Feynman diagrams where QCD radiation dominates.
 1456 Currently, cross sections calculated to LO do not offer a satisfactory description of the
 1457 processes, i.e., the results are only reliable for the shape of distributions; therefore,
 1458 NLO calculations have to be performed with the implication that the computing time
 1459 needed is highly increased.

1460

1461 The final parton content of the hard subprocess is subjected to the *parton shower*
 1462 which generates the gluon radiation. Parton shower evolves the partons, i.e., glouns
 1463 split into quark-antiquark pairs and quarks with enough energy radiate gluons giv-
 1464 ing rise to further parton multiplication, following the DGLAP (Dokshitzer-Gribov-
 1465 Lipatov-Altarelli-Parisi) equations. Showering continues until the energy scale is low
 1466 enough to reach the non-perturbative limit.

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

1467

1468 In the simulation of LHC processes that involve b quarks, like the single top quark
 1469 or Higgs associated production, it is needed to consider that the b quark is heavier
 1470 than the proton; hence, the QCD interaction description is made in two different
 1471 schemes [88]

1472 • four-flavor (4F) scheme. b quarks appear only in the final state because they
 1473 are heavier than the proton and therefore they can be produced only from the
 1474 splitting of a gluon into pairs or singly in association with a t quark in high
 1475 energy-scale interactions; furthermore, during the simulation, the b -PDFs are set
 1476 to zero. Calculations in this scheme are more complicated due to the presence
 1477 of the second b quark but the full kinematics is considered already at LO and
 1478 therefore the accuracy of the description is better.

1479 • five-flavor (5F) scheme. b quarks are considered massless, therefore they can
 1480 appear in both initial and final states since they can now be part of the proton;
 1481 thus, during the simulation b -PDFs are not set to zero. In this scheme, calcu-
 1482 lations are simpler than in the 4F scheme and possible logarithmic divergences
 1483 are absorbed by the PDFs through the DGLAP evolution.

1484 In this thesis, the tHq events are generated using the 4F scheme in order to reduce
 1485 uncertainties, while the tHW events are generated using the 5F scheme to eliminate
 1486 LO interference with $t\bar{t}H$ process [53].

1487

1488 Partons involved in the pp collision are the focus of the simulation, however, the rest
 1489 of the partons inside the incoming protons are also affected because the remnants are
 1490 colored objects; also, multiple parton interactions can occur. The hadronization of
 1491 the remnants and multiple parton interactions are known as *underlying event* and it

1492 has to be included in the simulation. In addition, multiple pp collisions in the same
 1493 bunch crossing (pile-up mentioned in 3.2) occurs, actually in two forms

1494 • *in-time PU* which refers to multiple pp collision in the bunch crossing but that
 1495 are not considered as primary vertices.

1496 • *Out-of-time PU* which refers to overlapping pp collisions from consecutive bunch
 1497 crossings; this can occur due to the time-delays in the detection systems where
 1498 information from one bunch crossing is assigned to the next or previous one.

1499 While the underlying event effects are included in generation using generator-specific
 1500 tools, PU effects are added to the generation by overlaying Minimum-bias (MB) and
 1501 Zero-bias (ZB) events to the generated events. MB events are inelastic events se-
 1502 lected by using a loose trigger with as little bias as possible, therefore accepting a
 1503 large fraction of the overall inelastic event; ZB events correspond to random events
 1504 recorded by the detector when collisions are likely. MB models in-time PU and ZB
 1505 models out-of-time PU.

1506

1507 The next step in the generation process is called *hadronization*. Since particles with
 1508 a net color charge are not allowed to exits isolated, they have to recombine to form
 1509 bound states. This is precisely the process by which the partons resulting from the
 1510 parton shower arrange themselves as color singlets to form hadrons. At this step, the
 1511 energy-scale is low and the strong coupling constant is large, therefore hadronization
 1512 process is non-perturbative and the evolution of the partons is described using phe-
 1513 nomenological models. Most of the baryons and mesons produced in the hadronization
 1514 are unstable and hence they will decay in the detector.

1515

1516 The last step in the generation process corresponds to the decay of the unstable
 1517 particles generated during hadronization; it is also simulated in the hadronization
 1518 step, based on the known branching ratios.

1519 **4.2 Monte Carlo Event Generators.**

1520 The event generation described in the previous section has been implemented in
 1521 several software packages for which a brief description is given.

1522 • **PYTHIA 8.** It is a program designed to perform the generation of high energy
 1523 physics events which describes the collisions between particles such as electrons
 1524 and protons. Several theories and models are implemented in it, in order to
 1525 describe physical aspects like hard and soft interaction, parton distributions,
 1526 initial and final-state parton showers, multiple parton interactions, beam rem-
 1527 nants, hadronization² and particle decay. Thanks to extensive testing, several
 1528 optimized parametrizations, known as *tunings*, have been defined in order to
 1529 improve the description of actual collisions to a high degree of precision; for
 1530 analysis at $\sqrt{s} = 13$ TeV, the underline event CUETP8M1 tune is employed [90].
 1531 The calculation of the matrix element is performed at LO which is not enough
 1532 for the current required level of precision; therefore, pythia is often used for
 1533 parton shower, hadronization and decays, while other event generators are used
 1534 to generate the matrix element at NLO.

1535 • **MadGraph5_aMC@NLO.** MadGraph is a matrix element generator which
 1536 calculates the amplitudes for all contributing Feynman diagrams of a given pro-
 1537 cess but does not provide a parton shower while MC@NLO incorporates NLO

² based in the Lund string model [89]

1538 QCD matrix elements consistently into a parton shower framework; thus, Mad-
 1539 Graph5_aMC@NLO, as a merger of the two event generators MadGraph5 and
 1540 aMC@NLO, is an event generator capable to calculate tree-level and NLO cross
 1541 sections and perform the matching of those with the parton shower. It is one of
 1542 the most frequently used matrix element generators; however, it has the partic-
 1543 ular feature of the presence of negative event weights which reduce the number
 1544 of events used to reproduce the properties of the objects generated [91].

1545

1546 • **POWHEG.** It is an NLO matrix element generator where the hardest emis-
 1547 sion of color charged particles is generated in such a way that the negative event
 1548 weights issue of MadGraph5_aMC@NLO is overcome; however, the method re-
 1549 quires an interface with p_T -ordered parton shower or a parton shower generator
 1550 where this highest emission can be vetoed in order to avoid double counting of
 1551 this highest-energetic emission. PYTHIA is a commonly matched to POWHEG
 1552 event generator [92].

1553 Events resulting from the whole generation process are known as MC events.

1554 4.3 CMS detector simulation.

1555 After generation, MC events contain the physics of the collisions but they are not
 1556 ready to be compared to the events recorded by the experiment since these recorded
 1557 events correspond to the response of the detection systems to the interaction with
 1558 the particles traversing them. The simulation of the CMS detector has to be applied
 1559 on top of the event generation; it is simulated with a MC toolkit for the simulation
 1560 of particles passing through matter called Geant4 which is also able to simulate the

1561 electronic signals that would be measured by all detectors inside CMS.

1562

1563 The simulation takes the generated particles contained in the MC events as input,
1564 makes them pass through the simulated geometry, and models physics processes that
1565 particles experience during their passage through matter. The full set of results from
1566 particle-matter interactions corresponds to the simulated hit which contains informa-
1567 tion about the energy loss, momentum and position. Particles of the input event are
1568 called *primary*, while the particles originating from GEANT4-modeled interactions of
1569 a primary particle with matter are called a *secondary*. Simulated hits are the input
1570 of subsequent modules that emulate the response of the detector readout system and
1571 triggers. The output from the emulated detection systems and triggers is known as
1572 digitization [93, 94].

1573

1574 The modeling of the CMS detector corresponds to the accurate modeling of the
1575 interaction among particles, the detector material, and the magnetic field. This
1576 simulation procedure includes the following standard steps

1577 • Modeling of the Interaction Region.

1578 • Modeling of the particle passage through the hierarchy of volumes that compose
1579 CMS detector and of the accompanying physics processes.

1580 • Modeling of the effect of multiple interactions per beam crossing and/or the
1581 effect of events overlay (Pile-Up simulation).

1582 • Modeling of the detector's electronics response, signal shape, noise, calibration
1583 constants (digitization).

1584 In addition to the full simulation, i.e., a detailed detector simulation, a faster simu-
 1585 lation (FastSim) have been developed, that may be used where much larger statistics
 1586 are required. In FastSim, detector material effects are parametrized and included in
 1587 the hits; those hits are used as input of the same higher-level algorithms³ used to an-
 1588 alyze the recorded events. In this way, comparisons between fast and full simulations
 1589 can be performed [96].

1590

1591 After the full detector simulation, the output events can be directly compared to
 1592 events actually recorded in the CMS detector. The collection of MC events that
 1593 reproduces the expected physics for a given process is known as MC sample.

1594 **4.4 Event reconstruction.**

1595 The CMS experiment use the *particle-flow event reconstruction algorithm (PF)* to do
 1596 the reconstruction of particles produced in pp collisions. Next sections will present
 1597 a basic description of the *Elements* used by PF (tracker tracks, energy clusters, and
 1598 muon tracks), based in the References [97, 98] where more detailed descriptions can
 1599 be found.

1600 **4.4.1 Particle-Flow Algorithm.**

1601 Each of the several sub detection systems of the CMS detector is dedicated to identify
 1602 a specific type of particles, i.e., photons and electrons are absorbed by the ECAL
 1603 and their reconstruction is based on ECAL information; hadrons are reconstructed
 1604 from clusters in the HCAL while muons are reconstructed from hits in the muon

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

1605 chambers. PF is designed to correlate signals from all the detector layers (tracks and
 1606 energy clusters) in order to reconstruct and identify each final state particle and its
 1607 properties as sketched in Figure 4.2.

1608

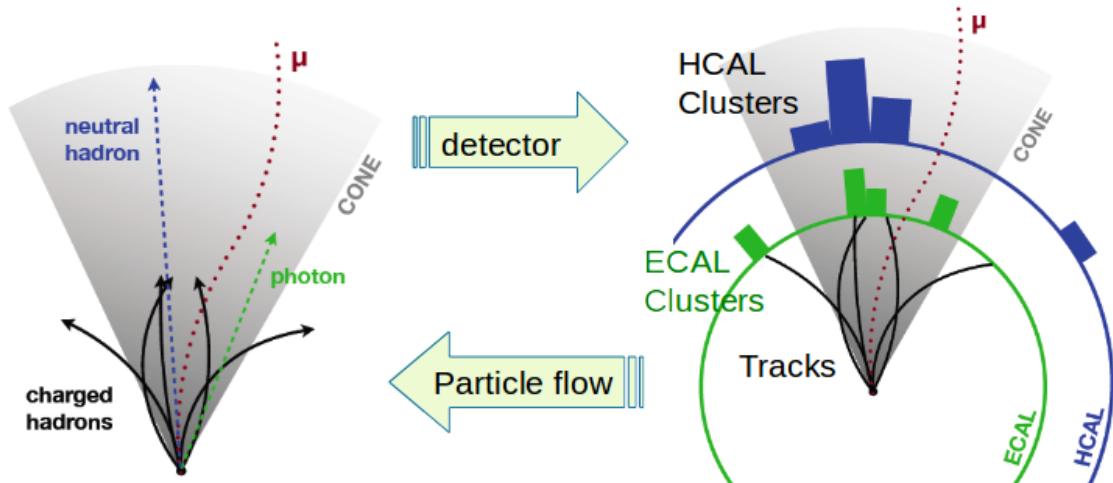


Figure 4.2: Particle flow algorithm. Information from the several CMS detection systems is provided as input to the algorithm which then combine it to identify and reconstruct all the particles in the final state and their properties. Reconstruction of simulated events is also performed by providing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

1609 For instance, a charged hadron is identified by a geometrical connection, known as
 1610 *link*, between one or more calorimeter clusters and a track in the tracker, provided
 1611 there are no hits in the muon system; combining several measurements allows a better
 1612 determination of the energy and charge sign of the charged hadron.

1613 Charged-particle track reconstruction.

1614 The strategy used by PF in order to reconstruct tracks is called *Iterative Tracking*
 1615 which occurs in four steps

- 1616 • Seed generation where initial track candidates are found by looking for a combi-
 1617 nation of hits in the pixel detector, strip tracker, and muon chambers. In total

1618 ten iterations are performed, each one with a different seeding requirement.
 1619 Seeds are used to estimate the trajectory parameters and uncertainties at the
 1620 time of the full track reconstruction. Seeds are also considered track candidates.

- 1621 • Track finding using a tracking software known as Combinatorial Track Finder
 (CTF) [100]. The seed trajectories are extrapolated along the expected flight
 path of a charged particle, in agreement to the trajectory parameters obtained
 in the first step, in an attempt to find additional hits that can be assigned to
 the track candidates.
- 1626 • Track-fitting where the found tracks are passed as input to a module which
 provides the best estimate of the parameters of each trajectory.
- 1628 • Track selection where track candidates are submitted to a selection which dis-
 cards those that fail a set of defined quality criteria.

1630 Iterations differ in the seeding configuration and the final track selection as elaborated
 1631 in References [97, 98]. In the first iteration, high p_T tracks and tracks produced near
 1632 to the interaction region are identified and those hits are masked thereby reducing
 1633 the combinatorial complexity. Next, iterations search for more complicated tracks,
 1634 like low p_T tracks and tracks from b hadron decays, which tend to be displaced from
 1635 the interaction region.

1636 **Vertex reconstruction.**

1637 During the track reconstruction, an extrapolation toward to the calorimeters is per-
 1638 formed in order to match energy deposits; that extrapolation is performed also toward
 1639 the beamline in order to find the origin of the track known as *vertex*. The vertex re-
 1640 construction is performed by selecting from the available reconstructed tracks, those

1641 that are consistent with being originated in the interaction region where pp collisions
 1642 are produced. The selection involves a requirement on the number of tracker (pixel
 1643 and strip) hits and the goodness of the track fit.

1644

1645 Selected tracks are clustered using a *deterministic annealing algorithm* (DA)⁴. A set
 1646 of candidate vertices and their associated tracks, resulting from the DA, are then fit-
 1647 ted with an *adaptive vertex fitter* (AVF) to produce the best estimate of the vertices
 1648 locations.

1649

1650 The p_T of the tracks associated to a reconstructed vertex is added, squared and used
 1651 to organize the vertices; the vertex with the highest squared sum is designated as the
 1652 *primary vertex* (PV) while the rest are designated as PU vertices.

1653 Calorimeter clustering.

1654 After traversing the CMS tracker system, electrons, photons and hadrons deposit their
 1655 energy in the ECAL and HCAL cells. The PF clustering algorithm aims to provide
 1656 a high detection efficiency even for low-energy particles and an efficient distinction
 1657 between close energy deposits. The clustering runs independently in the ECAL barrel
 1658 and endcaps, HCAL barrel and endcaps, and the two preshower layers, following two
 1659 steps

- 1660 ● cells with an energy larger than a given seed threshold and larger than the energy
 1661 of the neighboring cells are identified as cluster seeds. The neighbor cells are
 1662 those that either share a side with the cluster seed candidate, or the eight closest
 1663 cells including cells that only share a corner with the seed candidate.

⁴ DA algorithm and AVF are described in detail in References [102, 103]

1664 • cells with at least a corner in common with a cell already in the cluster seed
 1665 and with an energy above a cell threshold are grouped into topological clusters.

1666 Clusters formed in this way are known as *particle-flow clusters*. With this clustering
 1667 strategy, it is possible to detect and measure the energy and direction of photons and
 1668 neutral hadrons as well as differentiate these neutral particles from the charged hadron
 1669 energy deposits. In cases involving charged hadrons for which the track parameters
 1670 are not determined accurately, for instance, low-quality and high- p_T tracks, clustering
 1671 helps in the energy measurements.

1672 **Electron track reconstruction.**

1673 Although the charged-particle track reconstruction described above works for elec-
 1674 trons, they lose a significant fraction of their energy via bremsstrahlung photon radi-
 1675 ation before reaching the ECAL; thus, the reconstruction performance depends on the
 1676 ability to measure also the radiated energy. The reconstruction strategy, in this case,
 1677 requires information from the tracking system and from the ECAL. Bremsstrahlung
 1678 photons are emitted at similar η values to that of the electron but at different values
 1679 of ϕ ; therefore, the radiated energy can be recovered by grouping ECAL clusters in a
 1680 η window over a range of ϕ around the electron direction. The group is called ECAL
 1681 supercluster.

1682

1683 Electron candidates from the track-seeding and ECAL super clustering are merged
 1684 into a single collection which is submitted to a full electron tracking fit with a
 1685 Gaussian-sum filter (GSF) [101]. The electron track and its associated ECAL su-
 1686 percluster form a *particle-flow electron*.

1687 **Muon track reconstruction.**

1688 Given that the CMS detector is equipped with a muon spectrometer capable to iden-
 1689 tify and measure the momentum of the muons traversing it, the muon reconstruction
 1690 is not specific to PF; therefore, three different muon types are defined

- 1691 • *Standalone muon.* A clustering on the DTs or CSCs hits is performed to form
 1692 track segments; those segments are used as seeds for the reconstruction in the
 1693 muon spectrometer. All DTs, CSCs, and RPCs hits along the muon trajectory
 1694 are combined and fitted to form the full track. The fitting output is called a
 1695 *standalone-muon track*.
- 1696 • *Tracker muon.* Each track in the inner tracker with p_T larger than 0.5 GeV and
 1697 a total momentum p larger than 2.5 GeV is extrapolated to the muon system.
 1698 A *tracker muon track* corresponds to a extrapolated track that matches at least
 1699 one muon segment.
- 1700 • *Global muon.* When tracks in the inner tracker (inner tracks) and standalone-
 1701 muon tracks are matched and turn out being compatibles, their hits are com-
 1702 bined and fitted to form a *global-muon track*.

1703 Global muons sharing the same inner track with tracker muons are merged into a
 1704 single candidate. PF muon identification uses the muon energy deposits in ECAL,
 1705 HCAL, and HO associated with the muon track to improve the muon identification.

1706 **Particle identification and reconstruction.**

1707 PF elements are connected by a linker algorithm that tests the connection between any
 1708 pair of elements; if they are found to be linked, a geometrical distance that quantifies
 1709 the quality of the link is assigned. Two elements may be linked indirectly through

1710 common elements. Linked elements form *PF blocks* and each PF block may contain
 1711 elements originating in one or more particles. Links can be established between
 1712 tracks, between calorimeter clusters, and between tracks and calorimeter clusters.
 1713 The identification and reconstruction start with a PF block and proceed as follows

1714 • Muons. An *isolated global muon* is identified by evaluating the presence of
 1715 inner track and energy deposits close to the global muon track in the (η, ϕ)
 1716 plane, i.e., in a particular point of the global muon track, inner tracks and
 1717 energy deposits are sought within a radius of $\Delta R = 0.3$ (see eqn. 3.7) from the
 1718 muon track; if they exit and the p_T of the found track added to the E_T of the
 1719 found energy deposit does not exceed 10% of the muon p_T then the global muon
 1720 is an isolated global muon. This isolation condition is stringent enough to reject
 1721 hadrons misidentified as muons.

1722 *Non-isolated global muons* are identified using additional selection requirements
 1723 on the number of track segments in the muon system and energy deposits along
 1724 the muon track. Muons inside jets are identified with more stringent criteria
 1725 in isolation and momentum as described in Reference [104]. The PF elements
 1726 associated with an identified muon are masked from the PF block.

1727 • Electrons are identified and reconstructed as described above plus some addi-
 1728 tional requirements on fourteen variables like the amount of energy radiated,
 1729 the distance between the extrapolated track position at the ECAL and the po-
 1730 sition of the associated ECAL supercluster, among others, which are combined
 1731 in an specialized multivariate analysis strategy that improves the electron iden-
 1732 tification. Tracks and clusters used to identify and reconstruct electrons are
 1733 masked in the PF block.

- 1734 ● Isolated photons are identified from ECAL superclusters with E_T larger than 10
 1735 GeV, for which the energy deposited at a distance of 0.15, from the supercluster
 1736 position on the (η,ϕ) plane, does not exceed 10% of the supercluster energy;
 1737 note that this is an isolation requirement. In addition, there must not be links
 1738 to tracks. Clusters involved in the identification and reconstruction are masked
 1739 in the PF block.

- 1740 ● Bremsstrahlung photons and prompt photons tend to convert to electron-positron
 1741 pairs inside the tracker, therefore, a dedicated finder algorithm is used to link
 1742 tracks that seem to originate from a photon conversion; in case those two tracks
 1743 are compatible with the direction of a bremsstrahlung photon, they are also
 1744 linked to the original electron track. Photon conversion tracks are also masked
 1745 in the PF block.

- 1746 ● The remaining elements in the PF block are used to identify hadrons. In the
 1747 region $|\eta| \leq 2.5$, neutral hadrons are identified with HCAL clusters not linked
 1748 to any track while photons from neutral pion decays are identified with ECAL
 1749 clusters without links to tracks. In the region $|\eta| > 2.5$ ECAL clusters linked to
 1750 HCAL clusters are identified with a charged or neutral hadron shower; ECAL
 1751 clusters with no links are identified with photons. HCAL clusters not used yet,
 1752 are linked to one or more unlinked tracks and to an unlinked ECAL in order to
 1753 reconstruct charged-hadrons or a combination of photons and neutral hadrons
 1754 according to certain conditions on the calibrated calorimetric energy.

- 1755 ● Charged-particle tracks may be liked together when they converge to a *sec-
 1756 ondary vertex (SV)* displaced from the IP where the PV and PU vertices are
 1757 reconstructed; at least three tracks are needed in that case, of which at most one

1758 has to be an incoming track with hits in tracker region between a PV and the SV.

1759

1760 The linker algorithm, as well as the whole PF algorithm, has been validated and
 1761 commissioned; results from that validation are presented in the Reference [97].

1762 **Jet reconstruction.**

1763 Quarks and gluons may be produced in the pp collisions, therefore, their hadronization
 1764 will be seen in the detector as a shower of hadrons and their decay products in the
 1765 form of a *jet*. The anti- k_t algorithm [105] is used to perform the jet reconstruction
 1766 by clustering those PF particles within a cone (see Figure 4.3); previously, isolated
 1767 electrons, isolated muons, and charged particles associated with other interaction
 1768 vertices are excluded from the clustering.

1769 The anti- k_t algorithm proceeds in a sequential recombination of PF particles; the
 1770 distance between particles i and j (d_{ij}) and the distance between particles and the
 1771 beam are defined as

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

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

1772 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-
 1773 pidity and azimuth of particle i respectively and R is the called jet radius. For all
 1774 the remaining PF particles, after removing the isolated ones, d_{ij} and d_{iB} are calcu-
 1775 lated⁵ and the smallest is identified; if it is a d_{ij} , particles i and j are replaced with

⁵ Notice that this is a combinatorial calculation.

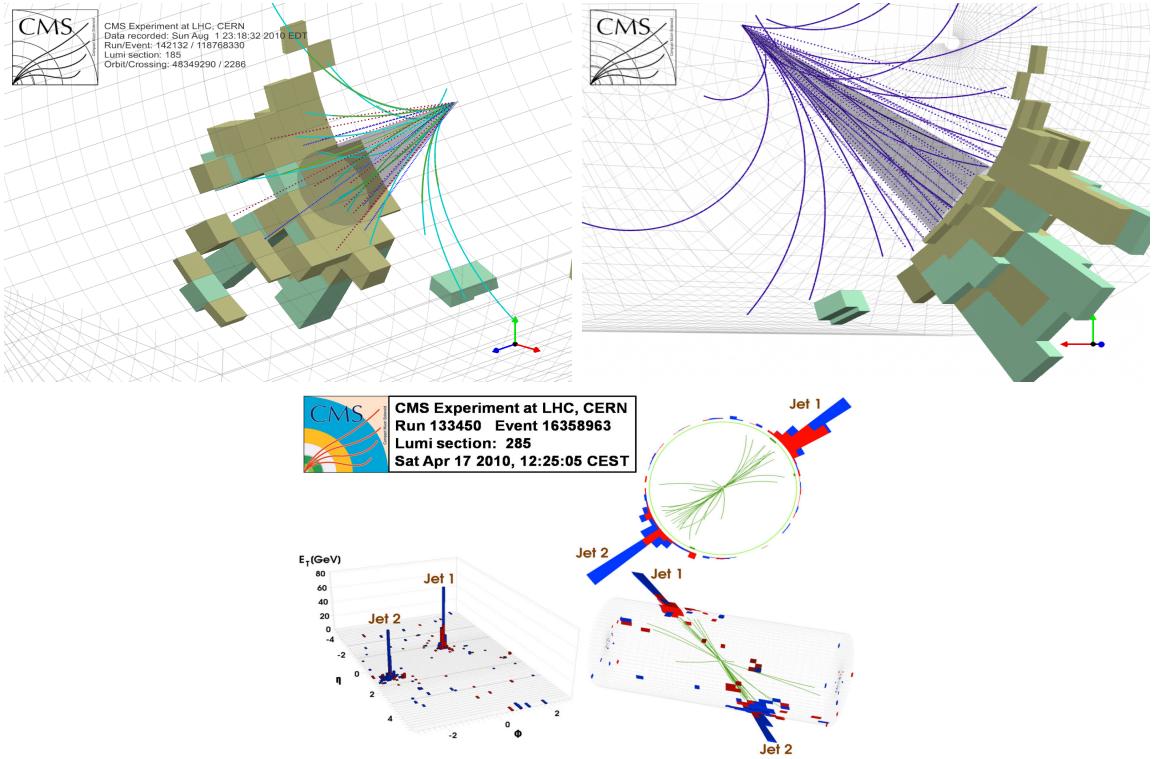


Figure 4.3: Jet reconstruction performed by the anti- k_t algorithm. Top: Two different views of a CMS recorded event are presented. Continuous lines correspond to tracks left by charged particles in the tracker while dotted lines are the imaginary paths followed by neutral particles. The green cubes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

1776 a new object whose momentum is the vectorial sum of the combined particles. If the
 1777 smallest distance is a d_{iB} the clustering process ends, the object i (which at this stage
 1778 should be a combination of several PF particles) is declared as a *Particle-flow-jet* (PF
 1779 jet) and all the associated PF particles are removed from the detector. The clustering
 1780 process is repeated until no PF particles remain.

1781 Even though jets can be reconstructed efficiently, there are some effects that are not in-
 1782 cluded in the reconstruction and that lead to discrepancies between the reconstructed
 1783 results and the predicted results; in order to overcome these discrepancies, a factor-
 1784 ized model has been designed in the form of jet energy corrections (JEC) [108, 109]

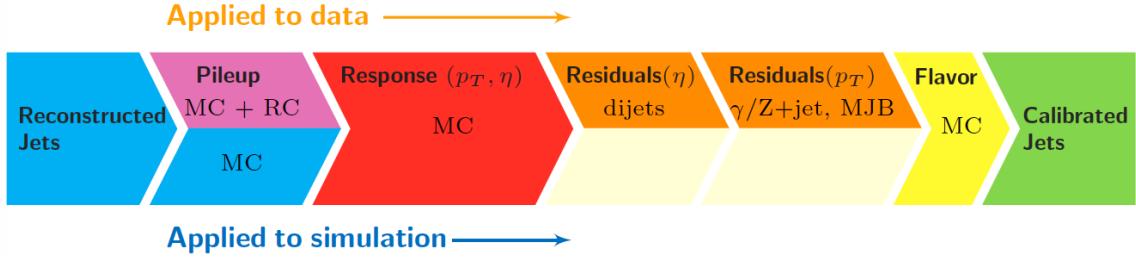


Figure 4.4: Jet energy correction diagram. Correction levels are applied sequentially in the indicated fixed order [109].

1785 applied sequentially as shown in the diagram of Figure 4.4.

1786 At each level, the jet four-momentum is multiplied by a scaling factor based on jet
1787 properties, i.e., η , flavor, etc.

1788 • Level 1 correction removes the energy coming from pile-up. The scale factor is
1789 determined using a MC sample of QCD dijet (2 jets) events with and without
1790 pileup overlay; it is parametrized in terms of the offset energy density ρ , jet
1791 area A , jet η and jet p_T . Different corrections are applied to data and MC due
1792 to the detector simulation.

1793 • MC-truth correction accounts for differences between the reconstructed jet en-
1794 ergy and the MC particle-level energy. The correction is determined on a QCD
1795 dijet MC sample and is parametrized in terms of the jet p_T and η .

1796 • Residuals correct remaining small differences within jet response in data and
1797 MC. The Residuals η -dependent correction compares jets of similar p_T in the
1798 barrel reference region. The Residuals p_T -dependent correct the jet absolute
1799 scale (JES vs p_T).

1800 • Jet-flavor corrections are derived in the same way as MC-truth corrections but
1801 using QCD pure flavor samples.

1802 ***b*-tagging of jets.**

1803 A particular feature of the hadrons containing bottom quarks (*b*-hadrons) is that
 1804 their lifetime is long enough to travel some distance before decaying, but it is not as
 1805 long as those of light quark hadrons; therefore, when looking at the hadrons produced
 1806 in pp collisions, *b*-hadrons decay typically inside the tracker rather than reaching the
 1807 calorimeters as some light-hadrons do. As a result, a *b*-hadron decay gives rise to a
 1808 displaced vertex (secondary vertex) with respect to the primary vertex as shown in
 1809 Figure 4.5; the SV displacement is in the order of a few millimeters. A jet resulting
 1810 from the decay of a *b*-hadron is called *b* jet; other jets are called light jets.

1811

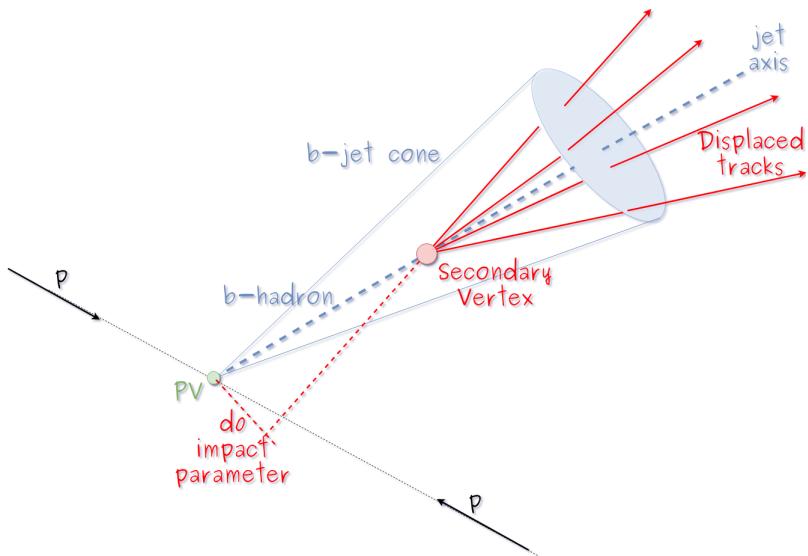


Figure 4.5: Secondary vertex in a *b*-hadron decay.

1812 Several methods to identify *b*-jets (*b*-tagging) have been developed; the method used
 1813 in this thesis is known as *Combined Secondary Vertex* algorithm in its second version
 1814 (CSVv2) [110]. By using information of the impact parameter, the reconstructed
 1815 secondary vertices, and the jet kinematics as input in a multivariate analysis that
 1816 combines the discrimination power of each variable in one global discriminator vari-

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

4.4.1.1 Missing transverse energy.

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

1831

1832 The PF algorithm assigns the negative sum of the momenta of all reconstructed PF
1833 particles to the *particle-flow MET* according to

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

1834 JEC are propagated to the calculation of the \vec{E}_T as described in the Reference [111].

1835

1836 **4.4.2 Event reconstruction examples**

1837 Figures 4.6-4.8 show the results of the reconstruction performed on 3 recorded events.

1838 Descriptions are taken directly from the source.

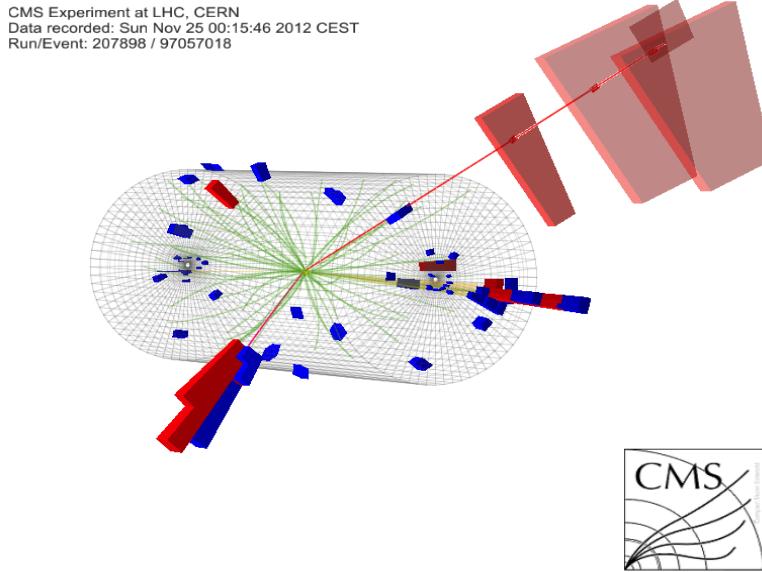


Figure 4.6: HIG-13-004 Event 1 reconstruction results; “HIG-13-004 Event 1: Event recorded with the CMS detector in 2012 at a proton-proton center-of-mass energy of 8 TeV. The event shows characteristics expected from the decay of the SM Higgs boson to a pair of τ leptons. Such an event is characterized 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.” [112].

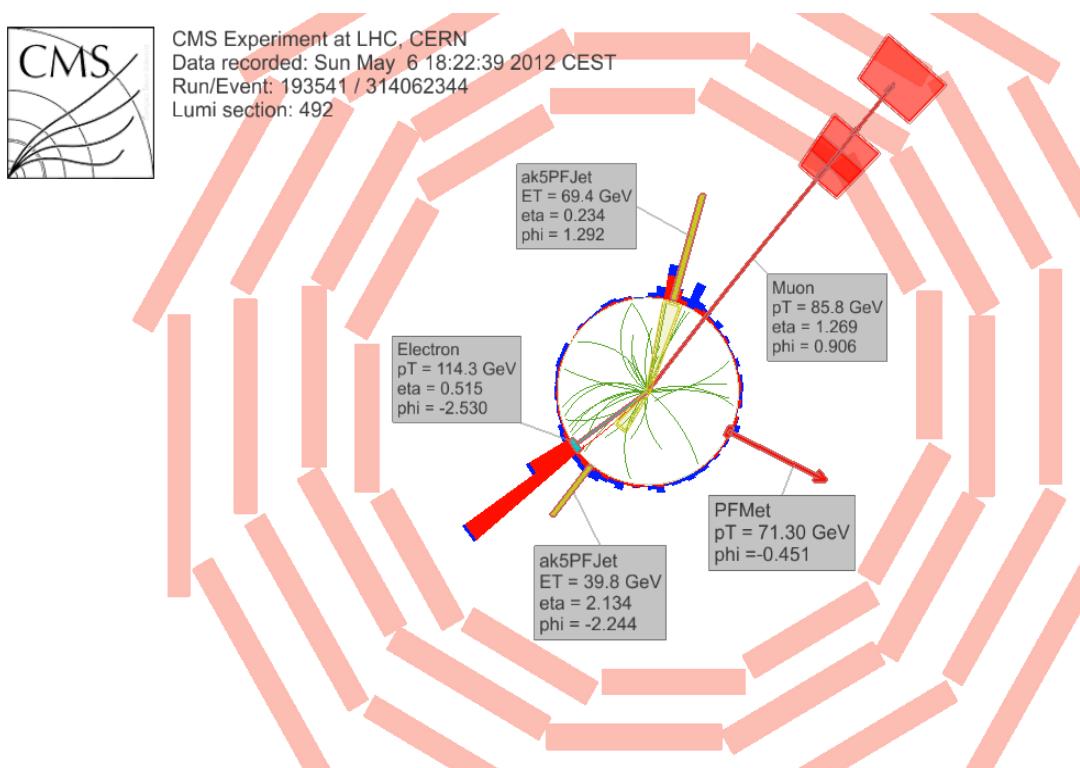


Figure 4.7: $e\mu$ event reconstruction results; “An $e\mu$ event candidate selected in 8 TeV data, as seen from the direction of the proton beams. The kinematics of the main objects used in the event selection are highlighted: two isolated leptons and two particle-flow jets. The reconstructed missing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

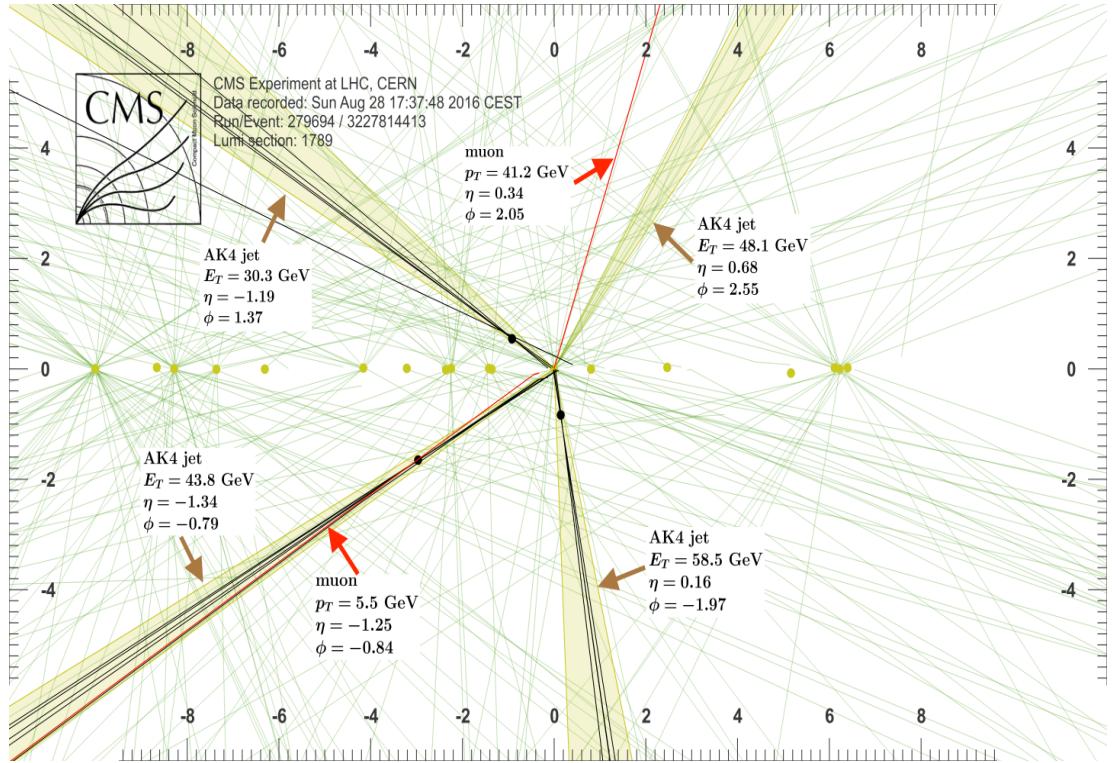


Figure 4.8: Recorded event reconstruction results;“Recorded event (ρ - z projection) with three jets with $p_T > 30$ GeV with one displaced muon track in 2016 data collected at 13 TeV. Each of the three jets has a displaced reconstructed vertex. The jet with $p_T(j) = 43.8$ GeV, $\eta(j) = -1.34$, $\phi(j) = -0.79$ 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” [114].

1839 **Chapter 5**

1840 **Statistical methods**

1841 In the course of analyzing the data sets provided by the CMS experiment and used in
1842 this thesis, several statistical tools have been employed; in this chapter, a description
1843 of these tools will be presented, starting with the general statement of the multivariate
1844 analysis method, followed by the particularities of the Boosted Decision Trees (BDT)
1845 method and its application to the classification problem. Statistical inference methods
1846 used will also be presented. This chapter is based mainly on the references [115–117].

1847 **5.1 Multivariate analysis**

1848 Multivariate data analysis (MVA) makes reference to statistical techniques that an-
1849 alyze data containing information of more than one variable, commonly taking into
1850 account the effects of all variables on the response of the particular variable under
1851 investigation, i.e., considering all the correlations between variables. MVA is em-
1852 ployed in a variety of fields like consumer and market research, quality control and
1853 process optimization. From a MVA it is possible to identify the dominant patterns
1854 in the data, like groups, outliers and trends, and determine to which group a set of

1855 values belong; in the particle physics context, MVA methods are used to perform the
 1856 selection of certain type of events, from a large data set, using a potentially large
 1857 number of measurable properties for each event.

1858 Processes with small cross section, as the tHq process, normally are hidden behind
 1859 more common processes; therefore, the data set results in a subset of events with
 1860 characteristic features of interest (signal) mixed in randomly with a much larger
 1861 number of SM events that can mimic these features of interest (background) which
 1862 implies that it is not possible to say with certainty that a given event is signal or
 1863 background. In that sense, the problem can be formulated as one where a set of
 1864 events have to be classified according to some features; these features correspond to
 1865 the measurements of several parameters like energy or momentum, organized in a
 1866 set of *input variables*. The measurements for each event can be written in a vector
 1867 $\mathbf{x} = (x_1, \dots, x_n)$ for which

- 1868 • Signal hypotheses $\rightarrow f(\mathbf{x}|s)$ is the probability density (*likelihood function*) that
 1869 \mathbf{x} is the set of measured values given that the event is a signal event.
- 1870 • Background hypotheses $\rightarrow f(\mathbf{x}|b)$ is the probability density (*likelihood function*)
 1871 that \mathbf{x} is the set of measured values given that the event is a background event.

1872 Figure 5.1 shows three ways to perform a classification of events for which mea-
 1873 surements of two properties, two input variables, have been performed; blue circles
 1874 represent signal events while red triangles represent background events. The classi-
 1875 fication on (a) is *cut-based* requiring $x_1 < c_1$ and $x_2 < c_2$; usually the cut values are
 1876 chosen according to some knowledge about the event process. In (b), the classification
 1877 is performed by stating a cut involving a linear function of the input variables and
 1878 so the boundary, while in (c) the relationship between the input variables is not
 1879 linear thus the boundary is not linear either.

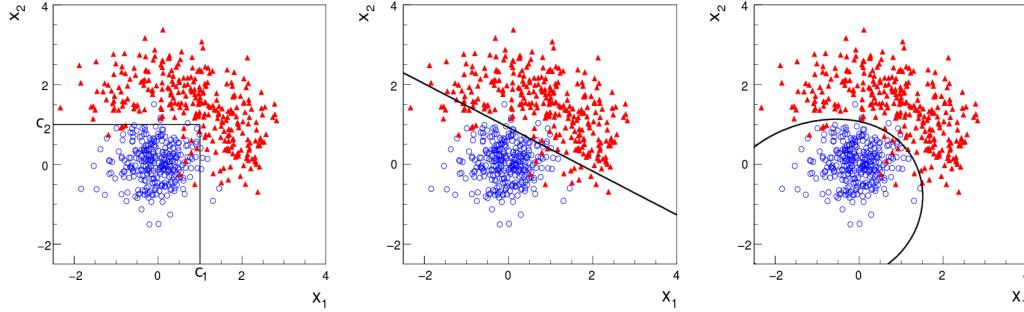


Figure 5.1: Scatter plots-MVA event classification. Distribution of two input variables x_1 and x_2 measured for a set of events; blue circles represent signal events and red triangles represent background events. The classification is based on (a) cuts, (b) linear boundary, and (c) nonlinear boundary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

1880 The boundary can be parametrized in terms of the input variables such that the
 1881 cut is set on the parametrization instead of on the variables, i.e., $y(\mathbf{x}) = y_{cut}$ with
 1882 y_{cut} a constant; thus, the acceptance or rejection of an event is based on what side
 1883 of the boundary is the event located. If $y(\mathbf{x})$ has functional form, it can be used to
 1884 determine the probability distribution functions $p(y|s)$ and $p(y|b)$ and then perform
 1885 a scalar test statistic with a single cut on the scalar variable y .

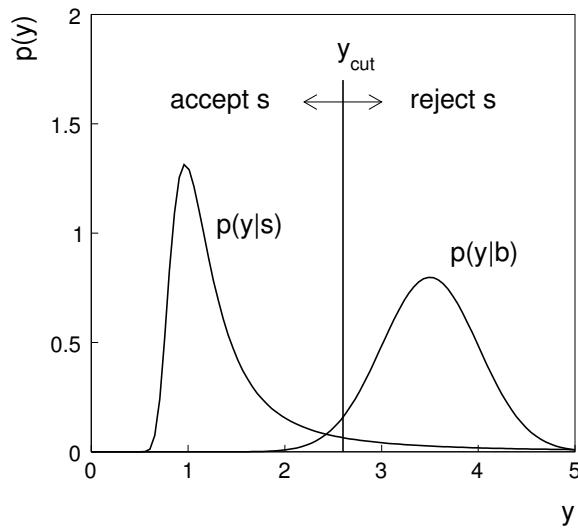


Figure 5.2: Distributions of the scalar test statistic $y(\mathbf{x})$ under the signal and background hypotheses. [115]

1886 Figure 5.2 illustrates what would be the probability distribution functions under
 1887 the signal and background hypotheses for a scalar test statistic with a cut on the
 1888 classifier y . Notice that the tails of the distributions indicate that some signal events
 1889 fall on the rejection region and some background events fall on the acceptance region;
 1890 therefore, it is convenient to define the *efficiency* with which events of a given type
 1891 are accepted, thus, the signal and background efficiencies are given by

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

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

1892 where A is the acceptance region. Under these conditions, the background hypothesis
 1893 corresponds to the *null hypothesis* (H_0), the signal hypothesis corresponds to the
 1894 *alternative hypothesis* (H_1), the background efficiency is the significance level of the
 1895 test, and signal efficiency is the power of the test; what is sought in an analysis is to
 1896 maximize the power of the test relative to the significance level.

1897 5.1.1 Decision trees

1898 For this thesis, the implementation of the MVA strategy, described above, is per-
 1899 formed through decision trees by using the TMVA software package [116] included in
 1900 the the ROOT analysis framework [118]. In a simple picture, a decision tree classifies
 1901 events according to their input variables values by setting a cut on each input variable
 1902 and checking which events are on which side of the cut, just as proposed in the MVA
 1903 strategy, but in addition, as a machine learning algorithm, decision trees offer the
 1904 possibility to be trained and then perform the classification efficiently.

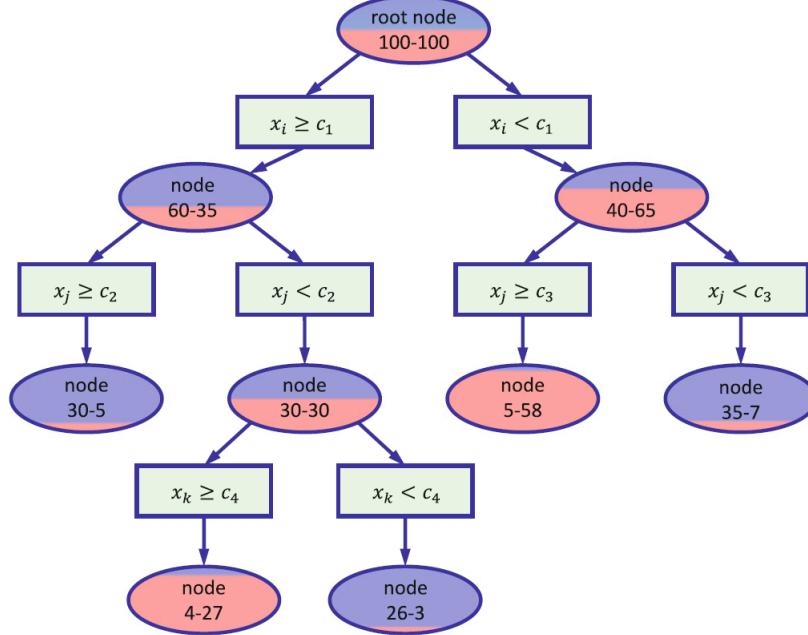


Figure 5.3: Example of a decision tree. Each node is fed with a MC sample mixing signal and background events (left-right numbers); nodes colors represent the relative amount of signal/background events [117].

1905 The training or growing of a decision tree is the process that defines the rules for
 1906 classifying events; this process is represented in figure5.3 and consist of several steps

1907 • take MC samples of signal and background events and split them into two parts
 1908 each; first parts form the training sample which will be used in the decision tree
 1909 training, while the second parts form the test sample which will be used for
 1910 testing the final classifier obtained from the training. Each event has associated
 1911 a set of input variables $\mathbf{x} = (x_1, \dots, x_n)$ which serve to distinguish between signal
 1912 and background events. The training sample is taken in at the root *node*.

1913 • pick one variable, say x_i
 1914 • pick one value of x_i , each event has its own value of x_i , and split the training
 1915 sample into two subsamples B_1 and B_2 ; B_1 contains events for which $x_i < c_1$

- 1916 while B_2 contains the rest of the training events;
- 1917 • scan all possible values of x_i and find the splitting value that provides the *best*
 1918 classification¹, i.e., B_1 is mostly made of signal events while B_2 is mostly made
 1919 of background events.
- 1920 • It is possible that variables other than the picked one produce a better classi-
 1921 fication, hence, all the variables have to be evaluated. Pick the next variable,
 1922 say x_j , and repeat the scan over its possible values.
- 1923 • At the end, all the variables and their values will have been scanned, the *best*
 1924 variable and splitting value will have been identified, say x_1, c_1 , and there will
 1925 be two nodes fed with the subsamples B_1 and B_2 .
- 1926 Nodes are further split by repeating the decision process until: a given number of
 1927 final nodes is obtained, nodes are largely dominated by either signal or background
 1928 events, or nodes has too few events to continue. Final nodes are called *leaves* and they
 1929 are classified as signal or background leaves according to the class of the majority of
 1930 events in them. Each *branch* in the tree corresponds to a sequence of cuts.
- 1931 The quality of the classification at each node is evaluated through a separation
 1932 criteria; there are several of them but the *Gini Index* (G) is the one used in the
 1933 decision trees trained for the analysis in this thesis. G is written in terms of the
 1934 purity (P), i.e. the fraction of signal events, of the samples after the separation is
 1935 made; it is given by

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

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

1936 notice that $P=0.5$ at the root node while $G=0$ for pure leaves. For a node A split
 1937 into two nodes B_1 and B_2 the G gain is

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

1938 the *best* classification corresponds to that for which the gain of G is maximized; hence,
 1939 the scanning over all event's variables and their values is of capital importance.

1940 In order to provide a numerical output for the classification, events in a sig-
 1941 nal(background) leaf are assigned an score of 1(-1) each, defining in this way the
 1942 decision tree *classifier or weak learner* as

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

1943 Figure 5.4 shows an example of the classification of a sample of events, containing
 1944 two variables, performed by a decision tree.

1945 5.1.2 Boosted decision trees (BDT).

1946 Event misclassification occurs when a training event ends up in the wrong leaf, i.e., a
 1947 signal event ends up in a background leaf or a background event ends up in a signal
 1948 leaf. A way to correct it is to assign a weight to the misclassified events and train
 1949 a second tree using the reweighted events; the event reweighting is performed by a
 1950 boosting algorithm, events with increased weight are known as *boosted* events, in such
 1951 a way that when used in the training of a new decision tree they get correctly classified.
 1952 The process is repeated iteratively adding a new tree to a forest and creating a set
 1953 of classifiers which are combined to create the next classifier; the final classifier offers

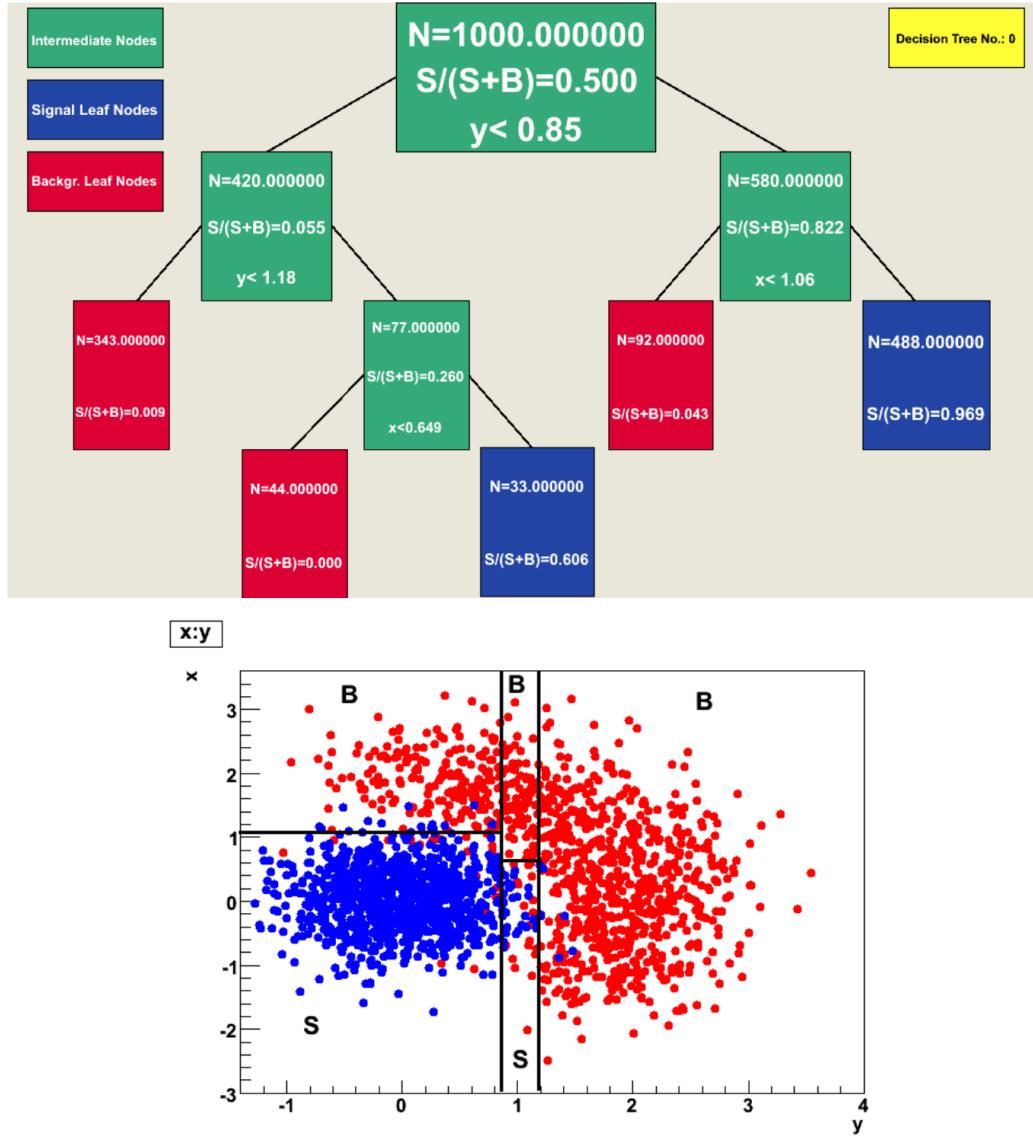


Figure 5.4: Example of a decision tree output. Each leaf, blue for signal events and red for background events, represent a region in the variables phase space [119].

1954 more stability² and has a smaller misclassification rate than any individual ones. The
 1955 resulting tree collection is known as a *boosted decision tree (BDT)*.
 1956 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.

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

1957 where w_s and w_b are the weights of the events; the Gini index is also generalized

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

1958 with n the number of events in the node. The final score of an event, after pass-
 1959 ing through the forest, is calculated as the renormalized sum of all the individual
 1960 (possibly weighted) scores; thus, high(low) score implies that the event is most likely
 1961 signal(background).

1962 The boosting procedure, implemented in the *Gradient boosting* algorithm used
 1963 in this thesis, produce a classifier $F(\mathbf{x})$ which is the weighted sum of the individual
 1964 classifiers obtained after each iteration,i.e.,

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

1965 where M is the number of trees in the forest. The *loss function* $L(F, y)$ represent the
 1966 deviation between the classifier $F(\mathbf{x})$ response and the true value y obtained from the
 1967 training sample (1 for signal events and -1 for background event), according to

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

1968 thus, the reweighting is employed to ensure the minimization of the loss function;
 1969 a more detailed description of the minimization procedure can be found in reference
 1970 [120]. The final classifier output is later used as a final discrimination variable, labeled
 1971 as *BDT output/response*.

1972 **5.1.3 Overtraining.**

1973 Decision trees offer the possibility to have as many nodes as wished in order to
 1974 reduce the misclassification to zero (in theory); however, when a classifier is too much
 1975 adjusted to a particular training sample, the classifier response to a slightly different
 1976 sample may leads to a completely different classification results; this effect is know
 1977 as *overtraining*.

1978 An alternative to reduce the overtraining in BDTs consist in pruning the tree by
 1979 removing statistically insignificant nodes after the tree growing is completed but this
 1980 option is not available for BDTs with gradient boosting in the TMVA-toolkit, there-
 1981 fore, the overtraining has to be reduced by tuning the algorithm, number of nodes,
 1982 minimum number of events in the leaves, etc. The overtraining can be evaluated
 1983 by comparing the responses of the classifier when running over the training and test
 1984 samples.

1985 **5.1.4 Variable ranking.**

1986 BDTs have the couple of particular advantages related to the input variables; on one
 1987 side, they are relatively insensitive to the number of input variables used in the vector
 1988 \mathbf{x} . The ranking of the BDT input variables is determined by counting the number of
 1989 times a variable is used to split decision tree nodes; in addition, the separation gain-
 1990 squared achieved in the splitting and the number of events in the node are accounted
 1991 by applying a weighting to that number. Thus, those variables with small or no power
 1992 to separate signal and background events are rarely chosen to split the nodes,i.e., are
 1993 effectively ignored.

1994 On the other side, variables correlations play an important role for some MVA
 1995 methods like the Fisher discriminant algorithm in which the first step consist of

1996 performing a linear transformation to a phase space where the correlations between
 1997 variables are removed; in case of BDT algorithm, correlations do not affect the per-
 1998 formance.

1999 **5.1.5 BDT output example.**

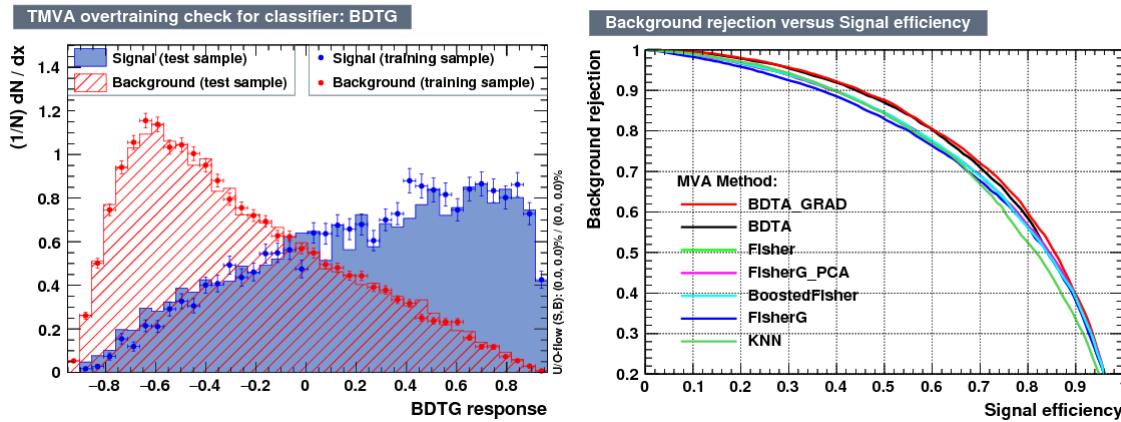


Figure 5.5: Left: Output distributions for the gradient boosted decision tree (BDTG) classifier using a sample of signal($pp \rightarrow tHq$) and background($pp \rightarrow t\bar{t}$) events. Right: Background rejection vs signal efficiency (ROC curves) for various MVA classifiers running over the same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

2000 Left side of figure 5.5 shows the BDT output distributions for signal($pp \rightarrow tHq$)
 2001 and background($pp \rightarrow t\bar{t}$) events; this plot is the equivalent to the one showed in
 2002 figure 5.2. A forest with 800 trees, maximum depth per tree = 3, and gradient
 2003 boosting have been used as training parameters. The BDTG classifier offers a good
 2004 separation power; while there is a small overtraining in the signal distribution, the
 2005 background distribution seems to be well predicted which might indicate that the
 2006 sample is composed of more background than signal events.

2007 Right side of figure 5.5 shows the background rejection vs signal efficiency curves
 2008 for several combinations of MVA classifiers-boosting algorithms; these curves are
 2009 known as ROC curves and give an indication of the performance of the classifier. The

2010 best performance is achieved with the BDTG classifier (BDTA_GRAD).

2011 5.2 Statistical inference.

2012 Once events are classified, the next step consists in finding the parameters that define
 2013 the likelihood functions $f(\mathbf{x}|s), f(\mathbf{x}|b)$ for signal and background events respectively.
 2014 In general, likelihood functions depend not only on the measurements but also on
 2015 parameters (θ_m) that define their shapes; the process of estimating these *unknown*
 2016 *parameters* and their uncertainties from the experimental data is called *inference*.
 2017 The likelihood function for N the events the in a sample is the combination of all the
 2018 likelihoods functions

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

2019 Thus, the estimation of the unknown parameters from experimental data samples
 2020 is written in terms of a central value using the notation

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

2021 where the interval $[\hat{\theta} + \delta\theta, \hat{\theta} - \delta\theta]$ is called *confidence interval*; it is usually inter-
 2022 preted, in the limit of infinite number of experiments, as the interval where the true
 2023 value of the unknown parameter θ is contained with a probability of 0.6827 (if no
 2024 other convention is stated).

2025 5.2.1 Nuisance parameters.

2026 The unknown parameter vector $\boldsymbol{\theta}$ is made of two types of parameters: on one side,
 2027 those parameters that provide information about the physical observables of interest

2028 for the experiment (*parameters of interest*); on the other side, the *nuisance parameters*
2029 that are not of direct interest for the experiment but that needs to be included in
2030 the analysis in order to achieve a satisfactory description of the data. They represent
2031 effects of the detector response like the finite resolutions of the detection systems,
2032 miscalibrations, and in general any source of uncertainty introduced in the analysis.

2033 In some cases the nuisance parameters are estimated using dedicated data samples,
2034 for instance data from test beams for calibration purposes, when MC samples are
2035 not suitable. The nuisance parameter uncertainties produce *systematic uncertainties*
2036 while the uncertainties associated to fluctuations in data and related to the estimation
2037 of the parameters of interest produce *statistical uncertainties*.

2038 5.2.2 Maximum likelihood estimation method

2039 The function that produce the estimate of a parameter is called *estimator*, there-
2040 fore, estimators are usually constructed using mathematical procedures encoded in
2041 algorithms. The estimation method used in this thesis is the *Maximum Likelihood*
2042 *Estimation* method (MLE); it is based on the combined likelihood function defined
2043 by eqn. 5.9 and the procedure seeks for the parameter set that corresponds to the
2044 maximum value of the combined likelihood function, i.e., the *maximum likelihood*
2045 *estimator* of the unknown parameter vector $\boldsymbol{\theta}$ is the function that produce the vec-
2046 tor $\hat{\boldsymbol{\theta}}$ for which the likelihood function $L(\boldsymbol{\theta})$ evaluated at the measured sample \mathbf{x} is
2047 maximum.

2048 Usually, the logarithm of the likelihood function is used in the numerical algo-
2049 rithms implementations in order to avoid underflow the numerical precision of the
2050 computers due to the product of low likelihoods. In addition, it is usual minimize the
2051 negative logarithm of the likelihood function instead of maximizing the logarithm of

2052 it because in this way the procedure consist of differentiate a sum of therms and set
 2053 the sum to zero; therefore

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

2054 The minimization process is performed by the software MINUIT [121] imple-
 2055 mented in the ROOT analysis framework. In case of large data samples the compu-
 2056 tational resources needed to calculate the likelihood function are too big; therefore,
 2057 the parameter estimation is performed using binned distributions of the variables of
 2058 interest for which the *binned likelihood function* is given by

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

2059 with s_i and b_i the expected number of signal and background yields for bin i respec-
 2060 tively, n_i is the observed number of events in the bin i and $\mu = \sigma/\sigma_{SM}$ is the signal
 2061 strength. Notice that the number of entries per bin follows a Poisson distribution.
 2062 The analysis presented in this thesis is based on the binned distribution of the ratio
 2063 signal/background obtained from the BDT outputs.

2064 5.2.3 Hypothesis test

2065 The test statistic mentioned in section 5.1 involving
 2066 ; it is achieved, according to the Neyman-Pearson lemma [122],
 2067 by defining the acceptance region such that, for \mathbf{x} inside the region, the likelihood
 2068 ratio, i.e., the ratio of probability distribution functions for signal and background,

₂₀₆₉ **5.3 exclusion limits**

₂₀₇₀ **5.4 asymptotic limits**

2071 **Chapter 6**

2072 **Search for production of a Higgs
2073 boson and a single top quark in
2074 multilepton final states in pp
2075 collisions at $\sqrt{s} = 13$ TeV**

2076 **6.1 Introduction**

2077 The Higgs boson discovery, supported on experimental observations and theoretical
2078 predictions made about the SM, gives the clue of the way in that elementary particles
2079 acquire mass through the Higgs mechanism; therefore, knowing the Higgs mass, the
2080 Higgs-boson and Higgs-fermion couplings can be tested. In order to test the Higgs-top
2081 coupling, several measurements have been performed, as stated in the chapter 2, but
2082 they are limited to measure the square of the coupling; however, the production of a
2083 Higgs boson in association with a single top quark (tH) not only offers access to the
2084 sign of the coupling, but also, to the CP phase of the Higgs couplings.

2085 This chapter presents the search for the associated production of a Higgs boson
 2086 and a single top quark events, focusing on leptonic signatures provided by the Higgs
 2087 decay modes to WW , ZZ , and $\tau\tau$; the 13 TeV dataset produced in 2016, which
 2088 corresponds to an integrated luminosity of 35.9fb^{-1} , is used. Constraints on the sign
 2089 of the Higgs-top coupling (y_t) have been derived from the decay rate of Higgs boson
 2090 to photon pairs [45] and from the cross section for associated production of Higgs and
 2091 Z bosons via gluon fusion [123], with recent results disfavoring negative signs of the
 2092 coupling [56, 58, 124]. It expands previous analyses performed at 8 TeV [125, 126] and
 2093 searches for associated production of $t\bar{t}$ pair and a Higgs boson in the multilepton final
 2094 state channel [127]; it also complements searches in other decay channels targeting
 2095 $H \rightarrow b\bar{b}$ [128].

2096 As shown in section 2.5, the SM cross section of the associated production of a
 2097 Higgs boson and a single top quark (tHq) process is driven by a destructive interfer-
 2098 ence between two contributions (see Figure 2.14), where the Higgs couples to either
 2099 the W boson or the top quark; however, if the sign of the Higgs-top coupling is flipped
 2100 with respect to the SM prediction, a large enhancement of the cross section occurs,
 2101 making this analysis sensitive to such deviation. A second process, where the Higgs
 2102 boson and top quark are accompanied by a W boson (tHW) has similar behavior,
 2103 albeit with a weaker interference pattern and lower contribution to the tH cross sec-
 2104 tion, therefore, a combination of both processes would increase the sensitivity; in
 2105 this analysis both contributions are combined and referred as tH channel. A third
 2106 contribution comes from $t\bar{t}H$ process. The purpose of this analysis is to investigate
 2107 the exclusion of the presence of the $tH + t\bar{t}H$ processes under the assumption of the
 2108 anomalous Higgs-top coupling modifier ($\kappa_t = -1$). The analysis exploits signatures
 2109 with two leptons of the same sign (*2lss channel*) and three leptons (*3l channel*) in
 2110 the final state.

2111 The first sections present the characteristic tHq signature as well as the expected
 2112 backgrounds. The MC samples, data sets, and the physics object definitions are
 2113 then defined. Following, the background predictions, the signal extraction, and the
 2114 statistical treatment of the selected events as well as the systematic uncertainties are
 2115 described. The final section present the results for the exclusion limits as a function
 2116 of the ratio of κ_t and the dimensionless modifier of the Higgs-vector boson κ_V .

2117 **6.2 tHq signature**

2118 In order to select events of tHq process, its features are translated into a set of
 2119 selection rules; figure 6.1 shows the Feynman diagram and an schematic view of the
 2120 tHq process from the pp collision to the final state configuration. A single top quark
 2121 is produced accompanied by a light quark, denoted as q ; this light quark is produced
 2122 predominantly in the forward region of the detector. The Higgs boson which can
 2123 be either emitted by the exchanged W boson or directly by the singly produced top
 2124 quark.

2125 The top quark and Higgs boson decay after their production in the detector due to
 2126 their high masses/low lifetimes. The Higgs boson is required to decay into a W boson
 2127 pair¹. The top quark almost always decays into a bottom quark and a W boson, as
 2128 encoded in the CMK matrix. The W bosons are required to decay hadronically in
 2129 the 2lss channel case and leptonically in the 3l channel case, while τ leptons are not
 2130 reconstructed separately and only their leptonic decays into either electrons or muons
 2131 are considered in this analysis.

2132 In summary, the signal process is characterized by a the final state with

- 2133 • one light-flavored forward jet,

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

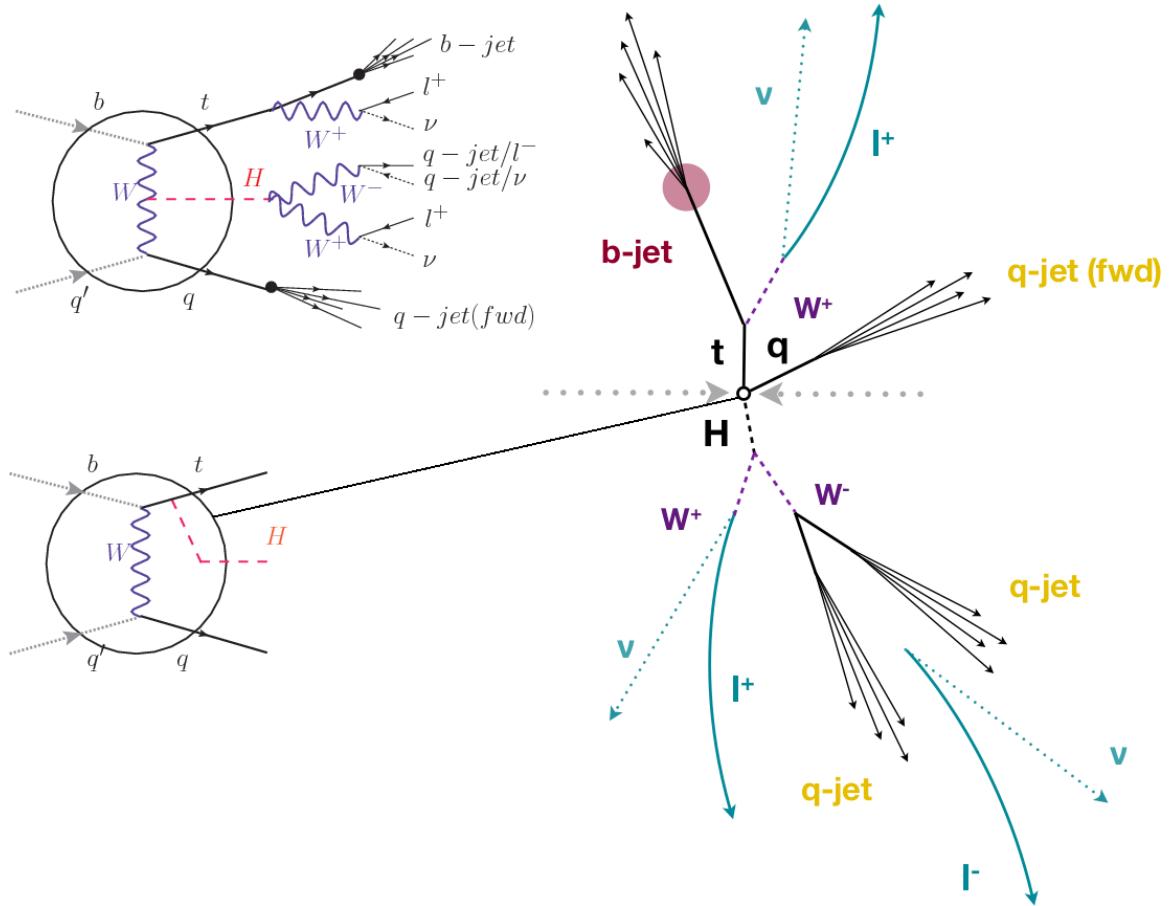


Figure 6.1: tHq event signature. Left: Feynman diagram including the whole evolution up to the final state for the case of the Higgs boson emitted by the W boson (top); Feynman diagram for the case where the Higgs boson is emitted by the top quark. Right: Schematic view as it would be seen in the detector;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

- 2134 • one central b-jet,
 - 2135 • 2lss channel \rightarrow two leptons of the same sign, two neutrinos and two light (often
2136 soft) jets,
 - 2137 • 3l channel \rightarrow three leptons, three neutrinos and no central light-flavored jets,
- 2138 The presence of neutrinos is inferred from the presence of MET. The analysis has

2139 been made public by CMS as a Physics Analysis Summary [129] combining the result
 2140 for the three lepton and two lepton same-sign channels. Currently, an effort to turn
 2141 the analysis into a paper is ongoing.

2142 **6.3 Background processes**

2143 The background processes are those that can mimic the signal signature or at least
 2144 can be reconstructed as that as a result of certain circumstances. The backgrounds
 2145 can be classified as

- 2146 • Irreducible backgrounds where genuine prompt leptons are produced in on-
 2147 shell W and Z boson decays; they can be reliably estimated directly from MC
 2148 simulated events, using higher-order cross sections or data control regions for
 2149 the overall normalization.
- 2150 • Reducible backgrounds where at least one of the leptons is *non-prompt*, i.e., pro-
 2151 duced within a hadronic jet, either a genuine lepton from heavy flavor decays.
 2152 misreconstructed jets, also known as *mis-ID leptons* or *fake leptons*, are consid-
 2153 ered non-prompt leptons as well. These non-prompt leptons leave tracks and
 2154 hits in the detection systems as would a prompt lepton, but correlating those
 2155 hits with nearby jets could be a way of removing them. Reducible backgrounds
 2156 are not well predicted by simulation, and are estimated using data-driven meth-
 2157 ods.

2158 The main sources of background events in the case of tHq process are $t\bar{t}$ process
 2159 and $t\bar{t} + X(X = W, Z, \gamma)$ processes, here represented together as $t\bar{t}V$ process. Figure
 2160 6.2 shows the signature for $t\bar{t}$ and $t\bar{t}W$ processes;

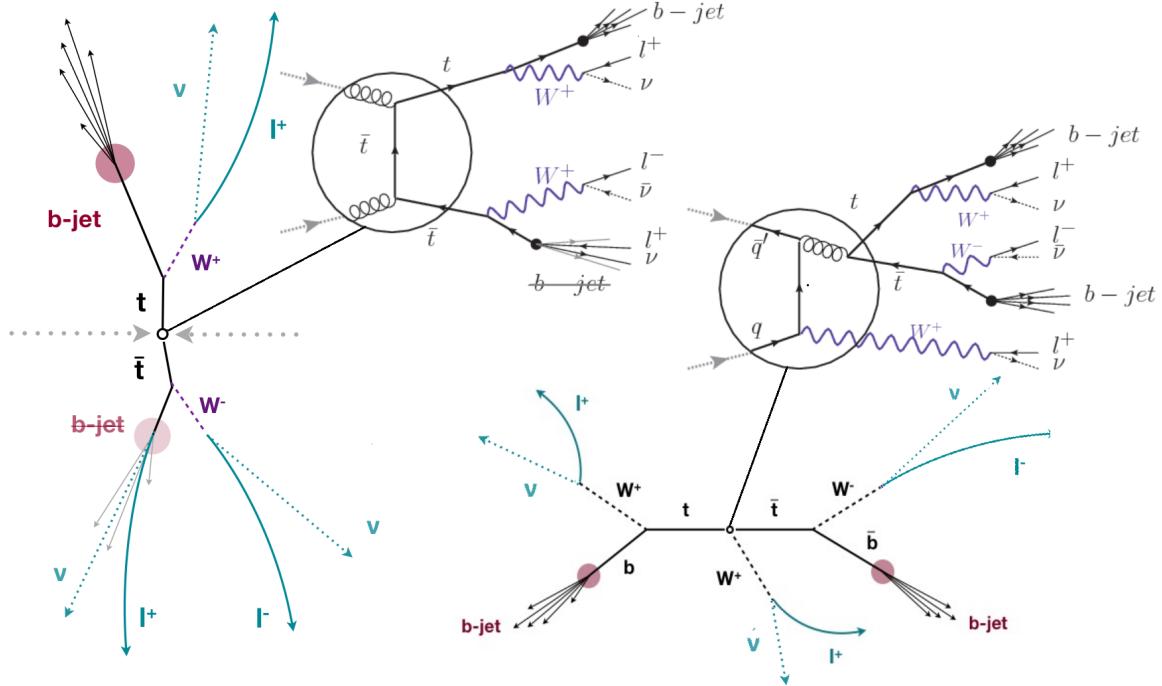


Figure 6.2: $t\bar{t}$ (left) and $t\bar{t}W$ (right) events signature as they would be seen in the detector; the Feynman diagrams including the whole evolution up to the final state are also showed. The $t\bar{t}$ process signature is very similar to that of the signal process with one fake lepton and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

2161 The largest contribution to irreducible backgrounds involving prompt leptons
 2162 comes from $t\bar{t}W$, $t\bar{t}Z$, processes for which the number of ($b-$)jets (($b-$)jet multiplicity)
 2163 is higher than that of the signal events, while for other contributing background
 2164 events, WZ , ZZ , and rare SM processes like $W^\pm W^\pm qq$, $t\bar{t}t\bar{t}$, tZq , tZW , WWW ,
 2165 WWZ , WZZ , ZZZ , the ($b-$)jet multiplicity is lower compared to that of the signal
 2166 events. None of the irreducible backgrounds present activity in the forward region of
 2167 the detector.

2168 On the side of the reducible backgrounds, the largest contribution comes from the
 2169 $t\bar{t}$ events which have a very similar signature to the signal events but does no present
 2170 activity in the forward region of the detector either; A particular feature of the $t\bar{t}$
 2171 events is their charge-symmetry which is also a difference with the signal events.

2172 The charge misidentification plays an important role in the the 2lss channel since
 2173 leptons in processes like $t\bar{t}$ + jets or Z + jets can be charge misidentified, leading to
 2174 backgrounds increments. An identification variable have been designed in order to
 2175 reject this type of background events.

2176 6.4 Data and MC Samples

2177 Technical developments on the event generator side allow for an event-wise reweight-
 2178 ing that can change the event kinematics based on specific generation parameters.
 2179 This way not only the case of $C_t = \sqrt{1}$, but a whole range of κ_t and κ_V values can
 2180 be investigated.

2181 The data considered in this analysis were collected by the CMS experiment dur-
 2182 ing 2016 and correspond to a total integrated luminosity of $35.9 fb^{-1}$. Only periods
 2183 when the CMS magnet was on were considered when selecting the data samples, that
 2184 corresponds to the 23 Sep 2016 (Run B to G) and PromptReco (Run H) versions
 2185 of the datasets. The MC samples used in this analysis correspond to the RunI-
 2186 ISummer16MiniAODv2 campaign produced with CMSSW 80X. The two signal sam-
 2187 ples (for tHq and tHW) were produced with MG5_aMC@NLO (version 5.222), in
 2188 leading-order order mode, and are normalized to next-to-leading-order cross sections,
 2189 see Tab. 6.1. Each sample is generated with a set of event weights corresponding to
 2190 different values of κ_t and κ_V couplings as shown in Tab. 6.2.

2191 6.4.1 Full 2016 dataset and MC samples

2192 Different MC generators were used to generate the background processes. The dom-
 2193 inant sources ($t\bar{t}$, $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}H$) were produced using AMC@NLO interfaced to
 2194 PYTHIA8, and are scaled to NLO cross sections. Other processes are simulated us-

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

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

6.4.2 Triggers

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

Trigger efficiency scale factors

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

		<i>tHq</i>		<i>tHW</i>		
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 6.2: κ_V and κ_t combinations generated for the two signal samples and their NLO cross sections. The *tHq* cross section is multiplied by the branching fraction of the enforced leptonic decay of the top quark (0.324). See also Ref. [138].

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

Sample	σ [pb]
ttWJets_13TeV_madgraphMLM	0.6105
ttZJets_13TeV_madgraphMLM	0.5297/0.692

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

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

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

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

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

2212 6.5 Object Identification

2213 In this section, the specific definitions of the physical objects in terms of the numerical
 2214 values assigned to the reconstruction parameters are presented; thus, the provided
 2215 details summarize and complement the descriptions presented in previous chapters.
 2216 The object reconstruction and selection strategy used in this thesis is inherited from
 2217 the analyses in references [127, 132], thus, the information provided in this section is
 2218 extracted from those documents unless other references are stated.

2219 6.5.1 Jets and b -jet tagging.

2220 In this analysis, jets are reconstructed by clustering PF candidates using the anti- k_t
 2221 algorithm with parameter distance $\Delta R = 0.4$; those charged hadrons that are not
 2222 consistent with the selected primary vertex are discarded from the clustering. The
 2223 jet energy is then corrected for the varying response of the detector as a function
 2224 of transverse momentum p_T and pseudorapidity η . Jets are selected for use in the
 2225 analysis only if they have $p_T > 25$ GeV and are separated from any selected leptons
 2226 by $\Delta R > 0.4$.

2227 Jets coming from the primary vertex and jets coming from pile-up vertices are
 2228 distinguished using a MVA discriminator based on the differences in the jet shapes,
 2229 in the relative multiplicity of charged and neutral components, and in the different
 2230 fraction of transverse momentum which is carried by the hardest components. Jet

2231 tracks are also required to be compatible with the primary vertex.

2232 Jets originated from the hadronization of a b quark are selected using a MVA
 2233 likelihood discriminant which uses track-based lifetime information and reconstructed
 2234 secondary vertices (CSV algorithm). Only jets within the CMS tracker acceptance
 2235 ($\eta < 2.4$) are identified with this tool. Data samples are used to measure the efficiency
 2236 of the b -jet tagging and the probability to misidentify jets from light quarks or gluons;
 2237 in both cases the measurements are parametrized as a function of the jet p_T and η
 2238 and later used to correct differences between the data and MC simulation in the b
 2239 tagging performance, by applying per-jet weights to the simulation, dependent on
 2240 the jet p_T , η , b tagging discriminator, and flavor (from simulation truth) [130]. The
 2241 per-event weight is taken as the product of the per-jet weights, including those of the
 2242 jets associated to the leptons. The weights are derived on $t\bar{t}$ and Z+jets events.

2243 Two working points are defined, based on the CSV algorithm output: *loose*' work-
 2244 ing point (CSV>0.46) with a b signal tagging efficiency of about 83% and a mistagging
 2245 rate of about 8%; and *medium* working point (CSV>0.80) with b -tagging efficiency of
 2246 about 69% and mistagging rate of order 1% [131]. Tagging of jets from charm quarks
 2247 have efficiencies of about 40% and 18% for loose and medium working points re-
 2248 spectively. Separate scale factors are applied to jets originating from bottom/charm
 2249 quarks and from light quarks in simulated events to match the tagging efficiencies
 2250 measured in the data.

2251 6.5.2 Missing Energy MET.

2252 As stated in section 4.4.1.1, the MET vector is calculated as the negative of the vector
 2253 sum of transverse momenta of all PF candidates in the event and its magnitude is
 2254 referred to as E_T^{miss} . Due to pile-up interactions, the performance in determining

2255 MET is degraded; in order to correct for that, the energy from the selected jets and
 2256 leptons that compose the event is assigned to the variable H_T^{miss} . It is calculated in
 2257 the same way as E_T^{miss} and although it has worse resolution than E_T^{miss} , it is more
 2258 robust in the sense that it does not rely on the soft part of the event. The event
 2259 selection uses a linear discriminator based on the two variables given by

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

2260 taking advantage of the fact that the correlation between E_T^{miss} and H_T^{miss} is less
 2261 for events with instrumental missing energy than for events with real missing energy.
 2262 The working point $E_T^{miss} LD > 0.2$ was chosen to ensure a good signal efficiency while
 2263 keeping a good background rejection.

2264 6.5.3 Lepton reconstruction and identification

2265 Two types of leptons are defined in this analysis: *signal leptons* are those coming from
 2266 W, Z and τ decays which usually are isolated from other particles; *background leptons*
 2267 are defined as leptons produced in b -jet hadron decays, light-jets misidentification,
 2268 and photon conversions.

2269 The process of reconstruction and identification of electron and muon candidates
 2270 was described in chapter4, hence, the identification variables used in order to retain
 2271 the highest possible efficiency for signal leptons while maximizing the rejection of
 2272 background leptons are listed and described in the following sections ².

2273 The identification variables include not only observables related directly to the re-
 2274 constructed leptons themselves, but also to the clustered energy deposits and charged
 2275 particles in a cone around the lepton direction (jet-related variables); an initial loose

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

2276 preselection of leptons candidates is performed and then an MVA discriminator, re-
 2277 ferred to as *lepton MVA* discriminator, is used to distinguish signal leptons from
 2278 background leptons.

2279 **Muons.**

2280 The Physics Objects Groups (POG) at CMS, are in charge of studying and defining
 2281 the set of selection criteria applied on the course of reconstruction and identification
 2282 of particles. These selection criteria are implemented in the CMS framework in the
 2283 form of several object identification working points according to the strength of the
 2284 requirements.

2285 The muon candidates are reconstructed by combining information from the tracker
 2286 system and the muon detection system of CMS detector and the POG defined three
 2287 working points for muon identification *MuonID* [133];

- 2288 • *POG Loose Muon ID* is a particle identified as a muon by the PF event re-
 2289 construction and also reconstructed either as a global-muon or as an arbitrated
 2290 tracker-muon. This identification criteria is designed to be highly efficient for
 2291 prompt muons and for muons from heavy and light quark decays; it can be com-
 2292 plemented by applying impact parameter cuts in analyses with prompt muon
 2293 signals.
- 2294 • *POG Medium Muon ID* is a Loose muon with additional track-quality and
 2295 muon-quality (spatial matching between the individual measurements in the
 2296 tracker and the muon system) requirements. This identification criteria is de-
 2297 signed to be highly efficient in the separation of the muons coming from decay
 2298 in flight of heavy quarks and muons coming from B meson decays as well as
 2299 prompt muons. An additional category *MVA Prompt ID* is defined in this iden-

2300 tification criteria directed to discriminated muons from B mesons and prompt
 2301 muons (from W,Z and τ decays). The Medium ID provides the same fake rate as
 2302 the Tight Muon ID but a higher efficiency on prompt and B-decays muons. [134]

- 2303 • *POG Tight Muon ID* is a global muon with additional muon-quality require-
 2304 ments Tight Muon ID selects a subset of the PF muons.

2305 Only muons within the muon system acceptance $|\eta| < 2.4$ and minimum p_T of 5
 2306 GeV are considered.

2307 **Electrons.**

2308 Electrons are reconstructed using information from the tracker and from the electro-
 2309 magnetic calorimeter and identified by an MVA algorithm (*MVA eID* discriminant)
 2310 using the shape of the calorimetric shower variables like the shape in η and ϕ , the clus-
 2311 ter circularity, widths along η and ϕ ; track-cluster matching variables like E_{tot}/p_{in} ,
 2312 E_{Ele}/p_{out} , $\Delta\eta_{in}$, $\Delta\eta_{out}$, $\Delta\phi_{in}$, $1/E - 1/p$; and track quality variables like ξ^2 of the
 2313 GSF tracks, the number of hits used by the GSF filter [135].

2314 A loose selection based on η -dependent cuts on this discriminant is used to prese-
 2315 lect electron candidates, the full shape of the discriminant is used in the lepton MVA
 2316 selection to separate signal leptons from background leptons (described in section
 2317 6.5.3).

2318 In order to reject electrons from photon conversions, electron candidates with
 2319 missing hits in the pixel tracker layers or matched to a conversion secondary vertex
 2320 are discarded. Electrons are selected for the analysis if they have $p_T > 7$ GeV and
 2321 are located within the tracker system acceptance region ($|\eta| < 2.5$).

2322 **Lepton vertexing and pile-up rejection.**

2323 The impact parameter in the transverse plane d_0 , impact parameter along the z
 2324 axis d_z , and the impact parameter significance in the detector space SIP_{3D} , are
 2325 considered to perform the identification and rejection of pile-up, misreconstructed
 2326 tracks, and background leptons from b-hadron decays; pile-up and misreconstructed
 2327 track mitigation is achieved by imposing loose cuts on the impact parameter variables.
 2328 The full shape of the those variables is used in a lepton MVA classifier to achieve the
 2329 best separation between the signal and the background leptons.

2330 **Lepton isolation.**

2331 PF is able to recognize leptons from two different sources: on one side, leptons from
 2332 the decays of heavy particles, such as W and Z bosons, which are normally isolated
 2333 in space from the hadronic activity in the event; on the other side, leptons from the
 2334 decays of hadrons and jets misidentified as leptons, which are not isolated as the
 2335 former. For highly boosted systems, like the lepton and the b -jet generated in the
 2336 semileptonic decay of a boosted top, the decay products tend to be more closer and
 2337 sometimes they even overlap; thus, the PF standard definition of isolation in terms of
 2338 the separation between the lepton candidates and other PF objects in the η - ϕ plane,

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

2339 which considers all the neutral, charged hadrons and photons in a cone around the
 2340 leptons, is refocused to the local isolation of the leptons through the mini-isolation
 2341 I_{mini} [136] defined as the sum of particle flow candidates p_T within a cone around

2342 the lepton, corrected for the effects of pileup and divided by the lepton p_T

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

2343 where ρ is the pileup energy density, h^\pm, h^0, γ, l , represent the charged hadron, neutral
 2344 hadrons, photons, and the lepton, respectively. The radius R of the cone depends on
 2345 the p_T of the lepton according to

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

2346 The p_T dependence of the cone size allows for greater signal efficiency. Setting a
 2347 cut on I_{mini} below a given threshold ensures that the lepton is locally isolated, even
 2348 in boosted systems. The effect of pileup is mitigated using the so-called effective area
 2349 correction \mathcal{A} listed in Table 6.7.

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

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

2350 A loose cut on I_{mini} is applied to pre-select the muon and electron candidates;
 2351 however, the full shape is used in the lepton MVA discriminator when performing the
 2352 signal lepton selection.

2353 **Jet-related variables.**

2354 In order to reject misidentified leptons from b -jets, mostly coming from $t\bar{t}$ +jets,
 2355 Drell-Yan+jets, and W+jets events, the vertexing and isolation described in previous
 2356 sections are complemented with additional variables related to the closest recon-
 2357 structed jet to the lepton, i.e., the PF jets reconstructed³ around the leptons with
 2358 $\Delta R = \sqrt{(\eta^l - \eta^{jet})^2 + (\phi^l - \phi^{jet})^2} < 0.5$. The identification variables used in the lep-
 2359 ton MVA discriminator are the ratio p_T^l/p_T^{jet} , the CSV b-tagging discriminator value
 2360 of the jet, the number of charged tracks of the jet, and the relative p_T given by

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

2361 **LeptonMVA discriminator.**

2362 Electrons and muons passing the basic selection process described above are referred
 2363 to as *loose leptons*. Additional discrimination between signal leptons and background
 2364 leptons is crucial considering that the rate of $t\bar{t}$ production is much larger than the
 2365 signal, hence, an overwhelming background from $t\bar{t}$ production. To maximally ex-
 2366 ploit the available information in each event to that end, the dedicated lepton MVA
 2367 discriminator, based on a boosted decision tree (BDT) algorithm, has been built so
 2368 that all the identification variables can be used together.

2369 The lepton MVA discriminator training is performed using simulated signal Loose
 2370 leptons from the $t\bar{t}H$ MC sample and fake leptons from the $t\bar{t}$ +jets MC sample,
 2371 separately for muons and electrons. The input variables used include vertexing, iso-
 2372 lation and jet-related variables, the p_T and η of the lepton, the electron MVA eID
 2373 discriminator and the muon segment-compatibility variables. An additional require-
 2374 ment known as *tight-charge* requirement, is imposed by comparing two independent

³ charged hadrons from PU vertices are not removed prior to the jet clustering.

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

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

Selection definitions

Electron and muon object identification is defined in three different sets of selections criteria; the *Loose*, *Fakeable Object*, and *Tight* selection. These three levels of selection are designed to serve 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 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 6.8 and 6.9 list the full criteria for the different selections of muons and electrons.

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

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

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

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

Table 6.9: Criteria for each of the three electron selections. In cases where the cut values change between selections, those values are listed in the table. Otherwise, whether the cut is applied is indicated. In some cases, the cut values change for different 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). For the two p_T^{ratio} and CSV rows, the cuts marked with a \dagger are applied to leptons that fail the lepton MVA cut, while the loose cut value is applied to those that pass the lepton MVA cut.

2400 6.5.4 Lepton selection efficiency

2401 Efficiencies of reconstruction and selecting loose leptons are measured both for muons
 2402 and electrons using a tag and probe method on both data and MC, using $Z \rightarrow \ell^+ \ell^-$
 2403 [137]. The scale factors are derived from the ratio of efficiencies $\varepsilon_i(p_T, \eta)$ measured
 2404 for a given lepton in data/MC, according to

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

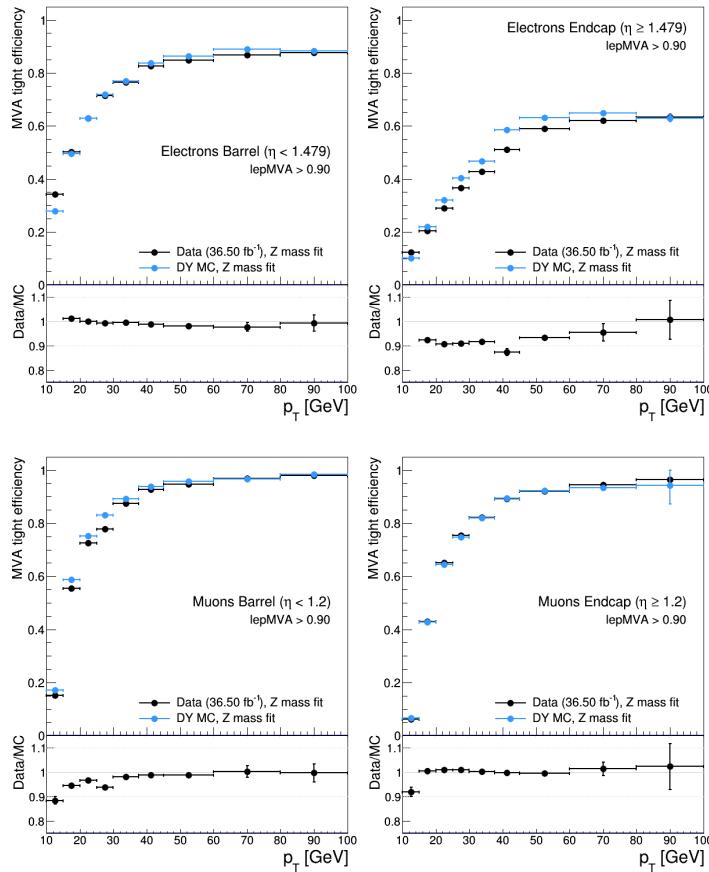


Figure 6.3: Tight vs loose selection efficiencies for electrons (top), and muons (bottom), for the 2lss definition, i.e., including the tight-charge requirement.

2405 The scale factor for each event is used to correct the weight of the event in the

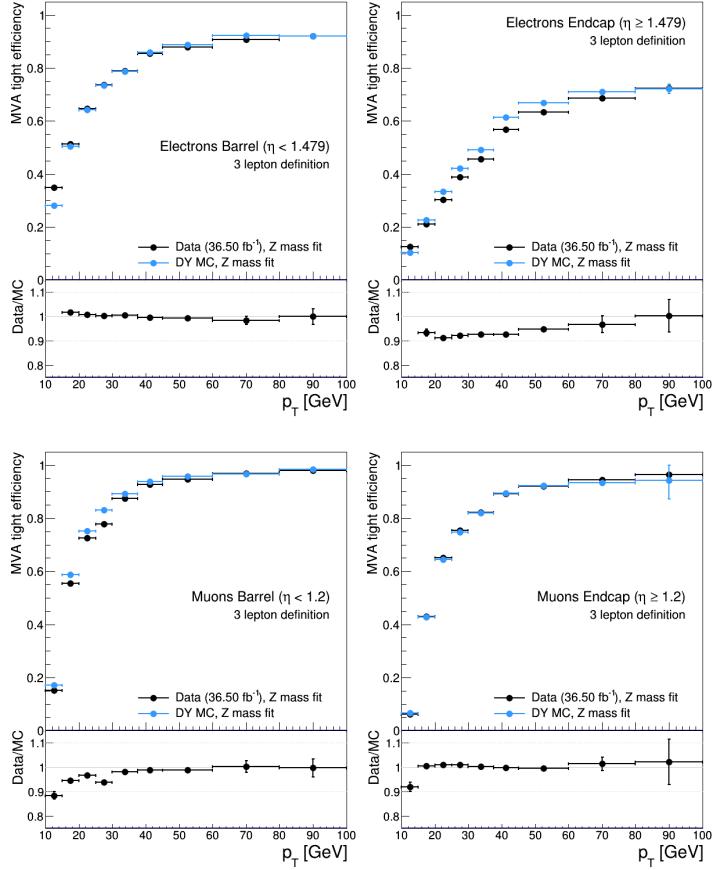


Figure 6.4: Tight vs loose selection efficiencies for electrons (top), and muons (bottom), for the 3l channel not including the tight-charge requirement.

2406 full sample; therefore, the full simulation correction is given by the product of all
 2407 the individual scale factors. The scale factors used in this thesis are inherited from
 2408 the reference [132] which in turns inherited them from leptonic SUSY analyses using
 2409 equivalent lepton selections.

2410 The efficiency of applying the tight selection as defined in Tables 6.8 and 6.9, on the
 2411 loose leptons are determined by using a tag and probe method on a sample of Drell-
 2412 Yan enriched events. Figures 6.3 and 6.4 show the efficiencies for the 2lss channel and
 2413 3l channel respectively. Efficiencies in the 2lss channel have been produced including
 2414 the tight-charge requirement, while for the 3l channel it is not included. Number

2415 of passed and failed probes are determined from a fit to the invariant mass of the
 2416 dilepton system.

2417 Simulation is corrected using these scale factors; note that they depends on η and
 2418 p_T .

2419 **6.6 Event selection**

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2430 The analysis is designed to efficiently identify and select prompt leptons from
 2431 on-shell W and

2432 Z boson decays and to reject non-prompt leptons from b quark decays and spurious
 2433 lepton

2434 signatures from hadronic jets. Events are then selected in the various lepton
 2435 channels, and are

2436 required to contain hadronic jets, some of which must be consistent with b quark
 2437 hadronization. Finally, the signal yield is extracted by simultaneously fitting the
 2438 output of two dedicated

2439 multivariate discriminants (trained to separate the tHq signal from the two dom-
 2440 inant backgrounds) in all categories

2441 . Multivariate techniques are used to discriminate the signal from the dominant
 2442 backgrounds. The analysis yields a 95% confidence level (C.L.) upper limit on the
 2443 combined $tH + ttH$ production cross section times branching ratio of 0.64 pb, with
 2444 an expected limit of 0.32 pb, for a scenario with $kt = \sqrt{1.0}$ and $kV = 1.0$. Values
 2445 of kt outside the range of $\sqrt{1.25}$ to $\sqrt{1.60}$ are excluded at 95% C.L., assuming kV
 2446 $= 1.0$.

2447 Dont forget to mention previous constrains to ct check reference ?? and references
 2448 <https://link.springer.com/content/pdf/10.1007%2FJHEP01%282013%29088.pdf> (para-
 2449 graph after eq 2)

2450 We selects events with three leptons and a b -jet tagged jet in the final state. The tHq
 2451 signal contribution is then determined in a fit of the observed data to two multivariate
 2452 classifier outputs, each trained to discriminate against one of the two dominant back-
 2453 grounds of events with non-prompt leptons from $t\bar{t}$ and of associated production of $t\bar{t}$
 2454 and vector bosons ($t\bar{t}W$, $t\bar{t}Z$). The fit result is then used to set an upper limit on the
 2455 combined $t\bar{t}H$, tHq and tHW production cross section, as a function of the relative
 2456 coupling strengths of Higgs and top quark and Higgs and W boson, respectively.

2457 6.7 Background predictions

2458 The modeling of reducible and irreducible backgrounds in this analysis uses the exact
 2459 methods, analysis code, and ROOT trees used for the $t\bar{t}H$ multilepton analysis. We
 2460 give a brief description of the methods and refer to the documentation of that analysis
 2461 in Refs. [127, 132] for any details.

2462 The backgrounds in three-lepton final states can be split in two broad categories:

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

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

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

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

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

2489 events, limited statistics in the data control regions due to necessary prescaling of
 2490 lepton triggers, and the uncertainty in the subtraction of residual prompt leptons
 2491 from the control region.

2492 The fake background where the leptons pass the looser selection are weighted
 2493 according to how many of them fail the tight criteria. Events with a single failing
 2494 lepton are weighted with the factor $f/(1-f)$ for the estimate to the tight selection
 2495 region, where f is the fake rate. Events with two failing leptons are given the negative
 2496 weight $-f_i f_j / (1-f_i)(1-f_j)$, and for three leptons the weight is positive and equal
 2497 to the product of $f/(1-f)$ factor evaluated for each failing lepton.

2498 Figures 6.5 show the distributions of some relevant kinematic variables, normalized
 2499 to the cross section of the respective processes and to the integrated luminosity.

2500 6.8 Signal discrimination

2501 The tHq signal is separated from the main backgrounds using a boosted decision
 2502 tree (BDT) classifier, trained on simulated signal and background events. A set
 2503 of discriminating variables are given as input to the BDT which produces a output
 2504 distribution maximizing the discrimination power. Table 6.10 lists the input variables
 2505 used while Figures 6.6 show their distributions for the relevant signal and background
 2506 samples, for the three lepton channel. Two BDT classifiers are trained for the two
 2507 main backgrounds expected in the analysis: events with prompt leptons from $t\bar{t}W$ and
 2508 $t\bar{t}Z$ (also referred to as $t\bar{t}V$), and events with non-prompt leptons from $t\bar{t}$. The datasets
 2509 used in the training are the tHq signal (see Tab. 6.1), and LO MADGRAPH samples
 2510 of $t\bar{t}W$ and $t\bar{t}Z$, in an admixture proportional to their respective cross sections (see
 2511 Tab. 6.4).

2512 The MVA analysis consist of two stages: first a “training” where the MVA method

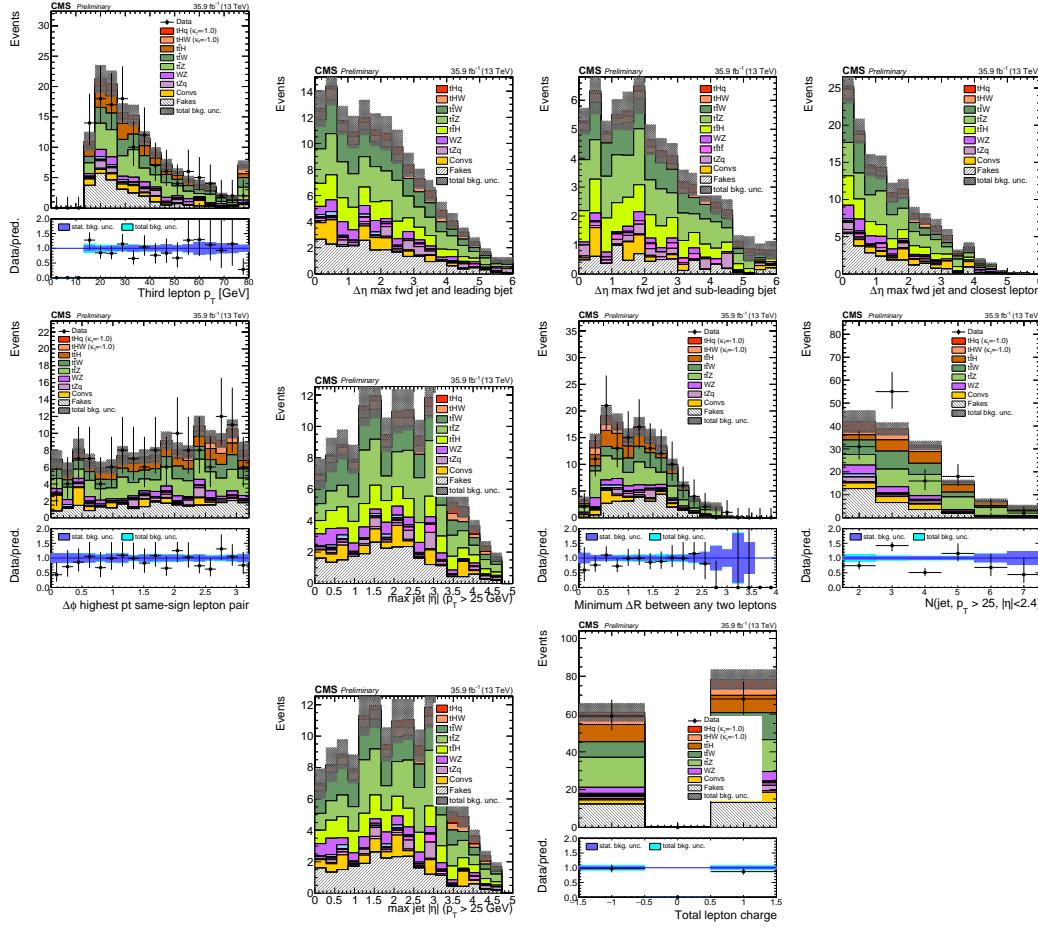


Figure 6.5: Distributions of input variables to the BDT for signal discrimination, three lepton channel, normalized to their cross section and to 35.9fb^{-1} .

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

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

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

Table 6.10: MVA input discriminating variables

2522 the distributions are similar in both background cases.

2523 From table 6.10, it is clear that the input variables are correlated to some extend.
 2524 These correlations play an important role for some MVA methods like the Fisher
 2525 discriminant method in which the first step consist of performing a linear transfor-
 2526 mation to an phase space where the correlations between variables are removed. In
 2527 case a boosted decision tree (BDT) method however, correlations do not affect the
 2528 performance. Figure 6.9 show the linear correlation coefficients for signal and back-
 2529 ground for the two training cases (the signal values are identical by construction). As
 2530 expected, strong correlations appears for variables related to the forward jet activity.
 2531 Same trend is seen in case of the same sign dilepton channel in Figure ??.

2532 **6.8.1 Classifiers response**

2533 Several MVA algorithms were evaluated to determine the most appropriate method
 2534 for this analysis. The plots in Fig. 6.10 (top) show the background rejection as a
 2535 function of the signal efficiency for $t\bar{t}$ and $t\bar{t}V$ trainings (ROC curves) for the different

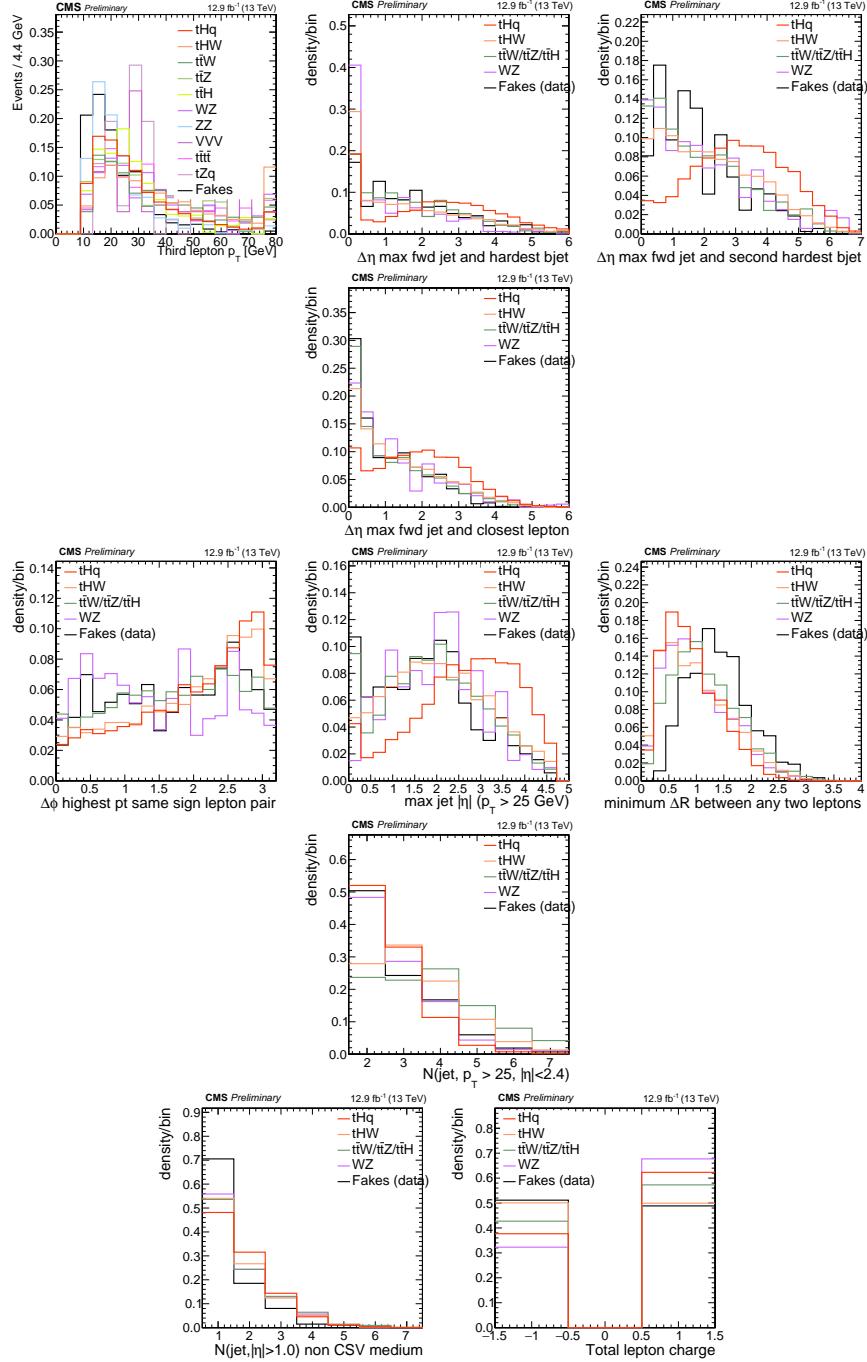


Figure 6.6: Distributions of input variables to the BDT for signal discrimination, three lepton channel.

2536 algorithms that were evaluated.

2537 In both cases the gradient boosted decision tree (“BDTA_GRAD”) classifier offers

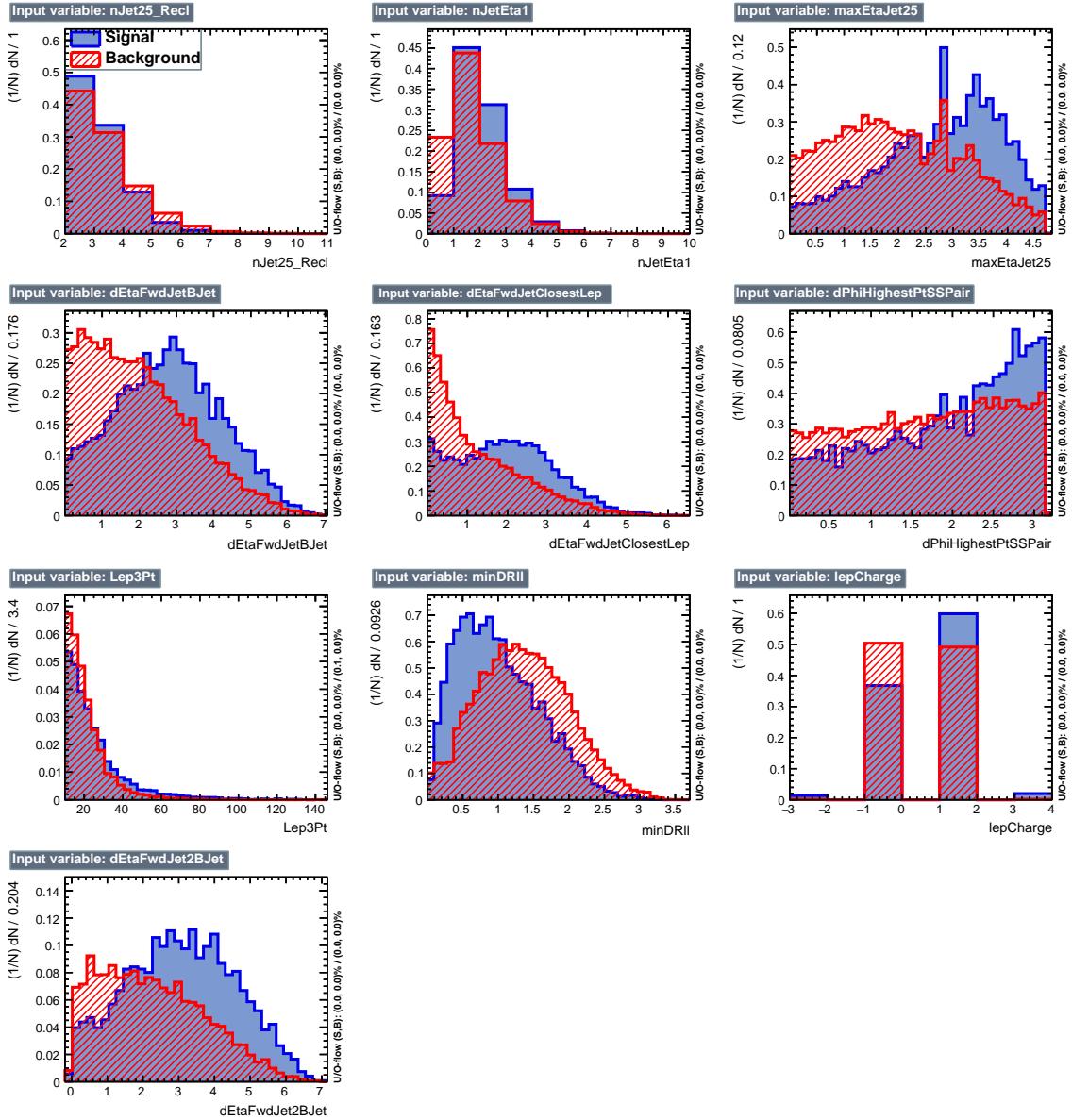


Figure 6.7: BDT inputs as seen by TMVA (signal, in blue, is tHq , background, in red, is $t\bar{t}$) for the three lepton channel, discriminated against $t\bar{t}$ (fakes) background.

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

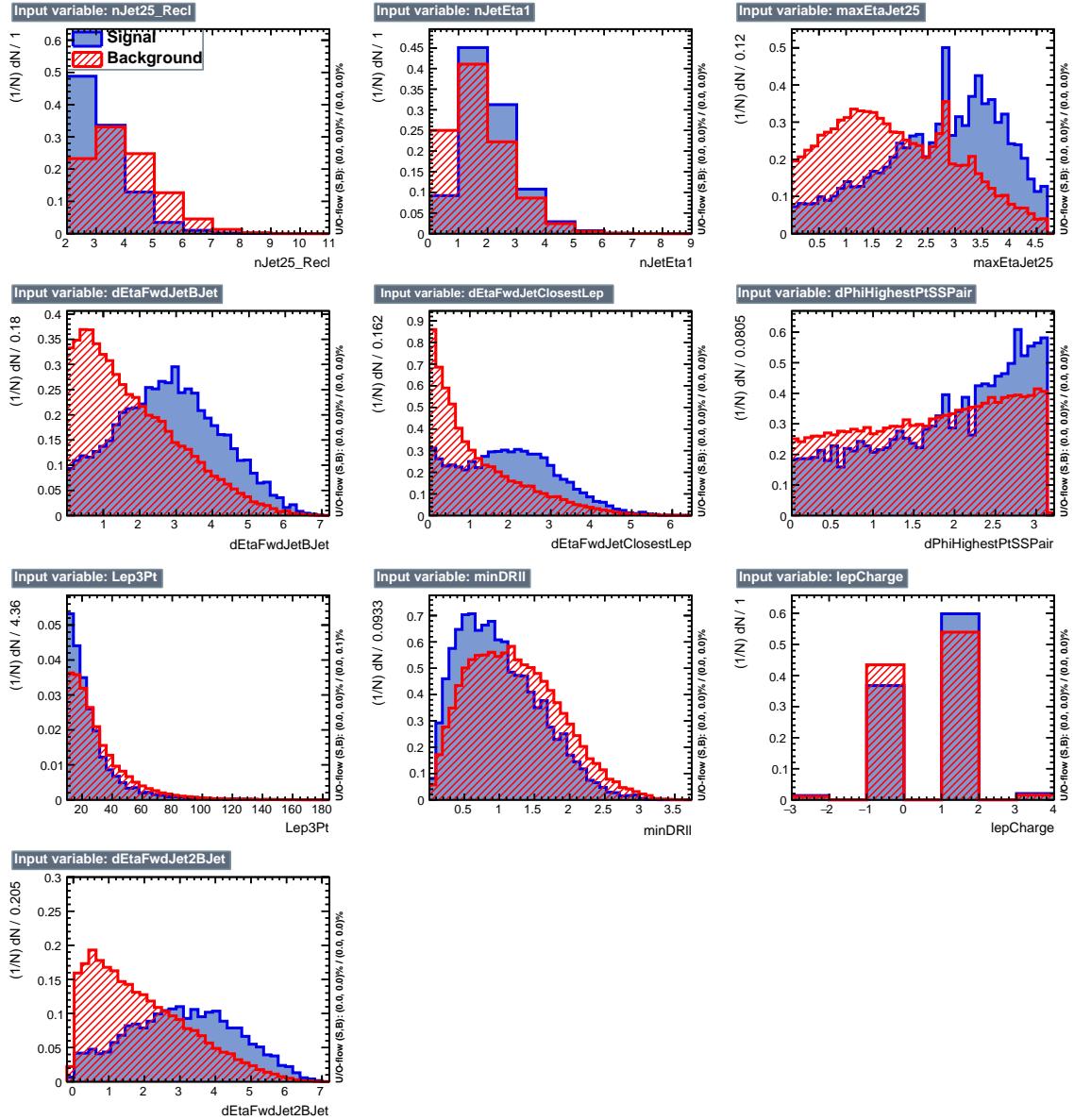


Figure 6.8: BDT inputs as seen by TMVA (signal, in blue, is tHq , background, in red, is $t\bar{t}W+t\bar{t}Z$) for the three lepton channel, discriminated against $t\bar{t}V$ background.

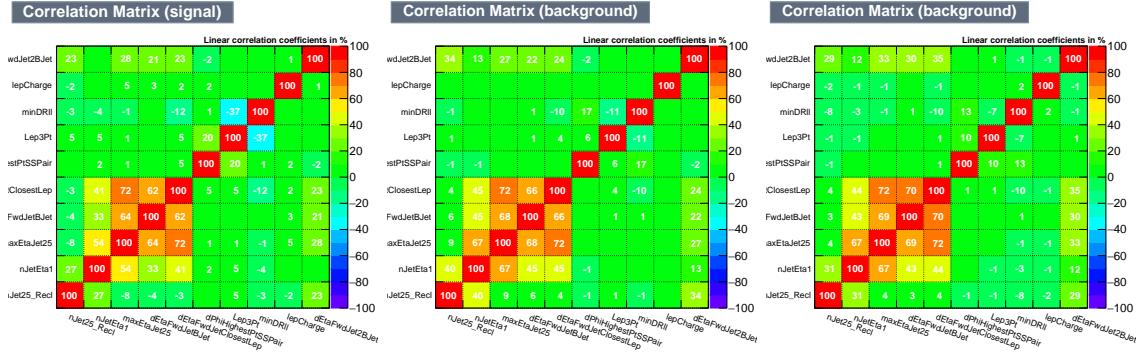


Figure 6.9: Signal (left), $t\bar{t}$ background (middle), and $t\bar{t}V$ background (right.) correlation matrices for the input variables in the TMVA analysis for the three lepton channel.

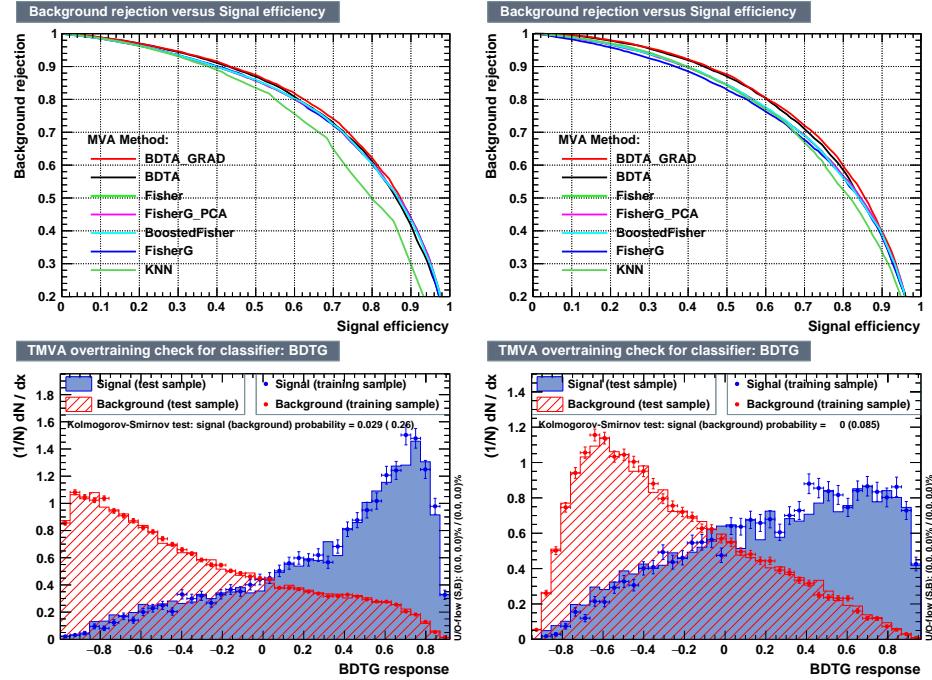


Figure 6.10: Top: background rejection vs signal efficiency (ROC curves) for various MVA classifiers (top) in the three lepton channel against $t\bar{t}V$ (left) and $t\bar{t}$ (right). Bottom: classifier output distributions for the gradient boosted decision trees, for training against $t\bar{t}V$ (left)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

2544 6.9 Additional discriminating variables

2545 Two additional discriminating variables were tested considering the fact that the
 2546 forward jet in the background could come from the pileup; since we have a real forward

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

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

```

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

```

Table 6.12: TMVA configuration used in the BDT training.

2547 jet in the signal, it could give some improvement in the discriminating power. The
 2548 additional variables describe the forward jet momentum (fwdJetPt25) and the forward
 2549 jet identification(fwdJetPUID). Distributions for these variables in the three lepton
 2550 channel are shown in the figure 6.11. The forward jet identification distribution show
 2551 that for both, signal and background, jets are mostly real jets.

2552 The testing was made including in the MVA input one variable at a time, so we
 2553 can evaluate the dicrimination power of each variable, and then both simultaneously.
 2554 fwdJetPUID was ranked in the last place in importance (11) in both training (ttV
 2555 and tt) while fwdJetPt25 was ranked 3 in the ttV training and 7 in the tt training.
 2556 When training using 12 variables, fwdJetPt25 was ranked 5 and 7 in the ttV and tt

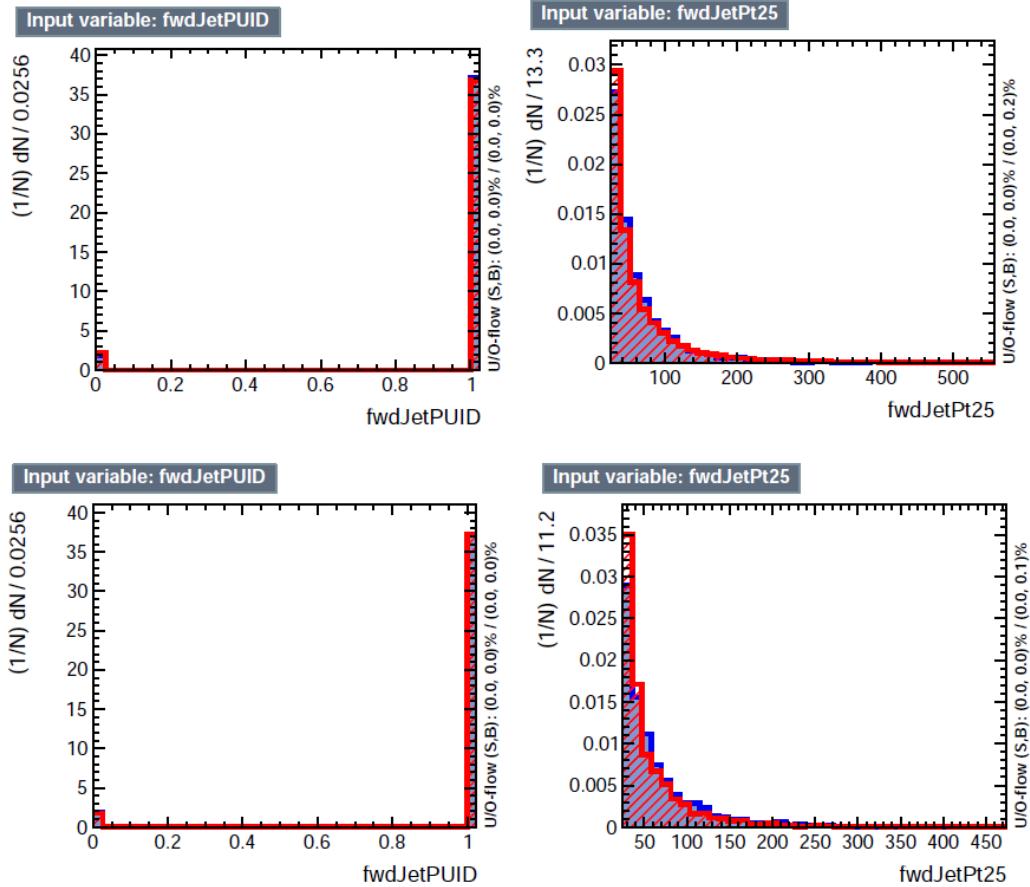


Figure 6.11: Additional discriminating variables distributions for ttv training (Top row) and tt training (bottom row) in the three lepton channel. The origin of the jets in the forward jet identification distribution is tagged as 0 for “pileup jets” while “real jets” are tagged as 1.

2557 trainings respectively, while `fwdJetPUID` was ranked 12 in both cases.

2558 The improvement in the discrimination performance provided by the additional
 2559 variables is about 1%, so it was decided not to include them in the procedure. Table
 2560 6.13 show the ROC-integral for all the testing cases we made.

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

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

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