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Chiara Rizzi

Searches for Supersymmetric Particles in Final States with Multiple Top and Bottom Quarks with the Atlas Detector

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Chiara Rizzi

Searches for Supersymmetric Particles in Final States with Multiple Top and Bottom Quarks with the Atlas Detector

Doctoral Thesis accepted by
Universitat Autònoma de Barcelona,
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Supervisor's Foreword

This Ph.D. thesis documents two of the highest-profile searches for supersymmetry performed at the ATLAS experiment using up to 80 fb^{-1} of proton-proton collision data at a center-of-mass energy of 13 TeV delivered by the Large Hadron Collider (LHC) during its Run 2 (2015–2018). The signals of interest feature a high multiplicity of jets originating from the hadronisation of b -quarks and large missing transverse momentum, which constitutes one of the most promising final state signatures for discovery of new phenomena at the LHC. The first search is focused on the strong production of a pair of gluinos, with each gluino decaying into a neutralino and a top-antitop-quark pair or a bottom-antibottom-quark pair. The second search targets the pair production of higgsinos, with each higgsino decaying into a gravitino and a Higgs boson, which in turn is required to decay into a bottom-antibottom-quark pair. Both searches employ state-of-the-art experimental techniques and analysis strategies at the LHC, resulting in some of the most restrictive bounds available to date on the masses of the gluino, neutralino, and higgsino in the context of the models explored.

Barcelona, Spain

Prof. Aurelio Juste Rozas

Abstract

This dissertation presents two searches for Supersymmetry in proton-proton collisions at CERN's LHC, targeting signal models that lead to the production of multiple top quarks or bottom quarks in the final state.

The first search targets gluino pair production, where each gluino decays through a top squark (Gtt model) or a bottom squark (Gbb model) to a top-antitop quark pair or a bottom-antibottom quark pair, respectively, and a neutralino, which is the Lightest Supersymmetric Partner (LSP). Each top quark in turn decays to a W boson and a bottom quark. Thus, the final state is characterized by a high multiplicity of b -jets, which are collimated sprays of particles originating from the hadronization of bottom quarks, and missing transverse momentum from the LSP that escapes the detection.

The second search targets a GGM model of higgsino pair production, where each higgsino decays to a Standard Model Higgs boson and a gravitino, which in this case plays the role of the LSP. This search focuses on the decay of the two Higgs bosons to bottom-antibottom quark pairs, yielding again final states with multiple b -jets. This is the first ATLAS analysis targeting this signature, which had been previously considered in searches performed by the CMS Collaboration.

Both searches in the thesis use the data collected by the ATLAS experiment at the LHC between 2015 and 2016, at a center-of-mass energy $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 36.1 fb^{-1} . The gluino search, without further reoptimization, is also extended using the data collected in 2017, for a total integrated luminosity of 79.8 fb^{-1} .

No significant excess of events above the Standard Model expectation is observed in any of the search regions, and the results are used to set upper limits on the production of supersymmetric particles. The first search excludes at 95% confidence level gluino masses up to 2.25 TeV for the Gtt model and up to 2.17 TeV for the Gbb model, in both cases for neutralino masses below 800 GeV. The second search excludes higgsino masses in the range 240–880 GeV, assuming that the higgsino decays exclusively to a Higgs boson and a gravitino.

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During the last few years, I have had the opportunity to work and share fun times with a lot of brilliant and kind people, and this has really been one of the best aspects of my Ph.D.

First of all, I would like to thank my Ph.D. supervisor, Aurelio Juste, who has always been extremely supportive of my work; he has let me free to explore my ideas, while being constantly available to provide guidance and advice. Aurelio and Martine Bosman have been able to create a great working environment, and all the people who are (or have been) part of the IFAE group have been precious colleagues and good friends. All the post-docs in the group have always been available to help me with anything from technicalities to long physics discussions, and I am particularly indebted to Loïc Valery and Trisha Farooque, who have helped me in growing as a scientist and have offered me their friendship. Carlos, Davide, Julian, Mirko, Nicola and Tal have been great office mates and a pleasure to spend the time with.

This Ph.D. has not been the beginning of my experience in ATLAS, and I am extremely grateful to Tommaso Lari, who supervised me during my bachelor and master thesis at the University of Milan, and continued being a reference figure also during my Ph.D.; he taught me how to appreciate the most interesting aspects of High Energy Physics research and how to have fun while doing it.

Since the beginning of the Ph.D., I have found in the multi- b team a group of people who kept me motivated and helped me in gaining independence in my work, in an atmosphere that always enhanced collaboration. I am particularly grateful to Max Swiatlowski, whose expertise, energy and dedication have been invaluable ingredients in building a wonderful team, and to Giordon Stark, who has always been available to kindly help me and many others (and to whom goes the credit for the awesome event display on the cover).

I have had the chance to work with many great people in the ATLAS SUSY group, and I want to thank particularly Iacopo Vivarelli, Till Eifert and Zach Marshall, who have been conveners of the group, and all the subconveners who in the past years have put a lot of effort and passion in organizing the group and providing support and critical review to each analysis.

I would like to thank the people working in TileCal luminosity group, and I am especially grateful to Ilya Korolkov, Richard Hawkins and Witold Kozanecki for their patience and their inspiring ideas. I also would like to thank all the people of the HistFitter team, particularly Sophio Patariaia and Jeanette Lorenz.

Moving to a new place is always somehow scary, but since the beginning of my stay at CERN in 2014, I have had the opportunity to rely on Andrea, a fellow Ph.D. student in the IFAE group. Her amazing human skills and optimism have helped me making a lot of good friends, including Dott. Ing. Carlo Zaroni, who has been an important part of my everyday life.

During the last few years, a lot of people that are currently studying in Milan, or that like me studied in Milan to then continue working somewhere else, created a lively CERN-based community that makes me feel closer to home. Thanks to Alessandra, Carlo, Davide, Ettore, Giacomo, Giulia, Maria Giulia, Stefano and the rest of the lunch crew! A special thank you goes to the SUSY-enthusiast Claudia, Sonia and Lorenzo who have helped me a lot in the last-minute panic moments.

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Acronyms

AMSB	Anomaly-mediated supersymmetry breaking
ATLAS	A Toroidal LHC Apparatus
BCID	Bunch-crossing identifier
BCM	Beam Conditions Monitor
BDT	Boosted decision tree
BR	Branching ratio
BSM	Beyond Standard Model
CERN	European Organization for Nuclear Research
CKM	Cabibbo–Kobayashi–Maskawa
CL	Confidence level
CL_s	Modified confidence level
CMS	Compact Muon Solenoid
corrJVF	corrected jet vertex fraction
CR	Control region
CSC	Cathode strip chambers
CST	Calorimeter soft term
CTP	Central Trigger Processor
DR	Diagram removal
DS	Diagram subtraction
EB	Extended barrel
ECal	Electromagnetic calorimeter
EM	Electromagnetic
FSR	Final-state radiation
GGM	General gauge mediation
GMSB	Gauge-mediated supersymmetry breaking
GRL	Good run list
GSC	Global sequential calibration
HCal	Hadronic Calorimeter
HLT	High-level trigger
HPD	Hybrid photon detectors

IBL	Insertable B-Layer
ID	Inner Detector
IP	Interaction point
IR	Infrared
ISR	Initial-state radiation
JER	Jet energy resolution
JES	Jet energy scale
JVF	Jet vertex fraction
JVT	Jet vertex tagger
L1	Level 1
L1Calo	Level 1 Calorimeter trigger
L1Muon	Level 1 Muon trigger
L1Topo	Level 1 Topological trigger
LAr	Liquid Argon
LB	Long barrel
LB	Luminosity block
LEIR	Low Energy Ion Ring
LEP	Large Electron-Positron Collider
LHC	Large Hadron Collider
LL	Leading logarithm
LLR	Log-likelihood ratio
LO	Leading order
LSP	Lightest supersymmetric partner
MC	Monte Carlo
MCP	Microchannel plates
MDT	Monitored Drift Tubes
ME	Matrix element
MLE	Maximum likelihood estimate
MS	Muon spectrometer
MSSM	Minimal Supersymmetric Standard Model
NLL	Next-to-leading logarithmic
NLO	Next-to-leading order
NLSP	Next to lightest supersymmetric partner
NNLL	Next-to-next-to-leading logarithmic
NNLO	Next-to-next-to-leading order
NP	Nuisance parameters
OP	Operating point
OR	Overlap removal
PDF	Parton distribution function
PDF	Probability density function
PLR	Profiled likelihood ratio
PMSB	Planck-scale-mediated supersymmetry breaking
pMSSM	phenomenological Minimal Supersymmetric Standard Model
PMT	Photonmultiplier tube
POI	Parameter of interest

<i>pp</i>	Proton-proton
PS	Parton shower
PS	Proton Synchrotron
PSB	Proton Synchrotron Booster
PV	Primary vertex
QCD	Quantum chromodynamics
QED	Quantum electrodynamics
RDO	Raw data object
RF	Radiofrequency
RMS	Root mean square
RoI	Region of interest
RPC	R-parity conserving
RPC	Resistive plate chambers
RPV	R-parity violating
SCT	Semiconductor Tracker
SF	Scale factor
SM	Standard Model
SPS	Super Proton Synchrotron
SR	Signal region
SSB	Spontaneous symmetry breaking
SUSY	Supersymmetry
TDAQ	Trigger and data acquisition
TF	Transfer factor
TGC	Thin gap chambers
TileCal	Tile barrel calorimeter
TRD	Transition radiation detector
TRT	Transition Radiation Tracker
TST	Track soft term
UL	Upper limit
vdM	van der Meer
VEV	Vacuum expectation value
VR	Validation region

Chapter 1

Preamble



At the Large Hadron Collider (LHC) proton-proton (pp) collisions are used to probe the nature of particles in energy regimes that were not accessible before. After the discovery of the Higgs boson in 2012, the LHC is now continuing its operations with the dual goal of measuring the Higgs boson properties in great detail but also to continue the quest for new particles.

ATLAS is one of the two general purpose experiments on the LHC ring, and this thesis focuses on the data that it has collected between 2015 and 2016, at a center-of-mass energy $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of approximately 36 fb^{-1} .

The Standard Model (SM) is the theory that as of today best describes the experimental results on subatomic particles. Nevertheless, there are strong theoretical and experimental arguments to believe that the SM is the low-energy limit of a more general theory, yet to be determined. Supersymmetry (SUSY) is one of the most promising SM extensions, addressing some of its shortcomings. SUSY predicts the existence of partners for SM particles, which cancel the SM corrections to the Higgs boson mass, solving the naturalness problem. In “natural” SUSY models, several particles are expected to be light and therefore observable at the LHC. First of all higgsinos, which share the same tree-level mass parameter as the Higgs boson. Then top squarks (stops), that provide a one-loop correction to its mass, and gluinos, that give a two-loop correction since they contribute at one-loop at the stop mass. The requirement on the stop mass reflects also on the sbottom mass, to which is related through the weak-isospin symmetry. These particles are exactly the target of the searches presented in this thesis. Furthermore, in the framework of R-parity conserving (RPC) SUSY, supersymmetric particles are produced in pairs and the lightest supersymmetric partner (LSP) is stable. In several models the LSP is neutral and weakly interacting, providing a good candidate for dark matter.

In this dissertation I discuss two searches for SUSY in final states enriched in b -jets, the collimated sprays of particles originating from the hadronization of a

b -quark. I have been strongly involved in both analyses, and in this thesis I describe with more emphasis the topics where I have given direct contribution.

The first analysis discussed is a search for gluino pair production, where each gluino decays through a stop or a sbottom to respectively four top or four bottom quarks and the LSP, which is assumed to be neutral and stable. Since the top quark decays to a b -quark and a W -boson, both the gluino decay chain through stop and sbottom lead to a final state with multiple b -jets and missing transverse momentum (E_T^{miss}).

The second search targets a general gauge mediation (GGM) model of higgsino pair production, where each higgsino then decays promptly to a Higgs boson and a gravitino, which in this case is the LSP. The high branching ratio of the Higgs boson into a pair of b -quarks makes a final state rich in b -jets promising to tackle this signature.

The content of this dissertation is organized as follows. Chapter 2 presents an introduction to the SM, moving then to its shortcomings and possible extensions, with particular focus on SUSY. Chapter 3 describes the LHC accelerator complex, the general techniques used in detectors for high-energy physics and the details of the ATLAS detector. Chapter 4 discusses the physics of pp interactions and how they are simulated with Monte Carlo (MC) techniques. The event reconstruction and the identification of the physics objects used in the analyses is presented in Chapter 5. Chapter 6 describes the main statistical procedures used to derive quantitative results in the analysis of the LHC data. Chapter 7 gives a general introduction to the strategies common to both the analyses discussed in this thesis, which are discussed in Chap. 8 and Chap. 9 for the gluino search and the higgsino search respectively. Chapter 10 presents a comparison of the analyses discussed in this thesis with other searches carried out by the ATLAS and CMS collaborations targeting similar signal models. Finally, the conclusions are discussed.

The results presented in this dissertation have lead to the following publications:

- ATLAS Collaboration, “Search for Supersymmetry in final states with missing transverse momentum and multiple b -jets in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, JHEP 06 (2018) 107.
- ATLAS Collaboration, “Search for supersymmetry in final states with missing transverse momentum and multiple b -jets in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, ATLAS-CONF-2018-041.
- ATLAS Collaboration, “Search for pair production of higgsinos in final states with at least three b -tagged jets in $\sqrt{s} = 13$ TeV pp collisions using the ATLAS detector”, [arXiv:1806.04030](https://arxiv.org/abs/1806.04030) [hep-ex], Submitted to: Phys. Rev. (2018).

While the paper mentioned above is the first ATLAS result for the signal model with higgsino pair production, the high cross-section for gluino pair-production made strong-production multi- b signals among the ones that were targeted since Run 1. I have been heavily involved in all the strong-production multi- b results since the beginning of Run 2, in particular:

- ATLAS Collaboration, “Search for pair production of gluinos decaying via stop and sbottom in events with b -jets and large missing transverse momentum in pp

collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, Phys. Rev. D 94 (2016) 032003.

- ATLAS Collaboration, “Search for pair production of gluinos decaying via top or bottom squarks in events with b -jets and large missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, ATLAS-CONF-2016-052.

Beside physics analyses, I have also been involved in studies related to the performance of the ATLAS hadronic calorimeter: as discussed in Appendix D, I have evaluated the impact of a non-linearity in the response of the photomultiplier tubes of the hadronic calorimeter on the measurement of the ATLAS luminosity. I have also carried out studies related to the identification of b -jets, performing studies on the b -tagging efficiency for jets with high transverse momentum and contributing to the development and validation of a tool to facilitate the use of truth-tagging; this technique allows to reduce the statistical uncertainty on samples of simulated events when requiring a high number of b -jets.

Chapter 2

Introduction to Standard Model and Supersymmetry



This chapter presents an introduction to the SM of particle physics, the theory that nowadays best describes the subatomic world. In Sect. 2.1 a general overview of the SM is given. Section 2.2 discusses the limitations of the SM, and some of the theoretical extensions proposed to overcome them. Finally Sect. 2.3 focuses on Supersymmetry, arguably one of the most promising of these extensions. Throughout this chapter (as well as in the rest of this thesis) we will use natural units; we will thus use energy units to describe masses, as the speed of light (c) and the Planck constant ($\hbar$) are set to unity.

2.1 The Standard Model of Particle Physics

The SM is a renormalizable gauge quantum field theory based on the group $SU(3) \times SU(2) \times U(1)$. It was developed in the second half of the 20th century [1–3], and since then the description that it gives of the elementary particles and of their interactions has been accurately tested by several experiments. Many experimental discoveries have been guided by the SM predictions, including the discovery of the top quark [4, 5] and up to the latest one, the observation of the Higgs boson at the LHC in July 2012 [6, 7].

2.1.1 Particle Content of the Standard Model

In the SM, particles are described as excitations of quantum fields. In the following paragraphs, we introduce the quantum field theory description of fermions and bosons.

Table 2.1 Fermion content of the Standard Model. Each particle is listed with its electric charge and mass [8]

Generation	Leptons			Quarks		
	Flavor	Charge	Mass (GeV)	Flavor	Charge	Mass (GeV)
1st	ν_e	0	$<2 \times 10^{-9}$	u	+2/3	2.2×10^{-3}
	e	-1	5.1×10^{-4}	d	-1/3	4.8×10^{-3}
2nd	ν_μ	0	$<2 \times 10^{-9}$	c	+2/3	1.27
	μ	-1	0.10566	s	-1/3	0.096
3rd	ν_τ	0	$<2 \times 10^{-9}$	t	+2/3	173.2
	τ	-1	1.77	b	-1/3	4.66

2.1.1.1 Fermions

Matter constituents are half-integer spin fields (fermions). Fermions are further divided into two categories based on the type of interaction they experience:

Leptons which experience only the electromagnetic and weak interactions.

Quarks which experience both the electroweak and the strong interaction.

Both leptons and quarks come in three generations, and conventionally the numbering of these generations follows an order of increasing mass. A summary of the SM fermions is presented in Table 2.1. While it is possible to observe free leptons, quarks exist only in bound states (hadrons); this is because of the confinement property of the strong interaction, discussed in Sect. 2.1.3. Hadrons built of three quarks have spin $\frac{1}{2}$ and are named baryons, while mesons are formed by two quarks and have integer spin.

The free Lagrangian of a fermion is given by:

$$\mathcal{L}_{free} = \bar{\psi} (i\gamma^\mu \partial_\mu - m) \psi, \quad (2.1)$$

where ψ is the fermion field, m its mass, γ are the Dirac matrices and ∂_μ is the four-momentum derivative.

2.1.1.2 Bosons

Particles with integer spin are referred to as bosons. In the SM, force carriers are described through spin-1 fields. The SM includes also a spin-0 particle, the Higgs boson. It is the interaction with the Higgs boson field that allows all the other elementary particles to acquire mass, as described in Sect. 2.1.4.

The Klein-Gordon Lagrangian governs the kinematics of spin-0 neutral particles:

$$\mathcal{L}_{free} = \frac{1}{2} \partial^\mu \phi \partial_\mu \phi - \frac{1}{2} m^2 \phi^2,$$

while in the case of charged particles (described through a complex field) the Lagrangian becomes:

$$\mathcal{L}_{\text{free}} = \partial^\mu \phi \partial_\mu \phi^* - m^2 \phi \phi^*.$$

The two equations above describe scalar particles. In the case of a vector field A^μ , the expression of the Lagrangian is the following:

$$\mathcal{L}_{\text{free}} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \frac{1}{2} m^2 A^\mu A_\mu. \quad (2.2)$$

This is the Proca Lagrangian. In the case of a massless particle, this reduces to the Maxwell Lagrangian:

$$\mathcal{L}_{\text{free}} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu}, \quad (2.3)$$

where $F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$.

2.1.2 Interactions and Gauge Invariance

The SM describes all the interactions among elementary particles, except for gravity, for which nowadays no renormalizable quantum field theory is formulated. Table 2.2 presents a summary of the SM interactions and the properties of the corresponding force carriers. More details about the strong and electroweak interactions are given in the following sections.

The interaction terms in the SM Lagrangian are introduced by promoting an already existing global symmetry of the Lagrangian (θ) to a local one ($\theta(x)$) function of the space-time coordinates. In general, given a Lagrangian which is invariant under a symmetry group, the fields transform as:

$$\psi \rightarrow e^{ig\theta^k \tau^k} \psi,$$

where g is the coupling constant of the field ψ under the interaction and τ^k are the generators of the group and obey commutation relations:

Table 2.2 Interaction in the Standard Model. Here the different force carriers are listed, with their electric charges and masses [8]

Interaction	Carrier	Electric Charge	Mass (GeV)
Strong	Gluons (g)	0	0
Electromagnetic	Photon (γ)	$<10^{-27}$	0
Weak	W^+, W^-	$+1, -1$	80.385
	Z	0	91.1876

$$[\tau^i, \tau^j] = if^{ijk}\tau^k.$$

In the equation above, f^{ijk} is the structure constant of the group and is always zero for Abelian groups. Promoting this global invariance to a local one ($\theta^k \rightarrow \theta^k(x)$) implies adding to the theory:

- A number of massless gauge fields W_μ^k equal to the number of generators of the symmetry group, that transform as

$$W_\mu^k \rightarrow W_\mu^k + \partial_\mu \theta^k + gf^{klm} W_\mu^l \theta^m.$$

- A covariant derivative:

$$D_\mu = \partial_\mu - ig\tau^k W_\mu^k,$$

that substitutes the standard derivative in the Lagrangian.

- A free Lagrangian for the vector fields as in Eq. 2.2, with:

$$F_{\mu\nu}^k = \partial_\mu W_\nu^k - \partial_\nu W_\mu^k + gf^{klm} W_\mu^l W_\nu^m.$$

Note that the last term, of second order in the field, is present only for non-Abelian symmetry groups, since it is proportional to the structure constant. This has non-trivial consequences as the second-order term leads to self-interaction among the gauge fields.

The SM is a theory invariant under $SU(3)_C \times SU(2)_L \times U(1)_Y$. Imposing local invariance under $SU(3)_C$ leads to the theory of strong interactions, while $SU(2)_L \times U(1)_Y$ is the symmetry whose breaking gives origin to the electroweak interactions.

2.1.3 Strong Interaction

Quantum chromodynamics (QCD) is the theory that describes strong interactions, based on the symmetry group $SU(3)_C$, where the subscript C refers to the color, the quantum number associated with these interactions. This can assume three possible values denoted with red, blue, and green. The observable states, hadrons, are color singlets, while quarks (anti-quarks) carry only one color (anti-color) charge. Since the symmetry group is non-Abelian, also the corresponding eight gauge bosons (gluons) carry a color charge (bi-color, with one color and one different anti-color) and therefore interact not only with quarks but also among themselves. Since $SU(3)_C$ is believed to be an exact symmetry, gluons are massless.

The renormalization of a gauge theory leads to the definition of running coupling constants, whose value depend on the energy scale at which they are evaluated. In QCD, at leading order the dependence of the coupling constant on the energy scale Q is given by:

$$\alpha_s(Q^2) = \frac{12\pi}{(11N_C - 2n_f) \log \frac{Q^2}{\Lambda_{\text{QCD}}^2}}, \quad (2.4)$$

where N_C is the number of colors, n_f is the number of quark flavors that are active (i.e. whose mass is lower than the energy scale) and Λ_{QCD} is the infrared cutoff scale that sets the limit of validity of the perturbative approximation. In QCD $N_C = 3$, so for $n_f < 16$ the coupling constant decreases with the increase of the energy scale of the process considered. This behavior has important consequences on the properties of the strong interaction:

- At high Q^2 (i.e. at small distances), α_s becomes small enough for the perturbative approximation to be correct. In this case quarks and gluons behave as free particles; this behavior is referred to as asymptotic freedom [9, 10].
- When the momentum transfer is small (i.e. at large distances) α_s is large; this gives rise to confinement: quarks cannot be observed as isolated particles, as it is not possible to extract individual quarks from hadrons. When the distance between two quarks is increased, the potential energy increases as well, up to the point when it is energetically more favorable to create from the vacuum a quark-antiquark pair and thus a new hadron is formed.
- In a collider experiment, quarks and gluons will create a collimated spray of hadrons, referred to as jet.

The evolution of the QCD coupling constant with the energy scale has been verified experimentally, as shown for example in Fig. 2.1.

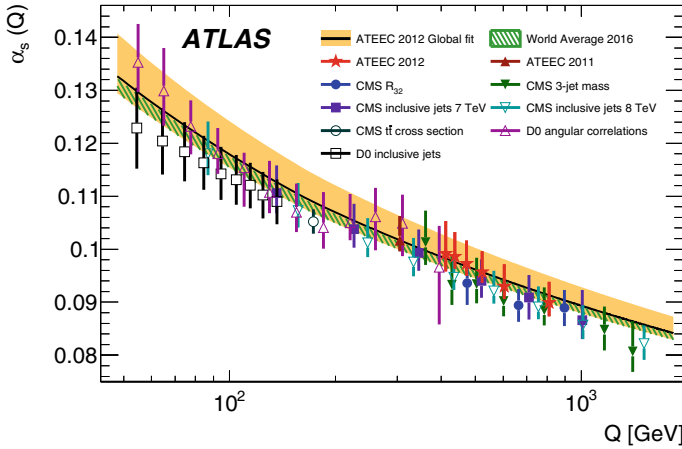


Fig. 2.1 Experimental determinations of the QCD coupling constant α_s . The 2016 world average is shown in the green hatched band. Figure from Ref. [11]

2.1.4 Electroweak Interaction and Higgs-Englert-Brout Mechanism

The theory of electroweak interactions is based on the symmetry group $SU(2)_L \times U(1)_Y$. This symmetry breaks at a scale around 100 GeV giving rise to the electromagnetic interaction, mediated by the photon, and to the weak interaction, mediated by the Z and $W^\pm$ bosons for neutral currents and charged currents respectively. The number of mediators, four, is the same as the number of generators of the symmetry group.

The $SU(2)_L$ part of the symmetry group governs the weak interactions, and the subscript L indicates that only left-handed particles participate to them. Left-handed and right-handed fields (ψ_L and ψ_R respectively) are defined through the chirality projectors P_L and P_R :

$$\begin{aligned}\psi_L &= P_L \psi = \frac{(1 - \gamma_5)}{2} \psi , \\ \psi_R &= P_R \psi = \frac{(1 + \gamma_5)}{2} \psi ,\end{aligned}$$

where γ_5 is defined as $\gamma_5 = i\gamma^0\gamma^1\gamma^2\gamma^3$. Looking back at Eq. 2.1, it can be noted that, if we decompose the fermion field into its left-handed and right-handed components, the derivative term keeps ψ_L and ψ_R separated, while the mass term mixes them:

$$-m\bar{\psi}\psi = -m\bar{\psi}P_L^2\psi - m\bar{\psi}P_R^2\psi = -m\bar{\psi}_R\psi_L - m\bar{\psi}_L\psi_R .$$

The covariant derivative for the $SU(2)_L \times U(1)_Y$ group is:

$$\mathcal{D}_\mu = \partial_\mu - ig' B_\mu Y - ig W_\mu^k T^k , \quad (2.5)$$

and substituting with this the regular derivative results in the interaction Lagrangian:

$$\mathcal{L}_{int}^{EW} = -\frac{g'}{2} (\bar{\psi}\gamma_\mu Y \psi) B^\mu - g \sum_k (\bar{\psi}\gamma_\mu T^k \psi) W_k^\mu ,$$

where we have introduced T^k , the weak isospin operator, and Y , the hypercharge operator (associated to the $U(1)_Y$ group), and the respective coupling constants g and g' . The quantum numbers of the T^k and Y operators relate to the electric charge Q through the Gell-Mann Nishijima relation:

$$Q = \frac{Y}{2} + T_3 ,$$

where Y is the hypercharge quantum number and T_3 is the quantum number of the third component of the isospin.

In the case of an $SU(2)$ symmetry, it is not possible to add directly to the Lagrangian a mass term for the vector bosons of the form in Eq. 2.2, as it would spoil the $SU(2)$ local invariance. The Higgs-Englert-Brout mechanism [12–14] solves this problem through spontaneous symmetry breaking (SSB) of the $SU(2)_L \times U(1)_Y$ invariance. The SSB is obtained by adding to the theory one extra isospin doublet of complex scalar components, the Higgs field:

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} .$$

This doublet has hypercharge $Y = 1$ and isospin $T = \frac{1}{2}$; the first component has positive electric charge, while the second one is electrically neutral. The Lagrangian for this new field includes a kinetic and a potential term:

$$\mathcal{L}_\Phi = (\mathcal{D}_\mu \Phi)^\dagger (\mathcal{D}^\mu \Phi) - V(\Phi) , \quad (2.6)$$

where $\mathcal{D}_\mu$ is the covariant derivative defined in Eq. 2.5 and the potential $V(\Phi)$ is given by:

$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 .$$

The two real parameters μ^2 and λ relate respectively to the mass term and the strength of the self-interaction term. The shape of the potential depends on the value of these parameters:

- If $\lambda < 0$, the potential does not present any stable minima, and this case is therefore unphysical.
- If $\lambda > 0$ and $\mu^2 > 0$ there is only one solution to the minimization of the potential, $\Phi = 0$. This case is shown in Fig. 2.2a.
- If $\lambda > 0$ and $\mu^2 < 0$, the field acquires a vacuum expectation value (VEV) as the minima is not at zero; it lies instead on the points of the circumference such that:

$$\Phi^\dagger \Phi = \frac{\mu^2}{2\lambda} \equiv \frac{v^2}{2} . \quad (2.7)$$

Figure 2.2b illustrates this case.

Up to this point the $SU(2)_L \times U(1)_Y$ symmetry is still intact, but the explicit choice of one of the infinite possible vacuum states for the Higgs field breaks the symmetry. According to the Goldstone theorem [15], the breaking of a continuous symmetry leads to the appearance of new massless scalar particles as field excitations. These new degrees of freedom are absorbed by the existing gauge bosons, thus giving them mass. To meet the experimental requirement of a massless photon, the choice of the Higgs vacuum has not to break the electromagnetic symmetry, $U(1)_{EM}$, so the component of the Higgs doublet that acquires a VEV is the neutral one:

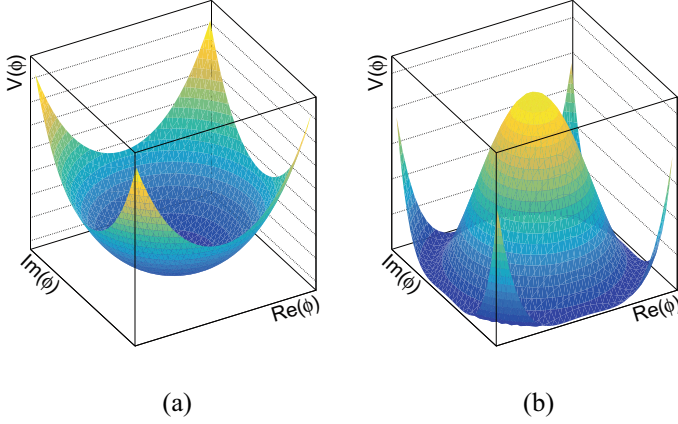


Fig. 2.2 Higgs potential in the case **a** $\lambda > 0$ and $\mu^2 > 0$ and **b** $\lambda > 0$ and $\mu^2 < 0$

$$\Phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}.$$

We can then expand the field Φ considering small excitations around the minimum:

$$\Phi = \frac{e^{i\vec{\sigma} \cdot \vec{\theta}(x)/v}}{\sqrt{2}} \begin{pmatrix} 0 \\ v + \phi(x) \end{pmatrix}, \quad (2.8)$$

where $\phi(x)$ is the physical field associated with the Higgs boson, $\vec{\sigma}$ the Pauli matrices and $\vec{\theta}(x)$ the three degrees of freedom absorbed to give masses to the Z and $W^\pm$ bosons. Inserting Eq. 2.8 into Eq. 2.6 relates the mass of the Higgs boson to the parameters in the potential:

$$m_H = \sqrt{-2\mu^2} = \sqrt{2\lambda}v. \quad (2.9)$$

Since the numeric value of the μ^2 and λ parameters is not set, the theory does not predict a specific value for m_H . The physical mass eigenstates of the gauge bosons are a rotation of the interaction eigenstates, given by:

$$\begin{aligned} W_\mu^\pm &= \frac{W_\mu^1 \mp W_\mu^2}{\sqrt{2}}, \\ A_\mu &= B_\mu \cos \theta_W + W_\mu^3 \sin \theta_W, \\ Z_\mu &= W_\mu^3 \cos \theta_W - B_\mu \sin \theta_W, \end{aligned}$$

where we have introduced the Weinberg angle θ_W such that:

$$\tan \theta_W \equiv \frac{g'}{g} .$$

The $(\mathcal{D}_\mu \Phi)^\dagger (\mathcal{D}^\mu \Phi)$ term in Eq. 2.6 gives rise to the physical mass of the gauge bosons: once applied to the Higgs field, the covariant derivative in Eq. 2.5 produces terms quadratic in the gauge fields, that we interpret as mass terms:

$$\mathcal{L}_\Phi = \left(1 + \frac{\phi}{v}\right)^2 \left\{ m_W^2 W_\mu^\dagger W^\mu + \frac{1}{2} m_Z^2 Z_\mu Z^\mu \right\} + \mathcal{L}_H ,$$

where $\mathcal{L}_H$ denotes all the terms in $\mathcal{L}_\Phi$ that involve only the Higgs field: Higgs boson mass, cubic and quadratic self-interaction. Note that the coupling of the gauge bosons with the Higgs field is proportional to the square of the boson mass. At tree level the resulting masses of the gauge bosons are:

$$\begin{aligned} m_\gamma &= 0 , \\ m_Z &= \frac{v\sqrt{g^2 + g'^2}}{2} , \\ m_W &= \frac{vg}{2} = \cos \theta_W m_Z . \end{aligned}$$

Therefore, the Higgs-Englert-Brout mechanism generates automatically a mass term for the gauge bosons, that does not break the global underlying $SU(2)_L \times U(1)_Y$ symmetry. The Higgs field is also used to make fermion mass terms arise, but in this case it is necessary to postulate a Yukawa interaction between the Higgs and fermion fields. The fermion masses are assumed to be proportional to the strength of the coupling and, unlike the masses of the gauge bosons, they are not related to other parameters of the theory. While the Higgs field itself is enough to give mass to down-type fermions, the mass term for the up-type fermions requires the introduction of the complex conjugate of the Higgs field (Φ_C):

$$\Phi_C = i\sigma^2 \Phi^* = i \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \begin{pmatrix} \phi^- \\ \phi^{0*} \end{pmatrix} = \begin{pmatrix} \phi^{0*} \\ -\phi^- \end{pmatrix} .$$

If we identify as y_f the coupling of the fermion f to the Higgs field, referred to as Yukawa coupling, the additional part of the Lagrangian that generates the fermion masses is:

$$\begin{aligned} \mathcal{L}_{Yukawa} &= - [y_d (\bar{u}_L \bar{d}_L) \Phi d_R + y_u (\bar{u}_L \bar{d}_L) \Phi_C u_R] + h.c. \\ &= - \frac{1}{\sqrt{2}} [y_d (v + \phi) \bar{d}_L d_R + h.c. + y_u (v + \phi) \bar{u}_L d_u + h.c.] . \end{aligned}$$

In this equation we can now easily identify the fermion mass terms, of the form: