STOCKHOLM UNIVERSITY

Doctoral Studies in Physics

Licensiate Thesis

# Search for in Mono-jet Final States with the ATLAS Experiment

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# Acknowledgments

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*Si sta,*
*come d'autunno,*
*sugli alberi,*
*le foglie*

[G. Ungaretti, Soldati]

# Introduction

# Part I

# Theoretical Overview

# Chapter 1

# The Standard Model of Particle Physics

## 1.1 The Standard Model

The *Standard Model* (SM) is a theoretical model which describes the elementary constituents of matter and their interactions. Up to now, we discovered four kind of different interactions, the *electromagnetic*, the *gravitational*, the *strong* and the *electro-weak interaction*; excluding gravity, all of them are described by means of a *quantum field gauge theory*.

The Standard Model is the collection of these gauge theories, it is based on the gauge symmetry group $SU(3)_C \times SU(2)_L \times U(1)_Y$ where $SU(3)_C$ is the symmetry group of the *Quantum Chromo-Dynamics* (QCD), the "C" subscript stand for *color charge* which is the conserved charge in the strong interaction. The $SU(2)_L$ is the weak isotopic spin group acting on *left-handed* doublet of fermions while the $U(1)_Y$ group is the *hypercharge* symmetry group of the *right-handed* fermion singlets. Together $SU(2)_L \times U(1)_Y$ form the electro-weak symmetry group.

The Standard Model also contains and (sometimes) predicts the existence of *elementary particles* that interacts between them via the forces mentioned above. The matter constituents are called *fermions*, the interaction are mediated by other particles called *gauge bosons*. Fermions are further categorized into *quark* and *leptons* and are the true fundamental constituents of matter; the gauge bosons arise by means of symmetry property of the Standard Model symmetry group.

The existence of all the leptons, quarks and gauge bosons is confirmed by experimental tests. Among the bosons, the Higgs boson is peculiar because, unlike the others, it is not associated with any interaction, instead is postulated as a consequence of the *spontaneously broken symmetry* of the electroweak sector which is the property, responsible of giving mass to all the elementary particles and the weak gauge bosons.

### 1.1.1 Electro-Weak Symmetry Group

We can now see how to find out the weak interaction symmetry group, to this end, let us start by writing out the *Hamiltonian*

$$H_{weak} = \frac{4G_F}{\sqrt{2}} J_\mu^\dagger J^\mu \tag{1.1.1}$$

where

$$J_\mu \equiv J_\mu^{(+)} = \bar{\psi}_{\nu_e}\gamma_\mu \frac{1}{2}(1-\gamma_5)\psi_e \equiv \bar{\nu}_{e_L}\gamma_\mu e_L$$
$$J_\mu^\dagger \equiv J_\mu^{(-)} = \bar{\psi}_e\gamma_\mu \frac{1}{2}(1-\gamma_5)\psi_{\nu_e} \equiv \bar{e}_L\gamma_\mu \nu_{e_L} \tag{1.1.2}$$

to easy the notation, let us write

$$\chi_L = \begin{pmatrix} \nu_{e_L} \\ e_L^- \end{pmatrix} \equiv \begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \tag{1.1.3}$$

and using the Pauli matrices

$$\tau_\pm = \frac{1}{2}(\tau_1 \pm i\tau_2) \tag{1.1.4}$$

we have

$$J_\mu^{(+)} = \bar{\chi}_L\gamma_\mu\tau_+\chi_L$$
$$J_\mu^{(-)} = \bar{\chi}_L\gamma_\mu\tau_-\chi_L \tag{1.1.5}$$

by introducing a "neutral" current

$$J_\mu^{(3)} = \bar{\chi}_L\gamma_\mu\frac{\tau_3}{2}\chi_L = \frac{1}{2}\bar{\nu}_L\gamma_\mu\nu_L - \frac{1}{2}\bar{e}_L\gamma e_L \tag{1.1.6}$$

we have a "triplet" of currents

$$J_\mu^i = \bar{\chi}_L\gamma_\mu\frac{\tau_i}{2}\chi_L. \tag{1.1.7}$$

Now if we pick up an $SU(2)_L$ transformation

$$\chi_L(x) \to \chi_L'(x) = e^{i\vec{\varepsilon}\cdot\vec{T}}\chi_L(x) = e^{i\vec{\varepsilon}\cdot\frac{\vec{\tau}}{2}}\chi_L(x), \tag{1.1.8}$$

where $T_i = \tau_i/2$ are the $SU(2)_L$ *generators*, and think the $\chi_L$ as the *fundamental representation*, then the current triplet is a triplet of $SU(2)_L$, the *weak isotopic spin*.

The right handed fermions are singlet for the $SU(2)_L$, thus

$$e_R \to e_R' = e_R. \tag{1.1.9}$$

Since we are considering the global transformations, we have no interaction, so the Lagrangian reads

$$\mathcal{L} = \bar{e}i\gamma^\mu\partial_\mu e + \bar{\nu}i\gamma^\mu\partial_\mu\nu \equiv \bar{\chi_L}i\gamma\partial\chi_L + \bar{e}_Ri\gamma\partial e_R; \tag{1.1.10}$$

for now we are bounded to set $m_e = 0$, in fact the mass term couples right and left fermion's components and it is not $SU(2)_L$ invariant. In 1973, experiments detected events of the type

$$\bar{\nu}_\mu e^- \to \bar{\nu}_\mu e^- \tag{1.1.11}$$

$$\begin{cases} \nu_\mu N \to \nu_\mu X \\ \bar{\nu}_\mu N \to \bar{\nu}_\mu X \end{cases} \tag{1.1.12}$$

which are evidence of a neutral current. Further investigations yielded that the neutral weak current is predominantly $V - A$ (i.e. left-handed) but not purely $V - A$ so the

$J_\mu^{(3)}(x)$ current introduced above can not be used as it involves only left handed fermions. We know a neutral current that mixes left and right components namely the electromagnetic current

$$J_\mu \equiv eJ_\mu^{(em)} = e\bar{\psi}\gamma_\mu Q\psi \tag{1.1.13}$$

where $Q$ is the charge operator with eigenvalue $Q = -1$ for the electron. $Q$ is the generator of the $U(1)_{(em)}$ group. So we have an isospin triplet and we have included the right hand components, the isospin singlet, what we want to do, is to combine them and define the hypercharge operator

$$Y = 2(Q - T_3) \to Q = T_3 + \frac{Y}{2}, \tag{1.1.14}$$

for the current we have

$$J_\mu^{(em)} = J_\mu^{(3)} + \frac{1}{2}J_\mu^Y \tag{1.1.15}$$

where

$$J_\mu^Y = \bar{\psi}\gamma_\mu Y\psi \tag{1.1.16}$$

so, by analogy, the hypercharge $Y$ generates a $U(1)_Y$ symmetry, and, as it is a $SU(2)_L$ singlet, leaves (1.1.10) invariant under the transformations

$$\begin{aligned} \chi_L(x) &\to \chi'_L(x) = e^{i\beta Y}\chi_L(x) \equiv e^{i\beta y_L}\chi_L \\ e_R(x) &\to e'_R(x) = e^{i\beta Y}e_R(x) \equiv e^{i\beta y_R}e_R. \end{aligned} \tag{1.1.17}$$

We thus have incorporated the electromagnetic interactions extending the group to $SU(2)_L \times U(1)_Y$ and instead of having a single symmetry group we have a direct product of groups, each with his own *coupling constant*, so, in addition to $e$ we will have another coupling to be found. Since we have a direct product of symmetry groups, the generators of $SU(2)_L$, $T_i$, and the generators of $U(1)_Y$, $Y$ commute, the commutation relations are

$$[T_+, T_-] = 2T_3 \quad ; \quad [T_3, T_\pm] = \pm T_\pm \quad ; \quad [Y, T_\pm] = [Y, T_3] = 0, \tag{1.1.18}$$

member of the same isospin triplet, have same hypercharge eigenvalue; the relevant quantum numbers are summarized in the table 1.1.

| **Lepton** | $T$ | $T^{(3)}$ | $Q$ | $Y$ |
|---|---|---|---|---|
| $\nu_e$ | $\frac{1}{2}$ | $\frac{1}{2}$ | 0 | -1 |
| $e_L^-$ | $\frac{1}{2}$ | $-\frac{1}{2}$ | -1 | -1 |
| | | | | |
| $e_R^+$ | 0 | 0 | -1 | -2 |

| **Quark** | $T$ | $T^{(3)}$ | $Q$ | $Y$ |
|---|---|---|---|---|
| $u_L$ | $\frac{1}{2}$ | $\frac{1}{2}$ | $\frac{2}{3}$ | $\frac{1}{3}$ |
| $d_L$ | $\frac{1}{2}$ | $-\frac{1}{2}$ | $-\frac{1}{2}$ | $\frac{1}{3}$ |
| $u_R$ | 0 | 0 | $\frac{2}{3}$ | $\frac{4}{3}$ |
| $d_R$ | 0 | 0 | $-\frac{1}{3}$ | $-\frac{2}{3}$ |

Table 1.1: Weak Isospin and Hypercharge Quantum Numbers of Leptons and Quarks

### 1.1.2 Electro-Weak Interactions

As stated before, interactions are mediated by a gauge boson, we now want to find out those for the electroweak interaction, to this end let us consider *local* gauge transformations

$$\begin{aligned} \chi_L &\to \chi'_L = e^{i\vec{\epsilon}(x)\cdot\vec{T} + i\beta(x)Y}\chi_L \\ \psi_R &\to \psi'_R = e^{i\beta(x)Y}\psi_R, \end{aligned} \tag{1.1.19}$$

introducing four gauge bosons, $W_\mu^{(1)}, W_\mu^{(2)}, W_\mu^{(3)}, B_\mu$ (same as the number of generators) and the *covariant derivative*

$$\begin{aligned} D_\mu \chi_L &= (\partial_\mu + ig\frac{\vec{\tau}}{2} \cdot \overrightarrow{W}_\mu(x) + i\frac{g'}{2} y_L B_\mu(x))\chi_L \\ &= (\partial_\mu + ig\frac{\vec{\tau}}{2} \cdot \overrightarrow{W}_\mu(x) - i\frac{g'}{2} B_\mu(x))\chi_L \\ D_\mu \psi_R &= (\partial_\mu + i\frac{g'}{2} y_R B_\mu(x))\psi_R \\ &= (\partial_\mu - i\frac{g'}{2} B_\mu(x))e_R \end{aligned} \tag{1.1.20}$$

the Lagrangian (1.1.10) reads

$$\begin{aligned} \mathcal{L} = &\bar{\chi}_L i\gamma\partial\chi_L + \bar{e}_R i\gamma\partial e_R - g\bar{\chi}_L\gamma^\mu \frac{\vec{\tau}}{2}\chi_L \overrightarrow{W}_\mu + \frac{g'}{2}(\bar{\chi}_L\gamma^\mu\chi_L + 2\bar{e}_R\gamma^\mu e_R)B_\mu \\ &- \frac{1}{4}\overrightarrow{W}_{\mu\nu}\overrightarrow{W}^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} \end{aligned} \tag{1.1.21}$$

where

$$\begin{aligned} \overrightarrow{W}_{\mu\nu} &= \partial_\mu \overrightarrow{W}_\nu - \partial_\nu \overrightarrow{W}_\nu - g\overrightarrow{W}_\mu \times \overrightarrow{W}_\nu \\ B_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\nu \end{aligned} \tag{1.1.22}$$

are the kinetic plus non abelian interaction term for the $SU(2)_L$ symmetry (first equation) and the kinetic term for the abelian symmetry group $U(1)_Y$. We can now split the Lagrangian terms to find out the field of the vector bosons coupled to the charged current and to the neutral current.

**Charged Currents Interaction** Let us consider the term

$$\mathcal{L}_{int}^{ew} = -g\bar{\chi}_L\gamma_\mu \frac{\vec{\tau}}{2}\chi_L \overrightarrow{W}_\mu + \frac{g'}{2}\bar{\chi}_L\gamma_\mu\chi_L B^\mu + g'\bar{e_R}\gamma_\mu e_R B^\mu \tag{1.1.23}$$

defining

$$W_\mu^\pm = \frac{1}{\sqrt{2}} W^{(1)} \mp iW^{(2)} \tag{1.1.24}$$

we can write

$$\mathcal{L}^{CC} = -\frac{g}{\sqrt{2}}(J_\mu^{(+)}W^{-\mu} + J_\mu^{(-)}W^{+\mu}) \tag{1.1.25}$$

and recognize two charged vector bosons with coupling given by “$g$”.

**Neutral Current Interaction** The relevant term left to consider for what concerns the electroweak currents is

$$\mathcal{L}^{NC} = -gJ_\mu^{(3)}W^{(3)\mu} - \frac{g'}{2}J_\mu^Y B^\mu, \tag{1.1.26}$$

the electromagnetic interaction, $-ieJ^{(em)\mu}A_\mu$, is embedded in this expression as will became clear considering the *spontaneously broken symmetry* phenomena, for now, is sufficient to define

$$\begin{aligned} W_\mu^{(3)} &= \quad \cos\theta_w Z_\mu + \sin\theta_w A_\mu \\ B_\mu &= -\sin\theta_w Z_\mu + \cos\theta_w A_\mu \end{aligned} \tag{1.1.27}$$

and invert to get

$$\begin{aligned} A_\mu &= \sin\theta_w W_\mu^{(3)} + \cos\theta_w B_\mu \\ Z_\mu &= \cos\theta_w W_\mu^{(3)} - \sin\theta_w B_\mu \end{aligned} \tag{1.1.28}$$

where $\theta_w$ is the electroweak *mixing angle*. Plugging this into (1.1.26) and rearranging terms

$$\begin{aligned} \mathcal{L}^{NC} &= -[(g\sin\theta_w J_\mu^{(3)} + \frac{g'}{2}\cos\theta_w J_\mu^Y)A^\mu \\ &+ \ (g\cos\theta_w J_\mu^{(3)} - \frac{g'}{2}\sin\theta_w J_\mu^Y)Z^\mu] \end{aligned} \tag{1.1.29}$$

since $A^\mu$ is the photon field, the first parenthesis must be identified with the electromagnetic current, thus

$$-(g\sin\theta_w J_\mu^{(3)} + \frac{g'}{2}\cos\theta_w J_\mu^Y)A^\mu = -eJ_\mu^{(em)}A^\mu \equiv -e(J_\mu^{(3)} + \frac{J_\mu^Y}{2})A^\mu \tag{1.1.30}$$

from which we get the relation

$$g\sin\theta_w = g'\cos\theta_w = e \tag{1.1.31}$$

and so we can rewrite (1.1.26),

$$\mathcal{L}^{NC} = -\frac{g}{\cos\theta_w}[J_\mu^{(3)} - \sin^2\theta_w J_\mu^{(em)}]Z^\mu \tag{1.1.32}$$

so that $Z^\mu$ can be identified with the field for the neutral vector boson.

## 1.2 The hierarchy problem and naturalness

The *naturalness criterion* states that one such [dimensionless and measured in units of the cut-off] parameter is allowed to be much smaller than unity only if setting it to zero increases the symmetry of the theory. If this does not happen, the theory is unnatural[1].

There are two important concepts in physics that enter in the formulation of the naturalness principle, symmetries and effective field theories. *Symmetries* are closely connected to conservation laws, moreover theory parameters that are protected by a symmetry, if smaller than the unit, are not problematic according to the naturalness criterion. *Effective field theories* are a sort of simplification of a more general theory that use less parameters to describe the dynamics of particles with energies less than a cut-off scale $\Lambda$.

Let us now consider the strength of the gravitational force, characterized by the Newton's constant, $G_N$ and the weak force, characterized by the Fermi's constant $G_F$, if we take the ratio of these we get:

$$\frac{G_F\hbar^2}{G_N c^2} = 1.738 \times 10^{33}. \tag{1.2.1}$$

The reason why this number is worth some attention is that theory parameters close to the order of the unit in the SM, may be calculated in a more fundamental theory, if any, using fundamental constants like $\pi$ or $e$ while very big numbers may not have such a simple mathematical expression and thus may lead to uncover new properties of the fundamental theory.

This number becomes even more interesting if we consider quantum effects. *Virtual particles* are not really particles but rather disturbances in a field, these disturbances are off-shell ($E \neq m^2 + p^2$) and according to the *uncertainty principle*, $\Delta t \Delta E \geq \hbar/2$, can appear out of nothing for a short time that depends on the energy of the virtual particle; according to quantum field theory, the vacuum is populated with such disturbances. The Higgs field, has the property to couple with other SM particles with a strength proportional to their mass. Now all these virtual particles have a mass determined by the available energy $\Lambda$ and when the Higgs field travels through space, it couples with these virtual particles and, due to quantum corrections, its motion is affected and its invariant mass squared gets a contribution proportional to $\Lambda$:

$$\delta m_H^2 = k\Lambda^2, \text{ with } k = \frac{3G_F}{4\sqrt{2}\pi^2}(4m_t^2 - 2m_W^2 - m_Z^2 - m_H^2). \tag{1.2.2}$$

Since $k \approx 10^{-2}$[2], the value of Higgs' mass $m_H \sim G_F^{-1/2}$, should be close to the maximum energy scale $\Lambda$ and if we assume this to be the Plank scale $M_{Pl} = G_N^{-1/2}$, the ration $G_F/G_N$, should be close to the unity which contradicts eq. (1.2.1), this goes by the name of *hierarchy's problem*.

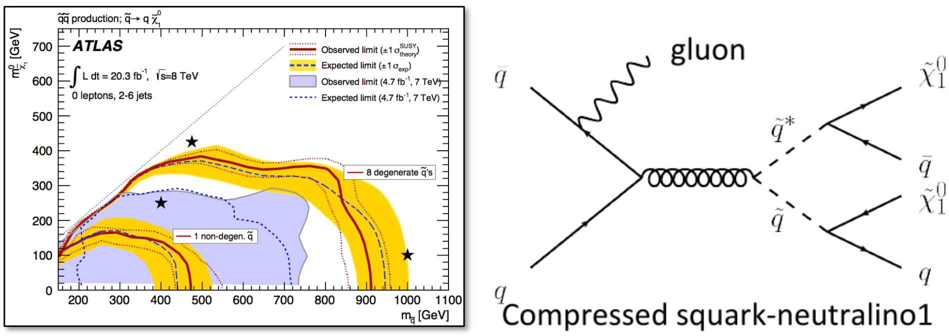
The large quantum corrections in (1.2.2) are mainly due to the fact that in the SM, there is no symmetry protecting the mass of the Higgs' field. Supersymmetry (SUSY) is capable of solving the hierarchy problem by canceling out the quantum corrections that bring $m_H$ close to $\Lambda$ thus restoring the naturalness of the SM.

# Chapter 2

# The Monojet signature

## 2.1 Seraches for new physics with the monojet signature

Events with an energetic jet $p_{\mathrm{T}}$and large $E_{\mathrm{T}}^{\mathrm{miss}}$in the final state, constitute a clean signature for new physics searches at hadron colliders. Signals that can be studied with this experimental signature include the production of WIMPS, the ADD model for large extra dimensions and SUSY.




(a) (b)

Figure 2.1

## Appendix A

# BDT Distribution Plots

# Bibliography

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[2] Gian Francesco Giudice. "Naturally Speaking: The Naturalness Criterion and Physics at the LHC". In: (2008). arXiv: 0801.2562 [hep-ph].