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National **T**echnical **U**niversity of **A**thens

Department of Physics
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DIPLOMA THESIS

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Inquiry of supersymmetric theories at LHC and a future higher energy hadron collider with the study of events containing a monojet

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Abstract

In the 20th century an important model to understand and describe the microworld and the universe was developed: The Standard Model. Experiments over the last decades have been a success for SM due to its precision in the results and its accurate predictions. However a big question remained: Why do particles have mass? The Higgs mechanism tries to give an answer to that question and its recent discovery at the LHC gave a new breath to the model.

The SM might be the best model we have but it appears that it is incomplete. Experimental astronomical data suggest the existence of an unknown matter. That is dark matter (DM) and is calculated to be about 26% of the matter in our universe. Additionally theoretical issues, like strong CP problem and hierarchy problem, suggest the existence of new physics.

One very promising theory beyond the SM is Supersymmetry (SUSY), a theory that extends spacetime, doubles the SM particles and could amongst other give a solution to what dark matter is. The thesis presents an analysis to find SUSY, based on the pMSSM model with a monojet and missing energy final state.

In Chapter 1 we demonstrate an introduction to the standard model and its basic formalism. Chapter 2 presents an introduction to theories beyond the standard model, most importantly SUSY and its formalism. In Chapter 3 there is a description of the LHC accelerator and CMS detector as well as their electronics. In the following Chapters, 4 and 5, we describe the simulation of events with Monte Carlo generators and the selection of our events. Finally there is a presentation of our results and a synopsis of the thesis.

Περίληψη

Τον 20ο αιώνα ένα σημαντικό μοντέλο για την κατανόηση και την περγαφή του μιρόκοσμου αναπτύχθηκε: Το καθιερωμένο πρότυπο. Πειράματα που έγιναν τις τελευταιες δεκετίες ήταν μια τεράστια επιτυχία για το καθιερωμένο πρότυπο εξαιτίας της ακρίβειας των αποτελεσμάτων και των ακριβών προβλέψεων. Παρόλαυτα παρέμεινε ένα μεγαλο ερώτημα: Γιατί έχουν τα σωματίδια μάζα; Ο μηχανισμός Higgs προσπαθεί να δώσει μια απάντηση στην ερώτηση αυτή και η πρόσφατη ανακάλυψή του στον LHC έδωσε νέα πνοή στο μοντέλο.
Το καθιερωμένο πρότυπο ίσως είναι το καλύτερο μοντέλο που έχουμε , αλλά φαίνεται να είναι ελλιπές. Πειραματικά αστρονομικά δεδομένα οδηγούν στο συμπέρασμα της ύπαρξης μιας άγνωστης μορφής ύλης. Αυτή ονομάζεται σκοτεινη ύλη και υπολογίζεται να είναι περίπου 26% της μάζας στο σύμπαν. Επιπλέον θεωρητικά ζητήματα, όπως η CP violation και το προβλημα της ιεραρχείας επιβάλλουν την ύπαρξη νεας φυσικής.
Μια πολλά υποσχόμενη θεωρία πέρα από το καθιερωμένο πρότυπο είναι η υπερσυμμετρία, μια θεωρία που επεκτείνει το χώρο και το χρόνο και μπορεί ανάμεσα σε άλλα να δώσει λύση στο ερώτημα του τι είναι η σκοτεινή ύλη. Η διπλωματική παρουσιάζει μια ανάλυση για να βρεθεί η υπερσυμμετρία βασισμένη στο pMSSM μοντέλο με τελική κατάσταση Monojet και missing energy.
Στο κεφάλαιο 1 παρουσιάζουμε μια εισαγωγή στο καθιερωμένο πρότυπο και το βασικό φορμαλισμό του. Στο κεφάλαιο 2 παρουσιάζουμε μια εισαγωγή στις θεωρίες πέρα από το καθιερωμένο πρότυπο και κυρίως την υπερσυμμετρία και το βασικό φορμαλισμό της. Στο κεφάλαιο 3 υπάρχει μια περιγραφή του LHC επιταχυντή και του CMS ανιχνευτή καθώς και των ηλεκτρονικών. Στα επόμενα κεφάλαια 4 και 5 περιγράφουμε την προσομοίωση γεγονότων με μόντε κάρλο και επιογή γεγονότων. Τέλος υπάρχει μια παρουσίαση των αποτελεσμάτων και μια σύνοψη της εργασίας.

Contents

“Sometimes the public says, 'What's in it for Numero Uno? Am I going to get better television reception? Well, in some sense, yeah. But let me let you in on a secret: We physicists are not driven to do this because of better color television. That's a spin-off. We do this because we want to understand our role and our place in the universe.”

-Michio Kaku-

Chapter 1

THEORETICAL OVERVIEW OF THE STANDARD MODEL

"Those who are not shocked when they first come across quantum theory cannot possibly have understood it."

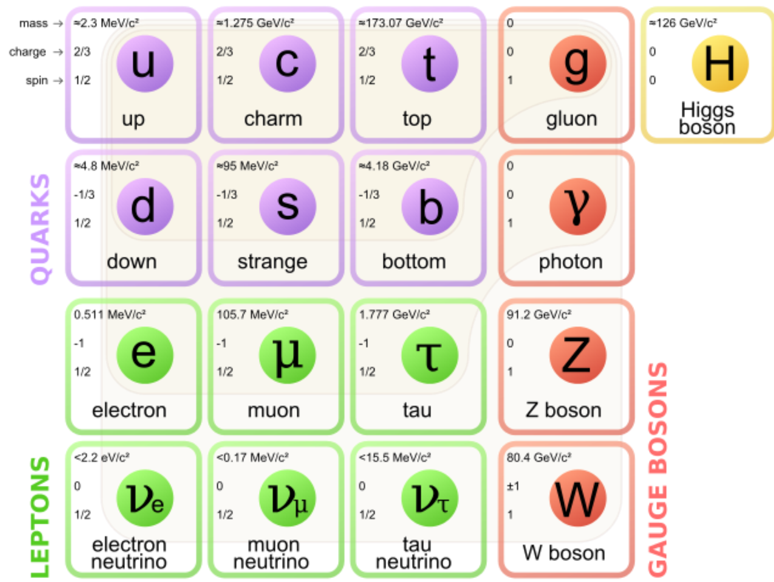
— *Niels Bohr*

The History of Particle Physics is probably as long as the history of Philosophy. It goes back to the very fundamental questions that bothered Thales of Miletus, Heraclitus, Democritus and Leucippus. What is matter?
Democritus first approached the question in a philosophical way, with the idea that *atoms* are the fundamental blocks of matter, but it took 2000 years before John Dalton described atomic theory in a scientific way. In 1803 Dalton orally presented his first list of relative atomic weights for a number of substances. Dalton's theory was improved in 1811 by Amedeo Avogadro.
Avogadro was able to offer more accurate estimates of the atomic mass of oxygen and various other elements, and made a clear distinction between molecules and atoms.
Atoms were thought to be the smallest possible division of matter until 1897 when J.J. Thomson discovered the electron.
Thomson suggested the "*Plum pudding model*" which stated that the negatively charged particles were distributed in a "sea" of positive charge.
Thomson's model was disproved in 1909 by Ernest Rutherford, who discovered that most of the mass and positive charge of an atom is concentrated in a very small area, the center. Together with Hans Geiger and Ernest Marsden they discovered the *nucleus*.
At the beginning of the century quantum theory changed the way we would look matter forever. Max Planck, Albert Einstein, Niels Bohr took a step closer to a quantum model of the atom.
At 1932, James Chadwick discovered the neutron.
Over the next decades it became clear that there are a lot more particles than scientists thought. First mesons were discovered as well as neutrinos.
At 1964 Murray Gell-Man and George Zweig put forth the idea of quarks. At 1973 John Iliopoulos presents, the theory now called the *Standard Model*.

Almost 50 years after Peter Higgs predicted a mechanism by which fundamental particles gain mass, the ATLAS and CMS experiments at the CERN lab discover the Higgs boson.

1.1 The Standard Model

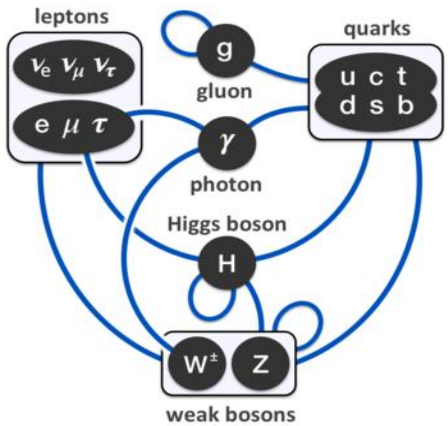
The Standard Model (SM) is the name given in the 1970s to a theory of fundamental particles and how they interact. It incorporated all that was known about subatomic particles at the time and predicted the existence of additional particles as well. It is a theory concerning the electromagnetic, weak, and strong nuclear interactions. There are seventeen particles in the standard model. The last particles discovered were the W and Z bosons in 1983, the top quark in 1995, the tau neutrino in 2000, and the Higgs boson in 2012.



According to the Standard Model there are three kinds of elementary particles:

- leptons
- quarks
- force mediators (gauge bosons)

The fermions of the Standard Model are classified according to how they interact. There are three "generations" (divisions of particles exhibiting similar physical behavior). Each generation contains two leptons and two quarks. Bosons in SM are: the gluons for the strong force, the photon for the electromagnetic, the two W's and the Z for the weak force and the graviton for gravity.



Summary of interactions between particles described by the Standard Model.

Fermions	Name	Symbol	Spin	EM charge	Weak charge*		Mass (MeV/c2)
Lepton	Electron	e^-	+1/2	-1	-1/2	0	0,51
	Muon	μ^-	+1/2	-1	-1/2	0	105,00
	Tau	τ^-	+1/2	-1	-1/2	0	1.777,00
	Electron Neutrino	ν_e	+1/2	0	+1/2	0	< 3 E-6
	Muon Neutrino	ν_μ	+1/2	0	+1/2	0	< 0,18
	Tau Neutrino	ν_τ	+1/2	0	+1/2	0	< 18,00
Quark !!						Color charge	
	up	u	+1/2	+2/3	+1/2	RGB	~2
	charm	c	+1/2	+2/3	+1/2	RGB	~1.200
	top	t	+1/2	+2/3	+1/2	RGB	>170.000
	down	d	+1/2	-1/3	-1/2	RGB	~5
	strange	s	+1/2	-1/3	-1/2	RGB	~92
	bottom	b	+1/2	-1/3	-1/2	RGB	~4.200

Standard Model particle masses, spins, charge (fermions)

BOSONS force carriers spin = 0, 1, 2, …

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W⁻	80.39	−1
W+ W bosons	80.39	+1
Z0 Z boson	91.188	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Higgs Boson spin = 0		
Name	Mass GeV/c^2	Electric charge
H Higgs	126	0

Standard Model particle masses, spin, charge (bosons)

From the tables is the graviton missing. The graviton, a theoretical spin-2 boson, is considered to carry the gravitational force. The electromagnetic force is carried by photons and acts between electrically charged particles. The weak interaction (nuclear β-decays, absorption and emission of neutrinos) has three gauge bosons: W± and Z. The gauge bosons of the strong interaction are the eight massless gluons (vector bosons).

1.2 The Standard Model Lagrangian and formalization

The dynamics of the quantum state and the fundamental fields are determined by the Lagrangian density $\mathcal{L}$. The standard model is furthermore a gauge theory, which means there are degrees of freedom than are redundant. In gauge theories the Lagrangian is invariant under a continuous group of local transformations.
Its symmetry is $SU(3)_c$ x $SU(2)_L$ x U(1), where U(1) acts on *B* and *φ*, SU(2) acts on *W* and *φ*, and SU(3) acts on *G*. The fermionic field *ψ* also transforms under these symmetries.

- B, W's, are electroweak fields, G is the gluon field and φ is the Higgs field.
- B,W's and G's are *vectors* under Lorentz transformation
- φ is a *scalar*
- Fermion fields transform under Lorentz transformation (like vectors do) but the rotation turns them by half the angle less than a vector. We call them *spinors*.

For ψ we use the notation ψ^L and ψ^R for left and right chirality components, since they are treated differently in the SM.
The electroweak boson fields $W_{1,2,3}$ and B create the states that are the particles we observe. Specifically,

$$Z = \cos\theta_w W_3 - \sin\theta_w B$$
$$A = \sin\theta_w W_3 + \cos\theta_w B \text{ (photon)}$$
$$W^{+-} = \frac{1}{\sqrt{2}}(W_1 \mp iW_2)$$

A Dirac field, *ψ*, representing a fermion, can be expressed as the sum of a left-handed part, ψ_L and a right-handed part ψ_R.

A free particle can be represented by a *mass* term, and a *kinetic* term which relates to the "motion" of the fields.

The ***kinetic term*** for a Dirac fermion is:

$$\bar{\psi}\gamma^\mu\partial_\mu\psi = \bar{\psi}_L\gamma^\mu\partial_\mu\psi_L + \bar{\psi}_R\gamma^\mu\partial_\mu\psi_R$$

Where $\bar{\psi}$ is defined to be $\psi^\dagger\gamma^0$.

A mass term mixes the two ***chiralities***:

$$m\bar{\psi}_R\psi_L + m\bar{\psi}_L\psi_R$$

For the gauge fields we define the ***field strength tensor*** as:

$$F^{\alpha}_{\mu\nu} = \partial_\mu A^{\alpha}_{\nu} - \partial_\nu A^{\alpha}_{\mu} + g f^{abc} A^{b}_{\mu} A^{c}_{\nu}$$

A is a gauge field, g is the coupling constant and f^{abc} is defined by the commutator and generators of the group: $[t_a, t_b] = if^{abc}\, t_c$. If the generators *t* commute with each other like they do in abelian groups, the *f* is obviously 0. Ex. U(1).

The *coupling* terms allow interactions between the gauge and the fermionic fields.
The SU(2) symmetry acts on left-handed fermion doublets.

1.2.1 SM Lagrangian

To write down the Lagrangian of a theory, one first needs to choose the symmetries (gauge and global) and the particle content, and then write down every allowed renormalizable interaction. To make things easier we assume neutrinos are massless as well as the existence of one family of quarks.

$$\mathcal{L}_{SM} = \mathcal{L}_{gauge\ bosons} + \mathcal{L}_{fermion\ masses} + \mathcal{L}_{fermion\ kinetic\ terms} + \mathcal{L}_{Higgs}$$

1.2.2 Kinetic terms for gauge Bosons:

$$\mathcal{L}_{gauge\ bosons} = -\frac{1}{4}F^{\alpha}_{\mu\nu}F^{\alpha\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \frac{1}{4}F^{A}_{\mu\nu}F^{A\mu\nu}$$

Here $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$ is the hypercharge field strength, the $-\frac{1}{4}F^{\alpha}_{\mu\nu}F^{\alpha\mu\nu}$ term contains the SU(2) field strength, so *a* runs from 1 to 3 (over the three vector bosons of SU(2)), and the term $-\frac{1}{4}F^{A}_{\mu\nu}F^{A\mu\nu}$ is the gluon kinetic term, therefore A runs from 1 to 8.

1.2.3 Fermion masses and Yukawa couplings

$\mathcal{L}_{fermion\ masses}$ gives the Yukawa interaction that describes the coupling between the Higgs Field, massless quark and electron fields.

$$\boldsymbol{\mathcal{L}}_{\boldsymbol{fermion\ masses}} = -Y_e \bar{l}_L^i \Phi_i e_R + -Y_d \bar{q}_L^i \Phi_i d_R + -Y_u \varepsilon_{ij} \bar{q}_L^i \Phi^{*j} u_R + h.c$$

1.2.4 Kinetic Terms for Fermions

$$\boldsymbol{\mathcal{L}}_{\boldsymbol{fermion\ kinetic\ terms}} = i\overline{l_L^T}\gamma_\mu \boldsymbol{D}^\mu l_L + i\overline{e_R^T}\gamma_\mu D^\mu e_R + i\overline{\nu_R^T} i\gamma_\mu \partial^\mu \nu_R + i\overline{q_L^T}\gamma_\mu \boldsymbol{D}^{\boldsymbol{\mu}} q_L +$$

$$i\overline{d_R}\gamma_\mu \boldsymbol{D}^{\boldsymbol{\mu}} d_R + i\overline{u_R}\gamma_\mu \partial^\mu u_R$$

The covariant derivatives D^μ include the hypercharge, SU(2) and SU(3) gauge bosons. For example:

$$\boldsymbol{D}^\mu = \partial^\mu + ig\boldsymbol{T}^\alpha W_\mu^\alpha + ig'Y(l_L)B_\mu, \quad \text{for } l_L$$
$$\boldsymbol{D}^\mu = \partial^\mu + ig_s\boldsymbol{T}_{\boldsymbol{s}}^\alpha G_\mu^\alpha + ig'Y(d_R)B_\mu, \quad \text{for } d_R$$
$$D^\mu = \partial^\mu + ig'Y(e_R)B_\mu, \quad \text{for } e_R$$

Where, the strong coupling is g_s, the 8 generators of SU(3) are the $\boldsymbol{T}_s$, the gluon fields are the G_μ^α and *Y(f)* is the hypercharge of the fermion *f*.

1.2.5 The Higgs Part and Gauge Boson Masses

The Higgs doublet Lagrangian should contain a “spontaneous symmetry breaking” potential which will give the Higgs:

- *vev* (vacuum expectation value) and self-interactions
- kinetic terms which will generate the gauge boson masses
- interactions between the Higgs and the gauge bosons

$$\mathcal{L}_{higgs} = |\mathbf{D}_\mu\Phi|^2 - \mu^2\Phi_i^\dagger\Phi^i + \lambda(\Phi_i^\dagger\Phi^i)^2$$

The SM has totally 18 free parameters:

- 9 fermion masses
- 3 CKM mixing angles + 1 phase
- 1 electromagnetic coupling constant α
- 1 strong coupling constant α_s
- 1 weak coupling constant $G_F = 1.16637 \times 10^{-5}$ GeV^{-2}
- 1 Z^0 mass
- 1 Higgs mass

We can add another 7 if neutrino mass is not 0.
In addition the neutrino oscillation, data provide us with two mass squared differences and two mixing angles. Thus we may claim to have about 8 parameters from physics beyond the SM: 4 parameters from cosmology and 4 parameters from neutrino oscillations.
One might consider adding the cosmological constant Λ_{cosmo} and Newton's gravitational constant G to these.
However, even then, we only obtain about 10 beyond the SM parameters compared to the circa 20 parameters in the SM Lagrangian. So our hope of getting numerical checks, in addition to bounds, for a candidate beyond the SM theory consists in fitting a total of about *30 parameters*.
So an important test for any candidate model for physics beyond the SM physics is whether or not it can predict or significantly fit the above mentioned SM coupling constant and mass parameters.
A simple quantum field theory will only be able to do so by introducing a *supplementary symmetry* or some other restricting principle.

1.3 Summary

- Weak interactions are mediated by the SU(2) gauge bosons, which act *only* on the left - handed components of the fermions.

- The left handed neutrinos v and electrons e are SU(2) doublets, while the right-handed are singlets. Same goes for quarks. For example:

$$l_L = \binom{v_L}{e_L}, u_R, e_R\{v_R\} \text{ etc}$$

- Left and right handed quarks transform under the weak hypercharge $U(1)_Y$ gauge symmetry. The relationship between the weak coupling g and the electron charge e is:

$$e = g\ sin\theta_W$$

- Before spontaneous symmetry breaking, fermions (except ν_R) with SU(2) gauge interactions are massless. The spontaneous symmetry breaking mechanism gives a vev to the scalar fields and generates the masses. The scalar multiplet that is responsible for the symmetry breaking carries weak hypercharge. The weak interactions proceed via the exchange of massive charged or neutral gauge bosons.

- Additional generations of quarks may be added, with gauge interactions copied from the first, but in this case one can have mass-mixing between quarks of different generations. Including a third generation, the mixing matrix is the CKM matrix. This matrix has four independent parameters, so that some of the matrix elements may be complex.
  The 3 weak isodoublets of left-handed fermions are:

$$\binom{u}{\tilde{d}}, \binom{c}{\tilde{s}}, \binom{t}{\tilde{b}},$$

Where the quarks with the bar, relate to the physical quarks by:

$$\begin{pmatrix} \tilde{d} \\ \tilde{s} \\ \tilde{b} \end{pmatrix} = \boldsymbol{V_{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Where CKM matrix is: $\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$

- In the formulation of the Lagrangian we presented the neutrinos are massless. However, we now know that neutrinos have a very small mass. There are two possible types of neutrino mass terms, *Dirac* and *Majorana*, because the neutrino has zero electric charge. This makes neutrino mass terms a bit different from those of the other fermions and may explain why neutrinos are much lighter than SM fermions.
  Introducing a right-handed neutrino allows us to write down the same kind of Yukawa coupling as for the u-type quarks. (See *Fermion masses and Yukawa couplings*)

Chapter 2

BEYOND THE STANDARD MODEL

"Physics is really nothing more than a search for ultimate simplicity, but so far all we have is a kind of elegant messiness."

— *Bill Bryson, A Short History of Nearly Everything*

2.1 Motivation for Supersymmetry

Supersymmetry (SUSY) - a symmetry relating bosonic and fermionic degrees of Freedom- is an exciting idea first introduced in the early 1970s.

Forty years have passed without any direct evidence of its existence. So someone may wonder: Why do we spend time learning its complicated formalism and search for it?

2.1.1 Hierarchy problem

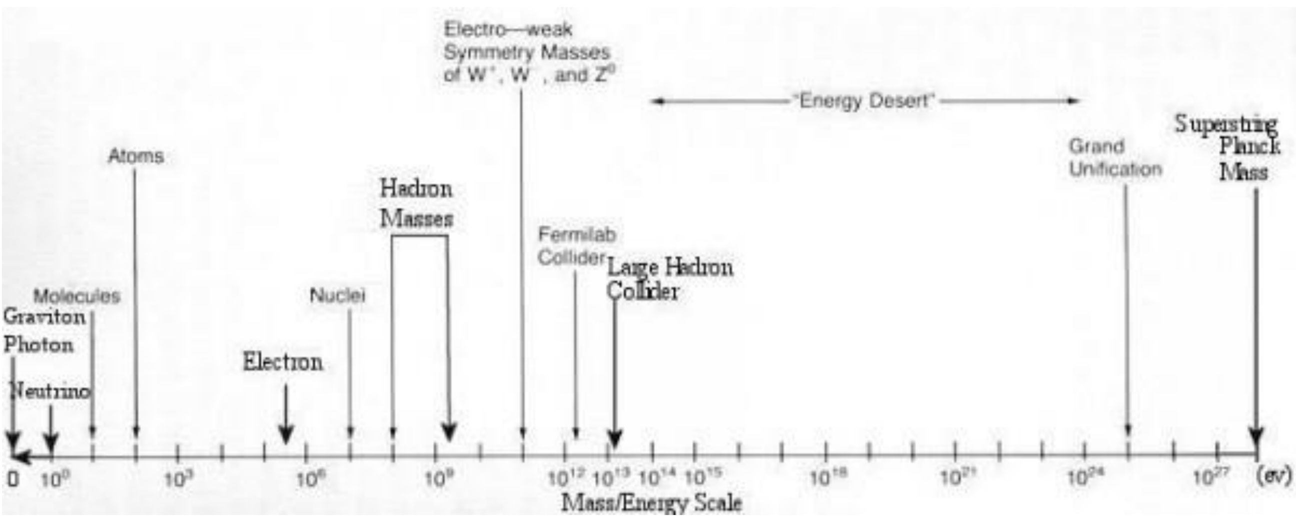
The *mass hierarchy problem* is connected to the question of how to avoid having to shuffle around the quadratic divergences in the SM Higgs mass squared M^2_H, which arise as one goes from one order in perturbation theory to the next.

A problem connected to the hierarchy problem is why the electroweak scale μ_{weak} is so extremely small compared to the fundamental scale, say the Planck scale. The Planck mass (scale) M_P is the unit of mass in the system of natural units known as Planck units. It is defined so that,

$$M_P = \sqrt{\frac{\hbar c}{G}} \sim 10^{19}\ \mathrm{GeV/c^2}.$$

The Planck mass has a scale conceivable to humans. It is said to be about the mass of a flea egg. The Planck mass is the maximum allowed mass for point-masses. Nature's stable point-mass particles, (electrons etc), are many orders of magnitude smaller than the Planck mass.

While trying to figure out a possible explanation, it was realized around 1970s that there was a serious problem hidden behind this question.
The masses of the W and Z particles are about 10^{16} times smaller than the Planck Mass. As a result there is a huge hierarchy in the mass scales of weak force and gravity.
The neutral Higgs field has a size of about 250 GeV, since we know W and Z particles are about 100 GeV. But theory implies that Higgs field should either be 0 or as big as Planck energy ~ 10^{16} GeV!
The large quantum contributions to the square of the Higgs boson mass would inevitably make the mass huge comparable to the scale at which new physics appears which, is not the case.
Supersymmetry gives a solution to the problem.



2.1.2 Fine tuning

In the Standard Model, a serious problem is considered to be the **SM fine-tuning problem**.
SUSY can suggest a solution to this problem, as long as the supersymmetric particles have masses no larger than a few TeV.
Fine-tuning refers to circumstances when the parameters of a model must be adjusted very precisely in order to agree with observations. Theories requiring fine-tuning are thought to be problematic since there is no known mechanism to explain why the parameters happen to have precisely the needed values.
(See also chapter 1.1)

The electroweak sector of the SM contains within it a parameter with the dimensions of energy which is $v \approx 246$ GeV, where $v/\sqrt{2}$ is the vacuum expectation value of the neutral Higgs field.
This parameter sets the scale of all masses in the theory.
For example mass of $W^{+,-}$ is given by

$$gv/2 \sim 80GeV$$

, while mass of Higgs is

$$v\sqrt{\lambda/2}\ ,$$

, and Higgs potential is

$$V = -\mu^2 \varphi^\dagger \varphi + \lambda/4(\varphi^\dagger \varphi)^2$$

The term $-\mu^2$ is the mass term and λ the strength of the Higgs self interaction. Its negative sign is essential for the spontaneous symmetry-breaking mechanism to work. $|\Phi|= \frac{\sqrt{2}\mu}{\sqrt{2}} = \frac{v}{\sqrt{2}}$.. The SM is renormalizable, which means that finite results are obtained for all higher-order (loop) corrections even if we extend the virtual momenta in the loop integrals all the way to infinity:

$$\int^{\Lambda} d^4k\ f(k, momenta)$$

Scientists vision the SM as part of a larger theory which includes "new physics" at high energy. Λ represents the scale at which this new physics appears, and where the SM must be modified. The 4-boson self-interaction (*V)* generates, at one-loop order, a contribution to the $\varphi\dagger\varphi$ term proportional to~

$$\lambda \int^{\Lambda} d^4k\ \frac{1}{k^2 - M_H^2}$$

Producing a correction ~ $\lambda\Lambda^2\varphi^\dagger\varphi$ to the $-\mu^2 \varphi^\dagger \varphi$ in *V*. (The '~' represents a numerical factor, such as $1/4\pi^2$, which is unimportant for the argument here.

Also $-\mu^2$ is then replaced by the one-loop corrected "physical" value $\mu_{phys}^2 = \mu^2 - \lambda\Lambda^2$.

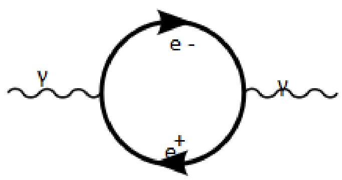
(The dependence of physical quantities, (electric charge, mass etc) on the scale Λ is hidden. We will only care about them again at the longer-distance scales at which the physical quantities are measured. This means that all observable quantities are finite, even for infinite Λ)

With *v* fixed **phenomenologically,** a relation between the two unknown parameters is provided (μ_{phys} and λ):

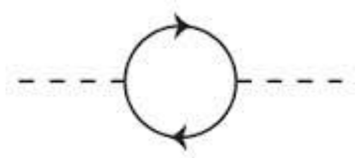
$$\mu_{phys} \sim \sqrt{\lambda}123\ GeV$$

As a result, if we want to be able to treat the Higgs coupling λ perturbatively, μ_{phys} cannot be much greater than ~ O(100 GeV) at most. A value significantly greater than this would imply that λ - the strength of the Higgs self interaction- is much greater than 1, and the Higgs sector would be *strongly interacting*.

On the other hand, if $\Lambda \sim M_P \sim 10^{19}$ GeV, the one-loop correction $\mu_{phys}^2 = \mu^2 - \lambda\Lambda^2$ is then vastly greater than ~(100 GeV)^2, so that to arrive at a value ~(100 GeV)^2 *after* we include the loop correction would seem to require that we start with an equally huge value of the Lagrangian parameter μ^2, relying on a remarkable ***fine-tuning***, to get us from ~(10^{19} GeV)^2 down to ~(10^2 GeV)^2. In the SM, this fine-tuning problem involving the parameter μ_{phys} affects not only the mass of the Higgs particle but at the very end, all masses in the SM, which derive from *v* and hence μ_{phys}.
We could have had this problem also for vector mesons and fermions masses. For fermions for example, such a *quadratic divergence** would imply an enormous quantum correction to the photon mass. However this divergence is missing, because the theory is regularized in a *gauge-invariant way*. In other words, unbroken gauge and chiral symmetries keep these particles massless and remove dangerous quadratic and linear divergences from the theory.



Let's now consider a possible fermion loop contribution to the Higgs self - energy. The contributions have the form



$$(\lambda - g_f^2)\Lambda^2\varphi^\dagger\varphi$$

If there was a boson-fermion coupling g_f related to the Higgs coupling by $g_f = \lambda$ then we would be really happy because the quadratic divergence would not occur. A relation between coupling constants (like the previous, we desire to have), is characteristic of a *symmetry*, but in this case it must be a symmetry which relates a purely bosonic vertex to a boson–fermion (Yukawa) one.

If we could find a symmetry which grouped scalar particles with either massless fermions or massless vector bosons, then the scalars would enjoy the same "protection" from dangerous divergences as their symmetry partners.
Supersymmetry is precisely such symmetry: It groups scalars together with fermions and vector bosons with fermions.
However, no superpartners for the SM particles have yet been discovered, so supersymmetry must be a (softly) broken symmetry, at the TeV mass scale, with the masses of the superpartners presumably lying at too high values to have been detected yet.

**Divergence occurs when a Feynman diagram diverges either because of contributions of objects with high energy, meaning physical phenomena at a very small scale, or it could just be a mathematical effect which can be removed though renormalization*.

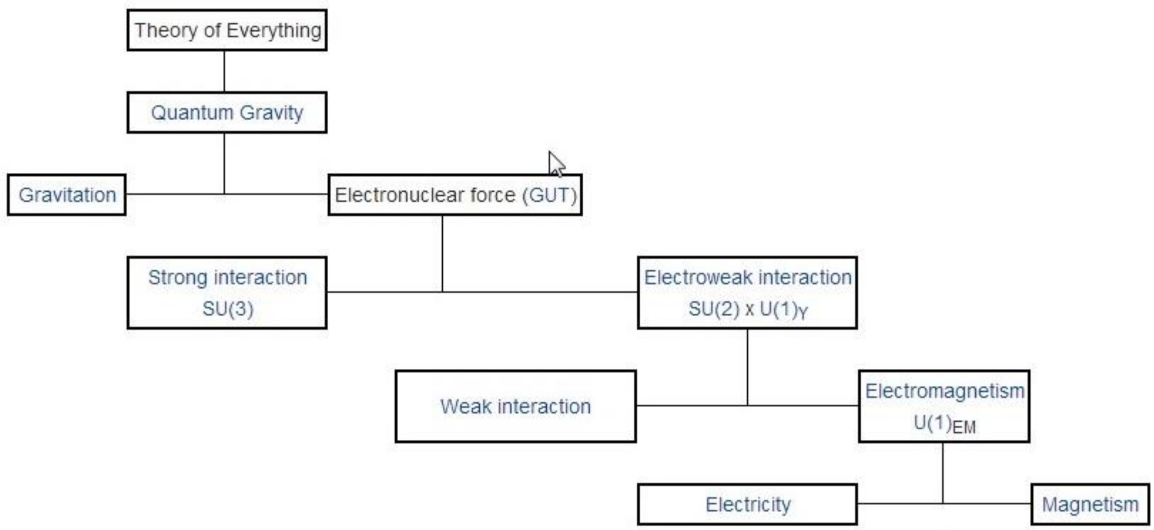
In the end, we can see that (softly) broken SUSY may solve the SM fine-tuning problem, provided that the new SUSY superpartners are not too much heavier than the scale of *v* (or *planck mass*), or else we are back to some form of fine tuning.
Of course, it all depends on how much fine-tuning we want to put up with, but the argument strongly suggests that the discovery of SUSY should be within the reach of the LHC.

2.1.3 Dark matter

Another reason for our persistence in a TeV-scale supersymmetry is the fact that it might provide a candidate dark matter particle at a mass scale consistent with thermal relic abundance calculations. We will return later to that.

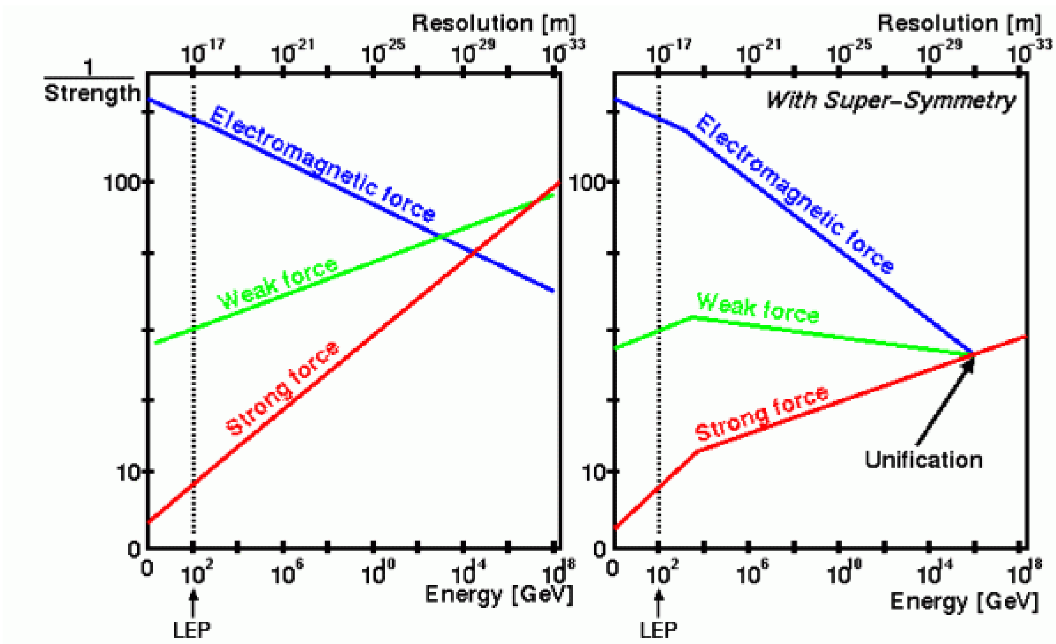
2.1.4 Grand Unified Theories (GUTs)

Probably the greatest ambition of Physics is to create and of course prove a theoretical framework that can fully explain and link together all physical aspects. This would require the unification of all the fundamental interactions of nature: gravitation, strong interaction, weak interaction, and electromagnetism. Until now gravity is treated classically and if we wanted to treat it at a quantum level we would be talking about a scale smaller than the Planck Mass. However at this scale General Relativity is non-renormalizable.



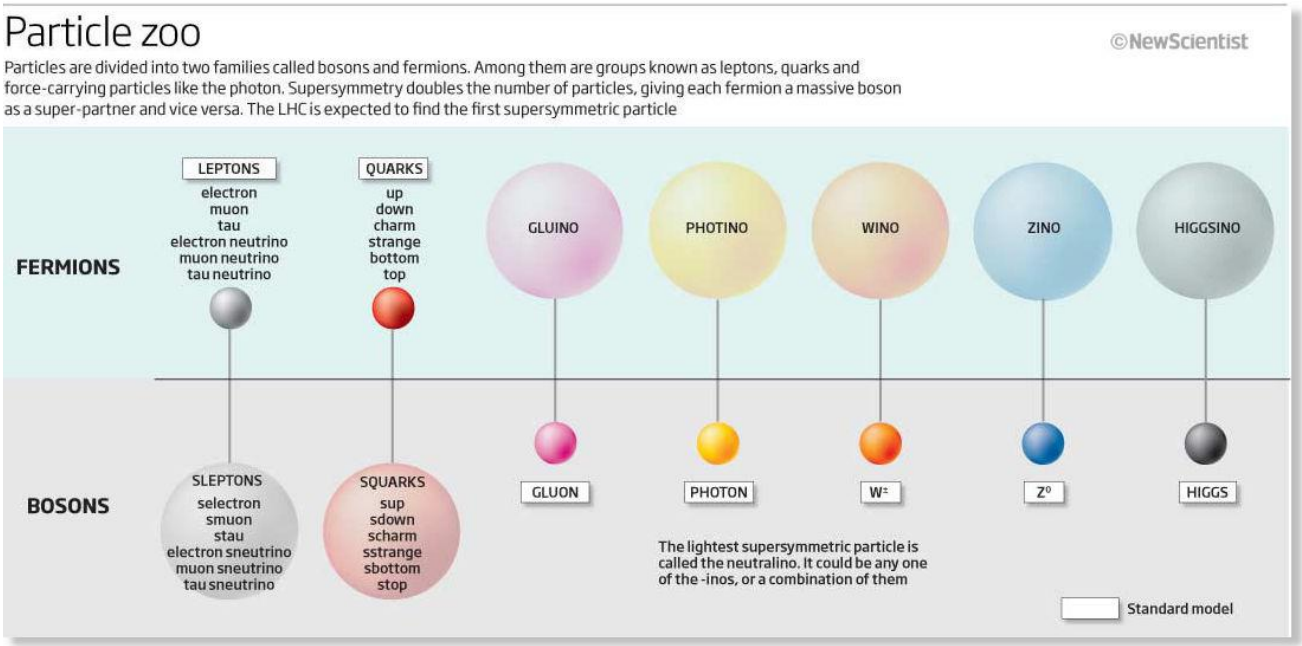
The unification of forces is possible because of the *energy scale dependence* of force coupling parameters in QFT. This means that parameters with much different values at usual energies can converge to a single value at a much higher energy scale. How does SUSY relate to that?

Supersymmetry is characterized by one gauge symmetry and therefore one unified coupling constant rather than three independent ones.
The three gauge couplings in the Standard Model has been found to meet almost at the same point if the hypercharge is normalized so that it is consistent with SU(5) or SO(10) GUTs. If the supersymmetric model is applied, -mssm in particular- the coupling constants of the strong and electroweak interactions meet exactly at the GUT scale: $\Lambda \sim 10^{16}$ GeV.



2.2 Supersymmetry

Supersymmetry is a theory that suggests the existence of a symmetry that relates bosons and fermions. Each boson is related with a fermion called its *superpartner* and vice versa. All their numbers are the same except for their spins that differ by 1/2. That is if susy was unbroken. But since no supersymmetric particle has been found so far, SUSY must be spontaneously broken. All SM particles are doubled. The superpartners of fermions are bosons with an “s” in front of their name and the superpartners of bosons have an “-ino” at the end of their name. This superpartner should *protect* the mass of all the particles all the way down to the scale at which SUSY is broken. At this scale the superpartners will have a heavier mass than the normal ones.



Something that characterizes every symmetry is the *algebra* that relates with the generators of the symmetry. A symmetry is in general defined by operators which generate the transformations under which the Lagrangian transforms to itself. These operators are called *generators*. For example SU(2) satisfies the relations :

$$[T_i, T_j] = i\, \varepsilon_{ijk} T_k$$

These relations constitute the SU(2) algebra and T_{ij} are the "charges" or generators.
In SM we are familiar with symmetry operators Q that are scalar, meaning that when they act on a state of definite spin they don't change it.

$$Q|\, spin > = |same\ spin>$$

It is proved that we cannot have any conserved operators that are not Lorentz scalars.*

This is proved by Coleman-Mandura theorem that states, that "space-time and internal symmetries cannot be combined in any but a trivial way. The only conserved quantities in a realistic theory with a mass gap, apart from the generators of the Poincaré group, must be Lorentz scalars." A generalization of this theorem is Haag–Lopuszanski–Sohnius theorem shows that "the possible symmetries of a consistent 4-dimensional quantum field theory do not only consist of internal symmetries and Poincaré symmetry, but can also include supersymmetry as a nontrivial extension of the Poincaré algebra."*

This however does not exclude “charges” which transform under Lorentz transformations as *spinors*. We could name this “charge” Q_a, where “a” is indicating the spinor component.
The new idea is that these charges will have *anticommutation* relations between them and not commutation as usual. These must transform as a spin1 object, which objects are described by a 4-vector that is conserved. The only such operator is the 4-momentum generator of space-time translations P_μ:

$$P_\mu = -i\partial_\mu$$

As a result, the new algebra will look approximately like this:

$$\{Q_a, Q_b\} \sim P_\mu$$

This equation roughly says that if you do two SUSY transformations generated by Q terms you get the energy-momentum operator or in different words the space-time translations operation, a *derivative*. The spinorial Q’s are like square roots of derivatives. If you can take a square root of 4-dimensional derivatives, that is like extending space –time, include more degrees of freedom!
A more common example of that would be the invention of the square root of an imaginary number *i*.
In the end, we could say that SUSY enlarges the space-time to a *superspace*!

Through a painful mathematical process, which is not in the concern of this thesis, we conclude that the super algebra is this:

$$\{\mathbf{Q}_a, \mathbf{Q}_b^\dagger\} = 2\sigma^{\mu}{}_{ab}\,\mathbf{P}_\mu$$
$$\{\mathbf{Q}_a, \mathbf{Q}_b\} = \{\mathbf{Q}_b^\dagger, \mathbf{Q}_b^\dagger\} = 0$$
$$\{\mathbf{Q}_a, \mathbf{P}_\mu\} = 0$$
$$\{\mathbf{Q}_a, \mathbf{M}_{\mu\nu}\} = i\,(\sigma_{\mu\nu})_a^b\, Q_b$$

A theory is supersymmetric if it is invariant under the group of transformations generated by $\mathbf{P}_\mu$, $\mathbf{M}_{\mu\nu}$ and $\mathbf{Q}_a$.
Now we know that $Q|b\rangle = |f\rangle$ and it’s known that $P^\mu P_\mu|\rangle = m^2|\rangle$ so we conclude that if we have two states $|b\rangle$ and $|f\rangle$ their masses are the same.
From the *superalgebra*, we also conclude that particles from the same supermultiplet have the same electric charge etc.

***mass gap is the difference between the vacuum (0) and the next lowest energy scale, which is mass of the lightest particle*

However, as we mentioned before, SUSY is broken or else all the particles would have been observed to have the same $SU(3)_c$ x $SU(2)_L$ x U(1) quantum numbers; which is not the case. If we want to keep the cancellation of quadratic divergences, we have to believe that the breaking of the symmetry is *soft*.

2.3 The Minimal Supersymmetric Standard Model

The MSSM is the simplest supersymmetric extension to the SM.

The Lagrangian in the MSSM has some very basic rules:

- Add a boson for all SM fermions, and a fermion for all SM bosons
- Add "SUSY breaking" mass terms to make them heavier than current experimental sensitivities since we have not discovered any susy particles, yet. These masses are called *soft* because the quadratic divergences still cancel.

In the MSSM the baryon number (*B*) and the lepton number (*L*) are not conserved by all the renormalizable couplings. However, these numbers conservation, has been tested very precisely and hence it must be true. As follows, the couplings have to be very small in order for the baryon and lepton numbers to be conserved, as experiment proves. R- Parity is a symmetry acting on the MSSM fields and forbids these couplings.

$$P_R = (-1)^{2S+3B+L}$$

All currently known particles have positive R-parity, and their supersymmetric partners, if they exist, would have negative R-parity. Supersymmetric theories are divided into two important classes: those in which the R-parity of a system is constant and those in which R-parity can change with time.

The conservation of R- parity might be very crucial in the search of dark matter. If R-parity is conserved, then at least one SUSY particle is stable (or else, if it decayed into normal matter, the R-parity would become positive). Consequently, a supersymmetric signature would definitely include many of these particles. In SUSY we call them LSP (Lightest Supersymmetric Particle), they are produced at the end of a reaction due to conservation of energy and they are color and electrically neutral.

Since LHC is a hadron collider they search best for strongly interacting particles, so the supersymmetric signatures will mainly contain squarks and gluinos. R-parity is conserved in the MSSM and therefore we have to "see" a missing energy signal.

The superpartners of a gauge field are called **gauginos**. The SM is a non-abelian gauge theory with a symmetry group $SU(3)_c$ x $SU(2)_L$ x U(1) containing the photon (U(1)), W+,W-,Z (SU(2)) and 8 gluons (SU(3)). There is also the hypothetical *gravitino*.
We name the SUSY fermions (superpartners of the SM bosons) with an *–ino* at the ending of their names. If they are added before the spontaneous symmetry breaking, $SU(2)_L$ x U(1) gauginos are the *Bino* and three *Winos*. After the symmetry breaking the W and B field mix to produce the physical fields:

- Photino
- Zino
- Two Winos

Gauginos mix with **higgsinos**, the superpartner of the Higgs field (2 higgsinos exist) and their mass eigenstates are:

- Neutralinos and
- Charginos

Neutralinos are electrically neutral and the lightest of them is stable in R-parity conserving models. We usually use the notation: $\widetilde{\chi_1^0}, \widetilde{\chi_2^0}, \ldots, \widetilde{\chi_4^0}$ to describe them. These states are formed as combinations of a zino, a photino and two higgsinos.
The heavier neutralinos typically decay through a Z^0 to a lighter neutralino or through a $W^{\pm}$ to chargino.

Charginos are electrically charged fermions we usually write as: $\widetilde{\chi_1^{\pm}}$, $\widetilde{\chi_2^{\pm}}$. The heavier chargino can decay through Z^0 to the lighter chargino. Both can decay through a $W^{\pm}$ to neutralino.

Squarks can typically decay to quarks and neutralinos or charginos. If R-parity is conserved squarks are produced in pairs and therefore typical signals are 2 jets + missing energy or 2 jets + missing energy + two leptons.

Gluinos are Majorana fermionic partners of the gluon. (meaning they are their own antiparticles) The only channel they decay to is a quark and a squark.
They either decay to quark + anti-squark or anti-quark + squark and the signature is 4 jets + missing energy.

Sleptons might be produced from the decay of charginos and neutralinos if they are light enough.

2.3.1 The MSSM superpotential

$$W_{mssm} = y_u^{ij}\bar{u}_i Q_j H_u - y_d^{ij}\bar{d}_i Q_j H_d - y_e^{ij}\bar{e}_i L_j H_d + \mu H_u H_d$$

Y_u, Y_d and Y_L are the respective Yukawa couplings for the up-type quarks, the down-type quarks and the leptons.

There are several other operators that can be added to the MSSM.

$$\mathrm{W} = W_{mssm} + a\bar{U}_i\bar{D}_R\bar{D}_R + \beta Q_L L\bar{D}_R$$

These operators are literally fatal: the proton becomes unstable to the decay $p \rightarrow \pi_0 e^+$! We do not want these operators and the most common way to get rid of them is R-parity which forbids any other operator except the ones already in the W_{mssm}.

2.3.2 Soft Susy breaking

Finally, in order to write the Lagrangian of MSSM completely we need the soft symmetry breaking Lagrangian. The MSSM is the extension of the SSM that includes supersymmetry breaking. Soft terms are those particular non-supersymmetric terms that can be added to a supersymmetric Lagrangian while preserving the property that all quadratic divergences cancel.

We could roughly say that the terms are divided in four categories:

- Masses for the scalar field
- Masses for the gaugino field
- Trilinear scalar A-terms (The A terms are 3x3 complex matrices much as the scalar masses are.)
- B term (This term only exists for the Higgs doublets)

2.4 pMSSM

A big problem with the MSSM is that it has 105 parameters in addition to the Standard Model parameters. This makes any phenomenological analysis very difficult. One usually assumes the existence of a high-scale theory such as mSUGRA. However this would limit our search to a specific theory.

There is another way of reducing the number of additional parameters (to 19 quantities in specific) if we assume the following principles:

- There is no new source of CP-violation
- Minimal Flavor Violation at the electroweak scale so that flavor physics is controlled by the CKM mixing matrix
- degenerate 1st and 2nd generation sfermion masses
- negligible Yukawa couplings and A-terms for the first two generations

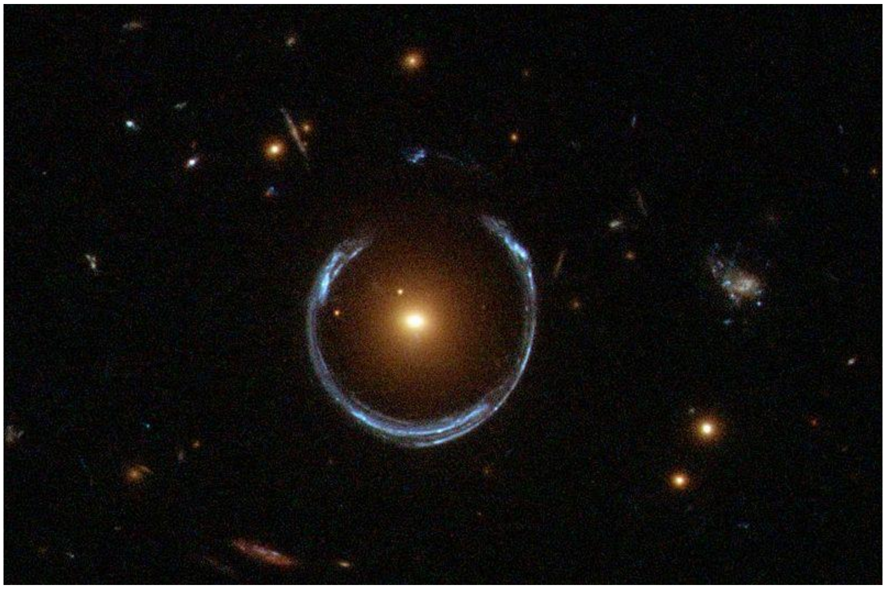
The large parameter space of pMSSM makes searches in pMSSM extremely challenging and makes pMSSM difficult to exclude. The 19 parameters are the ones that are listed on the following table (20 if the gravitino mass is included):

Symbol	Description	number of parameters
$\tan\beta$	the ratio of the vacuum expectation values of the two Higgs doublets	1
M_A	the mass of the pseudoscalar Higgs boson	1
μ	the higgsino mass parameter	1
M_1	the bino mass parameter	1
M_2	the wino mass parameter	1
M_3	the gluino mass parameter	1
$m_{\tilde{q}}, m_{\tilde{u}_R}, m_{\tilde{d}_R}$	the first and second generation squark masses	3
$m_{\tilde{l}}, m_{\tilde{e}_R}$	the first and second generation slepton masses	2
$m_{\tilde{Q}}, m_{\tilde{t}_R}, m_{\tilde{b}_R}$	the third generation squark masses	3
$m_{\tilde{L}}, m_{\tilde{\tau}_R}$	the third generation slepton masses	2
A_t, A_b, A_τ	the third generation trilinear couplings	3

2.5 Dark Matter

In 1933 Fritz Zwicky tried to measure the mass of a galactic cluster. He did this by evaluating the light galaxies shed and also by measuring their speed. When he compared the two results he found a tremendous difference.
But it was not until the 1970's that an American astronomer, Vera Rubin, measured the speed of stars in rotating galaxies accurately enough to convince the scientific community. She observed that stars in spinning galaxies were all rotating at about the same velocity, even if their distance to the galactic centre was very different. This is in contradiction with Kepler's law that describes the rotation of planets around the Sun.
This was as if the stars were not rotating around the visible centre of the galaxy but around many unknown centers, all providing additional gravitational attraction. This could only happen if huge amounts of matter filled the entire galaxy and beyond. A matter that we could however, not see.

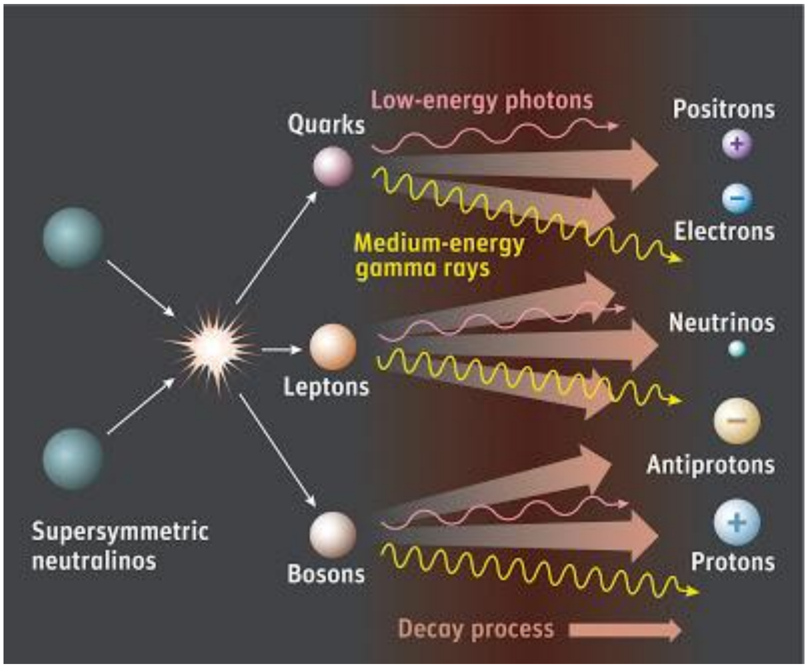
There is another phenomenon that led to the notion of *dark matter*: Gravitational lensing.
If the light comes from a distant galaxy it will bend when passing near a massive clump of dark matter. The galaxy will appear shifted, as if coming from different places. In three dimensions, all diverted light will form a ring.



What is the nature of this mysterious matter though? There is some evidence that DM is non-baryonic:

- The very accurate theory of Big Bang nucleosynthesis, which predicts the observed abundance of the chemical elements, also predicts that baryonic matter is only a 5% of the critical density, while DM is a 30%.
- Searches and analysis in the cosmic microwave background shows that 5/6 of the total matter does not interact with ordinary matter or photons.

DM also does not carry any electric charge. If the particles of which it is composed are supersymmetric, they can undergo annihilation interactions with themselves and might produce observable by-products such as gamma rays and neutrinos. The most widely discussed models for non-baryonic dark matter assume a cold dark matter, and the particle is assumed to be a *weakly interacting massive particle* (WIMP)
Consequently, we have very high hopes that an important DM candidate is the LSP.



Today dark matter is said to have frozen out at its current density because on average a dark matter particle will travel the entire distance across the before interacting with another dark matter particle. The density of dark matter today, Ω, is proportional to the inverse of the particle cross section times relative velocity at freeze-out, σ*v.

$$\Omega h^2 \sim 0.1 * \frac{3 * 10^{-26}}{< \sigma v >}$$

Uncertainty in the background (ex. positron excesses from local pulsars producing the observed cosmic ray anomalies) overwhelms our signal and makes it very hard to directly observe dark matter and only more careful observations will improve this situation.

2.6 Events with Monojet Final State

2.6.1 Introduction

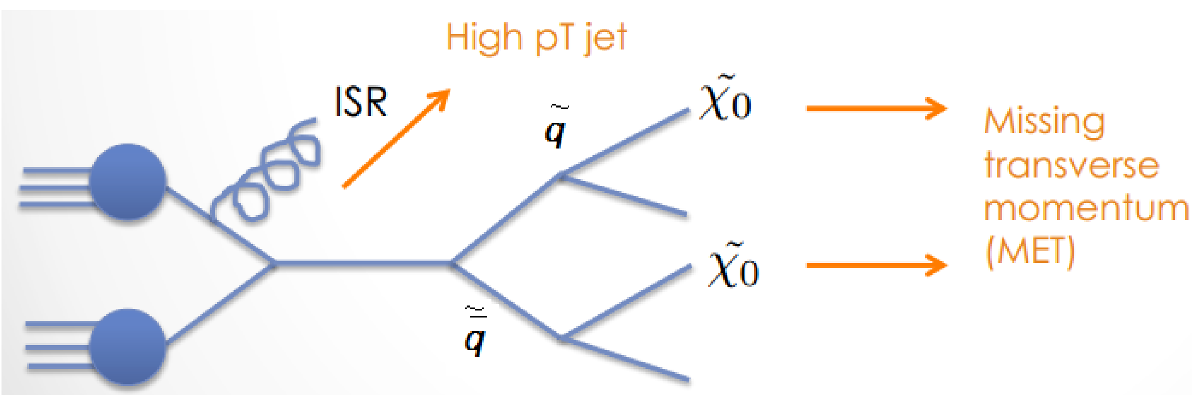
We search for supersymmetric particles in proton – proton collisions. Each time the beams are crossing, collisions are produced and collected by the detectors.
In the previous section we stated that for SUSY to be a natural theory, its mass scale must be of the order of TeV scale. No hints have however been found, so we must assume two things:

1. Susy mass scale lies above the limit we have looked for so far
2. There is a peculiarity in the model of SUSY that makes it particularly difficult to see at the LHC.

In order to separate signal from background the model must produce hard jets and/or leptons so that events can pass experimental triggers. We must also have an important amount of missing transverse energy due to LSP. If at least one of these conditions is missing we do not find SUSY.
A possible scenario is that SUSY spectrum could be compressed with small mass splittings (ΔM) between the colored superpartners and the LSP. "*Compressed*", means that a parent SUSY particle is close in mass to the LSP. These models have compressed spectra, which translates as less visible energy in the final states:

- small p_T, small H_T, MET
- The signal is very hard to distinguish from QCD and electroweak backgrounds.

Monojet signal is a powerful tool for compressed scenarios. (The accelerated colored particles produce QCD radiation, resulting in *parton showers* called initial state radiation **ISR,** in case it originates from incoming partons)



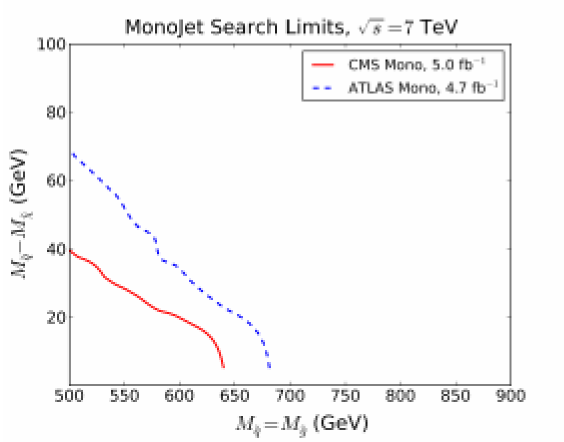
2.6.2 Searches

Compression leads to hidden SUSY at the LHC because the visible final state particles will only have energies of the order of the mass splitting between the SUSY states. Even if the parent SUSY state is produced with a large boost, due to relativistic kinematics, the majority of the momentum will be transferred to the heavy SUSY daughter (the LSP), so the hard event is invisible.

The expected topology from compressed spectra events is expected to be a single hard jet balanced by missing energy from two invisible LSPs. Therefore it is natural to also look at monojet searches at the LHC and examine how these can constrain our models.

One of the motivations of monojet searches has been to look for model independent dark matter when a jet recoils from the pair production of WIMPs. In compressed SUSY, the event signal will be identical and so we hope these searches may lead to competitive bounds.

Both CMS and ATLAS have a similar philosophy in monojet searches. For the initial selection, the jet requirement is softened with $p_T > 110$ GeV and missing energy is hardened: $E^{miss}_T > 200$ GeV. Events with a third jet $p_T > 30$ GeV are vetoed and the second jet direction cut is tightened slightly with $\Delta\varphi(p^{j1}_{T}, p^{j2}_{T}) < 2.5$. We will later present our analysis based on CMS. However, as soon as the degeneracy is broken, the monojet searches quickly lose their effectiveness.



SUSY limits are not smooth as the mass splitting is increased and they show discontinuities across the parameter space. The source of these discontinuities comes from the fact that we set limits only using the single search region that produces the most constraining bound. As we move across the parameter space we jump between different search regions and the discontinuities lie at these intersections. If we instead set limits by combining all search regions into a single variable, these would be removed and a more constraining bound may be produced.

Chapter 3

THE LARGE HADRON COLLIDER (LHC) THE COMPACT MUON SOLENOID EXPERIMENT (CMS) AND ATLAS

"It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong."
-Albert Einstein

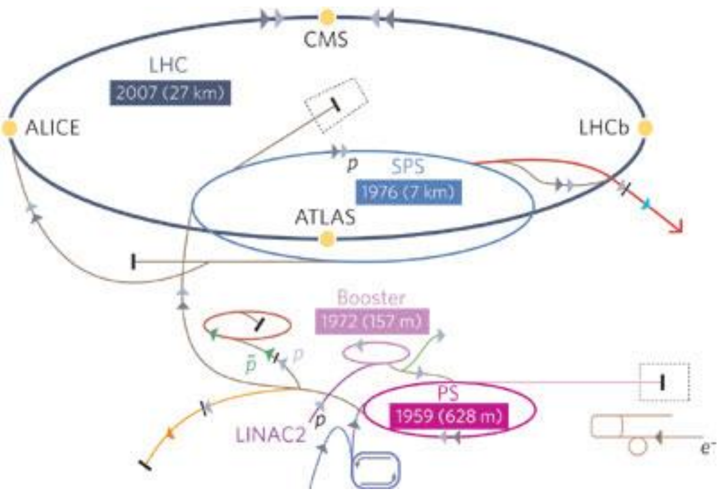
3.1 The Large Hadron Collider

The LHC (Large hadron collider) is the world's largest particle and high-energy accelerator.
It was built by the ***C**onseil **E**uropean pour la **R**echerché **N**ucleaire* (**CERN**) from 1998 to 2008.
Two opposing proton beams collide at an energy of 4 TeV or heavy ions (Pb) at 574 TeV per nucleus. Energy is roughly doubled to around 7 TeV which corresponds to collision energy of 14 TeV.
So far the LHC has discovered the Higgs boson at 125 GeV as well as a composite particle like bottomonium, which are flavorless mesons that constitute of a bottom and an antibottom.
There was also quark-gluon plasma created and the first decay of a *B* meson into two muons was observed.

3.1.1 The ring

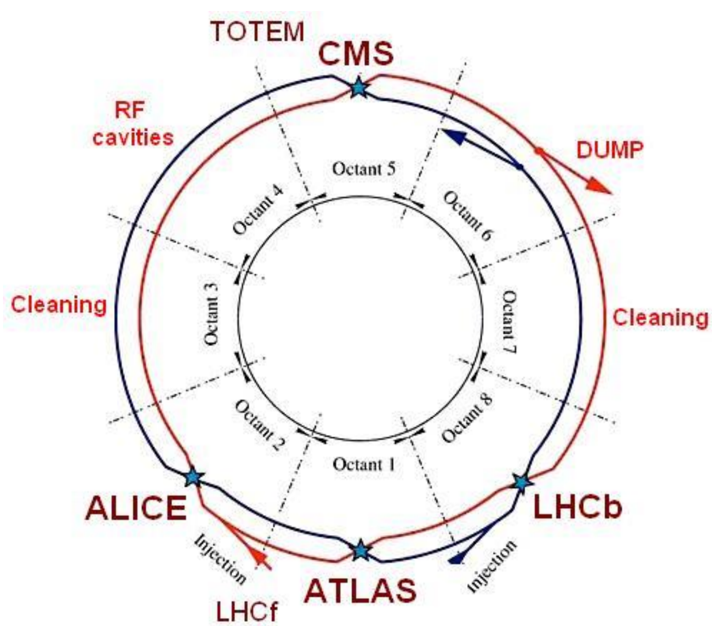
The collider is contained in a circular tunnel, with a circumference of 27 kilometers and lies 45-170 m beneath the Franco-Swiss border. The collider tunnel contains two adjacent parallel beamlines (or *beam pipes*) that intersect at four points, each containing a proton beam, which travel in opposite directions around the ring.
Dipole magnets keep the beams circular and quadrupole magnets are used to direct the beams to four intersection points, where interactions between accelerated protons will take place. To keep the magnets at their operating temperature (1.9 K) superfluid helium 4 is used.
At 14 TeV total collision energy the Lorentz factor γ of about 7500 and a speed of 0.999999991c. For a proton to travel once around the ring it takes 90 μs. The beam is not continuous but rather the protons are bunched together into 2808 bunches (of 115 billion protons in each bunch) every 25 nanoseconds maximum.
To increase their energy before the protons are accelerated, they are first prepared by the "linear particle accelerator" ***LINAC 2*** generating 50-MeV protons, which feeds the ***Proton Synchrotron Booster*** (PSB) that accelerates them to 1.4 GeV. Afterwards, the ***Proton Synchrotron*** (PS)

accelerates the beam to 26 GeV. In the end the particles are injected into ***Super Proton Synchrotron*** (SPS) and they gain the energy of 450 GeV. Now they are ready to enter the big ring.



The LHC is not a perfect circle. It is made of **eight arcs** and eight ‘insertions’**.** LHC consists of eight 2.45-km-long arcs, and eight 545-m-long straight sections.

The arcs contain the dipole ‘bending’ magnets, with 154 in each arc. An insertion consists of a long straight section plus two (one at each end) transition regions — the so-called “dispersion suppressors”. The exact layout of the straight section depends on the specific use of the insertion: beam collisions within an experiment, injection, beam dumping or beam cleaning.



3.1.2 Detectors

The LHC has four big experiments: ATLAS, CMS, ALICE and LHCb and three smaller ones: TOTEM, MoEDAL and LHCf.

ALICE is a ***l**arge **i**on **c**ollider **e**xperiment*: producing quark–gluon plasma by colliding lead nuclei at about 2.76 TeV.

ATLAS is a ***t**oroidal **LHC** **a**pparatu**s***: shedding light on the inconsistencies of the Standard Model.

LHCb is a specialized b-physics experiment that is measuring the parameters of CP violation in the interactions of B's. Such studies can help explain the Matter-Antimatter asymmetry of the Universe.

The number of events per second generated in the LHC collisions is given by:

$$N_{event} = \mathcal{L}\sigma_{event}$$

Where, σ_{event} is the cross section for the event under study and $\mathcal{L}$ the machine luminosity.
The design luminosity is $\mathcal{L} = 10^{34}\ cm^{-2}\ s^{-1}$ and it is given by:

$$\mathcal{L} = \frac{N^2 n_b f_{rev} \gamma_r}{4\pi\varepsilon_n \beta *} F$$

N is the number of particles per bunch, n_b is the number of bunches per beam, f_{rev} the revolution frequency, γ_r the relativistic gamma factor, ε_n the normalized transverse beam emittance, $\beta*$ the beta function at the collider point and F the geometric luminosity reduction factor due to the crossing angle at the interaction point. The integrated luminosity $L = \int \mathcal{L}\, dt$ is used to express the amount of available collision data.
On October 2011 the high luminosity experiments ATLAS and CMS reach 5 fb^{-1} of collected data. From 2015 to 2017 the LHC will operate with an energy of 13 TeV, which is almost double its current maximum energy. One might hope for a peak luminosity about 1.7×10^{34} $cm^{-2}s^{-1}$. At 2018 there will be a long shutdown in order to upgrade the injector complex including connection LINAC4 to the booster. From 2019 to 2021 given the increased performance of the injectors, it might possible to approach the ultimate performance of the LHC i.e. a luminosity of 2.3×10^{34} $cm^{-2}s^{-1}$.
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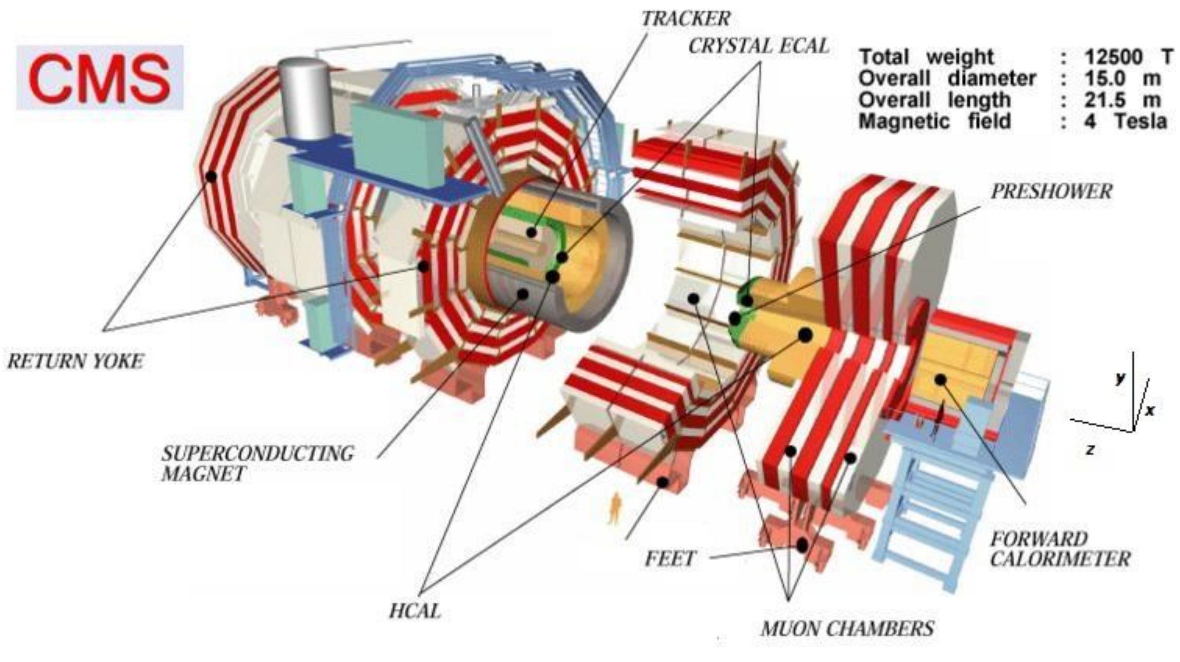
3.2 Compact Muon Solenoid (CMS)

CMS is one of the two largest experiments built on the LHC at CERN.
Its goals include exploring physics at TeV scale, look for evidence of physics beyond the standard model and study heavy ions collisions.
CMS has good muon identification, charged-particle momentum, electromagnetic energy and missing transverse energy resolution.
Its main features are: a full-silicon based inner tracking system, a high-filed solenoid and a homogeneous scintillating-crystals-based electromagnetic calorimeter.
The coordinate system we use has the origin located at the center of the detector at the collision point.
Instead of using the polar angle, positions within the detector are generally defined in terms of ***pseudorapidity*** (η):

$$\eta = -ln(tan\frac{\theta}{2})$$



CMS has 5 layers: The **inner tracker**, the **electromagnetic calorimeter** (ECAL), the **hadronic calorimeter**, the **magnet** and the **muon detectors** and **return yoke**.
The innermost layer is a silicon-based tracker. A scintillating crystal electromagnetic calorimeter is around the tracker, which is itself surrounded with a hadronic calorimeter. The tracker and the calorimeter are compact enough to fit inside the CMS Solenoid which generates a powerful magnetic field of 3.8 T. Outside the magnet are the large muon detectors, which are inside the

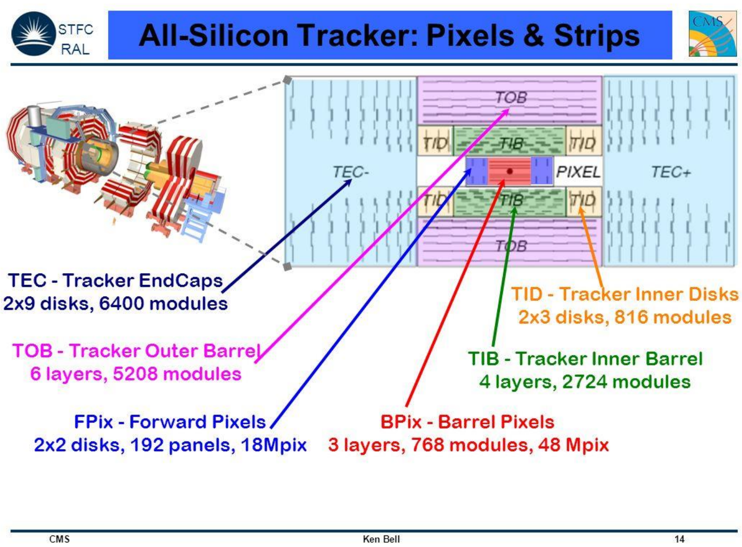
return yoke of the magnet. The return yoke reaches out 14 meters in diameter and also acts as a filter, allowing through only muons and weakly interacting particles such as neutrinos.

3.2.1. The inner tracking system

The tracker surrounds the interaction point. It helps us track the path of a particle (high energy muon, electron or hadron) through a magnetic field. We need to know the path in order to find the particles momentum. The more curved the path, the less momentum the particle had. The CMS tracker records the paths taken by charged particles by finding their positions at a number of key points.

The tracker needs to have efficient cooling due to the high power needed but also keep the amount of material low or else we would have unwanted interactions. That is why the tracker is made out of silicon.

In the barrel part, the silicon microstrip detectors are placed at a radius between 20 and 110 cm. The forward region has 2 pixel and 9 microstrip layers in each of the 2 endcaps. The acceptance is extended to $|\eta| = 2.5$. The barrel part is separated into an Inner and an Outer Barrel. There are an additional 3 Inner Disks in the transition region between the barrel and endcap parts, on each side of the Inner Barrel



3.2.2 The Electromagnetic Calorimeter

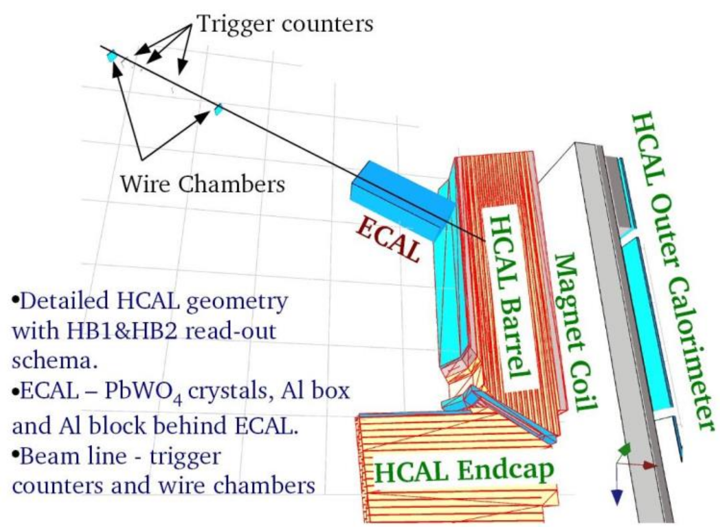
The Electromagnetic Calorimeter (ECAL) is a hermetic, homogeneous calorimeter comprising 61200 lead tungstate ($PbWO_4$) crystals mounted in the central barrel part, closed by 7324 crystals in each of the 2 endcaps.

It measures energies of electrons and photons with high accuracy. $PbWO_4$ scintillates when electrons and photons pass through. This means it produces light in proportion to the particle's energy.
The ECAL, made up of a *barrel section* (EB) and two *endcaps* (EE), forms a layer between the tracker and the HCAL. The flat ECAL endcaps seal off the barrel at either end and are made up of almost 15,000 further crystals.
ECAL also contains *preshower* detectors that sit in front of the endcaps. These allow CMS to distinguish between single high-energy photons close pairs of low-energy photons.

The preshower detector ES is a sampling calorimeter with two layers: lead radiators initiate electromagnetic showers from incoming photons or electrons and silicon strip sensors placed after each radiator, which measure the deposited energy. Its principal aim is to identify neutral pions in the endcaps within a fiducial region (a clearly defined region in phase-space in which the detector operates with high efficiency, without extrapolating to regions where the experiment has no sensitivity) $1{,}653 < \eta < 2{,}6$.

3.2.3 The Hadronic calorimeter

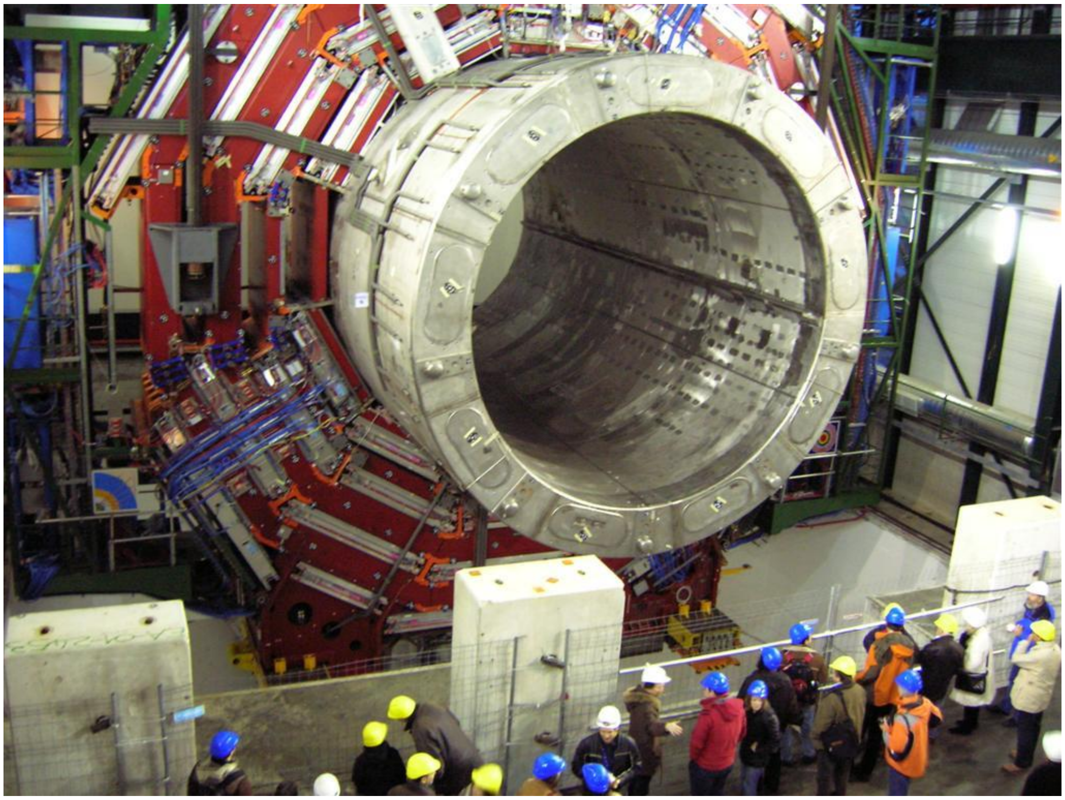
The Hadron Calorimeter (HCAL) measures the energy of hadrons. Additionally it provides indirect measurement of the presence of non-interacting, uncharged particles such as neutrinos.
The hadron calorimeter (HCAL) is restricted between the outer extent of the ECAL and the inner extent of the magnet coil.
The hadron calorimeters are very important for the measurement of hadron jets and neutrinos or other exotic particles resulting in apparent missing transverse energy. HCAL will also help the identification of electrons, photons and muons in conjunction with ECAL and the muon system. The coverage is up to $|\eta| = 3$. It is composed of four subdetectors (Barrel, Endcap, Outer and Forward).



3.2.4 The magnet

CMS's magnet is a large superconducting solenoid, with a field of 4 Tesla, a length of 12.9 m , 2168 turns, 19.5 kA current and 2.7 GJoule. The job of the big magnet is to bend the paths of particles emerging from high-energy collisions in the LHC. The more momentum a particle has the less its path is curved by the magnetic field, so tracing its path gives a measure of momentum.

The tracker and calorimeter detectors (ECAL and HCAL) fit adequately inside the magnet coil and the muon detectors are provided with a 12-sided iron structure that surrounds the magnet coils and contains and guides the field. Made up of three layers this system reaches out 14 meters in diameter and also acts as a filter, allowing through only muons and weakly interacting particles such as neutrinos.

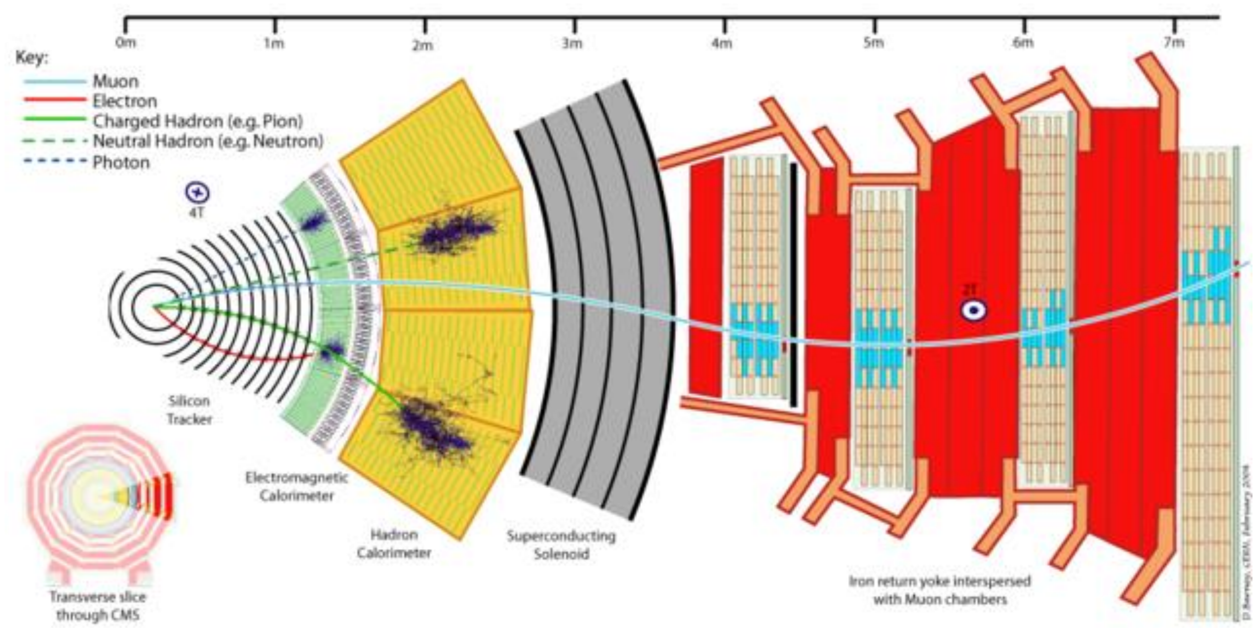


This huge magnet also provides most of the experiment's structural support, and hence it must be very strong itself to withstand the forces of its own magnetic field.

3.2.5 Muon detectors

Because muons can penetrate several meters of iron without interacting, unlike most particles they are not stopped by any of CMS's calorimeters. Therefore muon detectors are placed at the very edge of the experiment since there they are the only particles giving a signal.
Centrally produced muons are measured 3 times: in the inner tracker, after the coil, and in the return flux. Measurement of the momentum of muons using only the muon system is essentially determined by the muon bending angle at the exit of the 4 T coil, taking the interaction point as the origin of the muon.
The muon system performs three tasks: muon identification, momentum measurement and triggering

A particle is measured by fitting a curve to hits among the four muon stations, which sit outside the magnet coil and are interleaved with iron "return yoke" plates, shown in red below. In total there are 1400 muon chambers: 250 **drift tubes** (DTs) and 540 **cathode strip chambers** (CSCs) track the muons positions and provide a trigger, while 610 **resistive plate chambers** (RPCs) form a trigger system, that decides which data to keep.

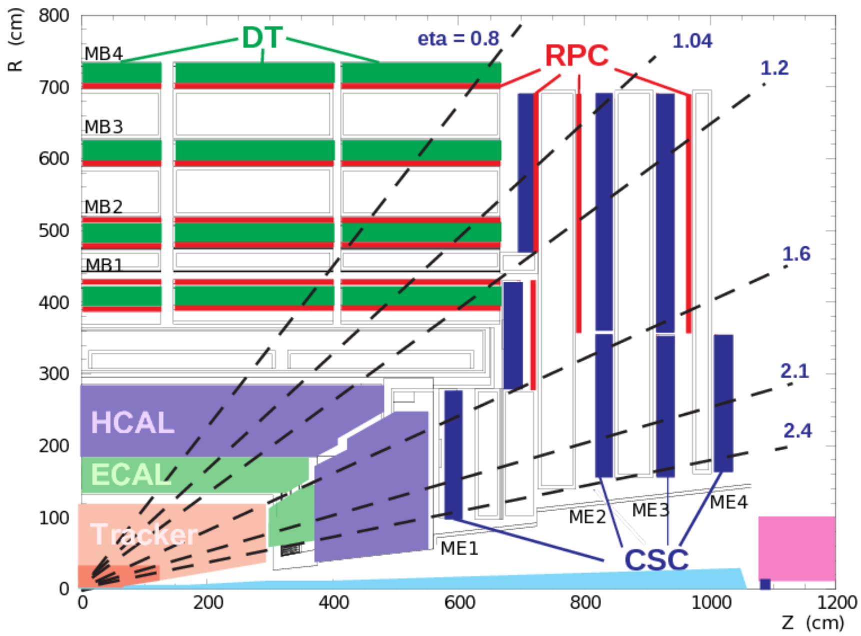


3.2.5.1 Drift tubes (DT)

he DT system measures muon positions in the barrel part of the detector, where the neutron-induced background is small, the muon rate is low and the 4 T magnetic field is uniform and at the most part contained in the steel yoke. They cover a pseudorapidity range of η< 1.2.
Each 4-cm-wide tube contains a stretched wire within a gas volume. By registering where along the wire electrons hit and by calculating the muon's original distance away from the wire drift tubes we get the coordinates for the muon's position.

3.2.5.2 Cathode strip chambers (CSC)

The Muon Endcap (ME) system is composed of 468 CSCs in the 2 endcaps. Each CSC is trapezoidal in shape and consists of 6 gas gaps, each gap having a plane of radial cathode strips and a plane of anode wires running almost perpendicularly to the strips. The magnetic field there is large and non-uniform and the identification is allowed between 0.9 < η <2.4.



The gas ionization and subsequent electron avalanche caused by a charged particle traversing each plane of a chamber produces a charge on the anode wire and an image charge on a group of cathode strips.

3.2.5.3 Resistive plate chambers (RPC)

RPCs are gaseous parallel plate detectors that consist of two parallel plates, a positively-charged anode and a negatively-charged cathode, both made of a very high resistivity plastic material and separated by a gas volume. RPCs are installed both in the barrel and in the endcaps and cover a region of $\eta < 1.6$. The trigger is fast, independent, and highly-segmented and provides a sharp pT threshold. They also help to resolve ambiguities in attempting to make tracks from multiple hits in a chamber.

3.2.6 Data and trigger acquisition systems

In order for a very rare particle to be produced, a large number of collisions is required. Of course most of the events are *soft* which means not of particular physical interest. The amount of data we would have at the 40MHz crossing rate would be 40Tbyte! This amount of data is so huge that we have to reduce it in order to process it properly.
The reduction is achieved in two steps: Level-1 trigger and High-Level trigger.

3.2.6.1 Level-1 trigger

Level-1 calculation is completed in around 1 μs, and event rate is reduced by a factor of about 1000 down to 50 kHz.

The L-1 Trigger has local, regional and global components.

- The Local Triggers

Trigger Primitive Generators (TPG), identify energy deposits in calorimeter trigger towers and track segments or hit patterns in muon chambers.

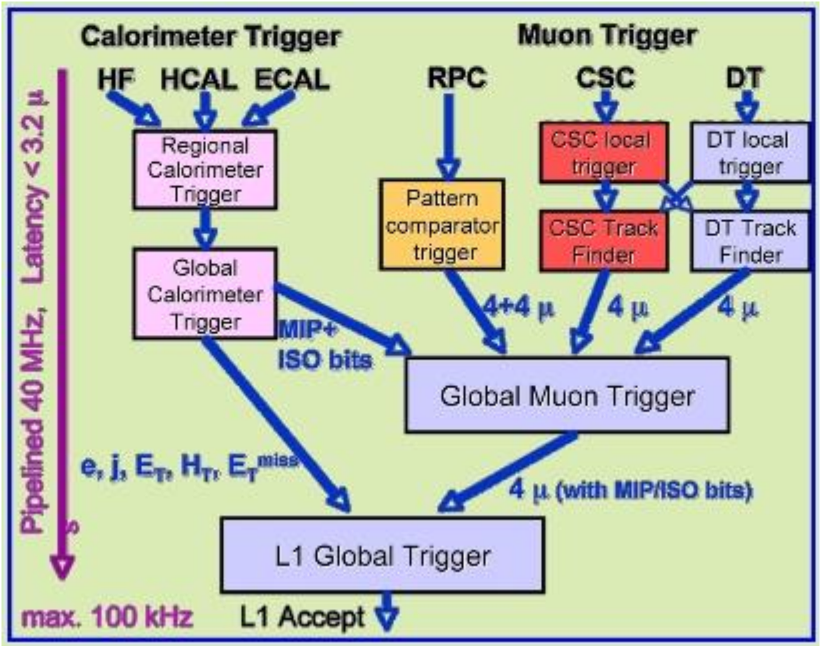
- Regional Triggers

Determine ranked and sorted trigger objects such as electron or muon candidates in limited spatial regions, by combining their information and using pattern logic.

- The Global Calorimeter (GCT) and Global Muon Triggers (GMT)

Determine the highest-rank calorimeter and muon objects across the entire experiment and transfer them to the Global Trigger (GT) which decides the rejection or the acceptance of an event for further evaluation by the High-level trigger.

The trigger system is presented in the picture below.



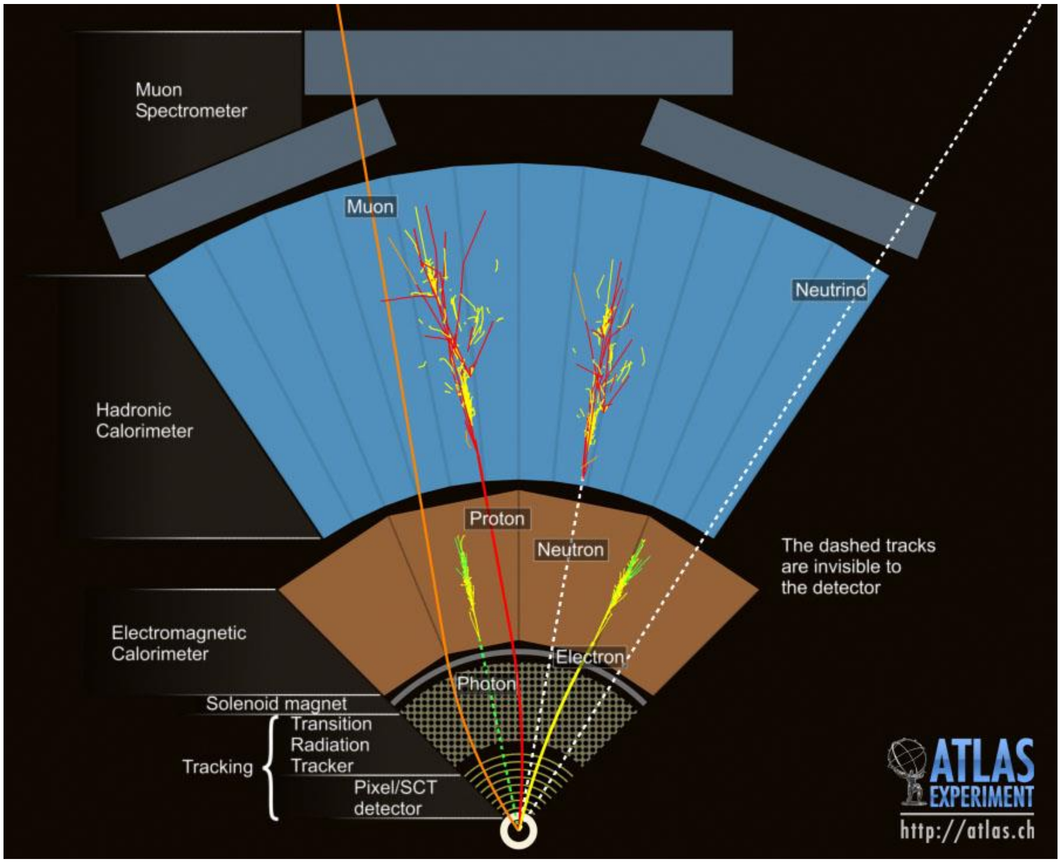
3.2.6.2 High level trigger

HLT is software that has access to all the data and the low event rate make is possible for a detailed analysis to be done**.** The HL triggers run very complex physics tests in order to look for specific signatures**,** for instance matching tracks to hits in the muon chambers, or spotting photons through their high energy. Overall, from every 100000 events per second they select about 10 of events and the remaining tens of thousands are thrown out. HLT is divided into internal steps. (level-2, level-2.5 etc)

For example level-3 refers to selection that includes the reconstruction of full tracks in the tracker. The data are stored on tapes for future analysis.

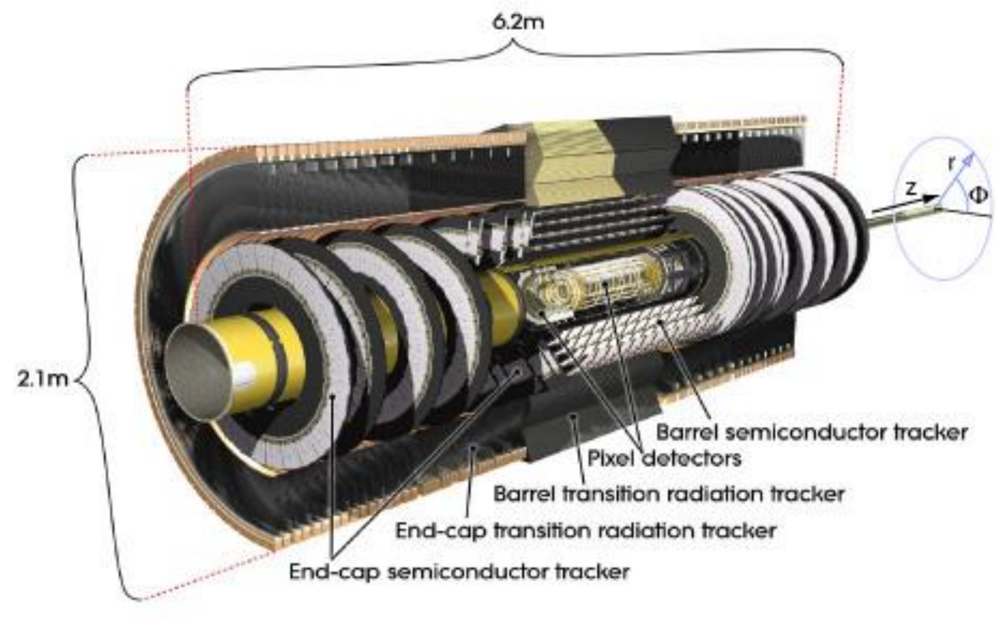
3.3 ATLAS

The ATLAS detector is 44m in length and 25m in height and it weighs 7000 tons. It is approximately forward-backward symmetric with respect to the Interaction Point (IP). It is divided in the barrel region, where the modules form cylindrical layers and two end-cap regions, where the detectors form disks to increase the detector coverage. ATLAS is mainly composed of six subsystems: the *Inner Detector*, the *calorimeters*, the *Muon Spectrometer*, the *magnet system*, the *trigger* and the *data acquisition system.*
The ATLAS experiment has been designed to exploit the full physics potential of the LHC. The high luminosity and the large center-of-mass energy of the proton proton collisions enable high precision tests on the Standard Model as well as tests on various models.
ATLAS uses a right-handed coordinate system, where the Interaction Point is at zero and the counter-clockwise beam direction defines the z-axis and the x-y plane and is transverse to the beam direction. The positive x-axis is pointing to the center of the LHC ring and the positive y-axis upwards. The pseudorapidity is defined as $\eta = -\ln(\tan(\theta/2))$.



3.3.1 Inner Detector

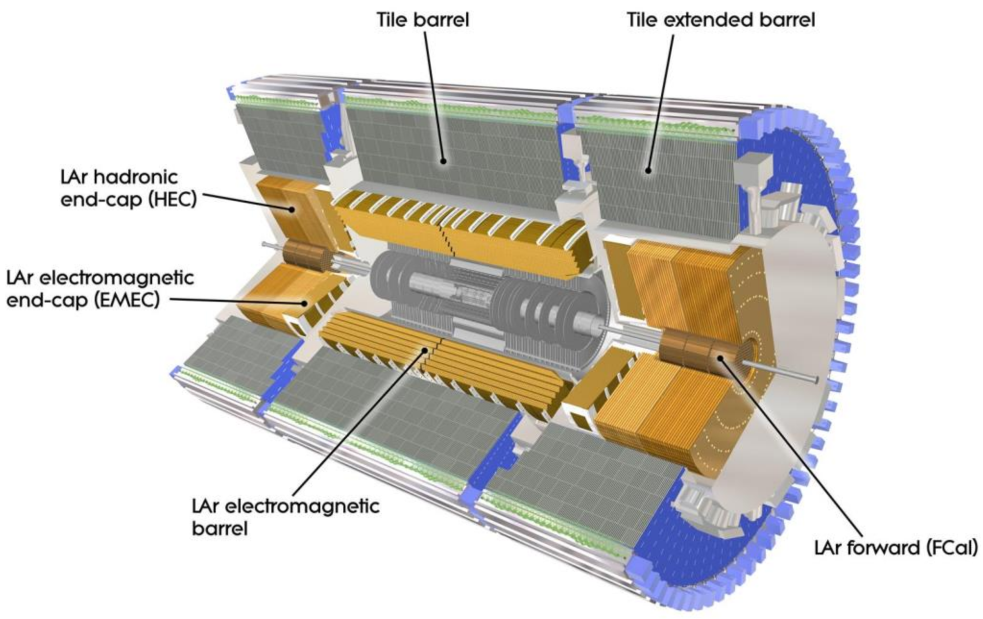
The inner detectors basic function is to track charged particles by detecting their interaction with material at discrete points, revealing detailed information about the types of particles and their momentum
The ATLAS Inner Detector (ID) is designed to provide hermetic and robust pattern recognition, excellent momentum resolution and both primary and secondary vertex measurements for charged tracks within the pseudorapidity range of $|\eta| < 2.5$. The Inner Detector consists of three independent but complementary subdetectors: the Pixel Detector, the Semi Conductor Tracker (SCT) and the Transition Radiation Tracker. The Pixel Detector and the SCT are arranged in



concentric cylinders around the beam axis, in the barrel, and on disks perpendicular to the beam axis, in the endcaps.

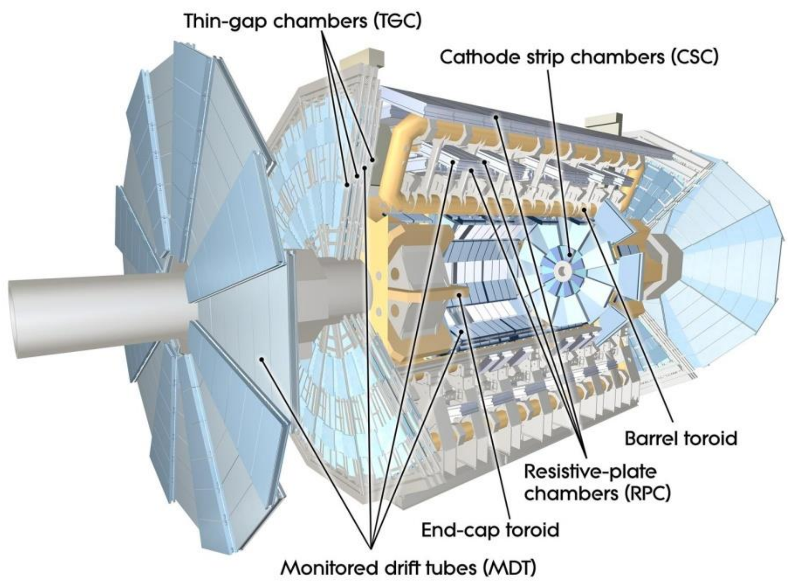
3.3.2 Calorimeters

The calorimeters measure the energy and position of the particles by sampling the energy deposit in them. They are designed to identify photons, electrons and jets with energies from 10GeV to 1TeV as well as for the determination of the missing energy. For the latter, a hermetic coverage is required. The calorimetric system consists of an *electromagnetic calorimeter* dedicated to electron and photon detection and their energy measurement, and a *hadronic calorimeter* assigned to detect and measure hadrons.



3.3.3 Muon Spectrometer

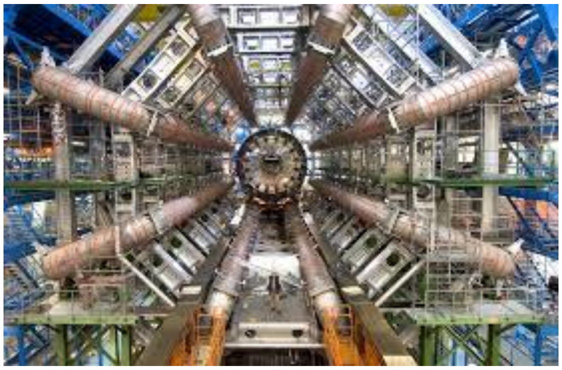
The aim of the Muon Spectrometer (MS) is to, identify, measure and trigger muons. The MS is even designed to provide standalone measurement of muons independently to the measurements of the Inner Detector. It consists of two subdetectors for precision measurements, the *Monitored Drift Tubes* (MDT) and the *Cathode Strip Chambers* (CSC), and two triggering technologies, the *Resistive Plate Chambers* (RPC) and the *Thin Gap Chambers* (TGC).



3.3.4 Magnets

The ATLAS detector contains two types of superconducting magnet systems in order to provide the bending power needed for the momentum measurement of the charged particles: the solenoid magnet surrounding the Inner Detector and the toroid magnet system embedded in the Muon Spectrometer. The *central superconducting solenoid* is aligned on the beam axis and is designed to provide a 2T axial magnetic field for the momentum measurements of the Inner Detector, minimizing the radiative thickness in front of the barrel EM calorimeter. The single-layer coil is wound with a high strength aluminum-stabilized niobium-titanium (NbTi) conductor inside a 12mm thick support cylinder. The inner and outer diameters of the solenoid are 2.46m and 2.56m and its axial length is 5.8m. It is housed in a cryostat which is shared with the calorimeter to minimize the usage of material and operates at 4.5◦ K.

The *air-core toroid magnet system* provides the magnetic field for momentum measurement in the Muon Spectrometer and has an average field strength of 0.5T.
The magnetic field which is toroidal and perpendicular to the one of the solenoid, is created by eight superconducting coils in the barrel and by two toroids with eight coils each in the endcap regions. The magnet coils are not placed in iron, which would increase the magnetic field strength, but are surrounded by air to minimize multiple scattering effects. The coil winding technology is the same as in the solenoid and is operating at a nominal current of 20.5 kA. The magnetic field strength varies with pseudorapidity for the barrel toroid and exhibits a maximum of 3.9T, while for the endcap toroids the peak value is 4.1T.



Chapter 4

FUTURE CIRCULAR COLLIDERS

"By 2100, our destiny is to become like the gods we once worshipped and feared. But our tools will not be magic wands and potions but the science of computers, nanotechnology, artificial intelligence, biotechnology, and most of all, the quantum theory."

― *Michio Kaku*

4.1 Introduction

All the scientific data and observations so far are telling us to keep looking for answers, which require new phenomena. Are those to be found at higher energies, or have they escaped detection because of very small couplings?

For these questions to be answered CERN is considering beams of 100 TeV, and is considering two options:

1. A huge upgrade of LHC, called **HE-LHC** (High Energy LHC), which would bring beams of 30 TeV, by replacing, pretty much the whole ring with stronger magnets (20 T ones – using a new superconductor)
2. A new 80 to 100 km circular accelerator "**Future Circular Colliders – FCC**", which purpose is to get beams of protons 80 to 100 TeV with 16-20 T magnets (and maybe, as well electron beams).

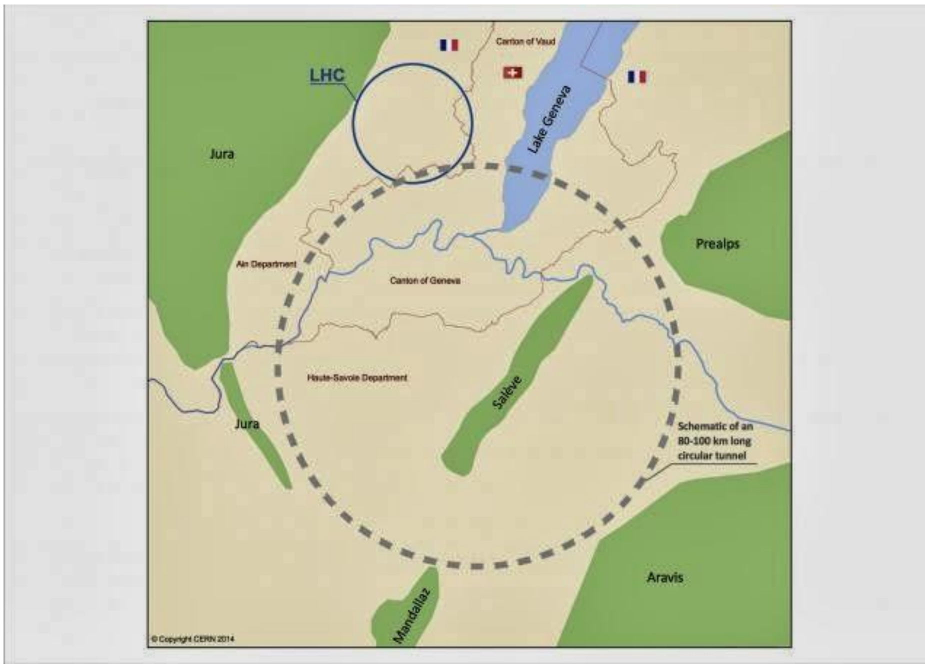
4.2 Future Circular Collider - FCC

The design study of the accelerators that would fit in a new 80-100 km "circular" tunnel, called the "Future Circular Colliders" was launched in a kick-off meeting held in University of Geneva on 12-15 February 2014, and aims at a Conceptual Design Report by 2018.

Effectively, the FCCs would be two colliders in one: the study comprises a high energy proton-proton collider with a centre-of-mass energy of 100 TeV (FCC-hh), as well as a 90-400 GeV high luminosity $e^+ e^-$ machine (FCC-ee a.k.a. "TLEP"). The machine is compatible with ion beam operation. The 100 TeV proton machine constitutes the ultimate goal while the $e^+ e^-$ machine provides a possible intermediate step. Assuming a nominal dipole field of 16 T with magnets based on the use of Nb_3Sn, such a machine would have a circumference of the order of

100 km. The machine should support two main proton experiments operated simultaneously and have a peak luminosity of 1 to 5 x $10^{34} cm^{-2} s^{-2}$.

This complex of machines bears promise of the most powerful search for new phenomena, either directly at high energies or in rare processes, or through the most sensitive and precise measurements of the Higgs boson and other Standard model particles. Either way, a sensitivity to a variety of new phenomena at energy scales of 30 to 50 TeV can be achieved.



4.2.1 Collider Parameters

4.2.1.1 Layout Baseline

There are two main ideas for the ring layouts:

1. A layout that will look like that of the LHC with arcs of equal length that are separated by straight sections. The straight sections could all have the same length or they could have different lengths, respecting some symmetry condition, for example the exactly opposite straight sections should have identical length.

2. A racetrack layout in which one has two arcs with almost 180^{o} each, connected by two long, almost straight sections.

The total length of the arcs is defined by the strength of the dipoles and the filling factor, i.e. the fraction of the arc that can be filled with dipoles. One can expect superconducting magnets that are based on the use of Nb_3Sn to reach operating fields of about 16 T. High temperature superconductors may achieve even higher fields; for such option we assume a field of 20 T. We also assume the arcs to have a total length of 82.9 km for the 16 T design and about 66.3 km for the 20 T case.

We have assumed that the integrated length of all straight sections is 4 times that of the LHC which corresponds to 16.8 km. In the case of an LHC-type layout the length of the different straight sections would need to be determined based on the different system. In the case of a racetrack layout the two straight sections would each be 8.4 km long. Detailed studies are required to review this estimate. Based on these considerations the tunnel circumference should be 99.7 km for the 16 T design and 83.1 km for the 20 T design.

4.2.1.2 Injection Energy Considerations

The minimum injection energy is defined by the field quality of the high-energy ring magnets when operated at the lower fields corresponding to the injection energy and during the start of the ramping to full field. We assume the same ratio of injection to full energy as for the LHC, which translates into a FCC -hh injection energy of 3.3 TeV. Studies of the magnet design and the associated magnet properties will have to confirm this value. This value of injection energy requires 1T magnets for an injector in the 100 km ring and 1.3 T magnets in the 80 km ring.

If the injector were installed in the LHC tunnel or the SPS a field strength of 13.5 T would be needed, so that the use of Nb3Sn would be necessary.

4.2.1.3 Beam Parameters

A wide parameter space exists for the beam parameters, which is constrained by many different limitations. Most critical for the experiments are beam energy and luminosity. The number of background events per bunch crossing is also important. It is proportional to the integrated luminosity per bunch crossing. In the scope definition, the target centre-of-mass energy and the peak luminosity have been chosen to be 100 TeV and 5 x 10^{34} cm-^{2}s^{-1}, respectively.

For the bunch spacing, we use 25 ns as a baseline and 5 ns as a case indicating the lower limit of the bunch spacing that one can reasonably expect to be able to achieve.

The lattice design work has not yet started. However, as a baseline we assume that the lattice would be a similar FODO design as in the LHC (main dipole magnets + quadrupole magnets + other multipoles magnets). In the LHC the cell length is 106.9 m. For FCC-hh a value in the order of 200 m appears adequate. The quadrupole field gradient required in this design needs to be about twice that of the LHC, which is can be achieved due to the larger field capabilities of Nb_3Sn and the reduced aperture. In FCC-hh, the synchrotron radiation emitted by the beam will cause a damping of the longitudinal and transverse emittances. This will be beneficial since it will overcome effects such as intra-beam scattering that increase the emittance with time. The following table presents an overview of the FCC parameters compared to LHC and HL-LHC parameters:

3. Parameter Overview

Table 1: FCC-hh baseline parameters compared to LHC and HL-LHC parameters.

	LHC (Design)	HL-LHC	HE-LHC	FCC-hh
Main parameters and geometrical aspects				
c.m. Energy [TeV]	14		33	100
Circumference *C* [km]	26.7		26.7	100 (83)
Dipole field [T]	8.33		20	16 (20)
Arc filling factor	0.79		0.79	0.79
Straight sections	8		8	12
Average straight section length [m]	528		528	1400
Number of IPs				2 + 2
Injection energy [TeV]	0.45		> 1.0	3.3
Physics performance and beam parameters				
Peak luminosity [10^{34} $cm^{-2}s^{-1}$]	1.0	5.0	5.0	5.0
Optimum run time [h]	15.2	10.2	5.8	12.1 (10.7)
Optimum average integrated lumi / day [fb^{-1}]	0.47	2.8	1.4	2.2 (2.1)
Assumed turnaround time [h]				5
Overall operation cycle [h]				17.4 (16.3)
Peak no. of inelastic events / crossing at - 25 ns spacing - 5 ns spacing	27	135 (lev.)	147	171 34
Total / inelastic cross section σ_{proton} [mbarn]	111 / 85		129 / 93	153 / 108
Luminous region RMS length [cm]				5.7 (5.3)
Beam lifetime due to burn off [h]	45	15.4	5.7	19.1 (15.9)
Beam parameters				
Number of bunches *n* at - 25 ns - 5 ns	2808		2808	10600 (8900) 53000 (44500)
Bunch population *N*[10^{11}] - 25 ns - 5 ns	1.15	2.2	1	1.0 0.2
Nominal transverse normalized emittance [µm] - 25 ns - 5 ns	3.75	2.5	1.38	2.2 0.44
Number of IPs contributing to ΔQ	3	2	2	2
Maximum total b-b tune shift ΔQ	0.01	0.015	0.01	0.01

Beam current [A]	0.584	1.12	0.478	0.5
RMS bunch length [cm]	7.55		7.55	8 (7.55)
IP beta function [m]	0.55	0.15 (min)	0.35	1.1
RMS IP spot size [μm] - 25 ns - 5 ns	16.7	7.1 (min)	5.2	6.8 3
Full crossing angle [μrad] - 25 ns - 5 ns	285	590	185	74 n/a
Other beam and machine parameters				
Stored energy per beam [GJ]	0.392	0.694	0.701	8.4 (7.0)
SR power per ring [MW]	0.0036	0.0073	0.0962	2.4 (2.9)
Arc SR heat load [W/m/aperture]	0.17	0.33	4.35	28.4 (44.3)
Energy loss per turn [MeV]	0.0067		0.201	4.6 (5.86)
Critical photon energy [keV]	0.044		0.575	4.3 (5.5)
Longitudinal emittance damping time [h]	12.9		1.0	0.54 (0.32)
Horizontal emittance damping time [h]	25.8		2.0	1.08 (0.64)
Initial longitudinal IBS ε rise time [h]* - 25 ns - 5 ns	57	23.3	40	1132 (396) 226 (303)
Initial horizontal IBS ε rise time [h]* - 25 ns - 5 ns	103	10.4	20	943 (157) 189 (29)
Dipole coil aperture [mm]	56		40	40
Beam half aperture [cm]	~2		1.3	1.3
Mechanical aperture clearance at any energy at any element				>12

*The growth times are only indicative. They have been calculated for a specific RF configuration and need to be estimated again once the RF system is defined.

Chapter 5

EVENT SIMULATION

"With four parameters I can fit an elephant, and with five I can make him wiggle his trunk".
-John von Neumann

5.1 Event reconstruction

Particles in an event are individually identified using a ***particle-flow reconstruction***.
Particle flow is an algorithm that reconstructs all stable particles in an event. It uses an optimized combination of information from the tracker, the calorimeters, and the muon system, and identifies the particles as charged hadrons, neutral hadrons, photons, muons, or electrons. The list of particles is returned as if it came from MC generator.

These particles are used as inputs to the ***anti-kT jet clustering algorithm*** with a distance parameter *D* of 0.5. *D* scales the distance between 2 particles i, j with respect to the distance between a particle i and the beam. The key feature is that the soft particles do not modify the shape of the jet (conical), while hard particles do.

Jet energies are corrected to particle level with p_T- and η-dependent correction factors. These corrections are derived from Monte Carlo (MC) simulation and, for data events, are supplemented by a correction, derived by measuring the p_T balance in dijet events from collision data. The E_T^{miss} in this analysis is defined as the magnitude of the vector sum of the transverse momentum of all particles reconstructed in the event excluding muons.
Muons are reconstructed by finding compatible track segments in the silicon tracker and the muon detectors and are required to be within $|\eta| < 2.1$. Electron candidates are reconstructed starting from a cluster of energy deposits in the ECAL that is then matched to the momentum associated with a track in the silicon tracker. Electron candidates are required to have $|\eta| < 1.44$ or $1.56 < |\eta| < 2.5$ to avoid poorly instrumented regions. Muon and electron candidates are required to originate within 2 mm of the beam axis in the transverse plane. A relative isolation parameter is defined as the sum of the p_T of the charged hadrons, neutral hadrons, and photon contributions computed in a cone of radius 0.3 around the lepton direction, divided by the lepton p_T. Lepton candidates with relative isolation values below 0.2 are considered isolated.
Hadronically decaying taus are reconstructed using the "hadron-plus-strips" (HPS) algorithm which reconstructs candidates with one or three charged pions and up to two neutral pions.

5.2 MC generators

Monte Carlo is very important in our search for new discoveries at the LHC. We need to make an accurate simulation of both signal and background.
The full simulation chain of a collision at CMS consists of three basic steps: Event generation, Detector simulation and Digitization.

5.2.1 Event generation

Event generation includes simulation of collisions produced by proton - proton interactions until the production of the final decay products. This includes everything from modeling the subatomic makeup of a proton, the calculation of scattering amplitudes, the decay of unstable particles, and the hadronization of quarks and gluons into jets.
The probability of finding a proton that has a momentum fraction x, is described by the ***Parton Distribution Functions*** **(PDFs)**.

The production of the particles that are of interest to us, as well as their decays, are described by ***matrix elements***. We first have to calculate the matrix elements according to the Feynman rules in quantum field theory and afterwards the cross section of the process we are interested in.
The partons produced in a process cannot exist as free particles (QCD confinement).
Their kinetic energy is transferred to the color field, producing additional partons from vacuum. As a consequence parton showers are grouped together into colorless hadrons, known as ***jets*** -a mechanism called ***hadronization***. The particles of interest for the event are generated by a ***hard process*** and the events of interest are called ***hard events***. Partons that might remain interact with other p - p interactions in the same beam crossing and contribute to our ***background***.

We can divide the event generators into two categories:

- Automatized Matrix Element generators (e.g. MADGRAPH)

Matrix Element generators are used for processes with complex multi-particle final states. They are capable of calculating next-to-leading order (NLO) corrections to matrix elements.

- Parton Shower MC event generators (e.g. PYTHIA)

They simulate every step of the event and the particles cross sections are calculated to leading order (LO) only. Generators like these are most suitable for processes with not more than two final state particles.

5.2.1.1 PYTHIA

Pythia is an event generator software that simulates

- Hard and soft interactions
- Parton distributions
- Initial/final-state parton showers
- Multiple interactions
- Fragmentation and decay

5.2.1.2 MadGraph

MadGraph is a framework that aims at providing all the elements necessary for SM and beyond SM phenomenology, such as the computations of cross sections, the generation of hard events and their matching with event generators, and the use of a variety of tools relevant to event manipulation and analysis. Processes can be simulated to LO accuracy for any user-defined Lagrangian, and the NLO accuracy in the case of QCD corrections to SM processes. Matrix elements at the tree- and one-loop-level can also be obtained.
However, since they do not include hadronization, they have to be interfaced with other generators in order to produce the full event such as PYTHIA.

5.3 Monte Carlo in our analysis

The dark matter samples are produced using MadGraph interfaced with PYTHIA 6.42.
In order to improve the agreement between MC and data the parameters of Pythia can be tuned. Here the reconnection is tuned from the Z2star tune for parton showering and hadronization and the CTEQ 6L1 parton distribution functions (PDF). Dark matter particles with masses M_χ = 1, 10, 200, 400, 700, and 1000 GeV/c ^{2} are generated for both vector and axial-vector interactions. The p_T of the associated parton is required to be greater than 80 GeV/c.
If we have a light mediator, the mediator mass (M) is varied between 50 GeV/c^2 and 3 TeV/c^2 for a dark matter mass of 50 GeV/c^2 and 500 GeV/c^2.

The Z + jets, W + jets, $t\bar{t}$, and single-top event samples are produced using MADGRAPH.
The QCD multijet sample is generated with PYTHIA 6.42, using tune Z2star and CTEQ 6L1 PDFs. The Z + jets and W + jets samples are generated with a cut on the transverse momentum of the boson, p_T > 100 GeV/c.
All the generated signal and background events are passed through a GEANT4 simulation of the CMS detector.

5.4 Monojet background in the SM

The Standard Model background is dominated by the following processes.
Electroweak background:

- Z → ν + ν + jets (largest and irreducible background)
- W → l + ν + jets where the lepton is not observed in the detector

QCD:

- E^{miss}_T originating from miss measured jet energies and is estimated using multi-jet events in which E^{miss}_T points along the direction of one of the jets.

The number of Z (→ νν) events can be predicted using:

$$N\,(Z\,(\nu\nu)) = \frac{N_{obs} - N_{bkg}}{A\ x\ \varepsilon}\ R\left(\frac{Z(\nu\nu)}{Z(\mu\mu)}\right)$$

,where $\mathbf{N_{obs}}$ is the number of dimuon events observed, $\mathbf{N_{bgk}}$ is the estimated number of background events contributing to the dimuon sample, **A** is the acceptance, **ε** is the selection efficiency for the event, and **R** is the ratio of branching fractions for the Z decay to a pair of neutrinos and to a pair of muons. The acceptance A is defined as the fraction of simulated events that pass all signal selection requirements, except muon veto and have two muons with $p_T > 20$ GeV/c and $|\eta| < 2.1$ and with an invariant mass within the Z mass window. The selection efficiency ε is defined as the fraction of events passing acceptance cuts that have two reconstructed muons with $pT > 20$ GeV/c and $|\eta| < 2.1$ and with an invariant mass within the Z mass window. The muon selection efficiency is also estimated from simulation but corrected to account for differences in the measured efficiency between data and MC.
Similarly, $W \rightarrow l + v + jets$ with a well reconstructed lepton are used to estimate the W + jets background to monojet events.

$$N\,(W \rightarrow lv + jets) =$$

$$= \frac{N_{obs} - N_{bkg}}{A\ x\ \varepsilon}\ x\ \frac{L_{met}}{L_{lept}}\ x\ \varepsilon_{met\ trig}\ \frac{N_{events}(pass\ all\ cuts)}{N_{events}(no\ veto\ requirement)}$$

Chapter 6

EVENT SELECTION

"The true worth of an experimenter consists in his pursuing not only what he seeks in his experiment, but also what he did not seek." – Claude Bernard

We search for new physics in supersymmetric events containing a jet and missing transverse energy using Monte Carlo simulations of pp collisions at the center-of-mass energy 8, 14 and 100 TeV.

In particular, the search is about dark matter and the lightest neutralino ($\widetilde{X^0}$) as WIMP (weak interactive massive particle) candidate in the minimal supersymmetric extension of the Standard Model.

Monojet events originate from the channel: pp-> χχ + jet and also from processes such as pp->$\widetilde{q}\ \tilde{\bar{q}} + jet$ and pp-> $\tilde{g}\ \tilde{g}\ + jet.$

Searches for Monojet events can extend the sensitivity to neutralino mass ($\widetilde{X^0}$) in the case where scalar quarks ($\tilde{q}$) have almost the same mass as the neutralino.

We have taken the cuts from the CMS physics analysis summary (CMS PAS EXO-12-048)

For the initial selection, the jet requirement is softened slightly with p_T > 110 GeV but the missing energy is hardened E_T^{miss} > 250.

The analysis is performed in 7 regions of missing transverse energy E_T^{miss} > 250, 300, 350, 400, 450, 500, 550 GeV. We've rejected events with more than 2 jets with p_T > 30 GeV and |η|< 2.3. A second jet is allowed if Δφ (j_1, j_2) <2.5. Events with electrons and muons with p_T>10 GeV are also rejected.

We used the MC simulations we previously described for the signal and the background for 8, 14 and 100 TeV.

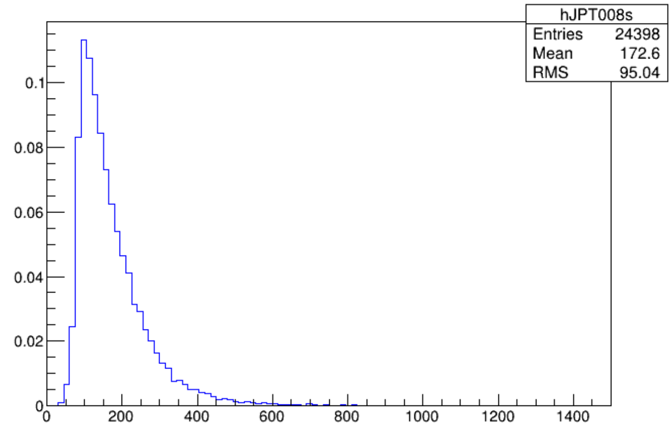
Chapter 7

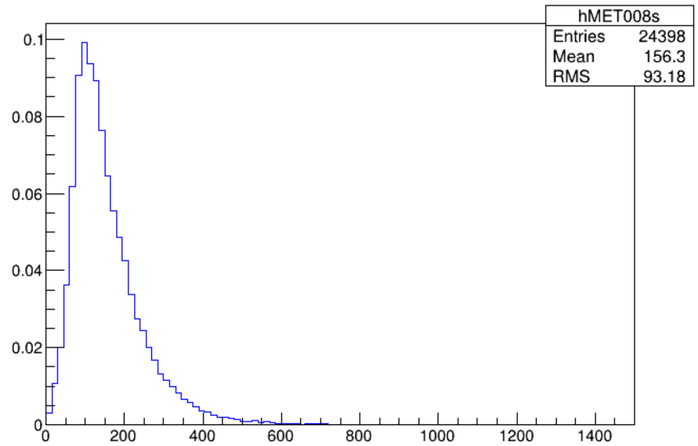
RESULTS

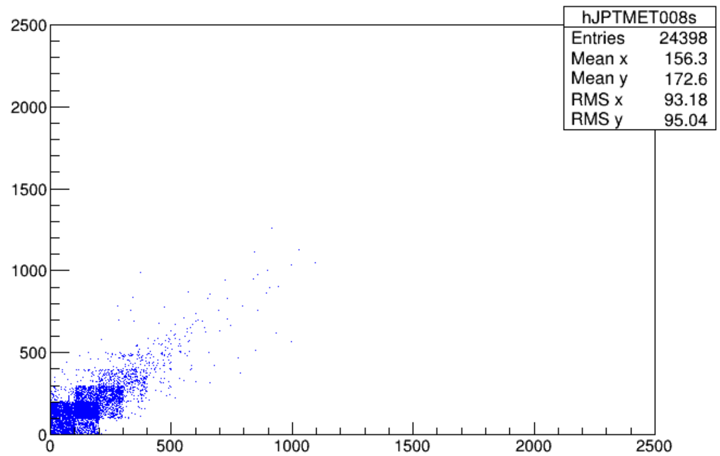
"There are three principal means of acquiring knowledge… observation of nature, reflection, and experimentation. Observation collects facts; reflection combines them; experimentation verifies the result of that combination." – Denis Diderot

In our analysis we created the following histograms:

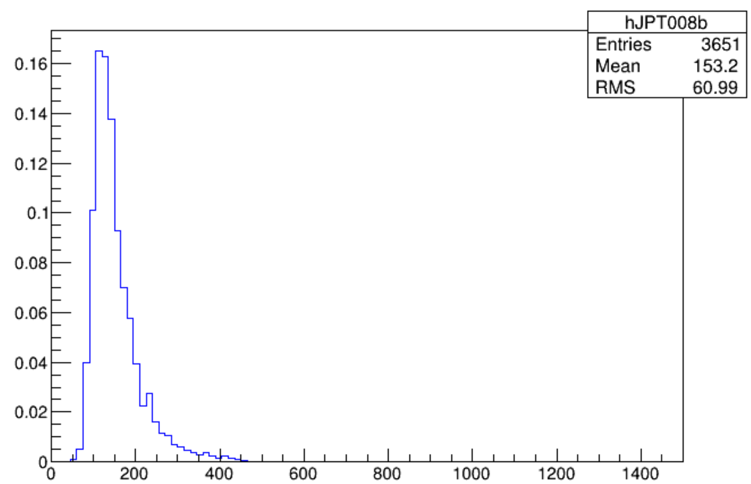
A. Energy 8 TeV: Transverse momentum (p_T) and Missing energy (met).

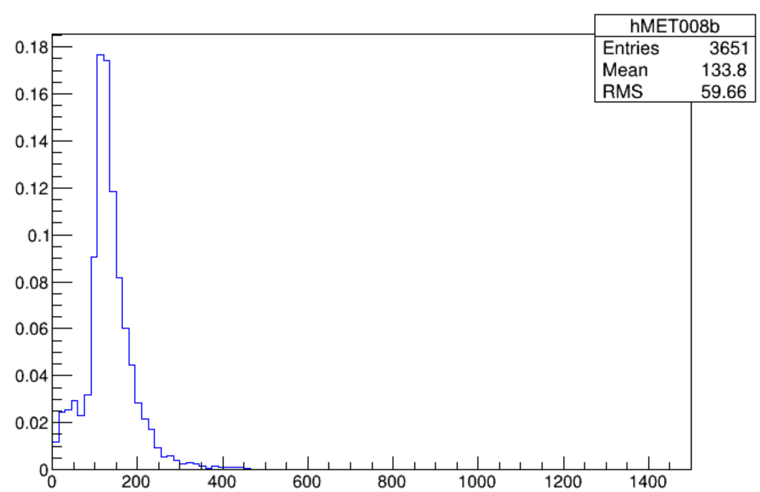


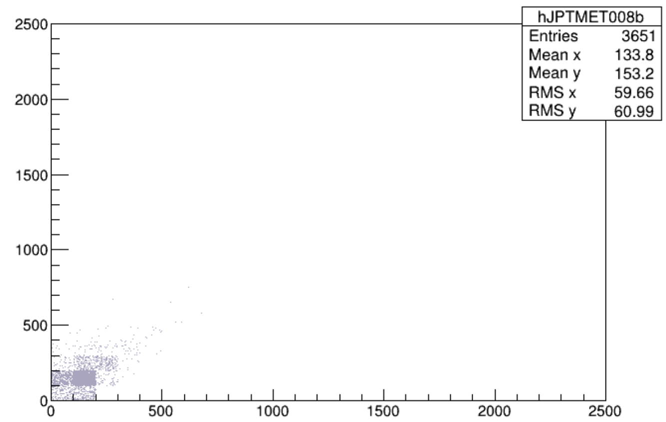




Similar histograms for the background p_T and met, at 8 TeV:

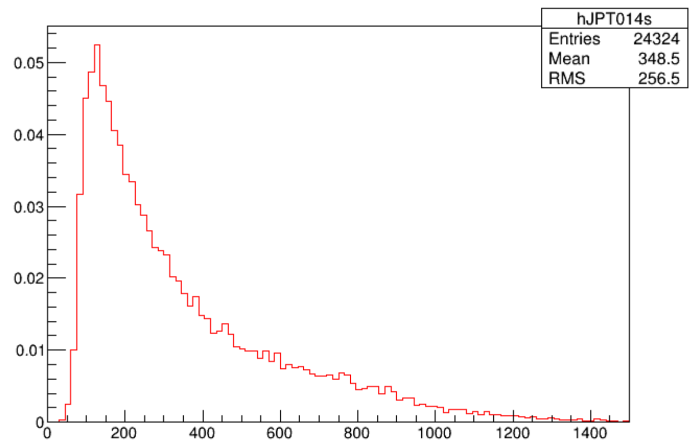




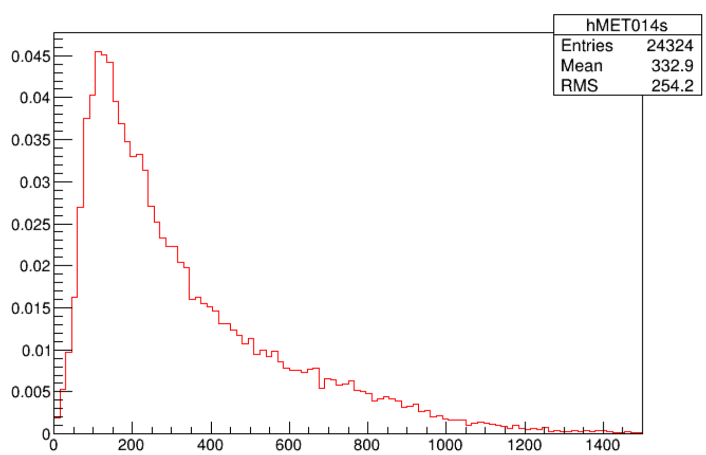


B. Energy 14 TeV:

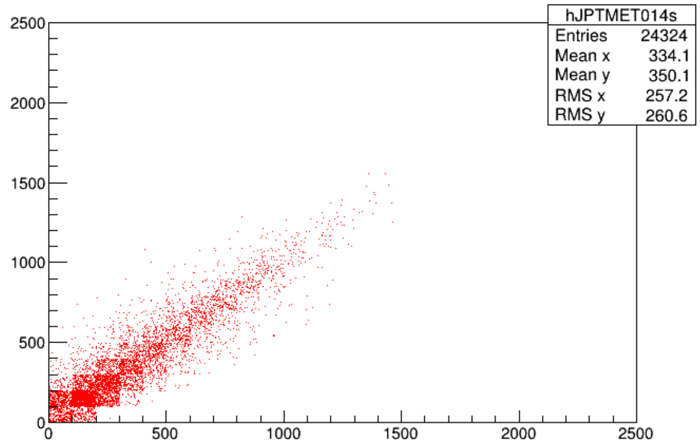
Signal P_T histogram at 14 TeV



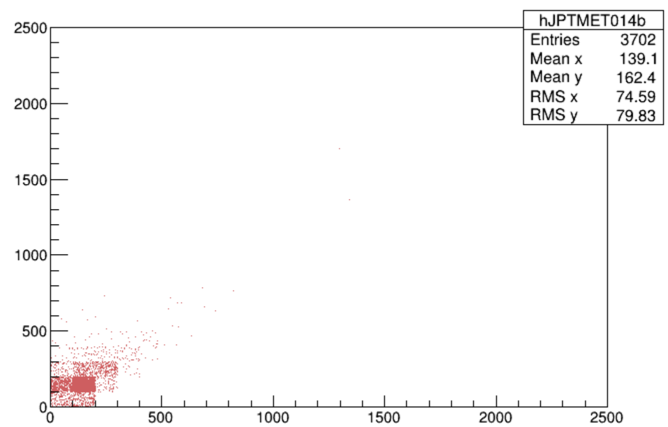
Signal missing energy histogram



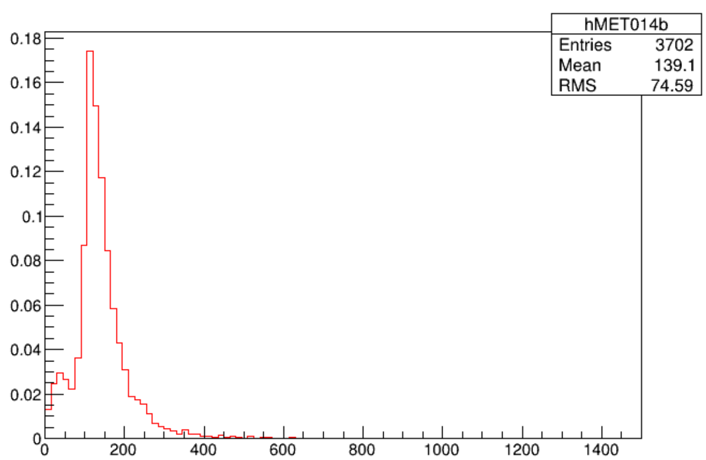
P_T vs MET signal presentation



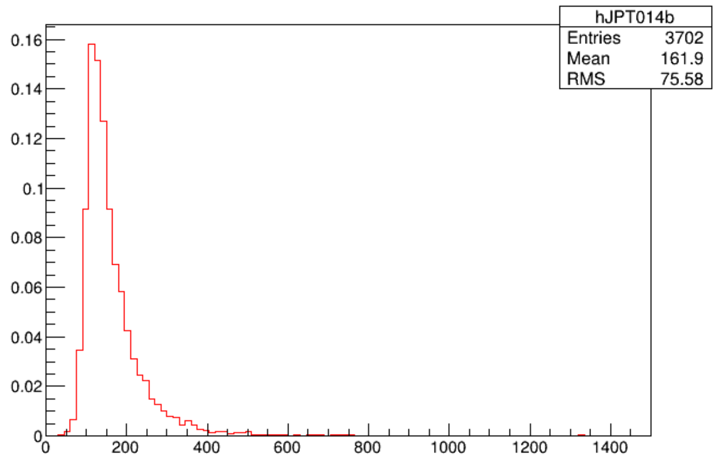
P_T vs MET background presentation



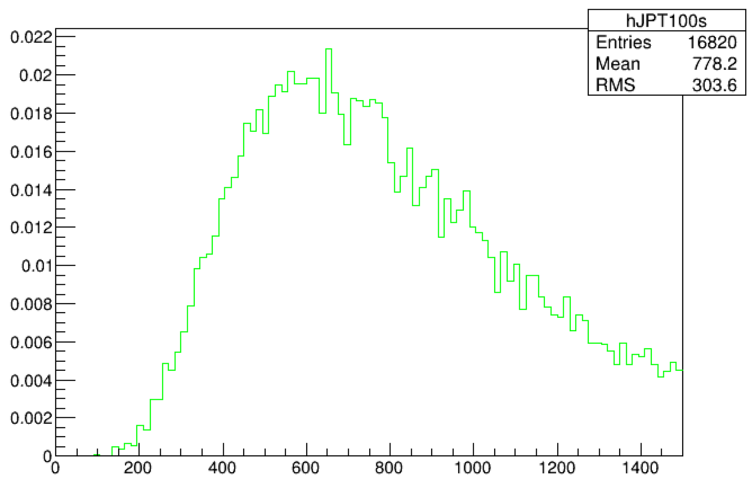
Background missing energy histogram:

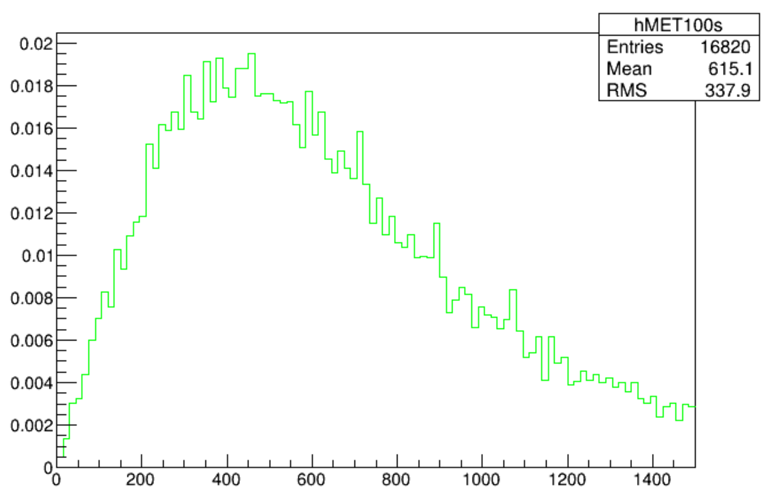


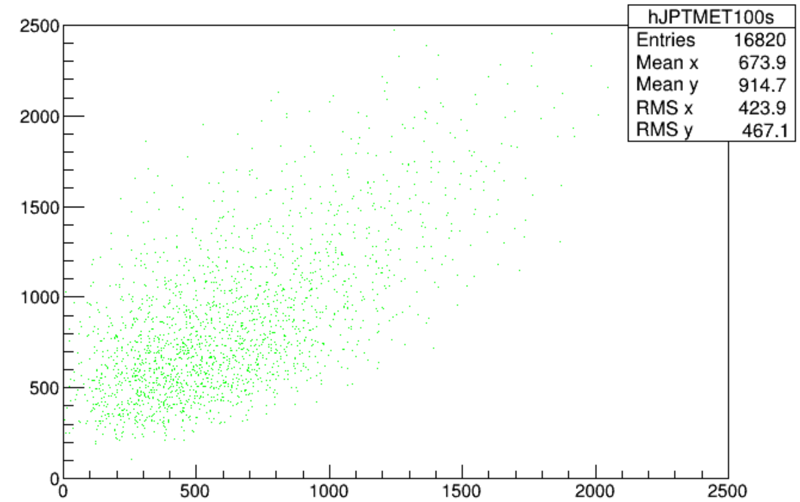
Background P_T histogram:

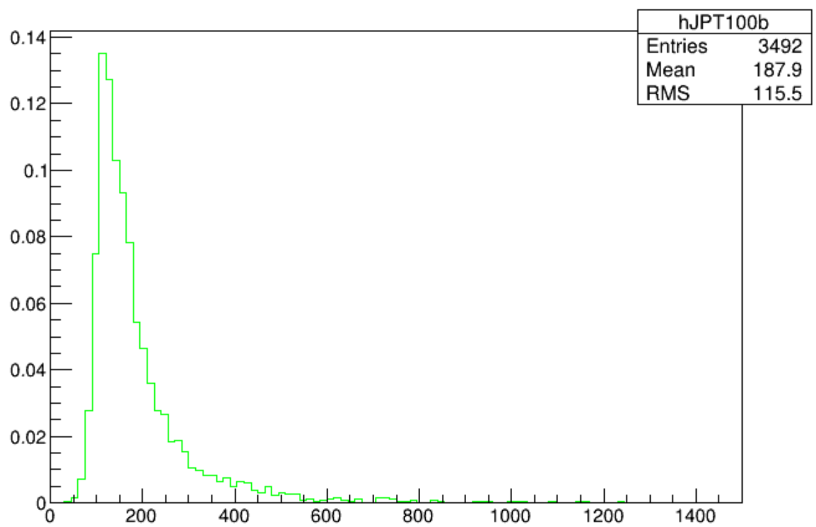


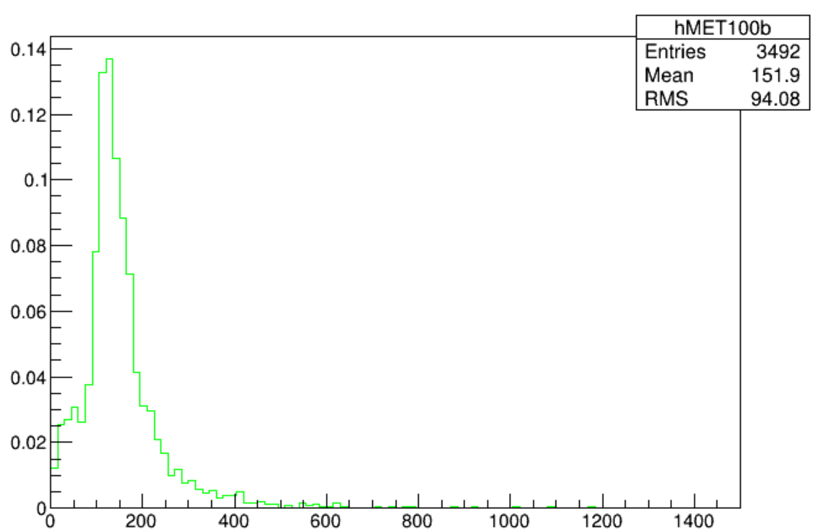
C. Energy 100 TeV:

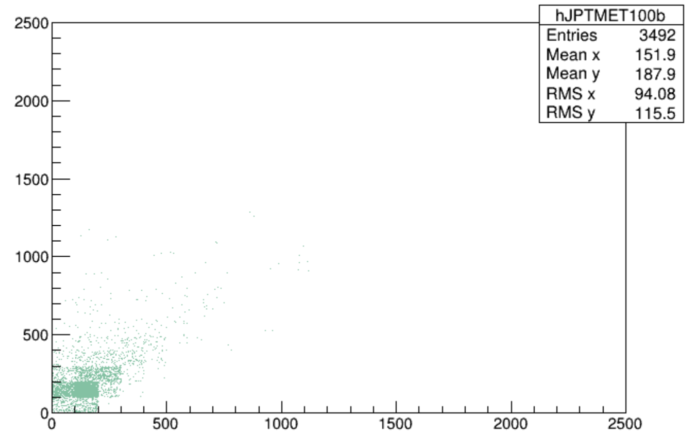




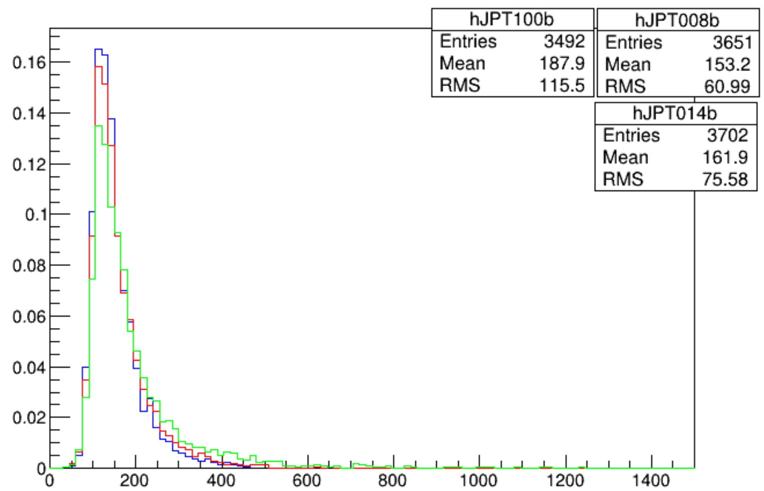

hJPTMET100s
Entries 16820
Mean x 673.9
Mean y 914.7
RMS x 423.9
RMS y 467.1


hJPT100b
Entries 3492
Mean 187.9
RMS 115.5

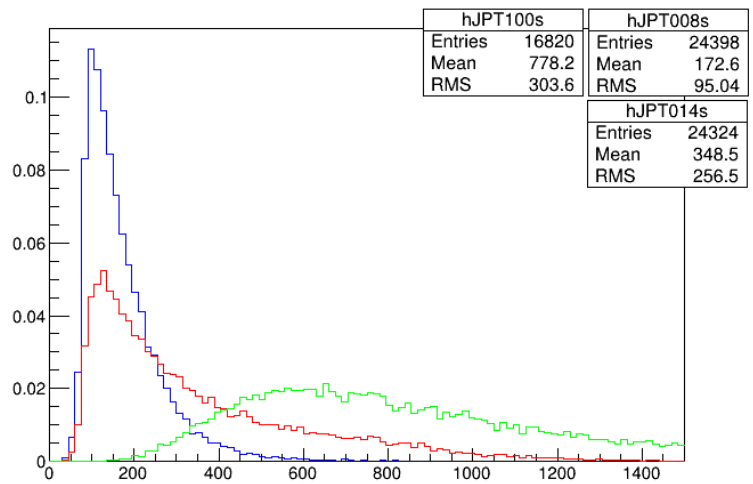

hMET100b
Entries 3492
Mean 151.9
RMS 94.08



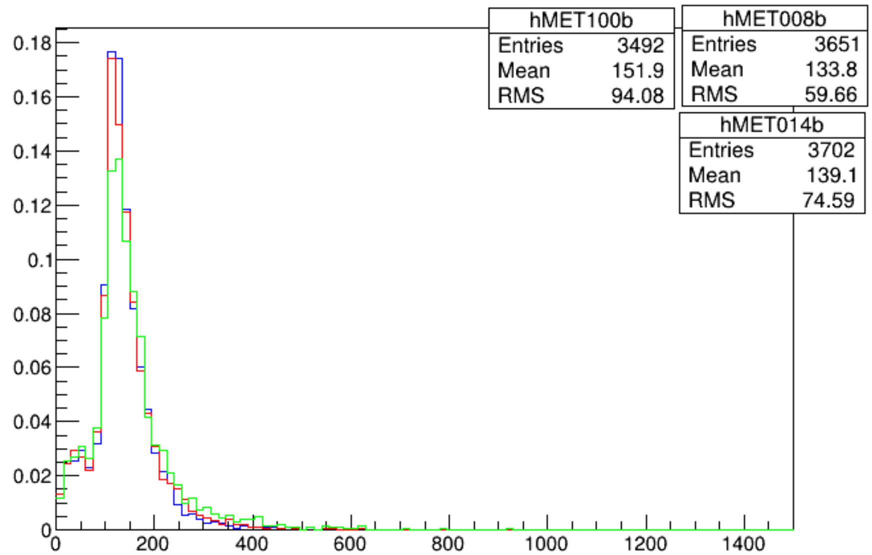
All the 3 histograms of the Jet Pt of the background for 8, 14 and 100 TeV in one:
(blue is 8 TeV, red is 14 TeV and green is 100 TeV)



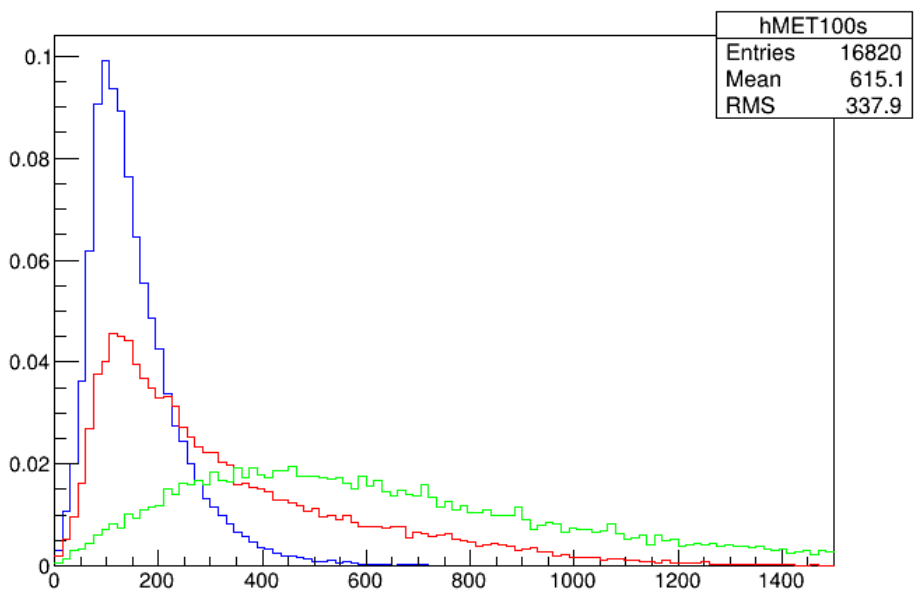
And for signal:



And we did the same for the missing energy for background:

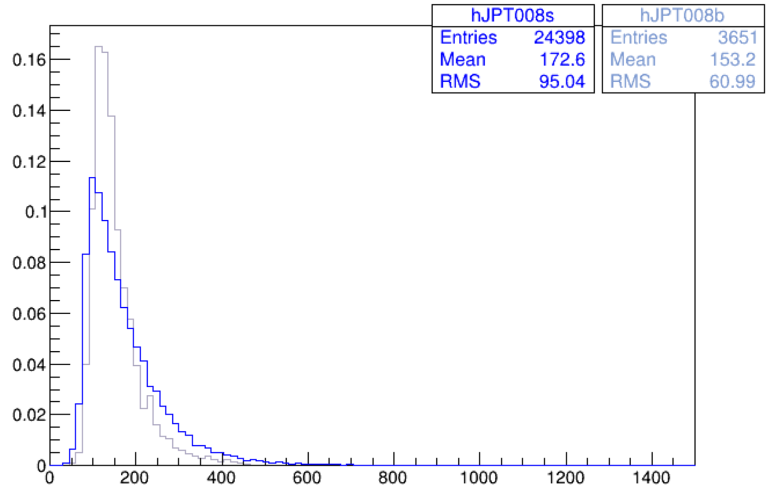


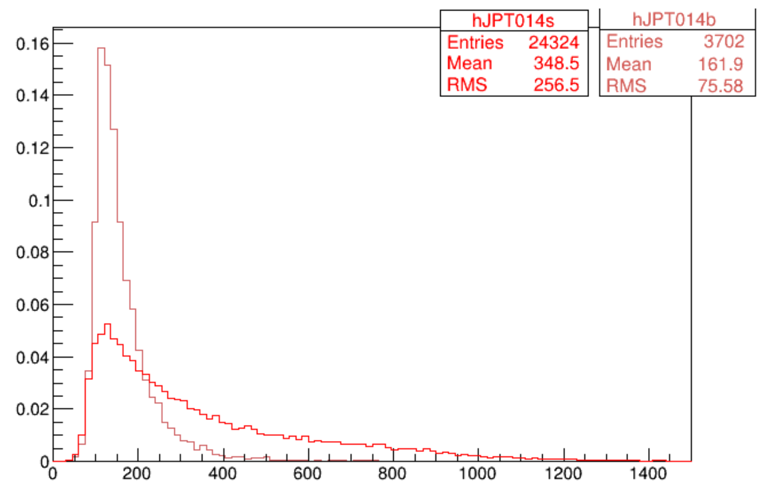
And signal:

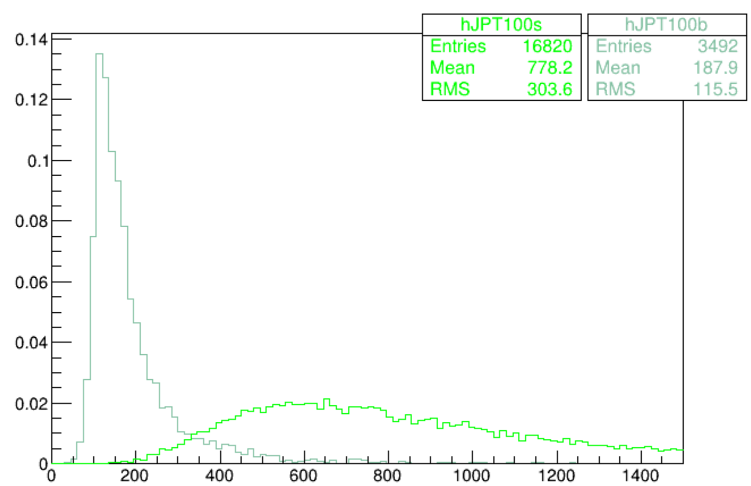


Afterwards, we created 3 histograms for Pt signal and background in one and 3 for missing energy signal and background for the energies of 8,14 and 100 TeV.

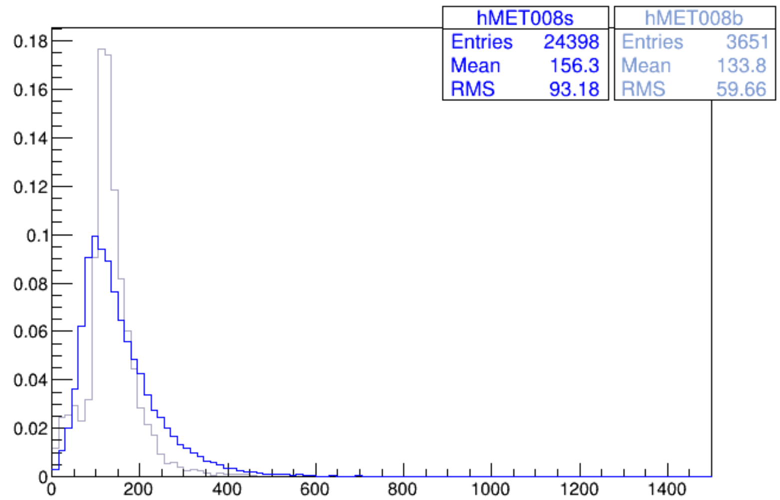
(P_T)

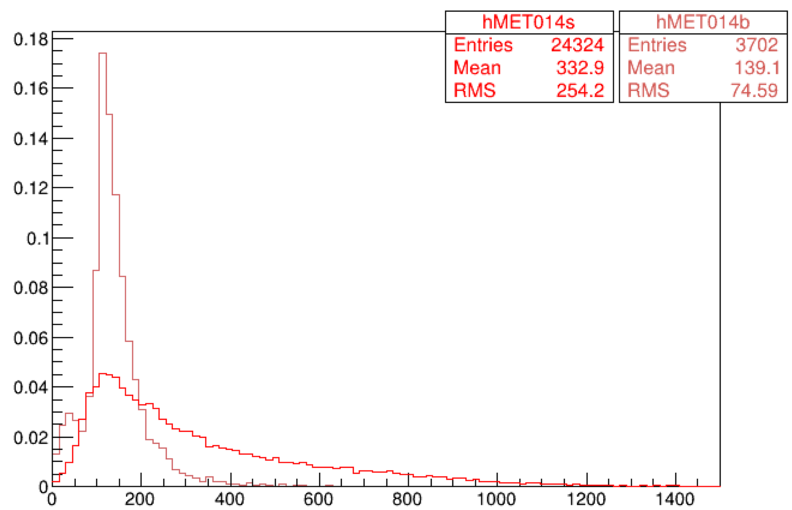

hJPT008s
Entries 24398
Mean 172.6
RMS 95.04
hJPT008b
Entries 3651
Mean 153.2
RMS 60.99
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
200
400
600
800
1000
1200
1400

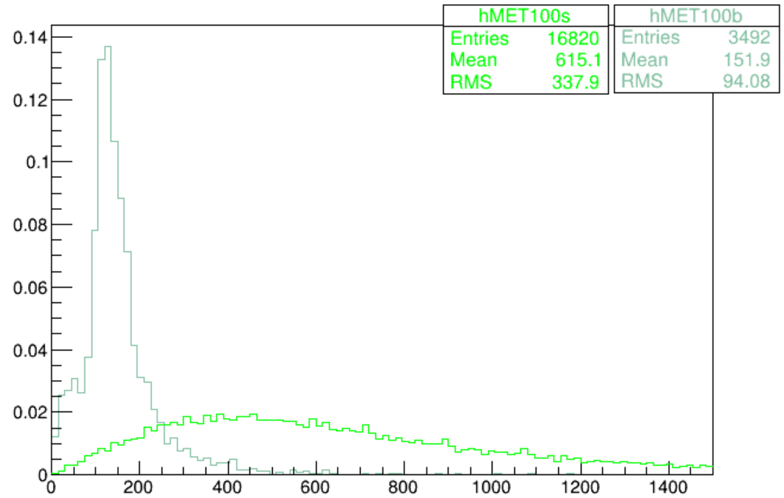

hJPT014s
Entries 24324
Mean 348.5
RMS 256.5
hJPT014b
Entries 3702
Mean 161.9
RMS 75.58
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
200
400
600
800
1000
1200
1400


hJPT100s
Entries 16820
Mean 778.2
RMS 303.6
hJPT100b
Entries 3492
Mean 187.9
RMS 115.5
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
200
400
600
800
1000
1200
1400

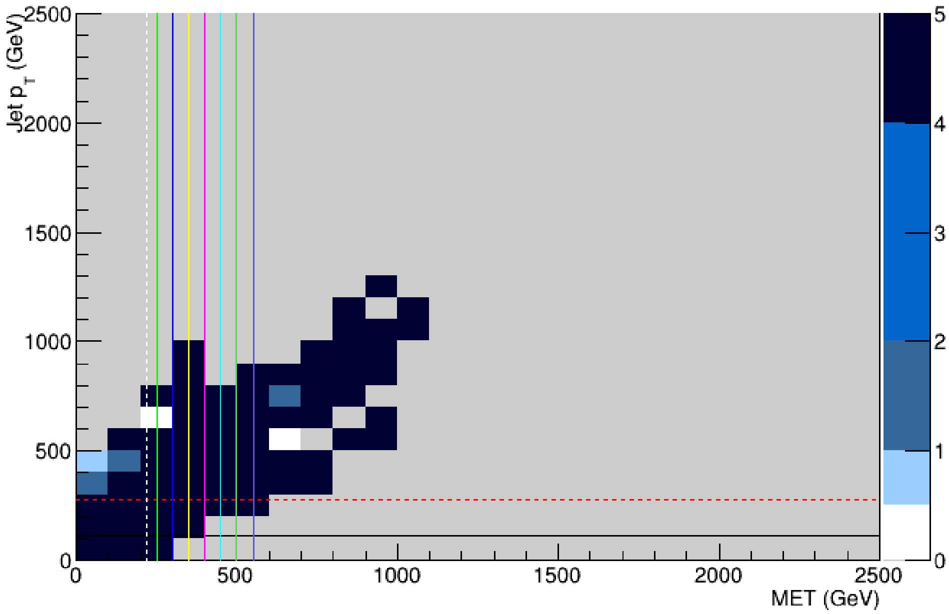
(missing energy- MET)

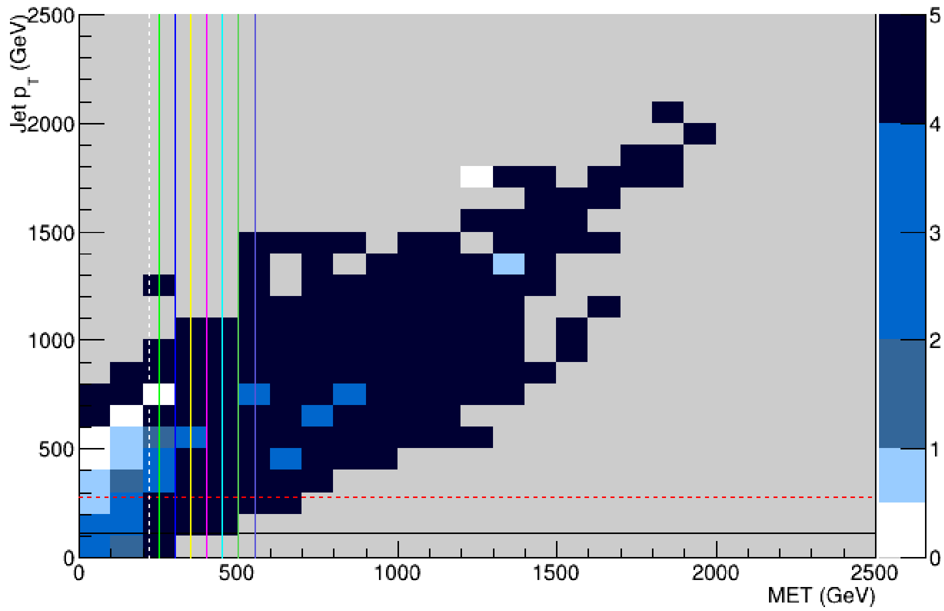


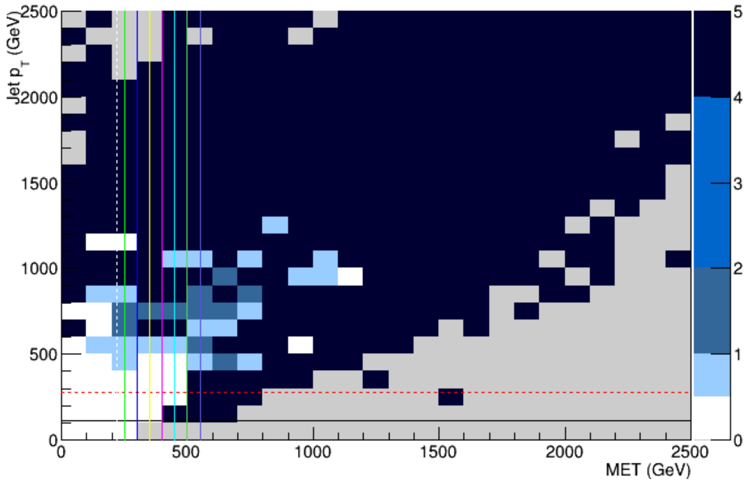




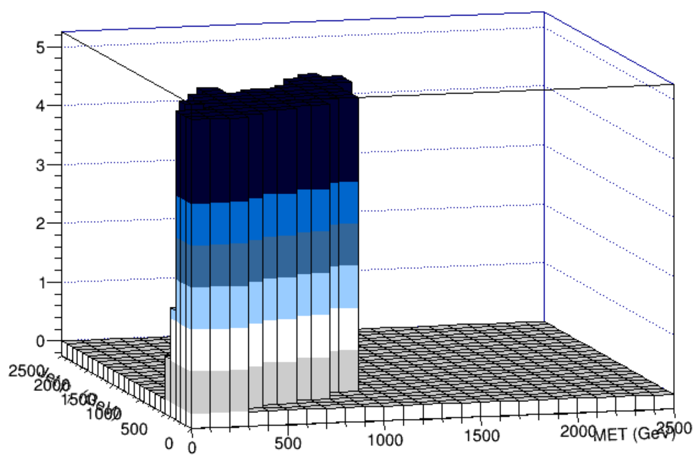
Finally we produced 3 histograms that show the significance of the correlation of Pt and Met, in every energy, using the definition $significance = \frac{signal}{\sqrt{signal+background}}$

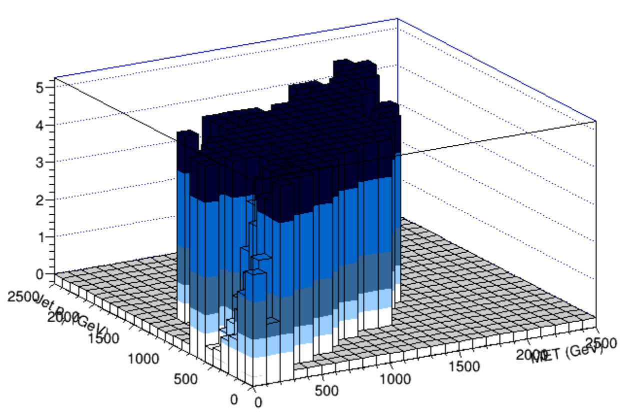


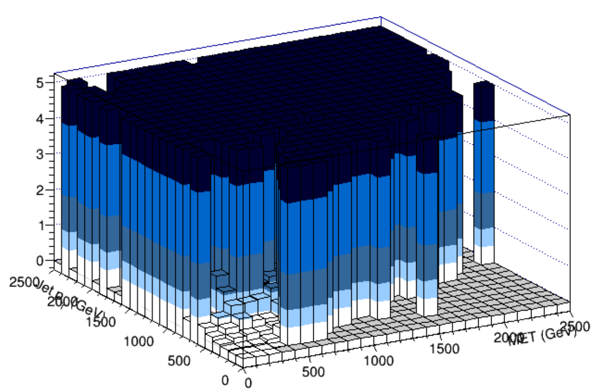




And the same is 3D plots (8,14 and 100 TeV respectively)





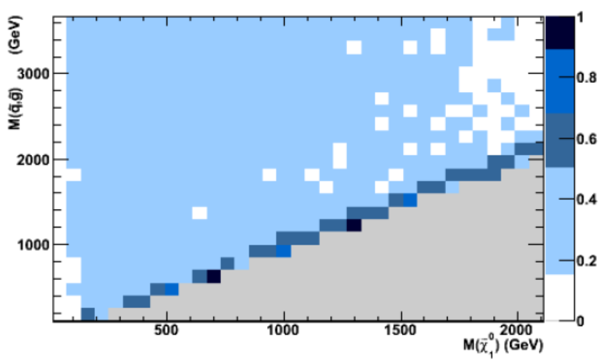


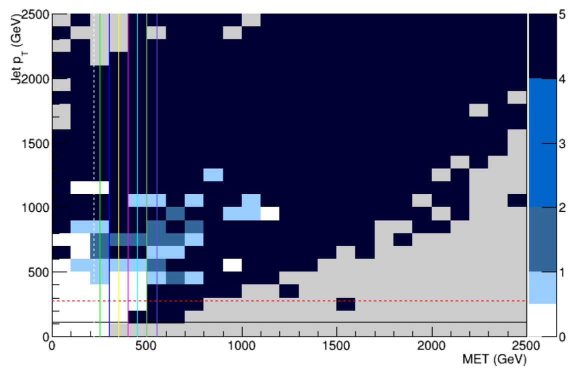
Synopsis

In this thesis a method for pMSSM SUSY searches in jets + E_T^{miss} final states using 8, 14 and 100 TeV Monte Carlo data with CMS analysis, was described. We described the theory behind those searches and the apparatus that made this analysis possible, the CMS detector as well as the LHC and the FCC. We described the event simulation, the Monte Carlo generators and the event selection.

In the case of SUSY neutralino WIMP, results are affected by the availability of multiple propagators and presence of other particles at small mass splitting, but still mono-jets add to the LHC sensitivity, notably in the kinematically difficult small ΔM region.

For 100 TeV physics we take analysis as performed at 8 TeV, no cut optimisation (yet), use SM background from CMS analysis and scale it up by appropriate factor to describe increase of rate in signal region of 100 TeV.





The analysis prospects seem to be considerably improved by a 100 TeV collider. Further studies with higher energy samples will make possible higher-precision measurements and so searches for new physics beyond the standard model in jet + missing E_T state will be enhanced and may lead to the identification of a new particle in the SUSY framework.

Future study plans could be developed along two main lines:

1. Assess collider energy & luminosity (1-10 ab^{-1}) requirements to achieve full coverage of pMSSM parameter space, when combined with DM search.
2. Characterize event features and explore detector requirements.

- Include more Susy search channels and optimize cuts: test the reach of 100 TeV.

- After setting exclusion limits, focus on observation and what could be learned at various energies and luminosities.

BIBLIOGRAPHY

Papers/Books

[1] M. Cahill-Rowley, R. Cotta2, A. Drlica-Wagner, S. Funk, J. Hewett, A. Ismail1, T. Rizzo1, and M. Wood, “Complementarity and Searches for Dark Matter in the pMSSM”, (2013), arXiv:1305.6921v2.

[2] Herbert Dreiner, Michael Kraemer, Jamie Tattersal, “Exploring QCD uncertainties when setting limits on compressed SUSY spectra”, (2012), arXiv:1211.4981v1.

[3] C. D. Froggatt, H. B. Nielsen, “Trying to understand the Standard Model parameters”, (2003), arXiv:hep-ph/0308144v2.

[4] W. N. Cottingham and D. A. Greenwood, “Standard Model Lagrangian (including neutrino mass terms) From *An Introduction to the Standard Model of Particle Physics, 2nd Edition*”, (2007), pdg.lbl.gov.

[5] Dr T Teubner “The Standard Model”, Lecture presented at the School for Experimental High Energy Physics Students Somerville College, Oxford, September 2009.

[6] Lectures by: Fernando Quevedo, Notes by: Sven Krippendorf, Oliver Schlotterer, “Cambridge Lectures on Supersymmetry and Extra Dimensions”, (2010), arXiv:1011.1491v1.

[7] Joseph Conlon, “A Bluffers’ Guide to Supersymmetry”, (2009).

[8] Eleni V. Ntomari, “SUSY Search in Photon(s) + jets + MET final state with the Jet-Gamma Balance method in CMS at the LHC and development of instrumentation for the LHC experiments”, (2012).

[9] M. Cahill-Rowley, J.L. Hewett, A. Ismail, T.G. Rizzo, “pMSSM Studies at the 7, 8 and 14 TeV LHC”, (2013), arXiv:1307.8444v2.

[10] C. Berger, J. Conley, R. Cotta, J. Gainer, J. Hewett, K. Howe, A. Ismail, M.-P. Le, T. Rizzo, M. Rowley, “SUSY w/o Prejudice: The pMSSM”, presentation, arXiv:0812.0980, 0903.4409, 0909.4088, 1007.5520,1009.2439, 1103.1697,1105.1199.

[11] Ian Altchison, “Supersymmetry in particle physics: An Elementary Introduction”, Cambridge.

[12] Matteo Cacciari, Gavin P. Salam, G. Soyez, “The anti-kt jet clustering algorithm”, (2008), arXiv:0802.1189v2.

[13] “CMS Physics Technical Design Report”, (2006), CERN/LHCC 2006-001.

[14] Robyn Lucas, “Searching for supersymmetry with compressed mass spectra at CMS”, Imperial College London & RAL IoP HEPP and APP Group Meeting, Royal Holloway 7-9 April 2014.

[15] Stephen P. Martin, “Compressed and Semi-natural Supersymmetry”, Northwest Terascale Research Projects Workshop on Natural Supersymmetry University of Oregon March 11, 2014.

[16] Mike Lamont, “Status of the LHC”, International Workshop on Discovery Physics at the LHC (Kruger2012), Journal of Physics: Conference Series **455** (2013) 012001

[17] Marco Battaglia, A Arbey, N Mahmoudi,”WIMPs and a 100 TeV collider”, BSM Opportunities at 100 TeV workshop, 10-11 february

[18] CMS Physics Analysis Summary, “Search for new Physics in monojet events in pp collisions at $\sqrt{s}$ = 8TeV.

[19] Alexandre Arbey, Marco Battaglia, Farvah Mahmoudi, “Complementarity of WIMP Sensitivity with direct SUSY, Monojet and Dark Matter Searches in the MSSM”, (2013), arXiv:1311.7641v1.

[20]Alexandre Arbey, Marco Battaglia, Farvah Mahmoudi, “Supersymmetry with Light Dark Matter confronting the recent CDMS and LHC Results”, (2013), arXiv:1308.2153v2.

[21] Eleni Mountricha “Αναζήτηση του μποζονίου Higgs του καθιερωμένου προτύπου με τον ανιχνευτή ATLAS στον LHC με αποτέλεσμα την παρατήρηση ενός νέου σωματιδίου συμβατού με το μποζόνιο Higgs”, 2014, Ntua

[22] “Future Circular Collider Study Hadron Collider Parameters” , Project Document identifier:FCC-ACC-SPC-0001

[23]Marco Battaglia, “LHC Physics Status and Perspectives”, CERN, 3-7 February 2014

[24] Marco Battaglia, A Arbey, N Mahmoudi, “Pmssm Studies at a 100 TeV Collider”, 1st Future Hadron Collider Workshop, CERN, 26-28 May 2014

Internet

[25] http://theastronomist.fieldofscience.com/2010/05/dark-matter-confronts-observations.html

[26] http://cms.web.cern.ch/news/superconducting-magnet

[27] http://profmattstrassler.com/articles-and-posts/some-speculative-theoretical-ideas-for-the-lhc/supersymmetry/supersymmetry-what-is-it/

[28] http://scienceblogs.com/startswithabang/2013/05/15/the-rise-and-fall-of-supersymmetry/

[29] https://inspirehep.net/record/1082990/plots

[30] http://www.particleadventure.org/other/history/smt.html

[31]https://twiki.cern.ch/twiki/bin/viewfile/Sandbox/Lecture?rev=1;filename=Philipp_Schieferdeckers_lecture.pdf

[32] http://www.nature.com/nature/journal/v448/n7151/box/nature06077_BX2.html

[33]http://iopscience.iop.org/1742-6596/455/1/012001/pdf/1742-6596_455_1_012001.pdf

[34]https://cp3.irmp.ucl.ac.be/projects/madgraph/

[35]http://www.hep.ph.ic.ac.uk/seminars/slides/2010/jarvis_20100302.pdf

[36]https://twiki.cern.ch/twiki/bin/view/Main/TunesAndCPM

[37] www.google.com

[38] www.wikipedia.org

[39] www.lhc-closer.es/1/3/1/0

[40] tlep.web.cern.ch/content/fccs

[41] www.joaopedroramos.com/2014/06/future-circular-colliders-a-100-km-accelerator/

Images

[42] www.lhc-closer.es

[43] https://briankoberlein.com/2014/08/19/known-dark-matter-isnt-enough/188434main_dkmatter_lg/

[44] http://lhc-machine-outreach.web.cern.ch/lhc-machine-outreach/lhc_in_pictures.htm

[45] http://scienceblogs.de/planeten/2009/02/13/wenn-da-vinci-teilchendetekoren-designt-hatte/

[46] http://www2.pv.infn.it/~vitulo/pict/

[47] http://twclark66.wordpress.com/2013/10/08/cern-shiva-ancient-fallen-angel-technology-the-illuminati/

[48] http://www.quantumdiaries.org/2013/06/26/does-dark-matter-really-exist/

[49] http://www.molwick.com/en/matter/070-elementary-particle.html

[50] http://scienceblogs.com/startswithabang/tag/supersymmetry/

[51] www.wikipedia.org