DARK MATTER, DARK ENERGY AND THE FUTURE OF PARTICLE PHYSICS*

L. Chevalier, M. Spiro

CEA-Saclay, Gif sur Yvette 91191, France

(Received January 29, 2015)

The existence of dark matter and dark energy would be evidence for physics beyond the Standard Model of particle physics and an essential ingredient to a Standard Model of cosmology. The main avenues to making progress in these topics are the search for Super-symmetry, the search for axions and the probing of the quantum vacuum. The crucial tools needed for this research program are future particle accelerators which are affordable and ultra high intensity lasers. The advancement of basic science is dependent on these developments.

DOI:10.5506/APhysPolB.46.729
PACS numbers: 01.10.Hx

1. Introduction

Nature is very well described by two theories: quantum physics which addresses the microscopic world of particles and forces, and general relativity which applies to the macroscopic world of the cosmos. The recent discovery of the Higgs particle at CERN, the European Laboratory for Particle Physics in Geneva, Switzerland, has provided us with the last missing piece and the keystone of the Standard Model. In this paper, we will first describe the large accelerator complex at CERN and the experiments which are conducted there. We will recall the main ingredients of the Standard Model and, in particular, the Higgs mechanism. We will then present the physics results obtained by the two experiments having discovered the Higgs particle. The Standard Model seems robust enough to make predictions at ultra high energies prevalent during the first moments of the Universe: the mechanism which gives rise to "inflation" could possibly be explained by the Higgs field. The connection between particle physics and cosmology will be discussed, in particular, when considering dark matter. Finally, we will

* Presented at the Zakopane Conference on Nuclear Physics "Extremes of the Nuclear Landscape", Zakopane, Poland, August 31–September 7, 2014.

discuss the remaining problems not solved by the Standard Model, mention some possible solutions, and present the current thinking about future accelerators and experiments for particle physics.

2. CERN

The CERN accelerator complex has provided experimenters with particle beams of higher and higher energies since 1954. A series of accelerators are linked together; each one increases the energy of particles, keeps them on their path, and feeds them to the next. The last element of the complex, the Large Hadron Collider (LHC) delivers two beams of colliding protons of record high energy (4 TeV) to the experiments. These are installed at each of the four colliding points along the 27 km long circular underground tunnel. The four experiments include ATLAS and CMS, general purpose experiments which have discovered the Higgs particle. Two other experiments are more specialized: ALICE studies collisions of heavy ions (iron, lead), and LHCb studies the matter–antimatter asymmetry present in interactions of B-particles, see figure 1.

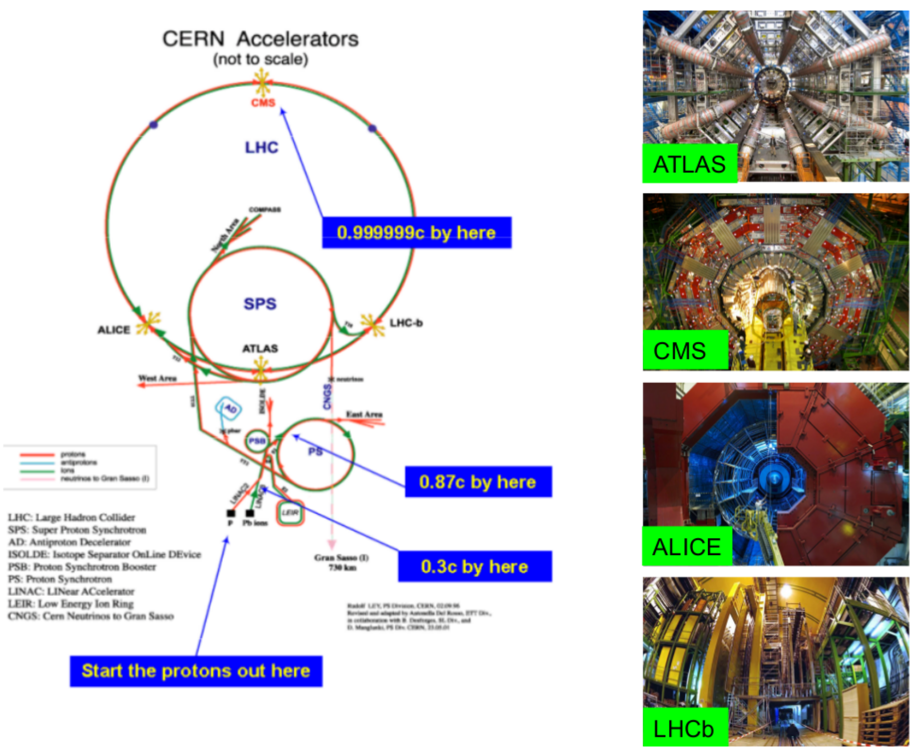

Fig. 1. The CERN accelerator complex and the four experiments at the LHC.

3. The Standard Model of particle physics

All the matter we know can be described by a theory called the Standard Model (SM). It was developed during the last 50 years and supplied with abundant experimental results over that period of time. Figure 2 (a) shows the building blocks of matter, from molecules to quarks. In figure 2 (b), the ingredients of the Standard Model are displayed:

— matter particles, quarks and leptons (fermions),

— force carriers (gauge bosons) are exchanged between matter particles,

— Higgs particle (scalar boson) the last missing piece.

Despite the SM's phenomenal success in describing the world of particles, it is nonetheless unable to account for the notions of dark matter and dark energy. A plausible explanation lies in the fact that the SM does not include the gravitational force which can be neglected in particle physics but not for the formation of large structures of matter in the Universe.

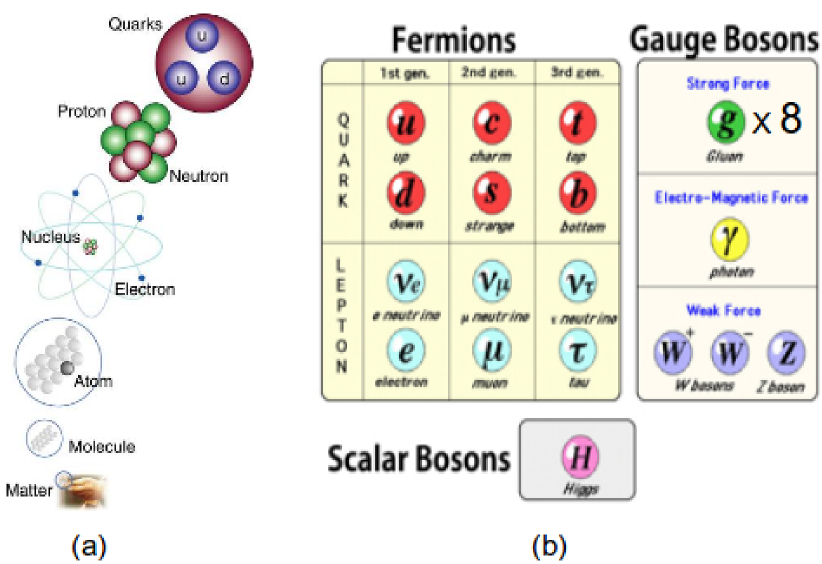

Fig. 2. (a) From matter to particles. (b) Schematic presentation of the fundamental particles of the Standard Model of particle physics.

3.1. The Higgs mechanism

The key element of the SM is the Higgs field and its associated boson. In 1964, Brout and Englert [1] and Higgs [2] independently published a solution to the problem of the massless photon and massive particles, mass not being an intrinsic property in the SM. With their "Higgs mechanism", the authors found a way to generate the mass of the gauge bosons and all other particles. The mechanism assumes the existence of a scalar field (the Higgs field) whose average value in the vacuum is not zero and spontaneously broken the local symmetry of the theory. The Lagrangian which described the elementary particles and their interactions stay invariants by a local transformation through this mechanism. Equation (1) is a simple description of all elementary particles and their interactions expressed in the Lagrangian

$$L = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\mathcal{D}\psi + i\psi_i y_{ij}\psi_j\phi + |D_\mu\phi|^2 - V(\phi) + \text{h.c.} \qquad (1)$$

The terms with an F or a D are associated with the gauge fields (photon, W, Z, gluon), the terms with a ψ include fermions, and the terms with a ϕ are associated with the Higgs boson.

3.2. Observation of the Higgs boson

A consequence of the Higgs mechanism is the existence of the Higgs boson but the SM does not predict its mass. The LHC was designed to reach a large energy scale, between 100 to 1000 GeV. Two general purpose experiments, ATLAS [4] and CMS [3], have been built to hunt for this particle. On July 4, 2012, CERN officially announce the observation of the Higgs boson at 5σ by these two experiments [3, 4]. Figure 3 shows the invariant mass into 4 leptons (ATLAS) and diphoton (CMS). The mass of the Higgs is around

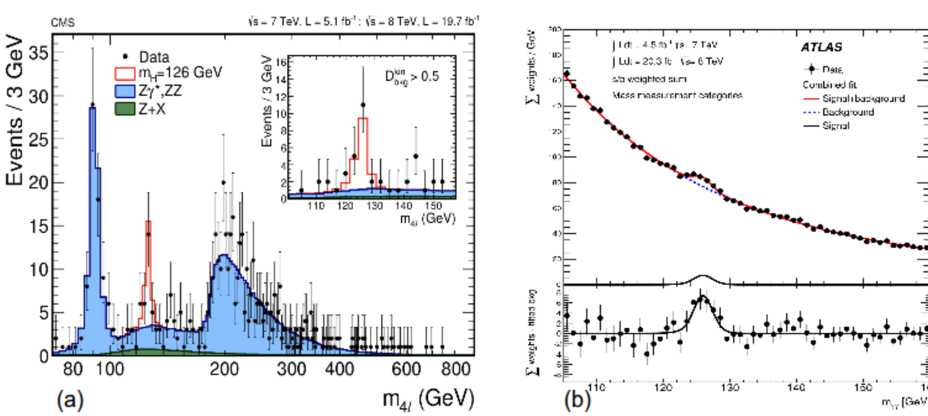

Fig. 3. (a) The distributions of the invariant mass of four leptons candidates after all selections for the combined 7 TeV and 8 TeV data sample by CMS. (b) The distributions of the invariant mass of diphoton candidates after all selections for the combined 7 TeV and 8 TeV data sample by ATLAS.

126 GeV [5, 6]. Such events recorded in ATLAS, where a Higgs boson decays into 4 leptons and in CMS, where a Higgs boson decays into diphoton are shown in figure 4.

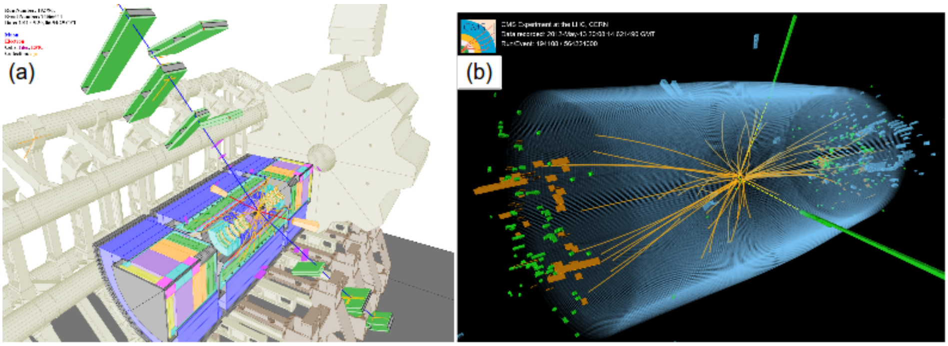

Fig. 4. (a) a candidate Higgs event decaying into four leptons seen by ATLAS. (b) a candidate Higgs decaying into diphoton by CMS.

4. Cosmology and the Standard Model

4.1. Inflation and Higgs field

In particle collisions at the LHC, we recreate the conditions which existed just one millionth of a millionth of a second after the beginning of the Universe. To account for the evolution of the Universe and its present structure, it must have been subject to a radical change just before that period. The presently favored model which describes this change is called Inflation [7, 8]. A possible solution to explaining Inflation, illustrated in figure 5, may be the existence of a scalar field, inducing a repulsive dark energy with an equation of state Pressure = − Density (see figure 5 (b)). The Higgs field could play this role [9] (with top and Higgs mass admitted currently).

4.2. Evidence from particle physics and cosmology for physics beyond the Standard Model

Despite years of experimental successes, one must keep in mind that the SM is an effective theory not applicable universally. There are unsolved problems which cannot be solved within the SM:

- Stabilisation of the Higgs mass against quantum loop corrections: the Higgs mass quantum loop corrections diverge quadratically with the cut-off energy. TeV supersymmetry would be an elegant solution to avoid excessive fine tuning.

— Nature of dark energy: Vacuum energy due to a scalar field or space-time curvature due to the cosmological constant or both?

— Nature of dark matter: supersymmetric particles, axions?

— Enigmatic neutrinos: very light masses compared to other elementary particles, Dirac or Majorana particles, possible existence of heavy or/and sterile species.

— Antimatter gone: neutrinos, study of ultra cold anti-hydrogen atoms (anti-gravity?).

— Random occurrences or fine tuning against new laws?

— Quantum gravity?

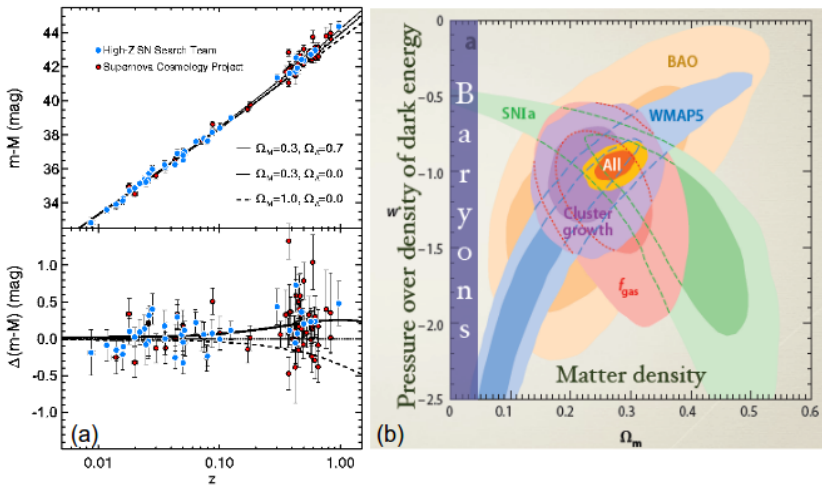

Fig. 5. (a) Evidence for dark energy from distant supernovae as observed by SNLS Collaboration. (b) Pressure/density of dark energy *vs.* dark matter.

5. Conclusion

The big questions for the future of cosmology, antiparticle physics, particle physics, need new instruments, new machines, new ideas and R&D for the long term future (laser, plasma acceleration which might be the long term future of the field?). Many experiments are planned today to explore the physics beyond the Standard Model — in cosmology, astrophysics and particle physics, with new satellite, new ground observatory and new linear or circular accelerators, testing neutrinos, searching wimps, axion. All these projects need to be thought globally with a long term strategy.

REFERENCES

[1] F. Englert, R. Brout, *Phys. Rev. Lett.* **13**, 321 (1964).
[2] P. Higgs, *Phys. Rev. Lett.* **13**, 508 (1964).
[3] S. Chatrchyan *et al.* [CMS Collaboration], *JINST* **3**, S08004 (2008).
[4] G. Aad *et al.* [ATLAS Collaboration], *JINST* **3**, S08003 (2008).
[5] CMS Collaboration, *Phys. Lett.* **B716**, 30 (2012).
[6] ATLAS Collaboration, *Phys. Lett.* **B716**, 1 (2012).
[7] A.H. Guth, *Phys. Rev.* **D23**, 347 (1981).
[8] A.D. Linde, *Phys. Lett.* **B108**, 389 (1982).
[9] I. Massina, A. Notari, *Phys. Rev.* **D85**, 123506 (2012).