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ASTROPARTICLE PHYSICS AND THE LHC*

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I discuss here some of the deeper connections between the physics studied at the LHC (electroweak phase transition, physics beyond the Standard Model, extra dimensions) and some of the most important issues in the field of particle astrophysics and cosmology (dark matter, primordial gravitational waves, black holes, ...).

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1. Introduction

The Standard Model, which we hope to fully probe with the long awaited discovery of the Higgs particle at the LHC, not only provides a complete theory of microscopic physics. It serves also as a basis for a complete picture of the Universe: as one goes back in time towards the big bang, the symmetries which rule the submicroscopic world (electroweak symmetry, supersymmetry, grand unification, ...) become apparent, towards an ultimate unification of all interactions, probably described by a string theory. Needless to say that this scenario may be disproved or modified at each stage of its experimental verification, the first one being provided by LHC. It remains, however, true that, until now, such a global scheme has been comforted by several decisive observations: the best illustration is provided by the inflation scenario, first devised in the context of grand unification, which has successfully predicted that our space is flat, *i.e.* that the energy density in the Universe is the critical energy density $\rho_{\rm c} \sim 10^{-26}\,{\rm kg\,m^{-3}}$.

Putting to test this general picture is particularly exciting at a time where, on one hand, LHC will confirm or infirm the Standard Model and, on the other hand, one expects decisive results from cosmology and particle astrophysics observations in the next decade. It is this rich interplay that I will try to explore in what follows, by taking some specific examples such as dark matter, gravitational waves, and extra spatial dimensions.

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1.1. Human made accelerators versus cosmic accelerators

At the time where more than a decade of a gigantic international effort is going to culminate in the first operations of LHC, it may be timely to consider as well the accelerators that nature is providing us with. Given the apparent diversity of violent cosmic phenomena observed, it may seem that there is a variety of possible types of acceleration sites. However, when one considers the spectrum of high energy cosmic rays, it is surprising to note that, contrary to the electromagnetic spectrum, the flux of cosmic rays is falling very regularly with energy, typically as E^{-3} over 12 decades of energy (see Fig. 1). This might point towards a single acceleration mechanism[1].

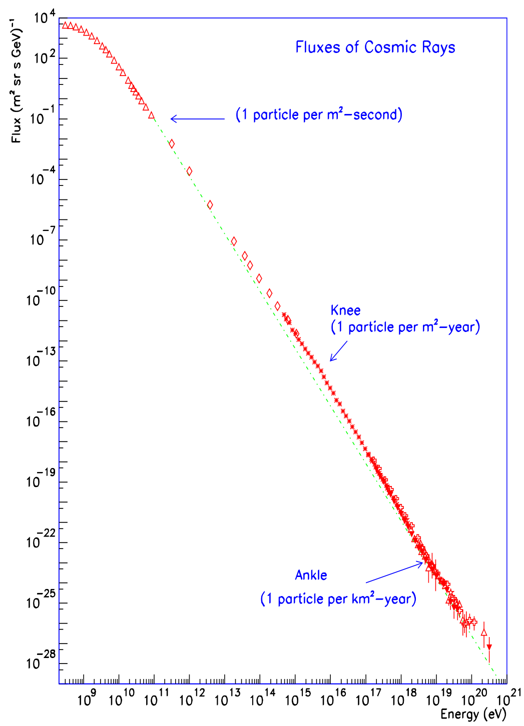


Fig. 1. Global energy spectrum of cosmic rays giving the differential flux in terms of energy.

[1] If one looks more closely, one identifies some structures: *(i)* the region centered around $10^{15.5}$ eV (the knee) where the spectrum steepens from $E^{-2.7}$ to $E^{-3.0}$, *(ii)* the spectrum deepens to $E^{-3.3}$ above $10^{17.7}$ eV, *(iii)* the spectrum flattens to $E^{-2.7}$ around $10^{18.5}$ eV (the ankle). The latter is widely believed to correspond to the transition between galactic and extragalactic origin.

A spectacular example is provided by Fig. 2 which gives the first image of the shell structure of a supernova remnant resolved with TeV γ rays (H.E.S.S. Collaboration): obviously, some constituents of these remants of a supernova explosion are accelerated beyond the TeV.

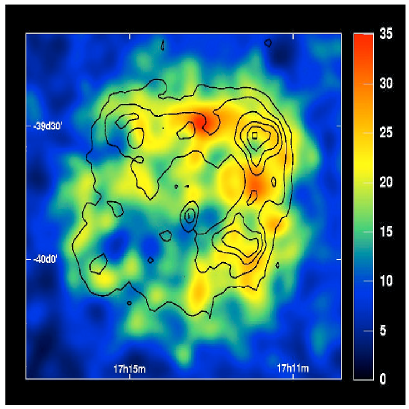


Fig. 2. γ-ray image of the supernova remnant RX J1713.7-3946 with the H.E.S.S. telescopes.

It is easy to convince oneself (see for example [3]) that one gets a power spectrum acceleration ($E^{-\gamma}$) if the particles have many encounters where they increase their energy. In the favoured scenario known as Fermi first order mechanism, the cosmic ray is accelerated through multiple encounters with a plane shock front (such as the one associated with a supernova remnant). More precisely, the average relative gain of energy at each encounter is first order in the velocity of the plasma flow V:

$$\left\langle \frac{\Delta E}{E} \right\rangle = \frac{4}{3} \frac{V}{c} \,. \tag{1}$$

It remains, however, to identify the accelerating sites. Hillas [2] has made use of a general criterion to draw the now classical Hillas diagram which identifies the possible acceleration sites in a plot $\log (B/1\,\mathrm{G})$ *versus* $\log (R/1\ \mathrm{km})$, as shown on Fig. 3. The Larmor radius of the particle $r_{\mathrm{L}} = E/(qBc)$ (in relativistic regime) may, with increasing energy E, become larger than the dimension R of the accelerating site. We thus have the condition ($q = Ze$)

$$E < E_{\max} = qBcR = Z \left(\frac{B}{1\ \mu\mathrm{G}} \right) \left(\frac{R}{1\ \mathrm{Mpc}} \right) 9.3 \times 10^{20} \mathrm{eV} \,. \tag{2}$$

Given species of cosmic particles accelerated at given energies are represented by diagonal lines (from top to bottom on the figure: protons of 10^{21} eV, protons of 10^{20} eV and iron nuclei of 10^{20} eV). It is striking from the Hillas diagram that very few sites appear able to generate protons of energy above 10^{20} eV (such as the ones searched for at the Pierre Auger Observatory), typically only active galactic nuclei, neutron stars and gamma ray bursts.

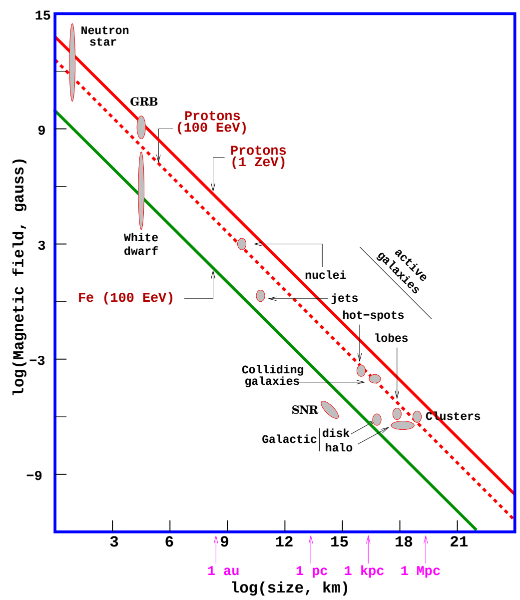


Fig. 3. Hillas diagram showing size and magnetic fields of potential acceleration sites. Sites below the diagonal lines cannot accelerate protons above 10^{21} eV, protons above 10^{21} eV and Fe nuclei above 10^{20} eV, respectively, from top to bottom.

1.2. Scalar fields in accelerators and in the Universe

The discovery of the Higgs particle at the LHC would be the first observation of a fundamental scalar particle. Besides providing a spectacular confirmation of the Standard Model, it would have far reaching consequences for the physics of the early universe. Indeed, scalar fields are to this date the best remedy to cure some of the most fundamental cosmological problems. For example, most models of inflation (proposed to cure the flatness, horizon and monopole problems) involve one or more scalar fields. Similarly, dark energy (invoked to understand the recent acceleration of the expansion of the Universe) is often attributed to a scalar component. And, models with extra spatial dimensions have a dynamics where the size of the compact dimensions is the value of a scalar field (a modulus).

One of the reason for invoking scalar fields in a cosmological context is that scalars tend to resist the gravitational clustering[2].

[2] More quantitatively, the speed of sound in a scalar-dominated universe is of the order of the speed of light: $c_s^2 = \delta p/\delta\rho \sim c^2$.

2. The dark side of LHC

It is well-known that models of particle physics provide candidates for dark matter, under the form of a Weakly Interacting Massive Particle (WIMP). The best known is the neutralino of supersymmetric models. I would like to stress here that the presence of a WIMP in a theory is deeply connected with the naturalness of the electroweak scale.

Let us start by recalling what is the naturalness problem (see for example [5]). As is well-known, the Higgs squared mass m_h^2 receives quadratically divergent corrections. In the context of an effective theory valid up to a cut-off scale Λ where a more fundamental theory takes over, Λ is the mass of the heavy degrees of freedom of the fundamental theory. Their contribution in loops, quadratic in their mass, destabilizes the Higgs mass and thus the electroweak scale ($m_h^2 \sim \lambda v^2$ where λ is the scalar self-coupling and $v \sim 1/(G_{\rm F}\sqrt{2})^{1/2} \sim 250\,{\rm GeV}$ is the Higgs vacuum expectation value), more precisely, we have at one loop

$$\delta m_h^2 = \frac{3m_t^2}{2\pi^2 v^2}\,\Lambda_t^2 - \frac{6M_W^2+3M_Z^2}{8\pi^2 v^2}\,\Lambda_g^2 - \frac{3m_h^2}{8\pi^2 v^2}\,\Lambda_h^2\,, \tag{3}$$

where for completeness we have assumed different cut-offs for the top loops (Λ_t), the gauge loops (Λ_g) and the scalar loops (Λ_h) [6]. The naturalness condition states that the order of magnitude of the Higgs mass is not destabilized by the radiative corrections *i.e.* $\left|\delta m_h^2\right| < m_h^2$. This translates into the conditions:

$$\Lambda_t > \sqrt{\frac{2}{3}}\,\frac{\pi v}{m_t} m_h \sim 3.5 m_h\ , \tag{4}$$

$$\Lambda_g > \frac{2\sqrt{2}\pi v}{\sqrt{6M_W^2+3M_Z^2}} m_h \sim 3.5 m_h\ , \tag{5}$$

$$\Lambda_h > \frac{2\sqrt{2}\pi v}{\sqrt{3}} m_h \sim 1.3\,{\rm TeV}\,. \tag{6}$$

Thus one should introduce new physics at a scale Λ_t or raise m_h to the 400 GeV range (in which case we have a theory that makes sense only up to the scale Λ_h). We will illustrate our argument with three examples: supersymmetry, extra dimensions, and the inert doublet model recently proposed by Barbieri, Hall and Rychkov [6]. In the first two cases, one introduces new physics at the scale Λ_t (supersymmetric particles or Kaluza–Klein modes). In the latter case, one introduces a second Higgs doublet H_2 which is not coupled to fermions (through a symmetry $H_2 \to -H_2$): this allows to raise the ordinary Higgs mass to the 400 GeV level.

Typically, these models require the presence of a symmetry that prevents direct coupling between the Standard Model (SM) fermions and the new fields that one has introduced: otherwise, such couplings introduce new mixing patterns incompatible with what is observed in flavor mixings (compatible with the Standard Model). This symmetry is usually a parity (*i.e.* a discrete symmetry) which is the low energy remnant of a continuous symmetry which operates at the level of the underlying fundamental theory: SM fermions are even under this parity whereas the new fields are odd. Among these new fields, the lightest odd-parity particle (we will refer to it as the LOP) is stable: it cannot decay into SM fermions because of the parity; it cannot decay into the new fields because it is the lightest. It is massive and weakly interacting. It thus provides an adequate candidate for a WIMP.

Let us take our examples in turn. In the case of supersymmetry, the parity operation is R-parity (which usually proceeds from a continuous R-symmetry broken by gaugino masses *i.e.* supersymmetry breaking). And the LOP is the Lightest Supersymmetric Particle, the famous LSP, the lightest neutralino in the simplest models.

In the case of extra dimensions, say a 5-dimensional model, the local symmetry is 5-dimensional Lorentz invariance. It ensures conservation of the Kaluza–Klein levels: if $A^{(n)}$ is the n-th Kaluza–Klein mode of the massless 5-dimensional field A (in other words, the 4-dimensional field with mass $m = n/R$, where R is the radius of the 5-th dimension), then in the reaction $A^{(n)} + B^{(p)} \to C^{(q)} + D^{(r)}$, we have $n + p = q + r$. At energies smaller than R^{-1}, this turns into a Kaluza–Klein parity $(-1)^n$. The LOP is then the lightest Kaluza–Klein mode, usually $B^{(1)}$, the first mode of the $U(1)_Y$ gauge boson [7].

In the final example of the inert doublet model [6], the parity operation is $H_2 \leftrightarrow -H_2$, the new fields are the inert scalars *i.e.* the components of this H_2 doublet and the LOP is the lightest inert scalar.

In all cases, one may compute the relic density (see for example [5]) in terms of the average annihilation cross-section times velocity $\langle\sigma_{\rm ann} v\rangle$:

$$\Omega_{\rm LOP} h_0^2 \sim \frac{10^9\,{\rm GeV}^{-1}}{g^{*1/2} M_{\rm P}}\,\frac{x_f}{\langle\sigma_{\rm ann} v\rangle}\,, \tag{7}$$

where g^* is the number of degrees of freedom at the time of decoupling, $x_f \sim 25$. Since the LOP mass is of the order of the electroweak mass $M_{\rm EW}$, we have $\langle\sigma_{\rm ann} v\rangle \sim \alpha_{\rm EW}/M_{\rm EW}^2$ and thus $\Omega_{\rm LOP} h_0^2$ is of order 10^{-1} to 1 to be compared with the WMAP result: $\Omega_{\rm DM} h_0^2 = 0.112 \pm 0.009$.

In realistic models, there is often the possibility that other odd-parity fields are almost degenerate in mass with the LOP. This leads to the possibility of co-annihilations, that is annihilations of the LOP against these almost degenerate fields. This leads to a modification of the relic density in the corresponding region of parameter space (a decrease in the supersymmetric case, an increase in the Kaluza—Klein case, as illustrated in Fig. 4).

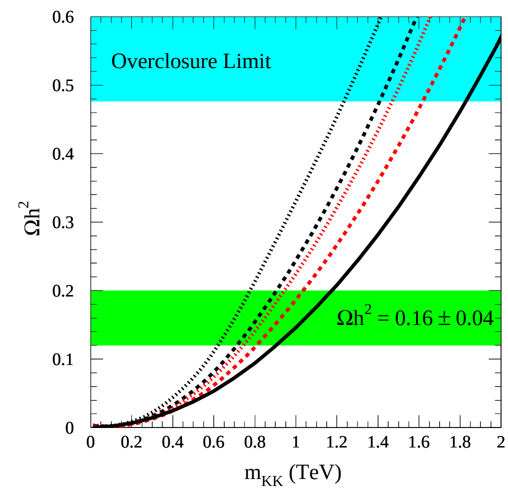
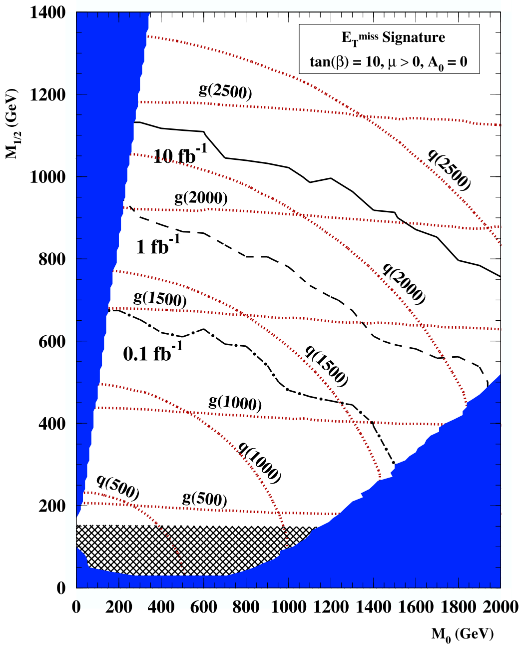


Fig. 4. Prediction for $\Omega_{B^{(1)}} h_0^2$. The solid line is the case for $B^{(1)}$ alone, and the dashed and dotted lines correspond to the case in which there are one (three) flavors of nearly degenerate $e_{\mathrm{R}}^{(1)}$. There are several curves associated with various values of the mass difference between the $e_{\mathrm{R}}^{(1)}$ and $B^{(1)}$ [7].

The search at LHC is based on the missing energy signal corresponding to the LOP (see left panel of Fig. 5). Since LOP are produced in pairs, they are difficult to reconstruct in all generality [10]. But, in the case of a specific model, one may be able to reconstruct the mass of the LSP as well as the relic density, as shown on Fig. 6 for the case of supersymmetry [11]. In parallel, one may search for the LOP through direct detection (see right panel of Fig. 5).

It should be stressed that one may be heading for surprises. In the context of indirect detection, one may cite the observation of INTEGRAL of an intense 511 keV line in the galactic bulge which implies the annihilation of some 10^{43} positrons per second. Such a large production of positrons seems difficult to account for with standard astrophysical sources. A possible alternative is the annihilation of a new form of light scalar dark matter [12]. Also, an excess found by EGRET in the galactic diffuse gamma ray flux [13] has been interpreted as resulting from dark matter annihilation, more specifically in a supersymmetric context, the annihilation of neutralinos in the 50 to 100 GeV mass range [14].



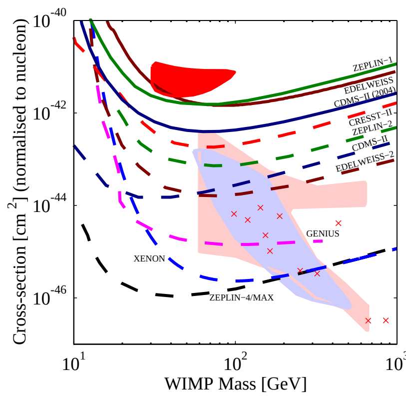


Fig. 5. Left: Contours in a parameter space of supersymmetry models for the discovery of the missing energy plus jets signature of new physics by the ATLAS experiment at the LHC. The three sets of contours correspond to levels of integrated luminosity at the LHC (in fb^{-1}), contours of constant squark mass, and contours of constant gluino mass [8]. Right: Sensitivities of some running a nd planned direct detection dark matter experiments to the spin-independent elastic scattering cross-section. Full curves correspond to limits from existing experiments, dashed curves to predicted sensitivities of future experiments. The full dark region corresponds to the 3 σ allowed region from the DAMA experiment. The full light regions correspond to predictions in the light of WMAP data. The crosses correspond to neutralino masses and cross-sections predicted for post-LEP benchmark CMSSM models [9].

3. The gravitational side of LHC

If the LHC is associated with tests of the three fundamental gauge interactions, its association with the gravitational interaction is not immediate. There are, however, remarkable connections. I will discuss two: how the space interferometer LISA may probe the electroweak phase transition; how the LHC may probe the formation and evaporation of black holes.

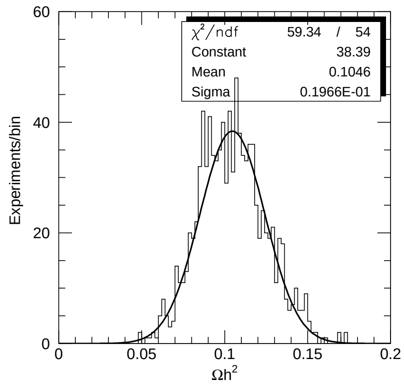


Fig. 6. Distribution of the predicted relic density $\Omega_\chi h_0^2$ for the SPA benchmark model incorporating the experimental errors (the uncertainty on the position of the $\tau\tau$ edge is assumed to be 5 GeV) [11].

3.1. Gravitational waves, LISA and electroweak phase transition

In a first order phase transition, bubbles of the true vacuum (corresponding to the global minimum of potential energy) nucleate inside the false vacuum (corresponding to a local minimum). The collision of bubbles, as well as the turbulent motions that it generates lead to the production of gravitational waves. What is of interest to us is that the gravitational waves thus produced during the electroweak phase transition fall precisely in the LISA frequency window $[10^{-4}, 1]$ Hz.

In order to see this, one first notes that gravitational waves produced at a temperature T are observed at a redshifted frequency[3]

$$f = 1.65 \times 10^{-7}\ \mathrm{Hz} \frac{1}{\varepsilon} \frac{T}{1\ \mathrm{GeV}} \frac{g^*}{100}\,, \tag{8}$$

where g^* is the number of degrees of freedom; when they are produced, the gravitational waves have a wavelength λ of the order of the horizon length H^{-1}: one writes $\lambda = \varepsilon H^{-1}$, $\varepsilon < 1$. We check that temperatures in the TeV range fall in the frequency range of LISA.

The prerequisite is, however, that the electroweak phase transition be of first order. This is presently not favored in the simplest models: in the Standard Model, this would require $m_h < 72$ GeV, which is excluded; in the MSSM, it requires a light stop, which is almost ruled out. It is, however,

[3] Note that gravitons produced after the Planck era never reach thermal equilibrium. Indeed, since the gravitational coupling is Newton's constant $G_{\mathrm{N}} \equiv m_{\mathrm{P}}^{-2}$, the interaction rate at temperature T is, on dimensional grounds, $\Gamma \sim G_{\mathrm{N}}^2 T^5 = T^5 m_{\mathrm{P}}^{-4}$. The expansion rate is, in a radiation-dominated universe, $H \sim T^2 m_{\mathrm{P}}^{-1}$. Hence, for $T < m_{\mathrm{P}}$, we have $\Gamma < H$.

possible to recover a strong first order phase transition by including non-renormalizable terms of order H^6 in the Higgs potential (such terms appear in effective theories and may be significant if the scale of the underlying theory is just above the TeV scale). If it is found out at LHC that the phase transition is indeed first order, then LISA would provide a remarkable complementary means of testing the phase transition with gravitational waves!

Even if the electroweak phase transition is not first order, we know that the phase transition associated with baryogenesis must be so: one of the Sakharov conditions for baryon number generation is to be out of equilibrium, which favors first order phase transitions over second order ones. The corresponding frequency at which one expects gravitational waves depends mainly on the scale at which the corresponding phase transition occurs, as can be seen from 8.

3.2. Black hole physics and the LHC

The proposal that there exists some large extra special dimensions allows to consider the (remote) possibility to produce mini black holes at LHC, thus giving a unique possibility to study the physics of black holes (production, Hawking radiation, ...). We recall that, in theories with n extra spatial dimensions of same radius R (to simplify), the 4-dimensional Planck constant is given in terms of the more fundamental ($D = 4 + n$)-dimensional gravitational constant as

$$m_{\mathrm{P}}^2 = M_{\mathrm{D}}^{2+n} R^n \,, \tag{9}$$

Taking R large enough allows to decrease M_{D} to the TeV range. This usually occurs for values of R which have been probed by non-gravitational interactions at colliders. Since the search for extra dimensions at high energy colliders has been negative, this means that, if they exist, these extra dimensions should only be probed by gravitational interactions[4]. It turns out that string theory provides models of spacetime where non-gravitational interactions are localized on dynamical surfaces known as p-branes (p stands for the number of space dimensions of the brane). In the case of a 3-brane, the non-gravitational interactions are localized in the 3-dimensional space of the brane; only gravitational interactions probe the extra dimensions.

In the case where M_{D} is in the TeV range, we are in the lucky situation where LHC is going to experimentally probe the gravitational realm. This means quite a dramatic departure from Standard phenomenology. In particular, collisions may lead to a such a localization of energy that black

[4] The law of gravitational attraction (in r^{-2} as is characteristic of 3 space dimensions) has been probed only down to the mm to μm range.

holes are formed, just as in the primordial universe where energy fluctuations generate primordial black holes. More precisely, the relevant scale for a black hole of mass $M_{\rm H}$ is the Schwarzschild radius:

$$r_{\rm S} \sim \frac{1}{M_{\rm D}} \left(\frac{M_{\rm BH}}{M_{\rm D}}\right)^{1/1+n} . \tag{10}$$

A black hole forms in a 2-particle collision if the impact parameter is smaller than $r_{\rm S}$. The cross section is

$$\sigma = \pi r_{\rm S}^2 . \tag{11}$$

Just as primordial black holes eventually disappear because of Hawking evaporation, the black holes produced evaporate rapidly. Hawking radiation is characterized by the temperature:

$$T_{\rm H} = \frac{n+1}{4\pi r_{\rm S}} . \tag{12}$$

The energy loss scales like $dE/dt \propto T_{\rm H}^{4+n}$. Thus the black hole lifetime is typically

$$\tau_{\rm BH} \sim \frac{1}{M_{\rm D}} \left(\frac{M_{\rm BH}}{M_{\rm D}}\right)^{3+n/1+n} . \tag{13}$$

Black holes decay visibly to SM particles with: *(i)* a large multiplicity ($N \sim M_{\rm BH}/(2T_{\rm H})$), *(ii)* a large total transverse energy, *(iii)* a characteristic ratio of hadronic to leptonic activity of 5:1.

For what concerns us here, there is a complementarity of searches at colliders (LHC) and in high energy cosmic rays. In the Pierre Auger Observatory, one is precisely looking for the highest energy cosmic rays. It is thus of interest to try to search for signals of black hole production. More precisely, in order to overcome the QCD background, one is looking for such a production by high energy neutrinos (found more frequently in horizontal showers since those are the ones that travel through more atmosphere). Fig. 7 gives, for $n = 6$ extra dimensions, the discovery reach for the LHC in the plane $(M_{\rm D}, x_{\rm min})$, to be compared with the region of parameter space excluded at 95% C.L. if no neutrino shower induced by black holes is observed at Pierre Auger observatory in 5 years. The parameter $x_{\rm min}$ defines the smallest black hole mass $(M_{\rm BH})_{\rm min} \equiv x_{\rm min} M_{\rm D}$ for which we can trust the semi-classical approximation.

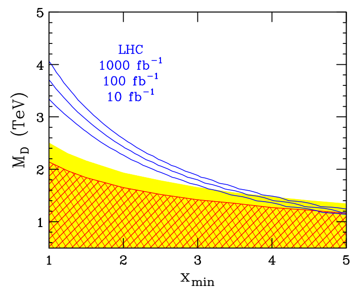


Fig. 7. Comparison of the regions covered by LHC (with respective integrated luminosities 1000, 100 and 10 fb^{-1}) and the Pierre Auger Observatory in 5 years in the plane $(M_{\mathrm{D}}, x_{\mathrm{min}})$ (see text) [15].

4. Conclusion

The experimental checklist of the decade 2008-2017 might read as such:

- light Higgs, heavy Higgs or no Higgs observed,
- observation or absence of supersymmetric partners,
- observation or absence of Kaluza–Klein modes, of microscopic black holes,
- direct detection of WIMPs, or limit on its mass; indirect signal of WIMP annihilation or no clear signal; detection of other kinds of dark matter; astrophysical observations pointing towards another solution of the dark matter problem (MOND, ...),
- detection or not of a gravitational background in CMB experiments; detection or not of a stochastic background of primordial gravitational waves at space or ground interferometers,

and so on[5]. There exists a standard scenario which has been alluded to in the introduction (supersymmetric version of the SM as a low energy effective theory of a string/brane theory valid at the Planck scale). In this scenario, one expects a light Higgs, supersymmetric partners, no low energy Kaluza–Klein modes; one is likely to detect a WIMP, directly and indirectly, but no background of gravitational waves. With such a variety of data expected, there are however, many ways to deviate from such a scenario. This is why the decade that we are entering is an exciting time for the field of particle and astroparticle physics, LHC being the lead actor in the play that is about to begin.

[5] I have not included here dark energy related questions since I think they are rather decorrelated from collider experiments.

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