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LHC, Astrophysics and Cosmology

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Abstract

In this paper we discuss the impact on cosmology of recent results obtained by the LHC (Large Hadron Collider) experiments in the 2011-2012 runs, respectively at $\sqrt{s} = 7$ and 8 TeV. The capital achievement of LHC in this period has been the discovery of a spin-0 particle with mass 126 GeV/c^2, very similar to the Higgs boson of the Standard Model of Particle Physics. Less exciting, but not less important, negative results of searches for Supersymmetric particles or other exotica in direct production or rare decays are discussed in connection with particles and V.H.E. astronomy searches for Dark Matter.

Keywords: HEP Physics - cosmology - dark matter - dark energy.

1 Introduction

On July 4th 2012 the ATLAS[1] and CMS[2] Collaboration has announced the discovery of a new massive boson, which subsequentely was shown to look like the Standard Model Higgs bosonn. This was possible only after the 2012 runs of LHC at $\sqrt{s} = 8$ TeV. The two central experiment ATLAS & CMS have collected during 2011 and 2012 an integrated luminosity of ≈ 40 fb^{-1}. Several reason support the general belief that this boson could be the long expected Higgs boson [3], in particular

- It is definitively a boson with spin $\neq 1$ because decays in γ-γ channel ($H \to \gamma\gamma$). Quantum numbers $J^P = 0^+$,predicted by SM are strongly favored [4, 5] ;
- The PDG averaged mass is [6] : $M_H = 125.9 \pm 0.4(stat) \pm 0.4(\text{syst})$ GeV/c^2 consistent with EW precision measurements that requires $M_H = 102^{-24}_{-20}$ GeV/c^2 [7];
- Production cross section $\sigma_{pp\to H}$ agrees well inside the errors to the prediction of SM, that are affected by the uncertainty of 15%.
- Branching ratios to leptons, hadrons and gauge bosons are close enough to the SM predictions, with some tension in the channels $H \to \gamma\gamma$ ($\mu \simeq 2$) and $H \to bb$ ($\mu < 1$) for ATLAS data.
- Angular distribution is slightly in favor of spin 1, but only with more data this could be confirmed, analyzing the decay $H \to WW \to 2\ell 2\nu$.

At present, from February 2013 to November 2014, LHC is engaged in the first Long Shutdown aimed at the consolidation of the accelerator for running at the full design c.m.s. energy $\sqrt{s} = 14$ TeV. After this point, hopefully, Supersymmetry (SUSY) hunting will be open.

2 Supersymmetric Higgs

From the Supersymmetry theory is expected a relation between the half-integer spin fermions to the integer spin bosons, introduced initially on a purely mathematical ground [8]. The real appeal of this theoretical framework is that it incorporates not only the three gauge fields of the SM but also gravity [9, 10].

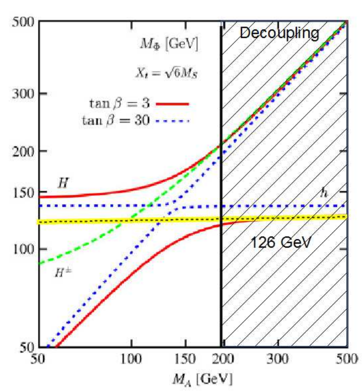

Figure 1: MSSM model Higgs masses, the hatched area indicates the decoupling SUSY parameters space $m_A > 2M_Z$ (Adapted from Ref. [11]).

The particle spectrum of SUSY is extremely more crowded then the particle spectrum of SM. The present Universe is constituted by matter fermions and force fields mediated by bosons, no SUSY particles has been identified. It means that at a time $M_{Pl}^{-1} \leq t_{SUSY} \leq t_{EW}$ the Supersymmetry has been broken, in the sense that masses of SUSY partners became $\tilde{m}_{SUSY} \gg m_{SM}$. For this reason the lightest neutral supersymmetric particles are excellent candidates for dark matter [12].

The Higgs sector of SUSY theories is more complicated then in the SM. In the Minimal Supersymmetric extension of the SM, the Higgs sector is schematically:

$$\begin{pmatrix} H_u^0 \\ H^- \end{pmatrix} \quad \begin{pmatrix} H^+ \\ H_d^0 \end{pmatrix} \quad A^0 \tag{1}$$

namely a CP-odd pseudo scalar field A^0 and two doublets of scalar CP-even fields. whose neutral components have V.E.V., assumed to be $\langle H_u^0 \rangle = v_u$ and $\langle H_d^0 \rangle = v_d$ normalized to the value of Fermi constant $v_u^2 + v_d^2 = \sqrt{2} G_F$, with a ratio parameterized as $v_u / v_d = \tan\beta$. The physical fields detectable at accelerator h and H are mixed states of the neutral components of the doublets with masses $m_h < m_H$, although it was never discarded the possibility to detect also the other states, especially the charged ones.

If the mass of the pseudo-scalar m_A and $\tan\beta$ are taken as free parameters, the masses of the other four are fixed by the equations [13]:

$$\begin{aligned} m_{H^\pm}^2 &= m_A^2 + m_z^2 + \Delta m_{H^\pm}^2 \\ m_{h,H}^2 &= \frac{1}{2}\left(m_A^2 + m_Z^2\right) + \\ &\mp \sqrt{m_A^2 + m_Z^2 - \left(2 m_A m_Z \cos 2\beta\right)^2} + \Delta m_{h,H}^2 \end{aligned} \tag{2}$$

where $\Delta m_{H^\pm}^2$ and $\Delta m_{h,H}^2$ are the appropriated radiative corrections.

Fig. 1 shows the predictions of Eq. (2) in which is clear that the light SUSY Higgs mass saturates in the limit of decoupling $m_A \gg m_Z$ to $m_h \to m_Z |\cos 2\beta| + \Delta m_h^2$. The actual value of this limit, that depends strongly from the radiative corrections, is estimated to be in the range 130-150 GeV/c^2 [15, 16]. Fig. (2) from CMS [14] shows the result of the search of Higgs like particles decaying to pairs of gauge bosons, giving evidence that a SUSY high mass Higgs with mass lower than 700 GeV/c^2 is excluded. In facts the total production cross sections for the neutral SUSY Higgs is essentially the same of that expected in SM, but the dominant decay channels are $H \to (W^\pm, Z)$ with vector bosons in final state [11]. Fig. 2 shows the results of the CMS search of Higgs with $m_H > 200$ GeV/c^2 [14], that clearly excludes any mass $m_H \leq 600$ GeV/c^2 at 95% CL.

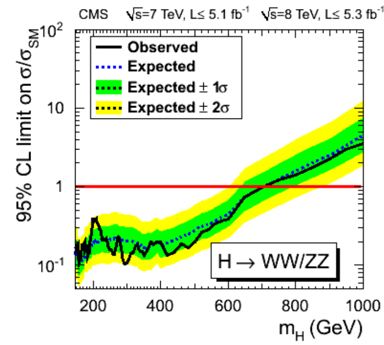

Figure 2: Observed (solid line) and expected (dashed line) 95% CL upper limit on the ratio of the product of production cross section and branching ratio to the SM expectation for the Higgs boson (from Ref. [14]).

3 Higgs Boson in Cosmology

Inflation is nowadays a well accepted paradigm in cosmology. The only problems is what is physically the "inflaton". The original field considered as inflaton by Guth was actually the Higgs field [17], whose potential $V(\phi) = \frac{1}{4}\lambda\phi^4$ can naturally produce inflation if λ is small [18]. but this model predicts that the amplitude of density perturbation is $\delta\rho/\rho \sim \sqrt{\lambda}$. Therefore, in order to explain the observed $\delta\rho/\rho \sim 10^{-4}$, it should be $\lambda \sim 10^{-10}$, absolutely irreconcilable with an Higgs mass $m_H = \sqrt{2\lambda} v$, with $v = \left(\sqrt{2} G_F\right)^{-\frac{1}{2}}$ given by the strengths of the weak interactions. A solution could be a coupling of the Higgs field with the gravity [19], with a Lagrangian density

$$\mathcal{L}_{GR+SM} = \left(\frac{1}{2} M_{Pl}^2 + \xi\phi^2\right)\mathcal{R} + \frac{1}{2}\left|\partial_\mu \phi\right|^2 - V_{SM}(\phi) \tag{3}$$

where $M_{Pl} = (8\pi G_N)^{-1}$ is the reduced Planck mass, $\mathcal{R}$ the Ricci scalar, $V_{SM}(\phi) = \frac{1}{4}\lambda\left(\phi^2 - v^2\right)^2$ is the potential of the SM Higgs field and $\xi \neq 0$ its coupling to the gravity. Applying a rescaling of the metric $\tilde{g}^{\mu\nu} = \left(1 + 2\xi\phi^2/M_{Pl}^2\right)^{-1} g^{\mu\nu}$ [20] the potential of the field becomes

$$V_{eff}(\phi) = \frac{\frac{\lambda}{4}\left(\phi^2 - v^2\right)^2}{\left(1 + \frac{2\xi\phi^2}{M_{Pl}^2}\right)^2} \tag{4}$$

For the present small value of the Higgs field $\phi \ll M_{Pl}/\sqrt{2\xi}$ we have $\widetilde{V}(\phi) \simeq$V$(\phi)$, while for $\phi \gtrsim M_{Pl}/\sqrt{2\xi}$ the effective potential of Eq. (4), has a plateau that allows a successful slow-roll inflation. A first constraint on the coupling ξ is obtained from the amount of expansion of the Universe reached at the end of the inflationary phase. The number of e-folding, defined from $a(t_f) = a(t_i)\exp(-N)$ is predicted to be, using the slow-roll approximation [21], the Higgs field that varies in the expansion from an initial value ϕ_i to a final one $\phi_f \approx M_{Pl}/\sqrt{2\xi}$. The ratio is $\phi_i/\phi_f \approx \sqrt{8N/3}$ for $\xi \gg 1$. The amplitude of anisotropy depends on the mass of the Higgs boson, which fixes the value of the quartic coupling λ. The predicted scalar amplitude is $\delta\rho/\rho \approx \frac{N}{\pi\sqrt{18}}\sqrt{\lambda}/\xi$.

In order to justify the observed $\delta\rho/\rho \approx 10^{-4}$ a strong coupling $\xi \gtrsim 10^4$ is required. More refined calculations, including the non negligible radiative corrections to the Higgs potential due the coupling with heavy quarks [22, 23], show that m_H =126 GeV/c^2 is compatible with the spectral index of the power law for scalar perturbations $n_s = 0.962 \pm 0.002$ and the upper limit for the tensor-to-scalar ratio $r < 0.11$ (95% C.L.) measured by Planck [24].

Theoretical studies have confirmed that SUSY inflation is possible, in many different scenarios [25] either with minimal [26] or non-minimal coupling [27]. As noted by Linde [28] we can expect that due to the rich structure of the Higgs sector in SUSY theories, the effective potential of the superfield will show several minima, interleaved by maxima where $V'(\Phi) \ll V(\Phi)$, suitable for slow-roll inflation in the minimal coupling case $\xi = 0$. The case of a non minimal coupling $\xi > 0$, is shown in Ref. [27]. In a recent paper Nakayama & Takahashi [29] examined a SUSY model in which the lightest neutral Higgs boson could be identified with the SM-like one.

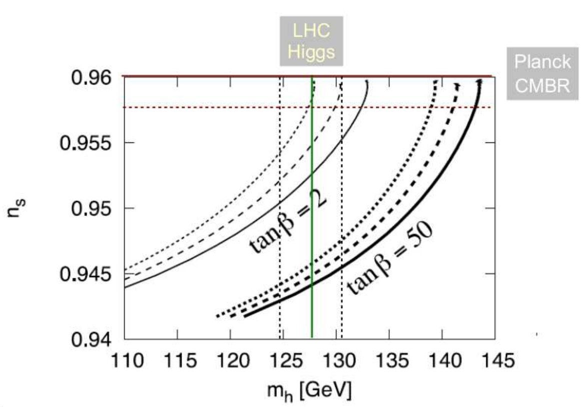

Figure 3: Planck best-fit value of the spectral index and $m_h = 126$ GeV/c^2 from LHC fits very well MSSM inflaton model with small β (adapted from Ref. [29]).

4 Dark Matter

Cosmological non-baryonic dark matter with $\Omega_{DM}h^2 = 0.120 \pm 0.003(\mathrm{stat}) \pm 0.03(\mathrm{syst})$ has been estimated by Planck [30].

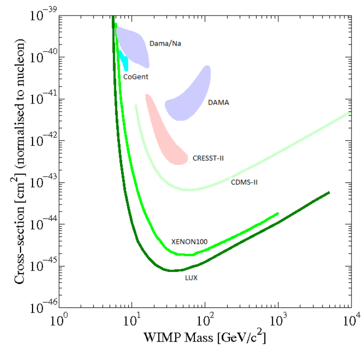

Figure 4: Status of experimental direct search for WIMPs. The 68% CL region of possible positive detection are shown as filled area, while solid line represents 95% CL upper limits.

The type of relics that can supply this density at "freeze out" should have a thermally averaged rate of annihilation at "*freeze-out*" ($T_f \simeq m_{DM}/20$) :

$$\langle\sigma_A v\rangle_{T_f} \simeq 2 \times 10^{-26}\left(\frac{0.12}{\Omega_{DM}h^2}\right)\ cm^3 s^{-1} \qquad (5)$$

for $m_{DM} > 10$ GeV/c^2 [31]. It is worth noticing that the DM particles will be non-relativistic at freeze-out with $\beta \approx 4 \times 10^{-2}$, that is dubbed "Cold Dark Matter" (CDM). In addition the annihilation cross section that produces a rate comparable to the one of Eq. (5) is close to the weak scale $\sigma \approx G_F^2 m^2/16\pi$ for an hypothetical Weakly Interacting Massive Particle (WIMP), not existing in the SM.

The density of WIMP's in the solar neighborhood is estimated to be $\rho_{local}^{DM} = 0.39 \pm 0.03$ GeV/cm^3 and is flowing with a velocity ≈ 200 km/s. WIMP of mass 10 GeV/c^2, scattering against nucleons with a cross section $\sigma^{SI} \approx 10^{-40}$ cm^2, give 0.5 interactions/100 kg-day in a suitable detector[32]. The present controversial status of the direct searches is summarized in Fig. 4. This figure shows that the claims for positive detections [33, 34, 35] seem to cluster around a "low" mass value $m_{WIMP} \approx 10$ GeV/c^2 and a "high" elastic scattering cross section $\sigma^{SI} \approx 0.5 \times 10^{-40}$ cm^2/nucleon. Particularly tantalizing is the claimed observation of a yearly modulation of the detected signal [36], that could be a clear signature of the association of the detected particles with the galactic halo. But unfortunately Fig. 4 shows also that all but DAMA/Libra experiments do not show evidence of a similar signal, even if it should be well inside their sensitivity [37].

Indirect searches for DM are based on the detection of radiation produced in the annihilation and decay of relic WIMP's. Neutrino, gamma and antimatter astronomy are the basic tools of this search. From the Eq. 5 it is possible to derive an order of magnitude of the annihilation rate. It is worth to stress however that this estimate is an average of $\sigma_A v$ over the thermal velocity distribution at $T_f \gg 1$ GeV, while annihilations in a galactic environment will take place at much lower temperature. Moreover the source function of the astrophysical radiation will be $Q_k = \langle\sigma_A v\rangle \mathcal{B}_k \rho^2/m^2$ in photons cm^{-3}s^{-1} being $\mathcal{B}_k$ the inclusive branching ratio to the SM particle k, ρ and m respectively the local energy in GeV/c^2 cm^{-3} and the mass of the WIMP in GeV/c^2.

The spectrum of the γ-rays (or neutrinos) produced is composed by a continuum, extending up to the kynematical limit $E_\gamma \lesssim m$ and several monochromatic lines, each corresponding to a two body final states. The latter very attractive signature was proposed since 1988 by the Compton Gamma Ray Obsevatory [38]. In facts the first indication of a possible DM component in the diffuse galactic γ-rays from the galactic plane was given by the EGRET spark-chamber calorimeter [39], that found a significant excess on the galactic plane for $E_\gamma \geq 1$ GeV. The poor energy resolution of the EGRET calorimeter for hard γ-rays did not allowed any search for lines, but the intensity and distribution in the galactic frame of this radiation was found to be close to what expected for annihilation or decay of particles with mass in the range 50-100 GeV/c^2. In the case of WIMP's the γ inclusive annihilation rate is $\sigma_\gamma v \approx 10^{-26}$ cm^{3}s^{-1} [40].

The diffuse $\gamma-$rays emission from selected regions on the galactic plane has been measured with high energy resolution ($\sim 8\%$ in the range 1-300 GeV) by the CsI scintillator tracker- calorimeter of the Fermi-LAT instrument [41, 42]. The observed γ-rays spectrum is fitted with a single power law $E_\gamma^{-\alpha}$ for $E_\gamma \geq 12.6$ GeV, with $\alpha = 2.44 \pm 0.01$. Narrow lines of width compatible with the instrumental resolution have been searched using background+signal max-likelihood method. Fermi-LAT has not detected any statistically significant γ-ray line in the range from 5 to 300 GeV. An upper limit of the rates $\sigma_{2\gamma} v \leq 0.02 - 3.6 \times 10^{-27}$ cm^{3}s^{-1}, for WIMP's masses $5 \leq m \leq 200$ GeV/c^2, can be estimated from the flux upper limit at 95% C.L., applying the most optimistic galactic halo WIMP density profile from N-body simulations [43]. If a simple isothermal profile is assumed, the limit increases by 50%. This limit starts to be close to the predicted rate for SUSY DM candidates [44]. Unfortunately with this new data the claimed line at ≈130 GeV [45, 46] corresponding to $\sigma_{2\gamma} v \approx (1.1 \pm 0.5) \times 10^{-27}$ $cm^3 s^{-1}$ has not gained statistical significance ($\approx 3.3\sigma$).

An excess of positrons in the energy range $4 \leq E_e \leq 50$ GeV in cosmic rays, was discovered by a balloon-borne instrument launched in 1974 from Palestine, TX, in the heroic age of astroparticle physics [47][1]. It is remarkable that after about 40 years we have a high precision mesurement of the positron flux covering the range $0.5 \leq E_e \leq 350$ GeV from the 8.5 tons particle's spectrometer AMS-02 installed on the International Space Station [48]. The AMS-2 positron fraction vs. energy is first decreasing from 8.42% at 1 GeV to a minimum of 5.1% at 7 GeV then increasing up to ≃ 15% at 260 GeV. An excellent fit to this behaviour can be obtained either from pair emission by pulsar[49] or WIMPs annihilation [50]. In the latter case the mass of the WIMP should be in the range 750 GeV $\leq m \leq$ 1.5 TeV and inclusive annihilation rate $10^{-23} \leq \sigma_{e^+} v \leq 10^{-22}$ cm^{3}s^{-1}[52] significantly larger then the one of Eq. 5 Ref. [51]. The discriminating observation is definitively the detection of an excess in the antiproton flux, because in the annihilation to lepton pair and quarks one is strongly correlated. Up to now the PAMELA data [53] do not support any deviation from cosmic rays secondary production. Alternatively, by assuming that the excess of positrons is all due to astrophysical sources, Ref. [54] finds an upper limit to the annihilation rate that varies from 10^{-26} cm^{3}s^{-1} at $m = 10$ GeV/c^2 to 10^{-23} cm^{3}s^{-1} at $m = 1$ TeV/c^2, assuming that the dominant annihilation channel is $\mu^+\mu^-$.

5 LHC Search for Dark Matter Candidates

The lower mass state of the four spin $\frac{1}{2}$ neutralinos $\chi_1^0, \chi_2^0, \chi_3^0, \chi_4^0$, predicted in R-parity conserving SUSY models, is a good candidate for the role of WIMP. Other candidates do exists, as for example the superpartner of the graviton, the spin $\frac{3}{2}$ gravitino, that would be a superWIMP because it couples with ordinary matter only via the gravitational interaction, making direct DM detection practically impossible [55].

At hadronic colliders such as LHC only WIMPs that couple with protons, such as the neutralino, can be directly produced. The production of neutralino candidate can be tested, quasi-model independently, using the process:

$$pp \to (\chi_1^0 \bar{\chi}_1^0) + X \tag{6}$$

where X can be one (or more) hadronic jet, hard leptons or photons, while the neutralino pair (if R-parity is conserved) do not interact with the detector, but uppears in the kinematics of the event as missing trans-

[1] Note that the young member of this SLAC team will be the Nobel laureate of 2006 for COBE.

verse energy E_T^{miss} [56]. The dominant SM physical background for the reaction (6) is $pp \to W^{\pm}/Z^0 \to \ell\ell$, where the leptons are neutrinos or are not detected, that can be subtracted and/or reduced by optimized kinematical cuts.

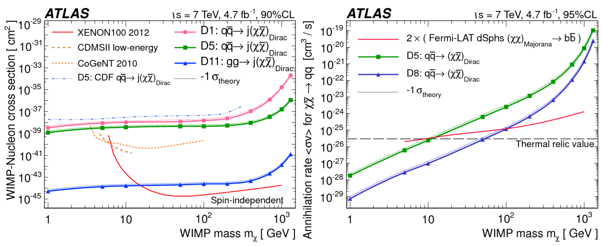

Figure 5: Upper limits on σ^{SI} (left) and $\sigma_{2\gamma}$v (right) inferred from monojet+E_T^{miss} ATLAS data [57].

Considering the simpler case that X is a single hadronic jet the cross section for neutralino pairs production, that contributes to process (6), will be $\sigma_{QQ\to\chi\bar{\chi}} \approx \alpha_s g_\chi^2 g_Q^2 p_T^{jet}/M_*^4$ where $\alpha_s = 0.64$ is the QCD constant, g_χ, g_Q the SUSY couplings being $Q = q, \bar{q}$ or g and finally $M_* \gg p_T$ is suppressing mass scale. The detection of a number of events significantly larger the the calculated SM background would be strong indication of a WIMP candidate, whose mass could be inferred from the missing energy distribution. In addition a comparison with direct DM search experiments, discussed in the previous section, would be possible because the scattering cross section, from the same coupling, is predicted to be $\sigma^{SI} \approx g_\chi^2 g_q^2 \mu^2/M_*^4$ being μ the reduced mass of the WIMP-nucleon system [58]. Moreover the same suppression factor M_*^{-4} enters, together with phase space factor depending only from the masses, in the annihilation rate of the neutralino (see for example Eq. (10) and (11) of Ref. [59]) that allows comparison with the DM relic density and the indirect searches. Fig. (5) shows the potentiality of this type of searches at LHC [57, 60].

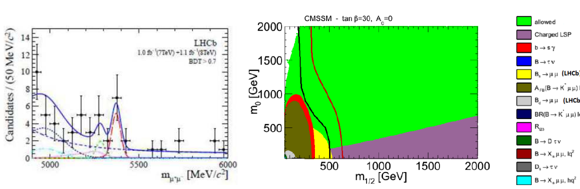

Figure 6: LHCb signal for $B_s^0 \to \mu^+\mu^-$ [62] (left) and presently CMSSM allowed region (green) on the plane $(m_0, m_{1/2})$ [55] (right).

Important constraints on the supersymmetries, beyond the effective field theories discussed before, that can also set limits to the WIMP candidates properties, are given by the search for rare decays of heavy neutral mesons like the B_d^0 and B_s^0 decays, copiously produced at LHC [61], performed by the LHCb experiment as well as the CMS experiment.

LHCb is the LHC experiment devoted to Flavor Physics. Both LHCb and CMS have measured the $BR(B_s \to \mu\mu)$ which is an important test bench for New Physics, because it strongly suppressed in the minimal SMit is enhanced by SUSY. Limit at 95% CL is $BR(B_s \to \mu\mu)_{SUSY} < BR(B_s \to \mu\mu)_{SM}$. [62] The limit on the $BR(B_s \to \mu\mu)$, combined with additional constraints coming from Flavor Physics, can be interpreted in terms of limits on the mass of SUSY particles. In particular, the most stringent limit on the mass of neutralino, corresponding to the point $m_0 = 1$ TeV/c^2, $m_{1/2} = 200$ GeV/c^2, is $m_{\chi_1^0} \geq 80$ GeV/c^2.

6 Summary

The Higgs boson has been discovered at LHC. The runs at 14 TeV, that will start in about 1 year, will provide the final check on its basic properties.

On a longer scale an upgrade of the LHC accelerator is foreseen which will bring the LHC luminosity up to $2 \times 10^{34}\ cm^{-2}s^{-1}$ (HL-LHC). In one year of run at HL-LHC it will be possible to collect about 100 fb^{-1} of integrated luminosity, which indeed are needed to definitively test the 1 TeV scale SUSY, providing a better chance to see rare processes and improving statistically marginal measurements.

Contrary to what many people thinks, accelerators cannot discover DM particles, as well as astronomy cannot discover SUSY. The two activities are strictly complementary, bridged only by physical models which can predict results at accelerator and in the sky [63].

More results are expected in the near future from Astroparticle Physics (γ -rays, neutrinos & antimatter) and HEP-Flavor physics.

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