Looking for supersymmetry: ∼1 TeV WIMP and the power of complementarity in LHC and dark matter searches

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Some doubts have been expressed about low energy supersymmetry (SUSY) following the first run of the LHC. In this talk I will try to present a more upbeat view based on data, rather than theoretical expectations. In particular, I will make the following points: (a) in my opinion the most attractive candidate for dark matter (DM) is now the lightest neutralino with mass around 1 TeV and with well defined properties (a nearly pure higgsino). This follows primarily from a combination of the properties of the discovered Higgs boson, in particular its mass close to 125 GeV, and the relic density of dark matter, and is most clearly visible in the context of unified, or constrained, SUSY frameworks, although the DM candidate is quite generic; (b) this DM candidate will be nearly fully tested in forthcoming one-tonne DM underground search detectors; (c) the CMSSM will be nearly fully tested in the next few years by a combination of expected data from LHC experiments and from direct DM searches, as well as potentially also by the Cherenkov Telescope Array; (d) if naturalness plays any real role in SUSY (which remains unclear), then the amount of fine tuning, which is very large in simple models like the CMSSM, can be significantly reduced (even down to 1 in 20) with properly selected boundary conditions at the unification scale; (e) the $(g-2)_\mu$ anomaly can be accommodated not only in the context of the general MSSM but also of some unified SUSY models with some superpartners to be within reach of the LHC.

The outcome of the first run of the LHC has brought some sense of confusion and disappointment to the “new physics” community. Not even a remotely convincing hint of any signature of physics beyond the Standard Model (SM) emerged. In particular, direct limits on superpartner masses were pushed up significantly and, in the case of colored particles, reached and exceeded the ballpark of 1 TeV, except for the stops. Likewise, in flavor violating processes measured at the LHC and elsewhere SM predictions agree well with experimental data, again implying that any potential new physics contributions have to be suppressed, most likely by the large mass scale of new physics states. In particular, the measurements by LHCb and then also CMS of $\text{BR}(B_s \rightarrow \mu^+\mu^-)$, both agreeing with SM expectations suggest that the pseudoscalar Higgs boson has to be heavy, at or beyond 1 TeV, thus setting the scale for the heavy Higgs sector of the MSSM. Note, however, that this does not apply to models with an extended Higgs sector, like the CNMSSM with an extra singlet Higgs, where some of the additional Higgs bosons can be much lighter, even lighter than the discovered Higgs boson.

These negative results (from the point of view of new physics searches) were actually independently reinforced by emerging properties of the Higgs boson discovered by ATLAS and

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CMS. Its couplings to SM fermions and gauge bosons came out to be SM-like, thus suggesting that the other MSSM Higgs bosons are heavy, and decouple.

Of course, one can take the “I believe in what I can see” approach that the SM has been confirmed in light of the above and there is simply no new physics beyond the SM, at least up to the few TeV scale. I believe that it is too quick to jump to such conclusions. Firstly, the discovery of the Higgs boson is consistent not only with the SM but also with the frameworks that predict a SM-like Higgs boson, in particular with the MSSM. Secondly, apart from its many well known theoretical puzzles (e.g., many free parameters, apparently ad hoc gauge group or fermion representations, etc) the SM lacks explanations for big cosmological questions: dark matter, baryogenesis, cosmic inflation, etc.

Thirdly, within the framework of low energy SUSY, the mass of the Higgs boson of around 125 GeV is rather high and requires large radiative corrections from the stop sector at, or above, the 1 TeV scale. In SUSY in the context of grand unification (GUT), where soft SUSY breaking parameters are unified, this sets the scale for the SUSY breaking scale $M_{SUSY}$ in the multi-TeV regime, again consistent with direct SUSY search limits and flavor processes. In my opinion, this is a very important implication stemming from the properties of the discovered Higgs boson that has perhaps not yet been appreciated widely enough in the community.

An additional important, and robust, constraint on SUSY parameter space is provided by requiring that the relic density of the lightest neutralino assumed to be DM agrees with the experimentally determined value in the Universe. Since in constrained SUSY models this calculated quantity tends to be too large, it can be satisfied only in some specific regions of parameter space. The outcome is illustrated in the case of the CMSSM in the left panel of Fig. 1 (taken from Ref. 1, which is an update of Ref. 2) where I present 1- and 2$\sigma$ (credible) regions of Bayesian total posterior probability (pdf).

Due to space limitation in this writeup I only summarize some of our main results and cite only our relevant papers. I skip the description of the procedure and of the constraints adopted in deriving our numerical results. The reader is referred to our papers for a detailed presentation of our analysis and a list of references.
followed, at larger \( m_0 \) and \( m_{1/2} \), by an A-funnel (AF) region (1\( \sigma \) region occupying about 30\% of total Bayesian probability). In both of these regions the neutralino is bino-like which in the pre-LHC era was considered to be the most attractive WIMP solution.

Finally, at multi-TeV \( m_0 \) and \( m_{1/2} / 2 \), one can clearly see the largest (about 70\%) high probability region which I will call a \( \sim 1 \) TeV higgsino DM region (1TH). This is because in this region the lightest neutralino is higgsino-like and its mass is set by the \( \mu \)-parameter and is close to 1 TeV in order to produce correct relic abundance.

For comparison, in the left panel of Fig. 1 dotted lines show the previously favored regions based on the information available at that time (before 2013). In particular, Higgs mass calculation was performed at two loops (using FeynHiggs) and its experimental value taken in the analysis was higher, 125.8 GeV (CMS). That is why the resulting ranges of \( M_{\text{SUSY}} \) were actually somewhat higher.

The \( \sim 1 \) TeV higgsino DM region is a new region relative to the pre-LHC studies of constrained SUSY models which explored much lower values of \( m_0 \) and \( m_{1/2} \), up to some 4 TeV and 2 TeV, respectively, although the existence of such a region in constrained SUSY was pointed out back in 2009, in the pre-LHC era, in the framework of the NUHM. In fact, some initial reactions following the discovery of the Higgs boson (whose mass at that time appeared even higher) were to jump to conclusions that such a large value cannot be accommodated in low energy SUSY. This is because in most analyses \( M_{\text{SUSY}} \) was taken below a few TeV on the basis of the theoretical expectation of “naturalness”. I will comment on this later.

Remarkably, in this region the correct relic abundance is achieved solely by the \( \mu \)-parameter being close to 1 TeV. No special mechanisms for reducing the relic density are required, unlike in the SC or AF regions, nor does one invoke a contribution from several unrelated (co)annihilation mechanisms. In this sense the 1TH region is most natural. All one needs to do is to go to the regime of large enough bino, and, wino, mass. In constrained models like the CMSSM this is achieved in regions of large enough \( m_{1/2} \). It is worth mentioning that, by enlarging the ranges of \( m_0 \) or \( m_{1/2} \) one does not find any new high probability regions. Also, in less constrained models like the NUHM the 1TH solution becomes even more pronounced than in the CMSSM.

In the likelihood function that we used in our Bayesian analysis and numerical scans all relevant constraints were actually included – they are listed in Table 1 of Ref. 1 where also the numerical procedure used in performing our scans is described – but it is primarily the Higgs mass value and the DM relic abundance that determine the shape of the favored regions. Some role is also played by direct limits on superpartner masses (which we include in our likelihood function through an approximate but accurate procedure described in Ref. 2) in setting a lower limit on \( m_{1/2} \) (and thus reducing the importance of the SC region to the mere 2\( \sigma \) level) and by the updated measurements of BR (\( B_s \to \mu^+ \mu^- \)) in giving more “weight” to the AF region relative to a previous study 2 and by current upper limits on \( \sigma_p^{\text{SI}} \) in basically ruling out the mixed neutralino DM region, characteristic of the hyperbolic branch/focus point region.

The result shown in Fig. 1 for the case of the CMSSM is actually much more general. It applies both to unified, as well as phenomenological models, with gaugino masses taken above the higgsino mass of \( \sim 1 \) TeV.

In the right panel of Fig. 1 the favored regions shown in the left panel are mapped onto the \( (m_\chi, \sigma_p^{\text{SI}}) \) plane. From left to right, in the direction of increasing neutralino WIMP mass and also \( \sigma_p^{\text{SI}} \), we can see the “tiny” stau-annihilation region (at 2\( \sigma \) only), followed by the A-funnel region and, the largest \( \sim 1 \) TeV higgsino DM region. For comparison we show also the current upper limits on \( \sigma_p^{\text{SI}} \) from LUX and Xenon100 which exclude the mixed neutralino DM region of

\[ \sigma_p^{\text{SI}} \]

It remains completely unclear to me whether the much emphasized criterion of naturalness in low-energy SUSY is actually not misguided. I am more inclined to take a less theoretically motivated and more pragmatic view that can be put bluntly as: “Natural is what is realized in Nature” - On a recent occasion I was very pleased to hear a very similar comment from Frank Wilczek.
HB/FP at a few hundred GeV.

The emerging picture looks to me highly encouraging. The most attractive $\sim 1$ TeV higgsino DM region falls basically all within the reach of upcoming one tonne detectors, like Xenon-1T which is expected to produce new results by 2017 or so. This will provide the most robust way of exploring this region.

Interestingly enough, this region should be independently probed within expected sensitivity reach of the forthcoming Cerenkov Telescope Array (CTA), a future gamma-ray telescope due to start in 2018 or so, from observations of diffuse radiation, assuming 500 hours of observation time plus, more importantly, a steep enough DM density profile (close to the Einasto profile) towards the Galactic Center. (This being the case in simple constrained models, in phenomenological scenarios like the pMSSM there is, however, more freedom\textsuperscript{5}.)

This can be seen in Fig. 2 which also shows an impressive complementarity of DM search experiments (both direct and indirect in CTA) with LHC searches for signatures of SUSY. Both the SC and the AF regions will be probably beyond the reach of one tonne DM detectors but are expected to be accessible to the LHC14. The first of them will hopefully be explored by direct detection searches for SUSY. In the AF region, on the other hand, the superpartners are too heavy to be detected at the LHC. Fortunately, a precise enough, but achievable (at the level of 5 – 7% of both experimental and theory error) determination of BR ($B_s \to \mu^+\mu^-$), if it comes out to be consistent with SM predictions, would rule out most of the AF region. This is because in this region $\tan \beta$ has to be large in order to enhance resonant annihilation of DM by the $s$-channel heavy pseudoscalar Higgs exchange but this, by the same token, also enhances the value of BR ($B_s \to \mu^+\mu^-$). Again, it is worth remembering, though, that in models with an extended Higgs sector, like the CNMSSM, the situation is more complicated and some of the Higgs bosons can be much lighter.

I will now briefly comment on two additional issues. The first is about so-called fine-tuning (FT) and is linked to “naturalness”. At $M_{\text{SUSY}} \gtrsim 1$ TeV FT is expected to be significant and indeed in simple constrained models like the CMSSM it is now very large, even in excess of 1 in 3000. Here I want to make a few points. Firstly, the validity of “low fine-tuning” as a guiding principle in effective theories like low-energy SUSY remains (and always has been) unclear to me. We worry about the sensitivity of $m_Z$ and other quantities at the EW scale to
input parameters defined at the GUT scale only because we don’t know the latter. In other words, we worry about FT because of our ignorance of physics at the high scale, while in fact FT in some effective theory may find its resolution in an underlying fundamental theory, or even in another effective, but more complete theory. A low energy analogue of this may be the GIM mechanism which provided a resolution to some divergencies in a three quark model by adding the charm quark to the picture. Secondly, following this spirit, by making a suitable choice of mass relations at the GUT scale among soft parameters and also by linking $\mu$ to the common scalar soft mass one can reduce FT in unified SUSY down to even 1 in 20. ][

The final point is about the long-standing so-called $(g-2)_\mu$ anomaly which suggests that the measured value of $(g-2)_\mu$ is over $3\sigma$ above SM estimates. Explaining it in terms of SUSY would require low enough smuon and (at least one) neutralino and/or muon sneutrino and (at least one) chargino masses in order to provide large enough SUSY loop contributions to the quantity. It is therefore no surprise that one fails to reproduce $\delta (g-2)_\mu$ in simple constrained SUSY models where slepton masses are unified with those of squarks, while in the general MSSM (or its 19-dim subset called pMSSM) this can be easily done. Hence there is “common wisdom” that constrained SUSY is incompatible with the $(g-2)_\mu$ anomaly. However, this is not quite true. One way is to simply disunify sleptons and squarks, another, less known, is to disunify gauginos. Some such possible constrained SUSY models with relaxed boundary conditions at the GUT scale have been shown to reproduce $\delta (g-2)_\mu$ with the bonus that some light enough states must appear there and be for the most part accessible to LHC14. In other words, if the $(g-2)_\mu$ anomaly is real then either some light SUSY states will be seen at the LHC or those models will be ruled out. ][

In conclusion, I’ve pointed out some distinct and well motivated phenomenological scenarios that can be put to a definitive experimental test at the LHC and in DM searches. While waiting for new data, and remaining open to surprises, I believe we have good reasons to remain optimistic. Long ago, before the LHC era began, I formulated the conjecture: “Low energy SUSY cannot be experimentally ruled out. It can only be discovered. Or else abandoned.” Indeed, while some specific SUSY models could in principle be excluded, I could not think of any experimental measurement that can be made in currently available facilities and that could rule out low energy SUSY as a framework. We should be able to know which way our field will go hopefully within the next few years.

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