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Naturalness, Supersymmetry, and Predictions for New Physics at the LHC[1]

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Abstract: Skepticism that naturalness implied that the LHC *must* find new physics beyond the Standard Model at the LHC was well in place before the LHC even turned on. Nevertheless, there is no contradiction between this skepticism and optimism that new physics is to be found.

Theorists did not worship naturalness

There exists a myth that all particle phenomenologists were smitten by the disease of extreme naturalness thinking[3], and that they were convinced that naturalness required that new particles absolutely had to show up at the LHC. That their blindness in the face of the bright lights of naturalness led them to think of nothing else, even at the expense of data, in their never-ending search for pure naturalness nirvana.

That is not how it went.

It is true that there was, and still is, a current of model-building research that explored theories based solely on their ability to mollify naturalness concerns in the electroweak sector. It is plausible that naturalness is a key to electroweak model building and some effort should always go into exploring plausible requirements. It was a legitimate exercise in my view as long as it did not dominate the field, which it did not. Most especially in the case of supersymmetry, naturalness was very often on the list of positive features, but it was never the only highlighted feature. It would never have attained its high status if it were just a one-trick naturalness pony.

A typical supersymmetry talk well before the LHC even turned on would usually list a half dozen reasons why the researcher was studying supersymmetric theories, and naturalness would be only one of those bullet points. Gauge coupling unification, dark matter, connections to string theory, radiative electroweak symmetry breaking, Yukawa unification, expanded space-time symmetry to explore, baryogenesis models, well-defined perturbative phenomenology explorations, and others were the reasons for why supersymmetry was explored in addition to naturalness. Most of these were data-driven reasons.

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[1]From *Physics Resource Manuscripts*. `http://umich.edu/~jwells/prms/`

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[3]Roughly speaking, naturalness requires no huge finetunings among parameters. In the present context, the Higgs boson appears unnatural to some since quadratically divergent quantum corrections to new physics at a higher scale requires very finetuned cancellation with counter term to get its weak scale value: $m_h^2 \simeq \Lambda_1^2 - \Lambda_2^2$, where $\Lambda_{1,2}^2 \gg m_h^2$. Light "new physics", such as supersymmetry or composite Higgs, is argued to rectify this problem.

Supersymmetry after LEP 2

Nevertheless, it was recognized very early on, and especially after LEP-2[4] did not find superpartners, that minimal supersymmetric was under pressure from the simplest interpretations of naturalness. It had not found superpartners, which many expected, nor had it found the Higgs boson. To most who thought about such things, not having found the Higgs boson was the bigger worry. After all, LEP 2 did not get to very impressive energies at all to find superpartners, but the correlating scale of superpartners to the lower limit of 114 GeV for the Higgs mass was a cause for concern[5].

In the face of null results from LEP 2 there were many directions to go: identify forms of supersymmetry that would give $m_h > 114\,\mathrm{GeV}$ without straining naturalness (e.g., adding an additional singlet Higgs boson, etc.), abandon supersymmetry (but other new physics ideas suffer from similar naturalness concerns), or abandon rigid naturalness criteria altogether. Since naturalness is not a hard-core data driven criteria, that's a direction that several of us pursued, *well before the LHC turned on.* This now sometimes goes under the name of split supersymmetry. Its hallmark is to put more emphasis on data requirements and less emphasis on extra-empirical concerns.

A prediction of abandoning naturalness in this approach was that there was no special reason to see supersymmetry at the LHC, but there was interesting new enhanced reasons to expect to see dark matter through annihilations in the center of the galaxy, and the electric dipole moment of the electrons might be within reach of experiment in the not-so-distant future, to name two examples.

Strong skepticism of precise notions of naturalness

Strong skepticism of naturalness as a precise guide to LHC predictions was thoroughly known and widely shared among experts. I don't have to tell experts that – those who actually show up to phenomenology conferences, publish in journals on the topic, and engage in the day-to-day fight to figure nature out. However, perhaps it is needed for the broader community who might be confused. For that reason, I present in the appendix a very small bibliography of papers from 2003-2004, well before the LHC turned on in 2009. These papers, which were sharply skeptical of naturalness, have between them thousands of citations, and were hardly unappreciated or unknown by the theory community.

Reaction to dogmatic anti-skeptical statements

Now, you will invariably find people who said that due to naturalness new particles beyond the Higgs boson *must* be found at the LHC, but it's hardly newsworthy unless it's a core belief of the community involved. The community was never behind any statements of "must." Also, the existence of bets that supersymmetry would be found at the LHC is far from proof that people felt it *must* be found, just as the existence of bets on Germany winning the 2018 World

[4]LEP-2 was an e^+e^- collider at CERN which looked for the Higgs boson and new physics without success, ending its run in 2000.

[5]In supersymmetry, the Higgs boson mass is a function of superpartner masses — the higher the superpartner masses the higher the Higgs mass, in general. LEP's $m_h > 114\,\mathrm{GeV}$ required superpartner masses to be unnaturally heavy in the eyes of some.

Cup of soccer was proof that the placer of the bet thought it was *guaranteed* Germany would win.

Well, but a few very good people seem to have said that they were sure new physics or supersymmetry would be found. Among those very good people who said it, I am sure that they said it with an ever-present, unsaid, implicit softening background assumption that we all understood. A full version of what was meant and understood by such statements in the context of supersymmetry has usually been (maybe even always been), "If a minimal version of supersymmetry is correct and the Higgs potential is not finetuned to more than a few percent I fully expect that superpartners will show up at the LHC unless we are unlucky and the kinematics turn out to be too challenging, such as small mass splittings that we can't trigger on very easily, etc." But you really don't want to say all those words every time you say, "I expect supersymmetry at the LHC." When you're in the field, you know. When you overhear or read it from the outside, you can easily misunderstand. There are an infinite number of "short hands" like that when you speak in a disciplinary field, and if you have to speak so carefully every time so that a robot can give it meaning then efficient communication really becomes impossible.

Now, if a theorist said *to the public or the press* that superpartners *had to be found* at the LHC, I will not defend them. The public and press have no conception of these understood attitudes from the previous paragraph. That would be a real shame if somebody had done that, from sloppiness or wanting to be provocative and interesting, just like it would be a real shame if somebody claims that real practitioners believed that there was a rigorous and absolute proof that new physics *had to be found* at the LHC because of naturalness, when in fact most, if not all, held no such belief.

Skepticism is not incompatible with optimism

One must keep straight that skepticism about "must statements" (e.g., "supersymmetry must show up at the LHC") is perfectly compatible with optimism. There is optimism that new physics will be found at the upgraded LHC, or at other future experimental facilities. There are many fascinating mysteries still outstanding in particle physics that we know about (such as dark matter, baryogenesis, flavor hierarchies, etc.), and I expect many more that we do not know about. The Higgs boson discovery is one of the most momentous discoveries in science of the last few decades and we must study it extensively and completely to know exactly what it couples to and with what strength. We are presently at a very rudimentary understanding of that.

The most alluring part of particle physics is that it is a frontier field, and thus it can never die given the practically infinite energy frontier in front of us. We are to reach into that frontier with everything we have, with colliders, table top experiments, satellites, mathematics, telescopes, symmetry principles, etc., and try to make sense of the universe. We extend with hopes of finding. Those that engage in this are explorers, but explorers have to be mentally tough. It's not for everyone. You can sail and sail and not find land, but do not make the fatal mistake of concluding that there is no land and dropping anchor. There is land.

Appendix

In this appendix are the promised quotes on skepticism to Naturalness in the original split supersymmetry literature from 2003-2004, well before LHC turn on in 2009. Between them, these papers were acknowledged, discussed, and cited extensively, which demonstrates that skepticism that the LHC *must find* superpartners due to naturalness and finetuning was widely recognized and appreciated by the theory community.

J. D. Wells, "Implications of supersymmetry breaking with a little hierarchy between gauginos and scalars," hep-ph/0306127, Presented at SUSY 2003 (University of Arizona, 5-10 June 2003).

> "It is often assumed that superpartner masses need to be less than *about* 1 TeV if the weak scale is not fine-tuned. The problem is that no one has a rigorous and defensible definition for "about." If superpartner masses are at 108 TeV most would agree that supersymmetry would have little to do with stabilizing the weak scale to the quadratic divergences of the Standard Model (SM) effective theory. But what about 3 TeV or 48 TeV? In the Yukawa coupling sector we have an apparent tuning of $y_e/y_t = m_e/m_t \simeq 3 \times 10^{-6}$. If $\tilde{m} \simeq 150\,\mathrm{TeV}$ we have a similar apparent finetuning in the electroweak sector of $v^2/\tilde{m}^2 \simeq y_e/y_t$. This is not a complete argument, but rather a meek invitation to be less restrictive in thinking about what is finetuned since an apparent finetuning might not be a real finetuning once we learn more about the origin of Yukawa couplings and superpartner masses." (p.1)
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> "Yet another soothing effect of heavy scalars is the compatibility with the Higgs boson mass constraint. If all scalar superpartner masses are above 5 TeV the lightest Higgs mass boson is generally always above 114 GeV [the current lower limit at the time] for all values of $\tan\beta$ consistent with perturbative top and bottom Yukawa couplings up to the GUT scale." (p.2)
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> "The unification successes of supersymmetry, both gauge and Yukawa unification, are not diminished when the scalars are very heavy [hundreds of TeV, even]. We have also seen that supersymmetric dark matter considerations do not cast dispersions on the idea either. Only the naturalness of the electroweak symmetry breaking potential apparently weakens with the increased scalar masses considered here. Interestingly, this aspect of supersymmetry is the least quantifiable success of supersymmetry, and it may be that data will end up adjusting what we presume as natural." (p.9-10)

N. Arkani-Hamed and S. Dimopoulos, "Supersymmetric unification without low energy supersymmetry and signatures for fine-tuning at the LHC," JHEP 0506, 073 (2005) [hep-th/0405159].

> "What if the observation of a tiny cosmological constant is telling us that UV sensitive parameters in the low energy theory beneath the SUSY breaking scale will appear incredibly finely tuned? This leads us to imagine that SUSY is broken in the SSM [supersymmetric Standard Model] at very high scales, far above the weak scale, with the Higgs mass parameter appearing finely-tuned in the low-energy effective theory, just as the CC [cosmological constant] appears finely tuned $m_h^2 \sim \epsilon_2 m_S^2$ [where $\epsilon_2 \ll 1$]." (p.4)

> "Although the cosmological constant problem casts a giant shadow on the principle of naturalness, the prevailing view has been that the LHC will reveal a natural theory for electroweak symmetry breaking, and that gauge coupling unification favors this to be low-energy SUSY, despite its nagging problems and the accompanying epicyclic model-building needed to address them.
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> "Here we have outlined an alternate viewpoint, where the usual problems of SUSY vanish, unification is evidence for high-energy SUSY, and where accelerators can convincingly demonstrate the presence of fine tuning in the electroweak sector. The first sign of this proposal at the LHC should be the Higgs, in the mass range of $\sim 120 - 150\,\mathrm{GeV}$. No other scalar should be present, since it would indicate a second, needless, fine-tuning." (p.29-30)

G. F. Giudice and A. Romanino, "Split supersymmetry," Nucl. Phys. B **699***, 65 (2004) Erratum: [Nucl. Phys. B* **706***, 487 (2005)] [hep-ph/0406088].*

> "The naturalness criterion applied to the cosmological constant implies a new-physics threshold at $10^{-3}\,\mathrm{eV}$. Either the naturalness criterion fails, or this threshold does not influence particle dynamics at higher energies. It has been suggested that the Higgs naturalness problem may follow the same fate. We investigate this possibility and, abandoning the hierarchy problem, we use unification and dark matter as the only guiding principles." (abstract)

> "It is conceivable to ponder whether such an explanation [for the cosmological constant] could also apply to the hierarchy problem, imagining a mechanism (not necessarily based on the anthropic principle) which allows to extrapolate SM calculations to energies much larger than the TeV, without the need of introducing new dynamics, besides the Higgs." (p.1)

N. Arkani-Hamed, S. Dimopoulos, G. F. Giudice and A. Romanino, "Aspects of split supersymmetry," Nucl. Phys. B **709***, 3 (2005) [hep-ph/0409232].*

> "Our concept of Naturalness — the principle that Nature abhors fine-tunings — is based on theories with a few vacua. It has led to the proposal of low-scale supersymmetry, in order to avoid tuning short-distance parameters to 30-decimals. But this principle faces a serious challenge from the cosmological constant problem, where we see no new physics at the scale $\sim 10^{-3}\,\mathrm{eV}$ required by naturalness." (p.1)

> "Having abandoned naturalness, the crucial ingredient pinning the gaugino and Higgsino masses to the TeV scale is the requirement for the lightest supersymmetric particle (LSP) to form the dark matter of the universe." (p.2)

J. D. Wells, "PeV-scale supersymmetry," Phys. Rev. D **71***, 015013 (2005) [hep-ph/0411041].*

> "... it is defensible to make the following claim:
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> "*In our present state of understanding, we cannot determine if the finetuning associated with the weak-to-Planck scale hierarchy is solved by a Principled Finetuning argument or by a Chance Finetuning argument.*
>
> "Therefore, if the above statement is agreed to, one is free to dismiss weak-scale Principled Finetuning arguments as a guide to model building, and investigate the consequences. This idea reaches its most intense expression in split supersymmetry, where a dramatic separation between gauginos and scalar superpartners are possible." (p.1)

> "Some experimental implications follow from PeV-scale supersymmetry. First, the Higgs mass is predicted to lie within $125\,\mathrm{GeV} \lesssim m_h \lesssim 155\,\mathrm{GeV}$...." (p.5)