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PeV-scale supersymmetry

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Although supersymmetry has not been seen directly by experiment, there are powerful physics reasons to suspect that it should be an ingredient of nature and that superpartner masses should be somewhat near the weak scale. I present an argument that if we dismiss our ordinary intuition of fine-tuning, and focus entirely on more concrete physics issues, the PeV scale might be the best place for supersymmetry. PeV-scale supersymmetry admits gauge coupling unification, predicts a Higgs mass between 125 GeV and 155 GeV, and generally disallows flavor changing neutral currents and CP-violating effects in conflict with current experiment. The PeV scale is motivated independently by dark matter and neutrino mass considerations.

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I. INTRODUCTION

Given the interesting results coming from string/M-theory/Landscape/Attractor studies [1–3], and the long-standing challenges of quantifying what fine-tuning really means, it is defensible to dismiss weak-scale fine-tuning arguments as a guide to model building, and investigate the consequences. This idea reaches its most intense expression in split supersymmetry [4–8], where a dramatic separation between gauginos and scalar superpartners are possible. I will follow a smaller subset of this general view, building from a conference discussion [9], which one could call loop-split supersymmetry, as the gauginos and scalar masses will be split by only a loop factor associated with anomaly mediation. Once we truly dismiss fine-tuning considerations, keeping an eye toward generic supersymmetry breaking mechanisms that are compatible with the data, I suggest that we are drawn to a scenario where the supersymmetry breaking mass (i.e., gravitino mass) is at the PeV-scale (PeV $= 10^{15}$ eV).

II. DATA PRESSURES ON SUPERSYMMETRY

First, we briefly review the negative pressures data has placed on supersymmetry. Results from flavor changing neutral current experiments ($K - \bar{K}$ mixing, $\mu \to e\gamma$, etc.), CP violation experiments (e.g., electric dipole moments of the neutron and electron), and Higgs mass searches ($m_h > 114$ GeV at 95% C.L.) all struggle to be consistent with weak-scale supersymmetry [10]. One must make additional assumptions about the superpartner spectrum, such as the squarks must be degenerate and CP phases of superpartner parameters (μ, gaugino masses, A-terms) must be nearly zero. Proton decay is another potential problem. Proposed solutions based on natural R-parity arguments mollify dimension-four concerns, but dimension-five operators still frighten the grand unified theory enthusiasts.

If scalar superpartner masses are all above a few hundred TeV the problems discussed above are solved. Predictions of flavor changing neutral currents in Kaon physics and B physics are identical to the predictions of the Standard Model if the scalar superpartners are in the PeV range. The experiments show no compelling deviations from the Standard Model predictions, and so PeV scale superpartners work. Unwanted CP violating effects are also no longer present. (There is a two-loop contribution to dipole moments that could be accessible at experiments in the near future if gauginos and Higgsinos are light [4], but we will not be pursuing that direction below.) Furthermore, as the squark masses increase, the troubling dimension-five proton decay operators are suppressed and proton decay is much less of a concern [11].

There is a dark matter concern which needs to be addressed when the scalar superpartner masses get too heavy. In ordinary supergravity models with a Bino lightest supersymmetric particle (LSP), the relic abundance increases to unacceptable levels in much of parameter space when the scalar masses are increased. This is because the Bino annihilates most efficiently through t-channel sleptons, but when those masses are too high the annihilation efficiency drops and the relic abundance climbs very high such that the universe is matter dominated too early. We will see shortly that the supersymmetry spectrum we will be led to in this paper gives the Wino the honor of being the LSP. The Wino LSP annihilates very efficiently through ordinary gauge bosons and so the masses of the scalars are mostly irrelevant to dark-matter issues. More will be said about dark-matter below.

Gauge coupling unification is a tantalizing indication that a higher unification of the Standard Model forces can be accomplished within supersymmetry. As has been emphasized in [4], low-scale fermionic superpartners, not the scalar superpartners, are what are responsible for this amazing coming together of the gauge couplings to within a fraction of a percent, well within the tolerances that a high-scale theory with its own threshold corrections would need for unification. The pressures above, which ask for TeV scale gauginos and much heavier scalar superpartners, are fully consistent with gauge coupling unification.

III. THEORY FOLLOWING FROM DATA

Gauge coupling unification likes gauginos well below the GUT scale, dark matter likes gauginos (or higgsinos) below several TeV, flavor changing neutral current constraints and CP violation constraints like scalar superpartner masses well above the tens of TeV scale, and the lightest Higgs boson mass constraint likes scalar superpartners well above the TeV scale.

The major tension in the data is the desire for TeV gauginos and substantially heavier scalars. Fortunately, charged supersymmetry breaking naturally accommodates such a tension. By "charged" I mean that there is no singlet to feel and transmit supersymmetry breaking. Supersymmetry breaking can be parametrized by a chiral supermultiplet $S = S + \sqrt{2}\psi\theta + F_S\theta^2$ whose nonzero F_S component is the source of supersymmetry breaking. Gaugino masses are generated via

$$\int d^2\theta \frac{S}{M_{\rm Pl}} \mathcal{W}\mathcal{W} \to \frac{F_S}{M_{\rm Pl}} \lambda\lambda. \tag{1}$$

The scalar masses are generated by

$$\int d^2\theta d^2\bar{\theta} \frac{S^\dagger S}{M_{\rm Pl}^2} \Phi_i^\dagger \Phi_i \to \frac{F_S^\dagger F_S}{M_{\rm Pl}^2} \phi_i^* \phi_i. \tag{2}$$

Thus, the gauginos and scalars are often of similar mass when considering usual supersymmetry breaking scenarios.

If S is charged (i.e., not a singlet), Eq. (2) is unaffected, whereas Eq. (1) is no longer gauge invariant. (I am neglecting the grand unified theory possibility that a representation of S charged under the unified group paired with that of the Adj^2 contains a singlet [12].) This is the generic expectation in dynamical supersymmetry breaking where supersymmetry breaking order parameters are charged and singlets are hard to come by [13].

In this case the leading-order contribution to the gaugino mass is the anomaly-mediated value [14,15],

$$M_\lambda = \frac{\beta(g_\lambda)}{g_\lambda} m_{3/2} \tag{3}$$

where λ labels the three SM gauge groups, and where $m_{3/2}^2 = \langle F_S^\dagger F_S \rangle / M_{\rm Pl}^2$. The gaugino masses are therefore one-loop suppressed compared to the persisting scalar mass result of Eq. (2). Some phenomenological implications of this anomaly-mediated scenario with heavier squark masses were presented in [15].

Charged supersymmetry breaking therefore generically creates a one-loop hierarchy between the gaugino masses (and A terms) and the scalar superpartners. To lowest order, the numerical values of the light gaugino spectrum are

$$M_1 \simeq m_{3/2}/120 \tag{4}$$

$$M_2 \simeq m_{3/2}/360 \tag{5}$$

$$M_3 \simeq m_{3/2}/40. \tag{6}$$

As discussed above, the heavy superpartner spectrum of squark, slepton and sneutrino masses $\tilde{m}_i$ generically should have masses within factors of $\mathcal{O}(1)$ near the gravitino mass $m_{3/2}$,

$$\tilde{m}_i \sim m_{3/2} (\text{scalar masses}). \tag{7}$$

Thus the scalar masses are several hundred times more massive than the lightest Wino mass.

IV. PEV-SCALE SUPERSYMMETRY FROM DARK-MATTER

In ordinary minimal supergravity the lightest superpartner is the bino, superpartner of the hypercharge gauge boson. The thermal relic abundance of this sparticle can be made compatible with the universe's cold dark-matter needs in sizeable regions of the parameter space. Weak-scale supersymmetry generally has a gravitino and moduli problem though. The gravitino, which is roughly the same mass as the LSP in the usual case, decays during big bang nucleosynthesis if its mass is less than a few TeV. The gravitino and moduli must be inflated away and not regenerated too copiously during the reheat phase in this scenario.

However, in our situation with anomaly-mediated gaugino masses, the Wino is the LSP.[1] The Winos annihilate and coannihilate very efficiently through SM gauge bosons. Furthermore, there is no gravitino/moduli problem as their masses should be well above the problematic range. The thermal relic abundance of the Winos is [5]

$$\Omega_{\tilde{W}}^{\rm th} h^2 \simeq 0.02 \left(\frac{M_2}{1\ \text{TeV}} \right)^2 \tag{8}$$

and is cosmologically insignificant for weak-scale gauginos, but cosmologically interesting for Winos with mass above the TeV scale.

The WMAP experiment has analyzed the cosmic microwave background data [16] at high precision. One infers from these results that the cold dark matter of the universe should have a relic abundance

$$\Omega_{\rm CDM} h^2 = 0.11 \pm 0.01 (\text{WMAP 68\% C.L.}). \tag{9}$$

Using Eq. (8) we find that the Wino can explain the cold

[1]For definiteness, I will assume only that $|\mu|$ is heavier than M_2 such that the Higgsino mixing has little effect on the thermal relic abundance of the LSP. If $|\mu| < M_2$, which is probably not generically expected in this framework, thermal relic abundance would still put the LSP in the TeV range.

dark- matter of the universe if its mass is

$$M_{\tilde{W}} \simeq 2.3 \pm 0.2 \text{ TeV(Wino dark matter)}. \tag{10}$$

Of course, there could be other sources of cold dark matter beyond-the LSP of supersymmetry. In that case, the above equation would set the upper limit on the Wino mass in an R-parity conserving theory.

Detecting TeV scale Wino dark matter is a severe challenge. When squarks and the μ-term are in the hundreds of TeV range, detection is not possible with table-top detectors of LSP-nucleon scattering. The coherent scattering cross-section falls like $1/\mu^2$. In other words, a Higgsino component of the LSP is necessary to be sensitive to LSP-Nucleon interactions, and if the LSP is nearly pure Wino the Higgsino component is not available for service. The spin-dependent contribution also goes to zero, and the sfermion contributions to the scattering go to zero as well. Therefore, the dark matter may be invisible to table-top experiments.

However, Winos annihilate very efficiently and so one expects that all experiments looking for LSP annihilations in the galactic halo would have an enhanced sensitivity. For example, annihilations that produce $\bar{p}$'s and e^+'s are enhanced. The annihilation channel that perhaps gains the most if nature has Wino dark-matter is the monochromatic two-photon final state [17,18]. The wino annihilation rate is even higher than the higgsino rate, which is known to be large. The cross section for Winos annihilating into two photons [19] is a fairly constant value

$$2\sigma v(\gamma\gamma) = (3 - 5) \times 10^{-27} \text{ cm}^3\text{s}^{-1} \tag{11}$$

for $m_{\tilde{W}} = 0.1$ TeV $-$ 1 PeV.

The virialized dark matter is moving at nonrelativistic speeds of only a few hundred kilometers per second, and so the photons that result from this annihilation are monochromatic with energy $E_\gamma = m_{\tilde{W}}$. Under some astrophysical models developed independently of dark-matter detection prospecting, next generation Cerenkov detectors may be able to see a signal for $\tilde{W}\tilde{W} \to \gamma\gamma$ in the galactic halo if the dark matter density profile is favorably clumped near the galactic center [18]. Another photon line from annihilations into $Z\gamma$ might also be detectable at the energy

$$E_\gamma = m_{\tilde{W}}\left(1 - \frac{m_Z^2}{4m_{\tilde{W}}^2}\right)(\text{from } \tilde{W}\tilde{W} \to Z\gamma). \tag{12}$$

which for sufficiently massive $m_{\tilde{W}}$ is not experimentally resolvable in energy from the photons that come from the $\gamma\gamma$ final state. The separation in energy between photons from $Z\gamma$ and photons from $\gamma\gamma$ final states is less than 1 GeV when $m_{\tilde{W}} \gtrsim 2$ TeV. An extraordinary energy resolution of $\Delta E/E \lesssim 0.1\%$ would be required to resolve the two lines; otherwise, the photons from $\gamma\gamma$ and $Z\gamma$ would add together in the same energy bin.

The experimental situation for a monochromatic $\gamma\gamma$ signal looks especially good for discovering sub-TeV Winos, which might be generated from some nonthermal sources [9]. However, the data pressures discussed above are pointing toward heavier scalar masses in the hundreds of TeV range. In charged supersymmetry breaking scenario this correlates with a trans-TeV Wino mass. An obvious prejudice to have, given these pressures, is that Winos have mass of about 2.3 TeV such that their relic abundance is created by a normal thermal freezeout process. We know from the generic relationship of gaugino masses to gravitino/scalar mass that

$$m_{\tilde{W}} \simeq 2.3 \text{ TeV} \longrightarrow m_{3/2} \simeq \tilde{m} \simeq 0.8 \text{ PeV} \tag{13}$$

which is our first indication that the scale of supersymmetry breaking (i.e., gravitino mass) could be the PeV scale.

V. PEV-SCALE SUPERSYMMETRY FROM NEUTRINOS

In the Standard Model the right-handed neutrino ν^c is a pure singlet under all gauge symmetries. However, in the spirit of "many sectors," which, for example, the string/M-theory landscape seems to imply, we suppose that it is unlikely that ν^c is a pure singlet under all gauge symmetries of nature. To be specific with an illustration, I will assume that the ν^c is charged under a new gauge symmetry $U(1)'$ in such a way that $LH_u\nu^c$ is not allowed in the superpotential.

The next higher order coupling the ν^c could have with SM states is through the nonrenormalizable interaction

$$W = \frac{\lambda}{M_{\text{Pl}}}\phi LH_u\nu^c \tag{14}$$

where ϕ is an exotic field which breaks the $U(1)'$ symmetry when it condenses, and has the right charge assignment such that the above operator is allowed but not $\phi^2\nu^{c2}$. When ϕ condenses, the Dirac neutrino mass that results is

$$m_\nu = \frac{\lambda}{M_{\text{Pl}}}\langle\phi H_u\rangle. \tag{15}$$

We know from atmospheric neutrino oscillation experiments that the participating neutrino masses must satisfy [20]

$$\Delta m_\nu^2 \simeq 10^{-3} \text{ eV}^2. \tag{16}$$

This implies that a natural value for the neutrino masses would be $m_\nu \simeq 0.1$ eV. If we plug this estimate into Eq. (15) we can compute the required value of $\langle\phi\rangle$:

$$\langle\phi\rangle \simeq \frac{(1 \text{ PeV})}{\lambda\sin\beta}. \tag{17}$$

Thus, we have another indication of the PeV scale, this time from an alternative explanation for neutrino masses.

It does not take much to motivate how $\langle\phi\rangle$ could be correlated directly with the gravitino and scalar superpartner masses. In a many-sectored theory of physics, we assume that the symmetry breaking potential for all the sectors is characterized by the $m_{3/2}$ scale and that our weak scale was one of the few sectors (or only sector) that happened to have the potential terms conspire to give a small scale. If we take this argument seriously, then at the $m_{3/2} \simeq 1$ PeV scale there should be many sectors and many states, only one of which needs to cooperate to give the neutrino masses. The PeV scale would then be very rich physics territory, and could in principle turn into a target for distant future collider physics programs if any kind of evidence surfaces for the PeV scale.

VI. GAUGE COUPLING UNIFICATION

Having established that the PeV scale is an interesting one for scalars, we should check that gauge coupling unification is ok in this scenario. It is well known that the μ term value is crucially important to gauge coupling unification details, and so we also have some anticipation of possibly restricting μ from this argument.

Gauge coupling unification is tested by running the dimensionless couplings up to the high scale using two-loop renormalization group equations and decoupling the contributions of superpartner states at scales below their mass thresholds. One needs to know all the masses of the superpartner states to do this properly. A dramatic simplification is to assume all superpartner masses are at a single scale $M_{\rm SUSY}$, and all superpartners decouple below that scale. It has been known for some time now [21] that if $M_{\rm SUSY} \lesssim$ few TeV the gauge couplings unify to within a percent, well within the range expected of high-scale threshold corrections.

The superpartner masses of PeV-scale supersymmetry are far separated, and it is not a good approximation that all superpartner masses should decouple at one scale. However, there is an effective scale, $M_{\rm SUSY}^{\rm eff}$, which takes into account the various mass splittings of a model [22,23]. This scale is introduced for the purpose of finding a single scale at which one can decouple all superpartners and yet retain the complete effect of all the thresholds corrections on the gauge coupling unification condition. Just as was the case for $M_{\rm SUSY}$, if $M_{\rm SUSY}^{\rm eff}$ is less than a few TeV gauge coupling unification is fine.

If we assume an anomaly-mediated spectrum for the gaugino masses, and assume that sleptons and squarks and the heavy Higgs boson doublet all have mass $\sim m_{3/2}$, the value of $M_{\rm SUSY}^{\rm eff}$ is

$$M_{\rm SUSY}^{\rm eff} \simeq |\mu| \left(\frac{\alpha_2}{3\alpha_3}\right)^{28/19} \left(\frac{\alpha_2}{4\pi}\right)^{4/19} \left(\frac{m_{3/2}}{|\mu|}\right)^{7/19}. \qquad (18)$$

Evaluating the numerical factors and writing it in a more suggestive form, we get

$$M_{\rm SUSY}^{\rm eff} \simeq \frac{m_{3/2}}{100} \left(\frac{|\mu|}{m_{3/2}}\right)^{12/19} < 10~{\rm TeV}, \qquad (19)$$

where the 10 TeV number comes from setting $|\mu|$ to its likely maximum value of $|\mu| \sim m_{3/2}$ and then setting $m_{3/2}$ to its maximum value of about 1 PeV. The numerical value of $M_{\rm SUSY}^{\rm eff}$ is coming out to be lower than one perhaps would naively expect. One technical reason for this is the relatively large ratio of gluino mass to Wino mass.

One might be tempted to be slightly uncomfortable at the very largest values of $|\mu| \sim m_{3/2}$, where $M_{\rm SUSY}^{\rm eff}$ may approach 10 TeV. If insisted upon, one could require $|\mu|/m_{3/2} \lesssim 1/30$ to reduce $M_{\rm SUSY}^{\rm eff}$ below the TeV scale. However, $M_{\rm SUSY}^{\rm eff} \simeq 10$ TeV is plenty compatible with reasonable grand unification threshold corrections. Even best fits to a common superpartner threshold mass that do not take into account high-scale threshold corrections allow values as large as 10^4 GeV [24].

Therefore, the conclusion of this section is that gauge coupling unification is fine for any value of $|\mu|$ between the Wino mass and the scalar mass. That is, a TeV-scale $M_{\rm SUSY}^{\rm eff}$, which is good for gauge coupling unification, is consistent with the descriptions of the PeV-scale supersymmetry approach discussed above.

VII. CONCLUSIONS

PeV-scale supersymmetry solves most of the vexing problems weak-scale supersymmetry faced (FCNC, CP violation, Higgs mass bound, etc.). However, it retains all the good features of low-scale supersymmetry—dark matter and gauge coupling unification, in particular. The only good feature not retained by PeV-scale supersymmetry is the lack of a Principled Fine-tuning explanation of the weak-to-Planck scale hierarchy. This might be too high of a price to pay for PeV-scale supersymmetry. Nevertheless, string/M-theory landscape considerations give us a plausible reason to dismiss our ordinary intuition of fine-tuning and follow the data. It is noteworthy that generic charged supersymmetry breaking, which gives rise to loop-suppressed anomaly-mediated gaugino masses, satisfies all the data pressures on the supersymmetry breaking scale. It is interesting that the same PeV numerical value for the supersymmetry scale can be argued independently from dark-matter and neutrino considerations.

Some experimental implications follow from PeV-scale supersymmetry. First, the Higgs mass is predicted to lie within 125 GeV $\lesssim m_h \lesssim$ 155 GeV, which can be gleaned by restricting to the $\tilde{m} \simeq 1$ PeV neighborhood in [5]. Furthermore, we expect the neutrinos to have Dirac masses generated from nonrenormalizable interactions in the superpotential; the dark-matter to be a Wino LSP with mass of about 2.3 ± 0.2 TeV; and, no deviations from the SM seen by FCNC or CP-violating experiments due to the superpartners of minimal supersymmetry. A positive beyond-the-SM experimental signature of this scenario, which there are precious few in the energy domains of current experiments, would be $\tilde{W}\tilde{W} \to \gamma\gamma, Z\gamma$ and e^+X annihilations in the galactic halo.

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