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Prospects of Focus Point Supersymmetry for Snowmass 2013

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We briefly review the motivations and features of focus point supersymmetry and in particular the focus point region of the CMSSM. Applying the constraint that the neutralino is a thermal relic, we examine current and projected collider and dark matter constraints on the focus point region. We demonstrate that the focus point region is currently constrained by multiple dark matter experiments, and future sensitivy on multiple fronts will probe large portions of the parameter space.

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One of the driving motivations for supersymmetry (SUSY) theories is the hierarchy problem of the Standard Model (SM). The presence of superpartners at the weak scale cancels quadratic divergences in the Higgs potential, drastically reducing the fine-tuning present in the theory. However, current LHC results generically imply squark masses of $\gtrsim 1$ TeV. In most SUSY models this implies reintroduction of fine-tuning, which, while far less severe than the fine-tuning present in the SM, weakens the motivation of SUSY theories.

This issue is compounded by the discovery of the Higgs boson at the LHC with a mass of $m_h \approx 125.6$ GeV [1, 2]. In the minimal supersymmetric standard model (MSSM), it is well-known that the tree-level Higgs mass cannot exceed $m_Z \simeq 91$ GeV, but radiative corrections raise the Higgs mass significantly. However, achieving a Higgs mass consistent with the experimental determination requires either stop masses of $\mathcal{O}(8-10)$ TeV or a large stop A-term. Large A-terms are non-generic, while stop masses of $\mathcal{O}(8-10)$ TeV reintroduce fine-tuning roughly two orders of magnitude worse than implied by current collider limits.

Relatively heavy scalars are also motivated from precision observables in the flavor and CP violation sectors. General weak-scale SUSY models suffer serious constraints from flavor violating observables, and though well-known mechanisms exist to escape such effects their severity is also reduced by increasing sfermions masses. Moreover, even in such mechanisms CP violation is generally present, and motivates sfermion masses in the multi-TeV range to avoid electron and neutron EDM constraints [3].

One framework which addresses this combination of issues is focus point (FP) supersymmetry [4, 5]. In the MSSM for $\tan\beta \gtrsim 5$, electroweak symmetry breaking requires

$$m_Z^2 \approx -2\mu^2 - 2m_{H_u}^2(m_W) \ , \tag{1}$$

at tree level. If $m_Z^2 \sim \mu^2 \approx \left|m_{H_u}^2\right|$, the theory is relatively natural, while it becomes fine-tuned when $m_Z^2 \ll \mu^2 \approx \left|m_{H_u}^2\right|$. The former condition condition is of course satisfied if all SUSY-breaking masses are $\mathcal{O}(M_{\rm weak})$, but it can also be satisfied if SUSY-breaking masses are significantly larger than m_Z at the SUSY-breaking scale but $m_{H_u}^2 \to 0$ at the weak scale. This mechanism is present in FP SUSY models, where the Higgs potential exhibits "radiative naturalness" due to renormalization group (RG) runnning.

The required boundary conditions are dependent on the SUSY-breaking scale, and for $M_{\rm SUSY-breaking} \sim M_{\rm GUT}$ one solution is the case of unified scalar masses, zero A-terms, and small gaugino masses. This scenario is realized in the constrained MSSM (CMSSM) with $A_0 = 0$ and $M_{1/2} \ll m_0$, producing the "focus point region" of the CMSSM where m_0 is in the multi-TeV range but μ remains weak scale. Fine-tuning in this region is reduced by approximately an order of magnitude relative to generic MSSM models with equivalent stop masses [6].

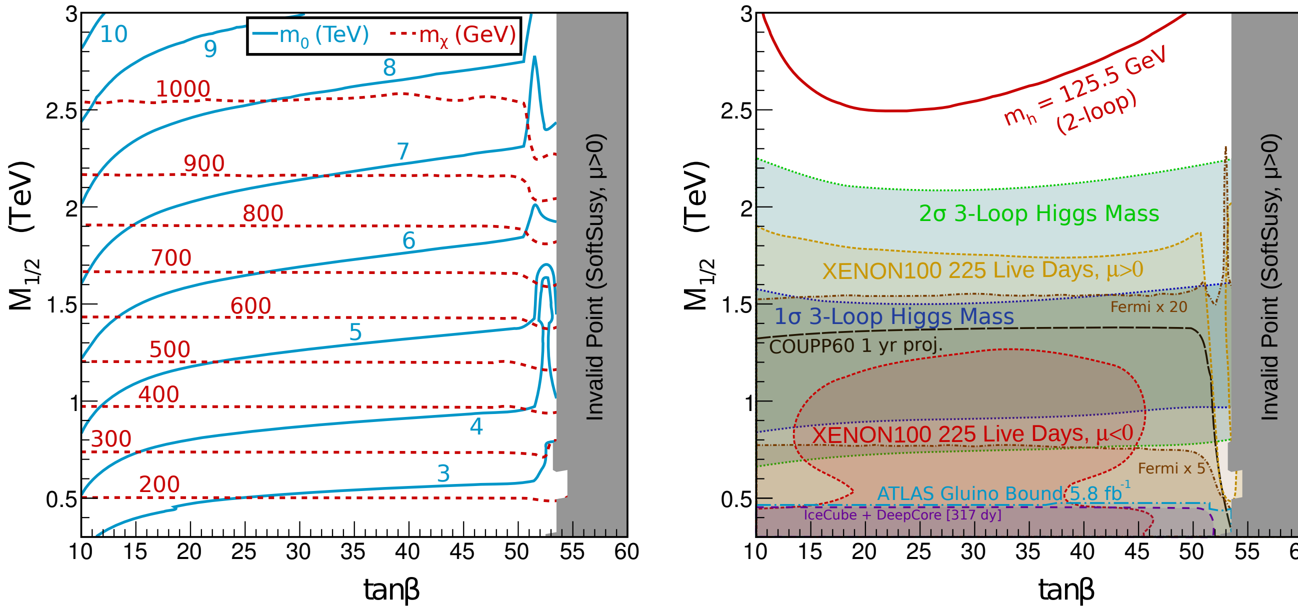
While the collider prospects for the FP region are poor due to large superpartner masses, large portions can be probed at a variety of dark matter experiments. Neutralino dark matter is perhaps the most studied dark matter candidate, and it is well-known that the simplest cases produce a thermal relic density either larger or smaller than the observed dark matter abundance. A pure Bino is generally overabundant while a pure Wino or Higgsino is underabundant for neutralino masses $m_\chi \lesssim 1$ TeV, and some further mechanism is required to bring the relic density in agreement with the observed dark matter abundance. One such mechanism is Bino-Higgsino mixing, which is realized in the FP region due to the relatively small values of μ required for reduced fine-tuning. Significant Bino-Higgsino mixing also enhances both direct detection and annihilation signals, improving the ability of dark matter experiments to probe FP models. Spin-independent direct detection is particularly interesting for such models, with cross-sections within the reach of current and near-future direct detection experiments [3].

In exploring the FP parameter space, a particularly interesting region is the slice wherein the neutralino thermal relic density saturates the observed relic density,

$$\Omega_\chi\left(m_0, M_{1/2}, A_0, \tan\beta, \mathrm{sign}\left(\mu\right)\right) = \Omega_{\rm DM} \ . \tag{2}$$

By fixing the sign of μ and setting $A_0 = 0$ to generate the desireable FP RG behavior, for a particular choice of $\left\{M_{1/2}, \tan\beta\right\}$ there exists a unique value of m_0 for which $\Omega_\chi = \Omega_{\rm DM}$ [7]. This allows the FP region to be studied in the $\left\{M_{1/2}, \tan\beta\right\}$ plane wherein *every point has the correct thermal relic density.* Applying this cosmological constraint allows a larger range of parameters to be studied.

Constraints on the FP region using this framework were studied in Refs. [7, 16], the latter of which (and plots here) used SOFTSUSY 3.1.7 [13] for spectrum generation, MicrOMEGAs 2.4 [17] to calculate the relic density and direct detection processes, and DarkSUSY 5.0.5 [18] to calculate indirect detection rates. Results are shown in Figure 1, using the relic density determination of WMAP with 7 years of data [19]. Figure 1(a) shows the value of m_0 required to achieve $\Omega_\chi = \Omega_{\rm DM}$ and the corresponding neutralino mass m_χ. Generally the required value of m_0 increases with increasing $M_{1/2}$ and decreases with increasing $\tan\beta$. However, for $\tan\beta \gtrsim 50$ the appropriate value shifts downward, as the pseudoscalar Higgs bosons becomes light enough in this region to signficantly alter the relic density calculation.



(a)m_0 and m_χ for $\Omega_\chi \approx 0.23$.

(b)Limits on FP SUSY for $\Omega_\chi \approx 0.23$.

FIG. 1. *The Focus Point Region for* $\Omega_\chi = \Omega_{DM}$. Shown are the values of m_0 and m_χ satisfying the thermal relic density (left) and relevant constraints (right). The collider constraint is extrapolated from ATLAS gluino searches using $5.8 fb^{-1}$ of data with $\sqrt{s} = 8$ TeV [8]. Current dark matter constraints use results from XENON100 with 225 live days [9] and IceCube (w/ DeepCore) results using 317 live days [10]. Projected limits are drawn from projected COUPP60 sensitivity after a 1 year physics run [11] and multiples of the current Fermi-LAT sensitivity from a stacked dwarf spheroidal analysis [12]. The two-loop Higgs mass is determined by SOFTSUSY [13], while the three-loop result uses H3M [14, 15]. Plots are taken from Ref. [16].

Figure 1(b) shows associated constraints upon the FP region. Due to the relatively high squark mass scale, the dominant constraints are derived from searches for gluino pair-production [8]. The associated reach is relatively limited, constraining $M_{1/2} \lesssim 500$ GeV almost independent of $\tan\beta$. Even with current data, direct detection experiments place significantly stronger bounds, with current XENON100 [9] results constraining $M_{1/2} \gtrsim 1.8$ TeV for nearly the entire range of $\tan\beta$ shown if $\mu > 0$, with somewhat stronger bounds at large and small $\tan\beta$. For $\mu < 0$ the constraints are weaker, requiring $M_{1/2} \gtrsim 1$ TeV for a moderate range of $\tan\beta$ but weakening to $M_{1/2} \gtrsim 500$ GeV for small $\tan\beta$ and placing no constraint for $\tan\beta \gtrsim 45$. Spin-independent limits were produced using a strange quark form factor of $f_s = 0.05$ [20–22]. While current spin-dependent results do not have sensitivity to the focus point parameter space, near future results from COUPP60 [11] are expected to constrain $M_{1/2} \lesssim 1.3 - 1.4$ TeV for $\tan\beta \lesssim 50$. Indirect detection experiments are also relevant, with current IceCube [10] results constraining $M_{1/2} \gtrsim 500$ GeV for $\tan\beta \lesssim 50$, producing a bound competitive with current LHC constraints. Moreover, while gamma ray searches currently do not probe the FP region, an order of magnitude improvement on current Fermi-LAT sensitivity from dwarf spheroidals [12] will provide significant sensitivity to $M_{1/2} \sim 700$ GeV $-$ 1.5 TeV. The generation of IceCube and Fermi-LAT bounds are detailed in Ref. [16]. Future experiments on all these fronts will have the ability to probe significantly larger regions of FP parameter space.

These sensitivities are especially important given recent computations of the Higgs mass with leading 3-loop effects included in models with multi-TeV scalars [16, 23]. Generally 2-loop determinations require stop masses of $\mathcal{O}(8 - 10)$ TeV, which in the FP region with $A_0 = 0$ places the appropriate Higgs mass at $M_{1/2} \gtrsim 2.5$ TeV, beyond the reach of current or near-future experiments. However, including 3-loop effects reduces the required stop mass to $3 - 4$ TeV even without left-right mixing, improving the prospect of dark matter and collider experiments to probe FP models, with a favored region of 700 GeV $\lesssim M_{1/2} \lesssim 2.2$ TeV [16].

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