LHC HIGGS BOSON IMPLICATIONS FOR SUPERSYMMETRY

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OUTLINE

- SUSY AND THE LHC
- NATURALNESS
- FOCUS POINT SUSY

Work with Matchev, Moroi, Wilczek (1998-2000)
Feng, Matchev, Sanford (1112.3021)
Feng, Sanford (1205.soon)

- GOLDILOCKS SUSY

Feng, Smith, Takayama (2007)
Feng, Surujon, Yu (1205.soon)

SUSY AND THE LHC

- Weak-scale SUSY has long been the dominant paradigm for BSM physics

- Three decades of strong motivations:
  - A natural solution to the gauge hierarchy problem
  - An excellent DM candidate
  - Gauge coupling unification

- This is now being challenged by the LHC
  - Null results from superpartner searches
  - Results from Higgs boson searches

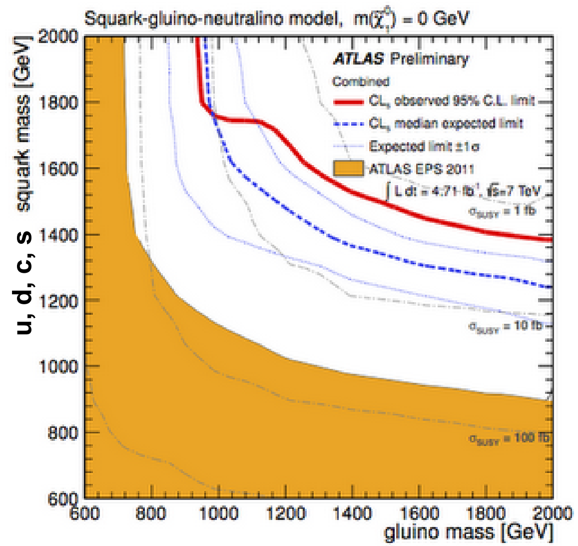
REACTIONS

- The LHC results have led to all sorts of statements that I disagree with. The Top 10:
  10. SUSY is now excluded
  9. Weak-scale SUSY is now excluded
  8. The CMSSM is now excluded
  7. Naturalness requires light top squarks
  6. A 125 GeV Higgs requires physics beyond the MSSM
  5. Particle physics is in trouble
  4. We should all be depressed
  3. We shouldn't be depressed, but we should start preparing to be depressed
  2. We should stop thinking about naturalness
  1. String theory predicts a 125 GeV Higgs

SUPERPARTNER SEARCHES

- In conventional scenarios, these require superpartner masses to be at or above 1 TeV
- Many find these results depressing, but why?
  - Naturalness: m ~ 1 TeV → 1% fine-tuning
  - DM: neutralinos still excellent candidates
  - Gauge coupling unification: fine even if scalars very heavy

Feng, Matchev (2000)



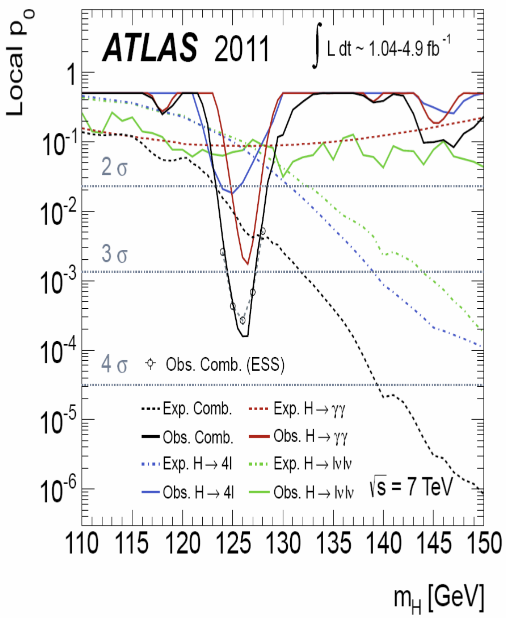
- In fact, there are good reasons to expect superpartners to be heavy. Consider 1st and 2nd generation squarks and sleptons
  - Naturalness allows masses far above the TeV scale
  - Flavor constraints generically require masses far above a TeV
  - Even in flavor-conserving scenarios (GMSB, AMSB, …), EDM constraints generically require masses well above a TeV

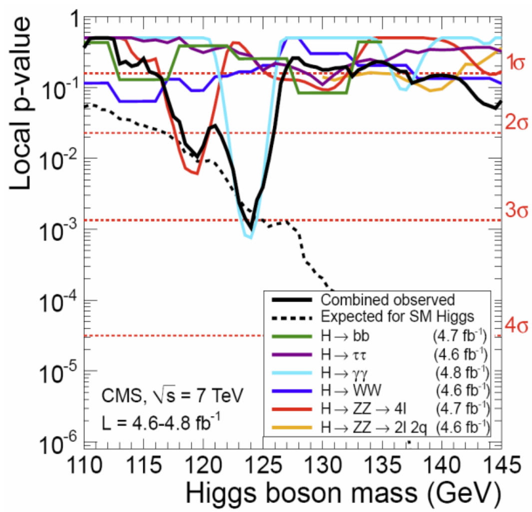
Drees (1986)

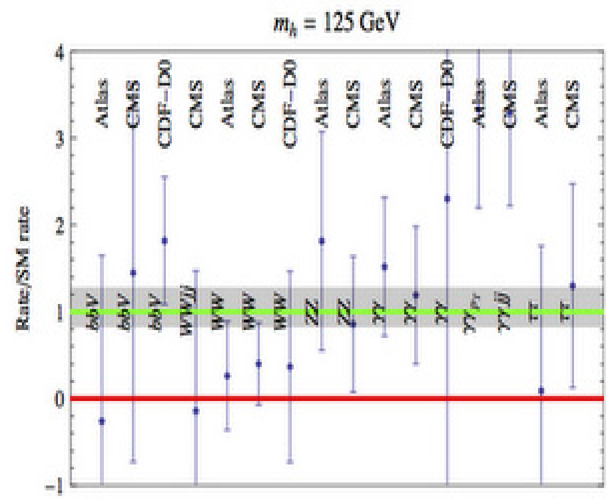
- LHC SUSY searches do little to diminish the appeal of SUSY

HIGGS BOSONS AT LHC

- Higgs search results are far more interesting





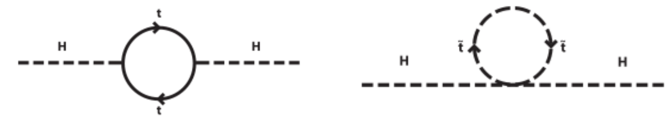


Giardino, Kannike, Raidal, Strumia (2012)

- Light Higgs windows (GeV): [117.5, 118.5], [122.5, 127.5]
- ~3σ signals around 126 GeV (ATLAS), 124 GeV (CMS)
- No strong indications of non-SM Higgs couplings

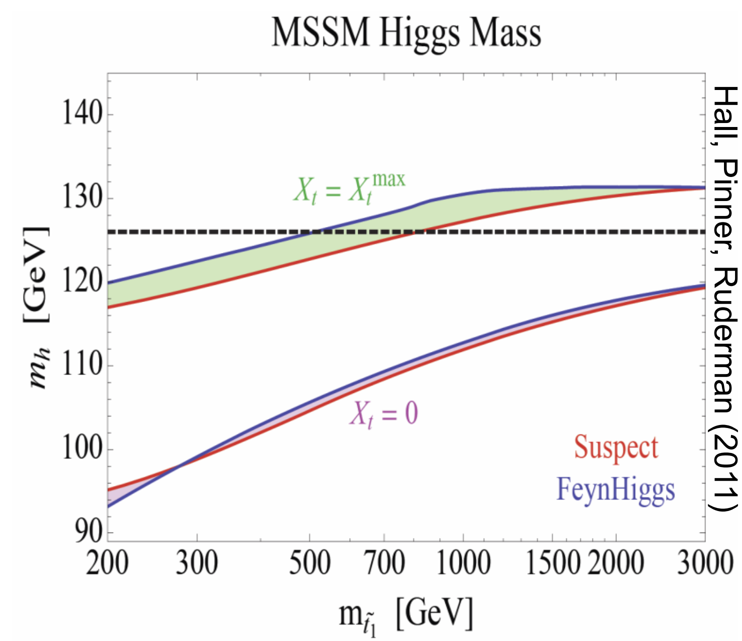
HIGGS RESULTS AND SUSY

- 30,000 foot view: great for SUSY



- Closer view: challenging for SUSY. Naively:
  - Higgs mass requires heavy top squarks
  - Naturalness requires light top squarks

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$



- This tension is much more direct than the tension created by bounds from superpartner searches

- It has been present (to a lesser degree) since LEP2

NATURALNESS

- Two approaches:

- Option 1: “I know it when I see it.” Justice Potter Stewart

- Option 2: Quantify with some well-defined naturalness prescription

- Option 1 acknowledges that naturalness is subjective, but is a non-starter. Option 2 provides an opportunity for discussion and insights, as long as its limitations are appreciated.

A NATURALNESS PRESCRIPTION

- Step 1: Choose a framework with input parameters. E.g., mSUGRA with

$$\left\{P_{\text{input}}\right\} = \left\{m_0, M_{1/2}, A_0, \tan\beta, \text{sign}(\mu)\right\}$$

- Step 2: Fix all remaining parameters with RGEs, low energy constraints. E.g., at the weak scale, tree-level,

$$\frac{1}{2}m_Z^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

- Step 3: Choose a set of parameters as free, independent, and fundamental. E.g., mSUGRA with

$$\{a_i\} = \{m_0, M_{1/2}, A_0, B_0, \mu_0\}$$

- Step 4: Define sensitivity parameters

$$c_i \equiv \left|\frac{\partial \ln m_Z^2}{\partial \ln a_i^2}\right|$$

Ellis, Enqvist, Nanopoulos, Zwirner (1986)
Barbieri, Giudice (1988)

- Step 5: Define the fine-tuning parameter

$$c = \max\{c_i\}$$

COMMENTS

- Step 1: Choose a framework with input parameters. E.g., mSUGRA with

$$\{P_{\text{input}}\} = \{m_0, M_{1/2}, A_0, \tan\beta, \text{sign}(\mu)\}$$

  This is absolutely crucial. Generic SUSY-breaking is excluded, there must be structure leading to correlated parameters, and the correlations impact naturalness. There is no model-independent measure of naturalness.

- Step 2: Fix all remaining parameters with RGEs, low energy constraints. E.g., at the weak scale

$$\frac{1}{2}m_Z^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

  Important to refine this to include 2-loop RGEs, 1-loop threshold corrections, minimize the potential at some appropriate scale (typically, the geometric mean of stop masses).

COMMENTS

- Step 3: Choose a set of parameters as free, independent, and fundamental. E.g., mSUGRA with $\{a_i\} = \{m_0, M_{1/2}, A_0, B_0, \mu_0\}$

  A popular choice is $\{a_i\} = \{\mu_0\}$, which leads to $c = 2\mu^2/m_Z^2$. This is a simple, but completely deficient and misleading, measure of naturalness.

  Should we include other parameters, like y_t?

  – No – Ellis, Enqvist, Nanopoulos, Zwirner (1986); Ciafaloni, Strumia (1996), Bhattacharyya, Romanino (1996); Chan, Chattopadhyay, Nath (1997); Barbieri, Strumia (1998); Giusti, Romanino, Strumia (1998); Chankowski, Ellis, Olechowski, Pokorski (1998); …
  – Yes – Barbieri, Giudice (1988); Ross, Roberts (1992); de Carlos, Casas (1993); Anderson, Castano (1994); Romanino, Strumia (1999); …

  No – we are trying understand the naturalness of the superpartner mass "cutoff," so include only dimensionful SUSY breaking parameters. Fine-tuning with respect to the top mass is better viewed as non-genericity.

  Note: this is not an issue of what is measured and what isn't: with our current understanding, if μ were measured to be 1 EeV ± 1 eV, it will be precisely measured, but completely unnatural.

COMMENTS

- Step 4: Define sensitivity parameters $c_i \equiv \left| \frac{\partial \ln m_Z^2}{\partial \ln a_i^2} \right|$.

Ellis, Enqvist, Nanopoulos, Zwirner (1986)
Barbieri, Giudice (1988)

Why not $c_i \equiv \left| \frac{\partial \ln m_Z^2}{\partial \ln a_i} \right|$ (original definition) or $c_i \equiv \left| \frac{\partial \ln m_Z}{\partial \ln a_i^2} \right|$?

Factors of 2 or 4 are completely insignificant.

- Step 5: Define the fine-tuning parameter $c = \max\{c_i\}$.

Why not add in quadrature? What if c is large for all possible parameter choices (cf. Λ_{QCD}).?

De Carlos, Casas (1993); Anderson, Castano (1994)

And finally, what is the maximal natural value for c – 10, 100, 1000, … ? If SUSY reduces c from 10^{32} to 1000, isn't that enough?

GENERAL STRATEGIES

- Focus Point SUSY: Dynamically generated naturalness

  Feng, Matchev, Moroi (1999); Feng, Matchev, Wilczek (2000); Feng, Matchev (2000); Abe, Kobayashi, Omura (2007); Horton, Ross (2009); Asano, Moroi, Sato, Yanagida (2011); Akula, Liu, Nath, Peim (2011); Feng, Matchev, Sanford (2011); Younkin, Martin (2012); …

- Hidden Higgs, Buried Higgs: Make m_h < 115 GeV compatible with collider constraints

  Dermisek, Gunion (2005); Bellazzini, Csaki, Falkowski, Weiler (2009); …

- Golden region, mirage mediation: Lower the messenger scale to the weak scale, generate large stop mixing (a version of FP SUSY)

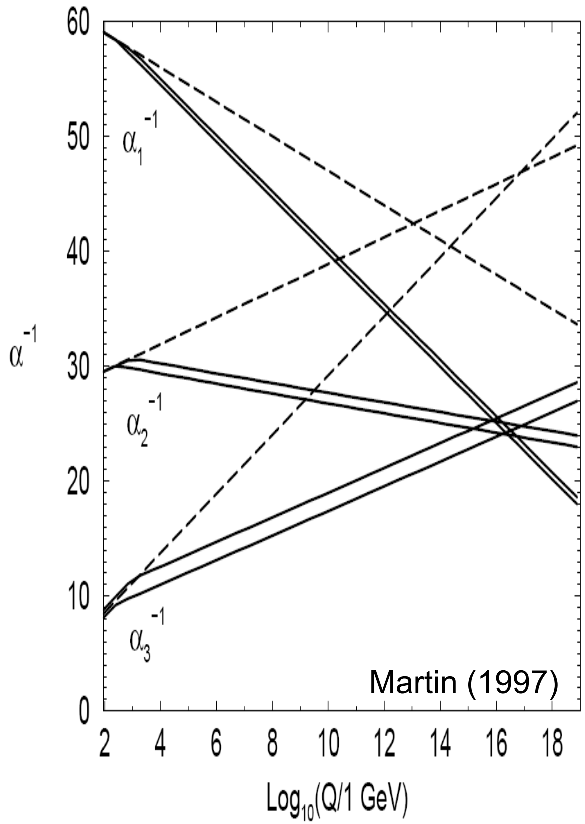
  Kitano, Nomura (2005); Perelstein, Spethmann (2007)…

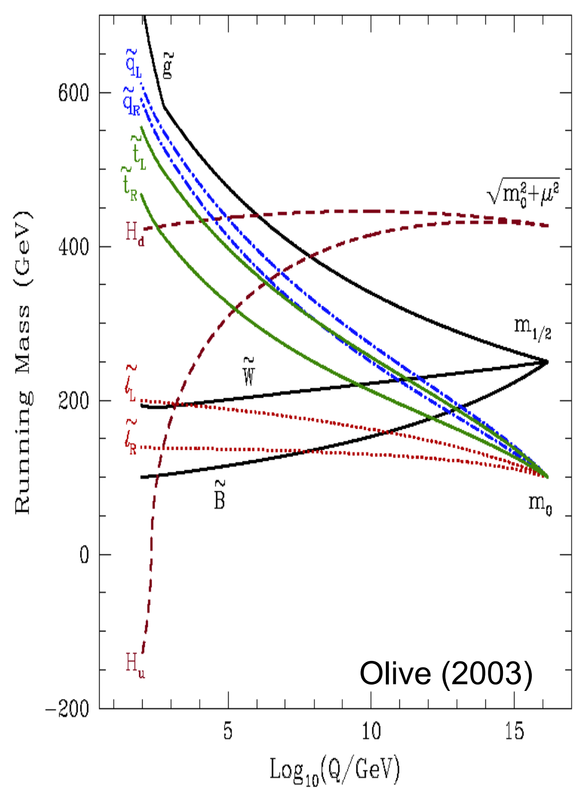
- Beyond the MSSM (NMSSM,…): Increase particle content to raise m_h naturally, accommodate non-SM Higgs properties

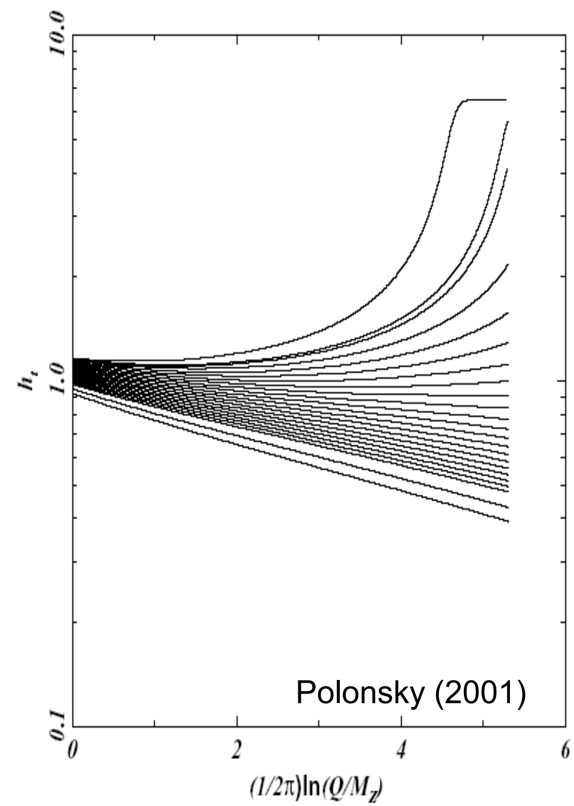
  Hall, Pinner, Ruderman (2011); Ellwanger (2011); Arvanitaki, Villadoro (2011); Gunion, Jiang, Kraml (2011); Perez (2012); King, Muhlleitner, Nevzorov (2012); Kang, Li, Li (2012);…

FOCUS POINT SUSY

- RGEs play a crucial role in almost all of the main motivations for weak-scale SUSY: coupling constant unification, radiative EWSB, top quark quasi-fixed point. What about naturalness?







FP SUSY: ANALYTIC EXPLANATION

- For low and moderate tanβ,

$$\frac{1}{2}m_Z^2 = -\mu^2 + \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1}$$
$$\approx -\mu^2 - m_{H_u}^2$$

- So focus on scalar mass $m_{H_u}^2$

- Schematic form of the RGEs:

$$\frac{dg}{d\ln Q} \sim -g^3$$
$$\frac{dy}{d\ln Q} \sim -g^2 y + y^3$$
$$\frac{dM}{d\ln Q} \sim -g^2 M$$
$$\frac{dA}{d\ln Q} \sim g^2 M + y^2 A$$
$$\frac{dm^2}{d\ln Q} \sim -g^2 M^2 + y^2 A^2 + y^2 m^2$$

- Assume m, A >> $M_{1/2}$

- If there is one dominant Yukawa,

$$\dot{\boldsymbol{m}}^2 = -\frac{y^2}{16\pi^2}\boldsymbol{N}\boldsymbol{m}^2$$

and the masses evolve as

$$\boldsymbol{m}^2(0) = \sum_i \kappa_i \boldsymbol{e}_i \to \boldsymbol{m}^2(t) = \sum_i \kappa_i \boldsymbol{e}_i e^{-\lambda_i \int^t \frac{y^2}{16\pi^2} dt'}$$

where $(\boldsymbol{e}_i, \lambda_i)$ are the eigenvectors and eigenvalues of *N*.

LOW AND MODERATE TANβ

$$\frac{d}{d\ln Q}\begin{bmatrix} m_{H_u}^2 \\ m_{\bar{U}_3}^2 \\ m_{Q_3}^2 \\ A_t^2 \end{bmatrix} = \frac{y_t^2}{8\pi}\begin{bmatrix} 3 & 3 & 3 & 3 \\ 2 & 2 & 2 & 2 \\ 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 12 \end{bmatrix}\begin{bmatrix} m_{H_u}^2 \\ m_{\bar{U}_3}^2 \\ m_{Q_3}^2 \\ A_t^2 \end{bmatrix}$$

$$\begin{bmatrix} m_{H_u}^2(Q) \\ m_{\bar{U}_3}^2(Q) \\ m_{Q_3}^2(Q) \\ A_t^2(Q) \end{bmatrix} = \kappa_{12}\begin{bmatrix} 3 \\ 2 \\ 1 \\ 6 \end{bmatrix} e^{12I(Q)} + \kappa_6 \begin{bmatrix} 3 \\ 2 \\ 1 \\ 0 \end{bmatrix} e^{6I(Q)} + \kappa_0 \begin{bmatrix} 1 \\ 0 \\ -1 \\ 0 \end{bmatrix} + \kappa_0' \begin{bmatrix} 0 \\ 1 \\ -1 \\ 0 \end{bmatrix}$$

- $I(Q) = \int_{\ln Q_0}^{\ln Q} \frac{y_t^2(Q')}{8\pi^2} d\ln Q'$. Using $e^{6I(m_W)} \simeq \frac{1}{3}$, we find

$$\begin{bmatrix} m_{H_u}^2(m_{\rm GUT}) \\ m_{\bar{U}_3}^2(m_{\rm GUT}) \\ m_{Q_3}^2(m_{\rm GUT}) \\ A_t^2(m_{\rm GUT}) \end{bmatrix} = m_0^2 \begin{bmatrix} 1 \\ 1+x-3y \\ 1-x \\ 9y \end{bmatrix} \to \begin{bmatrix} m_{H_u}^2(m_W) \\ m_{\bar{U}_3}^2(m_W) \\ m_{Q_3}^2(m_W) \\ A_t^2(m_W) \end{bmatrix} = m_0^2 \begin{bmatrix} 0 \\ \frac{1}{3}+x-3y \\ \frac{2}{3}-x \\ y \end{bmatrix}$$

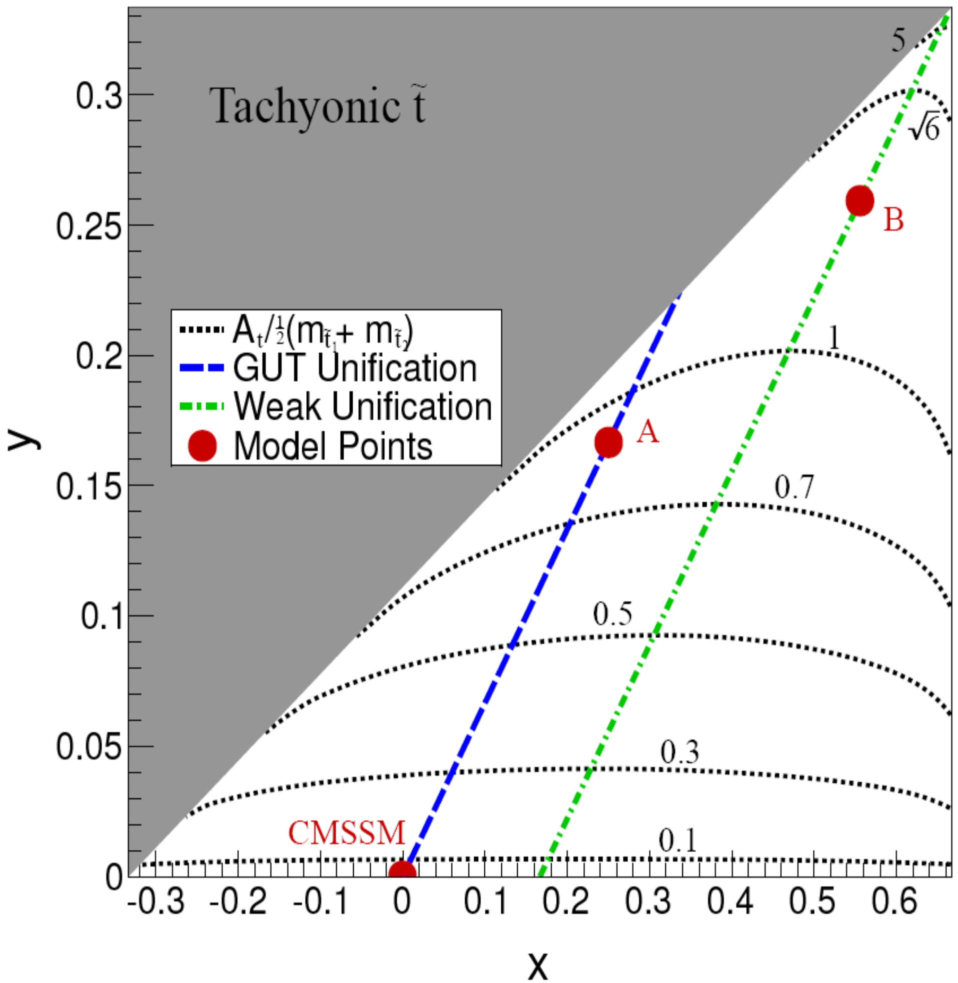
- Given the GUT-scale boundary conditions, m_{Hu} evolves to zero for any m_0, independent of x, y, and all other soft parameters.

FP SUSY PARAMETER SPACE

- This analysis contains
  - CMSSM: (x,y) = (0,0)
  - Previous work: y=0
  - GUT models: blue line

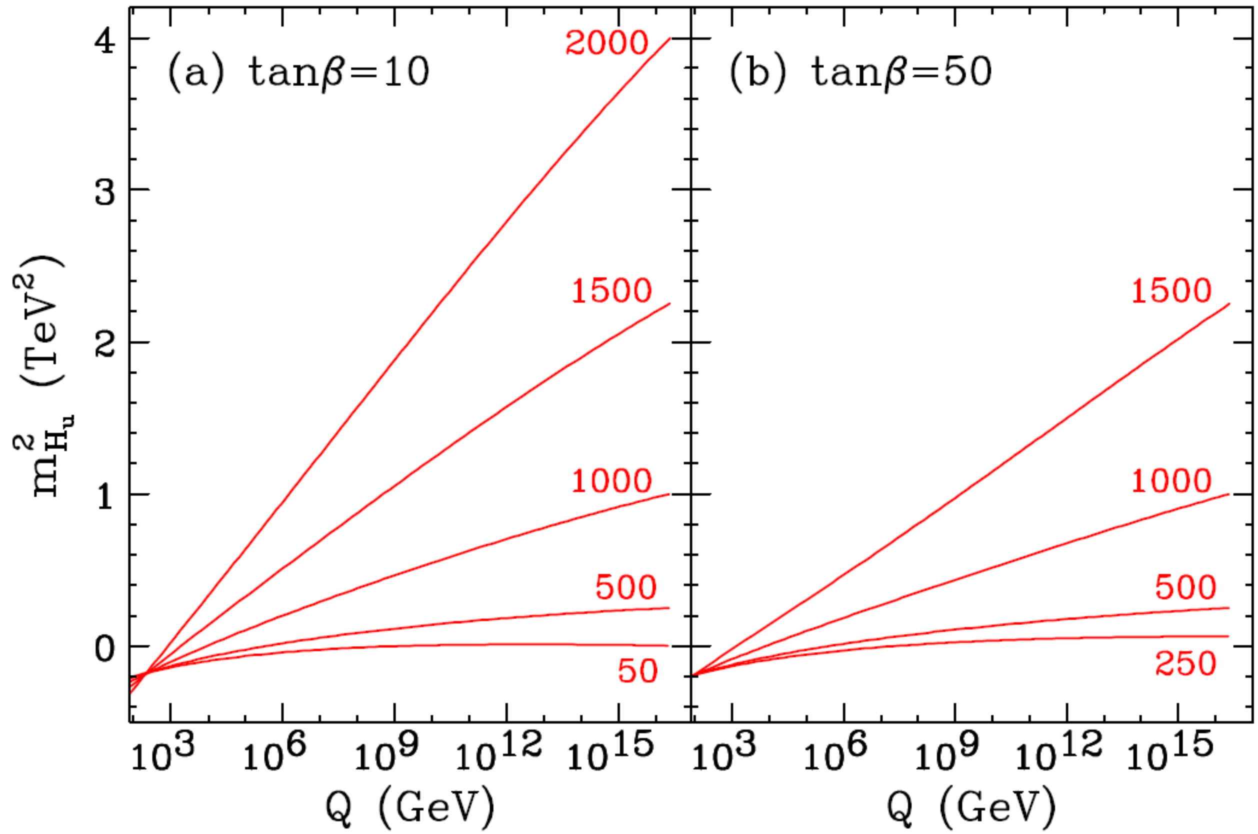
- Provides new FP SUSY models with large stop mixing

Feng, Sanford (2012)



FP SUSY: GRAPHICAL EXPLANATION

- Families of RGEs have a focus point (cf. fixed point)
- Dynamically-generated hierarchy between the stop masses and the weak scale



- The weak scale is insensitive to variations in the fundamental parameters
- All natural theories with heavy stops are focus point theories

FP SUSY: NUMERICAL EXPLANATION

- By dimensional analysis, can write m_{Hu} in the following form and see the FP numerically:

$$
\begin{aligned}
-2m_{Hu}^2(M_z) \;=\; & 5.45M_3^2 + 0.0677M_3M_1 - 0.00975M_1^2 \\
& +0.470M_2M_3 + 0.0135M_1M_2 - 0.433M_2^2 \\
& +0.773A_tM_3 + 0.168A_tM_2 + 0.0271A_tM_1 \\
& +0.214A_t^2 \boxed{-1.31m_{Hu}^2 + 0.690m_{Q_3}^2 + 0.690m_{U_3}^2}
\end{aligned}
$$

Abe, Kobayashi, Omura (2007)

- In fact, special cases of FP SUSY can be seen in the results of some early (pre-top quark) studies

Alvarez-Gaume, Polchinski, Wise (1983); Barbieri, Giudice (1988)

- The underlying structure is obscured by the numerical calculations, but this is also a way forward to find new FP possibilities, e.g., involving non-universal gaugino masses

Abe, Kobayashi, Omura (2007); Horton, Ross (2009); Younkin, Martin (2012)

IMPLICATIONS

- Naturalness is useful if it leads us toward theories that describe data. How does a theory with heavy scalars fare?
- FP SUSY beautifully fits all the data
  - Higgs boson mass
  - Coupling constant unification and proton decay
  - Natural suppression of EDMs
  - Excellent dark matter candidate (mixed Bino-Higgsino)

Feng, Matchev (2000); Feng, Matchev, Wilczek (2000)

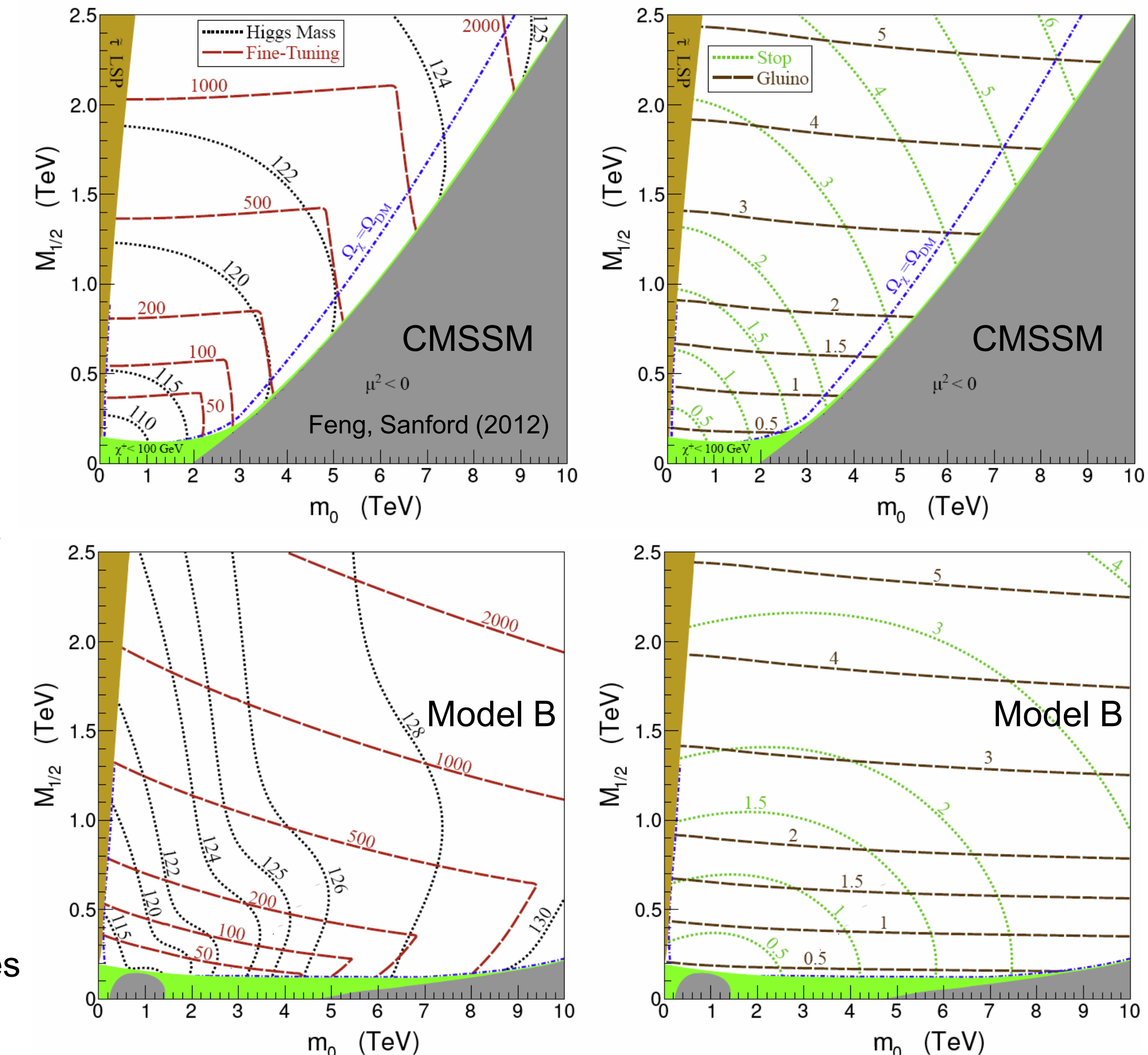
- Cf. split SUSY: Essentially identical phenomenology with the added features of being unnatural and motivated by the anthropic principle

Arkani-Hamed, Dimopoulos (2004); Giudice, Romanino (2004)

HIGGS BOSON

- Consider two representative cases:
  - CMSSM
  - Model B with large A-terms
- Higgs mass uncertainties
  - Experiment: ~1-2 GeV
  - Theory: ~ few GeV
- Can simultaneously get
  - 125 GeV Higgs
  - in the MSSM
  - with percent-level fine-tuning

  First models with these properties



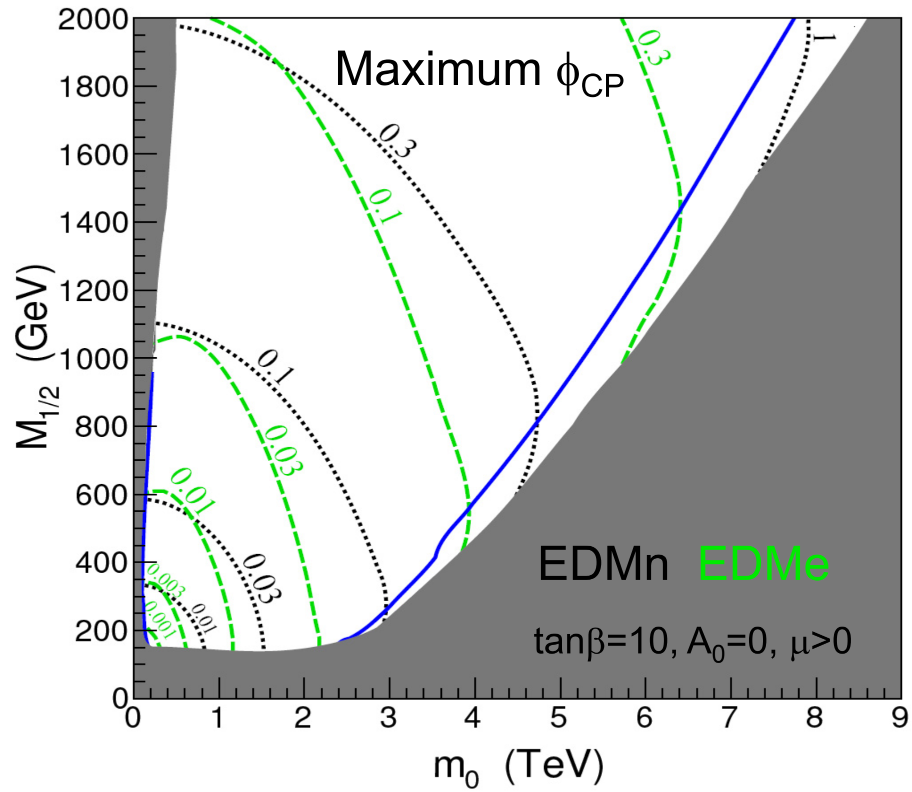
ELECTRIC DIPOLE MOMENTS

- EDMs are CP-violating, but flavor-conserving, not eliminated by scalar degeneracy
- Stringent bounds on electron and neutron EDMs

Regan et al. (2002)
Baker et al. (2006)

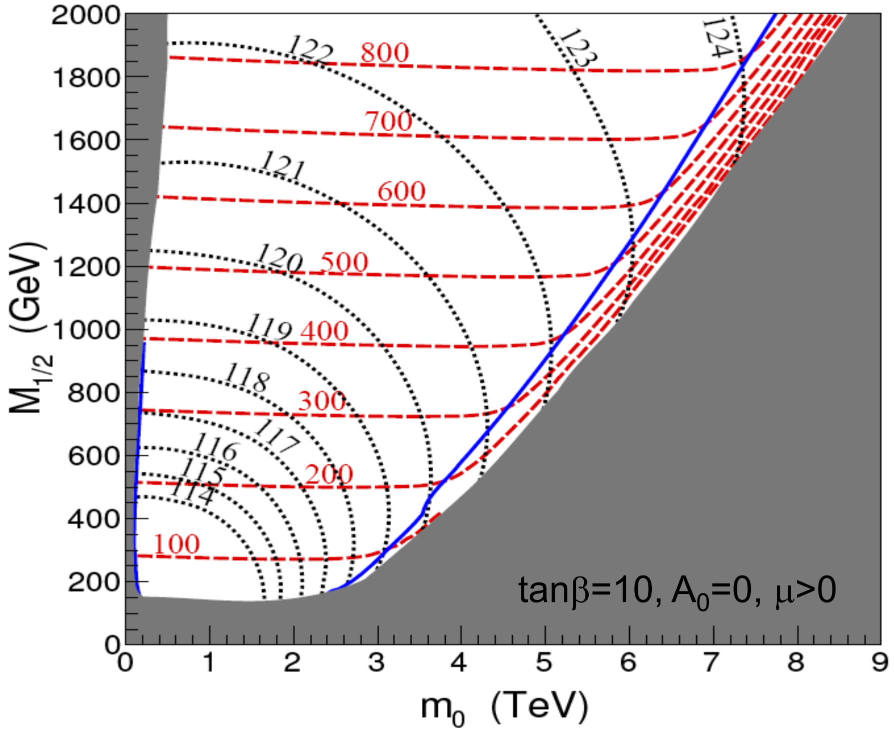
- O(1) phases → multi-TeV scalars
- EDMs naturally satisfied in FP SUSY, but just barely; ongoing searches promising

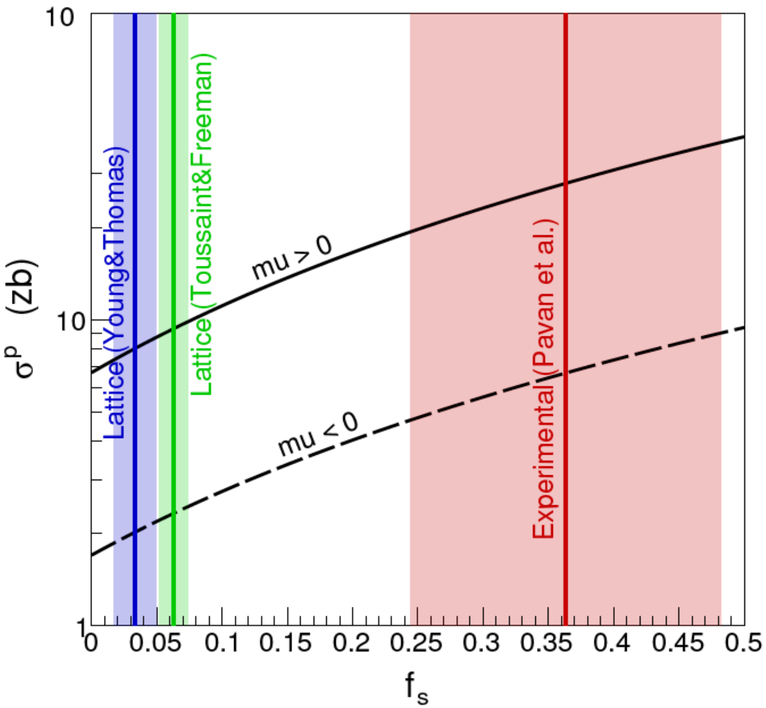
$$d_f = \frac{1}{2} e\, m_f\, g_2^2\, |M_2 \mu|\, \tan\beta\, \sin\phi_{\rm CP}\, K_C(m^2_{\tilde{f}_L}, |\mu|^2, |M_2|^2)$$



Feng, Matchev, Sanford (2011)

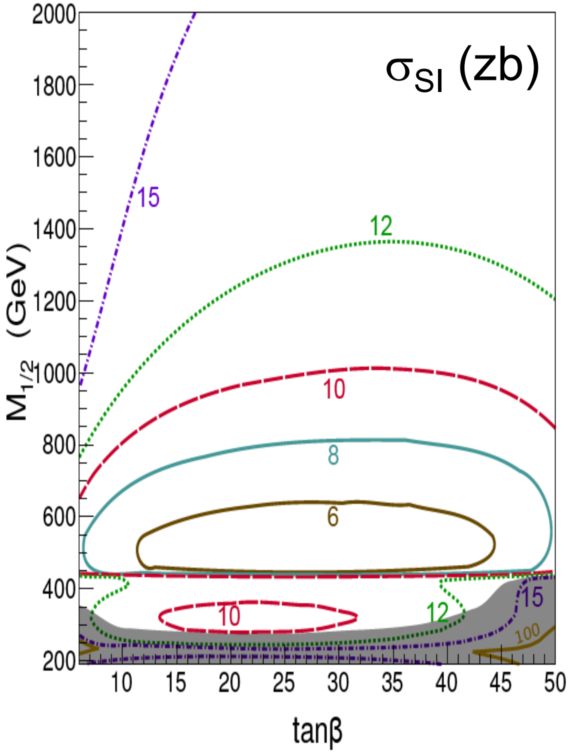
NEUTRALINO DARK MATTER



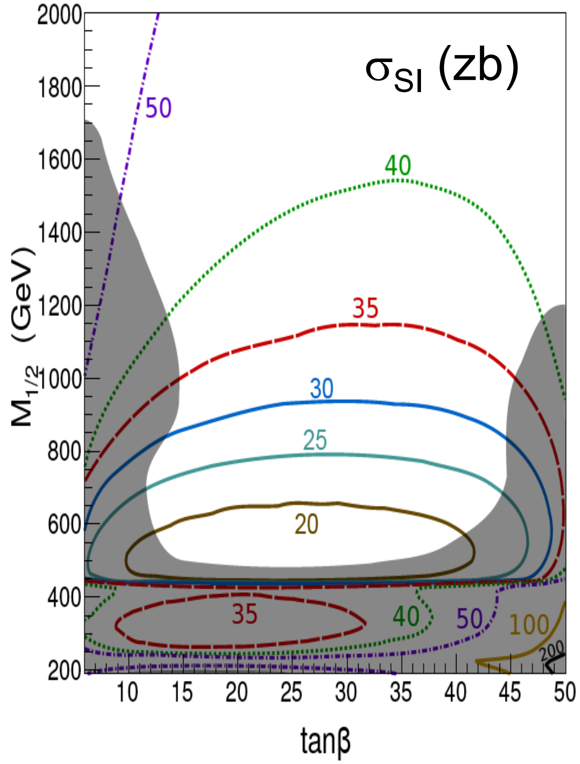


- Masses: ~ 60 GeV – TeV
- Direct detection cross section: strong dependence on strange content

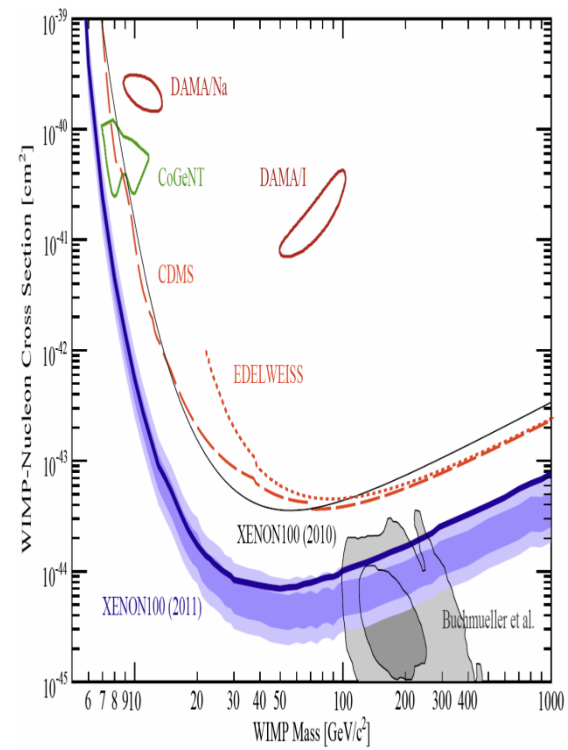
NEUTRALINO DIRECT DETECTION



(a) $f_s = 0.05,\ \mu > 0$



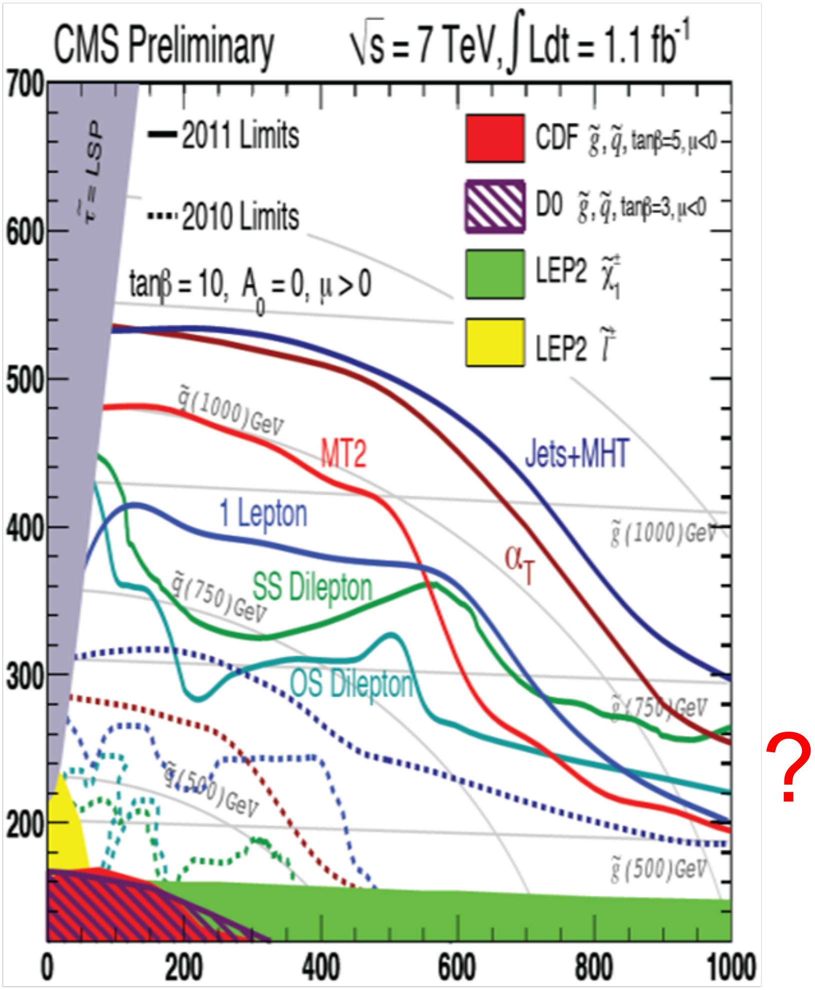
(b) $f_s = 0.36,\ \mu > 0$



- Not excluded, but a signal should be seen in the near future (e.g., XENON at IDM2012, …)

LHC

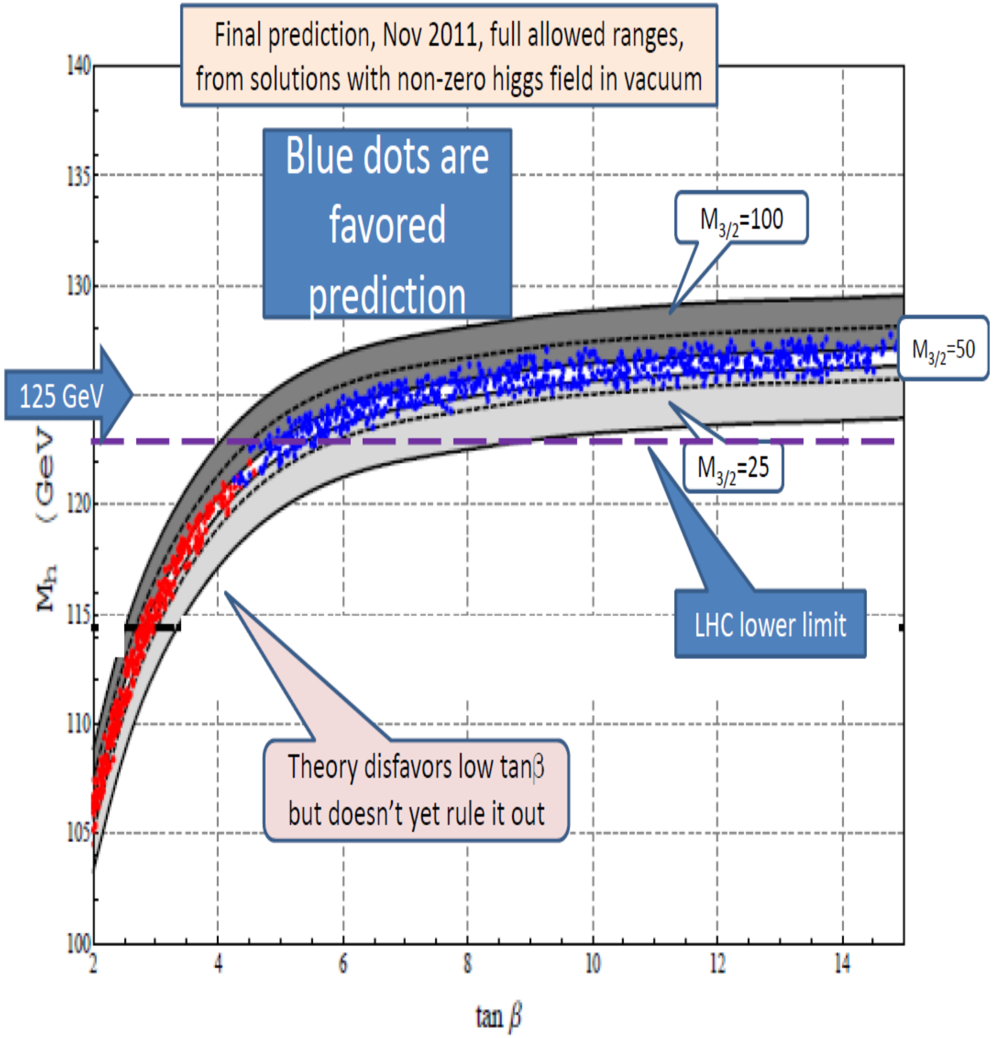
- Commonly heard statements: SUSY is in trouble, CMSSM is excluded
- Actually, the CMSSM has never been more useful and likely to be (effectively) correct
- Custom-built for analysis: Higgs results, etc. → SUSY is already a simplified model, with just a few parameters (μ, M_1, M_2, M_3, $\tan\beta$)
- More attention needed



STRING THEORY "PREDICTIONS"

- Kane: String theory is testable in the same sense as F=ma is testable. "String theory is already or soon being tested in several ways, including correctly predicting the recently observed Higgs boson properties and mass."

- String theory does not naturally predict a 125 GeV Higgs



GOLDILOCKS SUSY

Kitano, Low (2005); Feng, Smith, Takayama (2007); Feng, Surujon, Yu (2012)

- Consider GMSB: beautiful framework that suppresses flavor violation

- The Higgs mass is a special problem for GMSB: A = 0 → heavy stops

Draper, Meade, Reece, Shih (2011); Evans, Ibe, Shirai, Yanagida (2012)

- GMSB also has other special problems:

Dark Matter

- Neutralino DM not viable: solution to flavor problems → $m_{\tilde{G}} < 0.01\ m_\chi$
- keV gravitino DM not viable: $\Omega_{\tilde{G}}\ h^2 \approx 0.1\ (m_{\tilde{G}}\ /\ 80\ \text{eV})$, but Lyman-$\alpha$ → $m_{\tilde{G}} > 2$ keV

Viel et al. (2006); Seljak et al. (2006)

EDMs

- GMSB suppresses flavor, but not CP violation (e.g., from μ, $M_{1/2}$ phase difference)
- Electron EDM → selectrons > 2 TeV, GMSB relations → squarks > 5 TeV

MINIMAL GMSB

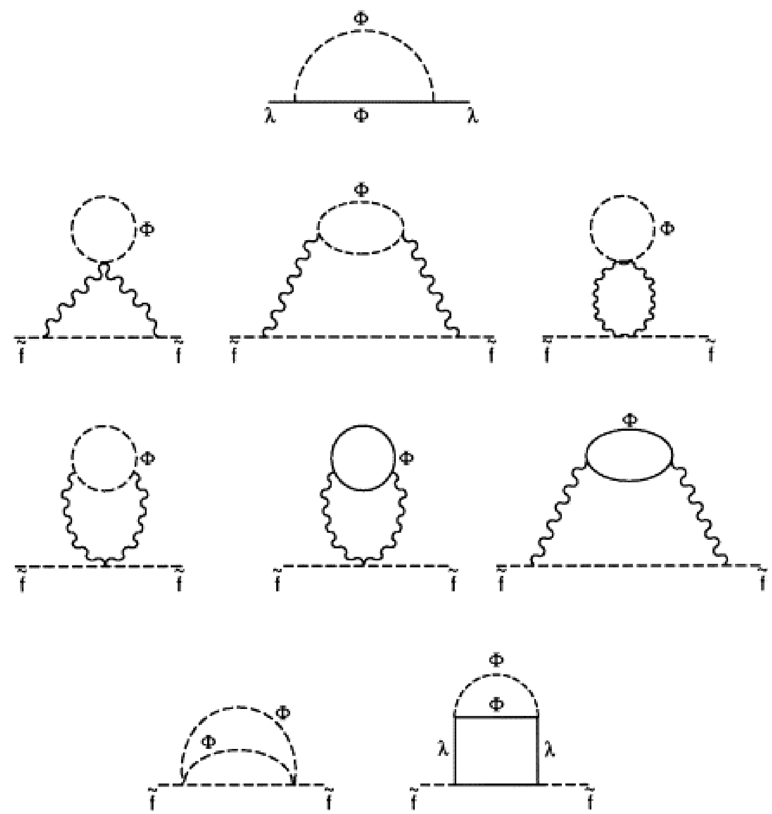
- Let's take all the data at face value, plug it into minimal GMSB

$$\Lambda = F/M_m$$

$$m_{\tilde{G}} = \frac{F}{\sqrt{3} M_*}$$

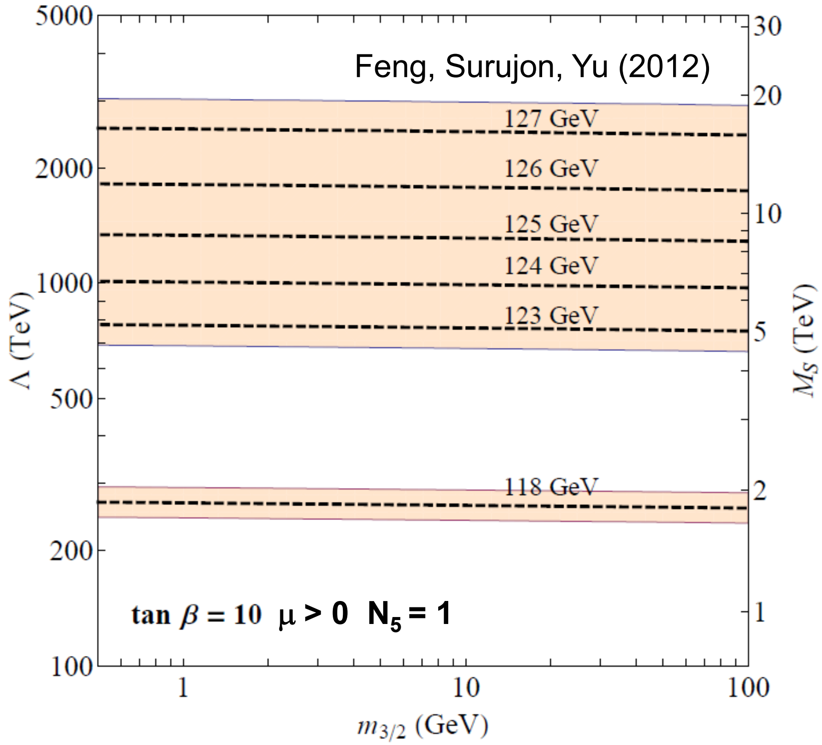
$$m_{\tilde{f}}^2(M_m) = 2 N_5 \Lambda^2 \sum_{a=1}^{3} C_a^f \left[\frac{\alpha_a(M_m)}{4\pi} \right]^2$$

$$M_a(M_m) = N_5 \Lambda \frac{\alpha_a(M_m)}{4\pi}$$

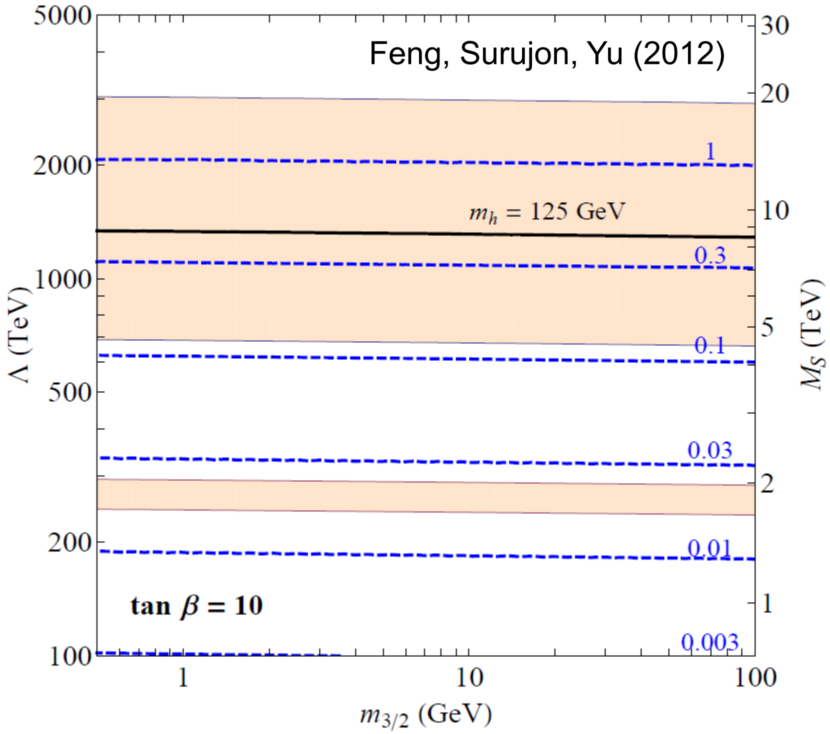


HIGGS AND EDMS

- Higgs Mass $\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} = M_S$



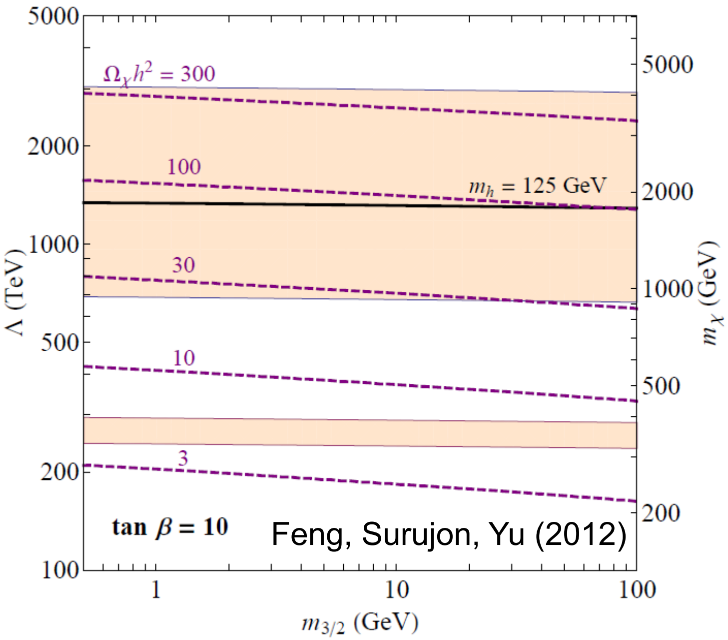
- Electron EDM (assumed CP phase in blue)



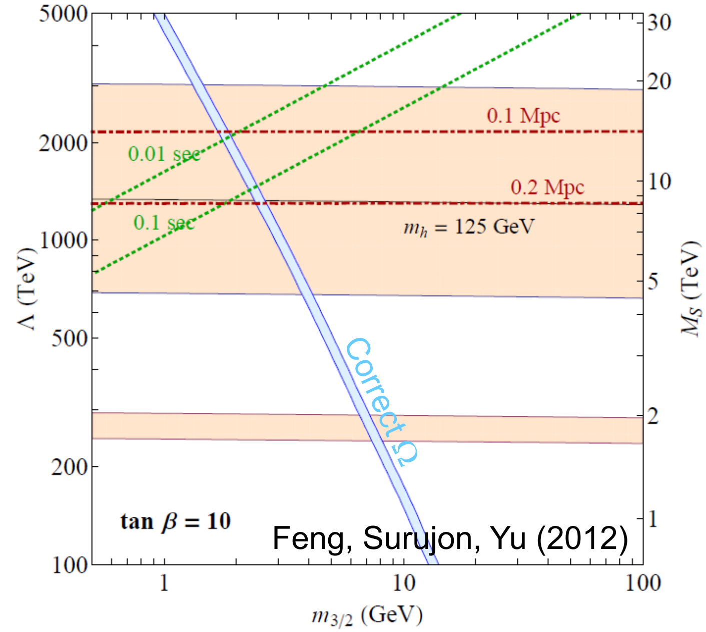
DARK MATTER

- Such large masses → neutralinos are vastly over-produced in the early universe. But then they can decay to gravitinos with the right relic density!

Neutralino Ω



Gravitino Ω



- Why "Goldilocks":
  - Gravitinos are light enough to solve the flavor problem
  - Gravitinos are heavy enough to be all of DM

GOLDILOCKS COSMOLOGY

- TeV χ → GeV gravitinos
- Several constraints
  - Relic density

$$\Omega_{\tilde{G}} h^2 = (m_{\tilde{G}}/m_\chi)\Omega_{\chi^0} h^2$$

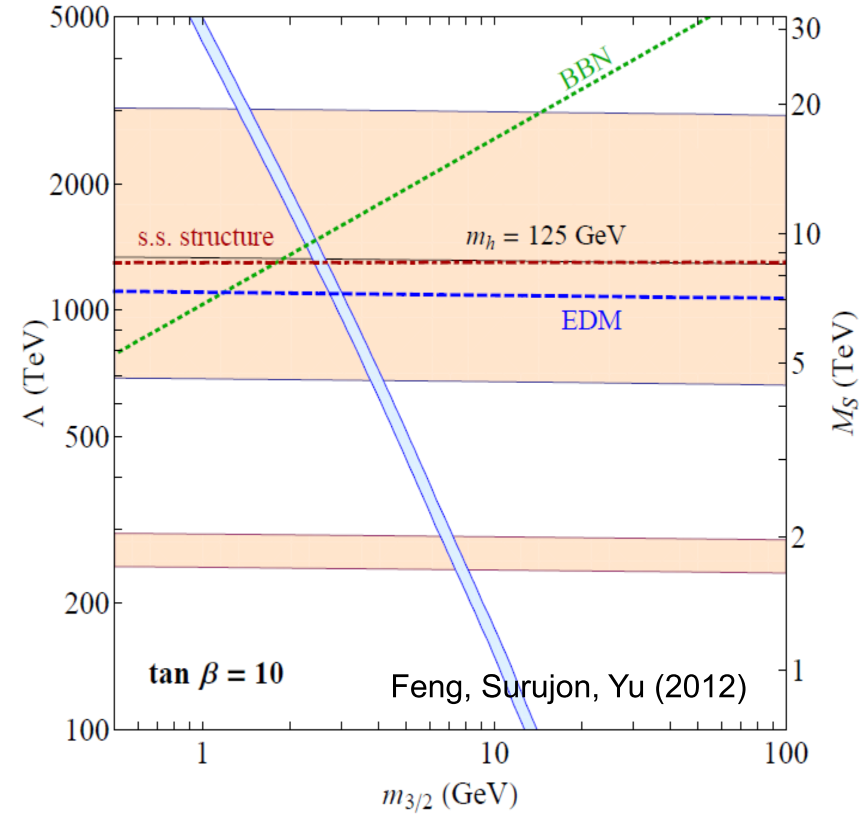
  - Decays before BBN

$$\tau_\chi \simeq \frac{48\pi m_{\tilde{G}}^2 M_*^2}{m_\chi^5} \simeq 0.02 \text{ sec} \left(\frac{m_{\tilde{G}}}{1 \text{ GeV}}\right)^2 \left(\frac{2 \text{ TeV}}{m_\chi}\right)^5$$

  - Cold enough

$$\lambda_f \simeq 1.0 \text{ Mpc} \left[\frac{u_\tau^2 \tau}{10^6 \text{s}}\right]^{1/2} \left[1 - 0.07 \ln\left(\frac{u_\tau^2 \tau}{10^6 \text{ s}}\right)\right]$$

$$u_\tau \equiv |\vec{p}_{\tilde{G}}|/m_{\tilde{G}} \approx \frac{m_\chi}{2m_{\tilde{G}}}$$



- All constraints point to the same region of parameter space
- Naturalness? Perhaps FP SUSY in GMSB

Agashe (1999)

SUMMARY

- LHC results do not exclude weak-scale SUSY, but Higgs boson results are changing what SUSY models are allowed, preferred

- Focus Point SUSY
  - 125 GeV Higgs in gravity-mediated SUSY
  - minimal field content and %-level fine-tuning are consistent
  - fits all data so far; gauginos, Higgsinos, possibly stops at LHC
  - DM is neutralino WIMPs, exciting prospects for near future

- Goldilocks SUSY
  - 125 GeV Higgs in GMSB SUSY
  - heavy superpartners, correct EDMs, cosmology
  - late decays of neutralinos to gravitino DM