3-LOOP HIGGS MASS AND DARK MATTER IMPLICATIONS FOR SUSY AT THE LHC

Based on work with
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[1304.1159,1306.2318]

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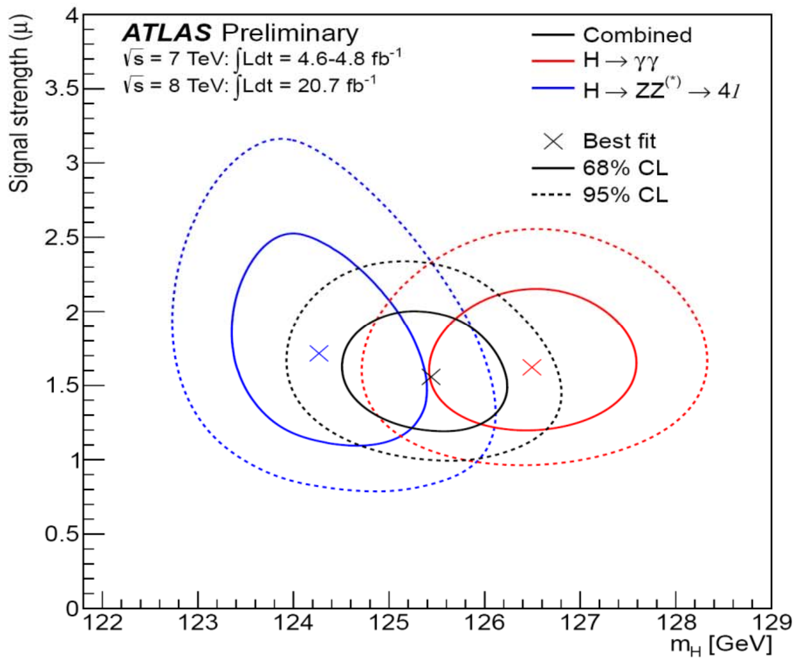
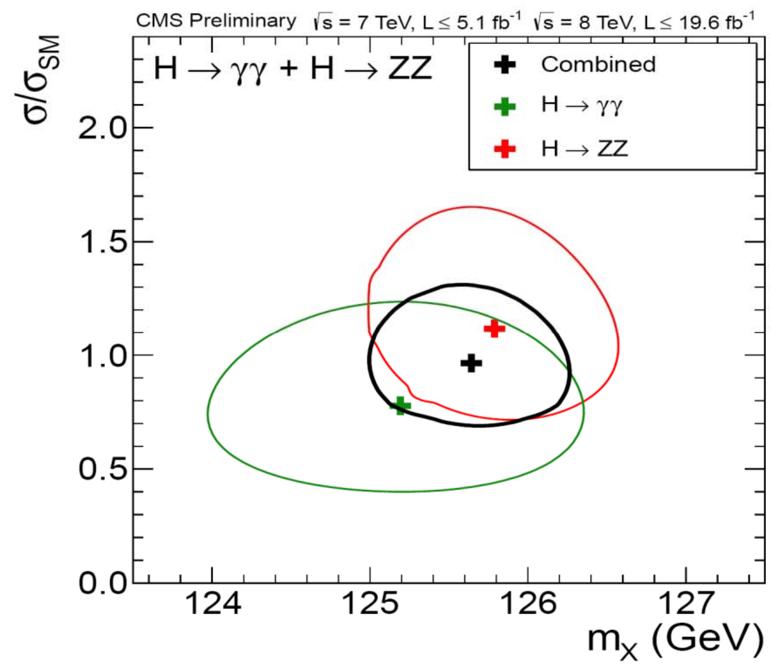
KITP, UC Santa Barbara, LHC Workshop, 10 July 2013

PRECISION HIGGS: EXPERIMENT





$$\left.\begin{array}{r}\text{ATLAS (combined)}: \ 125.5 \pm 0.2 \ {}^{+0.5}_{-0.6} \ \text{GeV} \\ \text{CMS (combined)}: \ 125.7 \pm 0.3 \pm 0.3 \ \text{GeV}\end{array}\right\} \Rightarrow 125.6 \pm 0.4 \ \text{GeV}$$

- In less than a year, the Higgs has gone from discovery to precision studies: its mass is now known with a fractional uncertainty smaller than any of the quarks

WHAT DOES THIS MEAN FOR NEW PHYICS?

- Especially interesting for supersymmetry
  - Quartic Higgs coupling is related to gauge couplings by SUSY
  - Radiative effects sensitive (mainly) to top squark sector

$$(\tilde{t}_L^*, \tilde{t}_R^*) \begin{pmatrix} m_{\tilde{t}_L}^2 + m_t^2 + \Delta_L & m_t X_t \\ m_t X_t & m_{\tilde{t}_R}^2 + m_t^2 + \Delta_R \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$

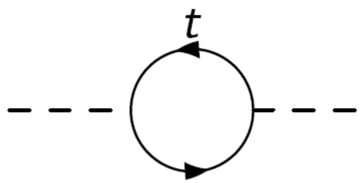
$$\Delta_L \equiv (\tfrac{1}{2} - \tfrac{2}{3} \sin^2 \theta_W) m_Z^2 \cos 2\beta \qquad \Delta_R \equiv \tfrac{2}{3} \sin^2 \theta_W m_Z^2 \cos 2\beta$$

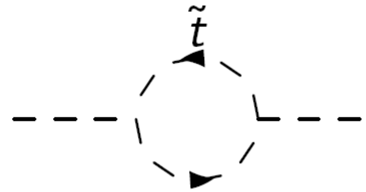
$$X_t \equiv A_t - \mu \cot \beta \qquad M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

- Conventional wisdom: the Higgs mass is large for SUSY, implies ~10 TeV stops, leading to NMSSM and more baroque models, questions of naturalness, anthropic principle, multiverse, and general existential angst

PRECISION HIGGS: THEORY

- 1-loop

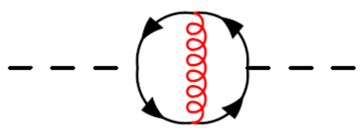


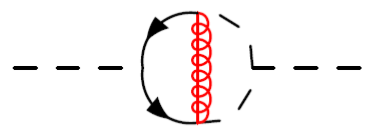


[from Philipp Kant]

Haber, Hempfling (1991); Ellis, Ridolfi, Zwirner (1991); Okada, Yamaguchi, Yanagida (1991)

- 2-loop





Brignole, Carena, Casas, Dedes, Degrassi, Espinosa, Haber, Hempfling, Heinemeyer, Hoang, Hollik, Martin, Quiros, Riotto, Rzehak, Slavich, Wagner, Weiglein, Zhang, Zwirner, … (1994-present)

Public codes: FeynHiggs; SOFTSUSY; SuSpect; SPheno

Degrassi, Frank, Hahn, Heinemeyer, Hollik, Rzehak, Slavich, Weiglein (1998, 2002, 2006); Allanach (2001); Djouadi, Kneur, Moultaka (2002); Porod, Staub (2003, 2011)

- Beyond 2-loops

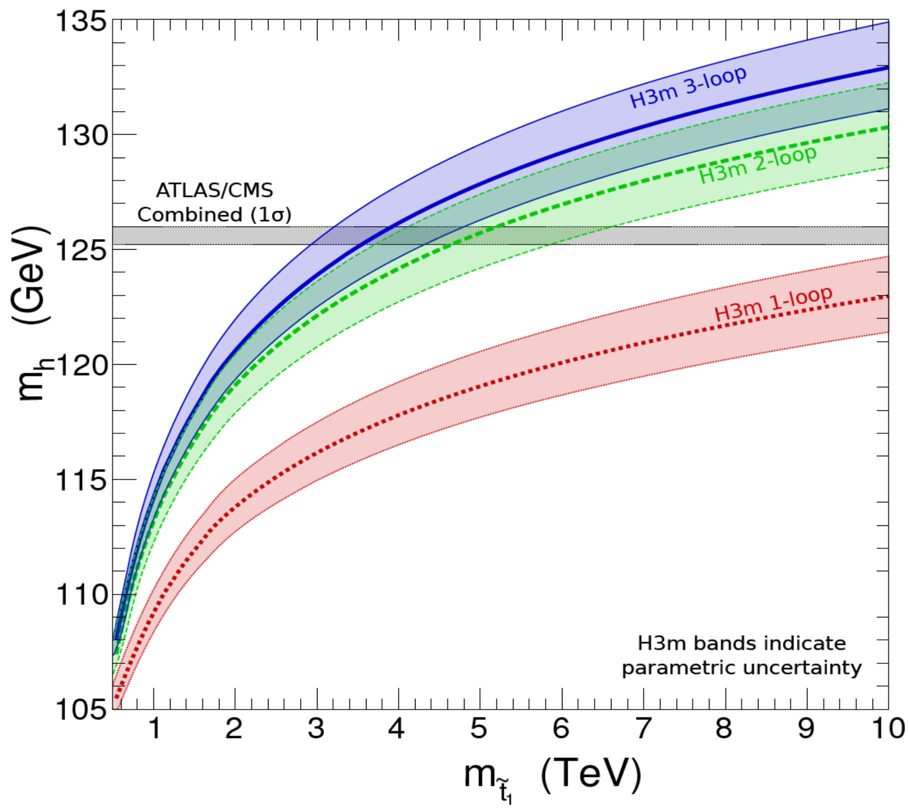
Martin (2006); Kant, Harlander, Mihaila, Steinhauser (2008, 2010); Degrassi, DiVita, Elias-Miro, Espinosa, Giudice, Isidori, Strumia (2012, 2013)

H3M: HIGGS MASS AT 3-LOOPS

Harlander, Kant, Mihaila, Steinhauser (2008)
Kant, Harlander, Mihaila, Steinhauser (2010)

- 5 years old, subjected to numerous cross-checks
- Publicly available: http://www.ttp.kit.edu/Progdata/ttp10/ttp10-23
- Starts with 1- and 2-loop contributions from FeynHiggs
- Then includes the ~30,000 3-loop diagrams at $O(\alpha_t \alpha_s^2)$, which are expected to be the leading 3-loop contributions
- Updated to include enhanced precision for cases with superpartners above the weak scale (e.g., in the conversion of the top quark pole mass to the running DRbar top mass)

RESULTS: WEAK-SCALE PARAMETERS



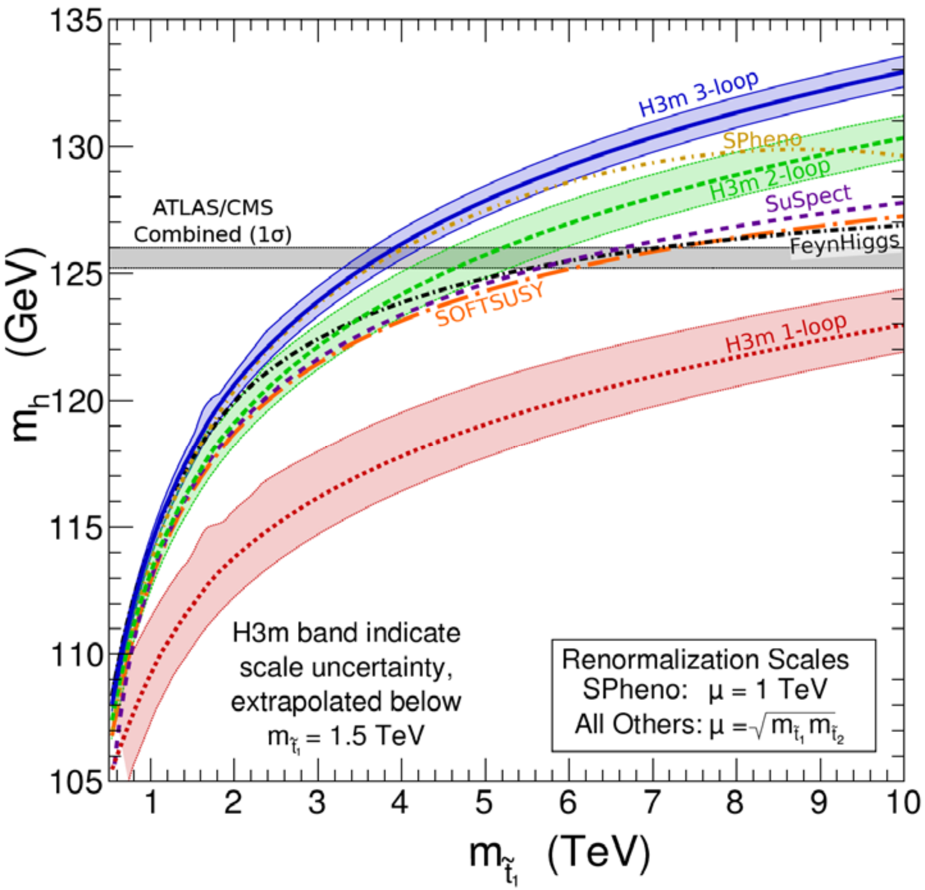
- Degenerate, unmixed stops

FIG. 1. The Higgs boson mass m_h from H3M at 1-, 2-, and 3-loops for nearly degenerate ($m_{\tilde{t}_L} = m_{\tilde{t}_R}$), unmixed ($X_t = 0$) top squarks, as a function of the physical mass $m_{\tilde{t}_1}$. The renormalization scale is fixed to $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$, we set $\tan\beta = 20$, $\mu = 200$ GeV, all other sfermion soft parameters equal to $m_{\tilde{t}_{L,R}} + 1$ TeV, and assume gaugino mass unification with $m_{\tilde{g}} = 1.5$ TeV. The bands indicate the parametric uncertainty from $m_t^{\rm pole} = 173.3 \pm 1.8$ GeV and $\alpha_s(m_Z) = 0.1184 \pm 0.0007$. The horizontal bar is the experimentally allowed range $m_h = 125.6 \pm 0.4$ GeV.

Feng, Kant, Profumo, Sanford (2013)

- For stop mass = 1 – 10 TeV, The Higgs mass increases by
  1-loop: 18-31 GeV; 2-loop: 4-7 GeV; 3-loop: 0.5-3 GeV ,
  indicating a well-behaved perturbation series
- Parametric uncertainty ~ 0.5 – 2 GeV, dominated by top mass

COMPARISON TO OTHER CODES



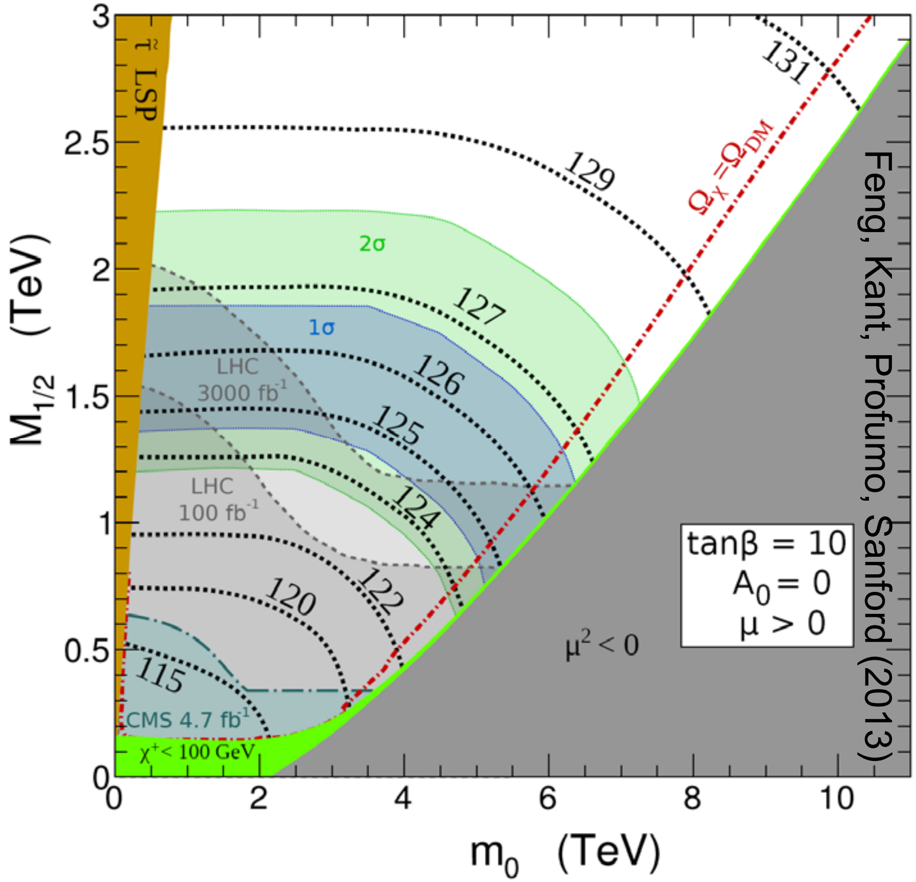
Feng, Kant, Profumo, Sanford (2013)

- Comparison to 2-loop codes: FeynHiggs, SOFTSUSY, SuSpect, Spheno
- Scale-dependence for

  $M_S/2 < \mu < 2M_S$
- 2-loop results agree within scale variation
- 2- and 3-loop results agree within scale variation for light stops

- 3-loop adds 0.5 to 3 GeV, reduces stop mass from 5-10 TeV to 3-4 TeV

LHC IMPLICATIONS: CMSSM/MSUGRA



- To determine collider implications, need full models. Consider CMSSM/mSUGRA
- Bands show Higgs mass with 1σ and 2σ perturbative uncertainties

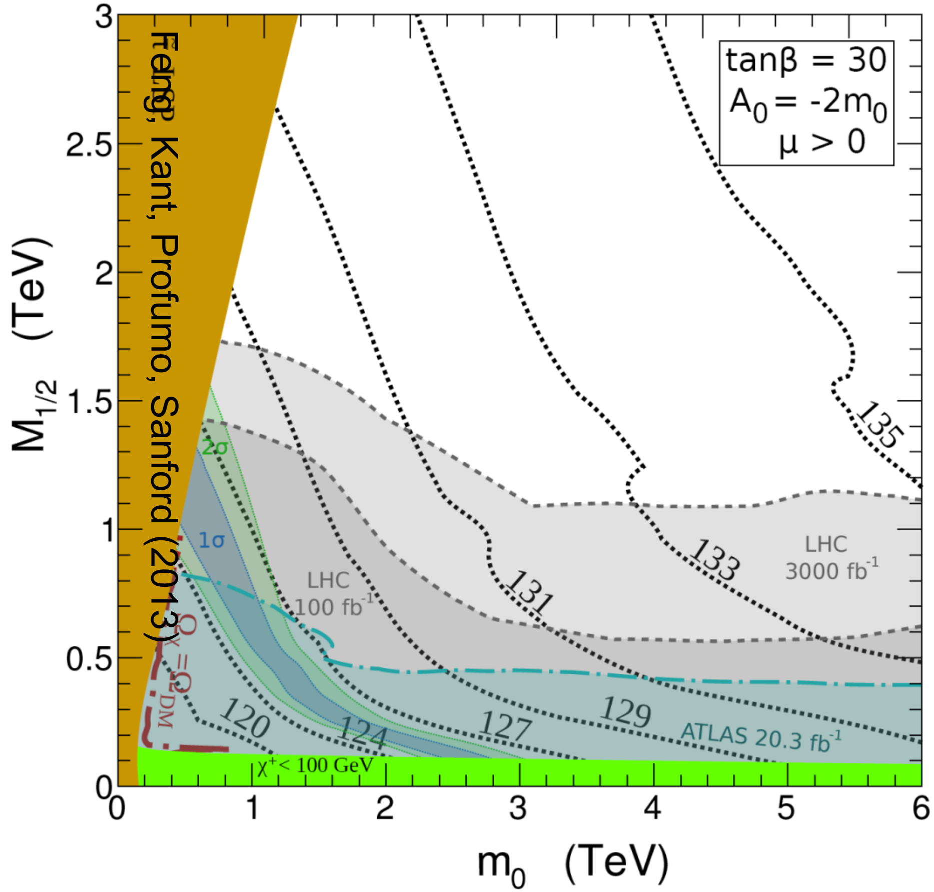
$$\Delta_{\rm pert} \equiv \frac{1}{2}\left| m_h^{(3\text{-loop})} - m_h^{(2\text{-loop})} \right|$$

- Projected LHC, HL-LHC reaches

Barger, Baer, Lessa, Tata (2012)

- Current bounds do not probe Higgs-preferred region
- But 3-loop effects shift this region to lower m_0, which may be probed by LHC and HL-LHC, including the focus point region with Ω_χ = 0.23

HIGGS-AWARE CMSSM/MSUGRA



- ATLAS and CMS also present results in the Higgs-aware mSUGRA/CMSSM plane with A_0 = -2 m_0, leading to significant, but not maximal, stop mixing
- 3-loop Higgs contributions shift preferred region to lower m_0, near overlap with co-annihilation region

- Current bounds cover some of the Higgs-preferred range
- LHC and HL-LHC will probe the entire preferred region, including the preferred region with co-annihilation leading to Ω_χ = 0.23

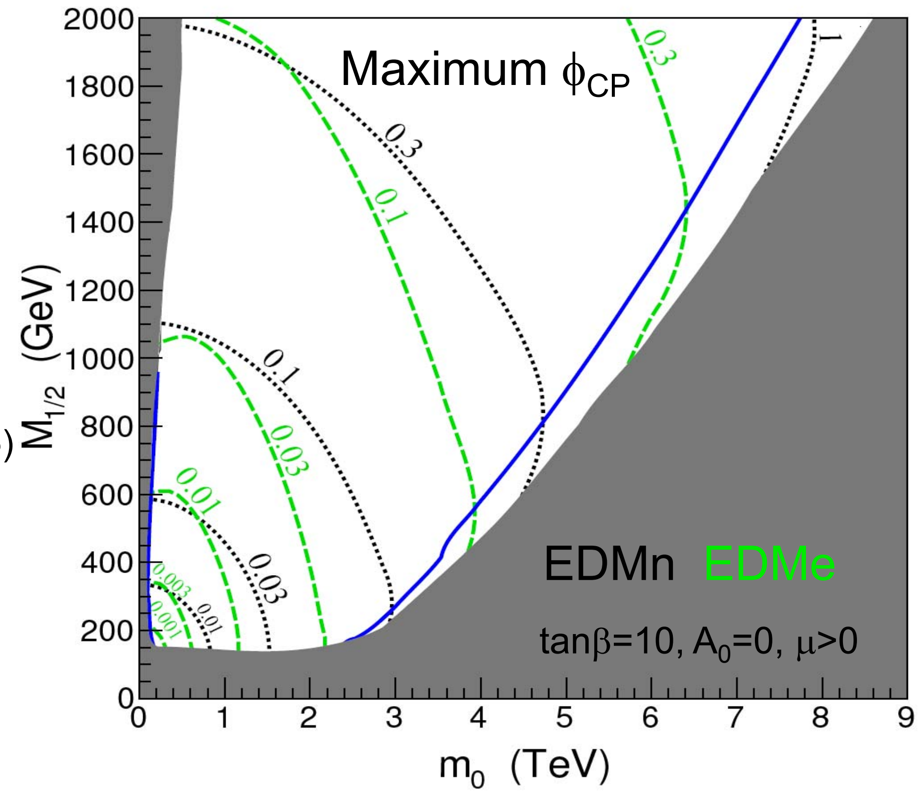
IMPLICATIONS FOR ELECTRIC DIPOLE MOMENTS

- Flavor violation eliminated by fiat in mSUGRA, but EDMs are flavor-conserving, CP-violating, generically present in mSUGRA (and GMSB, AMSB, ...)
- Stringent bounds on electron and neutron EDMs

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

- O(1) μ/gaugino mass phase mismatch → sub-TeV SUSY requires O(0.01) phases (or less)
- ~3-4 TeV scalars satisfy both the EDM and Higgs constraints

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



Feng, Matchev, Sanford (2011)

IMPLICATIONS FOR NATURALNESS

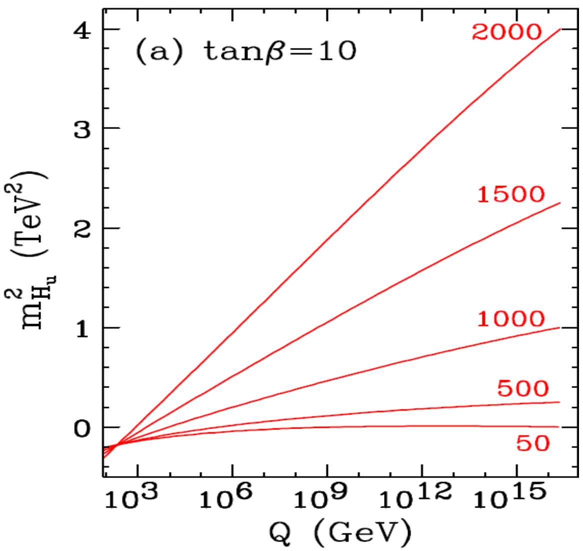
- Relative statement: 3-loop corrections move the preferred stop mass from ~10 TeV to 3 TeV, improving fine-tuning by an order of magnitude

- In more detail:

$$m_h^2 \quad = \quad (m_h^2)_0 \; + \; \frac{2N_f}{16\pi^2}\lambda^2(m_{\tilde{f}}^2 - m_f^2)\ln(\Lambda/m_h)$$

For $\Lambda \sim m_{GUT}$ (m_W), f = top, $N_f = 6$, 1% fine-tuning → $m_{\tilde{t}} < 1$ (5) TeV

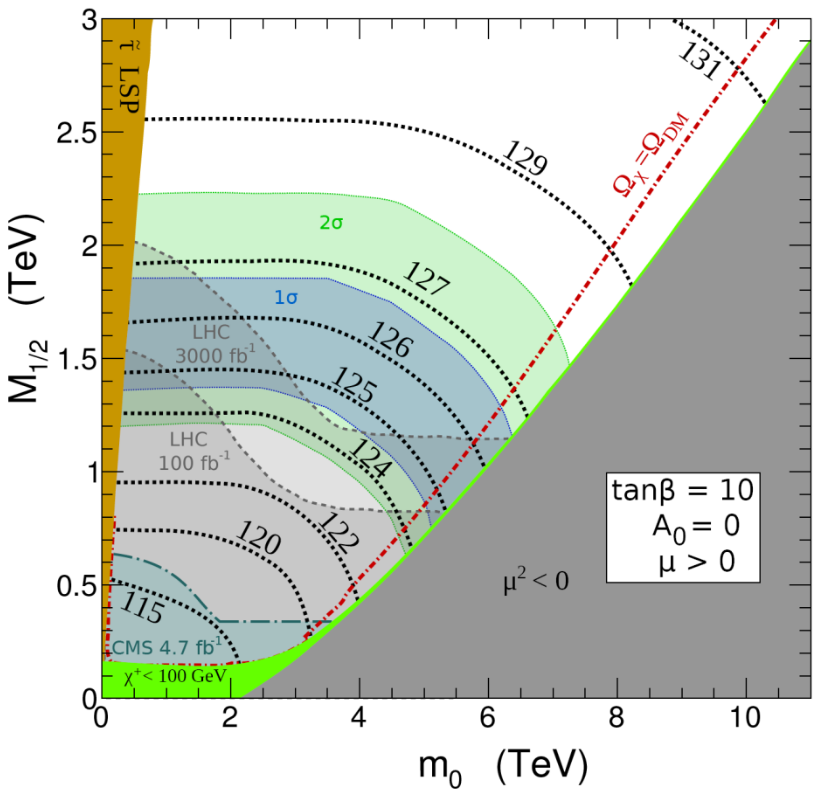
- The MSSM with unmixed stops and a 125 GeV Higgs boson is only ~1% fine-tuned, if the log enhancement can be removed by focus point SUSY, Supersoft SUSY, …



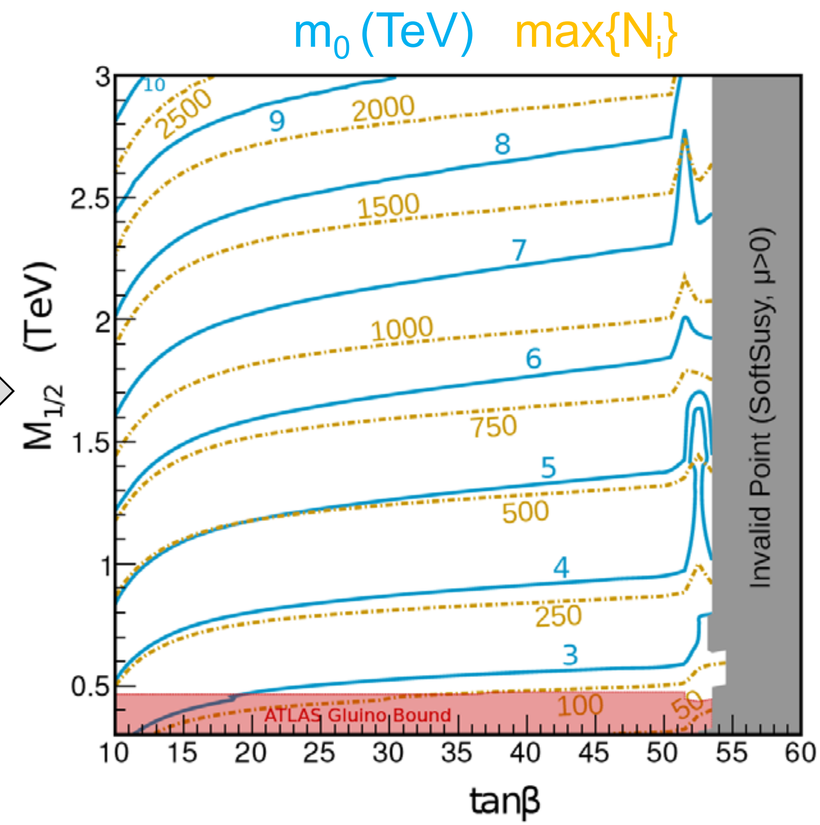
FINE-TUNING IN CMSSM/MSUGRA

- Focus on the cosmologically-preferred region: fix Ω_χ, vary $\tan\beta$
- Define fine-tuning $$\mathcal{N}_i \equiv \left| \frac{\partial \ln m_Z^2}{\partial \ln a_i^2} \right| = \left| \frac{a_i^2}{m_Z^2} \frac{\partial m_Z^2}{\partial a_i^2} \right|$$

Ellis, Enquist, Nanopoulos, Zwirner (1986); Barbieri Giudice (1988); Feng (2013)



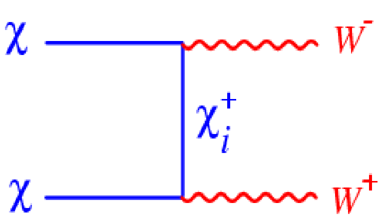
$\Omega_\chi = 0.23$

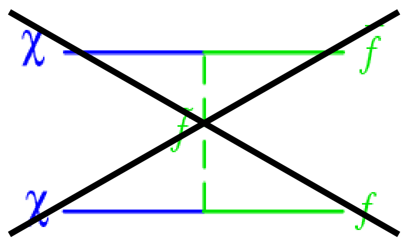


- ~1% fine-tuning consistent with 3-4 TeV scalars, 125 GeV Higgs

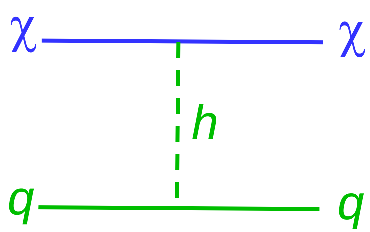
IMPLICATIONS FOR DARK MATTER

- Multi-TeV scalars effectively decouple from all DM phenomenology. For example, for relic density, if $M_2 > M_1$, Ω fixes the DM's coupling to Ws



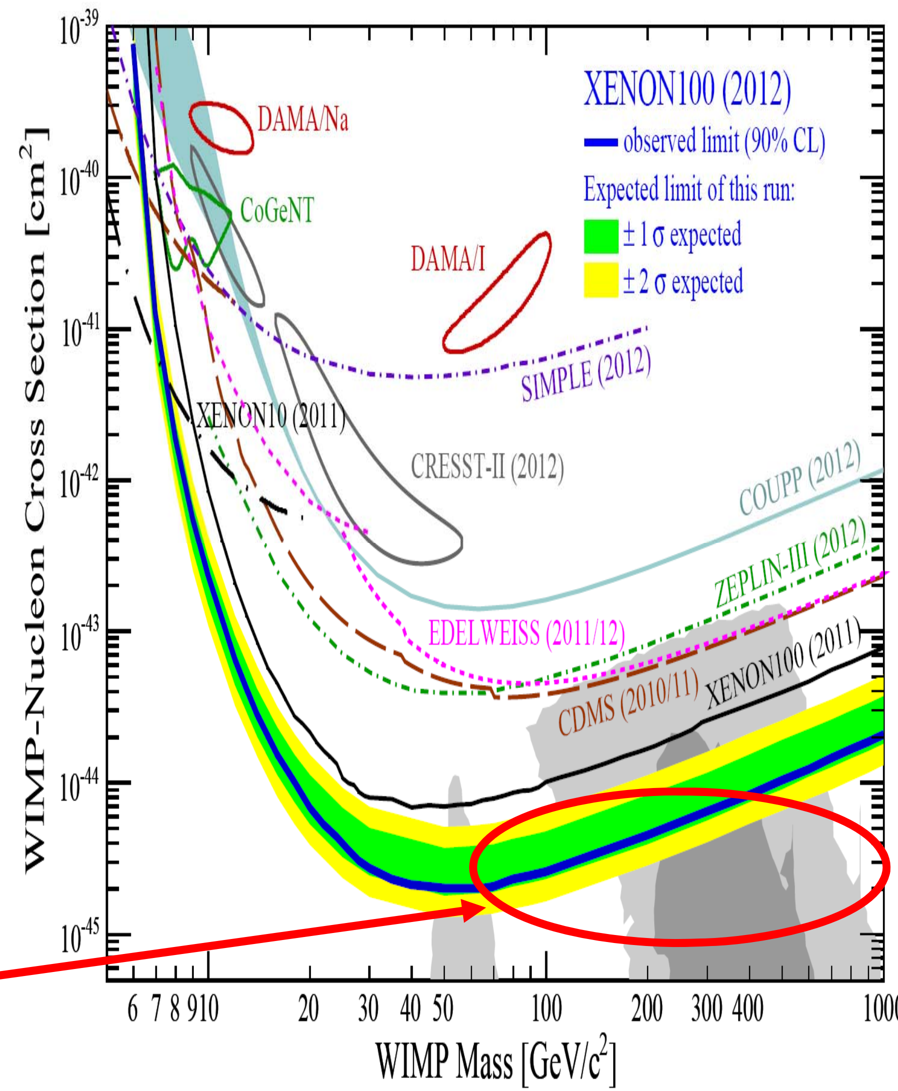


- But this also fixes the DM's coupling to the Higgs boson

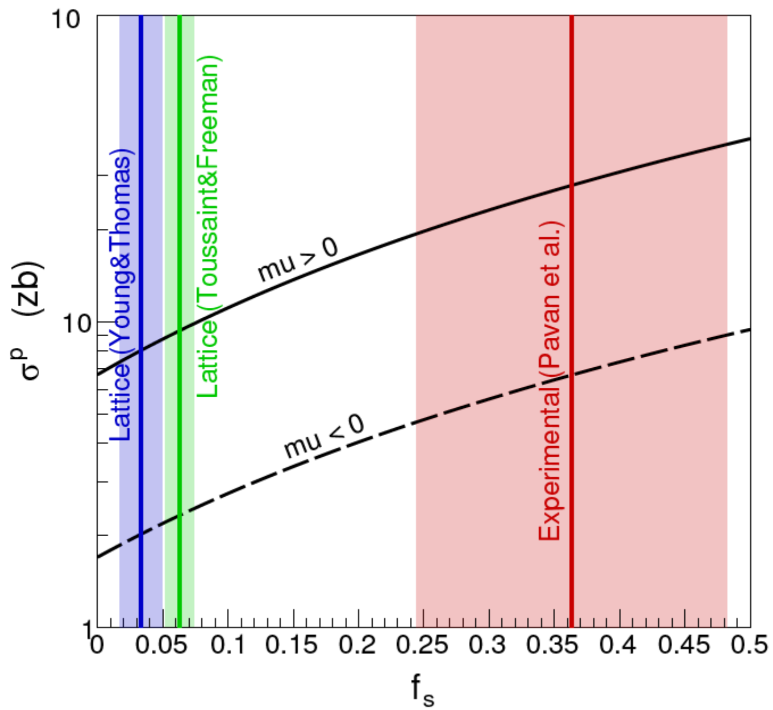


predictions typically lie in a small region with $\sigma \sim$ 1-10 zb

- Improvement by factors of a few will discover/exclude Bino-Higgsino DM



KEY POINTS FOR DIRECT DETECTION

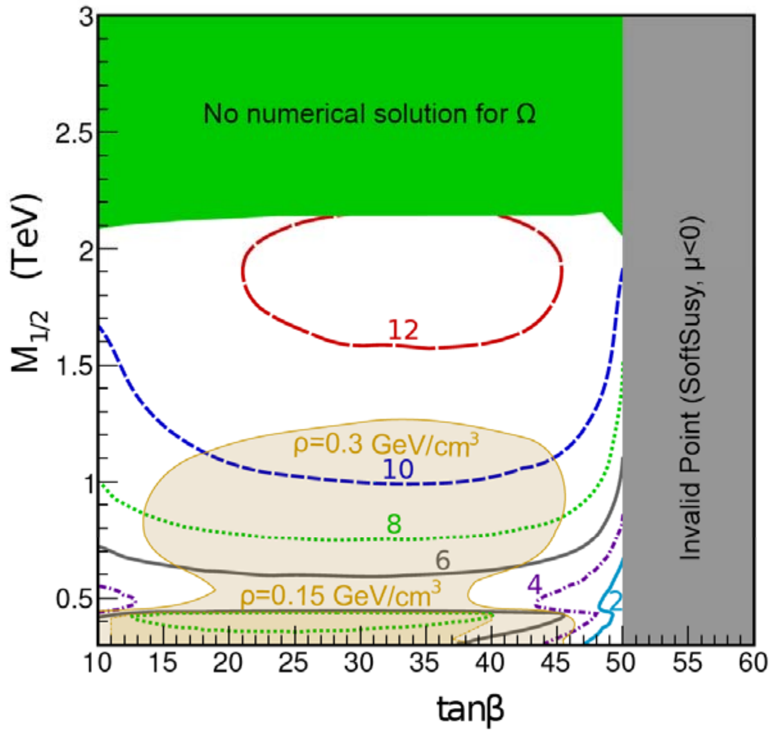


- Strong dependence on strange content; latest values all low
- Strong dependence on sign of μ (destructive interference for $\mu < 0$)

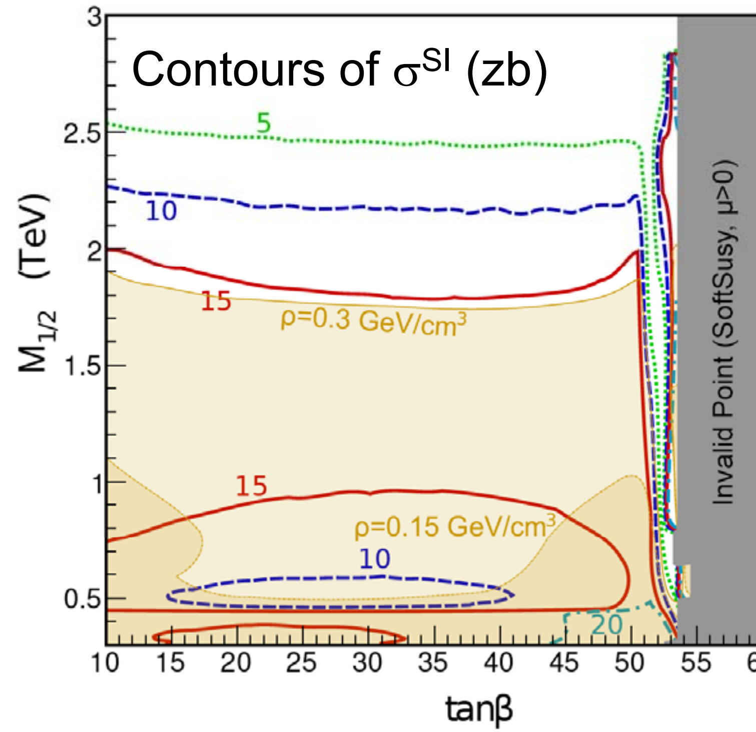
DIRECT DETECTION: SPIN-INDEPENDENT

- Shaded region excluded by current XENON bounds
- $\rho = 0.3$ GeV/cm^3 default; $\rho = 0.15$ GeV/cm^3 possible if some clumping

Kamionkowski, Koushiappas (2008)



(a) $\mu < 0$



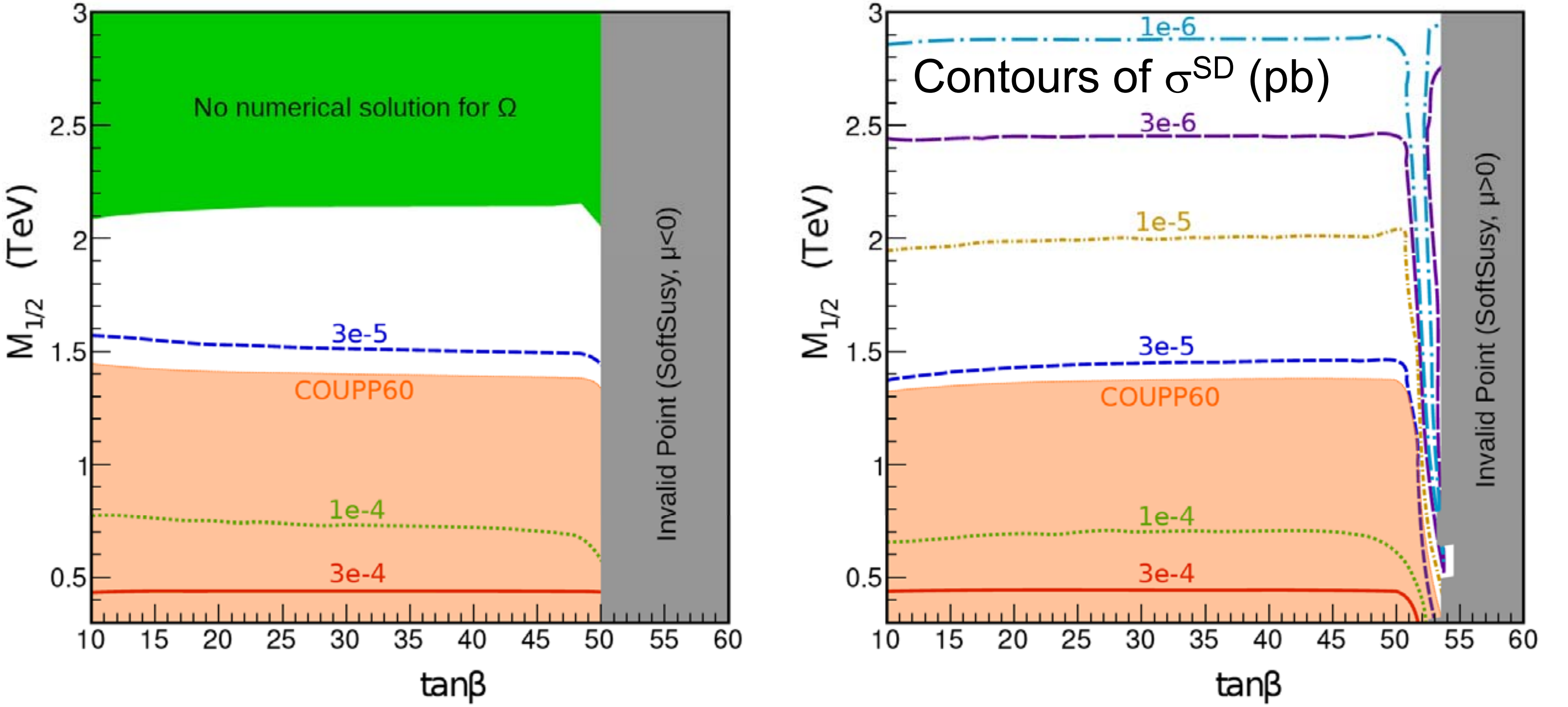
(b) $\mu > 0$

Draper, Feng, Kant, Profumo, Sanford (2013)

- Viable now, but signals predicted in near future

DIRECT DETECTION: SPIN-DEPENDENT

- Shaded region will be probed by COUPP60 after 1 year in SNOLAB



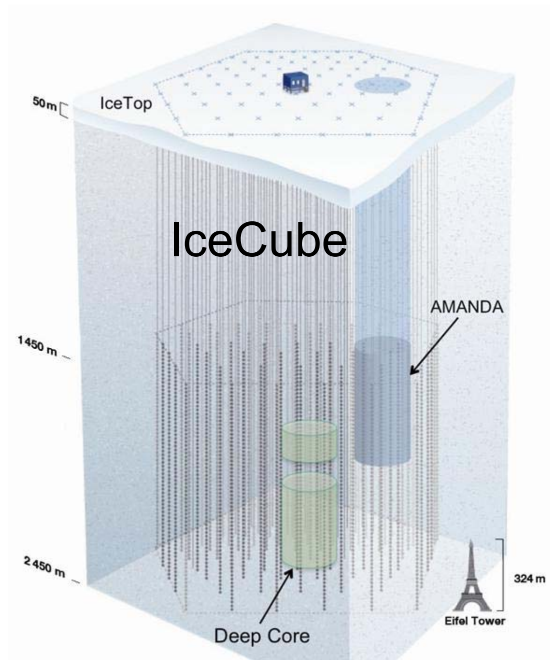
(a) $\mu < 0$ (b) $\mu > 0$

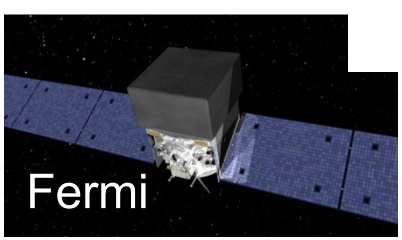
Draper, Feng, Kant, Profumo, Sanford (2013)

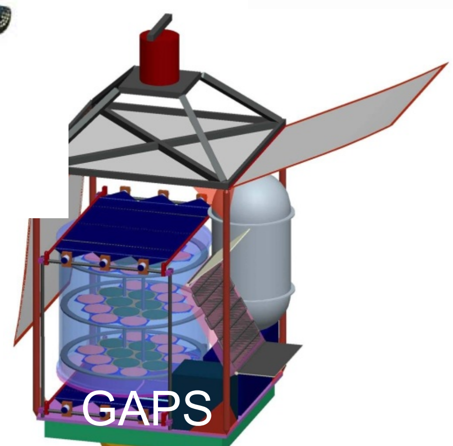
- Viable now, but signals predicted in near future

INDIRECT DETECTION

- Detection of dark matter pair annihilation in the galactic halo to
  - Neutrinos
  - Gamma rays
  - Positrons
  - Anti-protons
  - Anti-dueterons
- Many promising current and future projects

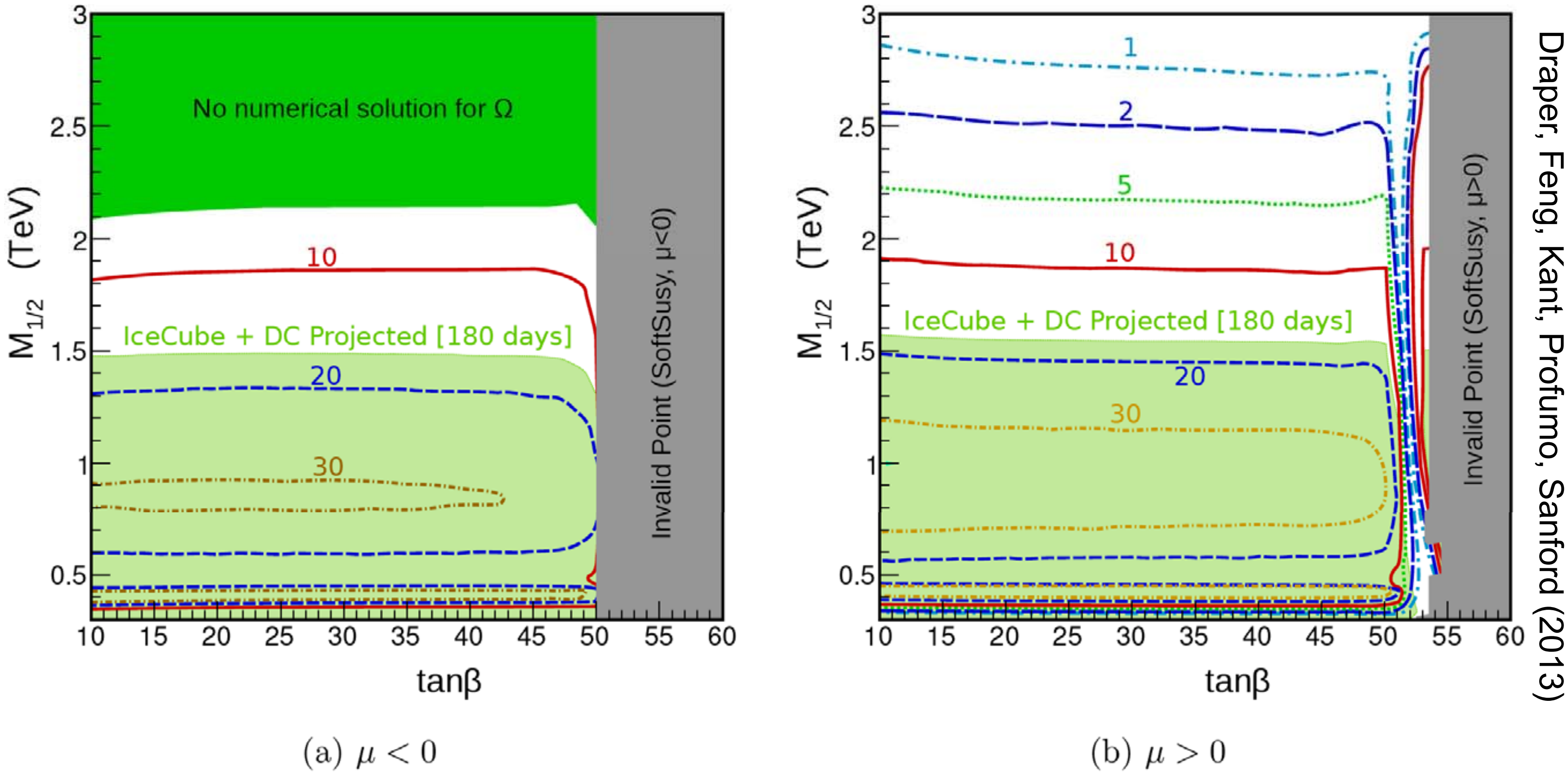






INDIRECT DETECTION: NEUTRINOS

- Contours for flux of >100 GeV muons / year in IceCube/DeepCore



- Viable now, but signals predicted in near future

SUMMARY

- The Higgs mass is now known to ~0.4 GeV, theory will forever be playing catch up: ~GeV-level uncertainties from higher order contributions, parametric uncertainties (top mass)

- 3-loop corrections raise the Higgs mass by 0.5-3 GeV, lower stop mass to 3-4 TeV, brighten prospects for SUSY at LHC

- Higgs mass, EDMs, naturalness → ~3-4 TeV scalars

- MSSM, even CMSSM, even cosmologically preferred CMSSM, is alive and kicking, implies promising prospects for LHC and HL-LHC, and both direct and indirect dark matter signals