3-Loop Higgs Mass and Focus Point SUSY

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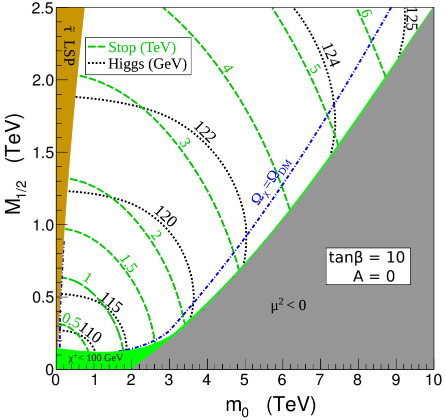
Work with P. Draper, J. Feng, P. Kant, S. Profumo (PhysRevD.88.015025)

Higgs Boson in the (C)MSSM

- Observed $m_h \sim 125$ GeV
- CMS: $125.7 \pm 0.3 \pm 0.3$ GeV ($24.7\ \mathrm{fb}^{-1}$)
- ATLAS: $125.5 \pm 0.2\ ^{+0.5}_{-0.6}$ GeV ($25.5\ \mathrm{fb}^{-1}$)
- Requires either heavy stops or significant LR mixing in the stop sector
- $m_{\tilde{t}} = 7 - 9$ TeV for $A_{\tilde{t}} = 0$ (at 2-loops)



- Consistent with relatively heavy superpartners
  - Places sfermions beyond the reach of the LHC
  - Results in significant fine-tuning

Fine-Tuning in (C)MSSM

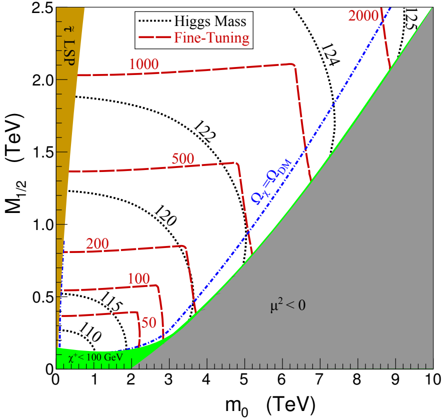
- Weak scale fine-tuning measure is typically $m_Z^2/m_{\tilde{t}}^2$
  - $\sim 0.01\%$ for $m_h \approx 125$ GeV
- Consider the fine-tuning measure for CMSSM

$$c_a \equiv \left| \frac{\partial \ln m_Z^2}{\partial \ln a^2} \right|$$

$$a \subset \{m_0, M_{1/2}, \mu, \sqrt{B}\}$$

$$c = \max\{c_a\}$$

- Fine-tuning improved in focus point region



Modifying boundary conditions can improve fine-tuning to $2\% - 10\%$ for $m_h \approx 125$ GeV

Feng and Sanford (2012), Baer, Barger, Huang, Mickelson, Mustafayev, Tata (2012)

Flavor and CP Constraints on the MSSM

Fine-tuning of the Higgs potential motivates light sfermions in contradiction with current collider searches

But what about precision flavor/CP sector observables?

- Many distinct constraints on sfermion masses and mixings
  - $\Delta m_K, \Delta m_D, \Delta m_B$
  - $K^0 - \bar{K}^0$ mixing
  - $D^0 - \bar{D}^0$ mixing
  - $B_d - \bar{B}_d$ mixing
  - $B_s - \bar{B}_s$ mixing
  - Meson decay asymmetries
  - $\mathrm{Br}(B \to X_s\gamma)$
  - $\mathrm{Br}(B_s \to \mu\mu)$
  - $\mathrm{Br}(\mu \to e\gamma)$
  - Electron/Neutron EDMs
- No significant evidence of new physics

Many (but not all) are suppressed if the new physics flavor sector is aligned with that of the Standard Model (MFV)

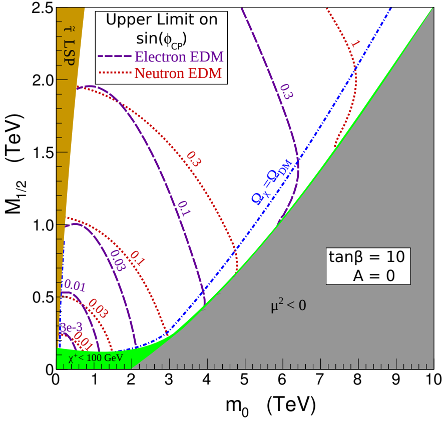
Also suppressed if sfermions have large masses reduce the size of flavor/CP violating observables

EDM Constraints on (Nearly) CMSSM CP Violation

- Generically (outside CMSSM) soft masses have CP phases
- EDM constraints become relevant and strongly constraining
- Gaugino mass/μ-term CP phases can be mismatched as

$$M_{1/2}\mu^* = |M_{1/2}\mu| e^{\phi_{\rm CP}}$$

- Simple extension of CMSSM and limits easily calculable



Feng, Matchev, Sanford (2011)

EDMs constrain phases even for multi-TeV scalar masses **even for scenarios with MFV**

Fine-Tuning in the Flavor/CP Sector

Flavor universality/absence of CP phases in CMSSM (and most low-energy MSSM frameworks) is motivated by pratical considerations

- Implemented to match experimental results
- Many observables are largely independent of detailed flavor sector

Does not motivate lack of fine-tuning in flavor sector

- $\sim$ 90 flavor/CP phases that must be tuned away in CMSSM

Introducing light stops, even in originally flavor universal theories, risks re-introduction of fine-tuning in flavor sector

Generating a proper combined fine-tuning measure is intractable, but the qualitative behavior of fine-tuning in the flavor/CP sector should be considered

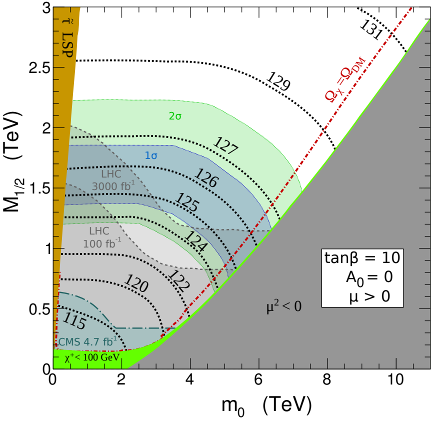
3-Loop Higgs in the CMSSM ($A_0 = 0$)

3-loop contributions have a profound effect on the preferred (C)MSSM parameter space

- Theory error defined as

$$
\begin{aligned}
\Delta_{\text{th}} &\equiv \sqrt{(\Delta_{\text{pert}})^2 + (\Delta_{\text{para}})^2} \\
\Delta_{\text{pert}} &\equiv \frac{1}{2}\left| m_h^{(\text{3-loop})} - m_h^{(\text{2-loop})} \right| \\
\Delta_{\text{para}} &\equiv \Big| m_h\Big(\substack{m_t = 175.1\ \text{GeV} \\ \alpha_s = 0.1177}\Big) \\
&\quad - m_h\Big(\substack{m_t = 173.3\ \text{GeV} \\ \alpha_s = 0.1184}\Big) \Big|
\end{aligned}
$$

- Preferred m_0 shifts from 9 TeV to 1 – 6 TeV
- $m_{\tilde{g}}$ as low as 2 TeV

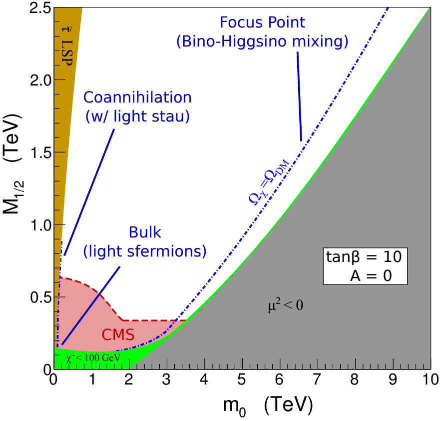


Reasonable detection prospects at high luminosity LHC

Projections from Baer, Barger, Lessa, and Tata (2009)

Neutralino Dark Matter in the CMSSM

- Neutralino is primarily bino over most CMSSM parameter space
- Weak scale bino overcloses the universe
- Generally need to enhance annihilation for $\Omega_\chi = 0.23$
- Low mass sfermions disfavored $\rightarrow$ look at focus point



Alvarez-Gaume, Polchinski, Wise (1983); Kane, Kolda, Roszkowski, Wells (1993); Ellis, Falk, Olive, Srednicki (2000); Feng, Matchev, Wilczek (2000); Baer, Balazs, Belyaev (2002)

Dark Matter in the Focus Point

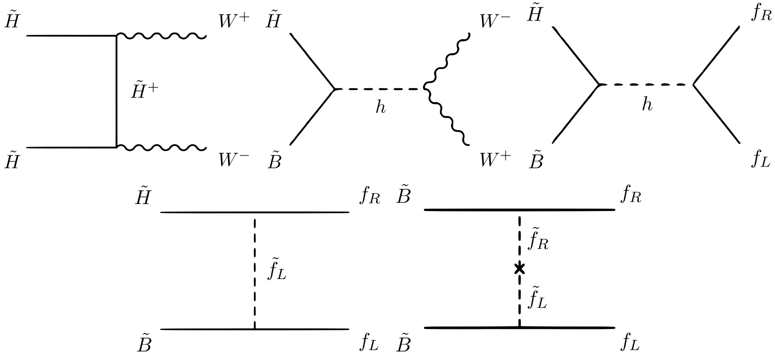
If M_1 is small, bino-higgsino mixing can be used to fix

$$\Omega_\chi = \Omega_{\rm DM}$$

Feng and Matchev (2000), Arkani-Hamed, Delgado, Guidice (2006)

- Bino annihilation too weak (barring coannihilation)
- Higgsino annihilation too strong below $\mu = 1$ TeV

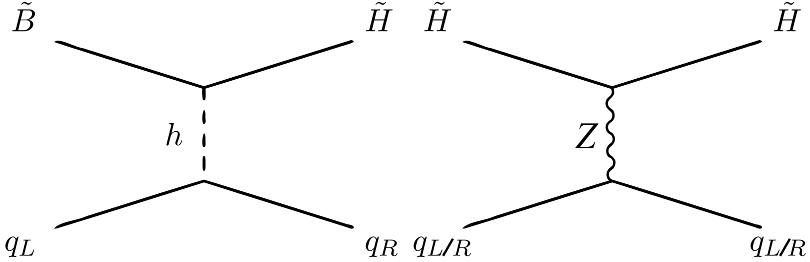
Processes for *S*-wave neutralino annihilation



Neutralino Scattering

Bino-Higgsino also mixing produces significant scattering cross-sections

Tree-level diagrams for scattering in $m_{\tilde{q}} \to \infty$ limit



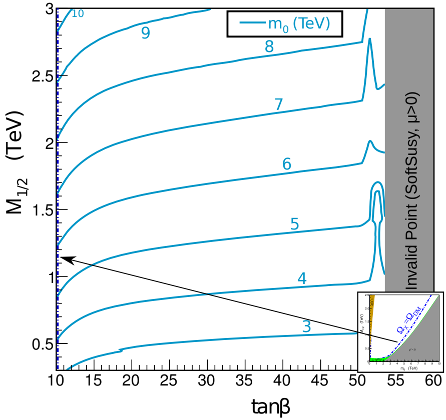
- Spin-independent requires bino-higgsino mixing
- Spin-dependent requires unequal $\tilde{H}_u$ and $\tilde{H}_d$ components to avoid cancellation

Focus Point with $\Omega_\chi = \Omega_{\rm DM}$

Want to study the focus point region for a broad range of parameter space

- Only a thin slice of relevant space in m_0-$M_{1/2}$ plane
- Wish to explore $\tan\beta$ dependence
- Focus point requires $A \ll m_0$

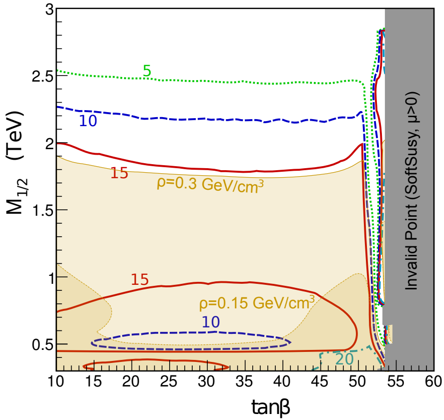
Scan over $M_{1/2} - \tan\beta$, using m_0 to set $\Omega_\chi = \Omega_{\rm DM}$



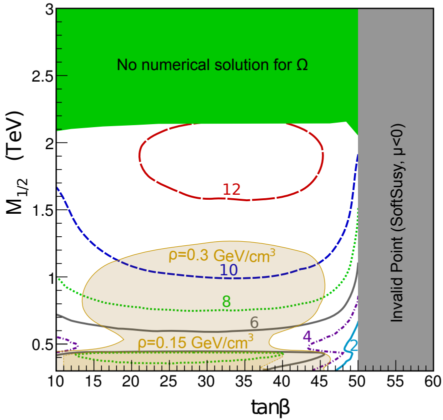
Feng, Matchev, and Sanford (2011)

Spin-Independent Direct Detection

σ^{SI} (zb) [$f_s = 0.05$] and XENON100 exclusion contours with 225 live days



$\mu > 0$



$\mu < 0$

with J. Feng, K. Matchev (2011)

with J. Feng, S. Profumo, P. Draper, P. Kant (2013)

Uncertainty in f_s

- $f_s \sim 0.36$ from chiral perturbation theory with from meson scattering data input

  Kaplan and Manohar (1988)

  Gasser, Leutwyler, and Sainio (1991)

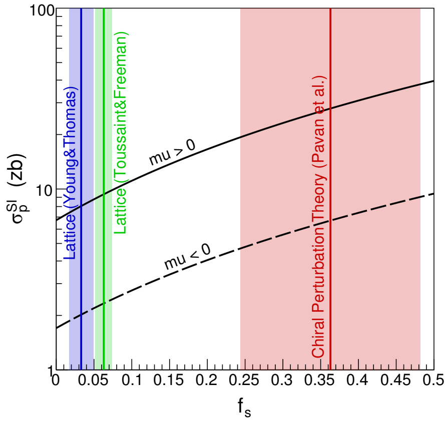
- $f_s \sim 0.05$ from direct lattice calculation

  Freeman and Toussaint (2009)

  Young and Thomas (2010)

- Factor of ≈ 3 difference between experimental and lattice predictions
- Including non-perturbative baryon octet contributions may produce consistency

  Alarcon, Geng, Camalich, Oller (2012)



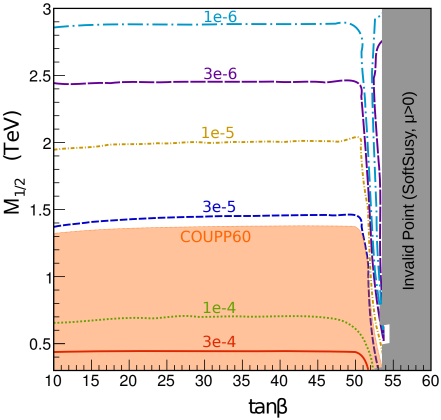
$\tan\beta = 10$, $m_{1/2} = 500$ GeV, $\Omega_\chi = \Omega_{\rm DM}$

Will consider $f_s = 0.05$ here

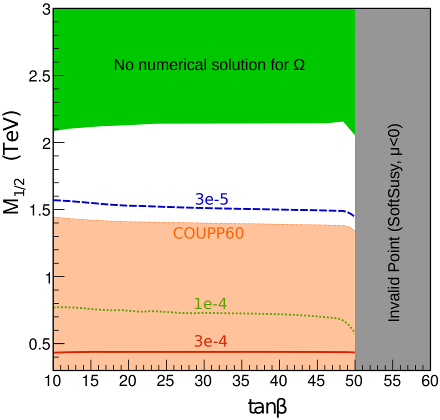
micrOMEGAs has adopted small f_s convention as default

Spin-Dependent Direct Detection

σ^{SD} (pb) and COUPP60 expected sensitivity after 1 year at SNOLAB

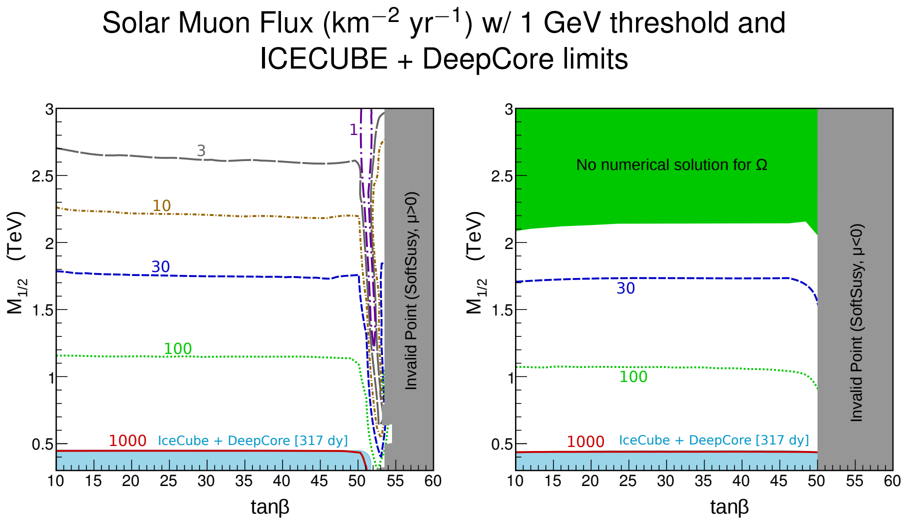


$\mu > 0$



$\mu < 0$

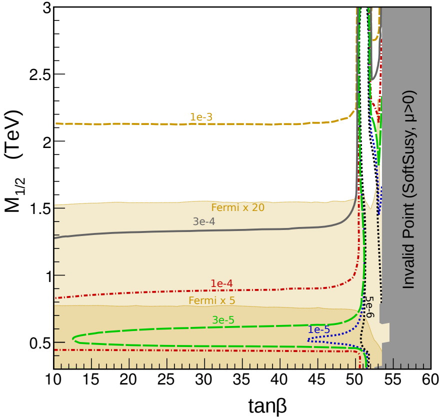
Solar Muon Flux



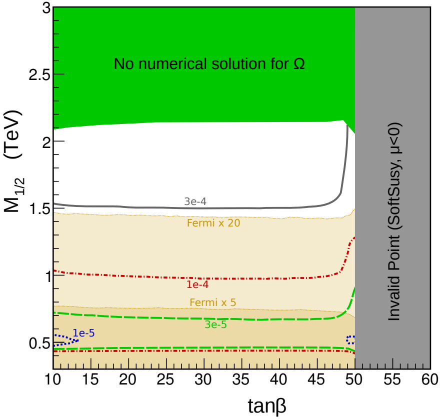
$\mu > 0$ $\mu < 0$

Gamma Ray Signals

$\mathcal{B}(\chi\chi \to \gamma\gamma)$ and FERMI sensitivity from dwarf galaxy probes



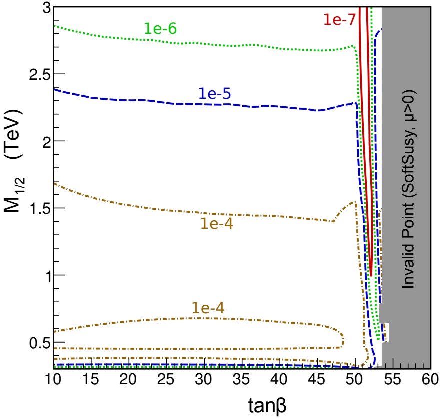
$\mu > 0$



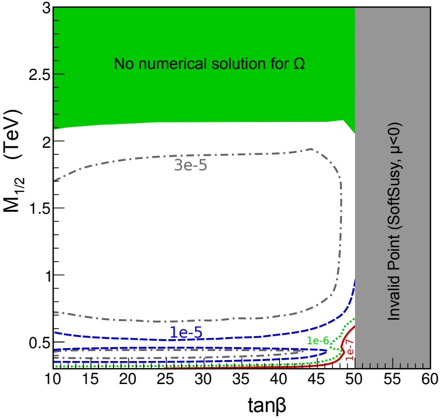
$\mu < 0$

Earth Neutrino Flux

Earth Neutrino Flux (km^{-2} yr^{-1}) w/ 100 GeV threshold and ICECUBE + DeepCore limits



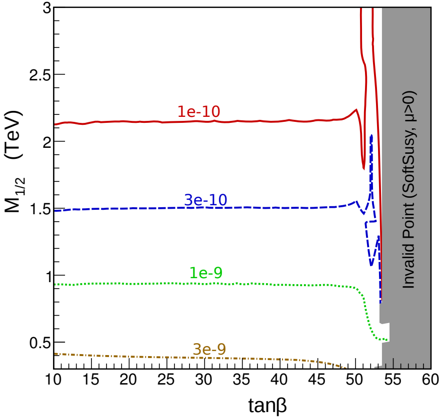
$\mu > 0$

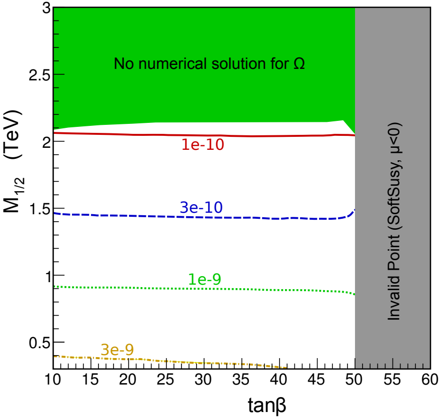


$\mu < 0$

Antiprotons

Antiproton flux (GeV^{-1} cm^{-2} s^{-1} sr^{-1})





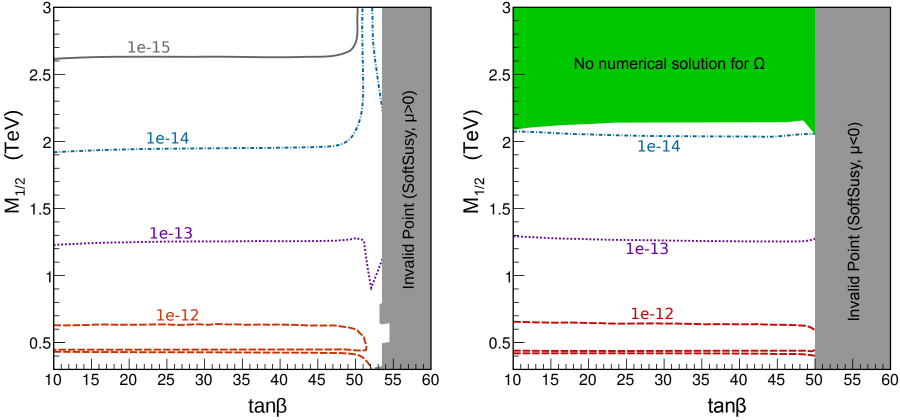
$\mu > 0$

$\mu < 0$striking

PAMELA reports flux of 7.2×10^{-8} with no striking features

Antideuterons

Antideuteron flux (GeV^{-1} cm^{-2} s^{-1} sr^{-1})

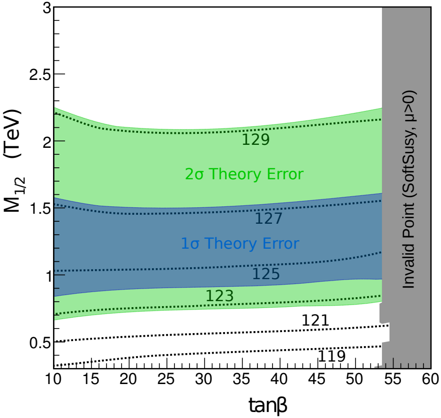


$\mu > 0$ $\mu < 0$

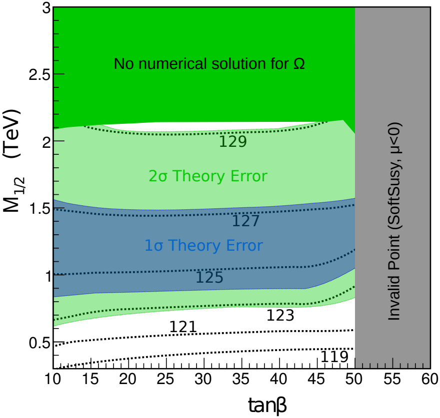
GAPS expects sensitivity of 10^{-11}

3-Loop Higgs Mass for $\Omega_\chi = \Omega_{\rm DM}$

3-loop Higgs calculation shift preferred region significantly

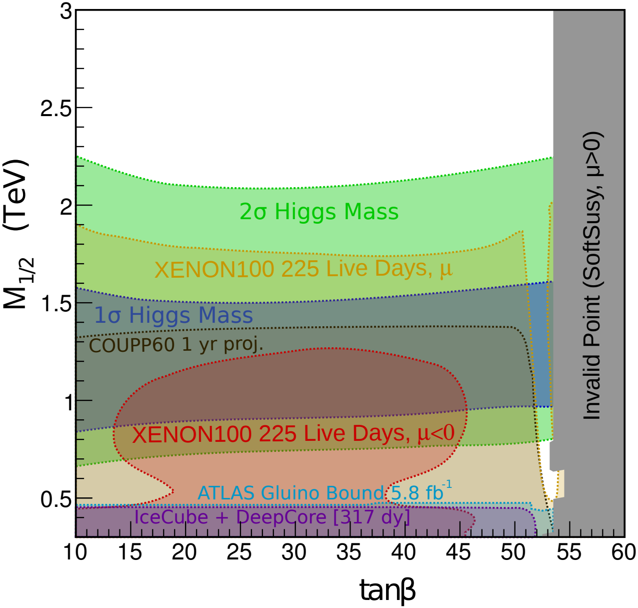


$\mu > 0$



$\mu < 0$

Dark Matter Bounds on 3-Loop Higgs Mass Region



Conclusion

- Various motivations exist to consider TeV-scale SUSY
  - $m_h \approx 125$ GeV motivates somewhat heavy superpartners
  - Flavor/CP observables are more easily satisfied
  - Fine-tuning issues may be ameliorated
- **3-loop contributions can mean the difference between strong discovery potential and no discovery potential on multiple fronts**