Status of the CMSSM and the Focus Point

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Cosmic Frontier Workshop @ SLAC
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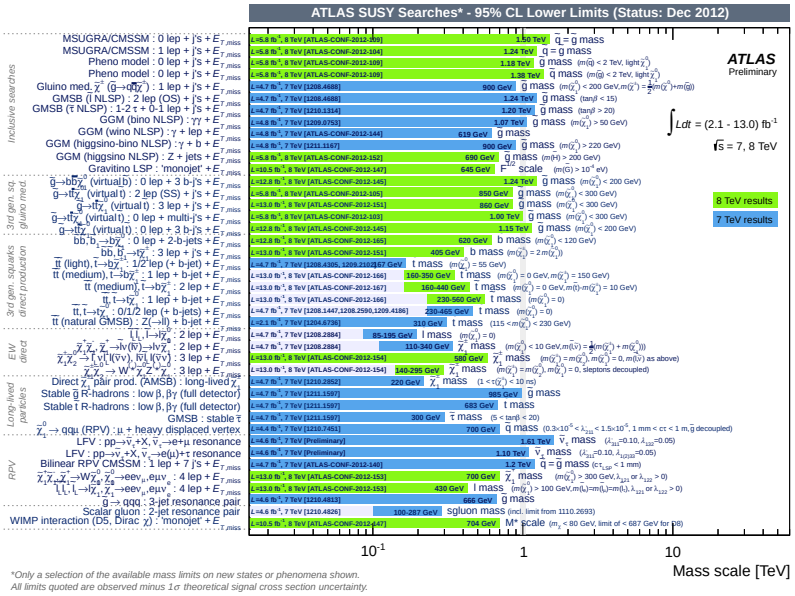
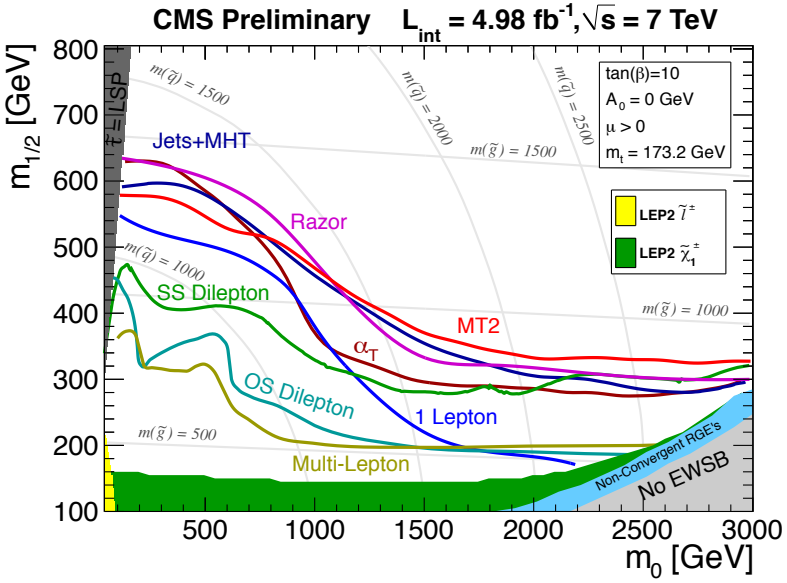
Colored Superpartner Bounds





Status of ATLAS SUSY Searches (4.7-13.0 fb^{-1})

CMS CMSSM Limits w/ 4.98 fb^{-1} @ 7 TeV

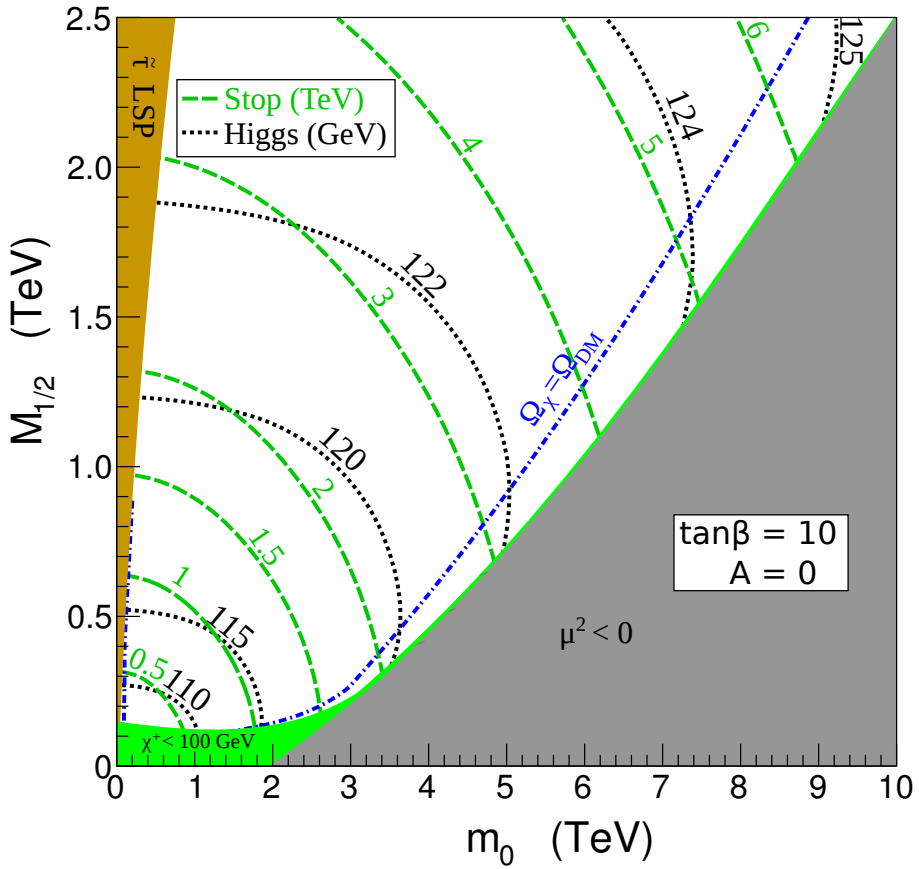
- LHC places stringent limits on the masses of colored superpartners (5-13 fb^{-1})

$$m_{\tilde{g}} \gtrsim 1 \text{ TeV}$$

$$m_{\{\tilde{u},\tilde{d},\tilde{c},\tilde{s}\}} \gtrsim 1.3 - 1.5 \text{ TeV}$$

Higgs Boson in the (C)MSSM

- Observed $m_h \sim 125$ GeV
  - CMS: $126.2 \pm 0.6 \pm 0.2$ ($17.3\ \text{fb}^{-1}$)
  - ATLAS: $125.2 \pm 0.3 \pm 0.6$ ($17.8\ \text{fb}^{-1}$)
- Requires either heavy stops or significant LR mixing in the stop sector
  - Low mixing case in plot ($A = 0$)



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

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)

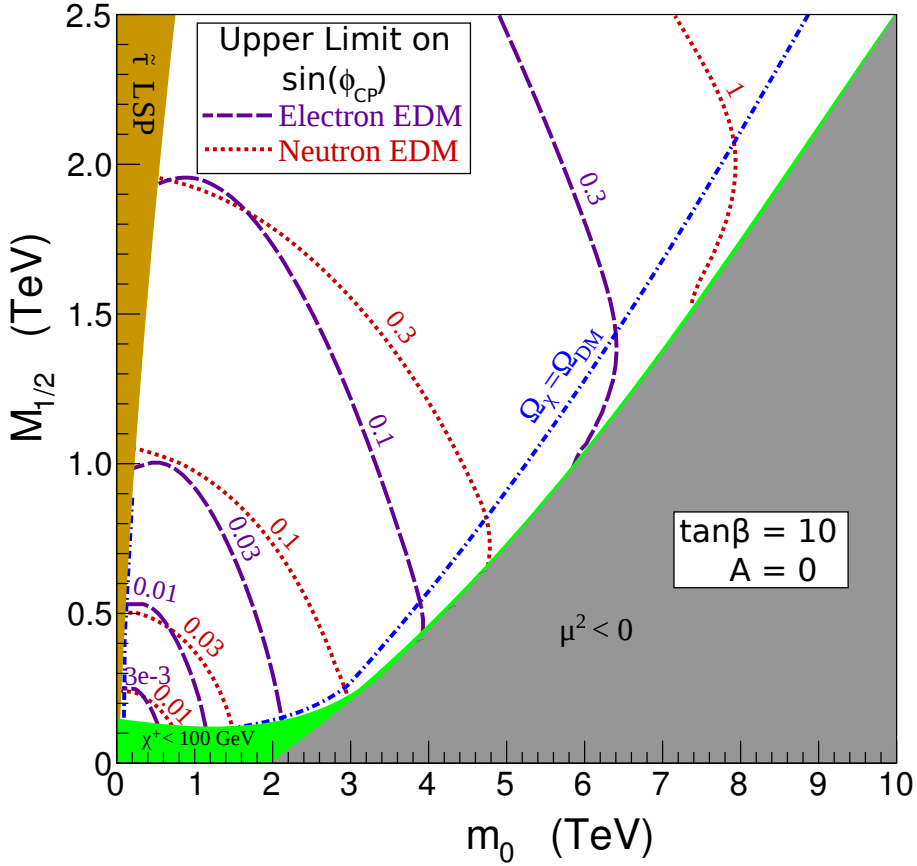
Also suppressed if sfermions have large masses reduce the size of flavor/CP violating observables

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

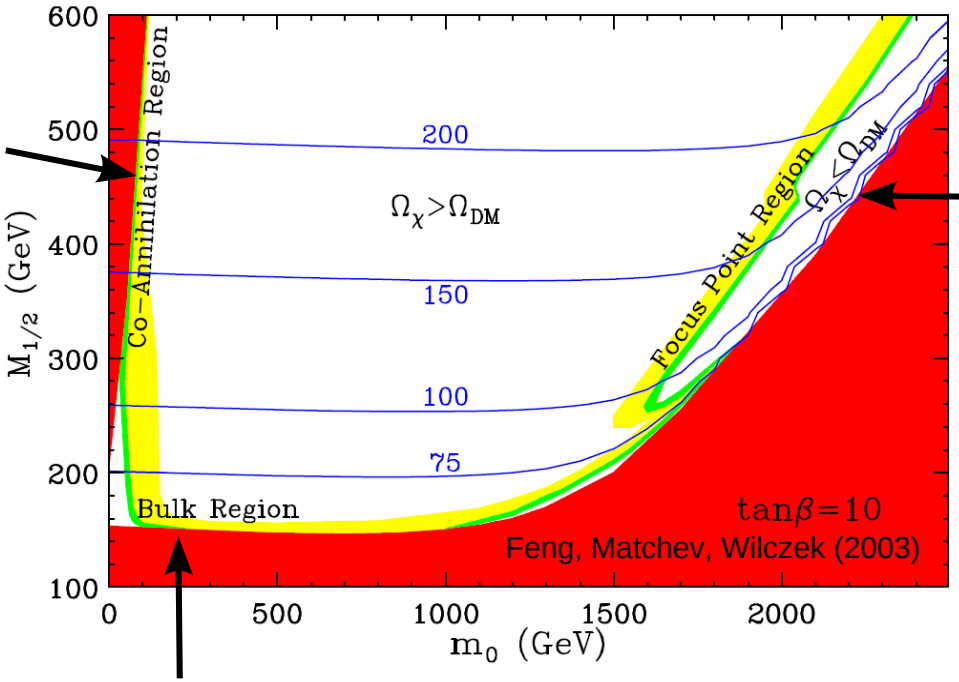


EDMs constrain phases even for multi-TeV scalar masses **even for scenarios with MFV**

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

Neutralino-Stau Coannihilation



Bino-Higgsino Mixing

Light Sfermions

Not Pictures: A funnel

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

Heavy Scalars and Fine-Tuning

$\sim$ 1 TeV superpartners imply $m_Z^2/M_{\rm SUSY}^2 \sim 1\%$ fine-tuning
$m_{\tilde{t}} \gtrsim$ 10 TeV required for $m_h \sim$ 125 GeV through radiative corrections

- Produces $\mathcal{O}(0.01\%)$ fine-tuning
- Even for left-right stop mixing, fine-tuning is $\mathcal{O}(0.1\%)$

Focus point scenario provides for "dynamically natural" heavy scalars

Matchev and Feng (2000)

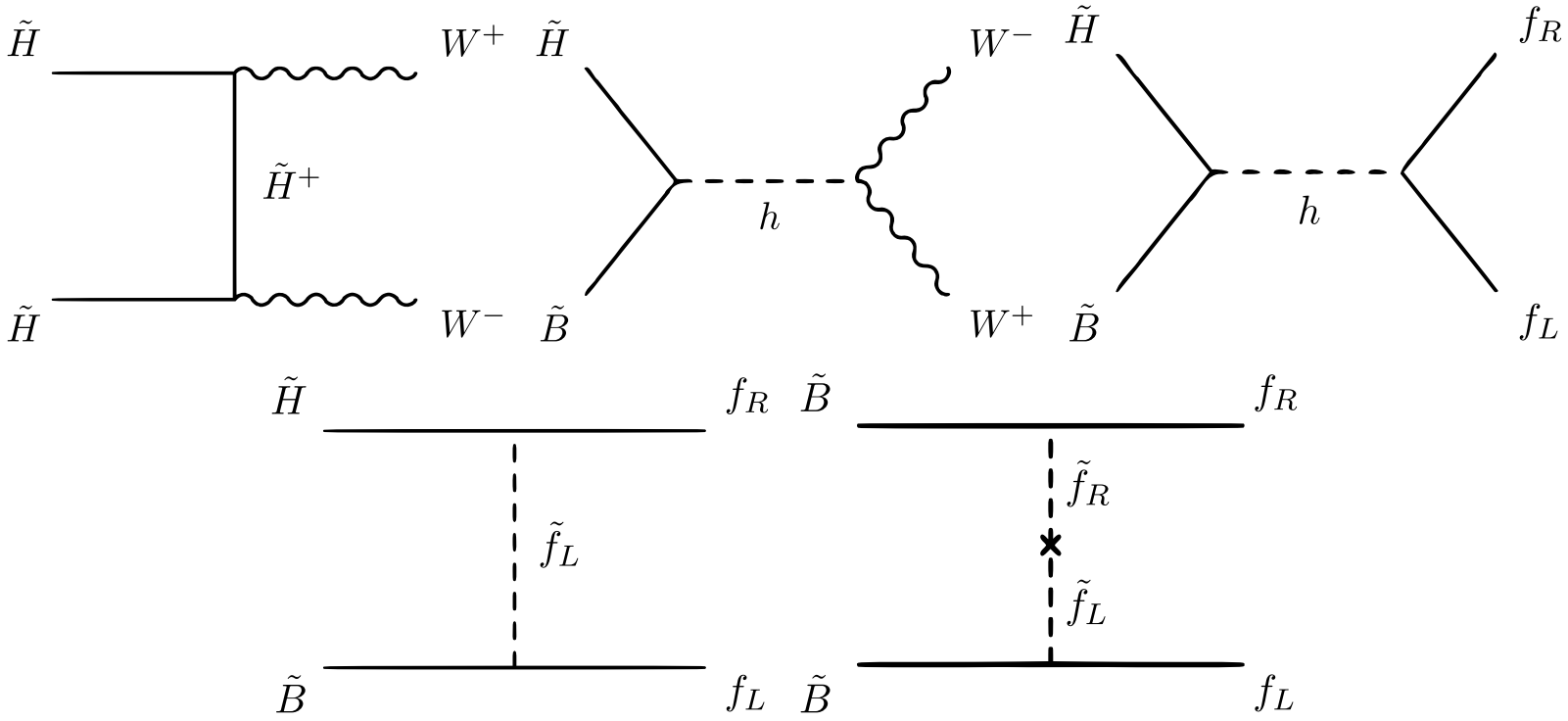
- Renormalization suppresses shifts in electroweak potential due to large scalar masses
- Improves fine-tuning for heavy scalars by an order of magnitude
- For $A_0 = 0$, the CMSSM unified mass condition produces the proper running $\rightarrow$ "focus point region" of CMSSM

Dark Matter in the Focus Point

- Low fine-tuning is associated with a relatively low μ-terms
- Allows for significant Bino-Higgsino mixing

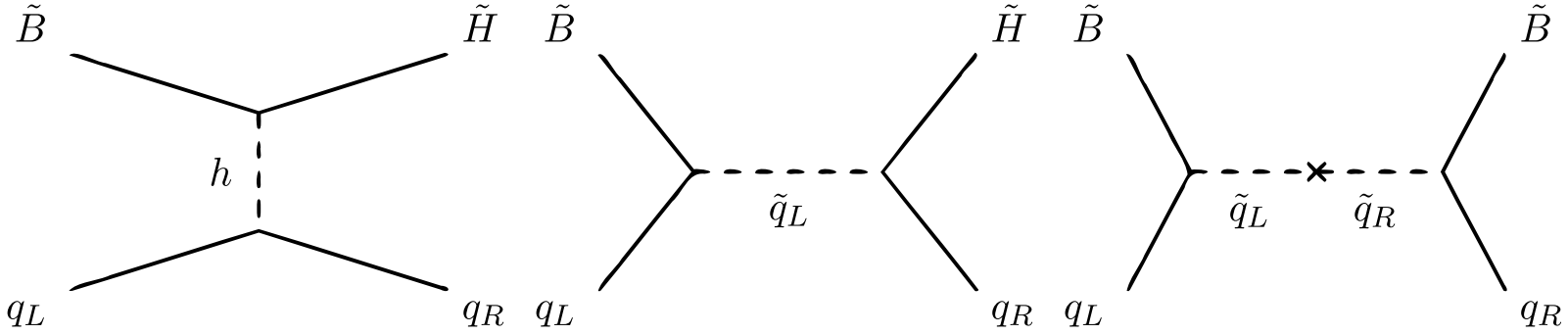
Bino-Higgsino mixing produces significant annihilation and scattering cross-sections

Processes for *S*-wave neutralino annihilation

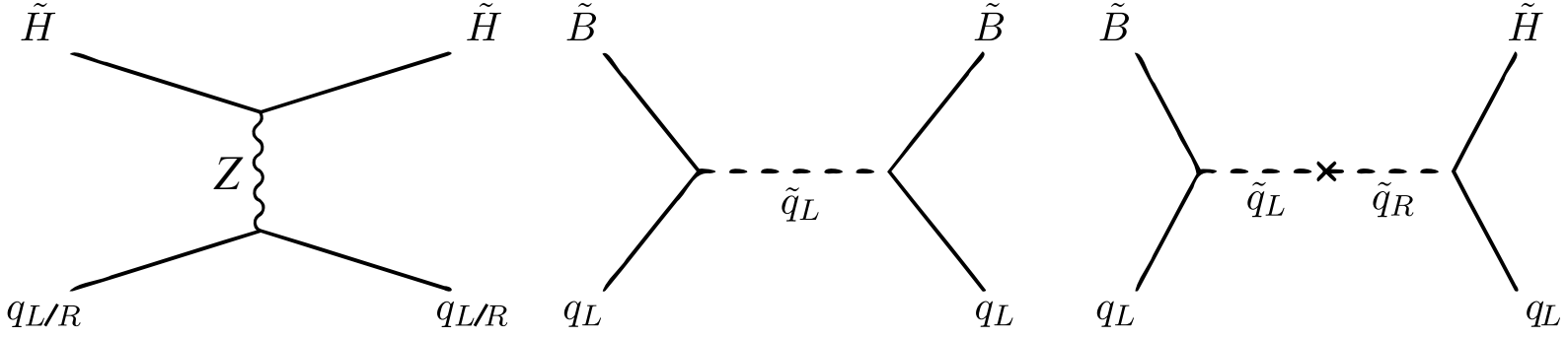


Neutralino Scattering

Tree-level diagrams for spin-independent scattering



Tree-level diagrams for spin-dependent scattering

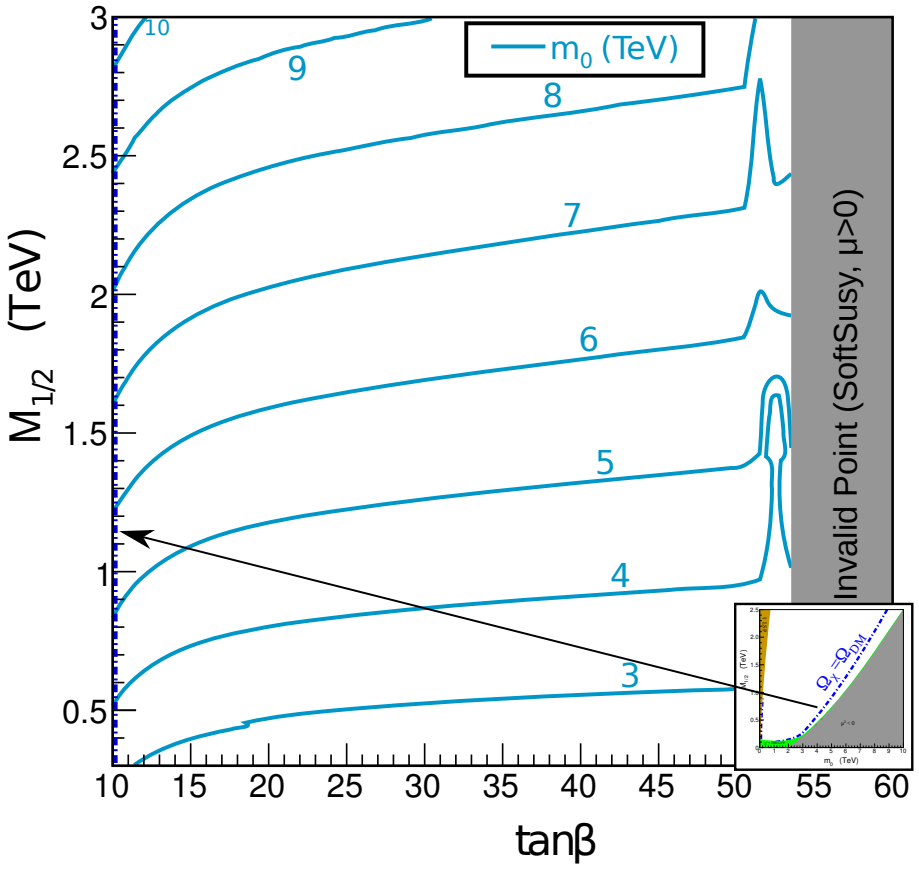


Focus Point with $\Omega_\chi = \Omega_{\rm DM}$

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 $A \ll m_0$

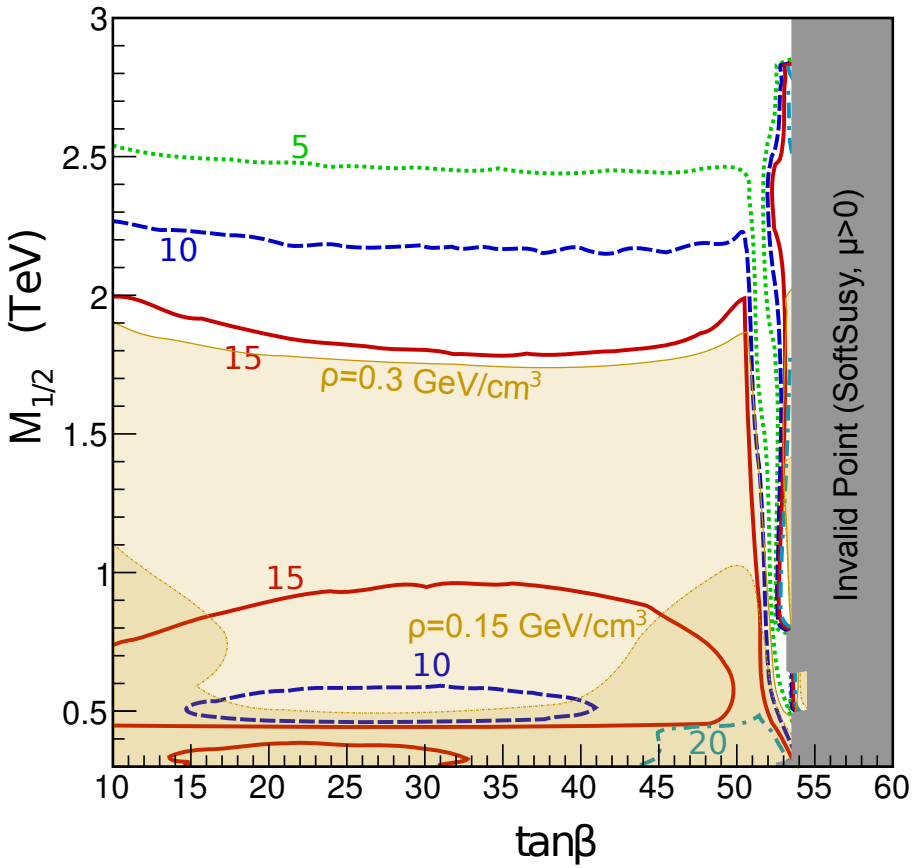
Scan over $M_{1/2} - \tan\beta$, using m_0 to set $\Omega_\chi = \Omega_{\rm DM}$



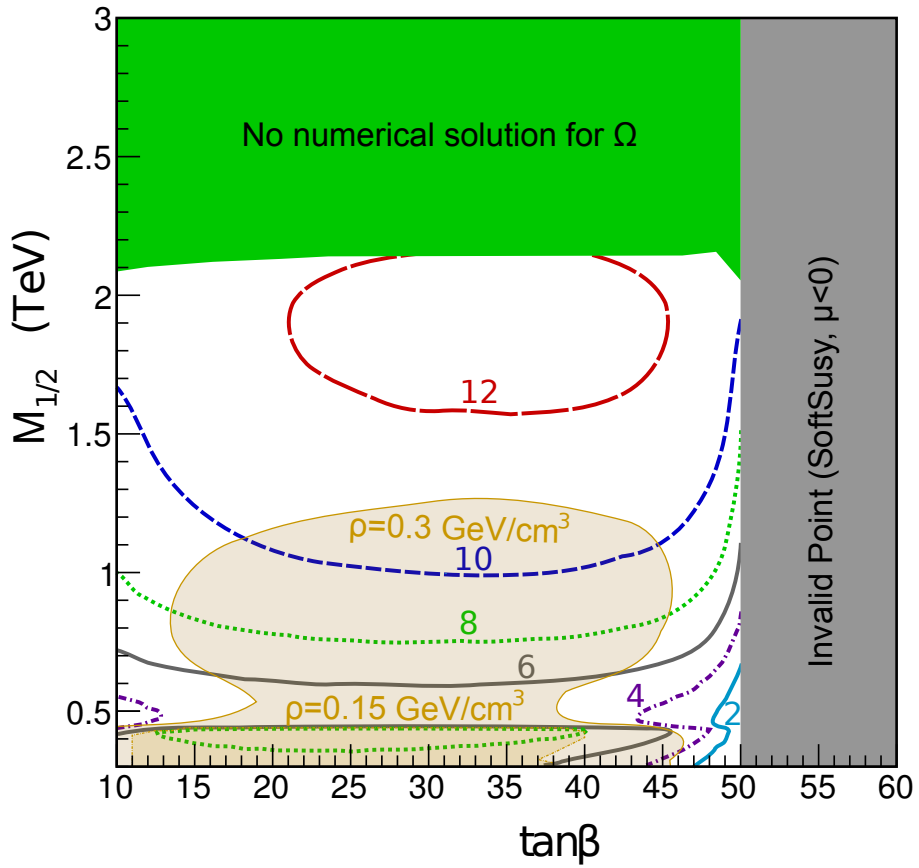
work with J. Feng and K. Matchev

Spin-Independent Direct Detection

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



$\mu > 0$



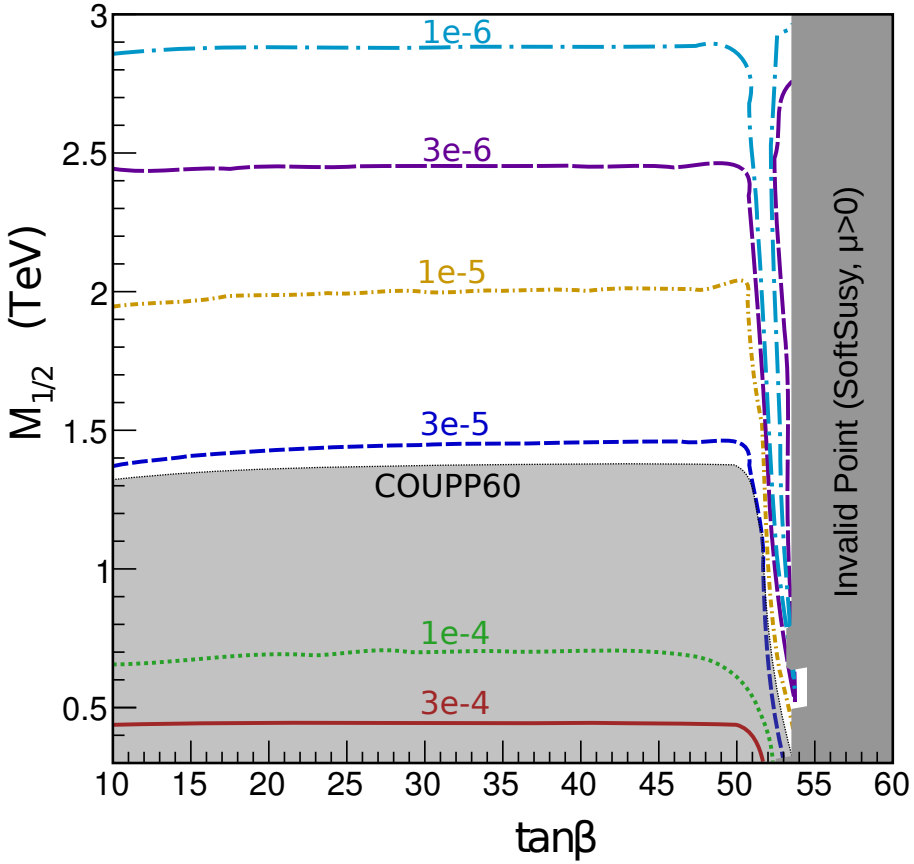
$\mu < 0$

with J. Feng, K. Matchev (2011)

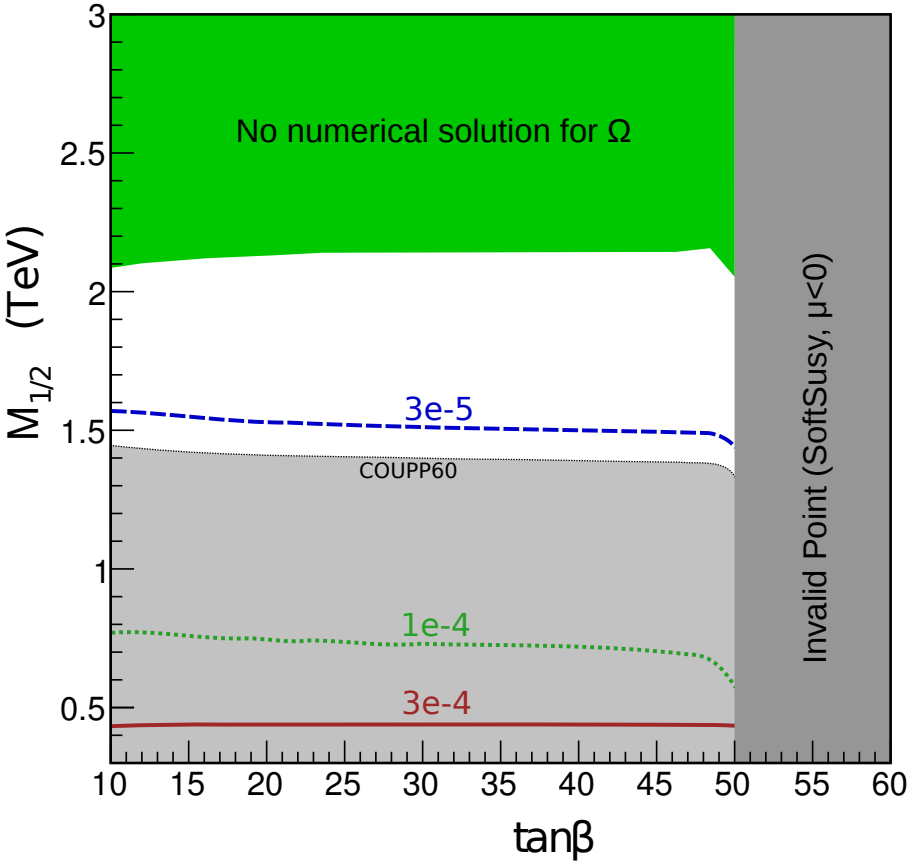
with J. Feng, S. Profumo, P. Draper, P. Kant (Forthcoming)

Spin-Dependent Direct Detection

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



$\mu > 0$

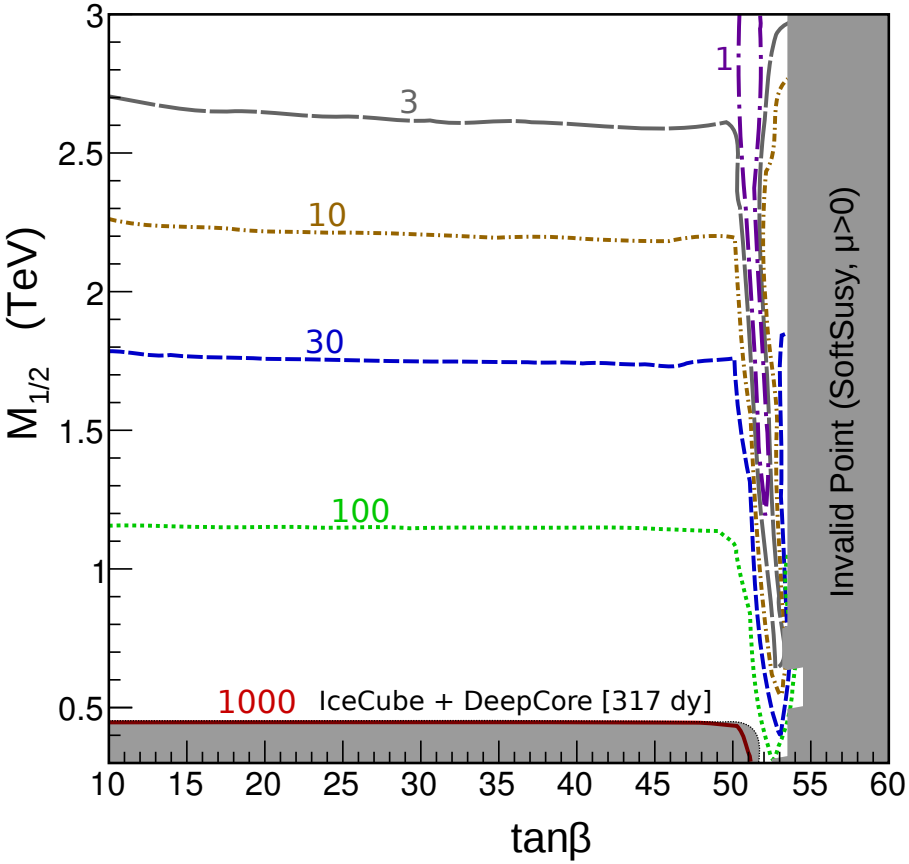


$\mu < 0$

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

Solar Muon Flux

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



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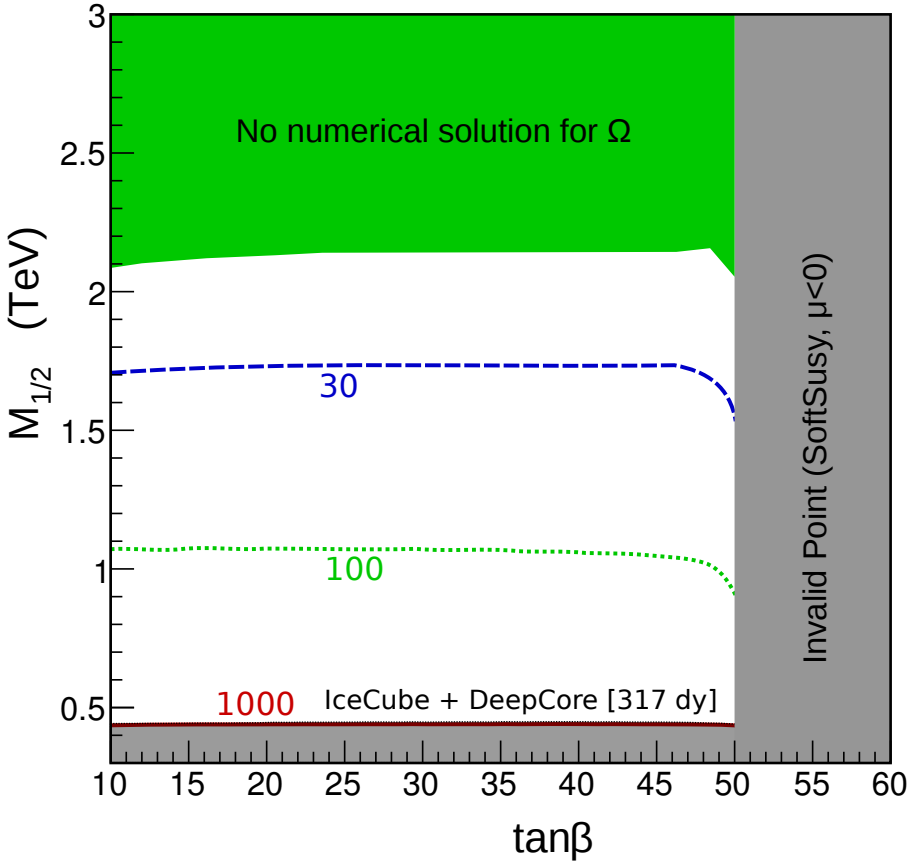
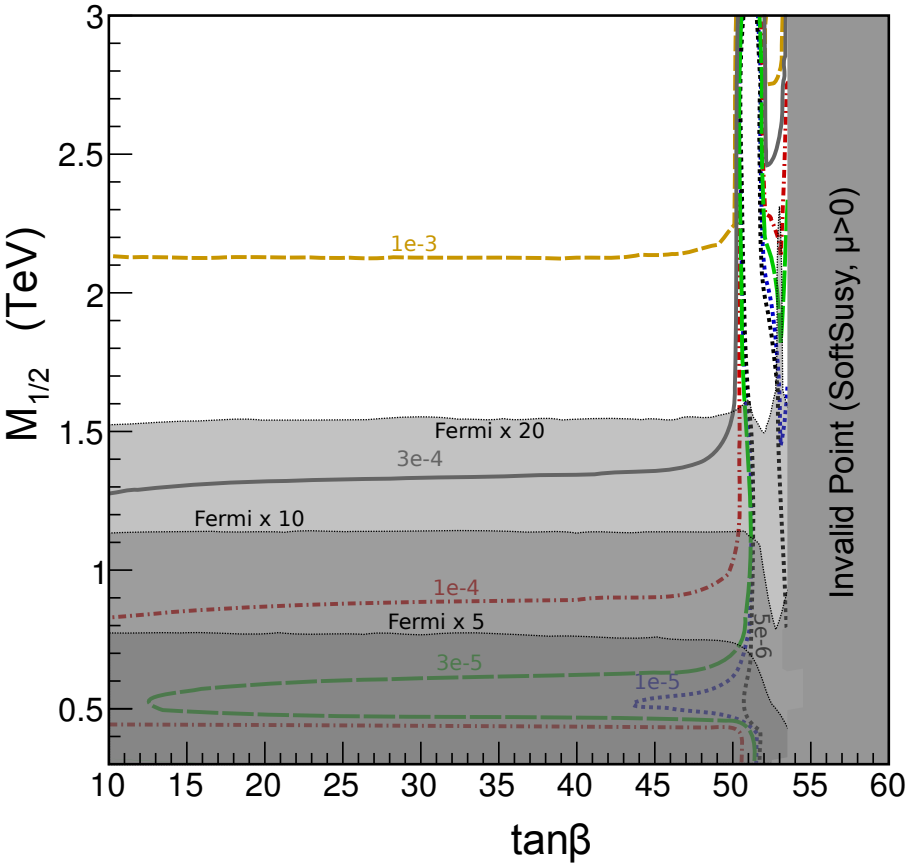


$\mu < 0$

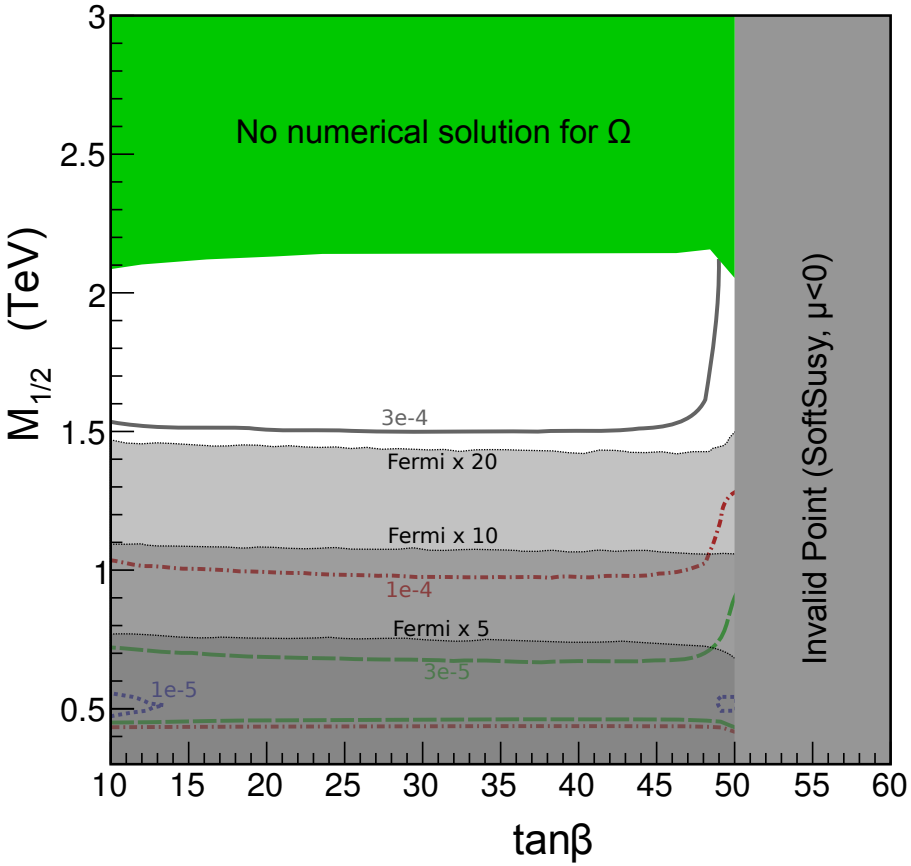
with J. Feng, S. Profumo, P. Draper, P. Kant (Forthcoming)

Gamma Ray Signals

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



$\mu > 0$

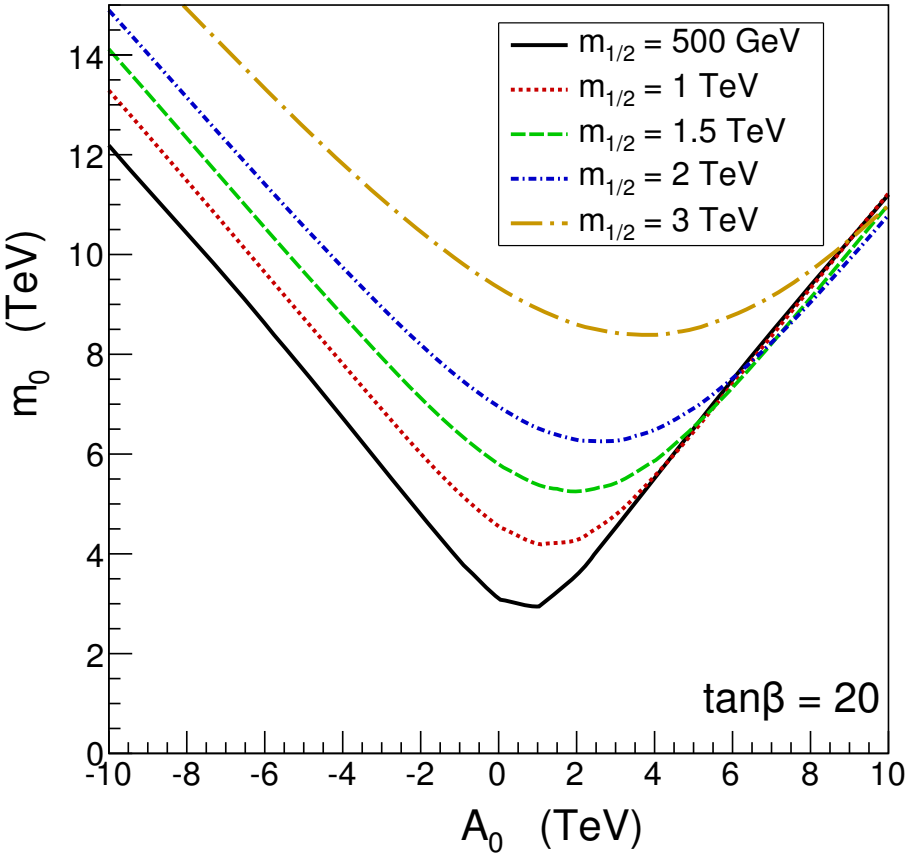


$\mu < 0$

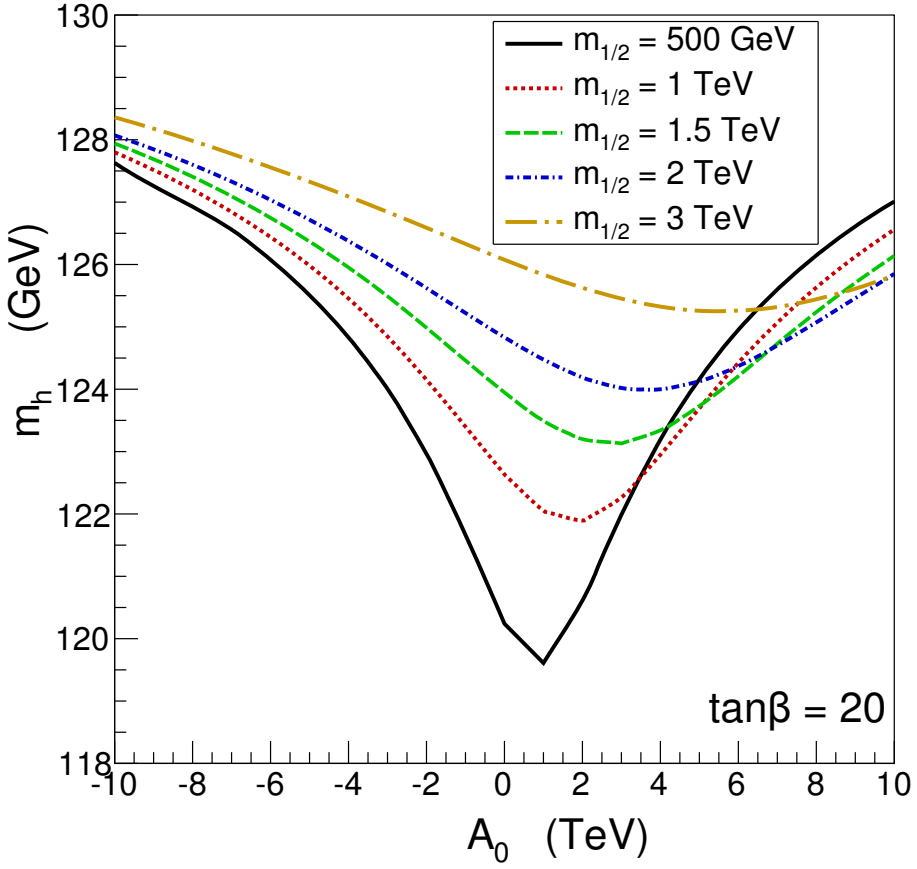
with J. Feng, S. Profumo, P. Draper, P. Kant (Forthcoming)

Focus Point Benchmarks: $\Omega_\chi + m_h$

Can use m_0 to fix $\Omega_\chi = \Omega_{\rm DM}$ and vary A_0 to vary m_h



$m_0 vs. A$



$m_h vs. A$

Focus Point Benchmark Points ($\mu < 0$)

- Set m_0 = 9 TeV to produce correct Higgs mass
- Choose A to produce $\Omega_\chi = \Omega_{\rm DM}$
- All points have m_h in range 125-126 GeV

$M_{1/2}$ (TeV)	A (TeV)	m_χ (GeV)	$m_{\tilde{g}}$ (TeV)	$\sigma_p^{\rm SI}$ (zb) $f_s = 0.05$	$\sigma_p^{\rm SD}$ (ab)	Solar μ Flux (km^{-2} yr^{-1})	$\mathcal{B}(\gamma\gamma)$ ($\times 10^{-4}$)
0.7	-4.81	302.5	1.79	5.34	89.8	30.4	0.338
0.8	-4.57	345.6	2.01	6.45	80.9	35.0	0.569
0.9	-4.34	388.9	2.23	7.43	71.8	34.5	0.858
1.2	-3.65	519.6	2.87	9.39	49.5	26.4	2.058
1.4	-3.18	606.7	3.29	10.2	39.0	19.2	3.176
1.6	-2.69	692.9	3.71	10.6	30.8	13.6	4.604
1.8	-2.16	777.4	4.11	10.3	23.6	9.37	6.387
2.0	-1.57	858.4	4.52	8.99	16.9	5.97	8.624
2.5	4.38	1010	5.50	2.93	39.1	1.47	16.82
3.0	1.24	1047	6.50	7.33	90.8	0.42	24.67

with J. Feng, K. Matchev, J. Gainer

Constrained by COUPP60 1 yr expected sensitivity

Focus Point Benchmark Points ($\mu > 0$)

$M_{1/2}$ (TeV)	A (TeV)	m_χ (GeV)	$m_{\tilde{g}}$ (TeV)	σ_p^{SI} (zb) $f_s = 0.05$	σ_p^{SD} (ab)	Solar μ Flux (km^{-2} yr^{-1})	$\mathcal{B}(\gamma\gamma)$ ($\times 10^{-4}$)
0.8	-4.61	337.6	2.01	14.2	68.5	35.9	0.964
0.9	-4.38	380.2	2.23	15.6	59.7	36.0	1.315
1.0	-4.15	423.1	2.45	16.5	51.6	33.7	1.704
1.2	-3.70	509.2	2.87	17.6	38.5	28.7	2.603
1.4	-3.23	595.2	3.29	18.1	29.1	21.9	3.680
1.6	-2.74	680.3	3.71	17.9	22.2	16.6	4.969
1.8	-2.21	763.4	4.11	16.8	16.6	12.2	6.530
2.0	-1.63	842.9	4.52	14.6	11.9	8.38	8.418
2.5	0.343	994.5	5.50	5.79	3.37	2.54	15.24
3.0	3.19	1039	6.48	1.73	0.910	0.81	22.72

with J. Feng, K. Matchev, J. Gainer

Constrained by COUPP60 1 yr expected sensitivity

Constrained by XENON100 w/ $\rho_{\rm local} = 0.3$ GeV/cm^3

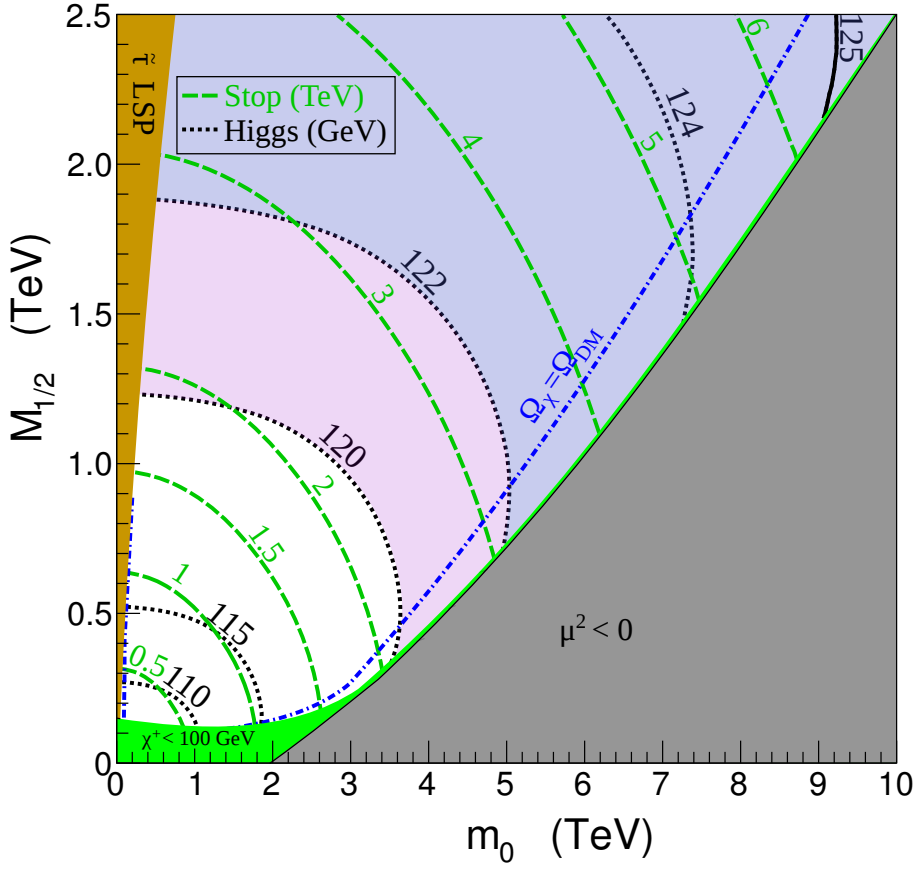
Constrained by XENON100 w/ $\rho_{\rm local} = 0.15$ GeV/cm^3

Uncertainty in Higgs Mass

- Previous estimates of theory uncertainty gave $\Delta m_h^{\text{theo}} \approx \pm 3 - 5$ GeV

  Allanach, Djouadi, Kneur, Porod, Slavich (2004)

  - Renormalization scheme dependence
  - Scale dependence
  - Zero external momentum approximation
- *Additional* uncertainty from experimental inputs
- Current spectrum generators use two-loop results



- Three-loop effects are expected to add 1-3 GeV

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

Conclusion

- The low mass region of the CMSSM are highly constrained by squark/gluino searches
- Observed Higgs mass and Flavor/CP constraints motivate even heavier scalars
- Focus Point scenario provides heavy Higgs and detectable dark matter
- Focus Point CMSSM benchmarks provide complementarity between LHC and DM sensitivity estimates

Backup Slides

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)

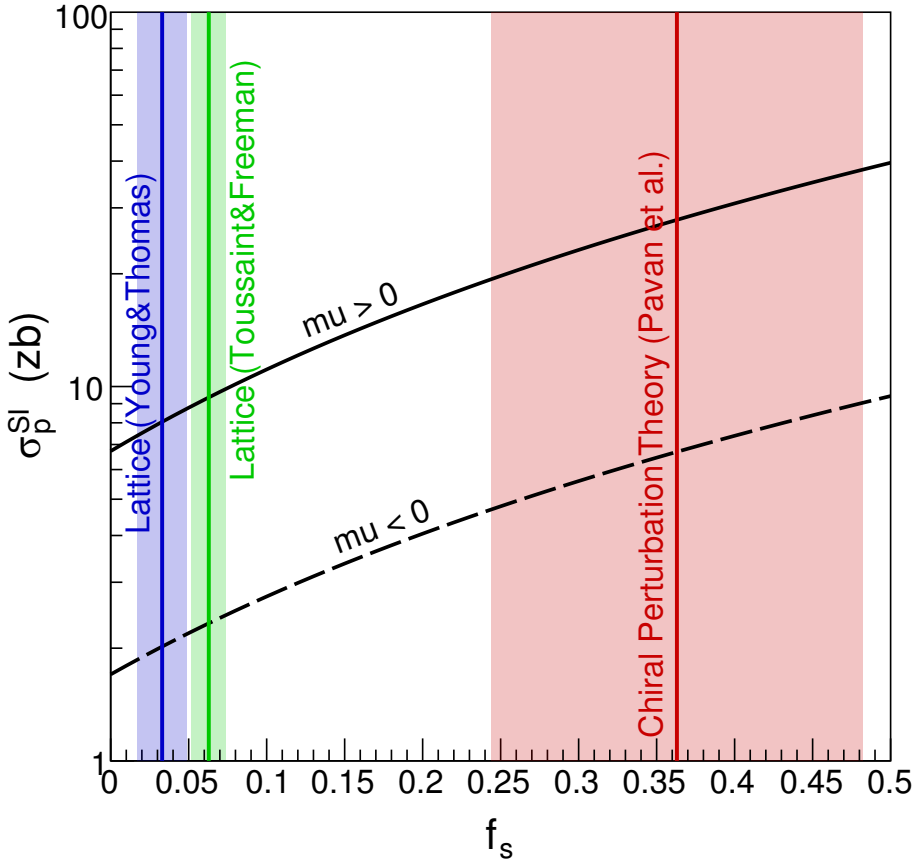
- $f_s \sim 0.05$ from direct lattice calculation

  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)

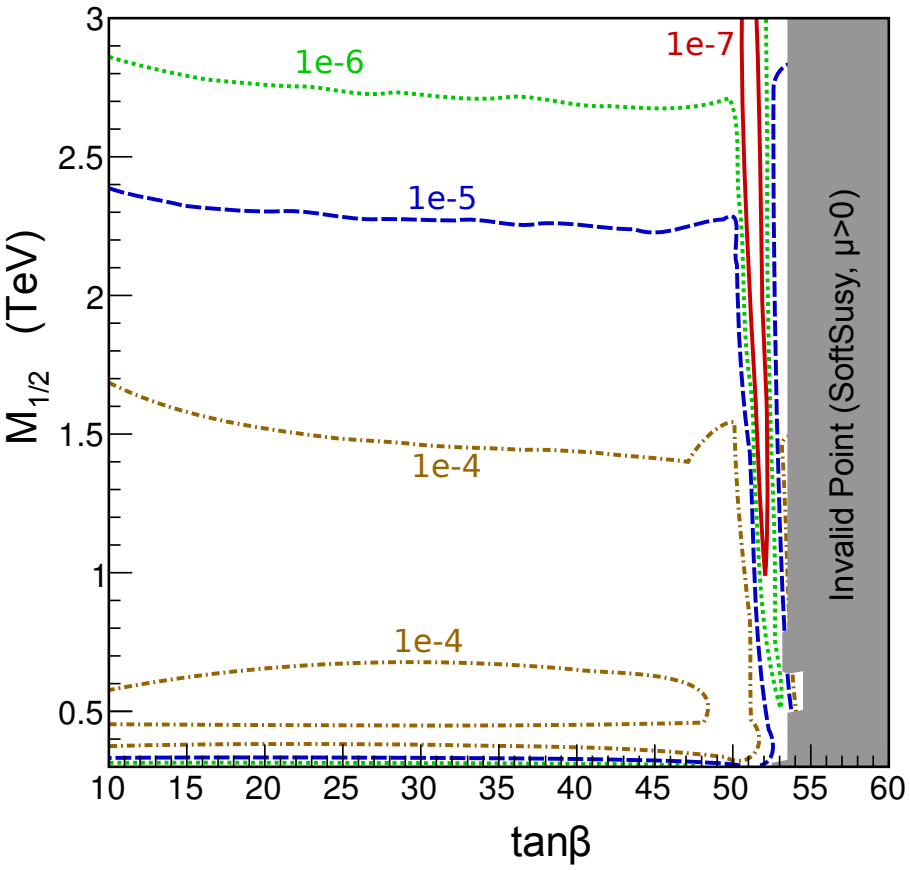


$\tan\beta = 10$, $m_{1/2} = 500$ GeV, $\Omega_\chi = \Omega_{DM}$

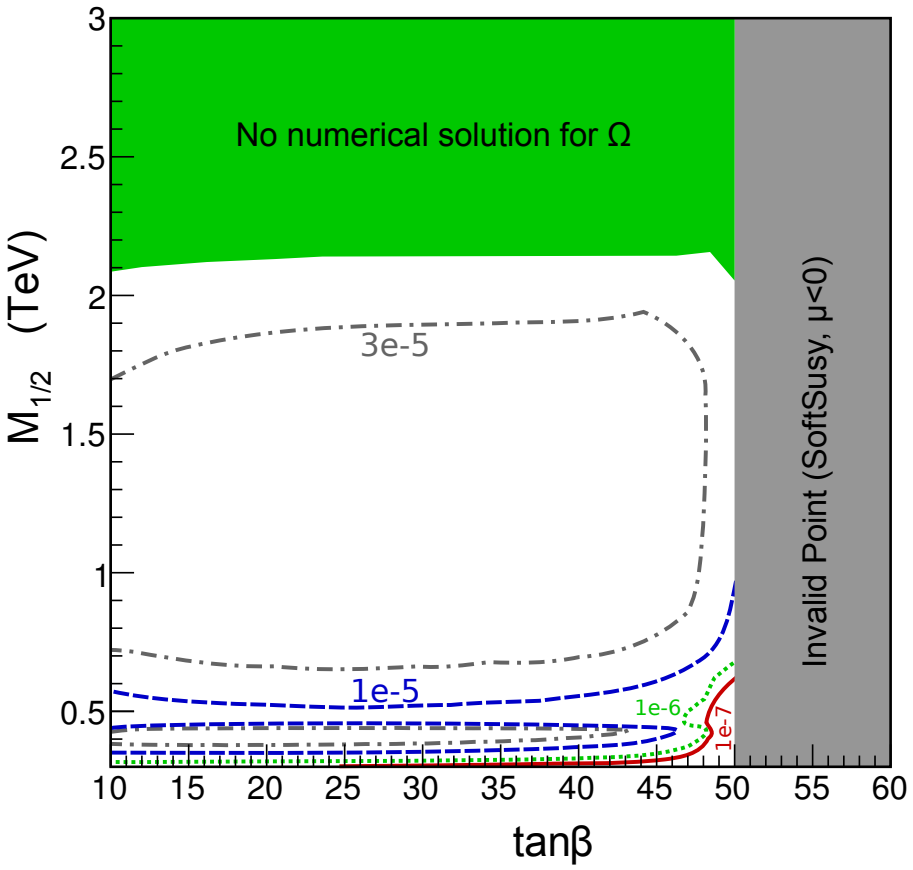
Will consider $f_s = 0.05$ here

Solar Neutrino Flux

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



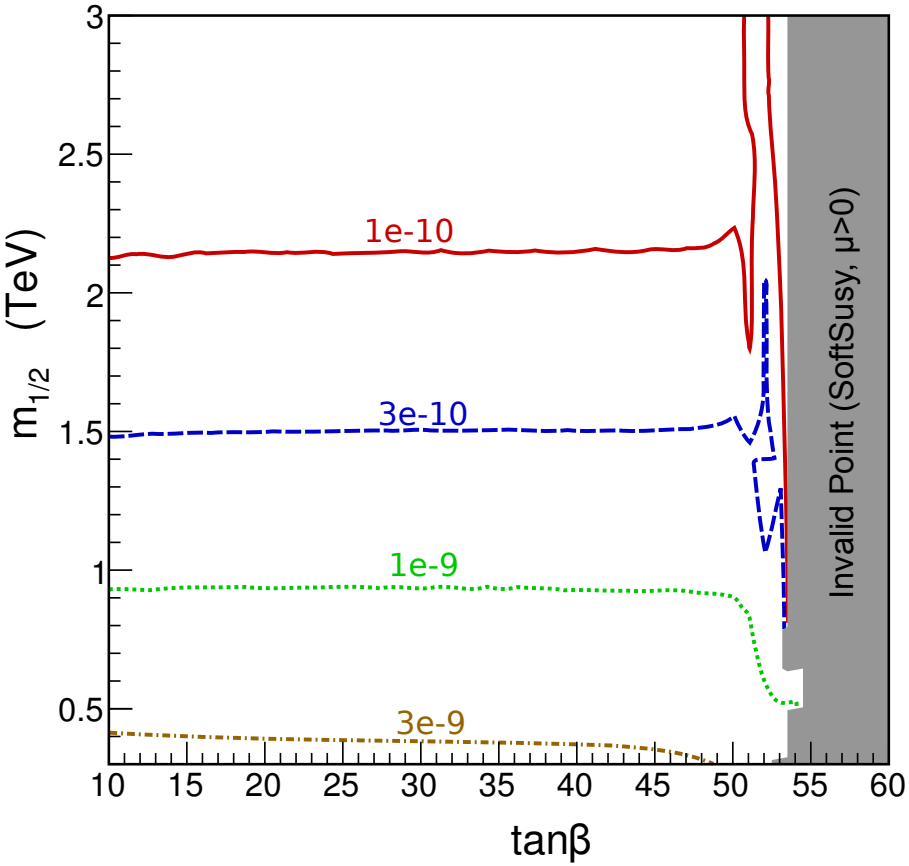
$\mu > 0$



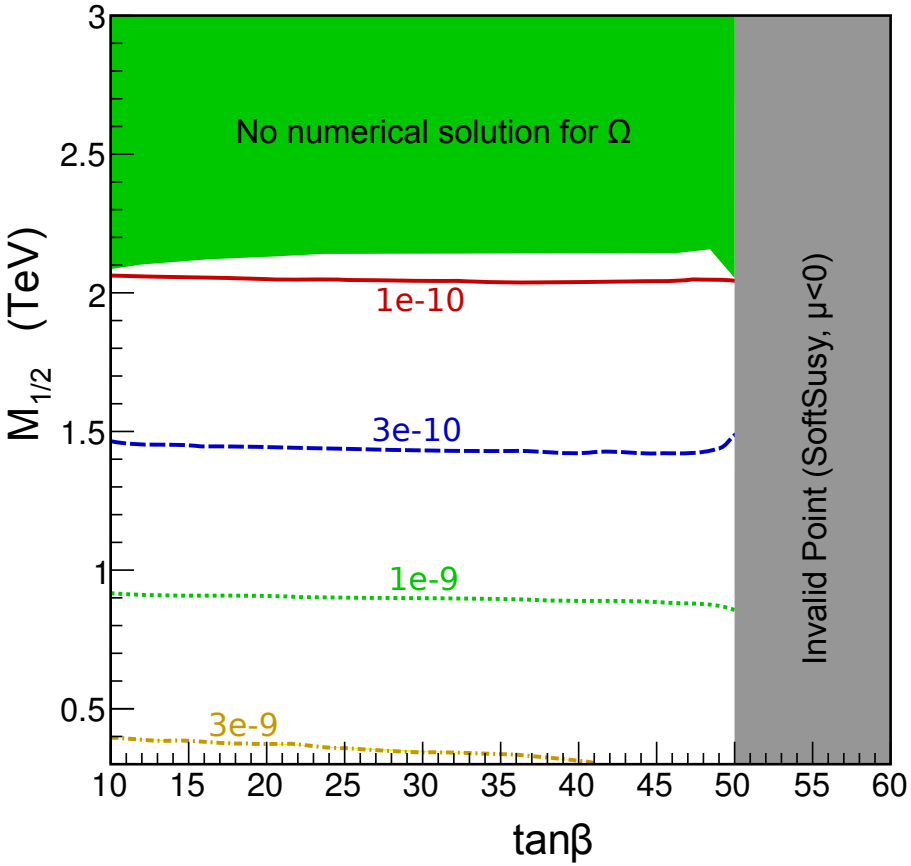
$\mu < 0$

Antiprotons

Antiproton flux ($km^{-2}\ yr^{-1}$)



$\mu > 0$

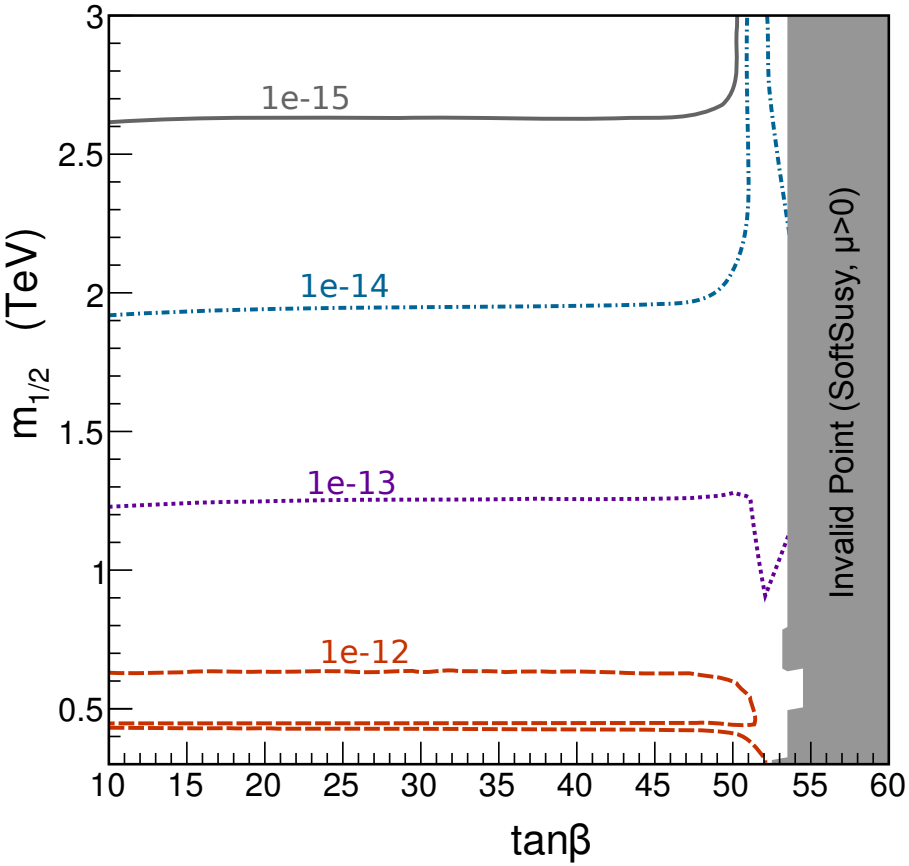


$\mu < 0$

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

Antideuterons

Antideuteron flux (km^{-2} yr^{-1})



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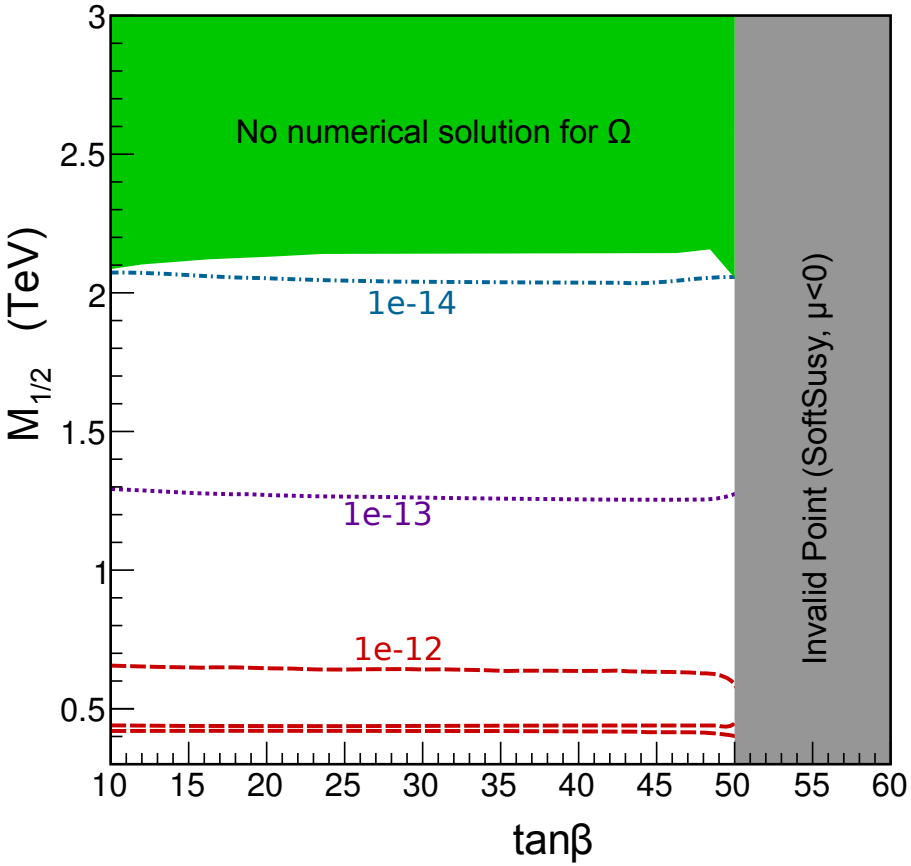

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