Dark matter in models with non-universal gaugino masses

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Research goals

- Extending mSUGRA to include non-universal gaugino masses can help solve the mu fine-tuning problem. mSUGRA with non-universal gaugino mass parameters is well-motivated by various models of gauge unification.
- In this study, I will scan important regions of non-universal gaugino mass parameter space to find model points with less fine-tuning.
- I will be looking for regions that have small a small μ parameter, relic density of thermal LSP dark matter in the range $0.09 < \Omega_{DM} h^2 < 0.13$, and that do not violate important constraints.

SUSY μ problem

- At the minimum of the MSSM scalar potential that breaks Electroweak symmetry, a typically large cancellation occurs between the supersymmetry-breaking Higgs mass terms H_u,H_d and the supersymmetry-respecting Higgs mass term μ.

$$m_Z^2 = 2(|m_{H_u}^2| - |\mu|^2) + \mathcal{O}\left(\frac{1}{\tan^2\beta}\right) + \text{loop corrections}$$

- Since $|\mu|$ can easily reach 1 TeV, it seems unnatural for the supersymmetry-breaking sector to be so finely tuned.
- Expanding in terms of the electroweak scale masses and running them up to the input scale shows that the fine-tuning is greatly exacerbated by the size of the gluino mass parameter [Kane and King 1998].

SUSY μ problem

- Carrying out this procedure (with universal scalar masses) shows that μ as a function of the input scale parameters takes the approximate form

$$|\mu|^2 = \alpha_1 \hat{M}_3^2 - \alpha_2 \hat{M}_2^2 + \alpha_3 \hat{M}_2 \hat{M}_3 - \alpha_4 \hat{M}_3 \hat{A}_t - \alpha_5 \hat{m}_0 + \text{terms with small coefficients}$$

  where the hats indicate an input scale value and the coefficients $\alpha_i > 0$ will depend on $\tan\beta$.
- Important features:
  - Decreasing M_3 will lower μ: α_1 tends to be very large and α_3 is usually small
  - Increasing M_2 will lower μ
  - M_1 has a minimal influence on mu
  - Increasing the scalar mass parameter decreases mu

SU(5)-motivated non-universal guagino masses

- Motivated by SU(5) and SO(10) gauge unification, I will consider mSUGRA models in which the F-term that breaks supersymmetry can transform as anything in the symmetric product of the adjoint representation of SU(5) with itself:

$$(\mathbf{24} \times \mathbf{24})_S = \mathbf{1} + \mathbf{24} + \mathbf{75} + \mathbf{200}$$

- It has been shown that the ratio of the gaugino mass parameters $M_1 : M_2 : M_3$ in these representations are

1	$1:1:1$	**75**	$5:-3:-1$
24	$1:3:-2$	**200**	$10:2:1$

- The **24** representation is well-suited to alleviate the mu problem, since increasing the contribution from this representation lowers the gaugino mass parameter and increases the wino mass parameter, thereby lowering $|\mu|$.

Parametrization of non-universality

- In my parametrization, the relative contribution of the singlet and **24** representation to the gaugino masses is given by $\sin\theta_{24}$, where $\sin\theta_{24} = 0$ is mSUGRA and $\sin\theta_{24} = 1$ has a pure **24** F-term.

$\sin\theta_{24}$ parametrization

$$
\begin{aligned}
M_1 &= m_{1/2}(\cos\theta_{24} + \sin\theta_{24}) \\
M_2 &= m_{1/2}(\cos\theta_{24} + 3\sin\theta_{24}) \\
M_3 &= m_{1/2}(\cos\theta_{24} - 2\sin\theta_{24})
\end{aligned}
$$

Parametrization of non-universality

- I will scan over slices of parameter space with M_1 held constant so that the other gaugino masses are a function of M_1 and $\sin\theta_{24}$

$\sin\theta_{24}$ parametrization, fixed M_1

$$M_2 = M_1\left(\frac{1+3\tan\theta_{24}}{1+\tan\theta_{24}}\right)$$
$$M_3 = M_1\left(\frac{1-2\tan\theta_{24}}{1+\tan\theta_{24}}\right)$$

- I will also make the choice $A_0 = -M_1$ in my scans.

Constraints

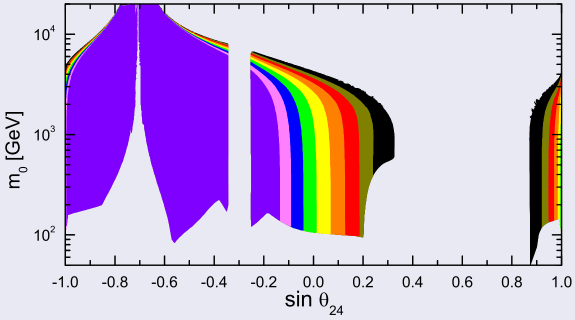
- I assume minimal flavor violation in the parameter space and will restrict scans to $sgn(\mu) = 1$.
- The important flavor constraints are $b \to s\gamma$, $B_S \to \mu^+\mu^-$, and $B \to \tau\nu$ through contributions from decays through the charged Higgs boson.

$$B_S \to \mu^+\mu^- < 4.3 \times 10^{-8} \quad \text{[CDF note 9892]}$$
$$b \to s\gamma > 2 \times 10^{-4}$$
$$\tan\beta < 7.4 \frac{m_{H^+}}{100 \text{ GeV}} \quad \text{[UTfit, 2009]}$$

- We require $m_{h^0} > 113$ GeV and exclude all model points where charged particles are the LSP or violate the approximately 100 GeV LEP bound.

Scans over fixed M_1, $\tan\beta$ planes

Map of mu parameter
$M_1 = -A_0 = 500$ GeV, $\tan\beta = 10$



Legend

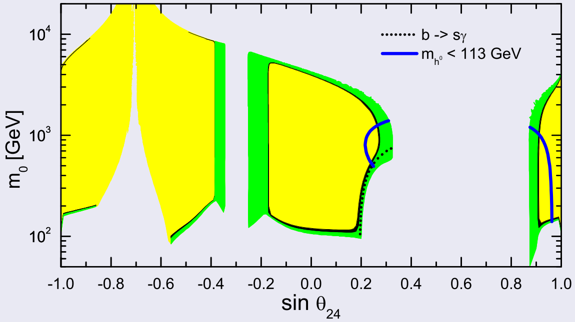
- $\mu < 300$ GeV
- $300 < \mu < 400$
- $400 < \mu < 500$
- $500 < \mu < 600$
- $600 < \mu < 700$
- $700 < \mu < 800$
- $800 < \mu < 900$
- $900 < \mu < 1000$
- $\mu > 1000$ GeV

- At small m_0, size of μ parameter governed entirely by M_2,M_3.
- The μ parameter gets smaller closer to the $M_3 = 0$ line at $\sin\theta_{24} = 1/\sqrt{5} = 0.48$. Increasing m_0 also makes the μ parameter smaller at the electroweak scale (in the focus point region).

Scans over fixed M_1, $\tan\beta$ planes

Relic density map

$M_1 = -A_0 = 500$ GeV, $\tan\beta = 10$



Relic Density

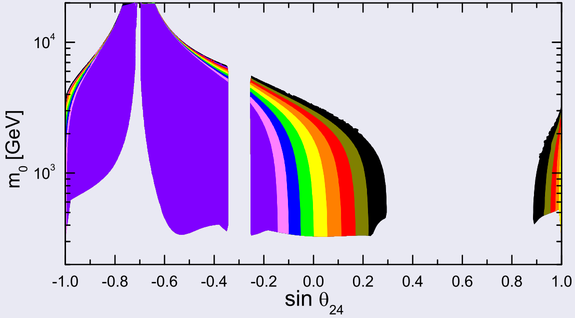
- $\Omega h^2 < 0.09$
- $0.09 < \Omega h^2 < 0.13$
- $\Omega h^2 > 0.13$

- Enhanced annihilation regions: annihilation to tops, focus point, stau co-annihilation, wino co-annihilation
- Solution boundary and $M_1 = 0$ asymptote
- Light higgs eliminates much of the low mu regions.

Scans over fixed M_1, $\tan\beta$ planes

Map of mu parameter

$M_1 = -A_0 = 500$ GeV, $\tan\beta = 40$



Legend

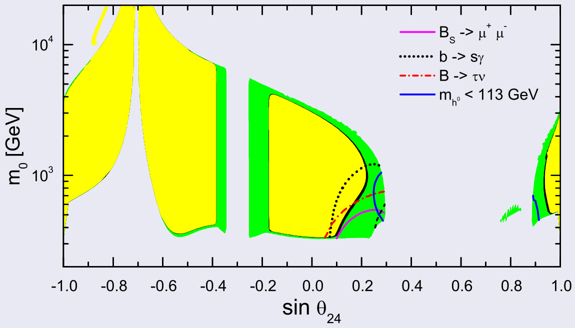
- $\mu < 300$ GeV
- $300 < \mu < 400$
- $400 < \mu < 500$
- $500 < \mu < 600$
- $600 < \mu < 700$
- $700 < \mu < 800$
- $800 < \mu < 900$
- $900 < \mu < 1000$
- $\mu > 1000$ GeV

- Increasing $\tan\beta$ further does not have a qualitative effect on the arrangement of the mu map.

Scans over fixed M_1, $\tan\beta$ planes

Relic density map

$M_1 = -A_0 = 500$ GeV, $\tan\beta = 40$



Relic Density

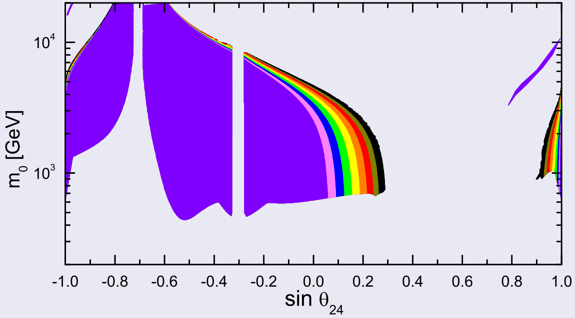
- (green) $\Omega h^2 < 0.09$
- (black) $0.09 < \Omega h^2 < 0.13$
- (yellow) $\Omega h^2 > 0.13$

- Higher $\tan\beta$ increases the Higgs mass, but causes low μ regions to violate flavor constraints.
- A^0 funnel has already replaced stop co-annihilation region

Scans over fixed M_1, $\tan\beta$ planes

Map of mu parameter

$M_1 = -A_0 = 900$ GeV, $\tan\beta = 45$



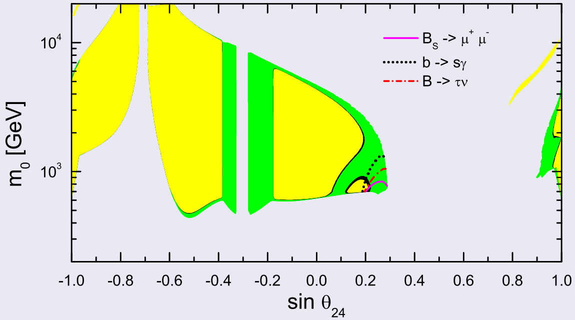
Legend

- ● $\mu < 300$ GeV
- ● $300 < \mu < 400$
- ● $400 < \mu < 500$
- ● $500 < \mu < 600$
- ● $600 < \mu < 700$
- ● $700 < \mu < 800$
- ● $800 < \mu < 900$
- ● $900 < \mu < 1000$
- ● $\mu > 1000$ GeV

- The more negative A_0 increases the derivative of μ in the M_3 direction due its dependence on input scale value of $-M_3 A_t$.

Scans over fixed M_1, $\tan\beta$ planes

Relic density map
$M_1 = -A_0 = 900$ GeV, $\tan\beta = 45$



Relic Density

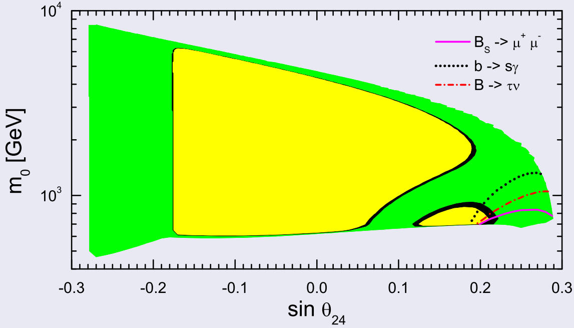
- $\Omega h^2 < 0.09$
- $0.09 < \Omega h^2 < 0.13$
- $\Omega h^2 > 0.13$

- Flavor constraints less problematic at higher M_1
- A^0 funnel moves to the left as $\tan\beta$ increases, eventually intersecting mSUGRA at $\sin\theta_{24} = 0$
- **Funnel separates a small region, the "confluence island", which has properties of focus point, stau co-annihilation, and funnel regions**

Scans over fixed M_1, $\tan\beta$ planes

Relic density map

$M_1 = -A_0 = 900$ GeV, $\tan\beta = 45$, zoomed in



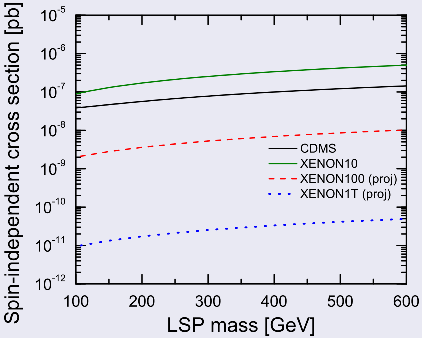
Relic Density

- $\Omega h^2 < 0.09$
- $0.09 < \Omega h^2 < 0.13$
- $\Omega h^2 > 0.13$

- Much of the confluence island lies outside flavor constraints, and has the thickest region in agreement with observed dark matter density.
- The part of the $\Omega h^2 < 0.09$ region in the A^0 funnel outside constraints is large and has a relatively small μ and $\tan\beta$ compared to typical mSUGRA A^0 funnel points.

LSP spin independent cross section

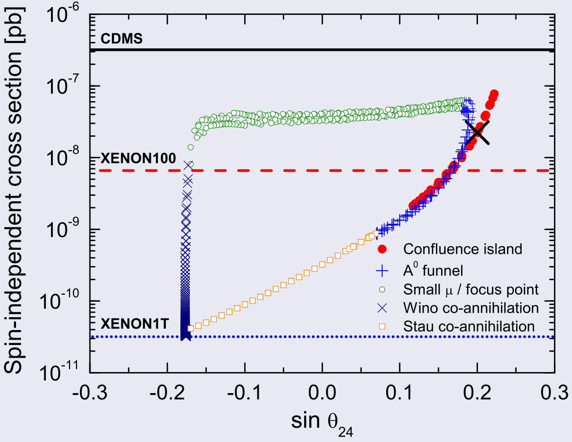
Current and projected reach of detectors



- The dominant limit on direct detection of LSP dark matter is the spin independent cross section.
- Large theoretical uncertainties prevent strict constraint on model points
- All points on the plane $M_1 = -A_0 = 900$, $\tan\beta = 45$ will have $m_{LSP} \approx 380$ GeV.

LSP spin independent cross section

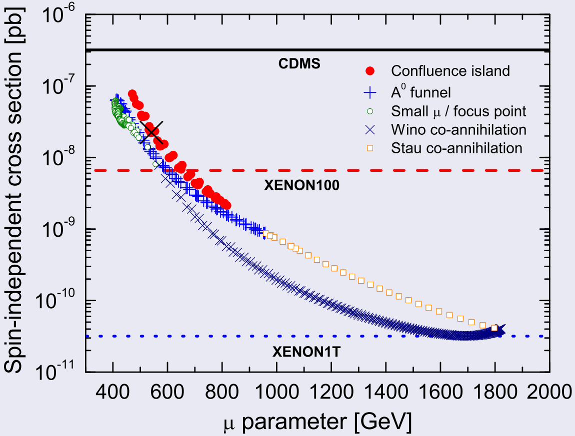
Spin independent cross section v. $\sin\theta_{24}$



- Large $\sin\theta_{24}$, small μ regions tend to be approximately within reach of next-generation detectors.

LSP spin independent cross section

Spin independent cross section v. μ parameter



- Confluence island and A^0 funnel have μ as small as focus point without the excessively narrow dark matter allowed region.

Example confluence island model point

- To understand the confluence island better, I will examine a model point on the top of the island close to the flavor constraints.

Confluence island model point

$M_1 = 900$ GeV	$m_0 = 870$ GeV	$\tan\beta = 45$
$A_0 =$ -900 GeV	$\sin\theta_{24} = 0.2$	$sgn(\mu) = 1$

- This point will demonstrate the hybrid nature of the confluence island, the inversion of the Wino-Higgsino hierarchy at positive $\sin\theta_{24}$, and the island's typical LHC signature.

LSP annihilation processes

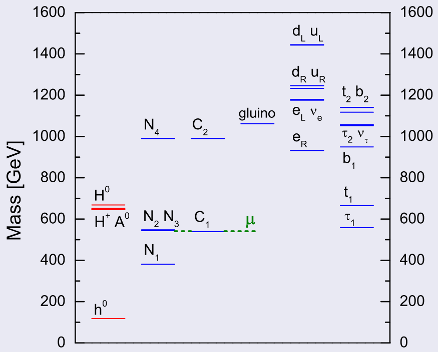
- This point on the confluence island is a mixture of the focus point and Higgs funnel. The relative contributions to dark matter annihilation are

$$\begin{aligned} \tilde{N}_1\tilde{N}_1 &\to b\bar{b} \quad (47\%) \\ \tilde{N}_1\tilde{N}_1 &\to Z\ H^0 \quad (17\%) \\ \tilde{N}_1\tilde{N}_1 &\to A^0\ h^0 \quad (9\%) \end{aligned} \qquad \begin{aligned} \tilde{N}_1\tilde{N}_1 &\to W^+H^- \quad (9\%) \\ \tilde{N}_1\tilde{N}_1 &\to W^-H^+ \quad (9\%) \\ \tilde{N}_1\tilde{N}_1 &\to \tau^+\tau^- \quad (5\%) \end{aligned}$$

- Like all points in the funnel region, dominant annihilation is to $b\bar{b}$ through pseudoscalar Higgs. This is also the process responsible for annihilation to taus.
- The other annihilation processes are typical of focus point models. The Higgsino content of the LSP is high enough (here, 5%) to allow annihilation or coannihilation to weak vector bosons.

Mass Spectrum

Higgs and R-parity odd sectors
$m_0 = 870$, $\sin\theta_{24} = 0.2$



- Pseudoscalar Higgs mass approaches twice the LSP mass, characteristic of A^0 funnel
- Models with $\sin\theta_{24} > 0$ typically have heavy, Wino-like N_4 and C_2, making these states inaccessible to production or decay processes at the LHC.

Branching fractions

- Assuming dominant LHC production is gluinos, the important tree-level branching fractions are

$$\tilde{g} \rightarrow \begin{cases} \tilde{t}_1 t & (87.2\%) \\ \tilde{b}_1 b & (12.7\%) \end{cases}$$

$$\tilde{t}_1 \rightarrow \begin{cases} \tilde{C}_1 b & (73.3\%) \\ \tilde{N}_1 t & (26.7\%) \end{cases}$$

$$\tilde{N}_3 \rightarrow \tilde{N}_1 Z \quad (100\%)$$

$$\tilde{N}_2 \rightarrow \begin{cases} \tilde{N}_1 h & (94.5\%) \\ \tilde{N}_1 Z & (5.5\%) \end{cases}$$

$$\tilde{b}_1 \rightarrow \begin{cases} \tilde{C}_1 t & (39.8\%) \\ \tilde{N}_3 b & (24.4\%) \\ \tilde{N}_2 b & (24.3\%) \\ \tilde{N}_1 b & (10.0\%) \\ \tilde{t}_1 W & (1.6\%) \end{cases}$$

$$\tilde{C}_1 \rightarrow \tilde{N}_1 W \quad (100\%)$$

$$\tilde{C}_2 \rightarrow \begin{cases} \tilde{N}_2 W & (25.3\%) \\ \tilde{C}_1 Z & (25.1\%) \\ \tilde{N}_3 W & (25.1\%) \\ \tilde{C}_1 h & (24.3\%) \end{cases}$$

- **As with virtually all high $\sin\theta_{24}$ models, the large mass of the Wino-like neutralino and chargino decouples them and sleptons from the LHC.**

Model point signature

- For this point, the tree level branching ratios for Standard Model final states resulting from gluino production are

$$\begin{aligned}
\tilde{g}\tilde{g} &\rightarrow bbbbWWWW + \not{E}_T \quad (85.4\%) \\
\tilde{g}\tilde{g} &\rightarrow bbbbWWZ + \not{E}_T \quad (6.0\%) \\
\tilde{g}\tilde{g} &\rightarrow bbbbWWh + \not{E}_T \quad (5.4\%) \\
\tilde{g}\tilde{g} &\rightarrow bbbbWW + \not{E}_T \quad (2.4\%)
\end{aligned}$$

- A good signal for this model point is four b-jets plus two like-sign charged leptons.

$$BR(\tilde{g}\tilde{g} \rightarrow 4b + l^+ l^+ / l^- l^- + \text{hadrons} + \not{E}_T) \approx 9\%$$

Model point signature

- Occasionally the LHC will produce squark + gluino or squark + squark, but these will produce very similar final states.

$$\tilde{u}_L \rightarrow \begin{cases} \tilde{g}u & (77.1\%) \\ \tilde{C}_2 d & (13.8\%) \end{cases} \qquad \tilde{u}_R \rightarrow \begin{cases} \tilde{g}u & (71.1\%) \\ \tilde{N}_1 u & (27.9\%) \end{cases}$$

$$\tilde{d}_L \rightarrow \begin{cases} \tilde{g}d & (77.5\%) \\ \tilde{C}_2 u & (14.1\%) \end{cases} \qquad \tilde{d}_R \rightarrow \begin{cases} \tilde{g}d & (89.8\%) \\ \tilde{N}_1 d & (9.8\%) \end{cases}$$

- The primary effect of squark production is an additional hard jet in the gluino-gluino final states.
- Chargino / neutralino decays will slightly enhance some of the rarer gluino-gluino final states.

Outlook

- Non-universal gaugino mass models can help to alleviate mSUGRA fine-tuning problems.
  - Opens up many new small μ regions
  - Large regions where $\Omega_{DM}h^2 < 0.09$ with low μ
- Flavor constraints affect A^0 funnel region, but large regions of non-universal parameter space survive.
- At relatively high $\tan\beta$ and M_1, there are promising "confluence islands" that are separated from the region containing mSUGRA and have a large area in which the relic density is in the observed range.