Invisible Higgs decays and the GCE in the NMSSM

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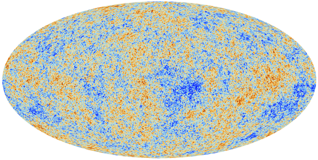
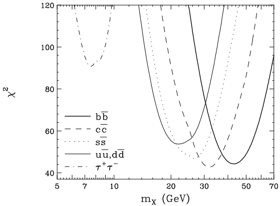
There is physics beyond the Standard Model!

- 26.8% dark matter
- Since 2009 observation of an excess of gamma ray photons in 3-4 GeV range from the galactic center by Fermi LAT [Hooper et al., Calore et al., Murgia for Fermi Collaboration]
- GCE can be explained by dark matter around a few GeV
- Observable at a collider?
- Higgs could decay in light dark matter !

→ Can we link GCE to an enhanced branching ratio $H_{125} \to inv$?



CMB as observed by Planck (Planck Collaboration)

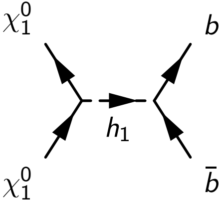


D. Hooper, et al., arXiv:1402.6703

What are the main constraints?

- $\Omega h^2 = 0.1187 \pm 0.0017\ _{st} \pm 0.0120\ _{th}$ (Planck)

- Dark matter annihilation before the freeze out
- Examples:
  $h-$funnel, $A-$funnel, $Z-$mediated, coannihilation [Drees, Nojiri], ...



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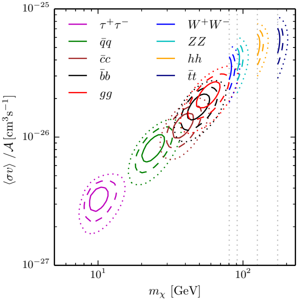
- $\sigma v|_{v=0} \approx 2 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$ (GCE)

- excess of γ-ray photons in the galactic center observed by Fermi LAT
- well fit by $30 - 70$ GeV dark matter annihilating via a **pseudoscalar** to $b\bar{b}$

$$\sigma v\Big|_{v=0} \approx \frac{3}{2\pi}\frac{g^2_{A\chi\chi}g^2_{Abb}m^2_\chi}{\left(m^2_A - 4m^2_\chi\right)^2 + m^2_A\Gamma^2_A}$$



Calore, Cholis, McCabe, Weniger, arXiv:1411.4647

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- BR $(H \to inv) < 23\%/36\%$ (ATLAS/CMS)

- Current measurements
  - CMS: WBF
  - ATLAS: combined associated production and gluon fusion
- Future: probing down to 3% with high luminosity run [Plehn et al.]

$\rightarrow$ We require BR$> 10\%$

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- $m_H = (125.1 \pm 0.2_{\,st} \pm 0.1_{\,sy} \pm 3.0_{\,th})\,\mathrm{GeV}$ (ATLAS/CMS)
- $\Gamma_{Z \to Inv} = (-1.9 \pm 1.5_{\,st} \pm 0.2_{\,th})\,\mathrm{MeV}$ (LEP)

- make sure that the coupling to the Z is small
- we require $\Gamma_{Z \to Inv} < 2$ MeV

Why SUSY?

Other hints at physics beyond the Standard Model

BSM

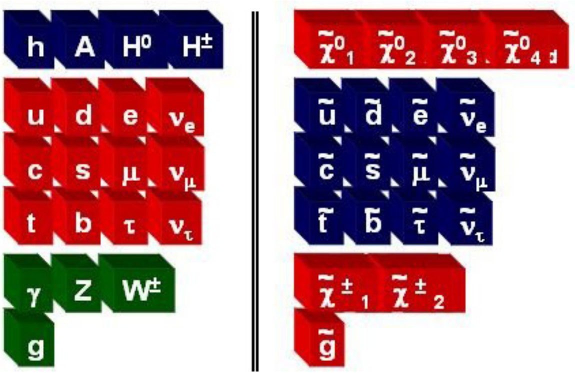
- Dark Matter, GCE
- Hierarchy Problem
- deviations in a_μ
- ...

SUSY

- stable LSP
- systematic cancellation
- additional loop contributions

→ promising setup but many models
→ Can we connect astronomical observations to LHC measurements in the SUSY framework?

The MSSM particle content



From MSSM to NMSSM

- μ-Problem, **light pseudoscalar** for GCE
- solution:

$$W_{NMSSM} = W_{MSSM} + \lambda S H_u H_d + \frac{1}{3}\kappa S^3$$

$\rightarrow$ additional singlet S

- vev of S generates effective μ-term: $\mu_{eff} = \lambda \cdot s$

New particle content

$\left.\begin{matrix} h_1, h_2, h_3 \\ A_1, A_2 \end{matrix}\right\}$ Higgs sector, $\left.\begin{matrix} \tilde{\chi}_1, \tilde{\chi}_2, \tilde{\chi}_3 \\ \tilde{\chi}_4, \tilde{\chi}_5 \end{matrix}\right\}$ neutralinos

The NMSSM parameters

- Scale invariant superpotential

$$W_{NMSSM} = W_{MSSM} + \lambda S H_u H_d + \frac{1}{3}\kappa S^3$$

- Additional soft SUSY breaking parameters appear:

$$-\mathcal{L}_{soft} \supset \lambda A_\lambda H_u H_d S + \frac{1}{3}\kappa A_\kappa S^3$$

Complete set of input parameters

$m_{\tilde{q},\tilde{\ell}}, M_{1,2,3}, A_{q,\ell}, tan\beta, \mu$ → as for MSSM

$\lambda, \kappa, A_\lambda, A_\kappa$ → additional parameters

- Decouple gluino and sfermion sector → $m_{\tilde{q},\tilde{\ell}} = M_3 = 10$ TeV, $A_{q,\ell} = 0$ → 8 free parameters left

Constraints on the spectrum

- Standard Model like Higgs at 125 GeV [H_{125}] $\rightarrow$ $m_{\tilde{t}} = 6$ TeV
- charged Higgs must be heavy
  $\rightarrow$ MSSM like scalar and pseudoscalar heavier than SM Higgs
- GCE:
  $\rightarrow$ $m_{\tilde{\chi}_1^0} \approx 30 - 70$ GeV
  $\rightarrow$ light (singlet like) pseudoscalar $m_{A_1} \approx 2 \cdot m_{\tilde{\chi}_1^0}$
  $\rightarrow$ $A_\kappa = -250$ GeV
- LEP constraints:
  $\rightarrow$ $m_{\tilde{\chi}_1^\pm} > 103$ GeV $\rightarrow$ $\mu, M_2 > 100\,\mathrm{GeV}$
  negligible wino contribution on LSP $\rightarrow$ set $M_2 = 2$ TeV
- BR $H_{125} \rightarrow \tilde{\chi}_1^0 + \tilde{\chi}_1^0$:
  $\rightarrow$ $m_{\tilde{\chi}_1^0} < 64$ GeV

Free parameters

$$M_1, \mu, A_\lambda, \tan\beta, \lambda, \kappa$$

Constraints on the couplings

- SM Higgs couplings:
  $\rightarrow$ no tree level mixing between singlet and H_{125}

$$A_\lambda = 2\mu\left(\frac{1}{s_{2\beta}} - \tilde{\kappa}\right) \quad \text{define } \tilde{\kappa} := \frac{\kappa}{\lambda}; \quad (m_{\tilde{\chi}_S} = 2\mu\tilde{\kappa})$$

- Z neutralino (Ωh^2, LEP)

$$g_{Z\tilde{\chi}_1\tilde{\chi}_1} = \frac{g}{2\cos\theta_W}\gamma_\mu\gamma_5\left(N_{13}^2 - N_{14}^2\right)$$

- A_S neutralino (GCE, Ωh^2)

$$g_{A_S\tilde{\chi}_1\tilde{\chi}_1} = \sqrt{2}\lambda\left(N_{13}N_{14} - \tilde{\kappa}N_{15}^2\right)$$

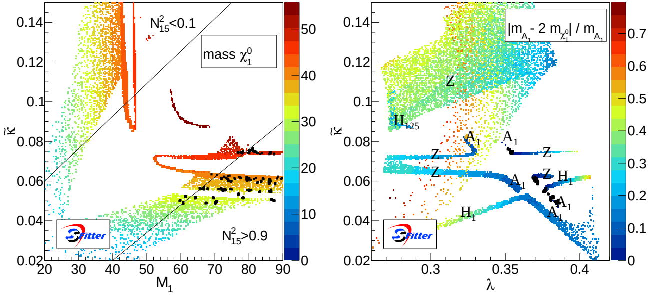
Fit parameters

$$M_1, \mu, \lambda, \tilde{\kappa}$$

SFitter

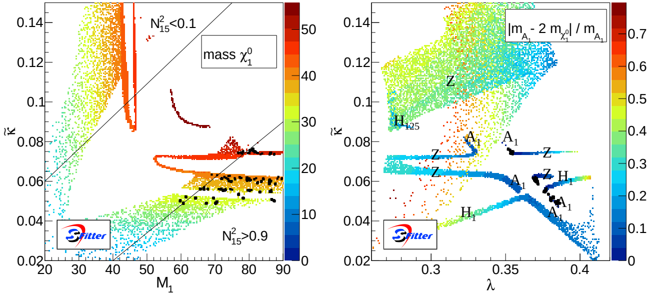
- Input: Model, Data
- Output:
  - best fit points
  - fully-dimensional log-likelihood map
  - likelihood projections on one and two dimensional plane (Bayesian and Frequentist)
- Algorithms:
  - Weighted Markov chain
  - Cooling Markov chain
  - Modified gradient fit (Minuit)
  - ...
- Errors
  - Gaussian
  - Poisson
  - box-shaped
- Tools
  - micrOMEGAs [Bélanger et al.]
  - NMSSMTools [Ellwanger et al.]
  - ...

Annihilation channels in the bino-singlino plane



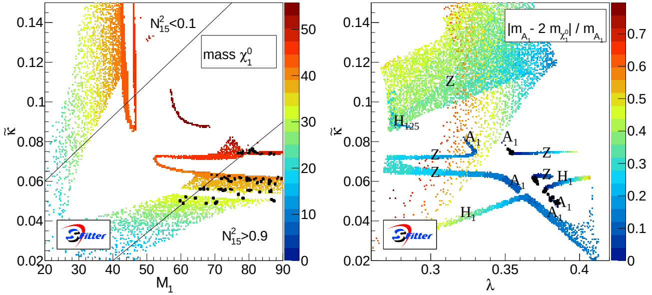
- choose $\mu = 320$ GeV, variable input parameters: $\lambda, \tilde{\kappa}, M_1$
- criteria: SM Higgs, relic density, Xenon100, BR$> 10\%$
- $\tilde{\kappa} - M_1$ plane:
  - asymptotic behaviour of the LSP mass
  - symmetric under bino singlino exchange

Annihilation channels in the bino-singlino plane



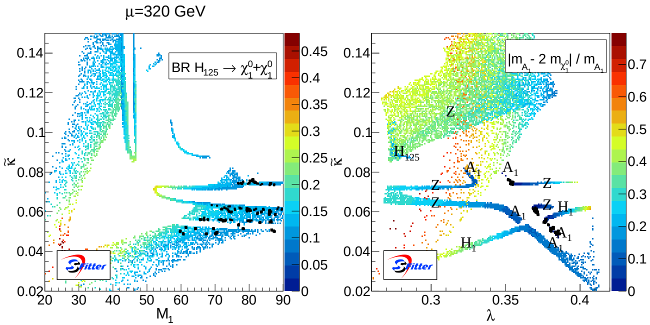
- Dark matter annihilation:
  - H_{125} – mediated annihilation for $m_{\tilde{\chi}^0_1} \approx 55$ GeV
  - Z – mediated for $m_{\chi^0_1} \approx 40$ and 48 GeV
  - cancellation of Higgsino components for $\tilde{\kappa} \approx 0.08$
  - H_1 – mediated annihilation for $m_{\tilde{\chi}^0_1} < 40$ GeV

Annihilation channels in the bino-singlino plane



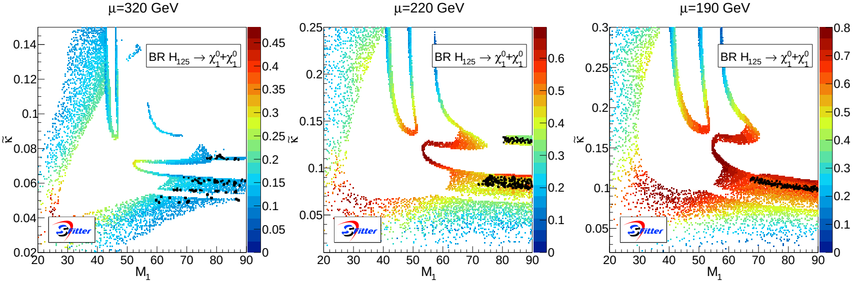
- The galactic center excess [black points]
  - neutralino mass constrained to $m_{\tilde{\chi}_1^0} > 30$ GeV [Weniger et al.]
  - m_{A_1} decreases with $\tilde{\kappa}$ and $1/\lambda$
  - GCE criteria fulfilled for $m_{A_1} \lesssim\gtrsim 2m_{\tilde{\chi}_1^0}$

Branching ratio $H_{125} \to \tilde{\chi}_1^0 + \tilde{\chi}_1^0$



- largest BR for mixed state (45% bino, 45 % singlino, 10% Higgsino)
  - $\to$ 0.45 not compatible with GCE
- BR $(H_{125} \to \tilde{\chi}_1^0 \tilde{\chi}_1^0) \approx 15\%$ compatible with the GCE
  - $\to$ requires singlino like dark matter

μ-dependence of the branching ratio

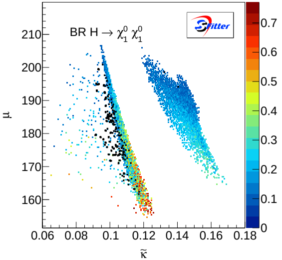


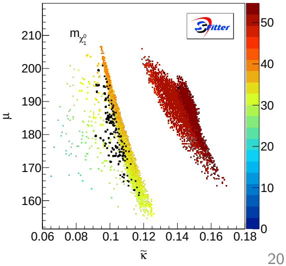
- larger Higgsino component $[1/\mu]$
- annihilation channels no longer well separated
- BR $(H_{125} \to \tilde{\chi}_1^0 \tilde{\chi}_1^0) \approx 60\%$ for $\mu = 190$ GeV

$\to$ scenarios with $\mu < 250$ GeV are excluded by ATLAS and CMS!

The NUH-NMSSM

- Non Unified Higgs mass
- Additional unification criteria:
  $m_0, m_{1/2}, A_0, A_\lambda, A_\kappa$ at GUT scale
  $\rightarrow M_1 > 200$ GeV [gluino searches]
- Free parameters $\tilde{\kappa}, \lambda, A_\kappa, \mu$
- Two regions correspond to Z-mediated annihilation
- GCE compatible with $m_{\tilde{\chi}_1^0} \approx 35$ GeV
- Invisible branching ratio up to 40 % for $\mu \approx 160$ GeV





Conclusion

- (NUH)-NMSSM is a suitable setup to describe the GCE
- Combining the GCE with the relic density and Xenon100 strongly constrains the parameter space
- $\text{BR}\left(H_{125} \to \tilde{\chi}_1^0 + \tilde{\chi}_1^0\right)$ up to 60% is possible in agreement with GCE and is tested by the LHC!

BACK UP

Neutralino mass matrix

$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_w & m_Z s_\beta s_w & 0 \\ 0 & M_2 & m_Z c_\beta c_w & -m_Z s_\beta c_w & 0 \\ -m_Z c_\beta s_w & m_Z c_\beta c_w & 0 & -\mu & -\lambda v s_\beta \\ m_Z s_\beta s_w & -m_Z s_\beta c_w & -\mu & 0 & -\lambda v c_\beta \\ 0 & 0 & -\lambda v s_\beta & -\lambda v c_\beta & 2\tilde{\kappa}\mu \end{pmatrix}$$

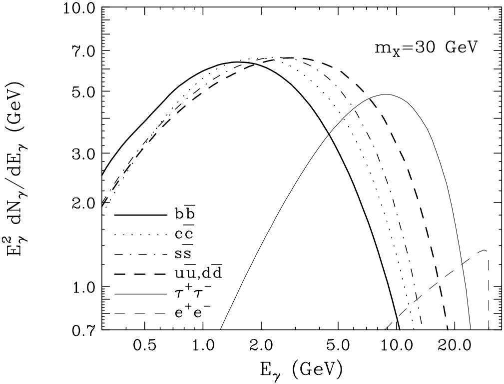
CP even Higgs mass marix in the basis (H, H_{125}, S)

$$M^2_{H,H_{125},S} = m_Z^2 \begin{pmatrix} s^2_{2\beta}\left(1-\tilde{\lambda}^2\right) + \frac{2\mu}{c_{2\beta}\, m_Z^2}\left(A_\lambda + \tilde{\kappa}\mu\right) & c_{2\beta}\, s_{2\beta}\left(1-\tilde{\lambda}^2\right) & -c_{2\beta}\,\frac{\tilde{\lambda}}{m_Z}\left(A_\lambda + \tilde{\kappa}\mu\right) \\ \cdot & c^2_{2\beta} + s^2_{2\beta}\tilde{\lambda}^2 & \frac{2\tilde{\lambda}}{m_Z}\left(\mu - s_{2\beta}\,\frac{A_\lambda}{2} + s_{2\beta}\,\tilde{\kappa}\mu\right) \\ \cdot & \cdot & s_{2\beta}\,\frac{\tilde{\lambda}^2 A_\lambda}{2\mu} + \frac{\tilde{\kappa}\mu}{m_Z^2}\left(A_\kappa + 4\tilde{\kappa}\mu\right) \end{pmatrix}$$

CP odd Higgs mass marix in the basis (A, S)

$$M^2_{A,S} = \begin{pmatrix} \frac{2\mu\left(A_\lambda + \tilde{\kappa}\mu\right)}{s_{2\beta}} & \tilde{\lambda} m_Z\left(A_\lambda - 2\tilde{\kappa}\mu\right) \\ \cdot & s_{2\beta}\,\tilde{\lambda}^2 m_Z^2\left(\frac{A_\lambda}{2\mu} + 2\tilde{\kappa}\right) - 3\tilde{\kappa}\mu A_\kappa \end{pmatrix}$$

γ spectrum for the GCE

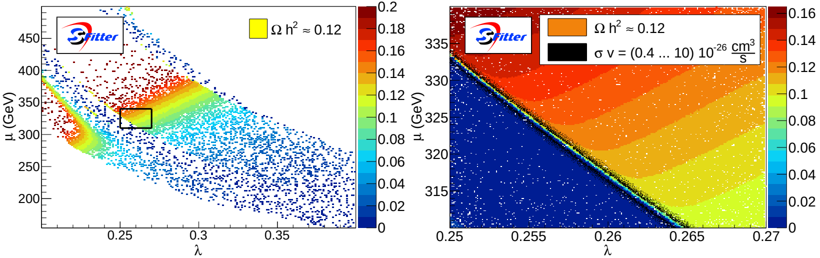


D. Hooper, et al., arXiv:1402.6703

γ spectrum:

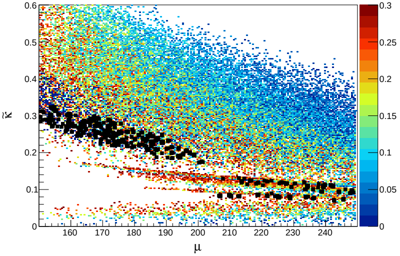
$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}x} \approx \frac{\alpha Q_{q/\ell}^2}{\pi} \frac{x^2 - 2x + 2}{x} \ln\left[\frac{m_{\tilde{\chi}_1^0}^2}{m_{q/\ell}^2}(1-x)\right]; \qquad x := \frac{E_\gamma}{m_{\tilde{\chi}_1^0}}$$

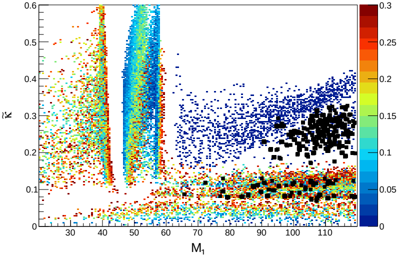
Relic density and GCE



- m_A increases with $(\lambda \cdot \mu)^{-1}$
- $g_{Z\tilde{\chi}_1^0\tilde{\chi}_1^0}$ increases with $\lambda \cdot \mu^{-1}$ [Higgsino component]
- region compatible with GCE and Ωh^2 is very narrow!
- Higgsino component too small for an enhanced BR

Minimal value of μ for a BR less than 0.3





- minimal value of $\mu \approx 200$ GeV
- for smaller values the branching ratio becomes too large
- other points with a smaller value of μ are possible, if we accept a BR of 0 %