Constraining Supersymmetry

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Global fits with SFitter

SFitter history and physics motivation

2007: MSSM setup [never just CMSSM!]

2009: Higgs setup

2010: MSSM unification study

2010: MSSM cross sections included

2012: Higgs couplings post-discovery

2013: Higgs at ILC

2013: MSSM global fit [Henrot-Versille etal]

2015: Higgs run I legacy

2015: NMSSM Hooperon [Butter etal]

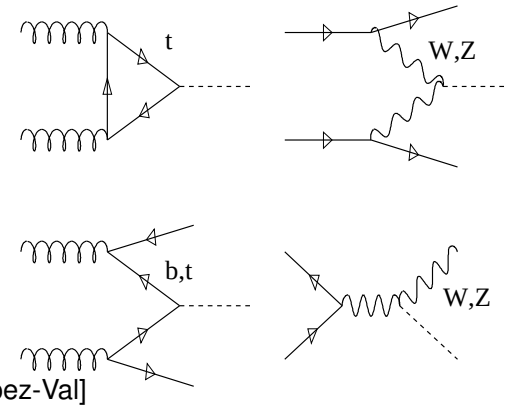
2016: Higgs-gauge EFT run I legacy

Many similar SUSY tools

- Fittino: really very similar
- MasterCode: very similar
- Bertone-de Austri-Trotta...: Bayesian
- Sheffield: Bayesian

and many more, but we are of course the best and coolest

Ingredients: light Higgs



Higgs fit [SFitter]

- search for BSM effects in Higgs@LHC
- assume: narrow CP-even scalar
  Standard Model operators
  loop-induced operators suppressed [Freitas, TP, Lopez-Val]
- Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \Delta_W \; g m_W H \; W^\mu W_\mu + \Delta_Z \; \frac{g}{2c_w} m_Z H \; Z^\mu Z_\mu - \sum_{\tau,b,t} \Delta_f \; \frac{m_f}{v} H \left(\bar{f}_R f_L + \text{h.c.}\right)$$
$$+ \Delta_g F_G \; \frac{H}{v} \; G_{\mu\nu} G^{\mu\nu} + \Delta_\gamma F_A \; \frac{H}{v} \; A_{\mu\nu} A^{\mu\nu} + \text{invisible}$$

- electroweak renormalizability through MSSM completion

$$\boxed{\begin{array}{l} gg \to H \\ qq \to qqH \\ gg \to t\bar{t}H \\ qq' \to VH \end{array}} \quad \longleftrightarrow \quad \boxed{g_{HXX} = g^{\text{SM}}_{HXX} \; (1 + \Delta_X)} \quad \longleftrightarrow \quad \boxed{\begin{array}{l} H \to ZZ \\ H \to WW \\ H \to b\bar{b} \\ H \to \tau^+\tau^- \\ H \to \gamma\gamma \end{array}}$$

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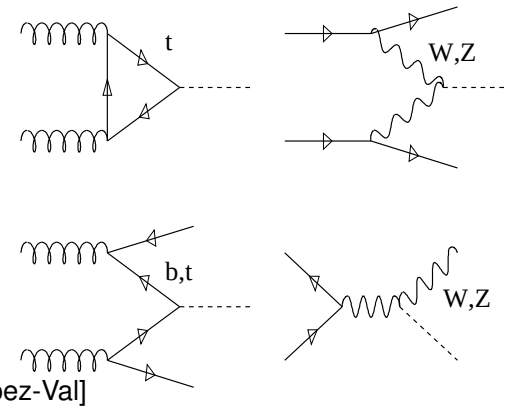

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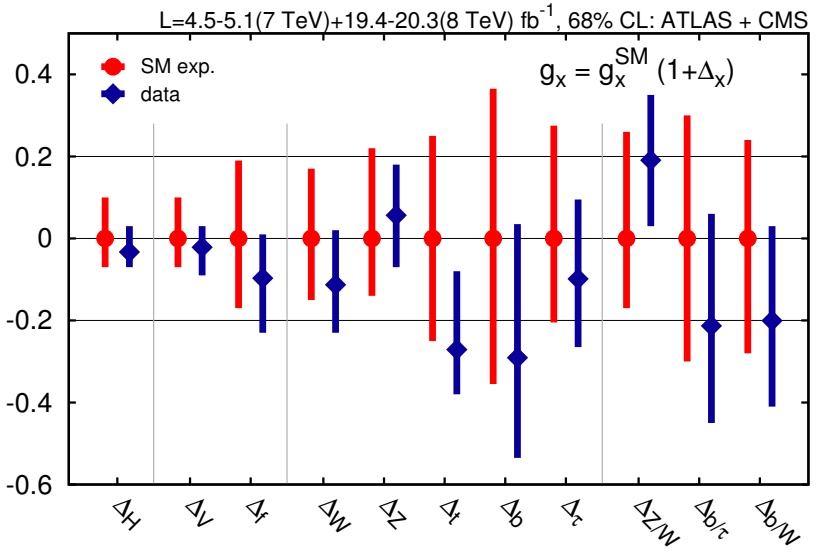
Run I legacy [Corbett, Eboli, Goncalves, Gonzalez-Fraile, Lopez-Val, TP, Rauch]

- assume SM-like [secondary solutions possible]
- SFitter: correct theory uncertainties



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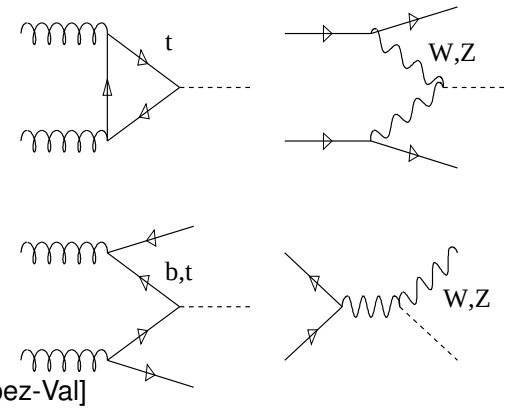

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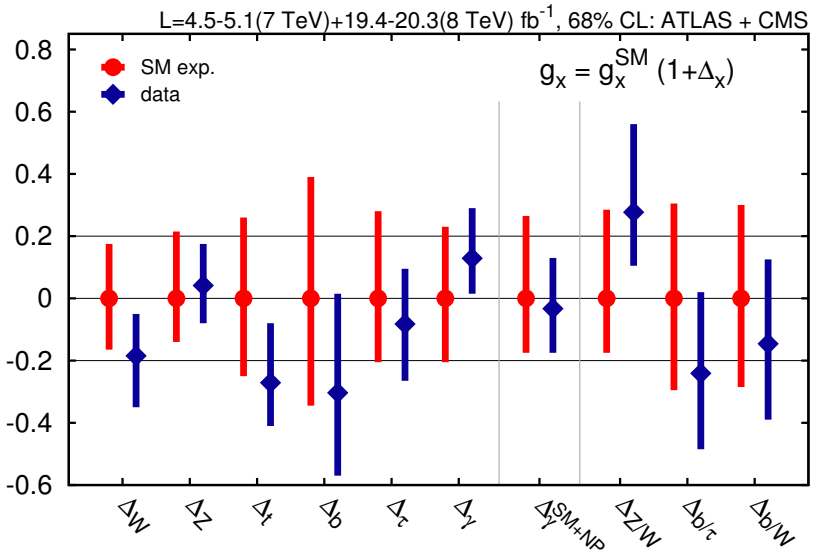

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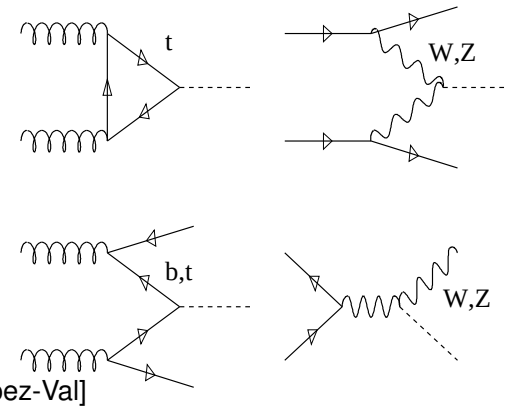

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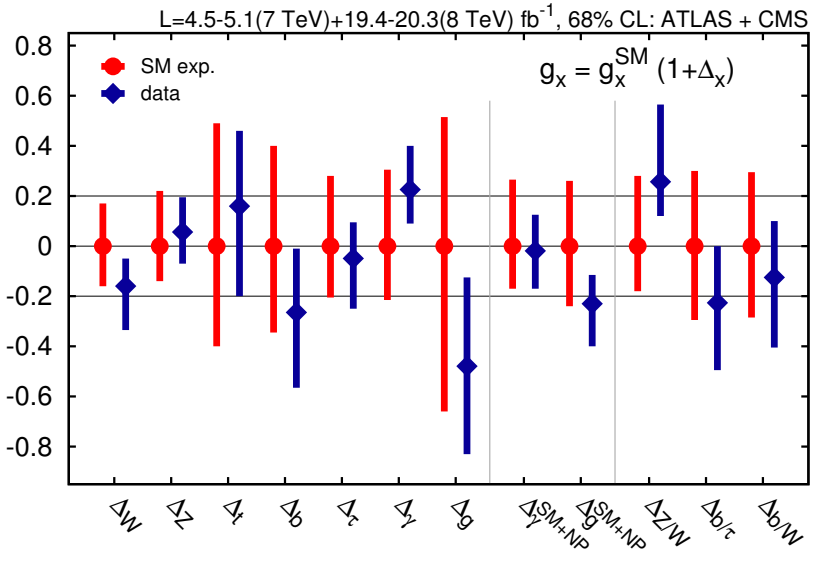

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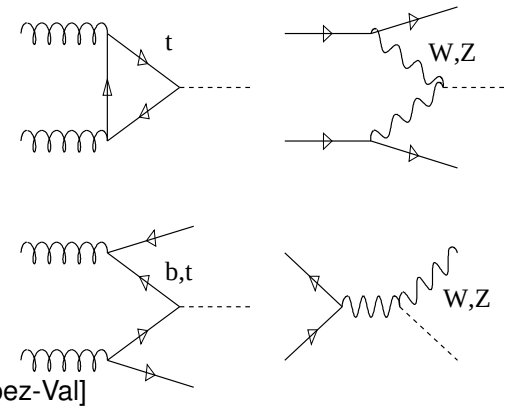

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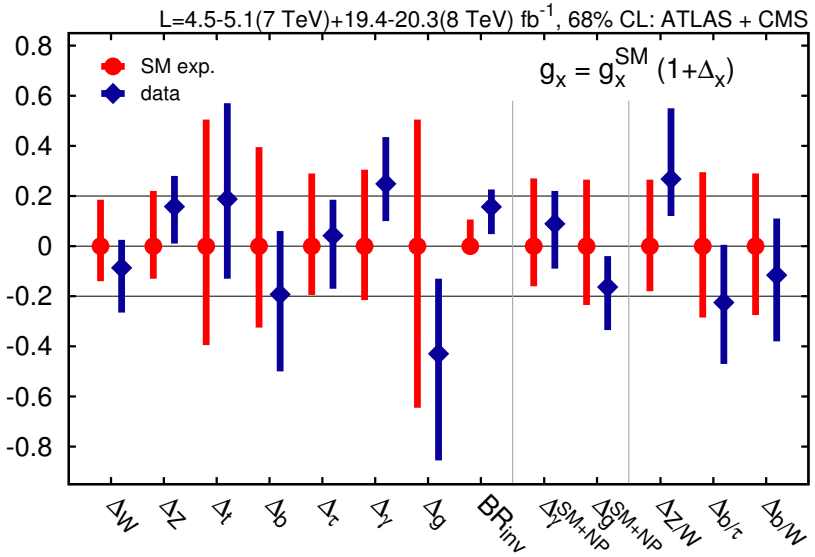
- g_γ with new loops
- g_g vs g_t barely possible
- including invisible decays

$\Rightarrow$ no hint of supersymmetry



Ingredients: LHC anomalies

Ingredients: relic density

Dark matter EFT fit [Tait etal]

- combine limits from collider, direct, indirect detection
- choose dark matter candidate [Majorana/Dirac fermion, scalar, dark photon]
- consider D6 scattering process $\chi\chi \to$ SM SM
- relic density from non-relativistic annihilation [$m_\chi / T \sim 30$]
- indirect detection even less relativistic
- direct detection totally non-relativistic [$E \sim 10$ MeV]
- LHC tricky: single scale $m_\chi \ll m_{\text{mediator}}$? [Felix Kahlhöfer's talk]
- example: scalar dark matter [they did not do Majorana fermions]

Label	Coefficient	Operator	σ_{SI}	$\langle \sigma_{\text{ann}} v \rangle$
	Real scalar			
R1	$\lambda_1 \sim 1/(2M^2)$	$m_q \chi^2 \bar{q} q$	✓	s-wave
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Ingredients: relic density

Relic density plus Hooperon [Liem, Bertone, Calore, Ruiz de Austri, Tait, Trotta, Weniger]

- default input: relic density
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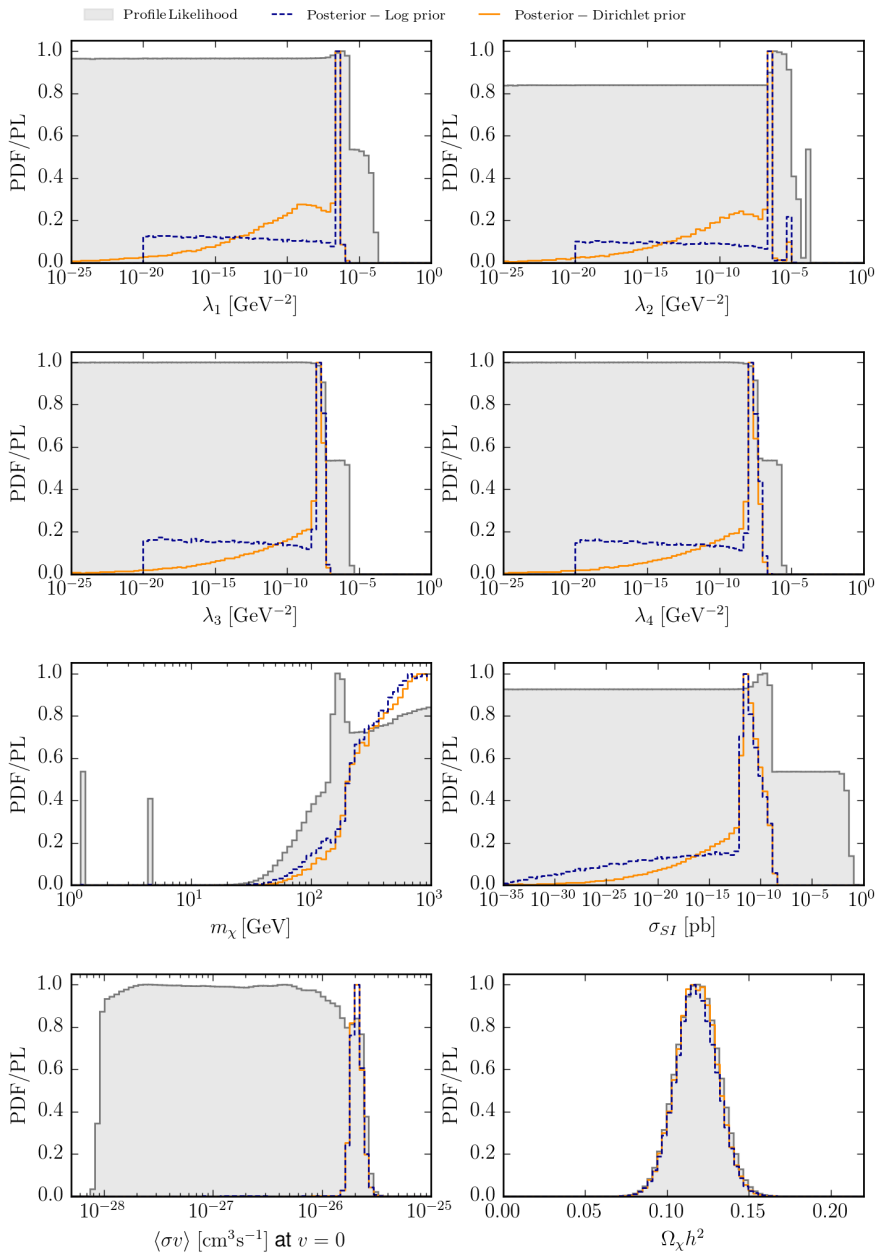
- profile likelihood
- flat prior on log λ_i [prior $1/\lambda_i$]
- Dirichlet prior prefering similar-sized Wilson coefficients



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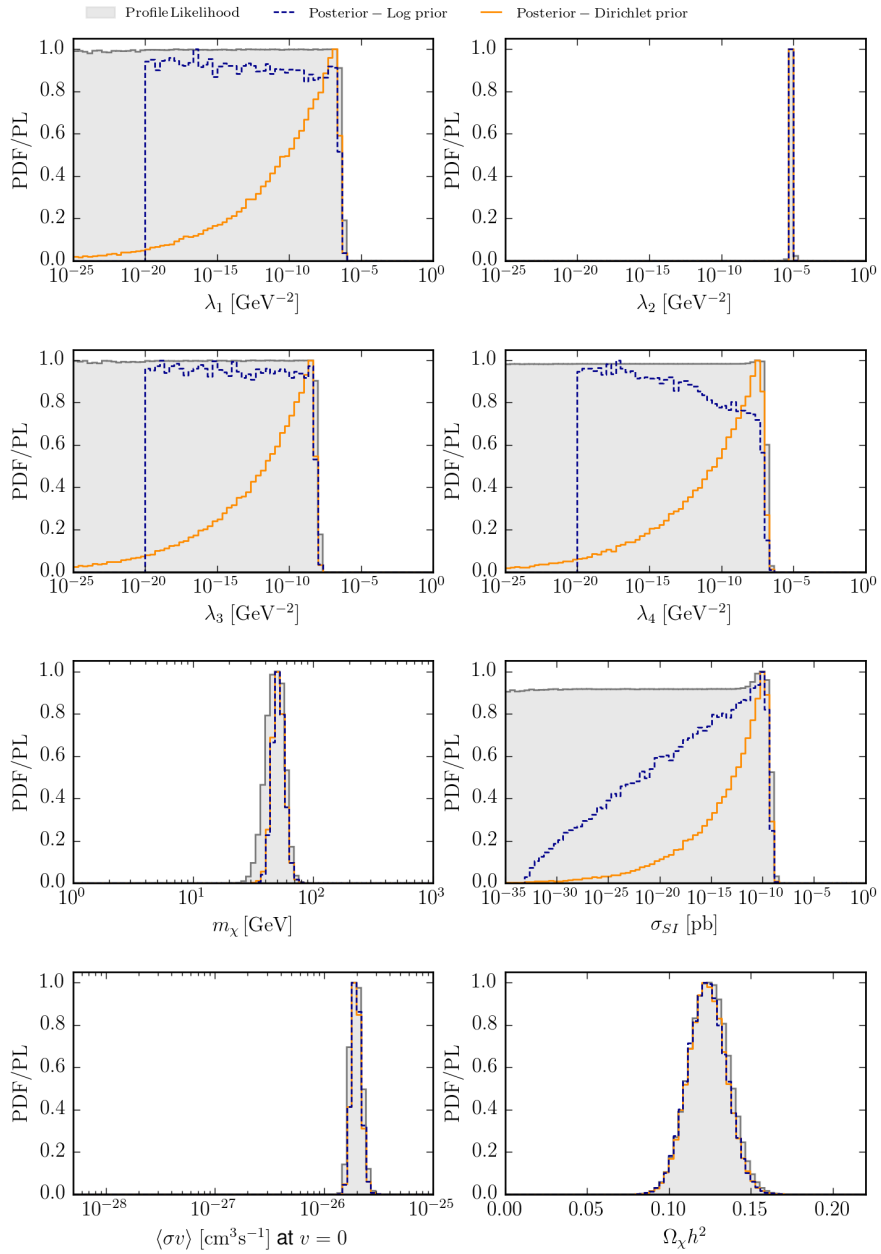
- Dirichlet prior prefering similar-sized Wilson coefficients
- Fermi: GCE plus dwarf galaxies

$\Rightarrow$ finally, one or two observable(s)



Ingredients: MSSM relic density

Majorana neutralino, different mediators [Henrot-Versille etal, Michael Tytgat's talk]

- SM Z-boson $\chi\chi \to Z \to$ jets [hard to get to work]
- SM-like Higgs $\chi\chi \to h \to b\bar{b}$ [$\Gamma/m = 1/25000$]
- heavy Higgs $H, A \to b\bar{b}, t\bar{t}$ [possibly wide]
- t-channel chargino $\chi\chi \to WW \to$ jets [e.g. focus point]
- stau co-annihilation $\tilde{\tau}\chi \to \tau + X$ [10% in mass]
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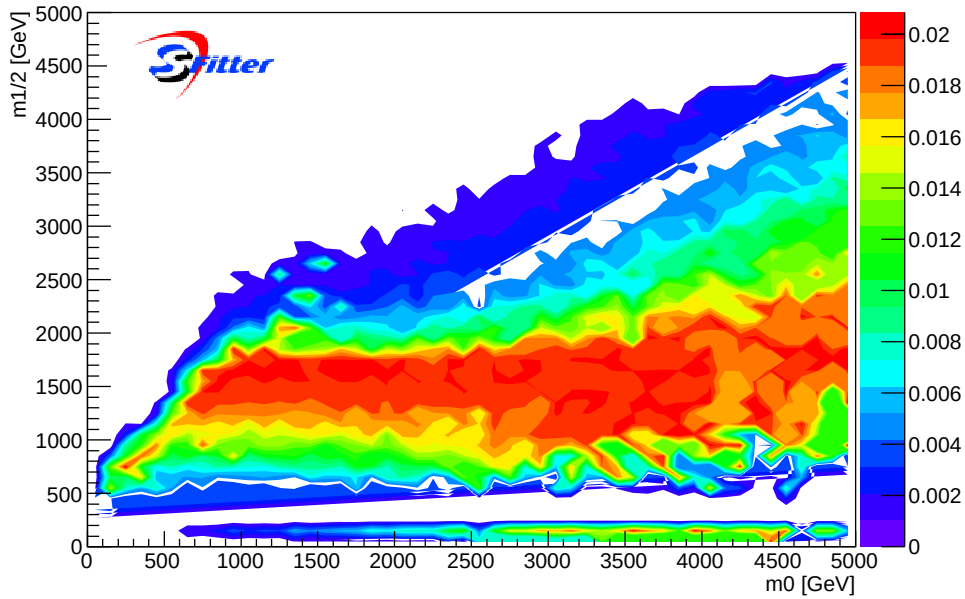

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Constraints [Henrot-Versille etal]

measurement	value and errors
m_h	$(126 \pm 0.4 \pm 0.4 \pm 3)$ GeV
Ω_{cdm} Planck	$0.1187 \pm 0.0017 \pm 0.012$
Ω_{cdm} WMAP-9year	$0.1157 \pm 0.0023 \pm 0.012$
BR($B_s \to \mu^+\mu^-$)	$(3.2^{+1.5}_{-1.2} \pm 0.2) \times 10^{-9}$
BR($b \to X_s\gamma$)	$(3.55 \pm 0.24 \pm 0.09) \times 10^{-4}$
Δa_μ	$(287 \pm 63 \pm 49 \pm 20) \times 10^{-11}$
m_t	$(173.5 \pm 0.6 \pm 0.8)$ GeV

$\Rightarrow$ fixing sign of μ, plus likelihood offset

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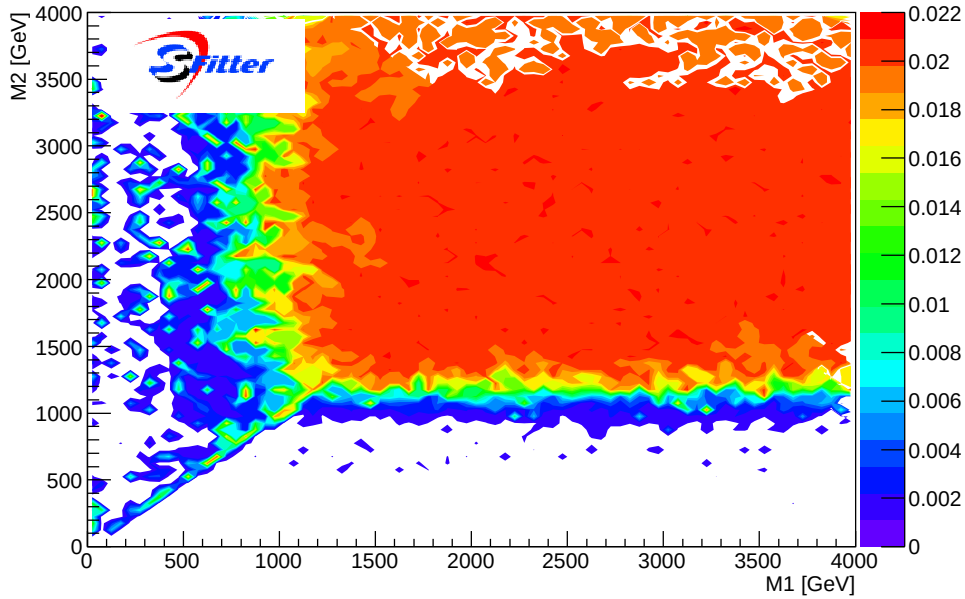


Motivating invisible Higgs searches

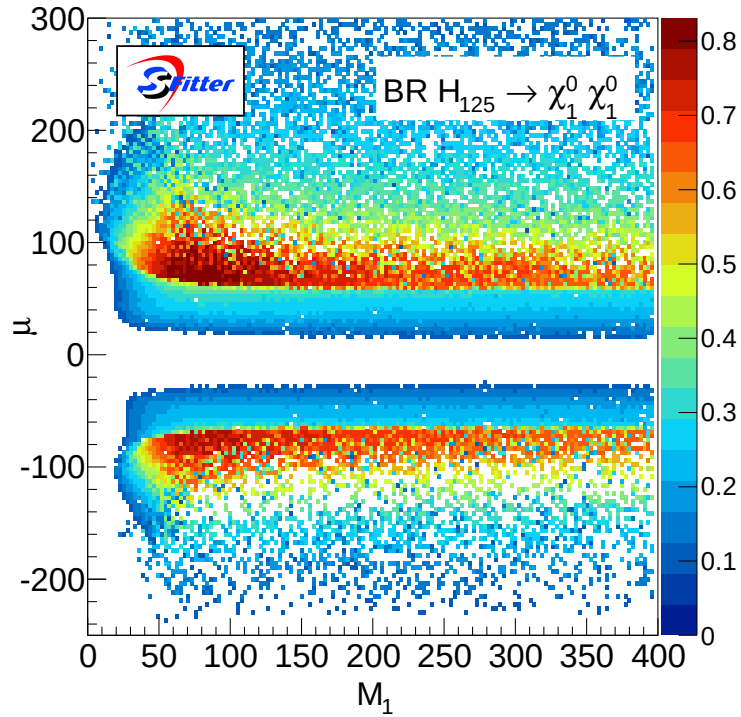
MSSM Higgs boson [Butter etal]

- take LHC hints and decouple squarks and gluinos
- decouple sleptons/squarks and their co-annihilation channels
- mass parameters: M_1, M_2, μ

  SM-like Higgs coupling requiring higgsino fraction

$$g_{H\tilde{\chi}\tilde{\chi}}\Big|_{\text{MSSM}} = (g_1 N_{11} - g_2 N_{12}) \; (\sin\alpha N_{13} + \cos\alpha N_{14})$$

1. require $m_h = 125$ GeV in M_1 vs μ [$\tan\beta = 40$]



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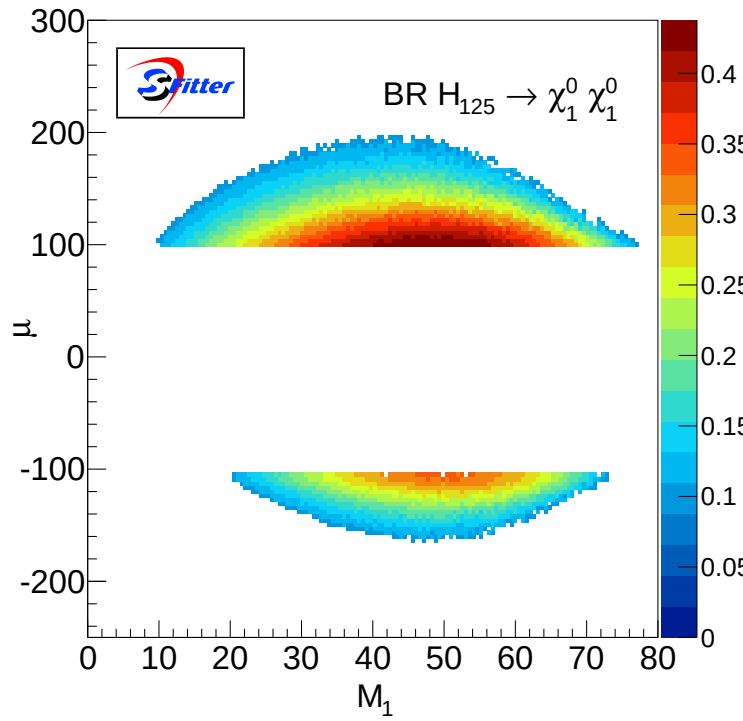

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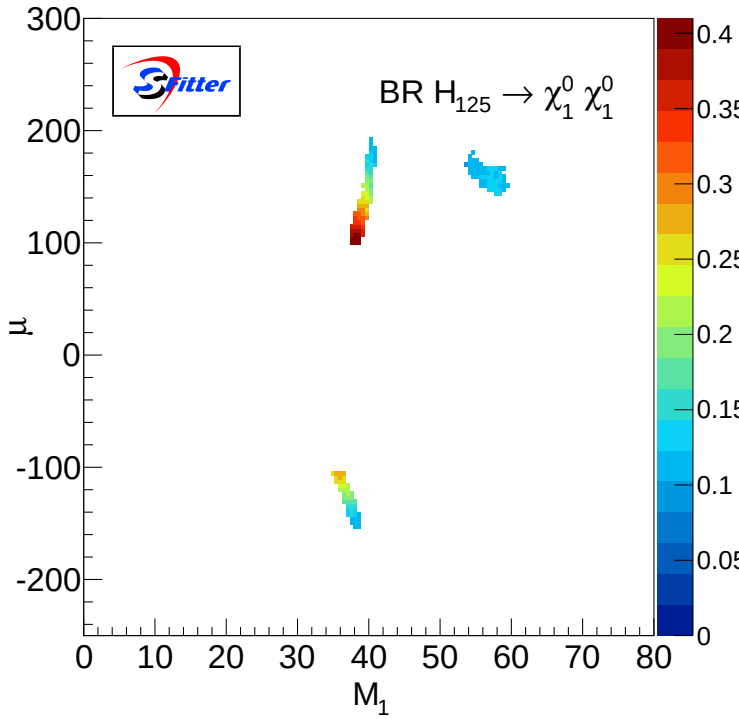

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1. require $m_h = 125$ GeV in M_1 vs μ [$\tan\beta = 40$]
2. add LEP chargino mass limit
3. add relic density
4. add direct detection

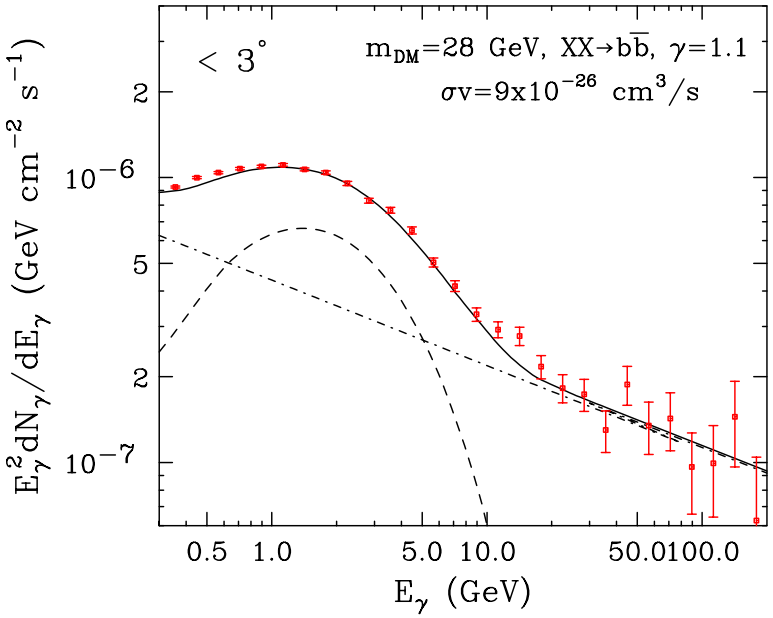
$$\text{BR}(H_{125} \to \tilde{\chi}\tilde{\chi}) \lesssim 50\% \qquad \text{for} \quad \mu = 100 \;\; \text{GeV}, \quad M_1 = 45 \;\; \text{GeV} \; ,$$

$\Rightarrow$ not generic, but possible...

Hooperon — fun with dark matter

Galactic center excess in FERMI data, by theorists [Goodenough & Hooper, Gabrijela Zaharijas' talk]

- look at gamma ray spectrum in galaxy
- remove all foregrounds
- check radial distributions
- explain by DM annihilation with photons
- $m_\chi \sim 30$ GeV from spectrum



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- remove all foregrounds
- check radial distributions
- explain by DM annihilation with photons
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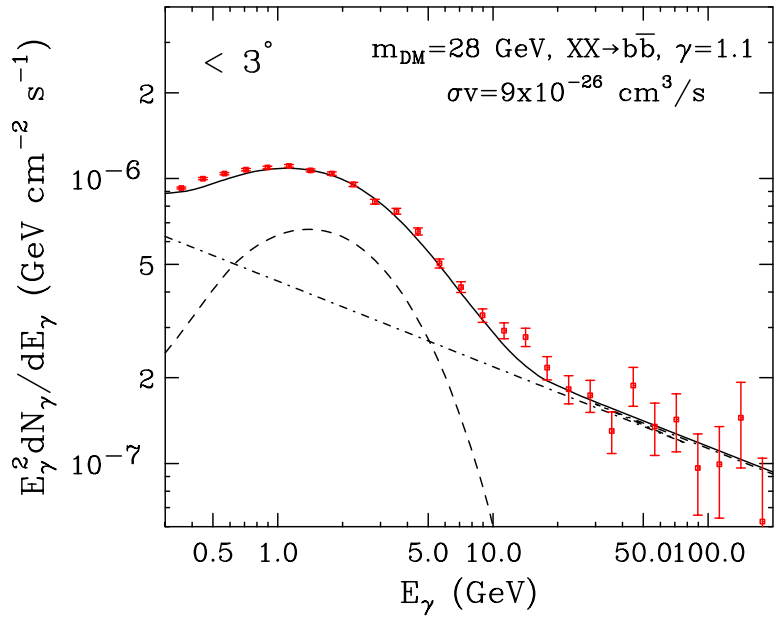

Kind of confirmed by FERMI [Murgia etal (2015)]

- analysis with all uncertainties
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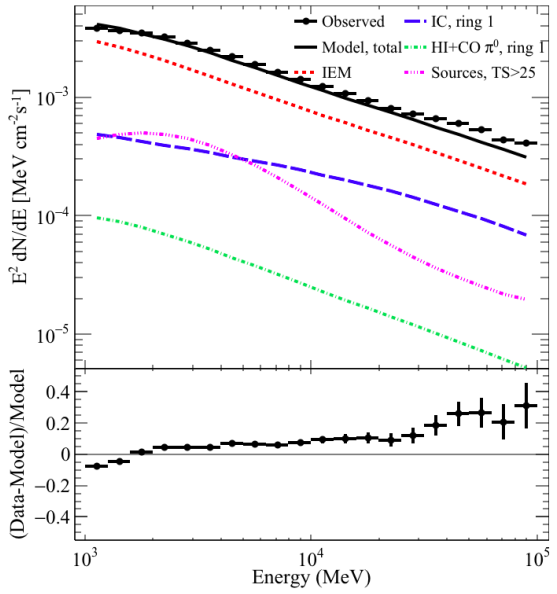

Hooperon — fun with dark matter

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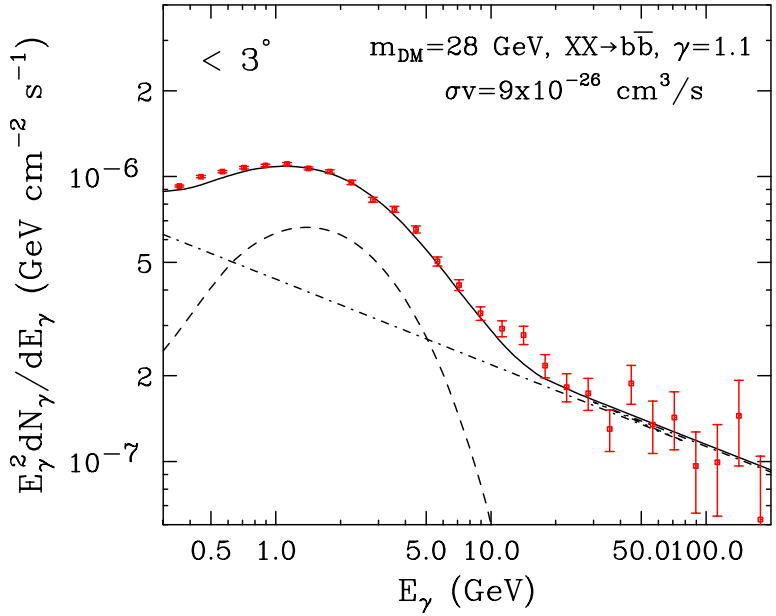

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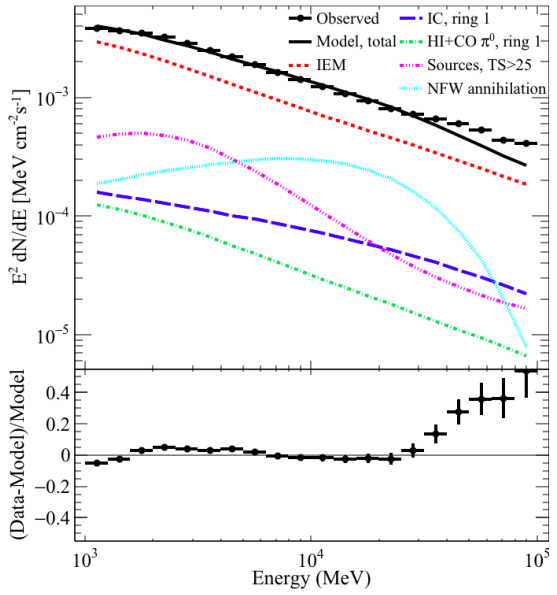

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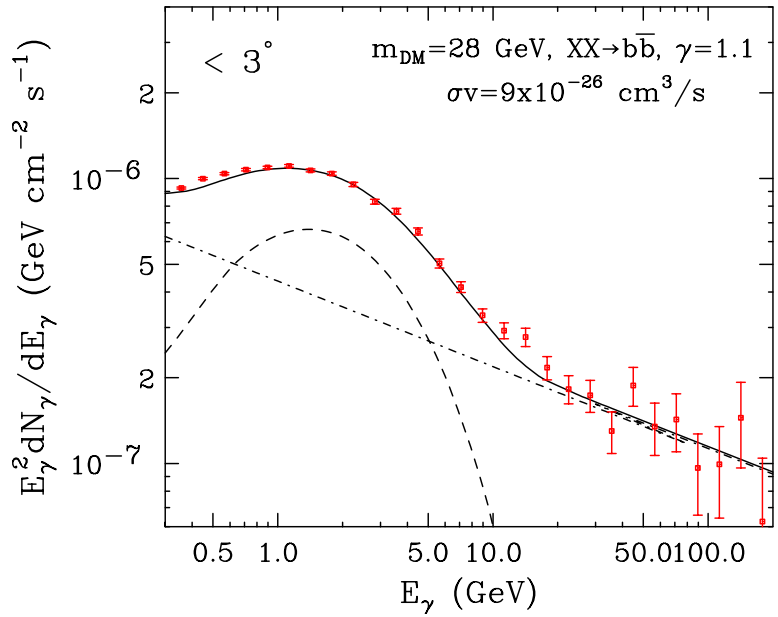

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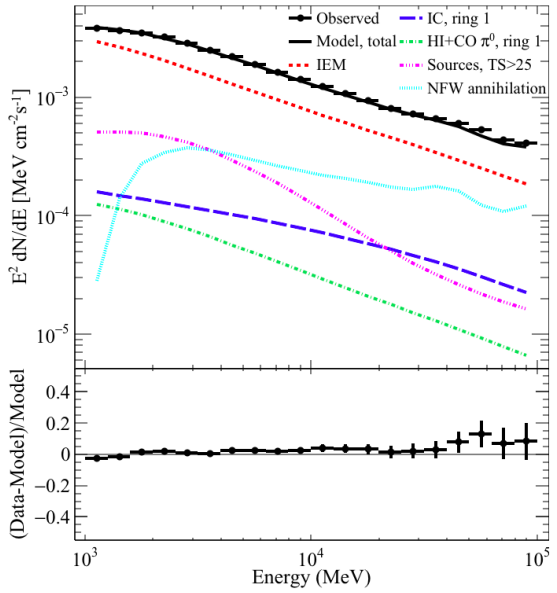

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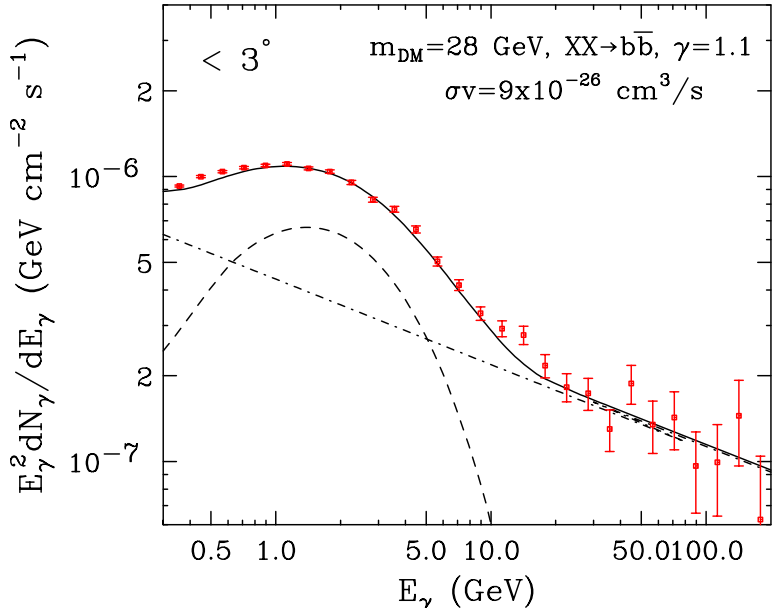

Kind of confirmed by FERMI [Murgia etal (2015)]

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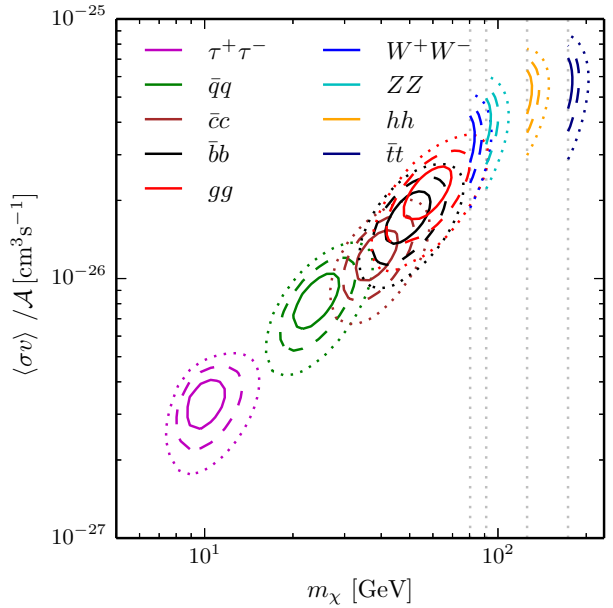
- fit without dark matter not good
- improved with NFW contribution
- even better with modified NFW contribution
- different DM candidates [Calore etal]

$\Rightarrow$ DM model playground, probably astrophysics...



NMSSM Hooperons

Hooperon in the NMSSM [Berlin, Hooper, McDermott; Butter etal]

- scalars largely decoupled from h_{125} [through A_λ]
- higgsino mass parameter μ
  singlino mass parameter $2\kappa\mu$
  singlino-higgsino mixing parameter λ

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

- s-channel mediators

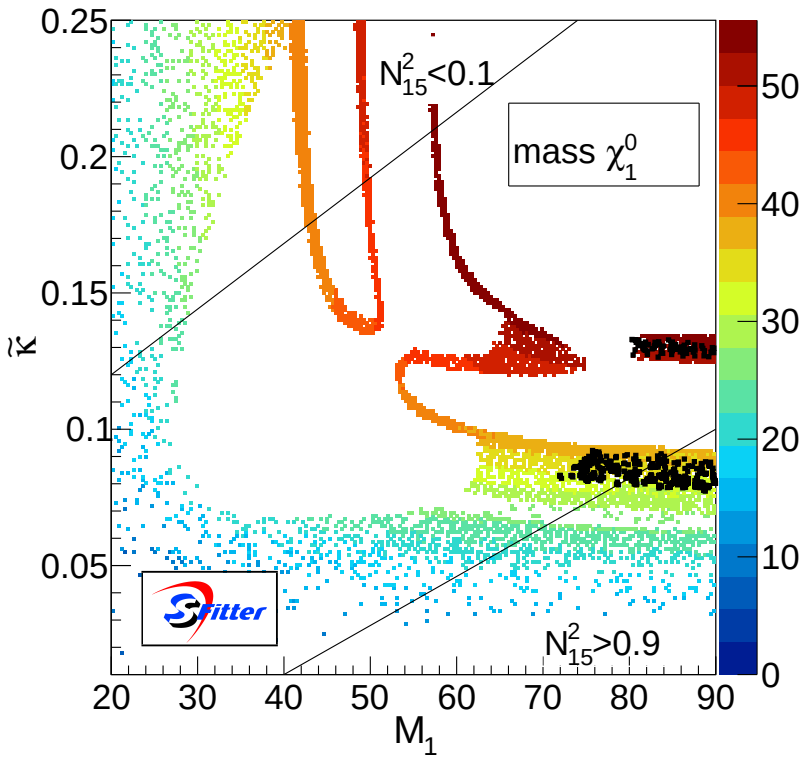
  Standard Model: Z, h_{125}
  new: heavy/singlet pseudoscalars
- Fermi: light pseudo-scalar mediator
  higgsino-admixed singlino DM

$\Rightarrow$ LHC signatures? [Cao, Zurek,...]

Higgs decays to Hooperons

LHC signatures [Butter etal]

- squarks, gluinos, sleptons decoupled [duh!]
  tan $\beta = 10$, Higgs mass correct,...
- singlino vs bino mass parameter space [slice $\mu = 220$ GeV]
- funnel off-pole annihilation: Z and h_{125}
  strips with $m_{\tilde{\chi}} = 40, 48, 55$ GeV
- Hooperon at $M_1 \gtrsim 70$ GeV



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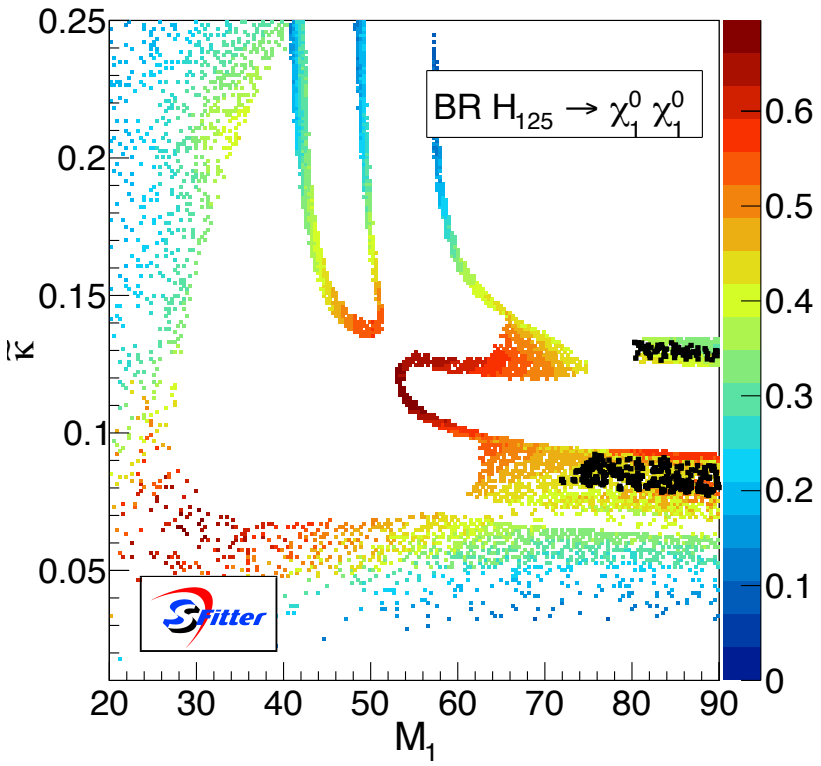
$\Rightarrow$ strong correlation with $h_{125} \to$ invisible



Where are we headed?

Global SUSY fits

...are underconstrained [good luck to Gambit]

...only work based on dark matter and indirect constraints

...would need a positive LHC result

...decouple just fine

...answer questions I do not care about [goodness of fit for CMSSM]

...do give us new ideas/justification for searches [simplified models spirit]

...need a physics point