

Constraining
SUSY

Tilman Plehn

Constraining Supersymmetry

Tilman Plehn

Universität Heidelberg

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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 et al]
- 2015: Higgs run I legacy
- 2015: **NMSSM Hooperon** [Butter et al]
- 2016: Higgs-gauge EFT run I legacy

Many similar SUSY tools

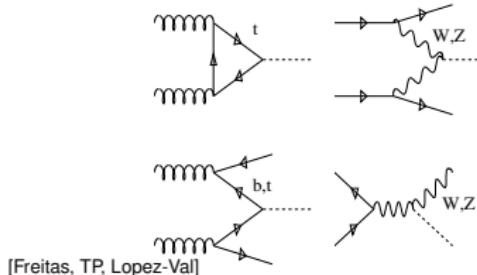
- Fittino: really very similar
- MasterCode: very similar
- Bertone-de Austri-Trotta...: Bayesian
- Sheffield: Bayesian

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
- Lagrangian



[Freitas, TP, Lopez-Val]

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

- electroweak renormalizability through MSSM completion

$$\begin{array}{l} gg \rightarrow H \\ qq \rightarrow qqH \\ gg \rightarrow ttH \\ qq' \rightarrow VH \end{array}$$



$$g_{HXX} = g_{HXX}^{\text{SM}} (1 + \Delta_x)$$



$$\begin{array}{l} H \rightarrow ZZ \\ H \rightarrow WW \\ H \rightarrow b\bar{b} \\ H \rightarrow \tau^+ \tau^- \\ H \rightarrow \gamma\gamma \end{array}$$

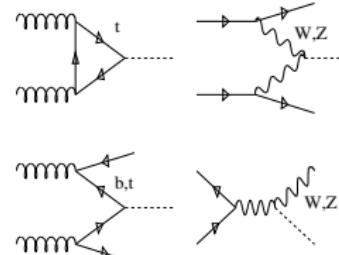
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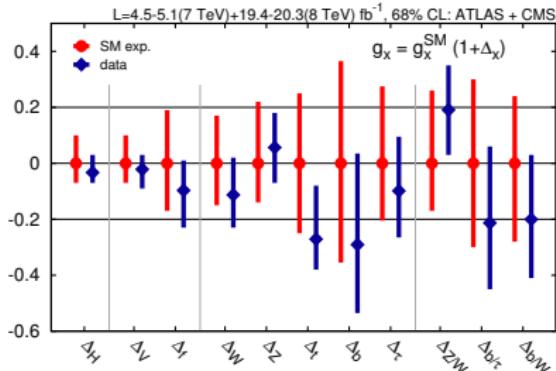
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Run I legacy [Corbett, Eboli, Goncalves, Gonzalez-Fraile, Lopez-Val, TP, Rauch]

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



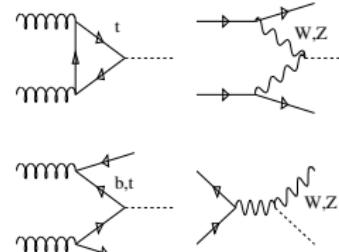
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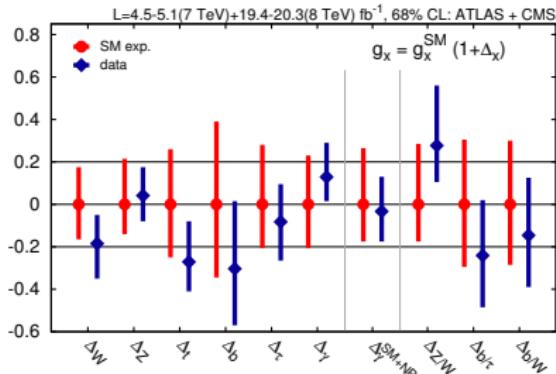
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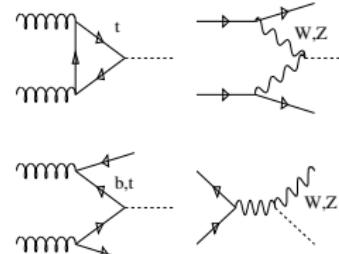
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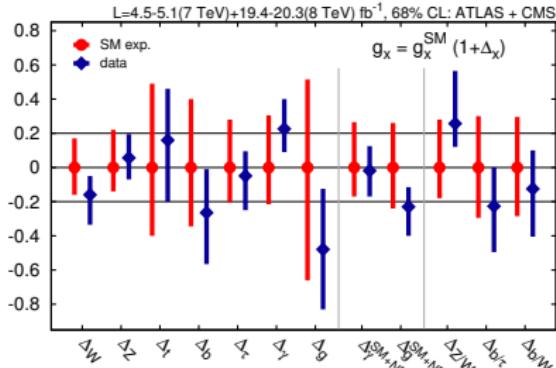
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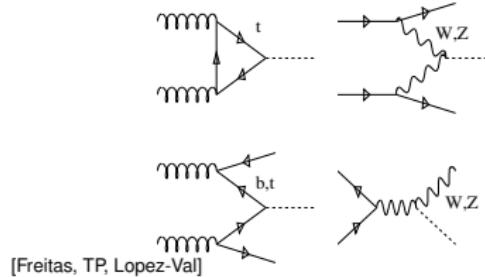
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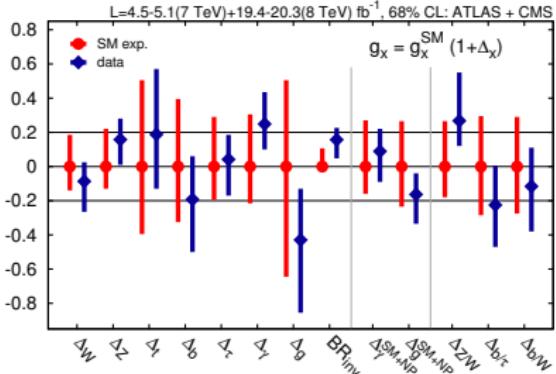
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- assume SM-like [secondary solutions possible]
 - SFitter: correct theory uncertainties
 - g_γ with new loops
 - g_g vs g_t barely possible
 - including invisible decays
- ⇒ no hint of supersymmetry



Ingredients: LHC anomalies

Ingredients: relic density

Dark matter EFT fit [Tait et al]

- combine limits from collider, direct, indirect detection
- choose dark matter candidate [Majorana/Dirac fermion, scalar, dark photon]
- consider D6 scattering process $\chi\chi \rightarrow \text{SM SM}$
- relic density from non-relativistic annihilation [$m_\chi / T \sim 30$]
- indirect detection even less relativistic
- direct detection totally non-relativistic [$E \sim 10 \text{ MeV}$]
- 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	$\sigma_{\text{SI}} \langle \sigma_{\text{ann}} v \rangle$
Real scalar			
R1	$\lambda_1 \sim 1/(2M^2)$	$m_q \chi^2 \bar{q} q$	✓ s-wave
R2	$\lambda_2 \sim 1/(2M^2)$	$i m_q \chi^2 \bar{q} \gamma^5 q$	s-wave
R3	$\lambda_3 \sim \alpha_s/(4M^2)$	$\chi^2 G_{\mu\nu} G^{\mu\nu}$	✓ s-wave
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Complex scalar			
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C5	$\lambda_5 \sim \alpha_s/(8M^2)$	$\chi^\dagger \chi G_{\mu\nu} G^{\mu\nu}$	✓ s-wave
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Ingredients: relic density

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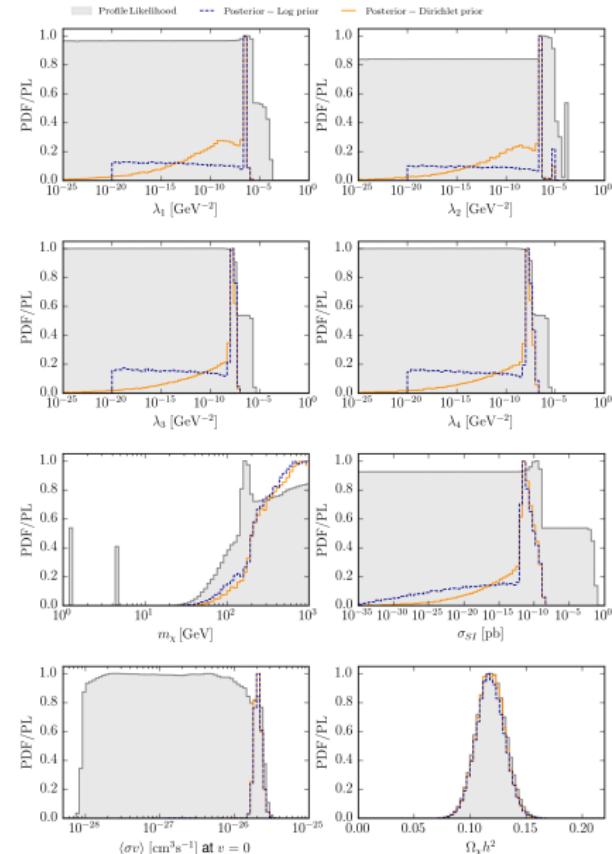
Ingredients: relic density

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

- default input: relic density
- scalar dark matter

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- profile likelihood
- flat prior on $\log \lambda_i$ [prior $1/\lambda_j$]
- Dirichlet prior preferring similar-sized Wilson coefficients



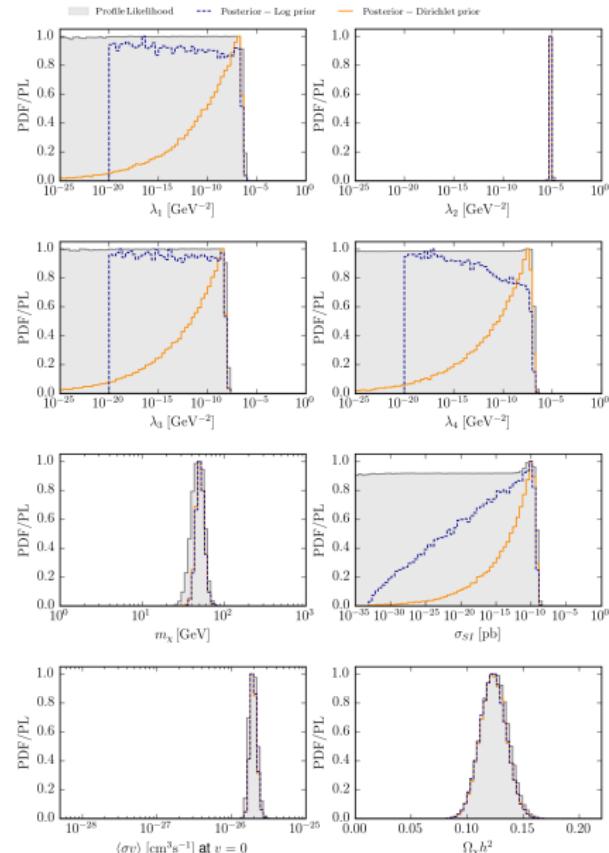
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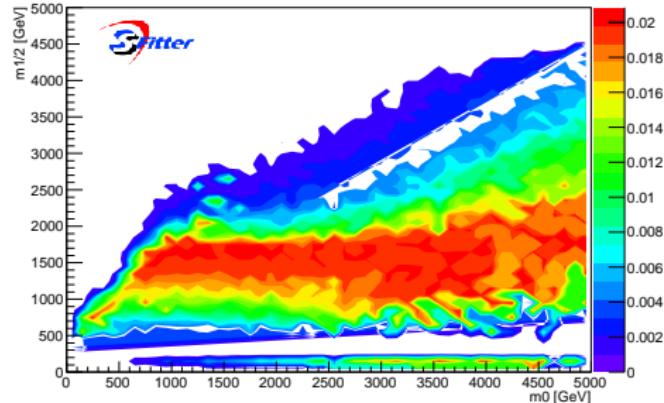
- profile likelihood
- flat prior on $\log \lambda_i$ [prior $1/\lambda_i$]
- Dirichlet prior preferring similar-sized Wilson coefficients
- Fermi: GCE plus dwarf galaxies
- ⇒ finally, one or two observable(s)



Ingredients: MSSM relic density

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

- SM Z -boson $\chi\chi \rightarrow Z \rightarrow \text{jets}$ [hard to get to work]
- SM-like Higgs $\chi\chi \rightarrow h \rightarrow b\bar{b}$ [$\Gamma/m = 1/25000$]
- heavy Higgs $H, A \rightarrow b\bar{b}, t\bar{t}$ [possibly wide]
- t -channel chargino $\chi\chi \rightarrow WW \rightarrow \text{jets}$ [e.g. focus point]
- stau co-annihilation $\tilde{\tau}\chi \rightarrow \tau + X$ [10% in mass]
- stop co-annihilation $\tilde{t}\chi \rightarrow t + X$ [10% in mass]
- chargino co-annihilation $\chi^0\chi^\pm \rightarrow W$ [10% in mass]



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Constraints [Henrot-Versille et al]

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

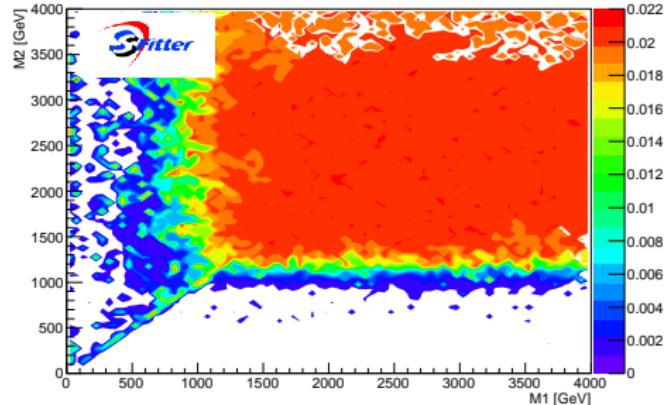
⇒ fixing sign of μ , plus likelihood offset

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Motivating invisible Higgs searches

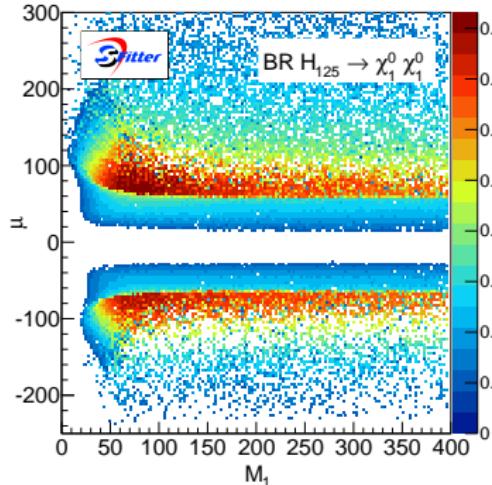
MSSM Higgs boson [Butter et al]

- 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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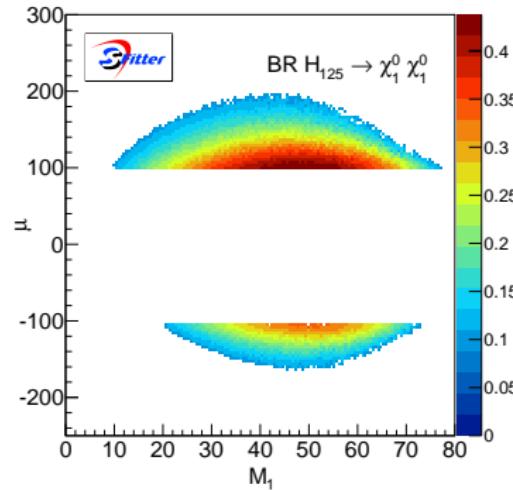
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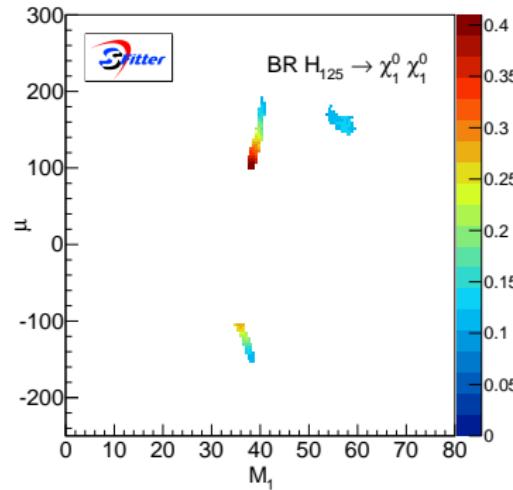
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3. add relic density



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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

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

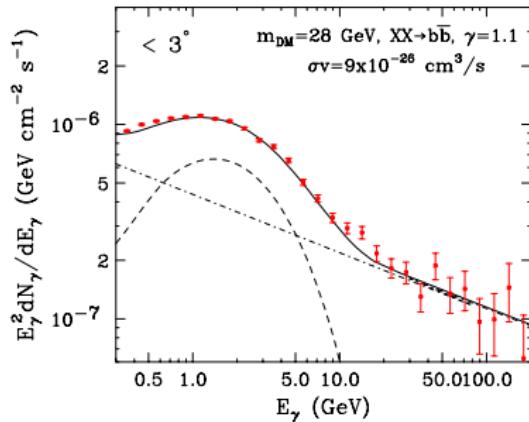
⇒ not generic, but possible...

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



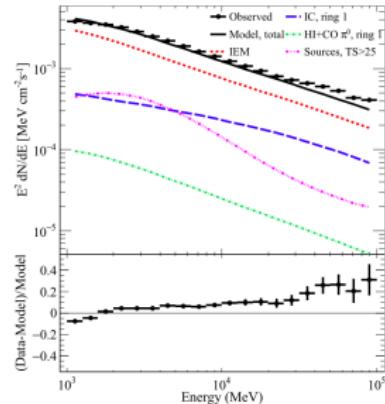
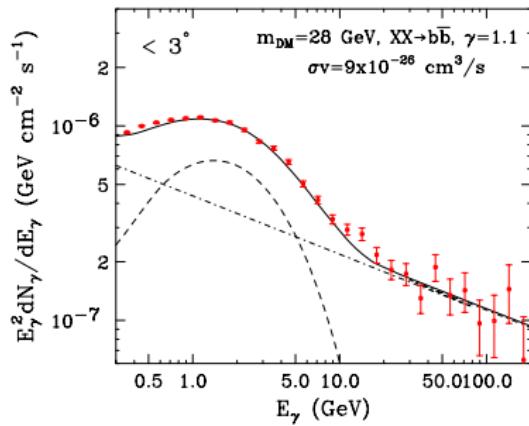
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Kind of confirmed by FERMI [Murgia et al (2015)]

- analysis with all uncertainties
- fit without dark matter not good



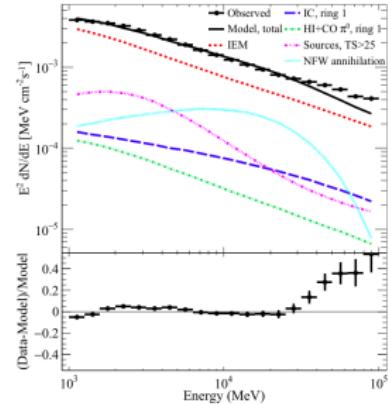
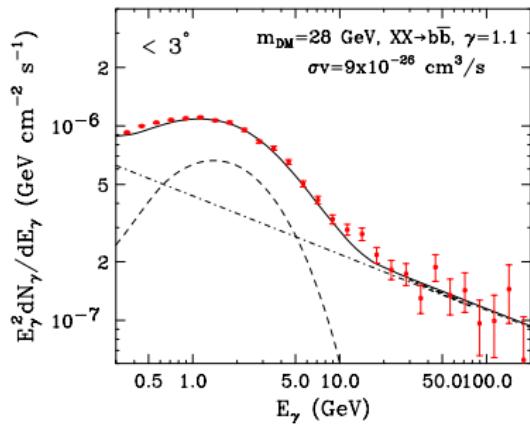
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- analysis with all uncertainties
- fit without dark matter not good
- improved with NFW contribution



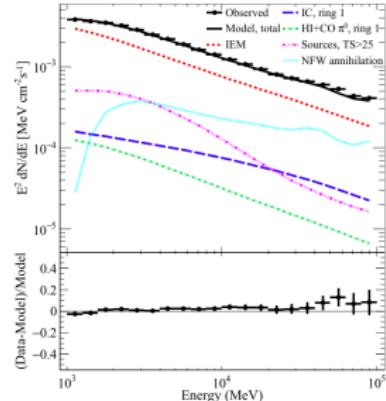
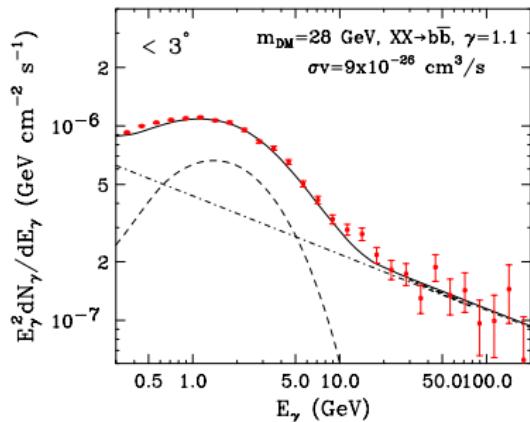
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- explain by DM annihilation with photons
- $m_\chi \sim 30$ GeV from spectrum

Kind of confirmed by FERMI [Murgia et al (2015)]

- analysis with all uncertainties
- fit without dark matter not good
- improved with NFW contribution
- even better with modified NFW contribution



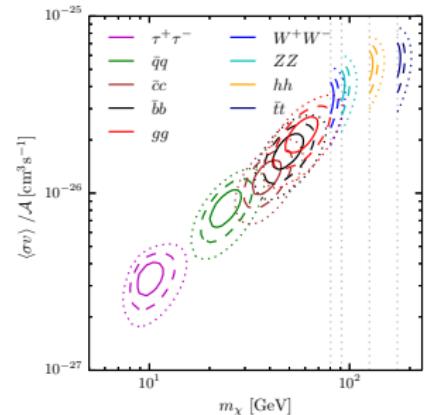
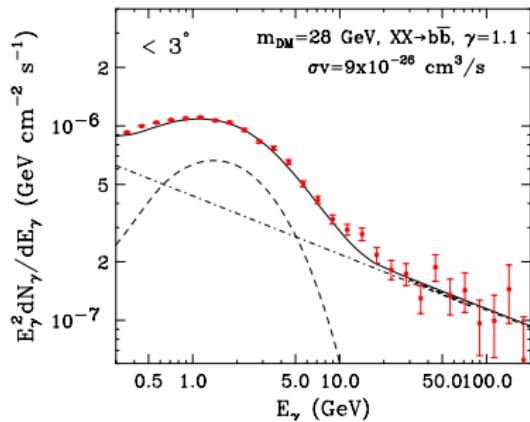
Hooperon — fun with dark matter

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

Kind of confirmed by FERMI [Murgia et al (2015)]

- analysis with all uncertainties
 - fit without dark matter not good
 - improved with NFW contribution
 - even better with modified NFW contribution
 - different DM candidates [Calore et al]
- ⇒ DM model playground, probably astrophysics...



NMSSM Hooperons

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

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

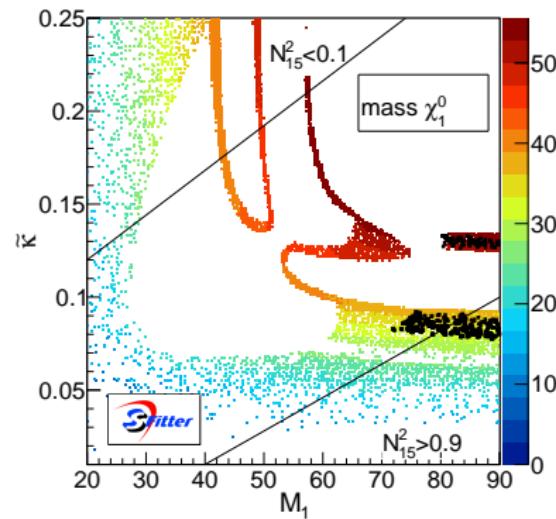
$$M_{\tilde{\chi}} = \begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_w & m_Z s_\beta s_w & 0 \\ 0 & M_2 & m_Z c_\beta c_w & -m_Z s_\beta c_w & 0 \\ -m_Z c_\beta s_w & m_Z c_\beta c_w & 0 & -\mu & -m_Z s_\beta \frac{\lambda}{g} \\ m_Z s_\beta s_w & -m_Z s_\beta c_w & -\mu & 0 & -m_Z c_\beta \frac{\lambda}{g}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

- s -channel mediators
 - Standard Model: Z, h_{125}
 - new: heavy/singlet pseudoscalars
 - Fermi: light pseudo-scalar mediator
higgsino-admixed singlino DM
- ⇒ LHC signatures? [Cao, Zurek,...]

Higgs decays to Hooperons

LHC signatures [Butter et al]

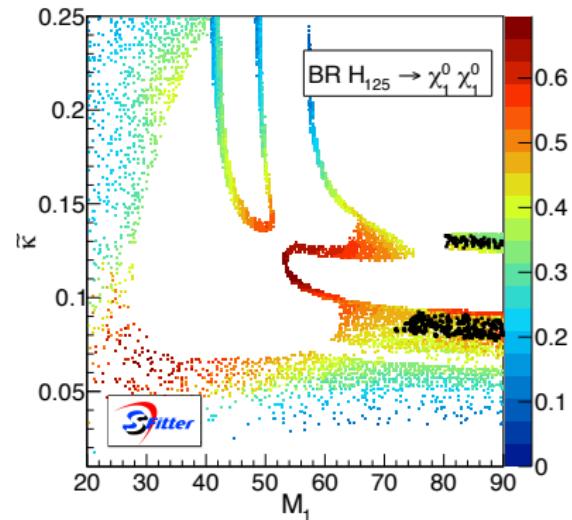
- squarks, gluinos, sleptons decoupled [duh!]
 $\tan \beta = 10$, Higgs mass correct,...
- singlino vs bino mass parameter space [slice $\mu = 220$ GeV]
- funnel off-pole annihilation: Z and h_{125}
strips with $m_{\tilde{\chi}} = 40, 48, 55$ GeV
- Hooperon at $M_1 \gtrsim 70$ GeV



Higgs decays to Hooperons

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 - Hooperon at $M_1 \gtrsim 70$ GeV
- ⇒ strong correlation with $h_{125} \rightarrow$ 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

Constraining SUSY

Tilman Plehn