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 [SFit]

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

- Lagrangian

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

- electroweak renormalizability through MSSM completion

\[
gg \rightarrow H
qq \rightarrow qqH
gg \rightarrow ttH
qq' \rightarrow VH
\]

\[
g_{HXX} = g_{HXX}^{\text{SM}} (1 + \Delta x)
\]

\[
H \rightarrow ZZ
H \rightarrow WW
H \rightarrow b\bar{b}
H \rightarrow \tau^+\tau^-
H \rightarrow \gamma\gamma
\]
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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

![Graph showing data and SM expectations with a shaded region indicating 68% CL limits for ATLAS + CMS](image)
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- assume SM-like [secondary solutions possible]
- SFitter: correct theory uncertainties
- $g_\gamma$ with new loops

$$L = 4.5-5.1(7 \text{ TeV}) + 19.4-20.3(8 \text{ TeV}) \text{ fb}^{-1} \text{, } 68\% \text{ CL: ATLAS + CMS}$$

$$g_x = g_{SM}^x (1 + \Delta x)$$
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- \( g_g \) vs \( g_t \) barely possible

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- assume SM-like [secondary solutions possible]
- SFitter: correct theory uncertainties
- \(g_\gamma\) with new loops
- \(g_g\) vs \(g_t\) barely possible
- including invisible decays
  \(\Rightarrow\) no hint of supersymmetry

\[
L=4.5-5.1(7\text{ TeV})+19.4-20.3(8\text{ TeV})\text{ fb}^{-1}, 68\%\text{ CL: ATLAS + CMS}
\]
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 $\chi\chi \rightarrow \text{SM SM}$
- 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 | $\sigma_{\text{SI}} \langle \sigma \text{ann} \rangle^V$ |
|-------|-------------|----------|--------------------------------------------------|
| Real scalar |
| R1 $\lambda_1 \sim 1/(2M^2)$ | $mq\chi^2\bar{q}q$ | ✓ s-wave |
| R2 $\lambda_2 \sim 1/(2M^2)$ | $imq\chi^2\bar{q}\gamma^5 q$ | s-wave |
| R3 $\lambda_3 \sim \alpha_s/(4M^2)\chi^2 G_{\mu \nu} G^{\mu \nu}$ | ✓ s-wave |
| R4 $\lambda_4 \sim \alpha_s/(4M^2)i\chi^2 G_{\mu \nu} \tilde{G}^{\mu \nu}$ | s-wave |
| Complex scalar |
| C1 $\lambda_1 \sim 1/(M^2)$ | $mq\chi^\dagger \bar{q}q$ | ✓ s-wave |
| C2 $\lambda_2 \sim 1/(M^2)$ | $imq\chi^\dagger \bar{q}\gamma^5 q$ | s-wave |
| C3 $\lambda_3 \sim 1/(M^2)$ | $\chi^\dagger \partial_\mu \chi \bar{q} \gamma^\mu q$ | ✓ p-wave |
| C4 $\lambda_4 \sim 1/(M^2)$ | $\chi^\dagger \partial_\mu \chi \bar{q} \gamma^\mu \gamma^5 q$ | p-wave |
| C5 $\lambda_5 \sim \alpha_s/(8M^2)\chi^\dagger \chi G_{\mu \nu} G^{\mu \nu}$ | ✓ s-wave |
| C6 $\lambda_6 \sim \alpha_s/(8M^2)i\chi^\dagger \chi G_{\mu \nu} \tilde{G}^{\mu \nu}$ | s-wave |
Ingredients: relic density

**Dark matter EFT fit** [Tait et al]

- combine relic density with Hooperon
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| Label | Coefficient | Operator | $\sigma_{SI} / \langle \sigma \text{ann} v \rangle$ |
|-------|-------------|----------|-----------------------------------------------|
|       |             | Real scalar | s-wave |
| R1    | $\lambda_1 \sim 1/(2M^2)$ | $m_q \chi^2 \bar{q}q$ | ✓ |
| 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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| C5    | $\lambda_5 \sim \alpha_s / (8M^2)$ | $\chi^\dagger \chi G_{\mu\nu} G^{\mu\nu}$ | ✓ s-wave |
| C6    | $\lambda_6 \sim \alpha_s / (8M^2)$ | $i \chi^\dagger \chi G_{\mu\nu} \tilde{G}^{\mu\nu}$ | s-wave |
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 $1/\lambda_i$]
- Dirichlet prior prefering similar-sized Wilson coefficients
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- profile likelihood
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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 $\chi\chi \rightarrow Z \rightarrow \text{jets}$  [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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$\Rightarrow$ some killed by direct detection
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Constraints  [Henrot-Versille etal]

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

$\Rightarrow$ fixing sign of $\mu$, plus likelihood offset
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**Constraints**  
[Henrot-Versille et al]
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: $M_1$, $M_2$, $\mu$

SM-like Higgs coupling requiring higgsino fraction

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

1. require $m_h = 125$ GeV in $M_1$ vs $\mu$ [tan $\beta = 40$]
Motivating invisible Higgs searches

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

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

$\Rightarrow$ not generic, but possible...
Hooperon — fun with dark matter

Galactic center excess in FERMI data, by theorists

- 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

![Graph](image-url)
Hooperon — fun with dark matter

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[Goodenough & Hooper, Gabrijela Zaharijas’ talk]

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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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- improved with NFW contribution
- even better with modified NFW contribution
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**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]

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

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

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

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

- 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 etal]

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

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  strips with \( m_{\tilde{\chi}} = 40, 48, 55 \text{ GeV} \)
- Hooperon at \( M_1 \gtrsim 70 \text{ GeV} \)
\[ \Rightarrow \text{strong correlation with } h_{125} \rightarrow \text{invisible} \]
Constraining SUSY

Tilman Plehn

Ingredients

Invisible Higgs

Hooperon

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
