Higgs coupling measurements and impact on the MSSM

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based on work with
G. Bélanger, G. Drieu La Rochelle, U. Ellwanger, R. M. Godbole, J.F. Gunion, S. Kraml,
S. Kulkarni and S. Sekmen
[arXiv:1306.2941, arXiv:1308.3735, arXiv:1312.7027]

DIS 2014 @ Warsaw

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in order to construct an approximation to the Higgs likelihood, one can:

i) fit a 2D Gaussian using the 68% CL contour for each final state

ii) combine the measurements from ATLAS and CMS final state by final state
include all results up to the LHCP 2013 conference

\[ \chi_i^2 = a_i (\mu_{ggF} - \hat{\mu}_{ggF})^2 + 2b_i (\mu_{ggF} - \hat{\mu}_{ggF})(\mu_{VBF} - \hat{\mu}_{VBF}) + c_i (\mu_{VBF} - \hat{\mu}_{VBF})^2 \]

without Tevatron

\begin{array}{|c|c|c|c|c|}
\hline
& \hat{\mu}_{ggF} & \hat{\mu}_{VBF} & a & b & c \\
\gamma\gamma & 0.98 & 1.72 & 14.94 & 2.69 & 3.34 \\
VV & 0.91 & 1.01 & 44.59 & 4.24 & 4.58 \\
bb/\tau\tau & 0.98 & 0.97 & 2.67 & 1.31 & 10.12 \\
bb & -0.23 & 0.97 & 0.12 & 0 & 7.06 \\
\tau\tau & 1.07 & 0.94 & 2.55 & 1.31 & 3.07 \\
\hline
\end{array}
validation with ATLAS and CMS

validation with benchmark scenarios of the ATLAS and CMS couplings fits

[ATLAS-CONF-2013-034]
[CMS-PAS-HIG-13-005]
invisible decays of the Higgs boson

includes ATLAS results for $ZH \rightarrow \ell \ell + \text{invisible}$

- **SM+invisible**
  $B(H \rightarrow \text{inv.}) < 0.21$ at 95% CL

- **SM+C_U+C_D+(C_V \leq 1)+invisible**
  $B(H \rightarrow \text{inv.}) < 0.31$ at 95% CL

- **SM+ΔC_g+ΔC_γ+invisible**
  $B(H \rightarrow \text{inv.}) < 0.39$ at 95% CL

- **SM+C_U+C_D+(C_V \leq 1)+ΔC_g+ΔC_γ+invisible**
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**global fit to the Higgs properties: indirect constraint on $H \rightarrow \text{invisible}$**

(more constraining than direct searches for invisible decays at the moment)
the p(henomenological) MSSM

19-parameter realization of general MSSM parameters defined at the weak scale, no SUSY breaking prejudices

**minimal assumptions:**

flavor-diagonal mass matrices, 1st and 2nd gen. degenerate, no new CP phases, R-parity & neutralino LSP

\[
(\widetilde{B}, \widetilde{W}^0, \widetilde{H}_d^0, \widetilde{H}_u^0) \xrightarrow{\text{EWSB}} (\widetilde{\chi}_1^0, \widetilde{\chi}_2^0, \widetilde{\chi}_3^0, \widetilde{\chi}_4^0)
\]

LSP and dark matter candidate

**we scan over:**

(flatt prior)

[BD, Gunion, Kraml, arXiv:1312.7027]

\[-3 \text{ TeV} \leq M_1, M_2, \mu \leq 3 \text{ TeV} ;
\]

\[0 \leq M_3, m_{\tilde{f}}, m_A \leq 3 \text{ TeV} ;
\]

\[-7 \text{ TeV} \leq A_t, A_b, A_\tau \leq 7 \text{ TeV} ;
\]

\[2 \leq \tan \beta \leq 60 .
\]

**Bayesian analysis using**

Markov Chain Monte Carlo (MCMC) methods

\[p(\theta|D) \sim L(D|\theta)p_0(\theta)\]
### Experimental Constraints

| Observable          | Constraint | Likelihood function |
|---------------------|------------|---------------------|
| $\mu_j(\theta)$    | $D_j^{\text{preHiggs}}$ | $L(D_j^{\text{preHiggs}} | \mu_j(\theta))$ |
| $\text{BR}(b \to s\gamma)$ | $(3.43 \pm 0.21^\text{stat} \pm 0.23^\text{th} \pm 0.07^\text{sys}) \times 10^{-4}$ | Gaussian |
| $\text{BR}(B_s \to \mu\mu)$ | $(2.9 \pm 0.7 \pm 0.29^\text{th}) \times 10^{-9}$ | Gaussian |
| $R(B_u \to \tau\nu)$ | $1.04 \pm 0.34$ | Gaussian |
| $\Delta a_\mu$ | $(26.1 \pm 8.0^{\text{exp}} \pm 10.0^\text{th}) \times 10^{-10}$ | Gaussian |
| $m_t$ | $173.20 \pm 0.87$ GeV | Gaussian |
| $m_b(m_b)$ | $4.19^{+0.18}_{-0.06}$ GeV | Two-sided Gaussian |
| $\alpha_s(M_Z)$ | $0.1184 \pm 0.0007$ | Gaussian |
| sparticle masses | LEP (via micrOMEGAs) | 1 if allowed / 0 if excluded |

- + prompt chargino decay ($cT < 10$ mm)
- "hsig": 125 GeV Higgs likelihood + CMS $A^0,H^0 \to \tau^+\tau^-$ constraint [CMS-PAS-HIG-13-021]
- "DMup": $\Omega_{DM} h^2 \lesssim 0.119$ and 90% CL LUX limit

Orthogonal to the CMS pMSSM studies (that incl. results from SUSY searches) [CMS-PAS-SUS-12-030, CMS-PAS-SUS-13-020]
results: $gg \rightarrow h \rightarrow \gamma \gamma$

- $p_0(\theta)$
- $p(\theta | \text{prmt } \tilde{\chi}_1^\pm)$
- $p(\theta | \text{preHiggs, prmt } \tilde{\chi}_1^\pm)$: MCMC
- $p(\theta | \text{preHiggs, prmt } \tilde{\chi}_1^\pm, 123 < m_h < 128)$

Probability density

low $M_A$
or light LSP
results: $gg \rightarrow h \rightarrow \gamma\gamma$

SUSY partners are typically too heavy to modify the Higgs properties
…so where are the deviations from a SM-like Higgs coming from?
why is $\mu \neq 1$

the SM Higgs width is dominated by $h \rightarrow bb$ (BR=57%)

SUSY correction to the bottom Yukawa coupling:

$$\Delta_b \equiv \frac{\Delta m_b}{m_b} \simeq \left[ \frac{2\alpha_s}{3\pi} \mu m_{\tilde{g}} I(m_{\tilde{g}}^2, m_{b_1}^2, m_{b_2}^2) + \frac{\lambda_t^2}{16\pi^2} A_t \mu I(\mu^2, m_{t_1}^2, m_{t_2}^2) \right] \tan \beta$$

can be large for a heavy SUSY spectrum

[Carena et al. '99]
[Eberl et al. '99]
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[pMSSM, $\tau < 10$ mm]

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$higgsino$-like LSP

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A-funnel annihilation

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[Carena et al. '99]

[Eberl et al. '99]
implications for dark matter

The LSP constitute only a fraction of the observed relic density.
implications for heavier Higgses

\[ p(\theta \mid \text{preHiggs}, m, h_{\text{sig}}) \]

| A mass [GeV] | 0 | 500 | 1000 | 1500 | 2000 | 2500 | 3000 |
|--------------|---|-----|------|------|------|------|------|
| BR(A → SUSY) | 0 | 0.2 | 0.4  | 0.6  | 0.8  | 1    |

\[ p(\theta \mid \text{preHiggs}, m, h_{\text{sig}}, \text{DMup}) \]

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light neutralino dark matter

[Bélanger, Drieu La Rochelle, BD, Goldbole, Kraml, Kulkarni, arXiv:1308.3735]

light neutralino dark matter motivated by:

✦ having a light SUSY spectrum
✦ hints from direct detection $\sim 10$ GeV 
  (... and maybe from indirect detection) [Hopper et al. claims]
✦ easy-to-exclude region
  • no resonance under $M_Z/2 = 45$ GeV
  • no co-annihilation under $\sim 100$ GeV
  (counterexample: [Arbey et al., arXiv:1308.2153])

[CDMS, arXiv:1304.4279]
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[CDMS, arXiv:1304.4279]
viable light neutralino dark matter

nature of the lightest neutralino?

• pure wino or higgsino dark matter?
  → excluded by chargino searches at LEP
• pure bino dark matter?
  → the relic density is too large

solution: mainly bino ($M_1 \ll M_2, \mu$) with some wino/higgsino admixture ($\mu$ and/or $M_2 \leq 200$ GeV)

other SUSY particles?

• gluino and squarks: constrained by LEP and LHC searches to be heavy → no influence on DM
• other Higgses: little influence expected on DM (constraints on $A^0, H^0 \rightarrow \tau^+\tau^-$ at the LHC)
• sleptons: ~100 GeV is allowed, contributions from staus to DM annihilation can be large

light sleptons are required for light neutralino DM [Albornoz Vasquez, Belanger, Boehm '11]
viable light neutralino dark matter

stau-mediated annihilation

RH stau annihilation is much more efficient, also higgsino enhancement (low $\mu$, high $\tan \beta$)

collider constraints on electroweakinos

- rather light charginos: need to check the LEP and LHC constraints
- invisible $Z$ decays, invisible Higgs decays (LEP and LHC limits, resp.)
- light neutralino 2 $\rightarrow$ LEP limit on $\sigma(e^+e^- \rightarrow \tilde{\chi}_2^0\tilde{\chi}_1^0)$

sleptons and staus: direct searches at LEP and at the LHC
setup of the analysis

pMSSM framework again

\[ M_3 = 1 \text{ TeV} \]
\[ M_{Q_3} = 750 \text{ GeV} \]
\[ M_{U_i} = M_{D_i} = M_{Q_1} = 2 \text{ TeV} \]
\[ A_b = 0 \]

\[
\begin{array}{c|c|c}
\tan \beta & [5, 50] & M_{L_3} & [70, 500] \\
M_A & [100, 1000] & M_{R_3} & [70, 500] \\
M_1 & [10, 70] & A_T & [-1000, 1000] \\
M_2 & [100, 1000] & M_{L_1} & [100, 500] \\
\mu & [100, 1000] & M_{R_1} & [100, 500] \\
\end{array}
\]

(all masses in GeV)

heavy 1st and 2nd generation squarks
moderately heavy gluino, stop and sbottom

variations in the
Higgs, electroweak and leptonic sectors

\[ A_T \text{ tuned in order to have } m_h \approx 125.5 \text{ GeV} \]

we perform flat random scans within micrOMEGAs 3.1, using SuSpect 2.4
we impose experimental constraints in the following order:

| Constraint                        | Condition                                                                 |
|-----------------------------------|---------------------------------------------------------------------------|
| LEP limits                         | $m_{\tilde{\chi}_1^\pm} > 100$ GeV                                      |
|                                   | $m_{\tilde{\tau}_1} > 84 - 88$ GeV (depending on $m_{\tilde{\chi}_0}$)  |
|                                   | $\sigma(e^+e^- \rightarrow \tilde{\chi}^0_2,3\tilde{\chi}^0_1 \rightarrow Z^{(*)}(\rightarrow q\bar{q})\tilde{\chi}^0_1) \lesssim 0.05$ pb |
| invisible $Z$ decay                 | $\Gamma_{Z\rightarrow \tilde{\chi}^0_1\tilde{\chi}^0_1} < 3$ MeV        |
| $\mu$ magnetic moment              | $\Delta a_\mu < 4.5 \times 10^{-9}$                                     |
| flavor constraints                 | $\text{BR}(b \rightarrow s\gamma) \in [3.03, 4.07] \times 10^{-4}$       |
|                                   | $\text{BR}(B_s \rightarrow \mu^+\mu^-) \in [1.5, 4.3] \times 10^{-9}$    |
| Higgs mass                         | $m_{h^0} \in [122.5, 128.5]$ GeV                                        |
| $A^0, H^0 \rightarrow \tau^+\tau^-$| CMS results for $L = 17$ fb$^{-1}$, $m_{h^0}^\text{max}$ scenario        |
| Higgs couplings                    | ATLAS, CMS and Tevatron global fit                                       |
| relic density                      | $\Omega h^2 < 0.131$ or $\Omega h^2 \in [0.107, 0.131]$                 |
| direct detection                   | XENON100 upper limit                                                     |
| indirect detection                 | Fermi-LAT bound on gamma rays from dSphs                                 |
| $pp \rightarrow \tilde{\chi}^0_2\tilde{\chi}^0_1$ | Simplified Models Spectra approach                                      |
| $pp \rightarrow \tilde{\ell}^+\tilde{\ell}^-$ |                                                                           |
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|             | $\sigma(e^+e^- \rightarrow \tilde{\chi}_{2,3}^0\tilde{\chi}_1^0 \rightarrow Z^*(\rightarrow q\bar{q})\tilde{\chi}_1^0) \lesssim 0.05$ pb |
| invisible Z decay | $\Gamma_{Z \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0} < 3$ MeV |
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decomposition of a pMSSM point into simplified models, then compare to the limits on \((\sigma \times \text{BR})\) using SmodelS \cite{Kraml:2013}. 

**direct RH selectron/smuon production**

ATLAS Preliminary

\[
\tilde{\ell}_1 \tilde{\ell}_1 \rightarrow \ell^+ \tilde{\chi}_1^0 \ell^- \tilde{\chi}_1^0
\]

L_\text{dt} = 20.3 \text{ fb}^{-1}, \sqrt{s} = 8 \text{ TeV}

- Observed limit \((\pm 1 \sigma_{\text{SUSY}})\)
- Expected limit \((\pm \sigma_{\text{exp}})\)
- LEP \(\tilde{\tau}_R\) excluded

All limits at 95% CL

still room above 20 GeV

[ATLAS-CONF-2013-049]

**chargino-neutralino \(\rightarrow\) WZ + MET**

CMS Preliminary

- \(\sqrt{s} = 8 \text{ TeV}, \text{ L}_{\text{int}} = 9.2 \text{ fb}^{-1}\)

- 95\% C.L. CLs NLO Exclusions
  - Observed 2/2j +3\ell \pm 1\sigma_{\text{theory}}
  - Expected 2/2j+3\ell \pm 1\sigma
  - Observed 3\ell only
  - Observed 2/2j only

black line overestimates the limit

“hidden” assumption: \(\tilde{\chi}_2^0, \tilde{\chi}_1^\pm\) wino-like

95\% CL upper limit on \(\sigma\) [fb]

[CMS-SUS-12-022]
LHC searches — implementation

There are no limits on direct stau production at the LHC but one has to consider intermediate stau decays from EWinos.

\[ \tilde{\chi}^0_1 \rightarrow \ell \nu \]

\[ \tilde{\chi}^0_2 \rightarrow \tilde{\ell} \tilde{\nu} \]

This assumption is problematic — we would need other values of the stau mass we extrapolate the limit for other stau masses from a similar measurement.

Also ATLAS results on 2τ+MET but the only interpretation available is for LH staus.
• upper bound on the relic density $\rightarrow$ lower bound on the neutralino mass of $\sim 15$ GeV
not possible to have 8–10 GeV dark matter in this context
• direct detection could soon exclude completely the low-mass region (up to 25 GeV)
• light region only possible for very light charginos ($\lesssim 200$ GeV) and staus ($\lesssim 100$ GeV)
  this is relaxed for higher masses, especially above 35 GeV (Z resonance)
• lightest chargino and neutralino 2 are mostly higgsino-like (and not excluded by direct searches)
invisible Higgs decays

- the Higgs boson couples to a mixture of higgsino and gaugino
  \[ \text{limit on the higgsino fraction } f_H \text{ from Higgs measurements} \]
- as expected, anticorrelation between \( \mu(gg \rightarrow h \rightarrow \gamma\gamma) \) and \( BR_{inv} \)
The Higgs boson couples to a mixture of higgsino and gaugino 
\( \rightarrow \) limit on the higgsino fraction \( f_H \) from Higgs measurements

As expected, anticorrelation between \( \mu(gg\rightarrow h \rightarrow \gamma\gamma) \) and \( BR_{inv} \)
Higgs signal strengths

light, maximally mixed staus (see [Carena et al., arXiv:1205.5842])
in this case $\mu \gtrsim 400$ GeV and light selectrons/smuons

$g_{hbb} = \sin(\beta - \alpha) - \tan \beta \cos(\beta - \alpha)$

→ promising way to probe light neutralino scenarios
conclusion

✦ in the pMSSM, significant deviations of the Higgs couplings are possible and are already constrained by the LHC results

✦ low-mass neutralino (~ 15–35 GeV) can be accommodated with light staus and/or charginos but is under pressure by direct detection and the LHC SUSY searches

✦ possible to go beyond the Gaussian approximation for Higgs results: full likelihood in the \((\mu_{ggF+ttH}, \mu_{VBF+VH})\) plane is given in several final states by ATLAS and CMS

✦ this is taken into account in Lilith: a new, friendly-user tool for constraining BSM scenarios from Higgs measurements—stay tuned!

[Jérémy Bernon and BD, in preparation]
backup slides
invisible decays of the Higgs boson

\[ C_V^2 B(H \rightarrow \text{inv.}) < 0.65 \text{ at } 95\% \text{ CL} \]

see also CMS limit on $ZH\rightarrow ll/bb+\text{invisible}$ [CMS-PAS-HIG-018/028]
and on $\text{VBF} \rightarrow \text{invisible}$ [CMS-PAS-HIG-013]
and the combination [arXiv:1404.1344]
prompt chargino decay

prompt chargino decay ($c\tau < 10$ mm):

**strong impact on $M_2$**

do not change main conclusions
masses of the SUSY partners
μ(Vh → bb)

\[ \mu(Vh \rightarrow bb) \]

- Probability density

pMSSM, cτ < 10 mm

\[ p(\theta \mid \text{preHiggs, } m_h) \]
\[ p(\theta \mid \text{preHiggs, } m_h^h, \text{hsig}) \]
\[ p(\theta \mid \text{preHiggs, } m_h^h, \text{hsig, DMup}) \]
charginos and staus again
viable light neutralino dark matter

searches for dark matter

[Combined

$\gamma$-rays

$\tau^+\tau^-$ channel

[Fermi-LAT, arXiv:1310.0828]

[LUX, arXiv:1310.8214]

WIMP–nucleon cross section (cm$^2$)

$\sigma_{WIMP-nucleon}$ (cm$^2$)

$\langle \gamma \rangle$ (GeV) $m_{DM}$ (GeV)

$\langle \gamma \rangle$ (cm$^3$s$^{-1}$)

$68\%$ Containment

$95\%$ Containment

68\% Containment

95\% Containment

Maximum Likelihood

Bayesian

Median Expected

68\% Containment

95\% Containment

$\tau^+\tau^-$ channel

$\gamma$-rays

$\langle \gamma \rangle$ (GeV) $m_{DM}$ (GeV)

$\langle \gamma \rangle$ (cm$^3$s$^{-1}$)

$\tau^+\tau^-$ channel

$\gamma$-rays

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$\langle \gamma \rangle$ (GeV) $m_{DM}$ (GeV)

$\langle \gamma \rangle$ (cm$^3$s$^{-1}$)

$\tau^+\tau^-$ channel

$\gamma$-rays

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$\langle \gamma \rangle$ (GeV) $m_{DM}$ (GeV)

$\langle \gamma \rangle$ (cm$^3$s$^{-1}$)

$\tau^+\tau^-
• update of the Fermi-LAT analysis on dwarf spheroidal galaxies: weaker limit
  (excess mainly driven by ultra-faint dwarf galaxies)
  ➞ no tension with indirect detection in the low-mass region

• in the bb channel the prediction is still two orders of magnitude below the experimental limit