Higgs coupling measurements and impact on the MSSM

Béranger Dumont
(LPSC Grenoble)

based on work with

DIS 2014 @ Warsaw

April 30, 2014
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
combined 2D $\mu$ plots

$\chi^2_i = a_i (\mu_{ggF,i} - \hat{\mu}_{ggF,i})^2$
$+ 2b_i (\mu_{ggF,i} - \hat{\mu}_{ggF,i})(\mu_{VBF,i} - \hat{\mu}_{VBF,i})$
$+ c_i (\mu_{VBF,i} - \hat{\mu}_{VBF,i})^2$

<table>
<thead>
<tr>
<th>without</th>
<th>$\gamma\gamma$</th>
<th>$VV$</th>
<th>$bb/\tau\tau$</th>
<th>$bb$</th>
<th>$\tau\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\hat{\mu}_{ggF}$</td>
<td>0.98</td>
<td>0.91</td>
<td>0.98</td>
<td>-0.23</td>
<td>1.07</td>
</tr>
<tr>
<td>$\hat{\mu}_{VBF}$</td>
<td>1.72</td>
<td>1.01</td>
<td>0.97</td>
<td>0.97</td>
<td>0.94</td>
</tr>
<tr>
<td>$a$</td>
<td>14.94</td>
<td>44.59</td>
<td>2.67</td>
<td>0.12</td>
<td>2.55</td>
</tr>
<tr>
<td>$b$</td>
<td>2.69</td>
<td>4.24</td>
<td>1.31</td>
<td>0</td>
<td>1.31</td>
</tr>
<tr>
<td>$c$</td>
<td>3.34</td>
<td>4.58</td>
<td>10.12</td>
<td>7.06</td>
<td>3.07</td>
</tr>
</tbody>
</table>

include all results up to the LHCP 2013 conference

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 $ZH\rightarrow ll+$invisible

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

- $\text{SM+C}_U+C_D+(C_V \leq 1)+\text{invisible}$
  \[ B(H \rightarrow \text{inv}) < 0.31 \text{ at 95\% CL} \]

- $\text{SM+}\Delta C_g+\Delta C_Y+\text{invisible}$
  \[ B(H \rightarrow \text{inv}) < 0.39 \text{ at 95\% CL} \]

- $\text{SM+C}_U+C_D+(C_V \leq 1)+\Delta C_g+\Delta C_Y+\text{invisible}$
  \[ B(H \rightarrow \text{inv}) < 0.39 \text{ at 95\% CL} \]

**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(phenomenological) 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

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

→ LSP and dark matter candidate

we scan over:
(flat 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

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

+ 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: $gg \rightarrow h \rightarrow \gamma \gamma$

![Graph showing probability density distributions for $\theta$ and $\mu(gg \rightarrow h \rightarrow \gamma \gamma)$ with different conditions on $\chi_1^\pm$, $\chi_1^0$, and $m_h$. The graph highlights low $M_A$ or light LSP results.](image-url)
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?

$\mu \approx 1 \pm 0.15$
why is $\mu \neq 1$

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

SUSY correction to the bottom Yukawa coupling:

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

can be large for a heavy SUSY spectrum

[Carena et al. '99]
[Eberl et al. '99]
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can be large for a heavy SUSY spectrum

[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

A mass [GeV]

<table>
<thead>
<tr>
<th>BR(A → SUSY) for A mass &lt; 1 TeV</th>
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<tr>
<td>pMSSM, ct &lt; 10 mm</td>
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BR(H⁺ → τ⁺ν) for H⁺ mass < 1 TeV

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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])

[Bélanger, Drieu La Rochelle, BD, Goldbole, Kraml, Kulkarni, arXiv:1308.3735]
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\[\text{WIMP-nucleon cross section [cm}^2\]\n
\[\text{WIMP-nucleon cross section [pb]}\]

\[\text{WIMP Mass [GeV/c}^2\]\n
[CDMS, arXiv:1304.4279]

[CDMS II Si, CoGeNT, DAMA/LIBRA, CRESST]

[light neutralino dark matter]

[Bélanger, Drieu La Rochelle, BD, Goldbole, Kraml, Kulkarni, arXiv:1308.3735]
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 $M_2 \lesssim 200$ 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 $A^0, H^0 \to \tau^+ \tau^-$ at the LHC)
- sleptons: $\sim 100$ 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]

[Diagram of neutralino decays]
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

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

\[
\begin{align*}
\text{tan } \beta & \quad [5, 50] & M_{L_3} & \quad [70, 500] \\
M_A & \quad [100, 1000] & M_{R_3} & \quad [70, 500] \\
M_1 & \quad [10, 70] & A_\tau & \quad [-1000, 1000] \\
M_2 & \quad [100, 1000] & M_{L_1} & \quad [100, 500] \\
\mu & \quad [100, 1000] & M_{R_1} & \quad [100, 500]
\end{align*}
\]

(All masses in GeV)

\[ \text{heavy 1st and 2nd generation squarks} \]
\[ \text{moderately heavy gluino, stop and sbottom} \]

\[ \text{variations in the} \]
\[ \text{Higgs, electroweak and leptonic sectors} \]

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

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

<table>
<thead>
<tr>
<th>Experimental Constraints</th>
<th>Conditions</th>
</tr>
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| **LEP limits**           | $m_{\tilde{\chi}_1^\pm} > 100$ GeV  
$ m_{\tilde{\tau}_1} > 84 - 88$ GeV (depending on $m_{\tilde{\chi}_0^0}$)  
$\sigma(e^+e^- \to \tilde{\chi}_2,3\tilde{\chi}_1^0 \to Z^{(*)} (\to q\bar{q})\tilde{\chi}_1^0) \lesssim 0.05$ pb |
| **Invisible $Z$ decay**  | $\Gamma_{Z\to\tilde{\chi}_1^0\tilde{\chi}_1^0} < 3$ MeV |
| **$\mu$ magnetic moment** | $\Delta a_\mu < 4.5 \times 10^{-9}$ |
| **Flavor constraints**   | $\text{BR}(b \to s\gamma) \in [3.03, 4.07] \times 10^{-4}$  
$\text{BR}(B_s \to \mu^+\mu^-) \in [1.5, 4.3] \times 10^{-9}$ |
| **Higgs mass**           | $m_{h^0} \in [122.5, 128.5]$ GeV |
| $A^0, H^0 \to \tau^+\tau^-$ | CMS results for $\mathcal{L} = 17$ 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 |
| $pp \to \tilde{\chi}_2^0\tilde{\chi}_1^0 \pm$ | Simplified Models Spectra approach |
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<td></td>
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</tr>
<tr>
<td></td>
<td>$\sigma(e^+e^- \rightarrow \tilde{\chi}_2^0\tilde{\chi}_1^0 \rightarrow Z(\rightarrow q\bar{q})\tilde{\chi}_1^0) \lesssim 0.05$ pb</td>
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<td>Simplified Models Spectra approach</td>
</tr>
<tr>
<td>$pp \rightarrow \tilde{\ell}^+\tilde{\ell}^-$</td>
<td></td>
</tr>
</tbody>
</table>
decomposition of a pMSSM point into simplified models, then compare to the limits on \((\sigma \times \text{BR})\) using SmodelS [Kraml et al., arXiv:1312.4175]

**direct RH selectron/smuon production**

<table>
<thead>
<tr>
<th>ATLAS Preliminary</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tilde{l}_1 \tilde{l}_1 \rightarrow l^+ \tilde{\chi}^0_1 l^- \tilde{\chi}^0_1)</td>
</tr>
<tr>
<td>L dt = 20.3 fb(^{-1}), (s=8\text{ TeV})</td>
</tr>
<tr>
<td>Red: Observed limit (±1 (\sigma_{\text{SUSY}}))</td>
</tr>
<tr>
<td>Yellow: Expected limit (± (\sigma_{\text{exp}}))</td>
</tr>
<tr>
<td>Orange: LEP (\tilde{\tau}_R) excluded</td>
</tr>
<tr>
<td>All limits at 95% CL</td>
</tr>
</tbody>
</table>

still room above 20 GeV

<table>
<thead>
<tr>
<th>CMS Preliminary</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp \rightarrow \tilde{\chi}^0_2 \tilde{\chi}^\pm_1</td>
</tr>
<tr>
<td>(\tilde{\chi}^0_2 \rightarrow Z \tilde{\chi}^0_1)</td>
</tr>
<tr>
<td>(\tilde{\chi}^\pm_1 \rightarrow W \tilde{\chi}^0_1)</td>
</tr>
<tr>
<td>(\sqrt{s}=8\text{ TeV}, L_{\text{int}}=9.2\text{ fb}^{-1})</td>
</tr>
<tr>
<td>95% C.L. CLs NLO Exclusions</td>
</tr>
<tr>
<td>Black: Observed 2(l)j +3(l) ± 1 (\sigma_{\text{theory}})</td>
</tr>
<tr>
<td>Pink: Expected 2(l)j+3(l) ± 1 (\sigma_{\text{exp}})</td>
</tr>
<tr>
<td>Red: Observed 3(l) only</td>
</tr>
<tr>
<td>Dashed: Observed 2(l)j only</td>
</tr>
</tbody>
</table>

black line overestimates the limit
"hidden" assumption: \(\tilde{\chi}^0_2, \tilde{\chi}^\pm_1\) wino-like
there are no limits on direct stau production at the LHC but one has to consider intermediate stau decays from EWinos

[CMS-SUS-12-022]

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
relic density and direct detection

- 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 \((\lesssim 200 \text{ GeV})\) and staus \((\lesssim 100 \text{ GeV})\)
  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
  → limit on the higgsino fraction $f_H$ 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 \( \text{BR}_{\text{inv}} \)
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
- High $\mu$ (no BR$_{inv}$) and low $M_A$, high $\tan \beta$
- $g_{hbb} = \sin(\beta - \alpha) - \tan \beta \cos(\beta - \alpha)$
- $\rightarrow$ promising way to probe light neutralino scenarios
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

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

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

prompt chargino decay ($c\tau < 10\,\text{mm}$):
strong impact on $M_2$
do not change main conclusions
masses of the SUSY partners

$p\text{MSSM, } \tau < 10 \text{ mm}$

Probability density

$\tilde{\chi}_1^0$ mass [GeV]

$p(\tilde{\chi}_1^0 | \text{preHiggs, } m_\tau)$
$p(\tilde{\chi}_1^0 | \text{preHiggs, } m_H^0, \text{hsig})$
$p(\tilde{\chi}_1^0 | \text{preHiggs, } m_H^0, \text{hsig, DMup})$

Probability density

$\tilde{\chi}_2^0$ mass [GeV]

$p(\tilde{\chi}_2^0 | \text{preHiggs, } m_\tau)$
$p(\tilde{\chi}_2^0 | \text{preHiggs, } m_H^0, \text{hsig})$
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$p(\tilde{\chi}_1^0 | \text{preHiggs, } m_H^0, \text{hsig, DMup})$

Probability density

$A_1$ [GeV]

$p(\tilde{\chi}_1^0 | \text{preHiggs, } m_\tau)$
$p(\tilde{\chi}_1^0 | \text{preHiggs, } m_H^0, \text{hsig})$
$p(\tilde{\chi}_1^0 | \text{preHiggs, } m_H^0, \text{hsig, DMup})$
$\mu(Vh \rightarrow bb)$

Probability density

$pMSSM, c\tau < 10$ mm

- $p(\theta | \text{preHiggs}, m)$
- $p(\theta | \text{preHiggs}, m^h, h\text{sig})$
- $p(\theta | \text{preHiggs}, m^h, h\text{sig}, \text{DMup})$
charginos and staus again
viable light neutralino dark matter

searches for dark matter

\[ m_{DM} \text{(GeV)} \]

\[ \sigma_{WIMP-nucleon} \text{(cm}^2\text{)} \]

\[ 10^{-22} \quad 10^{-23} \quad 10^{-24} \quad 10^{-25} \]

\[ 10^1 \quad 10^2 \quad 10^3 \]

\[ \gamma\text{-rays} \]

\[ \tau^+\tau^- \text{ channel} \]

[FERMI-LAT, arXiv:1310.0828]

[LUX, arXiv:1310.8214]
indirect detection

- 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