PRECISION MEASUREMENTS OF HIGGS/HIGGSINOS

Kyu Jung Bae,
Center for Theoretical Physics of the Universe,

based on
with H. Baer, N. Nagata and H. Serce

@HU-IBS Summer Institute

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SUPERSYMMETRY

• motivated by “Naturalness”, solving gauge hierarchy problem.

• successful gauge coupling unification

• “weak scale SUSY” provides natural electroweak symmetry breaking.

• weak scale dark matter candidates
• **gluinos/squarks**: *strongly interacting*, most promising at hadron colliders

• **Bino, Wino, Higgsinos**, sleptons: weakly interacting, hard to find at hadron colliders, possibly discovered at lepton colliders

• **New Higgs states**: 2 Higgs doublets, additional heavy Higgs states $H, A, H^\pm$
SUSY @ LHC-13 (1)

Limits on Direct Gluino Production

- Excluding **gluinos** up to 1.75 TeV and **neutralinos** up to 1.2 TeV

Francesco Pandolfi  
Search for SUSY with jets and ME$_T$ at CMS
**SUSY @ LHC-13 (2)**

**Limits on Direct Squark Production**

- **Excluding squarks (stops)** up to 1.4 (0.9) TeV and **neutralinos** up to 500 GeV

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**Francesco Pandolfi**: Search for SUSY with jets and ME_T at CMS

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**Slide by F. Pandolfi, ICHEP 16**
INTERPRETATION (II)

3L signal regions can be interpreted in the context of other chargino-neutralino production, assuming heavy sleptons, decay to W,Z and h bosons.
HEAVY HIGGSES?

MSSM Neutral Higgs Search (A/H→τ⁺τ⁻)

- We also show limits in the $m_h^{mod+}$ and hMSSM benchmark scenarios
- In the $m_h^{mod+}$ scenario, we exclude $\tan\beta > 16$ for $m_A = 600$ GeV and $\tan\beta > 35$ for $m_A = 1$ TeV
- In the hMSSM, we have sensitivity to exclude the low $m_A$-low $\tan\beta$ corner and the island around 350 GeV. Note: the features around 350 GeV are related to the $\sigma \times$ BR evolution near the A/H→ttbar threshold
- hMSSM plot shows Run-1 couplings exclusion ($\kappa_V$, $\kappa_u$ and $\kappa_d$)
HIGGS & HIGGSINOS

• Naive hope for SUSY discovery at LHC has been faded.
• But we could still see

Higgs couplings:
  • Higgs couplings can be modified by mixings and/or loop effects of new particles.
  • Precision measurements at LHC/ILC will examine coupling deviation from SM predictions.

Light Higgsinos:
  • Light Higgsinos are still possible and good for “naturalness.”
  • Bino/Wino contaminations in neutralino/chargino allow us to see effects of heavy states.
OUTLINE

1. Introduction
2. Precision measurement of Higgs couplings
3. Precision measurement of Higgsino masses
4. Summary
OUTLINE

1. Introduction

2. **Precision measurement of Higgs couplings**

3. Precision measurement of Higgsino masses

4. Summary
The ratios of the coupling modifiers are tested in the most generic parameterisation proposed in Ref. 129. The 2HDM is the 2HDM.

Common coupling modifications for up-type fermions versus down-type fermions or for leptons versus SM predictions. Figure 18:

Best fit values of parameters for the combination of ATLAS and CMS data, and separately for each experiment, for the parameterisation assuming the absence of BSM particles in the loops, B

Figure 19:

The fact that the error bars for the scenario HL–LHC (thick lines) and 2

HIGGS COUPLINGS @ COLLIDERS

Current Bound

Expected Bound

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<thead>
<tr>
<th>Parameter</th>
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Parameter value

BR($H \rightarrow NP$)

0.0 0.01 0.02 0.03 0.04 0.05

Expected Bound

HL – LHC ($\Gamma_{tot}$ free)
HL – LHC $\otimes$ ILC 250 ($\sigma_{ZH}^{tot}$)
HL – LHC $\otimes$ ILC 250
HL – LHC $\otimes$ ILC 500
HL – LHC $\otimes$ ILC 1000
HL – LHC $\otimes$ ILC 1000 (LumiUp)
HIGGS IN MSSM

- Higgs mass matrix

\[
\mathcal{M}^2_h = \begin{pmatrix}
(m^2_{H_u} + m^2_{H_d} + m^2_Z (1 - 2 \cos 2\beta)/2 & -(m^2_{H_u} + m^2_{H_d} + 2\mu^2 + m^2_Z) \sin 2\beta /2 \\
-(m^2_{H_u} + m^2_{H_d} + 2\mu^2 + m^2_Z) \sin 2\beta /2 & m^2_{H_d} + \mu^2 (1 + 2 \cos 2\beta)/2
\end{pmatrix} + \delta \mathcal{M}^2_h
\]

diagonalized by

\[
\begin{pmatrix}
h \\
H
\end{pmatrix} = \begin{pmatrix}
\cos \alpha & \sin \alpha \\
-\sin \alpha & \cos \alpha
\end{pmatrix} \begin{pmatrix}
h_{uR}^0 \\
h_{dR}^0
\end{pmatrix}
\]

\[0 \leq \alpha \leq \pi /2\]

- In the heavy \(A\) limit,

\[m^2_A = m^2_{H_u} + m^2_{H_d} + 2\mu^2\]

\[
\cos(\alpha + \beta) = \frac{m^2_Z \sin 4\beta}{2m^2_A} \left(1 - \frac{\delta \mathcal{M}^2_{h,11} + \delta \mathcal{M}^2_{h,22}}{2m^2_Z \cos 2\beta} - \frac{\delta \mathcal{M}^2_{h,12}}{m^2_Z \sin 2\beta}\right) + \mathcal{O} \left(\frac{m^4_Z}{m^4_A}\right)
\]

\[
\sin(\alpha + \beta) \approx 1 - \frac{1}{2} \cos^2(\alpha + \beta) = 1 - \mathcal{O} \left(\frac{m^4_Z}{m^4_A}\right)
\]

- MSSM/SM coupling ratios are determined by \(\alpha \& \beta\)
- Non-SM coupling from Higgs mixing

\[ g_{hVV} = g_{hVV}^{\text{SM}} \sin(\alpha + \beta) \quad \text{for} \quad V = W, Z. \]

\[ \kappa = g/g^{\text{SM}} \]

- Deviation \( \propto \cos^2(\alpha + \beta) \propto m_Z^4/m_A^4 \)

- Unless \( m_A \) is small, it doesn’t show a significant deviation; far less than HL-LHC / ILC500 reach.
Eff. Lagrangian from RGE & SUSY threshold

\[-L_{\text{eff}} = (f_b + \delta f_b) \bar{b}_R H_d Q_3 + \Delta f_b \bar{b}_R H_u^* Q_3 + (f_t + \delta f_t) \bar{t}_R H_u Q_3 + \Delta f_t \bar{t}_R H_d^* Q_3 + \text{h.c.}\]

\[
g_{hbb} = g_{hbb}^{\text{SM}} \left[ \sin(\alpha + \beta) - \frac{\cos(\alpha + \beta)}{1 + \Delta_b} \left\{ \tan \beta - \Delta_b \cot \beta + (\tan \beta + \cot \beta) \frac{\delta f_b}{f_b} \right\} \right]
\]

\[
g_{htt} = g_{htt}^{\text{SM}} \left[ \sin(\alpha + \beta) + \frac{\cos(\alpha + \beta)}{1 + \Delta_t} \left\{ (1 + \Delta_t) \cot \beta - (1 + \cot^2 \beta) \frac{\Delta f_t}{f_t} \right\} \right].
\]

- \textbf{B and Tau} coupling: Large deviation for small \(m_A\), probed by HL-LHC / ILC500
$H$-$F$-$F$ COUPLINGS (2)

- Probing non-holomorphic correction from SUSY threshold

\[
\frac{\Delta_b}{\Delta_{b'}} \approx \Delta_b
\]

\[
\Delta_b \approx \left[ \frac{2\alpha_s}{4\pi} M_3 \mu I(m_{b_1}^2, m_{b_2}^2, M_3^2) + \frac{f_t^2}{16\pi^2} m_A I(m_{t_1}^2, m_{t_2}^2, \mu^2) \right] \tan \beta
\]

- large value for heavy stop; anti-correlation with fine-tuning measure
- can be seen if B/tau precision measurements are conducted
**H-F-F COUPLINGS (3)**

**Higgs-top coupling:** no significant deviation

\[
g_{htt} = g_{htt}^{SM} \left[ \sin(\alpha + \beta) + \frac{\cos(\alpha + \beta)}{1 + \Delta_t} \left\{ (1 + \Delta_t) \cot \beta - (1 + \cot^2 \beta) \frac{\Delta f_t}{f_t} \right\} \right]
\]

![Graph showing the distribution of fitted values for \(K_t\) against \(\Delta_{EW}\) for different mass ranges of \(m_A\). The graph includes data points for different mass intervals, with markers indicating \(m_A\) values.

- Blue dots: \(m_A < 0.50\) TeV
- Orange dots: \(0.50\) TeV < \(m_A\) < 0.75 TeV
- Purple dots: \(0.75\) TeV < \(m_A\) < 1 TeV
- Black dots: \(m_A > 1\) TeV

The distribution shows a decrease in \(K_t\) values as \(\Delta_{EW}\) increases, with different colors highlighting various mass intervals.
Loop-induced couplings

The virtuality of the final state gauge boson allows to kinematically open this type of decay channels in some other cases where they were forbidden at the two–body level.

\[ H \rightarrow AZ^* \rightarrow A (H) f \bar{f}, H \rightarrow H^\pm W^\pm \rightarrow H^\pm f \bar{f} \]

At low tan \( \beta \) values, the branching ratio for some of these decays, in particular \( H^\pm \rightarrow AW^* \), can be sizable enough to be observable.

Finally, let us note that the direct radiative corrections to the \( H^\pm \rightarrow AW^* \) decays have been calculated in Ref. [215]. They are in general small, not exceeding the 10% level, except when the tree–level partial widths are strongly suppressed; however, the total tree–plus one–loop contribution in this case, is extremely small and the channels are not competitive.

The same features should in principle apply in the case of \( H^\pm \rightarrow hW^\pm \) and \( A \rightarrow hZ \) decays.

2.1.3 Loop induced Higgs decays

The \( \gamma\gamma \) and \( \gamma Z \) couplings of the neutral Higgs bosons in the MSSM are mediated by charged heavy particle loops built up by \( W \) bosons, standard fermions \( f \) and charged Higgs bosons \( H^\pm \) in the case of the CP–even \( \Phi = h, H \) bosons and only standard fermions in the case of the pseudoscalar Higgs boson; Fig. 2.8. If SUSY particles are light, additional contributions will be provided by chargino \( \chi^\pm_i \) and sfermion \( \tilde{f} \) loops in the case of the CP–even Higgs particles and chargino loops in the case of the pseudoscalar Higgs boson.

In the case of the gluonic decays, only heavy quark loops contribute, with additional contributions due to light squarks in the case of the CP–even Higgs bosons; Fig. 2.9.

In this subsection, we will discuss only the contributions of the SM and \( H^\pm \) particles, postponing those of the SUSY particles, which are assumed to be heavy, to the next section.

\[ Q_{h, H, A} g g \]

\[ h, H, A \]

\[ Q \]

\[ h, H \]

\[ \tilde{Q} \]
Loop-induced couplings

- If Higgsino-Wino mixing is large, chargino contribution can make a large deviation.
OUTLINE

1. Introduction

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3. **Precision measurement of Higgsino masses**

4. Summary
LIGHT HIGGSINOS (1)

EWSB condition: \[ m_Z^2 / 2 \simeq -\mu^2 - m_{H_u}^2 \]

“Natural” EWSB requires \[ \mu^2 \sim m_{H_u}^2 \sim m_Z^2 \ll m_{\text{soft}}^2 \sim \mathcal{O}(\text{TeV}^2) \]

Bino > 300 GeV \quad \text{if} \quad \text{gaugino masses are unified at } m_{\text{GUT}}
Wino > 600 GeV \quad \text{if} \quad \text{gluino mass } > 1.8 \text{ TeV}

Higgsino-like neutralinos/chargino: \( \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_1^\pm \)

- nearly degenerate near 100 GeV
- soft leptons(jets) in \( \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow l\nu \tilde{\chi}_1^0 qq' \tilde{\chi}_1^0 \)
  \( \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^0 l^+ l^- \tilde{\chi}_1^0 \)
- difficult to detect at LHC, but good at ILC
**LIGHT HIGGSINOS (2)**

**Neutralino mass**

$$\mathcal{M} = \begin{pmatrix} M_1 & 0 & -M_Z c_\beta s_W & M_Z s_\beta s_W \\ 0 & M_2 & -M_Z c_\beta c_W & M_Z s_\beta c_W \\ -M_Z c_\beta s_W & M_Z c_\beta c_W & 0 & -\mu \\ M_Z s_\beta s_W & -M_Z s_\beta c_W & -\mu & 0 \end{pmatrix}$$

$$m_{\tilde{\chi}_1^0} \simeq \mu - \frac{M_Z^2 s_W^2 (1 + s_\beta)}{2(M_1 - \mu)} - \frac{M_Z^2 c_W^2 (1 + s_\beta)}{2(M_2 - \mu)}$$

$$m_{\tilde{\chi}_2^0} \simeq \mu + \frac{M_Z^2 s_W^2 (1 - s_\beta)}{2(M_1 - \mu)} + \frac{M_Z^2 c_W^2 (1 - s_\beta)}{2(M_2 - \mu)}$$

**Chargino mass**

$$\left( \begin{array}{cc} M_2 & \sqrt{2} s_\beta m_W \\ \sqrt{2} c_\beta m_W & \mu \end{array} \right) \quad \rightarrow \quad m_{\tilde{\chi}_1^\pm} \simeq \mu - \frac{m_W^2}{M_2} s_2 \beta$$

- Due to Bino/Wino contamination, neutralino/chargino masses are modified from mu by $\mathcal{O}(m_Z^2 / M_{1,2})$

- from precision mass measurements of Higgsino-like states, we can also see the effects of Bino & Wino
RG running

\[
\frac{dM_1}{dt} = \frac{2}{16\pi^2} \left[ \frac{33}{5} g_1^2 M_1 + \frac{2 g_1^2}{(16\pi^2)^2} \left( \frac{199}{25} g_1^2 (2M_1) + \frac{27}{5} g_2^2 (M_1 + M_2) + \frac{88}{5} g_3^2 (M_1 + M_3) + 26 f_t^2 (A_t - M_1) + \frac{14}{5} f_b^2 (A_b - M_1) + \frac{18}{5} f_\tau^2 (A_\tau - M_1) \right) \right],
\]

\[
\frac{dM_2}{dt} = \frac{2}{16\pi^2} g_2^2 M_2 + \frac{2 g_2^2}{(16\pi^2)^2} \left[ \frac{9}{5} g_1^2 (M_2 + M_1) + 25 g_2^2 (2M_2) + 24 g_3^2 (M_2 + M_3) + 6 f_t^2 (A_t - M_2) + 6 f_b^2 (A_b - M_2) + 2 f_\tau^2 (A_\tau - M_2) \right],
\]

\[
\frac{dM_3}{dt} = \frac{2}{16\pi^2} (-3) g_3^2 M_3 + \frac{2 g_3^2}{(16\pi^2)^2} \left[ \frac{11}{5} g_1^2 (M_3 + M_1) + 9 g_2^2 (M_3 + M_2) + 14 g_3^2 (2M_3) + 4 f_t^2 (A_t - M_3) + 4 f_b^2 (A_b - M_3) \right],
\]

Can we extract the A-term contribution from Higgsino mass measurements?

A-terms contribute at 2-loop
How precise?

Benchmark study, e.g. $\mu = 150$ GeV with precision requirements

- Event cross section with 3% accuracy
- $e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow l\nu\tilde{\chi}_1^0q\tilde{\chi}_1^0$ $e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0l^+l^-\tilde{\chi}_1^0$
- Higgs mass $\pm 1$ GeV
- Higgs coupling (at the level of HL-LHC / ILC)
- Neutralino/chargino mass

1% precision

$\pm 0.4$ GeV precision

- 1% is not enough to extract $A$-term, but $0.4$ GeV (sub-percent level) can do.
SUMMARY

- Hope for SUSY discovery at LHC now becomes dim.

- We could still see the SUSY signal from precision measurements of Higgs couplings at LHC and ILC.

- Light Higgsinos are still allowed and good for naturalness. It may be possible to detect them at ILC.

- If we discover Higgsino-like states at ILC, we can extract the information of heavy states from precision measurements of Higgsinos.