HiggsBounds - using results from the Higgs searches at LEP and the Tevatron to constrain extensions to the Standard Model

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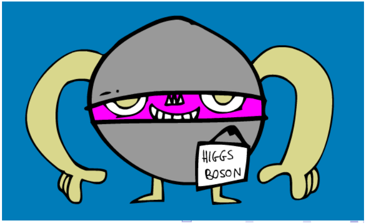
SUSY 2010

Higgs Searches

- There have been a wide variety of Higgs sectors predicted by models such as the Standard Model and its extensions.
- The results from Higgs searches at past and present colliders can be used to constrain these models.



Higgs Searches

The results from the Higgs searches are presented in 2 forms:

Model-dependent limits

The analysis has been carried out in the context of a particular model

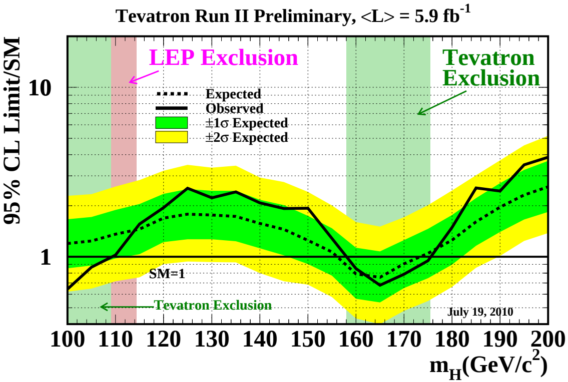
- E.g. Standard Model analysis $\rightarrow$ limits on the Higgs mass in the SM, certain benchmark MSSM scenarios ($m_h^{\max}$, no-mixing, large-μ, gluophobic, small α_{eff}, CPX, ...) $\rightarrow$ limits on the parameter space of these scenarios
- uses lots of search topologies, applies to one model only

Model-independent limits

Limits on the cross sections of a particular topology which can be used to constrain a wide variety of different models

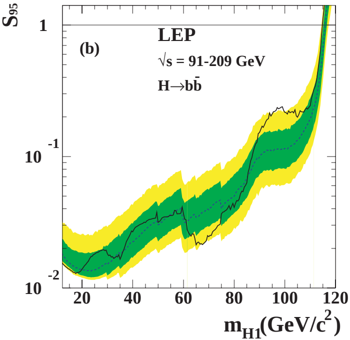
- E.g. $e^+e^- \rightarrow (h_i)Z \rightarrow (b\bar{b})Z$
- uses one search topology only, applies to lots of models

Example of model-dependent limits: Standard Model

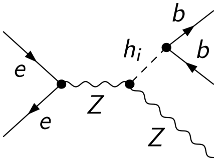


- $M_H < 114.4$ GeV is excluded by LEP searches [Phys.Lett.B565:61-75,2003]
- $158 < M_H < 175$ GeV is excluded by Tevatron searches [arXiv:1007.4587]
- These results combine the results from searches in many different channels.

Example of a model-independent cross-section limit



[Eur.Phys.J.C47:547-587,2006]

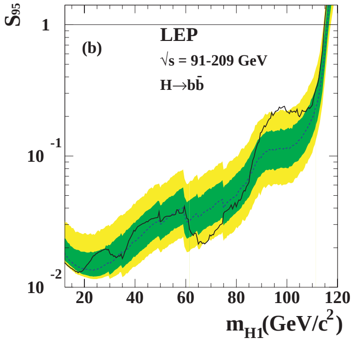


S_{95} is the maximum cross section compatible with the data at 95% CL, normalised to the LEP SM Higgsstrahlung cross section.

Solid line: observed limit

Dashed line: expected limit (based on simulations with no signal)

Example of a model-independent cross-section limit



[Eur.Phys.J.C47:547-587,2006]

To use these limits:

1. For each neutral Higgs h_i for a parameter point in a model, need to compare

$$S_{95}^{\rm theo} = \sigma^{\rm norm}(e^- e^+ \to h_i Z){\rm Br}(h_i \to b\bar{b})$$

with the observed S_{95} value for this mass.

[For example, at tree level in the MSSM, $\sigma^{\rm norm}(e^- e^+ \to h^0 Z) = \sin^2(\beta - \alpha)$]

2. If $S_{95}^{\rm theo} > S_{95}^{\rm obs}$, then this parameter point is excluded at 95% CL.

Using more than one model-independent limit

When using more than one model-independent limit, care needs to be taken to ensure that the exclusions are still at 95 % CL.

One possible method:

1. Calculate S_{95}^{theo} for each search channel.
2. Determine which search channel has the highest statistical sensitivity i.e. which search channel has the largest $S_{95}^{\mathrm{theo}}/S_{95}^{\mathrm{exp}}$, using the expected limits based on simulations with no signal.
3. Look at $S_{95}^{\mathrm{theo}}/S_{95}^{\mathrm{obs}}$ for this channel only. If $S_{95}^{\mathrm{theo}}/S_{95}^{\mathrm{obs}} > 1$, then parameter point is excluded at 95 % CL.

HiggsBounds

HiggsBounds http://www.ippp.dur.ac.uk/HiggsBounds

is a Fortran program which takes input from the user for a parameter point in a particular model and determines whether this parameter point has been excluded at 95% CL by Higgs searches at LEP and the Tevatron.

- Current release (2.0.0) contains neutral Higgs and charged Higgs search results. It can be applied to models containing between 1 and 9 neutral Higgs bosons.
- The user can either use
  - the web version
  - the command line version
  - the library of subroutines.
- Input: Higgs masses and widths, normalised Higgs production cross sections, Higgs branching ratios. (for Tevatron charged Higgs searches, also need t-quark branching ratios)
- Narrow width approximation must be applicable.

Input to *HiggsBounds*: some publicly available programs

There are many public programs which can be used to calculate the *HiggsBounds* input in the more common models e.g.

- *DarkSUSY*: *HiggsBounds* is included in the *DarkSUSY* package. *DarkSUSY* has a web interface at `http://www.physto.se/~edsjo/darksusy/` for mSUGRAm and MSSM-7+ scenarios.
- *FeynHiggs** (T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak, G. Weiglein) for the MSSM
- *CPsuperH** (J. S. Lee, A. Pilaftsis, M. Carena, S. Y. Choi, M. Drees, J. Ellis, and C. Wagner) for the complex MSSM
- *2HDMC*† (D. Eriksson, J. Rathsman, O. Stål) for the Two-Higgs-Doublet Model (vs. 1.0.2 and higher)
- *superISO*† F. Mahmoudi

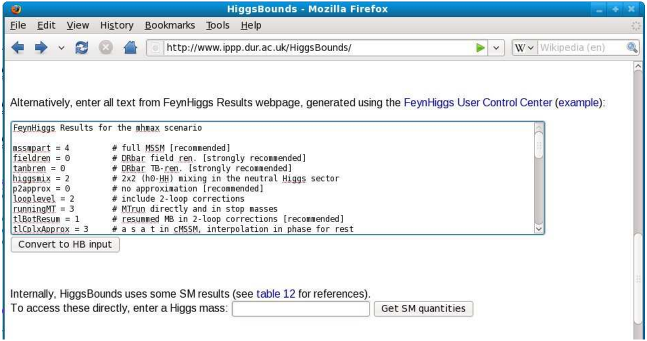
† includes interface to *HiggsBounds*

∗ interface to this program is included in *HiggsBounds* package

- A beta version of an SLHA interface to *HiggsBounds* is available at http://www.ippp.dur.ac.uk/HiggsBounds.

Input to *HiggsBounds*: using *FeynHiggs* User Control Center

The *FeynHiggs* User Control Center can be used to get MSSM parameters online. The FHUCC results page can then be copy-and-pasted into a box on the *HiggsBounds* website:



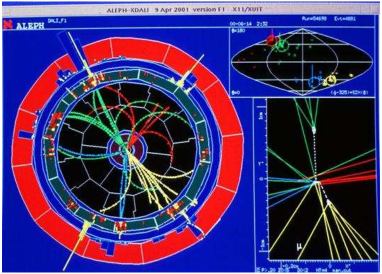
LEP topological cross section limits in *HiggsBounds*

Higgsstrahlung

1. $e^+e^- \to (h_k)Z \to (b\bar{b})Z$
2. $e^+e^- \to (h_k)Z \to (\tau^+\tau^-)Z$
3. $e^+e^- \to (h_k \to h_ih_i)Z \to (b\bar{b}b\bar{b})Z$
4. $e^+e^- \to (h_k \to h_ih_i)Z \to (\tau^+\tau^-\tau^+\tau^-)Z$
5. $e^+e^- \to (h_k \to h_ih_i)Z \to (b\bar{b})(\tau^+\tau^-)Z$
6. $e^+e^- \to (h_k)Z \to (...)Z$
7. $e^+e^- \to (h_k)Z \to (\gamma\gamma)Z$
8. $e^+e^- \to (h_k)Z \to (\text{invisible})Z$
9. $e^+e^- \to (h_k)Z \to (\text{ 2 jets })Z$

Higgs pair production

1. $e^+e^- \to (h_kh_i) \to (b\bar{b}b\bar{b})$
2. $e^+e^- \to (h_kh_i) \to (\tau^+\tau^-\tau^+\tau^-)$
3. $e^+e^- \to (h_k \to h_ih_i)h_i \to (b\bar{b}b\bar{b})b\bar{b}$
4. $e^+e^- \to (h_k \to h_ih_i)h_i \to (\tau^+\tau^-\tau^+\tau^-)\tau^+\tau^-$
5. $e^+e^- \to (h_k \to b\bar{b})(h_i \to \tau^+\tau^-)$
6. $e^+e^- \to (h_k \to \tau^+\tau^-)(h_i \to b\bar{b})$



Yukawa process (here, h_k is a CP-eigenstate)

- $e^+e^- \to b\bar{b}h_k \to b\bar{b}b\bar{b}$
- $e^+e^- \to b\bar{b}h_k \to b\bar{b}\tau^+\tau^-$
- $e^+e^- \to \tau^+\tau^-h_k \to \tau^+\tau^-\tau^+\tau^-$

charged Higgs production

- $e^+e^- \to H_k^+H_k^- \to \tau^+\nu\tau^-\nu$
- $e^+e^- \to H_k^+H_k^- \to q_i\bar{q}_jq_l\bar{q}_m$
- $e^+e^- \to H_k^+H_k^- \to q_i\bar{q}_j\tau^\pm\nu$

Tevatron topological cross section limits in *HiggsBounds*

neutral Higgs processes

- $p\bar{p} \to Wh_i \to l\nu b\bar{b}$
- $p\bar{p} \to Wh_i \to W^+W^-W^\pm$
- $p\bar{p} \to Zh_i \to l^+l^- b\bar{b}$
- $p\bar{p} \to Zh_i \to \nu\bar{\nu} b\bar{b}$
- $p\bar{p} \to Wh_i/Zh_i \to b\bar{b} + E_T^{\text{miss.}}$ (SM)
- $p\bar{p} \to h_i \to W^+W^- \to l^+l'^- \nu\nu$
- $p\bar{p} \to h_i/h_iW, h_i \to W^+W^-$(SM)
- $p\bar{p} \to (b/\bar{b})h_i, h_i \to b\bar{b}$
- $p\bar{p} \to h_i \to \tau^+\tau^-$
- $p\bar{p} \to h_i/h_iW/h_iZ/h_i$ via VBF, $h_i \to \tau^+\tau^-$ (SM)
- $p\bar{p} \to h_i/h_iW/h_iZ/h_i$ via VBF, $h_i \to \gamma\gamma$
- combined Higgs production and decay (SM)

(+ hadronic remainders)

- $p\bar{p} \to t\bar{t}h \to t\bar{t}b\bar{b}$ (h_k is CP-even)
- $p\bar{p} \to (h_k) + ... \to (Z\gamma) + ...$ (for M_{h_k} <320 GeV)

charged Higgs processes

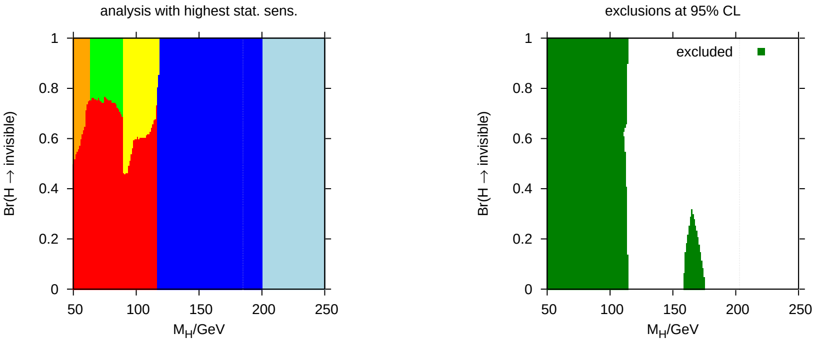
- $t \to H_k^+ b \to \tau^+\nu b$
- $t \to H_k^+ b \to q_i\bar{q}_j b$

HiggsBounds

- There are some additional complications, which *HiggsBounds* takes care internally, e.g.,
  - The tables of limits come with a variety of normalisations. *HiggsBounds* stores values for the SM Higgs production cross sections, branching ratios etc internally.
  - Some limits can only be used for Higgs bosons which fulfil certain conditions (SM-like, particular CP).
  - The possibility of combining cross section predictions for Higgs bosons with similar masses. E.g. useful for the real MSSM at high TB.

- *HiggsBounds* will be continuously updated in order to include the latest results. So far during the development of the code, we have included 159 tables, of which 82 are included in the current release (2.0.0).

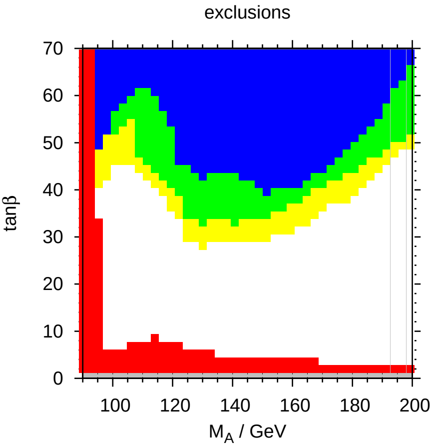
HiggsBounds Example 1: Invisible Higgs decays



Key to analysis colours:

- $= e^- e^+ \to HZ \to b\bar{b}Z$, hep-ex/0602042 (LEP)
- $= e^- e^+ \to HZ \to (\text{invisible})Z$, arXiv:0707.0373 (OPAL)
- $= e^- e^+ \to HZ \to (\text{invisible})Z$, hep-ex/0501033 (L3)
- $= e^- e^+ \to HZ \to (\text{invisible})Z$, arXiv:0107032v1 (LEP)
- $= p\bar{p} \to H \to W^+ W^-$, arXiv:1005.3216 (TEVNPHWG)
- $= p\bar{p} \to H + ... \to ...$ where H is SM-like, arXiv:1007.4587 (TEVNPHWG)

HiggsBounds Example 2: Real MSSM



The results from the Tevatron Higgs searches have significantly constrained MSSM parameter space.

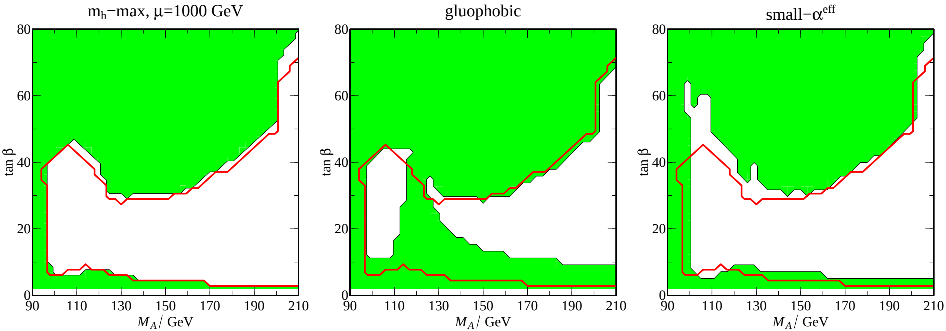
Plotted here:

- constraints from results submitted to arXiv
- Mhmax ($\mu = +200$ GeV) scenario but assuming narrow width approximation
- theoretical cross sections have been added when the Higgs mass separation is small.

■= excluded by LEP
■ + ■= excluded by LEP + Tevatron until July 2008
■ + ■ + ■= excluded by LEP + Tevatron until July 2009
■ + ■ + ■ + ■= excluded by LEP + Tevatron until July 2010

HiggsBounds Example 2: Real MSSM

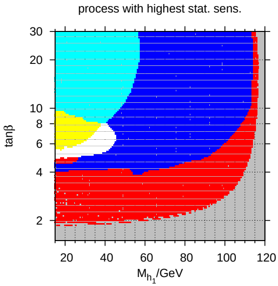
These Tevatron cross section limits are very useful in constraining other scenarios e.g.

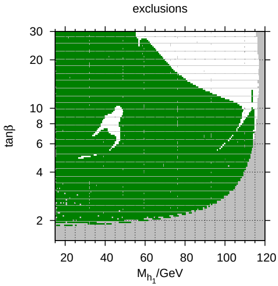


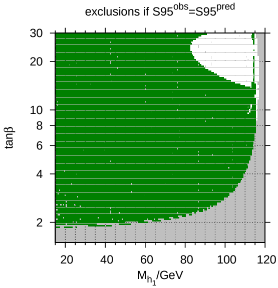
red line: $m_h - max$, $\mu = +200$ GeV. Note that narrow width approximation has been assumed.

HiggsBounds Example 3: CPX scenario

HiggsBounds results for the CPX scenario (with $A_t^{onshell} = 900$ GeV)







Channel with the highest statistical sensitivity

- red $= e^- e^+ \rightarrow h_1 Z \rightarrow b\bar{b}Z$
- blue $= e^- e^+ \rightarrow h_2 Z \rightarrow b\bar{b}Z$
- white $=$ $e^- e^+ \rightarrow h_2 Z \rightarrow h_1 h_1 Z \rightarrow b\bar{b}b\bar{b}Z$
- cyan $= e^- e^+ \rightarrow h_2 h_1 \rightarrow b\bar{b}b\bar{b}$
- yellow $= e^- e^+ \rightarrow h_2 h_1 \rightarrow h_1 h_1 h_1 \rightarrow b\bar{b}b\bar{b}b\bar{b}$

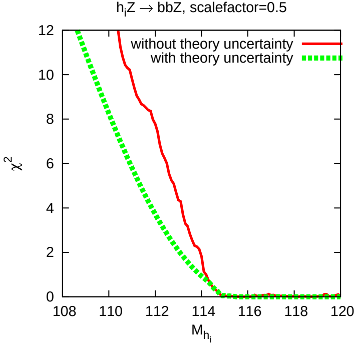
Exclusion region at 95 % CL

green = excluded
white = unexcluded

Exclusions in the hypothetical case where $S_{95}^{\rm obs} = S_{95}^{\rm pred}$

HiggsBounds + Chi-squared extension

For the LEP Higgs search channels, *HiggsBounds* can also output a chi-squared value, with and without a Gaussian theory uncertainty.



This information will then be used by the programs

- Fittino P. Bechtle, K. Desch, P. Wienemann
- MasterCode O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, S. Heinemeyer, G. Isidori, K. Olive, S. Rogerson, F. Ronga, G. Weiglein,

which extract SUSY Langrangian parameters from experimental data.

Contact us for more information about this extension.

Future Plans

(i.e. being worked on, but are not yet in the public code)

- SUSYBounds extension: We are starting to include some limits from sparticle searches. So far, we've implemented the OPAL limits on chargino and neutralino production cross sections [hep-ex/0401026]
- Beyond the narrow width approximation: see Georg Weiglein's talk on Friday
- Expected LHC limits

Summary

- Discussed the importance of the results from Higgs searches at LEP and the Tevatron for constraining the Standard Model and its extensions. Limits from the Higgs searches at LEP and the Tevatron will need to to be taken into account in the interpretation of any new physics seen at the LHC.

- Introduced the program *HiggsBounds*, which provides a very quick and convenient way for theorists to compare their Higgs sector predictions with a wide variety of experimental limits from Higgs searches at LEP and the Tevatron.

- The on-line version and downloadable versions of the program are available at http://www.ippp.dur.ac.uk/HiggsBounds

The End

HiggsBounds Example 3: CPX scenario

The CPX scenario is a benchmark scenario for the MSSM with complex phases (M.S.Carena, J.R.Ellis, A.Pilaftsis, C.E.M.Wagner 2000).

The LEP Higgs Working Group and LEP Collaborations did a dedicated analysis for this scenario [EP JC 46(2006)547] and found an unexcluded region at $M_{h_1} \sim 45\ \mathrm{GeV}$, $\tan\beta \sim 8$.

Since this analysis, new results have been obtained in the Feynman-diagrammatic approach, in particular:

- phase dependent $\mathcal{O}(\alpha_s \alpha_t)$ corrections to the Higgs self-energies (S.Heinemeyer, W.Hollik, H.Rzehak, G.Weiglein 2007)
- phase dependent 1-loop corrections to the Higgs decay $h_2 \to h_1 h_1$ (K.W., G.Weiglein 2008)

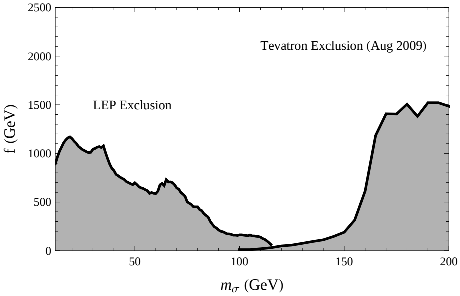
We can use *HiggsBounds* to look at the effect of these new corrections.

HiggsBounds Example 4: Dilaton-assisted Dark Matter

arXiv:0909.1319 (Y. Bai, M. Carena and J. Lykken)

- A dilaton could be the dominant messenger between the SM fields and dark matter.
- The dilaton can have an enhanced coupling to the gluons compared to a Higgs.

The authors of arXiv:0909.1319 used *HiggsBounds* to obtain the exclusions from LEP and Tevatron Higgs searches:



m_σ = dilaton mass

f = energy scale of the spontaneous symmetry breaking

Model likeness test

Some of the analyses have been performed under the assumption that model to be tested is similar to the Standard Model.

Therefore we only apply these analyses to parameter points which pass a Standard-Model likeness test:

We check that none of the normalised production cross sections s_i or normalised branching ratios b_i considered by the analysis

$$
\begin{aligned}
s_i &= \frac{\sigma_{\mathrm{model}}(P_i(h))}{\sigma_{\mathrm{SM}}(P_i(H))} \\
b_k &= \frac{\mathrm{BR}_{\mathrm{model}}(h \to F_k)}{\mathrm{BR}_{\mathrm{SM}}(H \to F_k)}
\end{aligned}
$$

differ much from the average normalised production cross section $\bar{s}$ or normalised branching ratio $\bar{b}$.

Some of the analyses assume a particular CP-state for the Higgs bosons. For some of the others, it is necessary to check that production or decay channels which are not considered by the analyses are negligible.

Standard Model results used within *HiggsBounds*

Internally, *HiggsBounds* uses

- SM Higgs branching ratios and total decay width from *HDecay* (A. Djouadi, J. Kalinowski and M. Spira)
- SM Higgs production cross sections (S. Catani et al 2003, O. Brein et al 2003, M. L. Ciccolini et al 2003, R. Harlander et al 2003, J. M. Campbell et al 1999, U. Aglietti et al 2006, K.A.Assamagan et al 2004, W. Beenakker et al 2001, L. Reina et al 2001, S. Dawson et al 2002)
- The SM ratio $\sigma(p\bar{p} \to H \,\text{via}\, WW \,\text{fusion})/\sigma(p\bar{p} \to H \,\text{via}\, ZZ \,\text{fusion})$ using *VBF@NLO* (T.Figy et al 2003)
- ratios of SM hadronic cross sections $\sigma(p\bar{p} \to nm \to H + ...)/\sigma(p\bar{p} \to H + ...)$, where nm are particular partons

to convert between different types of input and to ensure correct normalisation of experimental limits.

scenario definitions from hep-ex/0602042

Benchmark parameters						
	m_h-max	*no-mixing*	*large-μ*	*gluophobic*	*small-α_{eff}*	*CPX*
$M_{\rm SUSY}$ (GeV)	1000	1000	400	350	800	500
M_2 (GeV)	200	200	400	300	500	200
μ (GeV)	-200	-200	1000	300	2000	2000
$m_{\tilde{g}}$ ($\rm GeV/c^2$)	800	800	200	500	500	1000
$X_{\rm t}$ (GeV)	2 $M_{\rm SUSY}$	0	-300	-750	-1100	$A - \mu \cot\beta$
A (GeV)	$X_{\rm t} + \mu \cot\beta$	$X_{\rm t} + \mu \cot\beta$	$X_{\rm t} + \mu \cot\beta$	$X_{\rm t} + \mu \cot\beta$	$X_{\rm t} + \mu \cot\beta$	1000
$\arg(A)=\arg(m_{\tilde{g}})$	-	-	-	-	-	90°