Precision Analyses of the Lightest Higgs Bosons of mSUGRA, mGMSB and mAMSB at a Linear Collider

Shufang Su • Caltech

A. Dedes, S. Heinemeyer, SS
G. Weiglein, hep-ph/0302174

Motivation

- LEP results on Higgs searches
  95% CL $m_{HSM} > 114.4$ GeV , 2 σ m_{HSM} ¼ 116 GeV
- MSSM ➡ light Higgs boson h_0 $m_h \leq 135$ GeV
  Higgs searches ➡ soft SUSY-breaking parameters
- MSSM: 105 new SUSY breaking parameters out of control

  mechanism for SUSY breaking: (flavor blind)

low energy MSSM (visible sector) 105 parameters	⟷ something ⟷	SUSY-breaking (hidden sector) a few parameters

predictive, relate Higgs sector to other SUSY particles

- gravity-mediated SUSY breaking (SUGRA)
- gauge-mediated SUSY breaking (GMSB)
- anomaly-mediated SUSY breaking (AMSB)

Goal

Individual analysis for each scenario and MSSM exists (on m_h^{max})

We treat three soft SUSY-breaking scenarios <u>equal</u>
allow a direct comparison of results/phenomenology

- Observability
- Precision analysis

Outline

- Introduction
  - MSSM Higgs sector
  - soft SUSY-breaking scenario: mSUGRA, mGMSB, mAMSB
- Procedure and additional constrains
- Observability of h^0 at current and future colliders
- Precision analyses of h^0 decay branching ratio
  - Deviations in mSUGRA, mGMSB, mAMSB
  - Bounds on m_A and high-energy input parameters
  - Distinguish three SUSY-breaking scenarios
- Conclusions

MSSM Higgs sector

- **Two Higgs doublet**

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1^0 + \chi_1^0)/\sqrt{2} \\ \phi_1^- \end{pmatrix} \quad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2^0 + \chi_2^0)/\sqrt{2} \end{pmatrix}$$

- **Higgs potential**

$$\boxed{\bar{m}_i^2 = m_{H_i}^2 + \Sigma_{v_i} + \mu^2 = \bar{m}_{H_i}^2 + \mu^2}$$

$$V = \bar{m}_2^2 |H_2^0|^2 + \bar{m}_1^2 |H_1^0|^2 - (b H_1^0 H_2^0 + \text{h.c.}) + 1/8(g^2 + g'^2)(|H_2^0|^2 - |H_1^0|^2)^2$$

- **Electroweak symmetry breaking**

$$\mu^2(Q) = \frac{\bar{m}_{H_1}^2 - \bar{m}_{H_2}^2 \tan^2\beta}{\tan^2\beta - 1} - \frac{1}{2} m_Z^2(Q) \qquad b(Q) = -\frac{(\bar{m}_1^2 + \bar{m}_2^2)\sin 2\beta}{2}$$

$|\mu|$, b are replaced by m_Z, $\tan\beta = v_2/v_1$

Physical states: $h^0, H^0, A^0, H^\pm$, Goldstone bosons: $G^0, G^\pm$

CP-even Higgs h^0,H^0

- **In the ϕ_1^0-ϕ_2^0 basis**

$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix}$$

- **Mass matrix** $\boxed{m_A^2 = 2b/\sin 2\beta}$

$$\begin{pmatrix} m_Z^2\cos^2\beta + m_A^2\sin^2\beta & -(m_A^2+m_Z^2)\sin\beta\cos\beta \\ -(m_A^2+m_Z^2)\sin\beta\cos\beta & m_Z^2\sin^2\beta + m_A^2\cos^2\beta \end{pmatrix} \rightarrow \begin{pmatrix} m_{H^0}^{2,\text{tree}} & 0 \\ 0 & m_{h^0}^{2,\text{tree}} \end{pmatrix}$$

$$\mathbf{m_{h^0,H^0}^{2,tree} = 1/2(m_A^2 + m_Z^2 \mp \sqrt{(m_A^2+m_Z^2)^2 - 4m_Z^2 m_A^2 \cos^2 2\beta})}$$

- **Tree level** $m_h < |\cos 2\beta| m_Z < m_Z$

- **loop contribution to m_h from $\tilde{t}$-t sector (dominant)**

$$\Delta m_{h^0}^2 \approx \frac{m_t^4}{m_W^2}\log\left(\frac{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}{m_t^4}\right) \approx \frac{m_t^4}{m_W^2}\log\left(\frac{(M_{\text{SUSY}}^2+m_t^2)^2 - m_t^2 X_t^2}{m_t^4}\right)$$

Two loop calculation: $m_h \leq 135$ GeV

Measurement of Higgs masses and couplings
⟹ information about soft SUSY-breaking parameters

Present status of m_h prediction in MSSM

- Used for LEP analysis until 1999

  RG improved one-loop effective potential results

  ➡ Leading logs at two-loop level

  program: *subhole* (M. Carena, M. Quiros, C. Wagner '95)

- Used since end of 1999

  Feynman-diagrammatic two-loop results

  ➡ Complete one-loop + dominant two-loop corrections

  program: *FeynHiggs* (S. Heinemeyer, W. Hollik, G. Weiglein '98,'00,'01)

✓ Remaining theoretical uncertainties in m_h prediction

– Unknown higher-order corrections $\rightarrow \delta m_h \approx 3$ GeV

– Uncertainties in input parameters $m_t, \ldots, m_A, \tan\beta, m_{\tilde{t}1}, m_{\tilde{t}2}, \theta_{\tilde{t}}, m_{\tilde{g}}$

  $\delta m_t \approx 5$ GeV $\rightarrow \delta m_h \approx 5$ GeV

Precise knowledge of m_t is important

FD approach of MSSM Higgs sector

✓Most relevant parameters for MSSM Higgs sector:

m_A, $\tan\beta$, $m_{\tilde{t}1}$, $m_{\tilde{t}2}$, $\theta_{\tilde{t}}$, $m_{\tilde{b}1}$, $m_{\tilde{b}2}$, $\theta_{\tilde{b}}$, μ, $m_{\tilde{g}}$, M_1, M_2.

✓Use FD approach within on-shell renormalization scheme

m_h, m_H given by poles of the h^0-H^0 propagator matrix

$$(\Delta_{\text{Higgs}})^{-1} = -i \begin{pmatrix} q^2 - m_{H^0}^{2,\text{tree}} + \hat{\Sigma}_{H^0}(q^2) & \hat{\Sigma}_{h^0H^0}(q^2) \\ \hat{\Sigma}_{h^0H^0}(q^2) & q^2 - m_{h^0}^{2,\text{tree}} + \hat{\Sigma}_{h^0}(q^2) \end{pmatrix}$$

✓Effective mixing angle α_{eff}

$$\alpha_{\text{eff}} = \tan^{-1}\left[\frac{-(m_A^2 + m_Z^2)\sin\beta\cos\beta - \hat{\Sigma}_{\phi_1\phi_2}}{m_Z^2\cos^2\beta + m_A^2\sin^2\beta - \hat{\Sigma}_{\phi_1} - m_h^2}\right] \qquad -\frac{\pi}{2} < \alpha_{eff} < \frac{\pi}{2}$$

✓Fortran code: *FeynHiggs* **www.feynhiggs.de**

Minimal Super Gravity mediated SUSY-breaking (mSUGRA)

$\{ \quad m_0, M_{1/2}, A_0, \tan\beta, \text{sign}\ \mu \quad \}$

m_0 : common scalar mass at GUT scale
$M_{1/2}$: common gaugino mass at GUT scale
A_0 : common trilinear scalar coupling at GUT scale
$\tan\beta$: low energy input
sign μ : low energy input

Minimal Gauge mediated SUSY-breaking (mGMSB)

SUSY breaking is mediated by SM gauge interactions through messenger sector

{ M_{mess}, N_{mess}, Λ, tanβ, sign μ }

$$M_a(M_{\text{mess}}) = N_{\text{mess}}\Lambda g\left(\frac{\Lambda}{M_{\text{mess}}}\right)\alpha_a \qquad (a = 1, 2, 3)$$

$$m^2_{\text{scalar}}(M_{\text{mess}}) = 2N_{\text{mess}}\Lambda^2 f\left(\frac{N}{M_{\text{mess}}}\right)\sum_a\left(\frac{\alpha_a}{4\pi}\right)^2 c_a$$

$$A_f = 0 \quad \text{at messenger scale}$$

M_{mess} : messenger mass scale
N_{mess} : messenger index
Λ : soft SUSY-breaking mass scale

Minimal Anomaly mediated SUSY-breaking (mAMSB)

SUSY breaking on a separate brane is communicated to the visible sector via super-Weyl anomaly

{ m_{aux}, m_0, tanβ, sign μ }

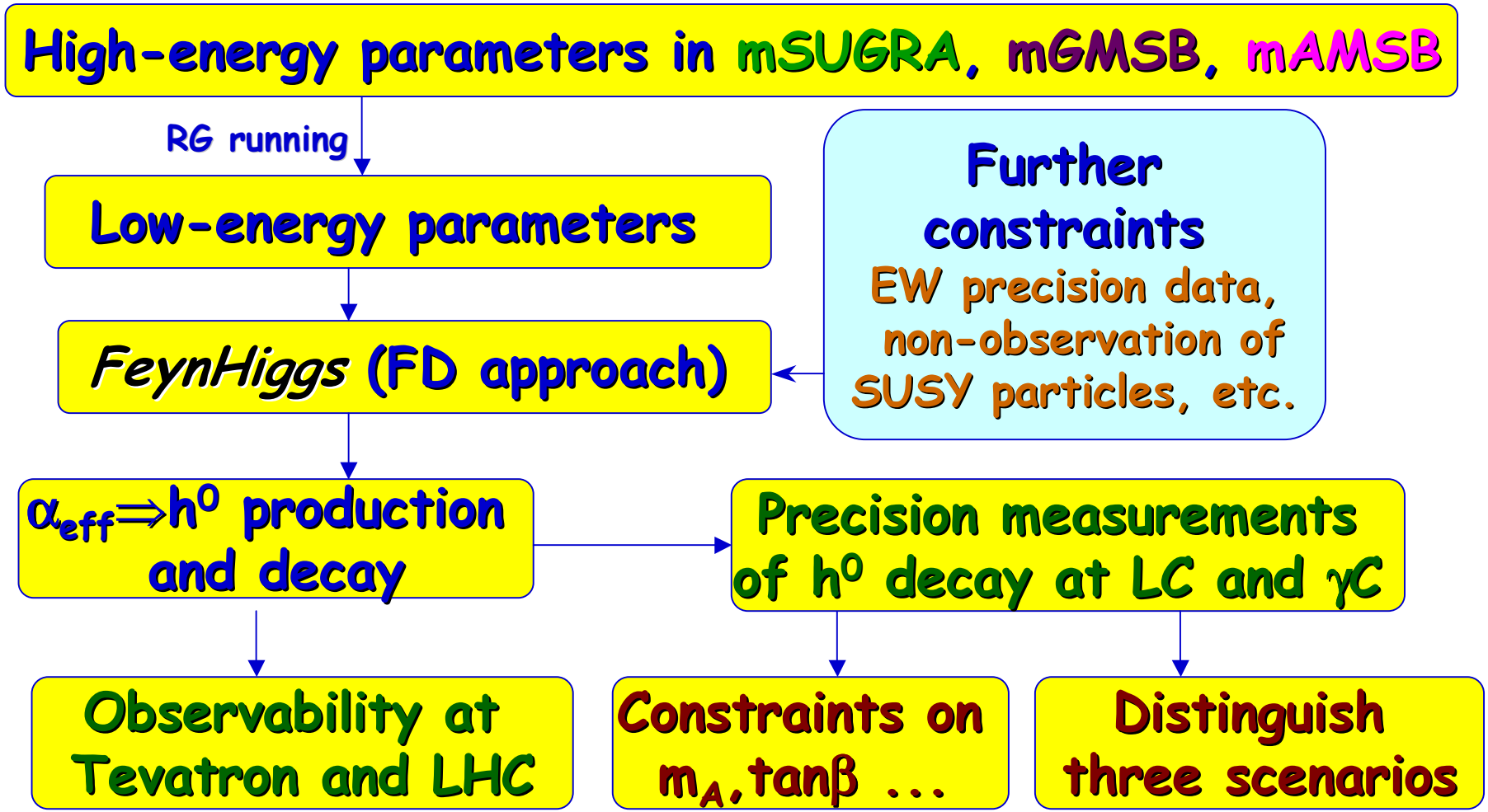
$$M_i = \frac{\beta_{g_i}}{g_i} m_{\text{aux}}$$

$$m^2_{\text{scalar}} = -\frac{1}{4}\left(\frac{\partial\gamma}{\partial g}\beta_g + \frac{\partial\gamma}{\partial y}\beta_y\right) m^2_{\text{aux}} + m_0^2$$

$$A_y = -\frac{\beta_y}{y} m_{\text{aux}}$$

m_{aux} : SUSY breaking scale (gravitino mass)
m_0 : additional mass scale for scalar (to keep $m_{\tilde{\tau}} < 0$)

Procedure


High-energy parameters in mSUGRA, mGMSB, mAMSB
RG running
Low-energy parameters
FeynHiggs (FD approach)
Further constraints
EW precision data, non-observation of SUSY particles, etc.
$\alpha_{eff} \Rightarrow h^0$ production and decay
Precision measurements of h^0 decay at LC and γC
Observability at Tevatron and LHC
Constraints on m_A, tanβ ...
Distinguish three scenarios

High-energy input parameter

mSUGRA	mGMSB	mAMSB
50 GeV$\leq$ m_0 $\leq$1 TeV	10 TeV$\leq$ Λ $\leq$200 TeV	20 TeV $\leq m_{aux} \leq$ 100 TeV
50 GeV$\leq$ $M_{1/2} \leq$1 TeV	1.01 $\Lambda \leq M_{mess} \leq 10^5$ Λ	0$\leq$ m_0 $\leq$2 TeV
-3 TeV$\leq$ A_0 $\leq$3 TeV	1$\leq$ N_{mess} $\leq$8	
1.5$\leq$ tanβ $\leq$60	1.5$\leq$ tanβ $\leq$55	1.5$\leq$ tanβ $\leq$60
signμ = + 1	signμ = + 1	signμ = + 1

✓ Positive μ: favored by g_μ-2 and BR(b! s γ)

Additional constraints

- LEP Higgs exclusion bounds
- Precision observable: $\Delta \rho^{SUSY} \leq 3 \times 10^{-3}$
- Experimental bounds on SUSY particle masses
- m_t=175 GeV ($\delta m_h / \delta m_t$ = 1 GeV/1 GeV)
- No SUSY *CP*-violating phases
- *R*-parity conserved
- Success REWSB
- No color/charge breaking minima
- LSP uncolored and uncharged (neutralino LSP in mSUGRA and mAMSB)
- Restrict to positive μ: favored by g_μ-2 and BR(b ! s γ)

Previous work

S. Ambrosanio, A. Dedes, S. Heinemeyer, SS, G. Weiglein NPB 624, 3 (2002)

- LEP Higgs searches : exclusion region in m_{h0}-tanβ

	MSSM	SUGRA	GMSB	AMSB
m_{h0}^{max} (GeV)	135	127	123	125
tanβ^{min}	$\leq$0.5 or $\geq$2.4	2.9	3.1	3.8

- Slight excess of 116 GeV Higgs
  - interpolated as light CP-even Higgs with SM-like coupling
  - corresponding SUSY particle spectrum
- Strong suppression of h ! bb possible in mSUGRA and mAMSB

Higgs production

Tevatron	qq!V!Vh (V=W,Z)	$\frac{\sigma_{hV}^{\rm SUSY}}{\sigma_{hV}^{\rm SM}} \approx \sin^2(\beta - \alpha_{\rm eff})$
LHC	gg!h qq,gg!tt!tth VV!h	$\frac{\sigma^{\rm SUSY}(gg \to h)}{\sigma{\rm SM}(gg \to h)} \approx \frac{\Gamma^{\rm SUSY}(h \to gg)}{\Gamma^{\rm SM}(h \to gg)}$ $\frac{\sigma^{\rm SUSY}(t\bar{t} \to t\bar{t}h)}{\sigma{\rm SM}(t\bar{t} \to t\bar{t}h)} \approx \frac{\cos^2\alpha_{\rm eff}}{\sin^2\beta}$ $\frac{\sigma_{VVh}^{\rm SUSY}}{\sigma_{VVh}^{\rm SM}} \approx \sin^2(\beta - \alpha_{\rm eff})$
LC	e^+e^-!Z!Zh VV!h	$\frac{\sigma_{hZ}^{\rm SUSY}}{\sigma_{hZ}^{\rm SM}} \approx \sin^2(\beta - \alpha_{\rm eff})$
γC	γγ!h	$\frac{\sigma^{\rm SUSY}(\gamma\gamma \to h)}{\sigma{\rm SM}(\gamma\gamma \to h)} \approx \frac{\Gamma^{\rm SUSY}(h \to \gamma\gamma)}{\Gamma^{\rm SM}(h \to \gamma\gamma)}$

Γ(h! bb,cc,$\tau^+\tau^-$,$\mu^+\mu^-$): higher-order correction included
Γ(h ! γγ,gg,WW): Hdecay

Channels for Higgs study

- **Higgs boson decay**

$$\frac{BR^{\mathrm{SUSY}}(h \to b\bar{b}, c\bar{c}, \tau^+\tau^-, \gamma\gamma, WW^*, gg)}{BR^{\mathrm{SM}}(h \to b\bar{b}, c\bar{c}, \tau^+\tau^-, \gamma\gamma, WW^*, gg)}$$

- **Higgs study channels**

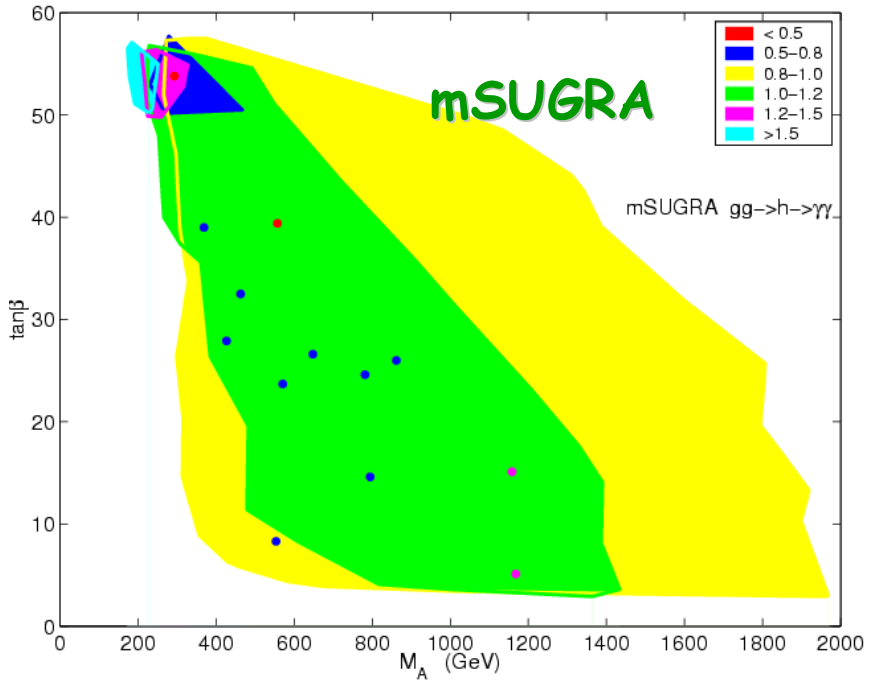
$$\frac{\sigma^{\mathrm{SUSY}}(\text{Higgs production})}{\sigma^{\mathrm{SM}}(\text{Higgs production})} \times \frac{BR^{\mathrm{SUSY}}(\text{Higgs decay})}{BR^{\mathrm{SM}}(\text{Higgs decay})}$$

Tevatron	qq ! V ! Vh ! Vbb (V=W,Z)
LHC	gg ! h ! $\gamma\gamma$, VV ! h ! $\tau^+\tau^-$, WW*, $\gamma\gamma$ qq,gg ! tt ! tth ! ttbb
LC	e^+e^- ! Z ! Zh ! Zbb,Zcc,Z$\tau^+\tau^-$,ZWW*,Zgg WW! h ! bb,cc,$\tau^+\tau^-$,WW*,gg
γC	$\gamma\gamma$! h ! bb, WW*, $\gamma\gamma$

Observability of h^0

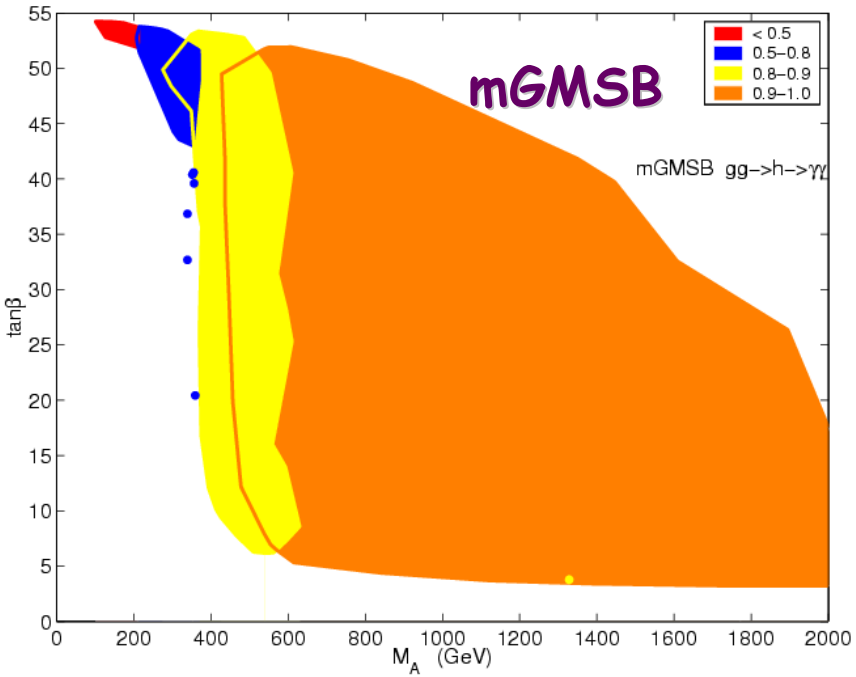
- **Tevatron**
  - ✓ V ! Vh ! Vbb suppressed not more than 10%
  - ✓ discovery potential as good as SM Higgs

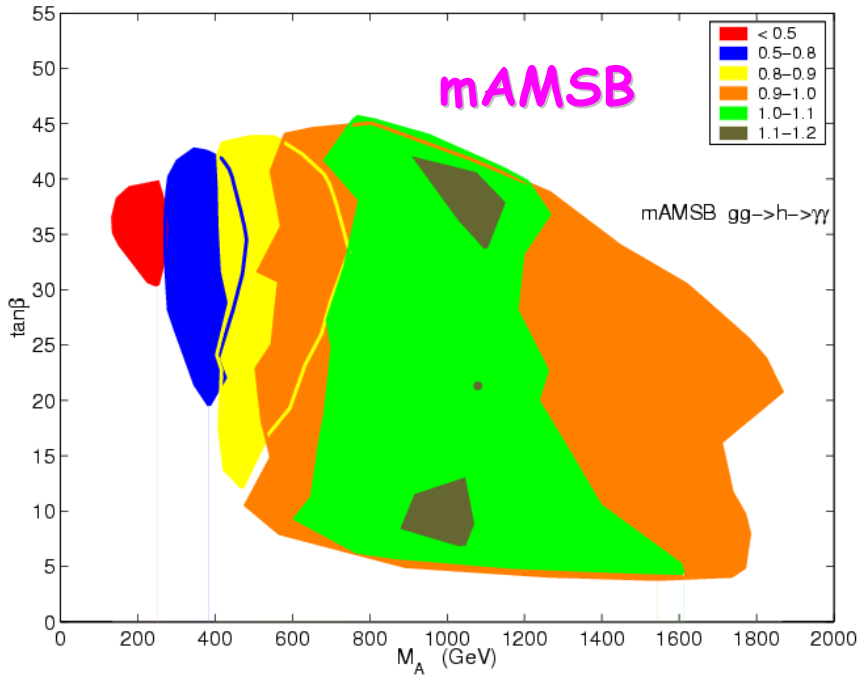
- **LHC**
  - ✓ gg ! h ! γγ suppression of 50% or more



Observability of h^0 (cont')

- LHC





Observability of h^0 (cont')

- **LHC**
  - ✓ qq,gg ! tt ! tth ! ttbb suppressed no more than 10%
  - ✓ VV ! h

	mSUGRA	mGMSB, mAMSB
WW ! h ! $\tau^+\tau^-$	differ < 10%	enhanced everywhere
small m_A, large tanβ	suppression	no suppression
WW ! h ! WW*, $\gamma\gamma$	suppression at small m_A	

- **LC**
  - ✓ easily observable even with strong suppression
- **γC**
  - ✓ similar to LHC VV ! h ! $\tau^+\tau^-$, WW*, $\gamma\gamma$

Precision analyses of Higgs coupling

- concentrate on LC and γC
- focus on Higgs sector

- direct detection of A^0 difficult
- deviation from SM Higgs coupling
  ⇒ indirect bound on m_A
- differ from previous analyses
  - all but one parameter kept fixed
    require knowledge of SUSY parameters
  - scan over parameter space
    reduced sensitivity
    "worst case" scenario

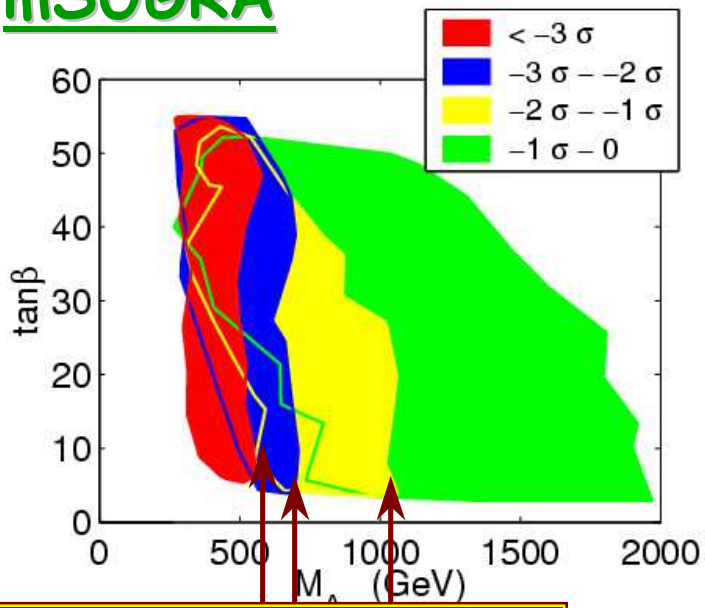
➢ Anticipated precision

LC	h ! bb	1.5%
	h ! $\tau^+\tau^-$	4.5%
	h ! cc	6%
	h ! gg	4%
	h ! WW*	3%
γC	h ! bb	2%
	h ! WW*	5%
	h ! γ γ	11%

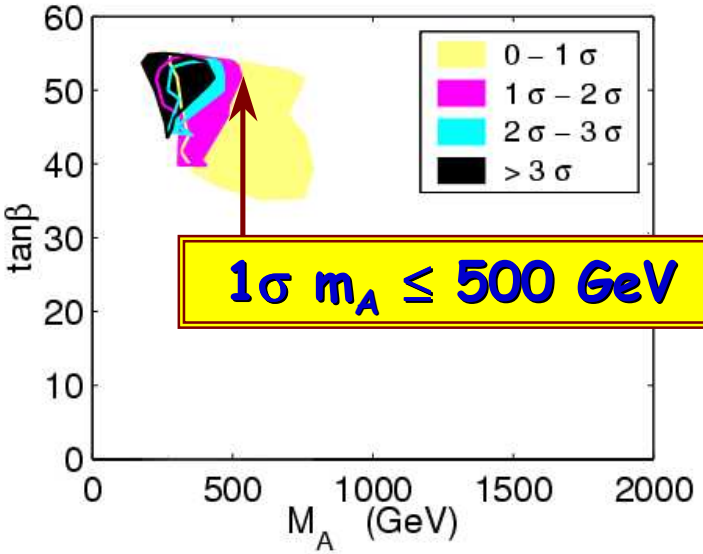
§ nσ: § n £ precision

Sensitivity in m_A-tanβ plane

- **mSUGRA**



LC: h! WW*



1σ $m_A \leq$ 500 GeV

3σ $m_A \leq$ 550 GeV

2σ $m_A \leq$ 700 GeV

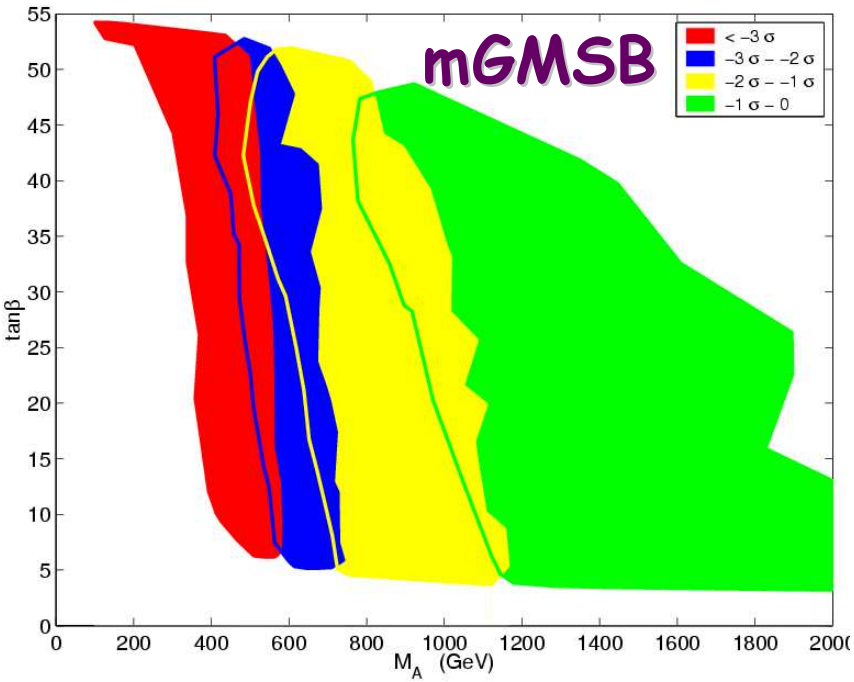
1σ $m_A \leq$ 1000 GeV

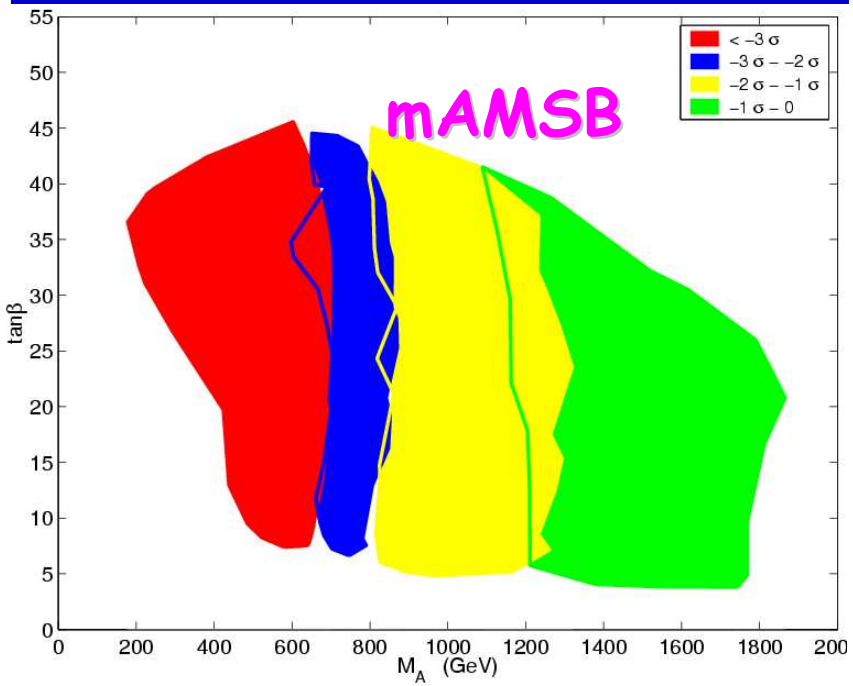
- suppression in h! bb, $\tau^+\tau^-$ enhancement in h! cc, WW*
  $\Rightarrow$ 35 ≤ tanβ ≤ 55
- sensitivity in γC worse

Sensitivity in m_A-tanβ plane (cont')

LC: h ! WW* no enhancement

m_A^{max} (GeV)	1 σ	2 σ	3 σ
mSUGRA	1000	700	550
mGMSB	1150	750	600
mAMSB	1300	850	700

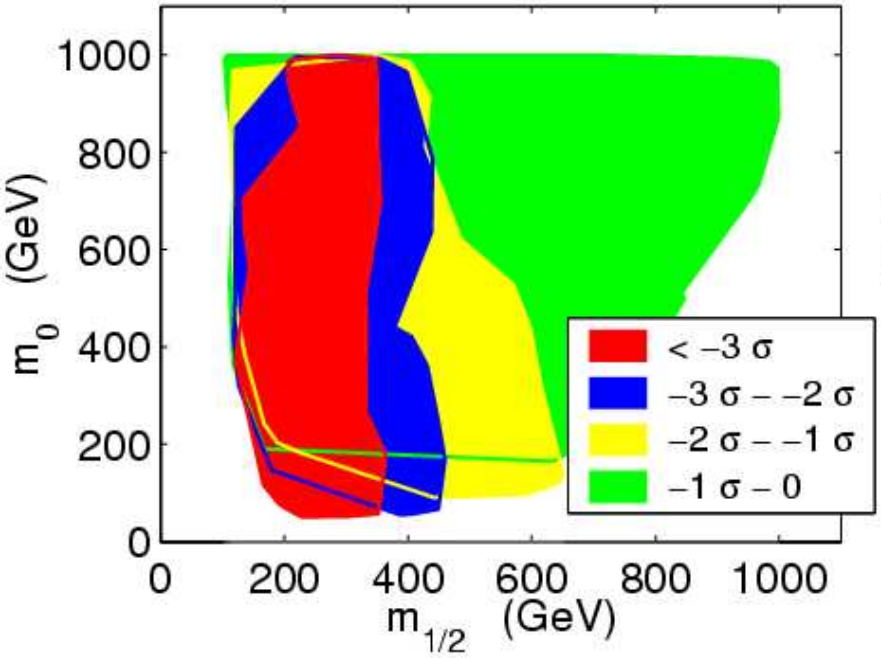


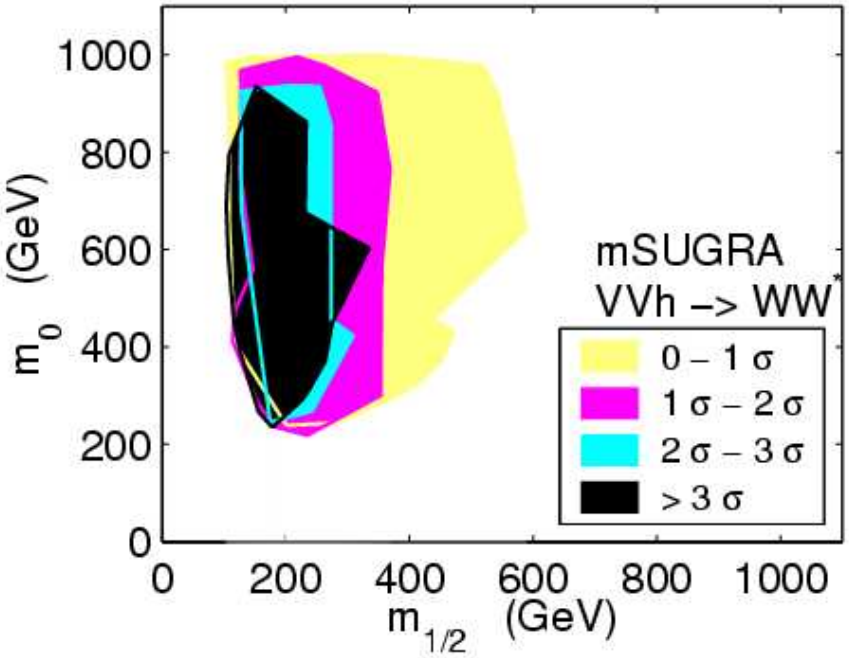


Sensitivity to high-energy parameters

- **mSUGRA**
  - ✓ mild bound on m_0
  - ✓ stronger bound on $m_{1/2}$

mSUGRA	-1 σ	-2 σ	-3 σ
$m_{1/2}^{max}$ (GeV)	650	450	350



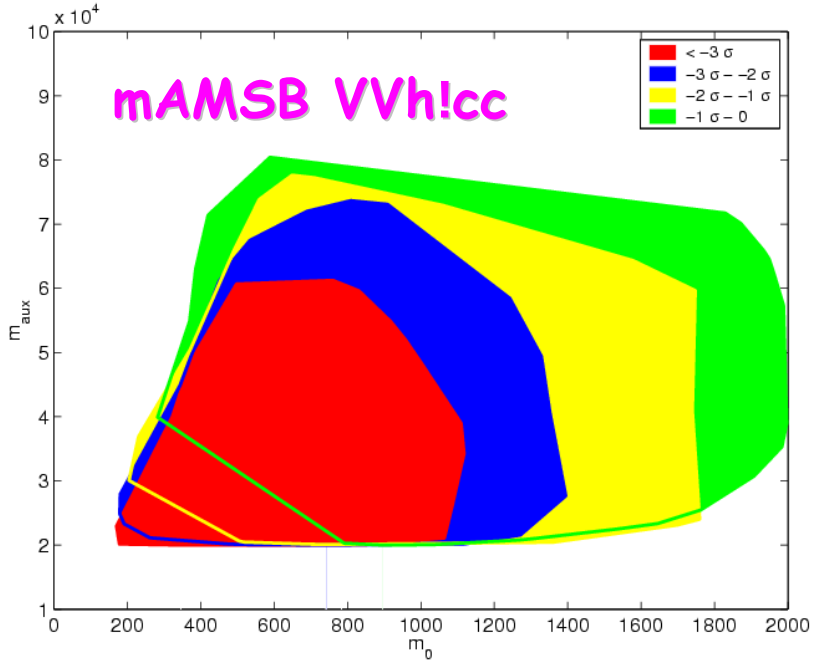


Sensitivity to high-energy parameters (cont')

- **mGMSB**
  - ✓ deviation from SM coupling
    not sufficient to constrain M_{mess} and Λ
  - ✓ small deviation $\Rightarrow$
    lower bound on M_{mess} and Λ

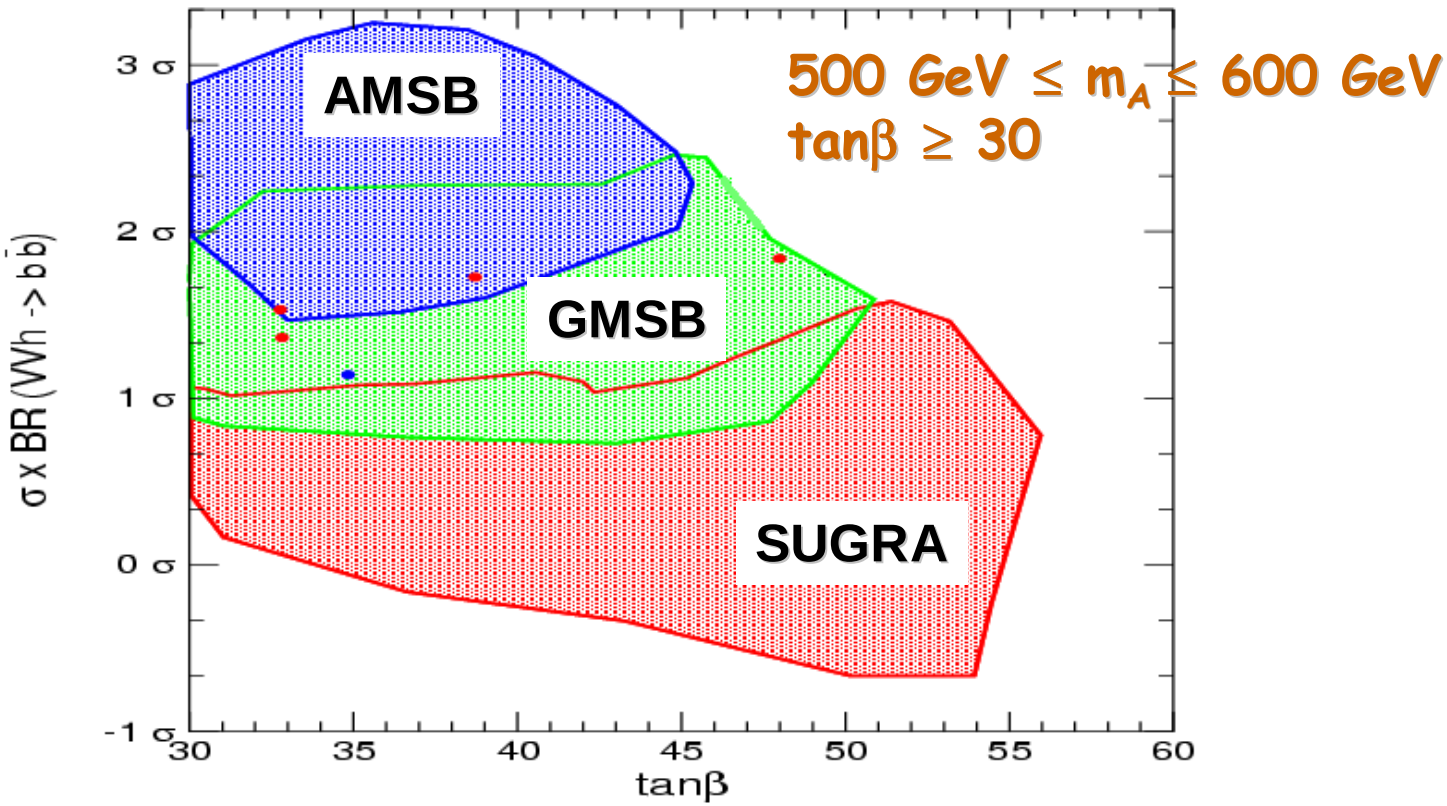
- **mAMSB**
  - ✓ 2 σ, 3 σ deviation
    wide range of m_0 and m_{aux}

mAMSB	2 σ	3 σ
m_0^{max} (GeV)	1400	1100
m_{aux}^{max} (GeV)	7.5£10^4	6£10^4



Distinguish SUSY Breaking Scenario

- if we know ranges of m_A, $\tan\beta$ from LHC
- if we see deviations of coupling at LC



Conclusion

- Investigate relevant production and decay channels of h^0
  - Tevatron, LHC, LC and γC -mSUGRA, mGMSB and mAMSB
- Observability
  - Tevatron: as good as SM Higgs; LC: ensured
  - LHC: gg ! h ! $\gamma\gamma$, γC: h ! bb, $\tau^+\tau^-$, small m_A, problematic (mGMSB, mAMSB)
- Precision measurement of BR at LC and γC
  - bound on m_A and $\tan\beta$: m_A<1 TeV for 2-3 σ deviation
    - biggest sensitivity from LC: h ! WW^*, cc
    - suppression in h ! bb, $\tau^+\tau^-$, enhancement in h ! cc, WW^*

      $\Rightarrow 35 \leq \tan\beta \leq 55$ (mSUGRA)
  - bound on high-energy input parameters
    - m_0 (mSUGRA), m_0 (mAMSB)
- Distinguish different SUSY breaking scenarios