SUPERSYMMETRY : THE SEARCH FOR THE HIGGS BOSONS

Connection : 1. Supersymmetry $\Rightarrow$ natural basis for fundamental scalar fields

2. Solution of the hierarchy problem / part II : Higgs boson light

3. Higgs mechanism can be generated dynamically [radiatively]

Golfand,Likhtman
Wess,Zumino
*****
Brout,Englert,Higgs
Guralnik,Hagen,Kibble

Layout : Higgs : Minimal Supersymmetric Standard Model / MSSM

– Summary of theoretical basis

– Status and perspectives: LEP; Tevatron, LHC; ILC/CLIC

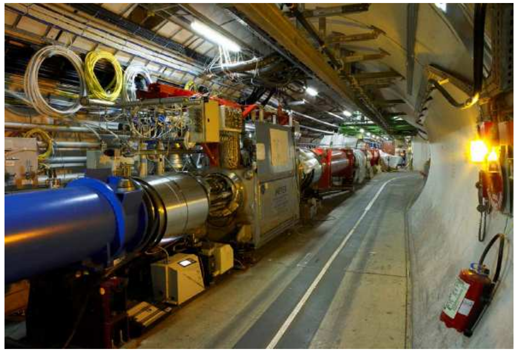
Beyond the minimal theory

– Links to grand unification

– CP violation

– Elements of NMSSM

– N=1/N=2 hybrid model



1. MSSM : Minimal Supersymmetric Standard Model

Fayet
Dimopoulos,Georgi

N=1 Supersymmetry : pairing of particles : bosons/fermions | spin $s/s+\frac{1}{2}$

chiral superfield : $\hat{\phi} = \phi + \sqrt{2}\theta\xi + \theta\theta F$ $\qquad \mathcal{E} : z = [x_\mu; \theta, \bar{\theta}]$

gauge superfield : $\hat{V} = \theta\sigma_\mu\bar{\theta}\, V_\mu + \bar{\theta}\bar{\theta}\,\theta\lambda + hb + \frac{1}{2}\theta\theta\,\bar{\theta}\bar{\theta}\, D$

actions : *gauge* : $\mathcal{S}_V = \frac{1}{4}\int d^6 z \hat{F}^2 + hb$ $\qquad \rightarrow \frac{1}{2}D^2$

matter,Higgs : $\mathcal{S}_m = \int d^8 z \hat{\phi}^\dagger \exp[+2g\hat{V}]\hat{\phi}$ $\qquad \rightarrow g|\phi|^2 D$

superpotential : $\mathcal{S}_W = \int d^6 z \hat{W} + hc$

$$\hat{W} = \mu \hat{H}_d \cdot \hat{H}_u - g_d \hat{H}_d \cdot \hat{Q} \hat{D}^c - g_u \hat{Q} \cdot \hat{H}_u \hat{U}^c + [\hat{L}'s]$$

consequences : superpotential analytic : $H_u \neq i\tau_2 H_d^*$

$\Rightarrow$ masses for down/up : 2 Higgs doublets H_d and H_u

solution of field equation for non-propagating auxiliary field : $D = -g|\phi|^2$

$\Rightarrow$ quartic cplg $\sim$ [small] gauge cplg^2 : $\lambda|\phi|^4 \sim \frac{g^2}{2}|\phi|^4$

SUSY breaking : Higgs part of soft susy brkg potential

$$\mathcal{V}_{soft} = m_d^2|H_d|^2 + m_u^2|H_u|^2 + m_{du}^2 H_d \cdot H_u + hc + Yukawa\ terms\ [\tilde{Q}, \tilde{L}, H]$$

Higgs potential :

$$\mathcal{V} = [m_d^2 + |\mu|^2]|H_d|^2 + [m_u^2 + |\mu|^2]|H_u|^2 + m_{du}^2 H_d \cdot H_u + hc$$
$$\tfrac{1}{8}(g^2 + g'^2)(|H_d|^2 - |H_u|^2)^2 + \tfrac{1}{2} g^2 |H_d^\dagger H_u|^2$$

$\mathcal{V}$ = bound from below,
min for $v_d, v_u \neq 0$:

$$m_d'^2 + m_u'^2 > 2|m_{du}^2|$$
$$m_d'^2 m_u'^2 < m_{du}^4$$

Parameters [Born] : $m_d'^2, m_u'^2, m_{du}^2 \quad \Rightarrow \quad v_d, v_u, m_{du}^2 \quad \Rightarrow$

$$M_Z^2 = \tfrac{1}{4}(g^2 + g'^2)(v_d^2 + v_u^2)$$
$$\tan\beta = v_u / v_d \qquad [:\ 1..M_t/M_b]$$
$$M_A^2 = m_{du}^2 (v_d/v_u + v_u/v_d)$$

subtracting vacuum : $H_d = \frac{1}{\sqrt{2}} \left\| \begin{matrix} v_d + h_d^0 \\ h_d^- \end{matrix} \right\| \qquad H_u = \frac{1}{\sqrt{2}} \left\| \begin{matrix} h_u^+ \\ v_u + h_u^0 \end{matrix} \right\|$

8 states:
3 Goldstone states
5 phys: $A, h, H, H^\pm$

diagonalizing phys $\Re$ *mass matrix* :

$$h = -\sin\alpha\, \Re h_d^0 + \cos\alpha\, \Re h_u^0$$
$$H = \cos\alpha\, \Re h_d^0 + \sin\alpha\, \Re h_u^0$$

Gunion
Haber

Masses

pseudo-scalar mass : M_A^2

charged masses : $M_\pm^2 = M_A^2 + M_W^2$

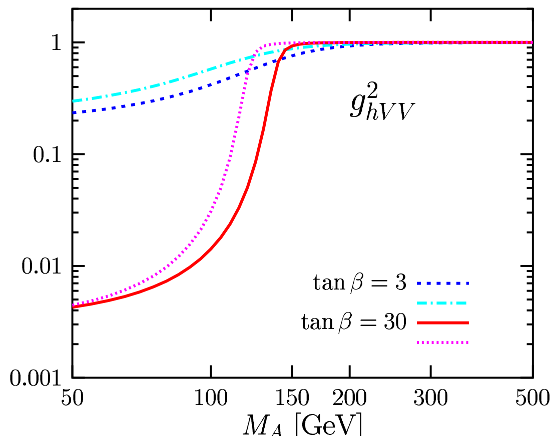
scalar masses : $M_{h,H}^2 = \frac{1}{2}\left[A + Z \pm \sqrt{(A+Z)^2 - 4AZ\cos^2 2\beta}\,\right]$

$$\tan 2\alpha = \tan 2\beta\,(M_A^2 + M_Z^2)/(M_A^2 - M_Z^2)$$

light h mass-bound : $M_h \leq M_Z\,|\cos 2\beta\,| \leq M_Z$

Couplings

Φ		g_u^Φ	g_d^Φ	g_V^Φ
SM	*H*	*1*	*1*	*1*
MSSM	*h*	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\beta-\alpha)$
	H	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\beta-\alpha)$
	A	$1/\tan\beta$	$\tan\beta$	*0*



 # A decoupled from elw vector bosons

 # decoupling : h ⇒ SM H : $M_A \geq$ *150/300 GeV* ▷

 # d couplings enhanced for large $\tan\beta$

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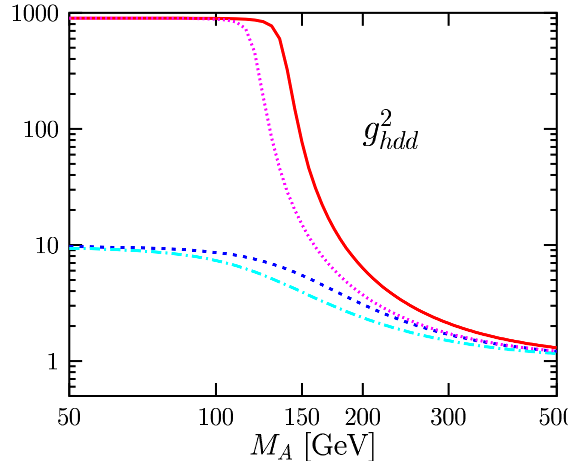

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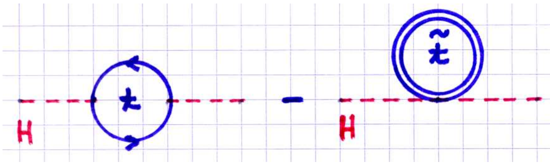
Radiative corrections

crucial : mass of lightest Higgs boson h lifted beyond Z-boson mass by rad.cor

Okada$_{ea}$,Ellis$_{ea}$,Haber$_{ea}$
... Martin$_{ea}$,Heinemeyer$_{ea}$

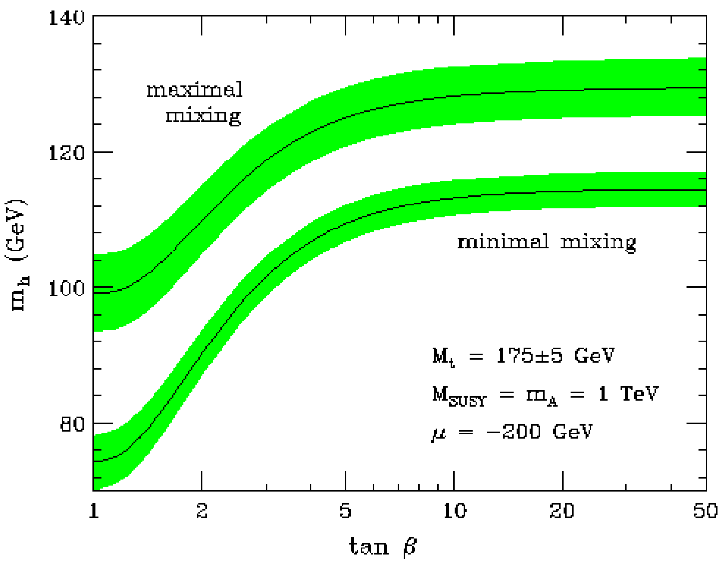
#1 Leading top/stop contributions :



$+ \cdots$

$$\epsilon = \frac{3G_F}{\sqrt{2}\pi^2} M_t^4 \log \frac{\langle M_{\tilde t}^2 \rangle}{M_t^2} \quad / \text{ incldg } \tilde t_R \tilde t_L \text{ mixing } \Rightarrow$$

$$M_h^2 \leq M_Z^2 + \frac{3G_F}{\sqrt{2}\pi^2} M_t^4 \left[\log \frac{\langle M_{\tilde t}^2 \rangle}{M_t^2} + \frac{X_t^2}{\langle M_{\tilde t}^2 \rangle} \left(1 - \frac{1}{12} \frac{X_t^2}{\langle M_{\tilde t}^2 \rangle} \right) \right]$$



mixing : $X_t = A_t - \mu \cot\beta$:

no-mix scenario : $X_t / \langle M_{\tilde t} \rangle = 0$

max-mix scenario : $X_t / \langle M_{\tilde t} \rangle = \sqrt{6}$

decoupling regime :

– M_h maximal : $M_h \leq 135$ GeV ▷

– $M_A \simeq M_H \simeq M_{H^\pm}$

status : relev 2-loop / leadg 3-loop contrib

... | FeynHiggs

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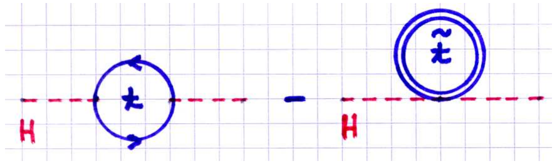

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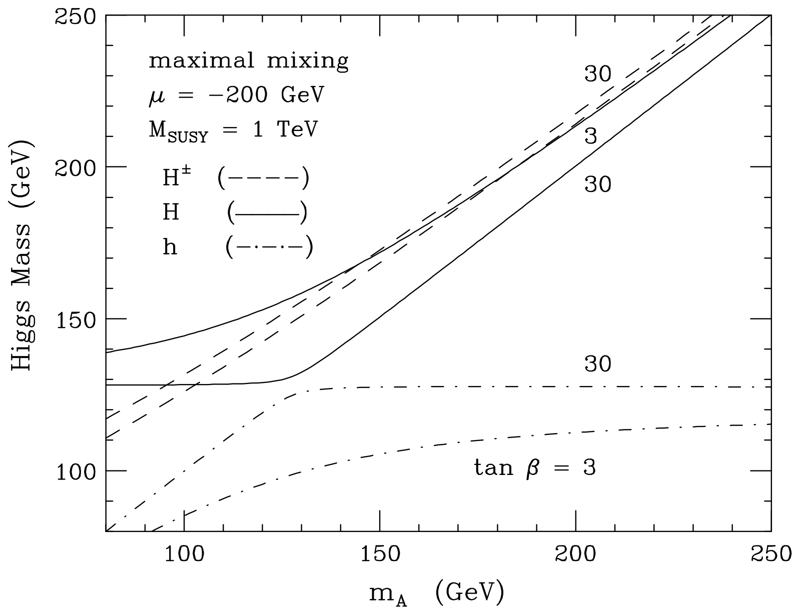

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Radiative corrections

most important in MSSM to lift mass of lightest Higgs boson h beyond Z-boson mass

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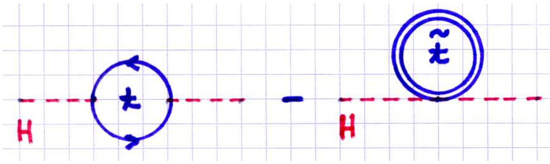

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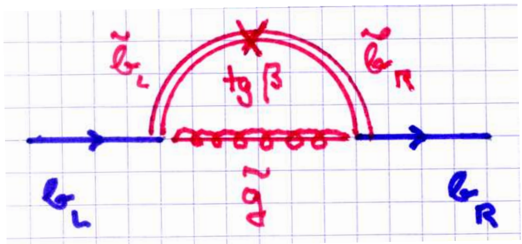
#2 Couplings *Abb etc* for large $\tan\beta$:

Carena$_{ea}$
Spira$_{ea}$

$$g[Abb] = g_H^{SM} \tan\beta / [1 + \Delta_b]$$

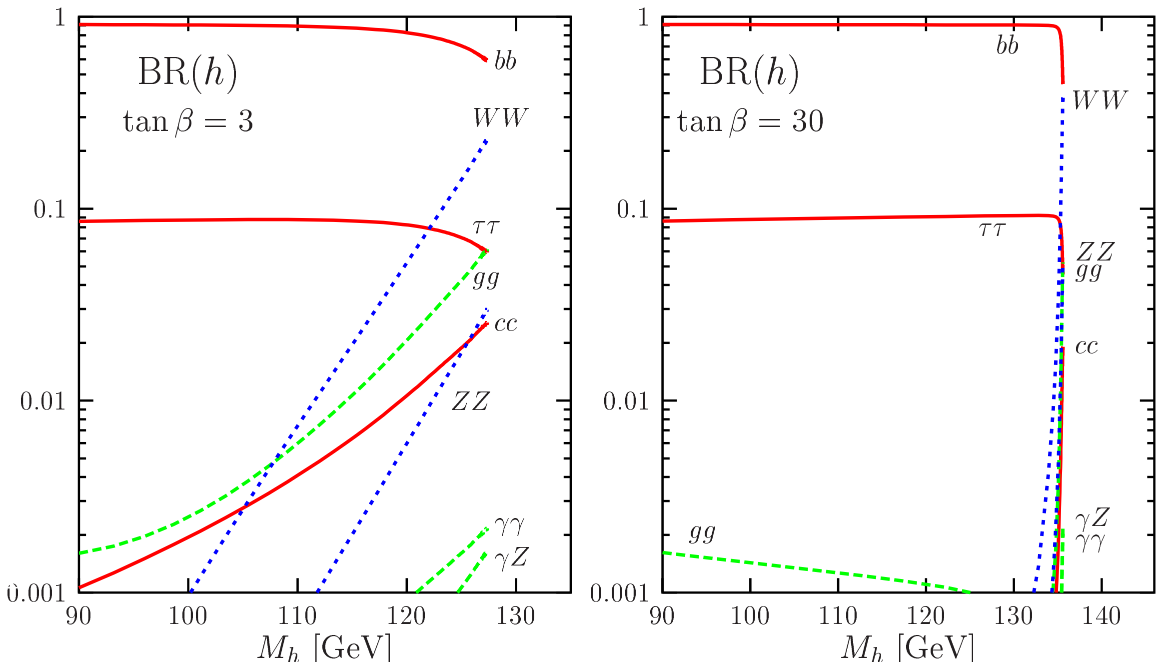
$$\Delta_b \sim \frac{2\alpha_s}{3\pi} M_{\tilde{g}} \mu \tan\beta / \max[\tilde{g}^2, \tilde{b}_1^2, \tilde{b}_2^2] + \frac{\alpha_t}{4\pi} A_t \mu \tan\beta / \max[\mu^2, \tilde{t}_1^2, \tilde{t}_2^2]$$



$\times = \lambda_b \mu v_d \tan\beta$

$\lambda_t A_t v_d \tan\beta$

Branching ratios :



Djouadi$_{ea}$

– overwhelming b decays | elw vector bosons suppressed | approach to decoupling ▷

– $\oplus$ decays to Higgs cascades, charginos/neutralinos, sleptons, . . .

Total widths :

moderate $\tan\beta$: Γ_{tot} remains small, $\sim$ 10 GeV, even for large Higgs masses,
due to suppression of elw vector boson decays [driving SM to sev 100 GeV]

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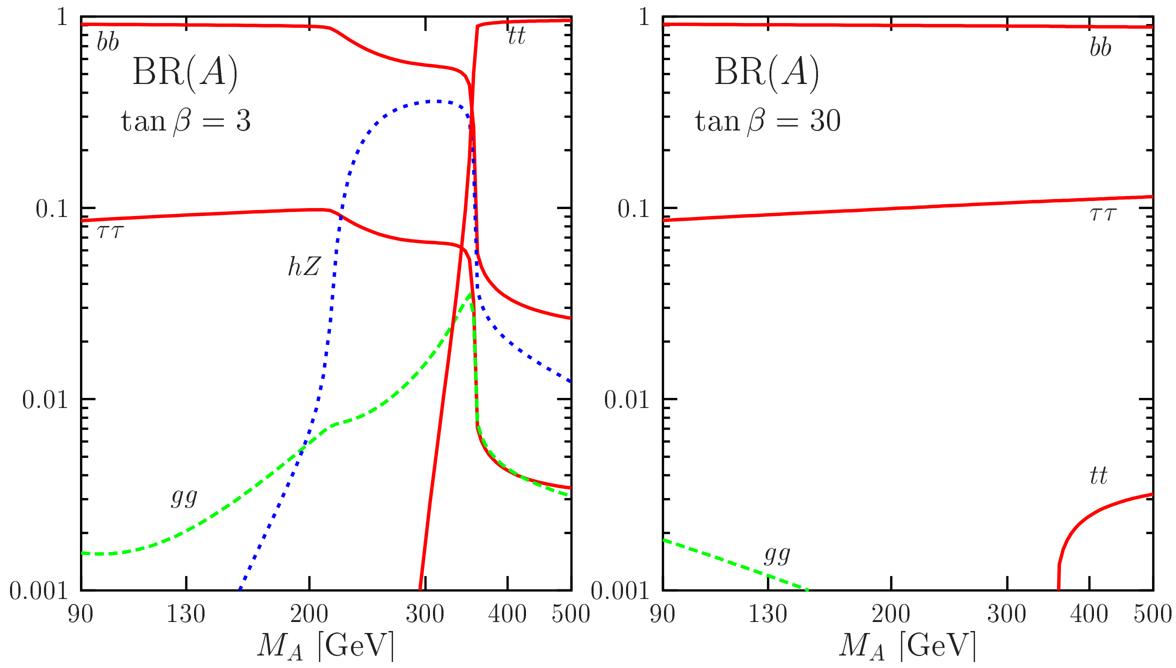

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Production channels :

large variety of channels at LEP, ILC/CLIC; Tevatron, LHC

1.) $e^+e^- \to Zh, \;\; Ah$ $\quad SM \times \sin^2\beta_\alpha, \; \cos^2\beta_\alpha$

$\to ZH, \;\; AH$ $\quad \cos^2\beta_\alpha, \; \sin^2\beta_\alpha$

$\to H^+H^-$ $\quad$ | *decplg regime : Zh and HA*

$e^+e^- \to \bar{\nu}\nu h, H$ $\quad SM \times \sin^2\beta_\alpha, \; \cos^2\beta_\alpha$ $\quad$ | *no A production*

Heavy Higgs mass reach : $M \leq \sqrt{s}/2$

$\gamma\gamma \to h, H, A$ through $t, b, W^\pm, H^\pm, \tilde{\chi}^\pm, \ldots$ loops $\Leftarrow$

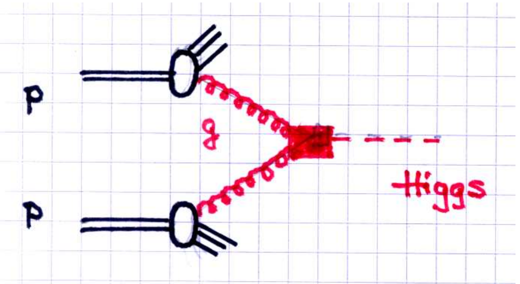
Resonance formation for masses up to $0.8 \times \sqrt{s_{ee}}$

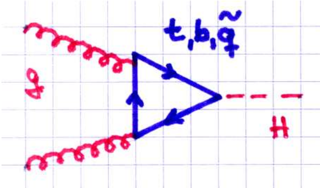
2.) $p\bar{p}/pp \to h, H, A + X$ via

- gluon fusion $gg \to h, H, A$ through colored triangles $\quad *$
- Higgs-strahlung $q\bar{q} \to Z \to Zh$, *etc*
- associated production $q\bar{q}' \to W^\pm \to hH^\pm$, *etc*
- vector-boson fusion $WW \to h, H, \neq A$, *etc*
- quark fusion $b\bar{b} \to A$, *etc* $\quad *$

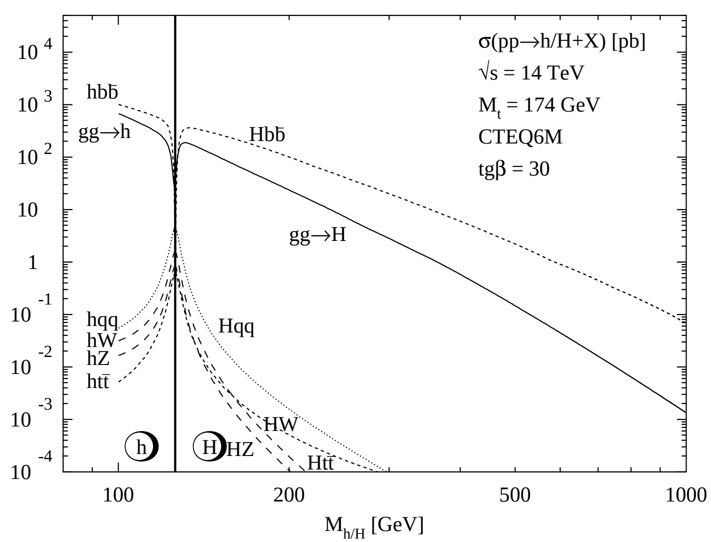
2 crucial channels :

a) gluon fusion at NLO :





Spira$_{ea}$



$$\langle\sigma_{pp}\rangle = \int dx_1 g(x_1;\mu_F) \int dx_2 g(x_2;\mu_F) \times$$
$$\sigma[gg \to Higgs; M_H^2 = x_1 x_2 s_{pp}; \mu_{R,F}]$$

$$\sigma[gg \to Higgs] = \alpha_s^2(\mu_R) g_Y^2 |F_\triangleright|^2 \times BW$$

tan β large : large cross sections

$$F_\triangleright = -2\tau[1 + (1-\tau)f] \quad \tau = 4M_{lp}^2/M_H^2$$

$$f = \left\| \begin{array}{ll} \arcsin^2\sqrt{\tau} & \tau > 1 \\ -\frac{1}{4}[\log\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi]^2 & \tau < 1 \end{array} \right\|$$

for spin 1/2 loop, *etc*

2 crucial channels :

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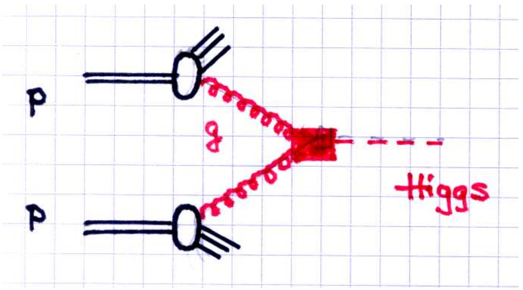
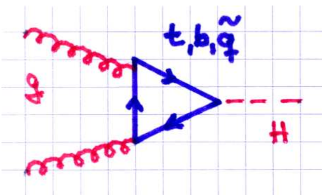
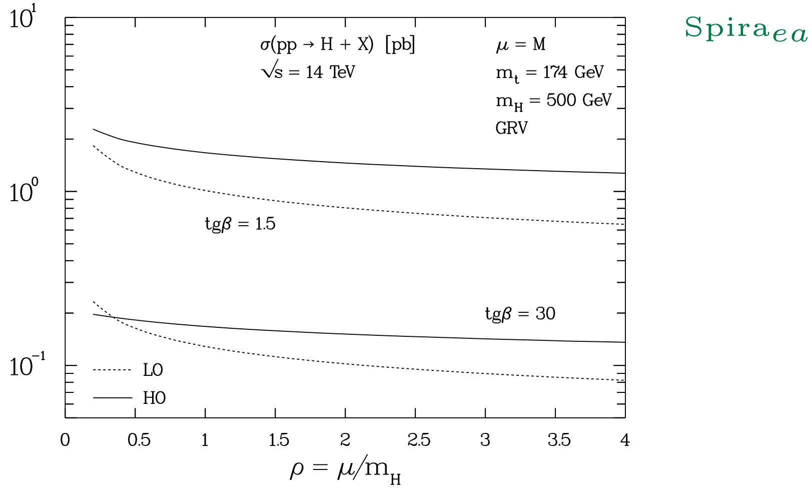




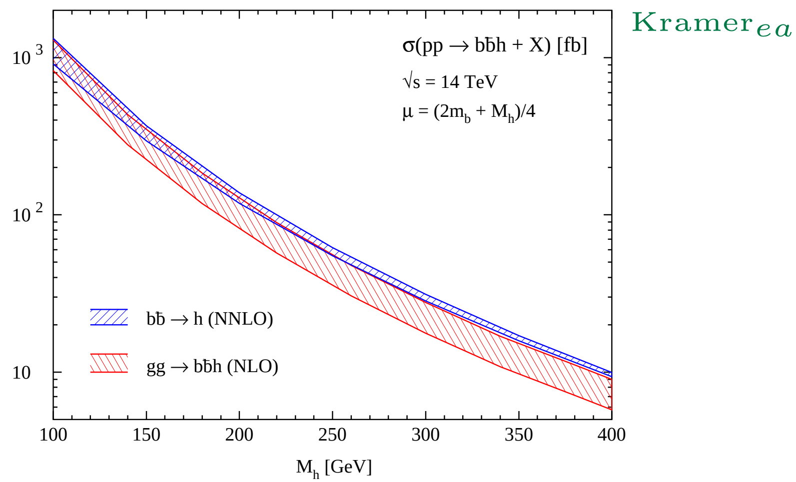


$K = \sigma_{NLO}/\sigma_{LO}$ [2 loops, incldg masses]

– *improving H,h Higgs production by* 50,20%

– *damping spurious* $\mu_{F,R}$ *dependence*

b) *b*-quark fusion :



parton : $b\bar{b} \to Higgs \sim \tan^2\beta_{eff}$

out of $\quad gg \to b\bar{b} + b\bar{b} \to b\bar{b}h$

equivalent descriptions

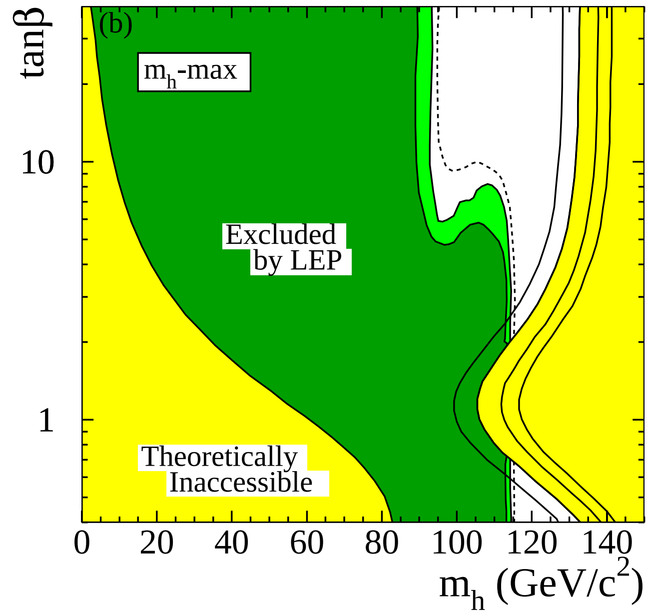
STATUS OF SEARCH

1.) LEP : Higgs-strahlung $Zh, \ldots$

associated production $Ah, \ldots$

$\Rightarrow$ small $\tan\beta$ disfavored

charged Higgs : $M_{H^\pm} \geq 80$ GeV

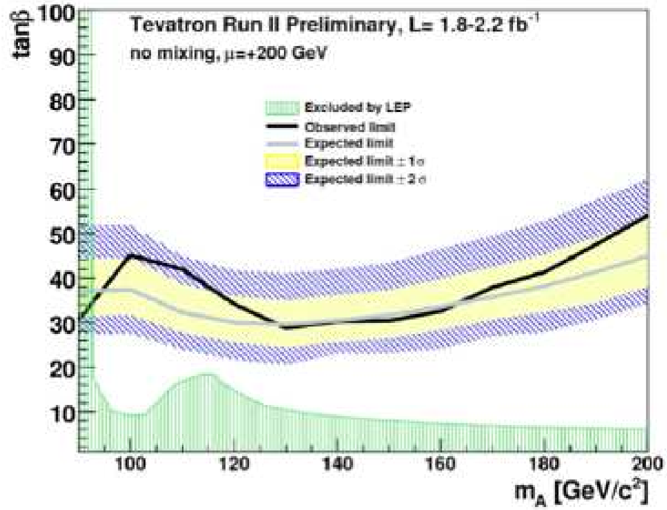


2.) Tevatron : b-quark fusion :

excldg large $\tan\beta$ / mod $M_{A,H}$

charged Higgs in t decay :

s/l $\tan\beta$: $M_{H^\pm} \geq 150$ GeV



EXPECTATIONS

Tevatron pres : 2σ dvlp in $bb \rightarrow Higgs \rightarrow bb$

II(III) : $3(4)\sigma$ at 115 GeV

LHC : $[M_A, \tan\beta]$ parameters of

Higgs discoveries $h \oplus H \oplus A \oplus H^{\pm}$:

light Higgs covered

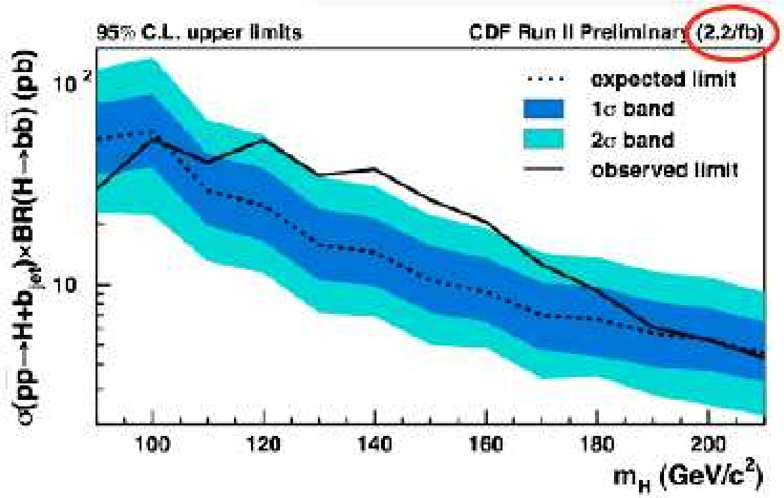
MSSM Higgs spectrum partly covered :
blind wedge $H \ldots$ at moderate $\tan\beta$
in decoupling regime

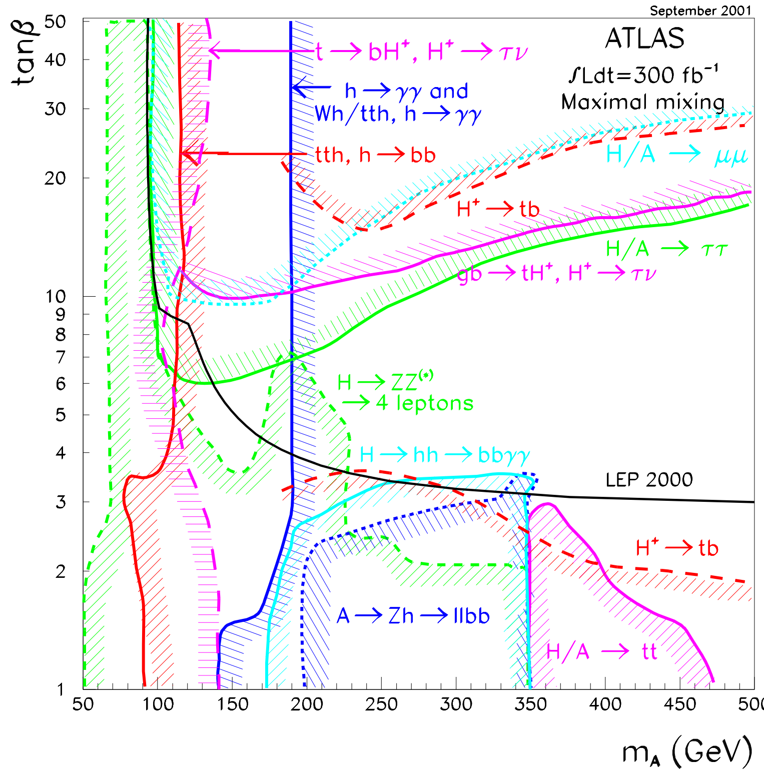
partly covered by Higgs $\rightarrow$ susy decays
for some favorable parameter ranges

ILC/CLIC : h in Higgs-strahlung $e^+e^- \rightarrow Zh$

e^+e^- : $M_{H,A,H^{\pm}} \leq \frac{1}{2}\sqrt{s} = 1.5$ TeV

$\gamma\gamma$: $M_{H,A} \leq 0.8 \times \sqrt{s} = 2.4$ TeV





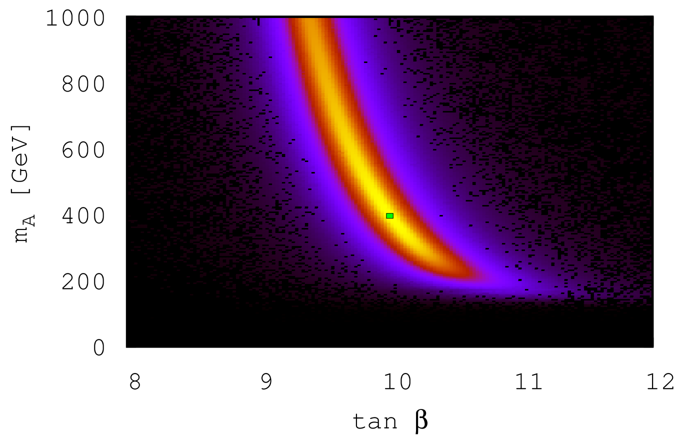
Profiling Higgs bosons

- *Higgs masses*
- $\tan\beta$ *and A parameters*
- *spin / CP quantum numbers*
- *couplings*

a) Masses : M_h to 0.25% [LHC] $\Rightarrow$ 0.05% [ILC]

$M_A, M_H, M_{H^\pm}$ to 1%

[μ absorbed in soft params | higgsinos] $\triangleright$



b) $\tan\beta$: Production of A bosons : $p\bar{p}/pp \to bbA \sim \tan^2\beta_{eff}$ acc $\sim$ 10%

$\gamma\gamma \to \tau\tau A$: $\tan\beta_{eff}$ at 2 to 5%

mSUGRA fit $\sim$ 3% [LHC] $\to$ 0.5% [ILC]

trilinear cplg A_t : $A_t + \mu\cot\beta \simeq A_t$: masses $\tilde{b}_L$ and $\tilde{t}_1$

e^+e^- production : mixing $\tilde{t}_L/\tilde{t}_R$

$$\Rightarrow \quad A_t = -560 \pm 25 \text{ GeV [SPS1a}'\text{]}$$

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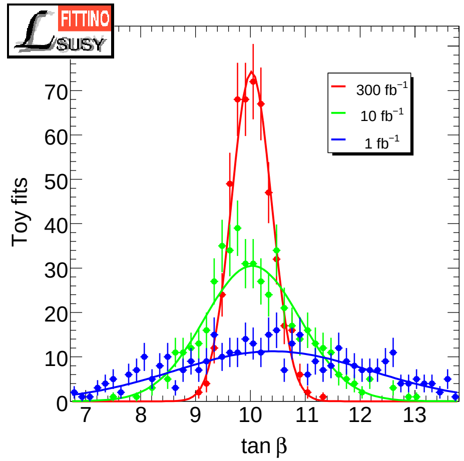

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accuracy $\sim 10\%$

$\gamma\gamma \to \tau\tau A$: $\tan\beta_{eff}$ at 2 to 5% Choi$_{ea}$

mSUGRA $\sim 3\%$ [LHC] $\to 0.5\%$ [ILC] Fittino,Sfitter

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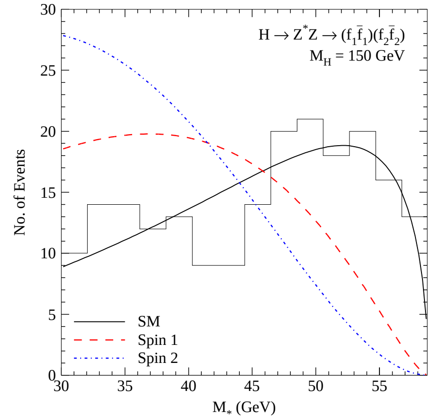
trilinear cplg A_τ : $A_\tau - \mu\cot\beta \simeq A_\tau$: $\frac{\Gamma(H,A\to\tilde{\tau}_1\tilde{\tau}_2)}{\Gamma(A,H\to\tau\tau)} = \lambda^{1/2}\frac{(A_\tau+\mu\cot\beta)^2}{M^2_{A,H}}$

$$\Rightarrow \quad A_\tau = -450 \pm 50 \text{ GeV [SPS1a}'\text{ in } e^+e^- \to HA]$$

c) $\mathcal{J}^{\mathcal{CP}}$ Quantum numbers :

angular correlations in decays h, H, A / *production*



spin = 0 : *ex1* : $H \to ZZ^{(*)} \to 4\ell$: unique : threshold

$\oplus$ polar angles

similarly : $e^+e^- \to Z^* \to Zh...$

ex2 : Yang theorem : $gg, \gamma\gamma \leftrightarrow h, H, A$: spin-1 excluded

spin-2 *etc* excluded if no non-trivial decay distrib $d^2_{\Delta\lambda_f, m}(\theta) \neq 0$ observed

$\Rightarrow$ *only spin-0 left*

$\mathcal{CP} = ++ / +-$: *ex1* : decays $H, A \to \tau^+\tau^-$ *etc* :

azimuthal correlations perpendicular to τ/τ flight direction :

$d\Gamma[0^{++}/0^{+-}]/d\phi = 1 \mp \left(\frac{\pi}{4}\right)^2 \cos\phi$ *[impact analysis]*

ex2 : $\gamma\gamma \to H \sim \vec{\epsilon}_1 \cdot \vec{\epsilon}_2 \neq 0$ lin parallel polarization

$\gamma\gamma \to A \sim \vec{\epsilon}_1 \times \vec{\epsilon}_2 \neq 0$ lin perpendicular polarization

d) Couplings :

$hff \sim mix \times SM$
$hWW \sim mix \times SM$: *ex* light h

Duhrssen$_{ea}$
Sfitter

LHC : $\sigma(pp \to h)_i \times BR(h)_f \sim \Gamma_i \Gamma_f / \Gamma_{tot}$

Γ_{tot} not determined $\Rightarrow$

ratios of couplings : $\frac{g_j}{g_k} = \frac{mix \times m_j}{mix \times m_k}$

continuation by hypothesis:

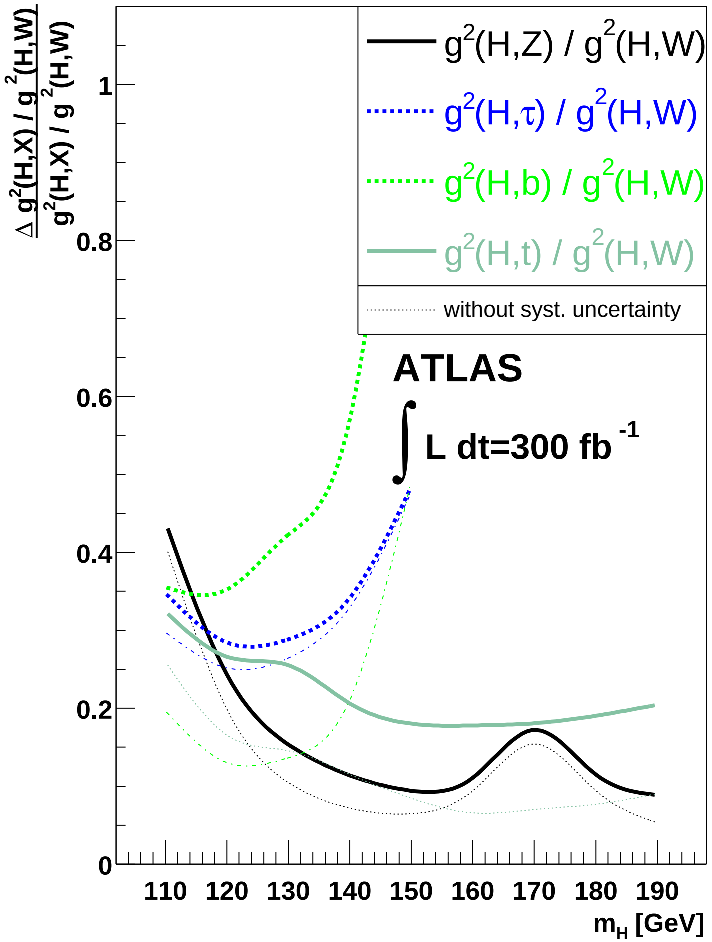
$g^2(hWW) \leq g^2(hWW)_{SM}$ for doublets/singlets

$\Rightarrow$ upper bound $\Gamma_{tot} \leq \Gamma^2_{W,SM}/\hat{\sigma}_W BR_W$

lower bound $\Sigma \hat{\sigma}_i BR_f \leq \Gamma_{tot}$

SM error in 15% range at LHC

$\sim$ decoupling regime in MSSM $\triangleright$



ILC : $e^+e^- \to Z^* \to Zh$ *inclusive*

$g(hZZ)$ determined [model-indep] $\Rightarrow$

absolute values % level of couplings

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$hff \sim mix \times SM$

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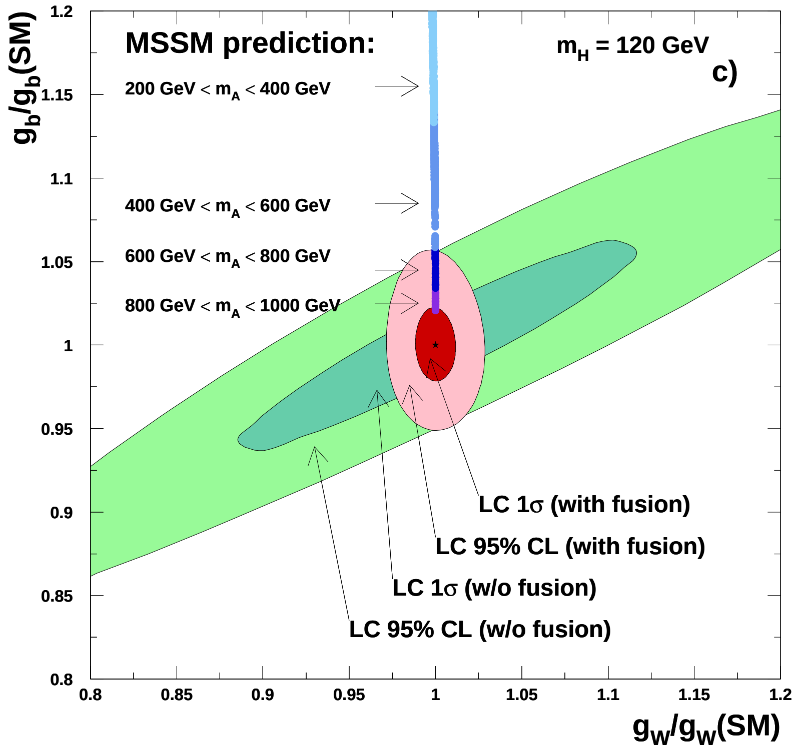


ILC

ILC : $e^+e^- \to Z^* \to Zh$ *inclusive*

$g(hZZ)$ determined [model-indep] $\Rightarrow$

absolute values % level of couplings

2. Extensions beyond the minimal scenario

– *impact of unification mechanisms*

– *$\mathcal{CP}$ violation*

– *NMSSM*

– *N=1/N=2 hybrid model*

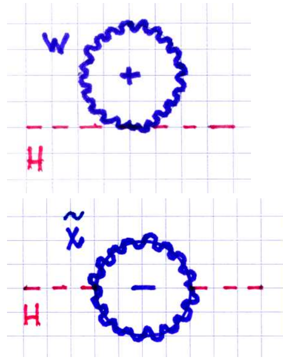
2.1 Links to unification

a) Hierarchy problem / fine-tuning for light Higgs :

rad.cor to SM Higgs mass : $\delta M_H^2 \simeq \alpha \Lambda^2$

for low-mass susy $\rightarrow \alpha\Lambda^2 - \alpha[\Lambda^2 - \tilde{M}^2] = \alpha \tilde{M}^2 \sim M_W^2$

[mod logs]



b) Radiative symmetry breaking :

evolution GUT $\rightarrow$ ELW : $dm_u^2 / d\log Q^2 = 3 \cdot \lambda_t^2 \, \Sigma m^2 + \ldots$: fast fall-off to below zero

$dm_{\tilde{t}_R}^2 / d\log Q^2 = 2 \cdot \lambda_t^2 \, \Sigma m^2 + \ldots$: fall-off less : positive

$dm_{\tilde{t}_L}^2 / d\log Q^2 = 1 \cdot \lambda_t^2 \, \Sigma m^2 + \ldots$: fall-off least : maximal

2. Extensions beyond the minimal scenario

– *impact of unification mechanisms*

– *$\mathcal{CP}$ violation*

– *NMSSM*

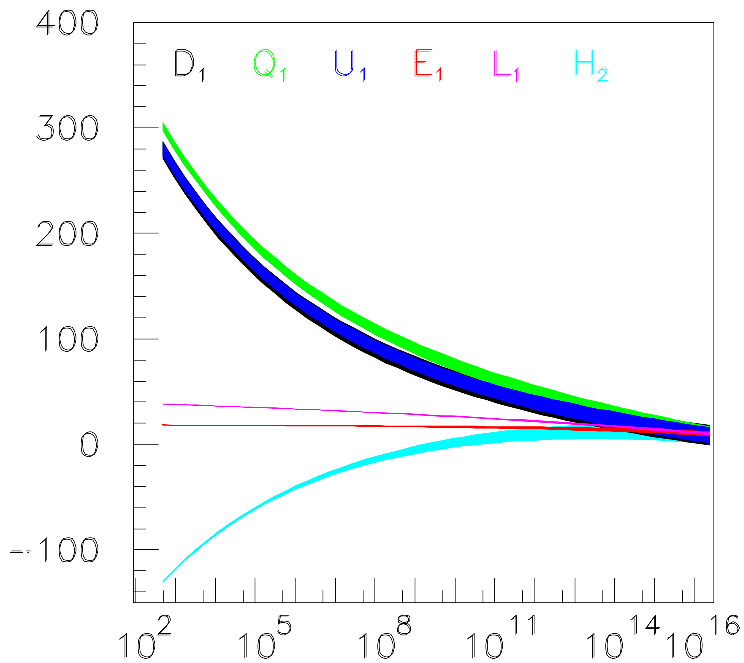
– *N=1/N=2 hybrid model*

2.1 Links to unification

b) Radiative symmetry breaking :

evolution from universal scalar mass at GUT generates negative mass^2 at ELW scale :

evolution checked in elw + susy precision data



Blair$_{ea}$
Adam$_{ea}$

2. Extensions beyond the minimal scenario

– *impact of unification mechanisms*

– *$\mathcal{CP}$ violation*

– *NMSSM*

– *N=1/N=2 hybrid model*

2.1 Links to unification

b) Radiative symmetry breaking :

evolution from universal scalar mass

at GUT generates negative mass^2

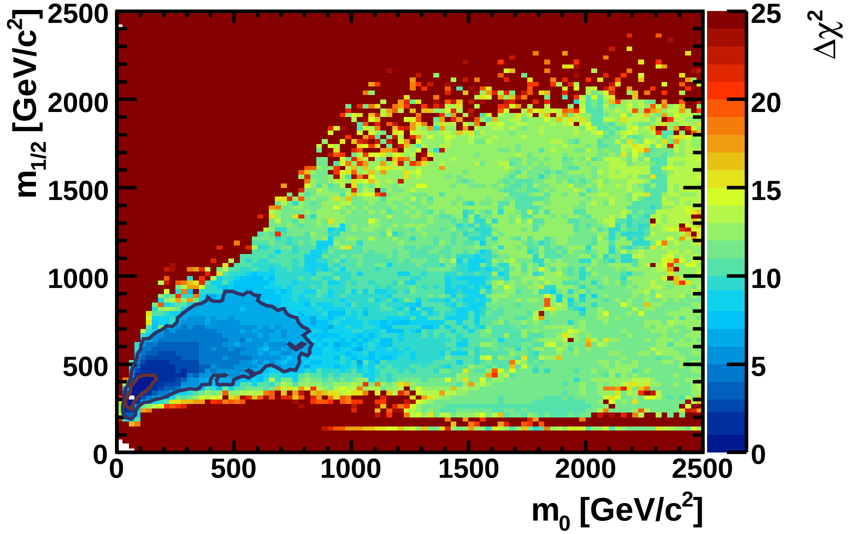
at ELW scale

compatible with elw data : $\simeq$ SPS1a$'$

$h = 114 \,|\, A = 440 \,|\, M_0 = 60 \,|\, M_{1/2} = 310$

elw only : bottom-up evolution not unique

$\Rightarrow$ *CMSSM as well as NUHM*



Buchmuller$_{ea}$

2.2 $\mathcal{CP}$ Violation

MSSM *Higgs sector Born level :* $\mathcal{CP}$ *conserving*

$\mathcal{CP}$ *violation at h.o. induced in MSSM by many sources for phases :* μ, M_i, M_s^2, A

$\Rightarrow$ $\mathcal{CP}$ mixing of Higgs states $[h, H, A] \Rightarrow [H_1, H_2, H_3]$

$\Rightarrow$ exciting mixing phenomena in regions of degenerate states, Choi$_{ea}$

e.g. decoupling regime $[M_H \approx M_A]$:

$$\mathcal{M}_{HA}^2 = \begin{Vmatrix} m_H^2 - iM_H\Gamma_H & \Delta_{HA}^2 \\ \Delta_{HA}^2 & m_A^2 - iM_A\Gamma_A \end{Vmatrix}$$

$\mathcal{CP}$ viol $\tilde{f}$ loop : $\Delta_{HA}^2 \sim M_t^4 \Im[\mu A_f]/\tilde{M}^2$

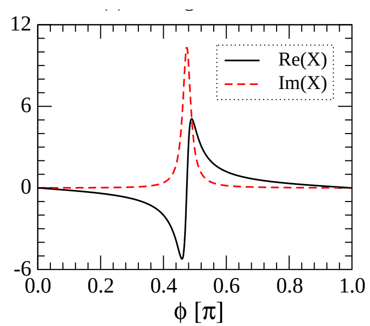
$$cplx\ rot \ : \ \mathcal{C} = \begin{Vmatrix} \cos\Theta & \sin\Theta \\ -\sin\Theta & \cos\Theta \end{Vmatrix}$$

$$X = \frac{1}{2}\tan 2\Theta = \frac{\Delta_{HA}^2}{[M_H^2 - M_A^2] - i[M_H\Gamma_H - M_A\Gamma_A]}$$

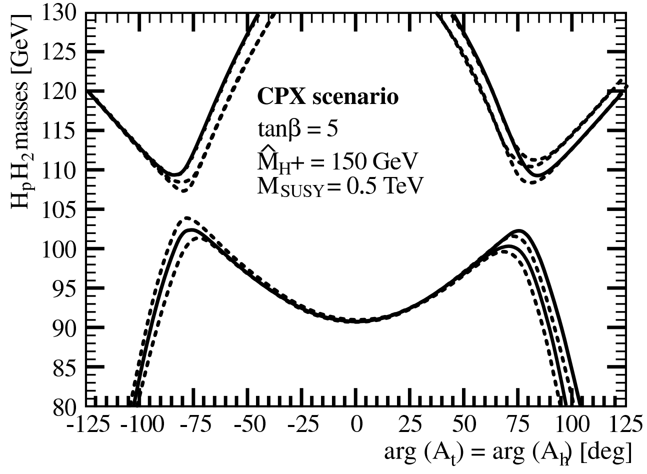
<u>EXP</u> : $\gamma\gamma_{pol} \to H_2$ or H_3 :

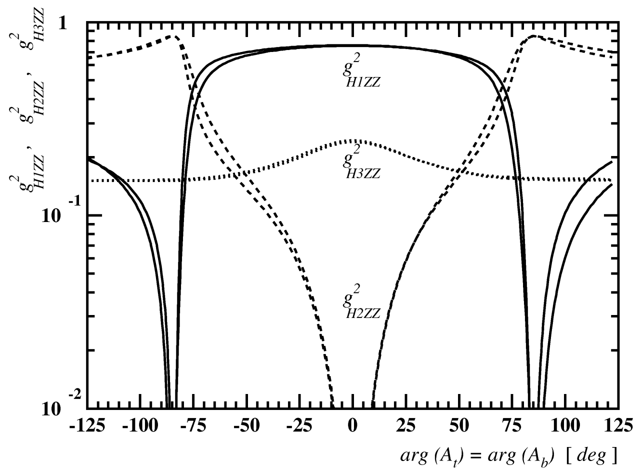
$$\mathcal{A}_{lin}[H_2] = -\mathcal{A}_{lin}[H_3] = \frac{|\cos\Theta|^2 - |\sin\Theta|^2}{|\cos\Theta|^2 + |\sin\Theta|^2}$$

$$\mathcal{A}_{cir}[H_2] = -\mathcal{A}_{cir}[H_3] = \frac{2\Im\cos\Theta\sin\Theta^*}{|\cos\Theta|^2 + |\sin\Theta|^2}$$



Masses and couplings :





Carena$_{ea}$

$arg\,(M_3) = 0, \pi/2$

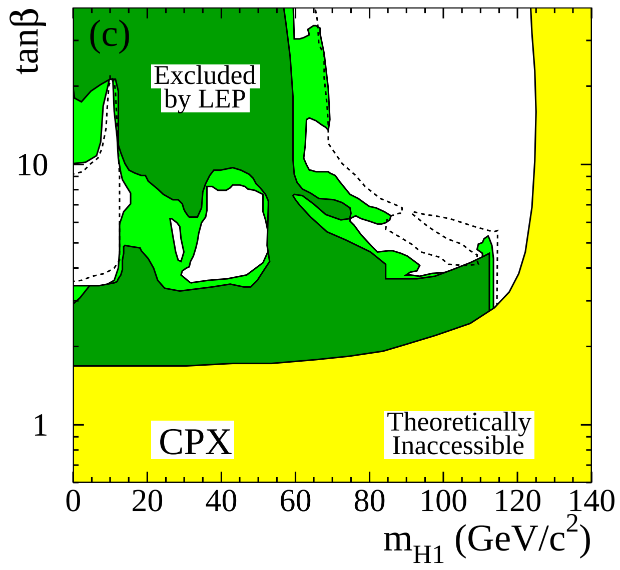
CPX LEP analysis :

$\phi_3, \phi_A = \pi/2$

$\mu = 2,\ A = 1,\ \tilde{M} = 0.5$

$\Rightarrow$ areas of small Higgs masses

exp not ruled out



2.3 NMSSM

motiv : MSSM, incorporating $\lambda_\phi = g^2$, very special $\Rightarrow$

– how stable are general patterns when susy scenario extended?

– solving μ problem?

$\mu \sim$ *sev. elw scale* $v \mid \neq 0, M_{Pl}$

– reducing little fine-tuning

Higgs mass increased by large stop mass $\tilde{M} \sim 4M_t$

Higgs pot: $\frac{1}{2}M_Z^2 \simeq -\mu^2 - m_u^2 \sim -\mu^2 + \frac{1}{2}\tilde{M}^2$ *[large* $\tan\beta$*]* $\Rightarrow\Rightarrow$

$\Rightarrow$ cancelation of TeV-type parameters : $\mathcal{O}(10^{-2})$

NMSSM = MSSM + isoscalar $\hat{S}$ — Fayet, Ellwanger$_{ea}$

superpotential $\mathcal{W}_{NMSSM} = \mathcal{W}_{MSSM}[\not{\mu}] + \lambda \hat{S}\hat{H}_d \cdot \hat{H}_u + \frac{\kappa}{3}\hat{S}^3$

$\langle S \rangle_0 = v_s \neq 0$: $\mu = \lambda v_s \mid \mu$ coupled to $v_s \sim$ sev. elw scale

fields weakly cpld up to M_{Pl} : $\lambda, \kappa \leq 0.6 \Rightarrow$ light Higgs $\sim M_Z + rc$

assume mechanisms to remove tadpole and cosmo domain wall problems

Consequences :

1.) Spectrum : charged states unaltered : $H^{\pm}$

neutral : scalar $h, H \oplus s \;\Rightarrow\; H_1, H_2, H_3$

pseudo-scalar $A \oplus a \;\Rightarrow\; A_1, A_2$

2.) Maximal mass of lightest Higgs boson :

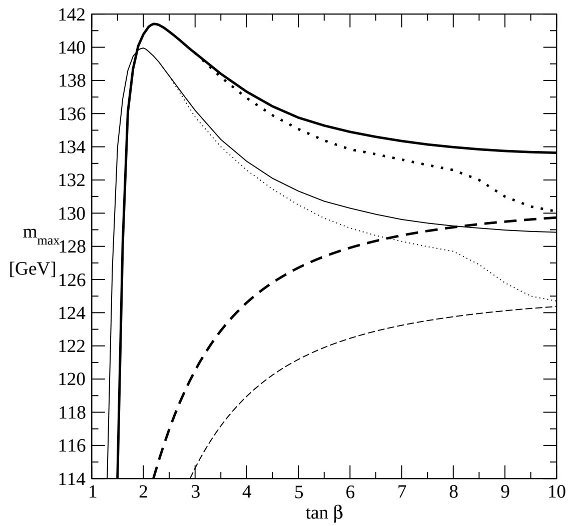
$$M_h^2 \leq M^2 \cos^2 2\beta \quad \Rightarrow \quad M_{H_1}^2 \leq M_Z^2 \, [\cos^2 2\beta + \frac{\lambda^2}{g^2} \sin^2 2\beta] + rad.cor$$

large Born improvement

at small/moderate $\tan\beta$

$[\lambda = 0.70, \kappa = 0.10, \tan\beta = 2.2$

$\tilde{M} = 1$ TeV, $A = 2.5$ TeV]



Ellwanger$_{ea}$

Consequences :

1.) Spectrum : charged states unaltered : $H^{\pm}$

neutral : scalar $h, H \oplus s \Rightarrow H_1, H_2, H_3$

pseudo-scalar $A \quad \oplus a \Rightarrow A_1, A_2$

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3.) Light pseudo-scalar A_1?

κ small $\Rightarrow$ approx PQ symmetry : $H_{d,u} \to \exp\,[i\alpha] H_{d,u}$

$S \to \exp\,[-2i\alpha] S$

$\Rightarrow$ spont. broken : light A_1 [pseudo-] Goldstone — Dermisek$_{ea}$

search for light A_1 : – mass shift $PS[b\bar{b}]$ mixing with $A_1 \Rightarrow hfs$

– Wilczek process : $V[b\bar{b}] \to A_1 + \gamma$

– $e^+e^- \to ZH_1 \quad H_1 \to A_1 A_1 \to bbbb, \tau\tau\tau\tau, \ldots$

no signal yet established

2.4 N=1/N=2 Hybrid Model

Nojiri$_{ea}$,Benakli$_{ea}$
Antoniadis$_{ea}$,Choi$_{ea}$

motiv : transition from Majorana to Dirac gauginos :

– suppression of flavor-changing diagrams

– Cold Dark Matter : $\chi\chi$ annihilation to light fermions not suppressed
new co-annihilation channels : widening parameter space

– phenomenology very different from MSSM

Spectrum : N=2 gauge hypermultiplet :

N=1 standard gaugino supermultiplet : G_μ $\tilde{G}$: $\hat{G}$

N=1 adjoint chiral supermultiplet : $\tilde{G}'$ Σ : $\hat{\Sigma}$

Dirac field : $\tilde{G} \oplus \tilde{G}' \;\Rightarrow\; \tilde{G}_D$ | scalar σ's in adjoint representation

N=2 Higgs hypermultiplet $\{\hat{H}_u^\dagger, \hat{H}_d\}$

N=1 matter supermultiplets [chiral character]

b) HIGGS/SCALAR SECTOR :

Spectrum :

h	H	s_I	s_Y	$\longrightarrow$	H_1	H_2	H_3	H_4
A		a_I	a_Y	$\longrightarrow$	A_1	A_2	A_3	
$H^\pm$		$s^\pm_{I1}$	$s^\pm_{I2}$	$\longrightarrow$	$S^\pm_1$	$S^\pm_2$	$S^\pm_3$	

$M_I[/M_Y]$ mass $\mathcal{O}(1$ TeV$)$ $\Rightarrow$

vev of σ_I small : $\Delta\rho < 10^{-3}$

Higgs potential *modified compared to MSSM | for large* σ, A *mass parameters* :

$$\mathcal{V} = m'^2_d|H^0_d|^2 + m'^2_u|H^0_u|^2 + m^2_{du}H^0_d \cdot H^0_u + hc$$
$$+\frac{1}{8}(g^2+g'^2)[|H^0_u|^2 - |H^0_d|^2]^2 + \frac{1}{2}(g^2+g'^2)|H^{0*}_d H^0_u|^2$$

Higgs mass matrix :

$$\mathcal{M}^2 = \begin{Vmatrix} M^2_Z c^2_\beta + M^2_A s^2_\beta & (M^2_A - M^2_Z)c_\beta s_\beta \\ (M^2_A - M^2_Z)c_\beta s_\beta & M^2_Z s^2_\beta + M^2_A c^2_\beta \end{Vmatrix} \longrightarrow \begin{Vmatrix} M^2_Z & 0 \\ 0 & M^2_A \end{Vmatrix}$$

$\Rightarrow$ Higgs masses at Born level independent of $\tan\beta$

$\Rightarrow$ upper limit : $M^2_h = M^2_Z \cos^2 2\beta + rad.cor \;\longrightarrow\; M^2_Z + rad.cor$

reducing fine-tuning

b) HIGGS/SCALAR SECTOR :

h	H	s_I	s_Y	$\rightarrow$	H_1	H_2	H_3	H_4
A		a_I	a_Y	$\rightarrow$	A_1	A_2	A_3	
$H^\pm$		$s^\pm_{I1}$	$s^\pm_{I2}$	$\rightarrow$	$S^\pm_1$	$S^\pm_2$	$S^\pm_3$	

Couplings [Born] :

$scalar \times H \times H \neq 0$

$scalar \times \tilde{g}_D \times \tilde{g}_D \neq 0$
$scalar \times \tilde{f} \times \tilde{f} \neq 0$

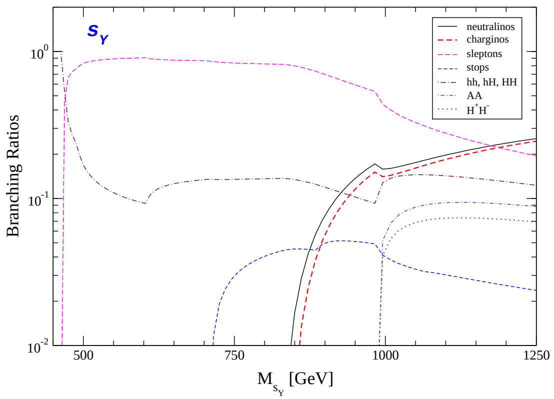
$scalar \times SM\ pair = 0$
$scalar\ pair \times SM \neq 0$

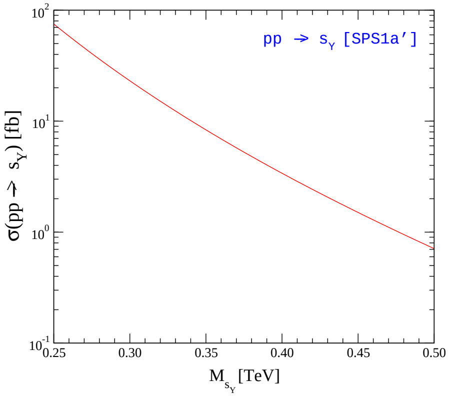
\# decay modes : $s_Y \rightarrow hh, \ldots \chi^+\chi^-, \ldots, \tilde{f}\tilde{f}^*, \ldots$

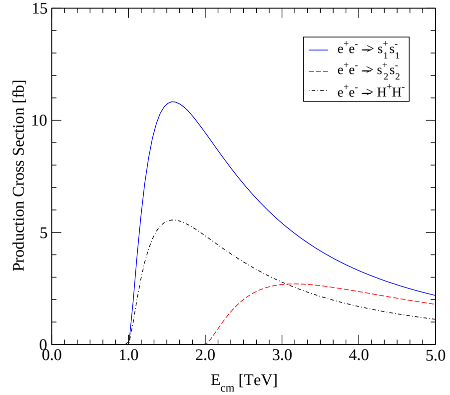
$a_Y \rightarrow \chi^+\chi^-, \ldots$: SM matter/gauge loop suppressed

\# production channels : loop cpld : $pp \rightarrow gg \rightarrow s_Y, \ldots$

direct : $e^+e^- \rightarrow S^+_1 S^-_1, \ldots$ | *low mass : Drell-Yan*







b) HIGGS/SCALAR SECTOR :

h	H	s_I	s_Y	$\to$	H_1	H_2	H_3	H_4
A		a_I	a_Y	$\to$	A_1	A_2	A_3	
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\# production channels : loop cpld : $pp \to gg \to s_Y, \ldots$
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c) COLOR SCALAR SECTOR / SGLUONS :

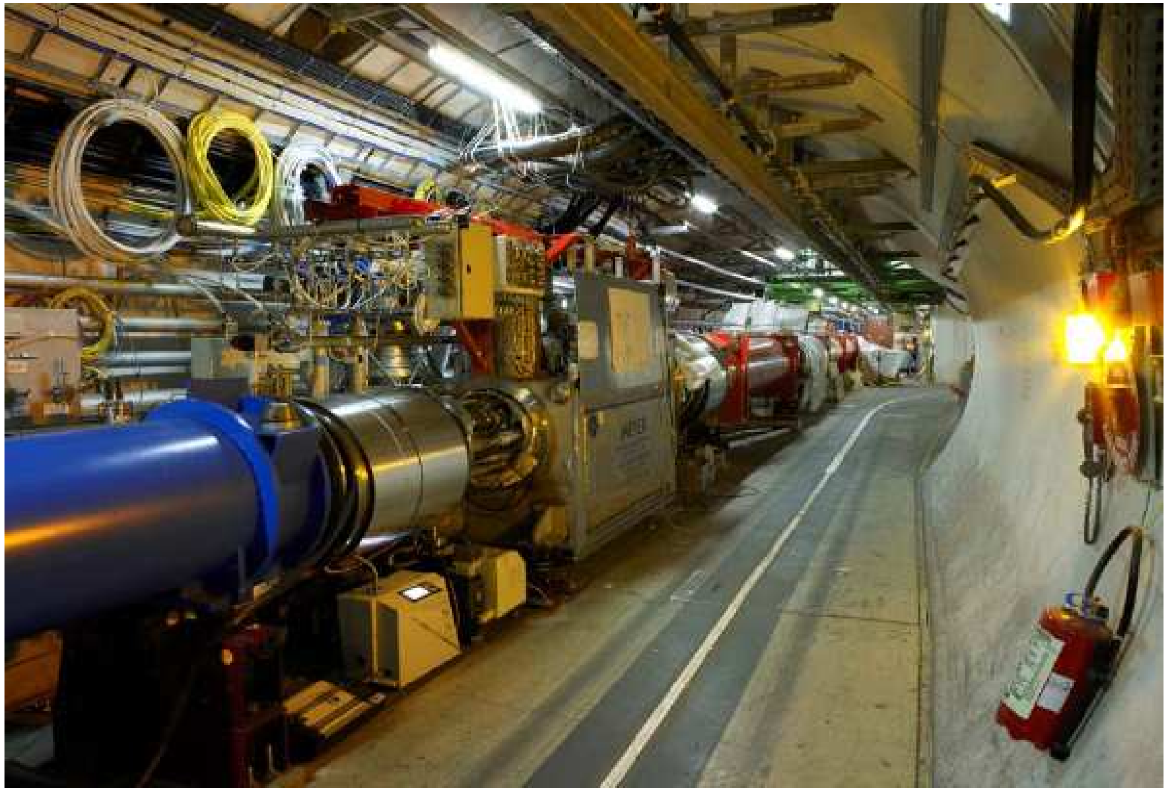
Plehn$_{ea}$
Choi$_{ea}$

partners to gluinos : colored octet scalars = sgluons

$$pp \to gg \to \sigma_c\sigma_c \qquad \sigma_c \to \tilde{g}\tilde{g} \qquad \tilde{g} \to q\tilde{q} \qquad \tilde{q} \to q\tilde{\chi}^0_1 \qquad \Rightarrow$$

$pp \to 8\, jets + 4\, \tilde{\chi}^0_1$: unusual susy signal [$vis\ 2\, jets + 2\, \tilde{\chi}^0_1$]

CONCLUSION



SUSY & HIGGS ? ... soon – experiments will decide ...