united nations
educational, scientific
and cultural
organization

international atomic
energy agency

the
abdus salam
international centre for theoretical physics

SMR.1508 - 30

SUMMER SCHOOL ON PARTICLE PHYSICS

16 June - 4 July 2003

LECTURES ON SUPERSYMMETRY

Lecture IV & V

G. WEIGLEIN
Dept. of Physics. IPPP
University of Durham
Durham
U.K.

Lectures on Supersymmetry

Georg Weiglein
IPPP Durham

Trieste, 06/2003

Lectures 4 and 5:

- Higgs mass bound in SUSY theories
- The LSP as a dark matter candidate
- Electroweak precision tests: SM vs. MSSM
- Prospects for SUSY searches at the next generation of colliders

Higgs mass bounds in SUSY theories

MSSM predicts upper bound on m_{h}:

tree-level bound: $m_{\mathrm{h}} < M_{\mathrm{Z}}$, excluded by LEP Higgs searches!

Large radiative corrections:

Yukawa couplings: $\frac{\mathrm{e}\, m_{\mathrm{t}}}{2 M_{\mathrm{W}} s_{\mathrm{W}}}, \frac{\mathrm{e}\, m_{\mathrm{t}}^2}{M_{\mathrm{W}} s_{\mathrm{W}}}, \ldots$

$\Rightarrow$ Dominant one-loop corrections: $G_\mu m_{\mathrm{t}}^4 \ln\left(\frac{m_{\tilde{\mathrm{t}}_1} m_{\tilde{\mathrm{t}}_2}}{m_{\mathrm{t}}^2}\right)$

Present status of m_{h} prediction in the MSSM:

Complete one-loop and ‘almost complete’ two-loop result available

Upper bound on m_{h} in the MSSM:

"Unconstrained MSSM":

M_{A}, $\tan\beta$, 5 parameters in $\tilde{\mathrm{t}}$–$\tilde{\mathrm{b}}$ sector, μ, $m_{\tilde{\mathrm{g}}}$, M_2

Diagrammatic result: *FeynHiggs*

[*S. Heinemeyer, W. Hollik, G. W. '98, '00, '02*]

`http://www.feynhiggs.de`

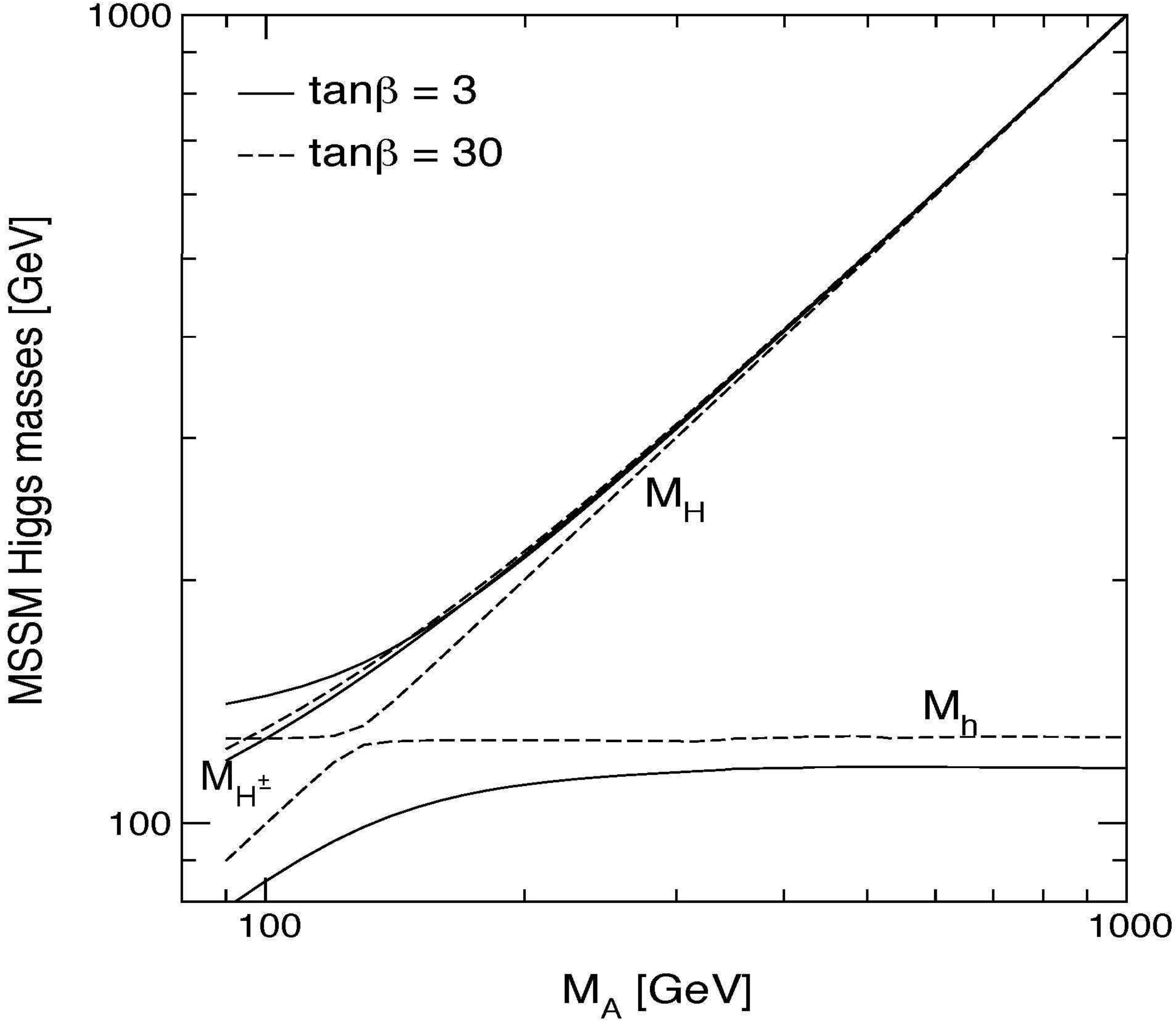
$$m_{\mathrm{h}} \lesssim 135\,\mathrm{GeV}$$

for $m_{\mathrm{t}} = 175\,\mathrm{GeV}$

no theoretical uncertainties from unknown higher orders included

Upper bound on m_{h} saturated for large M_{A}, large $\tan\beta$, significant mixing in $\tilde{\mathrm{t}}$ sector

[S. Heinemeyer, W. Hollik, G. W. '01]



Upper bound $m_h \lesssim 135$ GeV reduced by

$\approx 6, 11, 8$ GeV in mSUGRA, GMSB, AMSB scenarios

[*S. Ambrosanio, A. Dedes, S. Heinemeyer, S. Su, G. W. '01*]

Upper bound on m_h in extensions of MSSM: $m_h \lesssim 200$ GeV

[*G. Kane, C. Kolda, J. Wells '93*] [*J. Espinosa, M. Quirós '93, '98*]

⇒ **SUSY requires light Higgs boson:**

definite and robust prediction of SUSY models

testable at next generation of colliders

Remaining theoretical uncertainties in prediction for m_{h} in the MSSM:

[G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich, G. W. '02]

– From unknown higher-order corrections:
$\Rightarrow \Delta m_{\mathsf{h}} \approx 3$ GeV

– From uncertainties in input parameters

$m_{\mathsf{t}}, \ldots, M_{\mathsf{A}}, \tan\beta, m_{\tilde{\mathsf{t}}_1}, m_{\tilde{\mathsf{t}}_2}, \theta_{\tilde{\mathsf{t}}}, m_{\tilde{\mathsf{g}}}, \ldots$

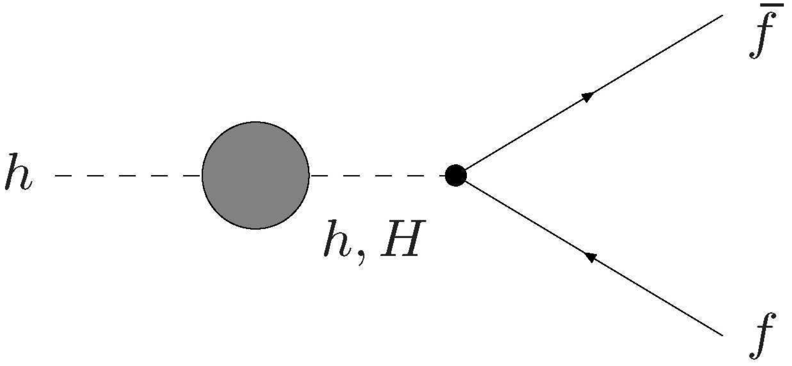
$\Delta m_{\mathsf{t}} \approx 5$ GeV $\Rightarrow \Delta m_{\mathsf{h}} \approx 5$ GeV

Higgs couplings, production cross sections

Also affected by large SUSY loop corrections

FD two-loop corrections implemented in results for $h \to f\bar{f}$, $e^+e^- \to hZ, hA$
[S. Heinemeyer, W. Hollik, G. W. '00]
[S. Heinemeyer, W. Hollik, J. Rosiek, G. W. '01]

$hf\bar{f}$ coupling:



$$A(h \to f\bar{f}) = \sqrt{Z_h}\left(\Gamma_h - \frac{\hat{\Sigma}_{\mathrm{hH}}(m_{\mathrm{h}}^2)}{m_{\mathrm{h}}^2 - m_{\mathrm{H}}^2 + \hat{\Sigma}_{\mathrm{HH}}(m_{\mathrm{h}}^2)}\Gamma_H\right)$$

⇒ Effective $hf\bar{f}$ coupling can vanish for large $\hat{\Sigma}_{\mathrm{hH}}$

Gluino vertex corrections to $h \to q\bar{q}$:

⇒ ratio $\Gamma(h \to \tau^+\tau^-)/\Gamma(h \to b\bar{b})$ can significantly differ from SM value for large $\tan\beta$

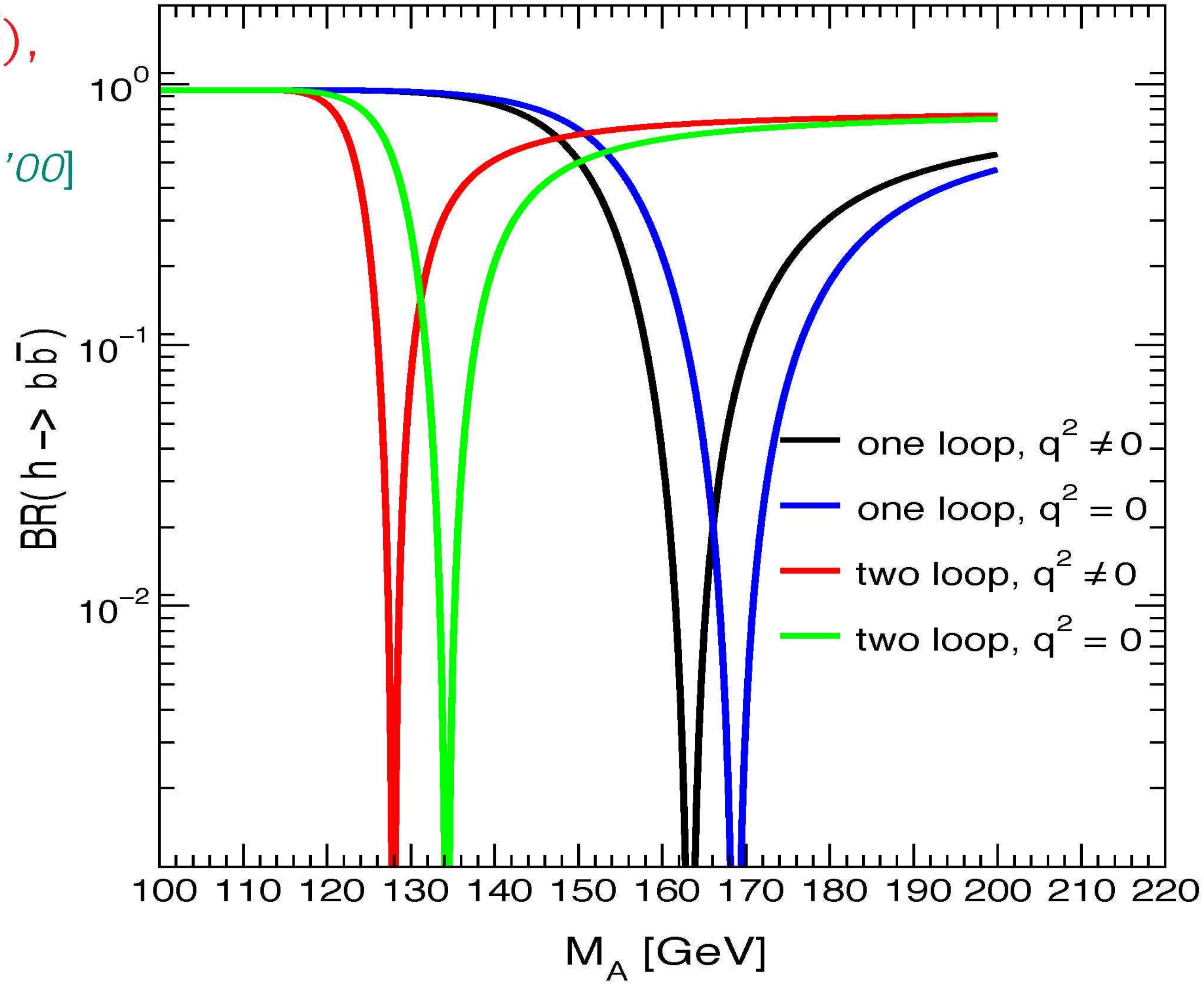
Effective $hf\bar{f}$ coupling can go to zero for large $\hat{\Sigma}_{\rm hH}$

⇒ "Pathological regions"

[*W. Loinaz, J. Wells '98*] [*M. Carena, S. Mrenna, C. Wagner '99*]

⇒ Suppression of BR($h \to b\bar{b}$), BR($h \to \tau\tau$), . . .

[*S. Heinemeyer, W. Hollik, G. W. '00*]



$\mathcal{CP}$ violation in the Higgs sector:

MSSM Higgs sector is $\mathcal{CP}$-conserving at tree level

Complex parameters enter via loop corrections:

- μ: Higgsino mass parameter
- $A_{t,b,\tau}$: trilinear couplings ⇒ $X_{t,b,\tau} = A_{t,b} - \mu^*\{\cot\beta, \tan\beta\}$ complex
- $M_{1,2}$: gaugino mass parameter (one phase can be eliminated)
- $m_{\tilde{g}}$: gluino mass

⇒ can induce $\mathcal{CP}$-violating effects

⇒ Mixing between neutral Higgs bosons h_1, h_2, h_3

Inclusion of higher-order corrections:

Propagator / mass matrix with higher-order corrections:

$$\begin{pmatrix} q^2 - M_{\mathsf{A}}^2 + \hat{\Sigma}_{AA}(q^2) & \hat{\Sigma}_{AH}(q^2) & \hat{\Sigma}_{Ah}(q^2) \\ \hat{\Sigma}_{HA}(q^2) & q^2 - m_{\mathsf{H}}^2 + \hat{\Sigma}_{HH}(q^2) & \hat{\Sigma}_{Hh}(q^2) \\ \hat{\Sigma}_{hA}(q^2) & \hat{\Sigma}_{hH}(q^2) & q^2 - m_{\mathsf{h}}^2 + \hat{\Sigma}_{hh}(q^2) \end{pmatrix}$$

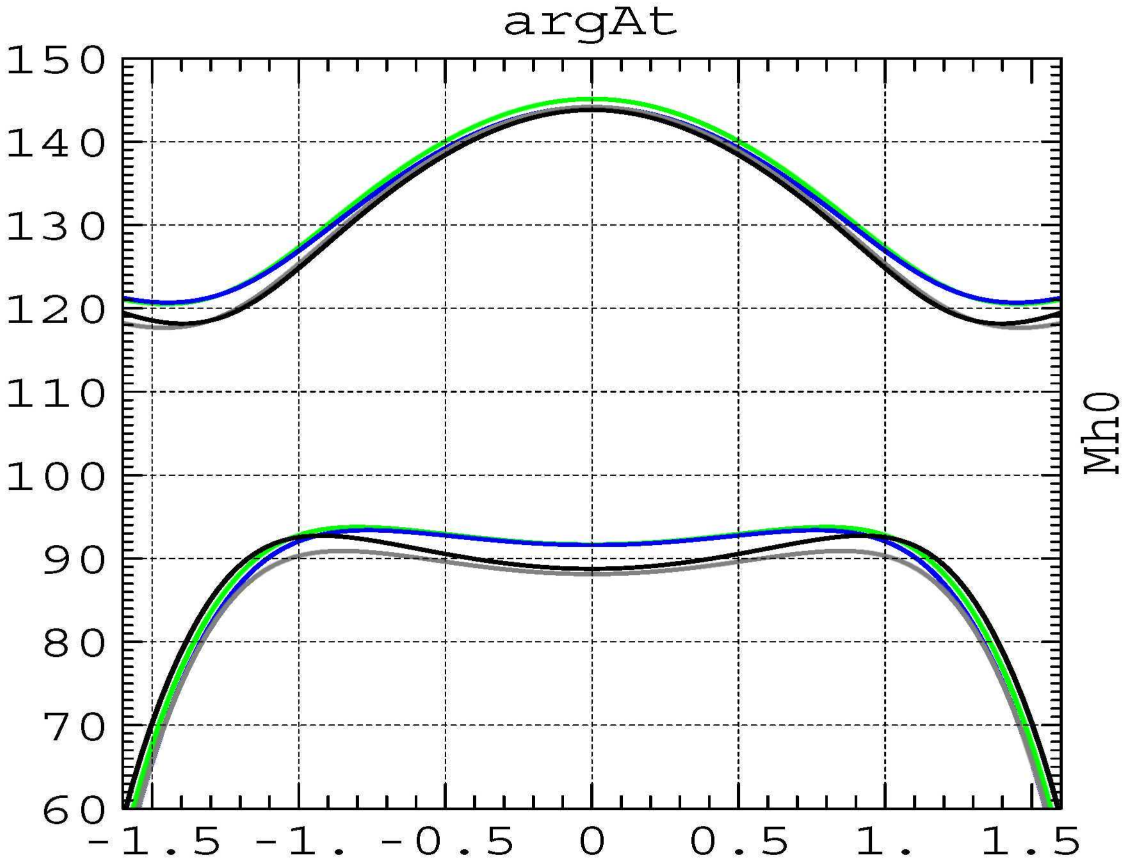
$\hat{\Sigma}_{ij}(q^2)$ $(i, j = h, H, A)$: renormalized Higgs self-energies

$\hat{\Sigma}_{Ah}, \hat{\Sigma}_{AH} \neq 0$ $\Rightarrow$ $\mathcal{CP}$V, $\mathcal{CP}$-even and $\mathcal{CP}$-odd fields can mix

Result: $(A, H, h) \to (h_3, h_2, h_1)$ with $m_{\mathrm{h}_3} > m_{\mathrm{h}_2} > m_{\mathrm{h}_1}$

Example: ϕ_{A_t} dependence of m_{h_1}, m_{h_2} ($\phi_\mu = 0$, $|A_\mathrm{t}| = 2\,M_{\mathrm{SUSY}}$):

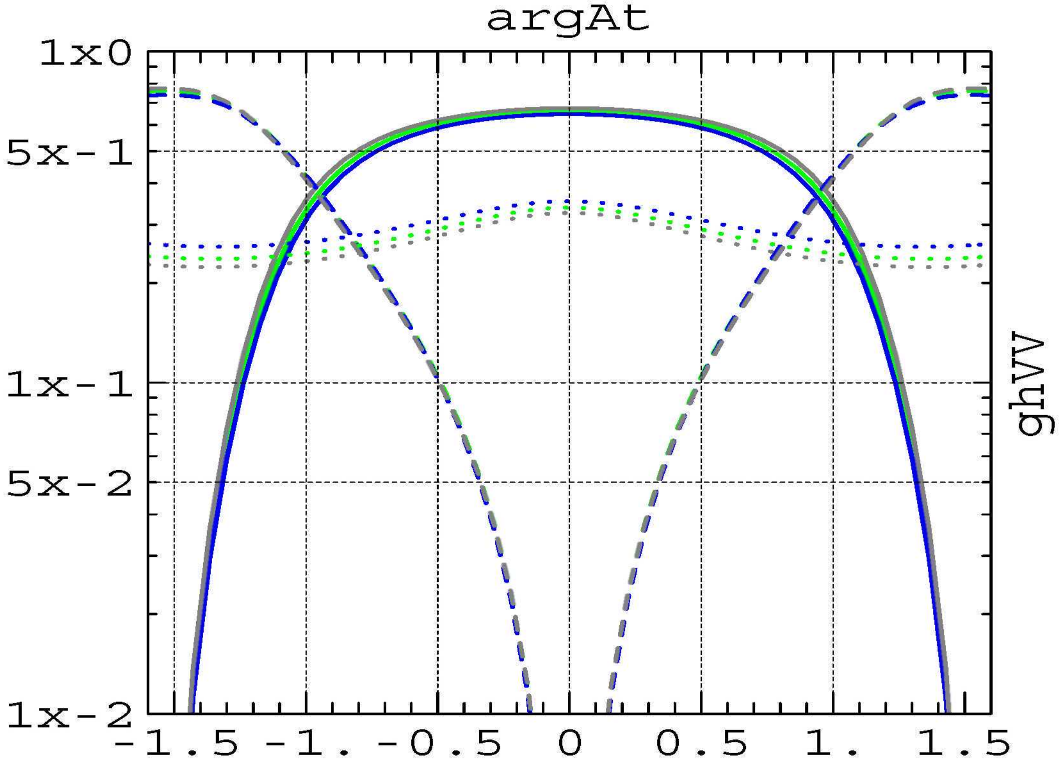
[M. Frank, S. Heinemeyer, W. Hollik, G. W. '03]



$\mathrm{t}/\tilde{\mathrm{t}}, \mathrm{b}/\tilde{\mathrm{b}}$, $q^2 = 0$, (s)fermion, $q^2 = 0$, full MSSM, $q^2 = 0$, full MSSM, $q^2 \neq 0$

Complex phases can have large effects on Higgs couplings

Example: g_{hVV} for h_1, h_2, h_3:
[*M. Frank, S. Heinemeyer, W. Hollik, G. W. '03*]

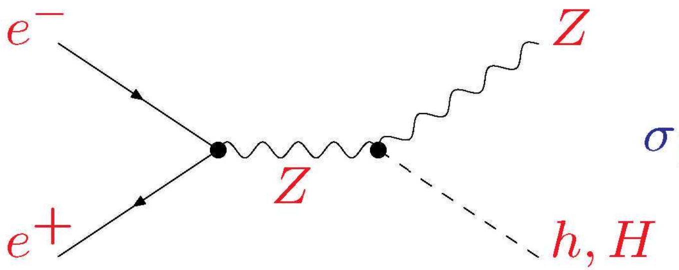


full: h_1, dashed: h_2, dotted: h_3

Parameters: $M_{\mathrm{SUSY}} = 500$ GeV, $M_2 = 500$ GeV, $\mu = 2000$ GeV, $|A_{\mathrm{t}}| = 1000$ GeV,
$M_{\mathrm{H}^\pm} = 150$ GeV, $\tan\beta = 5$

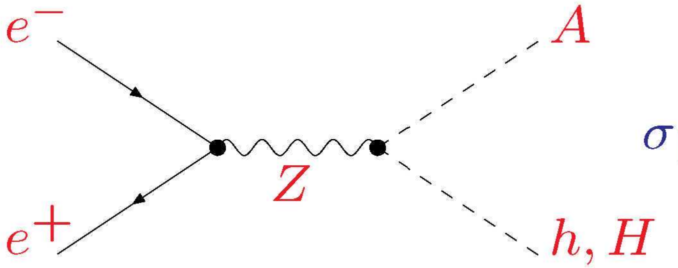
Search for neutral MSSM Higgs bosons at LEP:

$e^+e^- \to Zh, ZH$



$\sigma_{\mathrm{hZ}} \approx \sin^2(\beta - \alpha_{\mathrm{eff}})\sigma_{\mathrm{hZ}}^{\mathrm{SM}}$

$e^+e^- \to Ah, AH$

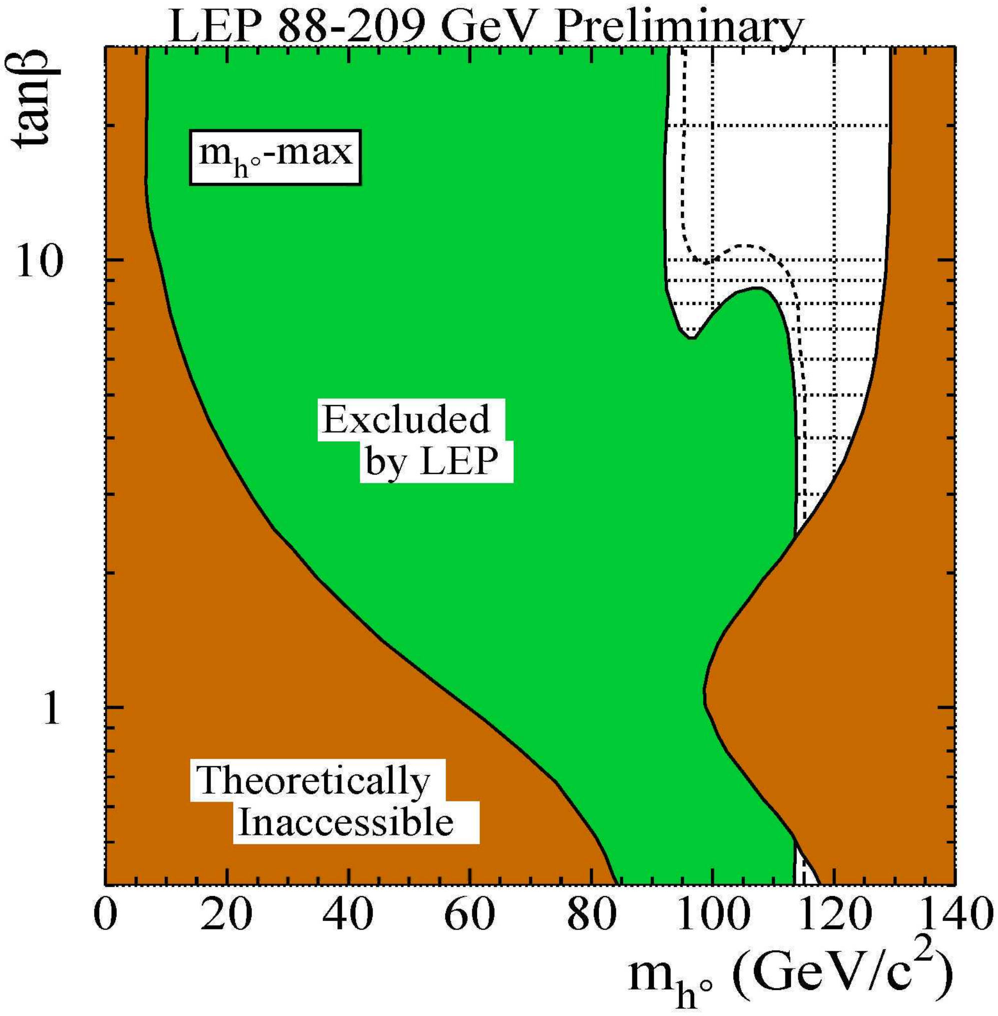


$\sigma_{\mathrm{hA}} \propto \cos^2(\beta - \alpha_{\mathrm{eff}})\sigma_{\mathrm{hZ}}^{\mathrm{SM}}$

Constraints from the Higgs search at LEP [*LEP Higgs Working Group '01*]

Experimental search vs. upper m_h-bound (*FeynHiggs* 1.0)

$m_\mathrm{h}^\mathrm{max}$-scenario ($m_\mathrm{t} = 174.3$ GeV, $M_\mathrm{SUSY} = 1$ TeV):



$m_\mathrm{h} > 91.0$ GeV
(expected: 94.6 GeV), 95% C.L.

$M_\mathrm{A} > 91.9$ GeV
(expected: 95.0 GeV)

Parameter region where experimental lower bound on m_{h} is significantly lower than SM bound, $M_{\mathrm{H}} > 114.4$ GeV, corresponds to $\sin^2(\beta - \alpha_{\mathrm{eff}}) \ll 1$

"Excluded" $\tan\beta$ region:

$$0.5 < \tan\beta < 2.4$$

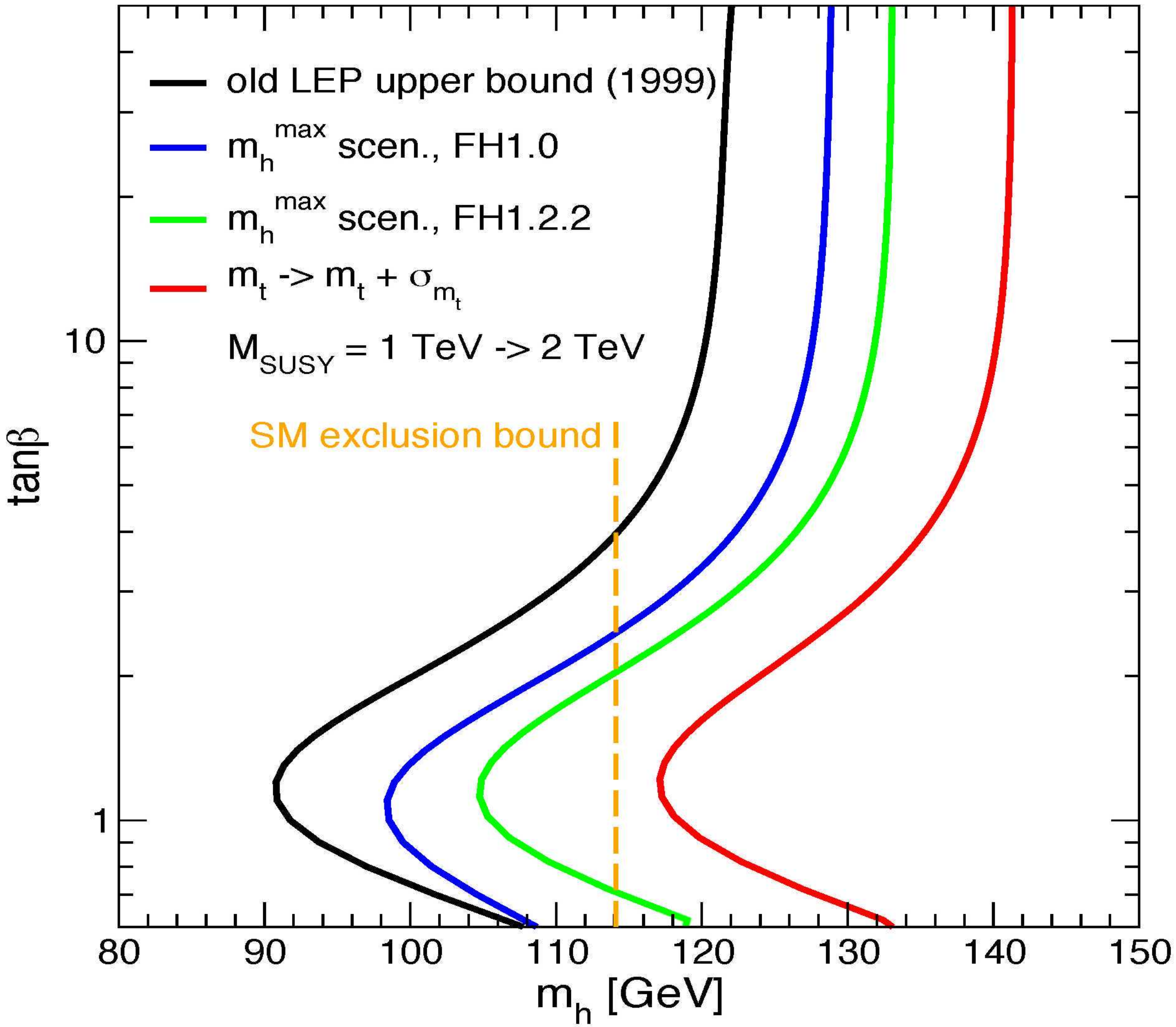
Note: this exclusion bound assumes

m_{t}, M_{SUSY} fixed, $m_{\mathrm{t}} = 174.3$ GeV, $M_{\mathrm{SUSY}} = 1$ TeV

no theoretical uncertainties included

Effect of new corrections and $m_{\rm t} \to m_{\rm t} + \sigma_{m_{\rm t}}$, $M_{\rm SUSY} = 1$ TeV → 2 TeV

[G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich, G. W. '02]



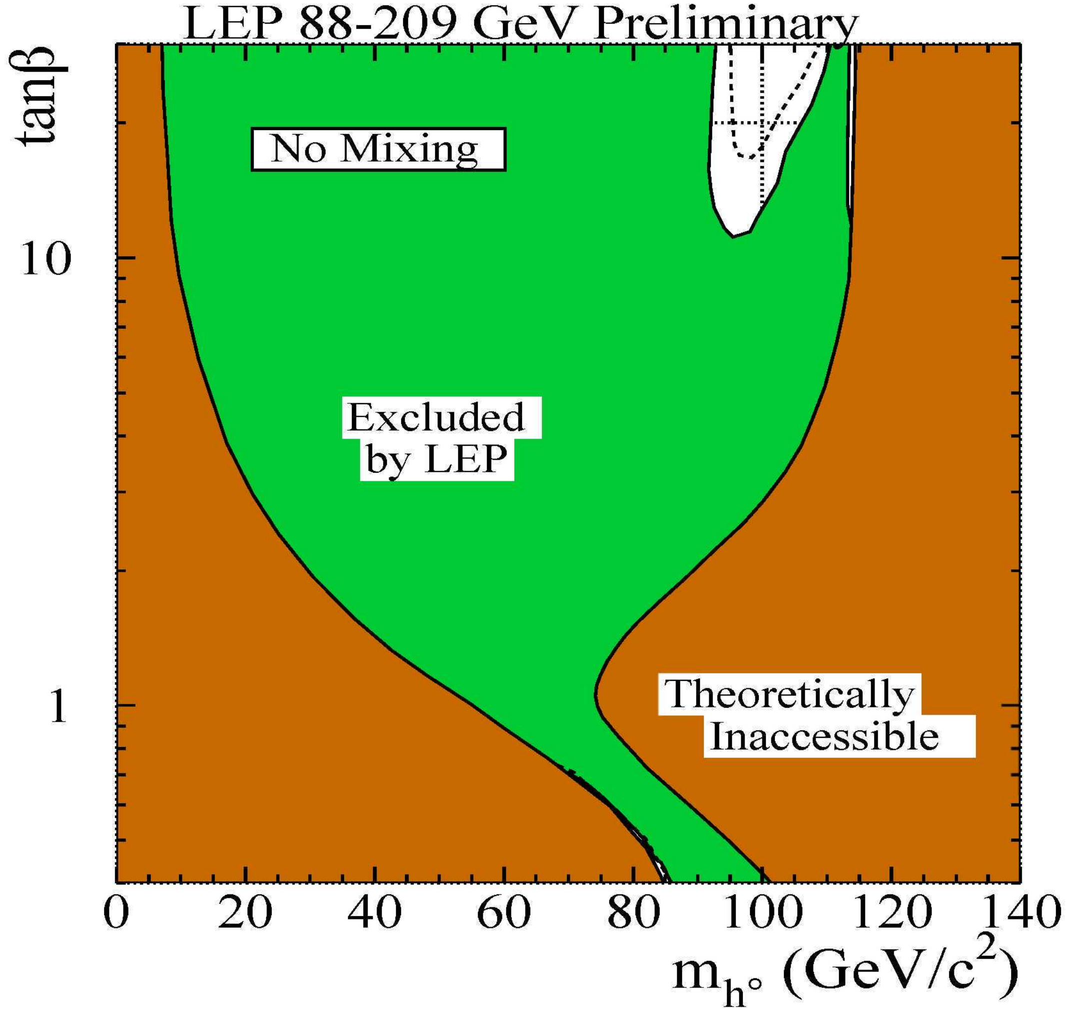
⇒ no $\tan\beta$ exclusion for $m_{\rm t} \to m_{\rm t} + \sigma_{m_{\rm t}}$, $M_{\rm SUSY} = 1$ TeV → 2 TeV

⇒ Low $\tan\beta$ region not fully excluded by LEP!

Experimental search vs. upper m_h-bound (*FeynHiggs*)

[*LEP Higgs Working Group '01*]

no-mixing scenario:



The LSP as a dark matter candidate

Astrophysical data (cosmic microwave background, . . .) ⇒ existence of non-baryonic cold dark matter in the Universe

SUSY with R parity conservation ⇒ LSP relic density falls naturally in favoured range if $m_{\mathrm{LSP}} \lesssim 1$ TeV

Most recent result (WMAP)

[*C. Bennet et al. '03*], [*D. Spergel et al. '03*]

⇒ cold dark matter density: $\Omega_{\mathrm{CDM}} h^2 = 0.1126^{+0.0161}_{-0.0181}$ at 95% C.L.
(h: expansion rate)

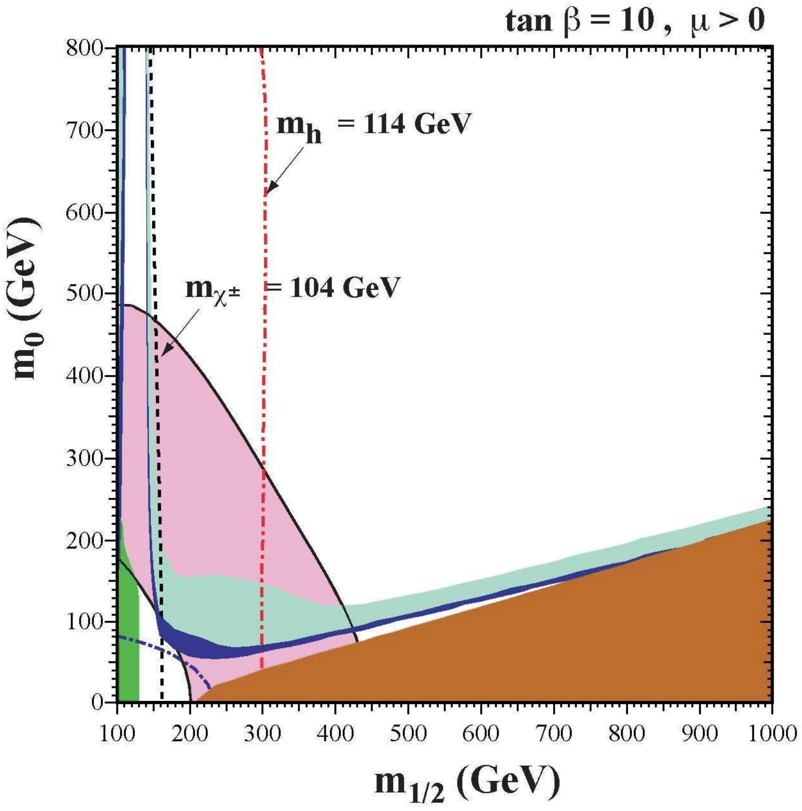
⇒ Constraints on the SUSY parameter space

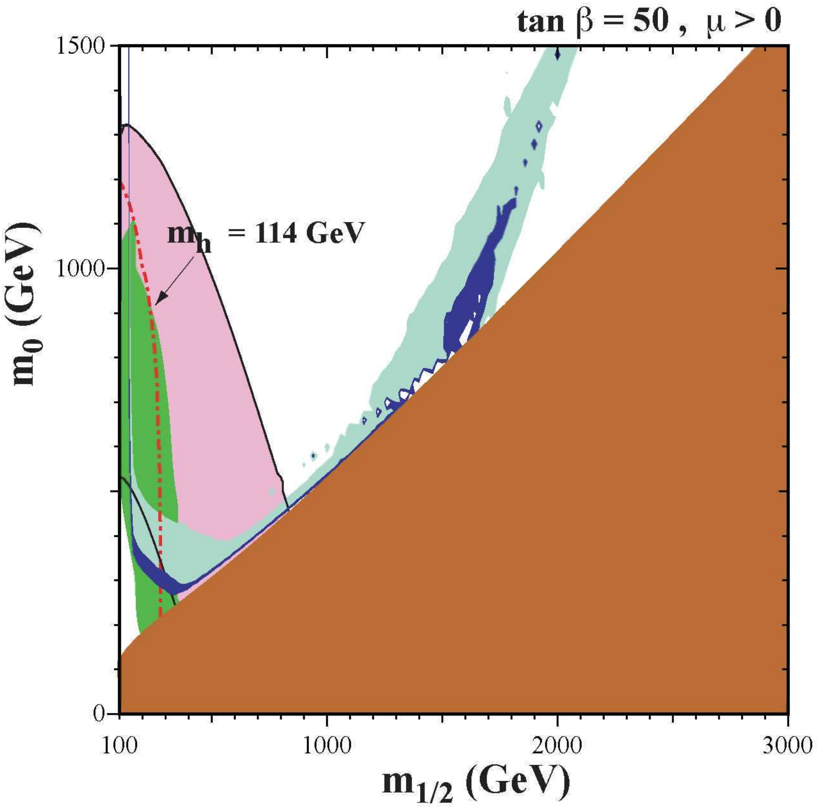
Example: mSUGRA scenario with $\mu > 0$, $A_0 = 0$, $\tan\beta = 10, 50$

Parameter region allowed by the CDM constraint in the $m_{1/2}$–m_0 plane with and without the new WMAP data

(also shown: favoured region from $(g_\mu - 2)$, region excluded by $b \to s\gamma$)

[*J. Ellis, K. Olive, Y. Santoso, V. Spanos '03*]



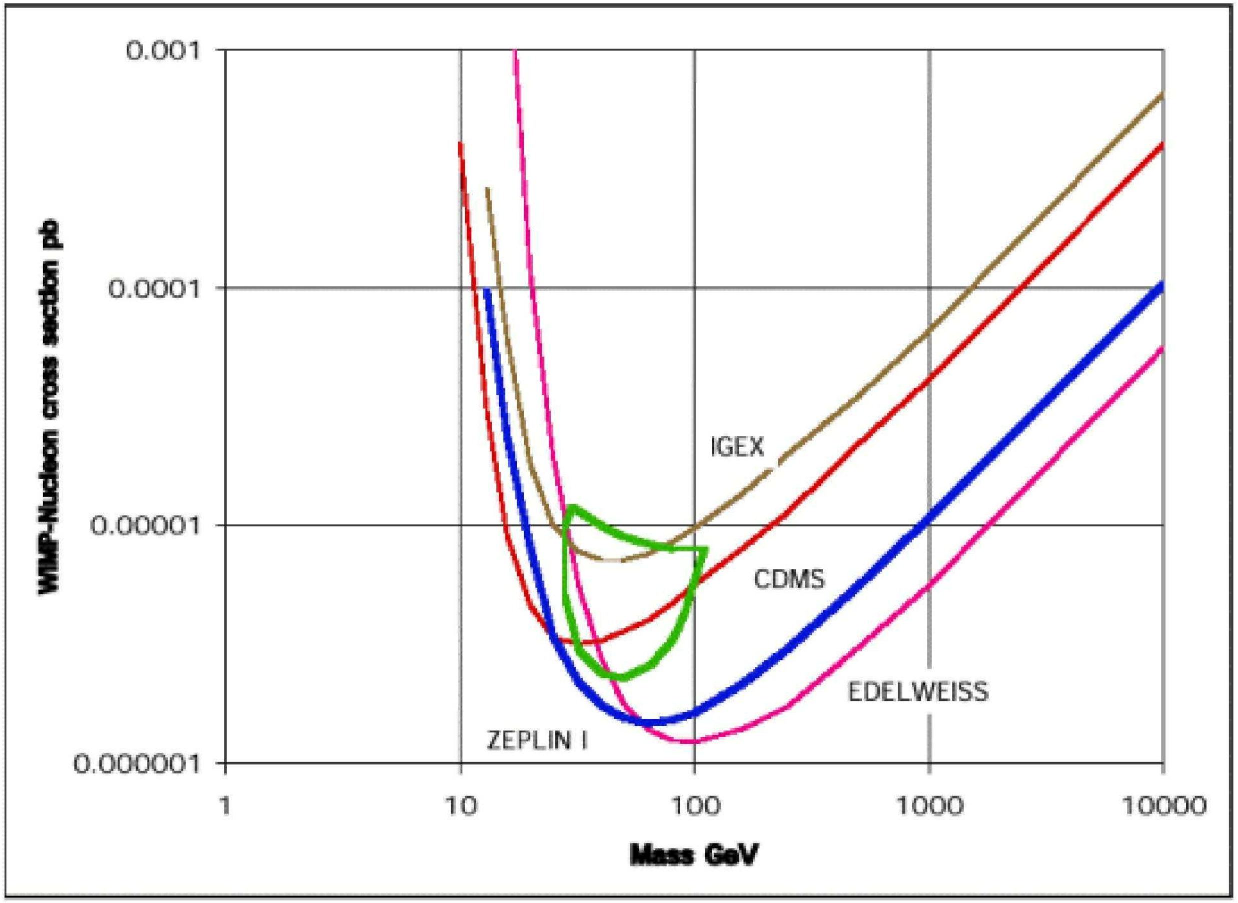


$\Rightarrow$ mSUGRA scenario consistent with all experimental constraints

Direct search for dark matter:

E.g.: scattering off nuclei ⇒ measurement of nuclear recoil

Present limits in the plane of m_{WIMP} and the WIMP–nucleon cross section σ_{SI} from different experiments



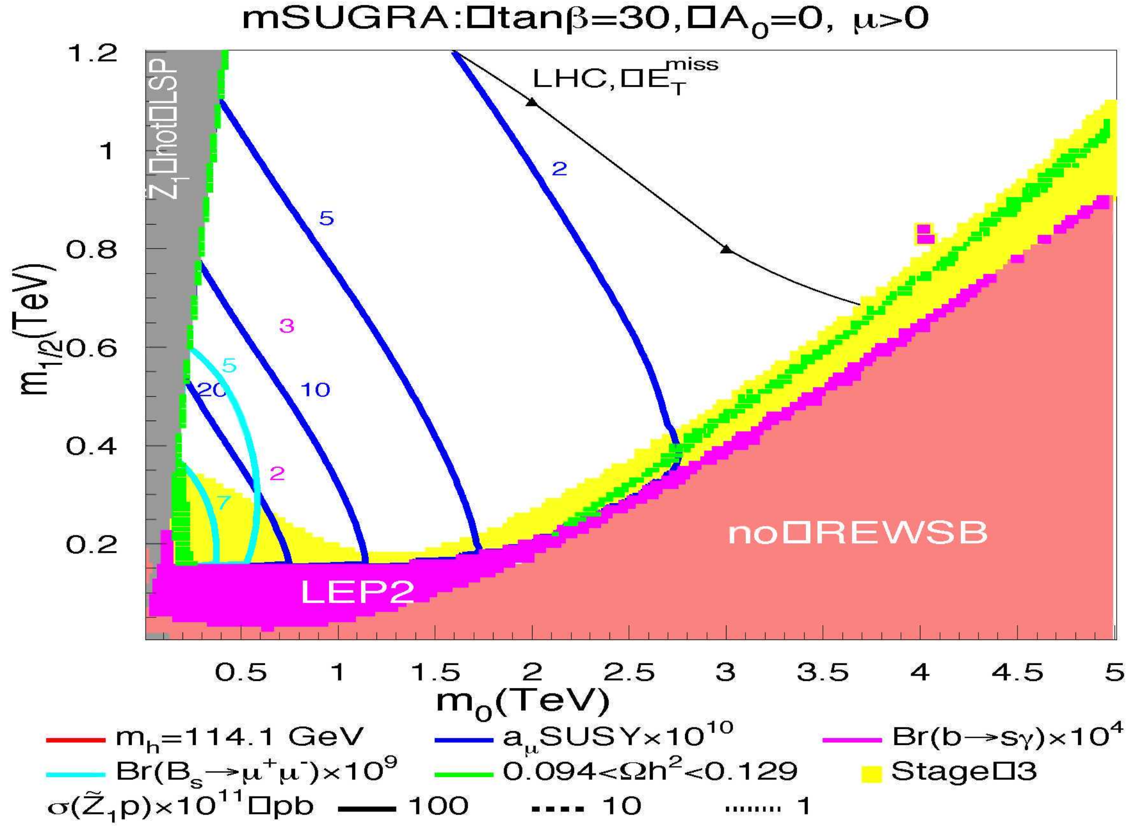
⇒ Present limits on $\sigma_{\rm SI}$ ("Stage 1" dark matter experiments): $\approx 10^{-5}$–10^{-6} pb

Anticipated sensitivity of possible future dark matter experiments ("Stage 3"): $\sigma_{\rm SI} \approx 10^{-9}$–$10^{-10}$ pb

Accessible parameter region (yellow) in mSUGRA scenario ($\tan\beta = 30$, $\mu > 0$, $A_0 = 0$) with Stage 3 sensitivity vs. CDM allowed region and LHC sensitivity

[*H. Baer, C. Bal'azs,*

A. Belyaev, J. O'Farrill '03]



Electroweak precision tests: SM vs. MSSM

Electroweak precision measurements:

$M_Z[\text{GeV}] = 91.1875 \pm 0.0021$ 0.002%

$G_\mu[\text{GeV}^{-2}] = 1.16637(1)\,10^{-5}$ 0.0009%

$m_t[\text{GeV}] = 174.3 \pm 5.1$ 2.9%

$M_W[\text{GeV}] = 80.426 \pm 0.034$ 0.04%

$\sin^2\theta_{\text{eff}}^{\text{lept}} = 0.23148 \pm 0.00017$ 0.07%

$\Gamma_Z[\text{GeV}] = 2.4952 \pm 0.0023$ 0.09%

$\dots$

Quantum effects of the theory: loop corrections: $\sim \mathcal{O}(1\%)$

SM: M_H is free parameter

precise measurement of M_W, $\sin^2\theta_{\text{eff}}$, $\dots \Rightarrow$ constraints on M_H

MSSM: m_h is predicted

precise meas. of M_W, $\sin^2\theta_{\text{eff}}$, m_h, $\dots \Rightarrow$ constr. on $m_{\tilde{t}}$, $\theta_{\tilde{t}}$, $m_{\tilde{b}}$, $\theta_{\tilde{b}}$, $\dots$

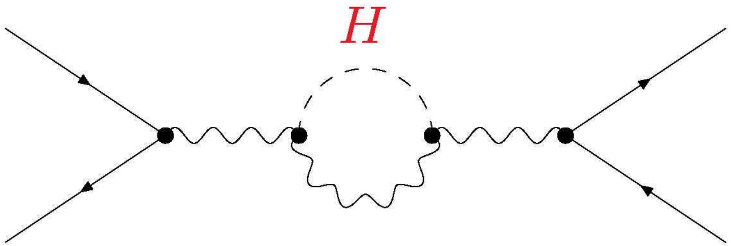
Comparison of ew precision data with theory:

EW precision data:
$M_Z, M_W, \sin^2\theta_{\rm eff}^{\rm lept}, \ldots$

Theory:
SM, MSSM, ...

$\Downarrow$

Test of theory at quantum level:



$\Downarrow$

Improve indirect constraints on unknown parameters: M_H, $m_{\tilde{t}}$, ...

effects of "new physics"?

Indirect determination of m_{t} from precision data:

$$m_{\mathrm{t}} = 180.3^{+11.7}_{-9.2}\ \mathrm{GeV}$$

Direct measurement:

$$m_{\mathrm{t}} = 174.3 \pm 5.1\ \mathrm{GeV}$$

Leading corrections to precision observables:

$$\sim m_{\mathrm{t}}^2$$

$$\sim \ln M_{\mathrm{H}}$$

⇒ Very high accuracy of measurements and theoretical predictions needed

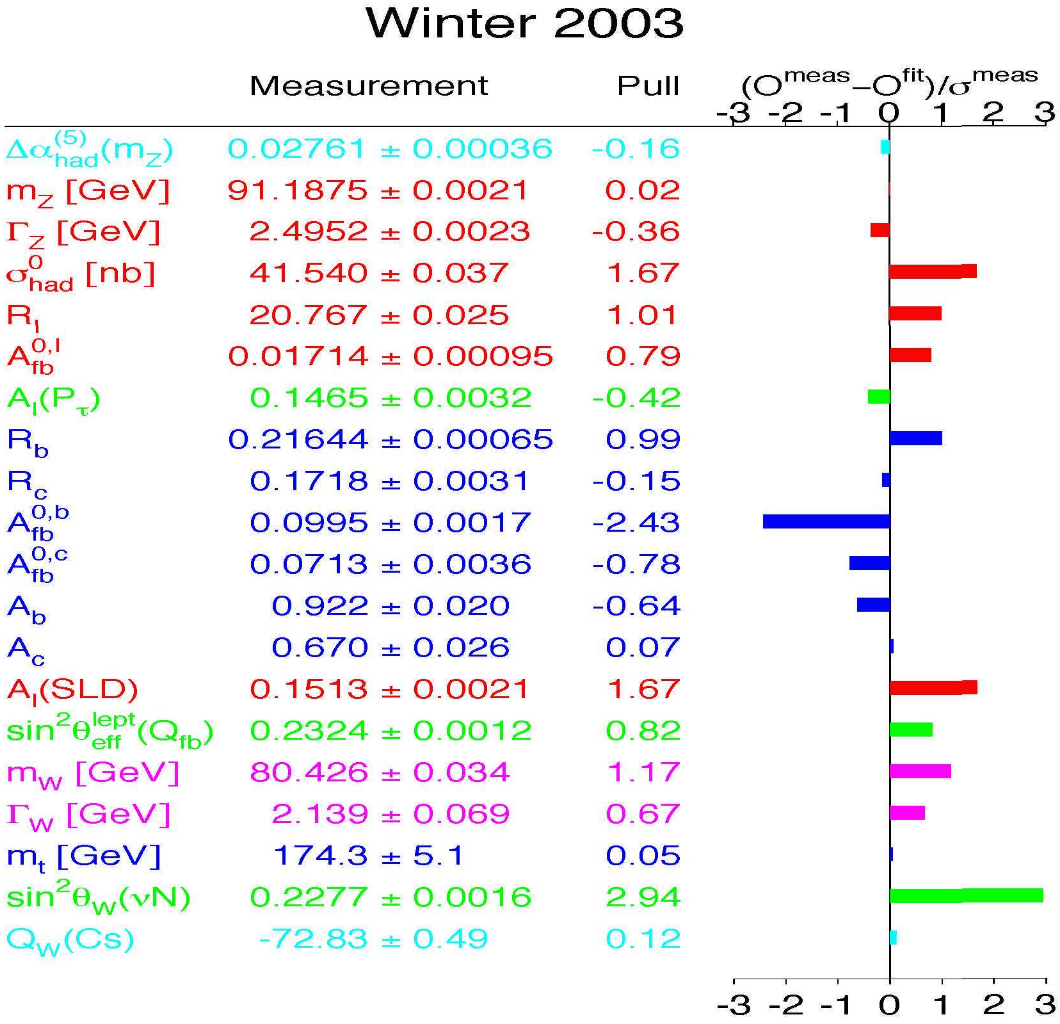
Theoretical uncertainties:

- unknown higher-order corrections
- experimental error of input parameters: m_{t}, $\Delta\alpha_{\mathrm{had}}$, ...

Global fit of the SM to all data:

Basic assumption: SM provides correct description of experimental data

Comparison of SM prediction with the data:
[*LEPEWWG '03*]



Winter 2003

	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-0.16
m_Z [GeV]	91.1875 ± 0.0021	0.02
Γ_Z [GeV]	2.4952 ± 0.0023	-0.36
σ^0_{had} [nb]	41.540 ± 0.037	1.67
R_l	20.767 ± 0.025	1.01
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.79
$A_l(P_\tau)$	0.1465 ± 0.0032	-0.42
R_b	0.21644 ± 0.00065	0.99
R_c	0.1718 ± 0.0031	-0.15
$A^{0,b}_{fb}$	0.0995 ± 0.0017	-2.43
$A^{0,c}_{fb}$	0.0713 ± 0.0036	-0.78
A_b	0.922 ± 0.020	-0.64
A_c	0.670 ± 0.026	0.07
A_l(SLD)	0.1513 ± 0.0021	1.67
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.82
m_W [GeV]	80.426 ± 0.034	1.17
Γ_W [GeV]	2.139 ± 0.069	0.67
m_t [GeV]	174.3 ± 5.1	0.05
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	2.94
Q_W(Cs)	-72.83 ± 0.49	0.12

Overall fit probability (quality of the fit): 4.4%

Comparison of current experimental errors with anticipated precision at

Run II of the Tevatron ($p\bar{p}$ collider, $E_{\mathrm{CM}} \approx 2$ TeV; ≥ 2001),

LHC (pp collider, $E_{\mathrm{CM}} \approx 14$ TeV; $\gtrsim 2007$,

LC (e^+e^- collider, $E_{\mathrm{CM}} \approx 500$–$1000$ GeV, $\gtrsim 201x$?)
with and without low-energy running mode (GigaZ)

	now	Tev. Run IIA	Run IIB	LHC	LC	GigaZ
$\delta \sin^2\theta_{\mathrm{eff}}(\times 10^5)$	17	78	29	14–20	—	1.3
δM_{W} [MeV]	34	27	16	15	10	7
δm_{t} [GeV]	5.1	2.7	1.4	1.0	0.1	0.1
δm_{h} [MeV]	—	—	$\mathcal{O}(2000)$	100	50	50

Additional sources for sizable radiative corrections in the MSSM:

- Mass and couplings of light $\mathcal{CP}$-even Higgs:
  Large Yukawa corrections: $\sim G_\mu m_\mathrm{t}^4 \ln\left(\frac{m_{\tilde{\mathrm{t}}_1} m_{\tilde{\mathrm{t}}_2}}{m_\mathrm{t}^2}\right)$, ...
- t / $\tilde{\mathrm{t}}$ loops, b / $\tilde{\mathrm{b}}$ loops (for large $\tan\beta$)
- Corr. to relation between bottom mass and bottom Yukawa coupling:

$$y_b = \frac{\sqrt{2}}{v\cos\beta}\frac{m_\mathrm{b}}{1+\Delta_b},$$

  $\Delta_b = \mu \tan\beta\,(\alpha_\mathrm{s} I(\ldots) + \alpha_\mathrm{t} I(\ldots))$

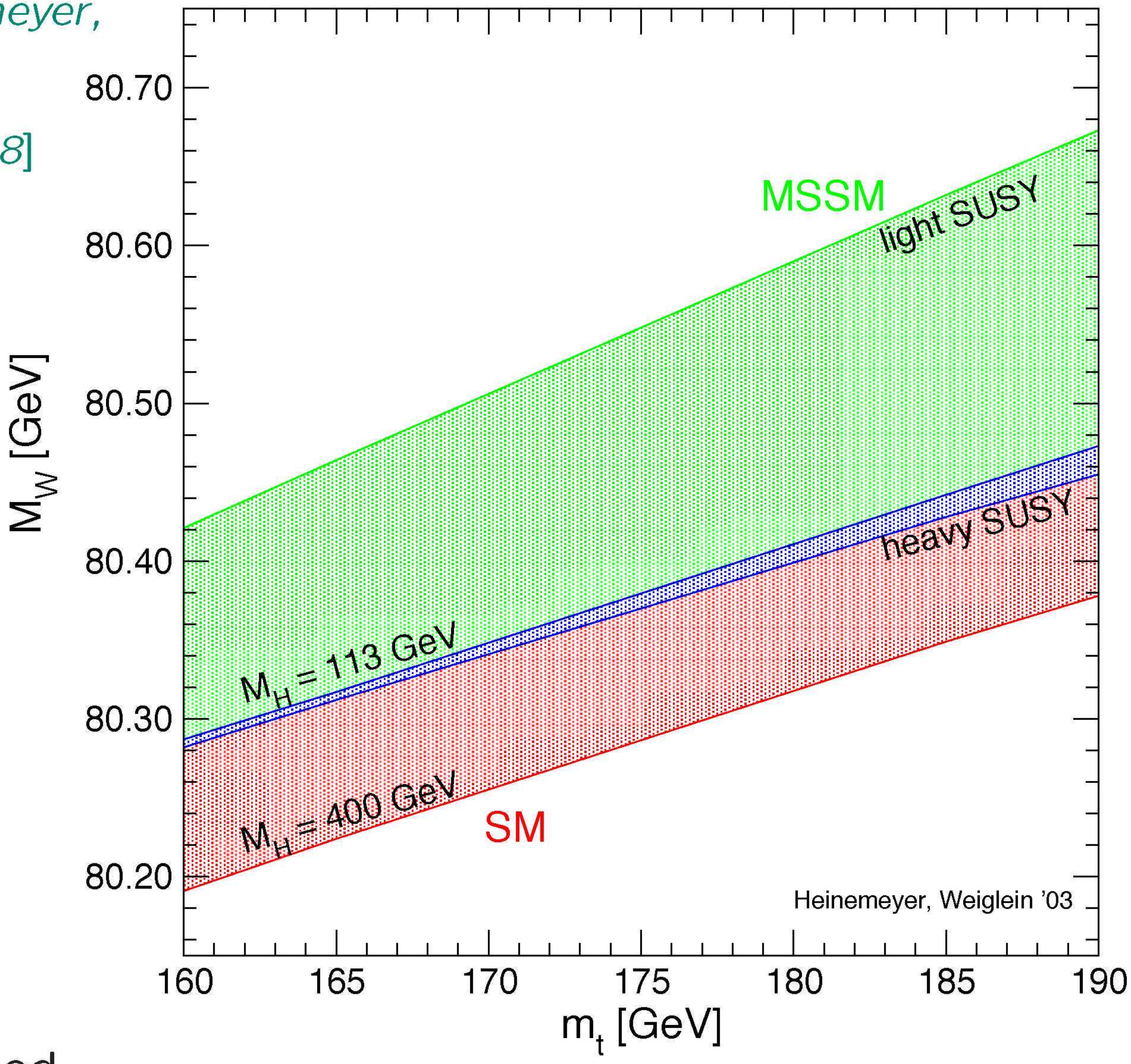
  $\Rightarrow$ Coupling non-perturbative for $\Delta_b \to -1$

- Loop contributions from light SUSY particles
- ...

Prediction for M_W in the SM and the MSSM:

[A. Djouadi, P. Gambino, S. Heinemeyer, W. Hollik, C. Jünger, G. W. '97]

[S. Heinemeyer, W. Hollik, G. W. '98]



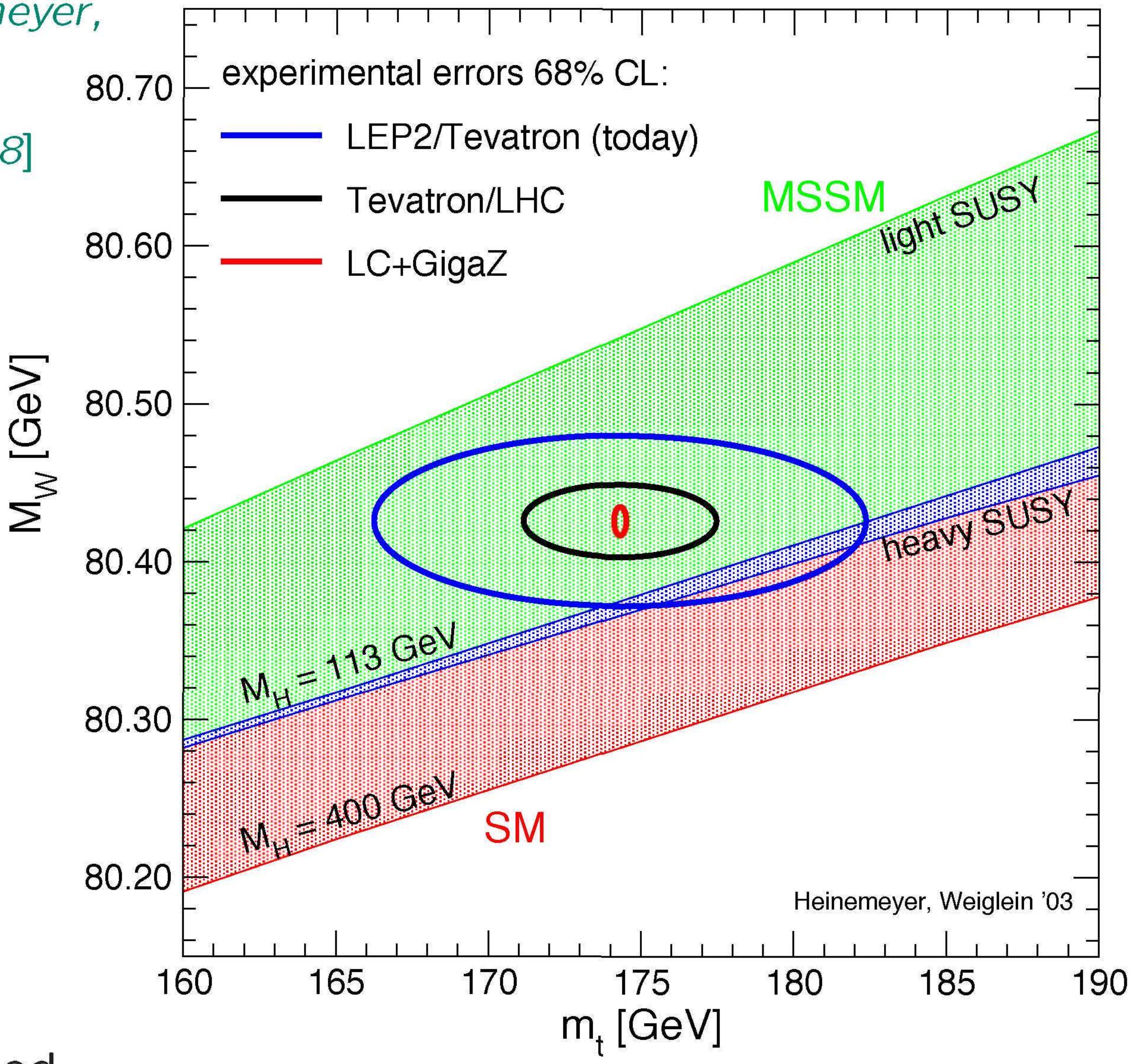
SM: M_H varied

MSSM: SUSY parameters varied

Prediction for M_W in the SM and the MSSM:

[A. Djouadi, P. Gambino, S. Heinemeyer, W. Hollik, C. Jünger, G. W. '97]

[S. Heinemeyer, W. Hollik, G. W. '98]

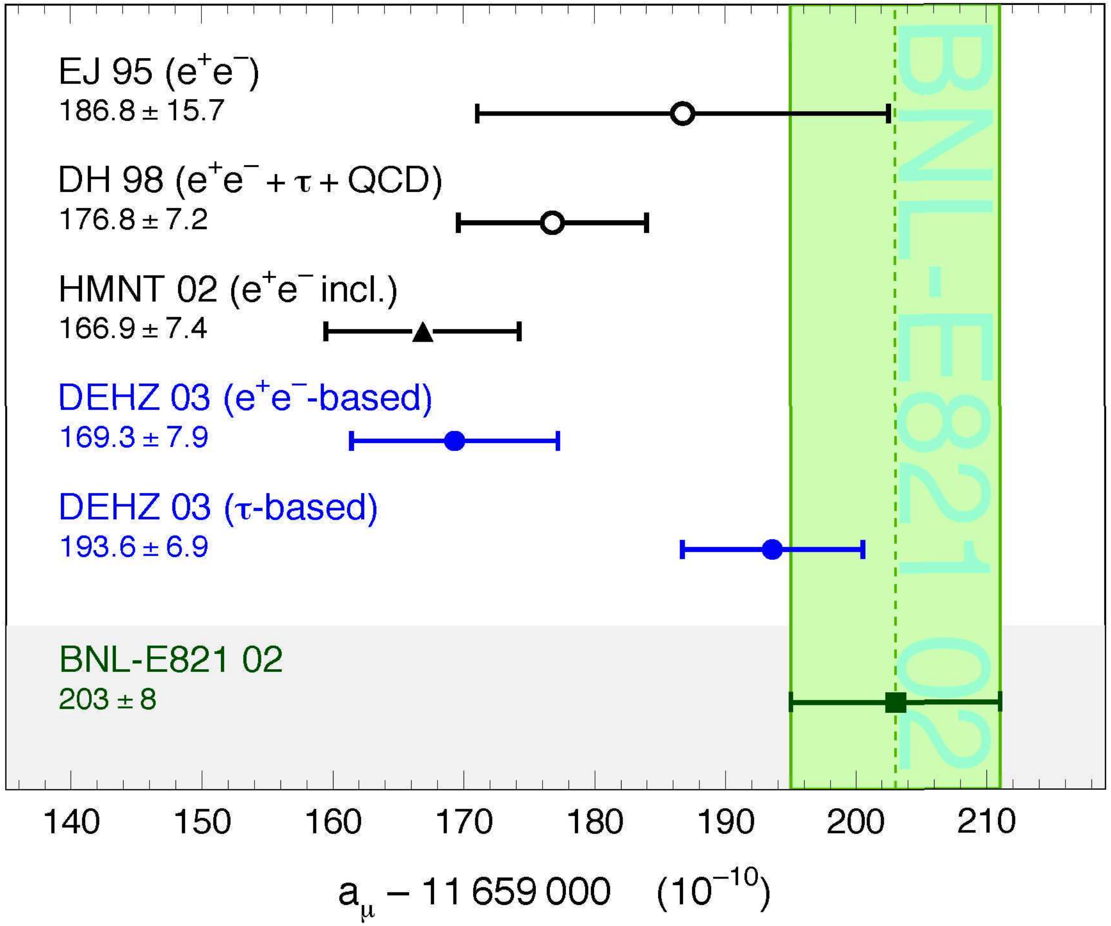


SM: M_H varied

MSSM: SUSY parameters varied

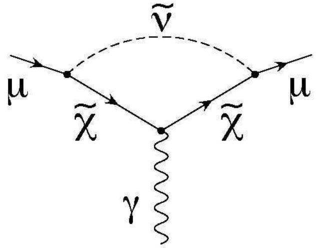
Experimental result for anomalous magnetic moment of the muon vs. SM prediction:

[*Muon* $(g-2)$ *Collaboration '02*]



$\Rightarrow$ a_μ(exp) − a_μ(SM): 1–3 σ deviation (sizable hadronic uncertainties)

Compatible with effect of SUSY contributions to a_μ:

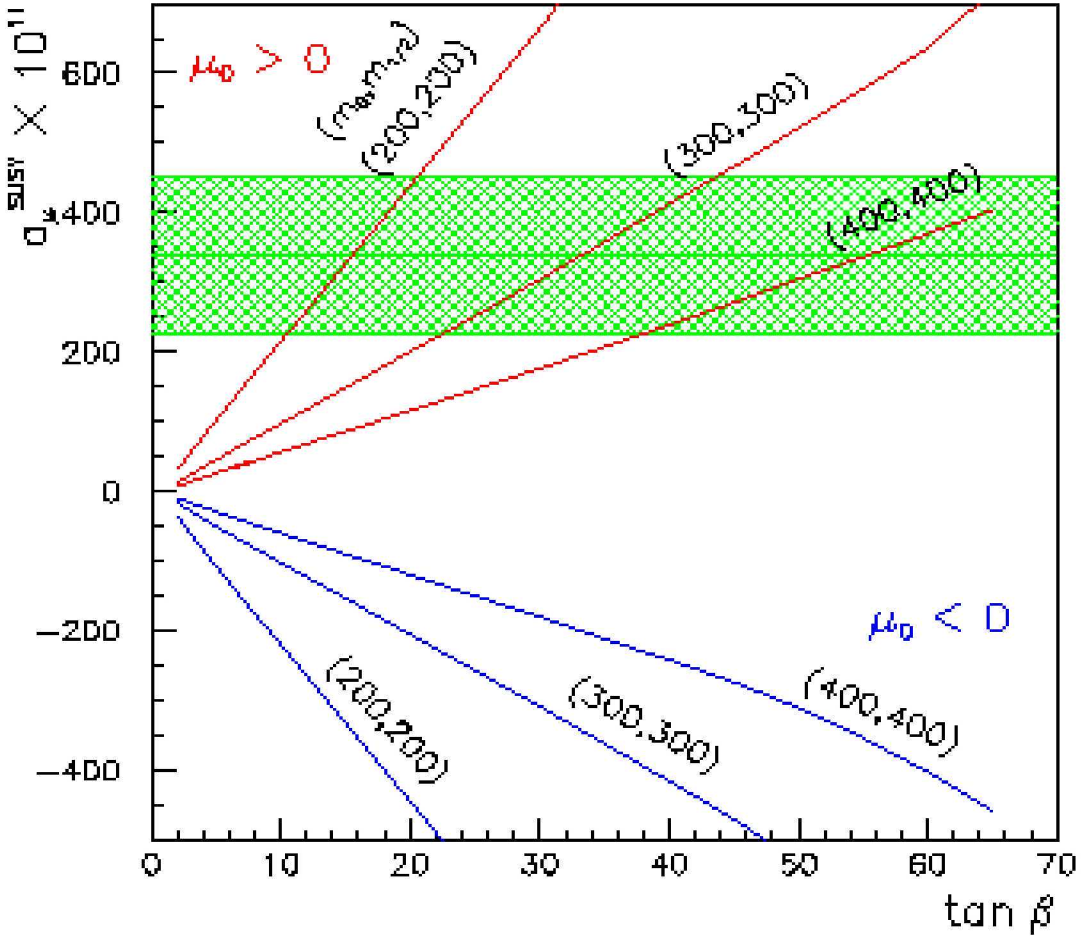


mSUGRA predictions for $(g_\mu - 2)$:

[*W. de Boer, C. Sander '02*]

$$a_\mu = \frac{1}{2}(g_\mu - 2)$$

$$a_\mu - a_\mu^{\mathrm{SM}} = (338 \pm 112) \times 10^{-11}$$



⇒ Preference for $\mu > 0$

note: influenced by hadronic uncertainties of SM result

No convincing new physics model for "explaining" deviations from SM in $\sin^2\theta_{\text{eff}}$ and ν–nucleon scattering from NuTeV

Note, however:
if NuTeV result interpreted as deviation in $Z\nu\bar{\nu}$ coupling:
(ν neutral current rate)/prediction:

0.995 ± 0.003	LEP1 lineshape (invisible Z width)
0.988 ± 0.004	NuTeV

Need some patience until experimental clarification:

A_{LR}, A_{FB}:	LC with GigaZ option?
ν–nucleon scatt.:	ν factory?

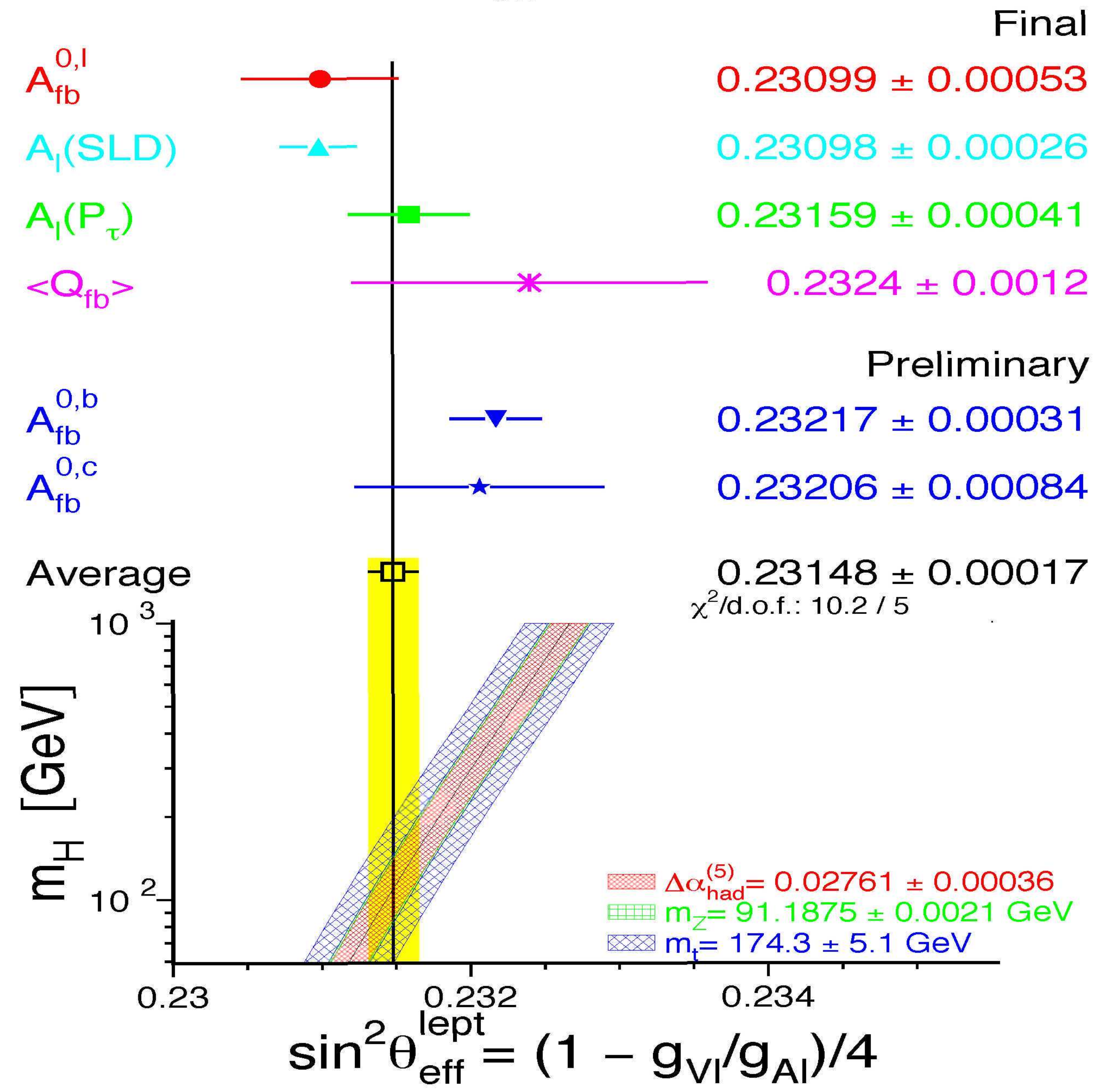
If hadronic data on A_{FB} and NuTeV data on ν–nucleon scattering were removed from fit:

much better fit quality, probability $\approx 70\%$

stronger preference for light Higgs: $M_{\text{H}} \lesssim 150$ GeV, 95% C.L.

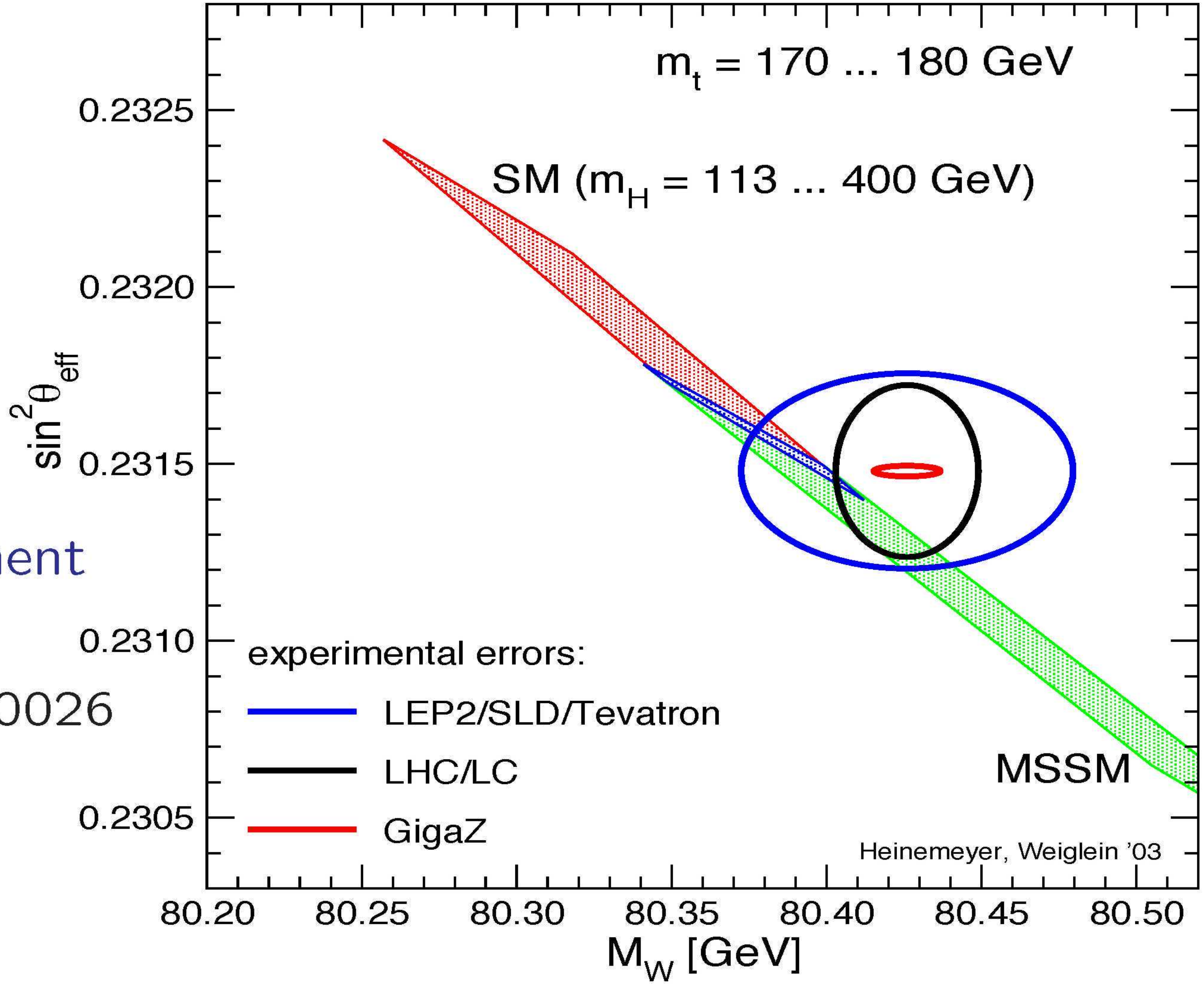
The effective weak mixing angle $\sin^2\theta_{\text{eff}}$:

[LEPEWWG '03]



Prediction for M_{W}, $\sin^2\theta_{\mathrm{eff}}$ in SM and MSSM:

[*S. Heinemeyer, G. W. '01*]



Scenario where measurement of $A_{\mathrm{FB}}^{\mathrm{b}}$ is discarded:

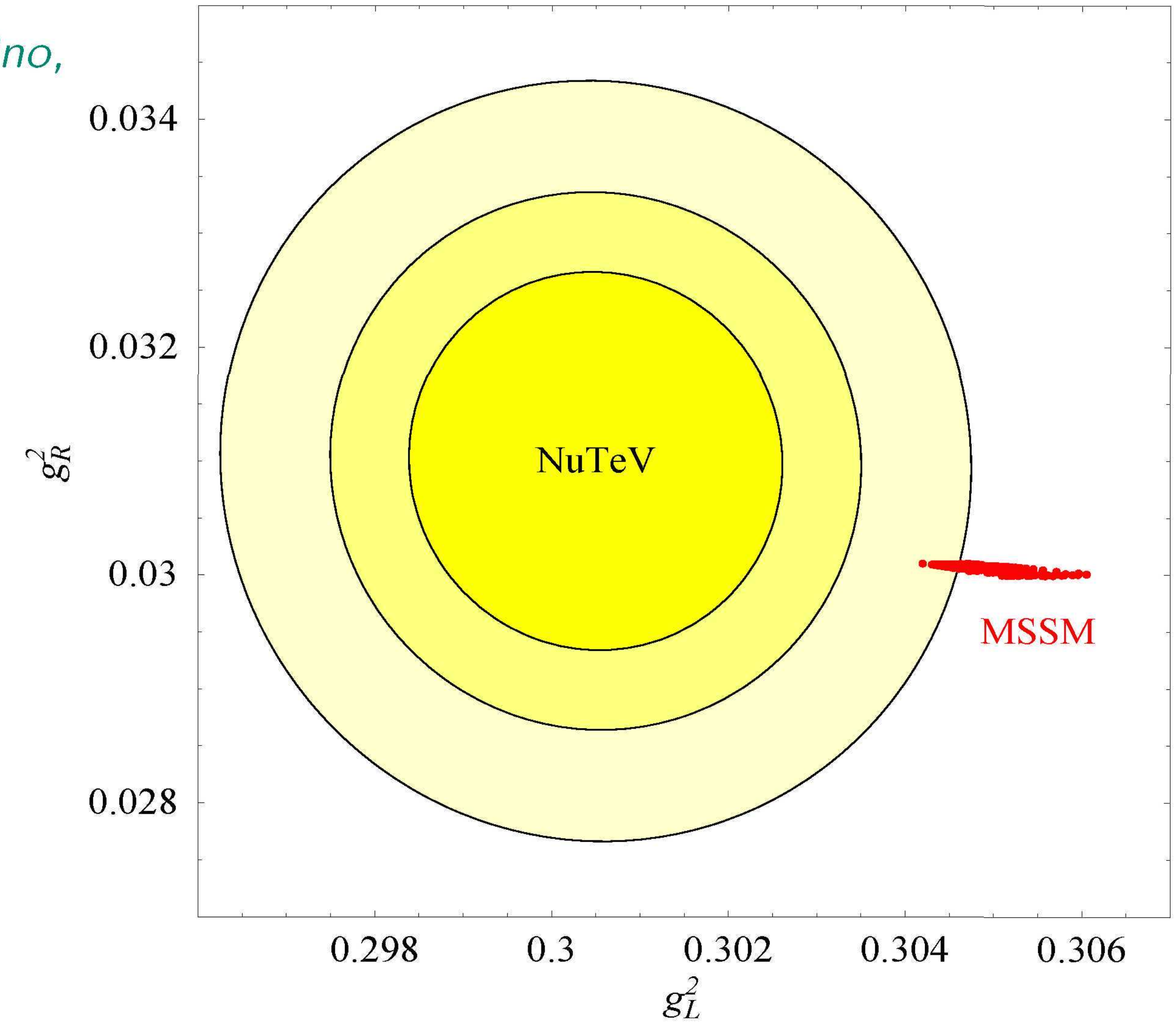
$\sin^2\theta_{\mathrm{eff}}^{\mathrm{SLD}} = 0.23098 \pm 0.00026$

⇒ good agreement with MSSM prediction

⇒ High sensitivity to deviations both from the SM and the MSSM

MSSM prediction for neutrino–nucleon scattering (measured at NuTeV):

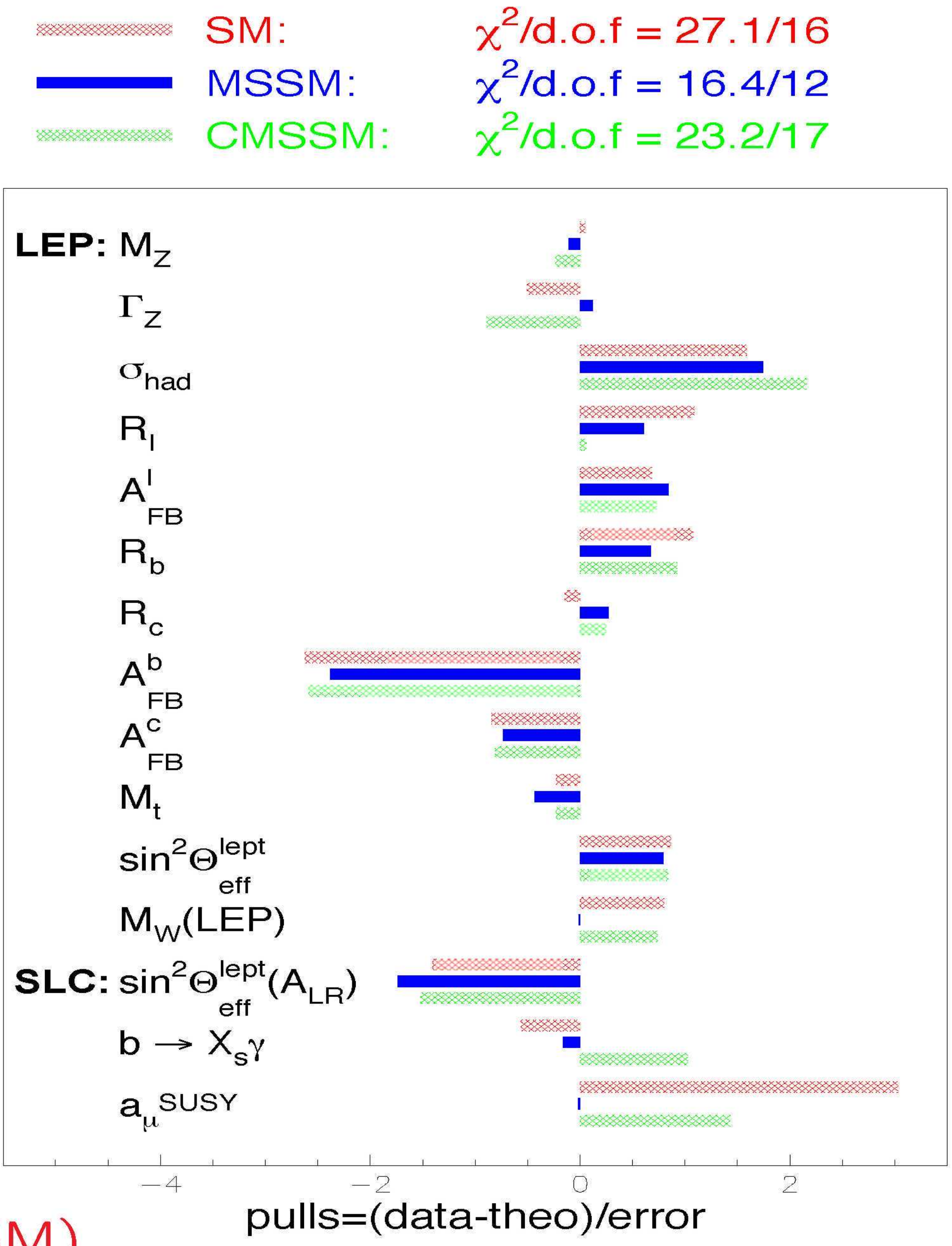
[S. Davidson, S. Forte, P. Gambino, N. Rius, A. Strumia '02]



$\Rightarrow$ Discrepancy cannot be explained in MSSM (light slepton corrections)

Global fit: SM / unconstrained MSSM / mSUGRA

[*W. de Boer, C. Sander '02*]



⇒ MSSM contributions can improve agreement with data for $g_\mu - 2$ (for large tan β) and $M_{\rm W}$

no significant improvement for $A^{\rm b}_{\rm FB}$ and neutrino–nucleon cross section

Similar quality of global fit
(slightly better in MSSM than in SM)

Prospects for SUSY searches at the next generation of colliders

Limits on SUSY particles from LEP, Tevatron Run I: $\mathcal{O}(100\,\text{GeV})$

But: some SUSY particles can be much lighter if they have small coupling to Z boson

E.g.:

- no strict lower bound on lightest neutralino if "GUT relation" between M_1 and M_2 is relaxed
- A light sbottom with $m_{\tilde{b}_1} \approx 5$ GeV is in agreement with electroweak precision tests, Higgs searches, . . .
  [M. Carena, S. Heinemeyer, C. Wagner, G. W. '01]
- . . .

SUSY searches at the Tevatron, Run II:

compared to Run I: $\approx 100\times$ higher luminosity, slightly increased energy (1.8 $\to$ 2 TeV)

Limited mass window in which discovery of SUSY particles above Run I is possible

Best prospects for:

- 'Trilepton signal': $\tilde{\chi}_2^0\tilde{\chi}_1^+ \to \ell^+\ell^-\tilde{\chi}_1^0\ell^+\nu\chi_1^0$
- $\tilde{t}$, $\tilde{b}$ searches
- light SUSY Higgs h in region of large $\tan\beta$

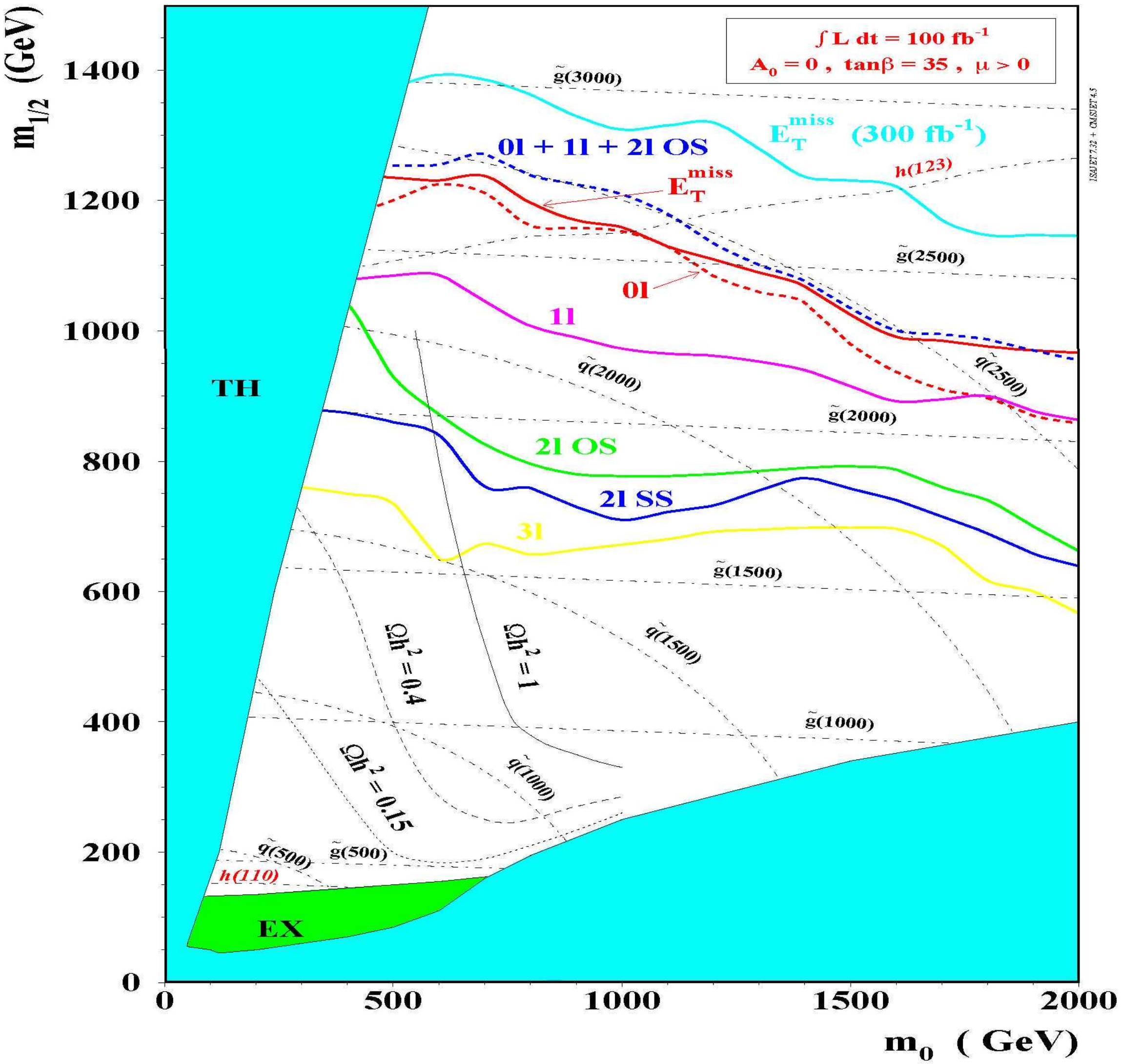
SUSY searches at the LHC:

Dominated by production of colored particles: gluino, squarks

Very large mass range in the searches for jets + missing energy

$\Rightarrow$ gluino, squarks accessible up to 2–3 TeV

Discovery reach contours in m_0–$m_{1/2}$ plane (mSUGRA scenario) for various final states with 100 fb^{-1}: [*CMS '99*]



⇒ discovery of SUSY particles expected if low-energy SUSY is realized

Production of SUSY particles at the LHC will in general result in complicated final states, e.g.

$$\tilde{g} \to \bar{q}\tilde{q} \to \bar{q}q\tilde{\chi}_2^0 \to \bar{q}q\tilde{\tau}\tau \to \bar{q}q\tau\tau\tilde{\chi}_1^0$$

Production of uncolored particles via cascade decays often dominates over direct production

Many states are produced at once

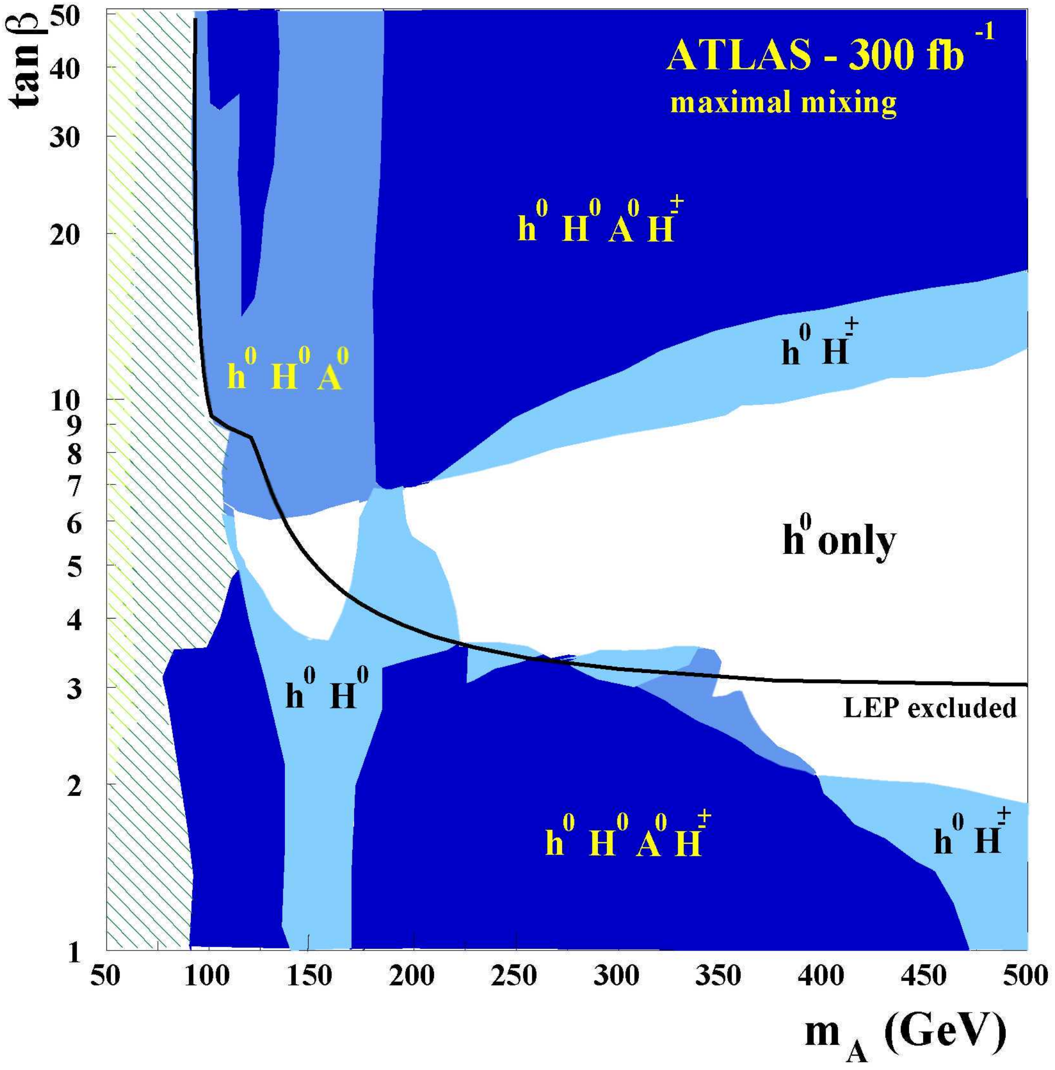
⇒ **Main background for SUSY is SUSY itself!**

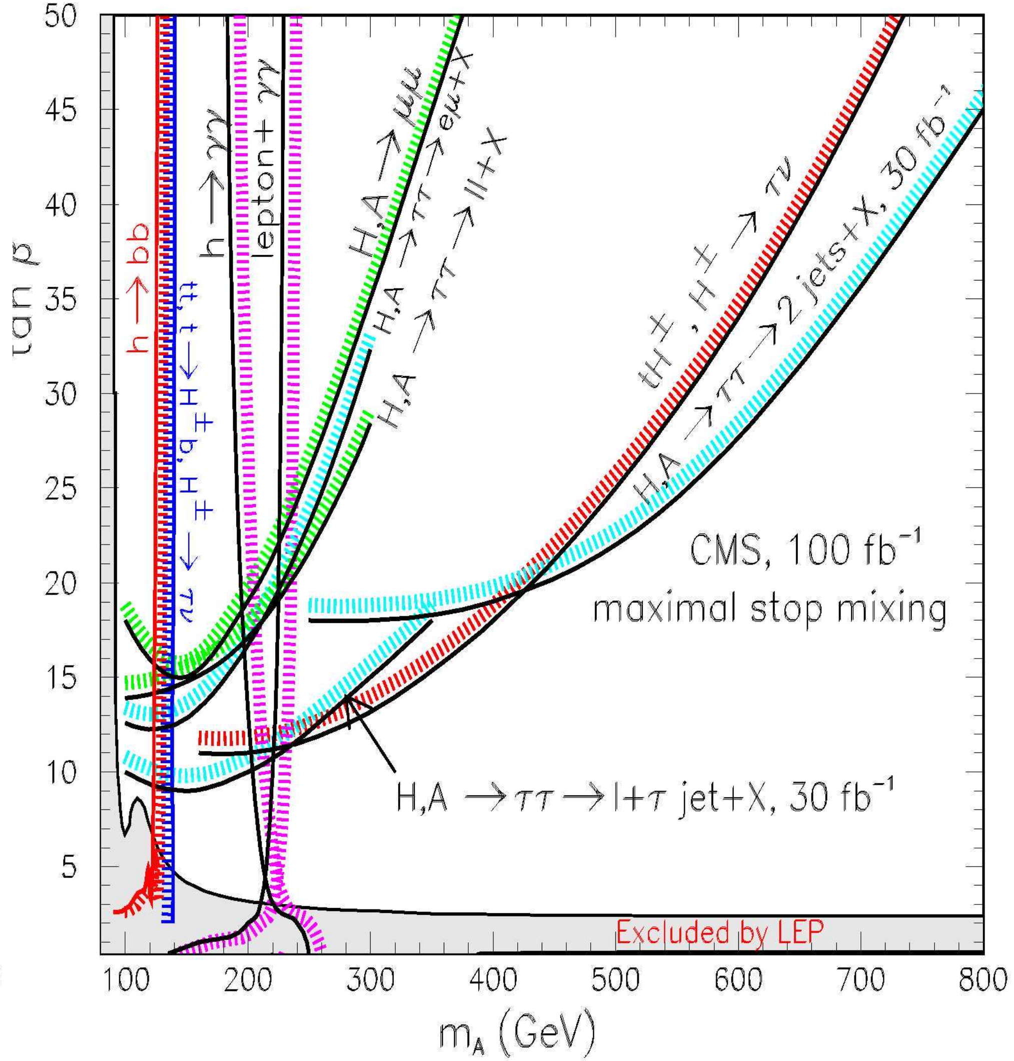
Searches for MSSM Higgs bosons:

good prospects for detecting light Higgs h

H/A discovery possible in significant part of parameter space

MSSM Higgs discovery contours in M_A–tan β plane ($m_h^{\max}$ benchmark scenario): [*ATLAS '99*] [*CMS '03*]





In order to establish SUSY experimentally:

Need to demonstrate that:

- every particle has superpartner
- their spins differ by 1/2
- their gauge quantum numbers are the same
- their couplings are identical
- mass relations hold

. . .

⇒ Precise measurements of masses, branching ratios, cross sections, angular distributions, . . . mandatory for

- establishing SUSY experimentally
- disentangling patterns of SUSY breaking

Requires clean experimental environment, high luminosity, beam polarization, . . .

$\Rightarrow$ High luminosity LC necessary, complementary to hadron machines

SUSY searches at the LC:

Clean signatures, small backgrounds

Thresholds for pair production of SUSY particles

$\Rightarrow$ precise determination of mass and spin of SUSY particles, mixing angles, complex phases, . . .

Limited by kinematic reach

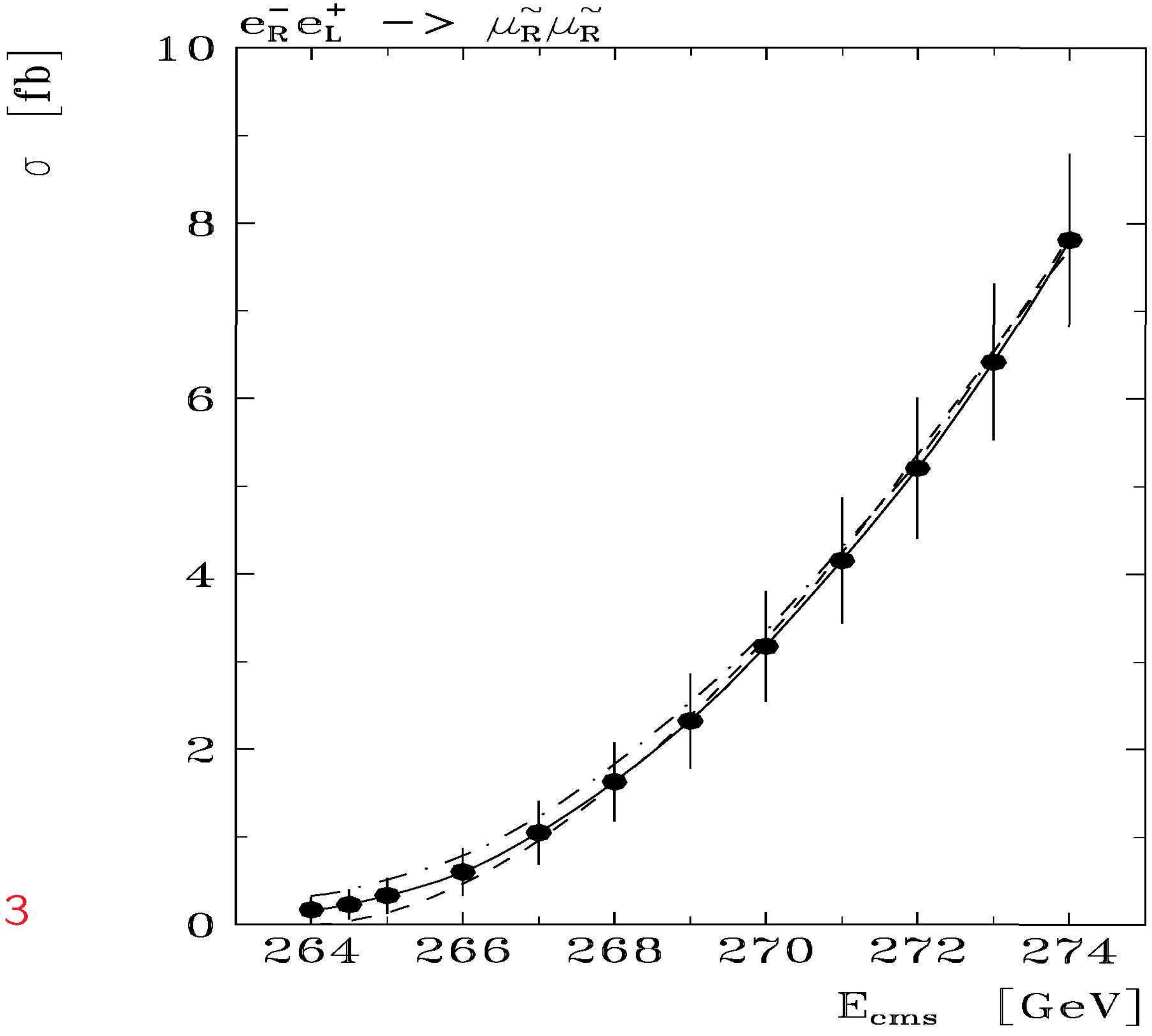
Good prospects for production of uncolored particles

$\Rightarrow$ LHC / LC complementarity

Examples for SUSY physics at the LC:

Determination of mass and spin of $\tilde{\mu}_R$ from production at threshold:

[TESLA TDR '01]

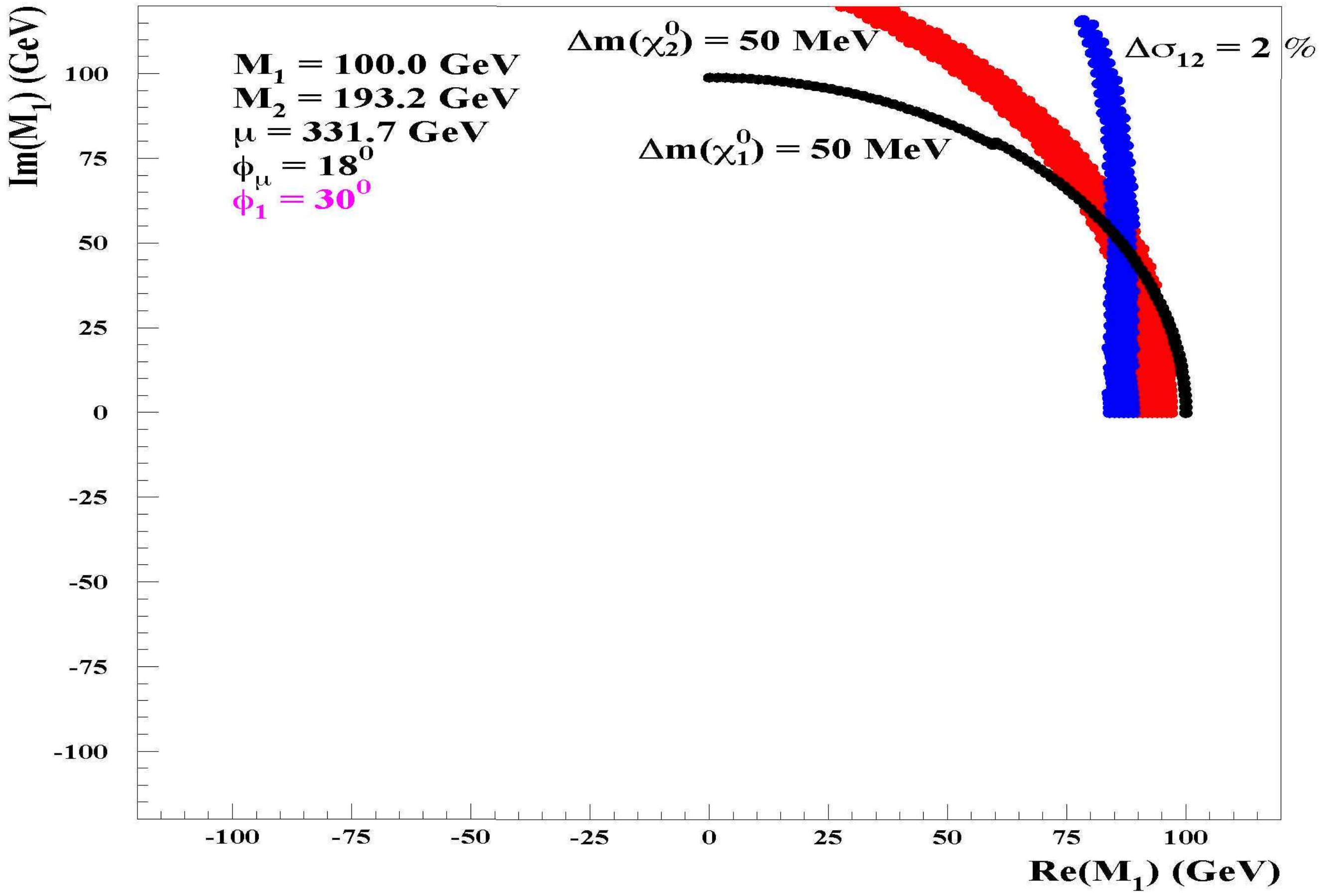


$$\Rightarrow \quad \frac{\Delta m_{\tilde{\mu}_R}}{m_{\tilde{\mu}_R}} < 1 \times 10^{-3}$$

$\Rightarrow$ test of $J = 0$ hypothesis

Determination of phase ϕ_1 in neutralino sector from measurement of $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2$ and $e^+e^- \to \tilde{\chi}^+_1\tilde{\chi}^-_1$, $\mathcal{L} = 500\ \mathrm{fb}^{-1}$:

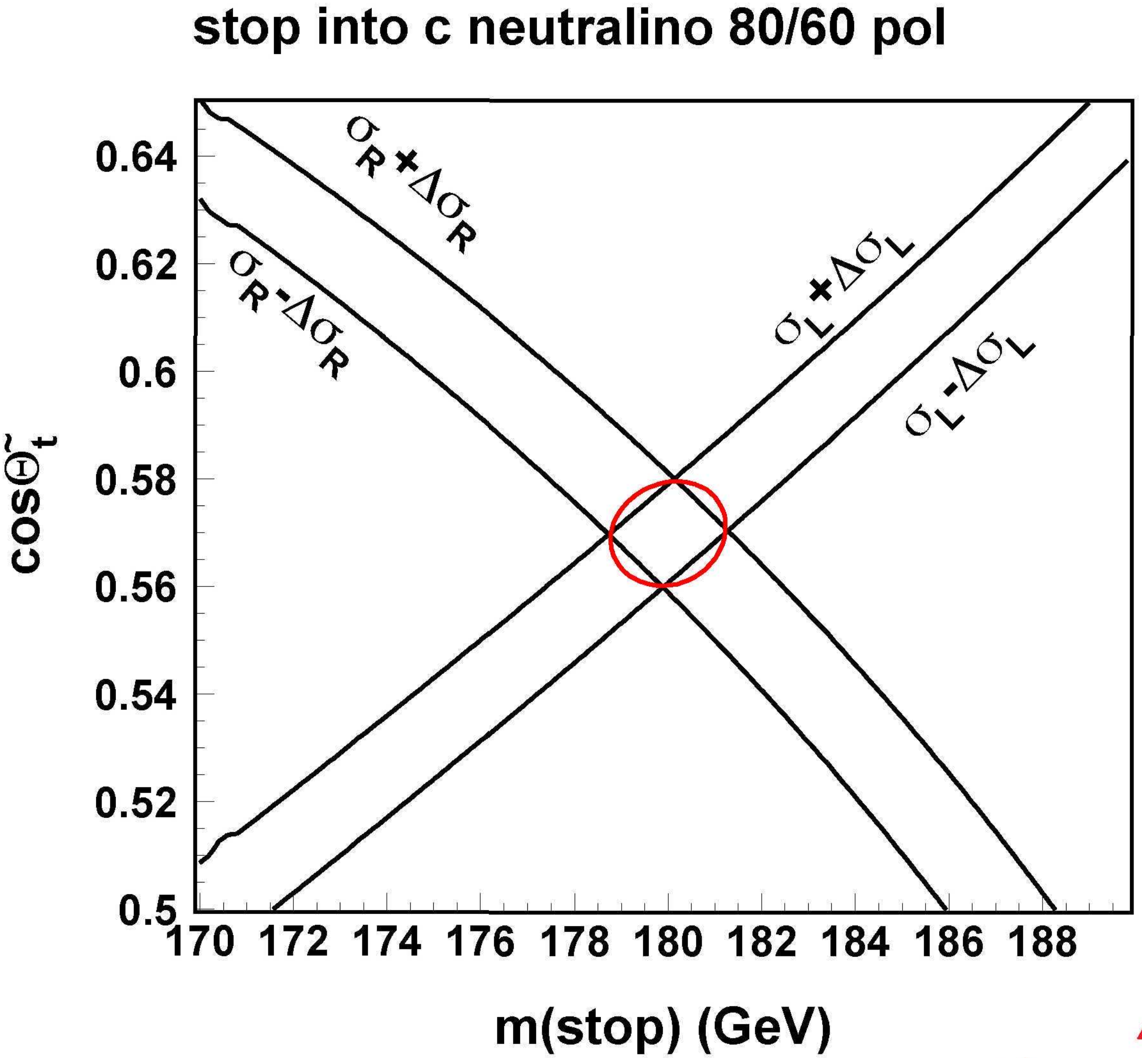
$m_{\tilde{\chi}^0_1} = 96.12 \pm 0.05$ GeV, $m_{\tilde{\chi}^0_2} = 177.13 \pm 0.05$ GeV, $m_{\tilde{\chi}^\pm_1} = 174.90 \pm 0.05$ GeV, $\Delta\sigma(\tilde{\chi}^0_1\tilde{\chi}^0_2) = \pm 2\%$ *[K. Desch, G. Moortgat-Pick '02]*



$\Rightarrow \Phi_1 = 30^0 \pm 3^0$

Determination of $m_{\tilde{t}_1}$, $\theta_{\tilde{t}}$ from $\sigma(e^+e^- \to \tilde{t}_1\tilde{t}_1)$ with polarized beams:

[R. Keränen, H. Nowak, A. Sopczak '00]



$$\Rightarrow \quad \frac{\Delta m_{\tilde{t}_1}}{m_{\tilde{t}_1}} \approx 0.5\%, \quad \frac{\Delta \cos\theta_{\tilde{t}}}{\cos\theta_{\tilde{t}}} \approx 1.5\%$$

Complementarity of LHC and LC:

⇒ Results obtained at one collider can be used for improving experimental analyses at the other

⇒ investigated in “LHC / LC Study Group”

`www.ippp.dur.ac.uk/~georg/lhclc`

Collaborative effort of Hadron Collider (HC) and Linear Collider (LC) community

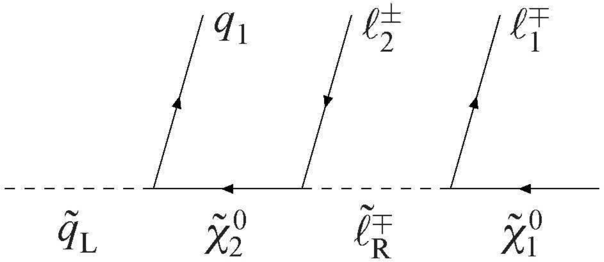
Started in spring 2002, currently about 190 working group members from ATLAS, CMS, LC working groups, theory + Tevatron contact person

Example: SUSY parameters at LHC and LC

Reconstruction of sparticle masses at the LHC

[B. Gjelsten, E. Lytken, D. Miller, P. Osland, G. Polesello, M. Chiorboli, A. Tricomi]

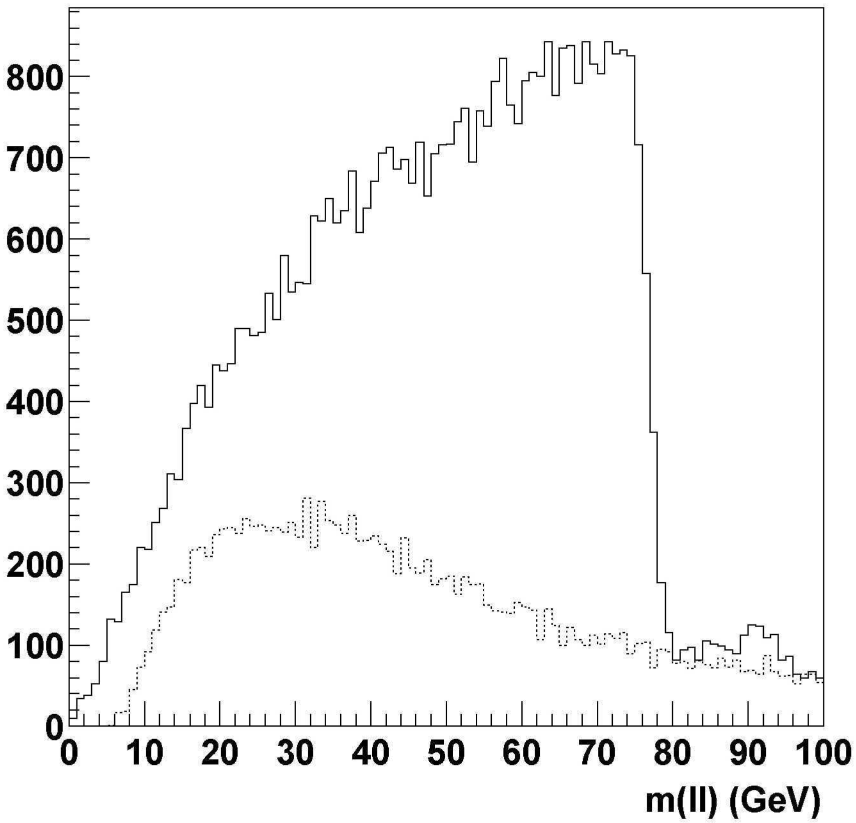
Complicated decay chains for squarks and gluinos

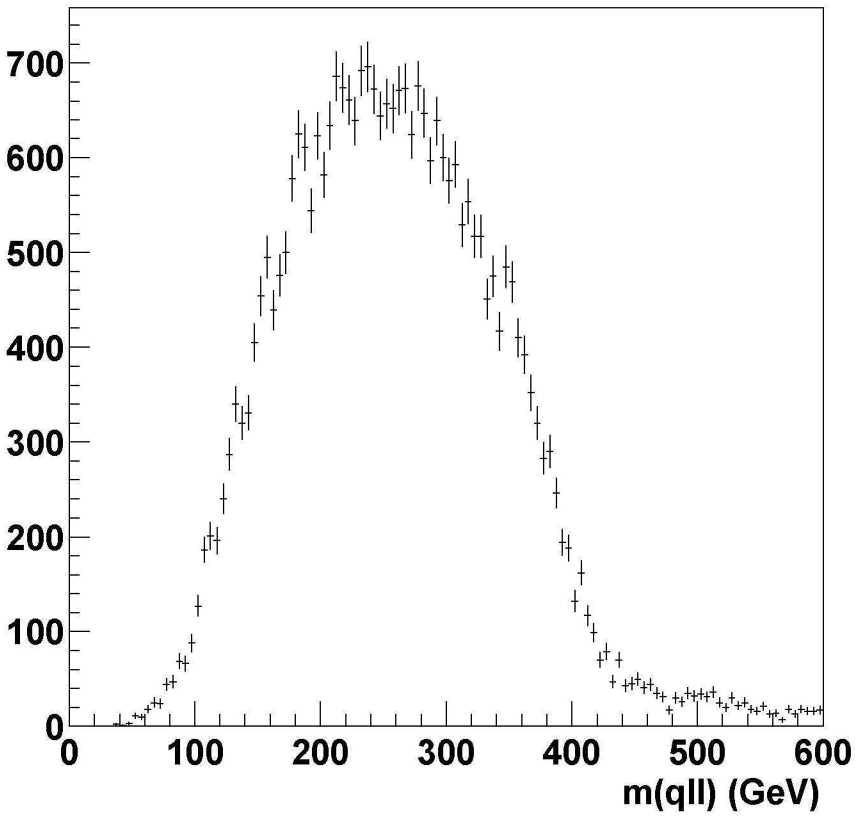


Examples worked out for SPS1a from ATLAS and CMS
main tool: dilepton "edge" from $\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0$

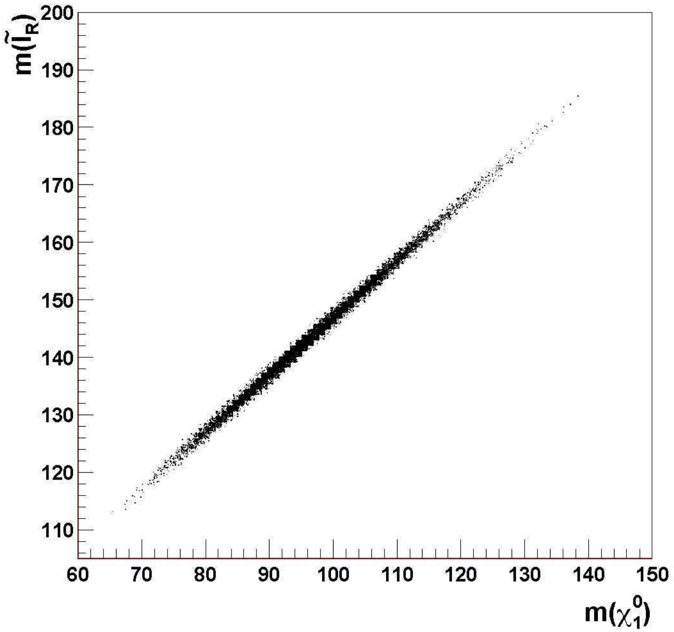
Sbottom/squark and gluino reconstruction:

Edge in same flavour-opposite sign lepton distribution (left), invariant mass distributions with kinematical endpoints (right)





Strong correlation between slepton mass and LSP mass, LSP mass can be constrained at LHC at the 10% level only:



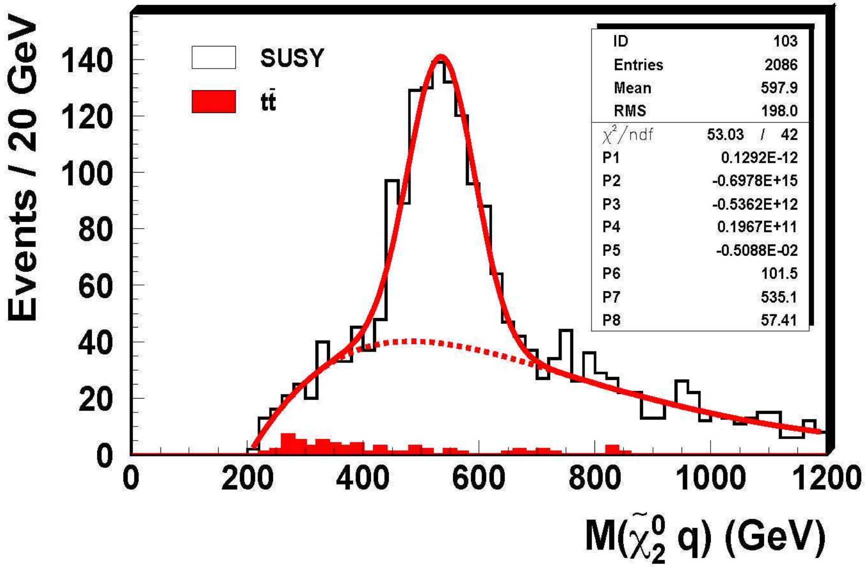
⇒ Take LSP mass as input from LC

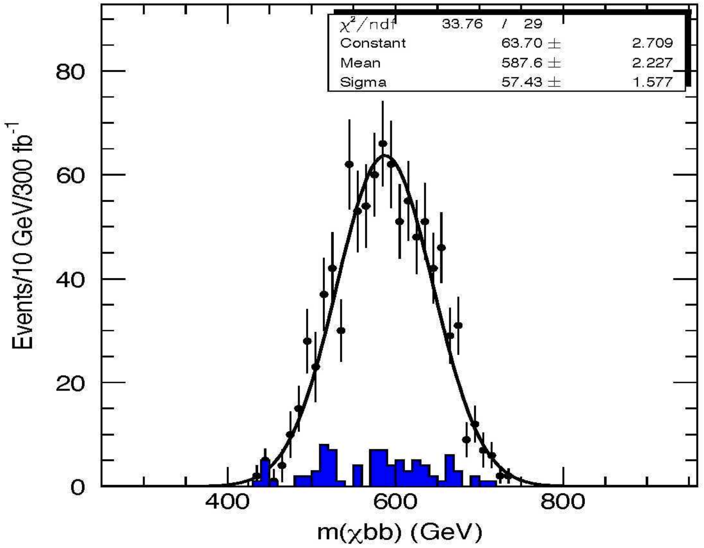
Select events close to the edge and combine with b-jet / q-jet

$$\vec{p}(\tilde{\chi}_2^0) = \left(1 - \frac{m(\tilde{\chi}_1^0)}{m(\ell\ell)}\right)\vec{p}_{\ell\ell}$$

⇒ Get sbottom/squark mass if LSP mass is known

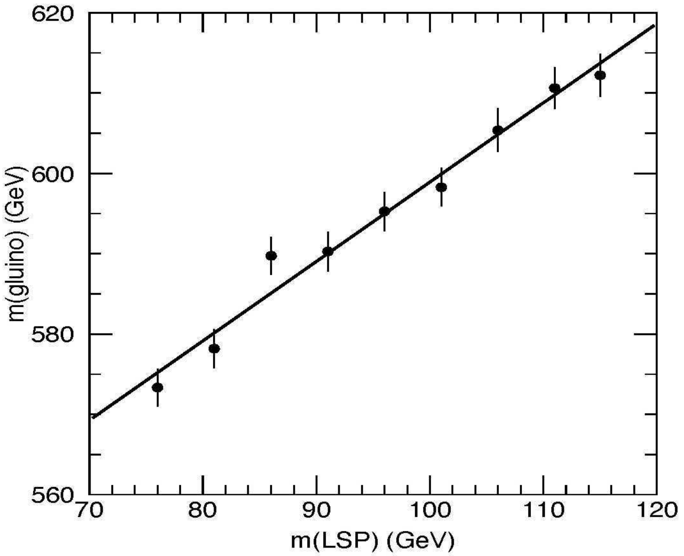
Squark peak (left) and gluino reconstruction from $(\chi_2^0 bb)$ invariant mass distribution (right):





$m_{\tilde{g}}$ as function of the LSP mass:

$\Rightarrow \Delta m_{\tilde{g}} \approx \Delta m_{\mathrm{LSP}}$



Accuracies for the case of the LHC alone (left) and with the LC measurement of the LSP mass with 0.2% accuracy (middle) and 1.0% accuracy (right column) in GeV:

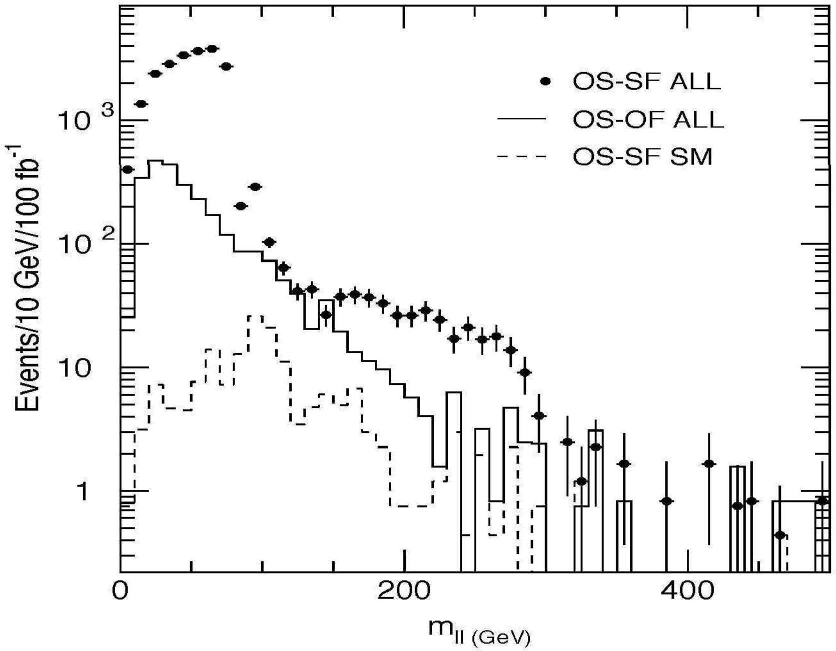
	LHC	LHC+LC (0.2%)	LHC+LC (1.0%)
$\Delta m_{\tilde{\chi}_1^0}$	9.2	0.2	1.0
$\Delta m_{\tilde{l}_R}$	9.2	0.5	1.0
$\Delta m_{\tilde{\chi}_2^0}$	9.0	0.3	1.0
$\Delta m_{\tilde{b}_1}$	23.1	16.9	17.0
$\Delta m_{\tilde{q}_L}$	15.0	5.1	5.3

⇒ LC input improves accuracy significantly

One step further:

Determination of the mass of the heaviest neutralino at the LHC using LC input from the neutralino/chargino sector:

[*J. Kalinowski, G. Moortgat-Pick, M. Nojiri, G. Polesello*]



⇒ Need besides LSP mass also masses of sleptons and charginos from LC in order to correctly identify $\tilde{\chi}_4^0$

⇒ Feeding $m(\tilde{\chi}_4^0)$ back into LC analysis improves accuracy of parameter determination at the LC

Even further:

Full reconstruction of stop/sbottom parameters with LHC $\otimes$ LC

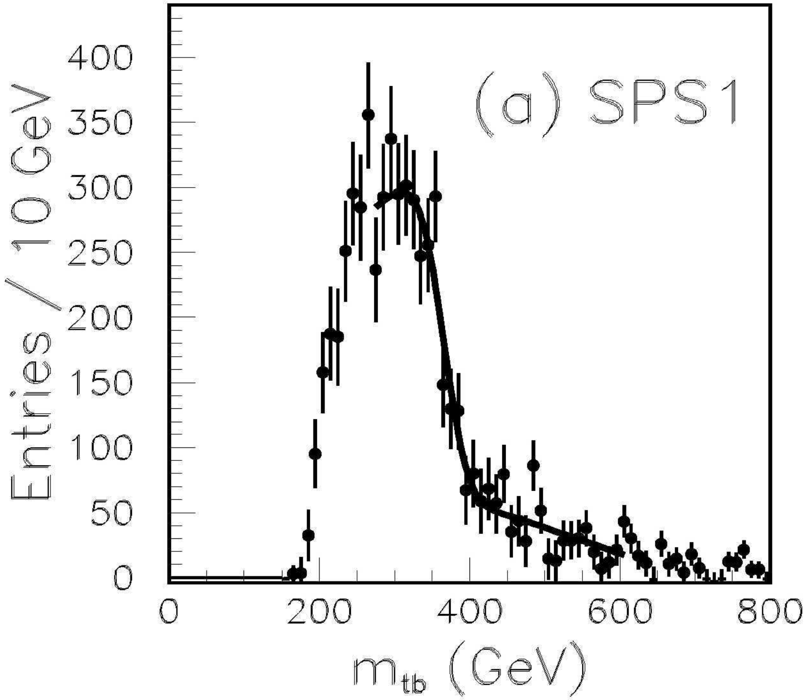
[*J. Hisano, K. Kawagoe, M. Nojiri*]

Complete set of electroweak SUSY parameters (from LC) and branching ratios used to exploit LHC rate measurements

Stop/sbottom sector determined by 5 parameters, e.g. $m_{\tilde{b}_1}$, $m_{\tilde{b}_2}$, $m_{\tilde{t}_1}$, $\theta_{\tilde{b}}$, $\theta_{\tilde{t}}$

- Take $m_{\tilde{b}_1}$, $m_{\tilde{b}_2}$ from previous study
- $\Rightarrow$ need three more observables:
  - tb invariant mass distribution
  - rate of “edge-events” in m_{tb} distribution (chargino chain)
  - rate of events in $\ell\ell b$ distribution ($\tilde{\chi}_2^0$ chain)

m_{tb} distribution for SPS1a:

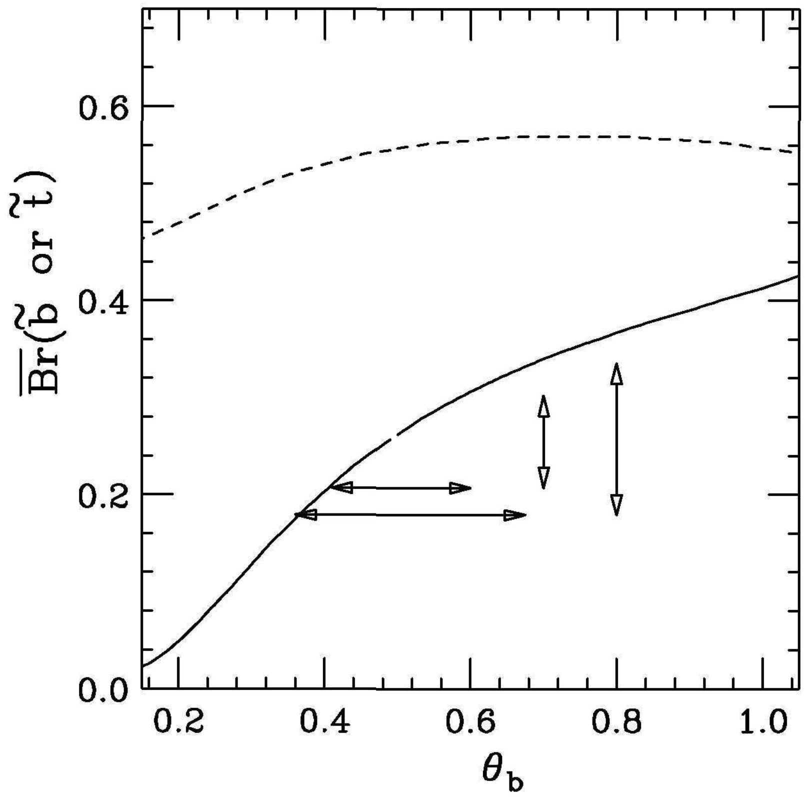


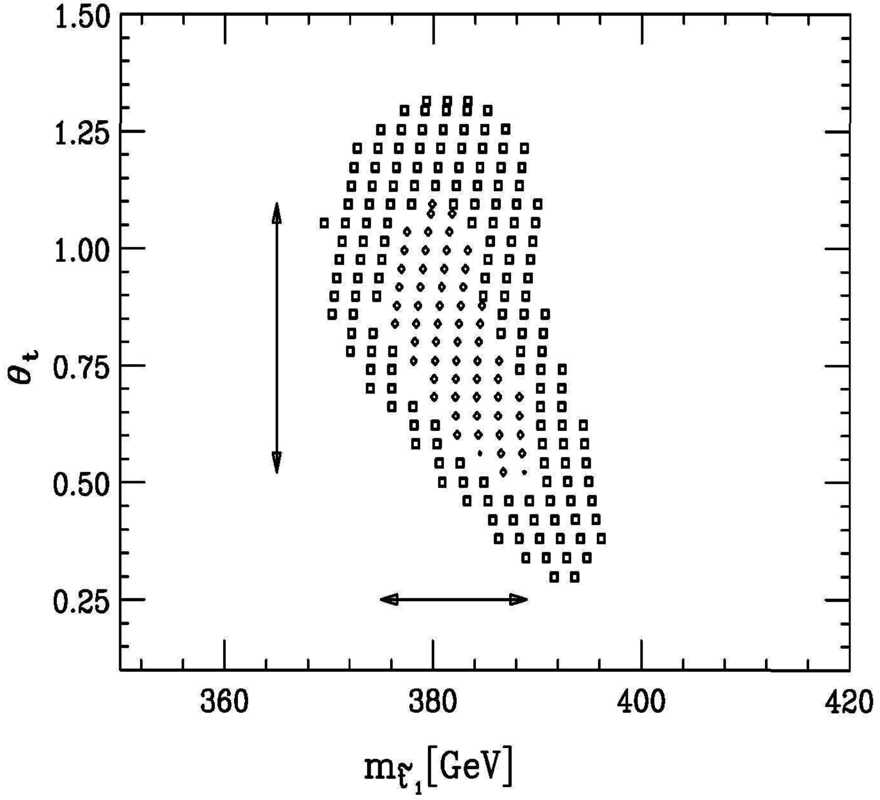
Involved couplings are stop–sbottom–W, top–sbottom–chargino and stop–bottom–chargino

⇒ If chargino couplings + BR's are known then observed rates are sensitive to sbottom/stop mixing parameters

Determination of $\theta_{\tilde{\mathrm{b}}}$ from $\mathrm{BR}(\tilde{g} \to b\tilde{b}_2 \to bb\tilde{\chi}_2^0)/\mathrm{BR}(\tilde{g} \to b\tilde{b}_1 \to bb\tilde{\chi}_2^0)$ in SPS1a, sbottom masses and parameters of chargino/neutralino sector are assumed to be known (left)

Determination of $m_{\tilde{\mathrm{t}}_1}$, $\theta_{\tilde{\mathrm{t}}}$ assuming also $\theta_{\tilde{\mathrm{b}}}$ is known (right)





$\Rightarrow \mathcal{O}(50\%)$ determination of mixing angles, $\Delta m_{\tilde{\mathrm{t}}_1}/m_{\tilde{\mathrm{t}}_1} < 5\%$

Results used for:

mSUGRA fit to LHC $\oplus$ LC data in SPS1a

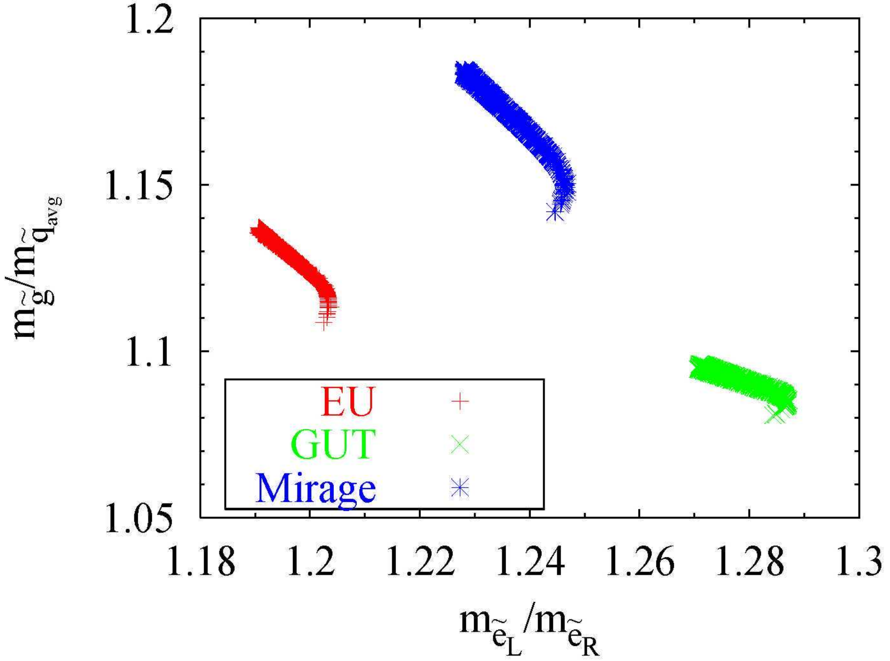
[*B. Allanach, S. Kraml, W. Porod*]

LHC / LC complementarity in mSUGRA fits

[*D. Tovey*]

Discrimination between different SUSY-breaking scenarios

[*B. Allanach, D. Grellscheid, F. Quevedo*]



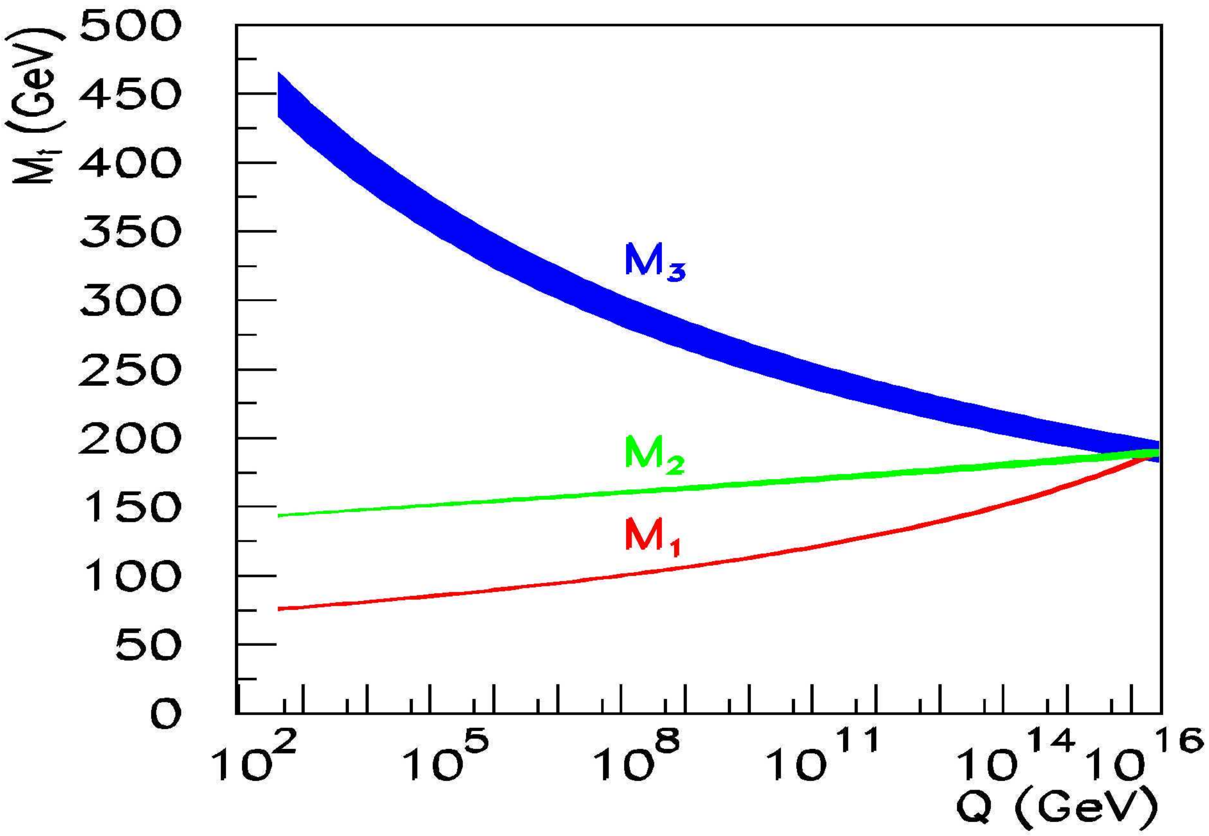
$\Rightarrow$ Need %-level accuracy to distinguish between different models

Extrapolation to physics at high scales

from combination of LHC and LC results, precise measurement of masses of SUSY particles, couplings

E.g.: Test of gaugino mass unification

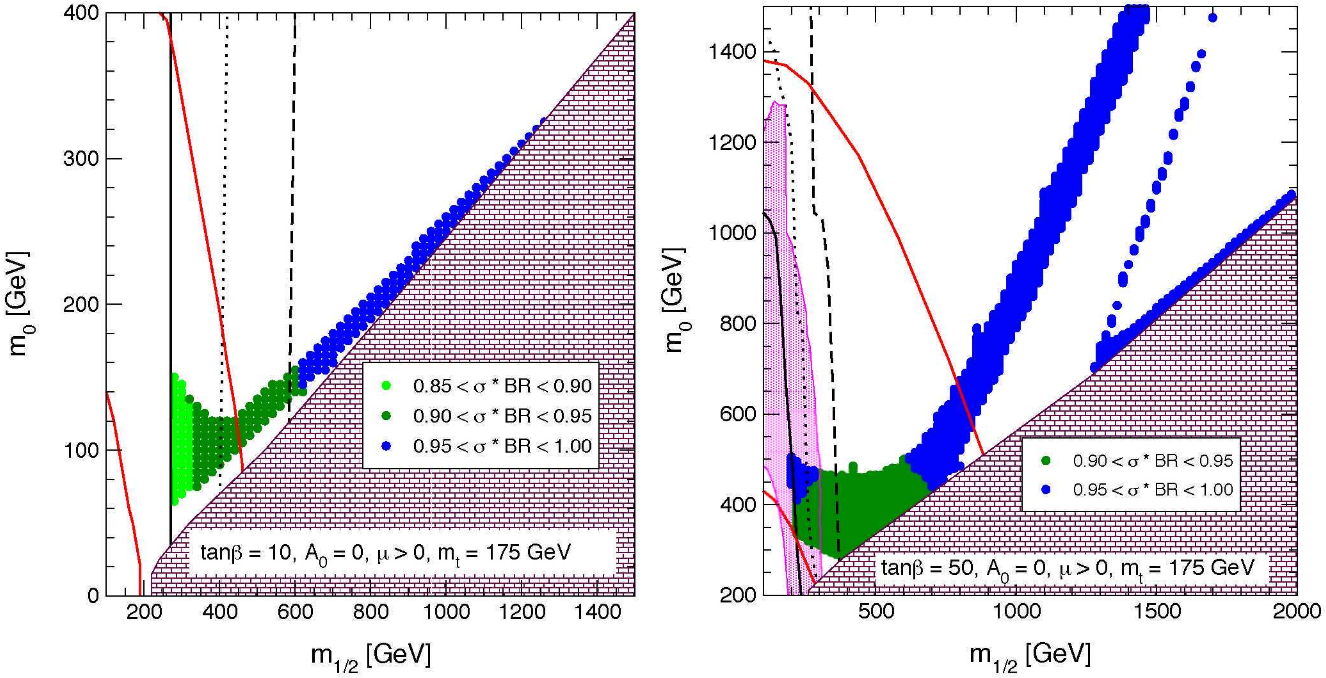
[*G. Blair, W. Porod, P. Zerwas '01*]



Higgs searches at the Tevatron and the LHC

mSUGRA scenario with CDM constraints

$\mu > 0$, $\tan\beta = 10, 50$: $\quad \Big[\sigma(gg \to h) \times \mathrm{BR}(h \to \gamma\gamma)\Big]_{\mathrm{CMSSM}} \Big/ \Big[\sigma(gg \to h) \times \mathrm{BR}(h \to \gamma\gamma)\Big]_{\mathrm{SM}}$:



⇒ no significant suppression of $\sigma(gg \to h) \times \mathrm{BR}(h \to \gamma\gamma)$ compared to SM

⇒ Discovery of lightest Higgs boson within about one year at LHC possible
[*J. Ellis, S. Heinemeyer, K. Olive, G. W. '01*]

Similar results in GMSB and AMSB scenarios [*A. Dedes, S. Heinemeyer, S. Su, G. W. '03*]

Suggested benchmarks for Higgs searches at the Tevatron and the LHC

[M. Carena, S. Heinemeyer, C. Wagner, G. W. '02]

Scenarios for general MSSM, no specific SUSY-breaking scenario assumed, no indirect constraints, M_A, $\tan\beta$ varied

- m_h^max-scenario: $X_\text{t} = 2\,M_\text{SUSY}$ (FD), $M_\text{SUSY} = 1$ TeV

  ⇒ maximal $m_\text{h}(\tan\beta)$ for fixed m_t, M_SUSY

- no-mixing scenario: $X_\text{t} = 0$, $M_\text{SUSY} = 2$ TeV

- gluophobic Higgs scenario: $M_\text{SUSY} = 350$ GeV, $X_\text{t} = -750$ GeV (FD)

  ⇒ suppression of $gg \to h$

- small α_eff scenario:

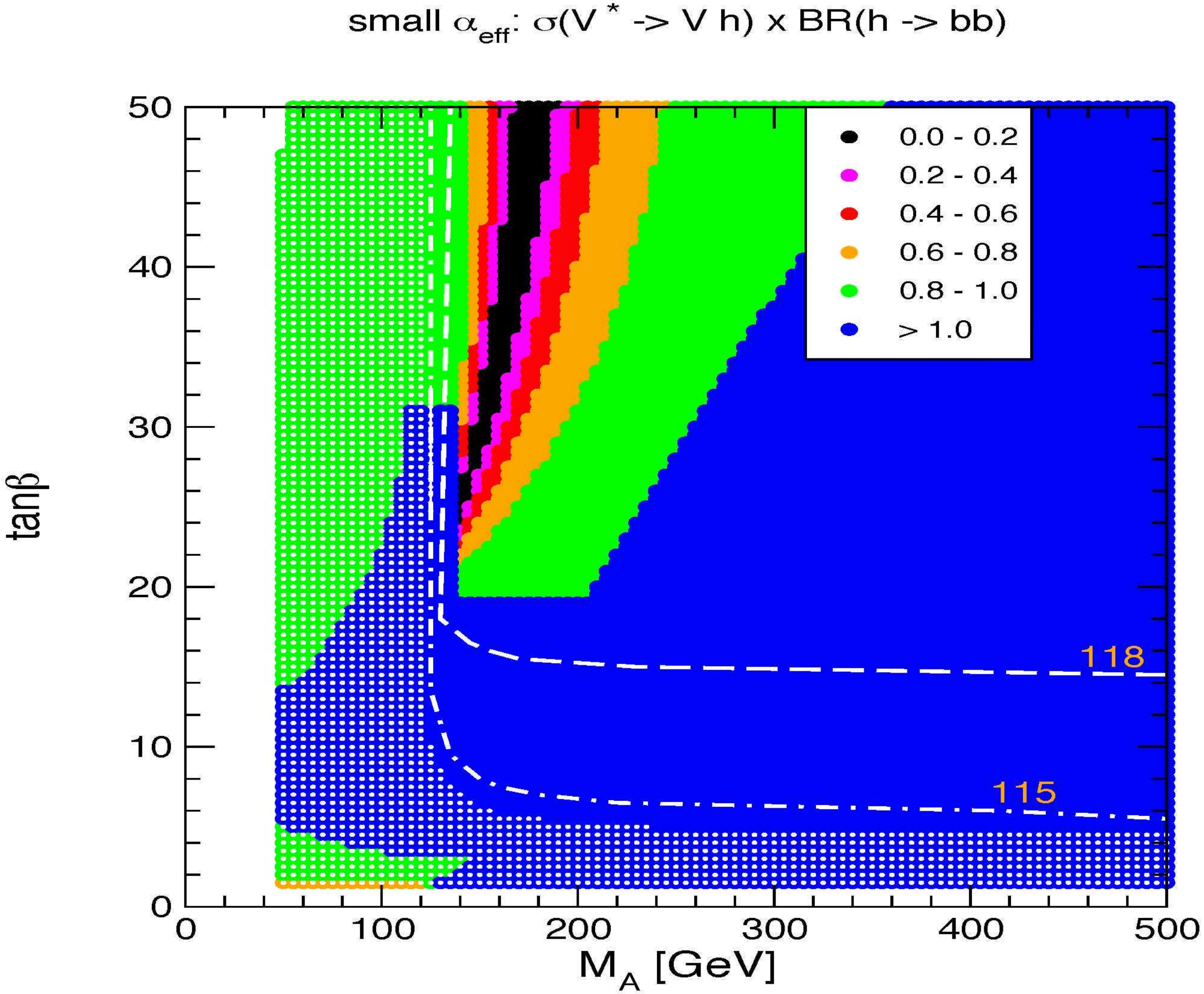
  $M_\text{SUSY} = 800\,\text{GeV}$, $\mu = 2.5\,M_\text{SUSY}$, $X_\text{t} = -1100$ GeV (FD)

  ⇒ suppression of $h \to b\bar{b}$, $h \to \tau\tau$

Small α_{eff} scenario:

$\sigma(q\bar{q} \to Vh) \times \text{BR}(h \to b\bar{b})$ at the Tevatron:

[M. Carena, S. Heinemeyer, C. Wagner, G. W. '02]

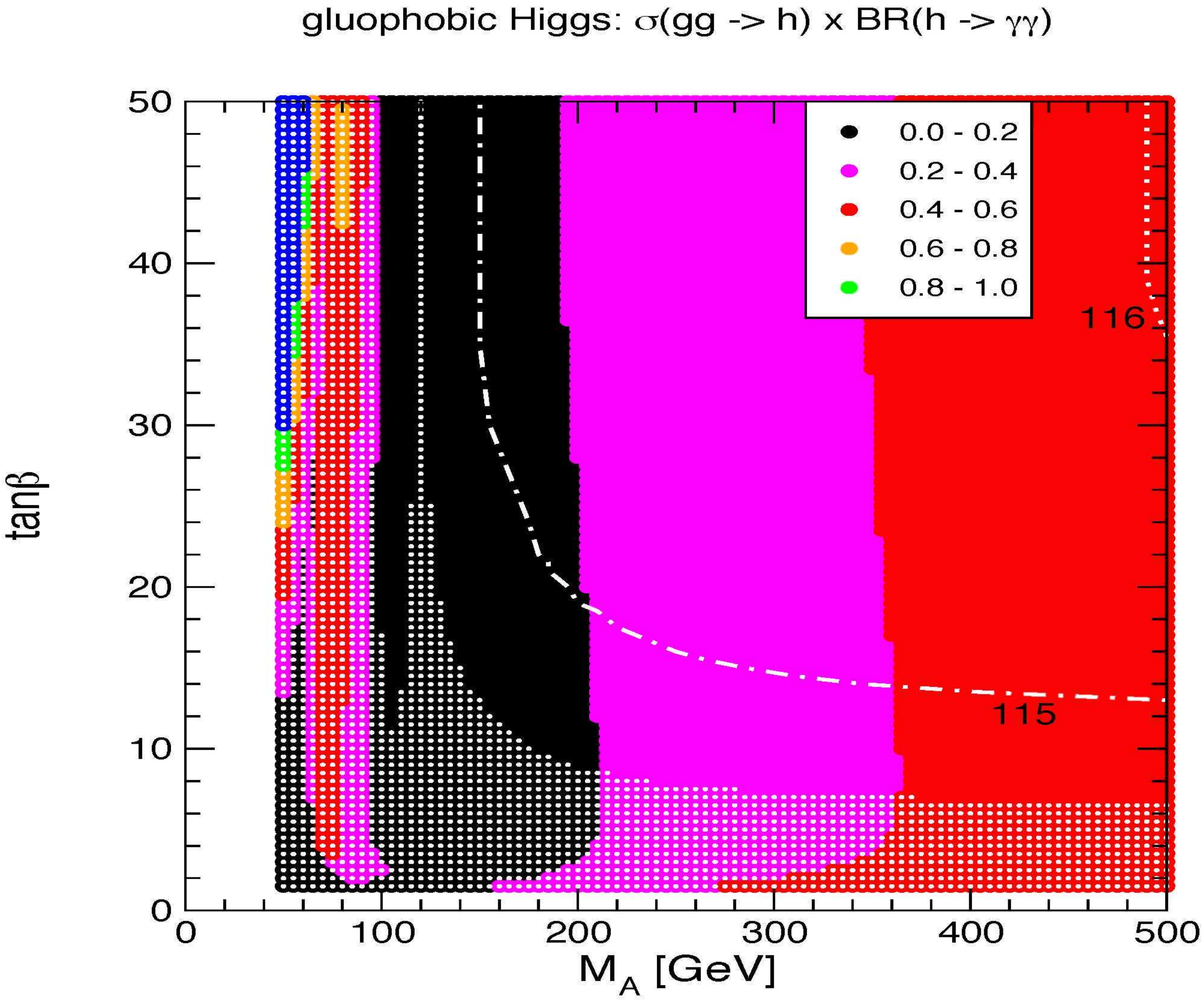


⇒ Significant suppression for $M_{\text{A}} \lesssim 250$ GeV

Gluophobic Higgs scenario:

$\sigma(gg \to h) \times \text{BR}(h \to \gamma\gamma)$ at the LHC:

[*M. Carena, S. Heinemeyer, C. Wagner, G. W. '02*]



⇒ Large suppression in whole M_A–$\tan\beta$ plane

Precision physics in the MSSM Higgs sector

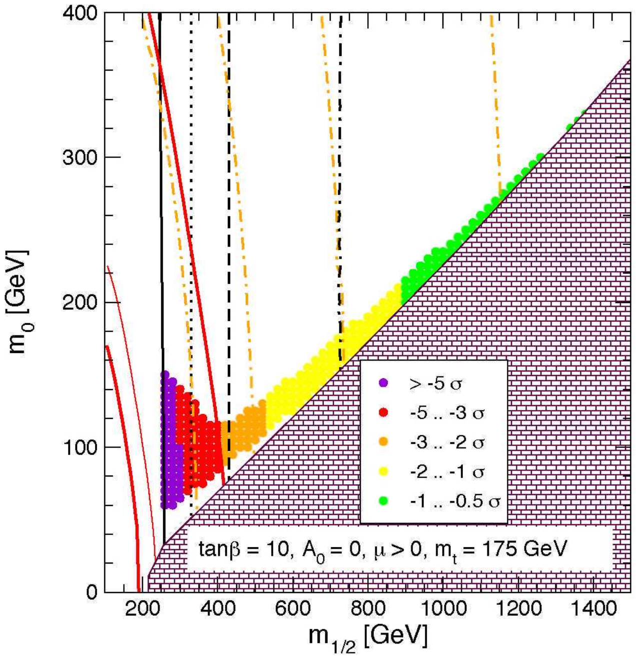
Precise measurement of Higgs branching ratios

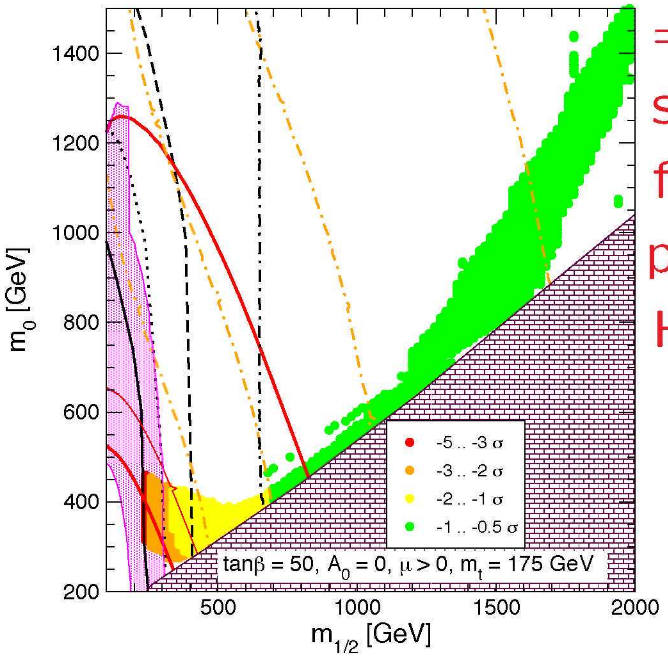
⇒ Sensitivity to deviations SM / MSSM

E.g.: Prediction for $\sigma(e^+e^- \to Zh) \times \mathrm{BR}(h \to WW^*)$ in parameter region allowed by cosmology: comparison mSUGRA – SM:

[*J. Ellis, S. Heinemeyer, K. Olive, G. W. '02*]

$\mu > 0$, $\tan\beta = 10, 50$:





⇒ In allowed parameter space: sizable deviations from SM predictions for precision observables in the Higgs sector possible

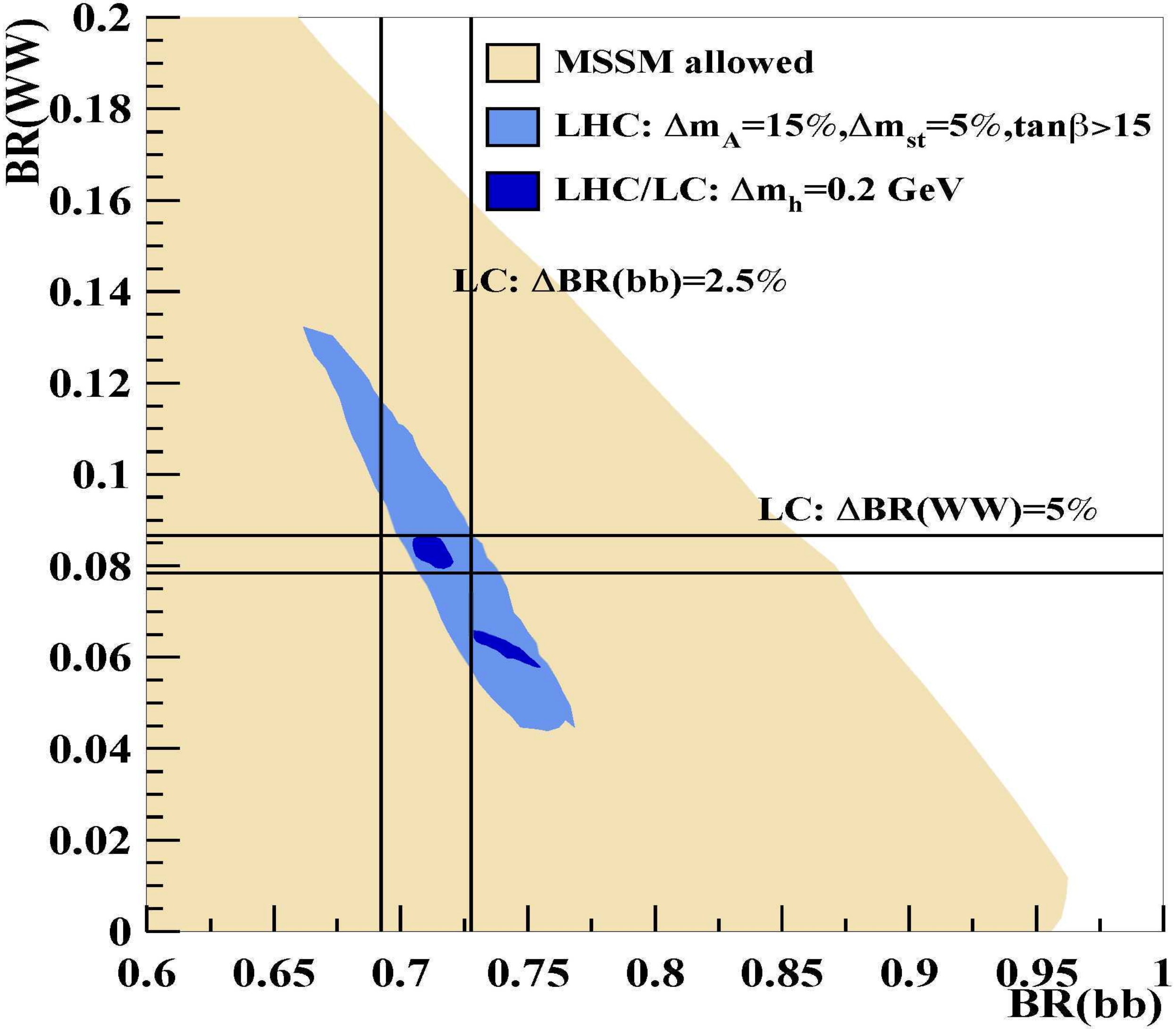
Combination of LHC data on heavy Higgs states with LC data on the light $\mathcal{CP}$-even Higgs

[*K. Desch, S. Heinemeyer, G.W.*]

Assume: LHC information on M_A, $\tan\beta$ $\oplus$ (LHC $\otimes$ LC) information on stop/sbottom masses $\oplus$ LHC / LC measurement of m_h:

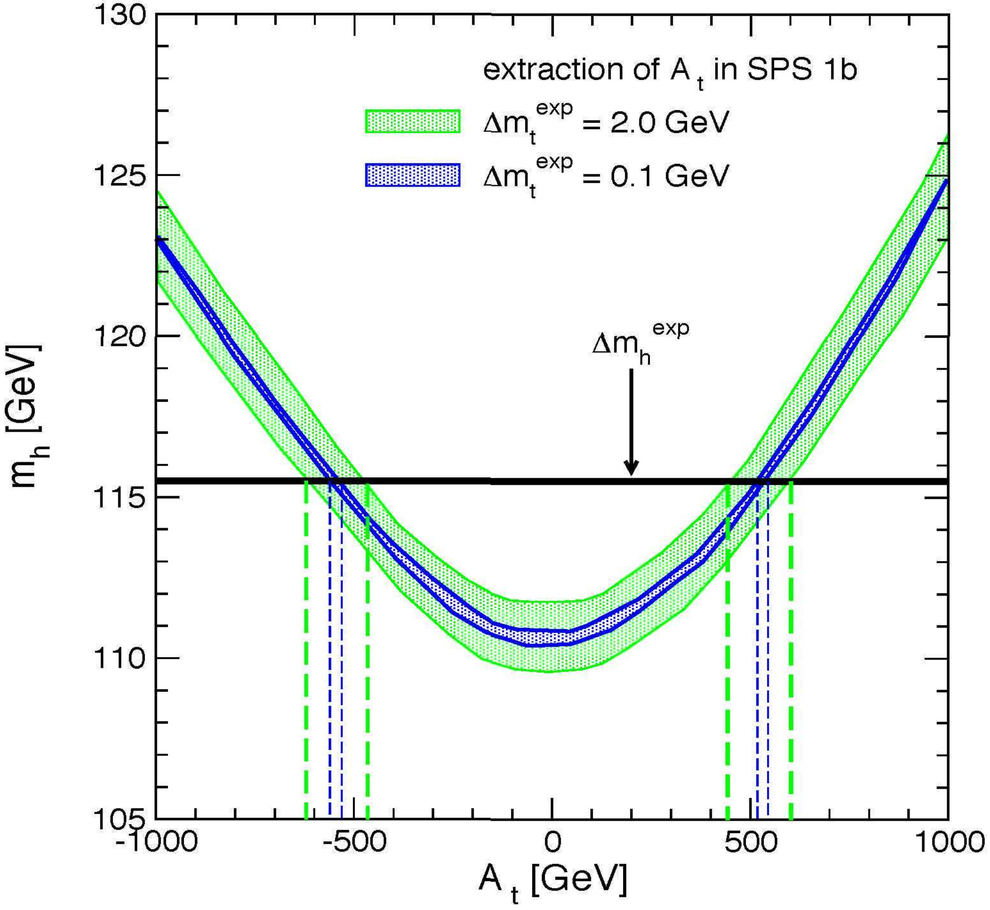
M_A: 15% accuracy, $m_{\tilde{\mathsf{t}}_1}, m_{\tilde{\mathsf{t}}_2}, m_{\tilde{\mathsf{b}}_1}, m_{\tilde{\mathsf{b}}_2}$: 5% accuracy, $\tan\beta > 15$

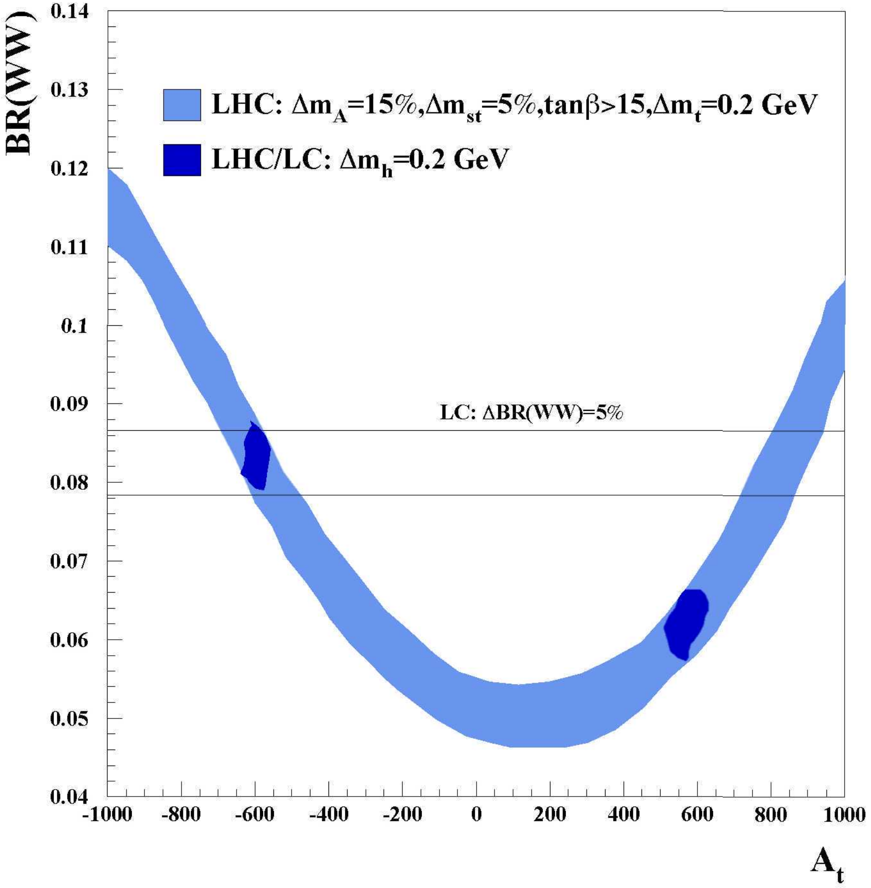
BR($h \to b\bar{b}$): 2.5% accuracy, BR($h \to WW^*$): 5% accuracy



⇒ Comparison of MSSM prediction based on assumed inputs with BR's measured at the LC yields very sensitive test of the model

⇒ Indirect determination of trilinear coupling A_t:





Precise measurement of m_t at the LC crucial, $\delta m_t \lesssim 100$ MeV

Δm_t^{LC} vs. Δm_t^{LHC} ⇒ accuracy of A_t determination improved by factor 3

Necessary improvements in accuracy of theoretical prediction in order to match experimental precision at LHC, $\delta m_h^{\mathrm{exp}} \approx 0.2$ GeV:

- Uncertainty from experimental errors of input parameters:

  ⇒ Complementarity example:

  In order to match

  experimental precision at LHC, $\delta m_h^{\mathrm{exp}} \approx 0.2$ GeV

  need

  LC precision on m_t, $\delta m_t^{\mathrm{exp}} \lesssim 0.2$ GeV

- Uncertainty from unknown higher-order corrections:

  ⇒ Need improvement by more than a factor 10!

Summary of Lectures 4 and 5:

- SUSY requires light Higgs boson:

  definite and robust prediction of SUSY theories, testable at next generation of colliders

- mSUGRA in agreement with exp. constraints from Higgs search, CDM, $(g_\mu - 2)$, $B \to X_s\gamma$

- EW precision tests: MSSM yields equally complete description as SM

  Global fit: better agreement of MSSM with data for $g_\mu - 2$, M_W than SM, no improvement for A_FB^b, NuTeV, similar fit quality

- SUSY searches (same for other kinds of new physics) at next generation of colliders:

  Tevatron and LHC: big discovery potential

  LC: high-precision physics

  ⇒ need both to

  - establish SUSY experimentally
  - disentangle patterns of SUSY breaking

- Complementarity LHC / LC can be exploited for improving analyses at both machines

- Precision physics in Higgs sector: ⇒ Very sensitive test of ew theory

Outlook:

- Low-energy Supersymmetry continues to be our best bet for physics beyond the Standard Model

- Data rules:

  We need experimental information from Tevatron, LHC, LC,
  ν experiments, dark matter searches, low-energy experiments, . . .
  to verify / falsify models of new physics understanding

- The experiments in the next years will bring a decisive test of our ideas about low-energy SUSY

$\Rightarrow$ Very exciting prospects for the coming years

Expect the unexpected!