Brief overview on some Higgs and SUSY activities

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RAL, 09/2007

- Higgs:

  Heavy Higgs bosons at the LHC, Higgs coupling determination, diffractive Higgs production, the Higgs as a composite object, the program *FeynHiggs*

- SUSY:

  What is the scale of Supersymmetry? $\mathcal{CP}$ properties of SUSY particles

- Conclusions

Heavy Higgs bosons at the LHC

- Signatures of extended Higgs sector $\leftrightarrow$ unique evidence for BSM physics

- Higgs sector of the MSSM: physical states $h, H, A, H^{\pm}$

  Described by two parameters at lowest order:
  $M_{\rm A}$, $\tan\beta \equiv v_2/v_1$

- Search for heavy MSSM Higgs bosons ($M_{\rm A}, M_{\rm H} \gg M_{\rm Z}$):
  Decouple from gauge bosons
  $\Rightarrow$ no HVV coupling
  $\Rightarrow$ no Higgs production in weak boson fusion
  $\Rightarrow$ no decay $H \to ZZ \to 4\mu$

  Large enhancement of coupling to $b\bar{b}$ (and $\tau^+\tau^-$) in region of high $\tan\beta$

Search for SUSY Higgs bosons

- Experimental results / future prospects are usually interpreted in the $M_{\rm A}$–$\tan\beta$ plane

  $\Rightarrow$ yield boundary of "LHC wedge region", where only one SM-like Higgs can be observed at the 5σ level

- Higher-order corrections, Higgs decays into SUSY particles

  $\Rightarrow$ full structure of the SUSY model enters

  $\Rightarrow$ other parameters are fixed in certain "benchmark scenarios"

How robust is the discovery reach in the $M_{\rm A}$–$\tan\beta$ plane w.r.t. other SUSY effects?

Analysis of the CMS discovery reach in the $b\bar{b}H, A$, $H, A \to \tau^+\tau^-$ *channel*

[*S. Gennai, S. Heinemeyer, A. Kalinowski, R. Kinnunen, S. Lehti, A. Nikitenko '07*]

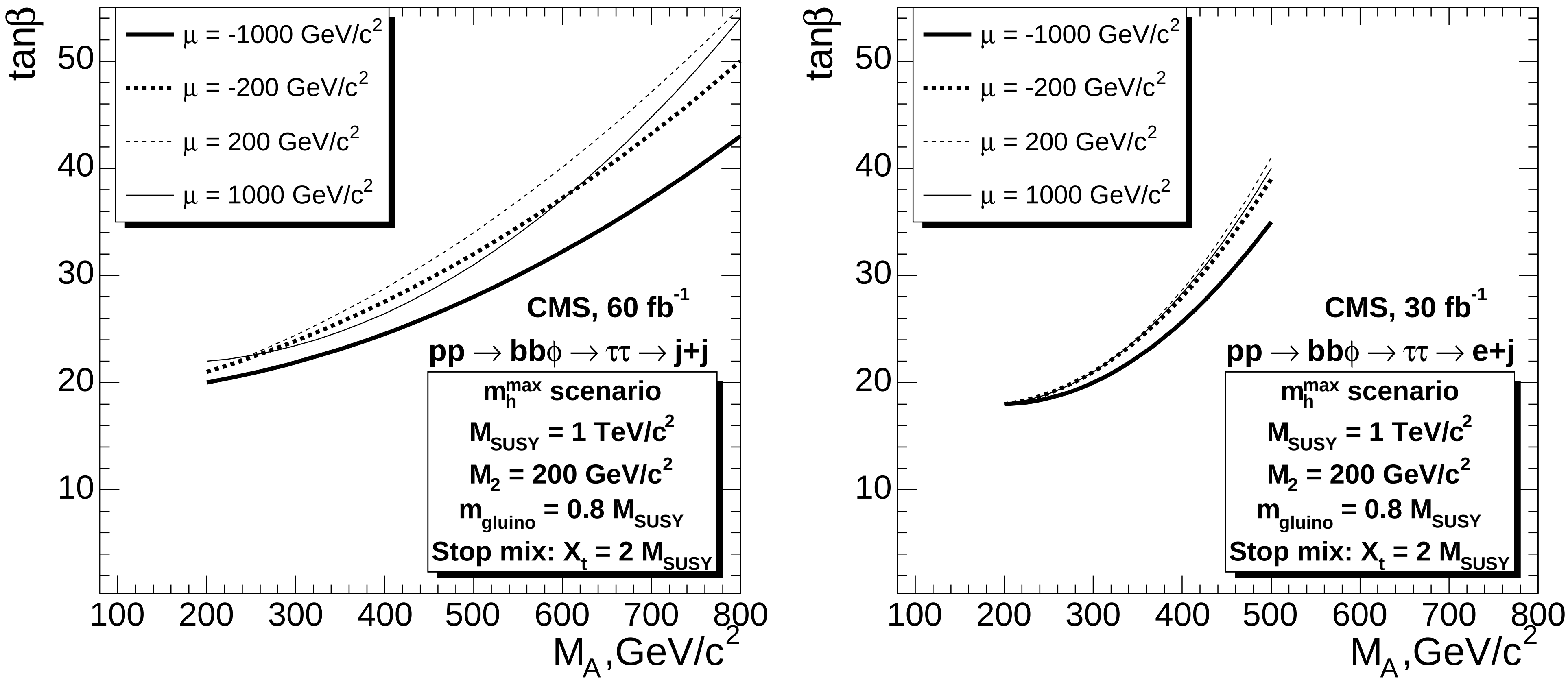
Experimental analysis:

- Full CMS detector simulation and reconstruction
- Final states of di-τ decays: $\tau^+\tau^- \to$ jets, $\tau^+\tau^- \to e +$ jet, $\tau^+\tau^- \to \mu +$ jet, $\tau^+\tau^- \to e + \mu$
- Selection: single b-jet tagging
- Main backgrounds: QCD multi-jet events (for $\tau\tau \to$ jets mode), $t\bar{t}, b\bar{b}$, Z, γ^*, W+jet, Wt, $\tau\tau b\bar{b}$

Theory analysis (*FeynHiggs*, *www.feynhiggs.de*):

- Detailed investigation of higher-order effects
- Impact of decays into SUSY particles

Variation of the 5σ discovery contours with μ (m_h^{max} scen.): $\tau^+\tau^- \to$ jets (left) and $\tau^+\tau^- \to e +$ jet (right)



$\Rightarrow$ Shift of discovery contour by up to $\Delta \tan\beta = 12$

Significant effect on “LHC wedge region”

Analysis for charged Higgs production in progress

Higgs coupling determination

Many theories have over large part of their parameter space a light Higgs with properties very similar to those of the SM Higgs boson

Example: SUSY in the “decoupling limit”, $M_{\rm A} \gg M_{\rm Z}$

Heavy Higgses may be difficult to detect (e.g. “wedge region” of the MSSM)

$\Rightarrow$ We may see only one Higgs that looks SM-like

$\Rightarrow$ High-precision measurements of Higgs properties will be crucial to reveal the nature of EWSB

Higgs coupling determination at the LHC

LHC does not provide a measurement of the total production cross section (no recoil method like LEP, ILC: $e^+e^- \to ZH$, $Z \to e^+e^-, \mu^+\mu^-$)

Production $\times$ decay at the LHC yields combinations of Higgs couplings ($\Gamma_{\rm prod,\,decay} \sim g^2_{\rm prod,\,decay}$):

$$\sigma(H) \times {\rm BR}(H \to a+b) \sim \frac{\Gamma_{\rm prod}\Gamma_{\rm decay}}{\Gamma_{\rm tot}},$$

Large uncertainty on dominant decay for light Higgs: $H \to b\bar{b}$

$\Rightarrow$ LHC can directly determine only ratios of couplings, e.g. $g^2_{H\tau\tau}/g^2_{HWW}$ [*M. Dührssen '03*]

Higgs coupling determination at the LHC

Absolute values of the couplings at the LHC can be obtained with an additional (mild) theory assumption:

[*M. Dührssen, S. Heinemeyer, H. Logan, D. Rainwater, G. W., D. Zeppenfeld '04*]

$$g^2_{HVV} \leq (g^2_{HVV})^{\mathrm{SM}}, \quad V = W, Z$$

$\Rightarrow$ Upper bound on Γ_V

Observation of Higgs production

$\Rightarrow$ Lower bound on production couplings and Γ_{tot}

Observation of $H \to VV$ in WBF

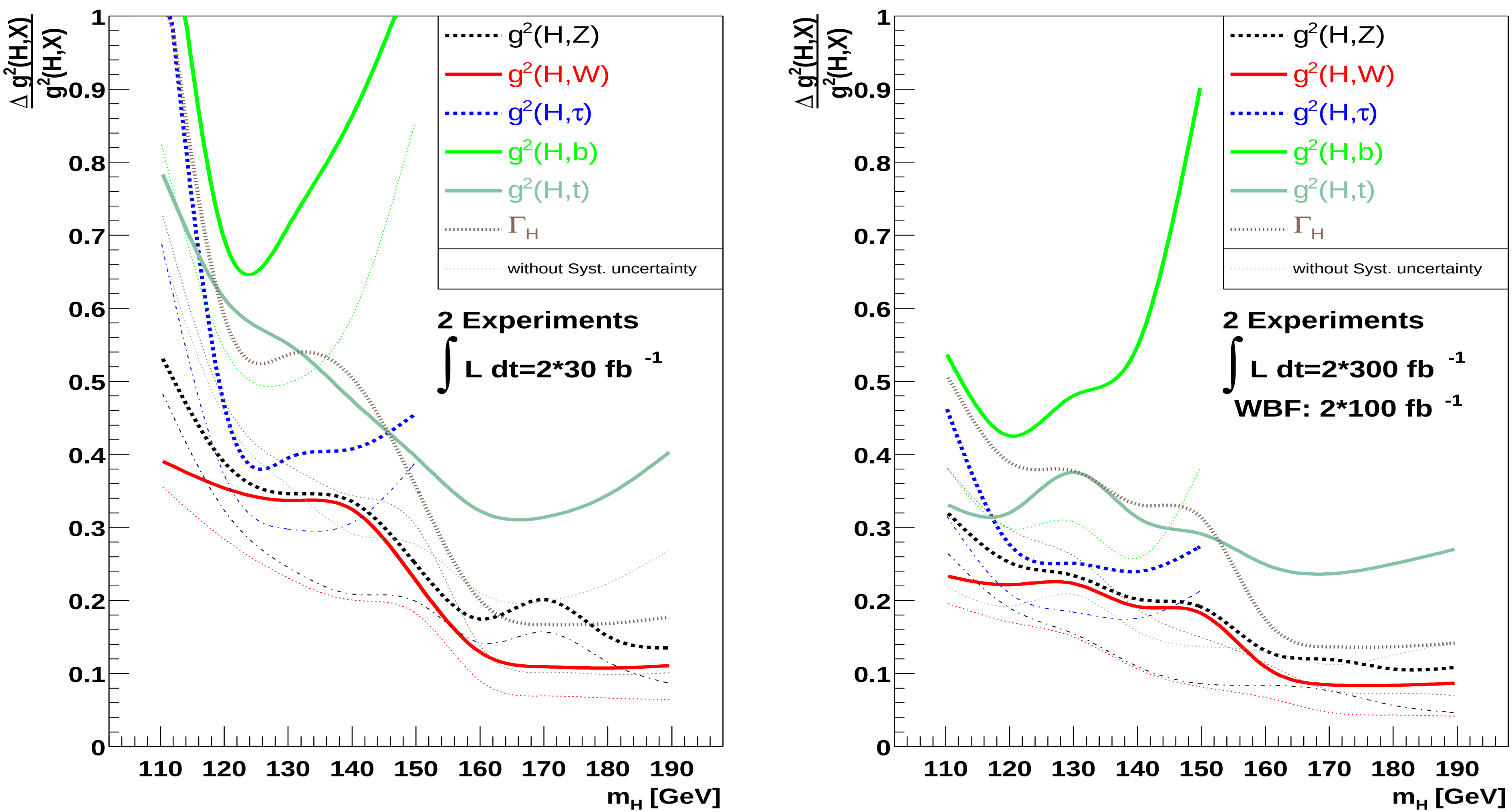
$\Rightarrow$ Determines $\Gamma^2_V/\Gamma_{\mathrm{tot}} \Rightarrow$ Upper bound on Γ_{tot}

$\Rightarrow$ Absolute determination of Γ_{tot} and Higgs couplings

Earlier approaches (more restrictive assumptions) [*D. Zeppenfeld, R. Kinnunen, A. Nikitenko, E. Richter-Was '00*] [*A. Belyaev, L. Reina '02*]

Absolute determination of Higgs couplings with (mild) theory assumption

[*M. Dührssen, S. Heinemeyer, H. Logan, D. Rainwater, G. W., D. Zeppenfeld ’04*]



⇒ Reachable for the couplings (with high lumi): ≈10–20%

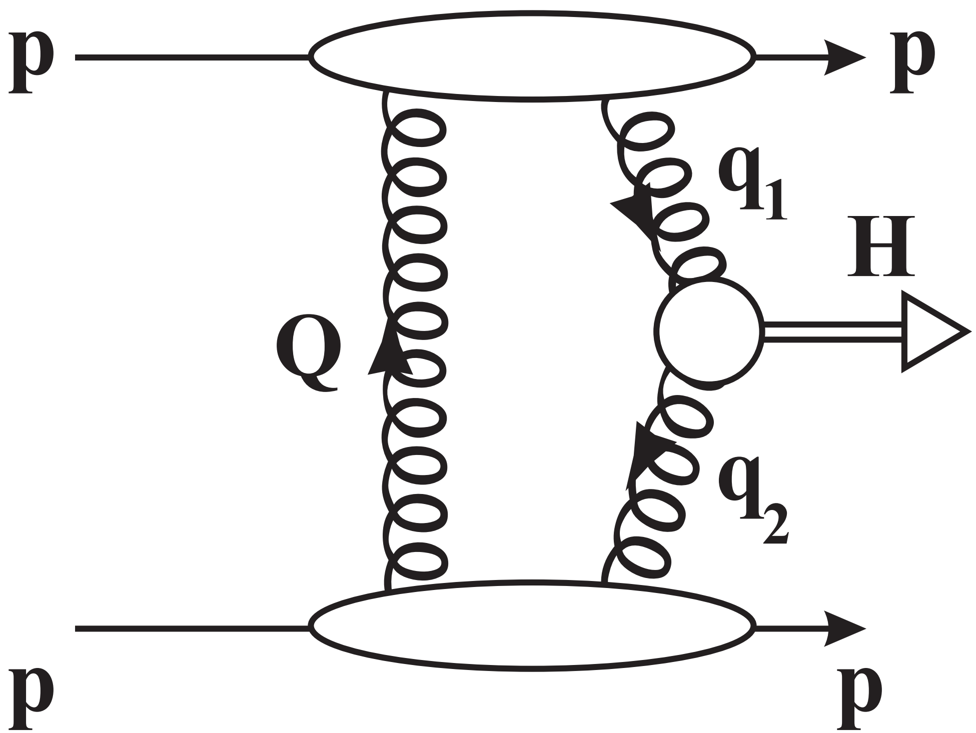
Analysis of Higgs coupling determination using latest CMS results?

Take into account:

- Degradation of the $t\bar{t}H$, $H \to b\bar{b}$ channel
- Impact of accuracy of Higgs mass determination
- Impact of suppression / enhancement of different channels
- ...

Diffractive Higgs production

Central exclusive diffractive (CED) Higgs prod., $pp \to p \oplus H \oplus p$



Protons remain undestroyed, forward proton tagging in “roman pot” detectors

exchange of colour-singlet

no hadronic activity between outgoing protons and Higgs decay products

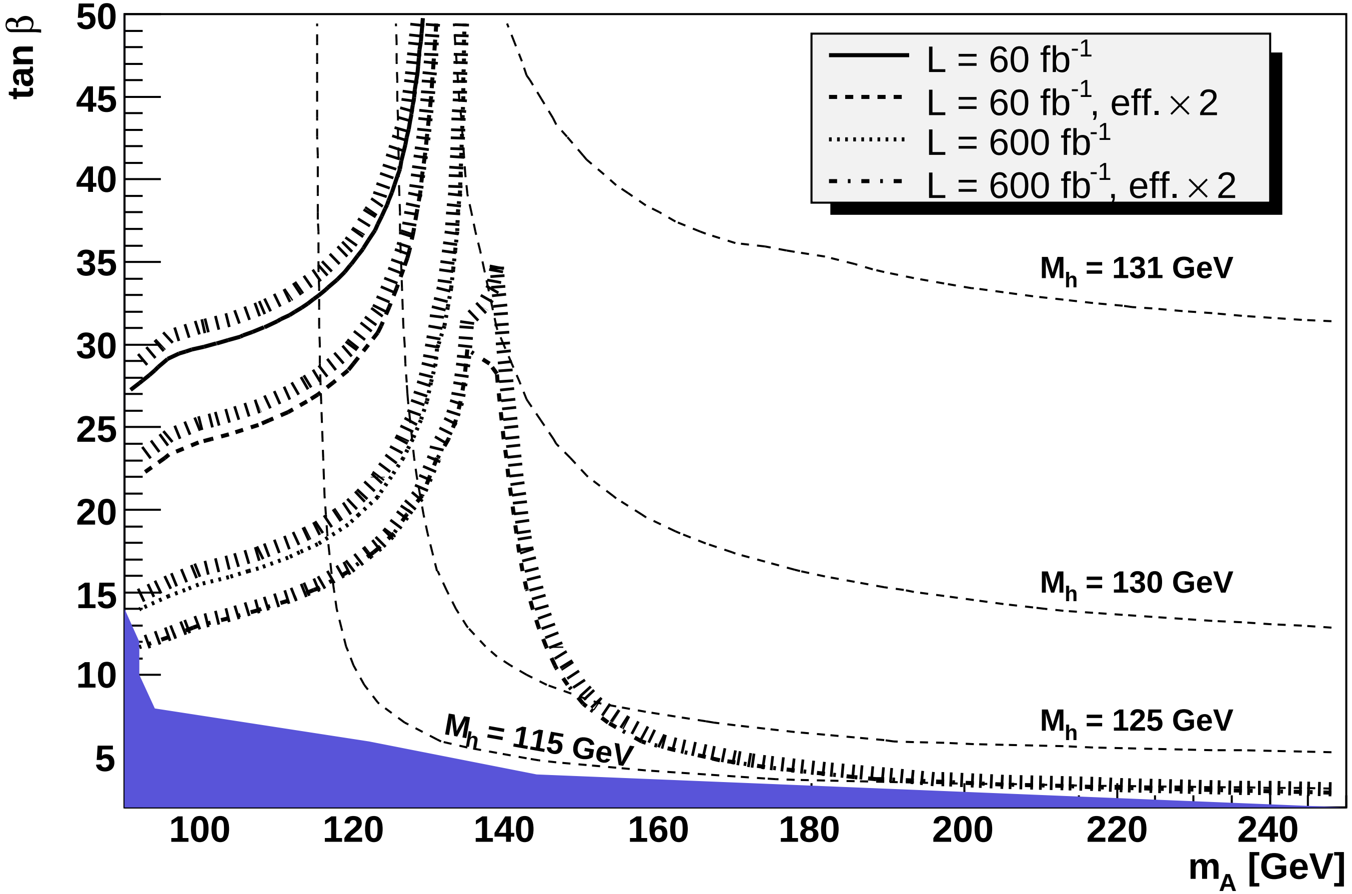
$J_z = 0$ selection rule

$\Rightarrow$ Good mass resolution, access to $H \to b\bar{b}$ decay mode

$\Rightarrow$ Experimentally very challenging (pile-up, in particular at high lumi, . . .), but may yield interesting information

3σ contours for CED production of the light MSSM Higgs boson in the $h \to b\bar{b}$ channel

[S. Heinemeyer, V.A. Khoze, M.G. Ryskin, W.J. Stirling, M. Tasevsky, G. W. '07]

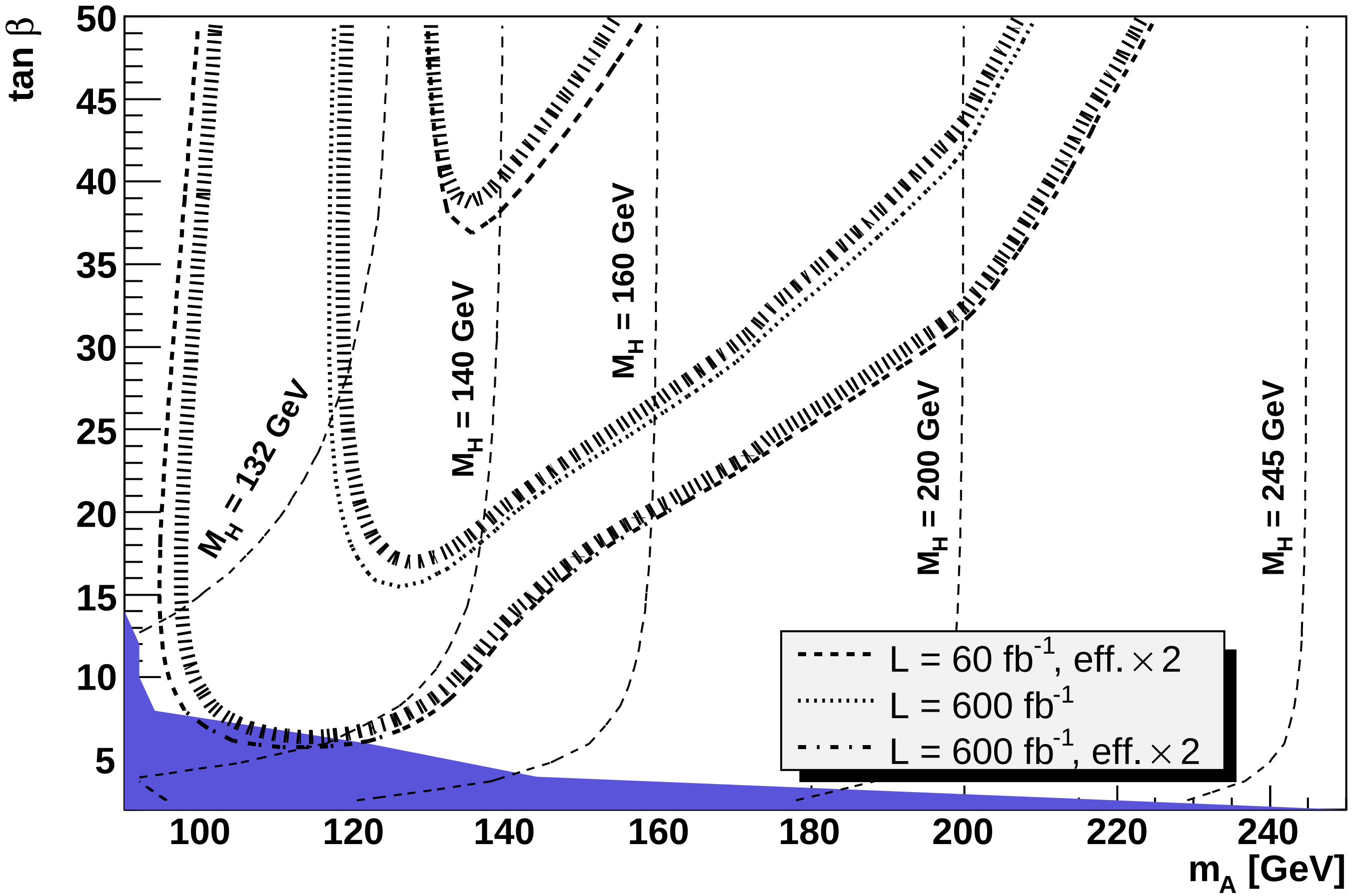


⇒ Almost complete coverage with high integrated luminosity

⇒ CED channel may yield crucial information on $hb\bar{b}$ coupling

5σ *discovery contours for CED production of the heavy* $\mathcal{CP}$*-even MSSM Higgs,* $H \to b\bar{b}$ *channel*

[*S. Heinemeyer, V.A. Khoze, M.G. Ryskin, W.J. Stirling, M. Tasevsky, G. W. '07*]



$\Rightarrow$ Significant discovery reach, discovery of a $140\ \mathrm{GeV}$ Higgs for all values of $\tan\beta$ with high integrated luminosity

The Higgs as a composite object

Renewed interest in composite Higgs models, mostly from extra dimensions

[*N. Arkani-Hamed, A. Cohen, H. Georgi '01*]

[*K. Agashe, R. Contino, A. Pomarol '05*], . . .

Composite Higgs: light remnant of a strong force

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Correspondence (AdS/CFT):

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Signatures at LHC: new resonances, W', Z', t', KK excitations

[*see Chris Hill's talk*]

Under pressure from electroweak precision tests

Strongly Interacting Light Higgs

Agreement with electroweak precision data can be improved if there is a strongly interacting light Higgs, e.g.

Little Higgs [*N. Arkani-Hamed, A. Cohen, E. Katz, A. Nelson '02*]

Holographic Higgs [*R. Contino, Y. Nomura, A. Pomarol '03*], [*K. Agashe, R. Contino, A. Pomarol '05*], ...

Effective Lagrangian formalism for model-independent analysis of effects of a strongly interacting light Higgs
[*G. Giudice, C. Grojean, A. Pomarol, R. Ratazzi '07*]

$\Rightarrow$ Specific pattern of modified Higgs couplings

Strong WW scattering at high energies despite light Higgs

$\Rightarrow$ Need precision measurement of Higgs couplings

$+$ test of longitudinal gauge-boson scattering

The program FeynHiggs

www.feynhiggs.de

[*T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak, G. W.*]

- Predictions for the Higgs masses, mixing angles and couplings in the MSSM (including complex phases, non-minimal flavour-violation, etc.)
- Higgs branching ratios in the SM and the MSSM
- Production cross sections for neutral Higgs bosons at the Tevatron and the LHC (charged Higgs in preparation)
- Provides estimate of remaining theoretical uncertainties from unknown higher-orders
- Evaluation of additional observables ($\to$ constraints on SUSY parameter space):
  $\Delta\rho$ (ew precision observables), $(g-2)_\mu$, $\mathrm{BR}(\mathrm{b} \to \mathrm{s}\gamma)$, EDMs

The program FeynHiggs

www.feynhiggs.de

- SUSY benchmarks predefined, respects SUSY Les Houches Accord, CDM-compatible M_A–$\tan\beta$ planes predefined, . . .

Program modes and usage:

- Fortran code, easy to install
- Command-line mode
- Can easily be called as a subroutine from Fortran or C$++$ code, can be called within *Mathematica*
- WWW mode: get results on-line directly from the web

The program FeynHiggs

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WWW mode of *FeynHiggs*:

Higgs phenomenology in CDM compatible parameter planes

Often assumed (CMSSM): universality at the GUT scale
common scalar mass m_0, common gaugino mass $m_{1/2}$,
common trilinear coupling A_0
further parameters (weak scale): $\tan\beta$, sgn(μ)

Universality of soft SUSY-breaking contributions to the Higgs scalar masses is less motivated than universality between squarks and sleptons

$\Rightarrow$ The Non-Universal Higgs Model (NUHM):

two additional parameters, can be traded for M_{A} and μ after imposing the electroweak vacuum conditions

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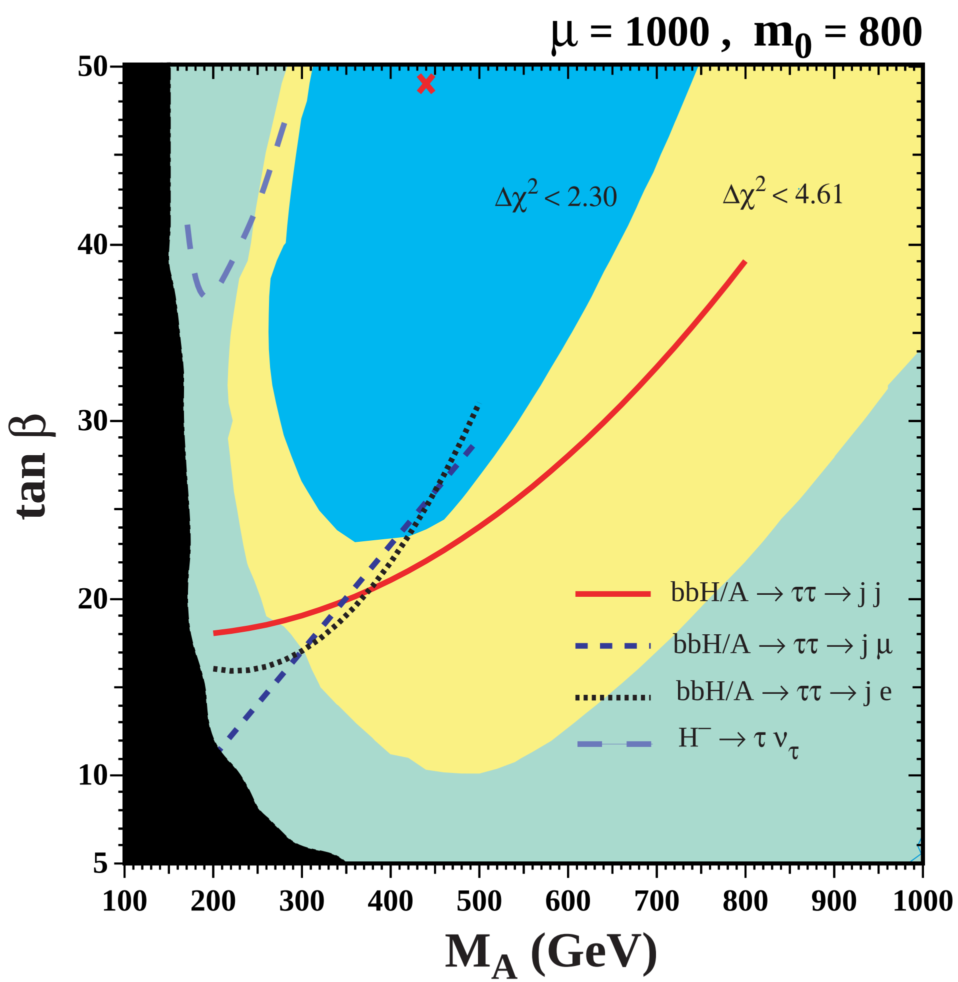
⇒ The Non-Universal Higgs Model (NUHM):

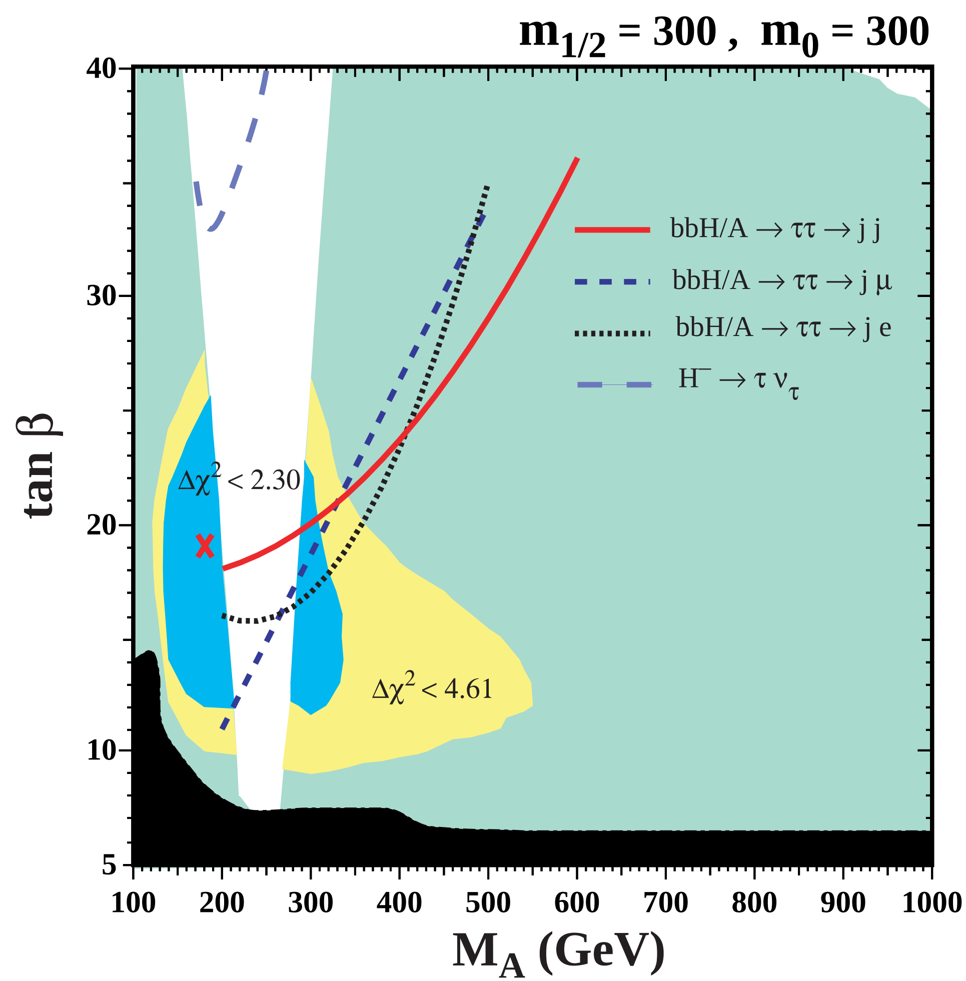
two additional parameters, can be traded for M_A and μ after imposing the electroweak vacuum conditions

⇒ Can vary $m_{1/2}$ or μ such that (essentially) the whole M_A–$\tan\beta$ plane is compatible with the WMAP constraint on dark matter relic density [*J. Ellis, S. Heinemeyer, K. Olive, G. W. '07*]

CDM-compatible M_A*–*$\tan\beta$ *planes: LHC discovery reach for heavy Higgses vs. EWPO* $+$ *BPO preferred region*

[*J. Ellis, S. Heinemeyer, K. Olive, G. W. '07*]





$\Rightarrow$ Large parts of preferred region covered

What is the scale of Supersymmetry?

Electroweak precision physics $\Leftrightarrow$ sensitivity to loop effects

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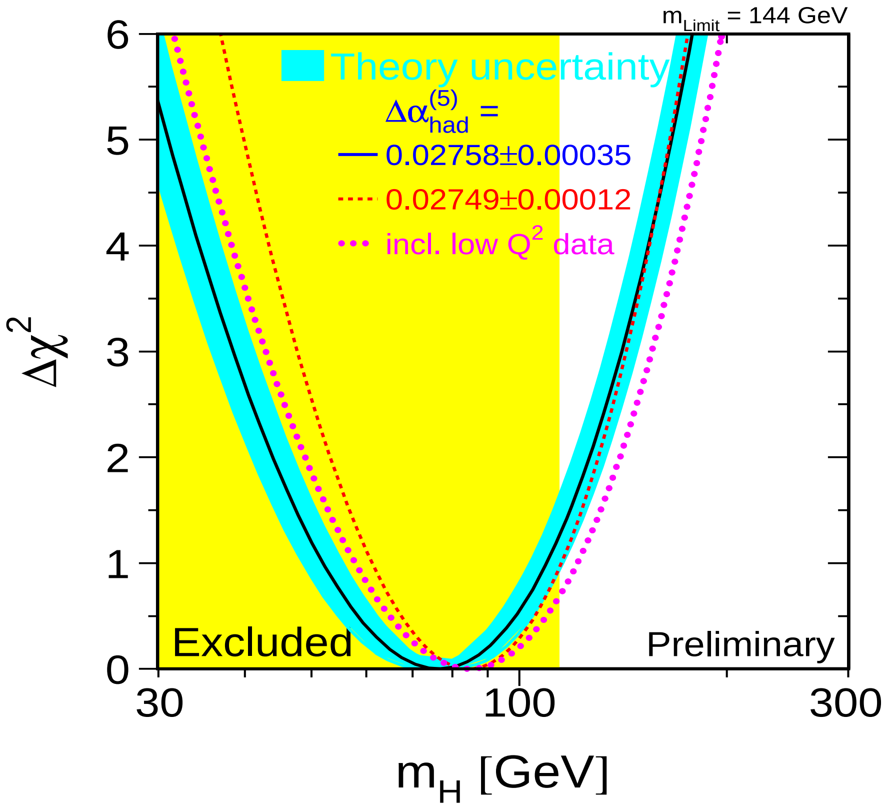
Example: indirect constraints on M_{H} in the SM

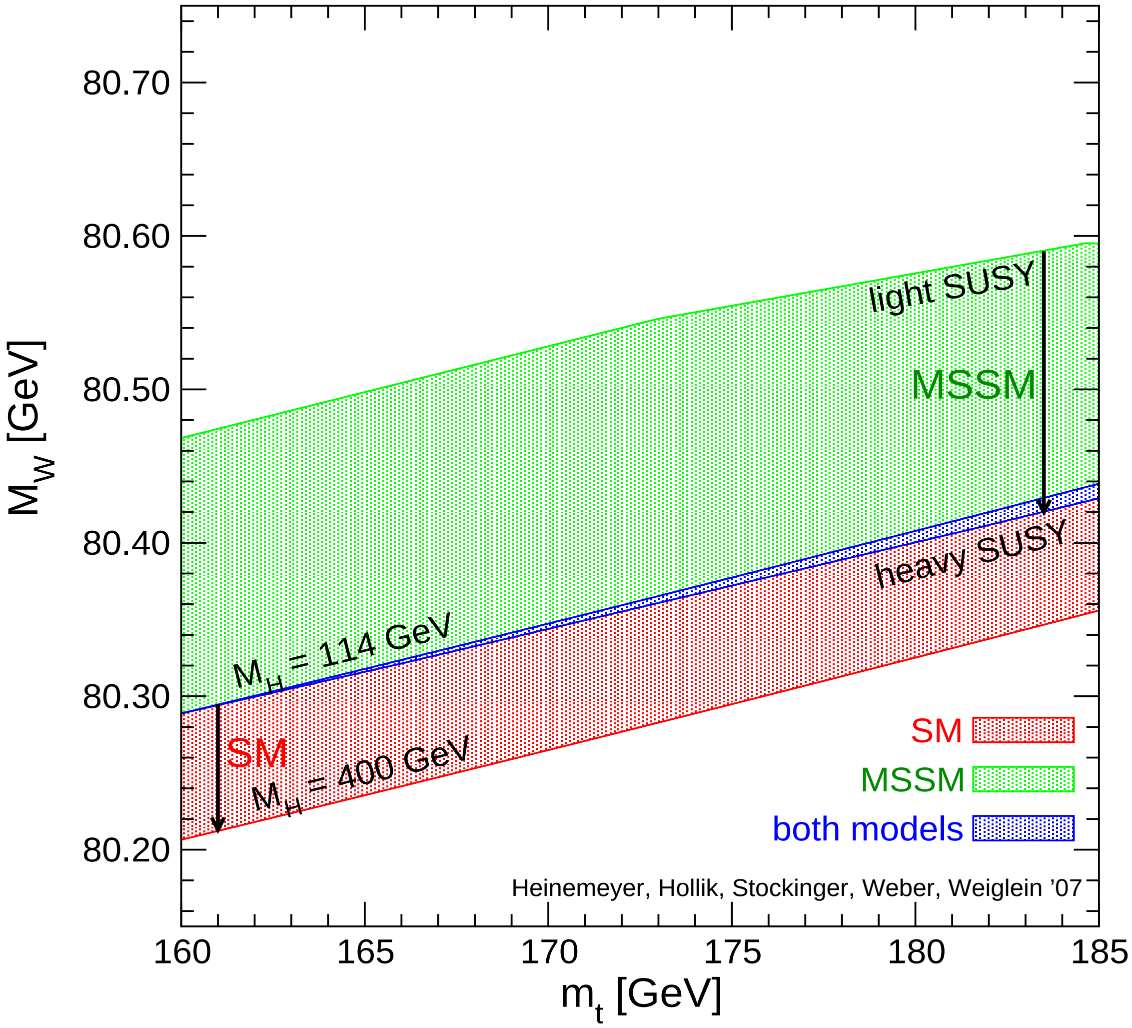
[*LEPEWWG '07*]



$\Rightarrow$ Tension between indirect bounds on M_{H} in the SM and direct search limit has increased

Prediction for M_{W} (parameter scan): SM vs. MSSM

Prediction for M_{W} in the SM and the MSSM:



[*S. Heinemeyer, W. Hollik, A.M. Weber, G. W. '07*]

MSSM: SUSY parameters varied

SM: M_{H} varied

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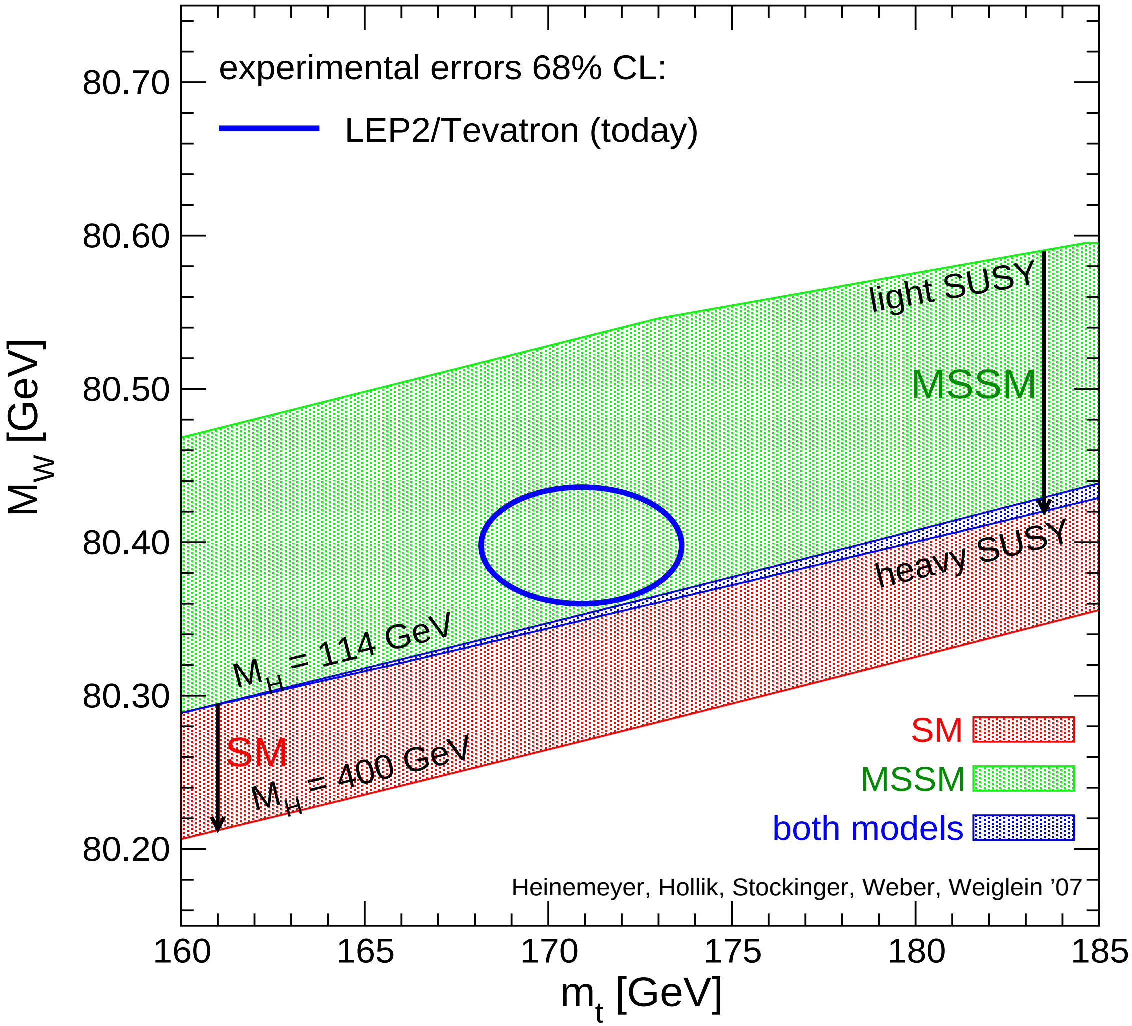

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$\Rightarrow$ Slight preference for MSSM over SM

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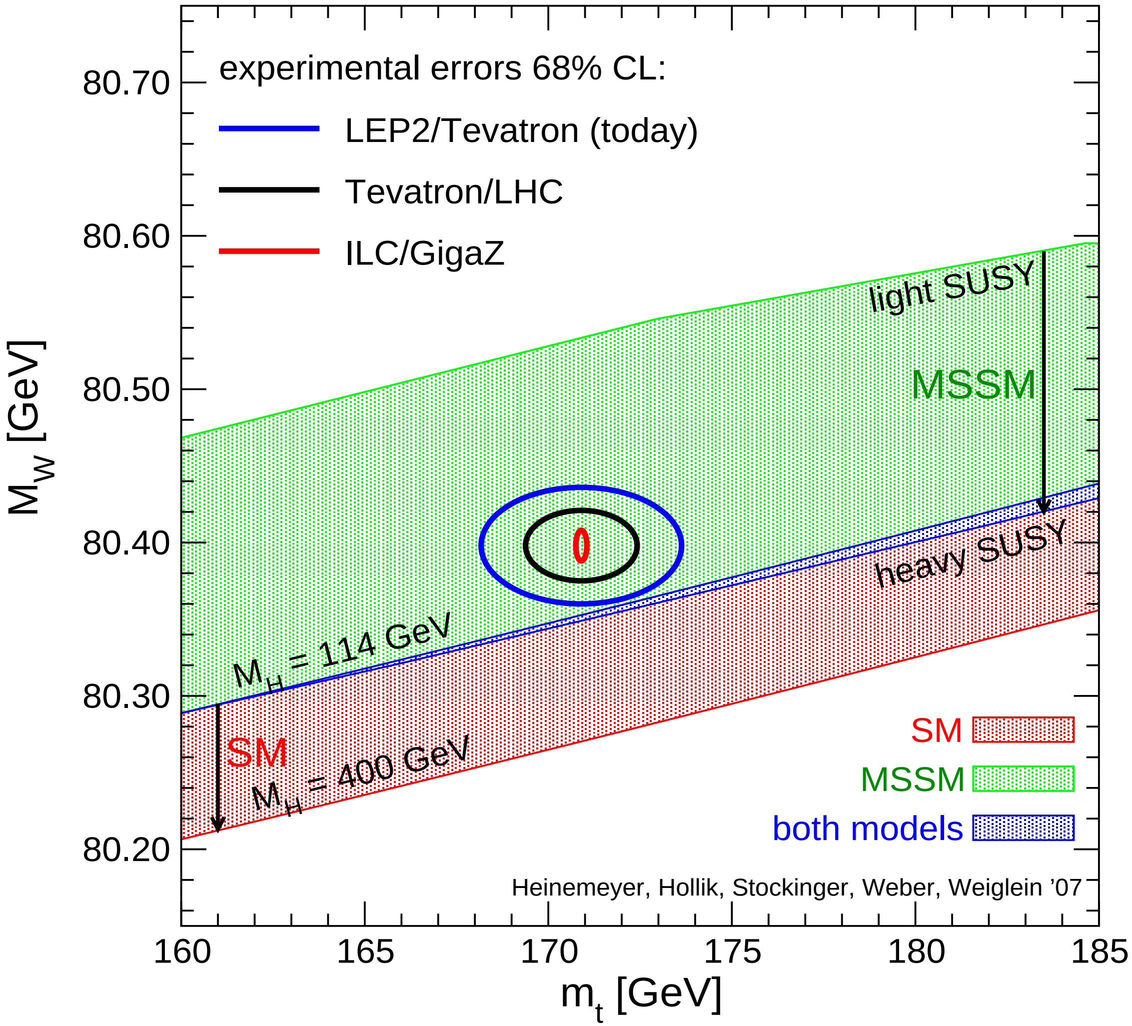

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Sensitivity to the scale of Supersymmetry

Global χ^2 fit in the Constrained MSSM (CMSSM):

$m_{1/2}$, m_0, A_0 (GUT scale), $\tan\beta$, $\mathrm{sign}(\mu)$ (weak scale)

$\Rightarrow$ Low-energy spectrum from renormalisation group running

Fit includes:

[*O. Buchmueller, R. Cavanaugh, A. De Roeck, S. Heinemeyer, G. Isidori, P. Paradisi, F. Ronga, A. Weber, G. W. '07*]

- All observables used in the SM fit of the LEPEWWG
- $+$ Cold dark matter (CDM) density (WMAP, ...), $0.094 < \Omega_{\rm CDM}\, h^2 < 0.129$
- $+ \, (g-2)_\mu$, $\mathrm{BR}(b \to s\gamma)$, $\mathrm{BR}(B_s \to \mu^+\mu^-)$

Global CMSSM fit, all CMSSM parameters and dark matter constraint included in the fit

Fit results vs. measured values in the CMSSM and the SM:

Variable	Measurement	Fit	$\lvert O^{meas} - O^{fit}\rvert / \sigma^{meas}$ (0 1 2 3)
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02774	
m_Z [GeV]	91.1875 ± 0.0021	91.1873	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4952	
σ^0_{had} [nb]	41.540 ± 0.037	41.486	
R_l	20.767 ± 0.025	20.744	
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01641	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479	
R_b	0.21629 ± 0.00066	0.21613	
R_c	0.1721 ± 0.0030	0.1722	
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037	
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0741	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1479	
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.398 ± 0.025	80.382	
m_t [GeV]	170.9 ± 1.8	170.8	
$R(b \to s\gamma)$	1.13 ± 0.12	1.12	
$B_s \to \mu\mu$ [$\times 10^{-8}$]	< 8.00	0.33	N/A (upper limit)
Δa_μ [$\times 10^{-9}$]	2.95 ± 0.87	2.95	
Ωh^2	0.113 ± 0.009	0.113	

Variable	Measurement	Fit	$\lvert O^{meas} - O^{fit}\rvert / \sigma^{meas}$ (0 1 2 3)
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$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481	
R_b	0.21629 ± 0.00066	0.21586	
R_c	0.1721 ± 0.0030	0.1722	
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038	
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742	
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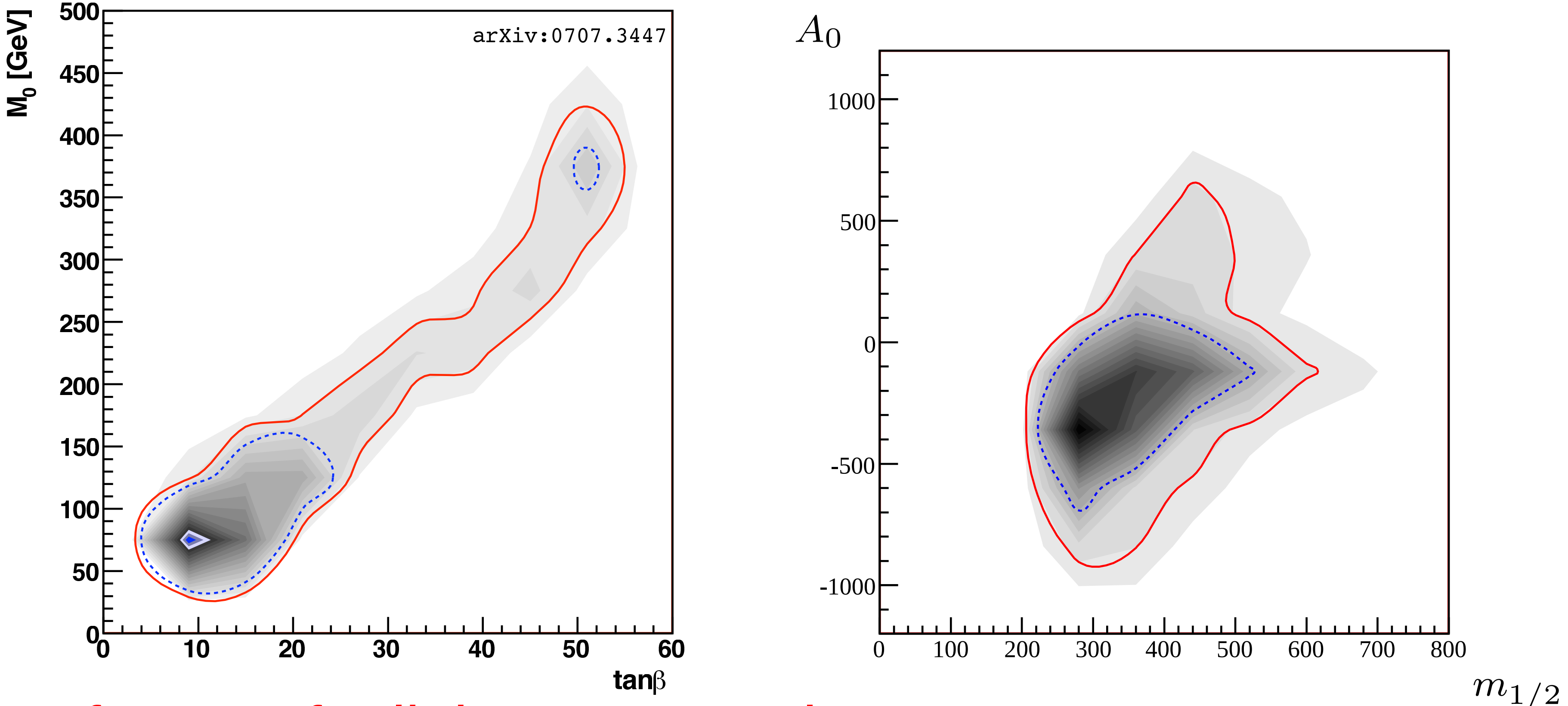
A_l(SLD)	0.1513 ± 0.0021	0.1481	
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.398 ± 0.025	80.374	
m_t [GeV]	170.9 ± 1.8	171.3	
Γ_W [GeV]	2.140 ± 0.060	2.091	

$\Rightarrow$ CMSSM yields good description of the data
Slightly higher goodness-of-fit probability than in the SM

Global CMSSM fit

68% (dotted) and 95% (solid) confidence level regions

[*O. Buchmueller, R. Cavanaugh, A. De Roeck, S. Heinemeyer, G. Isidori, P. Paradisi, F. Ronga, A. Weber, G. W. '07*]



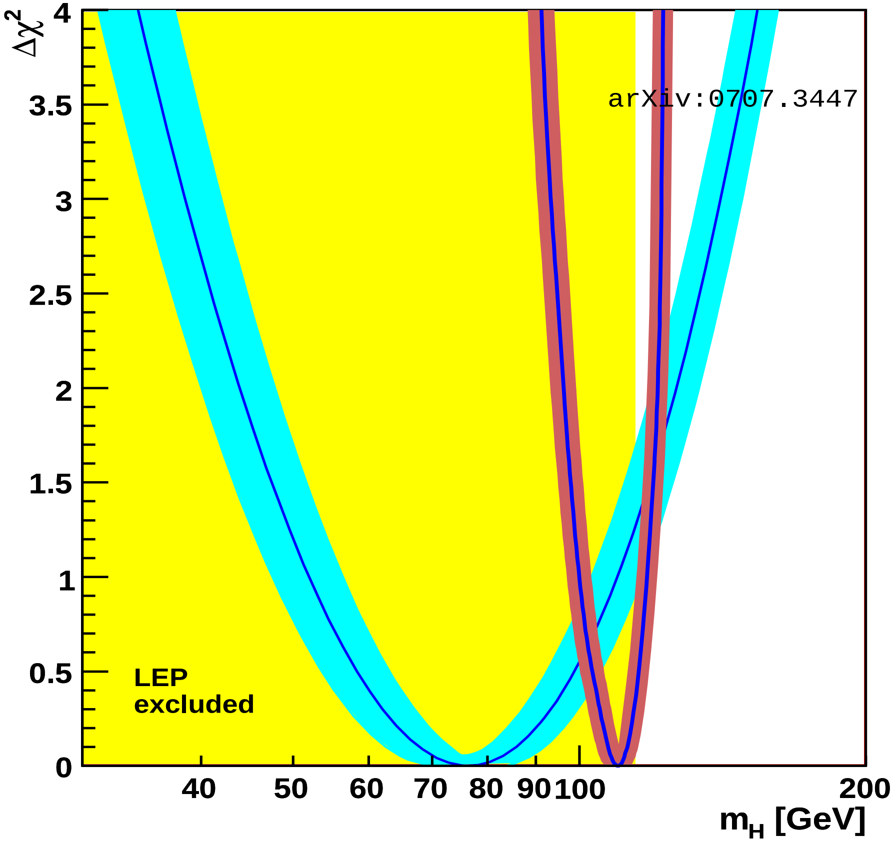
⇒ Preference for light SUSY scale

best fit values: $\tan\beta \approx 10$, $m_{1/2} \approx 300$ GeV

Indirect limits on the light Higgs mass in the CMSSM EWPO + BPO + dark matter constraints

χ^2 fit for M_h, without imposing direct search limit [*O. Buchmueller, R. Cavanaugh, A. De Roeck, S. Heinemeyer, G. Isidori, P. Paradisi, F. Ronga, A. Weber, G. W. '07*]

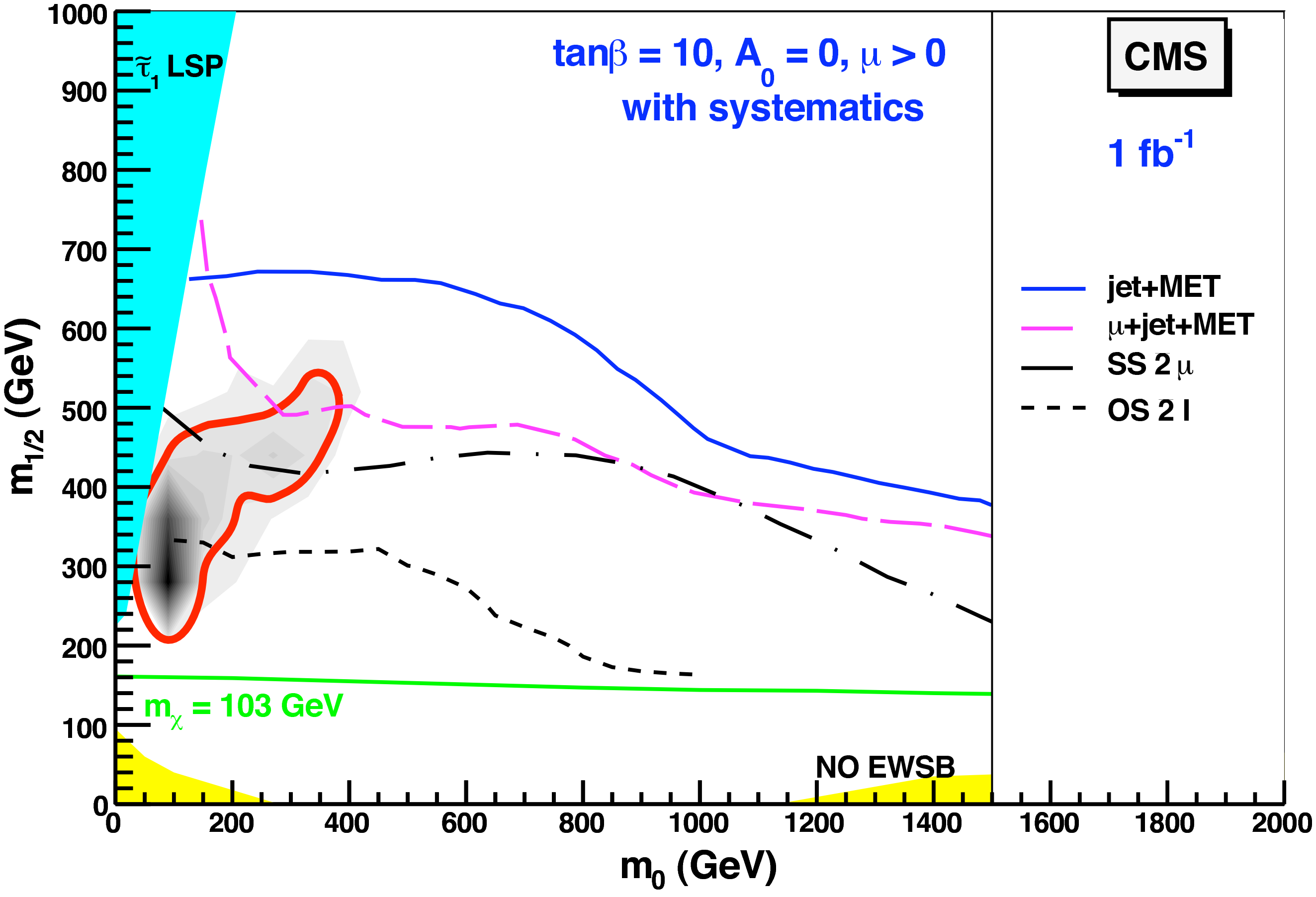
SM CMSSM



$\Rightarrow$ High sensitivity, less tension than in SM

Comparison: preferred region in m_0–$m_{1/2}$ plane, LHC discovery reach for $1\ \mathrm{fb}^{-1}$ of understood data

[O. Buchmueller, R. Cavanaugh, A. De Roeck, S. Heinemeyer, G. Isidori, P. Paradisi, F. Ronga, A. Weber, G. W. '07]



⇒ Preferred region would lead to early discovery

$\mathcal{CP}$ properties of SUSY particles

[*J. Ellis, F. Moortgat, G. Moortgat-Pick, J. Tattersall '07*]

Example: $gg \to \tilde{t}_i \tilde{t}_j \to \tilde{t}_i + \tilde{\chi}_k^0 t \to \tilde{t}_i + \tilde{\chi}_1^0 l^+ l^- + W^+ b$

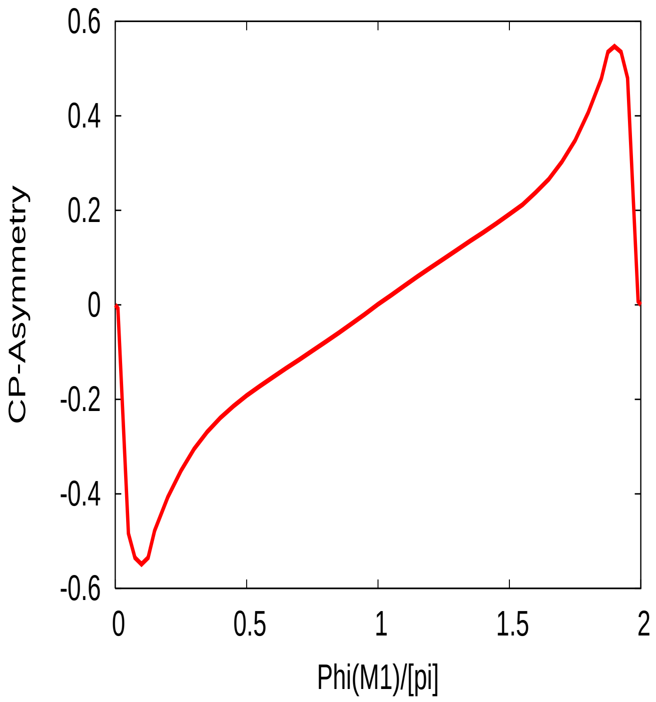
$\Rightarrow$ Find suitable $\mathcal{CP}$-odd observable between decay products

Example: $\mathcal{CP}$-asymmetries of triple products between tl^+l^-:

Large asymmetries possible
even for rather small phases

$\Leftrightarrow$ Important to analytically understand impact of complex couplings on asymmetries

So far parton-level study,
hadron-level simulation under work



Ongoing work on further asymmetries and other processes

Conclusions

- Discussed above: examples of existing, ongoing and possible future CMS–IPPP joint projects

  Not a comprehensive list

  $\Rightarrow$ Many opportunities for collaborations

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- Exploring the TeV scale:

  New physics can manifest itself in many (and maybe completely unexpected) ways

  ⇒ Exciting challenge for experiment and theory to figure out the nature of TeV-scale physics

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  New physics can manifest itself in many (and maybe completely unexpected) ways

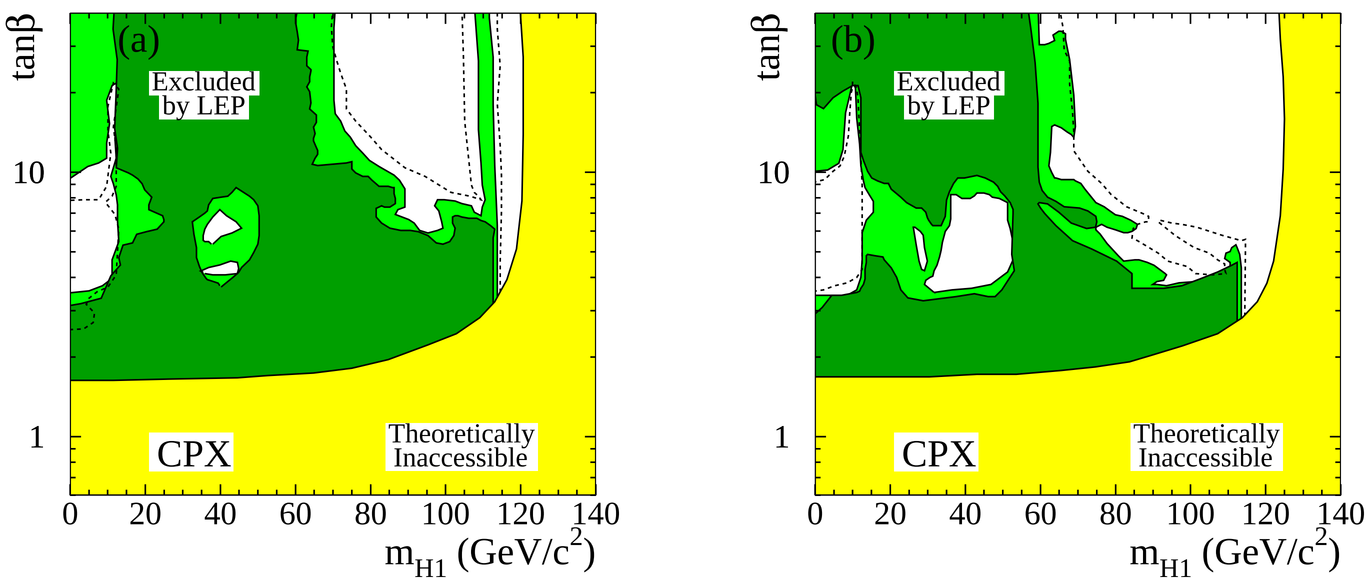
  $\Rightarrow$ Exciting challenge for experiment and theory to figure out the nature of TeV-scale physics

- Looking forward to the first LHC data from CMS!

SUSY Higgs: a very light non SM-like Higgs

- MSSM with $\mathcal{CP}$-violating phases (CPX scenario):
  Light Higgs, h_1: strongly suppressed h_1VV couplings
  Second-lightest Higgs, h_2, possibly within LEP reach (with reduced VVh_2 coupling), h_3 beyond LEP reach
  Large $\mathrm{BR}(h_2 \to h_1 h_1)$ $\Rightarrow$ difficult final state [*LEP Higgs WG '06*]

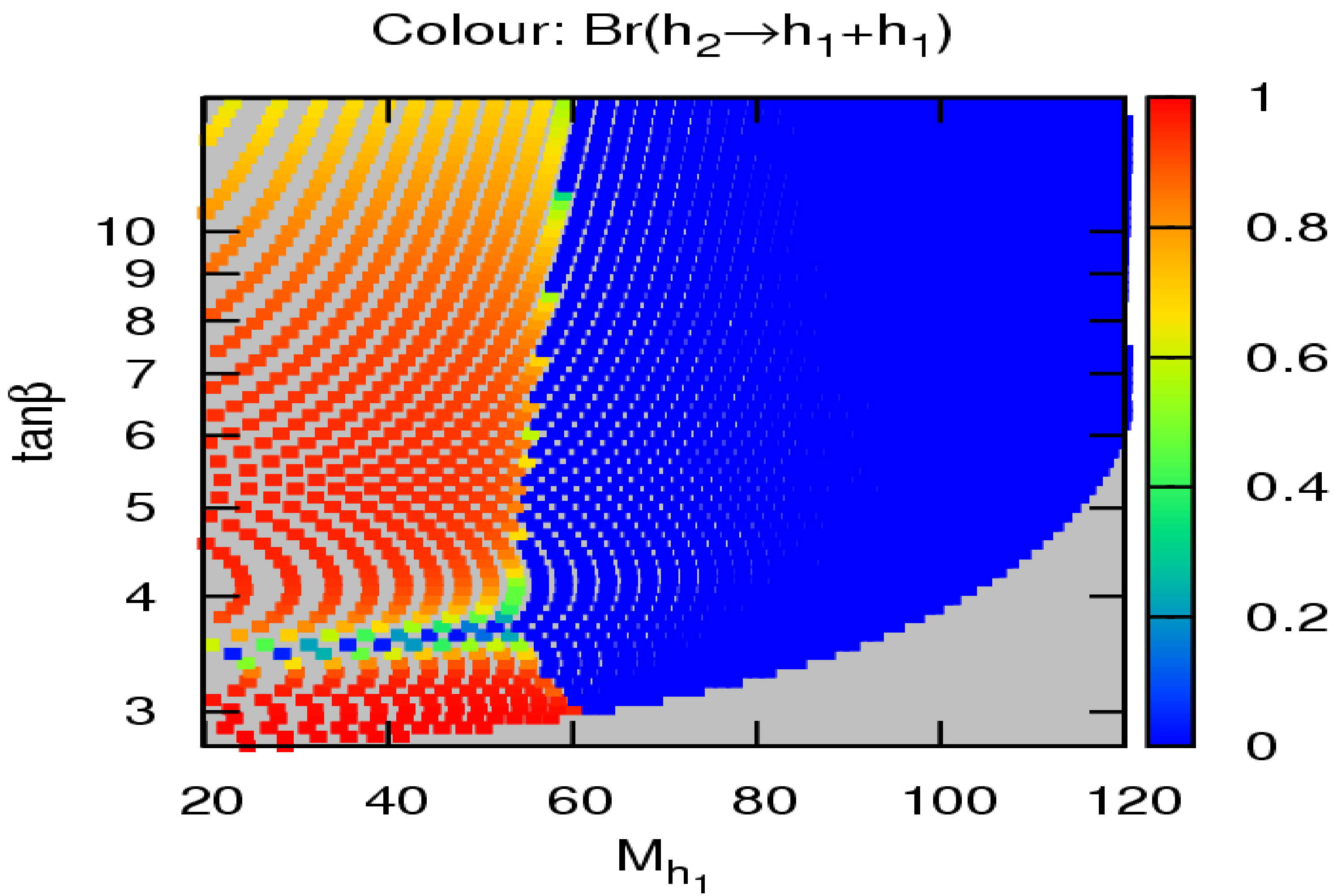
$m_\mathrm{t} = 169.3$ GeV $\qquad$ $m_\mathrm{t} = 174.3$ GeV



$\Rightarrow$ no lower limit on M_{h_1}: light SUSY Higgs not ruled out!

$\mathrm{BR}(h_2 \to h_1 h_1)$ ***in the LEP-unexcluded region***

Improved evaluation of $\mathrm{BR}(h_2 \to h_1 h_1)$: [*G. W., K. Williams '07*]



⇒ "CPX holes" confirmed

SUSY Higgs: a very light non SM-like Higgs

- $\mathcal{CP}$-conserving case: light Higgs with strongly suppressed coupling to gauge bosons, suppression of $\mathrm{BR}(h \to b\bar{b})$ via large higher-order corrections to bottom Yukawa coupling
[*A. Belyaev, Q.H. Cao, D. Nomura, K. Tobe, C.P. Yuan '06*]

- NMSSM: light pseudoscalar a, $m_a < 2m_b$, with $h \to aa \to 4\tau$
[*R. Dermisek, J.F. Gunion '07*]
[*S. Chang, P.J. Fox, N. Weiner '06*]

- ...

$\Rightarrow$ LHC Higgs searches needed also in the low-mass region