SUSY Higgs at IPPP

Georg Weiglein

IPPP Durham

Imperial College, 05/2009

Probing the electroweak symmetry breaking mechanism at the LHC

Our current description of the fundamental interactions breaks down at the TeV scale (unitarity violation, . . .) unless there is new physics:

Higgs, strong electroweak symmetry breaking, extra dimensions, . . .

Probing the electroweak symmetry breaking mechanism at the LHC

Our current description of the fundamental interactions breaks down at the TeV scale (unitarity violation, . . .) unless there is new physics:

Higgs, strong electroweak symmetry breaking, extra dimensions, . . .

$\Rightarrow$ We expect to see manifestations of the electroweak symmetry breaking mechanism at the LHC

Higgs physics: things that phenomenologists work on

- Predictions for Higgs production and decay in different models

  $\Rightarrow$ Prospects for discovery reach, . . .

- How to infer the underlying physics from the experimental signatures?
  - A Higgs or not a Higgs?
  - Fundamental or composite?
  - SM, MSSM or beyond?
  - . . .

Prospects for heavy Higgs discovery in the MSSM

[*IC–IPPP Collaboration*]

Experimental analysis in $b\bar{b}H, A$, $H, A \to \tau^+\tau^-$ channel:

- 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, $\tau\tau b\bar{b}$

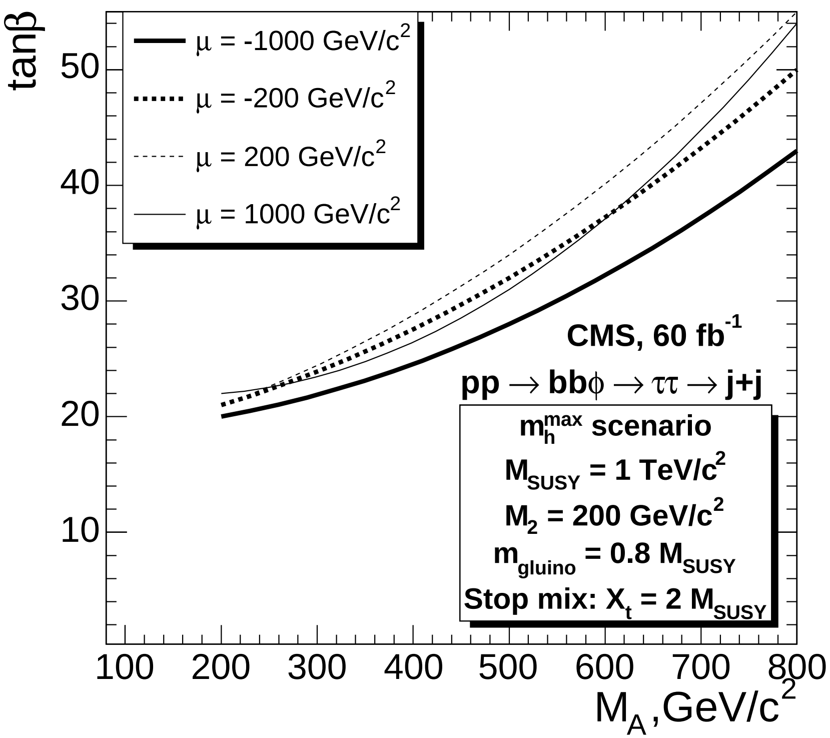
Theory analysis (*FeynHiggs*):

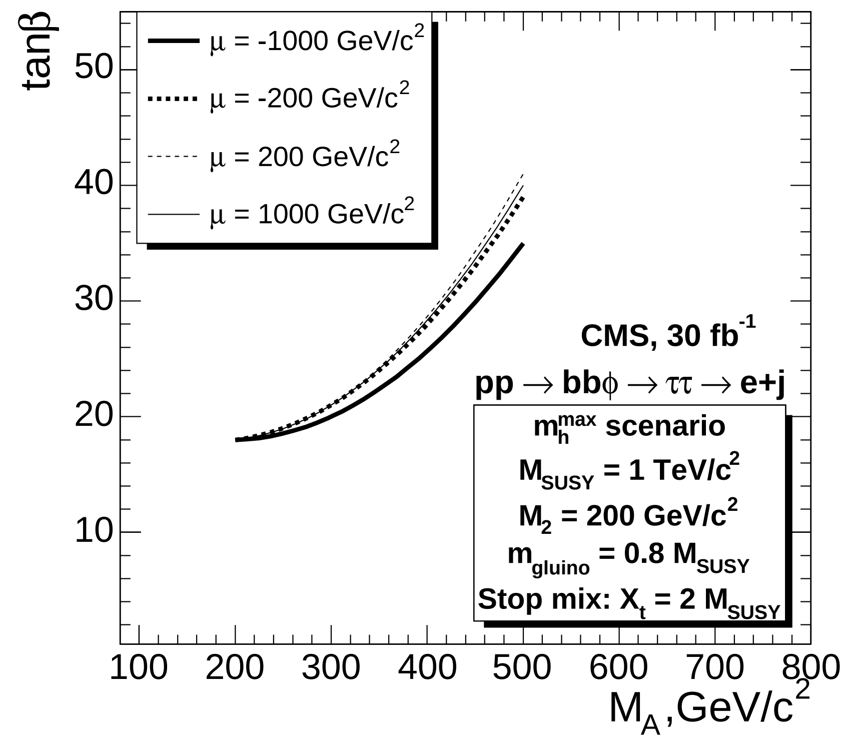
- Detailed investigation of higher-order effects
- Impact of decays into SUSY particles

Variation of the 5σ discovery contours with μ (m_h^{max} scen.):

$\tau^+\tau^- \to$ *jets (left) and* $\tau^+\tau^- \to e +$ *jet (right)*

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





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

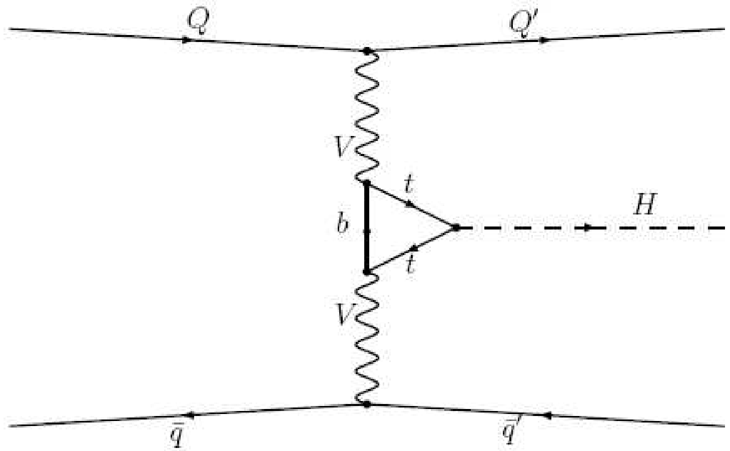
Significant effect on "LHC wedge region"

Update of analysis for charged Higgs production in progress

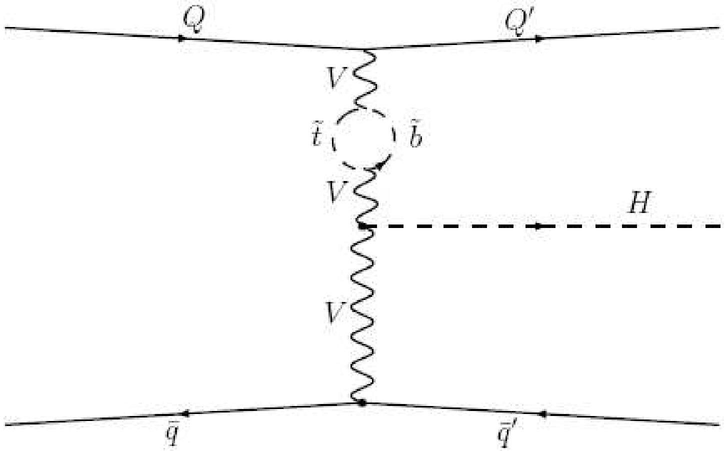
Higgs production in weak-boson fusion:

full SM-type one-loop + dominant SUSY loop corrections

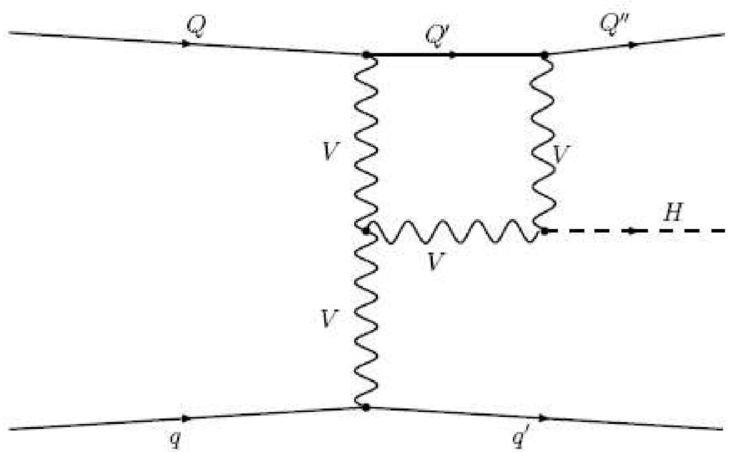
[*T. Figy, S. Palmer, G. W. '09*]



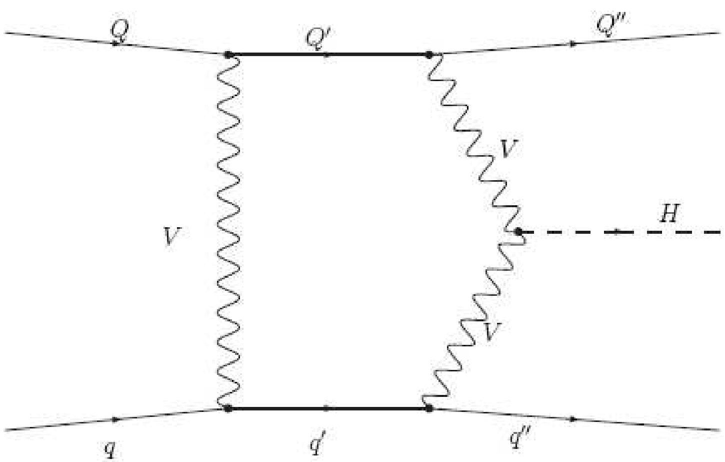
(a) Corrections to the VVH vertex



(b) Corrections to the VV self energy



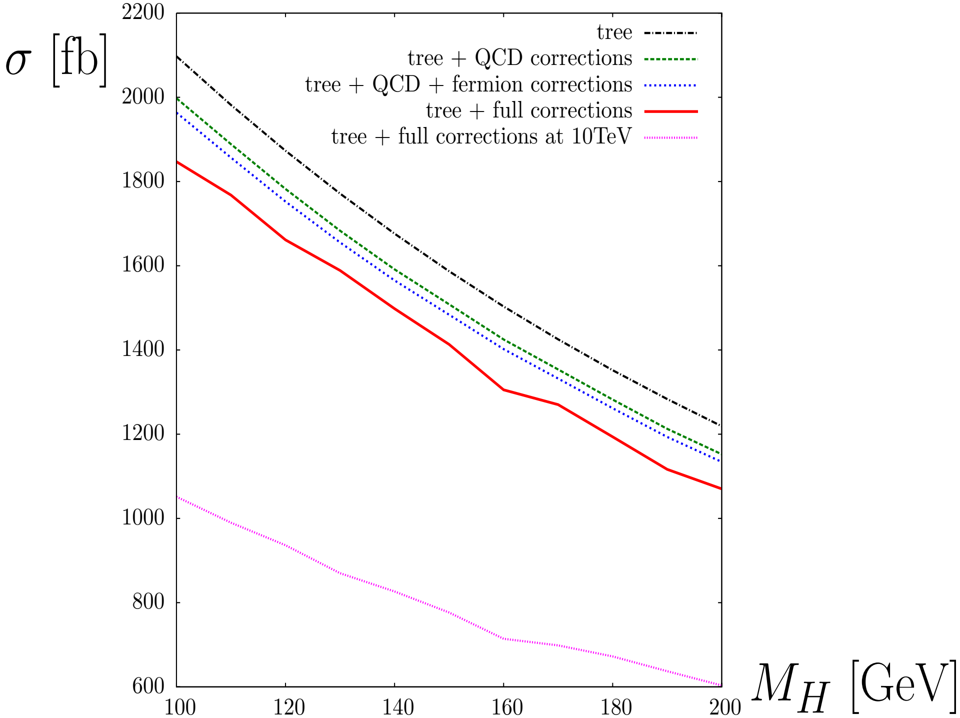
(c) Box diagrams

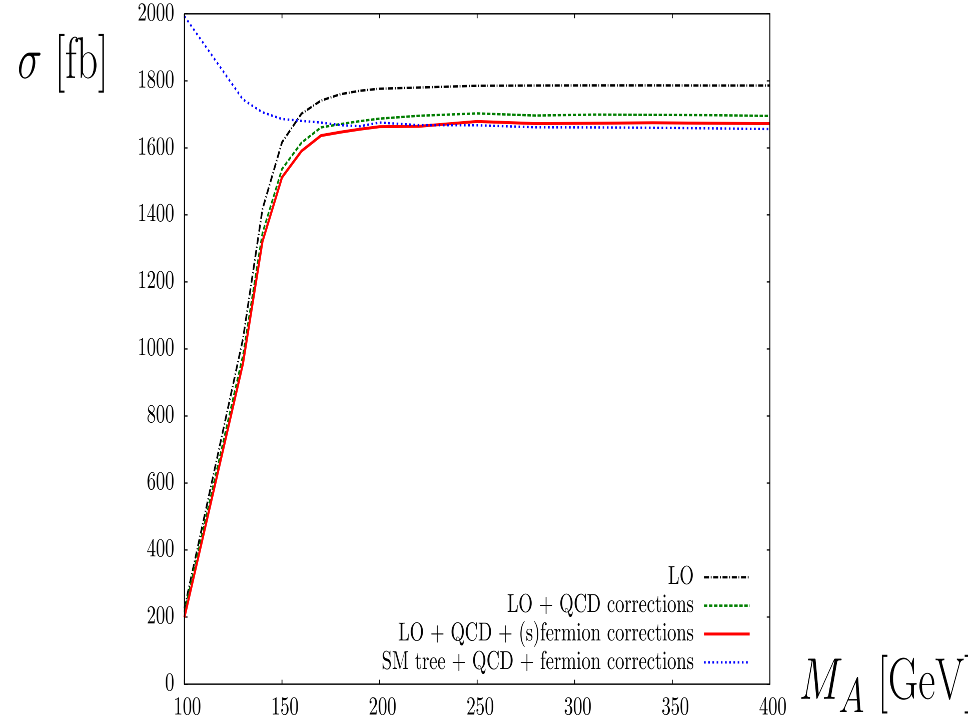


(d) Pentagon diagrams

Results for total cross section in the SM and the MSSM with WBF cuts

[*T. Figy, S. Palmer, G. W. ’09*]





$\Rightarrow$ Electroweak corrections are as big as the QCD corrections

Results have been implemented into the public *VBFNLO* Monte Carlo program

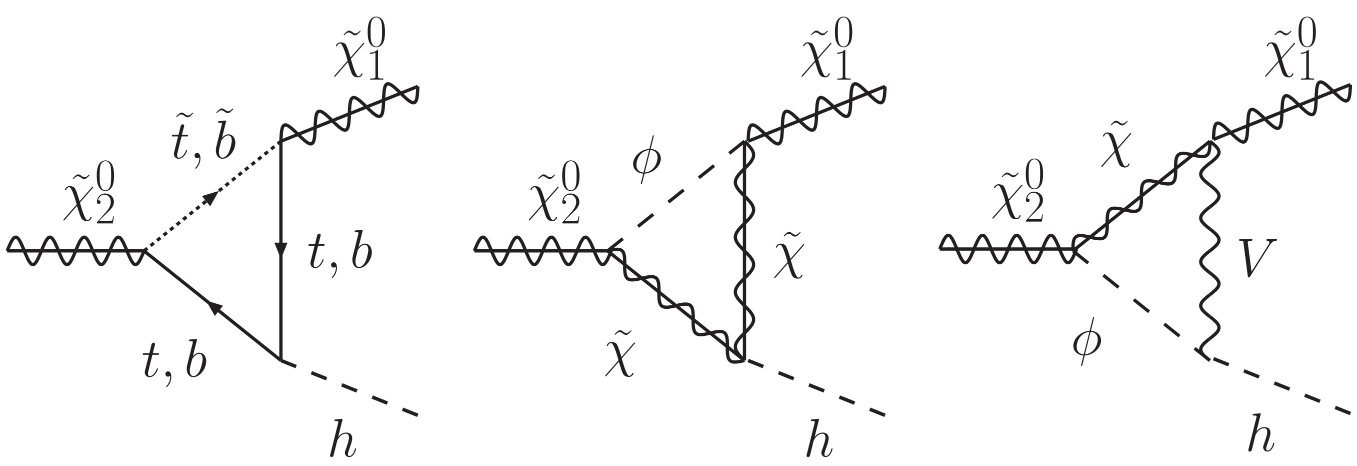
Higgs production in SUSY cascade decays

SUSY cascade decays could be a promising Higgs source

E.g. $\mathcal{CP}$-violating scenario: very light Higgs, $M_{\mathrm{h}_1} \approx 40\ \mathrm{GeV}$ not excluded by LEP, difficult to cover with standard search channels at the LHC

$\Rightarrow \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$ can dominate over $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 l\bar{l}$

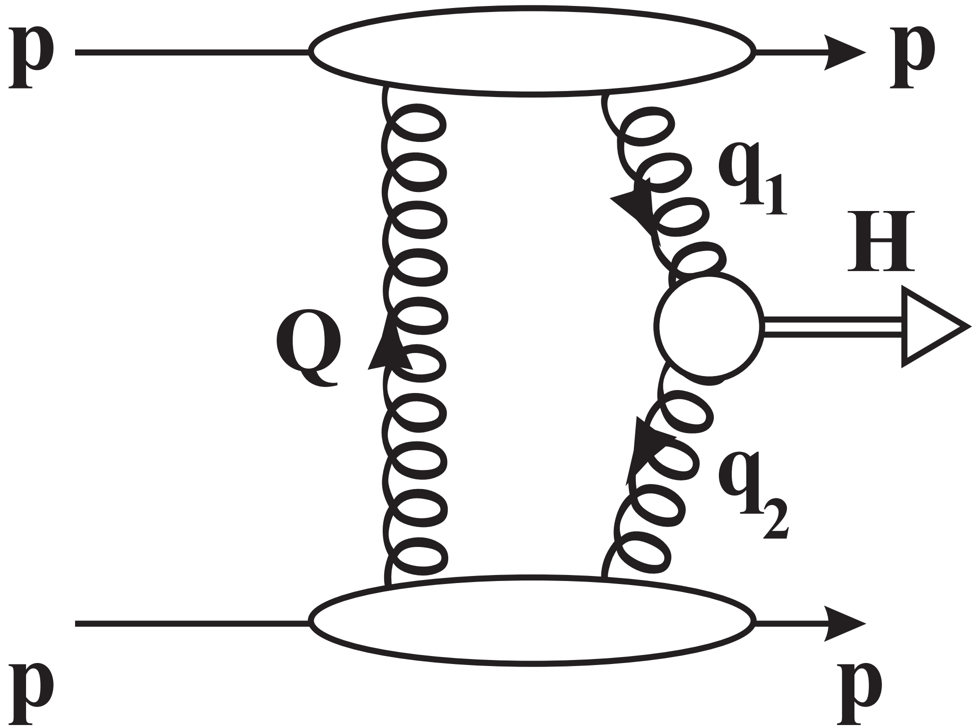
Genuine one-loop corrections in the MSSM with complex phases



$+$ 2-loop $\mathcal{O}(\alpha_{\mathrm{t}}\alpha_{\mathrm{s}})$ propagator-type corrections [*A. Fowler, G. W. '09*]

Diffractive Higgs production

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



Protons remain undestroyed, forward proton tagging at $220\ \mathrm{m}$ / $420\ \mathrm{m}$

exchange of colour-singlet

no hadronic activity between outgoing protons and Higgs decay products

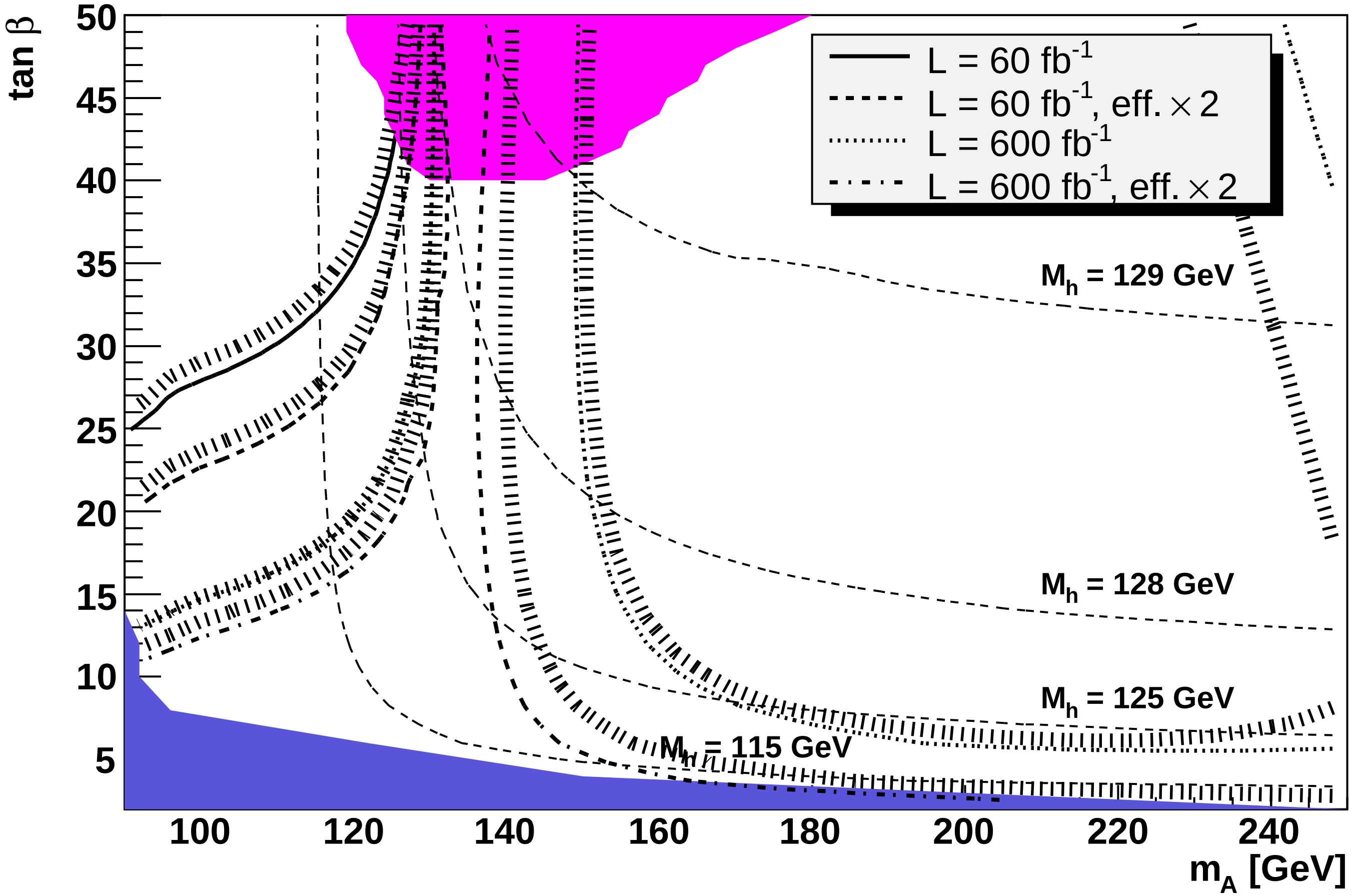
$J_\mathrm{z} = 0$ selection rule

$\Rightarrow$ 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. '08*]

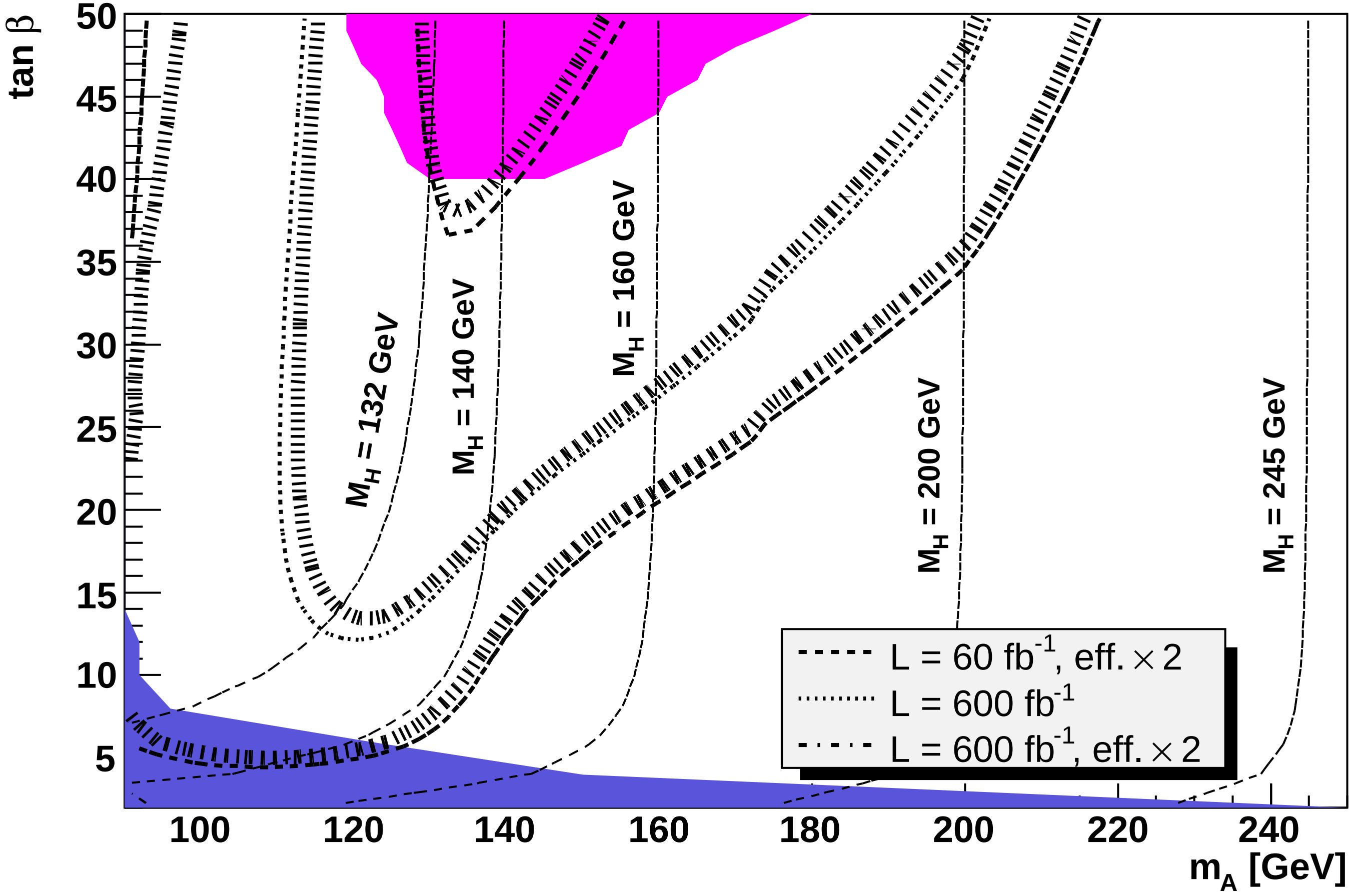


$\Rightarrow$ Almost complete coverage with high integrated luminosity

$\Rightarrow$ 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. '08*]



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

Tools

- Higgs:

  FeynHiggs, *HiggsBounds*, *VBFNLO*, . . .

- General:

  Herwig, *Sherpa*, *MSTWpdf*, *HepData*, *CEDAR*, . . .

Tools

- Higgs:

  FeynHiggs, *HiggsBounds*, *VBFNLO*, . . .

- General:

  Herwig, *Sherpa*, *MSTWpdf*, *HepData*, *CEDAR*, . . .

  SUSY: *MasterCode* [*IC–IPPP Collaboration*]

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 LHC (LHC results for $10\ \mathrm{TeV}$ in preparation)
- Provides estimate of remaining theoretical uncertainties from unknown higher-orders
- Evaluation of additional observables ($\rightarrow$ constraints on SUSY parameter space):
  $\Delta\rho$ (ew precision observables), $(g-2)_\mu$, $\mathrm{BR}(\mathrm{b} \rightarrow \mathrm{s}\gamma)$, 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 HiggsBounds

www.ippp.dur.ac.uk/HiggsBounds

HiggsBounds [*P. Bechtle, O. Brein, S. Heinemeyer, G. W., K. Williams '08*]

Tool for testing the theoretical predictions of models with arbitrary Higgs sectors against exclusion bounds from the search for neutral Higgs bosons at LEP and the Tevatron

Implemented: cross-section limits for different search topologies $+$ combined SM results (are applied to new a physics model if it is found that the model behaves sufficiently "SM-like" in the considered parameter region)

Required for each channel: observed and expected limit

expected limit: bound that one would obtain in the hypothetical case of an observed distribution that agrees precisely with the background expectation

Search channels implemented in HiggsBounds (expected and observed limits)

LEP:

$$e^+e^- \to (h_k)Z \to (b\bar{b})Z$$
$$e^+e^- \to (h_k)Z \to (\tau^+\tau^-)Z$$
$$e^+e^- \to (h_k \to h_i h_i)Z \to (b\bar{b}b\bar{b})Z$$
$$e^+e^- \to (h_k \to h_i h_i)Z \to (\tau^+\tau^-\tau^+\tau^-)Z$$
$$e^+e^- \to (h_k h_i) \to (b\bar{b}b\bar{b})$$
$$e^+e^- \to (h_k h_i) \to (\tau^+\tau^-\tau^+\tau^-)$$
$$e^+e^- \to (h_k \to h_i h_i)h_i \to (b\bar{b}b\bar{b})b\bar{b}$$
$$e^+e^- \to (h_k \to h_i h_i)h_i \to (\tau^+\tau^-\tau^+\tau^-)\tau^+\tau^-$$
$$e^+e^- \to (h_k \to h_i h_i)Z \to (b\bar{b})(\tau^+\tau^-)Z$$
$$e^+e^- \to (h_k \to b\bar{b})(h_i \to \tau^+\tau^-)$$
$$e^+e^- \to (h_k \to \tau^+\tau^-)(h_i \to b\bar{b})$$

Search channels implemented in HiggsBounds (expected and observed limits)

Tevatron:

$p\bar{p} \to ZH \to l^+l^-b\bar{b}$ (CDF with 1.0 fb^{-1})

$p\bar{p} \to ZH \to l^+l^-b\bar{b}$ (CDF with 2.4 fb^{-1})

$p\bar{p} \to ZH \to l^+l^-b\bar{b}$ (DØ with 2.3 fb^{-1})

$p\bar{p} \to WH \to l\nu b\bar{b}$ (DØ with 1.7 fb^{-1})

$p\bar{p} \to WH \to l\nu b\bar{b}$ (CDF with 2.7 fb^{-1})

$p\bar{p} \to WH \to W^+W^-W^\pm$ (DØ with 1.0 fb^{-1})

$p\bar{p} \to WH \to W^+W^-W^\pm$ (CDF with 1.9 fb^{-1})

$p\bar{p} \to H \to W^+W^- \to l^+l'^-$ (DØ with 3.0 fb^{-1})

$p\bar{p} \to H \to W^+W^- \to l^+l'^-$ (CDF with 3.0 fb^{-1})

$p\bar{p} \to H \to \gamma\gamma$ (DØ with 1.1 fb^{-1})

$p\bar{p} \to H \to \gamma\gamma$ (DØ with 2.68 fb^{-1})

$p\bar{p} \to H \to \tau^+\tau^-$ (DØ with 1.0 fb^{-1})

$p\bar{p} \to H \to \tau^+\tau^-$ (CDF with 1.8 fb^{-1})

$p\bar{p} \to bH, H \to b\bar{b}$ (CDF with 1.9 fb^{-1})

$p\bar{p} \to bH, H \to b\bar{b}$ (DØ with 1.0 fb^{-1})

$p\bar{p} \to bH, H \to b\bar{b}$ (DØ with 2.6 fb^{-1})

Search channels implemented in HiggsBounds (expected and observed limits)

Tevatron, combined SM results:

$p\bar{p} \to WH/ZH \to b\bar{b} + E_T^{\rm miss.}$ (CDF with 2.3 fb^{-1})

$p\bar{p} \to WH/ZH \to b\bar{b} + E_T^{\rm miss.}$ (DØ with 2.1 fb^{-1})

$p\bar{p} \to H/HW/HZ/H$ via VBF, $H \to \tau^+\tau^-$ (CDF with 2.0 fb^{-1})

Combined SM analysis (CDF & DØ with 0.9 – 1.9 fb^{-1})

Combined SM analysis (CDF & DØ with 1.0 – 2.4 fb^{-1})

Combined SM analysis (CDF & DØ with 3.0 fb^{-1})

Determination of 95% C.L. exclusion limits

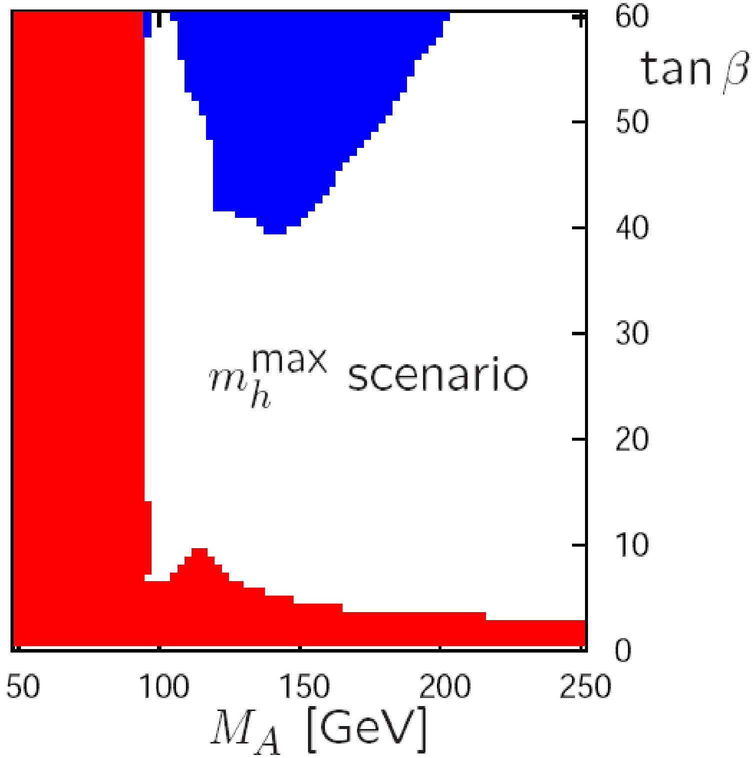
In order to obtain an exclusion limit having the correct statistical interpretation as a 95% C.L.:

- As a first step, *HiggsBounds* determines for every parameter point the search channel having the highest statistical sensitivity for setting an exclusion limit, on the basis of model predictions and the list of expected limits from LEP and the Tevatron

- For this single channel only, *HiggsBounds* compares the theoretical prediction for the Higgs production cross section times decay branching ratio with the actual experimental limit and determines whether or not the considered parameter point of the model is excluded at 95% C.L.

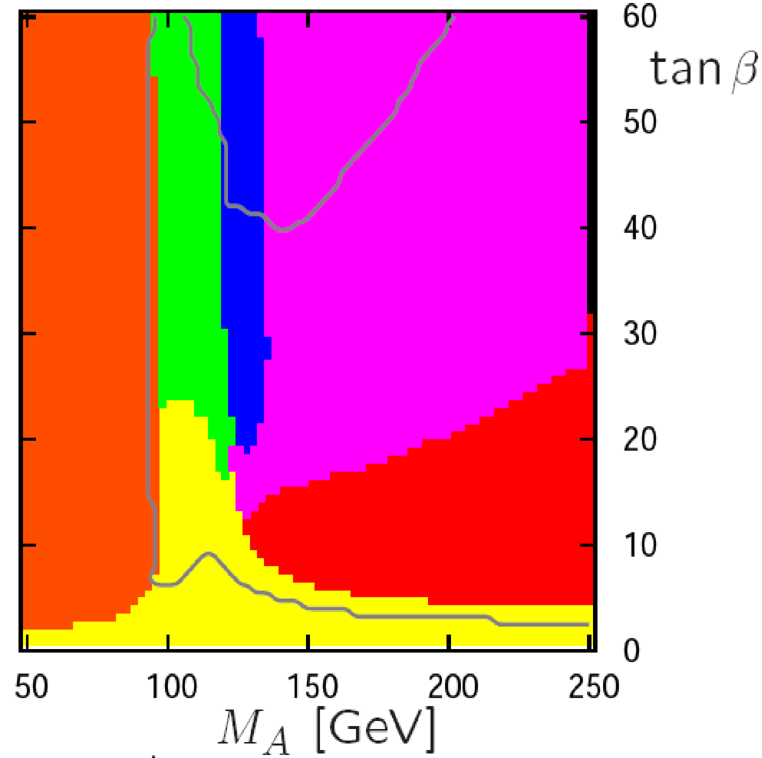
MSSM m_h^{max} benchmark scenario: 95% C.L. exclusions from LEP and Tevatron and channel of highest stat. sensitivity

[*P. Bechtle, O. Brein, S. Heinemeyer, G. W., K. Williams '08*]



■ : LEP exclusion

■ : Tevatron exclusion



■ : $e^+e^- \to hZ, h \to b\bar{b}$

■ : $e^+e^- \to hA \to b\bar{b}b\bar{b}$

■: $p\bar{p} \to h/A \to \tau^+\tau^-$ [CDF note 9071]

■: $p\bar{p} \to h/H/A \to \tau^+\tau^-$ [CDF note 9071]

■: $p\bar{p} \to H/A \to \tau^+\tau^-$ [CDF note 9071]

■: $p\bar{p} \to hW \to b\bar{b}l\nu$ [CDF note 9463]

■: $p\bar{p} \to H/A \to \tau^+\tau^-$ [DØ'08]

MasterCode: *indirect predictions for Higgs and SUSY from experimental constraints*

Global χ^2 fit in the CMSSM ($m_{1/2}$, m_0, A_0 (GUT scale), $\tan\beta$, $\mathrm{sign}(\mu)$ (weak scale)) and the NUHM1 (m_H^2 as add. param.)

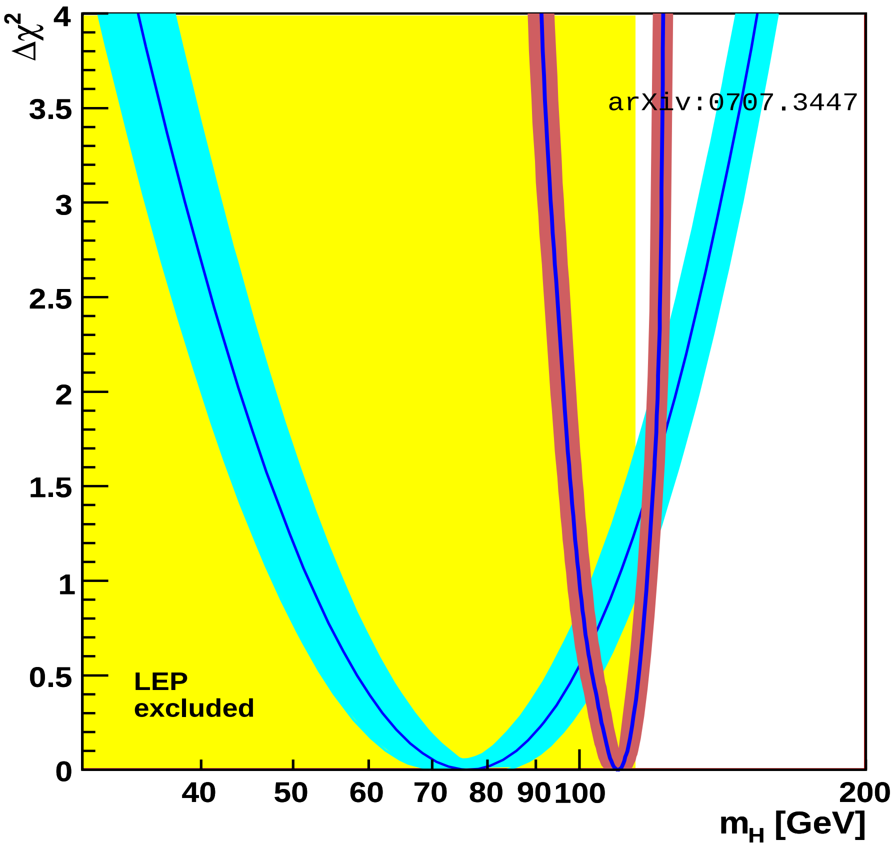
Fit includes (*MasterCode*, Markov-chain Monte Carlo sampling):
[*O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. W. '08*]

- All observables used in the SM fit of the LEPEWWG
- $+$ Cold dark matter (CDM) density (WMAP, ...), $\Omega_{\mathrm{CDM}}\, h^2 = 0.1099 \pm 0.0062$
- $+ (g-2)_\mu$
- $+$ BPO: $\mathrm{BR}(b \to s\gamma)$, $\mathrm{BR}(B_s \to \mu^+\mu^-)$, $\mathrm{BR}(B \to \tau\nu)$, ...
- $+$ Kaon decay data: $\mathrm{BR}(K \to \mu\nu)$, ...

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

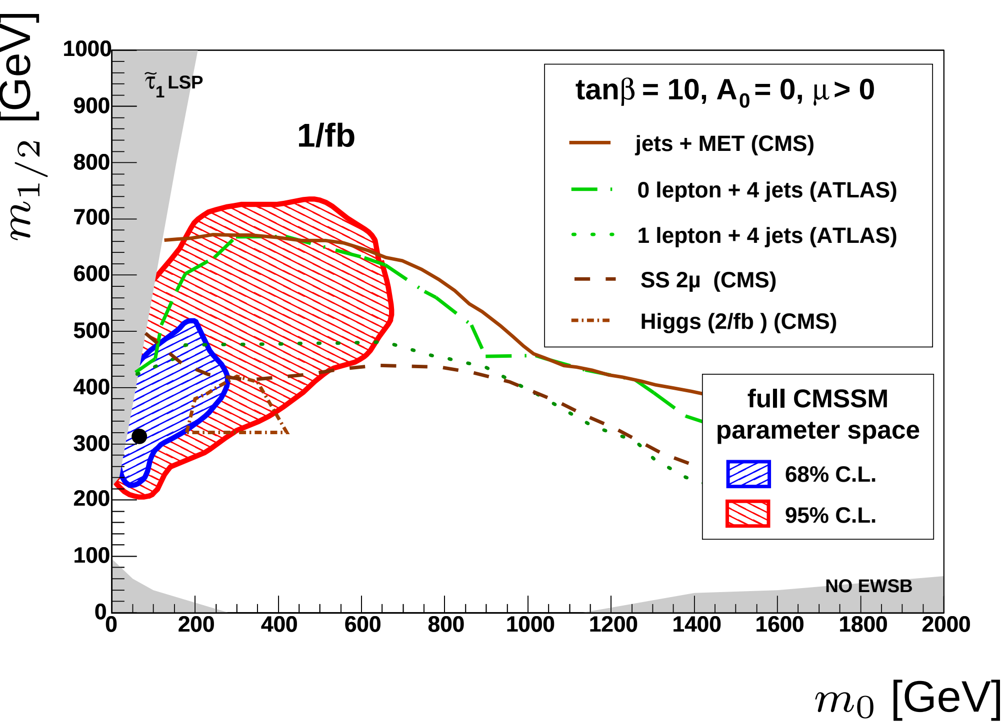


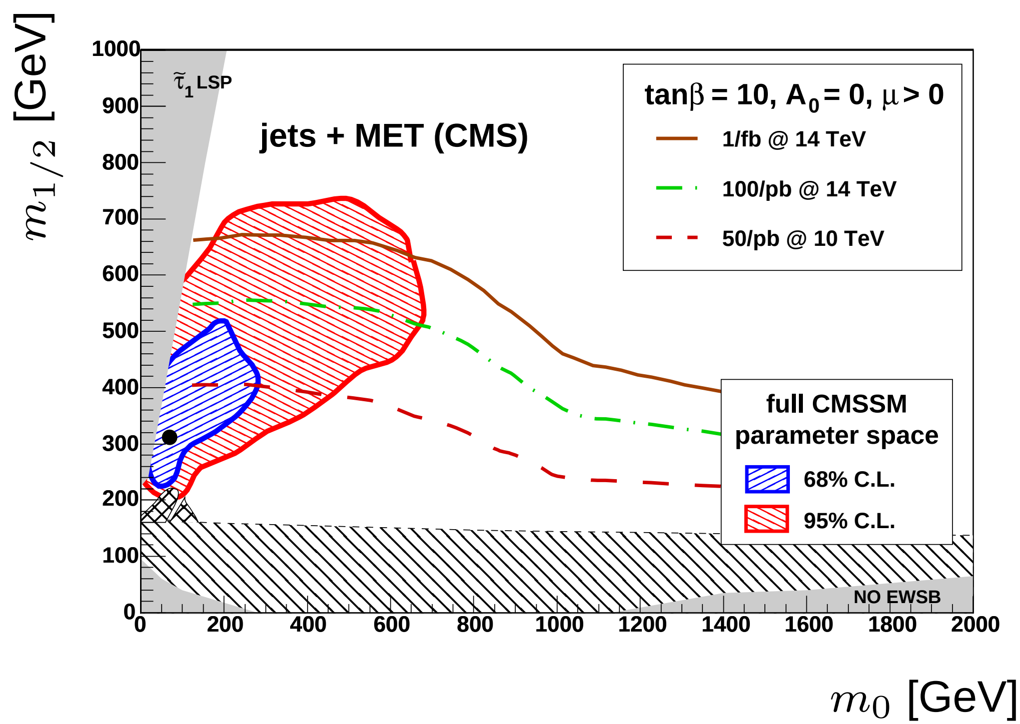
$\Rightarrow$ Accurate indirect prediction; Higgs "just around the corner"?

Comparison: preferred region in m_0–$m_{1/2}$ plane of the CMSSM vs. LHC discovery reach

68% and 95% C.L. contours from the fit vs. LHC discovery reach for $1, 0.1, 0.05\ \mathrm{fb}^{-1}$ of understood data

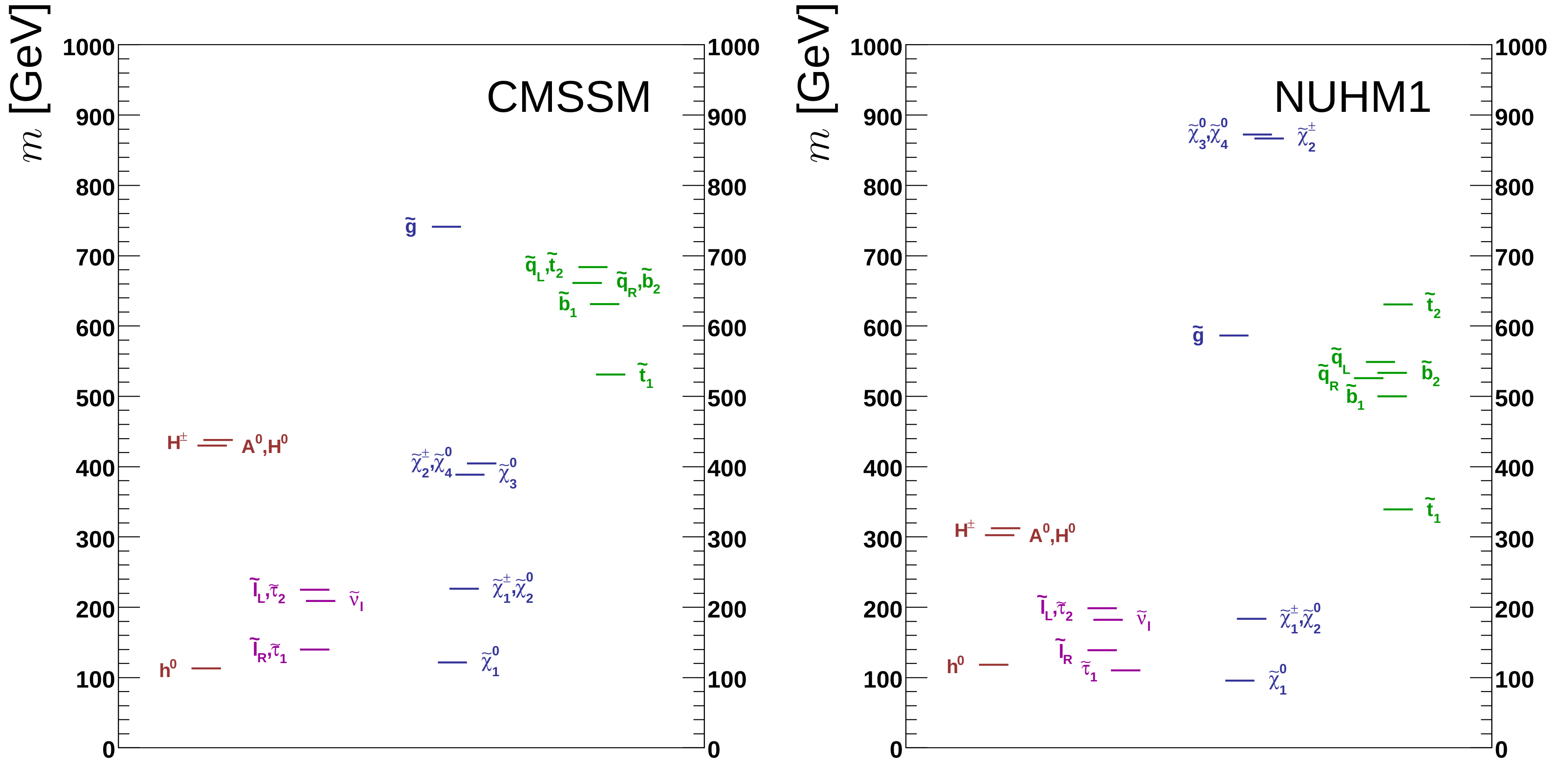
[O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. W. '08]





$\Rightarrow$ Preferred region would lead to early discovery

Spectra of the best-fit points in the CMSSM and the NUHM1

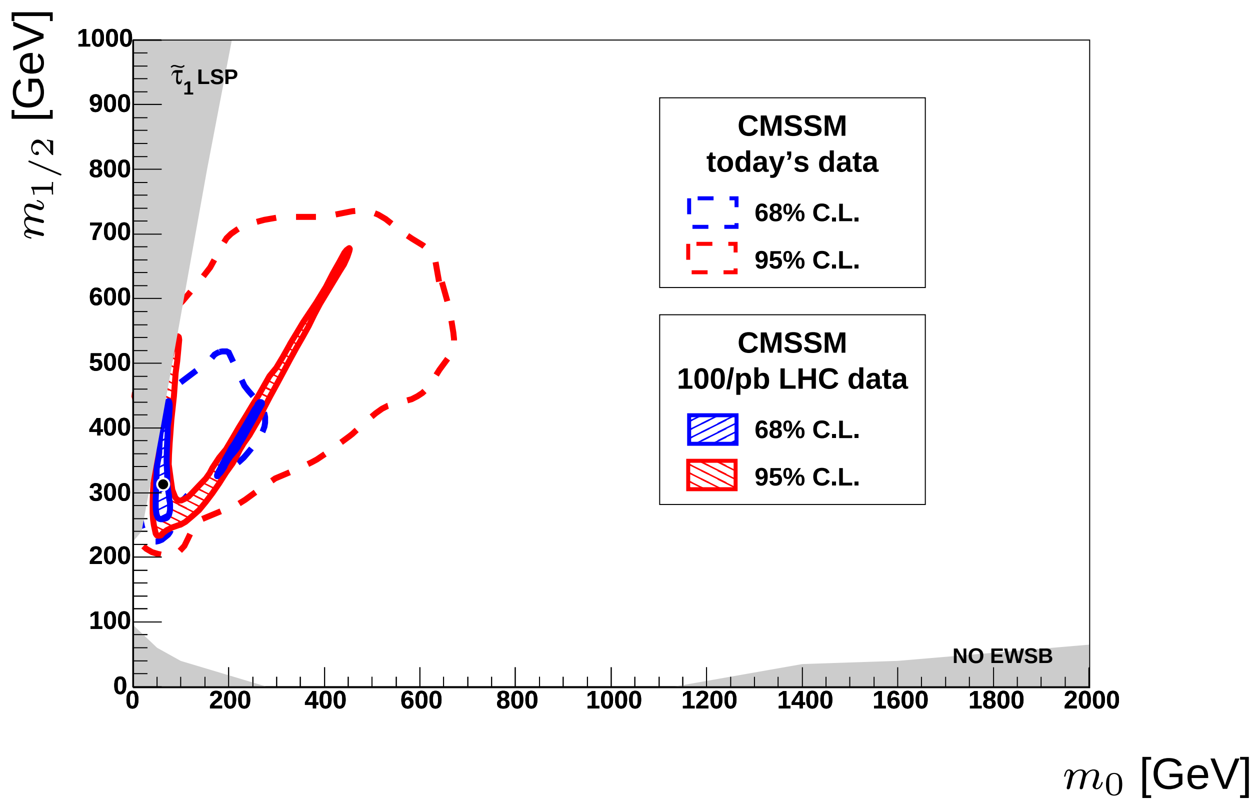


⇒ CMSSM: similar spectrum as SPS1a benchmark point

Similar fit probabilities for the two models

Improvements from measuring a dilepton edge

Fit with additional information from measuring the opposite-sign dilepton edge in $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-$ ($\ell = e, \mu$) with 1 fb^{-1}: [*O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. W. '08*]



$\Rightarrow$ Big improvement in determination of m_0, $m_{1/2}$

Conclusions

- Exploring the mechanism of electroweak symmetry breaking will be an exciting enterprise at the LHC

Conclusions

- Exploring the mechanism of electroweak symmetry breaking will be an exciting enterprise at the LHC

- Rich phenomenology possible

  It will be non-trivial to identify the underlying physics

Conclusions

- Exploring the mechanism of electroweak symmetry breaking will be an exciting enterprise at the LHC

- Rich phenomenology possible

  It will be non-trivial to identify the underlying physics

  $\Rightarrow$ A close interaction between experimentalists and theorists will be crucial

Conclusions

- Exploring the mechanism of electroweak symmetry breaking will be an exciting enterprise at the LHC

- Rich phenomenology possible

  It will be non-trivial to identify the underlying physics

  $\Rightarrow$ A close interaction between experimentalists and theorists will be crucial

- Looking forward to the first LHC collision data!