Higgs at LHC: a theorist's view

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DESY

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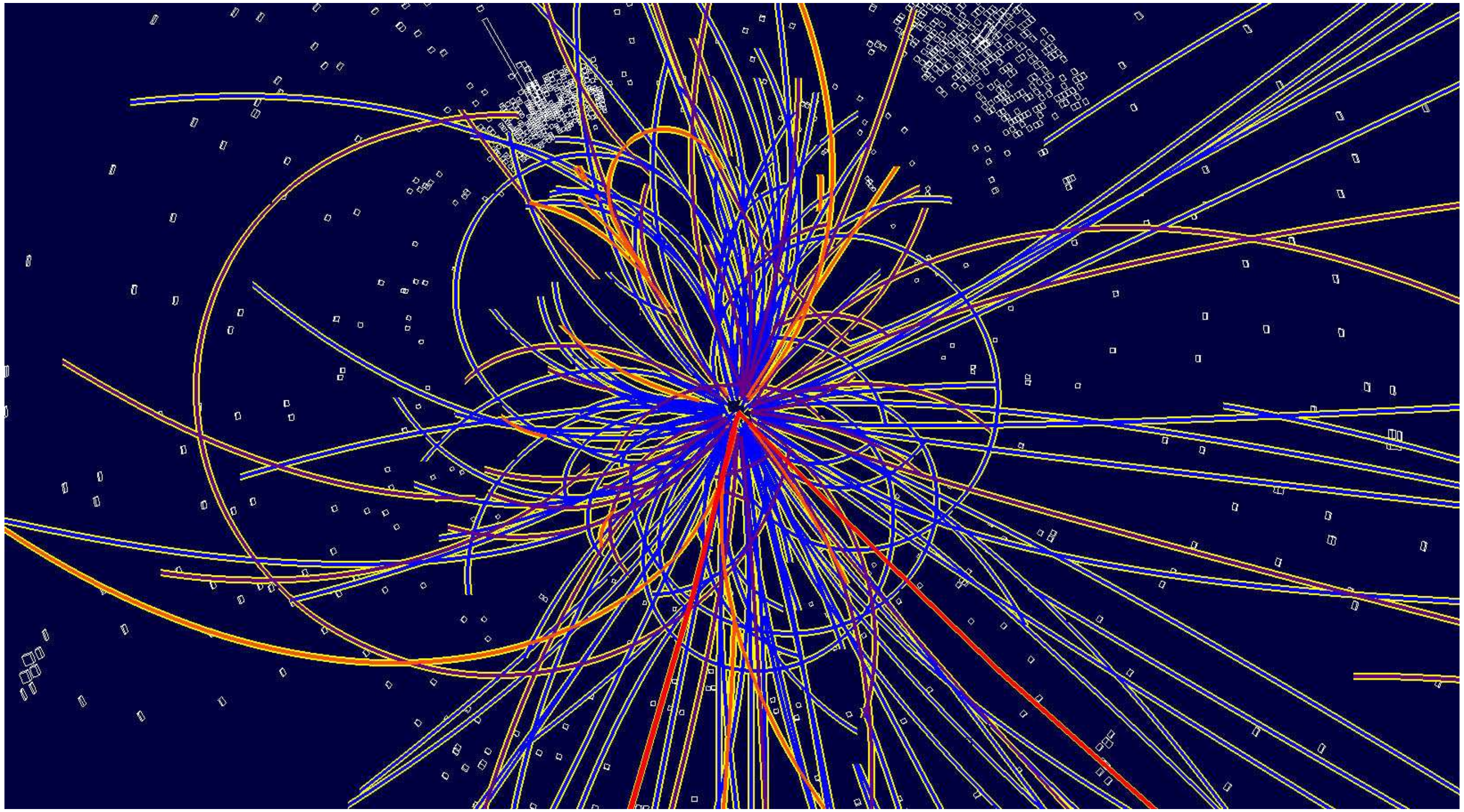
- Introduction: probing the electroweak symmetry breaking mechanism at the TeV scale
- Higgs phenomenology: SM and beyond
- Higgs hunting: cross section limits vs. benchmark scenarios
- A Higgs-like signal
- No Higgs signal in the early LHC data
- Conclusions

Introduction: probing the electroweak symmetry breaking mechanism at the TeV scale

Our current description of the fundamental interactions breaks down at the TeV scale without the onset of new physics

$\Rightarrow$ The mechanism of electroweak symmetry breaking will manifest itself at the TeV scale



What is the mechanism of electroweak symmetry breaking?

- Standard Model (SM), SUSY, . . . :

  Higgs mechanism, elementary scalar particle(s)

- Strong electroweak symmetry breaking:

  a new kind of strong interaction

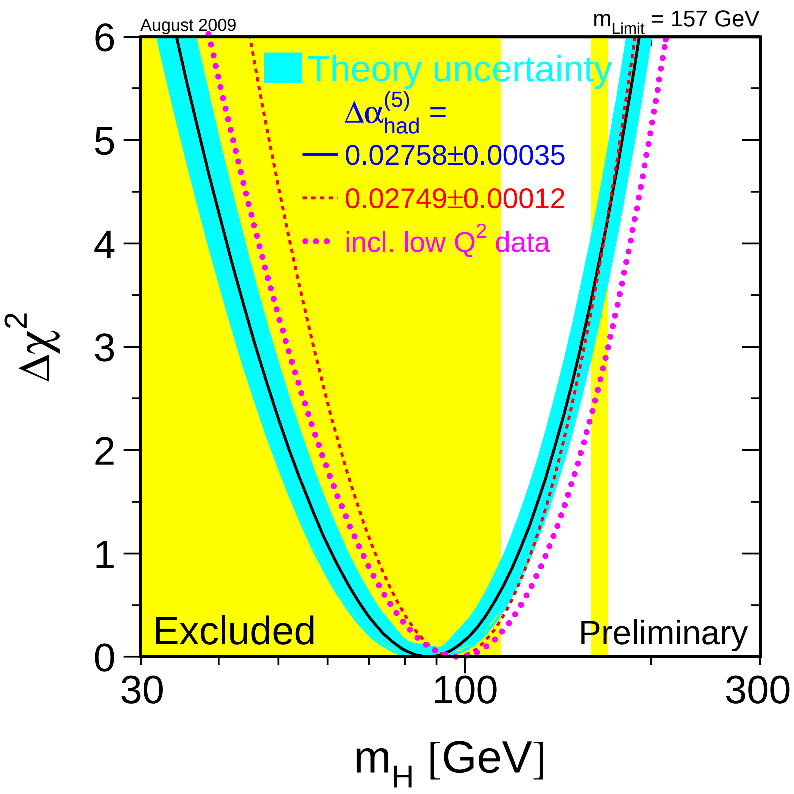
- Higgsless models in extra dimensions: boundary conditions for SM gauge bosons and fermions on Planck and TeV branes in higher-dimensional space

$\Rightarrow$ New phenomena required at the TeV scale

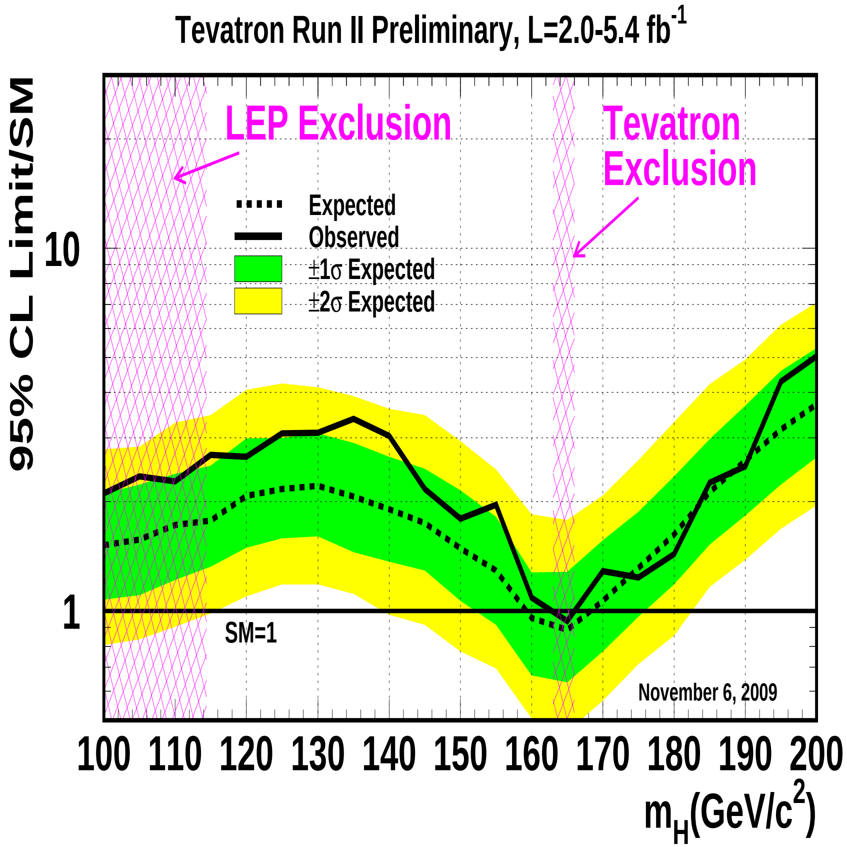
Constraints on the SM Higgs from electroweak precision data and direct searches

SM Higgs: ew. prec. data + direct search at LEP & Tevatron

[LEPEWWG '09]



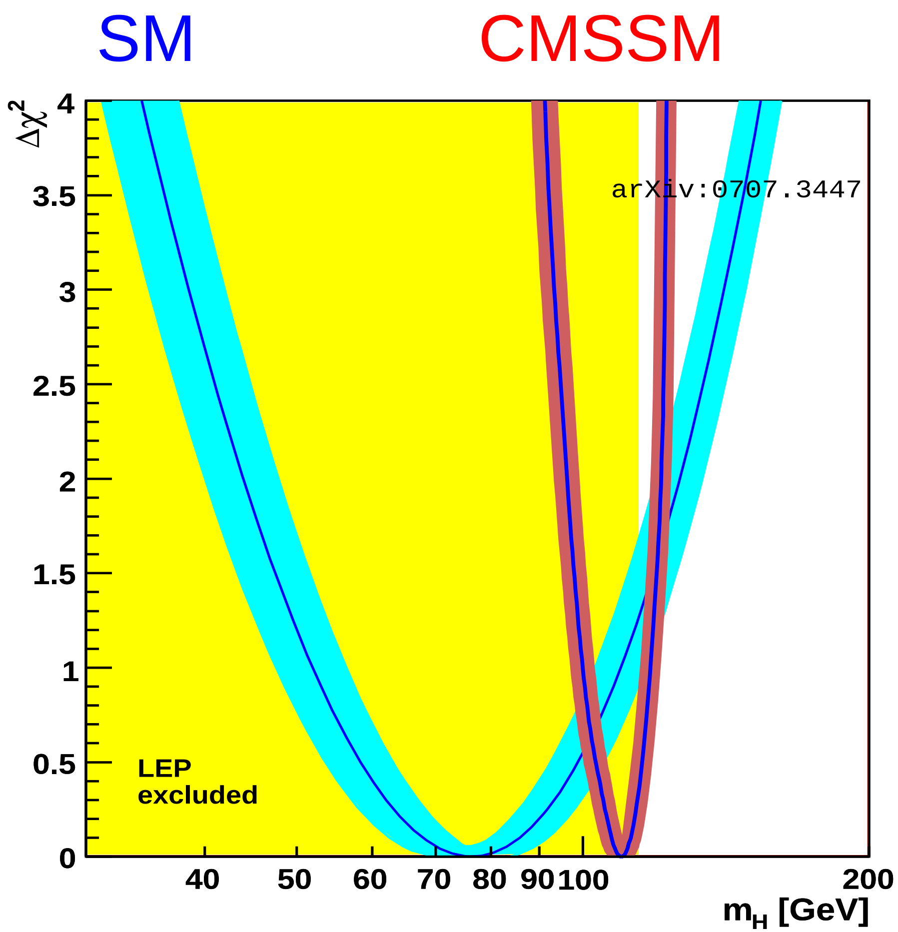
[TEVNPH Working Group '09]



⇒ Preference for a light Higgs

Indirect prediction for the Higgs mass in the SM and the constrained MSSM (CMSSM) from precision data

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*]

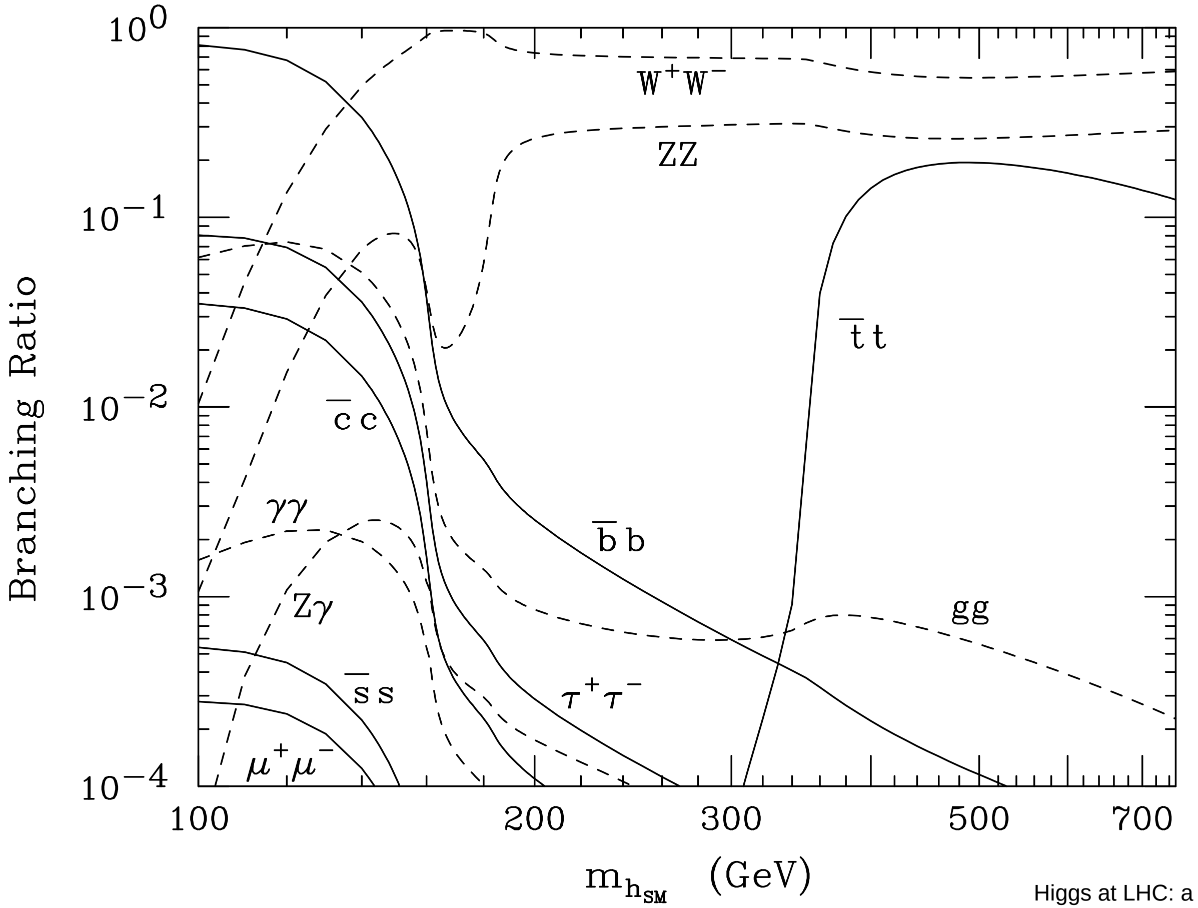


$\Rightarrow$ Accurate indirect prediction; Higgs "just around the corner"?

Higgs phenomenology: SM and beyond

Standard Model: a single parameter determines the whole Higgs phenomenology: M_{H}

Branching ratios of the SM Higgs:



$\Rightarrow$ dominant BRs:

$M_{\mathrm{H}} \lesssim 140$ GeV:
$H \to b\bar{b}$

$M_{\mathrm{H}} \gtrsim 140$ GeV:
$H \to W^+W^-, ZZ$

Higgs physics beyond the SM

In the SM the same Higgs doublet is used “twice” to give masses both to up-type and down-type fermions

$\Rightarrow$ extensions of the Higgs sector having (at least) two doublets are quite “natural”

$\Rightarrow$ Would result in several Higgs states

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

Example: SUSY in the “decoupling limit”

But there is also the possibility that none of the Higgs bosons is SM-like

Higgs physics in the MSSM

"Simplest" extension of the minimal Higgs sector:

Minimal Supersymmetric Standard Model (MSSM)

- Two doublets to give masses to up-type and down-type fermions (extra symmetry forbids to use same doublet)
- SUSY imposes relations between the parameters

⇒ Two parameters instead of one: $\tan\beta \equiv \frac{v_u}{v_d}, \quad M_\mathrm{A}$ (or $M_{\mathrm{H}^\pm}$)

⇒ Upper bound on lightest Higgs mass, M_h (*FeynHiggs*):
[*S. Heinemeyer, W. Hollik, G. W. '99*], [*G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich, G. W. '02*]

$$M_\mathrm{h} \lesssim 130\,\mathrm{GeV}$$

Very rich phenomenology

Higgs potential of the MSSM

MSSM Higgs potential contains two Higgs doublets:

$$V_H = m_1^2 H_{1i}^* H_{1i} + m_2^2 H_{2i}^* H_{2i} - \epsilon^{ij} (m_{12}^2 H_{1i} H_{2j} + {m_{12}^2}^* H_{1i}^* H_{2j}^*)$$

$$+ \frac{1}{8}(g_1^2 + g_2^2)(H_{1i}^* H_{1i} - H_{2i}^* H_{2i})^2 + \frac{1}{2} g_2^2 |H_{1i}^* H_{2i}|^2$$

$$\begin{pmatrix} H_{11} \\ H_{12} \end{pmatrix} = \begin{pmatrix} v_1 + \frac{1}{\sqrt{2}}(\phi_1 - i\chi_1) \\ -\phi_1^- \end{pmatrix}$$

$$\begin{pmatrix} H_{21} \\ H_{22} \end{pmatrix} = e^{i\xi} \begin{pmatrix} \phi_2^+ \\ v_2 + \frac{1}{\sqrt{2}}(\phi_2 + i\chi_2) \end{pmatrix}$$

Complex phases $\arg(m_{12}^2)$, ξ can be rotated away

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

Higher-order corrections in the MSSM Higgs sector

- Quartic couplings in the Higgs sector are given by the gauge couplings, g_1, g_2 (SM: free parameter)

  $\Leftrightarrow$ Upper bound on the lightest Higgs mass

- Large higher-order corrections from Yukawa sector:

  $\Rightarrow$ Leading corr.: $\Delta m_{\mathrm{h}}^2 \sim G_\mu m_{\mathrm{t}}^4$

  Can be of $\mathcal{O}(100\%)$

$\Rightarrow$ Higher-order corrections are phenomenologically very important (constraints on parameter space from search limits / possible future measurements)

Can induce $\mathcal{CP}$-violating effects

"Typical" features of extended Higgs sectors

- A light Higgs with SM-like properties, couples with about SM-strength to gauge bosons
  $\Rightarrow$ difficult to distinguish from SM Higgs
- Heavy Higgs states that decouple from the gauge bosons

For “non-standard” Higgs states:

$\Rightarrow$ Cannot use weak-boson fusion channels for production

$\Rightarrow$ Possible production channels: $gg \to H$, $b\bar{b}H$, . . .

Cannot use LHC “gold plated” decay mode $H \to ZZ \to 4\mu$

$\Rightarrow$ Search for heavy Higgs bosons $H, A, H^{\pm}$ is very different from the SM case

However: Higgs phenomenology for all MSSM Higgses may be very different from the SM case

Higgs phenomenology can be drastically different from the SM case even in the MSSM:

- Higgs may be much lighter than $114\ \mathrm{GeV}$

  Example: SUSY with $\mathcal{CP}$-violation

  $\Rightarrow$ no firm experimental lower bound on M_{H}

  $\Rightarrow$ LHC needs to look also for light Higgs bosons

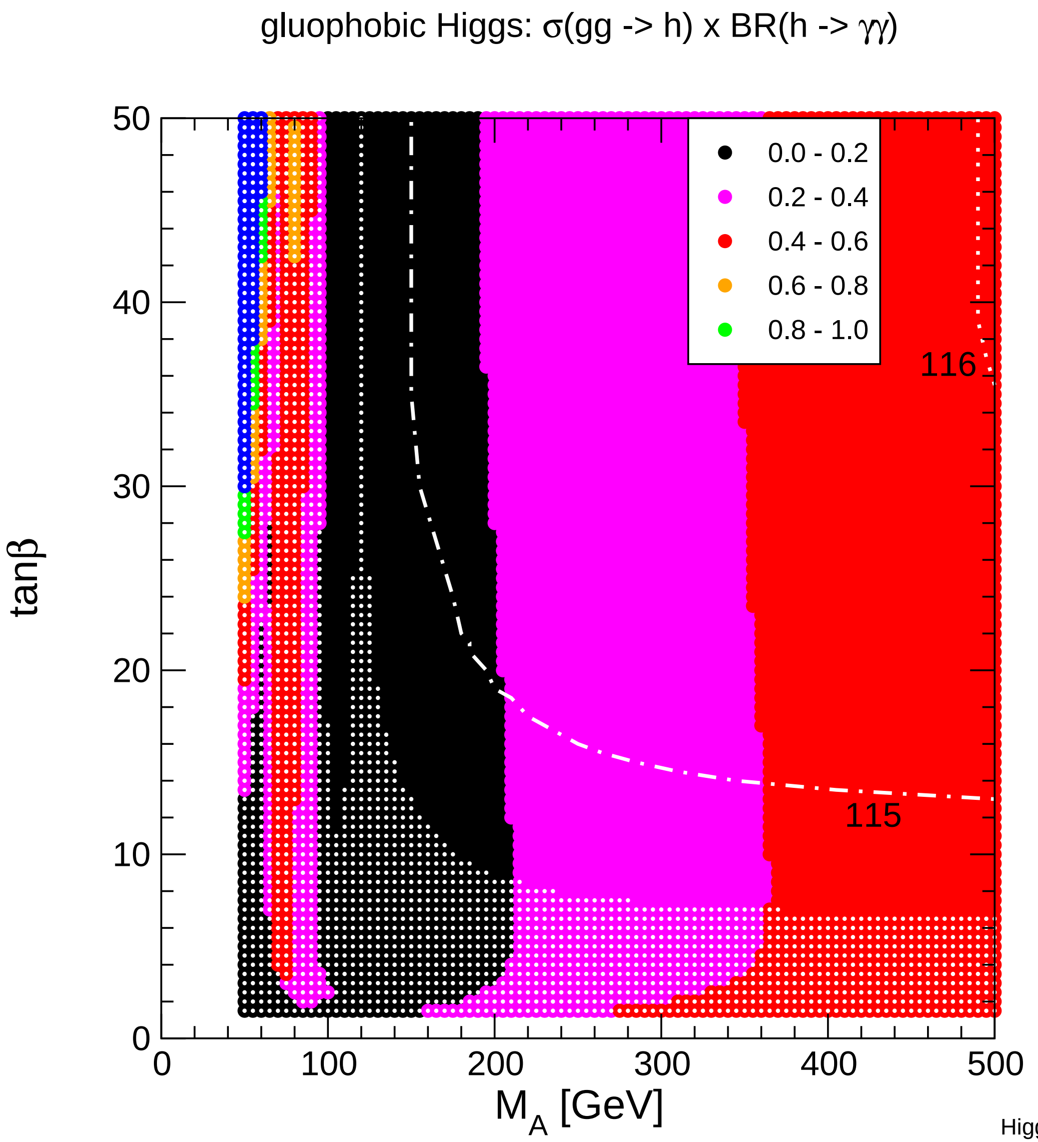
- Significant suppression / enhancement of various couplings possible with respect to the SM

  Example: large enhancement of $H\bar{b}b$ coupling

  $\Rightarrow$ large suppression of BR($h \to \gamma\gamma$), BR($h \to WW^*$), $\ldots$

"Gluophobic Higgs" scenario: interference between quark and squark loop contributions to gluon fusion

$\sigma(gg \to h) \times \mathrm{BR}(h \to \gamma\gamma)$ [*M. Carena, S. Heinemeyer, C. Wagner, G. W. '02*]



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

Higgs physics in the MSSM with complex parameters

Five physical states; tree level: $h^0, H^0, A^0, H^\pm$

Complex parameters enter via (often large) loop corrections:

– μ: Higgsino mass parameter

– $A_{t,b,\tau}$: trilinear couplings

– $M_{1,2}$: gaugino mass parameter (one phase can be eliminated)

– M_3: gluino mass $m_{\tilde{\mathrm{g}}}$ + complex phase

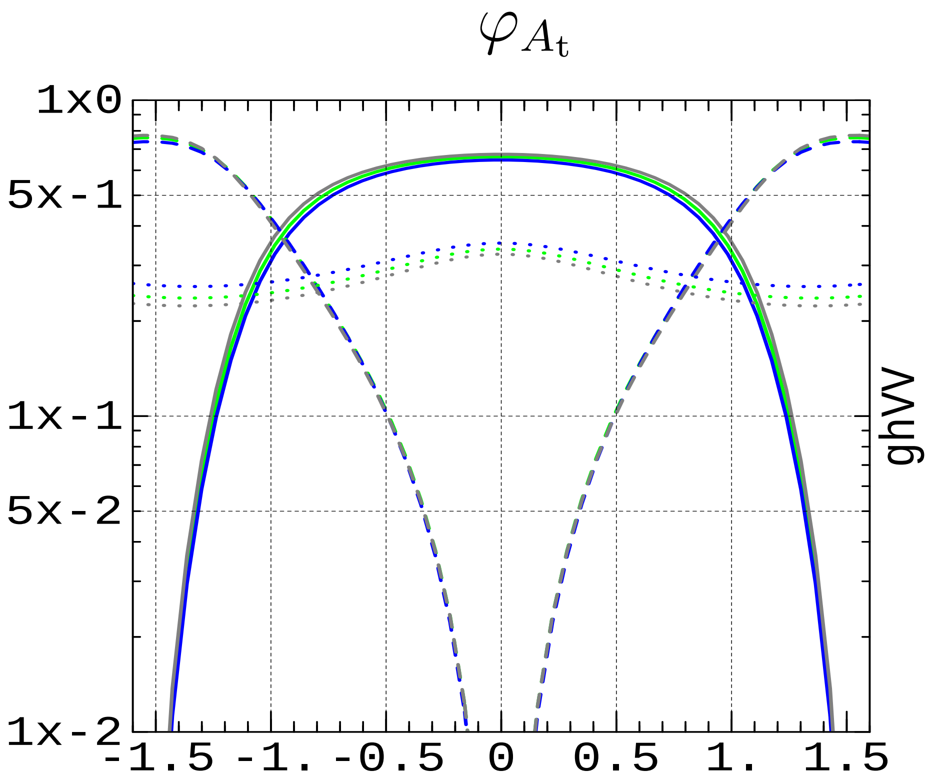
$\Rightarrow$ $\mathcal{CP}$-violating mixing between neutral Higgs bosons h_1, h_2, h_3

Lowest-order Higgs sector has two free parameters

$\Rightarrow$ choose $\tan\beta \equiv \frac{v_2}{v_1}$, $M_{\mathrm{H}^\pm}$ as input parameters

Impact of complex phases

Example: g^2_{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:

$M_{\rm SUSY} = 500$ GeV,

$M_2 = 500$ GeV,

$\mu = 2000$ GeV,

$|A_{\rm t}| = 1000$ GeV,

$M_{\rm H^\pm} = 150$ GeV, $\tan\beta = 5$

$\Rightarrow$ Complex phases can have large effects on Higgs couplings

Example: the MSSM with a very light Higgs

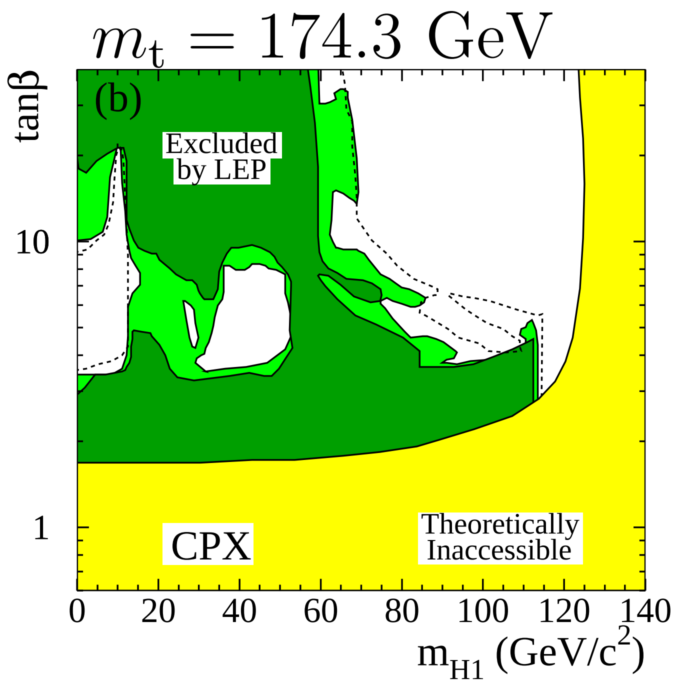
MSSM with $\mathcal{CP}$-violating phases (CPX scenario):

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*]



$\Rightarrow$ Light SUSY Higgs not ruled out!

Some motivation for a very light non SM-like Higgs

"Little hierarchy problem:"

Prediction for M_{h}:

$$M_{\mathrm{h}}^2 \approx M_{\mathrm{Z}}^2 \cos^2 2\beta + \frac{3G_\mu}{\sqrt{2}\pi^2} m_{\mathrm{t}}^4 \ln(M_{\tilde{\mathrm{t}}}^2/m_{\mathrm{t}}^2) + \ldots$$

$\Rightarrow$ Need $M_{\tilde{\mathrm{t}}} \gtrsim 500\ \mathrm{GeV}$ to satisfy exclusion bound on SM-like Higgs, $M_{\mathrm{h}} > 114.4\ \mathrm{GeV}$

RG running from M_{GUT}:

$$M_{\mathrm{Z}}^2 \approx 1.6\, M_{\tilde{\mathrm{t}}}^2 - 1.8\, \mu^2 + 5.9\, M_3^2 - 0.4\, M_2^2 - 1.2\, m_{H_u}^2 + \ldots$$

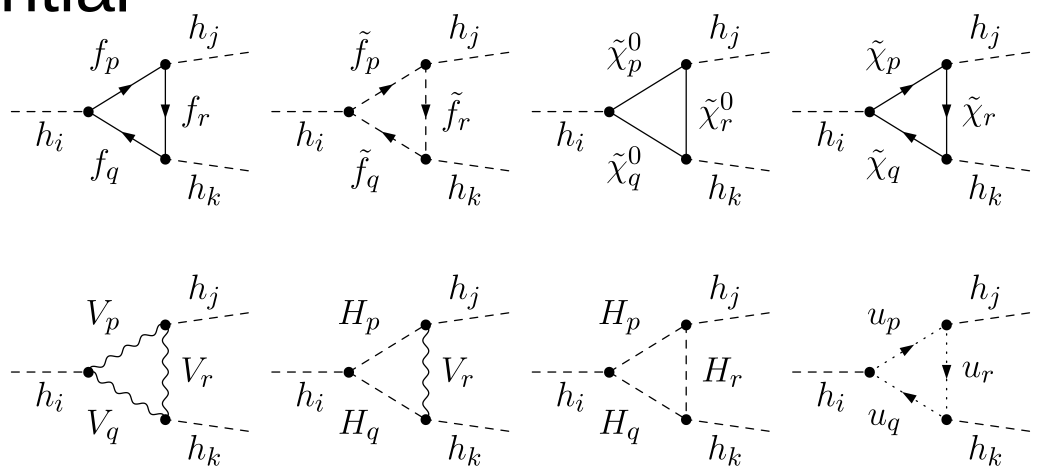
$\Rightarrow$ Need cancellations between soft SUSY-breaking parameters

$\Rightarrow$ (Slight) tension can be relaxed if Higgs is light

Higgs cascade decays: $h_2 \to h_1 h_1$, . . .

Higgs cascade decays:

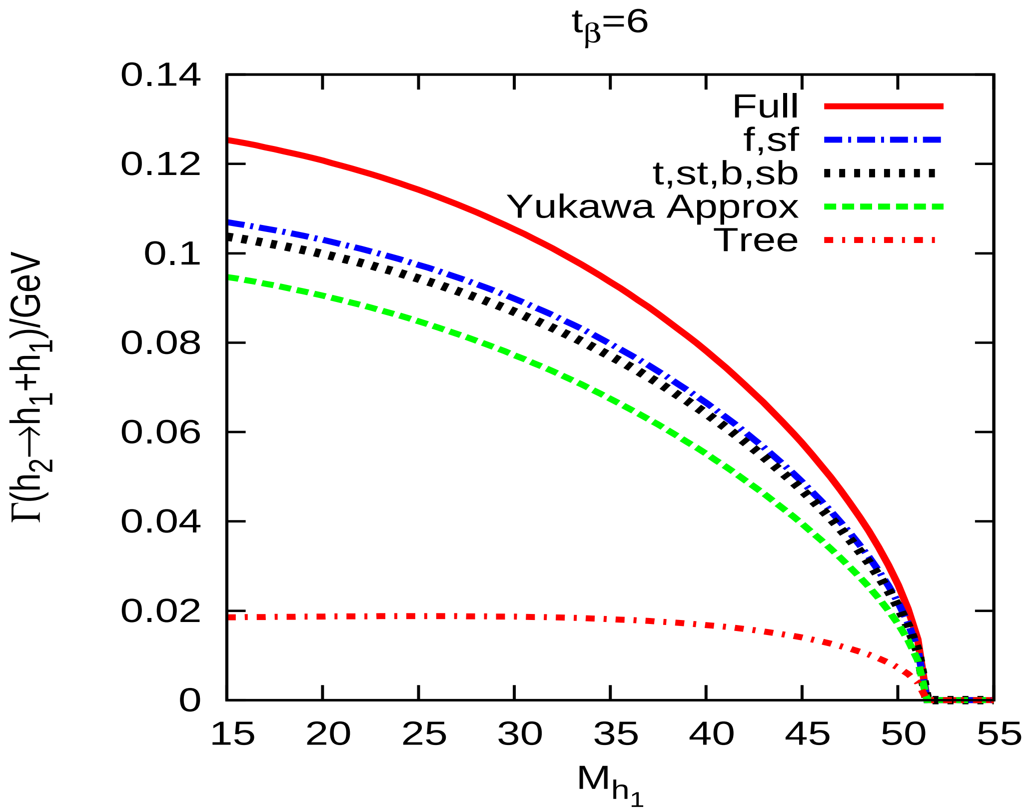
- Important for Higgs searches: $h_2 \to h_1 h_1$ is in general the dominant channel where it is kinematically allowed
- Access to Higgs self-coupling $\Rightarrow$ reconstruction of the Higgs potential



Complete one-loop results in the MSSM with complex parameters $+$ two-loop propagator-type corrections [*K. Williams, G. W. '07*]

Impact of higher-order corrections on prediction for $\Gamma(h_2 \to h_1 h_1)$

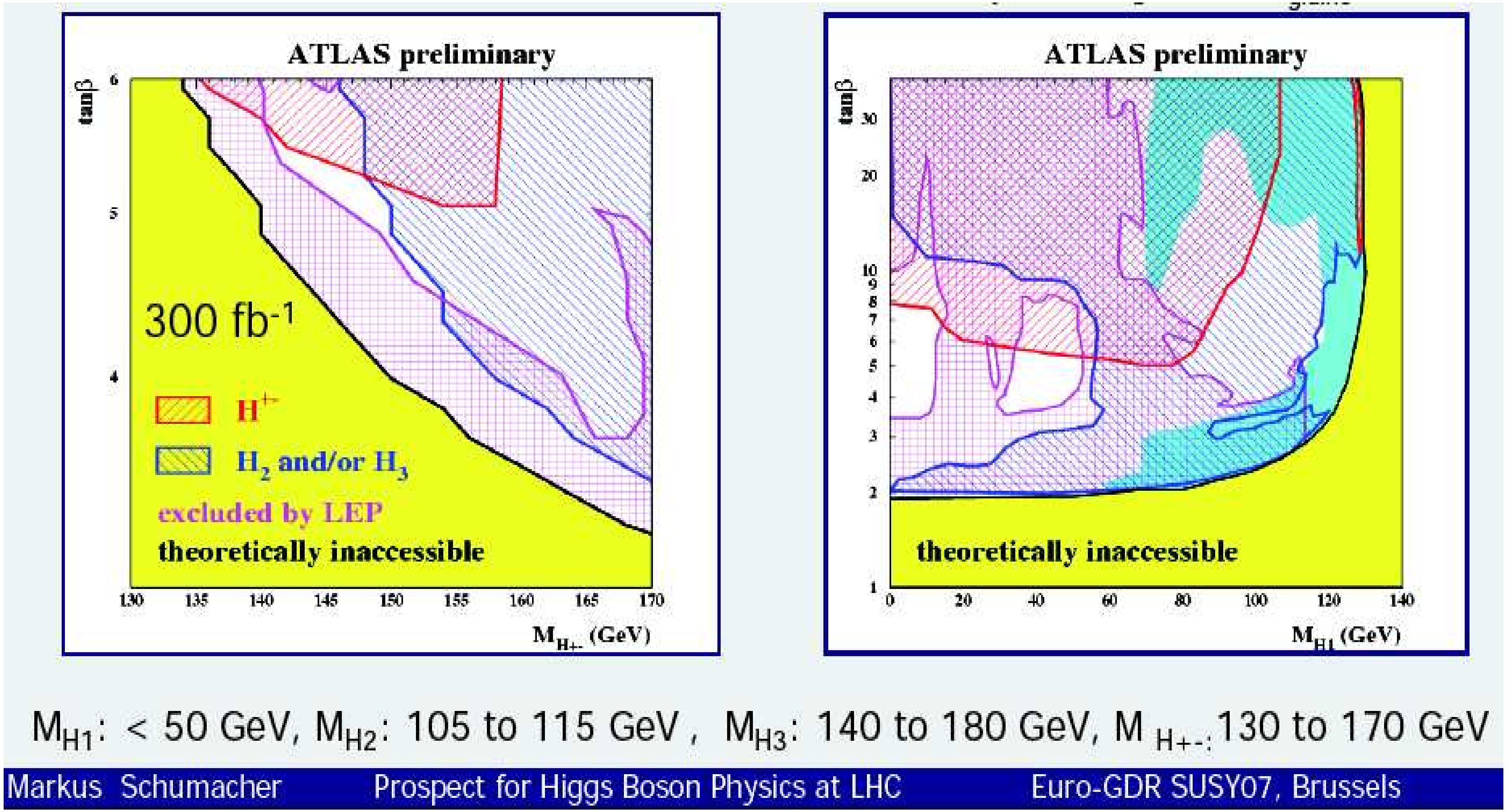
Complete 1-loop result for $(h_2 h_1 h_1)$ vertex contribution in the MSSM with complex parameters [*K. Williams, G. W. '07*]
$+$ 2-loop propagator corrections; CPX benchmark scenario
[*S. Heinemeyer, W. Hollik, H. Rzehak, G. W. '07*]



$\Rightarrow$ Huge effect from corrections to genuine $(h_2 h_1 h_1)$ vertex

CPX holes are difficult to cover at the LHC

[*M. Schumacher, ATLAS '07*]



$\Rightarrow$ "CPX holes" cannot be covered in conventional channels

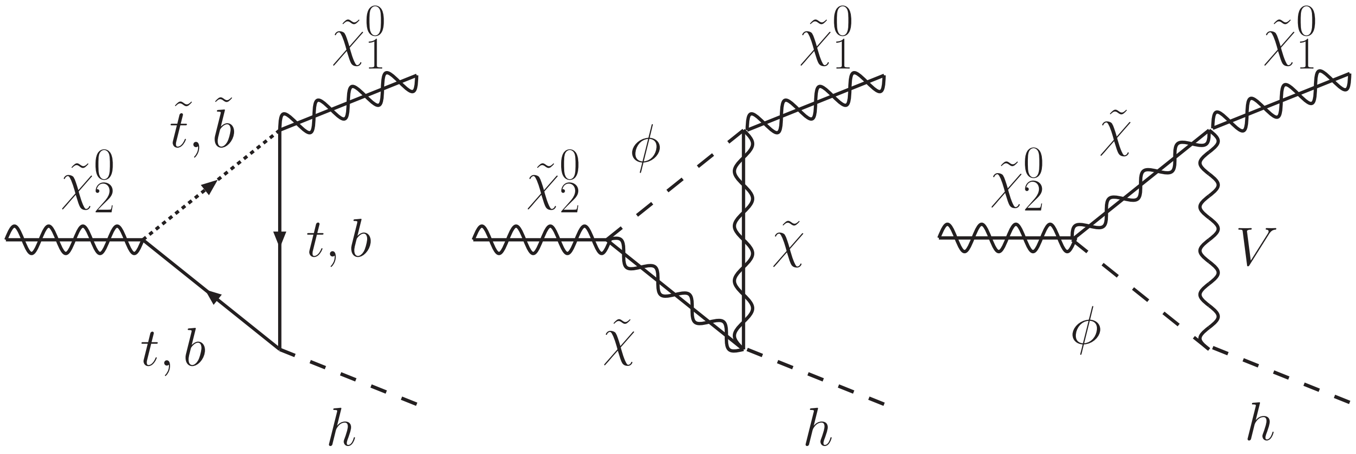
Higgs production in SUSY cascade decays

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 $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 l \bar{l}$

[*A. Fowler, G. W. '09*]



$\Rightarrow$ CPX scenario: 13% of the gluinos decay into h_1

Higgs phenomenology

We should be prepared for:

- more than just one Higgs state
- Higgs states that can be much lighter than the SM limit
- non-standard couplings, Higgs width, etc.
- interplay between Higgs(es) and other states of new physics (e.g.: Higgs decays into SUSY particles, $H \to$ invisible, $H \to$ soft jets, . . . ; SUSY decays into Higgs, . . . ; Higgs–radion mixing, “continuum” Higgs models, . . .)
- . . .

Higgs hunting: cross section limits vs. benchmark scenarios

Higgs searches at LEP and the Tevatron:

Searches in different production and decay channels

Limits have been presented in two ways:

- For a specific model: SM, MSSM benchmark scen., …

  $\Rightarrow$ combination of different channels possible

  difficult to interpret for other models or w.r.t. changes in the input parameters or the theoretical predictions

- As cross section limits for a certain search topology

  $\Rightarrow$ exclusion bounds have to be tested channel by channel

  fairly model-independent and generally applicable

Determination of 95% C.L. exclusion region from given cross section limits

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

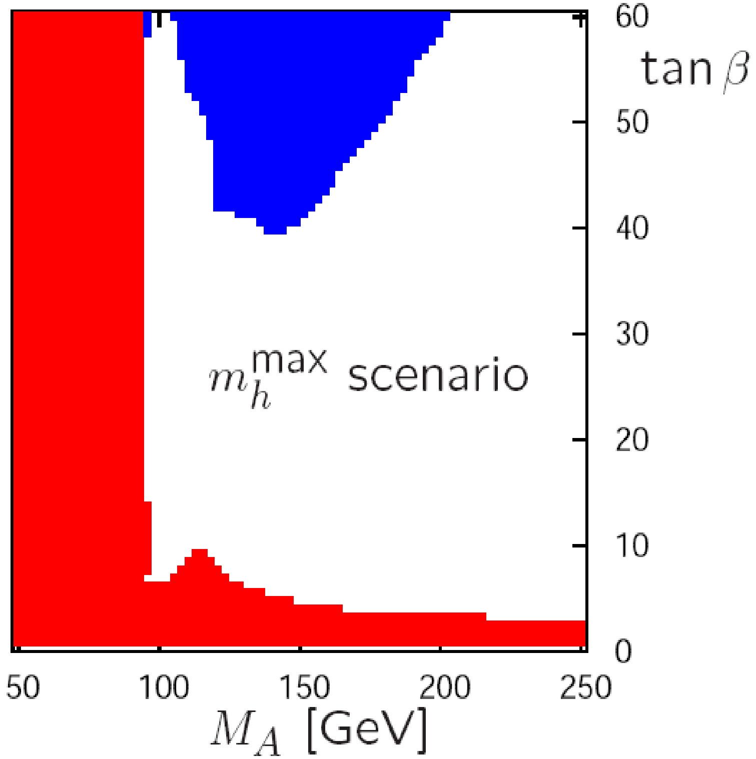
- On the basis of the expected search limits for different channels in a given model one needs to determine for every parameter point the search channel having the highest statistical sensitivity for setting an exclusion limit
- For this single channel only one needs to compare the observed limit with the theory prediction for the Higgs production cross section times decay branching ratio to determine whether or not the considered parameter point of the model is excluded at 95% C.L.

Implemented in program *HiggsBounds*

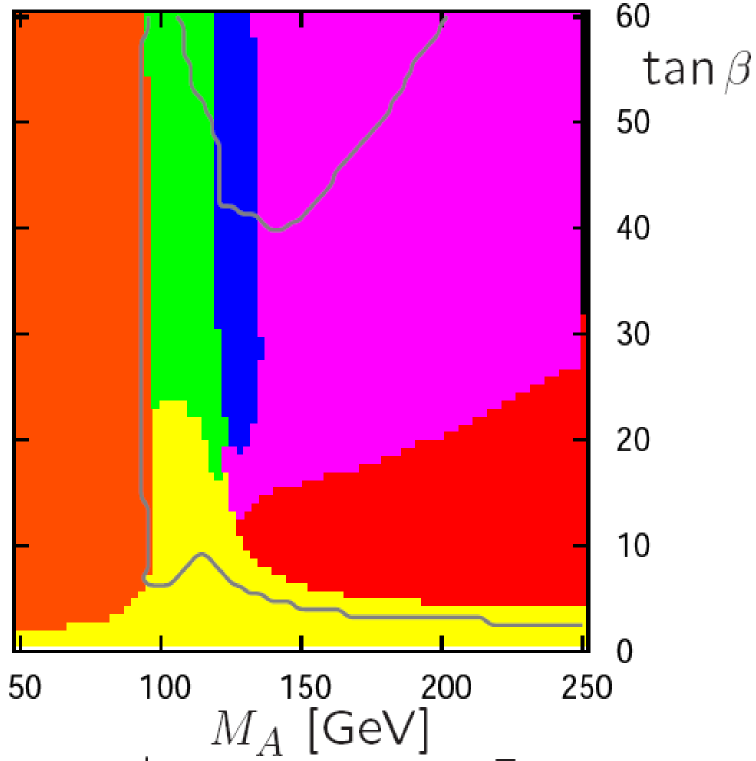
[*P. Bechtle, O. Brein, S. Heinemeyer, G. W., K. Williams '08*]

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]



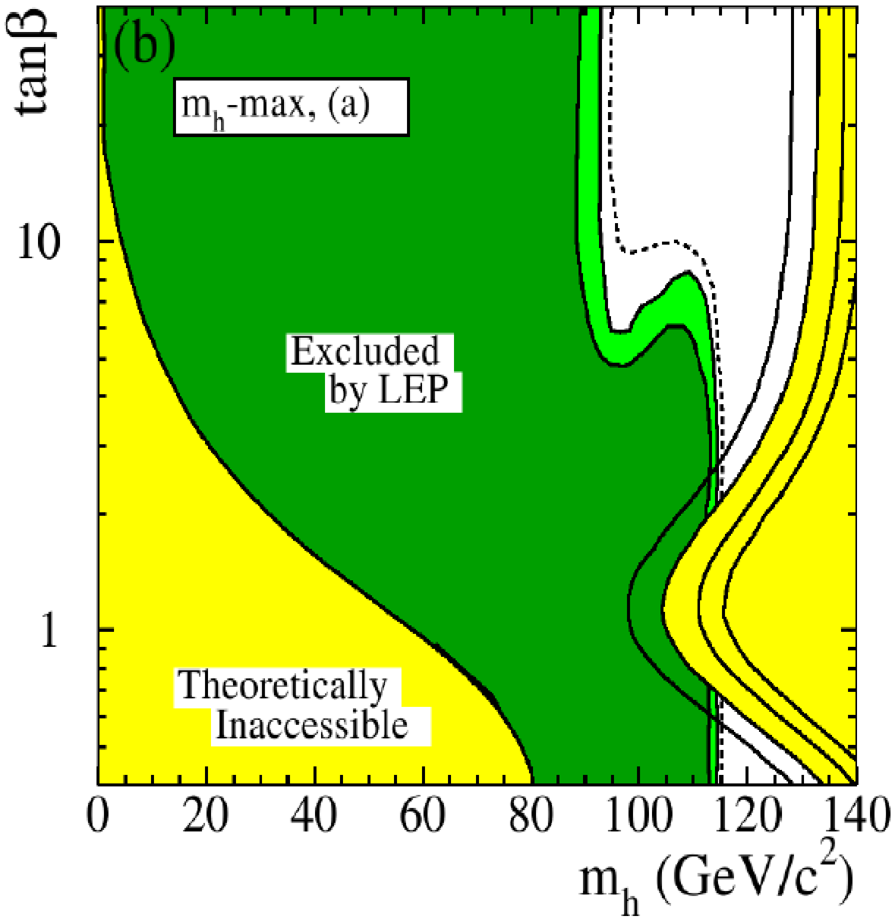
■ : LEP exclusion
■ : Tevatron exclusion



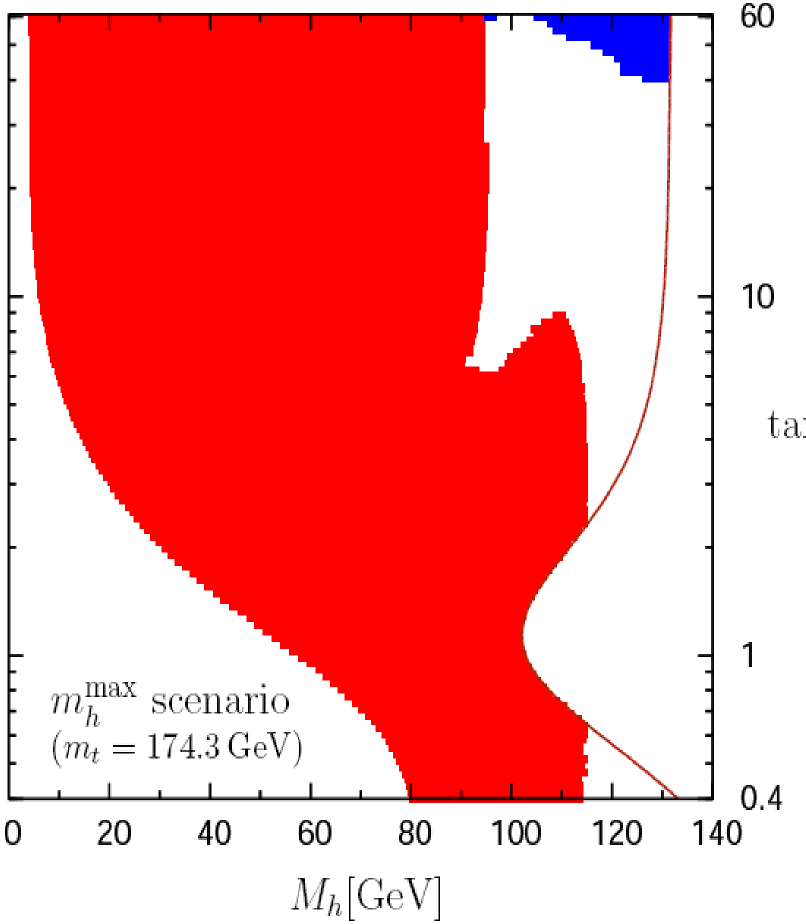
■ : $e^+e^- \to hZ, h \to b\bar{b}$
■ : $e^+e^- \to hA \to b\bar{b}b\bar{b}$
■: $p\bar{p} \to h/A \to \tau^+\tau^-$ [CDF note 9071]
■: $p\bar{p} \to h/H/A \to \tau^+\tau^-$ [CDF note 9071]
■: $p\bar{p} \to H/A \to \tau^+\tau^-$ [CDF note 9071]
■: $p\bar{p} \to hW \to b\bar{b}l\nu$ [CDF note 9463]
■: $p\bar{p} \to H/A \to \tau^+\tau^-$ [DØ'08]

MSSM $m_{\rm h}^{\rm max}$ benchmark scenario: comparison of HiggsBounds output with LEP Higgs Working Group results

Eur. Phys. J. **C 47** (2006) 547
[*LEP Higgs Working Group '06*]



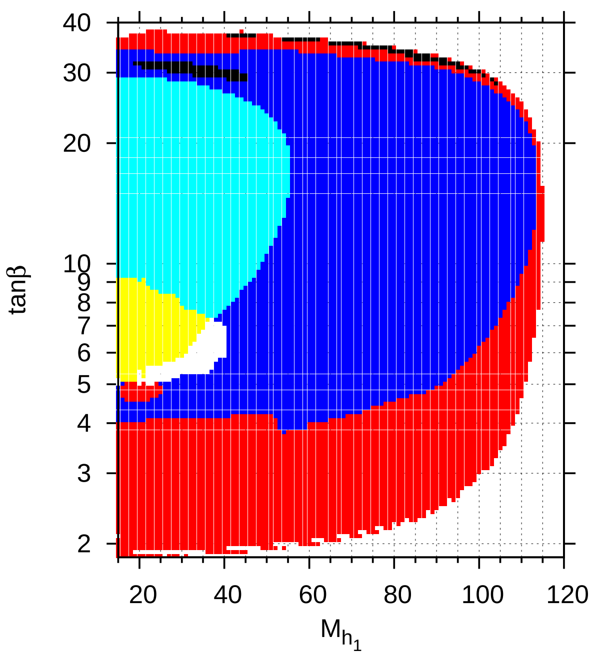
HiggsBounds: $m_{\rm t}$ set to benchmark value, improved $m_{\rm h}$ prediction, Tevatron res. included



Analysis of LEP coverage in CPX scenario with improved theoretical prediction

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

Use cross section limits (expected and observed) from LEP and the Tevatron; determine for every parameter point the search channel with the highest statistical sensitivity for setting an exclusion; comparison of prediction for this channel with observed limit yields 95% C.L. exclusion contour



Channels:

(■ red) $= (h_1 Z) \to (b\bar{b}Z)$

(■ blue) $= (h_2 Z) \to (b\bar{b}Z)$

(□) $= (h_2 Z) \to (h_1 h_1 Z) \to (b\bar{b}b\bar{b}Z)$

(■ cyan) $= (h_2 h_1) \to (b\bar{b}b\bar{b})$

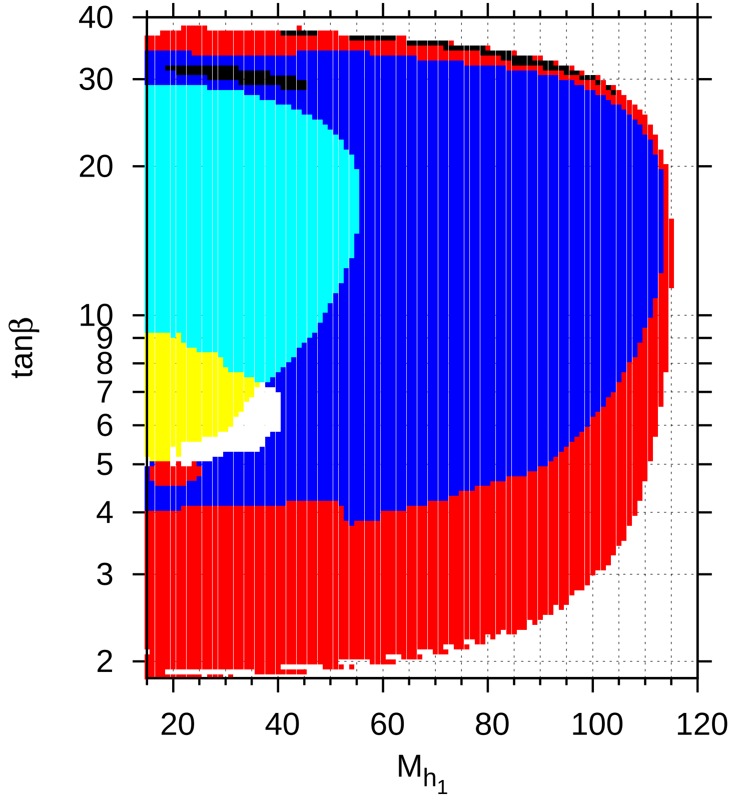
(■ yellow) $= (h_2 h_1) \to (h_1 h_1 h_1) \to (b\bar{b}b\bar{b}b\bar{b})$

(■ black) = other channels

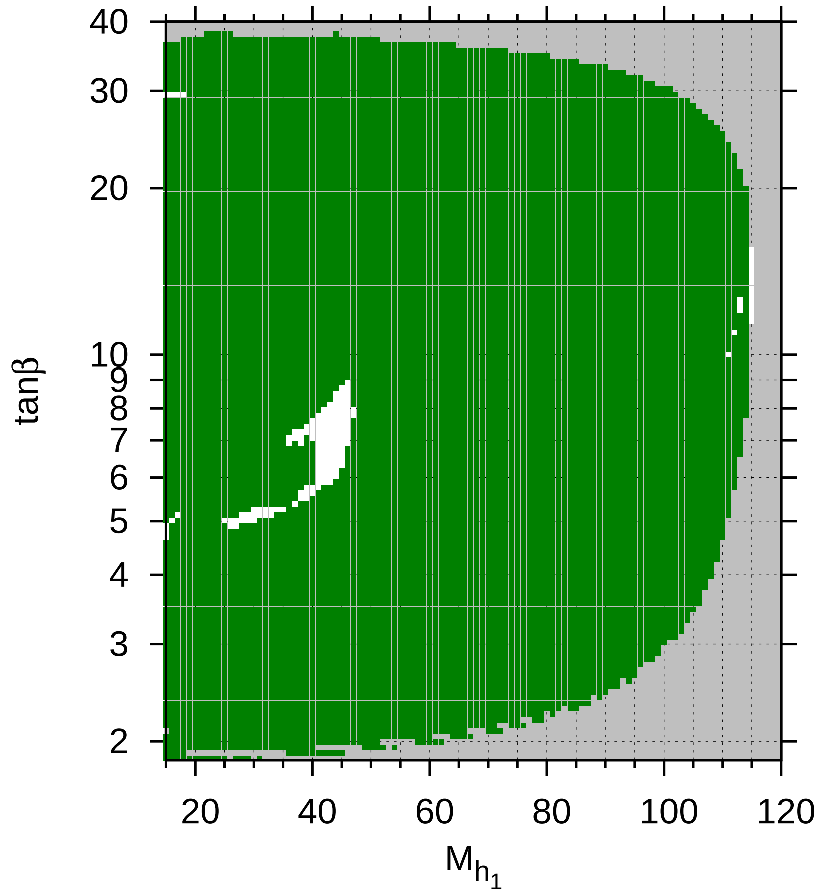
Impact on exclusion bounds from the LEP Higgs searches, CPX scenario, $m_{\rm t} = 170.9~\text{GeV}$

Channels (*HiggsBounds*)

$(\square) : (h_2 Z) \to (h_1 h_1 Z) \to (b\bar{b}b\bar{b}Z)$



Excluded region from LEP, 95% C.L. [*K. Williams, G. W. '07*]



$\Rightarrow$ Confirmation of the "hole" in the LEP coverage

$\Rightarrow$ Very light Higgs boson is not excluded

A Higgs-like signal

- A Higgs or not a Higgs?
- Fundamental or composite?
- SM, MSSM or beyond?
- Is there other new physics; what is it?
- How does the observed new physics fit into the global picture (ew precision observables, flavour physics, ...)?
- ...

$\Rightarrow$ Intense effort will be needed to identify the nature of electroweak symmetry breaking

Production of a SM-like Higgs at the LHC

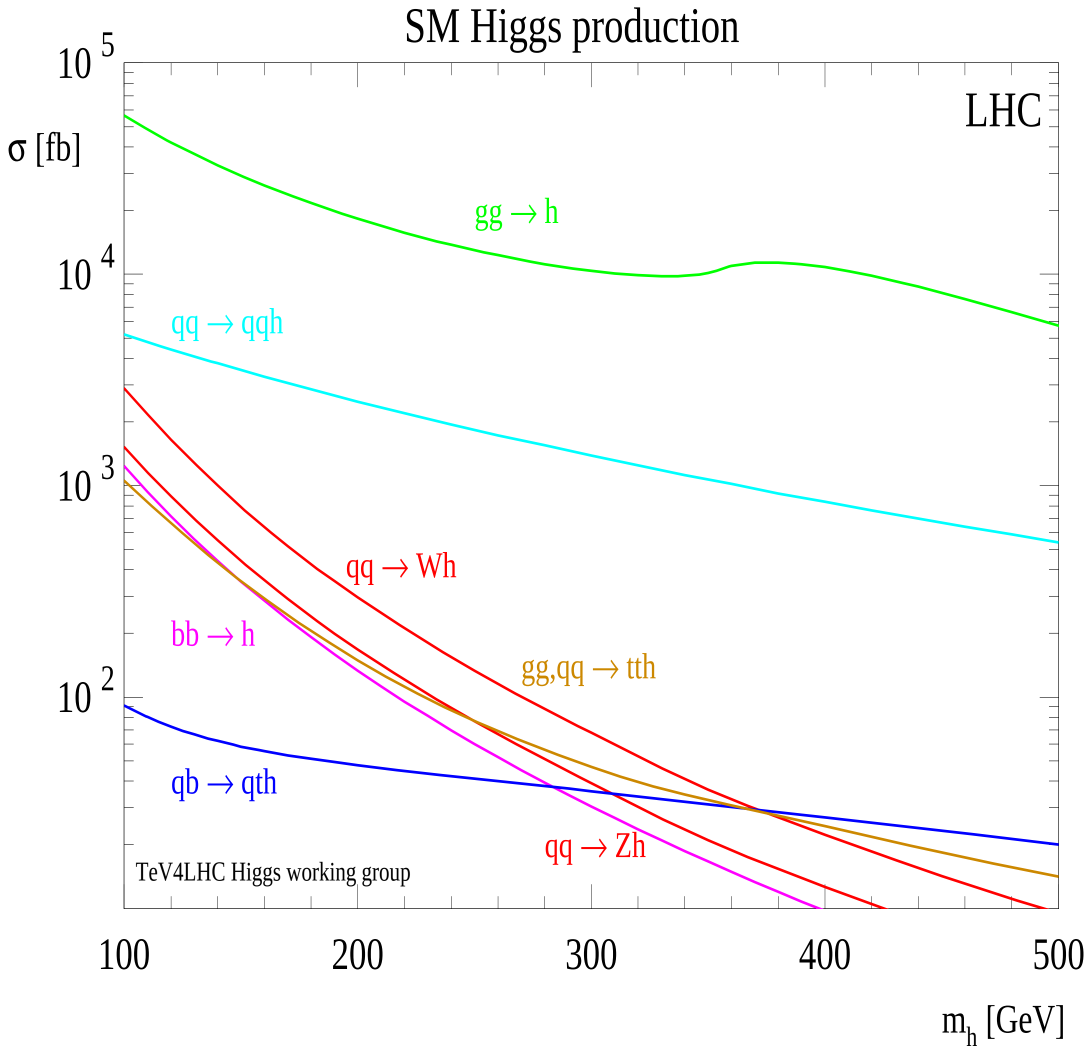
"Standard" production processes for SM-like Higgs:

Gluon fusion: $gg \to H$

Weak boson fusion (WBF): $q\bar{q} \to q'\bar{q}'H$

top-quark associated production: $gg, q\bar{q} \to t\bar{t}H$

weak boson associated production: $q\bar{q}' \to WH, ZH$



Other possibility: Central exclusive diffractive (CED) Higgs production, $pp \to p + H + p$

Higgs coupling determination at the LHC

LHC: no absolute measurement of 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 ($\Gamma_{\text{prod, decay}} \sim g^2_{\text{prod, decay}}$):

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

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

$\Rightarrow$ LHC can directly determine only ratios of couplings, e.g. $g^2_{H\tau\tau}/g^2_{HWW}$

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

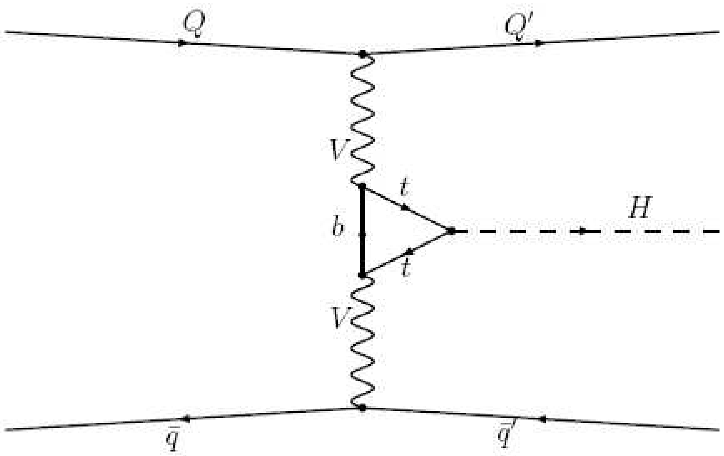
$\Rightarrow$ Determines $\Gamma^2_V/\Gamma_{\mathrm{tot}}$ $\Rightarrow$ Upper bound on Γ_{tot}

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

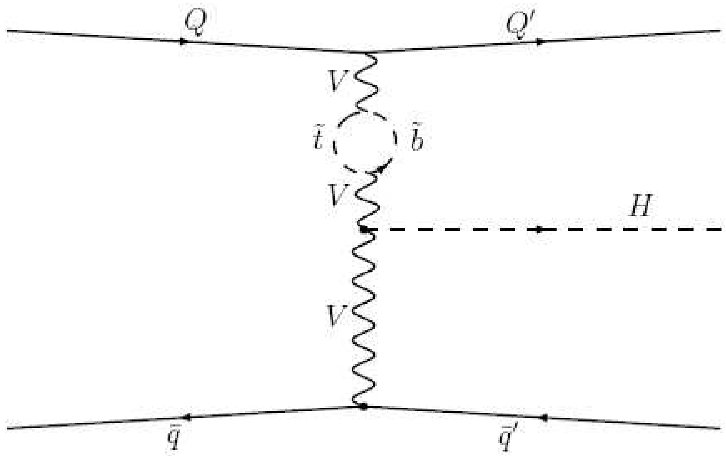
Higgs production in weak-boson fusion:

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

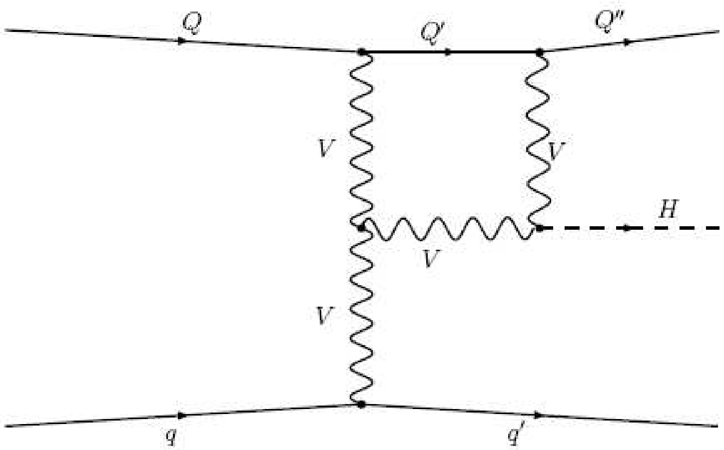
[T. Figy, S. Palmer, G. W. '10]



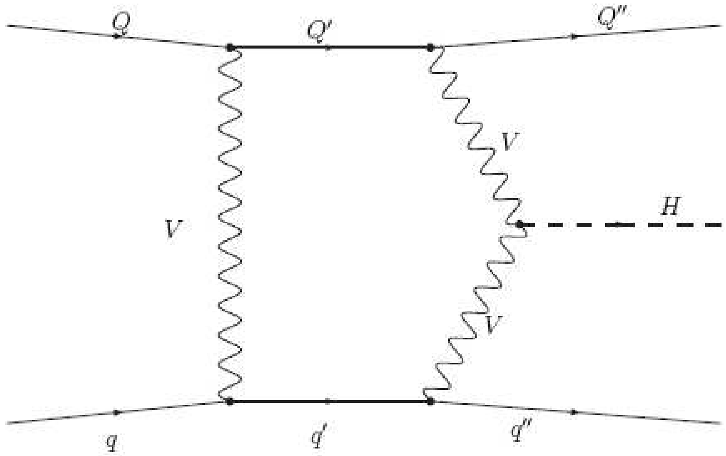
(a) Corrections to the VVH vertex



(b) Corrections to the VV self energy



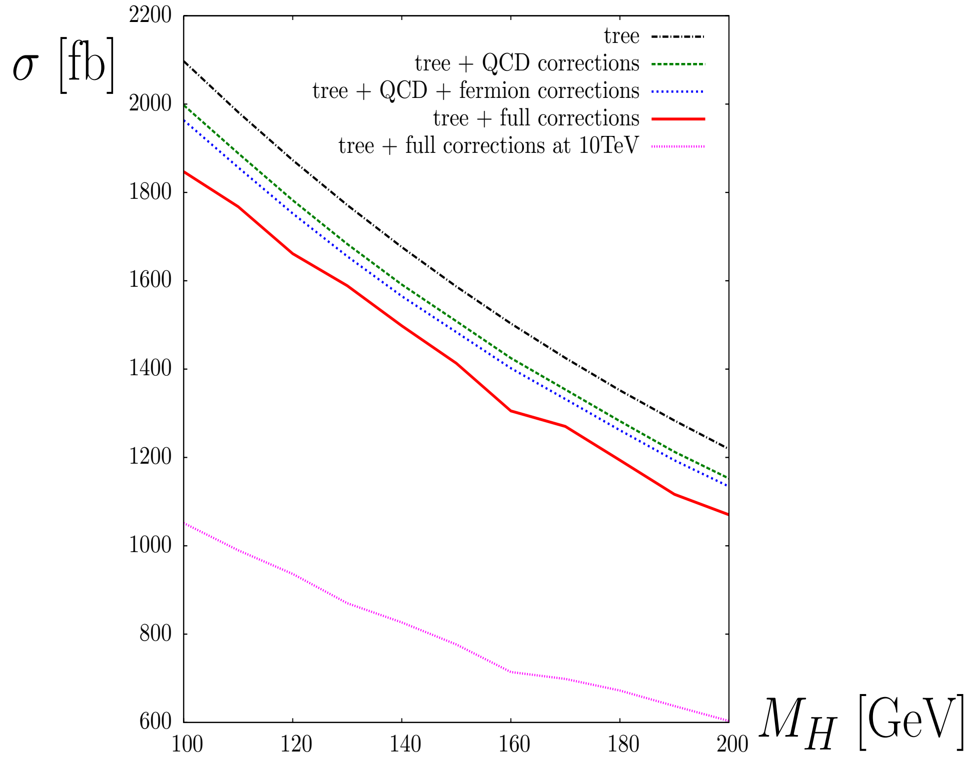
(c) Box diagrams

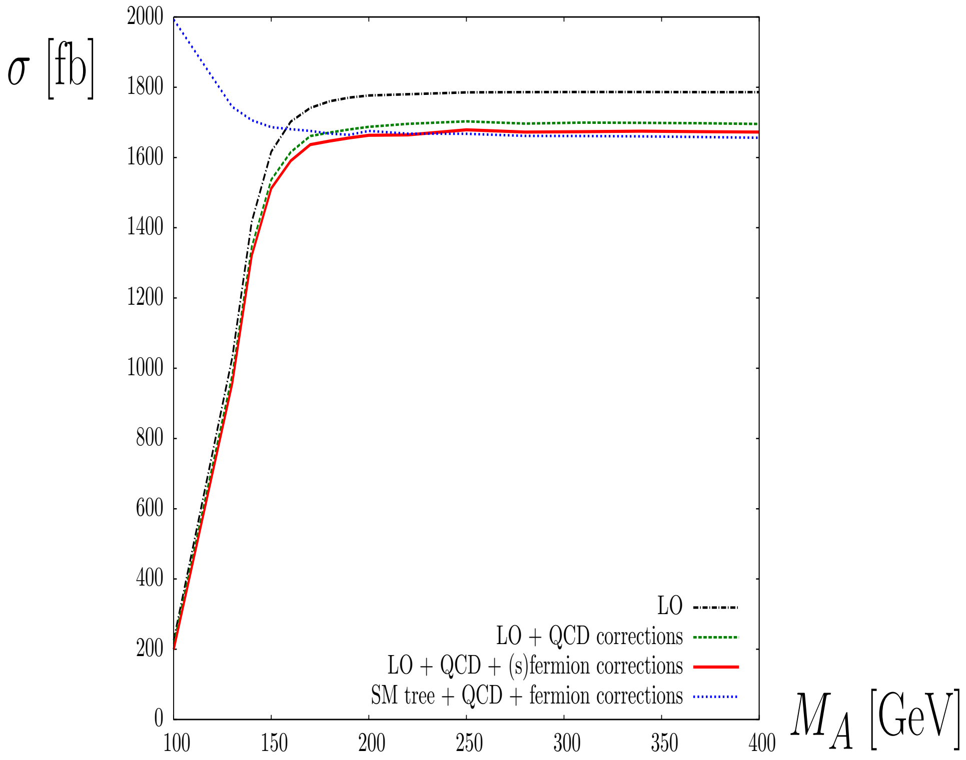


(d) Pentagon diagrams

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

[*T. Figy, S. Palmer, G. W. ’10*]



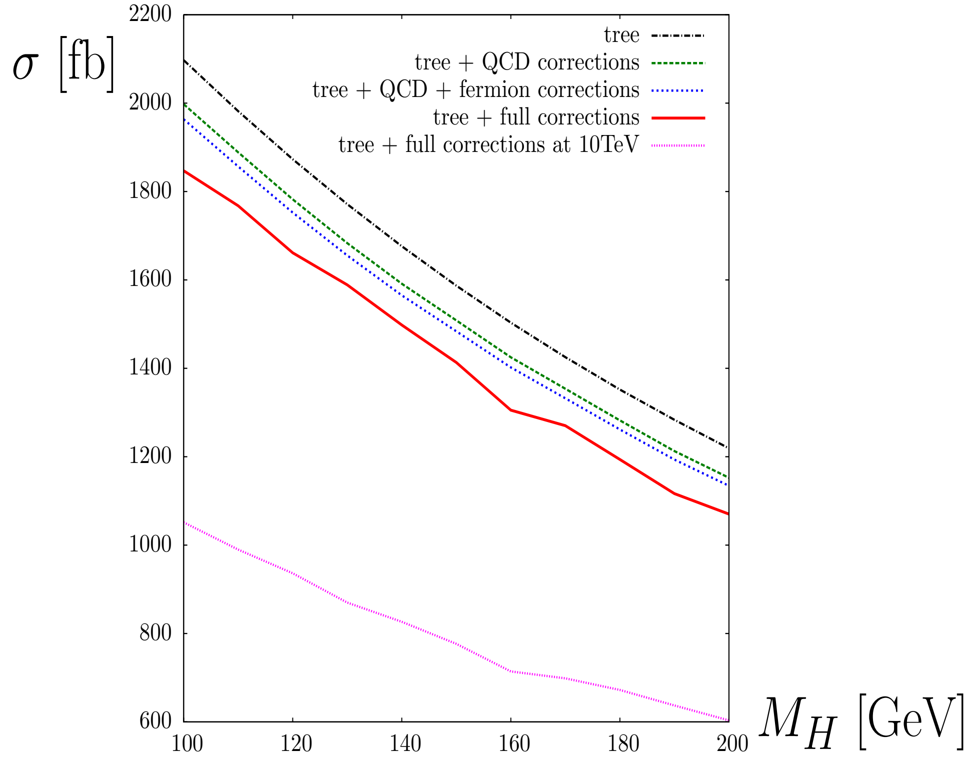


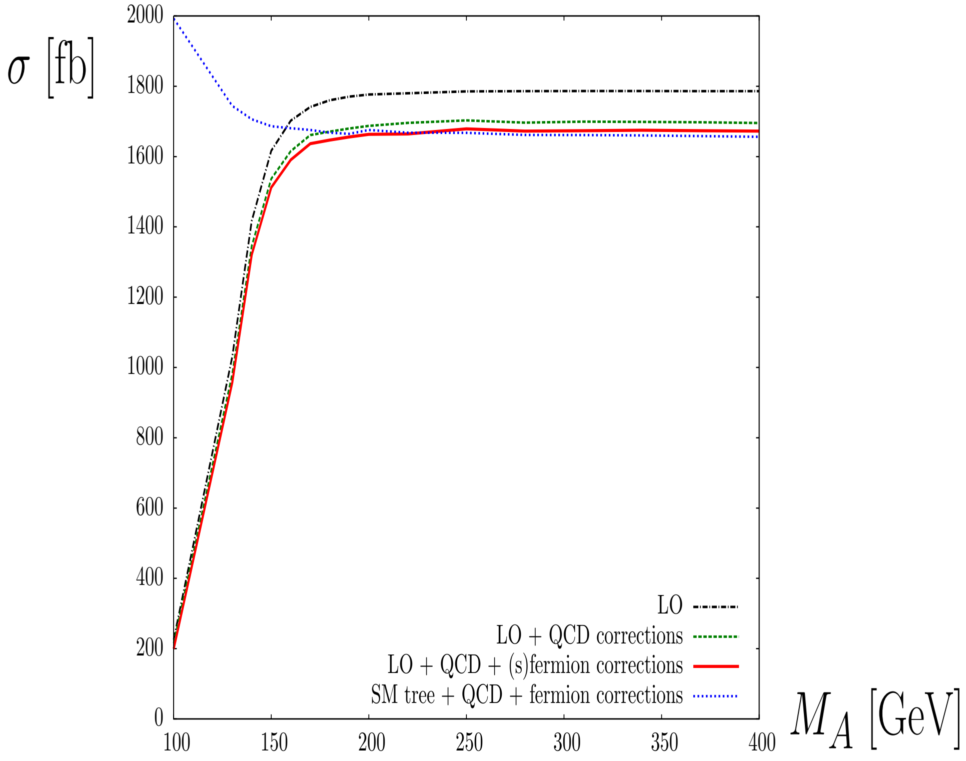
$\Rightarrow$ Electroweak and QCD corrections are of comparable size

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

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

[*T. Figy, S. Palmer, G. W. '10*]



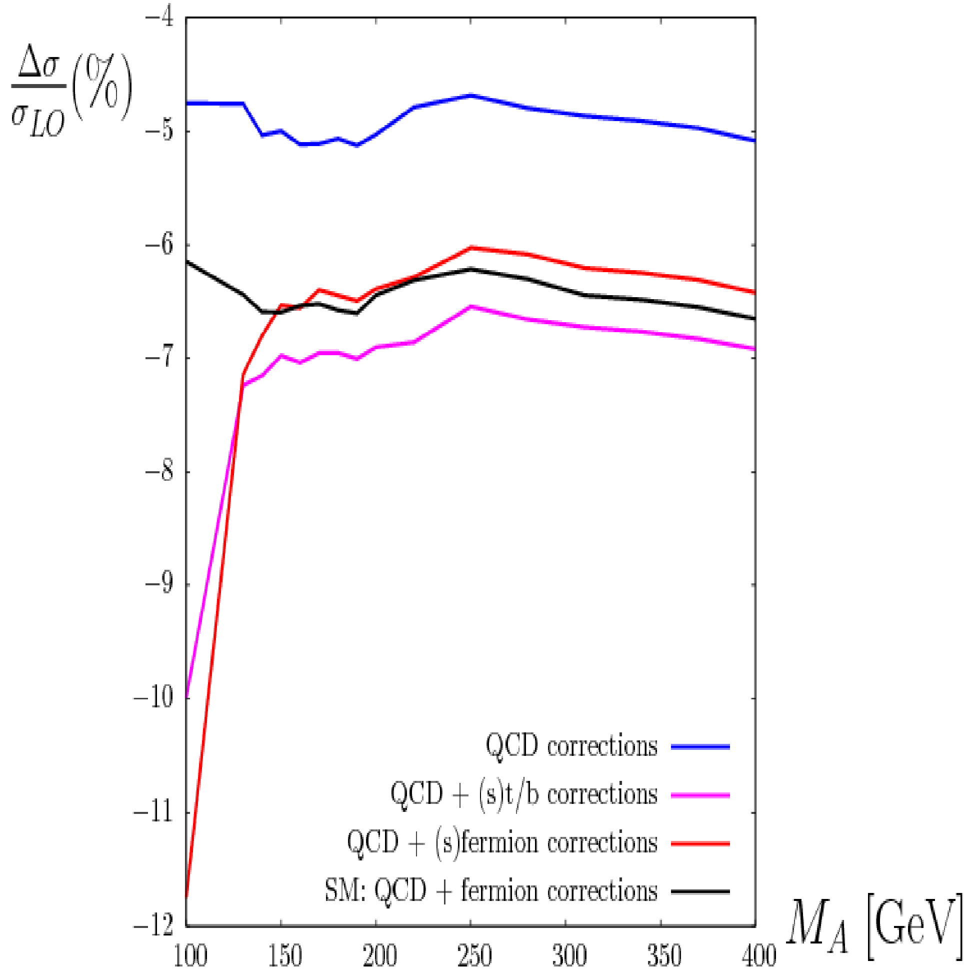


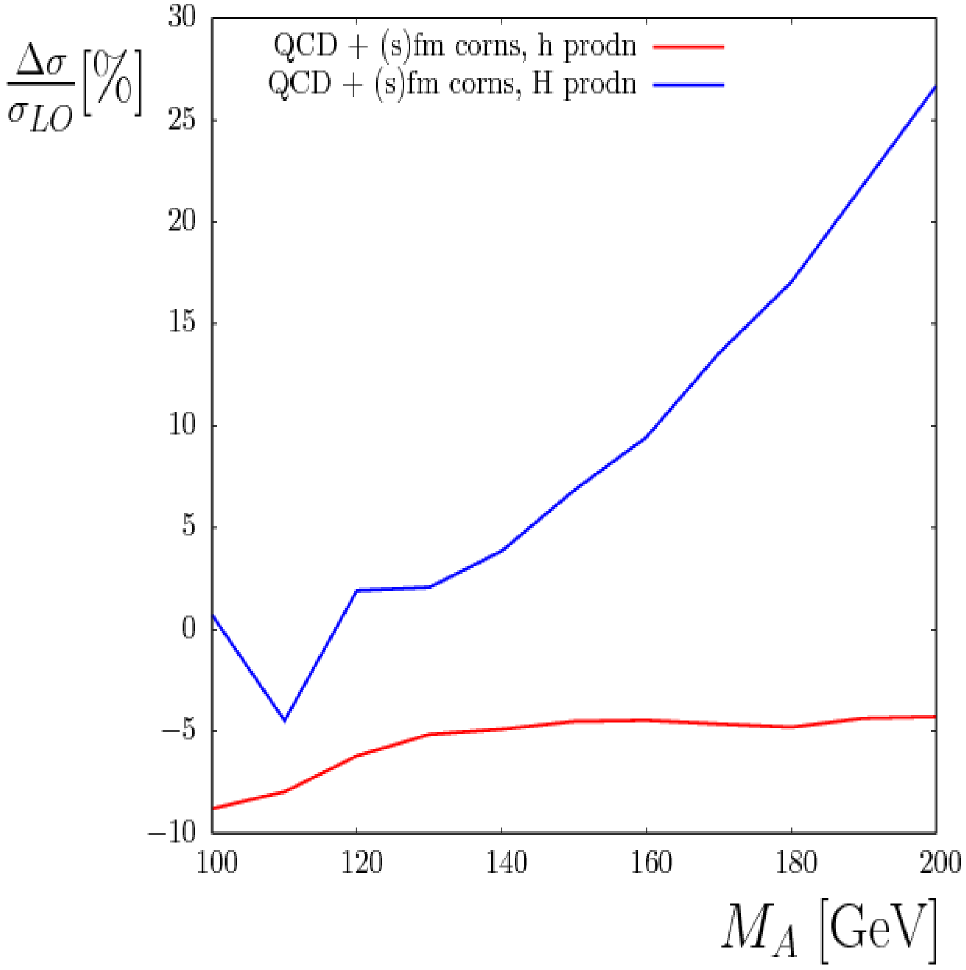
Pure SM-type corrections:
good agreement with [*M. Ciccolini, A. Denner, S. Dittmaier '07*]

Pure SUSY loop corrections:
good agreement with [*W. Hollik, T. Plehn, M. Rauch, H. Rzehak '08*]

Impact of SUSY loop effects: m_h^{max} *scenario,* $\tan\beta = 10$

[*T. Figy, S. Palmer, G. W. '10*]





⇒ Sizable effects possible in the non-decoupling region

Determination of the properties of possible Higgs candidates

- Higgs self-couplings are notoriously difficult at the LHC
  Higgs cascade decays?

- Higgs spin and $\mathcal{CP}$ properties:

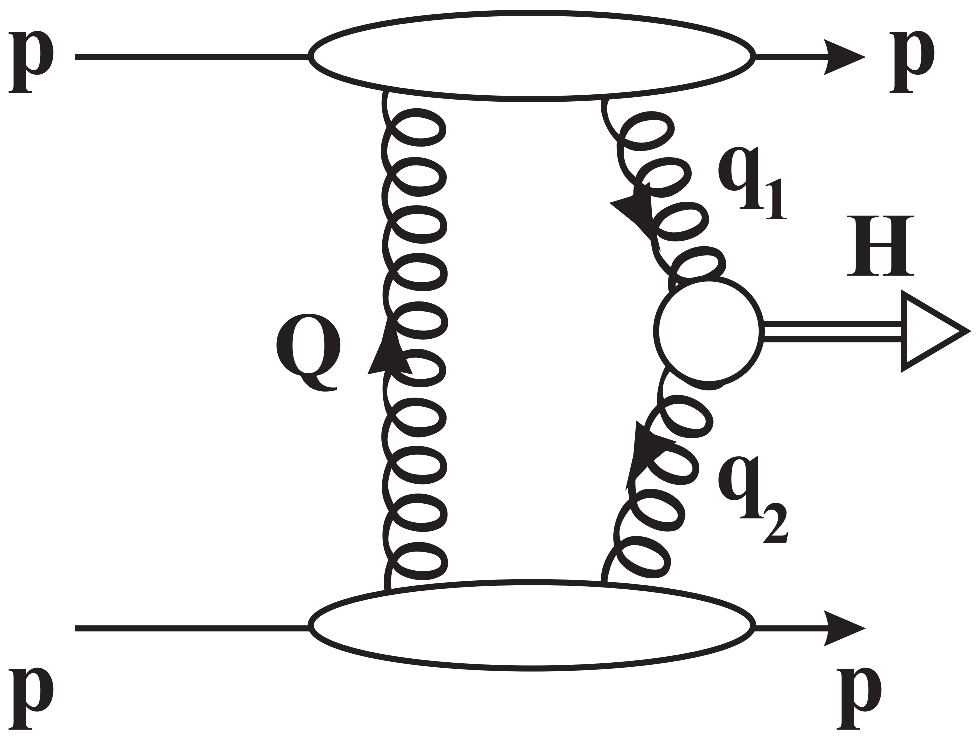
  Standard methods rely on $H \to ZZ^{(*)}, WW^{(*)}$ decays

  Many BSM models (example: MSSM) have light SM-like Higgs with $M_{\rm h} \ll 2M_{\rm W}$ and heavy Higgses that decouple from gauge bosons

  $\Rightarrow$ Standard methods may not be applicable

- ...

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



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 Information on Higgs spin and $\mathcal{CP}$ properties

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

Fundamental or composite Higgs?

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

Relation extra dimensions $\Leftrightarrow$ new strong forces?

Correspondence (AdS/CFT):

Warped gravity model $\Leftrightarrow$ Technicolour-like theory in 4D

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

Under pressure from electroweak precision tests

Effective field-theory description of a composite 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 (SILH) [*G. Giudice, C. Grojean, A. Pomarol, R. Ratazzi '07*]

$\Rightarrow$ Specific pattern of modified Higgs couplings

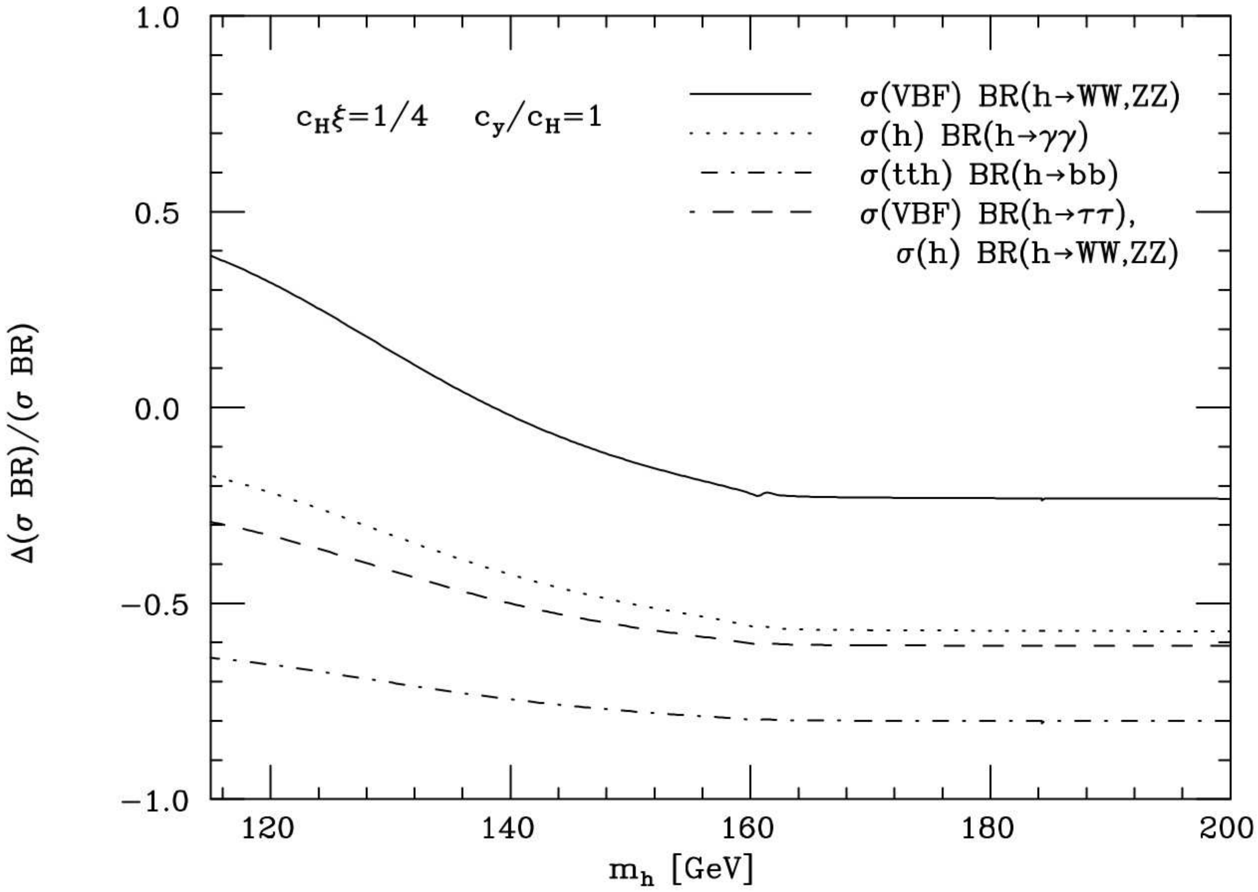
Strong WW scattering at high energies despite light Higgs

$\Rightarrow$ Need precision measurement of Higgs couplings

$+$ test of longitudinal gauge-boson scattering

Strongly-Interacting Light Higgs: deviation of $\sigma \times \mathrm{BR}$ from the case of a SM Higgs

[*G. Giudice, C. Grojean, A. Pomarol, R. Ratazzi '07*]



Sensitivity at LHC: 20–40%, ILC: 1%

⇒ ILC can test scales up to ~ 30 TeV

No Higgs signal in the early LHC data

Possible options:

- There is a Higgs boson (or more than one), but it has non-standard properties that make it difficult to detect:
  - Suppressed couplings to gauge bosons and / or fermions
  - Higgs decays into jets, invisible Higgs decays, . . .

  Examples: MSSM with complex parameters, NMSSM, Higgs–radion mixing, . . .

- There is really no Higgs boson:
  - Technicolour-like models, BESS models, . . .
  - Higgsless models in extra dimensions

  Impact on longitudinal vector boson scattering, gauge boson self-couplings: anom. couplings, resonances, . . .

Conclusions

- LHC will open up the new territory of TeV-scale physics

  $\Rightarrow$ Expect manifestations of mechanism(s) responsible for EWSB and for stabilising hierarchy M_{Planck} / M_{weak}

- 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 experiment and theory will be crucial

Looking forward to very exciting times ahead of us!