Prospects for Higgs Physics at the LHC

Cosmology meets Particle Physics

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References

1. M. Carena and H.E. Haber, "Higgs boson theory and phenomenology," Prog. Part. Nucl. Phys. **50**, 63 (2003) [arXiv:hep-ph/0208209].

2. *CPNSH: Workshop on CP Studies and Non-Standard Higgs Physics*, May 2004—December 2005, edited by S. Kraml et al., CERN Yellow Book, CERN-2006-009 (2006).

3. A. Djouadi, "The anatomy of electro-weak symmetry breaking. I: The Higgs boson in the Standard Model," Phys. Rept. **457**, 1 (2008) [arXiv:hep-ph/0503172].

4. A. Djouadi, "The anatomy of electro-weak symmetry breaking. II: The Higgs bosons in the minimal supersymmetric model," Phys. Rept. **459**, 1 (2008) [arXiv:hep-ph/0503173].

5. Gfitter, a Generic Fitter Project for HEP Model Testing, `http://gfitter.desy.de/`

Outline

1. Theoretical framework for electroweak symmetry breaking
   - Standard Model (SM) Higgs boson
   - Extended Higgs sectors—2HDM, MSSM Higgs and beyond
2. Present status of the Higgs boson
   - LEP and Tevatron searches
   - Precision electroweak constraints
   - Cosmological constraints
3. The LHC Higgs program
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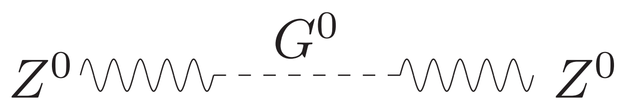
   - Determining Higgs properties
4. Higgs bosons of the MSSM
   - New Higgs signatures
   - Prospects for accessing new Higgs states
5. Conclusions

Framework for Electroweak Symmetry Breaking (EWSB)

The observed phenomena of the fundamental particles and their interactions can be explained by an SU(3)×SU(2)×U(1) gauge theory, in which the $W^\pm$, Z, quark and charged lepton masses arise from the interactions with (massless) Goldstone bosons $G^\pm$ and G^0, e.g.



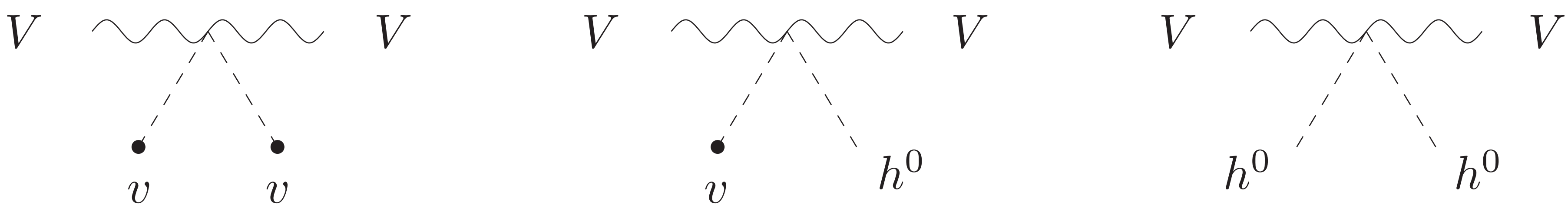
The Goldstone bosons are a consequence of (presently unknown) EWSB dynamics, which could be . . .

- weakly-interacting scalar dynamics, in which the scalar potential acquires a non-zero vacuum expectation value (vev) [$\Longrightarrow$ Higgs bosons]

- strong-interaction dynamics among new fermions (mediated perhaps by gauge forces) [technicolor, dynamical EWSB, Higgsless models, . . .]

Mass generation and Higgs couplings in the SM

Gauge bosons ($V = W^\pm$ or Z) acquire mass via interaction with the Higgs vacuum condensate.

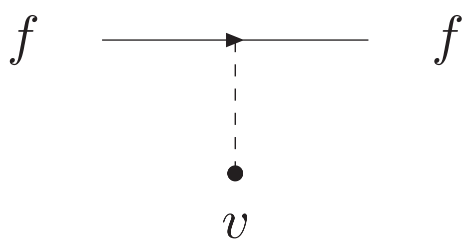


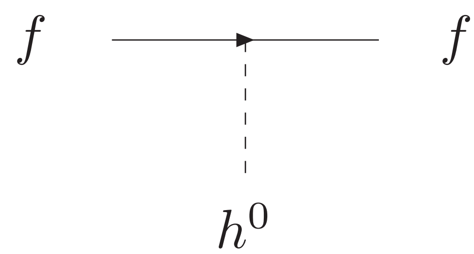
Thus, $g_{hVV} = 2m_V^2/v$ and $g_{hhVV} = 2m_V^2/v^2$, i.e. the Higgs couplings to vector bosons are proportional to the corresponding boson squared-mass.

Likewise, by replacing V with the Higgs field h^0 in the above diagrams, the Higgs self-couplings are also proportional to the square of the Higgs mass, m_h, which is a free parameter of the model,

$$g_{hhh} = \tfrac{3}{2}\lambda v = \frac{3m_h^2}{v}\,, \qquad \text{and} \qquad g_{hhhh} = \tfrac{3}{2}\lambda = \frac{3m_h^2}{v^2}\,.$$

The quarks and charged leptons likewise acquire mass:

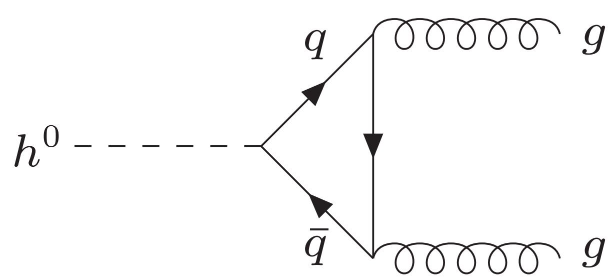




Hence, $g_{hf\bar{f}} = m_f/v$, i.e. Higgs couplings to fermions are proportional to the corresponding fermion mass.

Higgs boson coupling to gluons

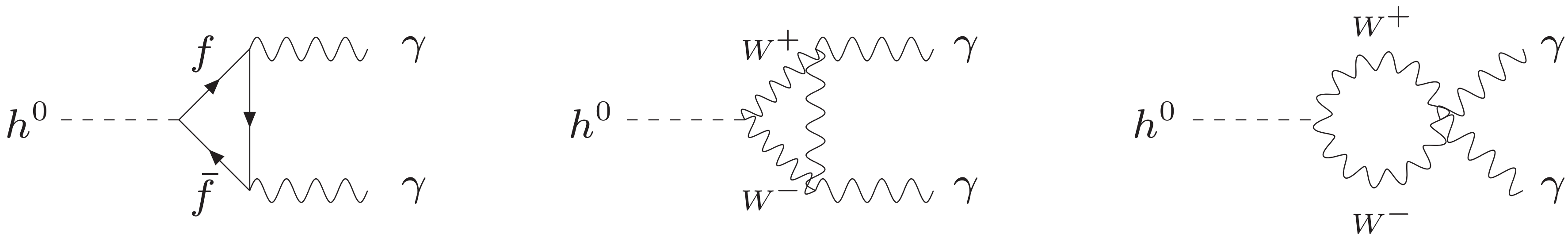
At one-loop, the Higgs boson couples to gluons via a loop of quarks:



Heavy quark loops do *not* decouple, whereas light quark loops are negligible.

Higgs boson coupling to photons

At one-loop, the Higgs boson couples to photons via a loop of charged particles:



If charged scalars exist, they would contribute as well.

Importance of the loop-induced Higgs couplings for the LHC Higgs program

1. Dominant LHC Higgs production mechanism: gluon-gluon fusion. At leading order,

$$\frac{d\sigma}{dy}(pp \to h^0 + X) = \frac{\pi^2 \Gamma(h^0 \to gg)}{8m_h^3} g(x_+, m_h^2) g(x_-, m_h^2)\,,$$

where $g(x, Q^2)$ is the gluon distribution function at the scale Q^2 and $x_\pm \equiv m_h e^{\pm y}/\sqrt{s}$, $y = \frac{1}{2}\ln\left(\frac{E+p_L}{E-p_L}\right)$.

2. For $m_h \simeq 120$ GeV, the discovery channel for the Higgs boson at the LHC is via the rare decay $h^0 \to \gamma\gamma$.

Extended Higgs sectors: 2HDM, MSSM and beyond

For an arbitrary Higgs sector, the tree-level ρ-parameter is given by

$$\rho_0 \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1 \quad \Longleftrightarrow \quad (2T+1)^2 - 3Y^2 = 1\,,$$

independently of the Higgs vevs, where T and Y specify the weak-isospin and the hypercharge of the Higgs representation to which it belongs. Y is normalized such that the electric charge of the scalar field is $Q = T_3 + Y/2$. The simplest solutions are Higgs singlets $(T, Y) = (0, 0)$ and hypercharge-one complex Higgs doublets $(T, Y) = (\frac{1}{2}, 1)$.

Thus, we shall consider non-minimal Higgs sectors consisting of multiple Higgs doublets (and perhaps Higgs singlets), but no higher Higgs representations, to avoid the fine-tuning of Higgs vevs.

Higgs boson phenomena beyond the SM

The two-Higgs-doublet model (2HDM) consists of two hypercharge-one scalar doublets. Of the eight initial degrees of freedom, three correspond to the Goldstone bosons and five are physical: a charged Higgs pair, $H^\pm$ and three neutral scalars.

In contrast to the SM, whereas the Higgs-sector is CP-conserving, the 2HDM allows for Higgs-mediated CP-violation. If CP is conserved, the Higgs spectrum contains two CP-even scalars, h^0 and H^0 and a CP-odd scalar A^0. Thus, new features of the extended Higgs sector include:

- Charged Higgs bosons
- A CP-odd Higgs boson (if CP is conserved in the Higgs sector)
- Higgs-mediated CP-violation (and neutral Higgs states of indefinite CP)

More exotic Higgs sectors allow for doubly-charged Higgs bosons, etc.

Higgs-fermion Yukawa couplings in the 2HDM

The 2HDM Higgs-fermion Yukawa Lagrangian is:

$$-\mathscr{L}_{\rm Y} = \overline{U}_L \Phi_a^{0\,*} h_a^U U_R - \overline{D}_L K^\dagger \Phi_a^- h_a^U U_R + \overline{U}_L K \Phi_a^+ h_a^{D\,\dagger} D_R + \overline{D}_L \Phi_a^0 h_a^{D\,\dagger} D_R + {\rm h.c.}\,,$$

where K is the CKM mixing matrix, and there is an implicit sum over $a = 1, 2$. The $h^{U,D}$ are 3×3 Yukawa coupling matrices and

$$\langle \Phi_a^0 \rangle \equiv \frac{v_a}{\sqrt{2}}\,, \qquad v^2 \equiv v_1^2 + v_2^2 = (246~{\rm GeV})^2\,.$$

If all terms are present, then tree-level Higgs-mediated flavor-changing neutral currents (FCNCs) and CP-violating neutral Higgs-fermion couplings are both present. Both are avoided by imposing a discrete symmetry to restrict the structure of the Higgs-fermion Yukawa Lagrangian. Different choices for the discrete symmetry yields:

- Type-I Yukawa couplings: $h_2^U = h_2^D = 0$,
- Type-II Yukawa couplings: $h_1^U = h_2^D = 0$,

The parameter $\tan\beta = \langle \Phi_2^0 \rangle / \langle \Phi_1^0 \rangle$ is physical and governs the structure of the Higgs-fermion couplings.

The Higgs basis

The 2HDM consists of two identical hypercharge-one scalar doublets. A particularly convenient convention is to define two linear combinations of these two fields, H_1 and H_2 such that:

$$\langle H_1^0 \rangle = v/\sqrt{2} \quad (v = 246~\text{GeV}) \qquad \text{and} \qquad \langle H_2^0 \rangle = 0\,.$$

This defines the Higgs basis (up to a rephasing of H_2^0, which is unphysical). If the Higgs-fermion coupling is completely general (e.g., no special symmetry is imposed on the Yukawa Lagrangian), then no other basis has any physical significance, in which case $\tan\beta$ is an unphysical parameter.

The Higgs sector of the MSSM

The Higgs sector of the MSSM is a Type-II 2HDM, whose Yukawa couplings and Higgs potential are constrained by supersymmetry (SUSY). Minimizing the Higgs potential, the neutral components of the Higgs fields acquire vevs:

$$\langle H_d \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_d \\ 0 \end{pmatrix}, \qquad \langle H_u \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_u \end{pmatrix},$$

where $v^2 \equiv v_d^2 + v_u^2 = 4m_W^2/g^2 = (246\ \mathrm{GeV})^2$. The ratio of the two vevs is an important parameter of the model:

$$\boxed{\tan\beta \equiv \frac{v_u}{v_d}}$$

The five physical Higgs particles consist of a charged Higgs pair $H^\pm$, one CP-odd scalar A^0, and two CP-even scalars h^0, H^0, obtained by diagonalizing All Higgs masses and couplings can be expressed in terms of two parameters usually chosen to be m_A and $\tan\beta$.

At tree level,

$$m_{H^\pm}^2 = m_A^2 + m_W^2 \,,$$
$$m_{H,h}^2 = \tfrac{1}{2}\left(m_A^2 + m_Z^2 \pm \sqrt{(m_A^2+m_Z^2)^2 - 4m_Z^2 m_A^2 \cos^2 2\beta}\right) \,,$$

where α is the angle that diagonalizes the CP-even Higgs squared-mass matrix. Hence,

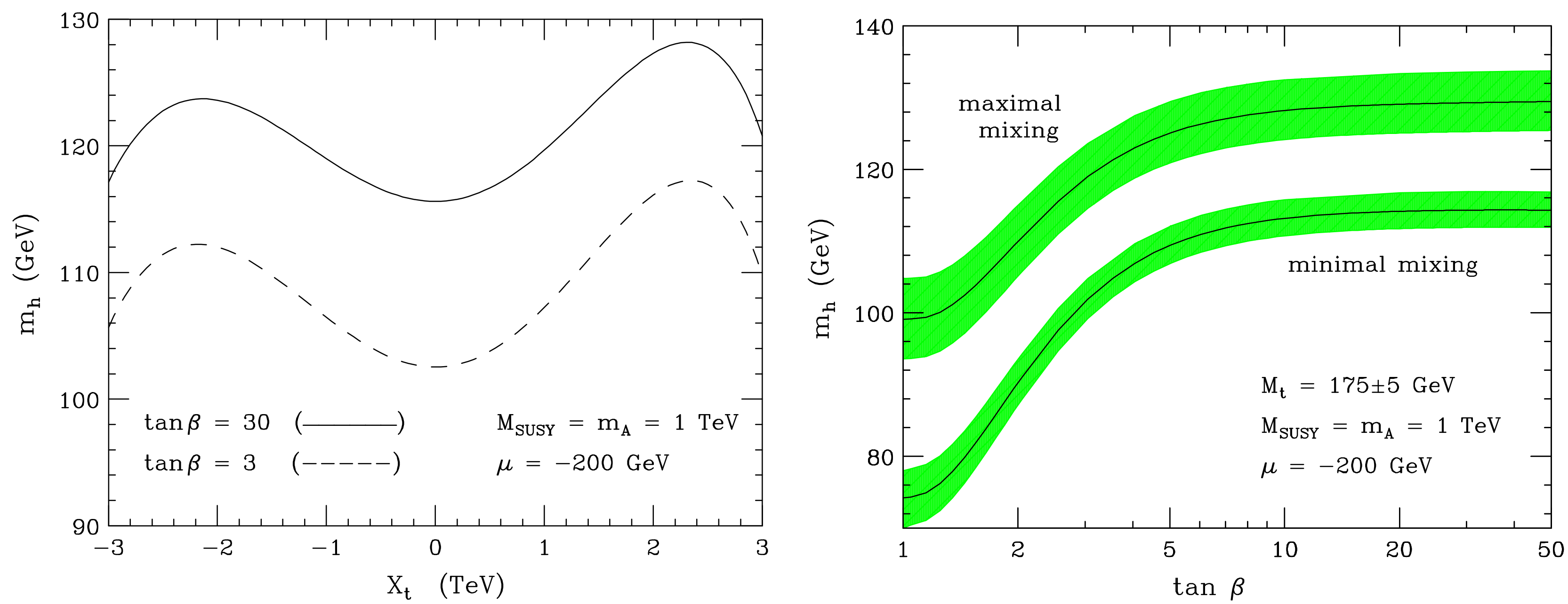
$$\boxed{m_h \leq m_Z |\cos 2\beta| \leq m_Z \,,}$$

which is ruled out by LEP data. But, this inequality receives quantum corrections. The Higgs mass can be shifted due to loops of particles and their superpartners (an incomplete cancelation, which would have been exact if supersymmetry were unbroken):

$$m_h^2 \lesssim m_Z^2 + \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right)\right] \,,$$

where $X_t \equiv A_t - \mu \cot\beta$ governs stop mixing and M_S^2 is the average top-squark squared-mass.

The state-of-the-art computation includes the full one-loop result, all the significant two-loop contributions, some of the leading three-loop terms, and renormalization-group improvements. The final conclusion is that $m_h \lesssim 130$ GeV [assuming that the top-squark mass is no heavier than about 2 TeV].



Maximal mixing corresponds to choosing the MSSM Higgs parameters in such a way that m_h is maximized (for a fixed $\tan\beta$). This occurs for $X_t/M_S \sim 2$. As $\tan\beta$ varies, m_h reaches is maximal value, $(m_h)_{\max} \simeq 130$ GeV, for $\tan\beta \gg 1$ and $m_A \gg m_Z$.

Tree-level MSSM Higgs couplings

Tree-level couplings of Higgs bosons with gauge bosons are often suppressed by an angle factor, either $\cos(\beta-\alpha)$ or $\sin(\beta-\alpha)$.

$\cos(\beta-\alpha)$	$\sin(\beta-\alpha)$	angle-independent
$H^0W^+W^-$	$h^0W^+W^-$	—
H^0ZZ	h^0ZZ	—
ZA^0h^0	ZA^0H^0	$ZH^+H^-\,,\ \gamma H^+H^-$
$W^\pm H^\mp h^0$	$W^\pm H^\mp H^0$	$W^\pm H^\mp A^0$

Tree-level Higgs-fermion couplings may be either suppressed or enhanced with respect to the SM value, $gm_f/2m_W$. The charged Higgs boson couplings to fermion pairs, with all particles pointing into the vertex, are :

$$g_{H^-t\bar{b}} = \frac{g}{\sqrt{2}m_W}\left[m_t\cot\beta\,P_R + m_b\tan\beta\,P_L\right],$$

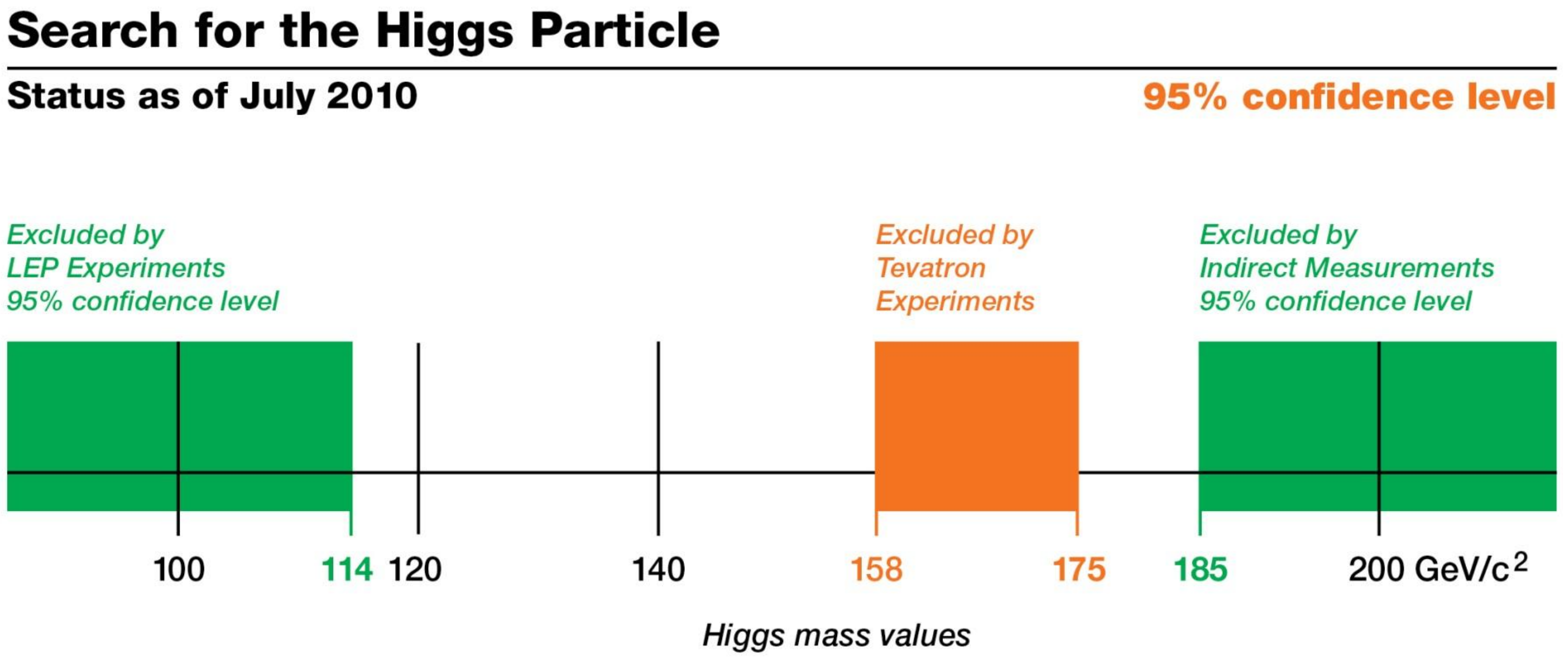
$$g_{H^-\tau^+\nu} = \frac{g}{\sqrt{2}m_W}\left[m_\tau\tan\beta\,P_L\right].$$

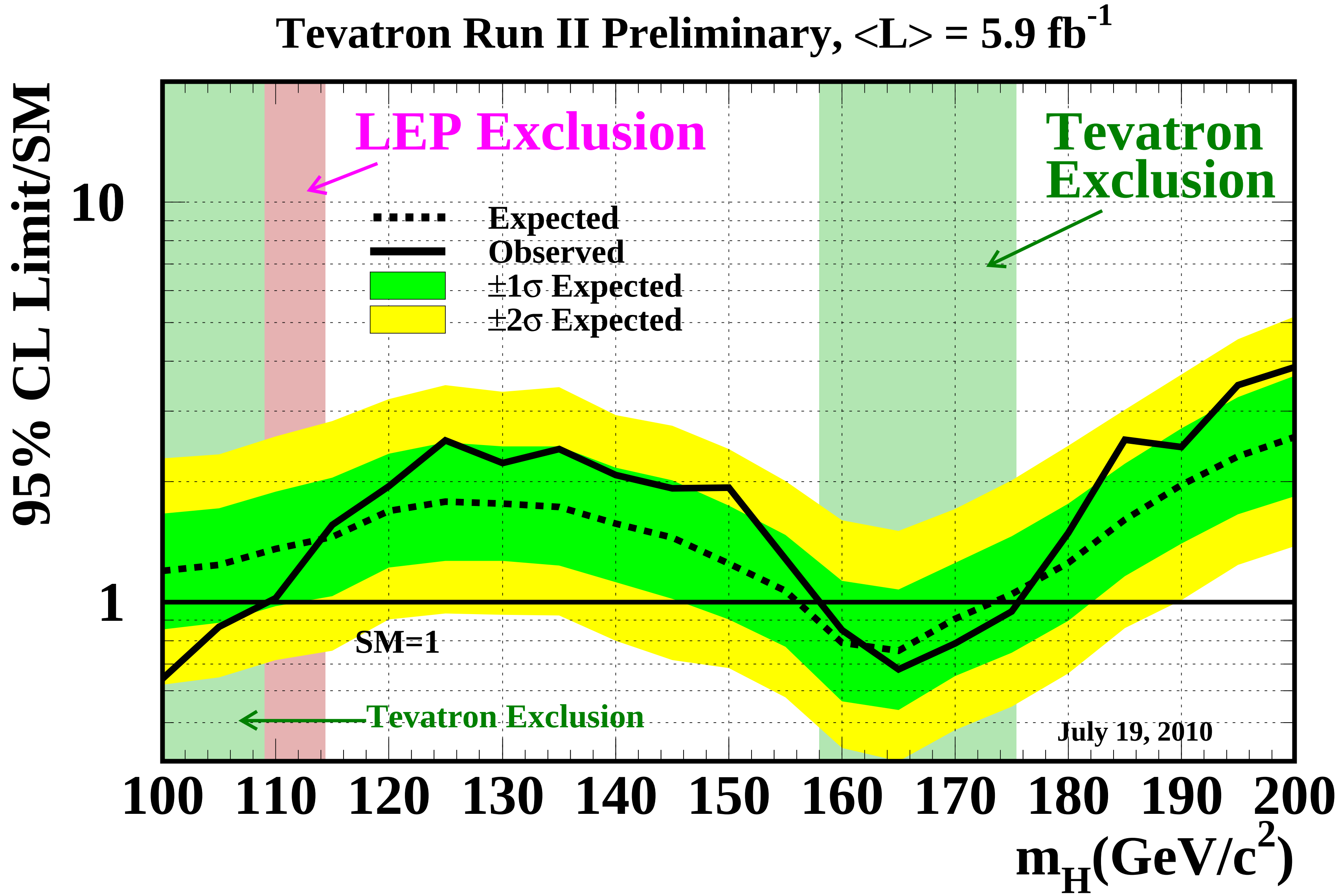
and the neutral Higgs boson couplings are (the γ_5 indicates a pseudoscalar coupling):

$$\begin{aligned}
h^0 b\bar{b} \quad (\text{or } h^0\tau^+\tau^-):& \qquad -\frac{\sin\alpha}{\cos\beta} = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)\,,\\
h^0 t\bar{t}:& \qquad \frac{\cos\alpha}{\sin\beta} = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)\,,\\
H^0 b\bar{b} \quad (\text{or } H^0\tau^+\tau^-):& \qquad \frac{\cos\alpha}{\cos\beta} = \cos(\beta-\alpha) + \tan\beta\sin(\beta-\alpha)\,,\\
H^0 t\bar{t}:& \qquad \frac{\sin\alpha}{\sin\beta} = \cos(\beta-\alpha) - \cot\beta\sin(\beta-\alpha)\,,\\
A^0 b\bar{b} \quad (\text{or } A^0\tau^+\tau^-):& \qquad \gamma_5\tan\beta\,,\\
A^0 t\bar{t}:& \qquad \gamma_5\cot\beta\,.
\end{aligned}$$

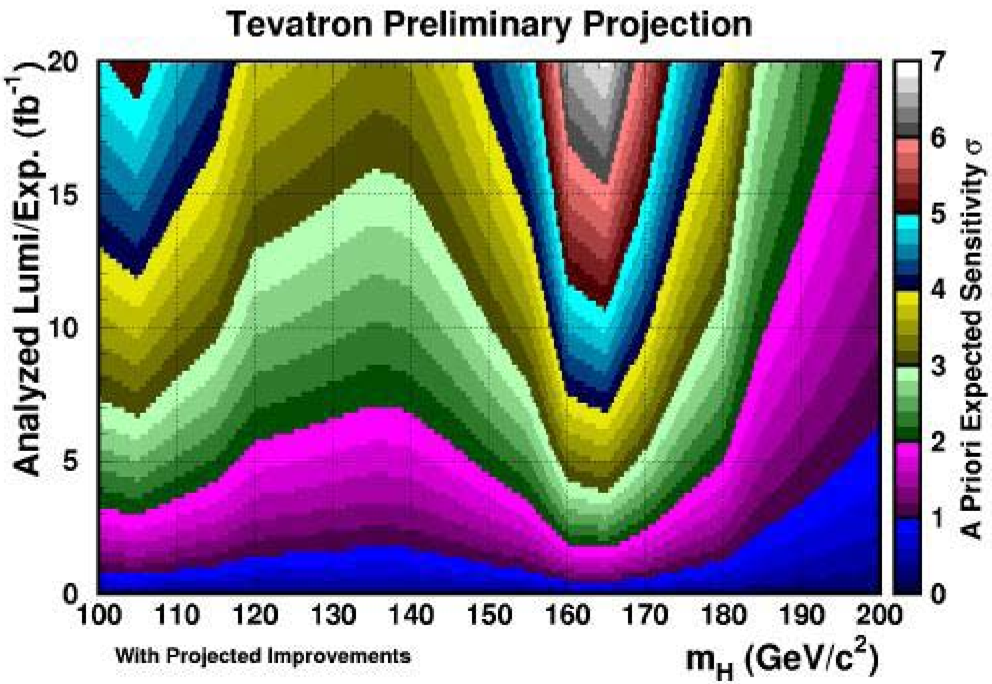
Especially noteworthy is the possible $\tan\beta$-enhancement of certain Higgs-fermion couplings. The general expectation in MSSM models is that $\tan\beta$ lies in a range: $1 \lesssim \tan\beta \lesssim m_t/m_b$.

Present Status of the SM Higgs Boson





Tevatron Run II Preliminary, <L> = 5.9 fb^{-1}
95% CL Limit/SM
10
1
LEP Exclusion
Tevatron Exclusion
Expected
Observed
±1σ Expected
±2σ Expected
SM=1
Tevatron Exclusion
July 19, 2010
100
110
120
130
140
150
160
170
180
190
200
m_H(GeV/c^2)

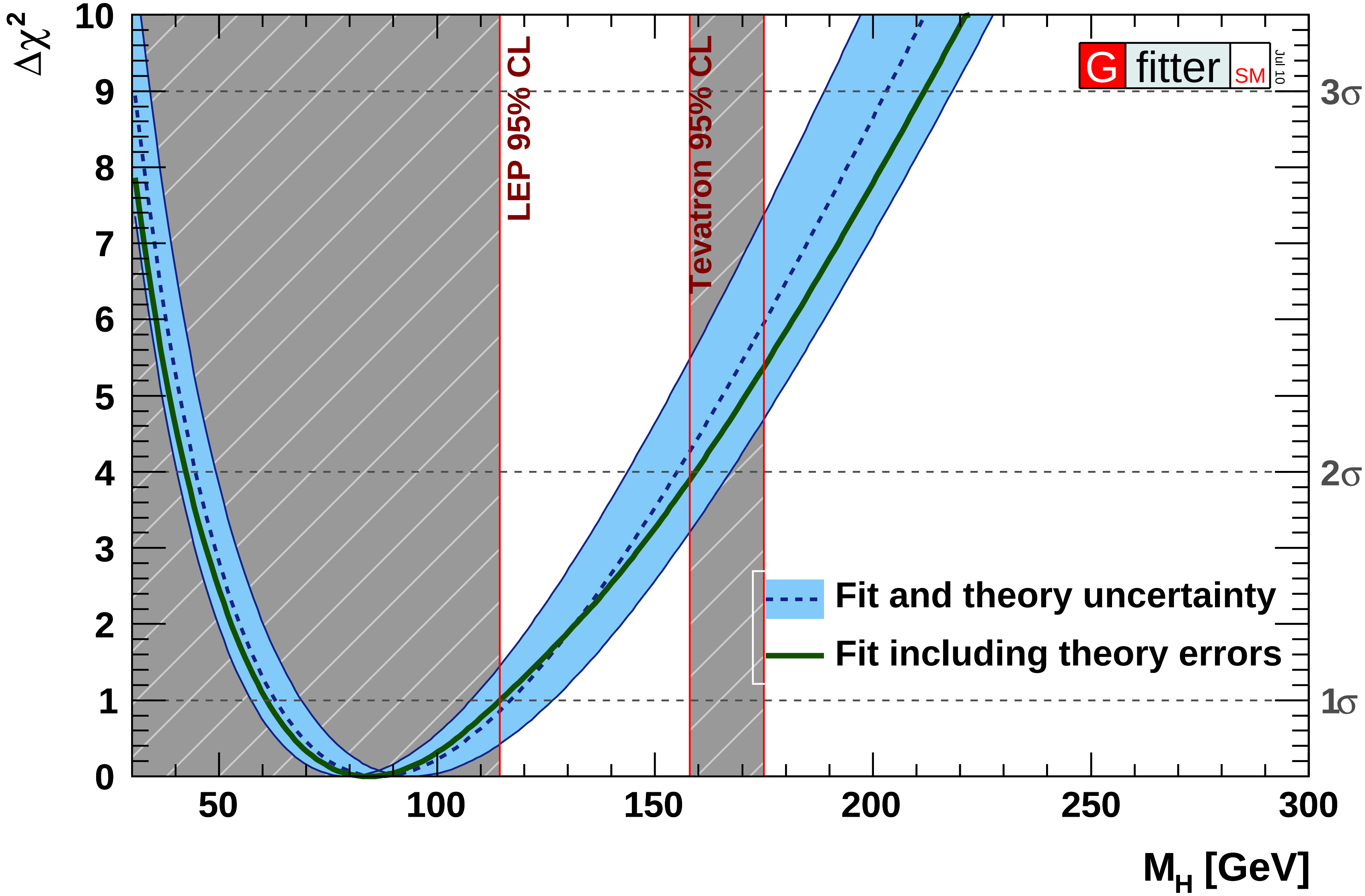


Higgs boson sensitivity with projected improvements per experiment. Taken from: M. Carena et al., *Run III: Continued Running of the Tevatron Collider Beyond 2011* (May 26, 2010)

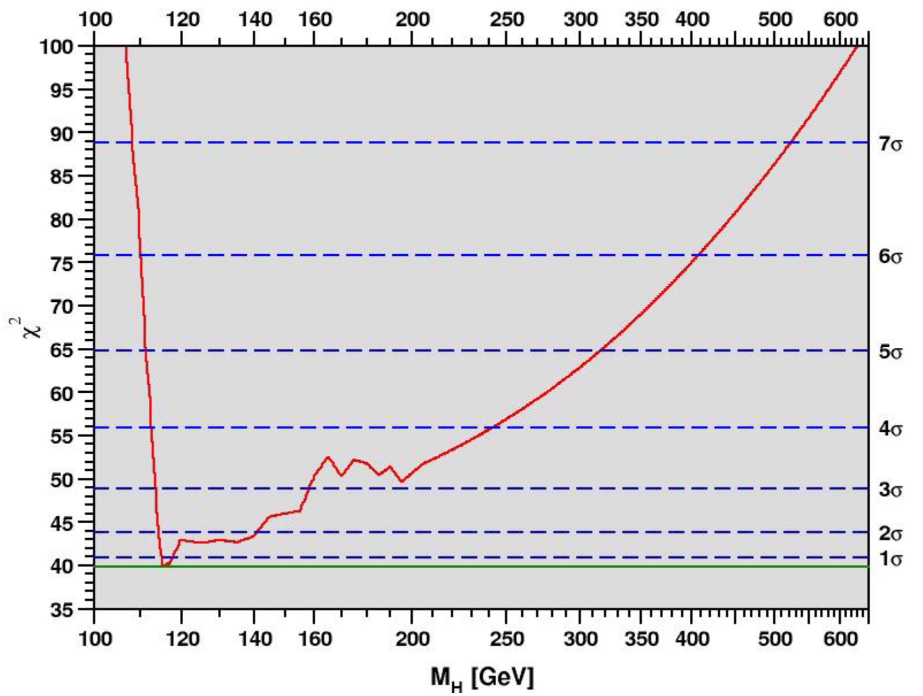
Analyzable Lum/Expt	115 GeV	130 GeV	145 GeV
5 fb^{-1}	2.2 σ	1.7 σ	1.9 σ
10 fb^{-1}	3.1 σ	2.5 σ	2.7 σ
15 fb^{-1}	3.8 σ	3.0 σ	3.2 σ
20 fb^{-1}	4.4 σ	3.5 σ	3.7 σ

Sensitivity to the Standard Model Higgs Boson combining all modes. The low mass $\leq$ 130 GeV mode is principally $q\bar{q} \to (W, Z) + (h \to b\bar{b})$; the higher mass $\geq$ 130 GeV mode is principally $gg \to h \to WW^*$.

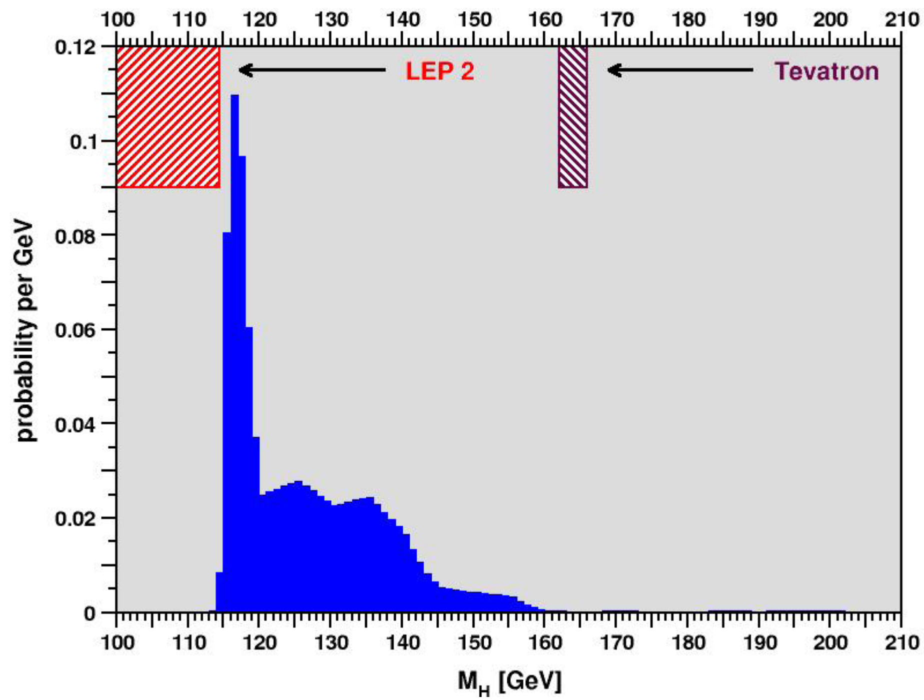
SM Higgs boson constraints from Precision EW Data



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



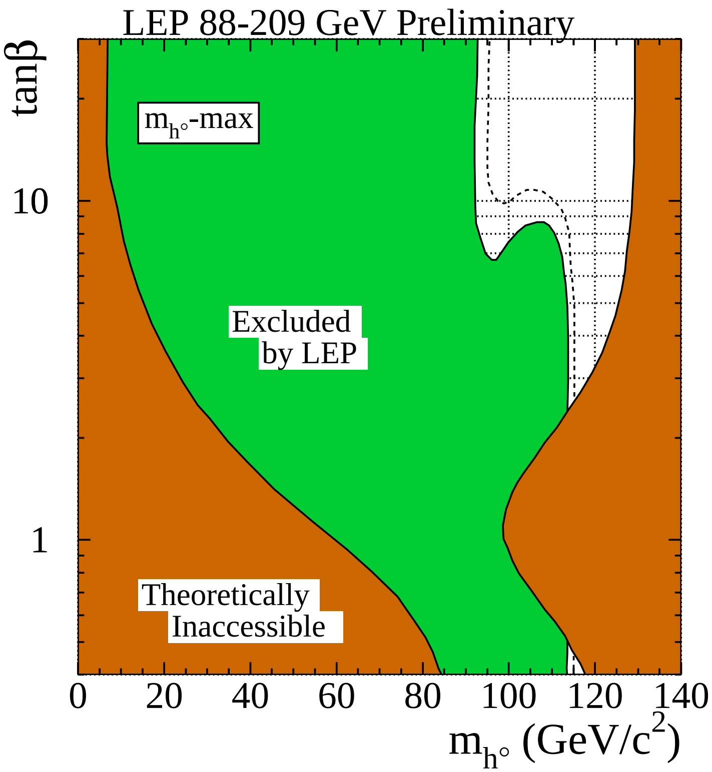
χ^2 distribution of M_H from all data. The horizontal solid green line marks the χ^2 minimum, $\chi^2 = 39.88$, while the dashed blue lines refer to integer values of $\sqrt{\chi^2 - \chi^2_{\rm min}}$. The combined effects of precision LEP 2 and Tevatron data result in a pronounced dip at $M_H = 115.8$ GeV. Values of $M_H > 141$ (158) GeV are excluded at the 2 (3) σ level.

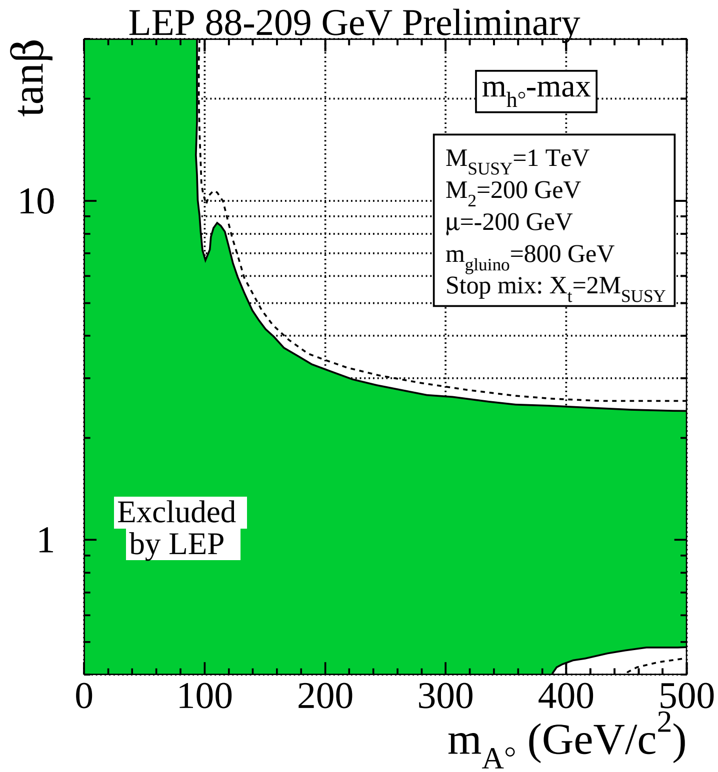


Probability distribution of M_H subject to all data. The nominal 95% CL exclusion ranges from LEP 2 and the Tevatron are also indicated.

Taken from Jens Erler, Phys. Rev. **D81,** 051301 (2010)

Summary of the LEP MSSM Higgs Search [95% CL limits]

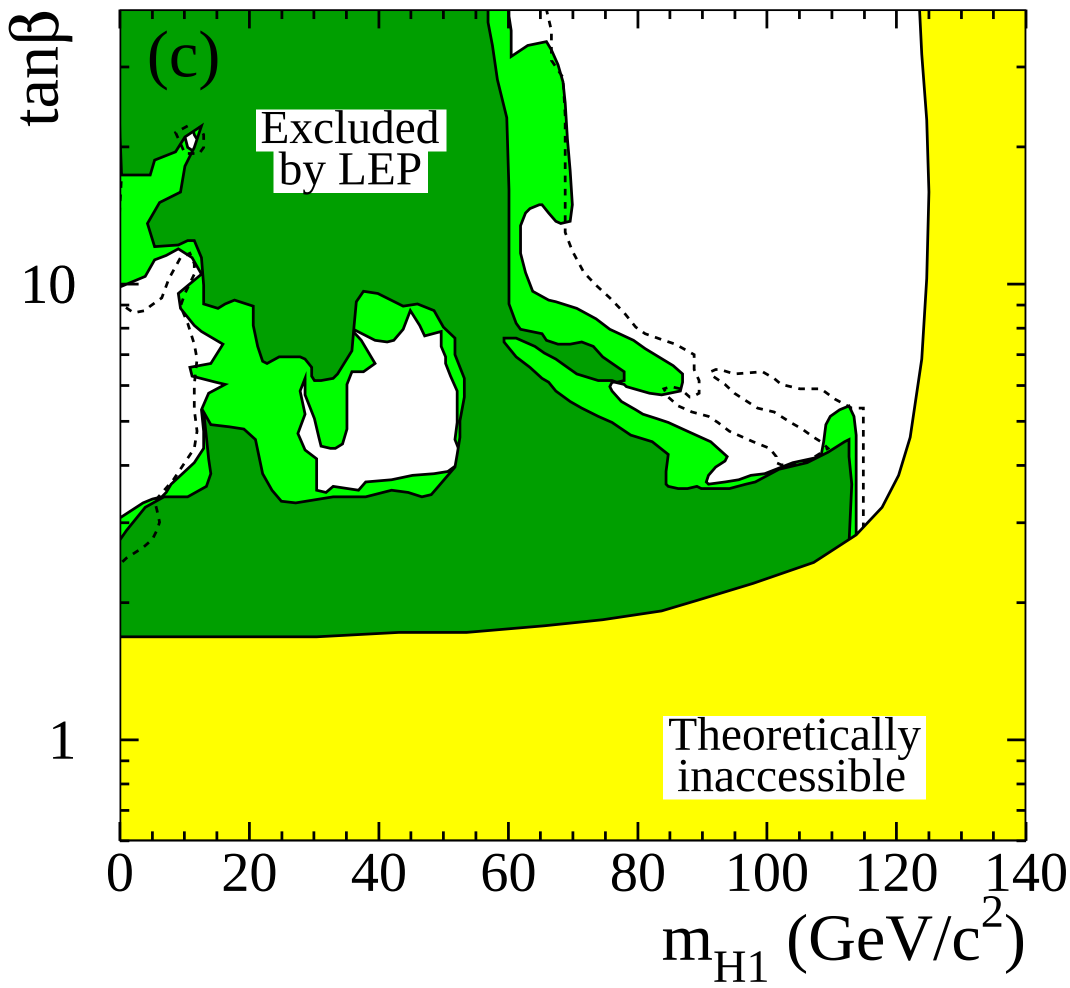




- Charged Higgs boson: $m_{H^\pm} > 79.3$ GeV
- MSSM Higgs: $m_h > 92.9$ GeV; $m_A > 93.4$ GeV [max-mix scenario]

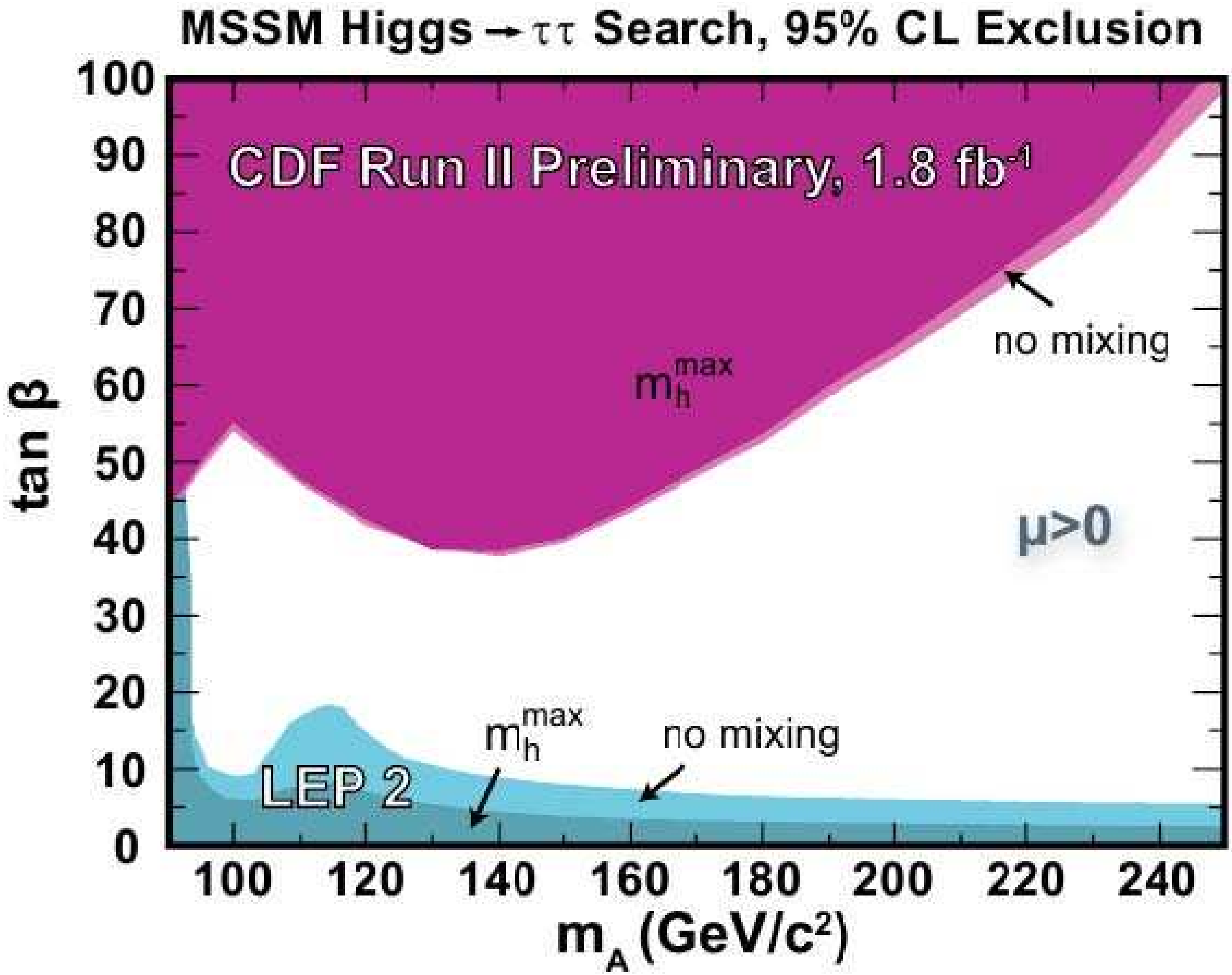
WARNING: Allowing for possible CP-violating effects that can enter via radiative corrections, large holes open up in the Higgs mass exclusion plots.

Exclusion limits may be significantly weakened in the CPX scenario

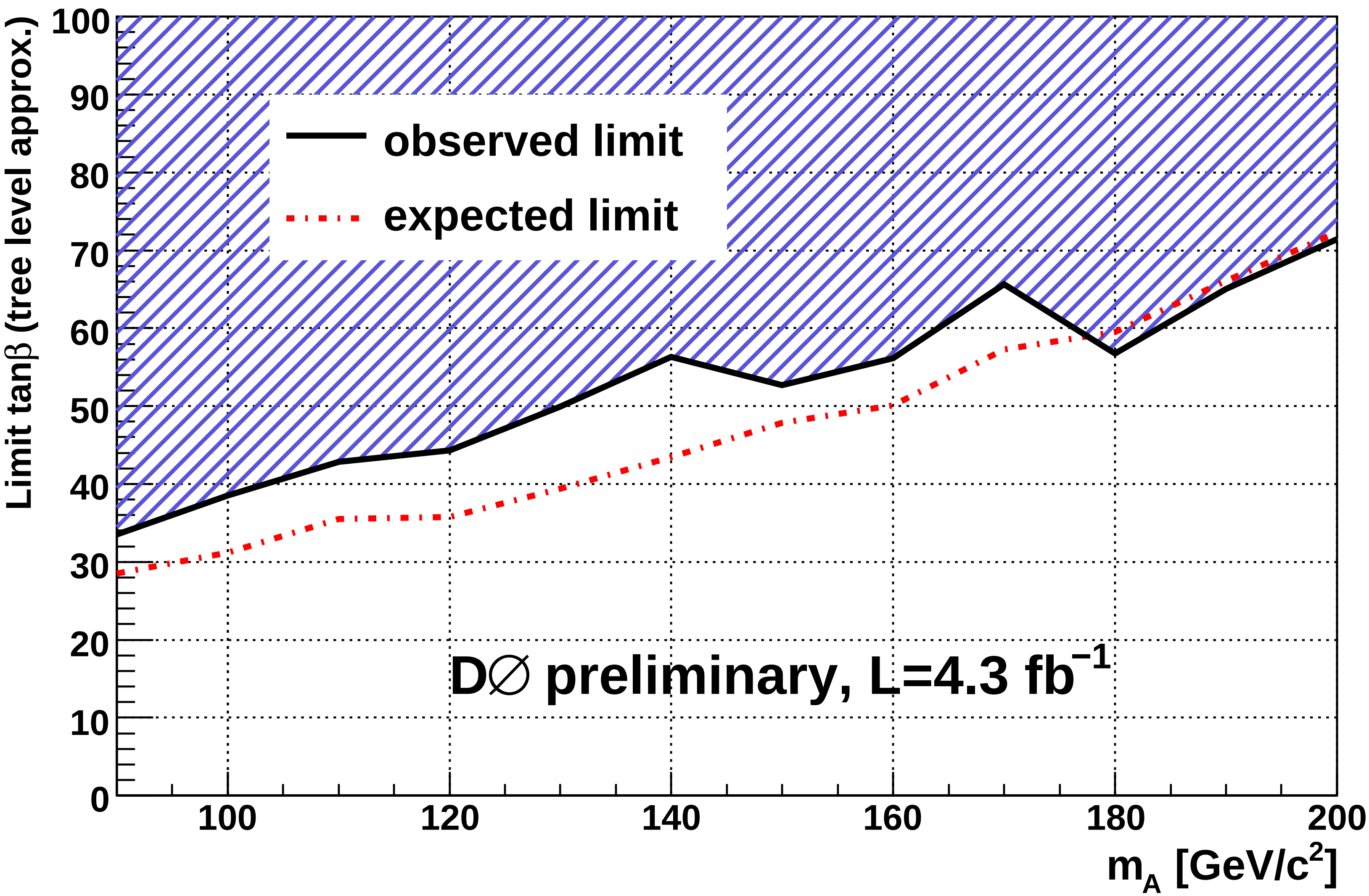


Exclusions at 95% CL (light-green) and at 99.7% CL (dark-green) for the CP-violating CPX scenario with $m_t = 174.3$ GeV. The yellow region corresponds to the theoretically inaccessible domains. In each scan point, the more conservative of the two theoretical calculations, FeynHiggs 2.0 or CPH, was used. Taken from S. Schael *et al.* [ALEPH, DELPHI, L3 and Opal Collaborations and the LEP Working Group for Higgs Boson Searches], Eur. Phys. J. **C47** (2006) 547.

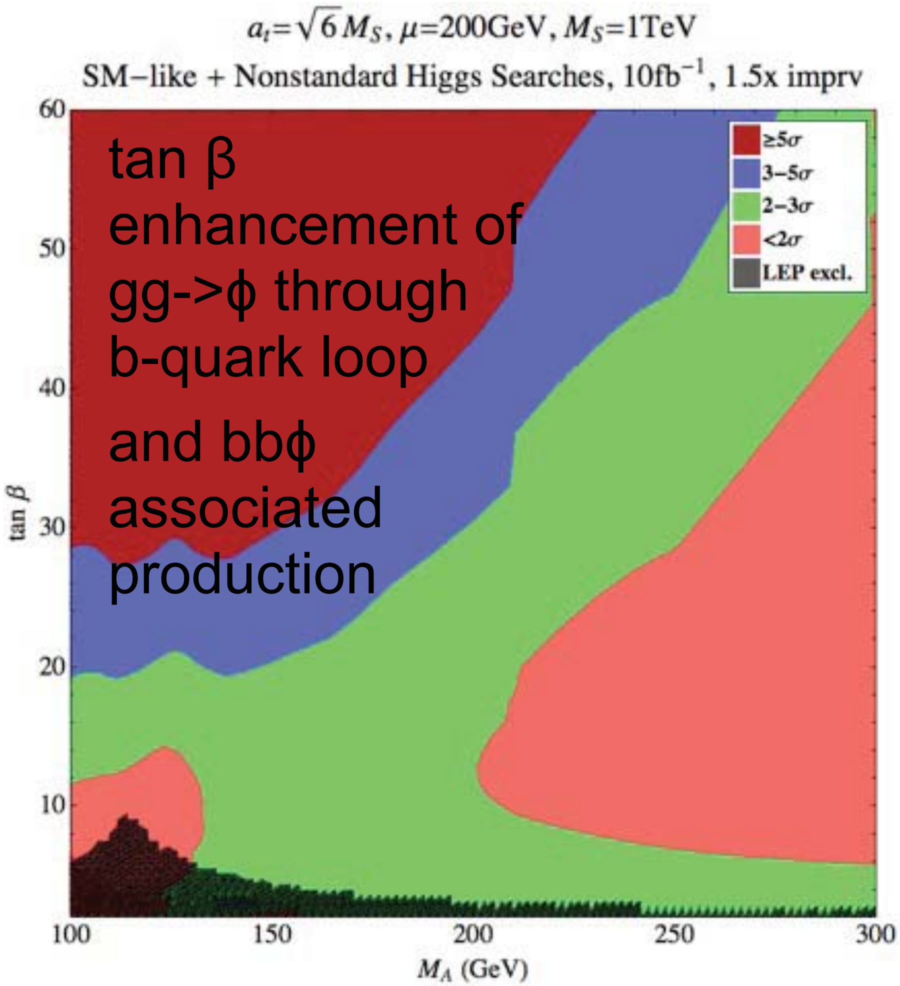
The Tevatron also contributes to the MSSM Higgs Mass Limits



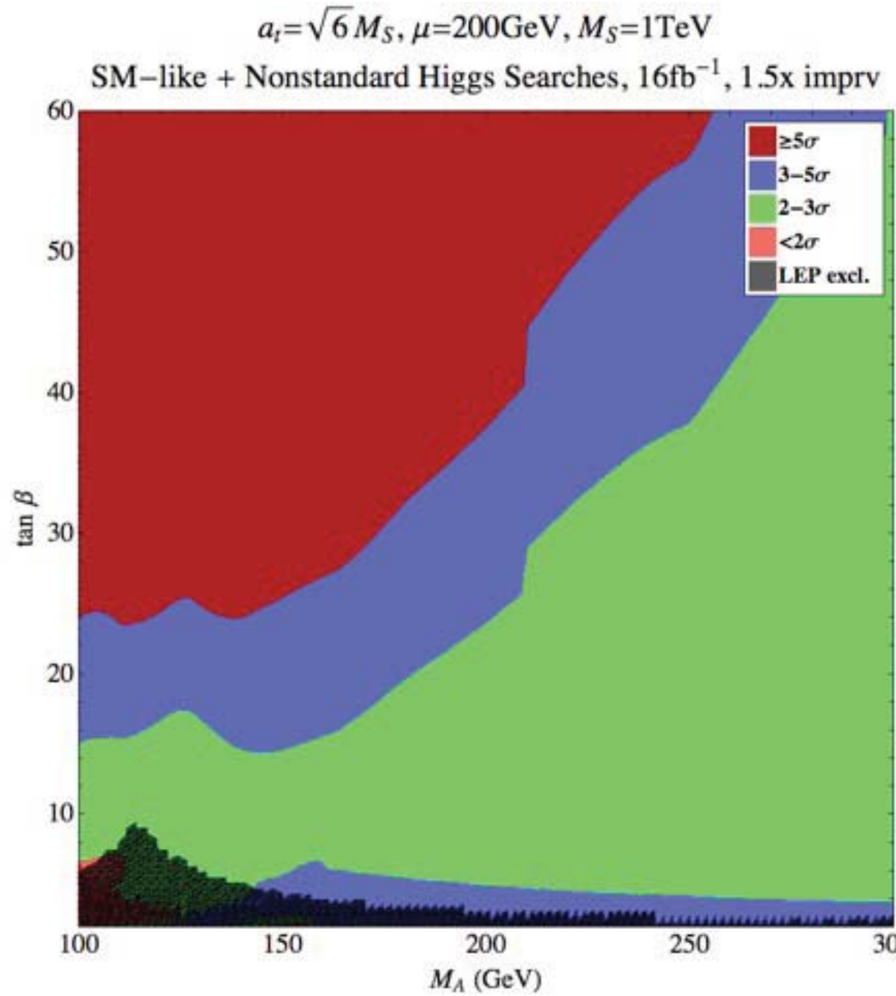
More recently, the DØ Collaboration has searched for $b\bar{b}h$ production, followed by $h \to \tau^+\tau^-$ decay.



Combination with Non-Standard Higgs channels



End of 2011



End of 2014

Maximal Mixing Scenario : More than two sigma sensitivity in all parameter space if running continues. Three sigma obtain in large regions of parameters

The MSSM Higgs sector in light of precision electroweak data

- In the decoupling limit (assuming that the SUSY particles are somewhat heavy), the effects of the heavy Higgs states and the SUSY particles decouple and the global SM fit applies.

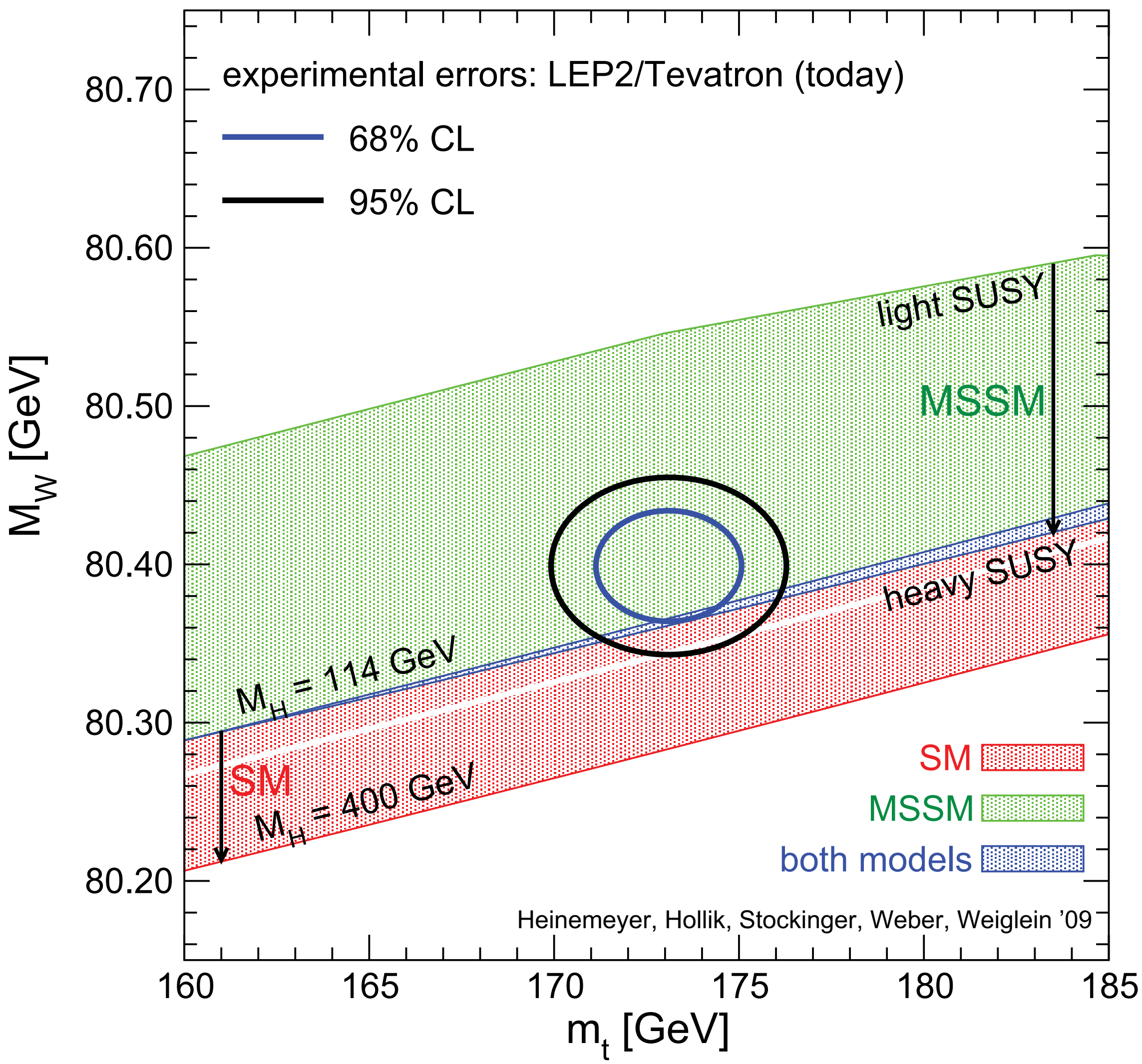
- In the latter case, h^0 is a SM-like Higgs boson whose mass lies below about 130 GeV in the *preferred* Higgs mass range!

- If SUSY particle masses are not too heavy, they can have small effects on the fit to precision electroweak data. With additional degrees of freedom, the goodness of fit can be slightly improved (and possibly argue for SUSY masses close to their present experimental limits).

- The MSSM fit is further improved if one wishes to ascribe deviations of $(g-2)_\mu$ from their SM expectations to the effects of superpartners.

Example: Prediction for M_W in the SM and the MSSM :

[*S.H., W. Hollik, D. Stockinger, A. Weber, G. Weiglein '07*]



MSSM band:
scan over
SUSY masses

overlap:
SM is MSSM-like
MSSM is SM-like

SM band:
variation of $M_H^{\rm SM}$

Cosmological Constraints on Higgs bosons

- Non-minimally coupled Higgs inflation field with gravity.

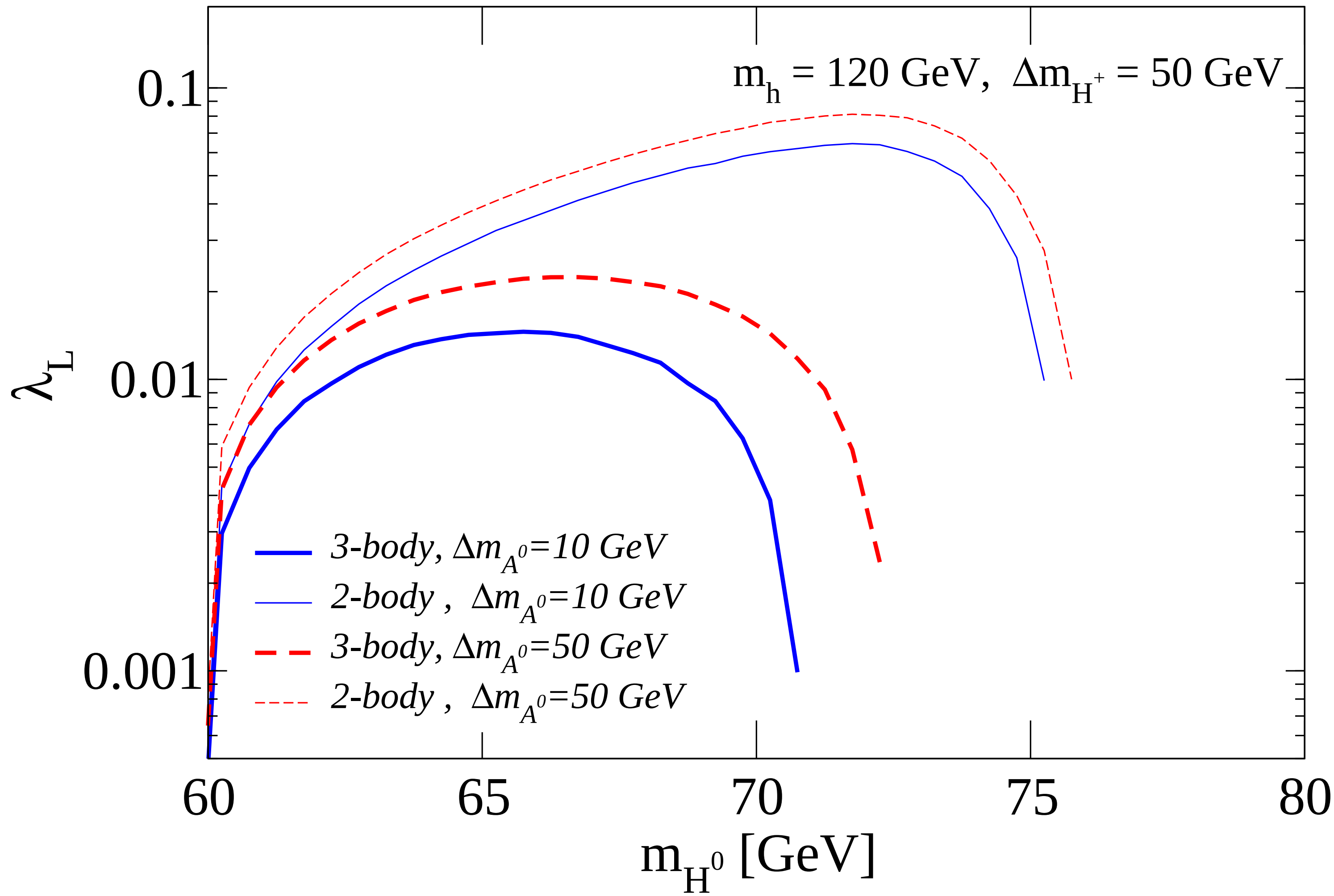
$$\mathcal{L} = \sqrt{-g}\left[\frac{1+\kappa^2\xi\Phi^2}{2\kappa^2}R + \tfrac{1}{2}g^{\mu\nu}\nabla_\mu\phi\nabla_\mu\Phi - \tfrac{1}{4}\lambda(\Phi^2-v^2)^2\right],$$

where R is the scalar curvature, $\kappa^2 \equiv 8\pi G_N$, and ξ is the non-minimal coupling parameter. For a viable model of the Higgs boson as inflaton, one needs $\xi \sim 10^3$—10^4. L.A. Popa and A. Caramete [arXiv:1009.1293] then obtain a Higgs mass bound of:

$$143.7 \text{ GeV} \leq m_H \leq 167 \text{ GeV} \quad \text{at 95\% CL}\,.$$

- The inert 2HDM and dark matter

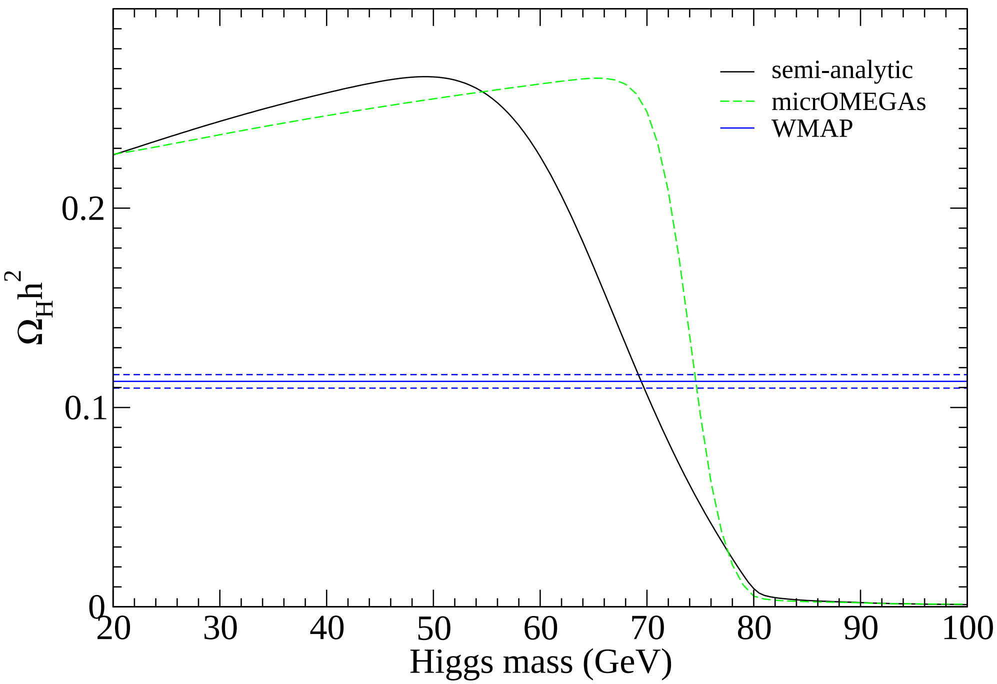
  The inert 2HDM is a type-I model in which a discrete symmetry $H_2 \to -H_2$ is imposed in the Higgs basis. Fermions only couple to H_1 (where the vev resides). Hence, the lightest scalar of the H_2 doublet (which can be arranged to be electrically neutral) is stable and is a candidate for dark matter.



The viable parameter space for $m_h = 120$ GeV. The dark matter particle is H^0, and $\lambda_L \equiv \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)$ is a combination of scalar potential parameters. The charged Higgs and CP-odd masses are given by $m_{H^\pm, A^0} = m_{H^0} + \Delta m_{H^\pm, A^0}$. The lines correspond to $\Omega h^2 = 0.11$. "Three body" indicates that $H^0 H^0$ annihilation into $WW^* \to W f \bar{f}'$ has been included. Taken from L.L. Honorez and C.E. Yaguna, JHEP **09** (2010) 046.

- The SM Higgs boson as cold dark matter

  In a class of gauge-Higgs unification models, the SM Higgs boson is a part of the extra-dimensional component of a higher-dimensional gauge field. The Higgs boson can become absolutely stable due to gauge invariance and a dynamically generated H-parity quantum number. The trilinear couplings of Higgs bosons to vector boson pairs and fermions are absent. It is not clear whether such models can be consistent with precision electroweak data and unitarity of WW scattering.



Taken from Y. Hosotani, P. Ko and M. Tanaka, Phys. Lett. B **680** (2009) 179.

Higgs phenomenology at the LHC

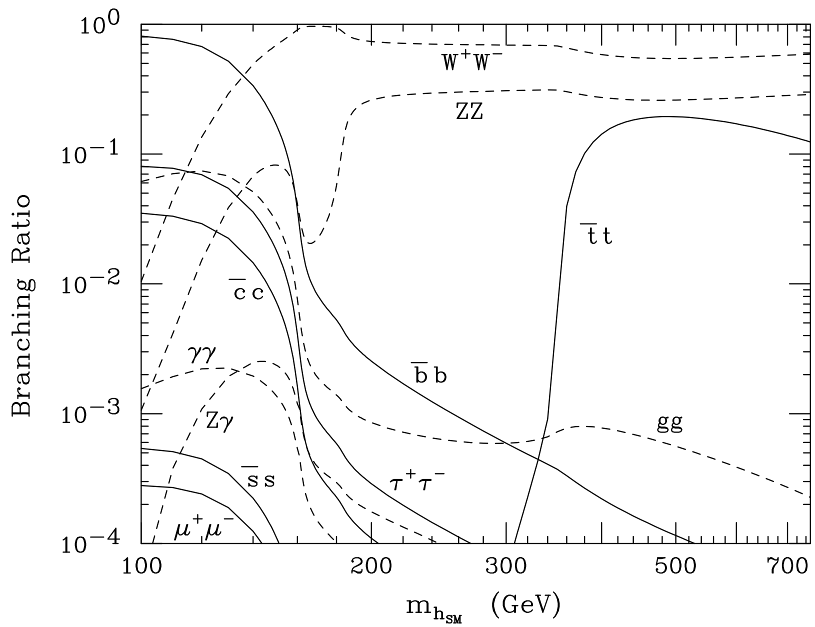
A program of Higgs physics at the LHC must address:

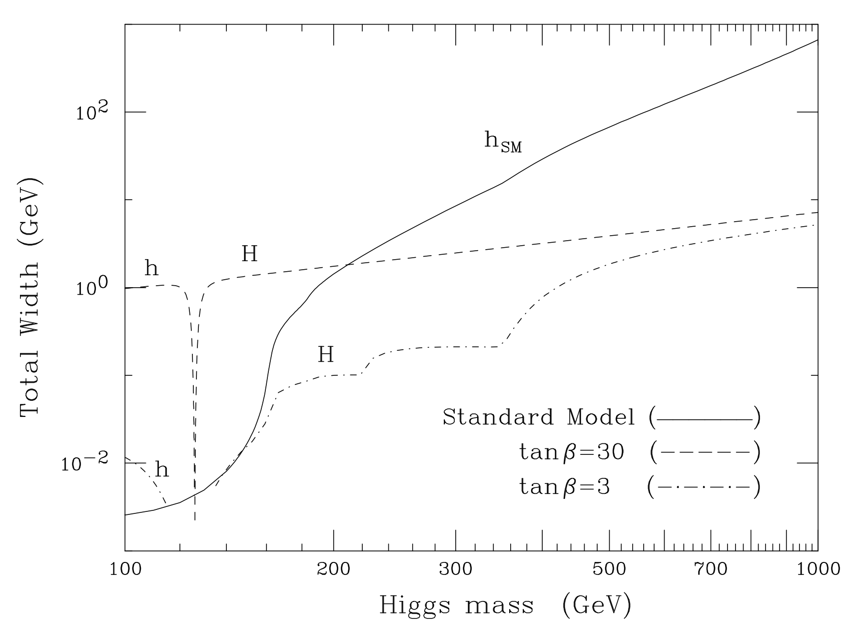
- Discovery reach for the SM Higgs boson
- How many Higgs states are there?
- Assuming one Higgs-like state is discovered
  - Is it a Higgs boson?
  - Is it the SM Higgs boson?

The measurement of Higgs boson properties will be critical in order to answer the last two questions:

- mass, width, CP-quantum numbers (CP-violation?)
- branching ratios and Higgs couplings
- reconstructing the Higgs potential

SM Higgs Branching Ratios and Width





Key features of the Higgs branching ratios:

- $h \to b\bar{b}$ is dominant for $m_h < 135$ GeV
- $h \to WW^{(*)}$ is dominant for $m_h > 135$ GeV
- BR$(h \to \gamma\gamma) \simeq 2 \times 10^{-3}$ for $m_h \simeq 120$ GeV.

SM Higgs production at hadron colliders

At hadron colliders, the relevant processes are

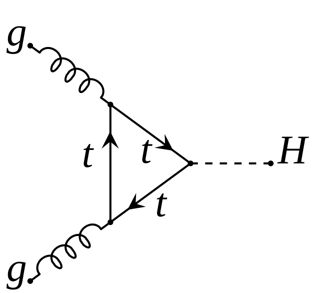
$$gg \to h^0 \,, \quad h^0 \to \gamma\gamma \,, VV^{(*)} \,,$$

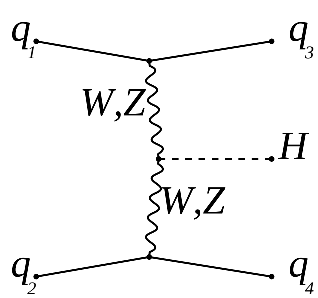
$$qq \to qqV^{(*)}V^{(*)} \to qqh^0, \quad h^0 \to \gamma\gamma, \tau^+\tau^-, VV^{(*)} \,,$$

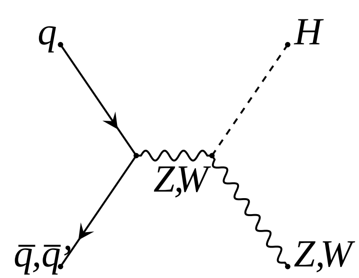
$$q\bar{q}^{(\prime)} \to V^{(*)} \to Vh^0 \,, \quad h^0 \to b\bar{b} \,, WW^{(*)} \,,$$

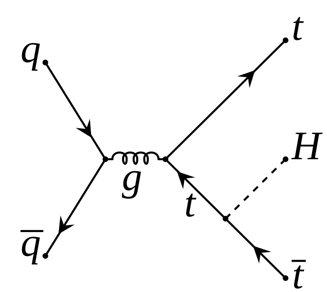
$$gg, q\bar{q} \to t\bar{t}h^0, \quad h^0 \to b\bar{b}, \gamma\gamma, WW^{(*)} \,.$$

where $V = W$ or Z.

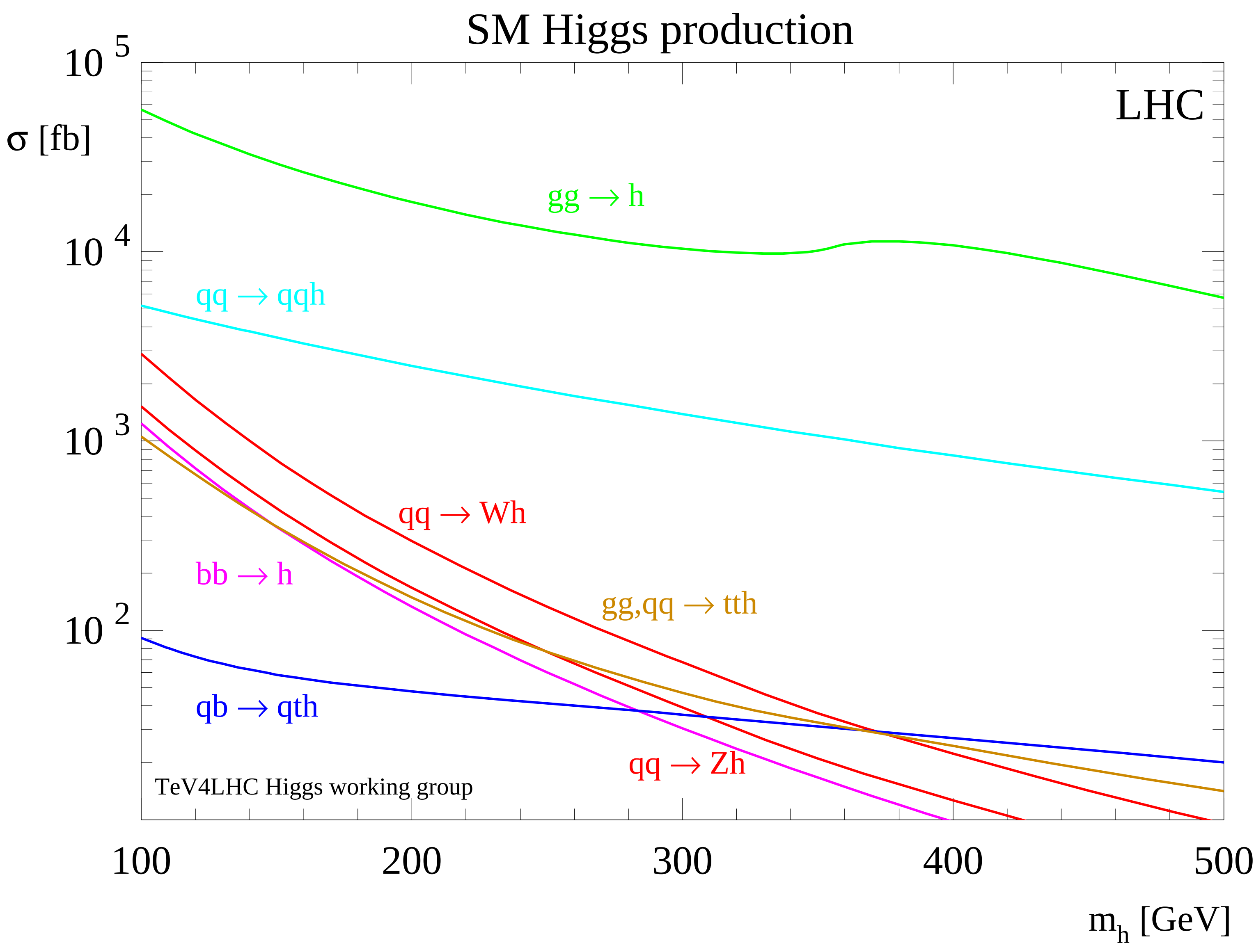




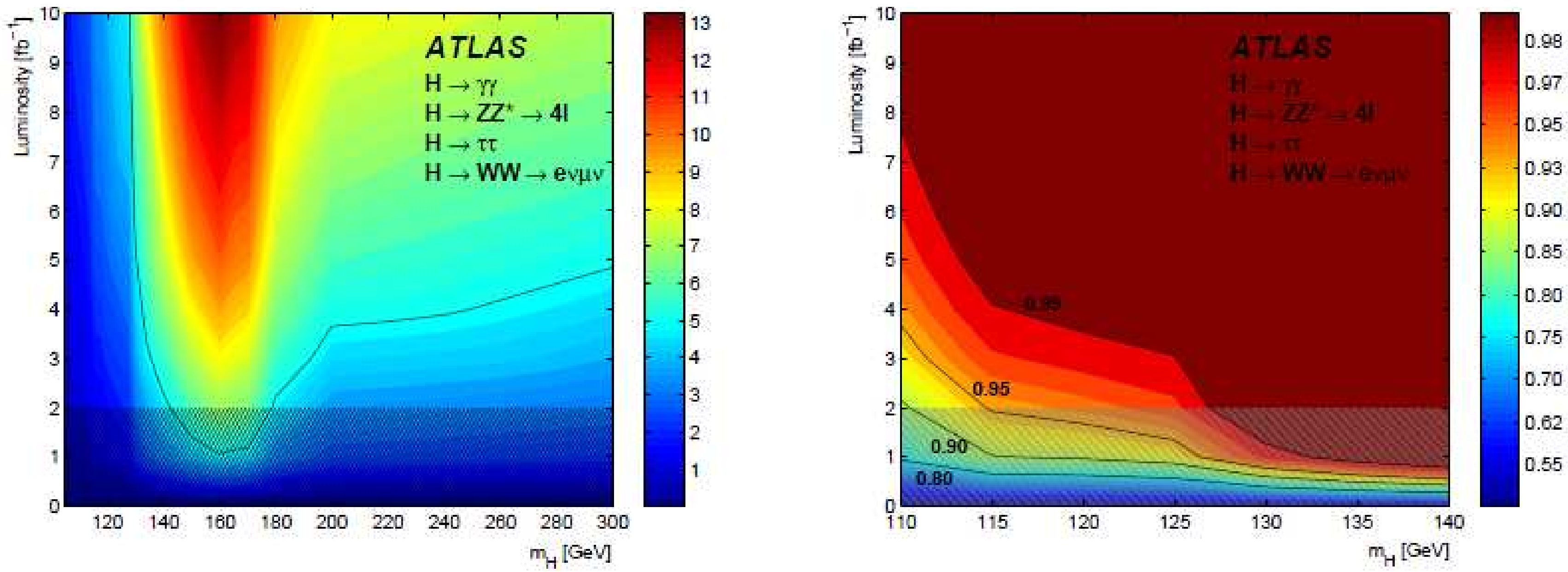




SM Higgs production cross-sections at the LHC

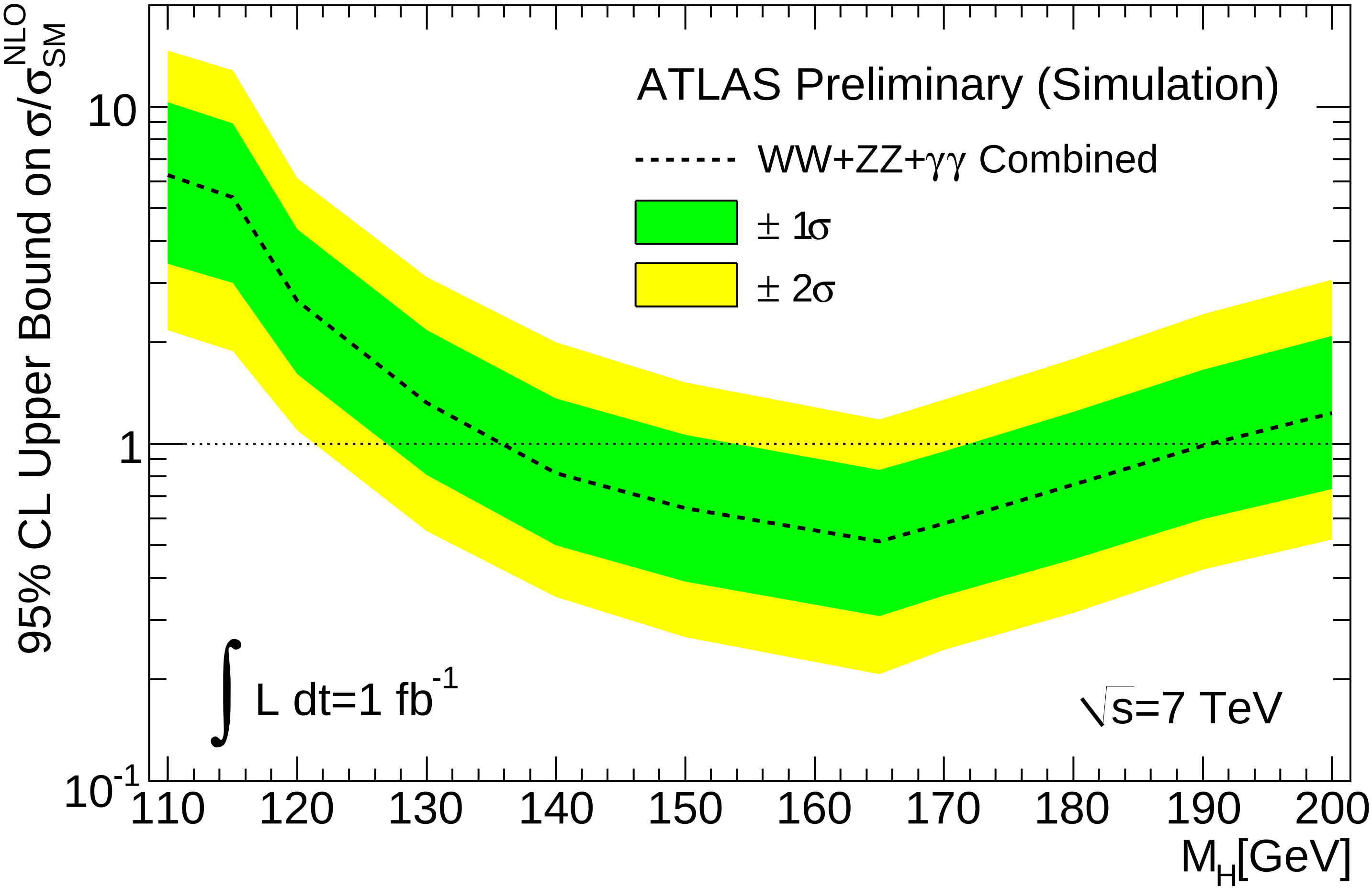


Discovery reach at the LHC



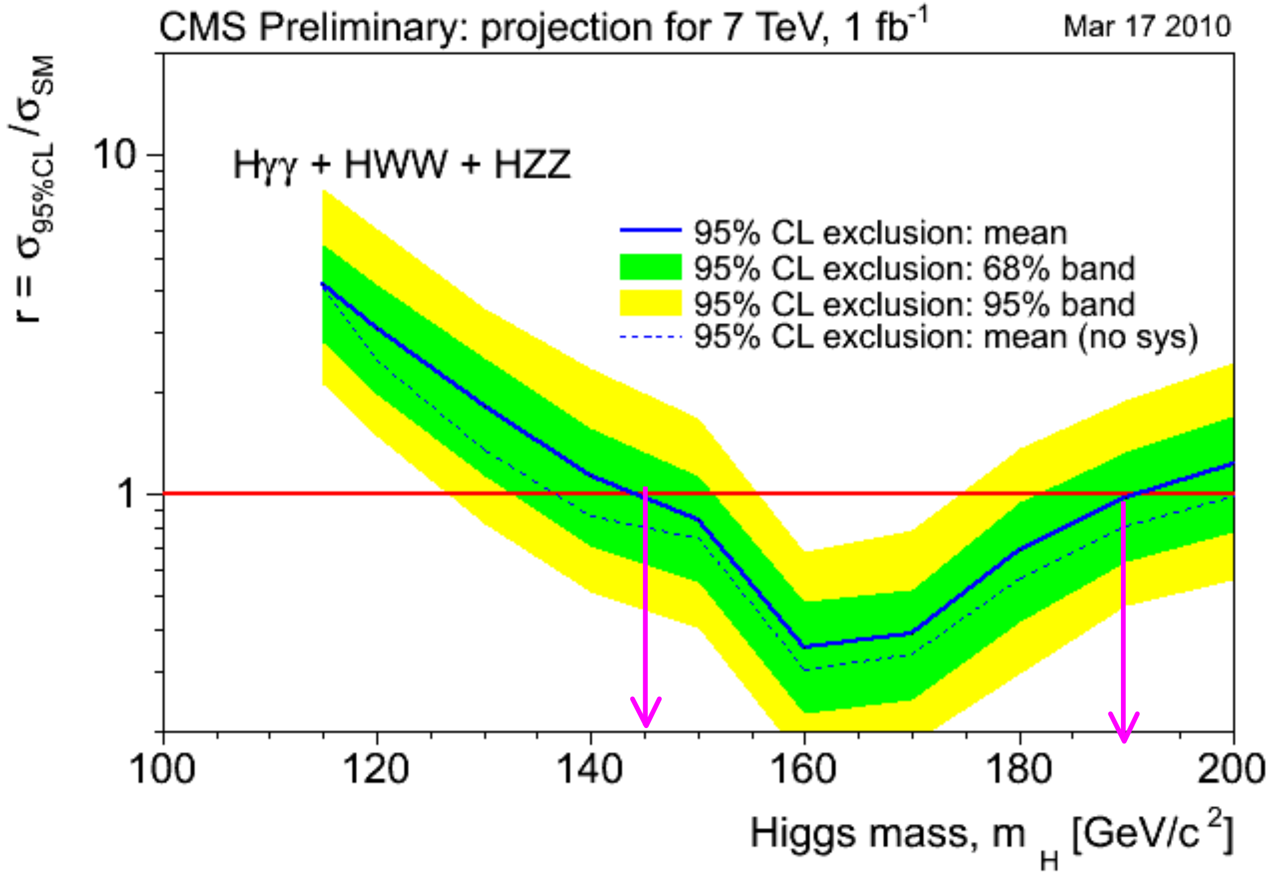
(a) (b)

Figure 11: (a) Significance contours for different Standard Model Higgs masses and integrated luminosities. The thick curve represents the 5σ discovery contour. The median significance is shown with a colour according to the legend. The hatched area below 2fb^{-1} indicates the region where the approximations used in the combination are not accurate, although they are expected to be conservative. (b) The expected luminosity required to exclude a Higgs boson with a mass m_H at a confidence level given by the corresponding colour. The hatched area below 2fb^{-1} indicates the region where the approximations used in the combination are not accurate, although they are expected to be conservative.



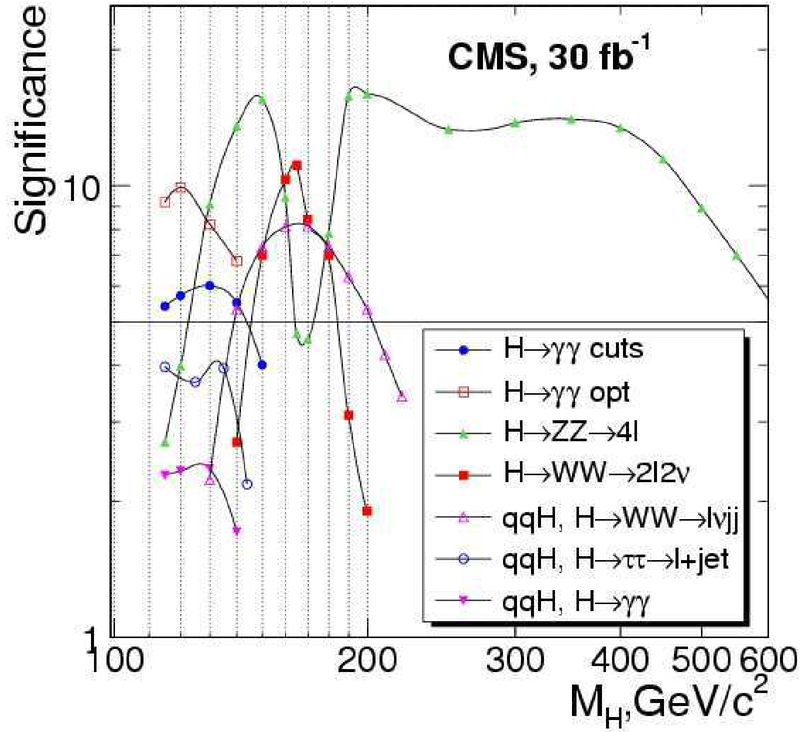
ATLAS Preliminary (Simulation)
WW+ZZ+γγ Combined
± 1σ
± 2σ
∫ L dt=1 fb^-1
√s=7 TeV
95% CL Upper Bound on σ/σ_SM^NLO
10
1
10^-1
110
120
130
140
150
160
170
180
190
200
M_H[GeV]

CMS: All Modes Combined

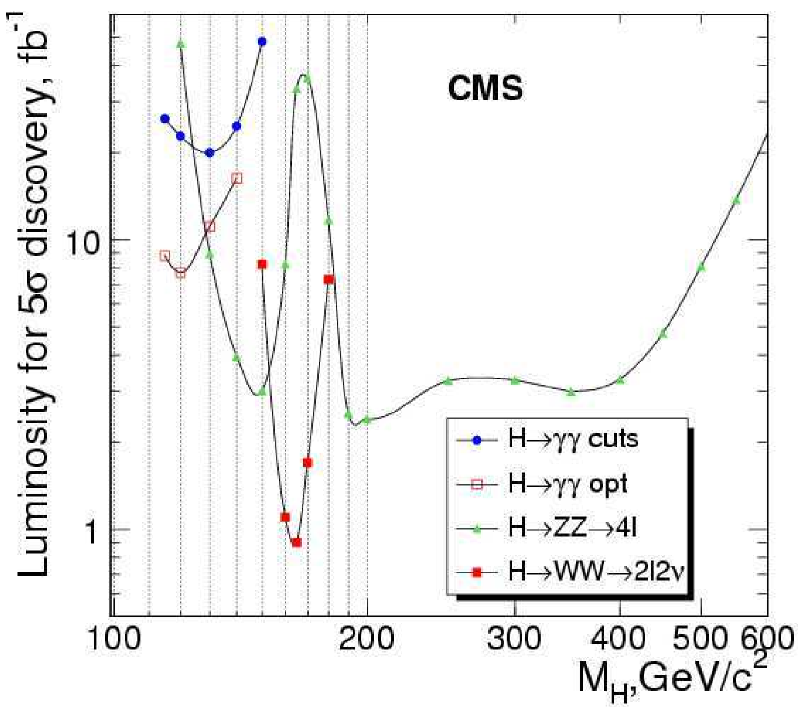


SM Higgs expected excluded range: **145-190 GeV**

SM Higgs with 4 fermion generations: **< ≈ 420 GeV**

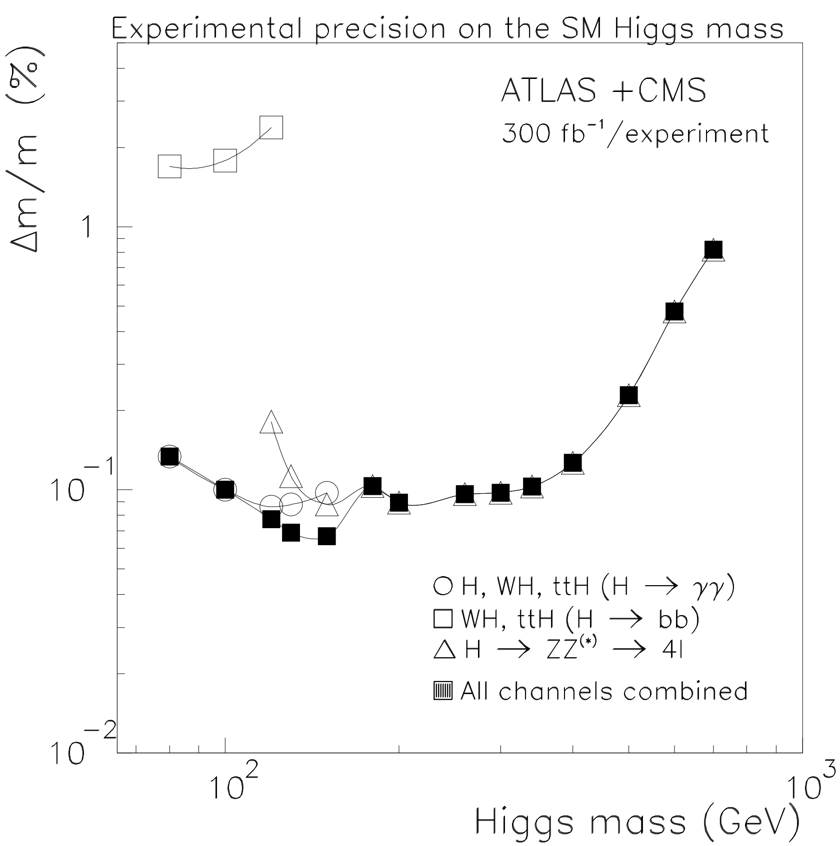


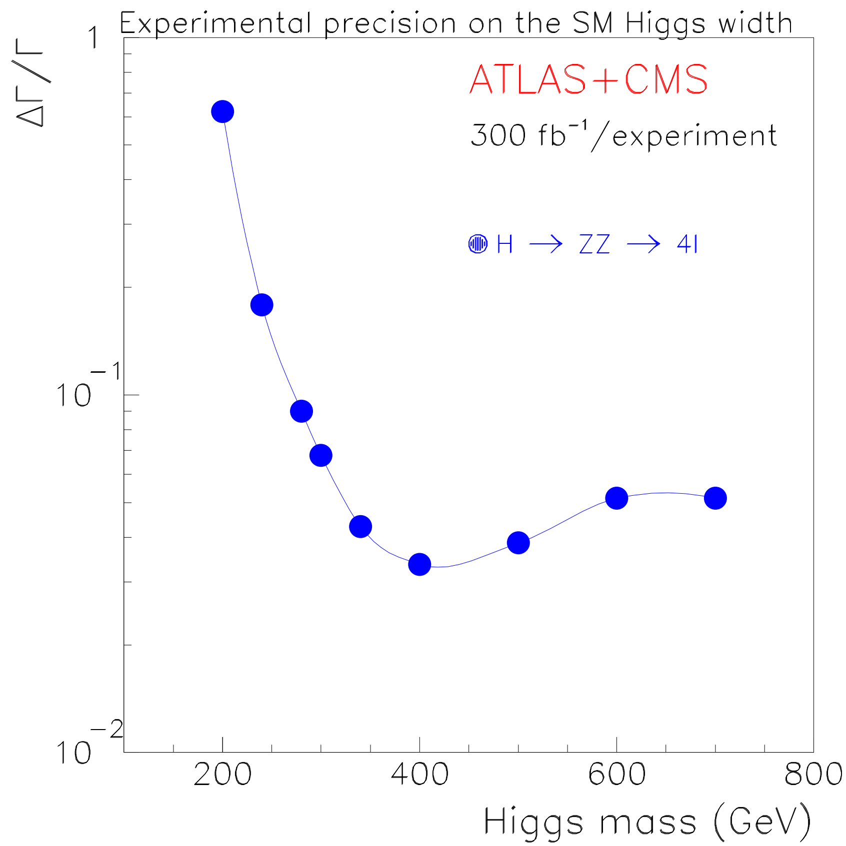
CMS, 30 fb^{-1}
Significance
H→γγ cuts
H→γγ opt
H→ZZ→4l
H→WW→2l2ν
qqH, H→WW→lνjj
qqH, H→ττ→l+jet
qqH, H→γγ
M_H,GeV/c^2



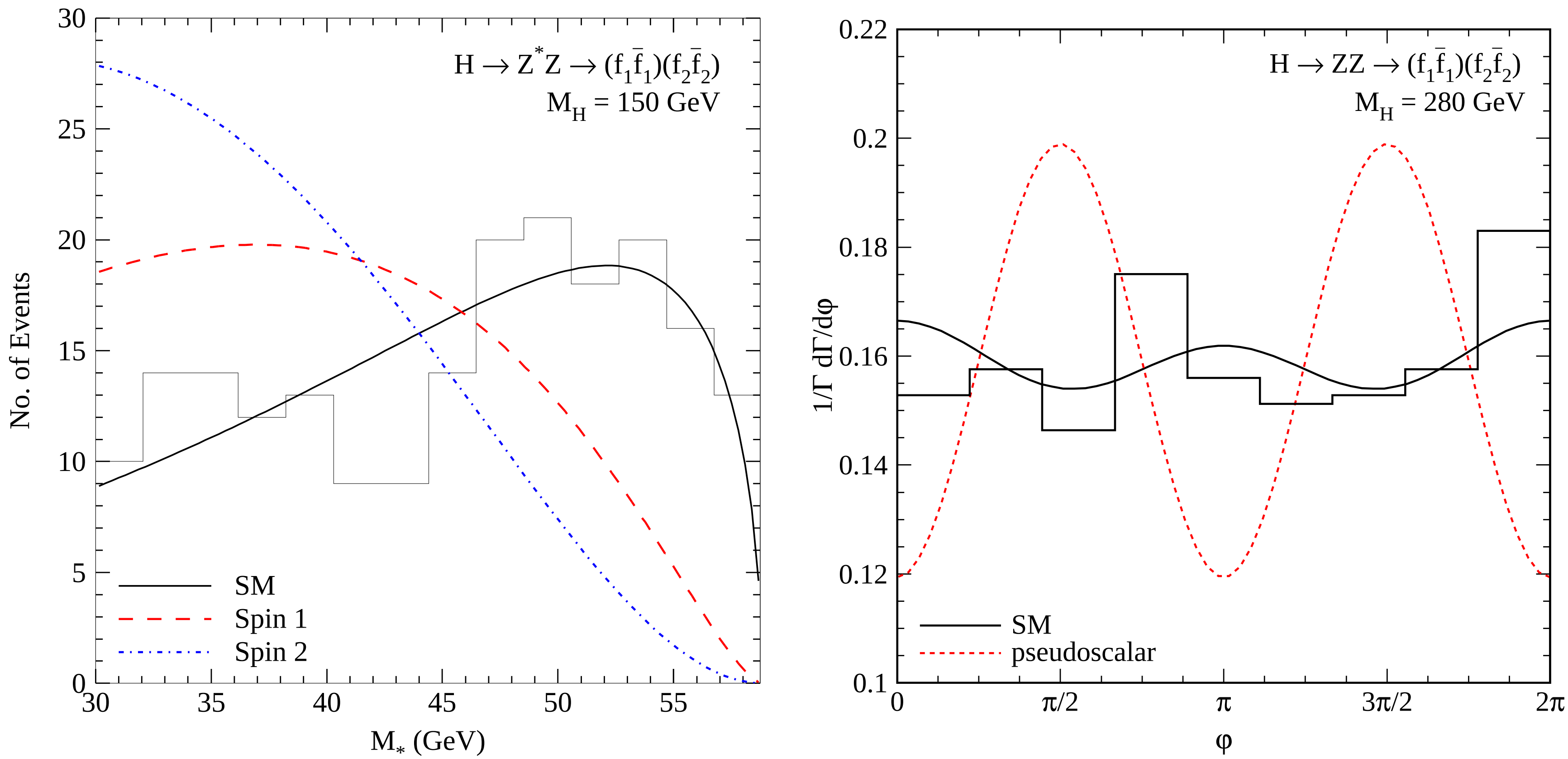
CMS
Luminosity for 5σ discovery, fb^{-1}
H→γγ cuts
H→γγ opt
H→ZZ→4l
H→WW→2l2ν
M_H,GeV/c^2

Higgs mass and width measurements at the LHC





Determination of the Higgs quantum numbers



Minimum number of observed events such that the median significance for rejecting $\mathbb{H}_0$ in favor of the hypothesis $\mathbb{H}_1$ (assuming $\mathbb{H}_1$ is right) exceeds $3\,\sigma$ and $5\,\sigma$, respectively, with m_H=145 GeV/c^2. Based on an analysis of the $H \to ZZ^*$ decay mode. Taken from A. De Rujula, J. Lykken, M. Pierini, C. Rogan and M. Spiropulu, arXiv:1001.5300 [hep-ph].

$\mathbb{H}_0 \Downarrow \mathbb{H}_1 \Rightarrow$	0^+	0^-	1^-	1^+
0^+	–	17	12	16
0^-	14	–	11	17
1^-	11	11	–	35
1^+	17	18	34	–

$\mathbb{H}_0 \Downarrow \mathbb{H}_1 \Rightarrow$	0^+	0^-	1^-	1^+
0^+	–	52	37	50
0^-	44	–	34	54
1^-	33	32	–	112
1^+	54	55	109	–

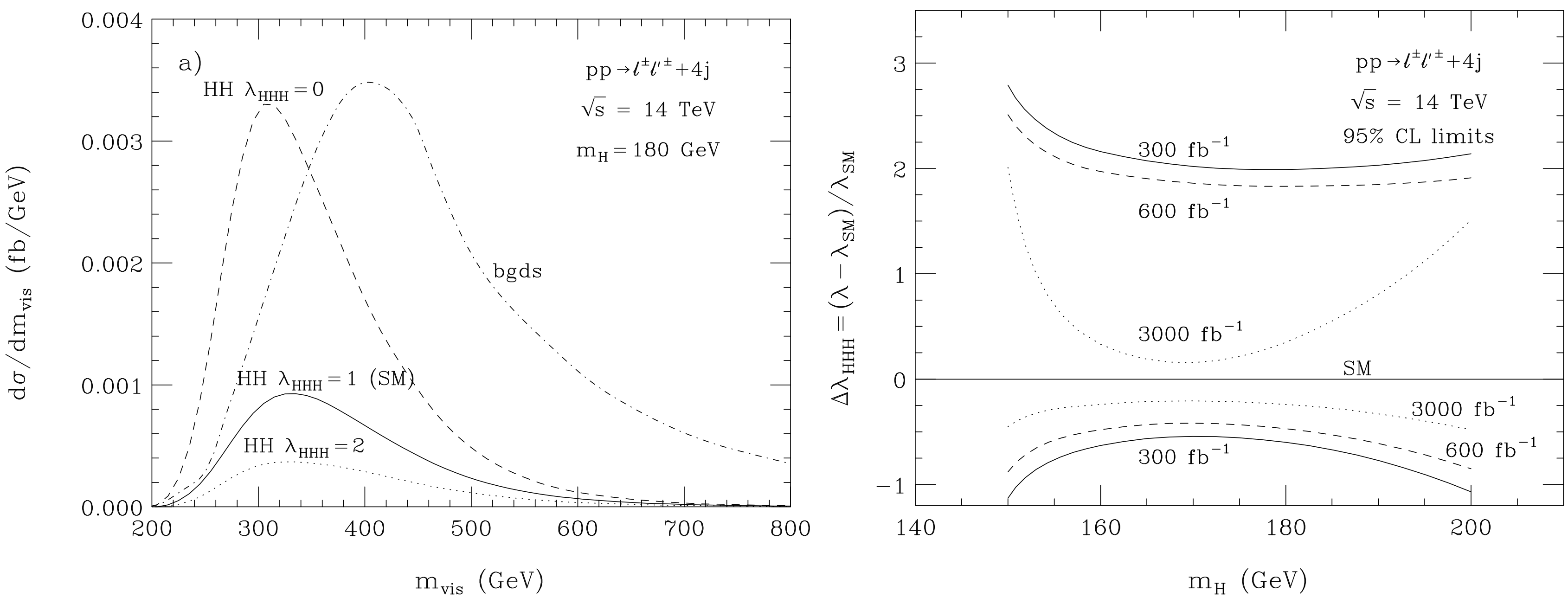
Higgs couplings

SFitter analysis [Dührssen, Lafaye, TP, Rauch, Zerwas]

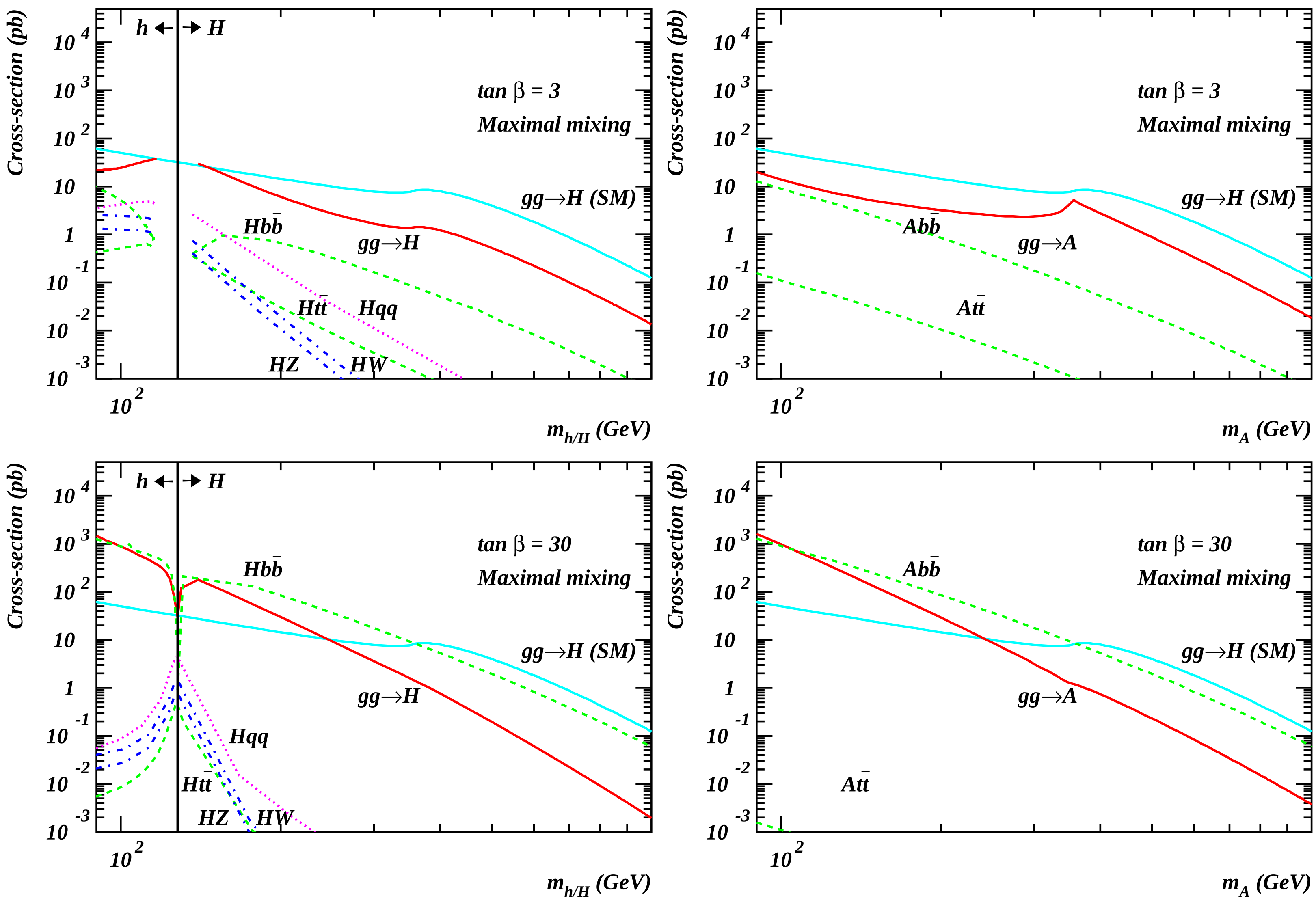
- all couplings varied around SM values $g_{HXX} = g_{HXX}^{\text{SM}} \, (1 + \delta_{HXX})$
  $\delta_{HXX} \sim -2$ means sign flip [$g_{HWW} > 0$ fixed]
- need assumption about loop-induced couplings $g_{ggH}, g_{\gamma\gamma H}$ [Ian's talk]
- likelihood map and local errors from SFitter
- experimental/theory errors on signal and backgrounds [do not ask theorists!]
- error bars for Standard Model hypothesis [smeared data point, 30fb^{-1}]

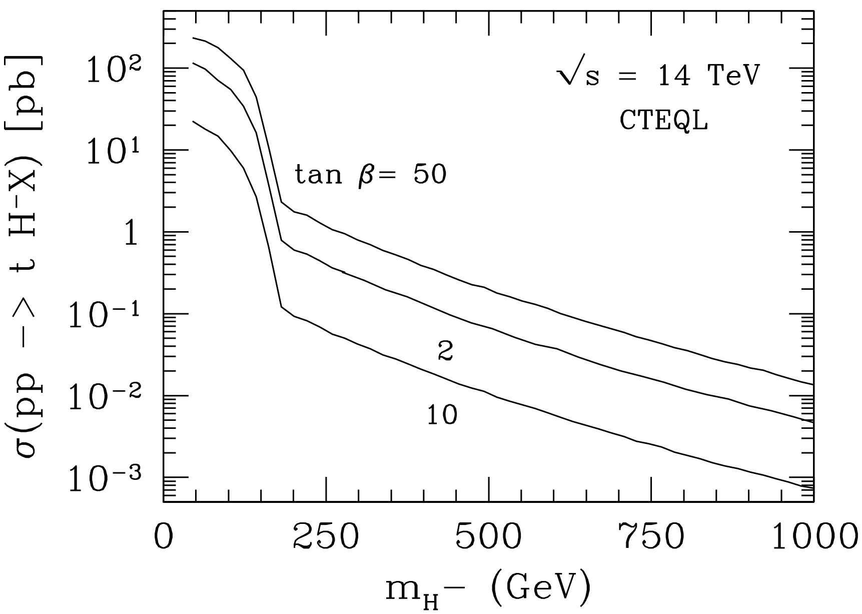
coupling	without eff. couplings			including eff. couplings		
	σ_{symm}	σ_{neg}	σ_{pos}	σ_{symm}	σ_{neg}	σ_{pos}
δ_{WWH}	± 0.23	-0.21	$+0.26$	± 0.24	-0.21	$+0.27$
δ_{ZZH}	± 0.50	-0.74	$+0.30$	± 0.44	-0.65	$+0.24$
$\delta_{t\bar{t}H}$	± 0.41	-0.37	$+0.45$	± 0.53	-0.65	$+0.43$
$\delta_{b\bar{b}H}$	± 0.45	-0.33	$+0.56$	± 0.44	-0.30	$+0.59$
$\delta_{\tau\bar{\tau}H}$	± 0.33	-0.21	$+0.46$	± 0.31	-0.19	$+0.46$
$\delta_{\gamma\gamma H}$	—	—	—	± 0.31	-0.30	$+0.33$
δ_{ggH}	—	—	—	± 0.61	-0.59	$+0.62$
m_H	± 0.26	-0.26	$+0.26$	± 0.25	-0.26	$+0.25$
m_b	± 0.071	-0.071	$+0.071$	± 0.071	-0.071	$+0.072$
m_t	± 1.00	-1.03	$+0.98$	± 0.99	-1.00	$+0.98$

The Higgs self-coupling at the LHC

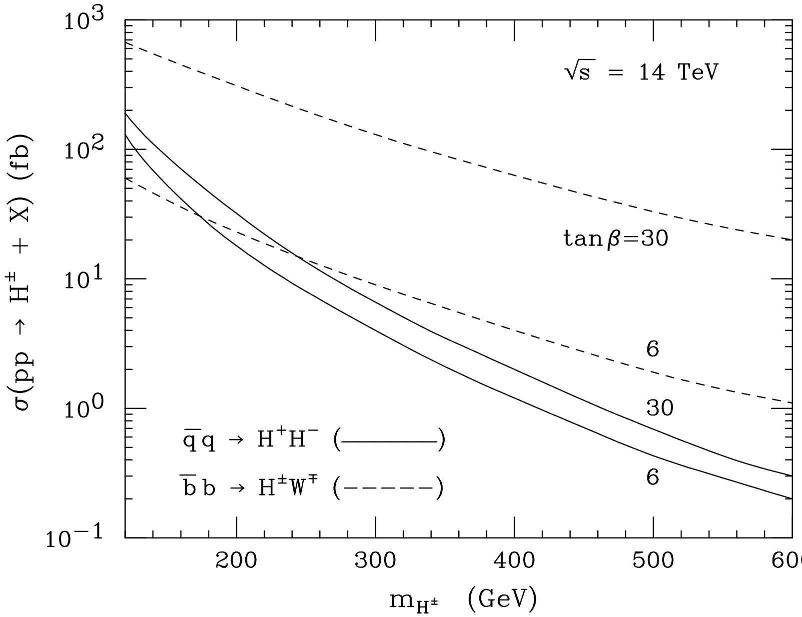


MSSM Higgs production cross-sections at the LHC





$\sqrt{s}$ = 14 TeV
CTEQL
tan β= 50
2
10
σ(pp -> t H-X) [pb]
$m_{H}-$ (GeV)



$\sqrt{s}$ = 14 TeV
tanβ=30
6
30
6
$\bar{q}q \to H^+H^-$ (———)
$\bar{b}b \to H^\pm W^\mp$ (- - - - -)
$\sigma(pp \to H^\pm + X)$ (fb)
$m_{H^\pm}$ (GeV)

MSSM Higgs Searches at the LHC

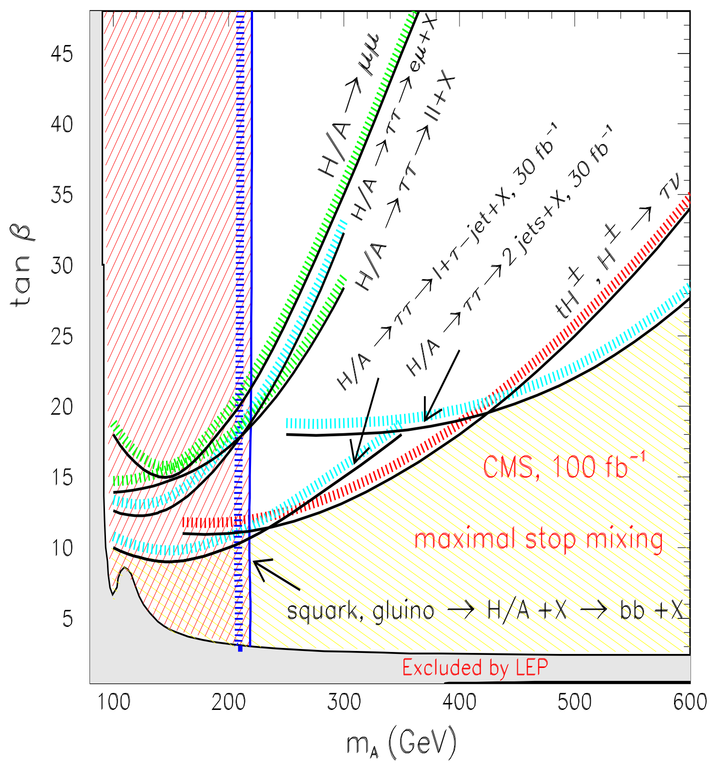
In addition to the standard SM-Higgs searches, new possibilities arise:

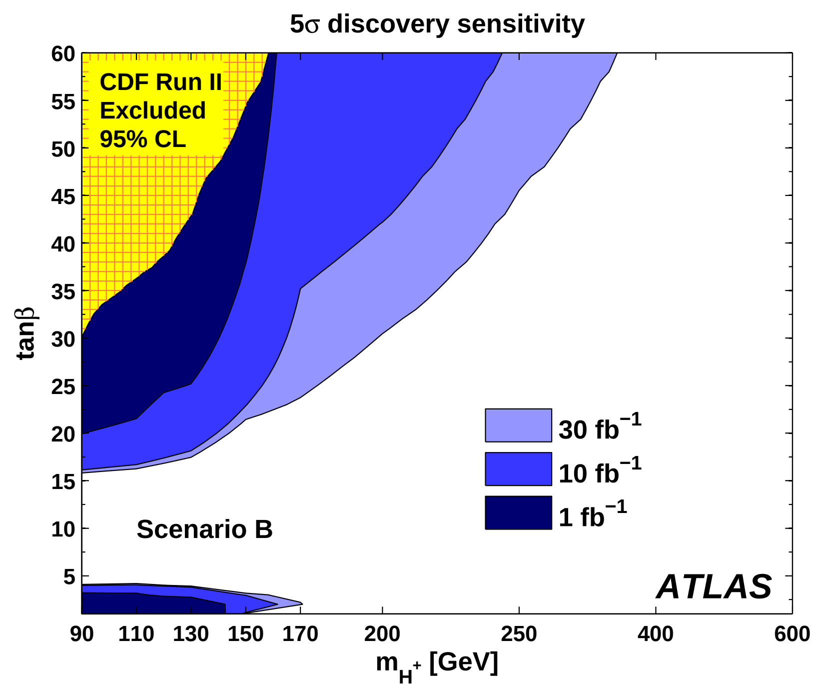
- gluon-gluon fusion can produce both CP-even and CP-odd Higgs bosons.
- VV fusion ($V = W$ or Z) can produce only CP-even Higgs bosons (at tree-level). Moreover, in the decoupling limit, the heavy CP-even Higgs boson is nearly decoupled from the VV channel.
- Neutral Higgs bosons can be produced in association with $b\bar{b}$ and with $t\bar{t}$ in gluon-gluon scattering.
- Charged Higgs bosons can be produced in association with $t\bar{b}$ in gluon-gluon scattering.
- If $m_{H^\pm} < m_t - m_b$, then $t \to bH^-$ is an allowed decay, and the dominant $H^\pm$ production mechanism is via $t\bar{t}$ production.

- Higgs bosons can be produced in pairs (e.g., H^+H^-, $H^\pm h^0$, h^0A^0).

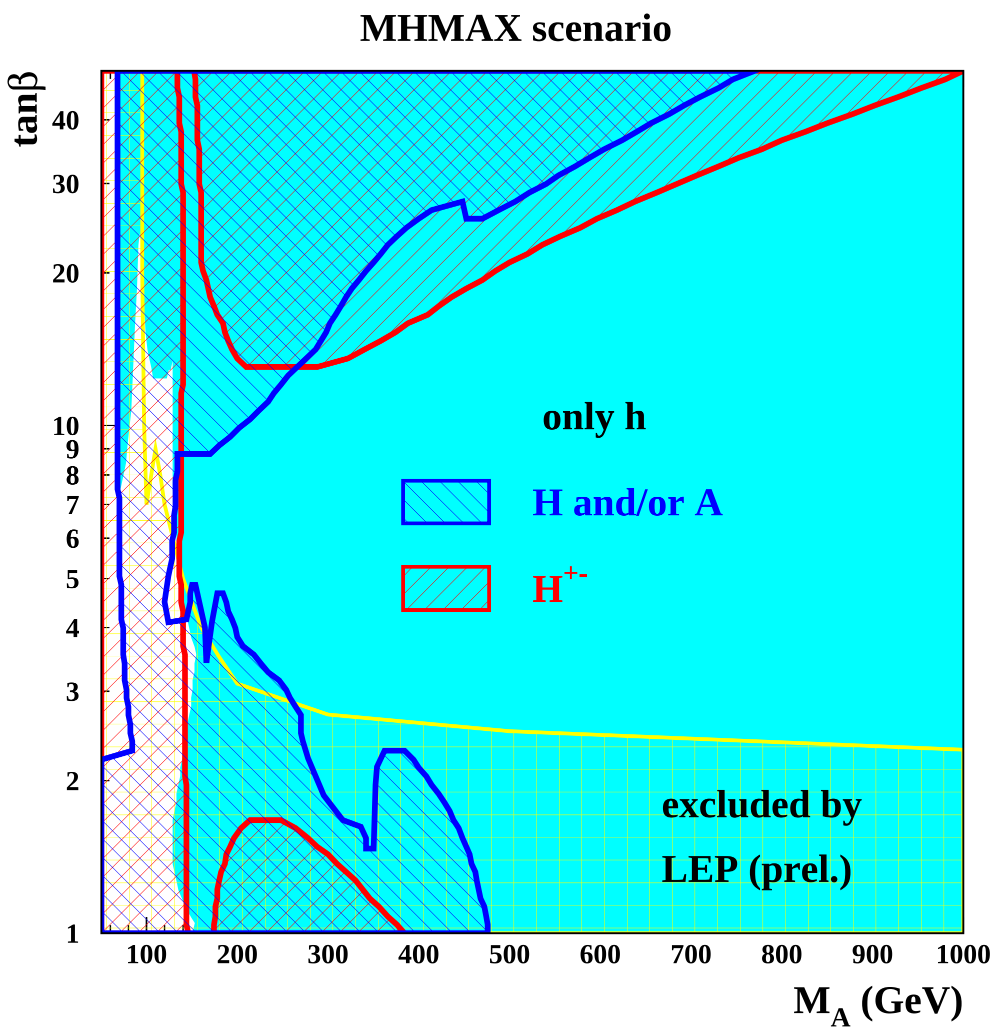
- Higgs bosons can be produced in cascade decays of SUSY particles.

- Higgs search strategies depend on the region of m_A–$\tan\beta$ plane





Discovery potential for one, two, three, ... many Higgs states at the LHC, assuming 300 fb^{-1} of data (M. Schumacher, arXiv:hep-ph/0410112):



... although there is a large region of MSSM parameter space (the "infamous LHC wedge") where only a SM-like Higgs boson can be discovered.

Conclusions

• The Standard Model is not yet complete. The nature of the dynamics responsible for EWSB (and generating the Goldstone bosons that provide the longitudinal components of the massive $W^{\pm}$ and Z bosons) remains unresolved.

• There are strong hints that a weakly-coupled elementary Higgs boson exists in nature (although loopholes still exist). If a weakly-coupled SM-like Higgs boson is not discovered at the LHC, then other new phenomena (that are responsible for "fixing up" the precision electroweak data) will be detected.

• Once (or if?) the Higgs boson is discovered, one must verify that its properties match expectations (a scalar state with couplings proportional to mass). Next, one must check whether its properties are consistent with SM Higgs predictions. Any departures from SM behavior will reveal crucial information about the nature of the EWSB dynamics.

• If TeV-scale supersymmetry is responsible for electroweak symmetry breaking, then the Higgs sector will be richer than in the SM. However, in certain regions of parameter space, the lightest Higgs boson will resemble the SM Higgs boson. It may be challenging to detect deviations from SM Higgs properties at the LHC or evidence for new scalar states beyond the SM-like Higgs boson.

• Ultimately, one must discover the TeV-scale dynamics associated with EWSB $e.g.$, low-energy supersymmetry and/or new particles and phenomena responsible for creating the Goldstone bosons. We expect the LHC to yield a very rich menu of new phenomena.

• Nature may still have some surprises up her sleeve. Even if no SM-like Higgs boson is found, it could happen that a weakly-coupled Higgs boson is present, albeit well hidden in the data. New techniques are being developed to address such cases.

• But what if there is only a SM Higgs boson and no evidence for new physics beyond the SM? . . .