Higgs Boson Physics

from discovery to identification

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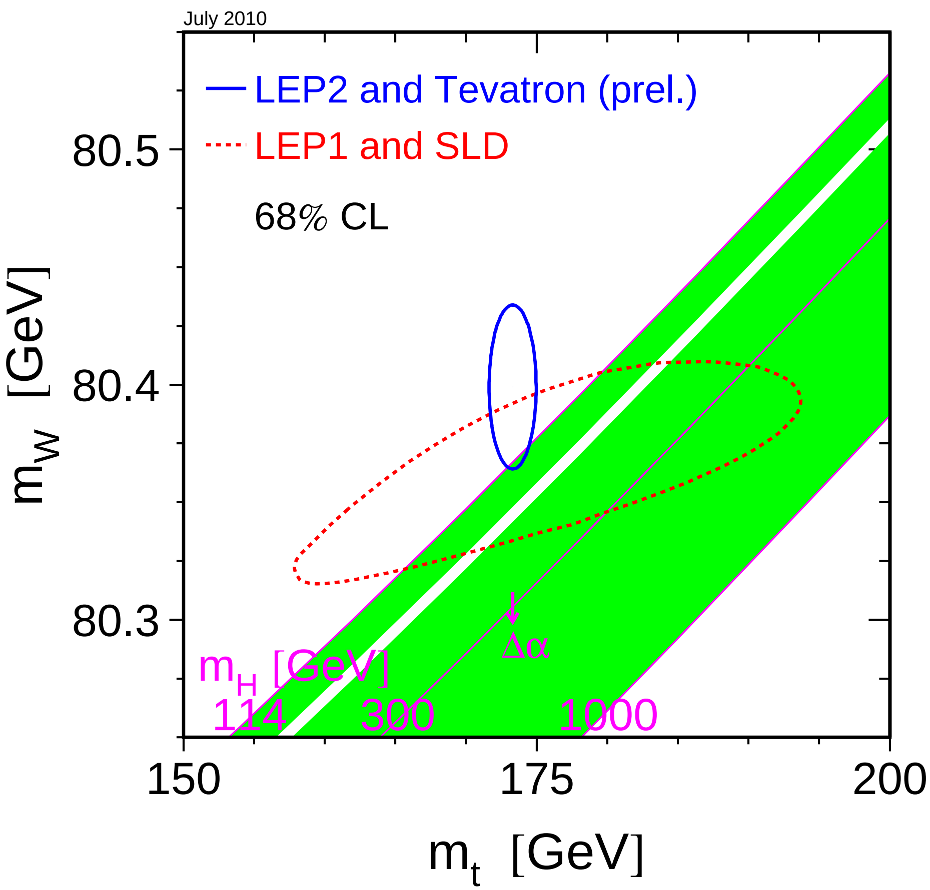
- Unveiling the origin of Electroweak Symmetry Breaking (EWSB): top priority of both the Tevatron and the LHC,
  - $\hookrightarrow$ Tevatron: can set exclusion limits;
  - $\hookrightarrow$ LHC: can discover related particles and their dynamics.

- Spectrum of ideas to explain EWSB: based on weakly or strongly coupled dynamics embedded into some more fundamental theory at a scale Λ ($\simeq$ TeV):
  - $\rightarrow$ Elementary Higgs: SM, 2HDM, SUSY (MSSM, NMSSM,...), ...
  - $\rightarrow$ Composite Higgs: technicolor, little Higgs models, ...
  - $\rightarrow$ Extra Dimensions: flat,warped, ...
  - $\rightarrow$ Higgsless models
  - $\rightarrow$ ...

- SM Higgs boson, has been and will be our learning ground:
  - $\mathcal{L}^{SM}_{Higgs} = (D^\mu\phi)^\dagger D_\mu\phi - \mu^2\phi^\dagger\phi - \lambda(\phi^\dagger\phi)^2 \;\; (\mu^2 < 0)$;
  - scalar particle, neutral, CP even, $m_H^2 = -2\mu^2 = 2\lambda v^2$;
  - minimally coupled to gauge bosons $\longrightarrow M_W = g\frac{v}{2}$, $M_Z = \sqrt{g^2 + g'^2}\frac{v}{2}$;
  - coupled to fermions via Yukawa interactions $\longrightarrow m_f = y_f\frac{v}{2}$;
  - $\hookrightarrow$ mass constrained by EW precision fits.

SM Higgs-boson mass range: constrained by EW precision fits

Increasing precision will continue to provide an invaluable tool to test the consistency of the SM and its extensions.



$$m_W = 80.399 \pm 0.023 \text{ GeV}$$

$$m_t = 173.3 \pm 1.1 \text{ GeV}$$

$$\Downarrow$$

$$M_H = 89^{+35}_{-26} \text{ GeV}$$

$$M_H < 158\,(185) \text{ GeV}$$

plus exclusion limits (95% c.l.):

$$M_H > 114.4 \text{ GeV (LEP)}$$

$$M_H \neq 158 - 173 \text{ GeV (Tevatron)}$$

focus is now on exclusion limits and discovery!

- New Precision Program: for signal and background processes in Higgs-boson production at hadron colliders, (... so many people ...)
  - ▷ theoretical predictions: stability and control of the systematic errors (including available higher orders of QCD and EW corrections);
  - ▷ theoretical predictions: test validity of existing results in different regimes and under different exclusive cuts;
  - ▷ enforce standards in multi-process studies/analyses (e.g.: combining different production channels, comparing signal and background, etc.);
  - ▷ make experimental selection process more transparent.

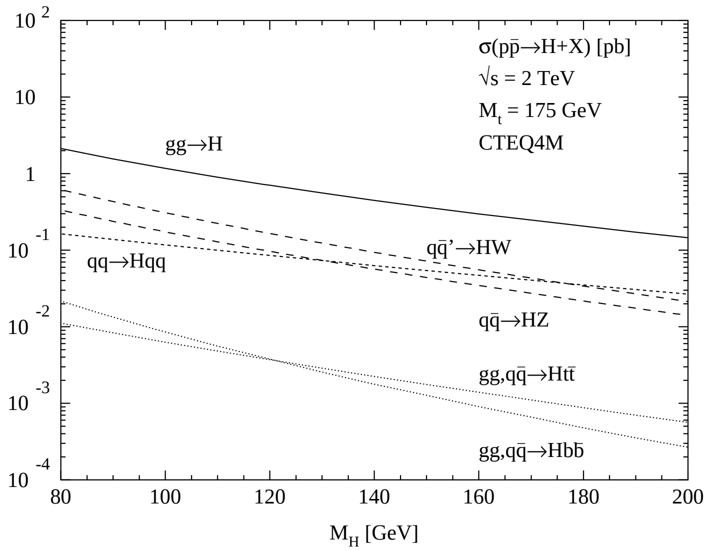
- Explore new techniques and new ideas to fully exploit the discovery potential,
  - ▷ boosted regimes (used for WH/ZH, and $t\bar{t}H$);
  - ▷ jet substructure (used for WH/ZH, and $t\bar{t}H$);

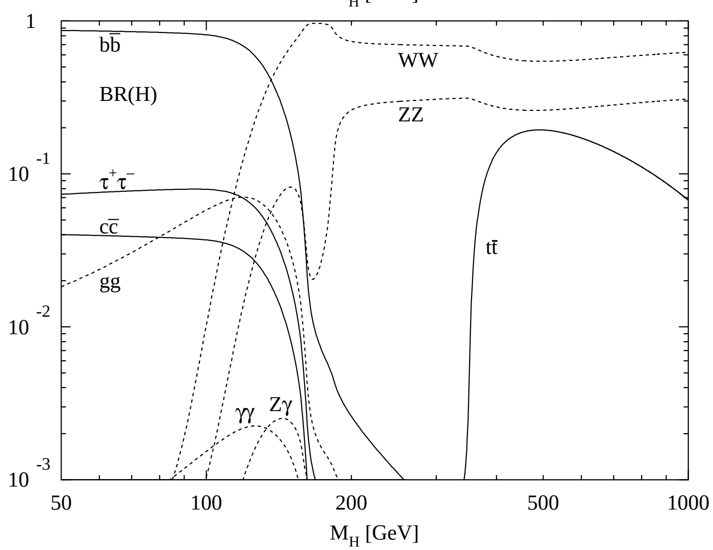
    (Butterworth, Davison, Rubin, Salam, arXiv:0802.2470),

    (Piacquadio,CERN-THESIS-2010-027, 2010),

    (Plehn, Salam, Spannowski, arXiv:0802.2470)
  - ▷ new variables (lower theoretical uncertainty, ...).

Tevatron: great potential for a light SM-like Higgs boson





(M. Spira, Fortsch.Phys. 46 (1998) 203)

Lower mass region:

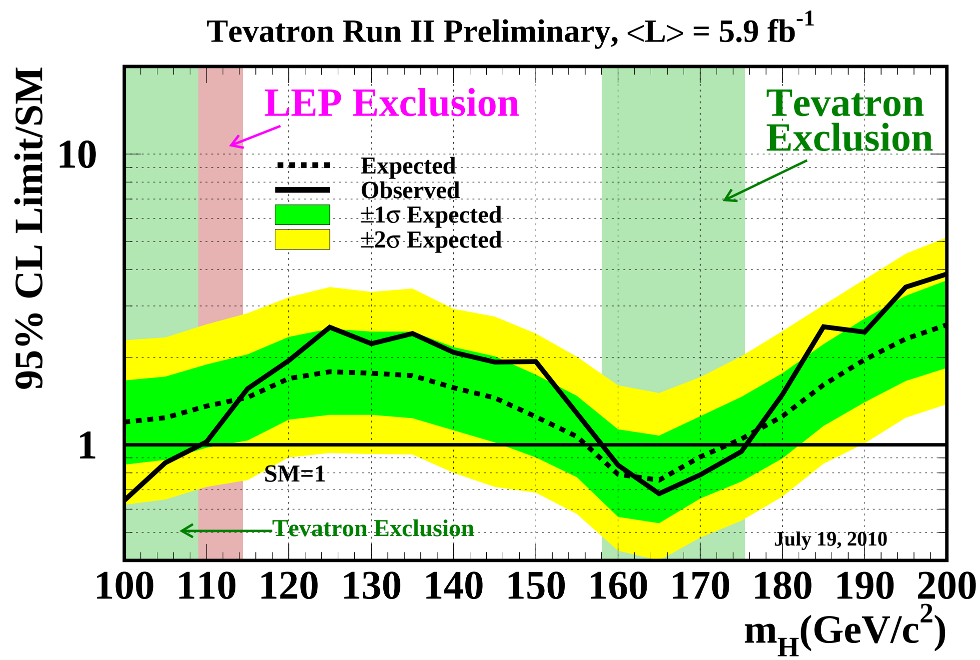
$$q\bar{q}' \to WH, H \to b\bar{b}$$

Higher mass region:

$$gg \to H, H \to W^+W^-$$

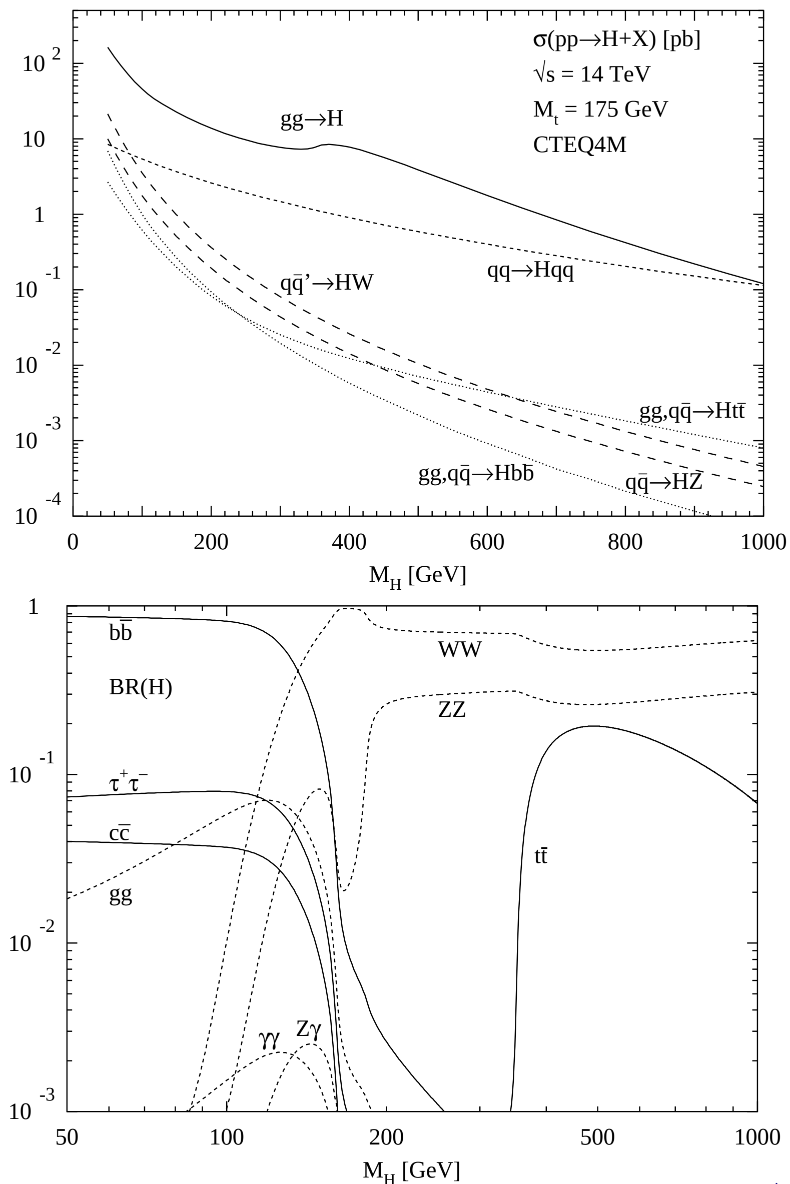
(smaller impact:

$q\bar{q} \to q'\bar{q}'H$, $q\bar{q}, gg \to t\bar{t}H$)



↪ Exclusion region very important for LHC search strategies.

LHC: entire SM Higgs-boson mass range accessible



(M. Spira, Fortsch.Phys. 46 (1998) 203)

Many channels have been studied:

Below 130-140 GeV:

$gg \to H\ ,\ H \to \gamma\gamma, WW, ZZ$

$qq \to qqH\ ,\ H \to \gamma\gamma, WW, ZZ, \tau\tau$

$q\bar{q}, gg \to t\bar{t}H\ ,\ H \to \gamma\gamma, b\bar{b}, \tau\tau$

$q\bar{q}' \to WH\ ,\ H \to \gamma\gamma, b\bar{b}$

Above 130-140 GeV:

$gg \to H\ ,\ H \to WW, ZZ$

$qq \to qqH\ ,\ H \to \gamma\gamma, WW, ZZ$

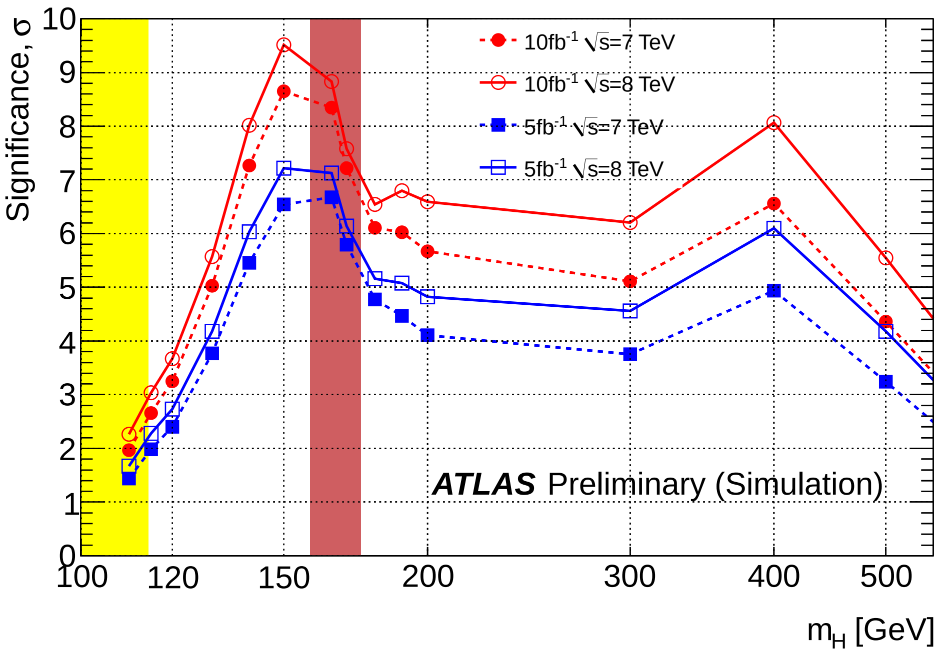
$q\bar{q}, gg \to t\bar{t}H\ ,\ H \to \gamma\gamma, WW$

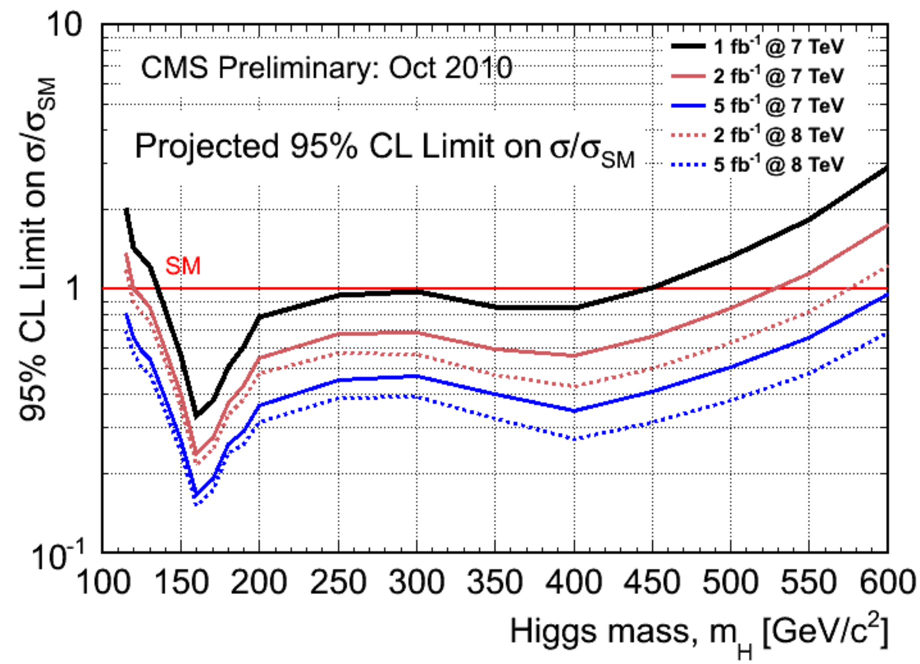
$q\bar{q}' \to WH\ ,\ H \to WW$

With $\sqrt{s} = 7$ TeV and a few fb^{-1} ...

Combining only $H \to W^+W^-$, $H \to ZZ$, $H \to \gamma\gamma$, ATLAS and CMS indicate that,

- if no signal, the SM Higgs can be excluded up to 500 GeV;
- a 5σ significance for a SM Higgs in the 140 – 170 GeV mass range;
- in the low mass region ($\longleftrightarrow$ new strategies, new ideas).





where also WH, $H \to b\bar{b}$ (highly boosted) and VBF with $H \to \tau\tau$ were used.

Crucial to have access to the best theoretical predictions for Higgs-boson cross sections and branching ratios.

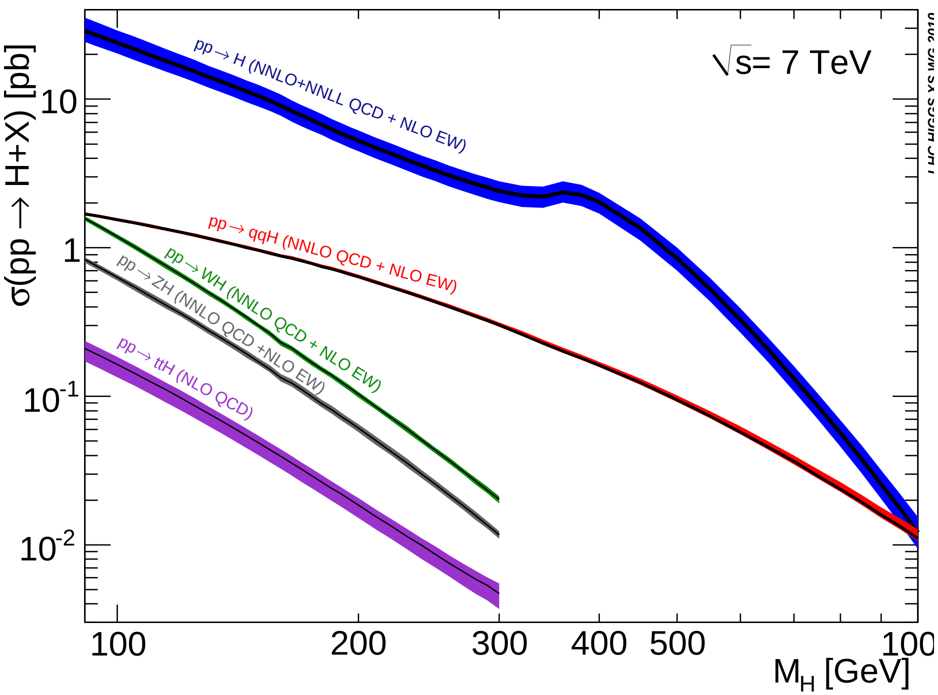
⇓

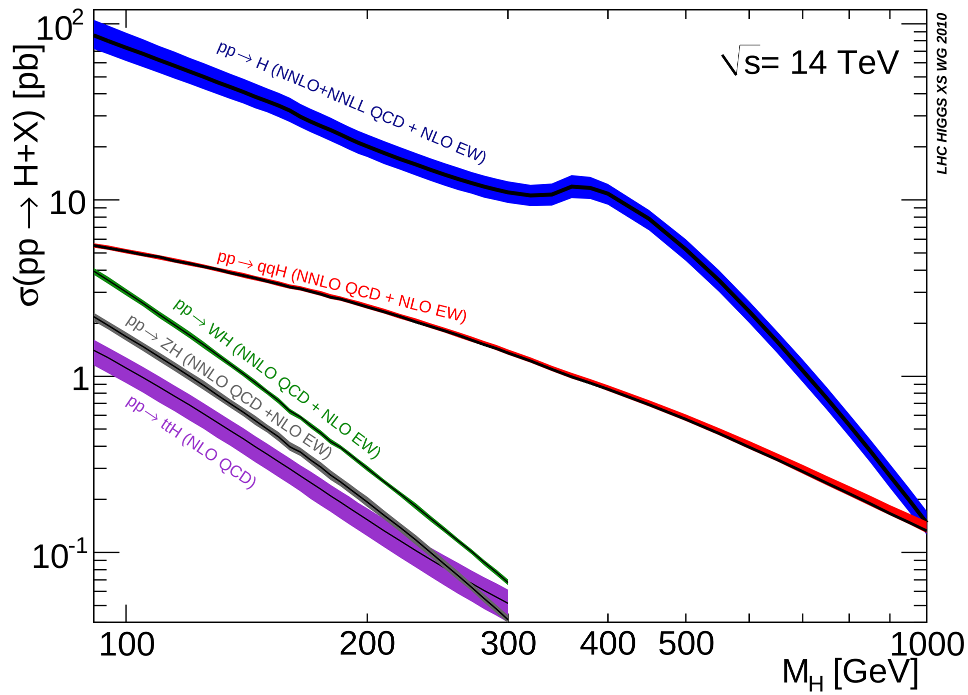
The LHC Higgs Cross Sections Working Group

(https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections)

Two stages:

- inclusive observables (studies done in 2010) (arXiv:1101.0593→ Yellow Book);
- exclusive observables (studies started in 2011).





Several subgroups:

- 4 SM production modes + 2 MSSM subgroups;
- branching ratios;
- PDF;
- NLO Monte Carlo;
- Higgs pseudo-observables;
- across channel studies: (Ex.: $H \to b\bar{b}$).

Goals:

- implementing a coherent Higgs precision program;
  - ↪ all orders of calculated higher orders corrections included (tested with all existing calculations);
  - ↪ common recipe for renormalization+factorization scale dependence;
  - ↪ PDF and α_s errors following PDF4LHC prescription;
  - ↪ all other parametric errors included;
  - ↪ theory errors combined according to common recipe.
- provide working tools to the experiments in a timely fashion.

Started Exclusive Studies:

- include decays in final state (with the least approximation);
- calculate signal and background consistently.

For as natural as this scenario may be . . . it is pretty ambitious!

A sound Higgs physics program should be preapared to focus on

- ▷ measuring mass (first crucial discriminator!) (LHC, LC);
- ▷ measuring couplings to gauge bosons and fermions (LHC, LC);
- ▷ measuring spin (LHC, LC);
- ▷ test the potential: measure self couplings (LC).

Moreover:

A light SM-like Higgs boson is consistent with new physics at $\Lambda \simeq$ TeV:
$\hookrightarrow$ new physics should be discovered at the LHC

and we will need to

- ▷ verify consistency with EW precision measurements (LHC, LC);
- ▷ measure masses/couplings of new degrees of freedom (LHC, LC).

Will the LHC be able to discriminate between different scenarios?

Experimental uncertainties, estimate

	Present	Tevatron/LHC	ILC	GigaZ
$\delta(M_W)$(MeV)	23	15	10	7
$\delta(m_t)$ (GeV)	1.1	1.0	0.2	0.1
$\delta(M_H)/M_H$ (indirect)	30%	20%	15%	8%
$\delta(M_H)/M_H$ (direct)		0.1-1%	0.04-0.01%	$< 0.01\%$

Intrinsic theoretical uncertainties

$\longrightarrow$ $\delta M_W \approx 4$ MeV: full $O(\alpha^2)$ corrections computed.

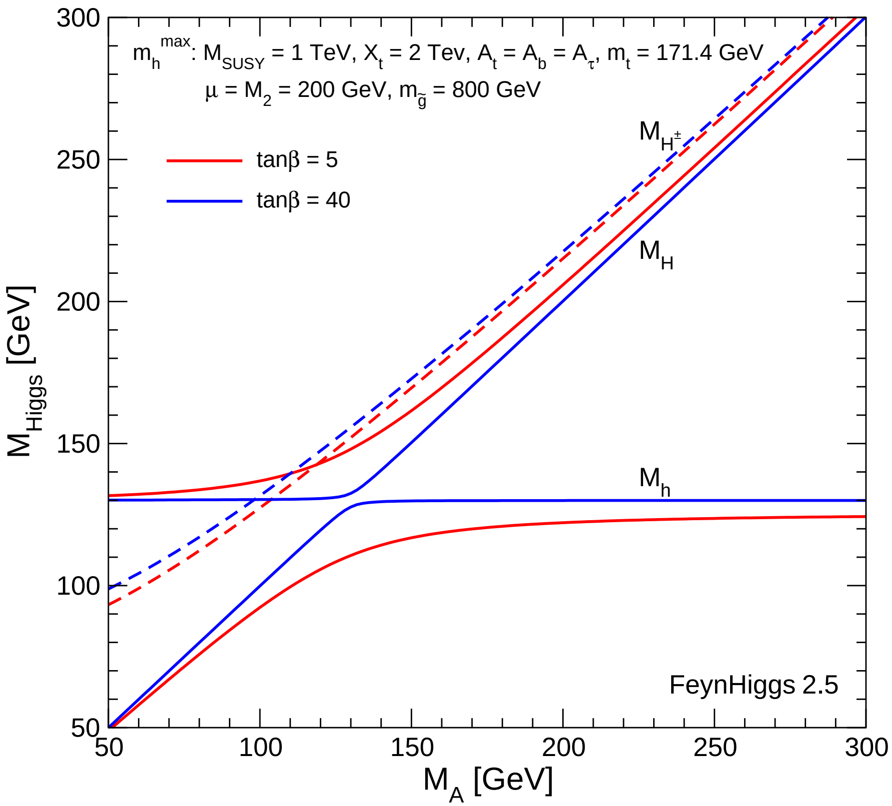
(M. Awramik, M. Czakon, A. Freitas, and G. Weiglein, PRD 69:053006,2004)

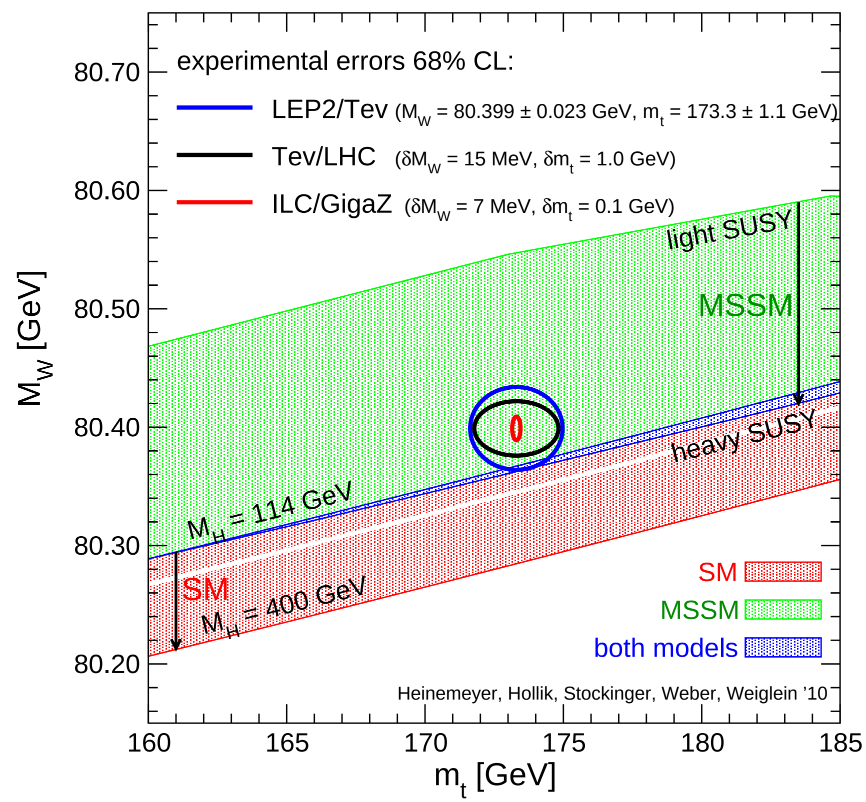
$\longrightarrow$ estimated: $\Delta m_t/m_t \sim 0.2 \Delta\sigma/\sigma + 0.03$ (LHC)

(R. Frederix and F. Maltoni, JHEP 0901:047,2009)

LC/GigaZ precisions will distinguish between different models with no ambiguities and theory accuracy can match that.

Beyond SM: example of new physics at the TeV scale

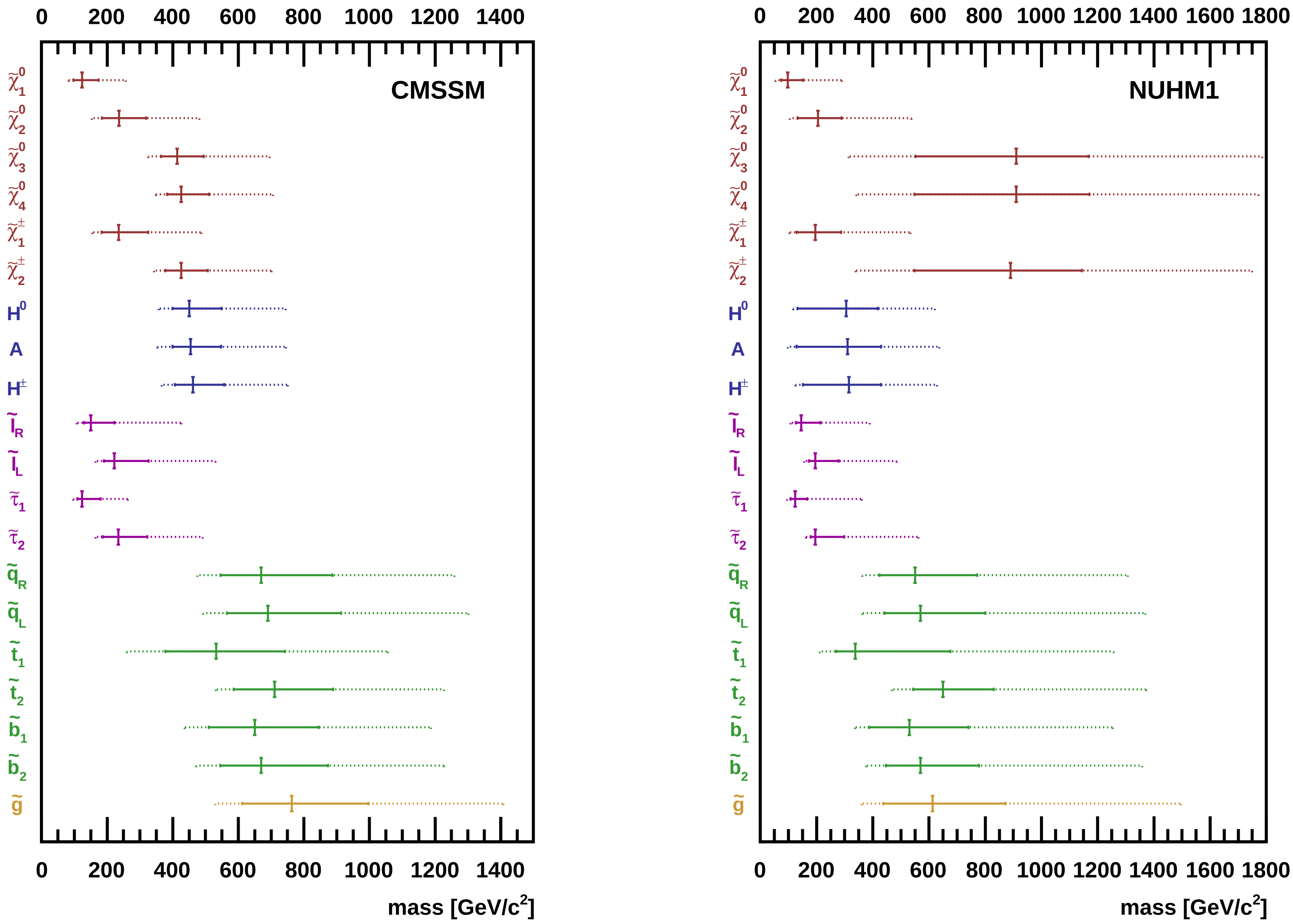




- ▷ a light scalar Higgs boson, along with a heavier scalar, a pseudoscalar and a charged scalar;
- ▷ similar although less constrained pattern in any 2HDM;
- ▷ MSSM main uncertainty: unknown masses of SUSY particles.
- ▷ precise measurement of mass spectrum and couplings will be crucial.

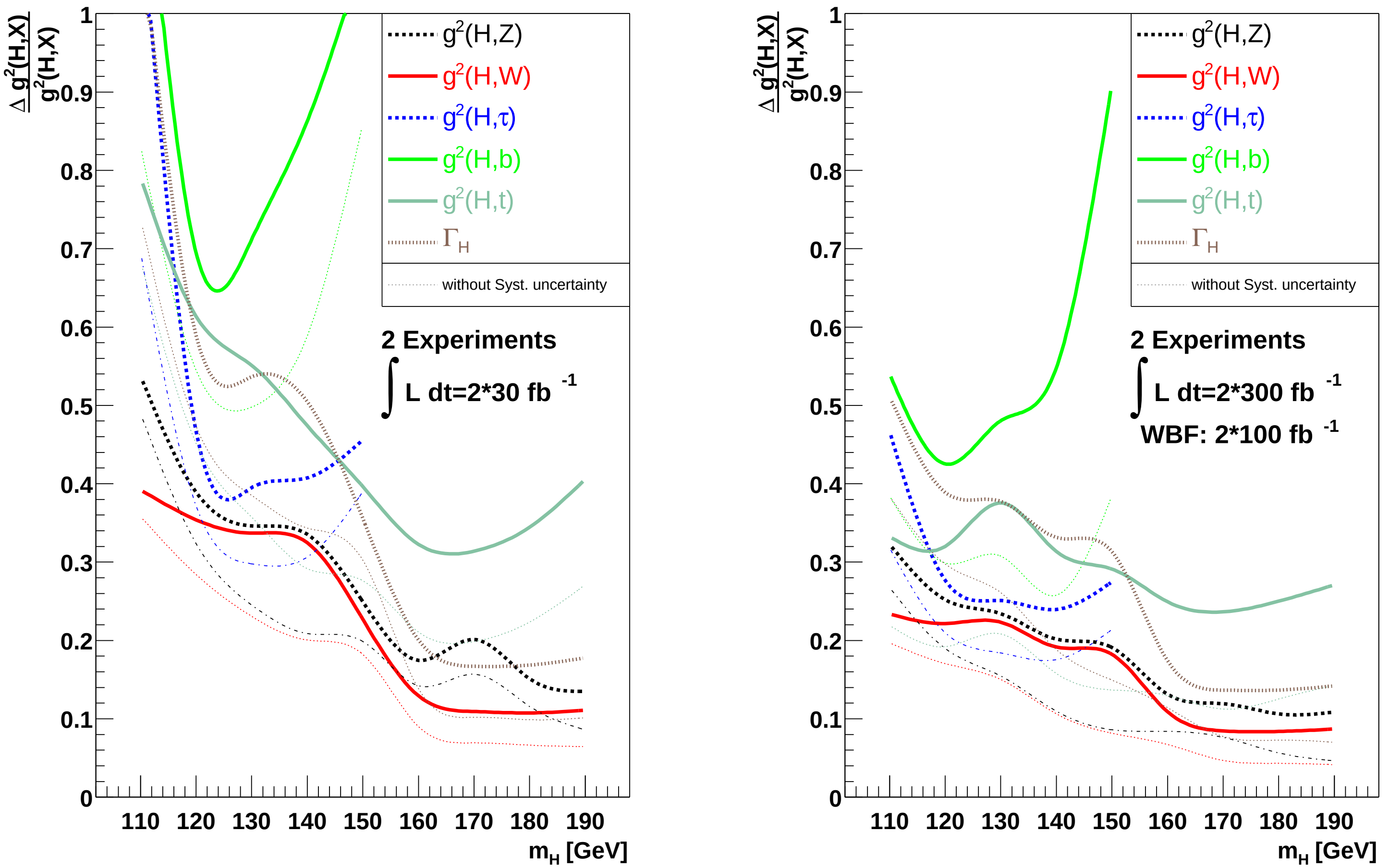
... mass spectrum at a glance ...

(MasterCode by Buchmüller et al., ’09)



- ▷ CMSSM/NUHM1 (different choice of soft SUSY breaking mass terms);
- ▷ all available data (exp.) and all known corrections (th.) included in fit;
- ▷ most masses accessible to early LHC, several within reach of ILC.

LHC: measure couplings, but model dependent



(M. Dührssen et al., '04)

- ▷ Most coupling within 10-40% at high luminosity (for light M_H);
- ▷ notice the impact of systematic uncertainties;
- ▷ of course, adding assumptions considerably lower the errors.

$\longrightarrow$ New study by Lafaye, Plehn, Rauch, Zerwas, and Dührssen ('09)

ILC Precision Program: towards ultimate precision.

- Higgs boson mass within $\delta M_H = 50$ MeV;
- Model independent determination of Higgs boson couplings
- All Higgs boson couplings known within few percents (but top Yukawa coupling!)
- Measure 3H coupling with high luminosity (ab^{-1}): first direct test of Higgs boson potential, impossible at the LHC.

Ex.: SM Higgs boson, $\sqrt{s}=500$ GeV, 500 fb^{-1} (Except HHH, 1 ab^{-1})

Coupling:	$Hb\bar{b}$	$H\tau^+\tau^-$	$Hc\bar{c}$	HWW	HZZ	$Ht\bar{t}$	HHH
($M_H=120$ GeV)	2.2%	3.3%	3.7%	1.2%	1.2%	3%	22%
($M_H=140$ GeV)	2.2%	4.8%	10%	2.0%	1.3%	6%	30%
Theory	1.4%	2.3%	23%	2.3%	2.3%	5%	

(Djouadi, '05, using HFITTER/HDECAY)

- Higgs boson quantum numbers and spin.

- Studies of couplings have evolved to open much more sofisticated possibilities: (see parallel talks at IWLC2010 and ALCPG11)

  ↪ precision on couplings at different M_H;

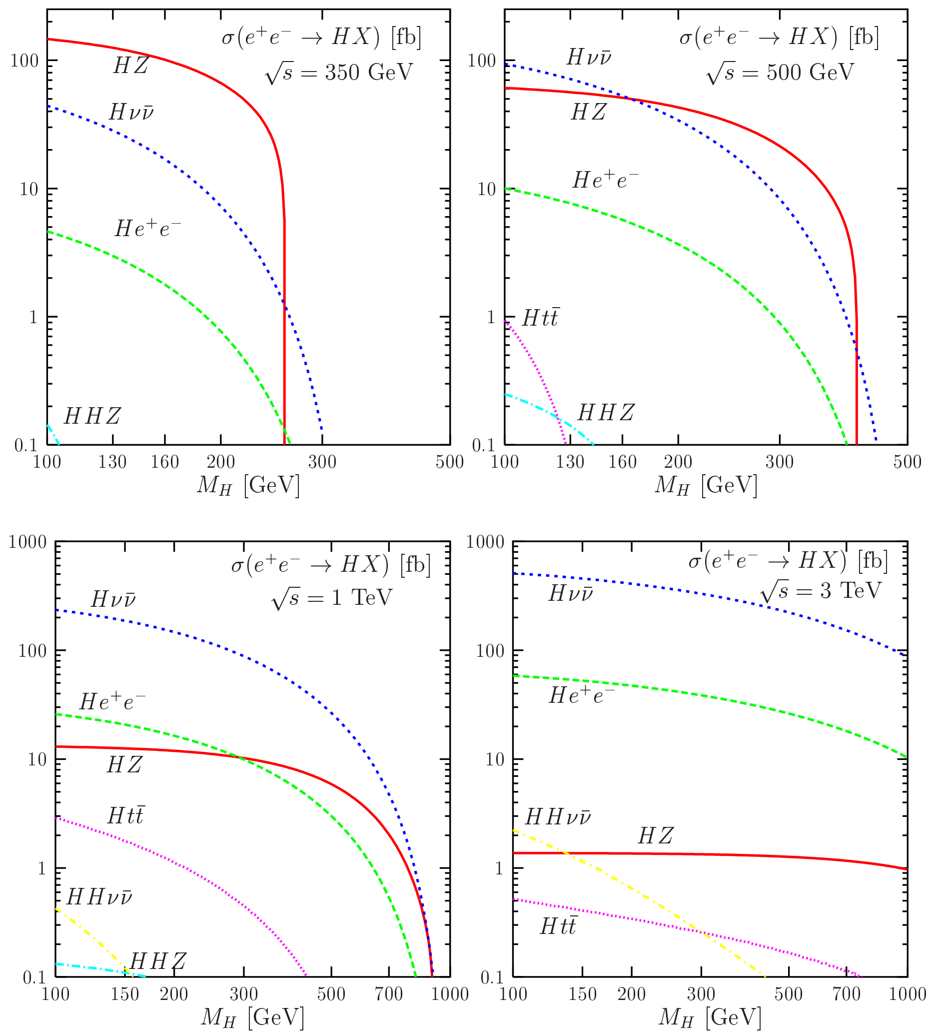
  ↪ combined analysis of $H\gamma\gamma$ and Hgg couplings: indirect test of new physics;

  ↪ measuring Higgs anomalous couplings: test Higgs compositness;

  ↪ new strategies for Higgs self-couplings.

The experimental precision of high energy LC requires very accurate theoretical predictions.

LC: SM Higgs scenario



Main production modes:

- $\triangleright$ $e^+e^- \to ZH$
- $\triangleright$ $e^+e^- \to H\nu_e\bar{\nu}_e$
- $e^+e^- \to He^+e^-$

top Yukawa coupling:

- $\triangleright$ $e^+e^- \to t\bar{t}H$

Higgs self-couplings:

- $\triangleright$ $e^+e^- \to ZHH$
- $\triangleright$ $e^+e^- \to \nu_e\bar{\nu}_e HH$

(A. Djouadi , 2005)

SM Higgs production: status of theoretical predictions

Process ($e^+e^- \to X$)	Comments
ZH	Fleischer, Jegerlehner (83)
	Kniehl (92)
	Denner, Kubelbeck, Mertig, Bohm (92)
$\nu_e\bar{\nu}_e H$	Belanger et al.
	Denner, Dittmaier, Roth, Weber (03)
	Jegerlehner, Tarasov (03)
$e^+e^- H$	Boudjema et al. (04)
$t\bar{t}H$	Dawson, Reina (99) (QCD)
	Dittmaier, Krämer, Liao, Spira, Zerwas (98) (QCD)
	Denner, Dittmaier, Roth, Weber (03) (EW)
	Belanger et al. (03) (EW)
	You, Ma, Chen, Zhang, Sun, Hou (04) (EW)
ZHH	Belanger et al. (03)
	Chen, Hou, Ma, Sun, Zhang (04)
$\nu_e\bar{\nu}_e HH$	Boudjema et al. (04)

- ▷ typical EW corrections $O(5-10\%)$, typical QCD corrections $O(10-15\%)$;
- ▷ systematic error reduced to few percent for all channels.
- ▷ Most MSSM channel known at same level of accuracy.

Main Higgs decays: highlights of most recent results

- $H \to b\bar{b}$
  - ▷ long list of past contributions;
  - ▷ recent $O(\alpha_s^2)$ s-qcd in MSSM computed in $M_H < m_t, m_{\tilde{g}}, m_{\tilde{q}}$ (Mihaila, Reisser,'10)
- $H \to \gamma\gamma$ and $H \to gg$:
  - ▷ long list of past contributions;
  - ▷ most recent: complete EW+QCD NLO corrections (Actis, Passarino, Sturm, Uccirati, '07)
- $H \to 4f$:
  - ▷ PROPHECY4f (Bredenstein, Denner, Dittmaier, Weber) MC generator including $O(\alpha)$ and $O(\alpha_s)$ corrections to $H \to WW/ZZ \to 4f$
  - ▷ HDECAY (Spira) Improved Born Approximation (accurate within 1%).
- $A_0 \to \gamma\gamma$
  - ▷ NLO (exact), NNLO ($m_t \to \infty$) known;
  - ▷ dominant EW NLO $O(G_f m_t^2)$ (Brod, Fugel, Kniehl, '08)

Conclusions and Outlook

- We are living through a new era in Higgs boson physics: looking for direct evidence.
- Higgs boson precision physics has given a first coherent set of predictions for inclusive observables: Higgs boson production cross sections and branching ratios.
- Short term: study exclusive observables, including decays, background processes, and experimental cuts.
- Long term: carry through a precision program that also include measurements of Higgs boson properties, to identify possible candidates:
  - the LHC will play an important role but need very high luminosity;
  - LHC measurements will be important indications but are intrinsically model dependent;
  - a high energy Linear Collider will be the best if not the only environment to complete and conclude the investigation of EWSB.