Higgs Physics

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1. The Higgs boson of the electroweak Standard Model
2. Higgs physics in the MSSM
3. Determination of Higgs boson properties
4. Conclusions

1. The Higgs boson of the electroweak Standard Model

Electroweak Standard Model (SM):

Construction principle: gauge invariance

Example: $\mathcal{L}_{\rm QED}$ invariant under $\Psi \to e^{ie\lambda(x)}\Psi$, $A_\mu \to A_\mu + \partial_\mu\lambda(x)$

Mass term, $m^2 A^\mu A_\mu$: not gauge-invariant

$\Rightarrow A_\mu$: massless gauge field

Problem: gauge fields Z, W^+, W^- are massive

explicit mass terms $\Leftrightarrow$ breaking of gauge invariance

Higgs mechanism, spontaneous electroweak symmetry breaking:

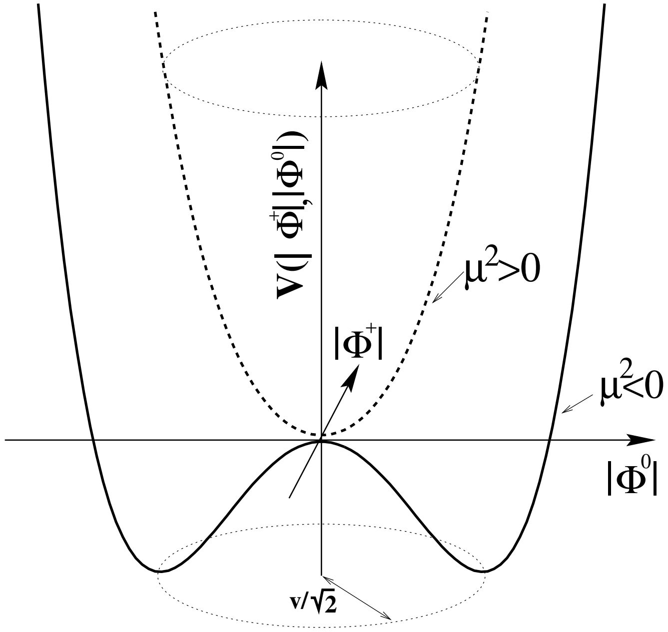
Scalar field postulated, gauge-invariant mass terms from coupling to Higgs field

Higgs sector of the Standard Model

scalar SU(2) doublet: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

Higgs potential: $V(\phi) = \mu^2 \left|\Phi^\dagger \Phi\right| + \lambda \left|\Phi^\dagger \Phi\right|^2, \quad \lambda > 0$

$\mu^2 < 0$: spontaneous symmetry breaking



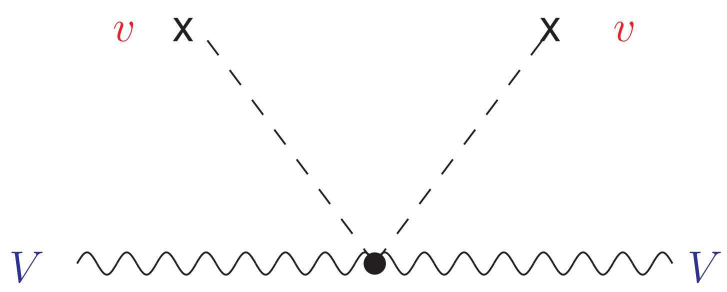
minimum of the potential at

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \sqrt{\frac{-\mu^2}{\lambda}} \equiv \frac{v}{\sqrt{2}}$$

Gauge-invariant interaction with gauge fields

$\mathcal{L}_{\text{Higgs}} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi)$; unitary gauge: $\Phi = \begin{pmatrix} 0 \\ v + H \end{pmatrix}$

$VV\Phi\Phi$ coupling:



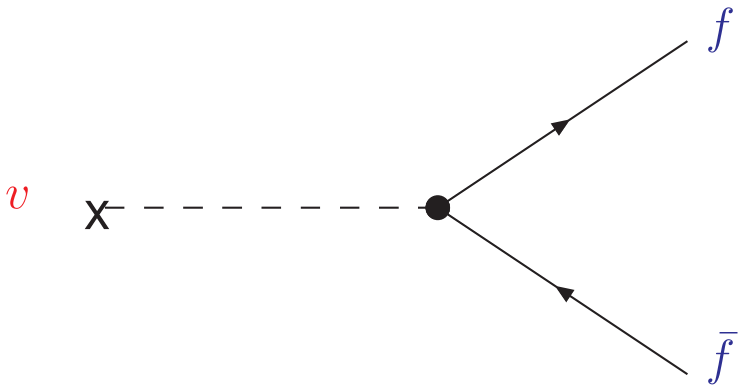
$\Rightarrow$ VV mass terms: $\frac{1}{2} g_2^2 v^2 \equiv M_{\text{W}}^2, \quad \frac{1}{2}(g_1^2 + g_2^2) v^2 \equiv M_{\text{Z}}^2$

3 components of Higgs doublet
$\longrightarrow$ longitudinal components of $W^\pm$, Z

H: elementary scalar field, Higgs boson

Fermion masses, Higgs mass

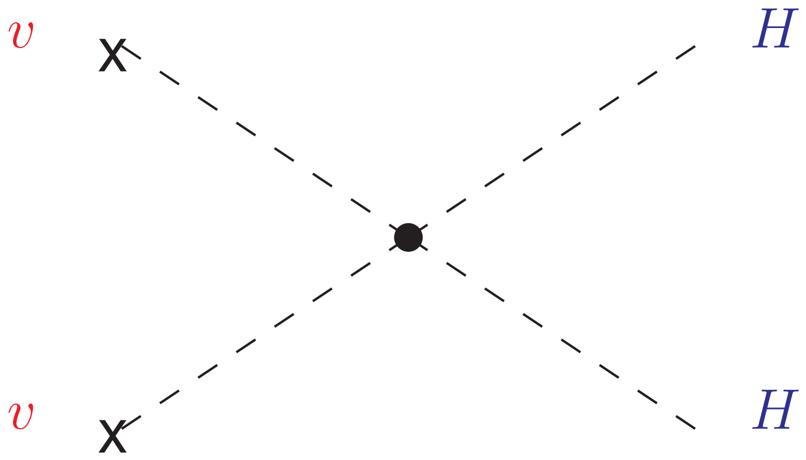
Fermion mass terms: Yukawa couplings



$$m_f = v \, g_f$$

free parameters

Mass of the Higgs boson: self-interaction



$$M_{\mathrm{H}} = v\sqrt{\lambda}$$

free parameter

$\Rightarrow$ Higgs couplings proportional to masses of the particles

Fermion masses in the SM

$$\mathcal{L}_{\rm SM} = \underbrace{m_d \bar{Q}_L H d_R}_{\text{d-quark mass}} + \underbrace{m_u \bar{Q}_L \tilde{H} u_R}_{\text{u-quark mass}}$$

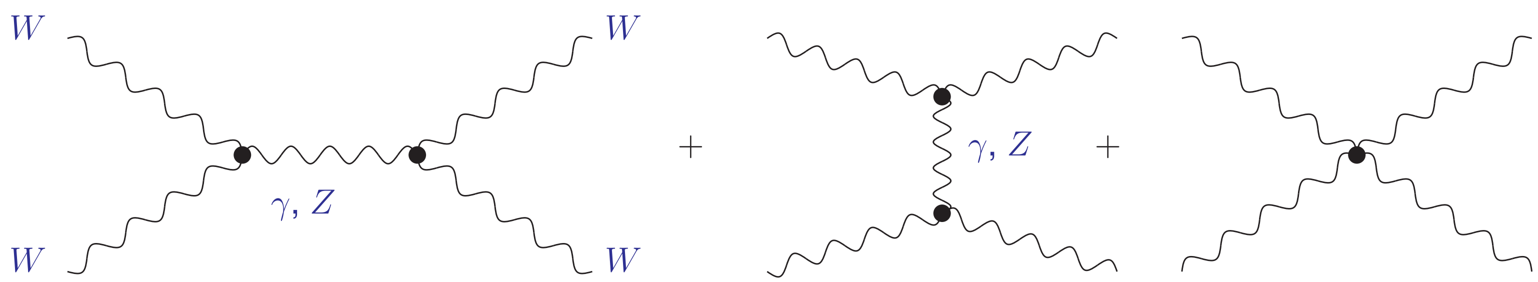
$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L, \quad \tilde{H} = i\sigma_2 H^\dagger, \quad H \to \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \tilde{H} \to \begin{pmatrix} v \\ 0 \end{pmatrix}$$

$\Rightarrow$ One Higgs doublet sufficient to give mass to both up-type and down-type fermions

Other reason why Higgs boson is needed: unitarity (probability conservation)

E.g.: WW scattering, longitudinally polarised: $W_L W_L \to W_L W_L$

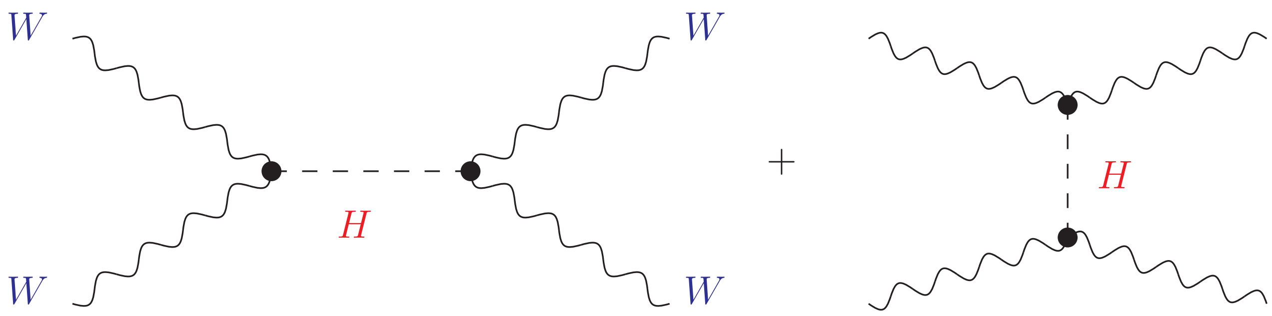
$\mathcal{M}_V =$



$$= -g^2 \frac{E^2}{M_W^2} + \mathcal{O}(1) \text{ for } E \to \infty$$ $\Rightarrow$ violation of probability conservation

Compensated by Higgs contribution:

$\mathcal{M}_S =$



$$= g_{WWH}^2 \frac{E^2}{M_W^4} + \mathcal{O}(1) \text{ for } E \to \infty, \quad g_{WWH} = g\, M_W$$

Unitarity bound on the Higgs mass

$\Rightarrow$ Upper limit on $M_{\rm H}$ (unitarity bound): $M_{\rm H} \lesssim 1$ TeV

Doesn't guarantee the existence of a fundamental Higgs,

but something has to happen when we probe the TeV scale

If no fundamental Higgs field exists:

strong interaction in gauge-boson sector for $E \gtrsim 1$ TeV

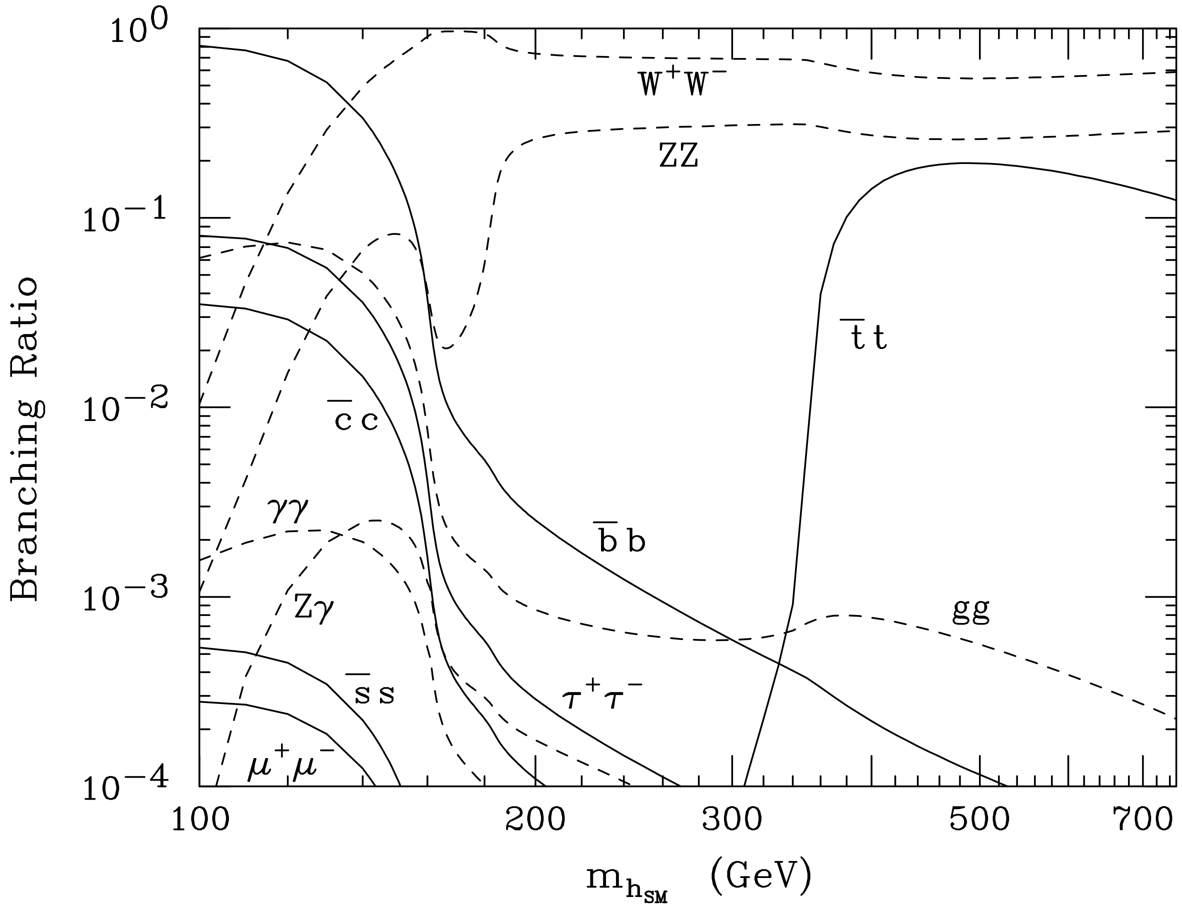
probability conservation via non-perturbative effects

Experimental tests: effects in W and Z scattering processes at high energy, resonances, ...

Higgs phenomenology in the Standard Model

A single parameter determines the whole SM Higgs phenomenology: M_H

Branching ratios of the SM Higgs:



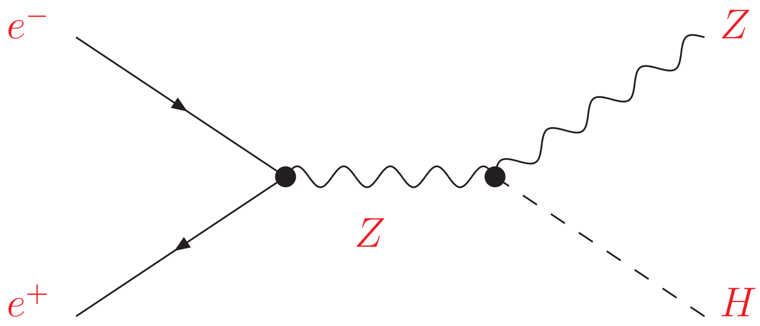
$\Rightarrow$ dominant BRs:

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

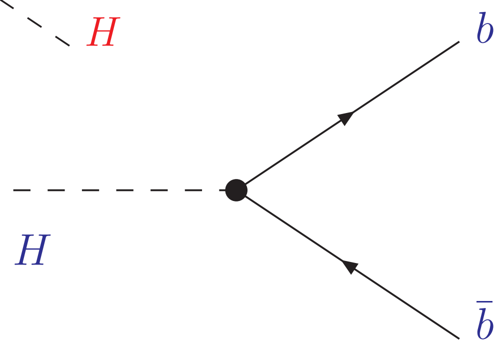
$M_\mathrm{H} \gtrsim 140$ GeV:
$H \to W^+W^-, ZZ$

Search for the Standard Model Higgs at LEP

Dominant production process: $e^+e^- \to ZH$



Dominant decay process: $H \to b\bar{b}$



Highest energy: $E_{\mathrm{CM}} \approx 206$ GeV

Exclusion limit, 95% C.L.: [*LEP Higgs Working Group '03*]

$M_{\mathrm{H}} > 114.4\,\mathrm{GeV}$ (expected: $115.3\,\mathrm{GeV}$)

1.7σ excess over background expectation

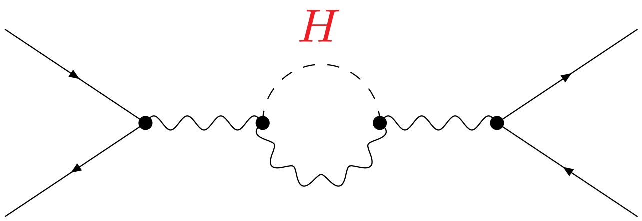
Constraints on the SM Higgs from electroweak precision tests

Comparison of electroweak precision data with theory predictions:

EW precision data:	Theory:
$M_Z, M_W, \sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}, \ldots$	SM, MSSM, ...

$\Downarrow$

Test of theory at quantum level: sensitivity to loop corrections



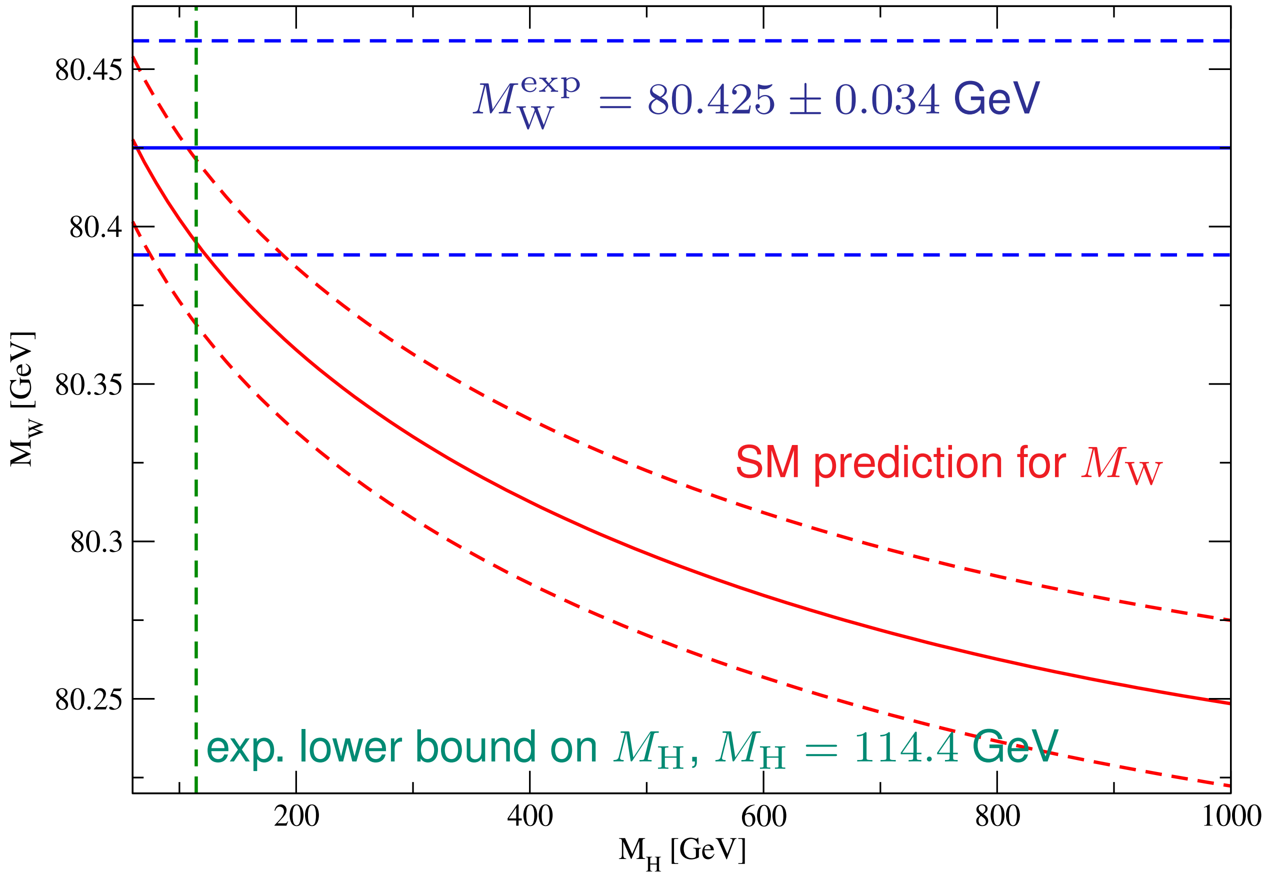
$\Downarrow$

Indirect constraints on unknown parameters: M_H, ...

Effects of “new physics”?

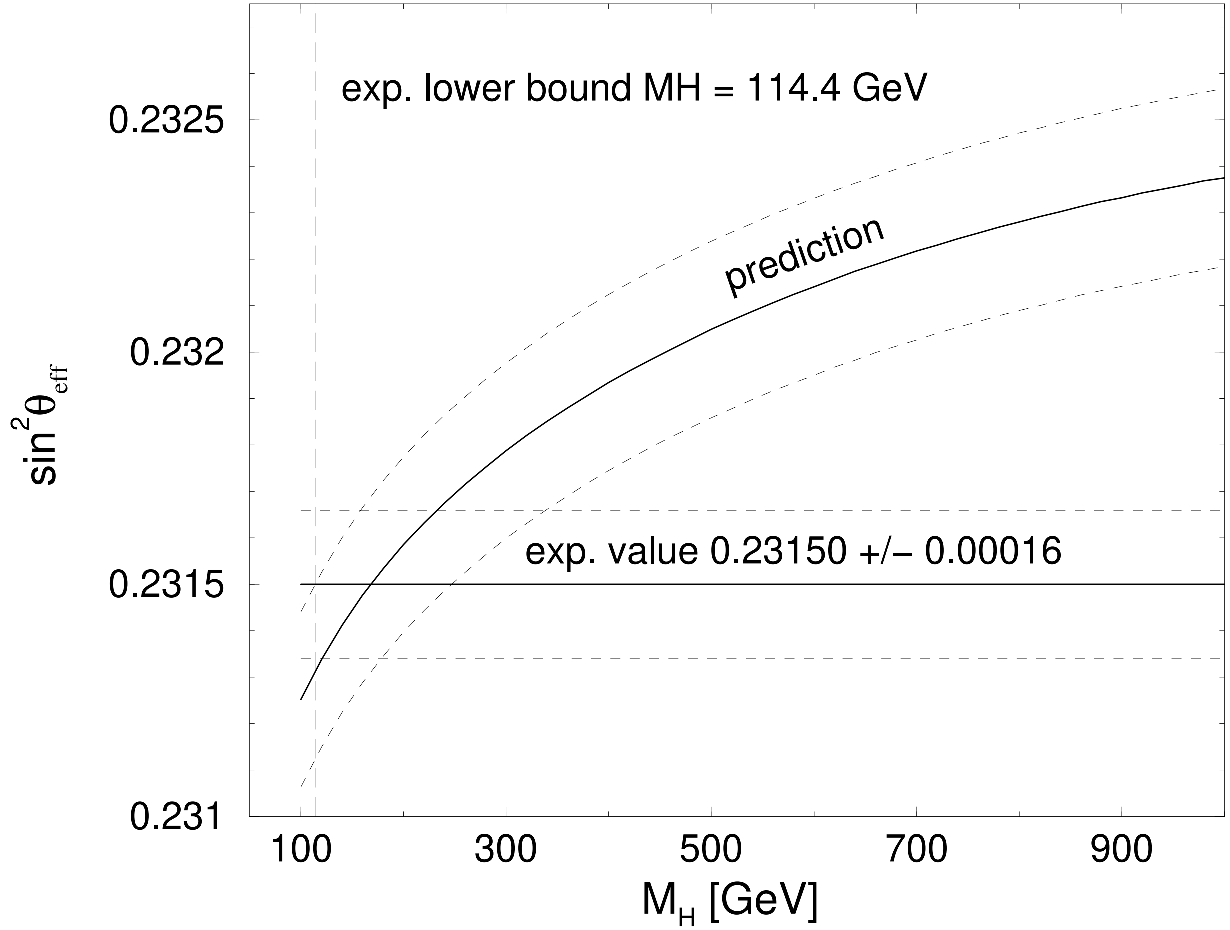
SM prediction for M_W (complete 2-loop result) vs. experimental result

[M. Awramik, M. Czakon, A. Freitas, G.W. '04]



$\Rightarrow$ Preference for light Higgs

SM prediction for $\sin^2\theta_{\mathrm{eff}}$ *(fermionic 2-loop result) vs. experimental result*



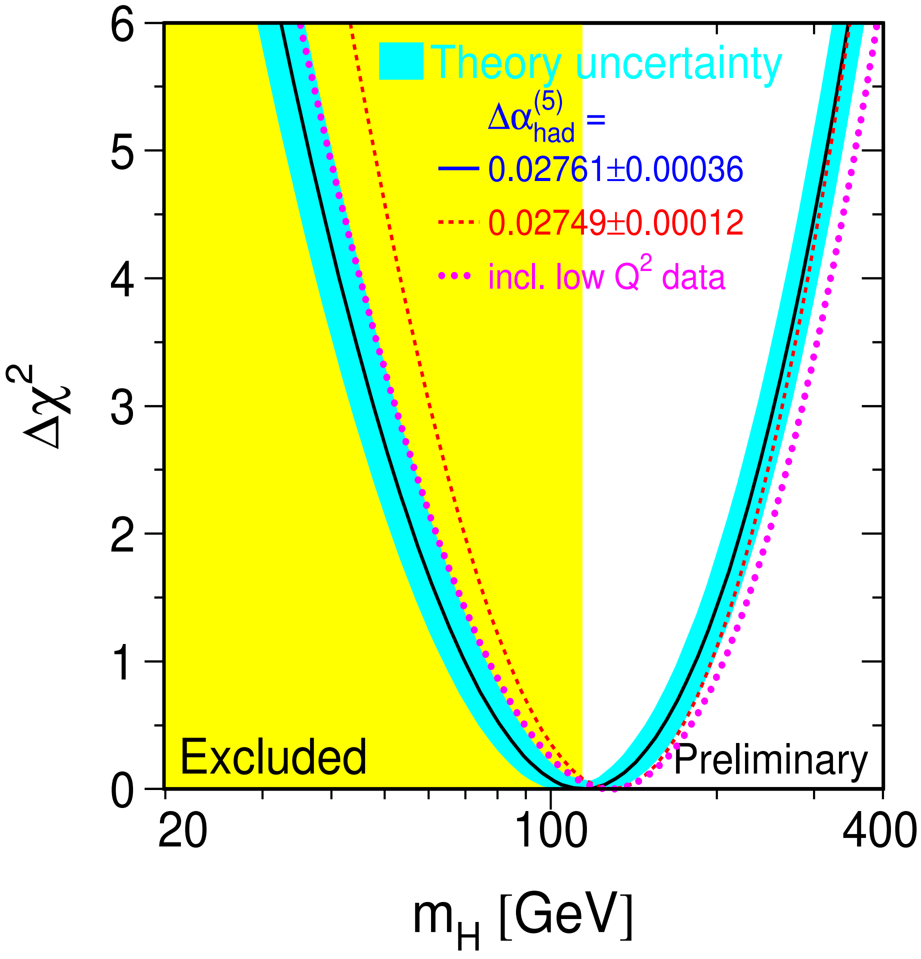
[*M. Awramik, M. Czakon, A. Freitas, G.W. '04*]

$\Rightarrow$ Preference for light Higgs

Main source of theoretical uncertainty: $\delta m_{\mathrm{t}} = 4.3$ GeV

$\Rightarrow \Delta M_{\mathrm{W}}^{\mathrm{para}} \approx 26$ MeV, $\Delta \sin^2\theta_{\mathrm{eff}}^{\mathrm{para}} \approx 14 \times 10^{-5}$

Global fit to all data in the SM



[*LEPEWWG '04*]

Theoretical uncertainties:

– exp. error of input parameters:

$m_{\rm t}$, $\Delta\alpha_{\rm had}$, . . .

$\Rightarrow$ large $m_{\rm t}$–$M_{\rm H}$ correlation

– unknown higher-order corrections

$\Rightarrow$ "blue band"

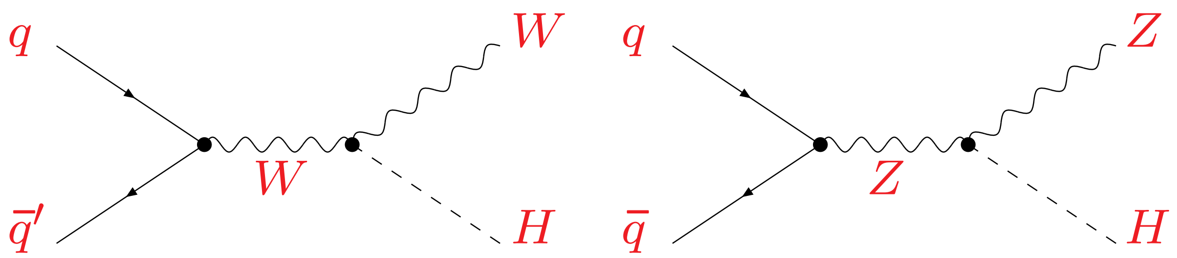
New $m_{\rm t}$ value, $m_{\rm t} = 178.0 \pm 4.3$ GeV, new result for $\sin^2\theta_{\rm eff}$

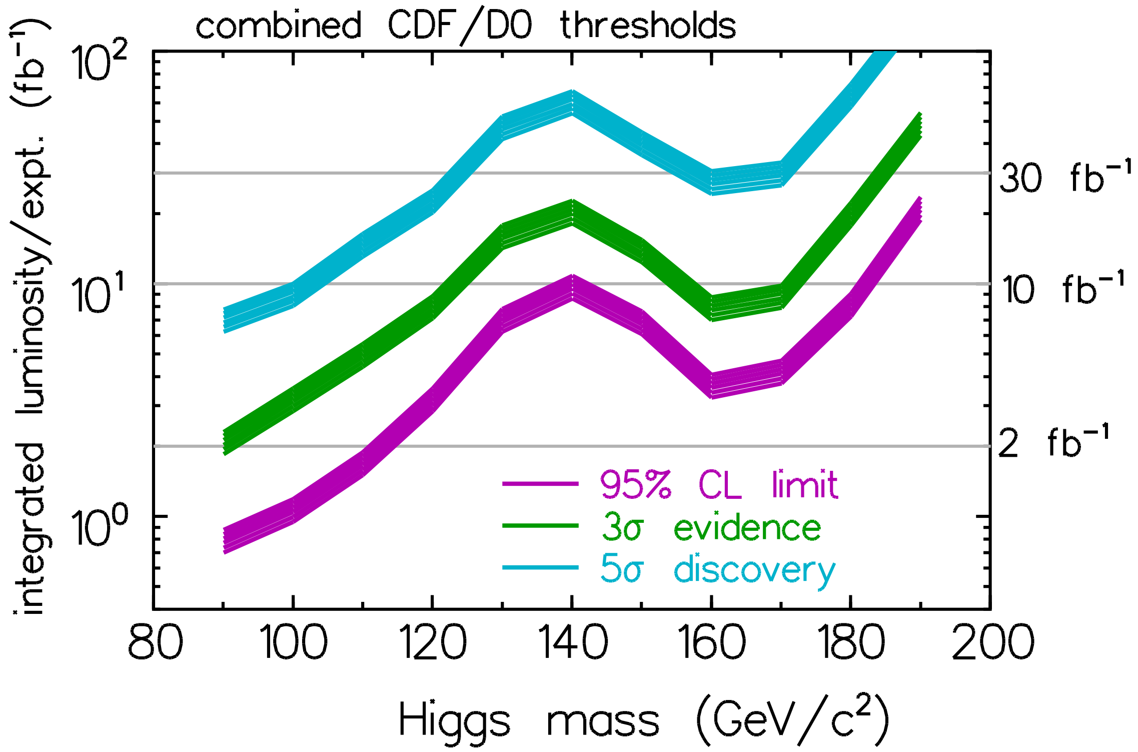
$\Rightarrow M_{\rm H} = 114^{+69}_{-45}$ GeV, $M_{\rm H} < 260$ GeV, 95% C.L.

Search for the SM Higgs at Tevatron, Run II

$p\bar{p}$ collider with $E_{\mathrm{CM}} \approx 2$ TeV

Dominant production processes:

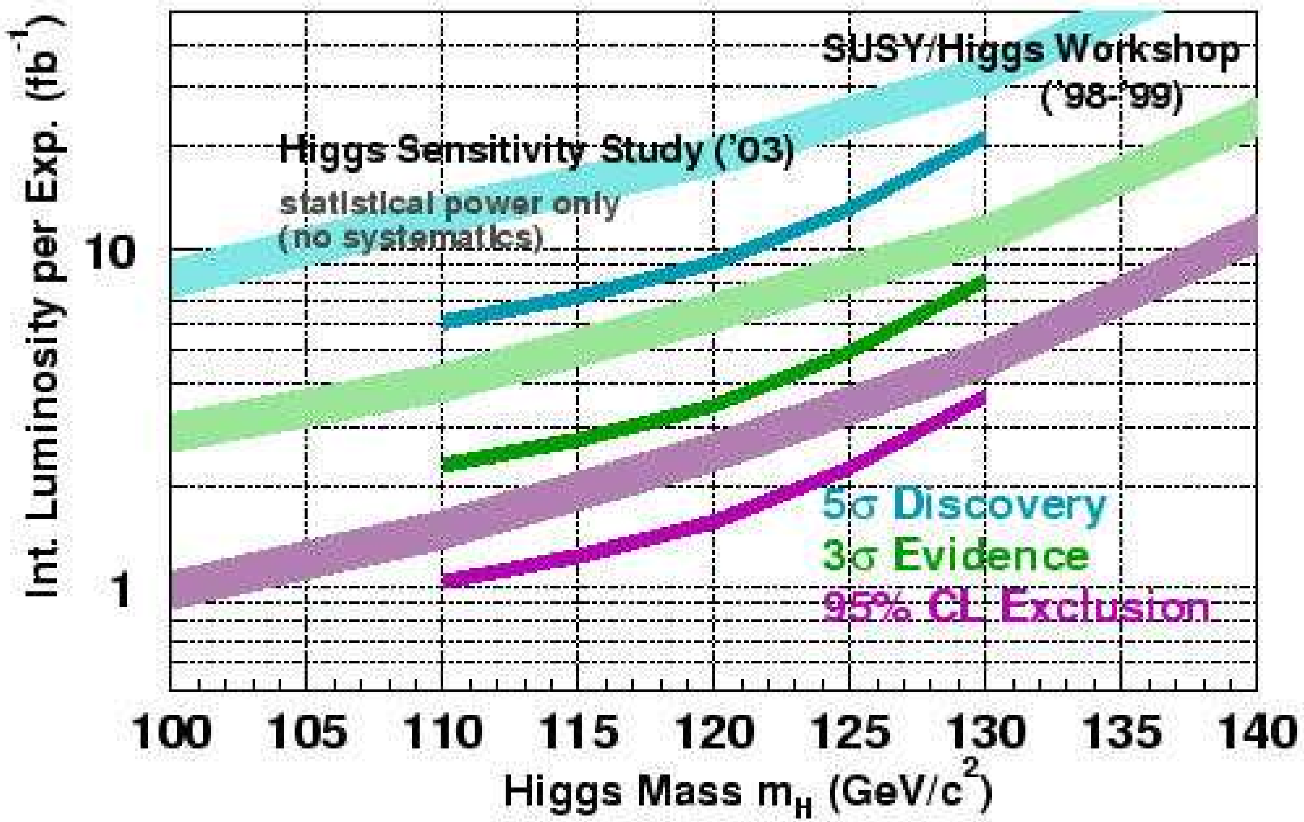




Integrated luminosity until $\approx$ 2009:

4–8 fb^{-1} per experiment

Update on Tevatron sensitivity for SM Higgs



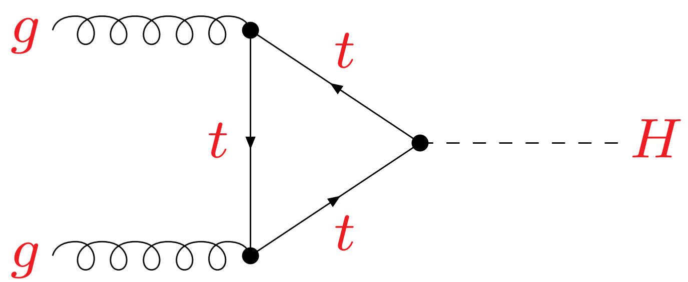
With 4–8 fb^{-1} per experiment:

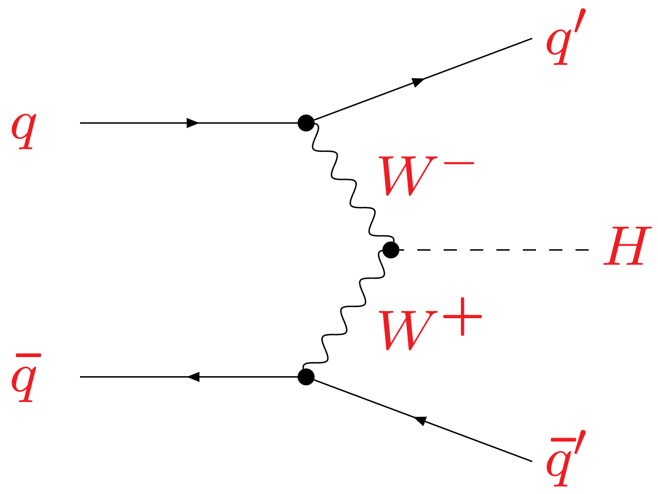
⇒ Exclusion of SM Higgs for $m_{\mathrm{h}} \lesssim 130$ GeV

Higgs production at the LHC

Dominant production processes:

gluon fusion: $gg \to H$, weak boson fusion (WBF): $q\bar{q} \to q'\bar{q}'H$





Higgs production at the LHC

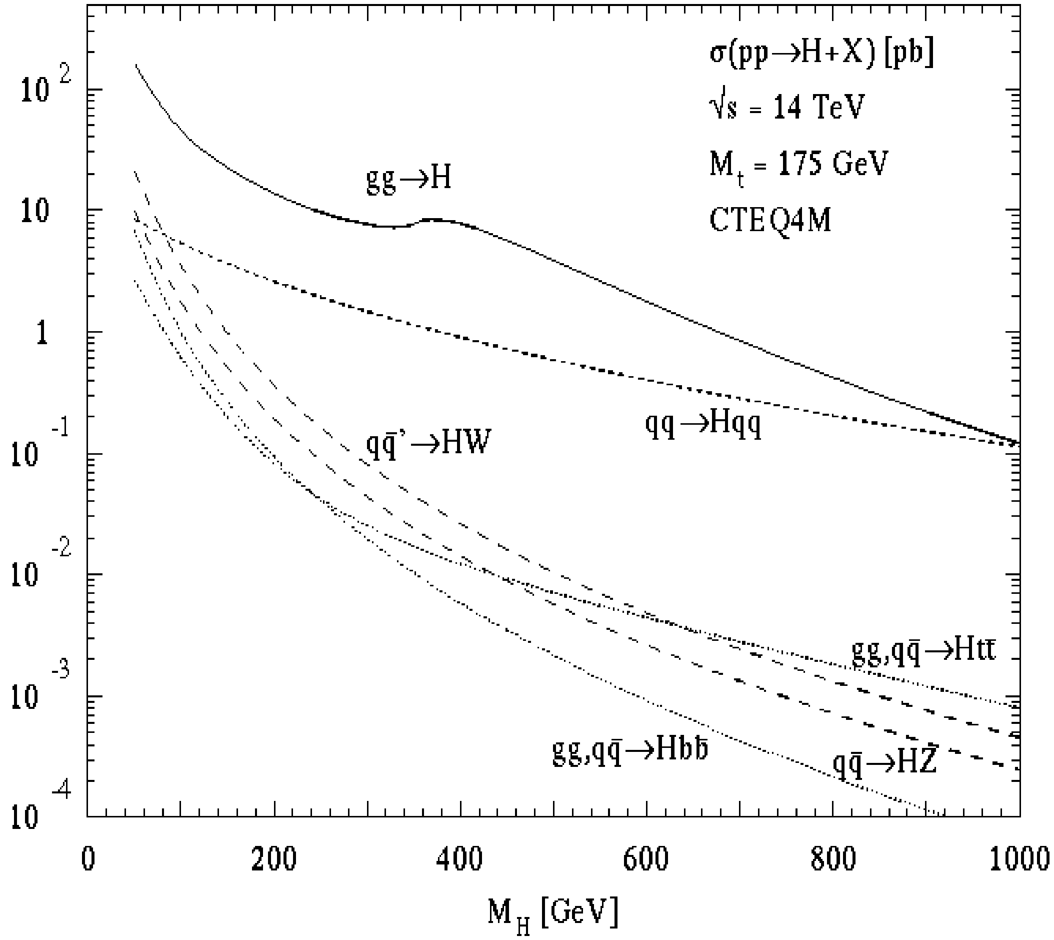
Relevant production processes for SM-like Higgs:

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: $q\bar{q}' \to WH, ZH$



How well does WBF channel work at high luminosity?

Higgs production at the LHC

Diffractive Higgs production: $pp \to p + H + p$

Low event rates in the SM; experimental feasibility?

Status of theory predictions for Higgs prod. and decay in the SM:

QCD corrections are important:

give large effects; radiative corrections are not just K-factors, change result also qualitatively:

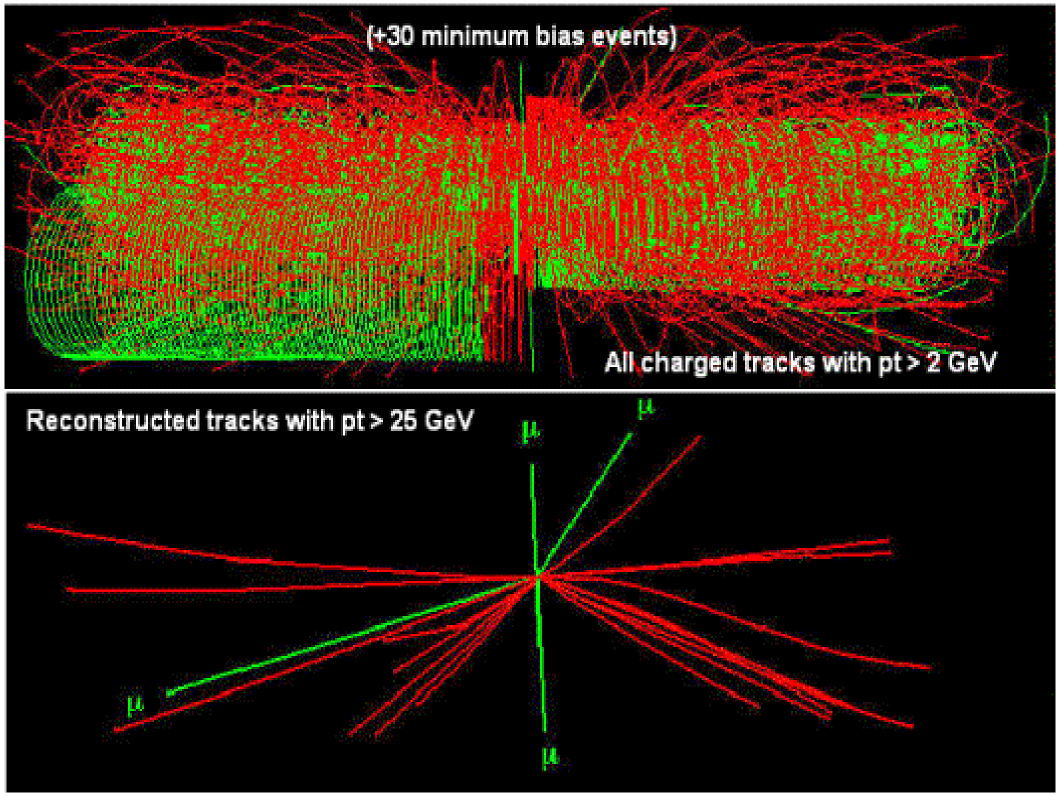
– more realistic kinematic features, e.g. for Higgs $+$ jets

– shape of distributions changed

More work needed on signal and many background processes, NLO Monte Carlos, etc.

Simulation of an LHC event: $gg \to H \to ZZ \to \mu^+\mu^-\mu^+\mu^-$

Computing in LHC experiments



1 Higgs decay in 4 muons in 10^{13} events

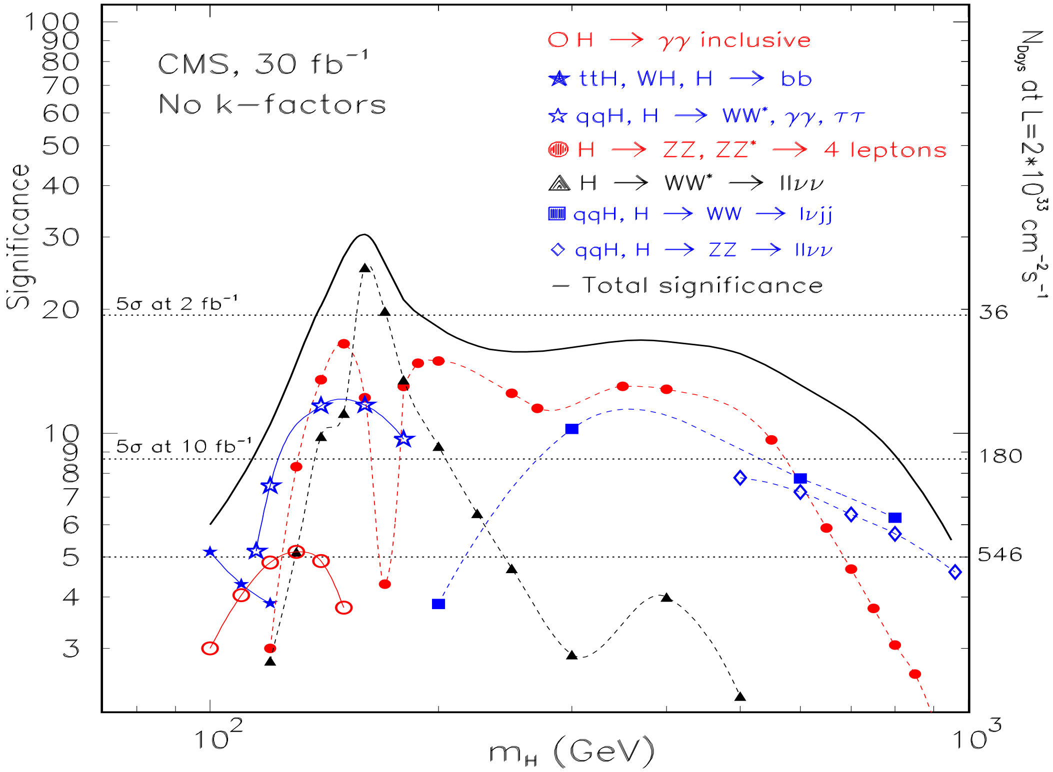
1000 charged tracks/event, most of them p<0.5 GeV

Prof. Dr. Stefan Schael, RWTH Aachen — Vorlesung 1, Maria-Laach, September 2001 — 25

Search for the SM Higgs at the LHC

The LHC will discover a SM-like Higgs, covers whole range

$M_{\rm H} \lesssim 1$ TeV



[CMS '03]

For light SM-like Higgs, $H \to \gamma\gamma$ decay mode:

$\Rightarrow$ LHC can do first precision measurement in Higgs sector:

$\delta M_{\rm H}^{\rm exp} \approx 0.2$ GeV   systematic uncertainties?

Higgs physics at the ILC

(e^+e^- LC, $E_{\rm CM} \approx 500$–1000 GeV, $\gtrsim 2015$?)

"Golden" production channel: $e^+e^- \to ZH$, $Z \to e^+e^-, \mu^+\mu^-$

Higgs discovery possible independent of decay modes

(from recoil against Z boson)

$\Delta\sigma_{\rm HZ}/\sigma_{\rm HZ} \approx 2\%$ ($E_{\rm CM} = 350$ GeV, $\int \mathcal{L}dt = 500$ fb^{-1})

ILC is a "Higgs factory"

e.g.: $E_{\rm CM} = 800$ GeV, 1000 fb^{-1}, $M_{\rm H} = 120$ GeV:

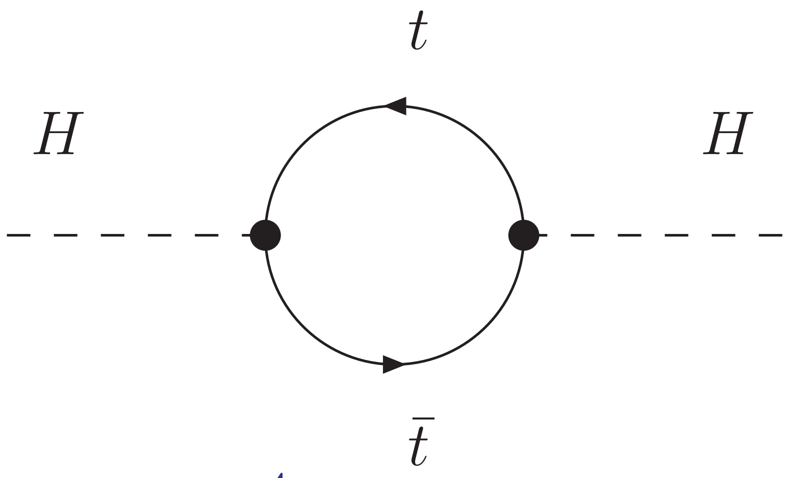
$\Rightarrow$ ≈ 160000 Higgs events in "clean" experimental environment

$\Rightarrow$ Precise measurement of Higgs mass ($\approx 4 \times 10^{-4}$) and couplings, determination of Higgs spin and quantum numbers, ...

$\Rightarrow$ Verification of Higgs mechanism

Precision Higgs physics

Large coupling of Higgs to top quark



One-loop correction $\sim G_\mu m_\mathrm{t}^4$

$\Rightarrow$ M_H depends sensitively on m_t in all models where M_H can be predicted (SM: M_H is free parameter)

SUSY as an example: $\Delta m_\mathrm{t} \approx \pm 4$ GeV $\Rightarrow$ $\Delta m_\mathrm{h} \approx \pm 4$ GeV

$\Rightarrow$ Precision Higgs physics needs precision top physics (ILC: $\Delta m_\mathrm{t} \lesssim 0.1$ GeV)

2. 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 for both)
- Supersymmetry imposes relations between the parameters

$\Rightarrow$ Two parameters instead of one:

$$\tan\beta \equiv \frac{v_2}{v_1}, \qquad M_{\rm A}$$

Higgs potential of the MSSM

MSSM Higgs potential contains two Higgs doublets:

$$\begin{aligned} V \;=\; & m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) \\ & + \underbrace{\frac{g'^2 + g^2}{8}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} \, |H_1 \bar{H}_2|^2 \end{aligned}$$

gauge couplings, in contrast to SM

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

Input parameters: $\tan\beta = \frac{v_2}{v_1}$, M_A

$\Rightarrow m_\mathrm{h}$, m_H, mixing angle α, $m_{\mathrm{H}^\pm}$: no free parameters

Higgs mass bound in the MSSM:

⇒ Prediction for $m_{\mathrm{h}}, m_{\mathrm{H}}, \ldots$

Tree-level result for $m_{\mathrm{h}}, m_{\mathrm{H}}$:

$$m^2_{\mathrm{H,h}} = \frac{1}{2}\left[M_{\mathrm{A}}^2 + M_{\mathrm{Z}}^2 \pm \sqrt{(M_{\mathrm{A}}^2 + M_{\mathrm{Z}}^2)^2 - 4M_{\mathrm{Z}}^2 M_{\mathrm{A}}^2 \cos^2 2\beta}\right]$$

⇒ $m_{\mathrm{h}} \leq M_{\mathrm{Z}}$ at tree level

MSSM tree-level bound (gauge sector): excluded by LEP!

Large radiative corrections (Yukawa sector, ...):

Yukawa couplings: $\frac{\mathrm{e}\, m_{\mathrm{t}}}{2M_{\mathrm{W}} s_{\mathrm{W}}}, \frac{\mathrm{e}\, m_{\mathrm{t}}^2}{M_{\mathrm{W}} s_{\mathrm{W}}}, \ldots$

⇒ Dominant one-loop corrections: $G_\mu m_{\mathrm{t}}^4 \ln\left(\frac{m_{\tilde{\mathrm{t}}_1} m_{\tilde{\mathrm{t}}_2}}{m_{\mathrm{t}}^2}\right), \quad \mathcal{O}(100\%)$!

Higgs mass bound in the MSSM:

Present status of m_h prediction in the MSSM:

Complete one-loop $+$ “almost complete” two-loop result available

Upper bound on m_h:

‘Unconstrained’ MSSM: M_A, $\tan\beta$, 5 param. in $\tilde{\mathrm{t}}$-$\tilde{\mathrm{b}}$ sector, μ, $m_{\tilde{\mathrm{g}}}$, M_2

$$m_\mathrm{h} \lesssim 136\,\mathrm{GeV}$$

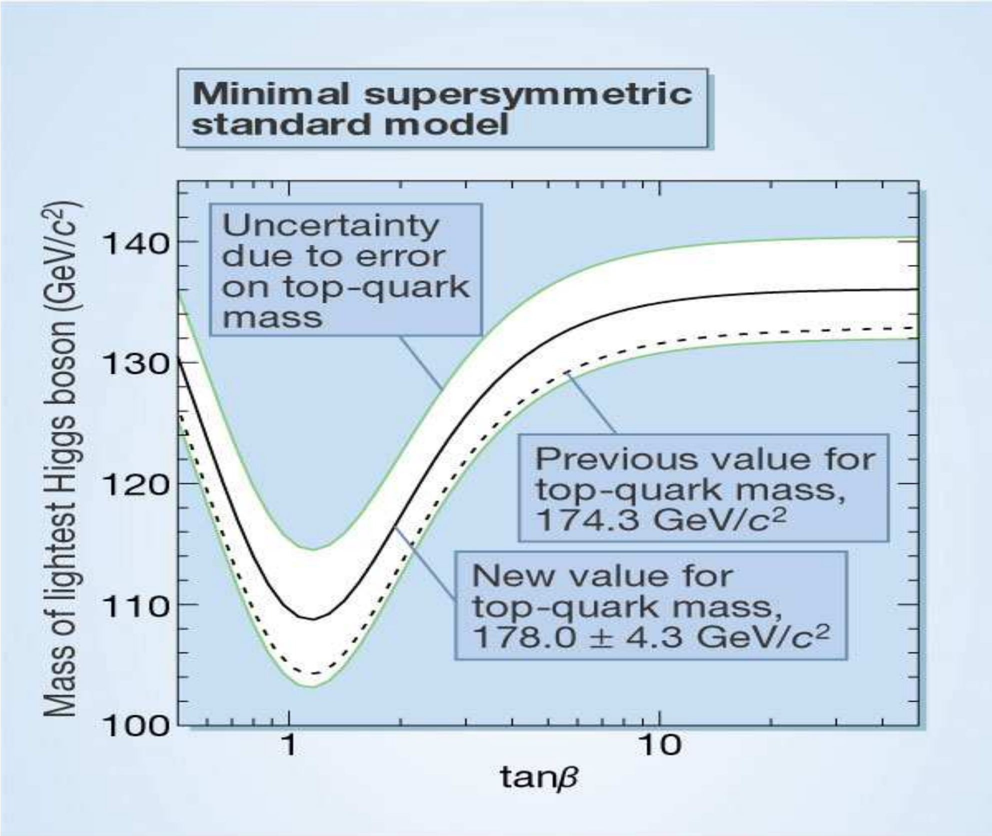
[*S. Heinemeyer, W. Hollik, G. W. ’99*], [*M. Frank, S. Heinemeyer, W. Hollik, G. W. ’02*] [*G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich, G. W. ’02*]

for $m_\mathrm{t} = 178\,\mathrm{GeV}$, no theoretical uncertainties included Upper bound reduced by $\approx 6, 11, 8$ GeV in mSUGRA, GMSB, AMSB scenarios [*S. Ambrosanio, A. Dedes, S. Heinemeyer, S. Su, G. W. ’01*]

Remaining theoretical uncertainties in prediction for m_h:

[*G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich, G. W. '02*]

- From unknown higher-order corrections: $\Rightarrow \Delta m_h \approx \pm 3$ GeV
- From input parameters: $\Delta m_t \approx \pm 4$ GeV $\Rightarrow \Delta m_h \approx \pm 4$ GeV



For 1-σ range of m_t:

$\Rightarrow$ upper bound beyond $m_h = 140$ GeV

LEP does not exclude any $\tan\beta$ value!

Higgs couplings

Higgs couplings, tree level:

$$g_{\mathrm{hVV}} = \sin(\beta-\alpha)\, g_{\mathrm{HVV}}^{\mathrm{SM}}, \quad g_{\mathrm{HVV}} = \cos(\beta-\alpha)\, g_{\mathrm{HVV}}^{\mathrm{SM}}, \quad V = W^{\pm}, Z$$

$$g_{\mathrm{hAZ}} = \cos(\beta-\alpha)\, \frac{g'}{2\cos\theta_{\mathrm{W}}}, \quad g_{\mathrm{HAZ}} = \sin(\beta-\alpha)\, \frac{-g'}{2\cos\theta_{\mathrm{W}}}$$

$\Rightarrow g_{\mathrm{hVV}} \le g_{\mathrm{HVV}}^{\mathrm{SM}}$, $\quad g_{\mathrm{hVV}}, g_{\mathrm{HVV}}, g_{\mathrm{hAZ}}, g_{\mathrm{HAZ}}$ cannot all be small

In decoupling limit, $M_{\mathrm{A}} \gg M_{\mathrm{Z}}$ (already realized for $M_{\mathrm{A}} \gtrsim 150$ GeV):
$\cos(\beta-\alpha) \to 0$

$\Rightarrow$ H and A decouple from gauge bosons (only g_{HAV} is sizable)

$\Rightarrow$ Cannot use WBF channels for production of heavy SUSY Higgses; no $H \to ZZ \to 4\mu$ decay

Higgs couplings

$$g_{\rm hb\bar b}, g_{\rm h\tau^+\tau^-} \;=\; -\frac{\sin\alpha}{\cos\beta}\, g^{\rm SM}_{\rm Hb\bar b, H\tau^+\tau^-}, \qquad g_{\rm ht\bar t} = \frac{\cos\alpha}{\sin\beta}\, g^{\rm SM}_{\rm Ht\bar t}$$

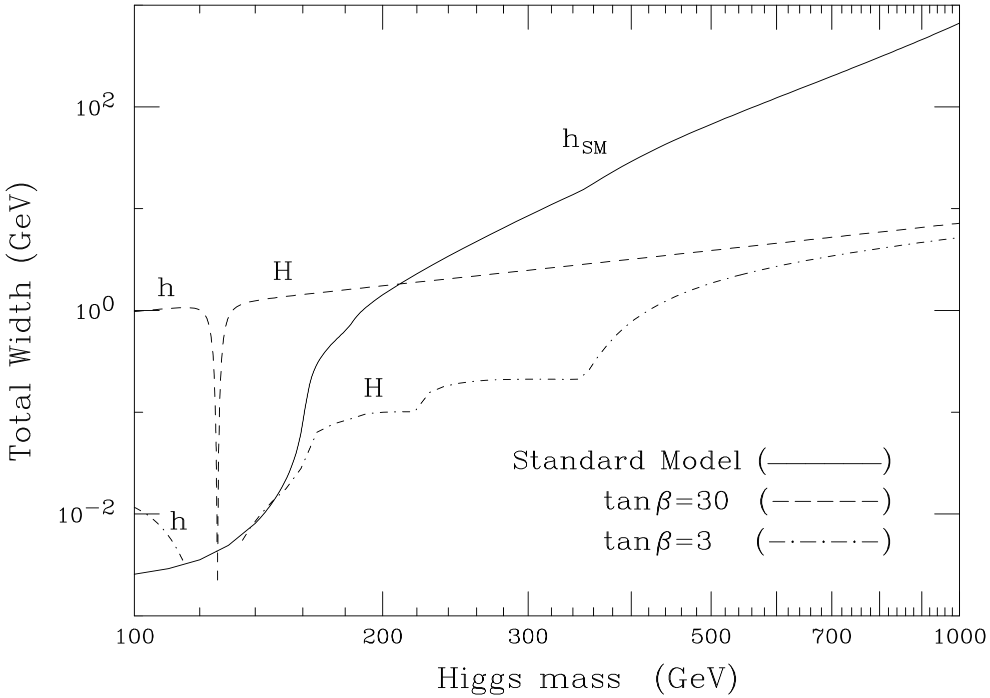
$$g_{\rm Ab\bar b}, g_{\rm A\tau^+\tau^-} \;=\; \gamma_5 \tan\beta\, g^{\rm SM}_{\rm Ab\bar b}$$

$\Rightarrow$ Significant suppression or enhancement w.r.t. SM couplings possible

For $M_{\rm A} \lesssim 200$ GeV, $\tan\beta \gtrsim 10$:

large enhancement of

$\Gamma(h \to b\bar b)$, $\Gamma(h \to \tau^+\tau^-)$, ...



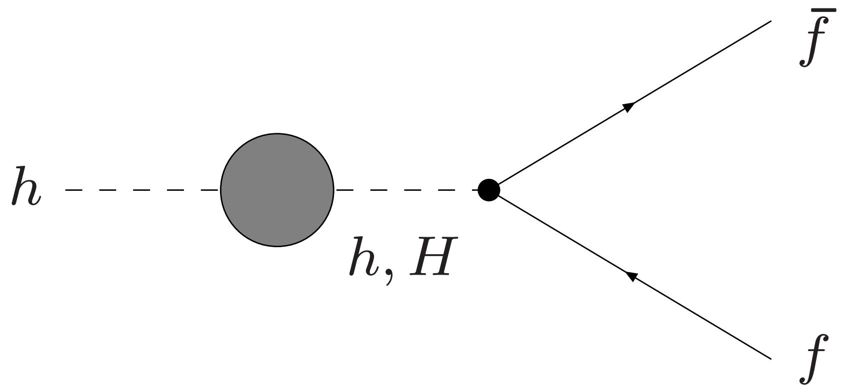
$\Rightarrow$ Total Higgs width can be much larger than in SM

$\Rightarrow$ Large suppression of BR$(h \to \gamma\gamma)$, BR$(h \to WW^*)$, ...

Higgs couplings

Higgs couplings, production cross sections also affected by large SUSY loop corrections

$h f \bar{f}$ coupling:



$$A(h \to f\bar{f}) = \sqrt{Z_h}\left(\Gamma_h - \frac{\hat{\Sigma}_{\mathrm{hH}}(m_{\mathrm{h}}^2)}{m_{\mathrm{h}}^2 - m_{\mathrm{H}}^2 + \hat{\Sigma}_{\mathrm{HH}}(m_{\mathrm{h}}^2)}\Gamma_H\right)$$

$\Rightarrow$ Effective $h f \bar{f}$ coupling can vanish for large $\hat{\Sigma}_{\mathrm{hH}}$: $\sin\alpha_{\mathrm{eff}} \to 0$

$\mathcal{CP}$ *violation in the Higgs sector*

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

Complex parameters enter via loop corrections:

– μ: Higgsino mass parameter

– $A_{t,b,\tau}$: trilinear couplings

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

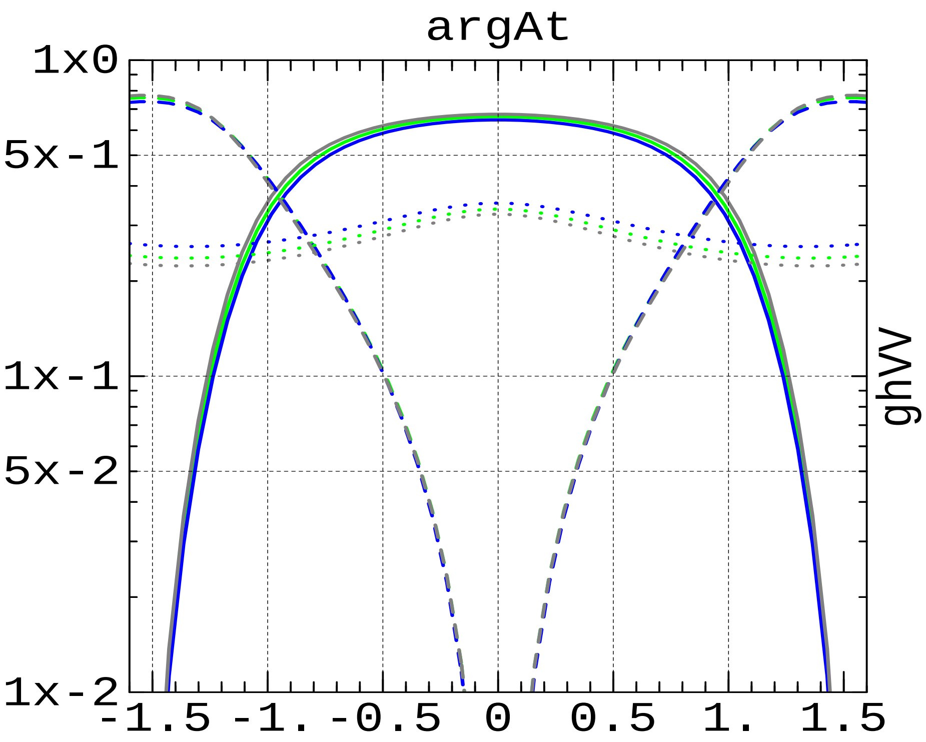
– $m_{\tilde{\mathrm{g}}}$: gluino mass

$\Rightarrow$ can induce $\mathcal{CP}$-violating effects

$\Rightarrow$ Mixing between neutral Higgs bosons h_1, h_2, h_3

$\mathcal{CP}$ violation in the Higgs sector

Example: g_{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:

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

$M_2 = 500$ GeV,

$\mu = 2000$ GeV,

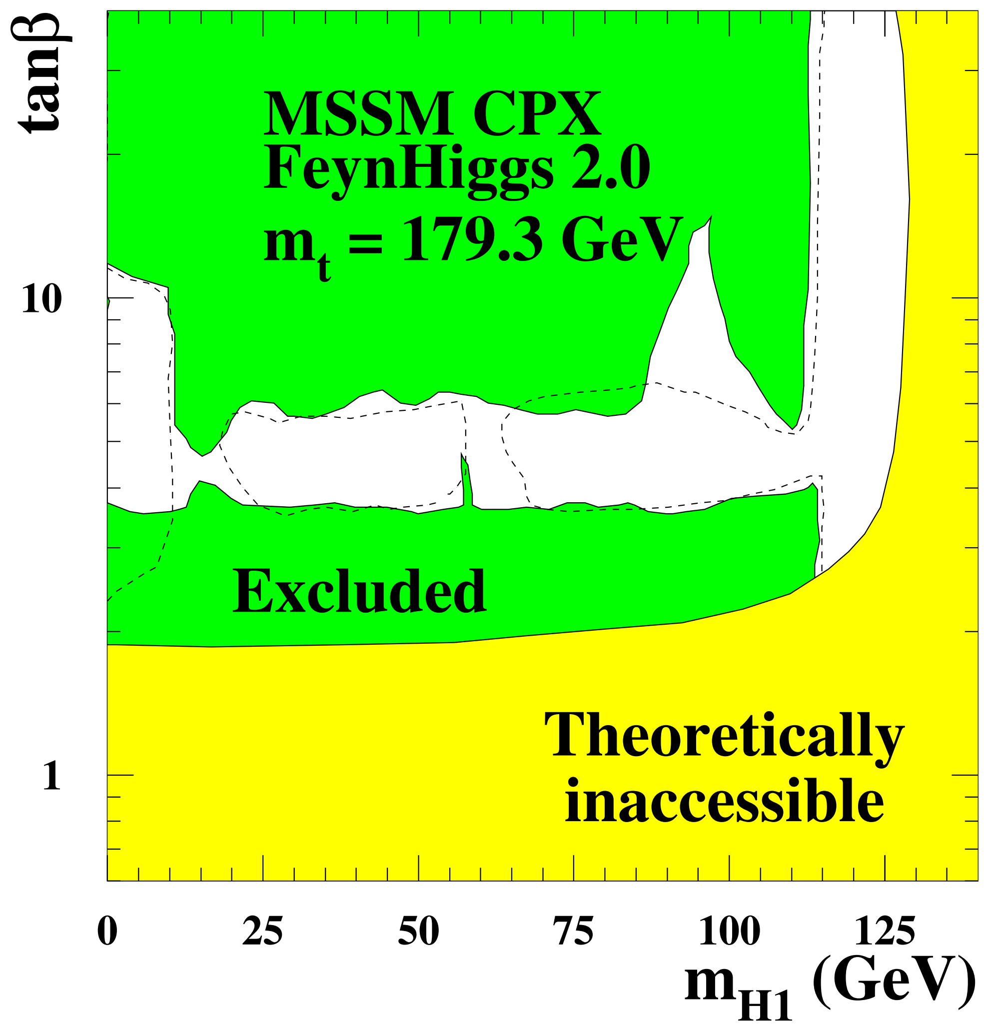
$|A_{\mathrm{t}}| = 1000$ GeV,

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

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

$\mathcal{CP}$-violating case: LEP exclusion bounds

[*LEP Higgs Working Group '04*]



$\Rightarrow$ light SUSY Higgs not ruled out!

Higgs detection difficulties: some examples

- Suppression of BR($h \to b\bar{b}$), BR($h \to \tau\tau$), ...
- SUSY Higgs h can have sizable branching fraction into invisible final state: $h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$
- Higgs with dominant decays into hadronic jets, possibly without definite flavor content
- NMSSM: $h \to aa$, singlet dominated light Higgs, ...
- More exotic scenarios:
  Higgs–radion mixing, “continuum” Higgs models, ...
- ...

3. Determination of Higgs boson properties

"Just" a discovery will not be sufficient

Need to measure quantities in the Higgs sector in order to

– determine the nature of the detected particle

– experimentally verify the Higgs mechanism

- Higgs mass(es), spin, $\mathcal{CP}$ properties

  particular challenge: $\mathcal{CP}$ properties of heavy SUSY Higgses

- Higgs couplings to different particles:

  $Hb\bar{b}$, $Ht\bar{t}$, $H\tau^+\tau^-$, HW^+W^-, HZZ, Hgg, $H\gamma\gamma$, HHH, $HHHH$, $\ldots$

Parameter determination at the LHC

Many “measurements” currently proposed for the LHC are on the same footing as the M_{H} bounds from the global fit in the SM, e.g.

- Determination of top Yukawa coupling from $\sigma \times \mathrm{BR}$ assuming the BR to be given by the SM
- Determination of $\tan\beta$ from $\sigma \times \mathrm{BR}$ assuming the MSSM values for the BRs, ...

$\Rightarrow$ It is crucial to make clear which kind of assumptions are made in a particular analysis

and to take into account theoretical uncertainties: from unknown higher orders / from experimental error of input parameters (e.g. m_{t}, $m_{\tilde{\mathrm{t}}}$, ...)

Example: Higgs coupling determination at LHC

LHC: no absolute measurement of total production cross section (no recoil method like LEP, ILC: $e^+e^- \to ZH$, $Z \to e^+e^-, \mu^+\mu^-$)

Measurement of $\sigma \times \mathrm{BR}$: narrow-width approximation

$$\Rightarrow \quad \sigma(H) \times \mathrm{BR}(H \to a + b) = \frac{\sigma(H)^{\mathrm{SM}}}{\Gamma_{\mathrm{prod}}^{\mathrm{SM}}} \cdot \frac{\Gamma_{\mathrm{prod}} \Gamma_{\mathrm{decay}}}{\Gamma_{\mathrm{tot}}}$$

Observation of different channels (or upper bound from non-observation) provides information on combinations of $\Gamma_g, \Gamma_W, \Gamma_Z, \Gamma_\gamma, \Gamma_\tau, \Gamma_b$, Y_t^2

Large uncertainty on $H \to b\bar{b}$, ...

$\Rightarrow$ Determination of ratios of partial widths

$\Rightarrow$ Additional theoretical assumptions needed for absolute determination of partial widths

Strategy

Consider general multi-Higgs-doublet models (with or without additional Higgs singlets), includes e.g. MSSM

$\Rightarrow$ HVV couplings bounded by SM values: $\Gamma_V \leq \Gamma_V^{\rm SM}$ $(V = W, Z)$

$\Rightarrow$ Upper bound on Γ_V

Observation of Higgs production

$\Rightarrow$ Lower bound on production couplings, lower bound on total Higgs width, $\Gamma_{\rm tot}$

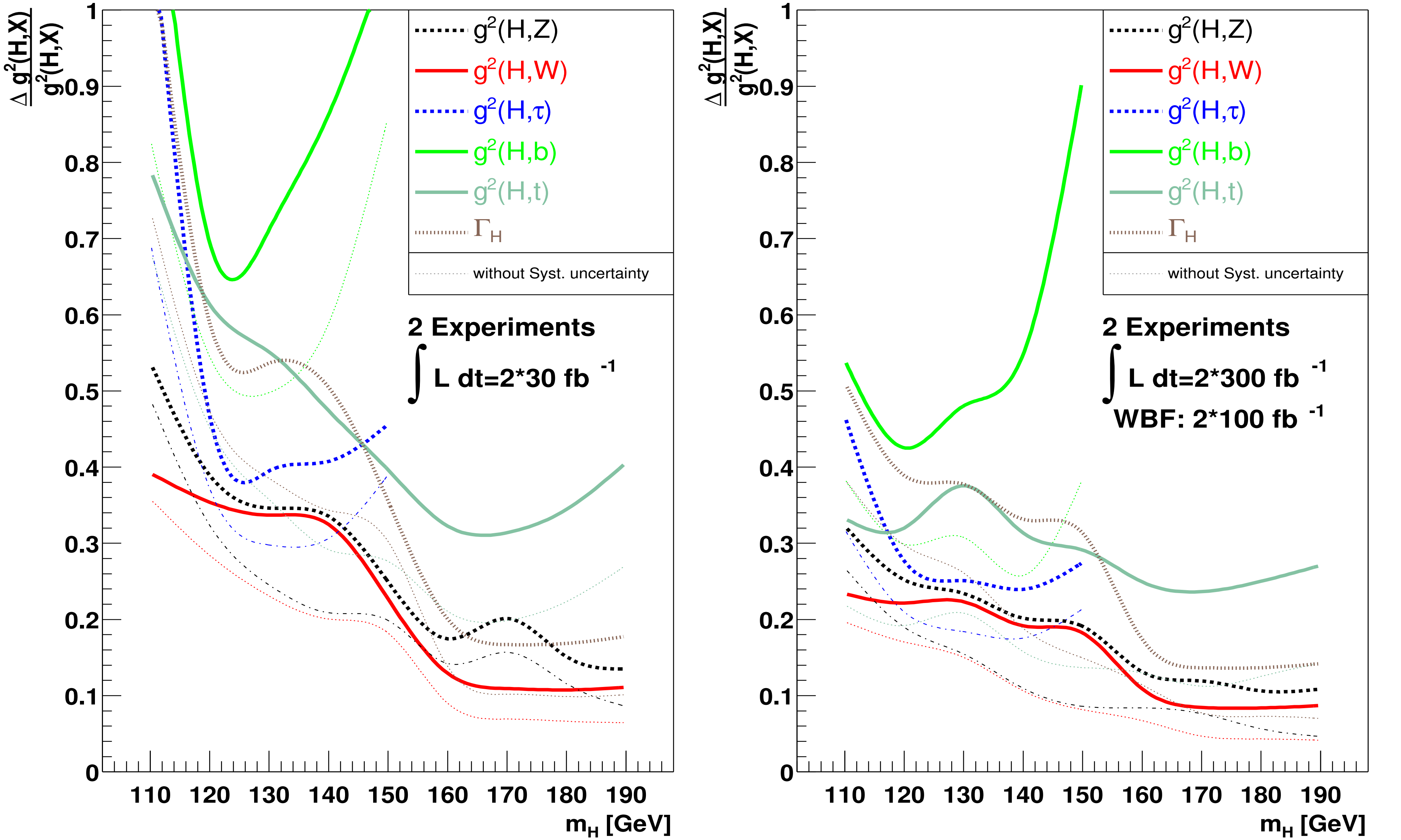
Observation of $H \to VV$ in WBF

$\Rightarrow$ Determines $\Gamma_V^2/\Gamma_{\rm tot}$ $\Rightarrow$ Upper bound on $\Gamma_{\rm tot}$

$\Rightarrow$ Absolute determination of $\Gamma_{\rm tot}$ and remaining Higgs couplings

Results for the couplings and the total Higgs width, relative precisions

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



Measurement of the top Yukawa coupling at LHC ⊕ ILC

Only crude measurement of tth coupl. at 500 GeV ILC (light Higgs)

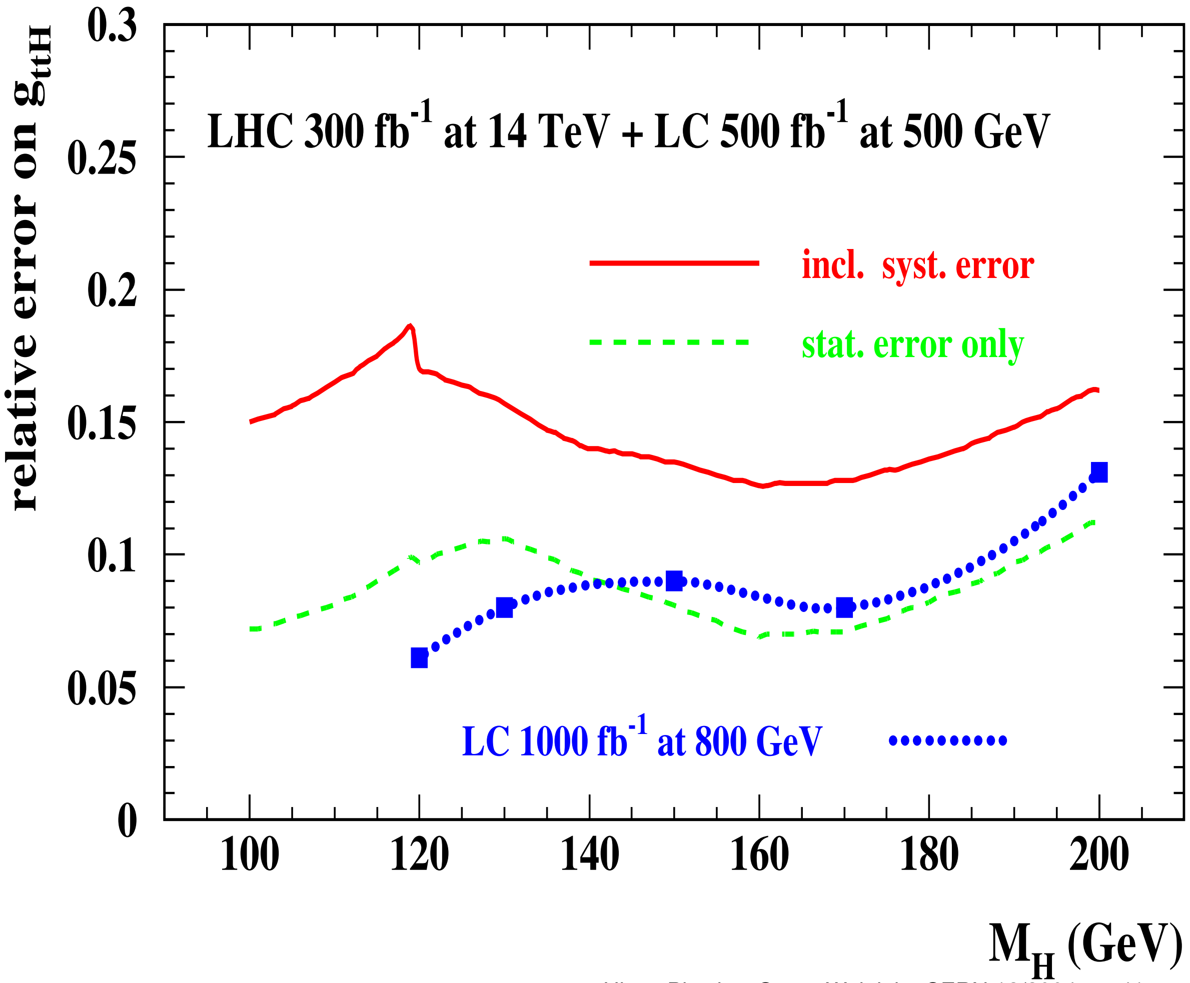
Precision measurement requires ILC with 800–1000 GeV

LHC measures ($\sigma \times \mathrm{BR}$)

$\Rightarrow$ Yukawa coupling can be extracted if precise measurement of Higgs BR's from ILC are used

LHC ⊕ ILC (500 GeV):

[*K. Desch, M. Schumacher '04*]



Higgs–radion mixing

[M. Battaglia, S. De Curtis, A. De Roeck, D. Dominici, J. Gunion '03]

Models with 3-branes in extra dimensions predict radion ϕ, can mix with the Higgs

$\Rightarrow$ Higgs properties modified, can be difficult to detect at the LHC

LHC may observe radion instead

ILC guarantees Higgs observation over full parameter space

$\Rightarrow$ precision measurements at ILC crucial to disentangle the nature of the observed state

LHC: large sensitivity to production of Kaluza-Klein excitations

4. Conclusions

- A Higgs sector with (at least) one light SM-like Higgs continues to be our best bet for what Higgs physics will be like
- However: things can be very different already in the MSSM:

  Completely different BRs, Higgs decays into undetectable modes, Higgs decays into SUSY particles, SUSY decays into Higgs, $\mathcal{CP}$ violation in the Higgs sector, ...

  In more exotic scenarios: Higgs–radion mixing, ...
- Discovering a Higgs can only be a first step, need to determine its properties $\Rightarrow$ make sure that it is really a Higgs, distinguish between different models
- LHC / ILC synergy extends physics potential of both machines, see `www.ippp.dur.ac.uk/~georg/lhclc`