Basics of Higgs Physics

Sven Heinemeyer, IFCA (Santander)

Karlsruhe, 07/2007

1. The Higgs Boson in the SM

2. The Higgs Boson in the MSSM

Basics of Higgs Physics (II)

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1. The Higgs Boson in the SM (2/3) + (1/3)
2. The Higgs Boson in the MSSM (1/3) + (2/3)

The Higgs Boson in the SM

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1. Higgs Theory
2. Electroweak Precision Observables
3. Properties of the SM Higgs boson
4. SM Higgs boson Searches at LEP
5. SM Higgs boson Searches at the Tevatron
6. SM Higgs boson Searches at the LHC
7. SM Higgs boson precision physics at the ILC

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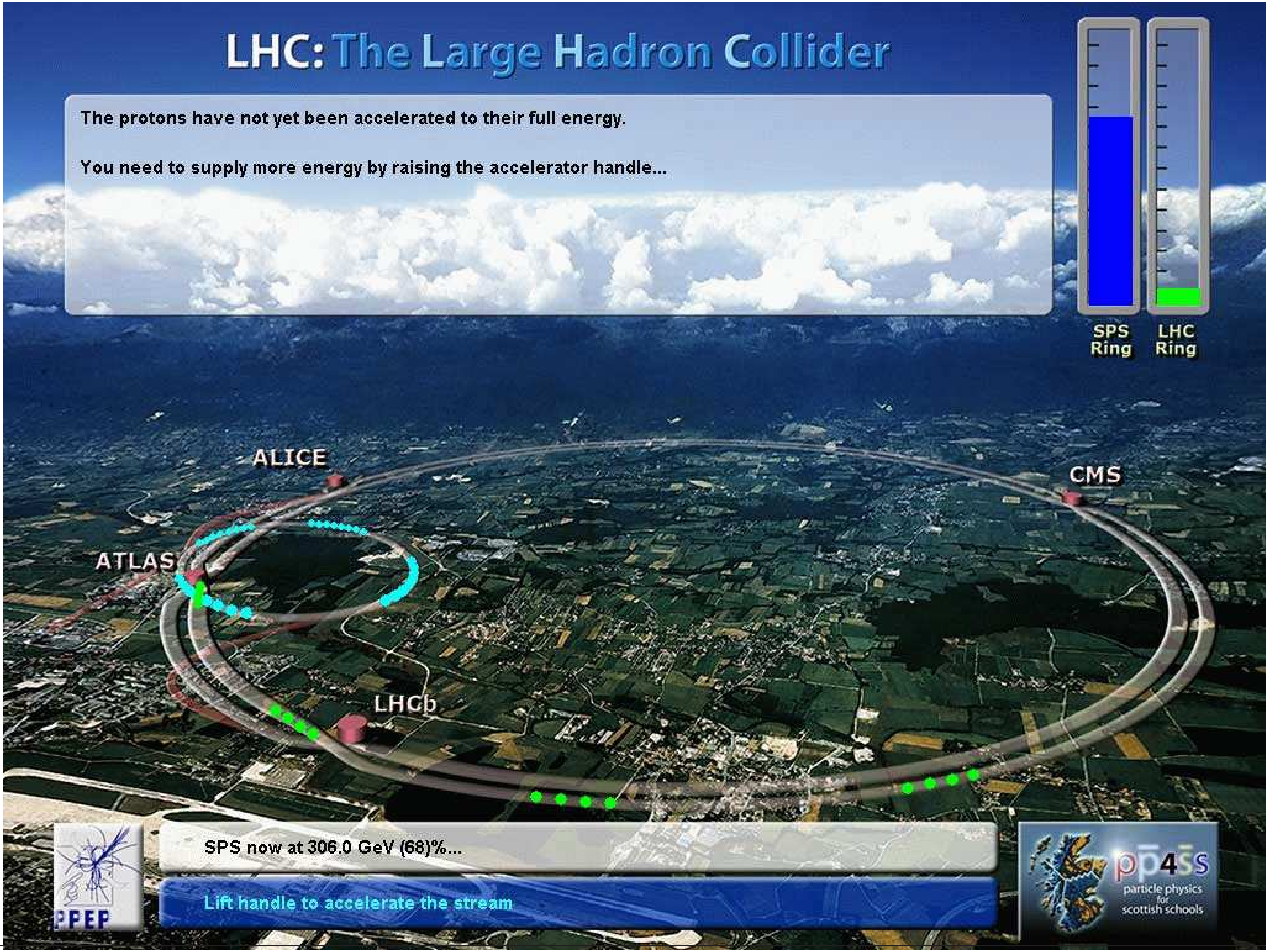
6. SM Higgs boson searches at the LHC

LHC: pp accelerator: start: fall 2007 $\longrightarrow$ T

The (un)official (optimistic?) LHC timeline:

2007 (11/07): fixing the inner triplets
collisions at $\sqrt{s} = 2 \times 450$ GeV canceled
2008 (05/08): first collisions
2008: 0.1 fb^{-1} – 1 fb^{-1} (at best) $\Rightarrow$ first physics results?
2009: $\mathcal{O}$(few) fb^{-1} $\Rightarrow$ first physics results?
2010 – 2012: 10 fb^{-1} per year $\Rightarrow$ physics results with "low" luminosity
2013 – ?: 100 fb^{-1} per year $\Rightarrow$ physics results with "high" luminosity
2015 + X (X > 0): upgrade to SLHC?


LHC: The Large Hadron Collider
The protons have not yet been accelerated to their full energy.
You need to supply more energy by raising the accelerator handle...
SPS Ring
LHC Ring
ALICE
CMS
ATLAS
LHCb
SPS now at 306.0 GeV (68)%...
Lift handle to accelerate the stream
PPEP
pp4ss
particle physics for scottish schools

6. SM Higgs boson searches at the LHC

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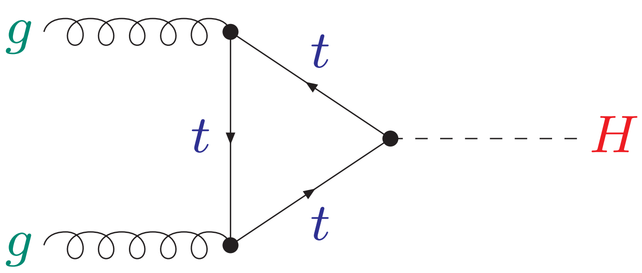
2015 + X (X > 0): upgrade to SLHC?

YOU live in an exciting time!!!

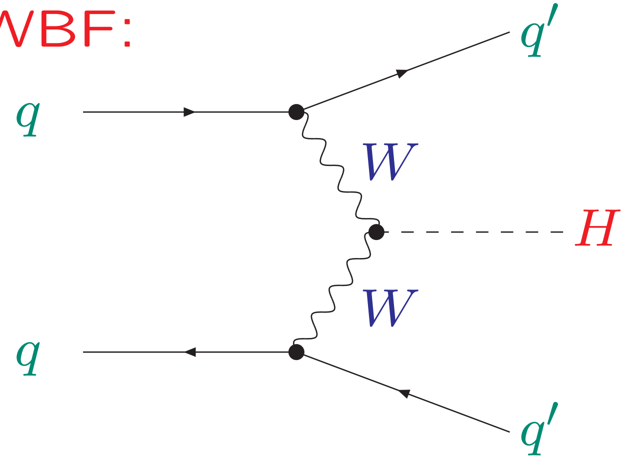
Examples for Higgs production and decay at the LHC:

Important production channel at the LHC:

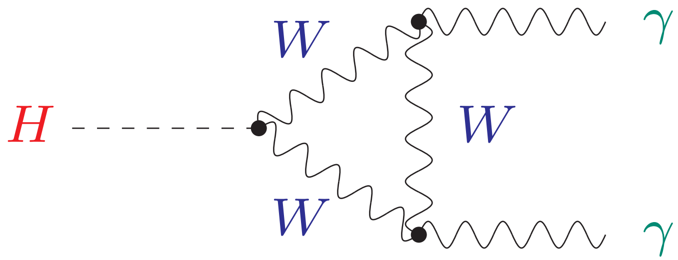
Gluon-Fusion:

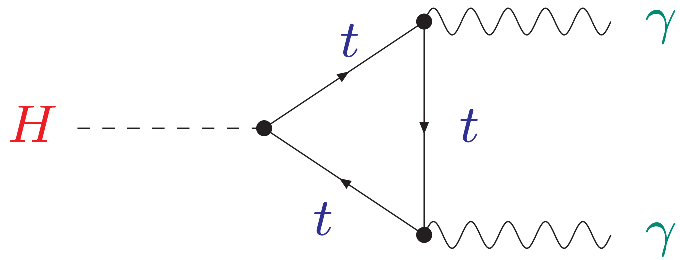


WBF:



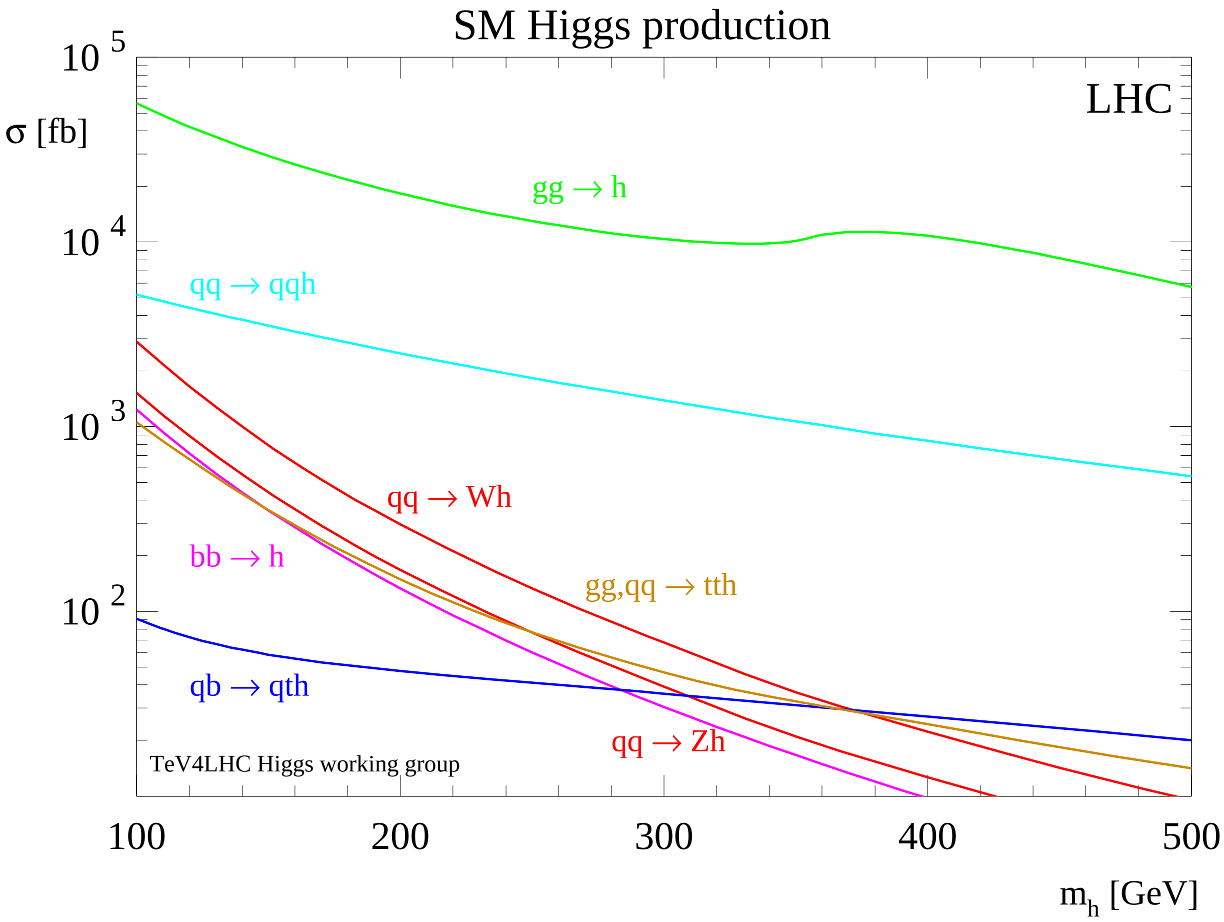
Important decay for Higgs mass measurement:





Step 1: Discovery of the new particle

SM Higgs production at the LHC:



gluon fusion: $gg \longrightarrow H$

weak boson fusion (WBF): $q\bar{q} \longrightarrow q'\bar{q}'H$

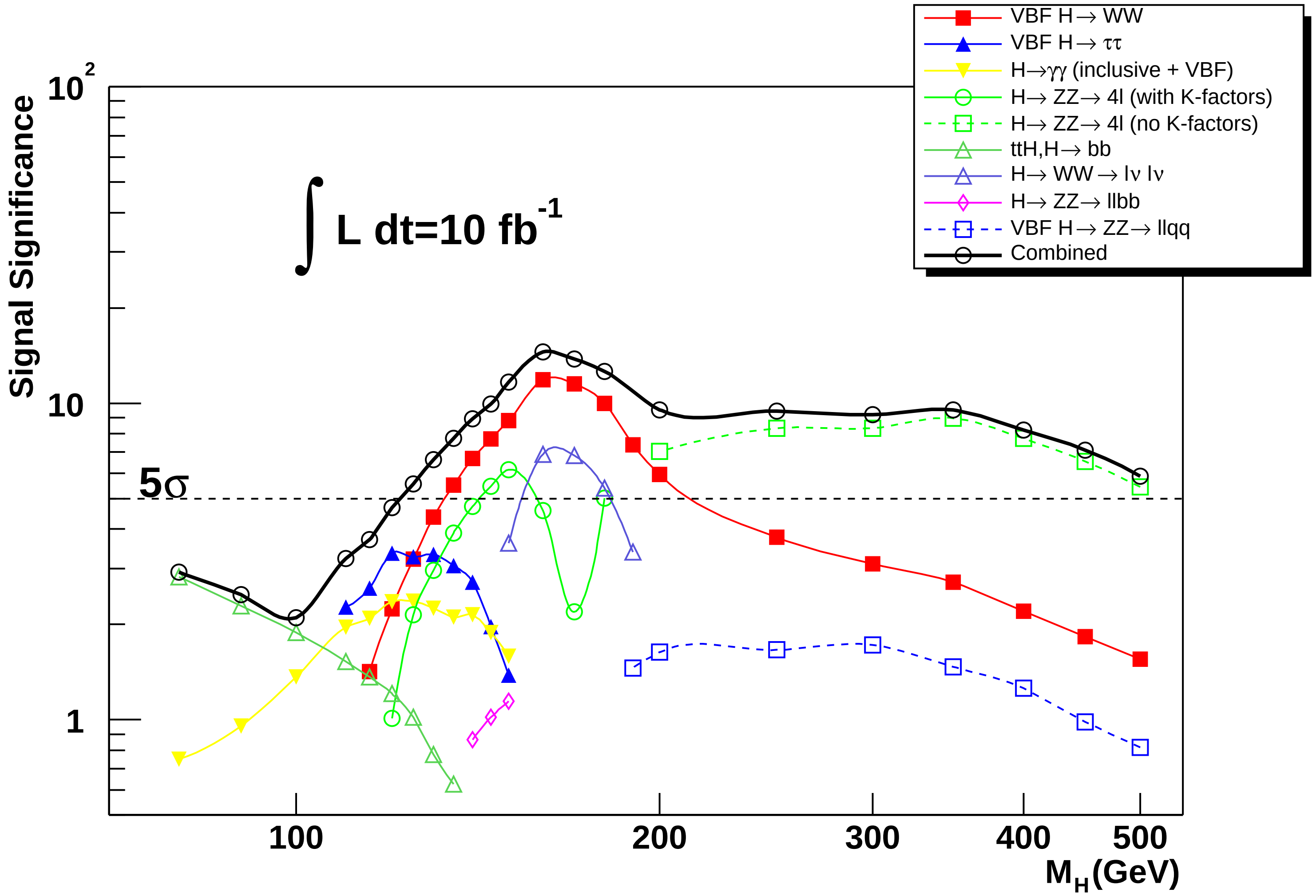
top quark associated production: $gg, q\bar{q} \longrightarrow t\bar{t}H$

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

SM Higgs search at the LHC: $\Rightarrow$ full parameter space accessible

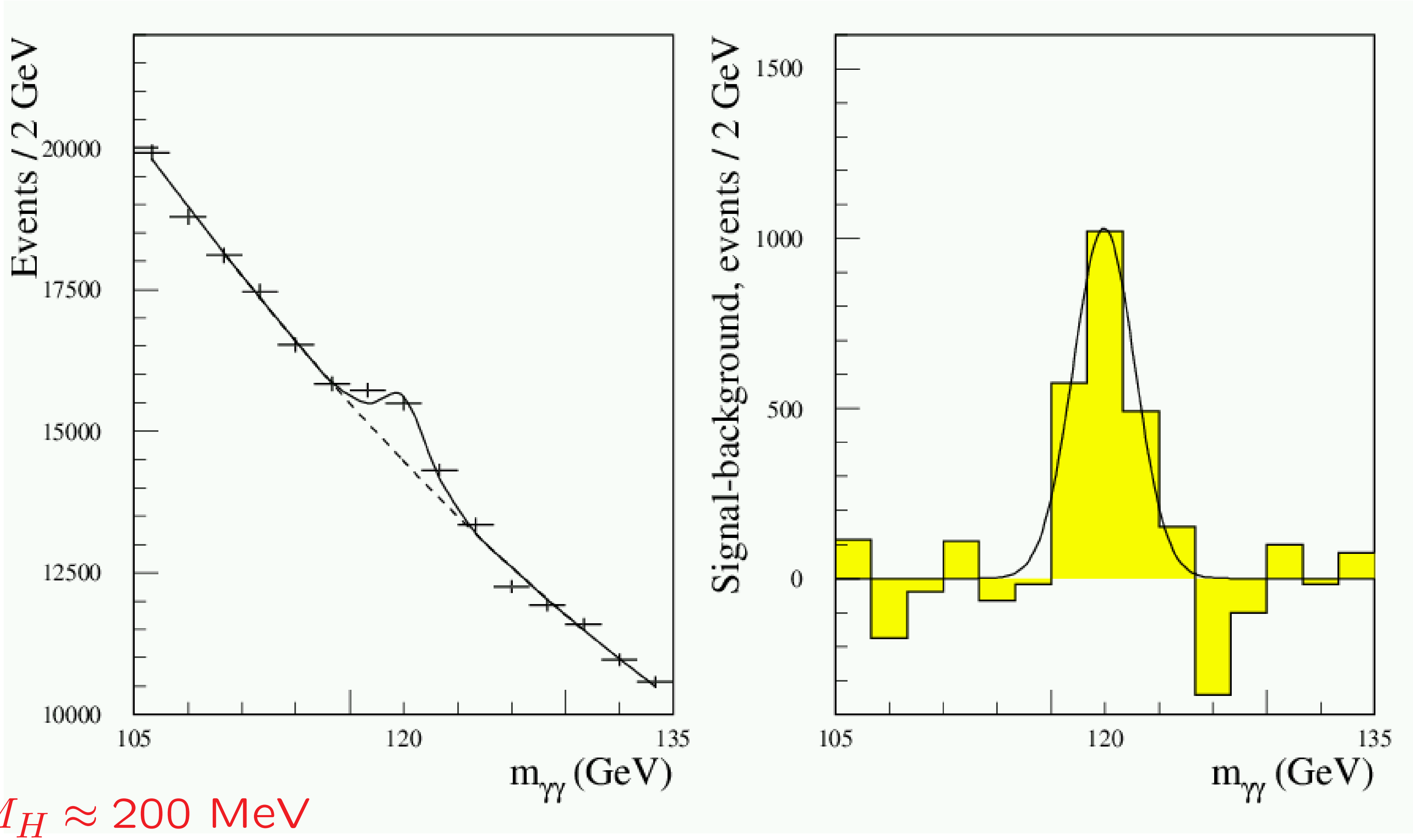
SM Higgs search at the LHC: ⇒ full parameter space accessible

[ATLAS '05]



Step 2: Measurement of the mass

Best channel for mass measurement in the SM: $H \to \gamma\gamma$
[*ATLAS '99*]



$\Rightarrow \delta M_H \approx$ 200 MeV

Step 3, 4: measurement of couplings to gauge bosons and fermions

Measurements for a SM Higgs (or SM-like MSSM Higgs) at the LHC:

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

$$\Rightarrow \sigma(H) \times \mathrm{BR}(H \to xx) \; = \; \sigma(H)^{\mathrm{SM}} \cdot \frac{\Gamma_{\mathrm{prod}}}{\Gamma_{\mathrm{prod}}^{\mathrm{SM}}} \times \frac{\Gamma_{\mathrm{partial}}}{\Gamma_{\mathrm{tot}}}$$

Observation of different channels

$\Rightarrow$ Information about combinations of $\Gamma_b, \Gamma_\tau, \Gamma_W, \Gamma_Z, \Gamma_g, \Gamma_\gamma, Y_t^2$

$\Rightarrow$ Additional theory assumptions necessary for absolute determination of partial widths

Only assumption:

$\rightarrow$ consider general multi Higgs-Doublet model
w/o additional Higgs-Singlets
($\Rightarrow$ includes e.g. MSSM)

$\Rightarrow$ Absolute Determination of Γ_{tot} and Higgs couplings in a global fit

$\Rightarrow$ (nearly) model independent analysis

Luminosity at the LHC:

- $2 * 30\ \text{fb}^{-1}$: 30 fb^{-1} in each of the two experiments
- $(2*300+2*100)\ \text{fb}^{-1}$: 300 fb^{-1} in each experiment, but only 100 fb^{-1} usable for gauge boson fusion

Estimate of errors:

1.) Statistical errors:

Assumption: SM rates for production and decay in all scenarios

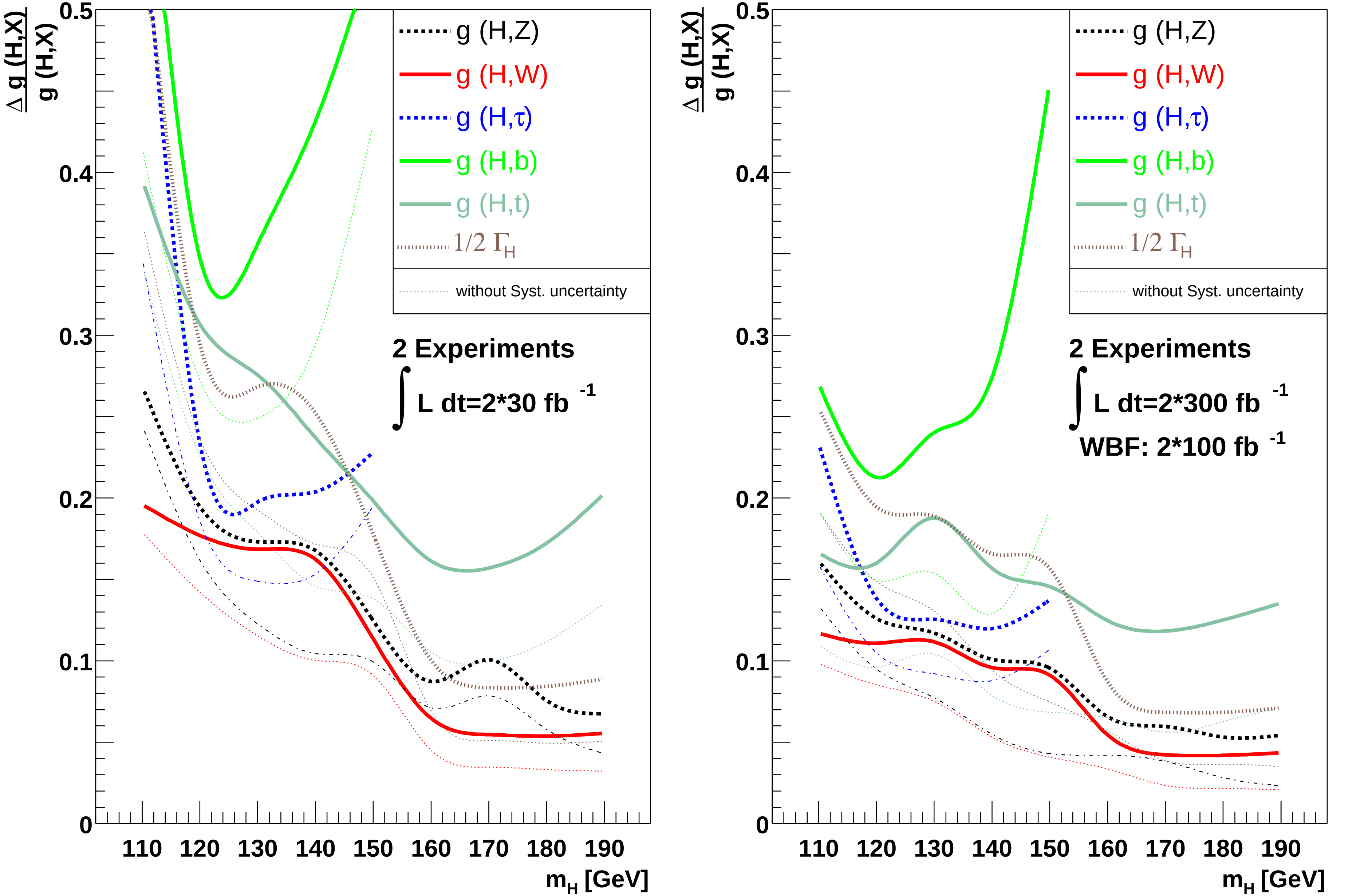
2.) Systematic errors:

$\rightarrow$ attempt to include realistically all possible errors

$\Rightarrow$ "log likelihood" function,
based on statistical and systematic errors

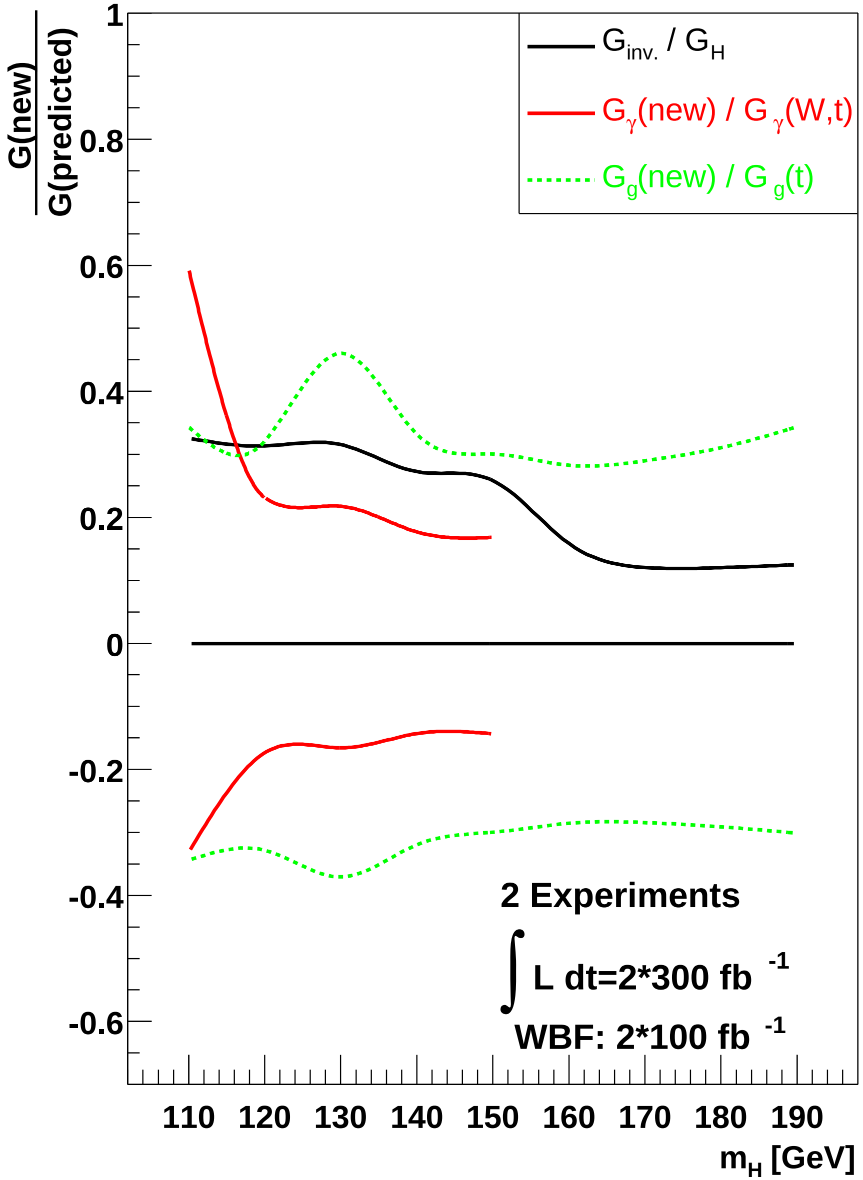
Relative precision for partial and total Higgs widths: two scenarios

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



Constraints on extra partial widths:

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



measurement of SM rates

$\Rightarrow$ constraints on widths:

$(2 * 300 + 2 * 100)$ fb^{-1} scenario:

$\Delta\Gamma_\gamma \leq 0.2 \times \Gamma_\gamma^{\rm SM}$

$\Delta\Gamma_g \leq 0.4 \times \Gamma_g^{\rm SM}$

$\Delta\Gamma_{\rm inv} \leq 0.2 \times \Gamma_{\rm tot}^{\rm SM}$

$\Rightarrow$ restrictions on new physics!

Results:

Absolute determination of Higgs couplings is possible!

Scenario with low luminosity: $2 * 30\ \text{fb}^{-1}$:

for a light Higgs: results significantly worse in comparison with higher luminosity

Scenario with higher luminosity: $(2 * 300 + 2 * 100)\ \text{fb}^{-1}$:

– typical precision of 15-25% for $m_H \lesssim 150$ GeV

– 5% accuracy for HVV couplings above WW threshold

Systematic errors contribute about 50% to the total error, especially at high luminosity

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– 5% accuracy for HVV couplings above WW threshold

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What happens with non-SM rates?

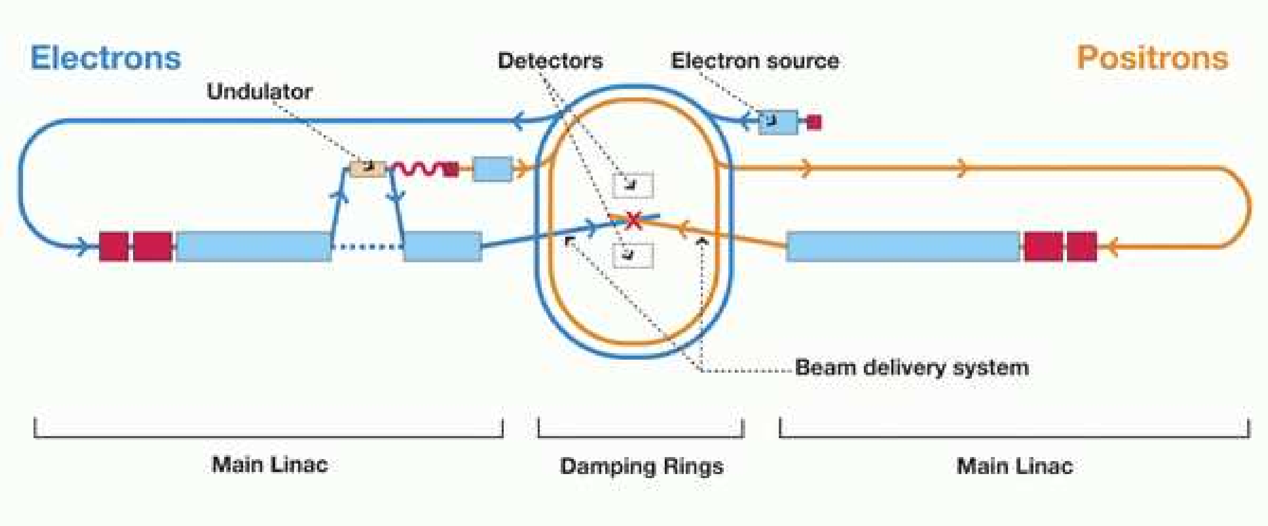
$\Rightarrow$ not analyzed yet . . .

7. SM Higgs boson precision physics at the ILC

Linear e^+e^- collider, $\sqrt{s} = 500 - 1000$ GeV

based on superconducting cavities (cold technology) (ITRP decision 2004)

Schematic:

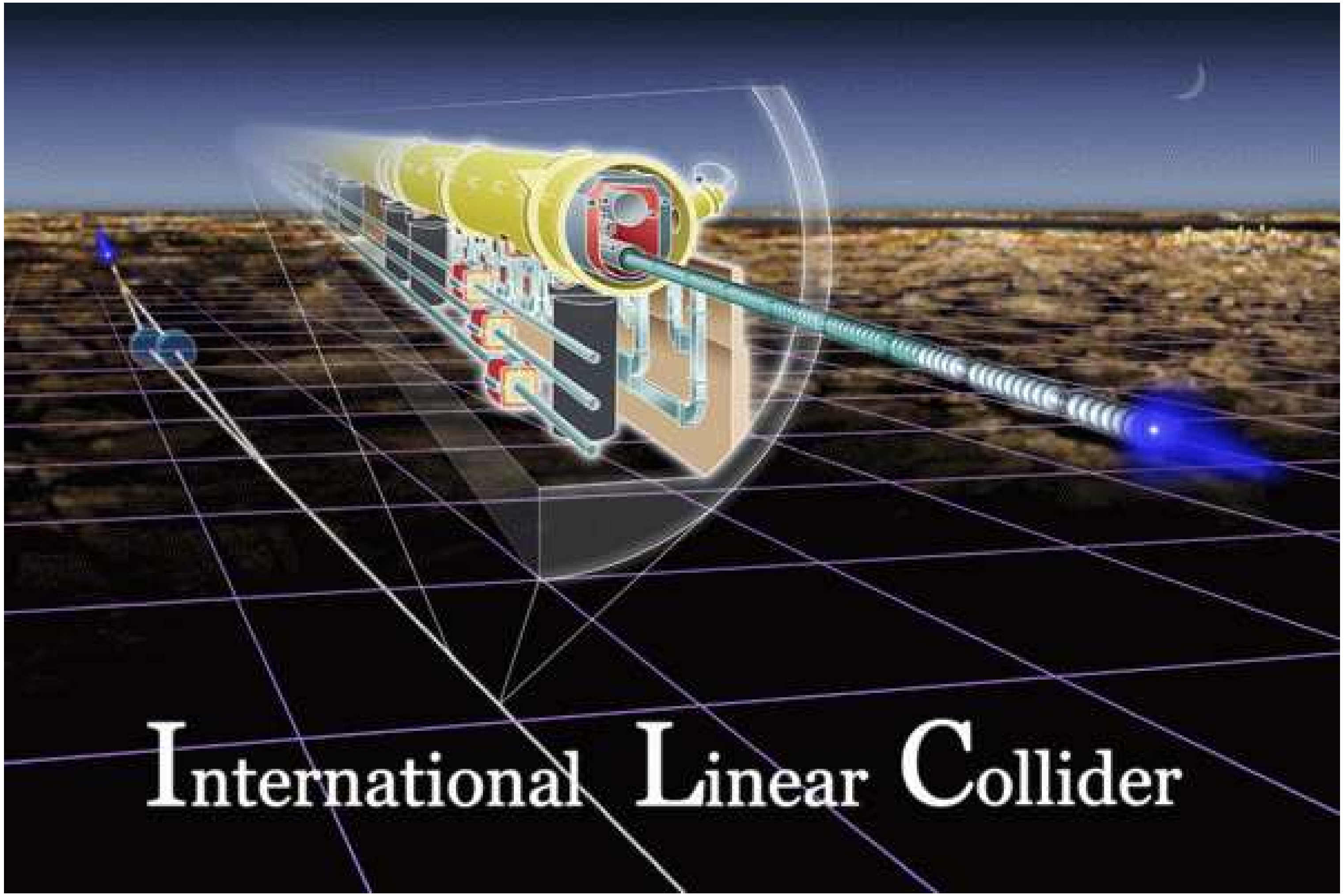


– 1 interaction regions (push-pull, with crossing angle)

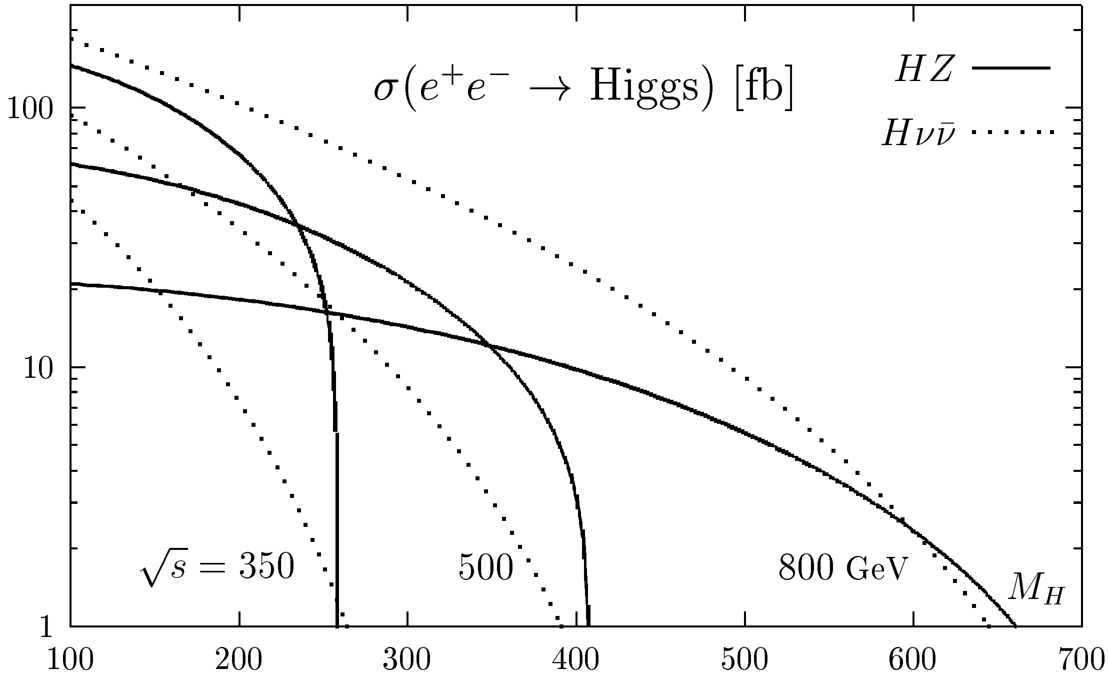
– undulator based e^+ source

– polarized beams for e^- and e^+ ($P_{e^-} = 80\%$, $P_{e^+} = 60\%$)

The tunnel and the tubes:

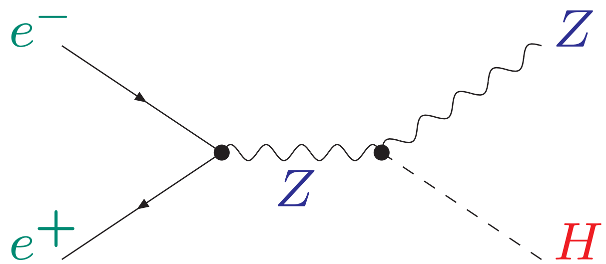


Higgs production at the ILC:



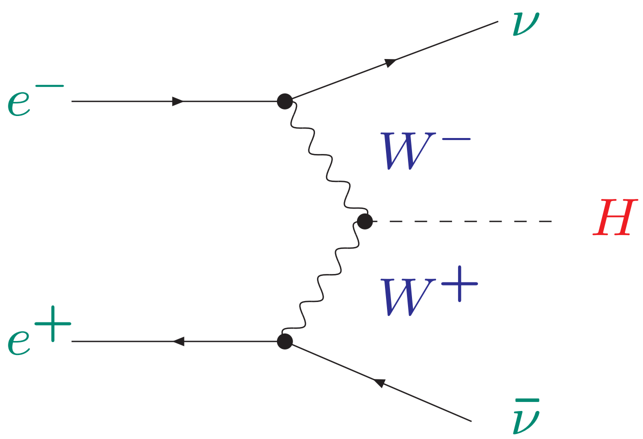
Higgs-strahlung:

$e^+e^- \to Z^* \to ZH$



weak boson fusion (WBF):

$e + e- \to \nu\bar{\nu}H$



$\Rightarrow$ Measurement of masses, couplings, ... in per cent/per mille

Some ILC specifics:

recoil method: $e^+e^- \to ZH$, $Z \to e^+e^-, \mu^+\mu^-$

$\Rightarrow$ total measurement of Higgs production cross section

$\Rightarrow$ NO additional theoretical assumptions needed for absolute determination of partial widths

$\Rightarrow$ all observable channels can be measured with high accuracy

Some ILC results (500 fb^{-1}@$\sqrt{s} = 350$ GeV):

$\delta M_H \approx 50$ MeV
$\delta g_{ZZH} \approx 2.5\%$, $\quad \delta g_{WWH} \approx 2 - 5\%$
$\delta g_{Hb\bar{b}} \approx 1 - 2\%$ (for $M_H \lesssim 150$ GeV)

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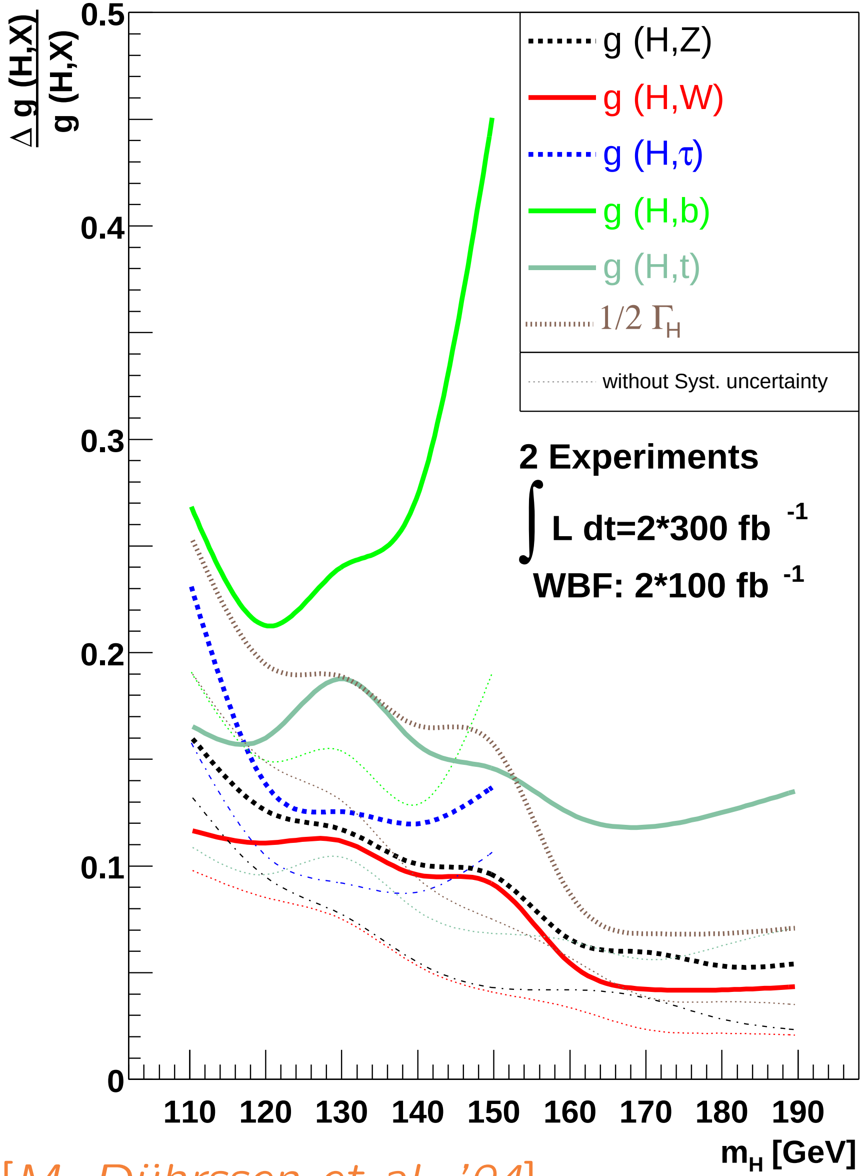
How does this compare to the LHC?

The LHC will find a Higgs and measure its characteristics:



[M. Dührssen et al. '04]

– mass: $\delta M_h \approx 200$ MeV

– couplings: $(2 * 300 + 2 * 100)$ fb^{-1} :

typical accuracies of 20-30%

for $m_H \leq 150$ GeV

10% accuracies for HVV couplings

above WW threshold

Assumption:

– $g^2_{HVV} \leq g^2_{HVV,\text{SM}} \times 1.05$

– SM rates for the Higgs

Problems:

– valid in weakly interacting models

– rates much lower than in SM ??

– physics can/will hide in 5% margin

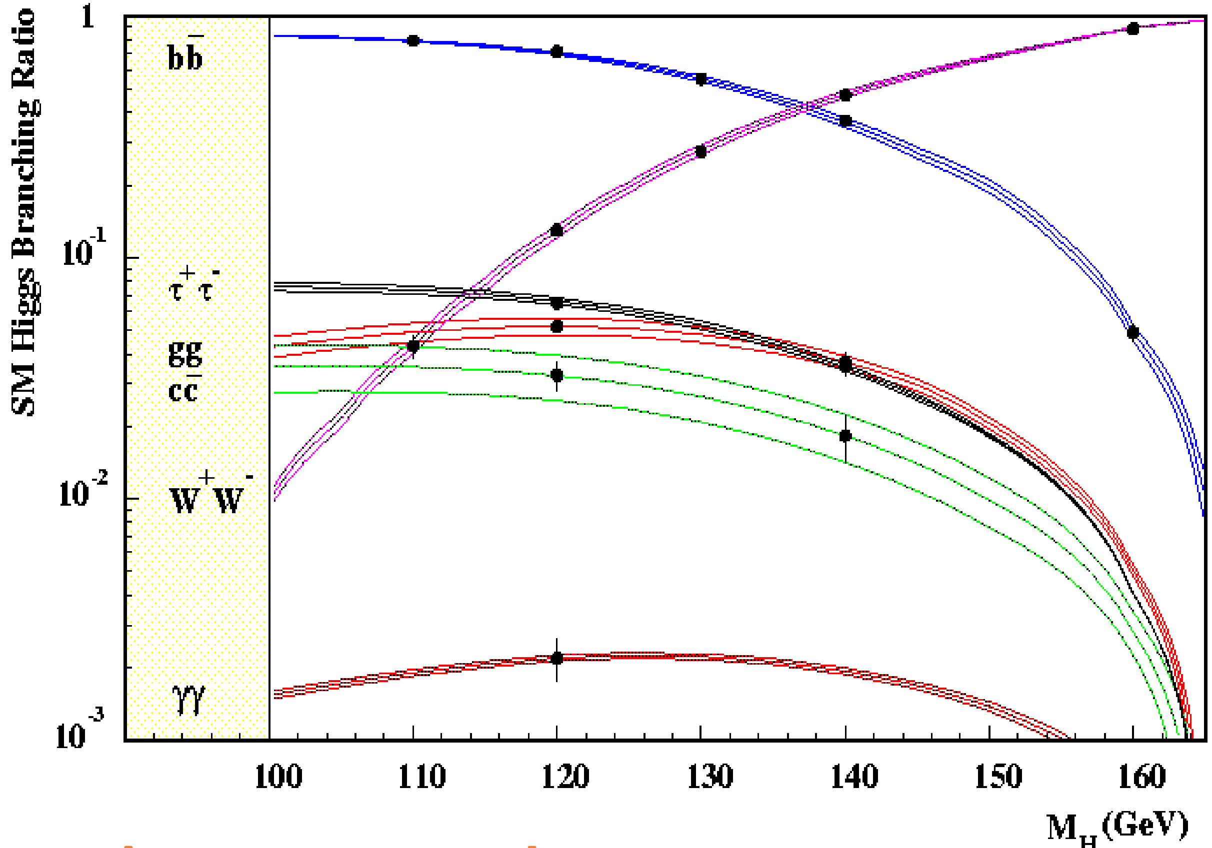
– self-couplings out of reach

$\Rightarrow$ ILC comes in

Compare to the ILC:

SM Higgs @ ILC:
Precise measurement of:

1. Higgs boson mass, $\delta M_H \approx 50$ MeV
2. Higgs boson width (direct/indirect)
3. Higgs boson couplings, $\mathcal{O}$ (few%) $\Rightarrow$
4. Higgs boson quantum numbers: spin, . . .



[*TESLA TDR '01*]

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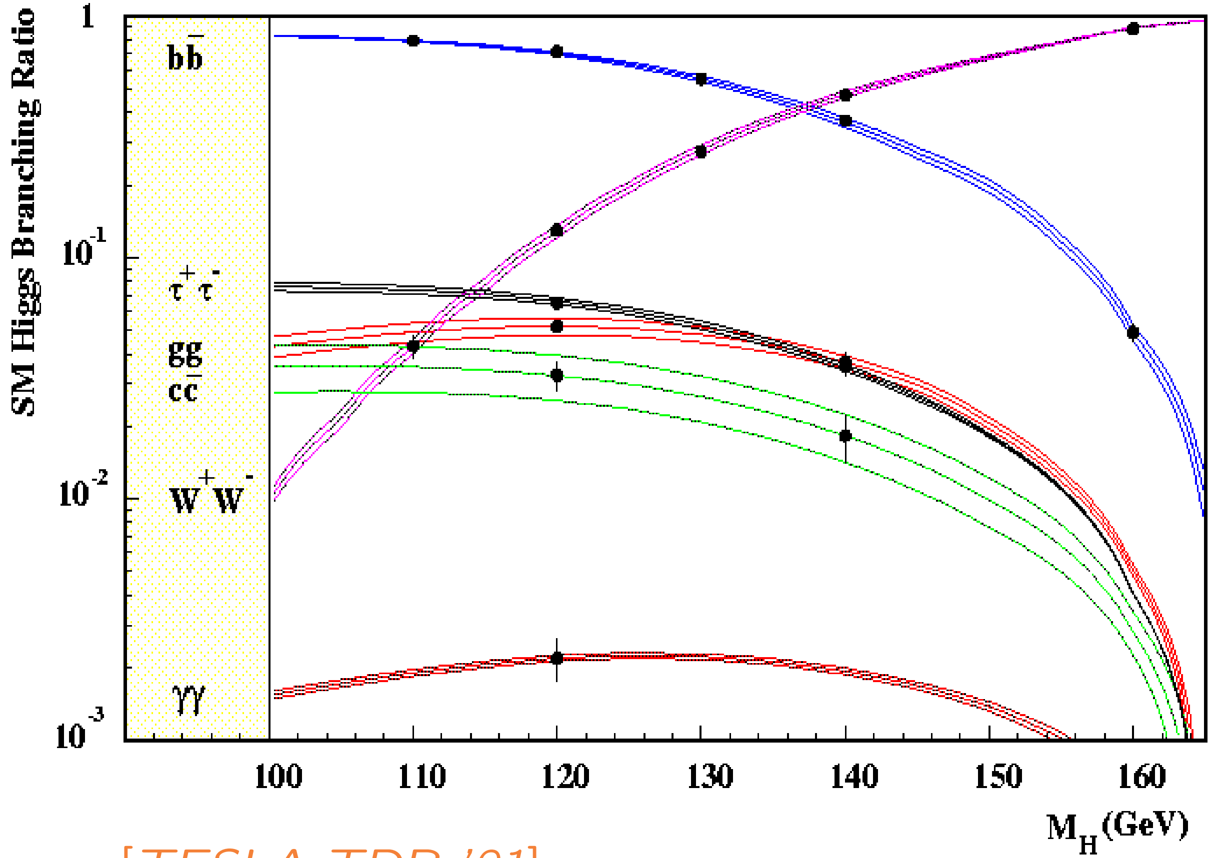

[*TESLA TDR '01*]

But do we need the ILC precision?

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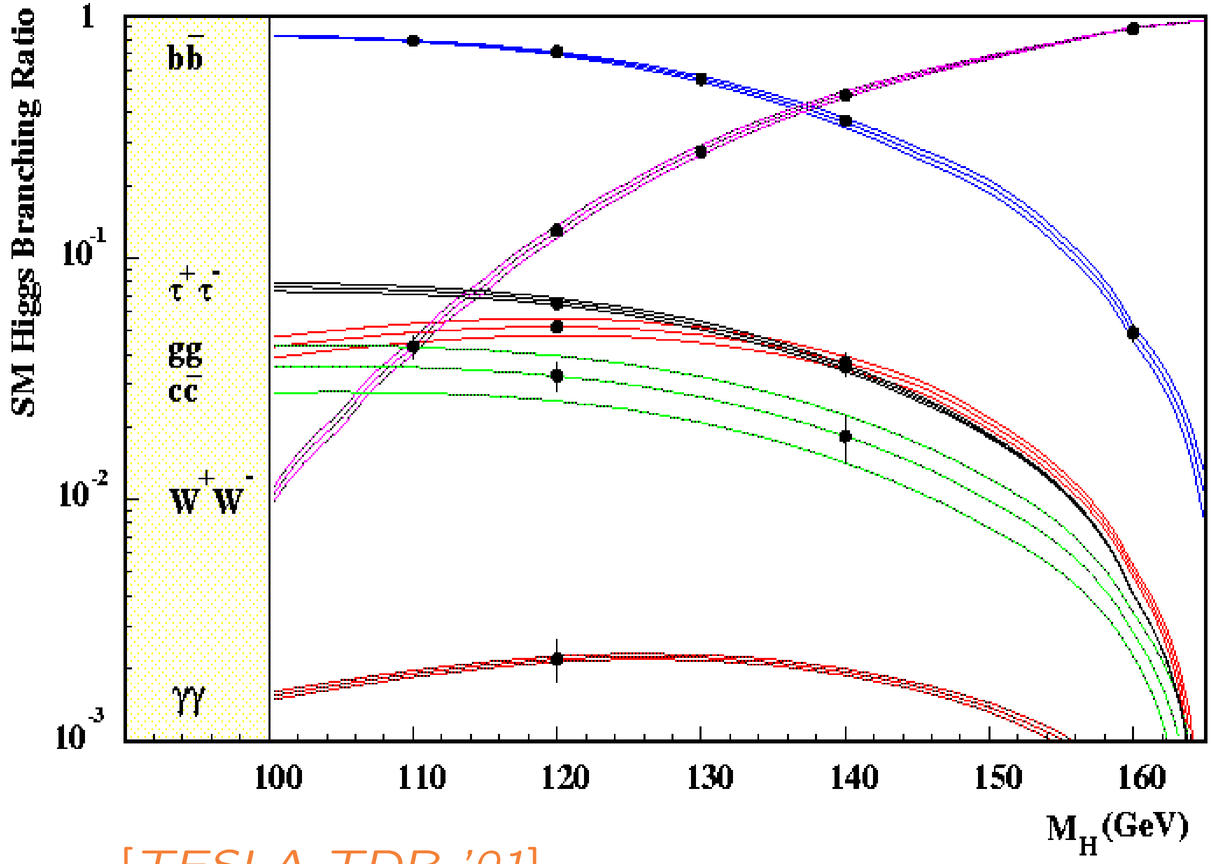


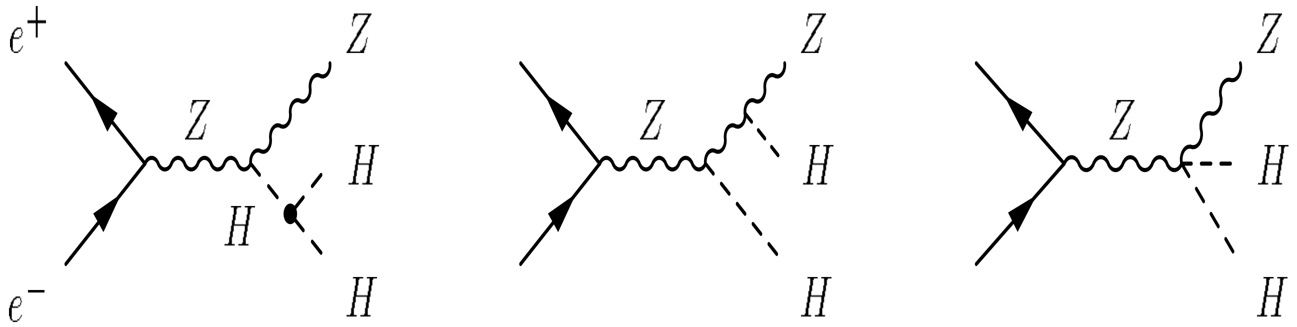
[*TESLA TDR '01*]

But do we need the ILC precision?

YES! To discriminate between the SM and extensions

Step 5: measurement of the Higgs boson self-coupling

$\Rightarrow$ only possible at the ILC



Parton-level study:

[*Djouadi, Kilian, Mühlleitner, Zerwas '99*]

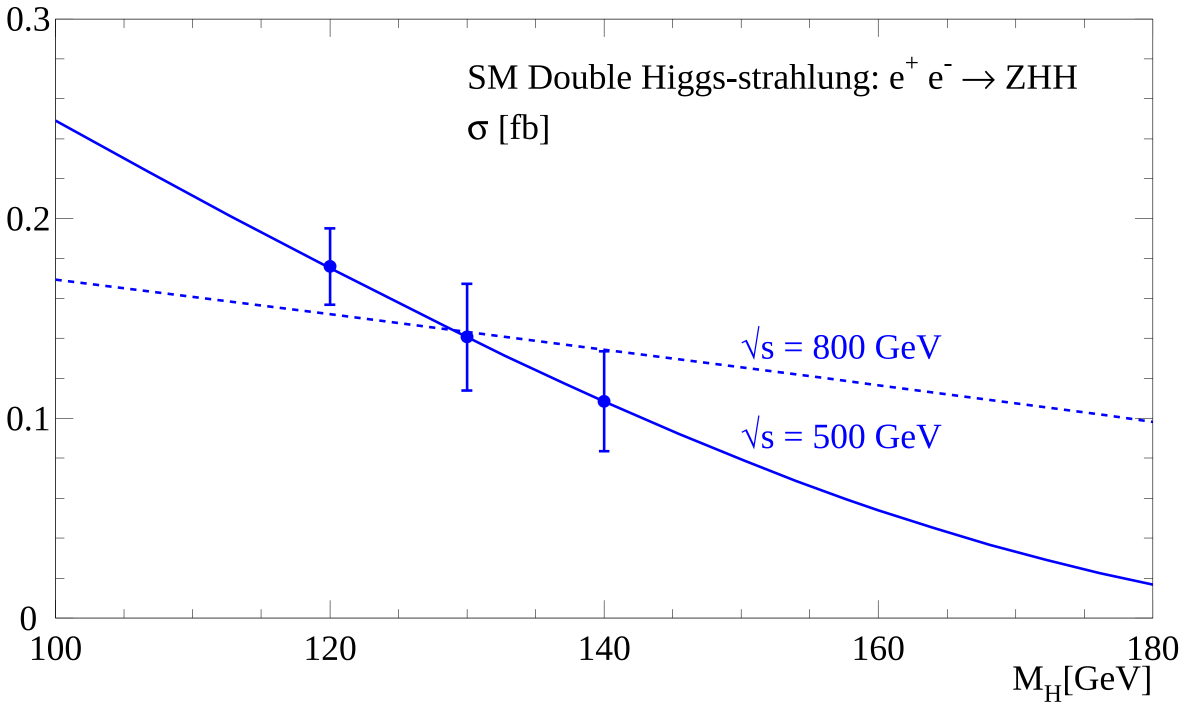
1 ab^{-1} $\Rightarrow$ 20–30%

measurement of $\lambda = \lambda_{HHH}$

However:

$\lambda = \lambda_{HHHH}$ out of reach

for all forseable colliders



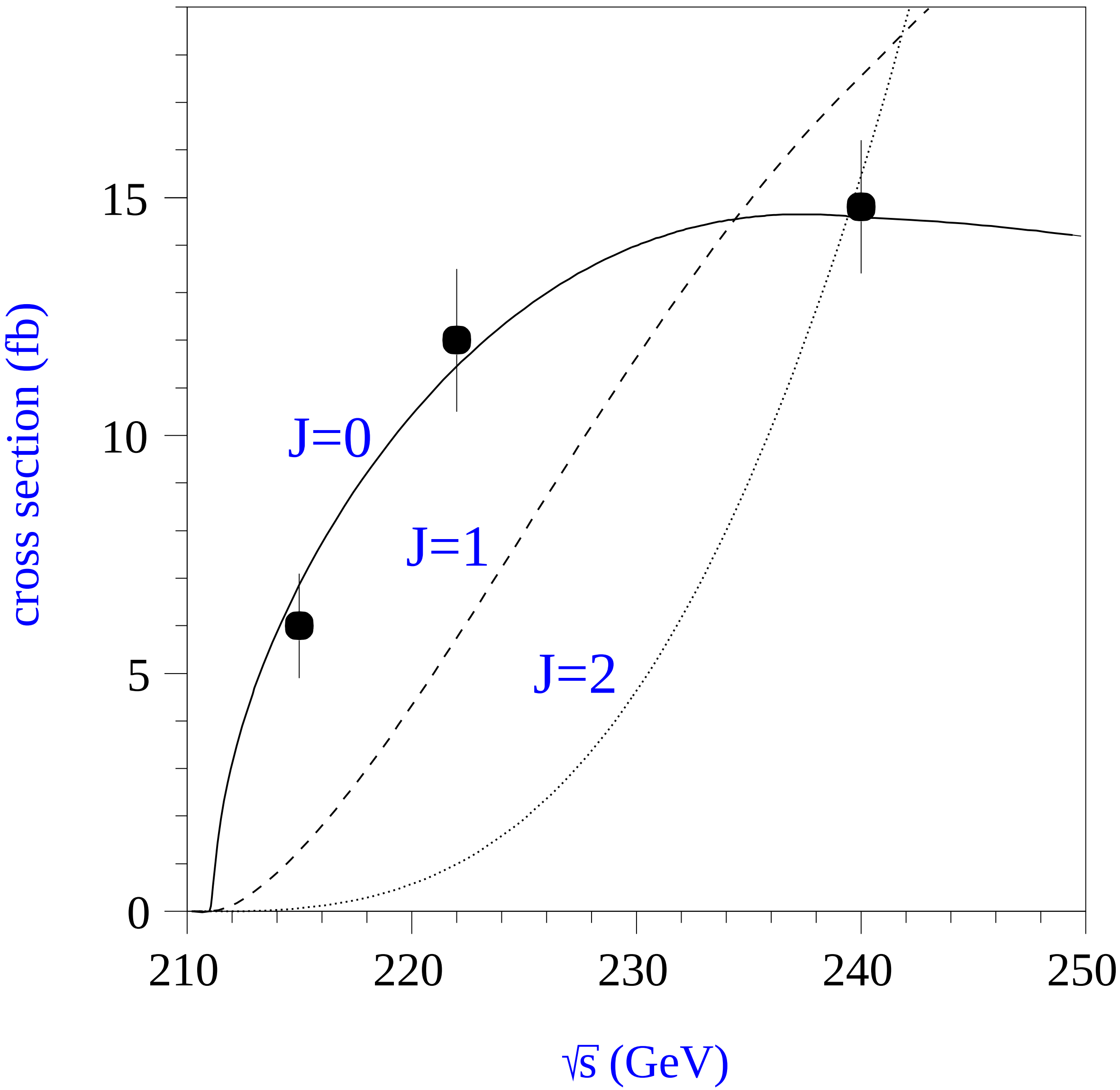
Step 6: measurement of the Higgs boson spin

$\Rightarrow$ easy at the ILC

Threshold scan for
$\sigma(e^+e^- \to ZX)$:

$X = H \Rightarrow \sigma \sim \beta$
(for β see eq. (1))

20 fb^{-1}
$\Rightarrow$ identification easy



The Higgs Boson in the MSSM

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1. Motivation for SUSY

The Standard Model (SM) cannot be the ultimate theory

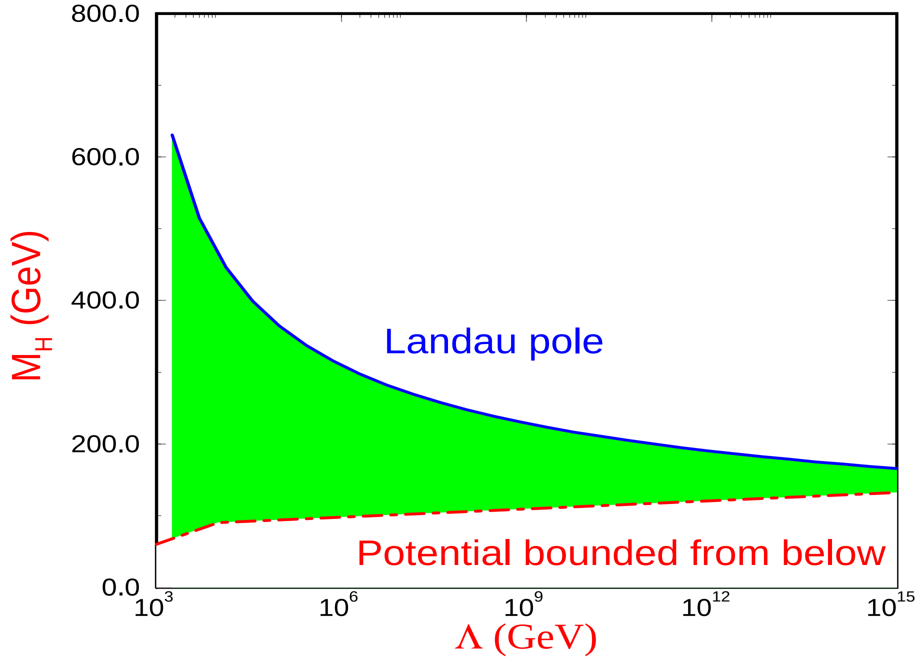
– The SM does not contain gravity

– Further problems: Hierarchy problem

Up to which energy scale Λ can the SM be valid?

– $\Lambda < M_{\mathrm{Pl}}$: inclusion of gravity effects necessary

– stability of Higgs potential: $\Rightarrow$

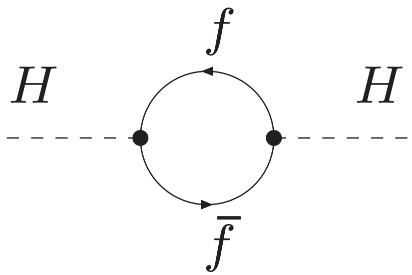


– Hierarchy problem :
Higgs mass unstable
w.r.t. quantum corrections
$\delta M_H^2 \sim \Lambda^2$
(but what does this mean?)

Mass is what determines the properties of the free propagation of a particle

Free propagation: 

inverse propagator: $i(p^2 - M_H^2)$

Loop corrections: 

inverse propagator: $i(p^2 - M_H^2 + \Sigma_H^f)$

QM: integration over all possible loop momenta k

dimensional analysis:

$$\Sigma_H^f \sim N_f \, \lambda_f^2 \int d^4k \left(\frac{1}{k^2 - m_f^2} + \frac{2m_f^2}{(k^2 - m_f^2)^2} \right)$$

$$\text{for } \Lambda \to \infty : \qquad \Sigma_H^f \sim N_f \, \lambda_f^2 \left(\underbrace{\int \frac{d^4k}{k^2}}_{\sim \Lambda^2} + 2m_f^2 \underbrace{\int \frac{dk}{k}}_{\sim \ln \Lambda} \right)$$

$\Rightarrow$ quadratically divergent!

For $\Lambda = M_{\rm Pl}$:

$$\Sigma_H^f \approx \delta M_H^2 \sim M_{\rm Pl}^2 \quad \Rightarrow \quad \delta M_H^2 \approx 10^{30}\, M_H^2$$

(for $M_H \lesssim 1$ TeV)

– no additional symmetry for $M_H = 0$

– no protection against large corrections

$\Rightarrow$ Hierarchy problem is instability of small Higgs mass to large corrections in a theory with a large mass scale in addition to the weak scale

E.g.: Grand Unified Theory (GUT): $\delta M_H^2 \approx M_{\rm GUT}^2$

Note however: there is another fine-tuning problem in nature, for which we have no clue so far – cosmological constant

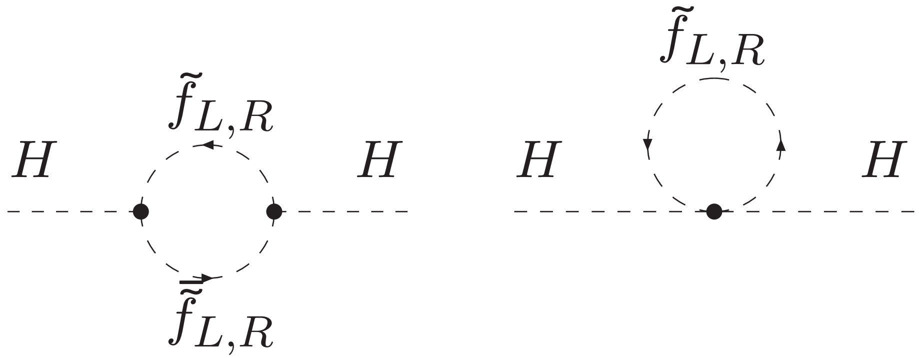
Supersymmetry:

Symmetry between fermions and bosons

$$Q|\text{boson}\rangle = |\text{fermion}\rangle$$
$$Q|\text{fermion}\rangle = |\text{boson}\rangle$$

Effectively: SM particles have SUSY partners (e.g. $f_{L,R} \to \tilde{f}_{L,R}$)

SUSY: additional contributions from scalar fields:



$$\Sigma_H^{\tilde{f}} \sim N_{\tilde{f}}\, \lambda_{\tilde{f}}^2 \int d^4k \left(\frac{1}{k^2 - m_{\tilde{f}_L}^2} + \frac{1}{k^2 - m_{\tilde{f}_R}^2} \right) + \text{ terms without quadratic div.}$$

for $\Lambda \to \infty$: $\quad \Sigma_H^{\tilde{f}} \sim N_{\tilde{f}}\, \lambda_{\tilde{f}}^2\, \Lambda^2$

$\Rightarrow$ quadratic divergences cancel for

$$N_{\tilde{f}_L} = N_{\tilde{f}_R} = N_f$$
$$\lambda_{\tilde{f}}^2 = \lambda_f^2$$

complete correction vanishes if furthermore

$$m_{\tilde{f}} = m_f$$

Soft SUSY breaking: $m_{\tilde{f}}^2 = m_f^2 + \Delta^2, \quad \lambda_{\tilde{f}}^2 = \lambda_f^2$

$$\Rightarrow \Sigma_H^{f+\tilde{f}} \sim N_f \, \lambda_f^2 \, \Delta^2 + \ldots$$

$\Rightarrow$ correction stays acceptably small if mass splitting is of weak scale

$\Rightarrow$ realized if mass scale of SUSY partners

$$M_{\text{SUSY}} \lesssim 1\,\text{TeV}$$

$\boxed{\Rightarrow \text{SUSY at TeV scale provides attractive solution of hierarchy problem}}$

Supersymmetry (SUSY) : Symmetry between

$$\text{Bosons} \leftrightarrow \text{Fermions}$$

$$Q\ |\text{Fermion}\rangle \rightarrow |\text{Boson}\rangle$$
$$Q\ |\text{Boson}\rangle \rightarrow |\text{Fermion}\rangle$$

Simplified examples:

$$Q\ |\text{top},\ t\rangle \rightarrow |\text{scalar top},\ \tilde{t}\rangle$$
$$Q\ |\text{gluon},\ g\rangle \rightarrow |\text{gluino},\ \tilde{g}\rangle$$

$\Rightarrow$ each SM multiplet is enlarged to its double size

Unbroken SUSY: All particles in a multiplet have the same mass

Reality: $m_e \neq m_{\tilde{e}} \Rightarrow$ SUSY is broken . . .

. . . via soft SUSY-breaking terms in the Lagrangian (added by hand)

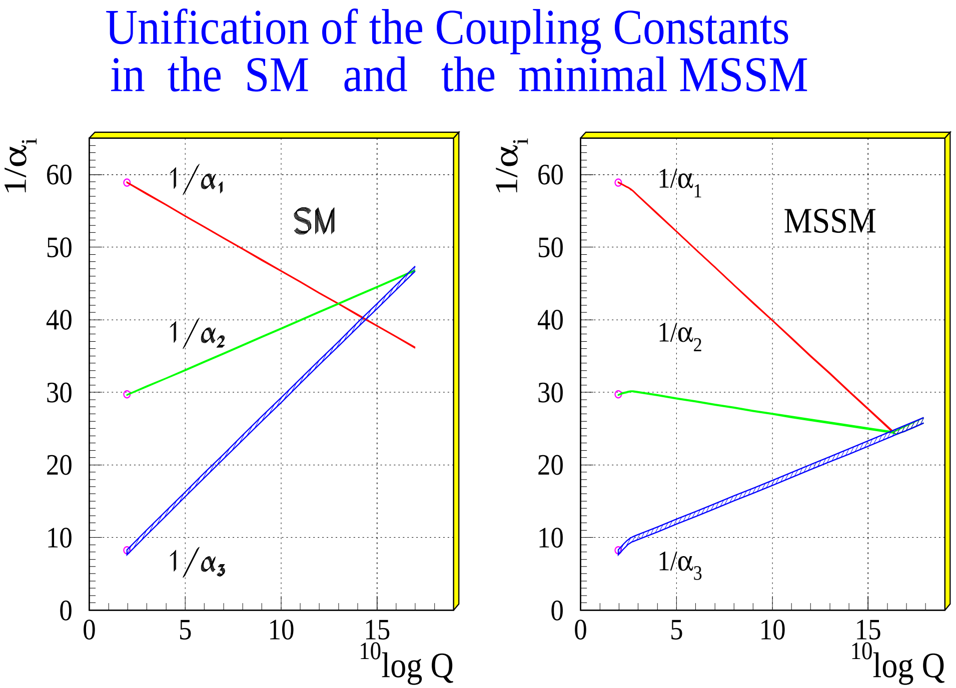
SUSY particles are made heavy: $\boxed{M_{\text{SUSY}} = \mathcal{O}(1\ \text{TeV})}$

Supersymmetry: Motivation

The SM is in a pretty good shape.

Why MSSM? (Is it worth to double the particle spectrum?)

1.) Stability of the Higgs mass against higher-order corr.
2.) Unification of gauge couplings: Not possible in the SM, but in the MSSM (although it was not designed for it.)
3.) Spontaneous symmetry breaking via Higgs mechanism is automatic in SUSY GUTs
4.) SUSY provides CDM candidate
5.) . . .



[*Amaldi, de Boer, Fürstenau '92*]

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

$$\Big[u, d, c, s, t, b\Big]_{L,R} \quad \Big[e, \mu, \tau\Big]_{L,R} \quad \Big[\nu_{e,\mu,\tau}\Big]_L \qquad \text{Spin } \tfrac{1}{2}$$

$$\Big[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}\Big]_{L,R} \quad \Big[\tilde{e}, \tilde{\mu}, \tilde{\tau}\Big]_{L,R} \quad \Big[\tilde{\nu}_{e,\mu,\tau}\Big]_L \qquad \text{Spin } 0$$

$$g \quad \underbrace{W^\pm, H^\pm} \quad \underbrace{\gamma, Z, H_1^0, H_2^0} \qquad \text{Spin 1 / Spin 0}$$

$$\tilde{g} \quad \tilde{\chi}^\pm_{1,2} \quad \tilde{\chi}^0_{1,2,3,4} \qquad \text{Spin } \frac{1}{2}$$

Enlarged Higgs sector: Two Higgs doublets

Problem in the MSSM: many scales

$\tilde{t}/\tilde{b}$ sector of the MSSM: (scalar partner of the top/bottom quark)

Stop, sbottom mass matrices ($X_t = A_t - \mu^*/\tan\beta$, $X_b = A_b - \mu^* \tan\beta$):

$$\mathcal{M}^2_{\tilde{t}} = \begin{pmatrix} M^2_{\tilde{t}_L} + m_t^2 + DT_{t_1} & m_t X_t^* \\ m_t X_t & M^2_{\tilde{t}_R} + m_t^2 + DT_{t_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{t}}} \begin{pmatrix} m^2_{\tilde{t}_1} & 0 \\ 0 & m^2_{\tilde{t}_2} \end{pmatrix}$$

$$\mathcal{M}^2_{\tilde{b}} = \begin{pmatrix} M^2_{\tilde{b}_L} + m_b^2 + DT_{b_1} & m_b X_b^* \\ m_b X_b & M^2_{\tilde{b}_R} + m_b^2 + DT_{b_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{b}}} \begin{pmatrix} m^2_{\tilde{b}_1} & 0 \\ 0 & m^2_{\tilde{b}_2} \end{pmatrix}$$

mixing important in stop sector (also in sbottom sector for large $\tan\beta$)

soft SUSY-breaking parameters A_t, A_b also appear in ϕ-$\tilde{t}/\tilde{b}$ couplings

$$SU(2) \text{ relation} \Rightarrow M_{\tilde{t}_L} = M_{\tilde{b}_L}$$

$\Rightarrow$ relation between $m_{\tilde{t}_1}, m_{\tilde{t}_2}, \theta_{\tilde{t}}, m_{\tilde{b}_1}, m_{\tilde{b}_2}, \theta_{\tilde{b}}$

2. MSSM Higgs Theory

Comparison with SM case:

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

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

In SUSY: term $\bar{Q}_L \Phi^\dagger$ not allowed

Superpotential is holomorphic function of chiral superfields, i.e. depends only on φ_i, not on φ_i^*

No soft SUSY-breaking terms allowed for chiral fermions

$\Rightarrow$ $H_d (\equiv H_1)$ and $H_u (\equiv H_2)$ needed to give masses to down- and up-type fermions

Furthermore: two doublets also needed for cancellation of anomalies, quadratic divergences

Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

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

gauge couplings, in contrast to SM

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

Goldstone bosons: $G^0, G^\pm$

Input parameters: (to be determined experimentally)

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_A^2 = -m_{12}^2(\tan\beta + \cot\beta)$$

Enlarged Higgs sector: Two Higgs doublets with $\mathcal{CP}$ violation

$$
\begin{aligned}
H_1 &= \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix} \\
H_2 &= \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix} e^{i\xi}
\end{aligned}
$$

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

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

2 $\mathcal{CP}$-violating phases: ξ, $\arg(m_{12})$ $\Rightarrow$ can be set/rotated to zero

Input parameters: (to be determined experimentally)

$$
\tan\beta = \frac{v_2}{v_1}, \qquad M_{H^\pm}^2
$$

$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix} \qquad \tan(2\alpha) = \tan(2\beta)\frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2}$$

$$\begin{pmatrix} G^0 \\ A^0 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \chi_1^0 \\ \chi_2^0 \end{pmatrix}, \quad \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix}$$

Three Goldstone bosons (as in SM): G^0, $G^\pm$

$\longrightarrow$ longitudinal components of $W^\pm$, Z

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

h, H: neutral, $\mathcal{CP}$-even, A^0: neutral, $\mathcal{CP}$-odd, $H^\pm$: charged

Gauge-boson masses:

$$M_W^2 = \frac{1}{2}g'^2(v_1^2 + v_2^2), \quad M_Z^2 = \frac{1}{2}(g^2 + g'^2)(v_1^2 + v_2^2), \quad M_\gamma = 0$$

Parameters in MSSM Higgs potential V (besides g, g'):

$$v_1,\ v_2,\ m_1,\ m_2,\ m_{12}$$

relation for M_W^2, M_Z^2 $\Rightarrow$ 1 condition

minimization of V w.r.t. neutral Higgs fields H_1^1, H_2^2 $\Rightarrow$ 2 conditions

$\Rightarrow$ only two free parameters remain in V, conventionally chosen as

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_A^2 = -m_{12}^2(\tan\beta + \cot\beta)$$

$\Rightarrow$ m_h, m_H, mixing angle α, $m_{\mathrm{H}^\pm}$: no free parameters, can be predicted

In lowest order:

$$m_{\mathrm{H}^\pm}^2 = M_A^2 + M_W^2$$

Predictions for m_h, m_H from diagonalization of tree-level mass matrix:

$\phi_1 - \phi_2$ basis:

$$M_{\text{Higgs}}^{2,\text{tree}} = \begin{pmatrix} m_{\phi_1}^2 & m_{\phi_1\phi_2}^2 \\ m_{\phi_1\phi_2}^2 & m_{\phi_2}^2 \end{pmatrix} =$$

$$\begin{pmatrix} M_A^2 \sin^2\beta + M_Z^2 \cos^2\beta & -(M_A^2 + M_Z^2)\sin\beta\cos\beta \\ -(M_A^2 + M_Z^2)\sin\beta\cos\beta & M_A^2 \cos^2\beta + M_Z^2 \sin^2\beta \end{pmatrix}$$

$$\Big\Downarrow \quad \longleftarrow \text{ Diagonalization}, \alpha$$

$$\begin{pmatrix} m_H^{2,\text{tree}} & 0 \\ 0 & m_h^{2,\text{tree}} \end{pmatrix}$$

Tree-level result for m_h, m_H:

$$m_{H,h}^2 = \frac{1}{2}\left[M_A^2 + M_Z^2 \pm \sqrt{(M_A^2 + M_Z^2)^2 - 4M_Z^2 M_A^2 \cos^2 2\beta}\right]$$

$\Rightarrow$ $m_h \leq M_Z$ at tree level

$\Rightarrow$ Light Higgs boson h required in SUSY

Measurement of m_h, Higgs couplings

$\Rightarrow$ test of the theory (more directly than in SM)

Higgs couplings, tree level:

$$
\begin{aligned}
g_{hVV} &= \sin(\beta-\alpha)\, g_{HVV}^{\text{SM}}, \qquad V = W^\pm, Z \\
g_{HVV} &= \cos(\beta-\alpha)\, g_{HVV}^{\text{SM}} \\
g_{hAZ} &= \cos(\beta-\alpha)\, \frac{g'}{2\cos\theta_W} \\
g_{hb\bar{b}}, g_{h\tau^+\tau^-} &= -\frac{\sin\alpha}{\cos\beta}\, g_{Hb\bar{b},H\tau^+\tau^-}^{\text{SM}} \\
g_{ht\bar{t}} &= \frac{\cos\alpha}{\sin\beta}\, g_{Ht\bar{t}}^{\text{SM}} \\
g_{Ab\bar{b}}, g_{A\tau^+\tau^-} &= \gamma_5 \tan\beta\, g_{Hb\bar{b}}^{\text{SM}}
\end{aligned}
$$

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

$g_{hb\bar{b}}, g_{h\tau^+\tau^-}$: significant suppression or enhancement w.r.t. SM coupling possible

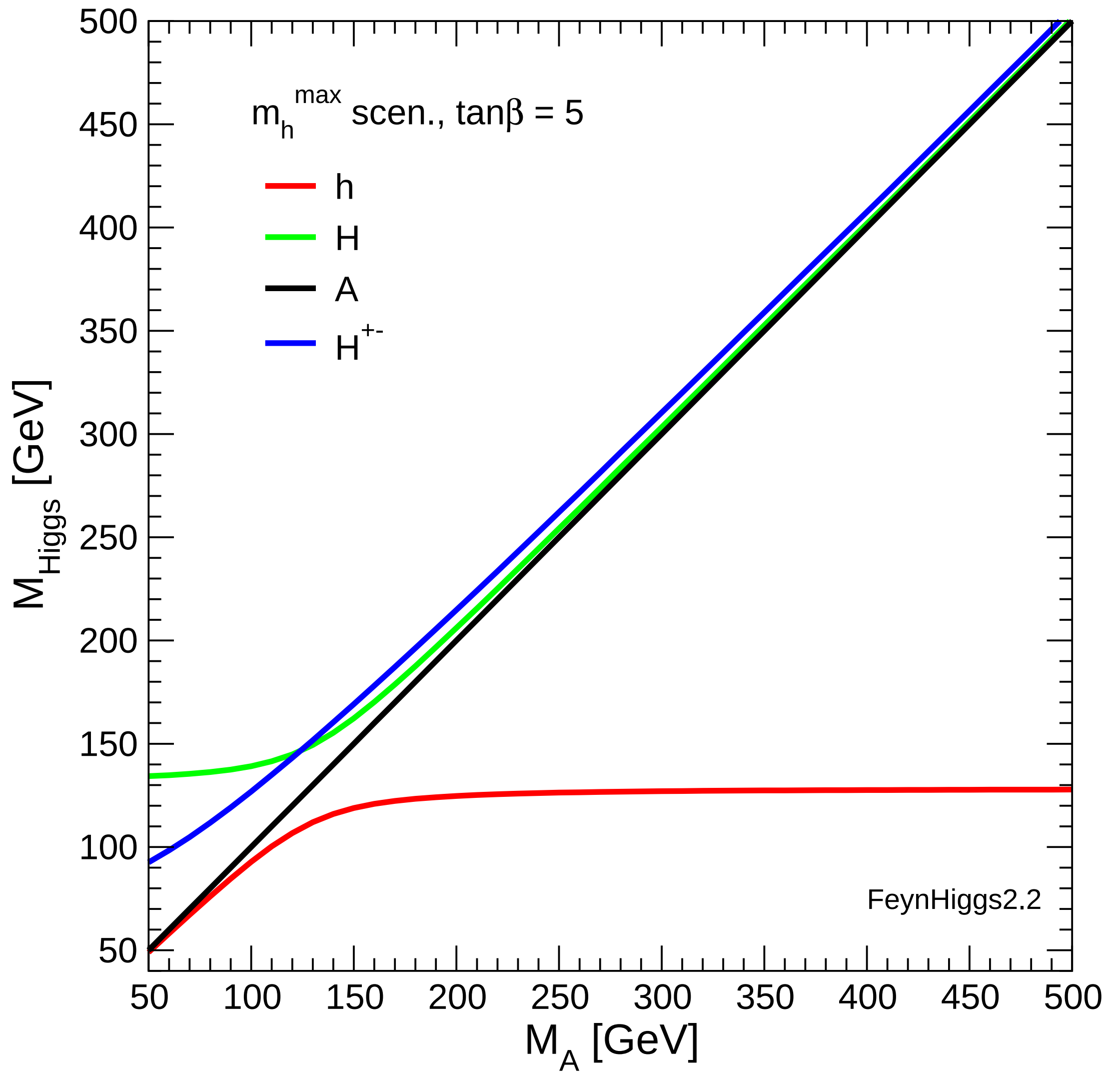
The decoupling limit:

For $M_A \gtrsim 150$ GeV:

The lightest MSSM Higgs is SM-like

The heavy MSSM Higgses:

$M_A \approx M_H \approx M_{H^\pm}$



of course there are exceptions . . .

Higgs mass bounds in SUSY theories

MSSM predicts upper bound on M_h:

tree-level bound: $m_h < M_Z$, excluded by LEP Higgs searches!

Large radiative corrections:

Yukawa couplings: $\frac{\mathrm{e}\, m_t}{2 M_W s_\mathrm{W}}, \frac{\mathrm{e}\, m_t^2}{M_W s_\mathrm{W}}, \ldots$

$\Rightarrow$ Dominant one-loop corrections: $\Delta M_h^2 \sim G_\mu m_t^4 \log \left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} \right)$

> The MSSM Higgs sector is connected to all other sector via loop corrections (especially to the scalar top sector)

Present status of M_h prediction in the MSSM:

Complete one-loop and ‘almost complete’ two-loop result available

Upper bound on M_h in the MSSM:

"Unconstrained MSSM":

M_A, $\tan\beta$, 5 parameters in $\tilde{t}$–$\tilde{b}$ sector, μ, $m_{\tilde{g}}$, M_2

$$\boxed{M_h \lesssim 135 \text{ GeV}}$$

for $m_t = 170.9 \pm 1.8\,\text{GeV}$

(including theoretical uncertainties from unknown higher orders)
$\Rightarrow$ observable at the LHC

Obtained with:

$\boxed{\textit{FeynHiggs}}$

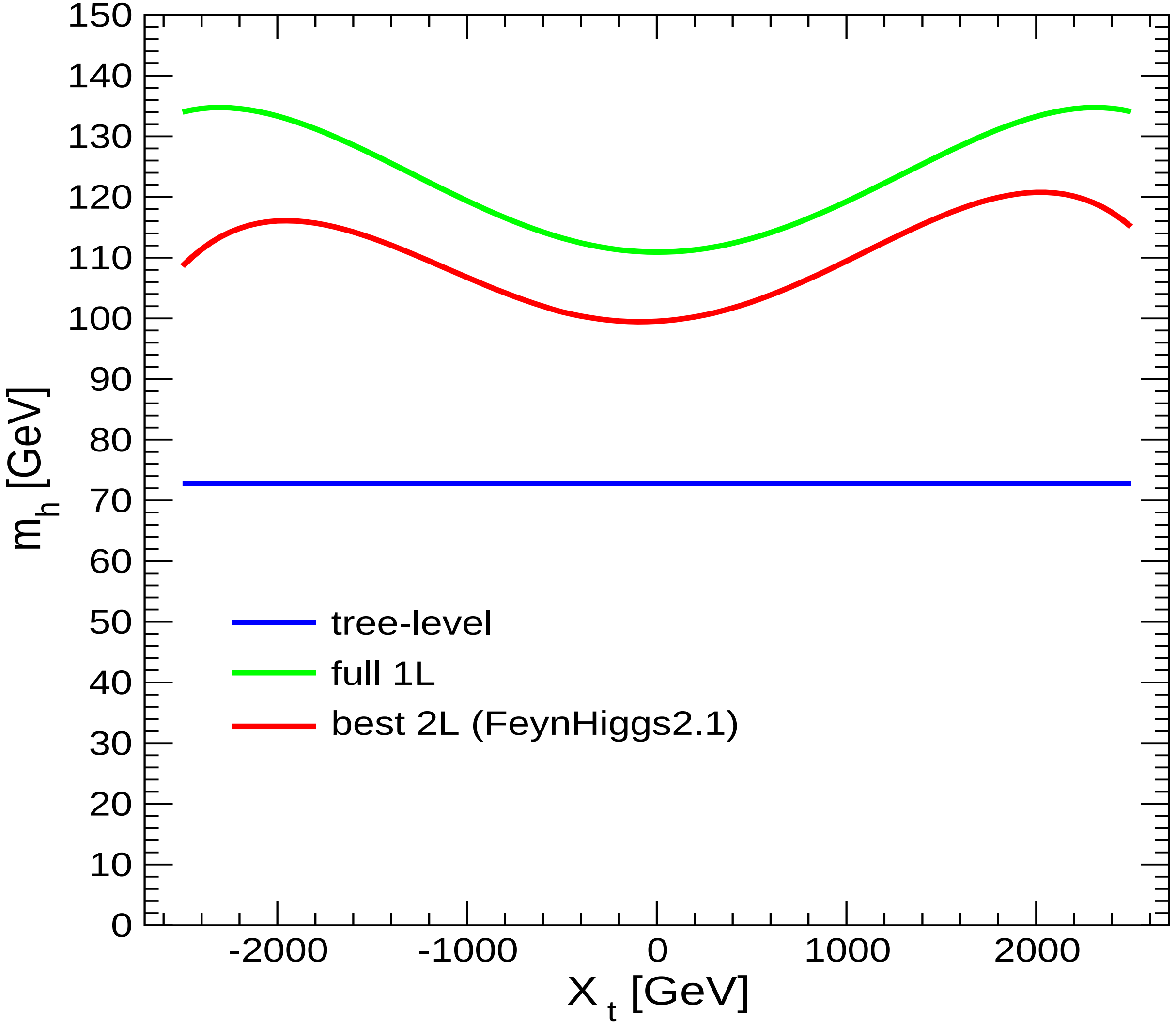
[*S.H., W. Hollik, G. Weiglein '98, '00, '02*]
[*T. Hahn, S.H., W. Hollik, G. Weiglein '03 – '07*]

$\boxed{\texttt{www.feynhiggs.de}}$

$\to$ all Higgs masses, couplings, BRs (easy to link, easy to use :-)
$\to$ talk by Thomas Hahn in the Higgs session

Effects of the two-loop corrections to the lightest Higgs mass:

Example for one set of MSSM parameters



$\rightarrow$ talk by Heidi Rzehak on the complex case in the Higgs session

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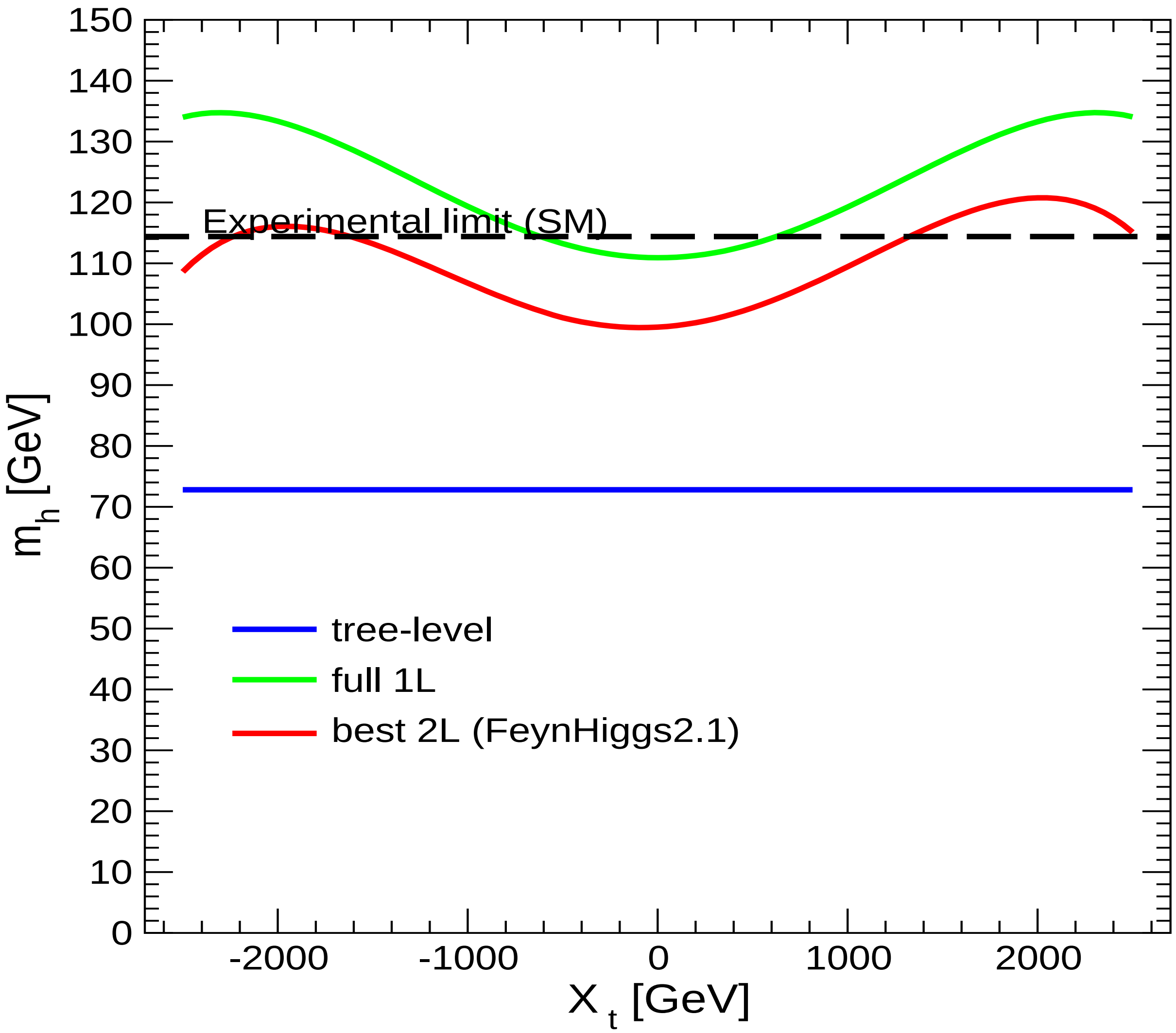

Comparison with experimental limits

$\Rightarrow$ strong impact on bound on SUSY parameters

$\rightarrow$ talk by Heidi Rzehak on the complex case in the Higgs session

Remaining theoretical uncertainties in prediction for M_h in the MSSM:

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

– From unknown higher-order corrections:
  $\Rightarrow \Delta M_h \approx 3$ GeV

– From uncertainties in input parameters

  $m_t, \ldots, M_A, \tan\beta, m_{\tilde{t}_1}, m_{\tilde{t}_2}, \theta_{\tilde{t}}, m_{\tilde{g}}, \ldots$

  $\Delta m_t \approx 2$ GeV $\Rightarrow \Delta M_h \approx 2$ GeV

Higgs couplings, production cross sections

$\Rightarrow$ also affected by large SUSY loop corrections

...see below

$\rightarrow$ talk by Karina Williams on loop effects on Higgs decays