Higgs Physics and QCD

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CTEQ Summer School
June, 2004

Outline

- The Standard Model & the Higgs Mechanism

- Agents of Electro-weak Symmetry Breaking

- The Higgs Boson

- QCD and the Higgs – Hadronic Production

- Impact of Radiative Corrections

- Elements of Precision Higgs Studies

The Standard Model

The Standard Model provides a concise and accurate description of all of the fundamental interactions except gravity.

It decribes the strong nuclear, weak nuclear and electromagnetic forces as quantized gauge field theories governed by the local symmetry group

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

Gauge Field Theories

Gauge Field Theories describe the forces between matter particles as the result of exchanging spin-1 vector bosons.

Quantum Electrodynamics (QED) is the prototype gauge field theory.

Spin ½ matter fields (electrons) ψ
Spin 1 vector bosons (photons) A_μ

Quantum Electrodynamics

$$\mathcal{L}_{QED} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \overline{\psi}i\slashed{D}\psi - m_e\overline{\psi}\psi$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial\, A_\nu$$

$$D^\mu = \partial^\mu + ieQ_e A^\mu$$

The gauge symmetry is manifest in the invariance of the Lagrangian under a gauge rotation:

$$A_\mu \to A_\mu - \partial_\mu \eta$$

$$\psi \to \exp\left(ieQ_e\eta\right)\psi$$

Non-Abelian Gauge Field Theories

When the local symmetry group underlying a gauge field theory is non-Abelian (i.e. the generators of the symmetry do not commute) the vector bosons carry gauge charges and interact with one another

Quantum Chromodynamics (QCD) is a pure non-Abelian (SU(3)$_c$) gauge field theory.

Spin ½ matter fields (quarks)

Spin 1 vector bosons (gluons)

$q_{i\ (i=1,2,3)}$

$A_\mu^{a\ (a=1,...,8)}$

Quantum ChromoDynamics

$$\mathcal{L}_{QCD} = -\frac{1}{4} F^{a\mu\nu} F^a_{\mu\nu} + \bar{q}_i \, i \slashed{D}_{ij} q_j - m_q \bar{q}_i q_i$$

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\nu + g f^{abc} A^b_\nu A^c_\nu$$

$$D^\mu_{ij} = \partial^\mu \delta_{ij} + ig \, t_{ij} A^{a\mu}$$

The gauge symmetry is manifest in the invariance of the Lagrangian under the infinitessimal gauge rotation:

$$A^a_\mu \to A^a_\mu - \partial_\mu \eta^a + g f^{abc} A^b_\mu \eta^c$$

$$q_i \to q_i + ig \, t^a_{ij} \eta^a q_j$$

QED and QCD are called unbroken gauge field theories because photons and gluons are massless.

In fact, gauge bosons must be massless because a mass term in the Lagrangian:

$$\frac{1}{2} M_A^2 A_\mu^a A^{a\mu}$$

violates gauge invariance.

But, the weak bosons, W and Z are massive.

M_W = 80.45 GeV, M_Z = 90.19 GeV.

How can they be gauge bosons?
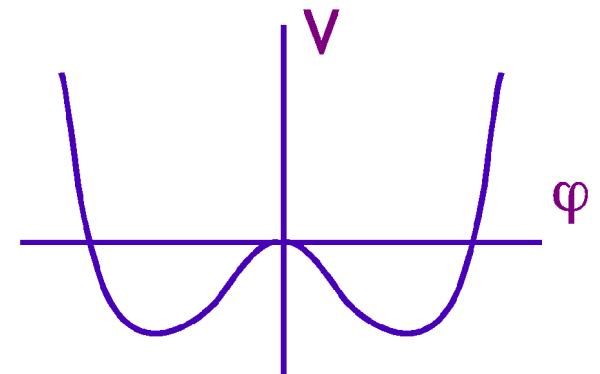
Spontaneous Symmetry Breaking

Consider a complex scalar field: $\phi = \dfrac{1}{\sqrt{2}}(\varphi_1 + i\varphi_2)$

$$\mathcal{L}_{SSB} = \partial^\mu\phi^\dagger \, \partial_\mu\phi - \mu^2\phi^\dagger\phi - \lambda(\phi^\dagger\phi)^2$$

If $\mu^2 > 0$, the potential, $V = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$, is minimized at $\langle\phi\rangle = 0$,

But, if $\mu^2 < 0$, the minimum is at $\langle\phi\rangle = \dfrac{v}{\sqrt{2}} = \sqrt{\dfrac{-\mu^2}{2\lambda}}$

Taking the vacuum expectation value to be in the φ_1 direction, and shifting so that the field oscillates about the minimum, $\varphi_1 \rightarrow h + v$, we can write the Lagrangian as

$$\mathscr{L}_{SSB} = \frac{1}{2} \partial^\mu h \, \partial_\mu h - \lambda v^2 h^2 + \frac{1}{2} \partial^\mu \varphi_2 \, \partial_\mu \varphi_2$$
$$+ \text{ interactions}$$

Notice that φ_2 is massless (a Goldstone Boson). The Goldstone Boson is a generic feature of Spontaneous Symmetry Breaking and would seem to exclude it in a theory of weak interactions since massless bosons are not observed.

The Goldstone Theorem

The Goldstone Theorem, which tells us that the spontaneous breakdown of a continuous symmetry results in a massless boson has one important caveat:

In the presence of a gauge field, the Goldstone Boson is not realized as a physical particle. Instead, it mixes with (is eaten by) and gives mass to the gauge boson.

This is the Higgs Mechanism.

The Higgs Mechanism

To see how this works, let the scalar field, ϕ just described carry charge under QED,

$$\mathcal{L} = \mathcal{L}_{QED} + D^\mu \phi^\dagger D_\mu \phi - \mu^2 \phi^\dagger \phi - \lambda(\phi^\dagger \phi)^2 \, , \, \mu^2 < 0$$

After shifting the field, $\varphi_1 \to h + v$, the Lagrangian becomes,

$$\mathcal{L} = \mathcal{L}_{QED} + \frac{1}{2} \partial^\mu h \, \partial_\mu h - \lambda v^2 h^2$$

$$+ \, \frac{1}{2} \partial^\mu \varphi_2 \, \partial_\mu \varphi_2 + ev A^\mu \partial_\mu \varphi_2 + \frac{e^2 v^2}{2} A^\mu A_\mu$$

$$+ \, \text{interactions}$$

The Higgs Mechanism (continued)

Because of the mixing with the photon, the Goldstone boson is not realized. This can be seen by making a gauge transformation (field redefinition) which removes φ_2 from the theory entirely, $\phi \to \frac{1}{\sqrt{2}}(h+v)\exp(i\varphi_2)$ leaving

$$\mathcal{L}^U = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{e^2v^2}{2}A^\mu A_\mu + \frac{1}{2}\partial^\mu h\,\partial_\mu h - \lambda v^2 h^2$$

$$+ \frac{e^2}{2}(2vh + h^2)A^\mu A_\mu - \frac{\lambda}{4}(4vh^3 + h^4)$$

This is called the Unitary Gauge.

The Electroweak Theory

The Electromagnetic and Weak interactions are described as the result of a spontaneously broken $SU(2)_L \otimes U(1)_Y$ symmetry.

$$\mathscr{L}_{EW} = -\frac{1}{4} B^{\mu\nu} B_{\mu\nu} - \frac{1}{4} W^{i,\mu\nu} W_{i,\mu\nu}$$
$$+ (D^{\mu}\Phi)^{\dagger} D_{\mu}\Phi + \mu^2 \Phi^{\dagger}\Phi - \lambda(\Phi^{\dagger}\Phi)^2,$$

With

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \varphi_1 + i\varphi_2 \\ \varphi_4 + i\varphi_3 \end{pmatrix} = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \quad Y_{\Phi} = \frac{1}{2},$$

$$D_{\mu}\Phi = \partial_{\mu}\Phi + i\frac{g_1}{2} B_{\mu}\Phi + i\frac{g_2}{2} W_{\mu}^i \ {}^i\Phi, \quad i = 1,2,3$$

The Electroweak Theory (continued)

Choosing the vacuum expectation value to point in the φ_4 direction, and shifting the field as before,

$$\mathcal{L}_{EW} = -\frac{1}{4} B^{\mu\nu} B_{\mu\nu} - \frac{1}{4} W^{i,\mu\nu} W_{i,\mu\nu} + \frac{1}{2} \partial^\mu H \, \partial_\mu H - \mu^2 H^2$$

$$+ \frac{1}{2} \partial^\mu \varphi_i \, \partial_\mu \varphi_i + \frac{g_1 v}{2} B^\mu \partial_\mu \varphi_3 + \frac{g_2 v}{2} W^{i,\mu} \partial_\mu \varphi_i$$

$$+ \frac{g_1^2 v^2}{8} B^\mu B_\mu + \frac{g_1 g_2 v^2}{4} B^\mu W_\mu^3 + \frac{g_2^2 v^2}{8} W^{i,\mu} W_\mu^i + \dots$$

Gauge Boson Masses

As in the Abelian model, a transformation to Unitary Gauge eliminates the φ_i entirely. The gauge boson mass eigenstates are:

$$W_\mu^\pm = \frac{W_\mu^1 \pm iW_\mu^2}{\sqrt{2}} \qquad\qquad M_W = \frac{g_2 v}{2}$$

$$Z_\mu = W_\mu^3 \cos\theta_W + B_\mu \sin\theta_W \qquad M_Z = \frac{\sqrt{g_1^2 + g_2^2}\, v}{2}$$

$$A_\mu = -W_\mu^3 \sin\theta_W + B_\mu \cos\theta_W \qquad M_A = 0$$

where $\tan\theta_W = \dfrac{g_1}{g_2},\qquad e = g_2 \sin\theta_W, \qquad v \sim 246\ GeV$

Fermions and Flavors

The matter content of the Standard Model:

Fermions come in two sorts: quarks, which feel the strong interactions, and leptons, which don't.

Left-handed quarks and leptons feel the weak-isospin interactions, right handed fermions don't.

There are three copies of each sort of quark and lepton, organized into generations.

The different quarks and leptons are collectively referred to as flavors. The differences in their properties are known as flavor physics.

Fermions of the Standard Model

$$l_L^1 = \begin{pmatrix} \nu_{e,L} \\ e_L \end{pmatrix} \qquad l_L^2 = \begin{pmatrix} \nu_{\mu,L} \\ \mu_L \end{pmatrix} \qquad l_L^3 = \begin{pmatrix} \nu_{\tau,L} \\ \tau_L \end{pmatrix} \qquad Y_{l_L} = -\frac{1}{2},$$

$$l_R^1 = e_R \qquad l_R^2 = \mu_R \qquad l_R^3 = \tau_R \qquad Y_{l_R} = -1,$$

$$q_L^1 = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad q_L^2 = \begin{pmatrix} c_L \\ s_L \end{pmatrix} \qquad q_L^3 = \begin{pmatrix} t_L \\ b_L \end{pmatrix} \qquad Y_{q_L} = +\frac{1}{6},$$

$$u_R^1 = u_R \qquad u_R^2 = c_R \qquad u_R^3 = t_R \qquad Y_{u_R} = +\frac{2}{3},$$

$$d_R^1 = d_R \qquad d_R^2 = s_R \qquad d_R^3 = b_R \qquad Y_{d_R} = -\frac{1}{3}$$

We now know that there are right handed neutrinos!

$\nu_R^1, \nu_R^2, \nu_R^3, Y_{\nu_R} = 0.$ They are singlets (uncharged) under all

Standard Model gauge groups and the generational mixing is Large.

Fermions and Flavors (continued)

The gauge interactions of the fermions are:

$$\mathcal{L}_{\text{fermi}} = \bar{l}_L^i \not{D} l_L^i + \bar{l}_R^i \not{D} l_R^i + \bar{q}_L^i \not{D} q_L^i + \bar{u}_R^i \not{D} u_R^i + \bar{d}_R^i \not{D} d_R^i,$$

where

$$D_\mu = \partial_\mu + ig_1 Q_Y B_\mu + ig_2 T_L^i W_\mu^i + ig_3 T_c^a A_\mu^a$$

Notice that fermion mass terms like

$$\mathcal{L}_{\text{mass}} = m_e \bar{e}_L e_R + m_e \bar{e}_R e_L$$

are forbidden by gauge invariance because the weak interactions are chiral gauge theories. But we know that the fermions have mass!

Fermion Masses in the Standard Model

The Higgs mechanism generates gauge invariant masses for the fermions:

$$\mathcal{L}_{\text{Yukawa}} = -\bar{l}_L^i \lambda_{ij}^l \Phi l_R^j - \bar{q}_L^i \lambda_{ij}^d \Phi d_R^j - \bar{u}_R^i (\lambda^u)_{ij}^\dagger \Phi^\dagger q_L^j + \text{h.c.}$$

$$\rightarrow -\frac{h+v}{\sqrt{2}} (\bar{E}_L^i \lambda_{ij}^l l_R^j - \bar{D}_L^i \lambda_{ij}^d d_R^j - \bar{U}_R^i (\lambda^u)_{ij}^\dagger q_L^j) + \text{h.c.}$$

Note that there is no symmetry governing the coupling matrices, $\lambda_{ij}^{l,u,d}$. Unlike the gauge couplings, they are not diagonal in generations.

Mass Eigenstates are not Gauge Eigenstates!

Fermion Mixing and Flavor Physics

In the mass basis, mixing only affects the W Boson (charged current) couplings.

There are no flavor-changing neutral couplings in the Standard Model.

$$\mathcal{L} \supset g_2 \overline{U'}^i_L \rlap{/}{W}^+ V^{ij} D'^j_L + g_{Z,u_L} \overline{U'}^i_L \rlap{/}{Z} U'^i_L + g_{Z,u_R} \overline{U'}^i_R \rlap{/}{Z} U'^i_R + \frac{2}{3} e \overline{U'}^i \rlap{/}{A} U'^i$$

The matrix V is called the Cabibbo-Kobayashi-Maskawa (CKM) matrix. The idea that all of flavor physics is determined by the fermion masses and the CKM matrix (i.e. By the Yukawa couplings of the Higgs) is called the CKM hypothesis.

Status of the Standard Model

The Standard Model is now over 35 years old and its essential goal

To describe electroweak interactions with a spontaneously broken SU(2)⊗U(1) gauge symmetry

has been spectacularly confirmed.

- Renormalizability
- Discovery of Neutral Currents
- Discovery of W and Z bosons
- Precision test of W and Z properties

But … The agent of electroweak symmetry breaking remains elusive

Agents of Symmetry Breaking

So far I have used a fundamental scalar field as the agent of spontaneous symmetry breaking. This need not be the case. Among the possibilities are:

- Standard Model Higgs Boson
- Supersymmetric Higgs Boson
- Strong Dynamics
    - Technicolor
    - Little Higgs
    - Extra Dimensions

Example: Superconductivity

Superconductivity:

The Abelian Higgs model I showed earlier:

$$\mathcal{L} = \mathcal{L}_{QED} + \frac{1}{2}\partial^\mu h \, \partial_\mu h - \lambda v^2 h^2$$

$$+ \frac{1}{2}\partial^\mu \varphi_2 \, \partial_\mu \varphi_2 + evA^\mu \partial_\mu \varphi_2 + \frac{e^2 v^2}{2}A^\mu A_\mu$$

$$+ \text{ interactions}$$

is equivalent to the Ginzburg-Landau theory of superconductivity.

BCS Superconductivity is an example of dynamical symmetry breaking!

The Minimal Standard Model

When theorists speak of a Higgs theory, we mean a theory in which symmetry breaking is accomplished by a perturbative, weakly-coupled, fundamental scalar field.

In the Minimal Standard Model, electroweak symmetry is broken by a single complex scalar Higgs doublet, resulting in the three massive gauge bosons $W^{\pm}$, Z, and a single Higgs Boson. The Standard Model Higgs is also responsible for giving mass to quarks and leptons.

Standard Model Higgs

The Standard Model Higgs Boson is an extraordinary particle.

To verify that any discovery is really a Higgs boson. We need to know:

- Couplings to W and Z Bosons
- Couplings to Fermions
- Spin and Parity Quantum Numbers
- Self Couplings

Higgs Caveats

Many theorists consider the Higgs boson unnatural.

- No other (fundamental) scalar matter is known.
- Electroweak symmetry is broken "by hand".
- It can accommodate flavor physics, but it doesn't explain it.

For these reasons (and others) many consider the Standard Model Higgs to be just a convenient stand-in for a real theory.

Supersymmetry (SUSY)

Supersymmetry relates fermions and bosons. It requires at least two Higgs doublets and doubles the spectrum of the Standard Model because each particle has a supersymmetric partner:

leptons (spin $\frac{1}{2}$) --> scalar leptons (spin 0)

quarks (spin $\frac{1}{2}$) --> scalar quarks (spin 0)

gauge bosons (spin 1) --> gauginos (spin $\frac{1}{2}$)

Higgs bosons (spin 0) --> higgsinos (spin $\frac{1}{2}$)

In pure supersymmetry, partners would have the same masses. Clearly, supersymmetry is broken.

Supersymmetry (continued)

Supersymmetry is the favorite theory of physics beyond the Standard Model. Why?

- The Boson-Fermion symmetry modifies radiative corrections, stabilizing hierarchies, Higgs masses.

- Below the SUSY scale, it closely approximates minimal Standard Model and is compatible with precision electroweak measurements.

- It provides dynamically driven EWSB (but SUSY is broken "by hand").

- It provides a Dark Matter candidate.

Supersymmetry has deep consequences. It is the maximal extension of the Poincare group.

Supersymmetric Higgs Bosons

In the Minimal Supersymmetric Standard Model (MSSM) there are two Higgs doublets, with vacuum expectation values v_u, v_d. After symmetry breaking, there are 5 physical Higgs Scalars:

$$h^0, \ H^0, \ A^0, \ H^\pm$$

In the "decoupling" limit, the light neutral scalar, h^0, has properties almost identical to the Standard Model Higgs. The heavy scalar, H^0, and the pseudoscalar, A^0, have very different interactions.

Tests of the Electroweak Theory

Many measurements have been made at the 0.1% level, including:

- Z Boson Mass
- Z Boson Decay Rate
- The Weak Mixing Angle
- Forward-Backward Asymmetries
- W Boson Mass

Many other measurements to a few percent:

- W Boson Width
- Top Quark Mass

Pulls to Precision Electroweak Fits

The Minimal Standard Model works remarkably well!

This is the strongest motivation for taking the Minimal Standard Model or SUSY seriously.

Winter 2004

[LEPEWWG, Winter 2004]

	Measurement	Fit	$|O^{meas} - O^{fit}|/\sigma^{meas}$ 0 1 2 3
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	0.02768	
m_Z [GeV]	91.1875 ± 0.0021	91.1873	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965	
σ_{had}^0 [nb]	41.540 ± 0.037	41.481	
R_l	20.767 ± 0.025	20.739	
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01642	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480	
R_b	0.21638 ± 0.00066	0.21566	
R_c	0.1720 ± 0.0030	0.1723	
$A_{fb}^{0,b}$	0.0997 ± 0.0016	0.1037	
$A_{fb}^{0,c}$	0.0706 ± 0.0035	0.0742	
A_b	0.925 ± 0.020	0.935	
A_c	0.670 ± 0.026	0.668	
$A_l(SLD)$	0.1513 ± 0.0021	0.1480	
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.425 ± 0.034	80.398	
Γ_W [GeV]	2.133 ± 0.069	2.094	
m_t [GeV]	178.0 ± 4.3	178.1	

0 1 2 3

No Obvious Deviations from SM

LEP2 studies of W^+W^- production confirm unitarity cancellations and show no evidence of non-Standard Model gauge boson vertices
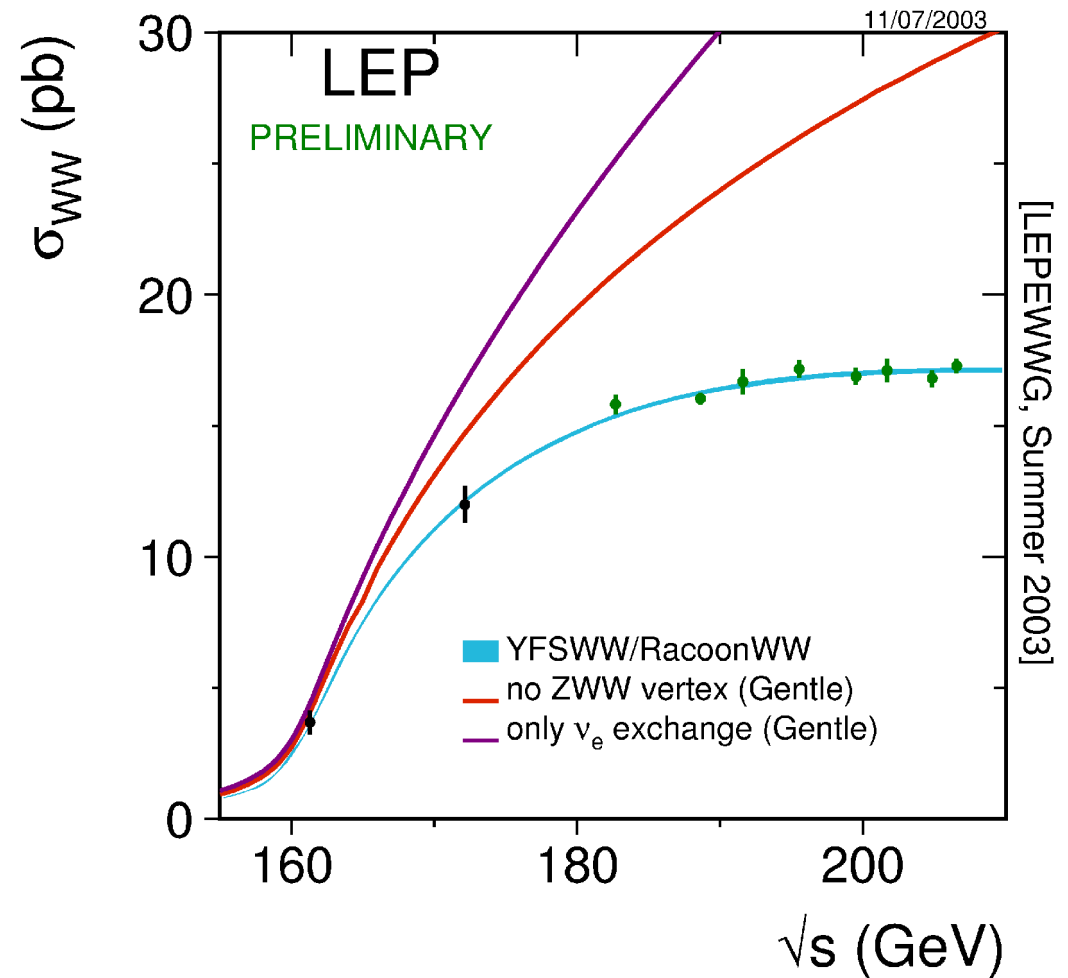
So ... Where is the Higgs?

The Standard Model, a priori, makes no prediction of, and places no constraint on the mass of the Higgs Boson. It can be constrained, however by:

- Theoretical prejudices

- Precision measurements

- Experimental search limits

Theoretical Prejudices

There are three primary considerations determining theoretical prejudices about the mass of the Higgs:

- Vacuum Stability

- Triviality

- Unitarity

triviality upper bound on m_H (GeV)

solid: $\lambda < 1$ for $\mu < \Lambda$
dotted: $\lambda < 10$ for $\mu < \Lambda$

dashed: stability lower bound
dot–dashed: metastability lower bound

[G. Ridolfi, hep-ph/0106300]
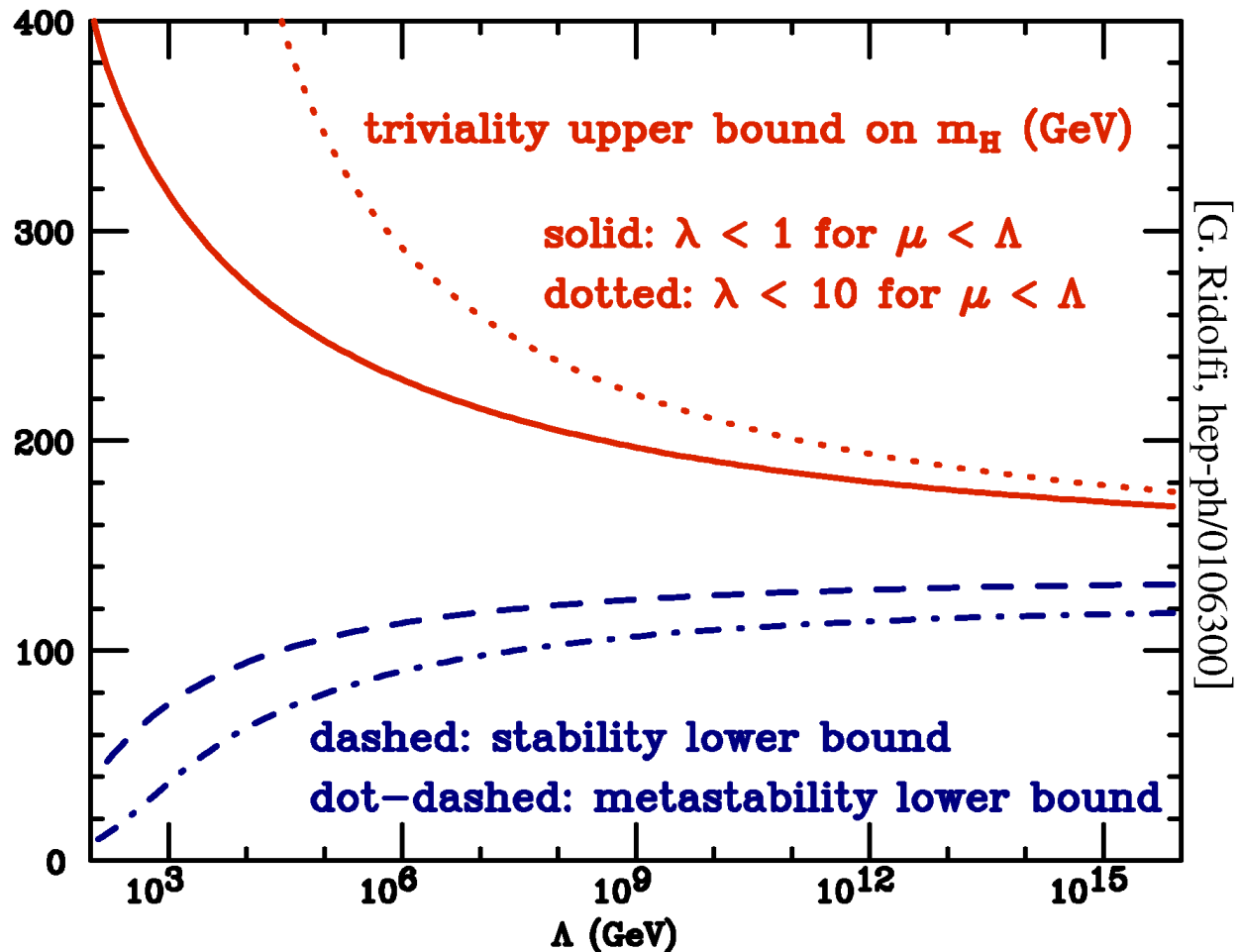
Unitarity Constraints

If the Higgs is too heavy, $W_L W_L$ scattering amplitudes would grow with energy and saturate partial wave unitarity
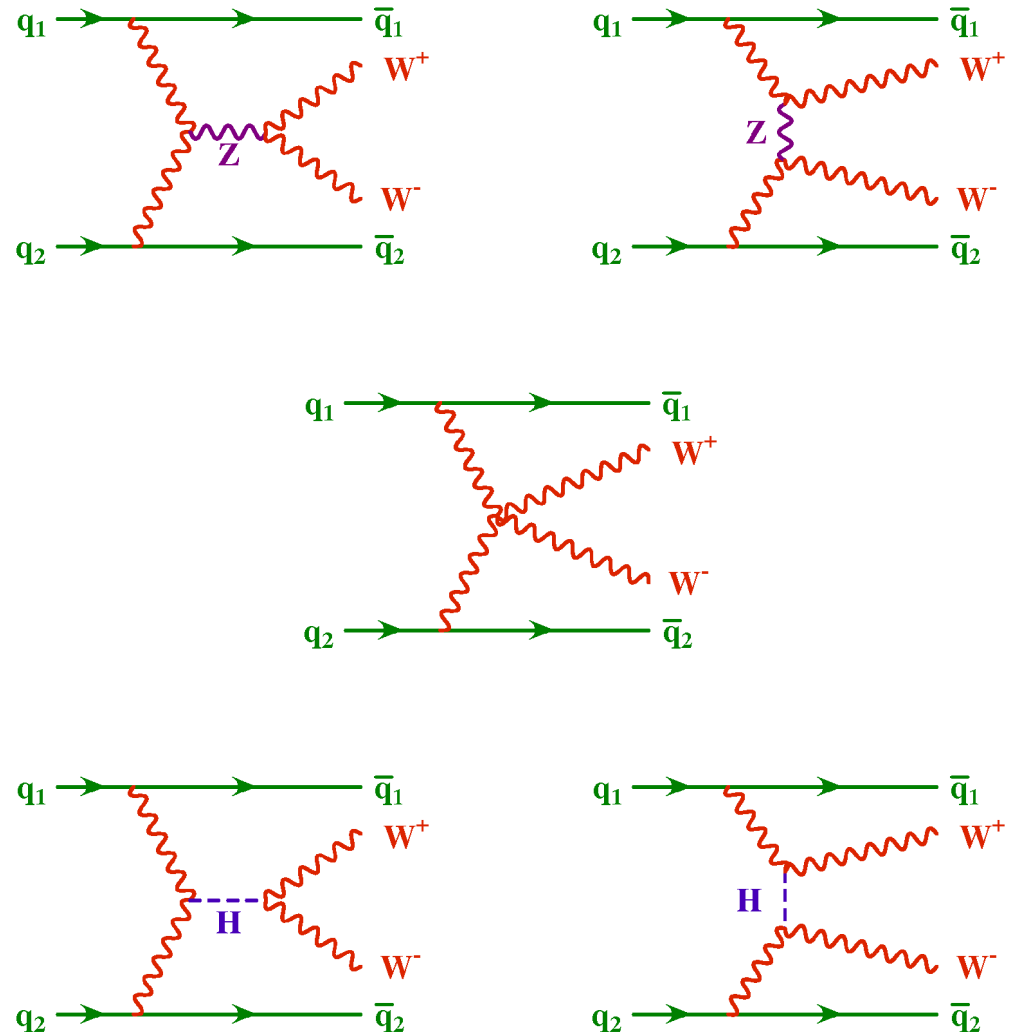
Supersymmetric Constraints

In the MSSM, there are theoretical constraints so that $m_h \leq 135$ GeV.

The limits are weakening:

Two-loop corrections to the SUSY Higgs masses weaken the limit from above.

Figure legend:

— m_h^{max} scen., RGiEP

— m_h^{max} scen., FH1.0

— m_h^{max} scen., FH1.3

— $m_t \rightarrow m_t + \sigma_{m_t}$

$M_{SUSY} = 1$ TeV $\rightarrow 2$ Tev

SM exclusion bound

$\tan\beta$

m_h [GeV]

[G. Degrassi et al., Eur.Phys.J. C28 (2003) 133]
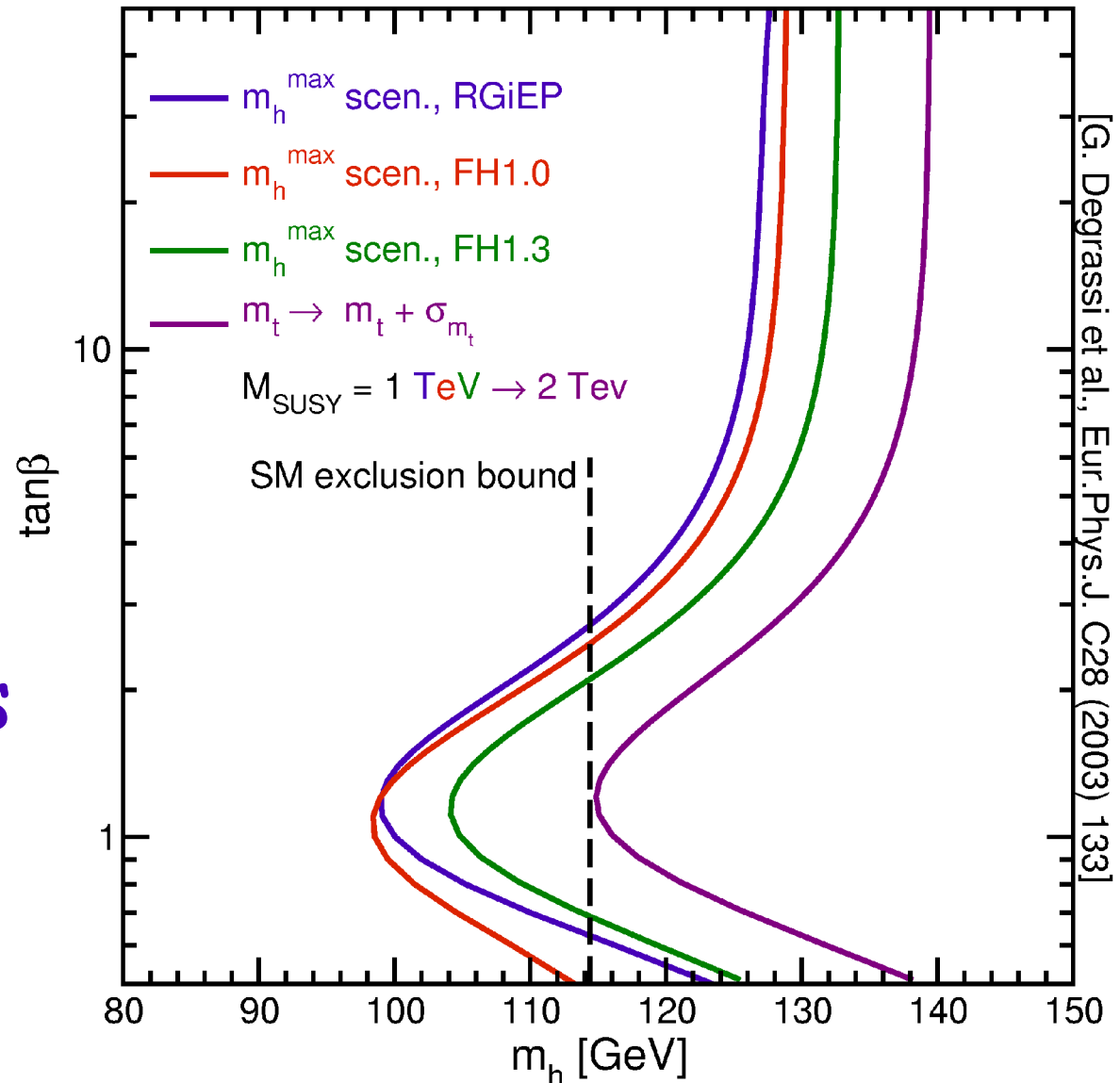
SUSY Higgs Limits

Any limit on SUSY is model dependent.

The most important parameters for the SUSY Higgs sector are m_A, and tan β.

In the "m_h-max" scenario:

LEP 88-209 GeV Preliminary

m_{A° (GeV/c^2)

m_{h°-max

Theoretically Inaccessible

Excluded by LEP

m_{h° (GeV/c^2)

[LHWG Note 2001-04]
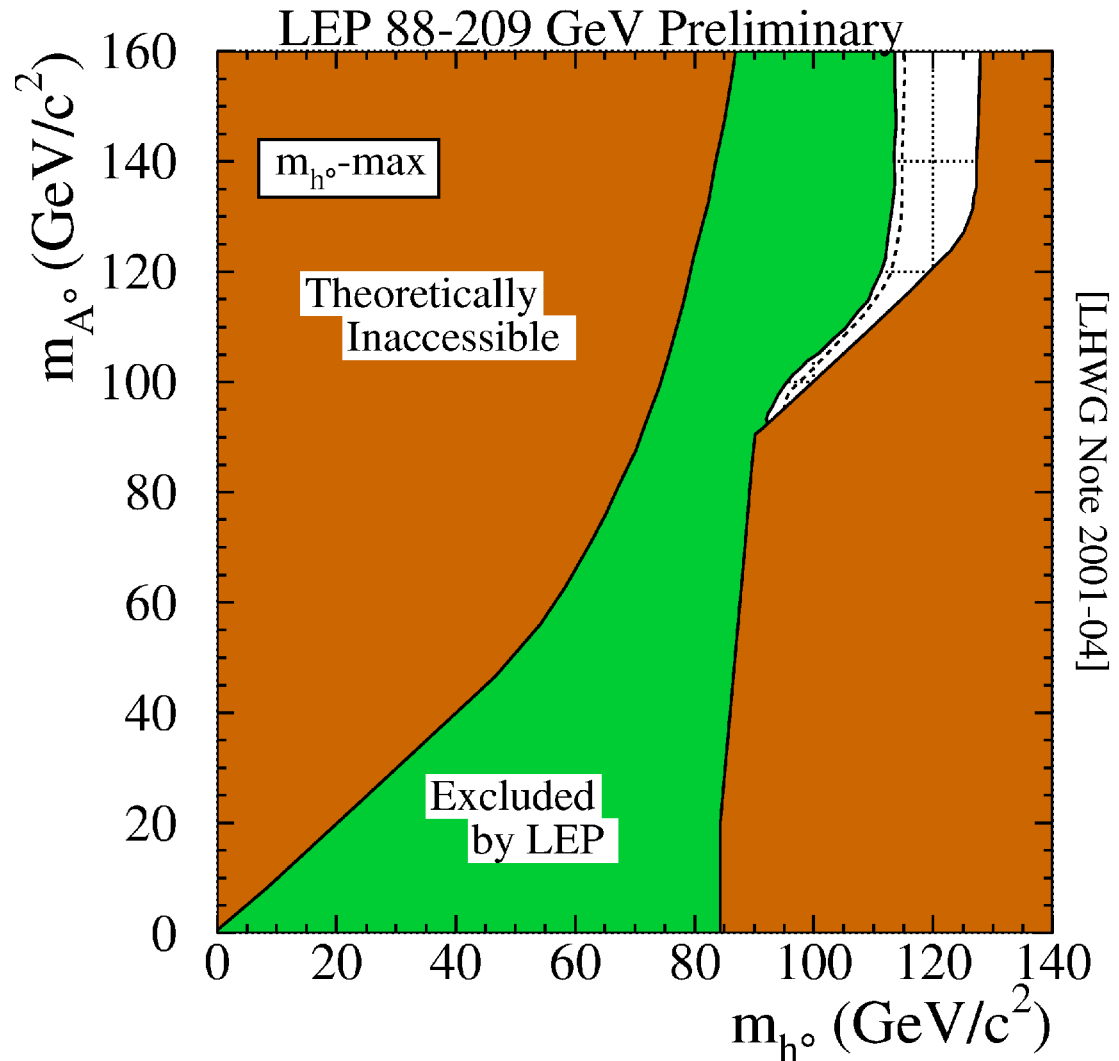
SUSY Higgs Limits

Note the tan β exclusion region.
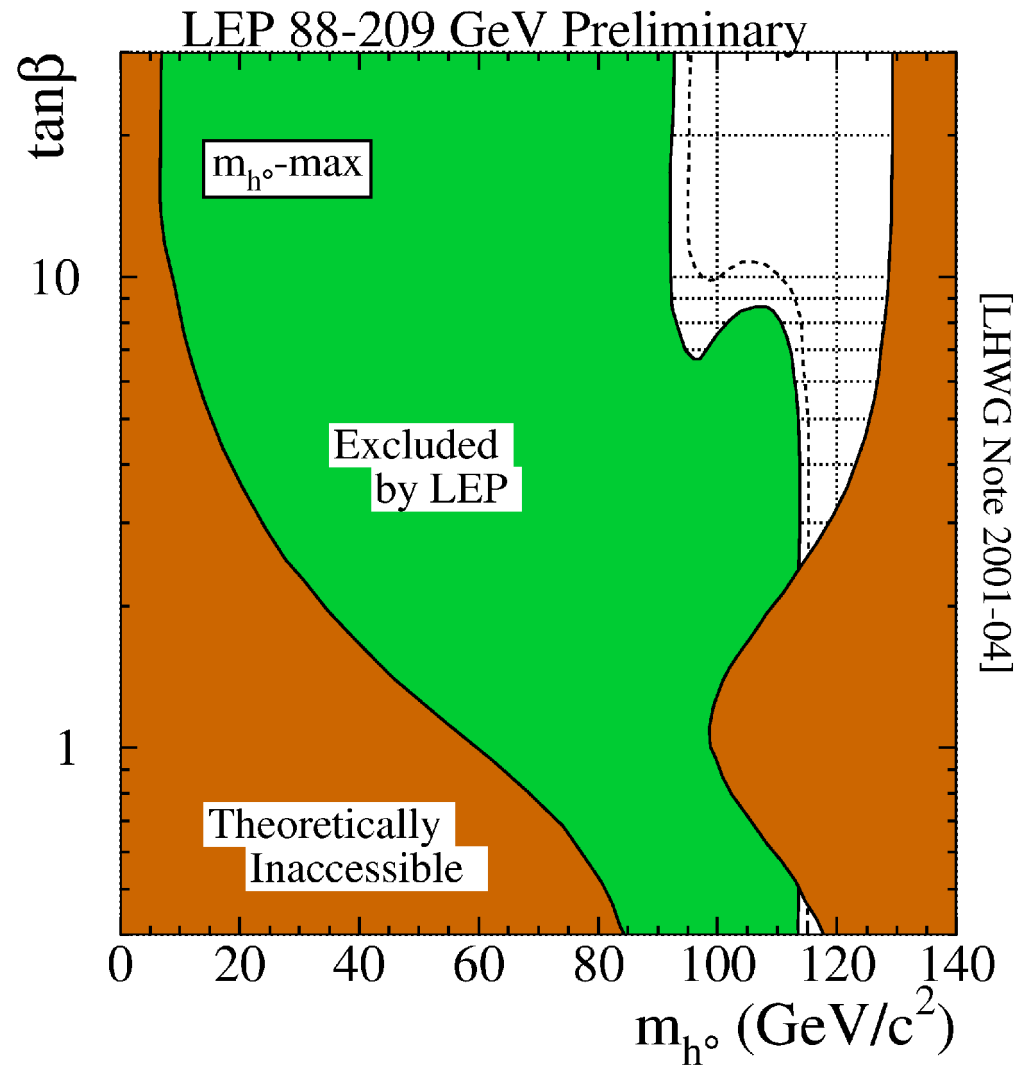
Limits on the Pseudoscalar

LEP 88-209 GeV Preliminary

$\tan\beta$

$m_{h\circ}$-max

M_{SUSY}=1 TeV
M_2=200 GeV
μ=-200 GeV
m_{gluino}=800 GeV
Stop mix: X_t=2M_{SUSY}

[LHWG Note 2001-04]

Excluded
by LEP

$m_{A\circ}$ (GeV/c^2)
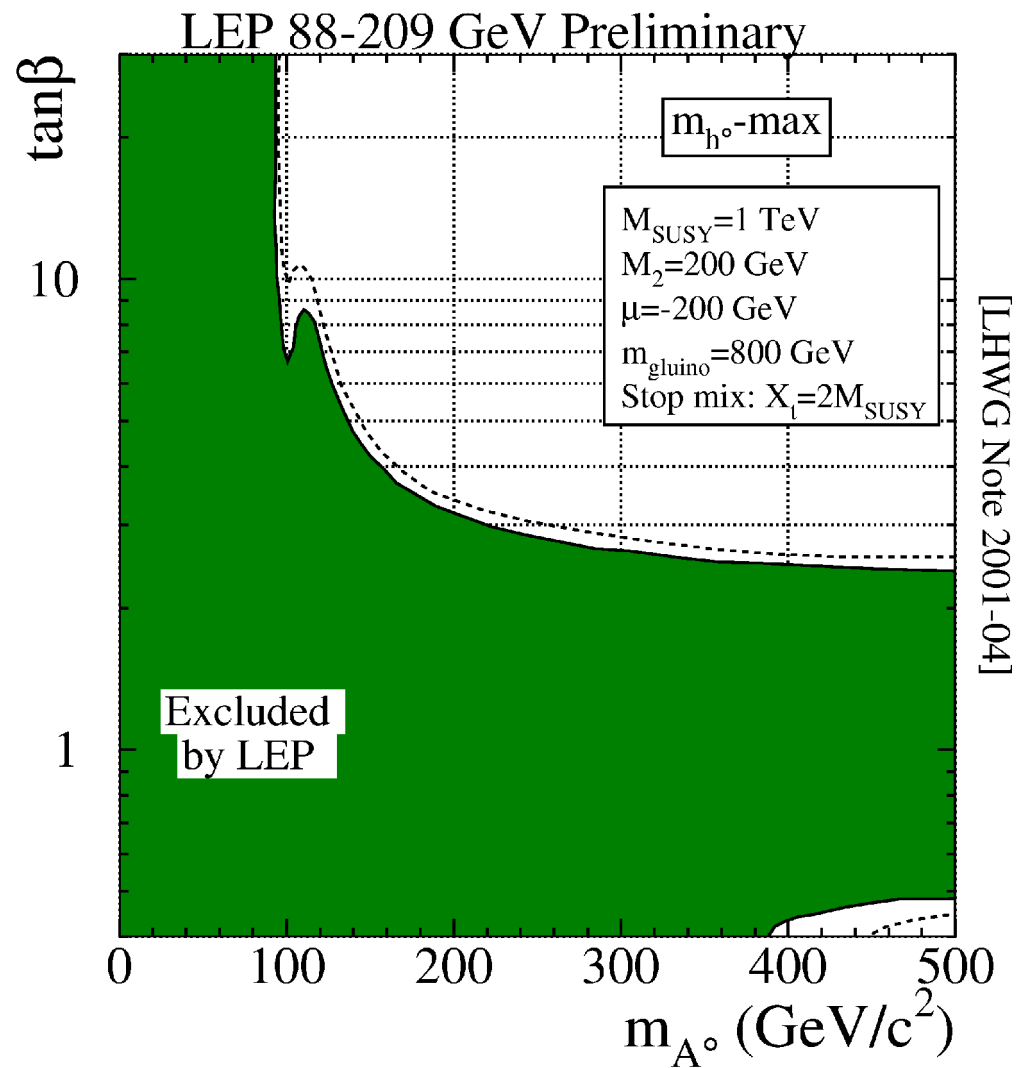
The limits are weakening!

With the shift in the top mass to 178 GeV, the tan β exclusion has completely disappear!
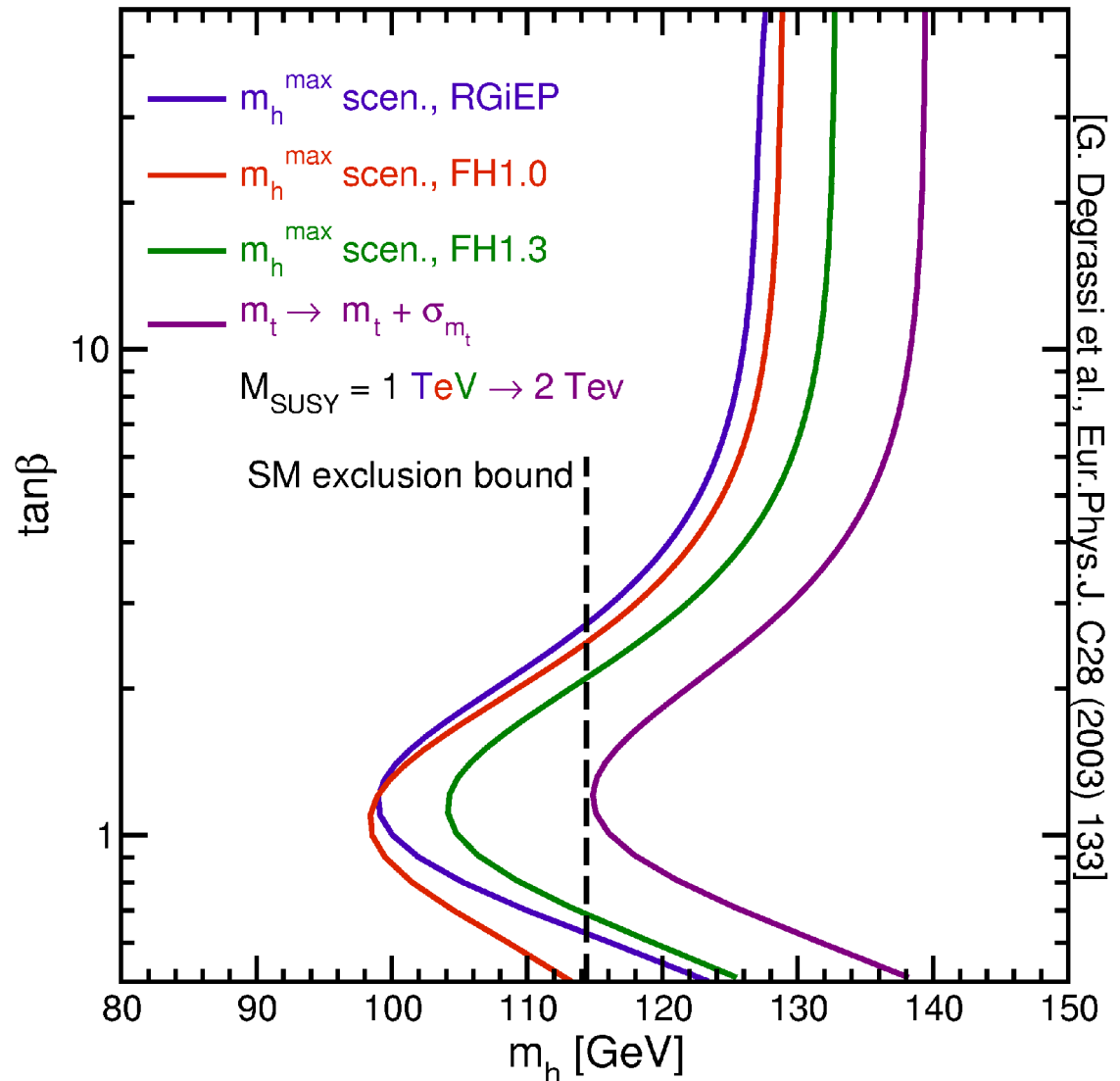
Direct Search/Precision Constraints

The direct search limit was set by LEP.
Precision Measurements from LEP, SLC, CDF, DØ and NuTeV provide indirect constraints.

As of the Summer of 2003:

LEP Search: $M_H \geq 114.4$ GeV

Precision Fits: $M_H = 96^{+60}_{-38}$ GeV

95% CL limit: $M_H < 219$ GeV
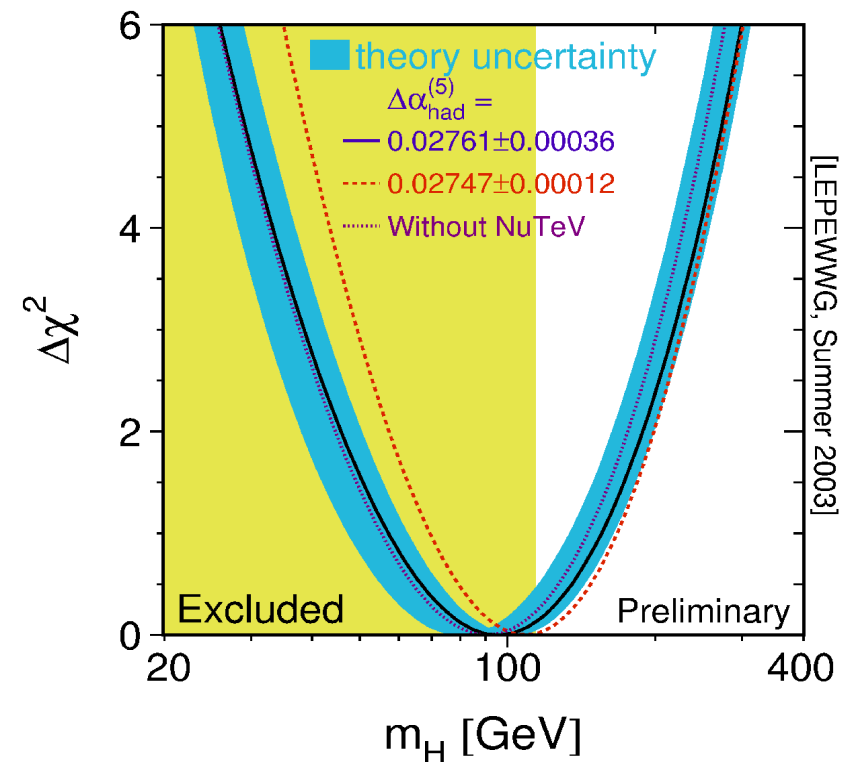
Some Parameters are More Equal than Others

The minimum of the Higgs fit is broad.

Changes to m_W and m_t have a strong effect on the m_H fit.
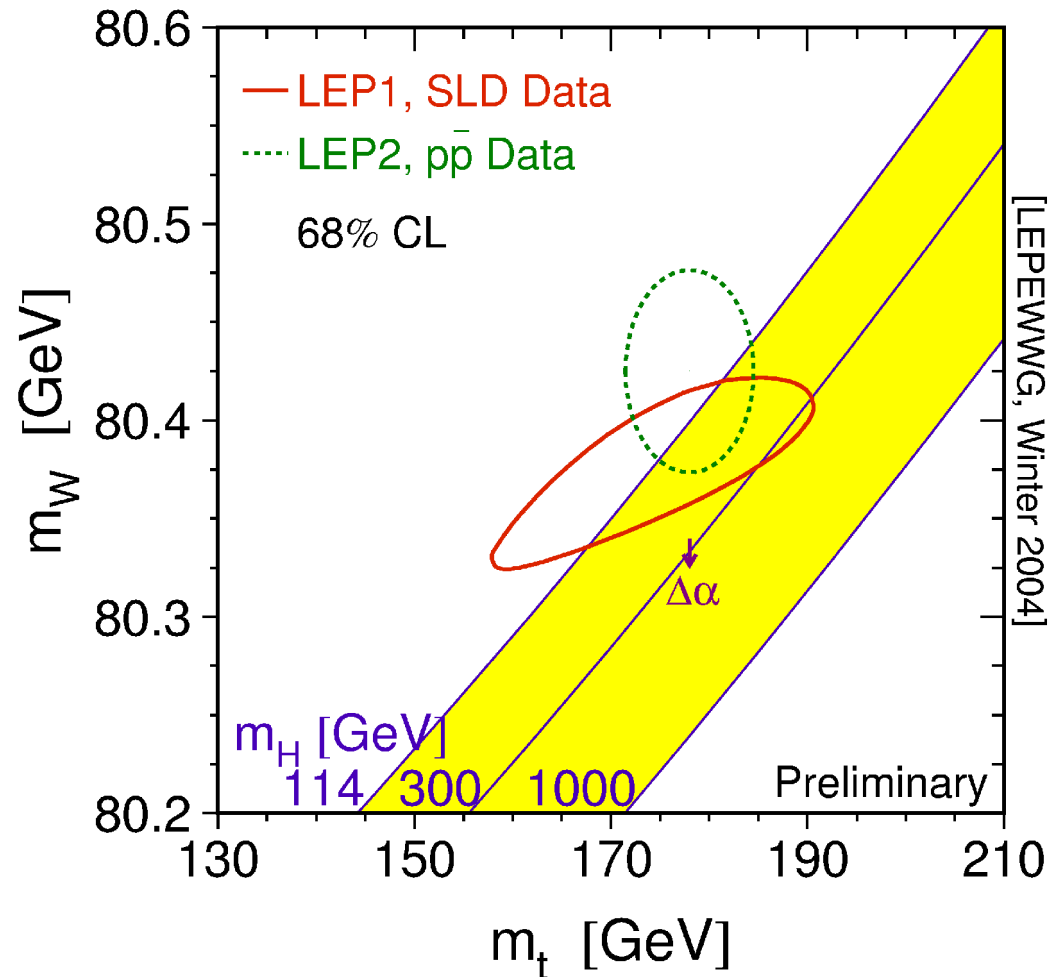
Is M$_W$ too high?

The fit to all precision electroweak observables would prefer a smaller W boson mass.

W-Boson Mass [GeV]

TEVATRON 80.452 ± 0.059

LEP2 80.412 ± 0.042

Average 80.425 ± 0.034
χ^2/DoF: 0.3 / 1

NuTeV 80.136 ± 0.084

LEP1/SLD 80.373 ± 0.033

LEP1/SLD/m$_t$ 80.386 ± 0.023

[LEPEWWG, Winter 2004]

m$_W$ [GeV]

Winter 2004

Γ_Z
σ_{had}^0
R_l^0
$A_{fb}^{0,l}$
$A_l(P_\tau)$
R_b^0
R_c^0
$A_{fb}^{0,b}$
$A_{fb}^{0,c}$
A_b
A_c
$A_l(SLD)$
$\sin^2\theta_{eff}^{lept}(Q_{fb})$
m_W
Γ_W

$Q_W(Cs)$
$\sin^2\theta_{\overline{MS}}(e^-e^-)$
$\sin^2\theta_W(\nu N)$
$g_L^2(\nu N)$
$g_R^2(\nu N)$

[LEPEWWG, Winter 2004]

M$_H$ [GeV]
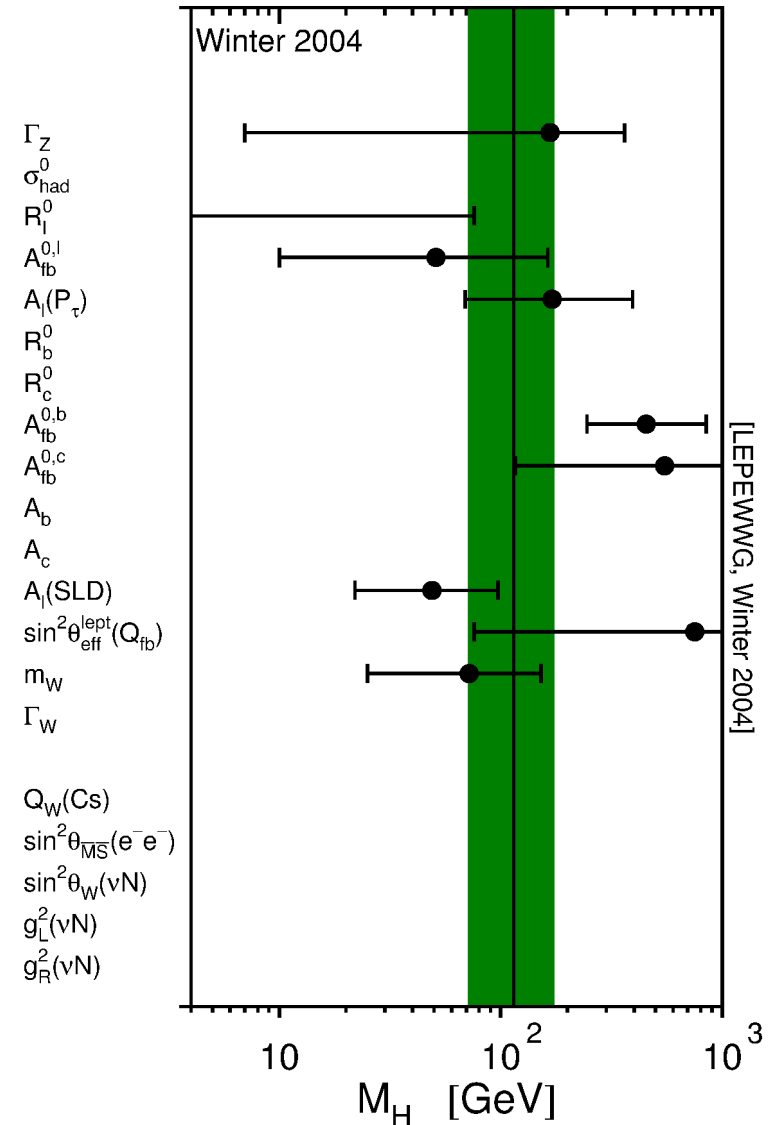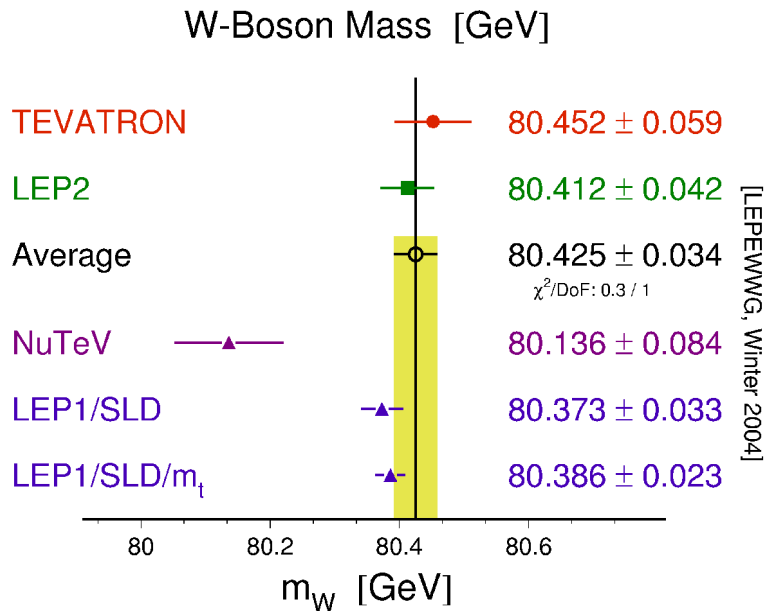
Why is M_{top} so important?

In QED and QCD, there is a "decoupling theorem".

- Couplings don't grow with energy.
- Removing a heavy particle does not affect renormalizability.

The Electroweak theory doesn't have a decoupling theorem (except for whole generations).

- Scattering Amplitudes of longitudinal gauge boson modes grow with energy without Higgs.
- Letting $M_{top} \rightarrow \infty$ spoils renormalizability.

Radiative corrections depend stongly on M_{top}.

The top mass has moved!

DØ has reported a new top mass from Run I data:

$M_{top} = 180.1 \pm 5.3 \text{ GeV/c}^2$.

This significantly shifts the best fit for the Higgs.

Mass of the Top Quark

Measurement		M_{top} [GeV/c^2]
CDF di-l		167.4 ± 11.4
DØ di-l		168.4 ± 12.8
CDF l+j		176.1 ± 7.3
DØ l+j		180.1 ± 5.3
CDF all-j		186.0 ± 11.5
		χ^2 / dof = 2.6 / 4
TEVATRON Run-I		178.0 ± 4.3

[J. Ellison, hep-ex/0405077]

150   175   200

M_{top} [GeV/c^2]
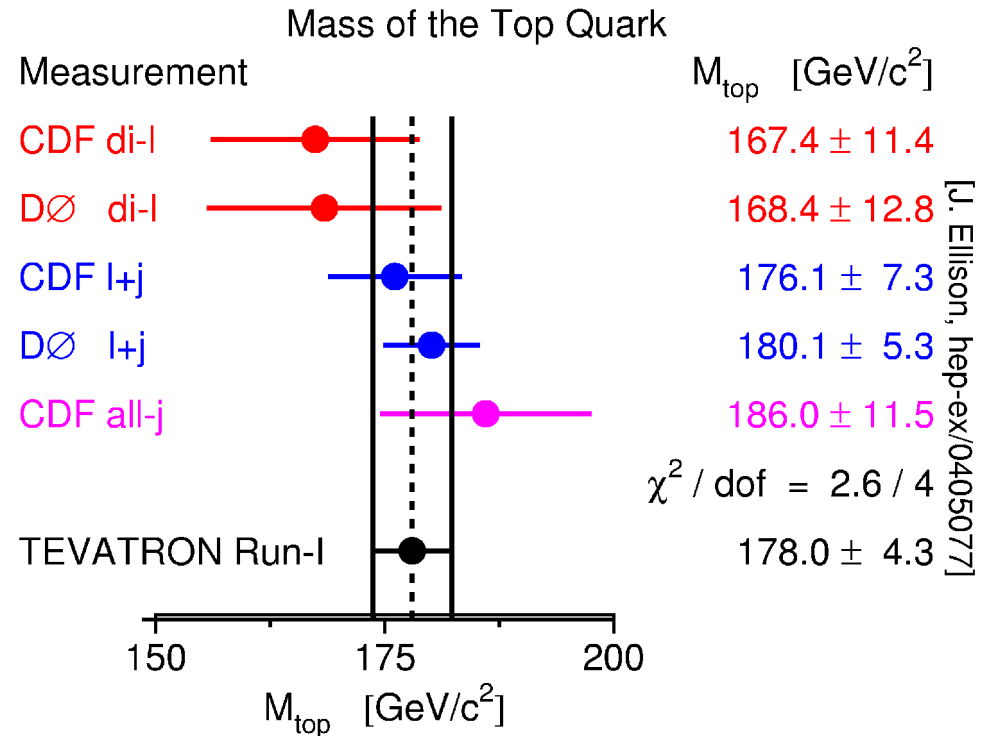
NEW! CDF has just announced a preliminary Run II result (162 pb^{-1}) that agrees with the new world average:

$$M_{top} = 177.8 \pm^{4.5}_{5.0} (\text{stat.}) \pm 6.2 (\text{syst.}) \text{ GeV/c}^2$$

Direct Search/Precision Constraints

LEP Search: $M_H \geq 114.4$ GeV

Precision EW Fits: $M_H = 117^{+67}_{-45}$ GeV

95% CL upper limit: $M_H < 251$ GeV

With the new top mass measurements, the best fit for the Higgs mass is NOT excluded!
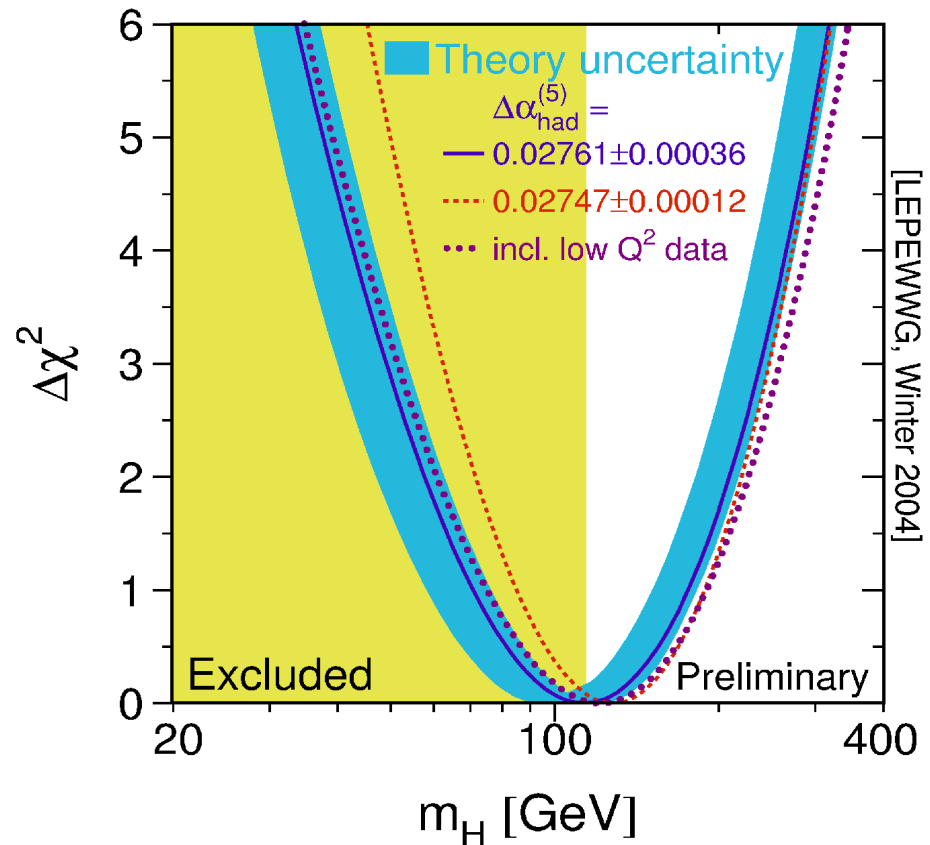
LEP2 Direct Search Limit

The direct search limit from LEP2 uses the "Higgs-strahlung" process.
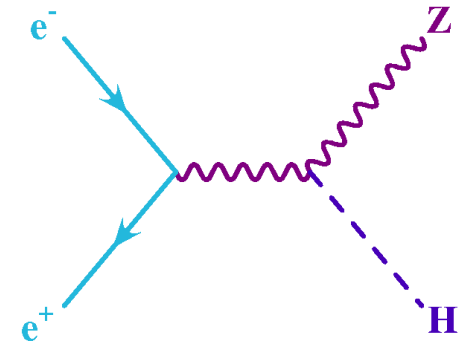
The cross section is readily calculated to be:

$$\sigma(e^+e^- \to ZH) = \frac{G_F^2 M_Z^4}{96\pi\hat{s}}\left(v_e^2 + a_a^2\right)\lambda^{\frac{1}{2}}\frac{\lambda + 12M_Z^2/\hat{s}}{\left(1 - M_Z^2/\hat{s}\right)^2}$$

where $\lambda = \dfrac{\left(\hat{s} - M_H^2 - M_Z^2\right)^2 - 4M_H^2 M_Z^2}{\hat{s}^2}$

is the familiar two body phase space factor.

LEP2 Direct Search Limit (cont.)

The "Higgs-strahlung" process has substantial cross section until just below threshold.

So ... with a 95% confidence level limit at 114.4 GeV, very little of the remaining 5% extends below 110 GeV.
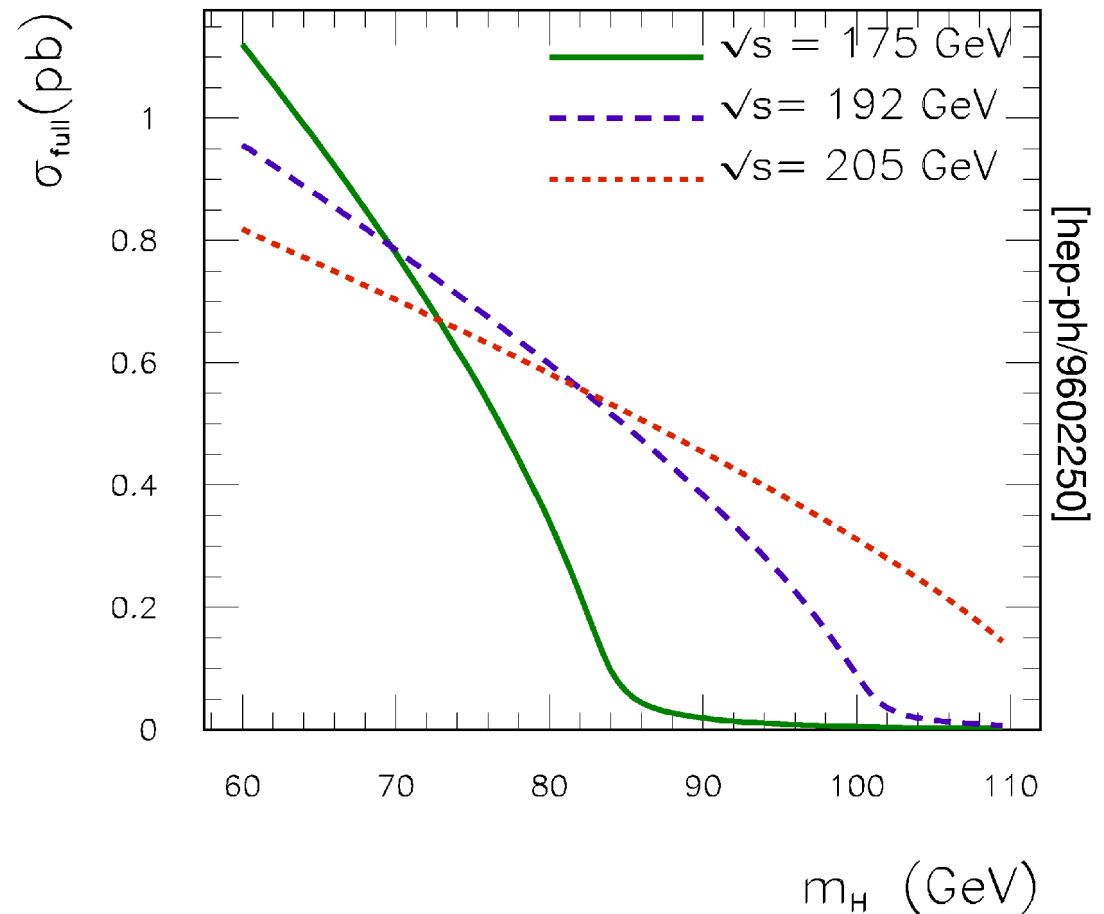
Why care about the Higgs Limits?

The search strategy for the Higgs changes dramatically with mass! A 200 GeV Higgs is very different from a 115 GeV Higgs.
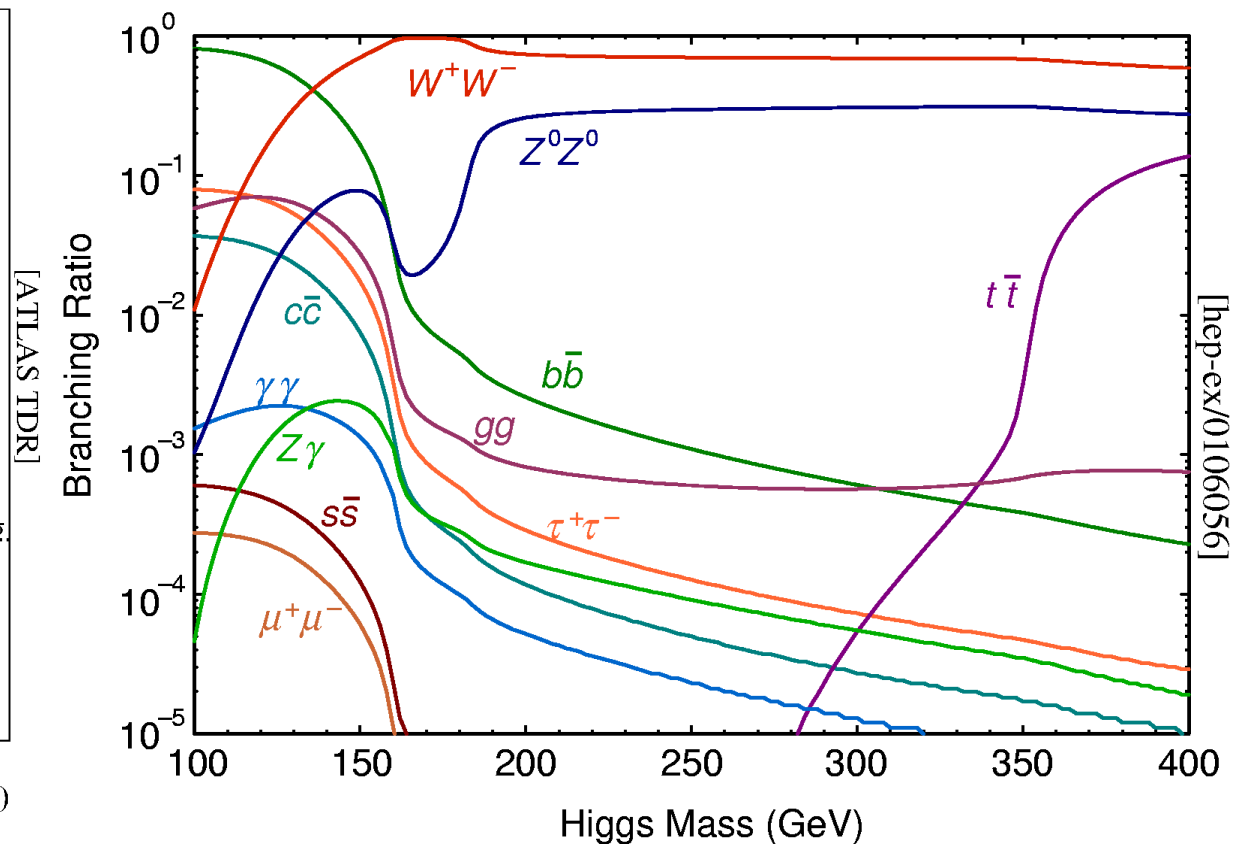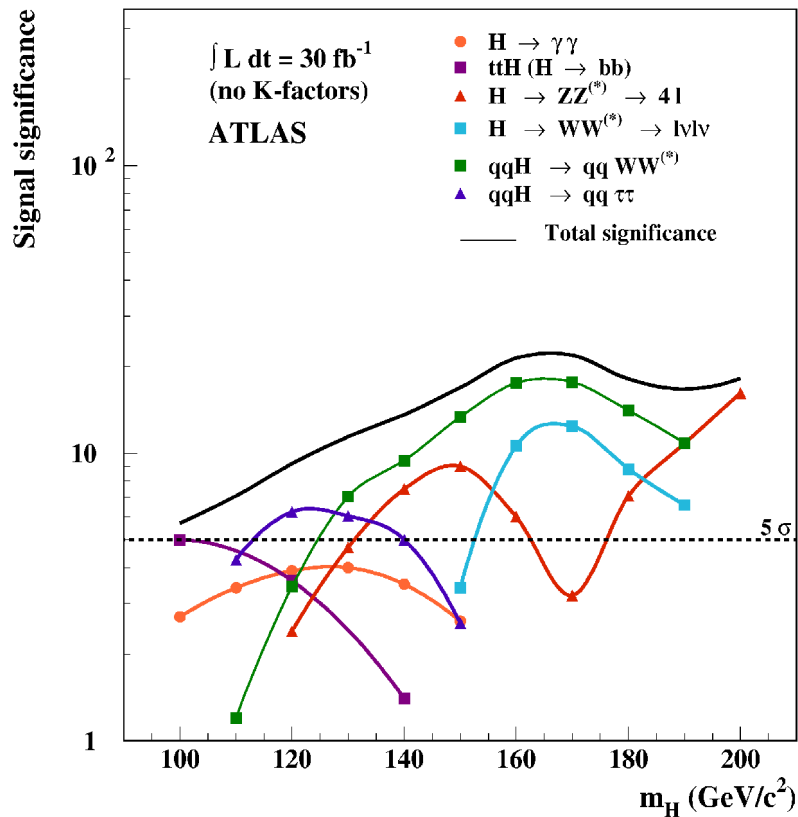
New Colliders to Complete the Picture

While it is possible that the Fermilab Tevatron will discover the Higgs or Supersymmetry, it is likely that the completion of the Standard Model will occur at two new facilities:

- The CERN Large Hadron Collider (LHC)
- A proposed high-energy (500-1000 GeV) e^+-e^- linear collider

These two machines will complement each other to provide a complete picture of particle physics below 1 TeV.

The Next Hadron Collider: The CERN LHC

- High Energy: 14 TeV in C.M.
- Very High Luminosity
- Scheduled to start in 2007
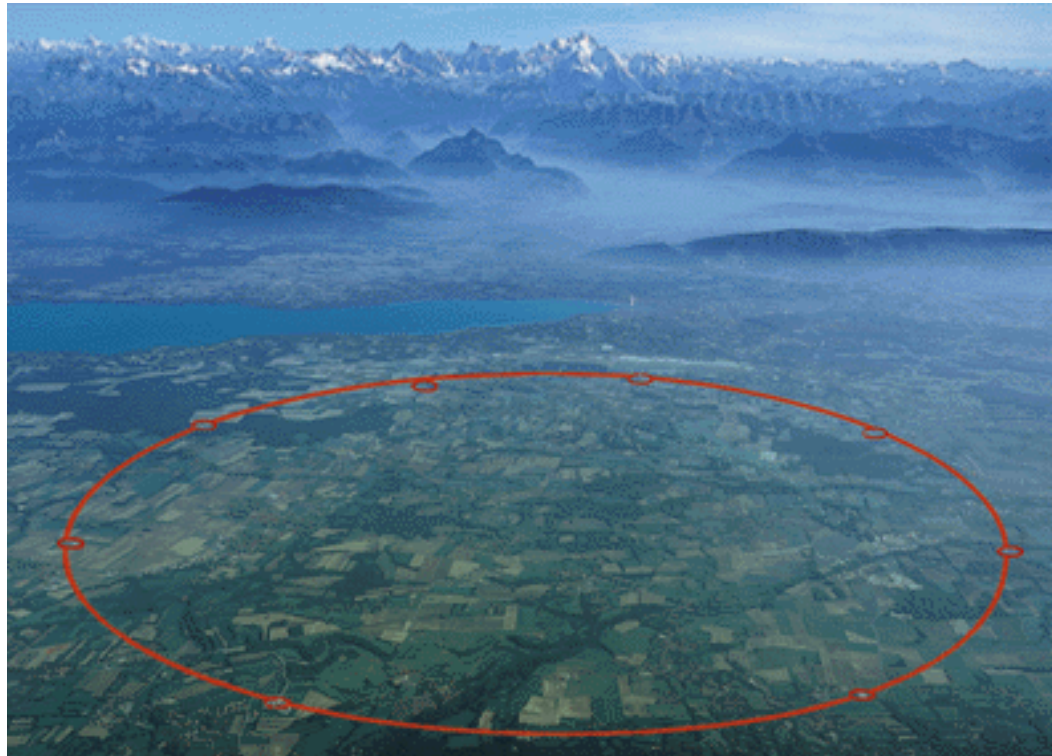
The Higgs will be found at LHC
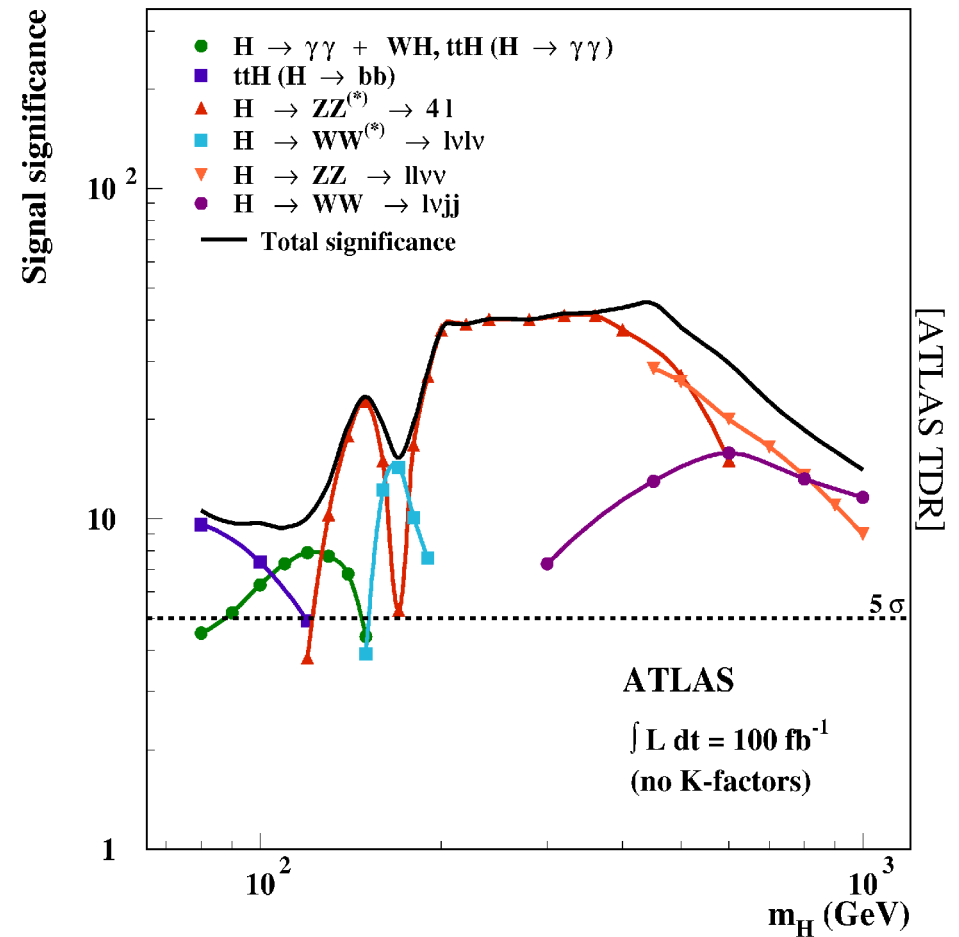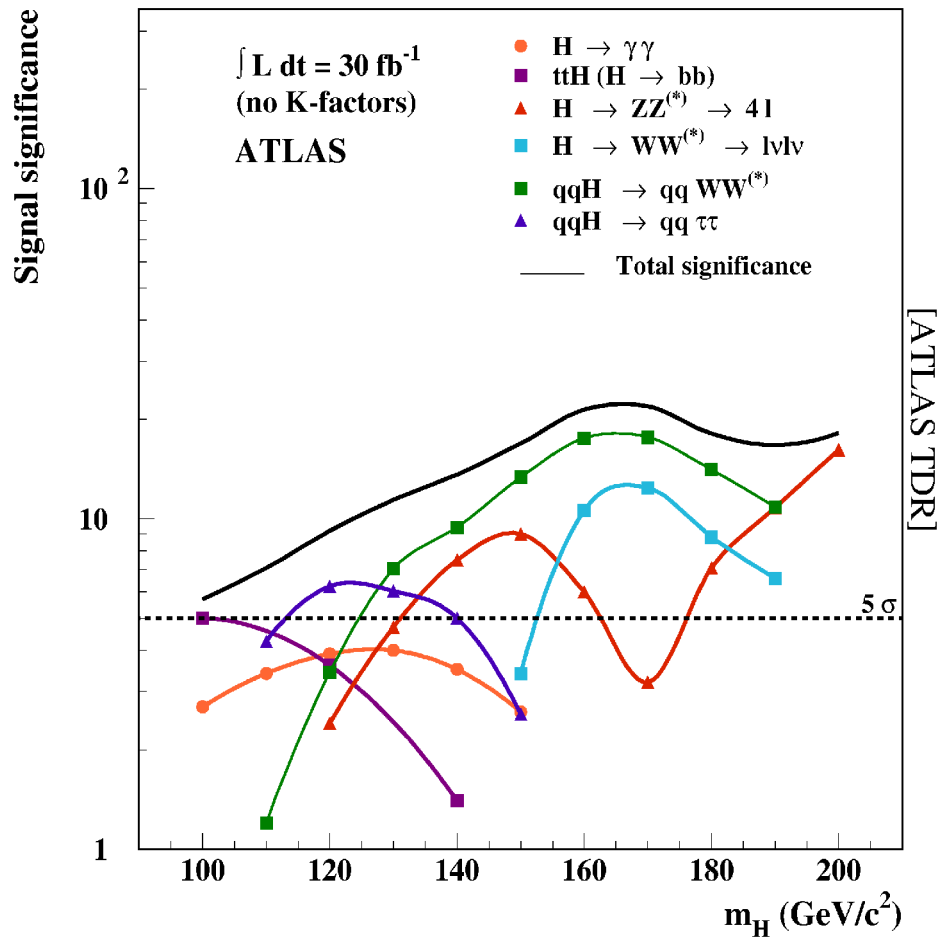
Higgs Production at the LHC

The most important channels are gluon fusion, WBF and t$\bar{\text{t}}$H.

$\sigma(pp \rightarrow H+X)$ [pb]

$\sqrt{s} = 14$ TeV

$M_t = 175$ GeV

CTEQ4M

gg $\rightarrow$ H

qq $\rightarrow$ Hqq

q$\bar{\text{q}}'$ $\rightarrow$ HW

gg, q$\bar{\text{q}}$ $\rightarrow$ Ht$\bar{\text{t}}$

gg, q$\bar{\text{q}}$ $\rightarrow$ Hbb

q$\bar{\text{q}}$ $\rightarrow$ HZ

M_H [GeV]

[M. Spira, Fort. Phys. 46, 203, 1998]
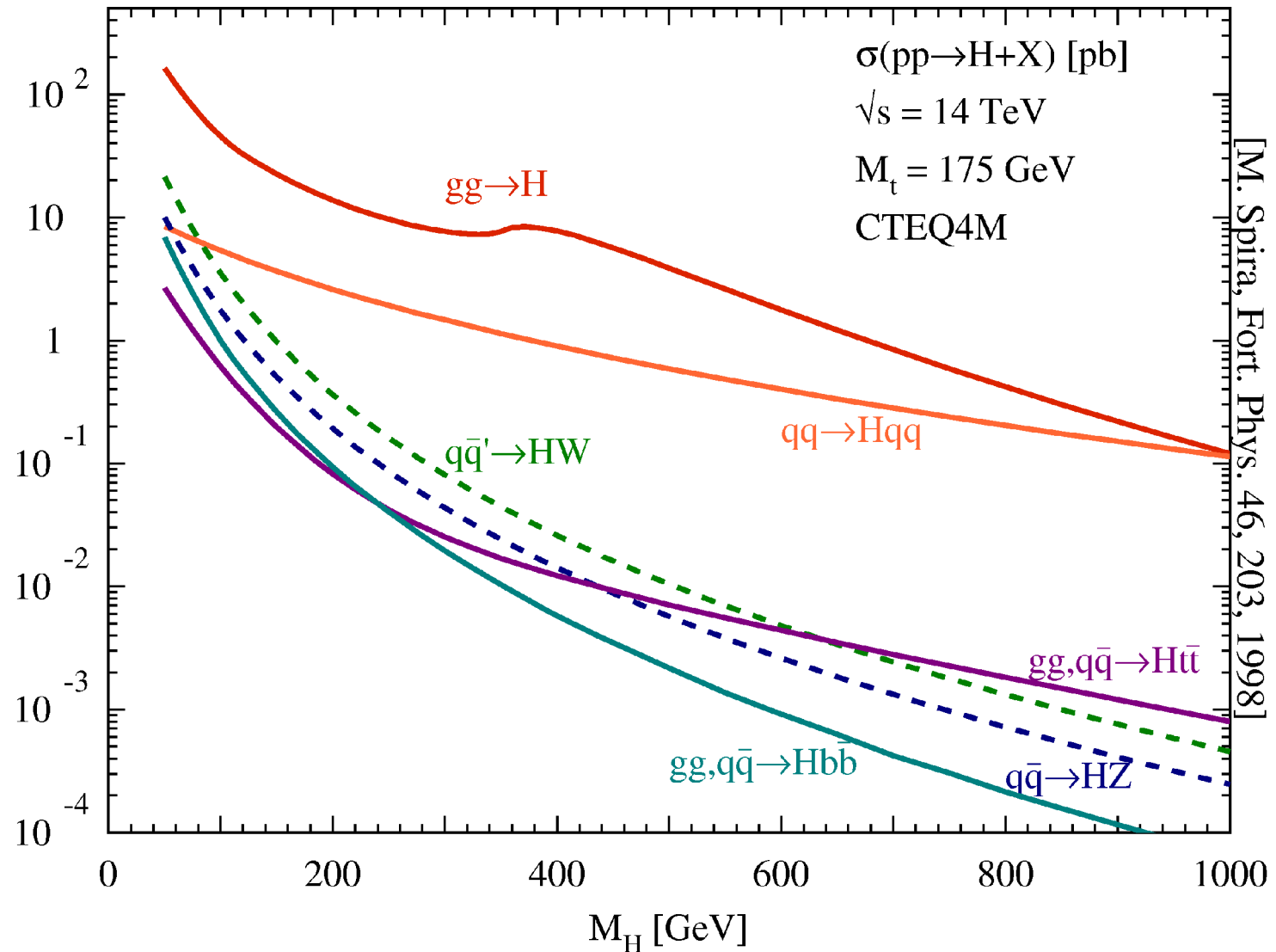
Supersymmetric Higgs' at LHC

The LHC can measure many signals to cover most of the supersymmetric parameter space.
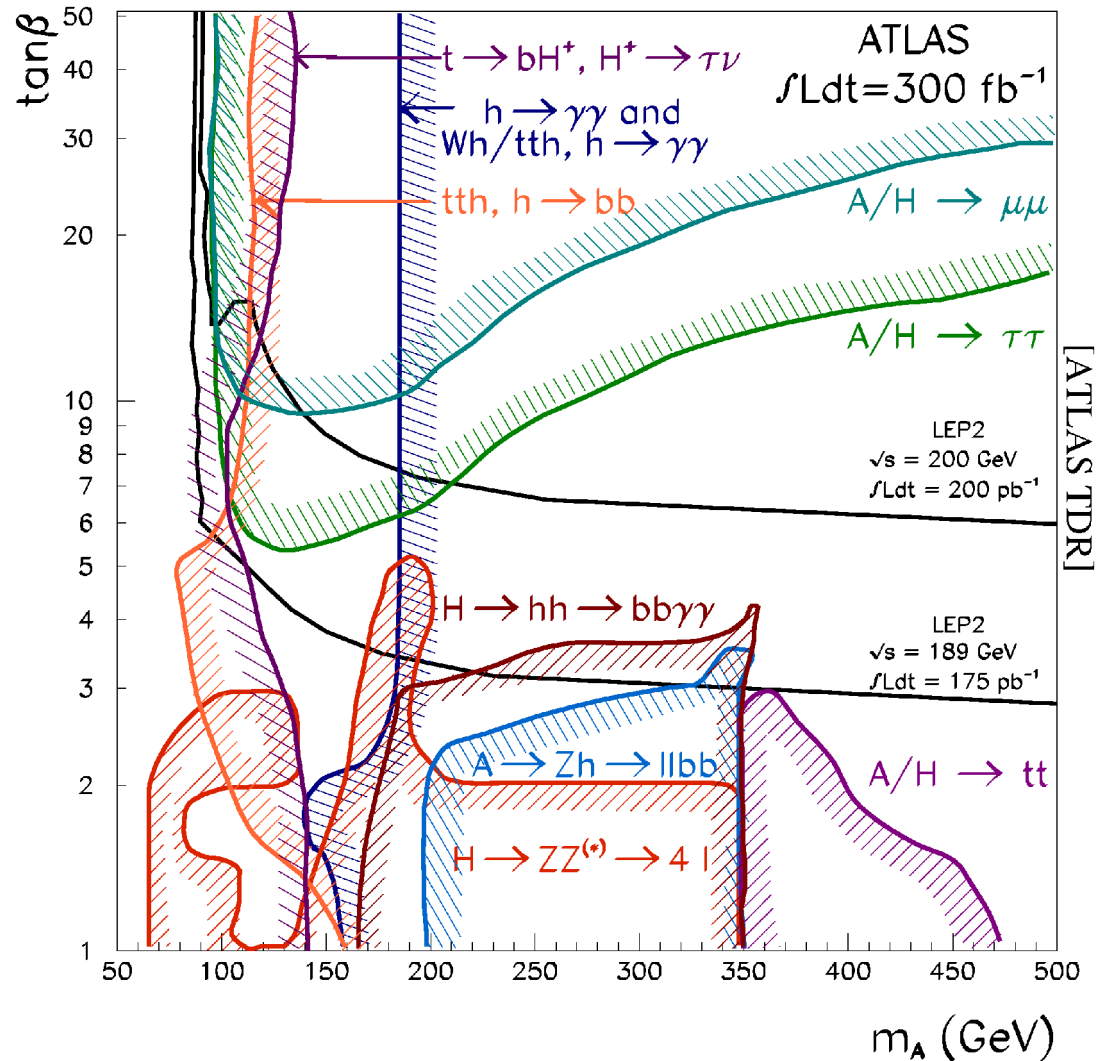
Supersymmetry at the LHC
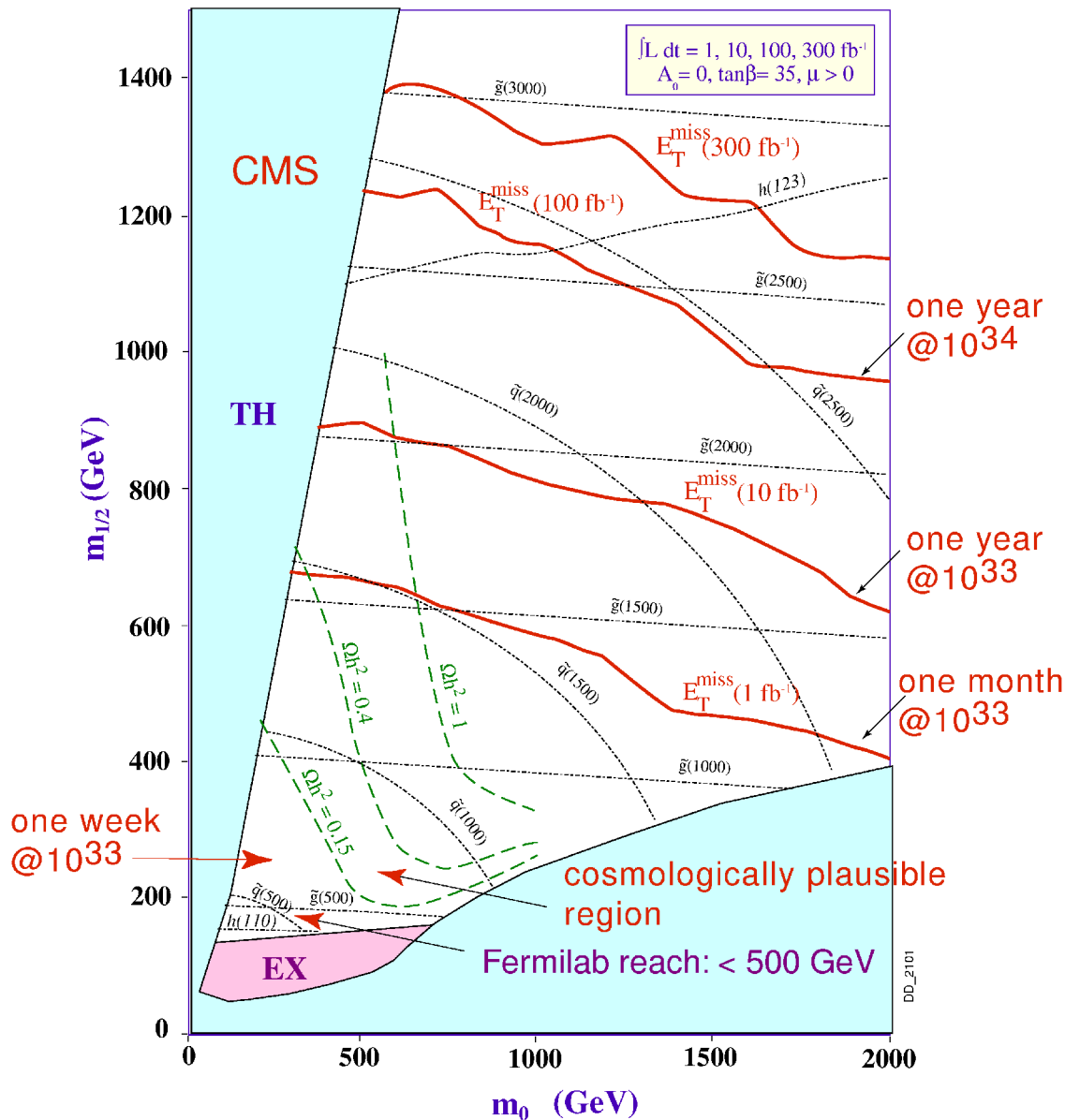
The LHC will be able to observe many supersymmetric particles. The difficulty will be in sorting out the signals.

The dominant backgrounds to most supersymmetry signals at the LHC are other supersymmetry signals.

e^+-e^- Linear Colliders

The international particle physics community has decided that the highest priority in particle physics should be the construction of a high energy (500-1000 GeV) e^+-e^- Linear Collider.

It has been named the top priority by European, Asian and American advisory panels

The LHC will be running before construction of a linear collider can begin. The purpose of a linear collider is perform high precision studies of the Standard Model and of physics beyond.

The Stanford Linear Accelerator:
A Small Prototype
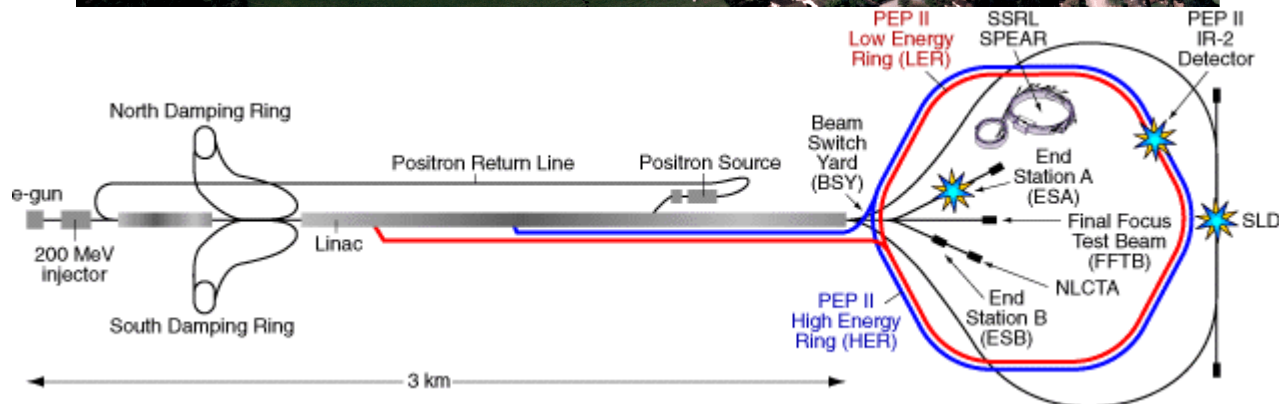
A High Energy Linear Collider Will be Much Bigger:
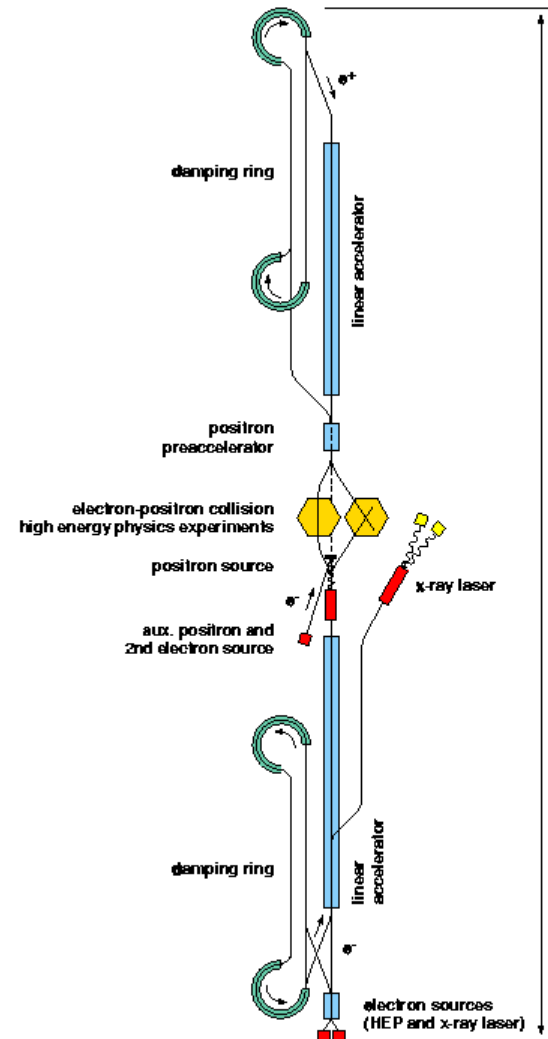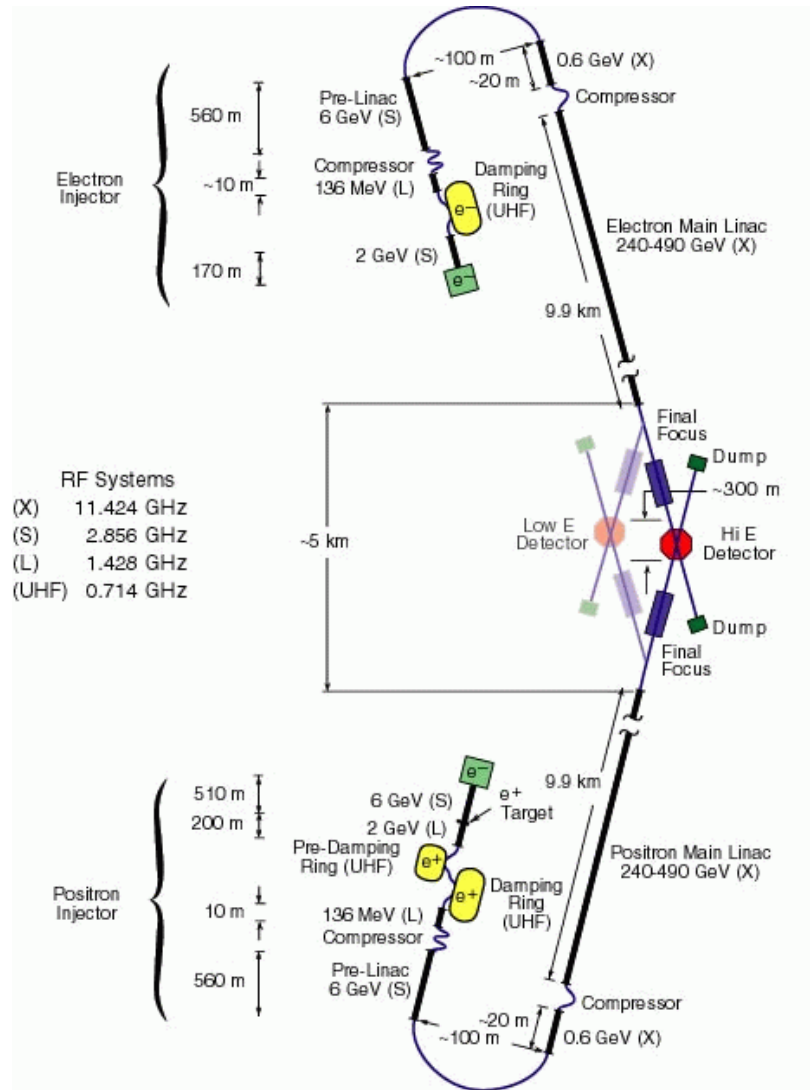
# The Linear Collider Advantage: Precision Measurements

One of the great advantages of the linear collider is its ability to perform precision measurements.

While the LHC can measure masses to a few percent, the linear collider can perform threshold scans and collect large, relatively pure samples from which particle properties can be extracted.
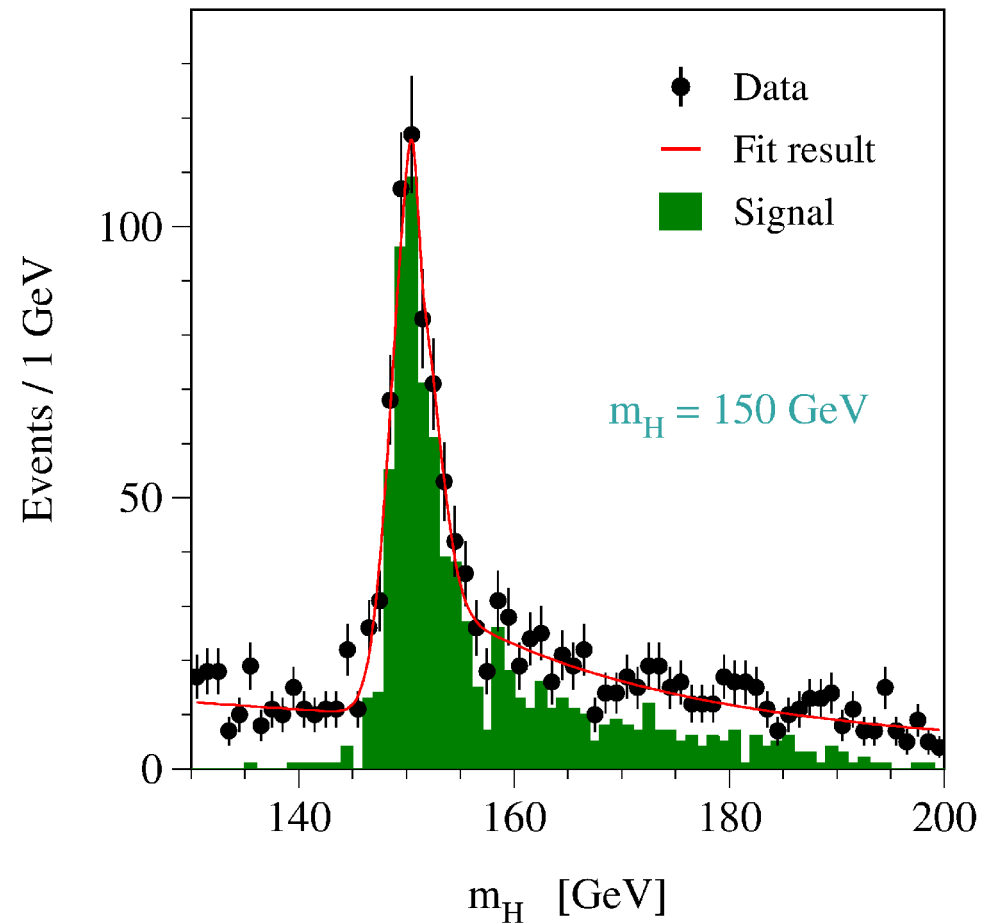
Measuring the Higgs couplings at a Linear Collider

[Battaglia & Desch, hep-ph/0101161]
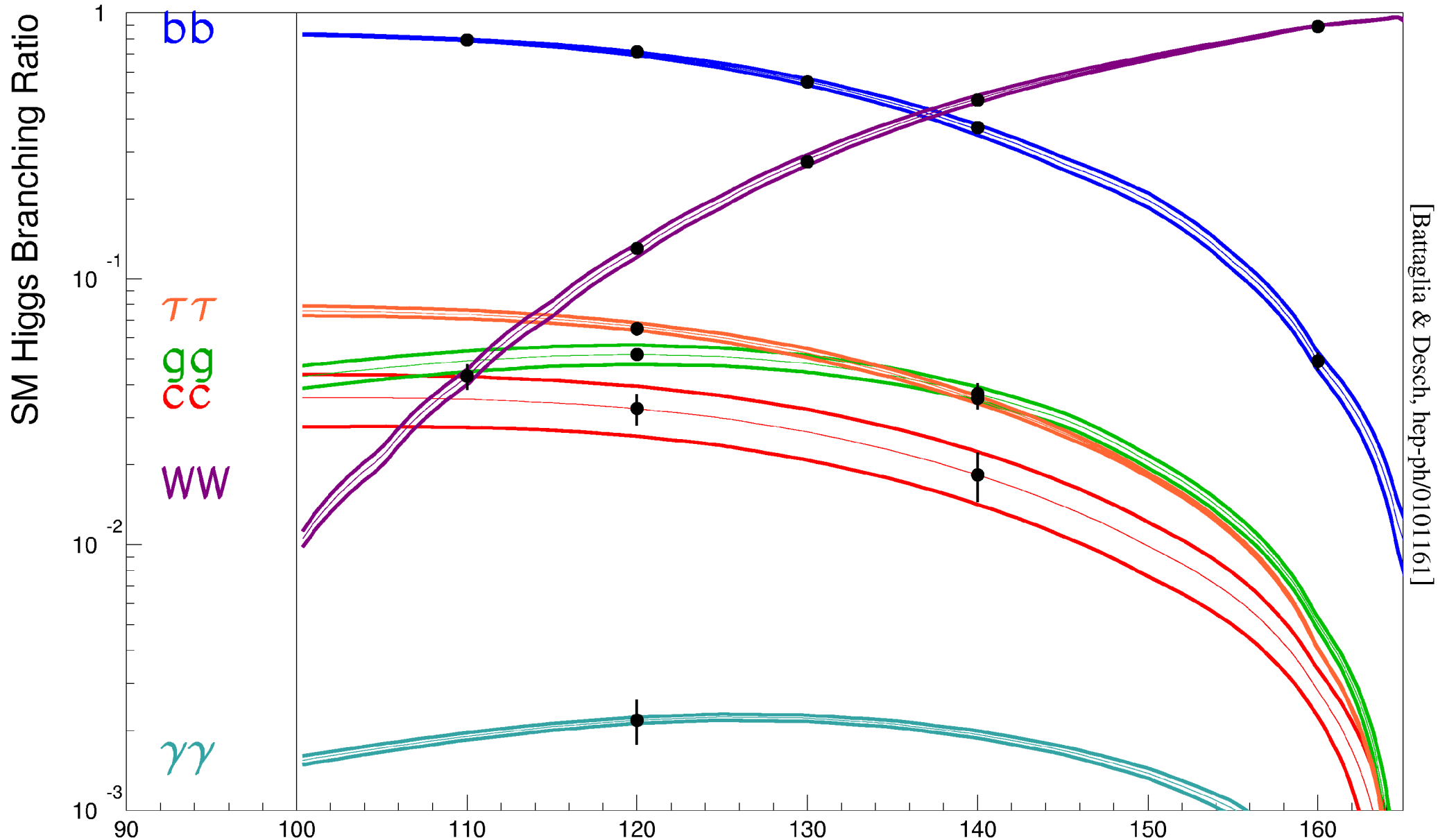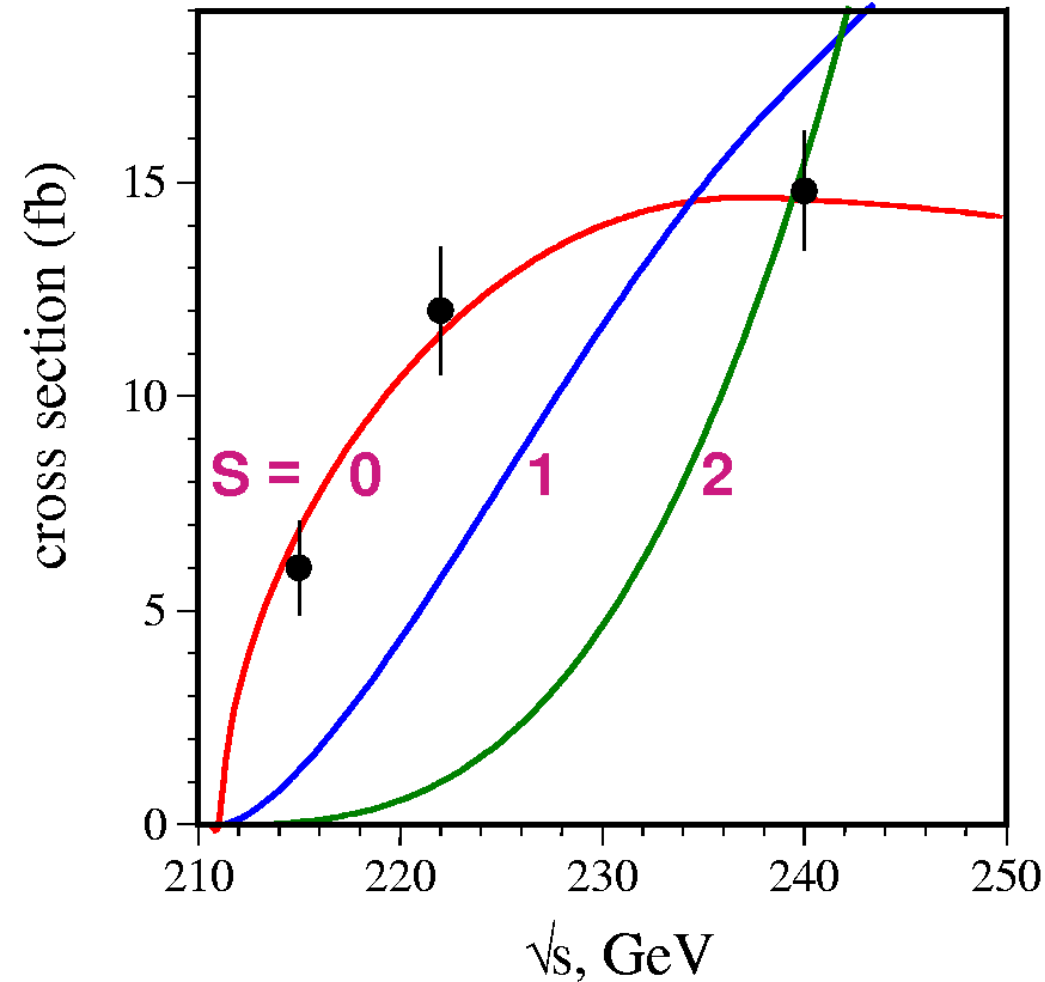
Higgs Observation at a Linear Collider
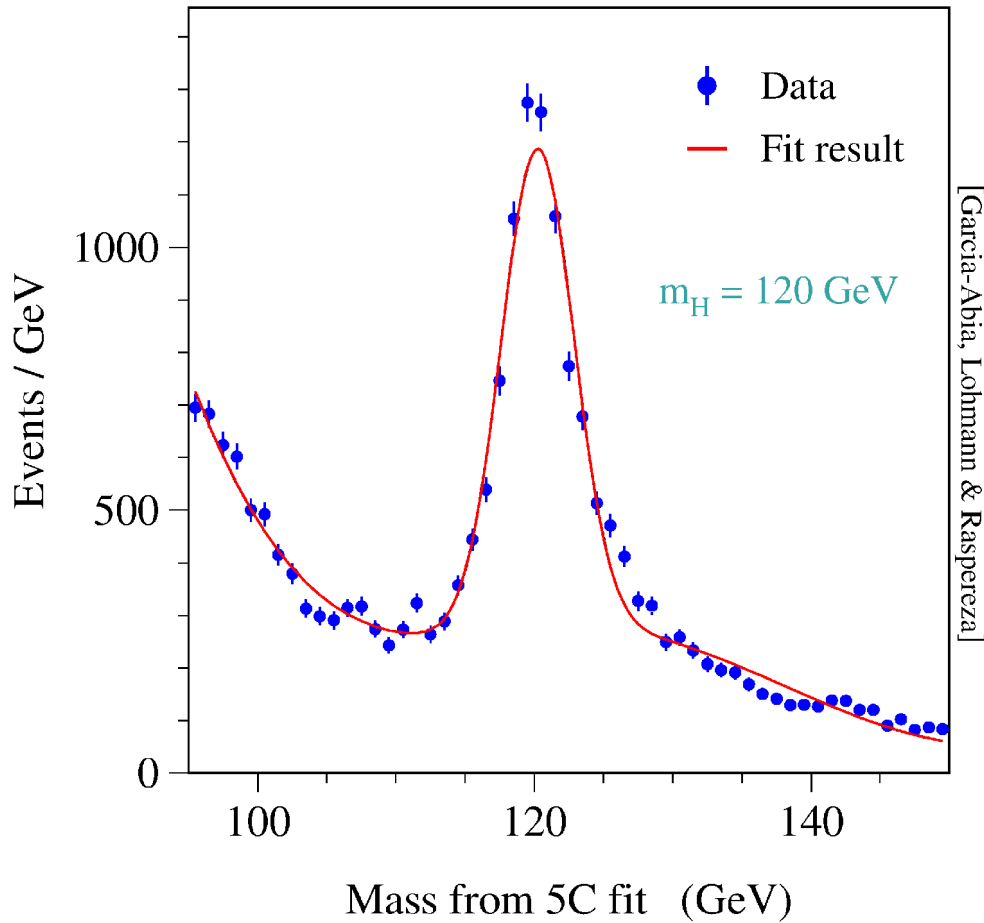
HZ -> q$\bar{q}$b$\bar{b}$

HZ -> l$^+$l$^-$b$\bar{b}$

Measuring Higgs Quantum Numbers at a Linear Collider
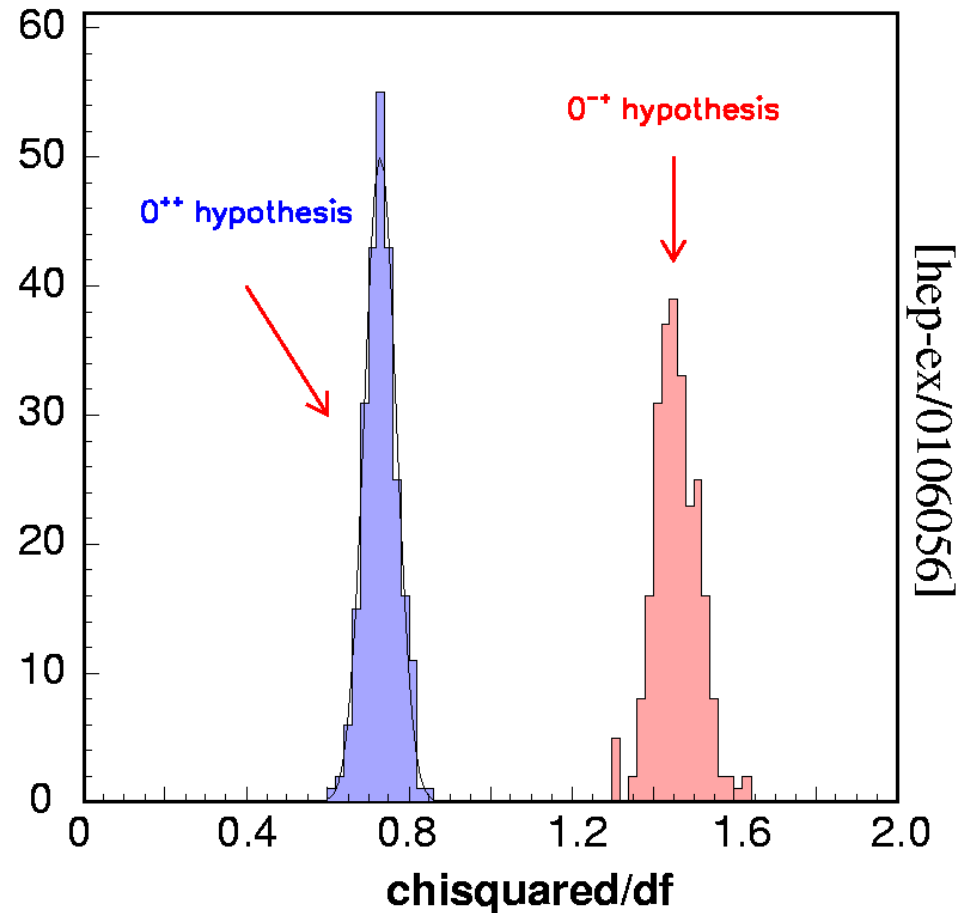
Multiple Higgs Bosons

One scenario with which the LHC has trouble is the case of multiple Higgs bosons. LHC may see only one of several light Higgs bosons.

The linear collider can easily detect multiple Higgs bosons and measure their masses, even if they decay invisibly, by measuring the recoil of the Z boson.