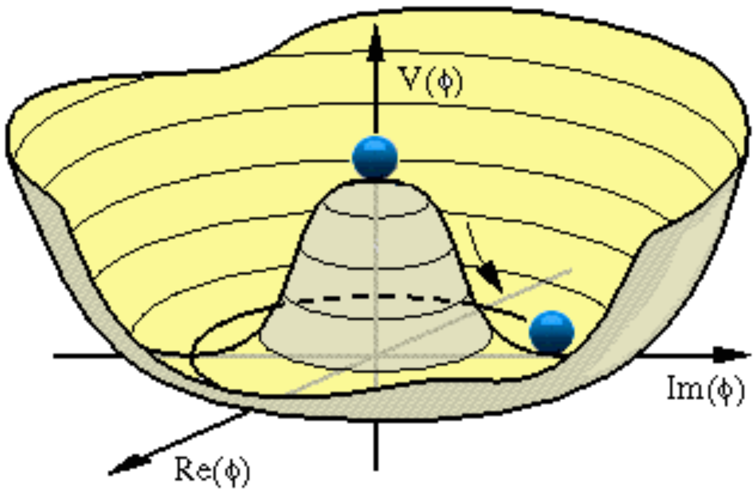
Higgs Theory Mini-Review



Tom Junk

Fermilab

CMS JTERM, 15 January 2009

- Recommended Reading
- A Little History
- SM Higgs Mechanism
- Current Constraints
- Extensions and Other Possibilities

Recommended Reading

G. Bernardi, M. Carena, T. Junk, Higgs Bosons, Theory and Searches.
Particle Data Group Review, updated Dec. 2007, and references therein.

J. Gunion, H. Haber, G. Kane and S. Dawson, The Higgs
Hunter's Guide (Perseus Publishing, 1990).

M. Carena and H. Haber, "Higgs Boson Theory and Phenomenology",
Prog. Part. Nucl. Phys. **50** 60 (2003). ArXiv:hep-ph/0208209

A. Djouadi "The Anatomy of Electro-Weak Symmetry Breaking
I and II", Phys. Rept. **457**, 1 (2008) and Phys. Rept **459**, 1 (2008)

Halzen and Martin, "Quarks and Leptons" (Wiley, 1984).

M. Peskin and D. Schroeder, "Introduction to Quantum Field
Theory" (Addison-Wesley, 1995)

Presentations at the Hadron Collider Physics Summer School 2008
http://projects.fnal.gov/hcpss/hcpss08/
G. Altarelli, SM/Precision Electroweak
H. Haber, Higgs Boson Theory and Phenomenology
S. Martin, Supersymmetry

Higgs Boson 2009: http://www.itp.uzh.ch/events/higgsboson2009
7-9 January 2009, Zurich

Parity Violation and the Beginnings of the SM of Electroweak Interactions

- Lee and Yang, "Question of Parity Conservation in Weak Interactions" Phys. Rev. 104, 254-258 (1956).

- C. S. Wu et al., "Experimental Test of Parity Conservation in Beta Decay" Phys. Rev. 105, 1413-1414 (1957).

- Garwin, Lederman and Weinrich, "Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon" Phys. Rev. 105, 1415-1417 (1957).

The Weirdness of Left-Handed Interactions

- Charged Weak currents violate parity maximally -- the $W^{\pm}$ boson couples only to left-handed fermions (and right-handed anti-fermions). The Z^0 also preferentially couples to left-handed fermions.

- Left-handed fermions have different quantum numbers than their right-handed counterparts! Specifically, left-handed fermions are in SU(2) doublets while the right-handed versions are in singlets.

- Weak eigenstates are not mass eigenstates. CKM matrix expresses the linear combinations.

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L \qquad \begin{matrix} \nu_{e,R}? & \nu_{\mu,R}? & \nu_{\tau,R}? \\ e_R & \mu_R & \tau_R \end{matrix}$$

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L \qquad \begin{matrix} u_R & c_R & t_R \\ d_R & s_R & b_R \end{matrix}$$

SU(2) x U(1) Model Consequences

- Analog to $U(1)_{EM}$ QED model -- Gauge symmetry naturally implies existence of a massless photon with observed gauge interactions. One free parameter -- α_{EM}. Spectacularly predictive!

- SU(2)xU(1) Gauge model predicts chiral structure of Weak interactions, and existence of $W^{\pm}$. Z^0 and γ

$$\mathcal{L}_{mass} = -m\overline{\psi}\psi = -m\left(\overline{\psi}_L\psi_R + \overline{\psi}_R\psi_L\right)$$

- Two problems --
  - Dirac Fermion mass terms in the Lagrangian violate gauge invariance -- mix Left and Right components together
  - Gauge boson mass terms also violate gauge invariance, just like the photon in QED.

  -- conflict with observations!

The Subterfuge -- Add a Minimal Set of New Fields and Interactions

Higgs, Guralnik, Kibble, Englert, Brout, Anderson, Glashow, Weinberg, Salam -- 1963-1968.

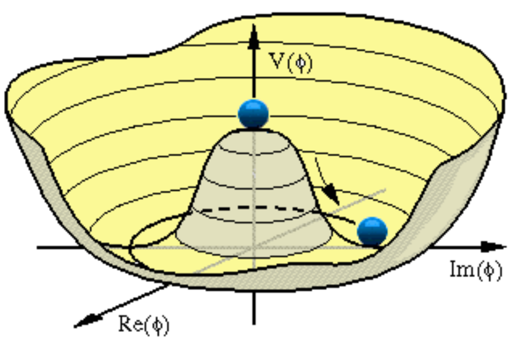
Complex Doublet of fields -- four real degrees of freedom

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

with a self-interaction

$$V(\Phi) = -\mu^2 \left|\Phi^* \Phi\right| + \lambda \left|\Phi^* \Phi\right|^2$$

Φ acquires a VEV (of order m_t), and three massless would-be Goldstone Boson degrees of freedom are absorbed by the $W^\pm$ and Z^0, while the fourth remains as a physical Higgs boson. $SU(2)_L xU(1)_Y$ is broken to $U(1)_{EM}$. Yukawa terms allow for Fermion masses.



Basic Relationships

$$v = \left(\frac{\mu^2}{\lambda}\right)^{1/2}$$

Vacuum Expectation Value of the Higgs field -- Minimizes V(ϕ)

$$m_H = \mu\sqrt{2} = v\sqrt{2\lambda}$$

$$g = \frac{e}{\sin\theta_W} \qquad g' = \frac{e}{\cos\theta_W}$$

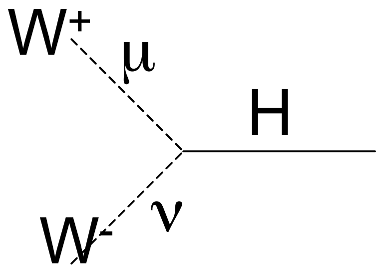
$$M_Z = \frac{v}{2}\sqrt{g^2 + g'^2} \qquad M_W = g\frac{v}{2} = M_Z\cos\theta_W$$

Fermion masses are the product of the VEV v and an arbitrary Yukawa coupling.

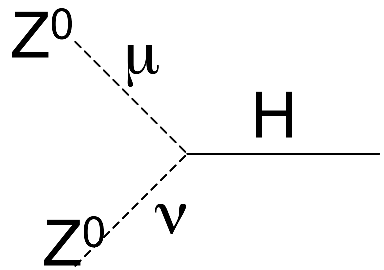
One free parameter: m_H

Conventions: Peskin and Schroeder "An Introduction to Quantum Field Theory"

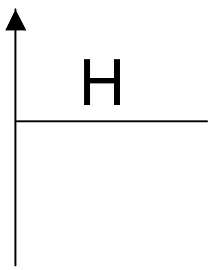
Couplings of Higgs Bosons



$$= 2i \frac{M_W^2}{v} g^{\mu\nu}$$

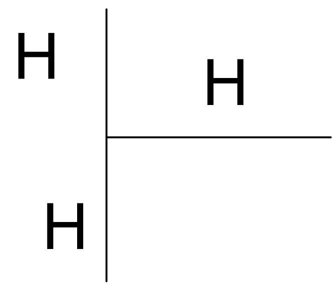


$$= 2i \frac{M_Z^2}{v} g^{\mu\nu}$$



$$= -i \frac{m_f}{v}$$

Fermions



$$= -3i \frac{m_H^2}{v}$$

Also: Quartic W^+W^-HH
Z^0Z^0HH
HHHH diagrams.

Conventions: Peskin and Schroeder “An Introduction to Quantum Field Theory”

Slide from G. Altarelli, HCPSS'08

The main problems for the SM show up in the Higgs sector

$$V_{Higgs} = V_0 - \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 + [\bar{\psi}_{Li} Y_{ij} \psi_{Rj} \phi + h.c.]$$

- V_0: Vacuum energy $V_{0exp} \sim (2.10^{-3}\ \mathrm{eV})^4$
- $\mu^2 \phi^\dagger \phi$: Origin of quadratic divergences. Hierarchy problem
- $\lambda (\phi^\dagger \phi)^2$: Possible instability depending on m_H
- Yukawa term: The flavour problem: large unexplained ratios of Y_{ij} Yukawa constants

With no Higgs unitarity violations for E_{CM} ~ 1-3 TeV

Unitarity implies that scattering amplitudes cannot grow indefinitely with the centre-of-mass energy s

In the SM, the Higgs particle is essential in ensuring that the scattering amplitudes with longitudinal weak bosons (W_L , Z_L) satisfy (tree-level) unitarity constraints
[Veltman, 1977; Lee-Quigg-Thacker, 1977; …]

Zwirner

An example: $\mathcal{A}(W_L^+ W_L^- \to Z_L Z_L) \quad (s \gg m_W^2)$

$$i\frac{s}{v^2}$$

$$-i\frac{s^2}{v^2(s-m_h^2)}$$

$$\rightarrow \quad -i\frac{m_h^2}{v^2}\frac{s}{s-m_h^2}$$

If no Higgs then something must happen!

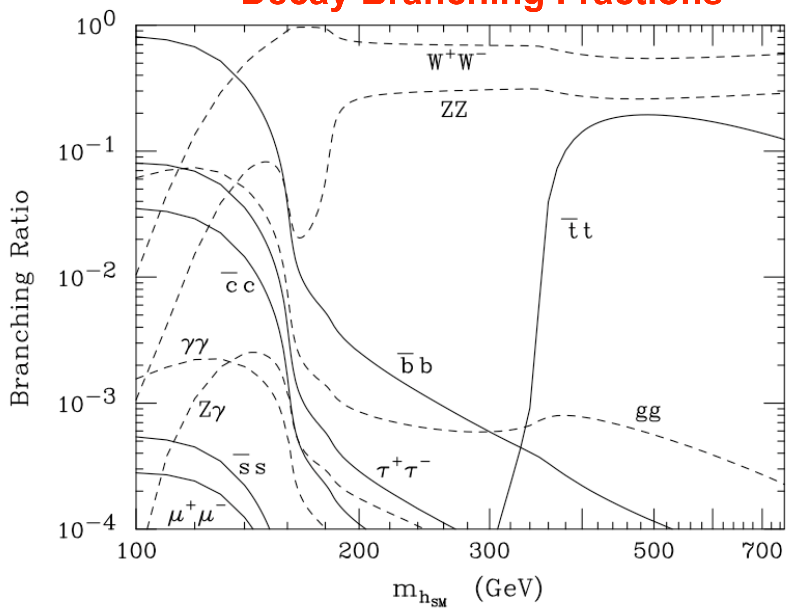
G. Altarelli, HCPSS 2008

Decay Properties of the SM Higgs Boson

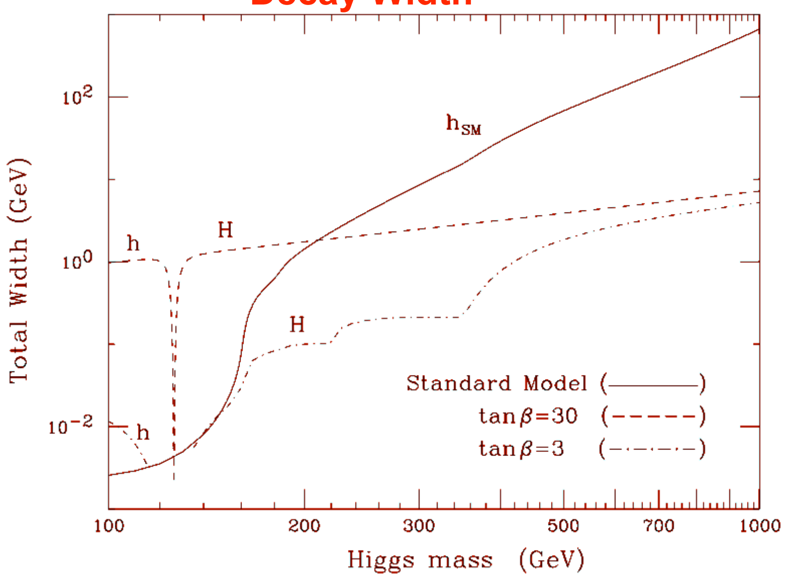
- Couplings of Higgs boson to Fermions ~ $m_{fermion}$
- Couplings of Higgs bosons to Gauge bosons ~ m^2_{boson}

- For the most part, the Higgs boson decays to the heaviest particle available. Fine points: color factors, identical particle counting, spin state counting.
- Higgs is a scalar: spin=0. Decay products have opposite spin.

Decay Branching Fractions

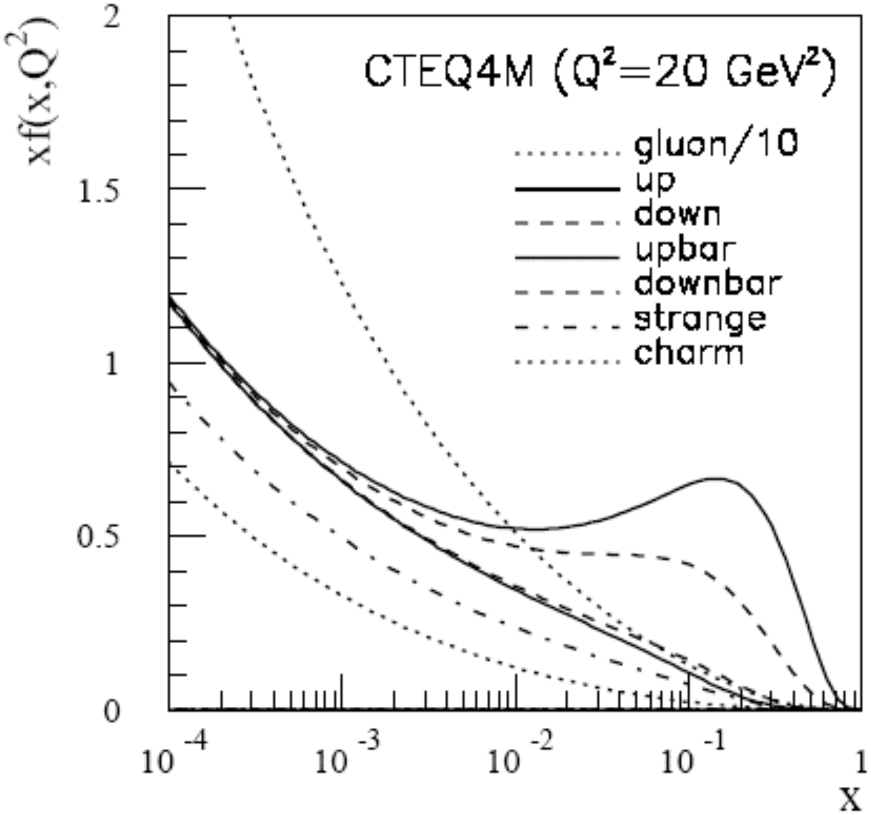


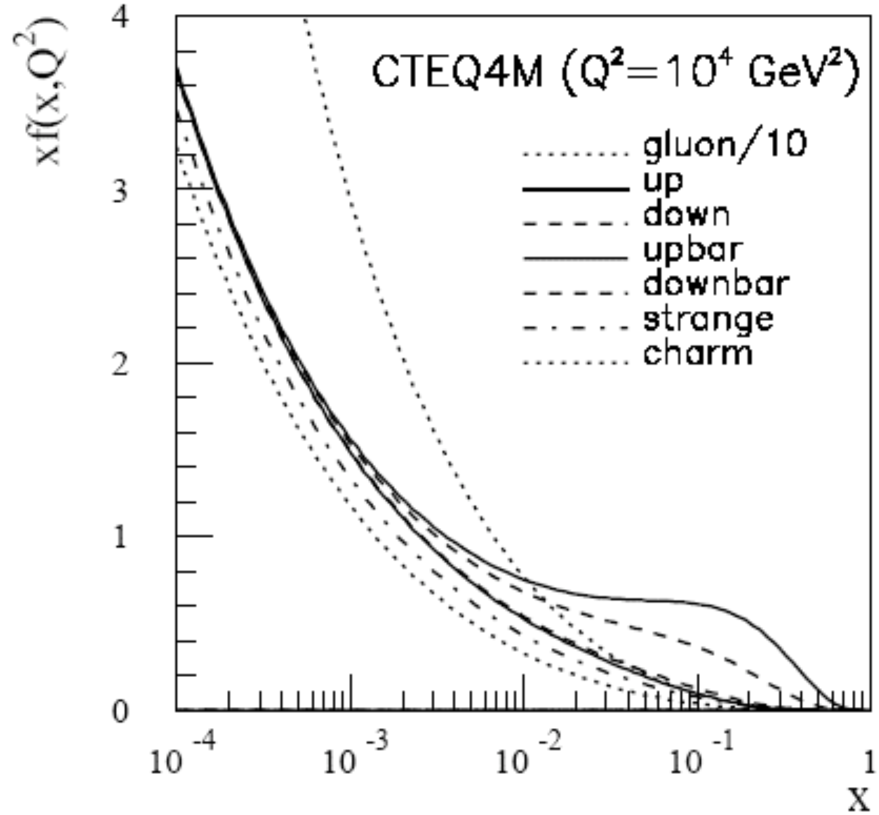
Decay Width



M. Spira: HDECAY http://people.web.psi.ch/spira/hdecay

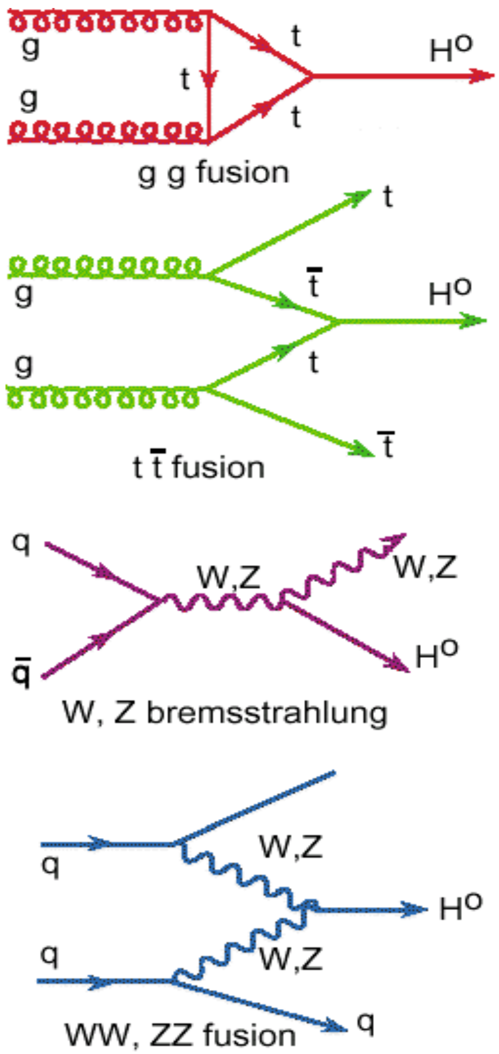
Parton Distribution Functions of the Proton

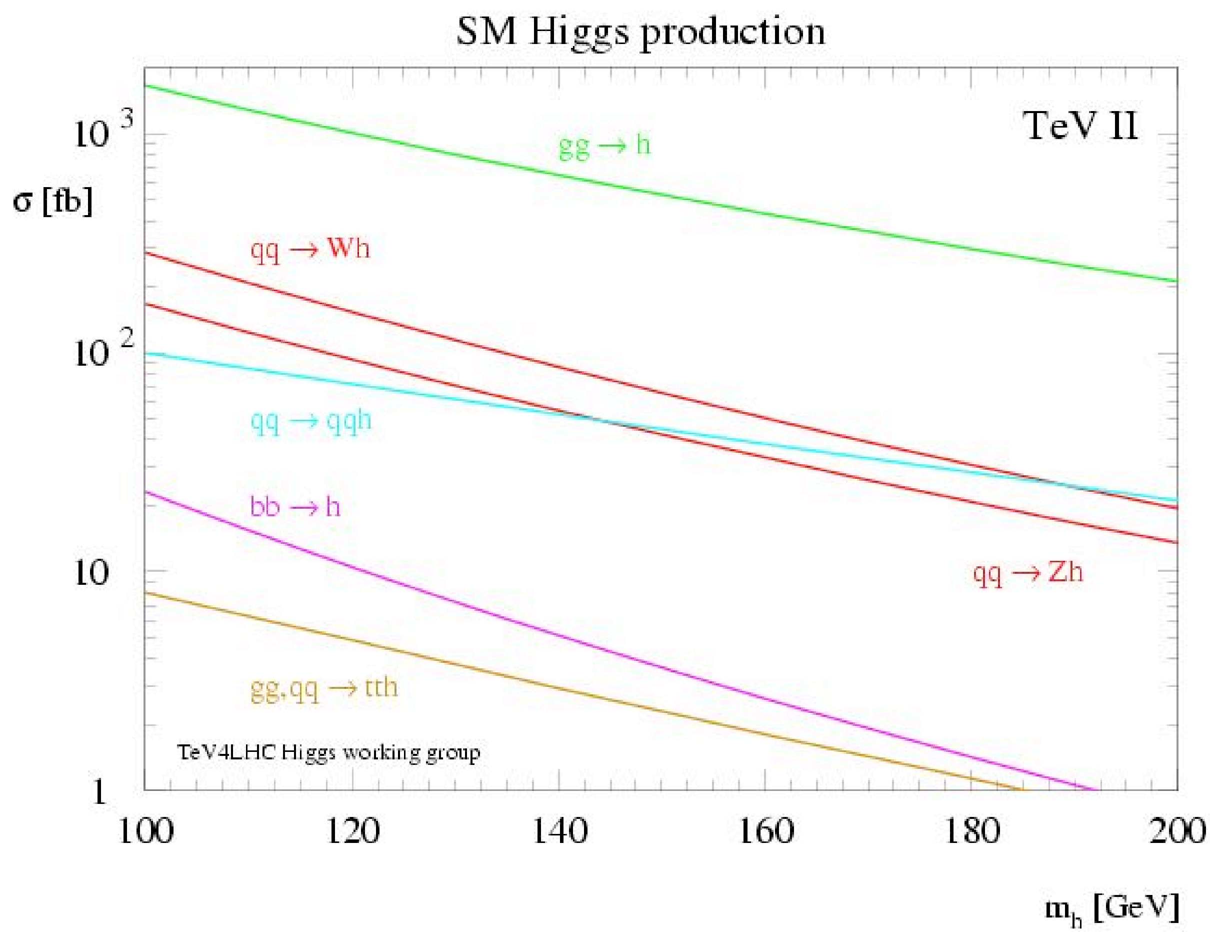




"The LHC is a gluon-gluon collider" (approximately).

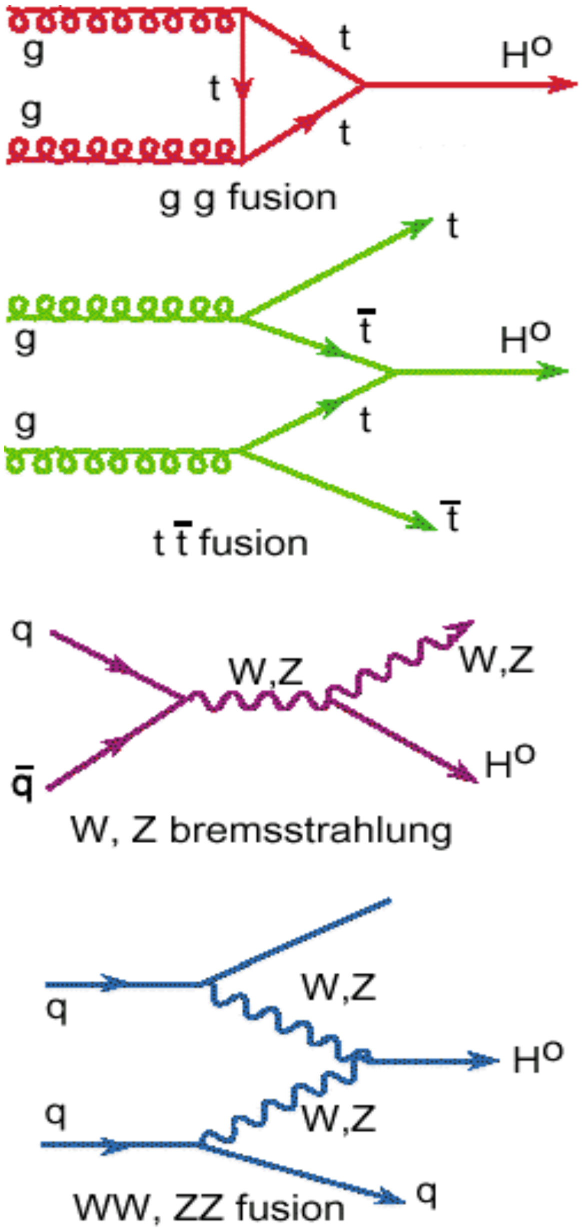
Higgs Boson Production Cross Sections at the Tevatron

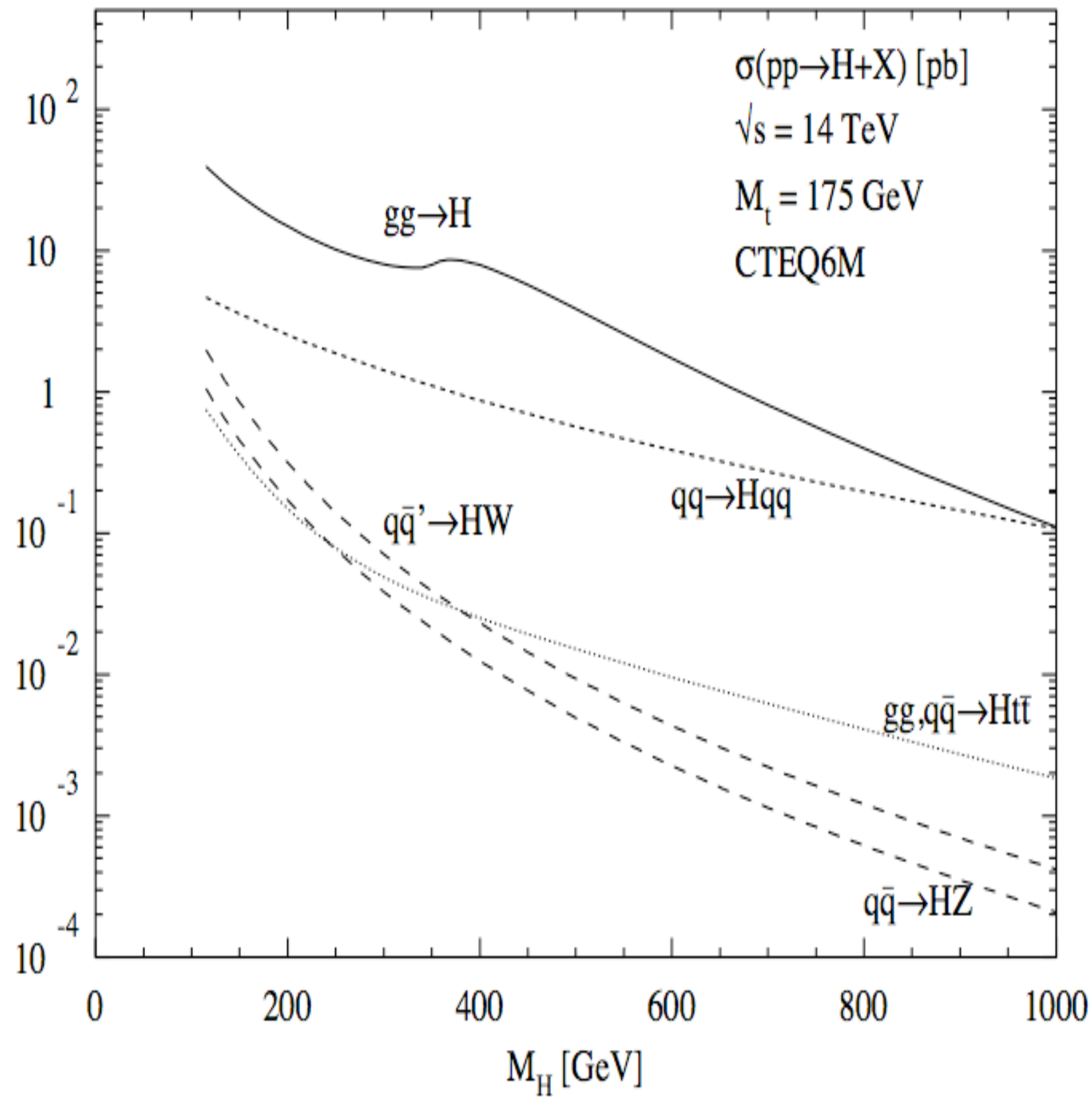




http://maltoni.home.cern.ch/maltoni/TeV4LHC/SM.html

SM Higgs Boson Production Rates at the LHC

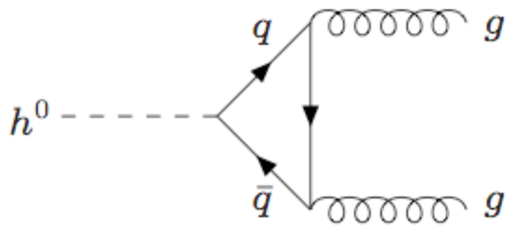




Higgs Boson Couplings to Gluons

H. Haber, HCPSS 2008

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



m_g=0 by $SU(3)_{color}$ symmetry

This diagram leads to an effective Lagrangian

Mostly top contributes

$$\mathcal{L}^{\rm eff}_{hgg} = \frac{g\alpha_s N_g}{24\pi m_W} h^0 G^a_{\mu\nu} G^{\mu\nu a}\,,$$

where N_g is roughly the number of quarks heavier than h^0. More precisely,

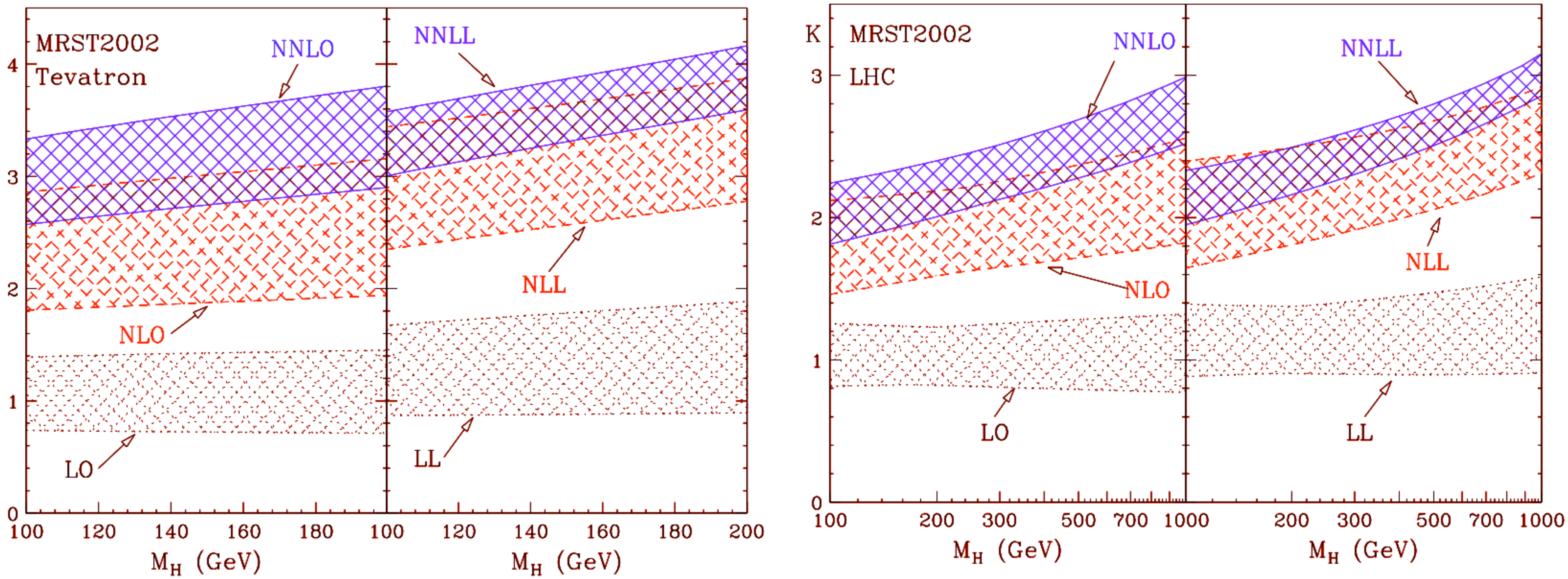
$$N_g = \sum_i F_{1/2}(x_i)\,, \qquad x_i \equiv \frac{m^2_{q_i}}{m^2_h}\,,$$

where the loop function $F_{1/2}(x) \to 1$ for $x \gg 1$.

A heavy fourth generation of quarks would scale
the gg→H production rate at colliders by a factor of ~9.
But watch out for $H\to\nu_4\bar{\nu}_4$ decays.
E. Arik et al., Acta Phys. Polon. B **37**, 2839 (hep-ph/0502050)

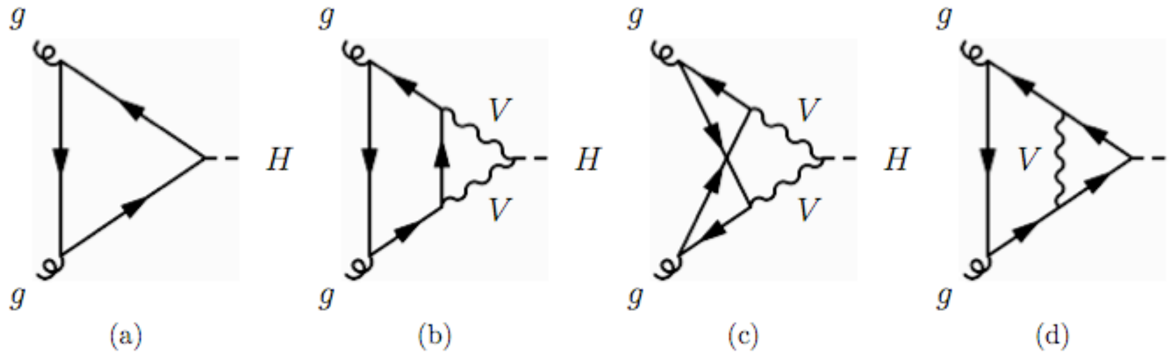
Recent gg→H Production Cross Section Progress

- Leading order is one-loop, so NLO involves more pieces -- gluon radiation from gluons, and more loops.
- NLO corrections -- ~80% (almost double the cross section)!
- NNLO QCD corrections -- An additional 40% on top of that! Residual uncertainty ~10%. Catani, de Florian, Grazzini, Nason JHEP **0307**, 028 (2003) hep-ph/0306211



NLO,NNLO bands: $0.5m_H<\mu_F,\mu_R<2M_H$. Bands on LO unreliable.

Recent gg→H Production Cross Section Progress



V=W,Z

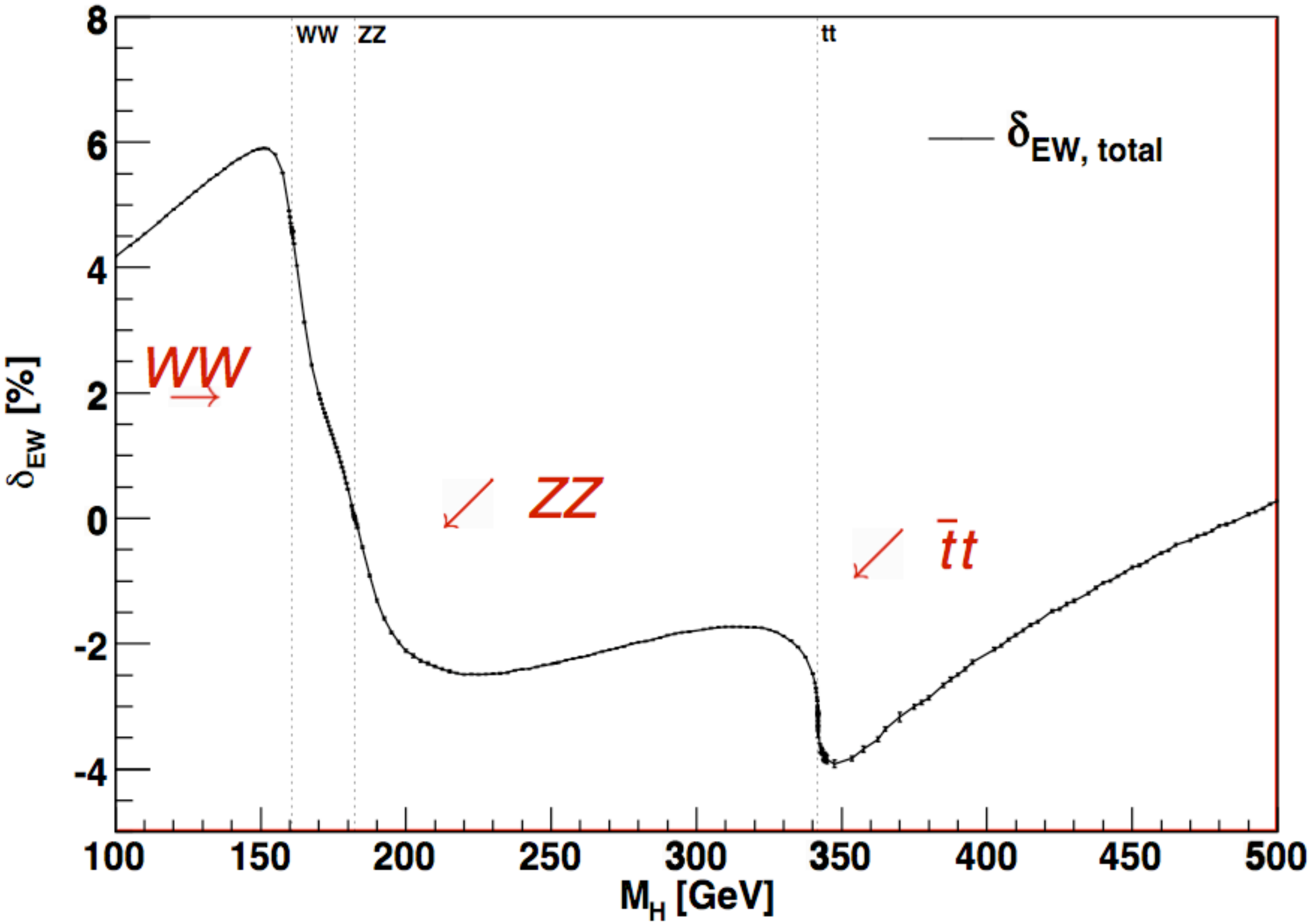
An active area of research. See
http://www.itp.uzh.ch/events/higgsboson2009 7-9 January 2009, Zurich

- Two-loop EW corrections yield up to an 8% boost in cross section near m_H=160 GeV. Aglietti, Bonciani, Degrassi and Vicini, arXiv:hep-ph/0610033 (used by the Tevatron at ICHEP 2008)
- Newer calculations: Anastasiou, Boughezal, Petriello, arXiv:0811.3458
  More modern PDF set -- MRST 2006 NNLO
  Bottom quark loops interfere destructively with top quark loops
  - Bottom quark loop contributions get smaller QCD corrections than top loops.
  - Running b mass is smaller than pole mass.

  Less contribution from b loops means more cross section

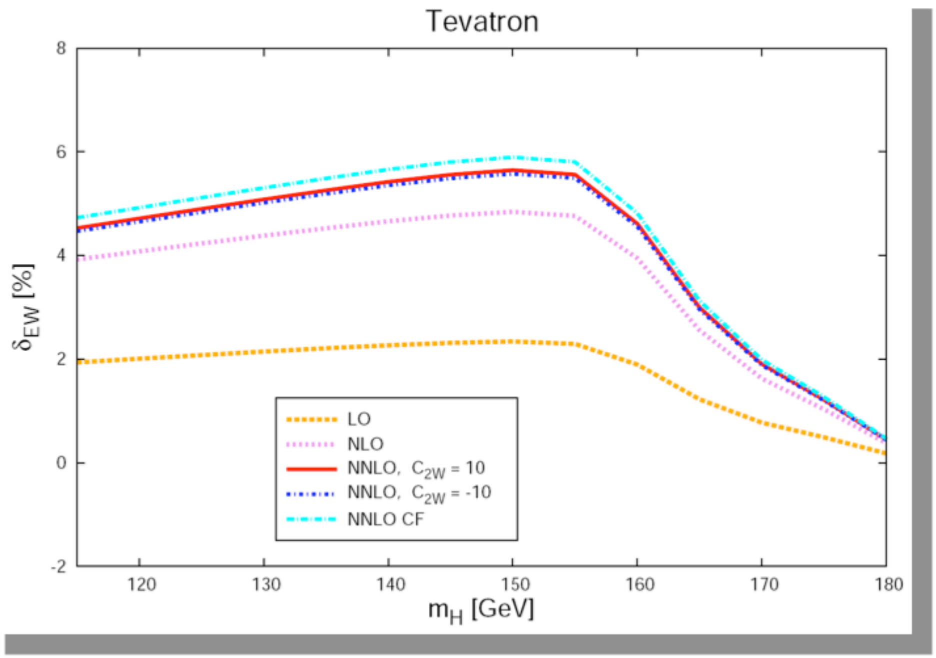
Total 14% bigger cross section relative to NNLO QCD (Catani et. al) at m_H=160 GeV -- 0.49 pb at the Tevatron.

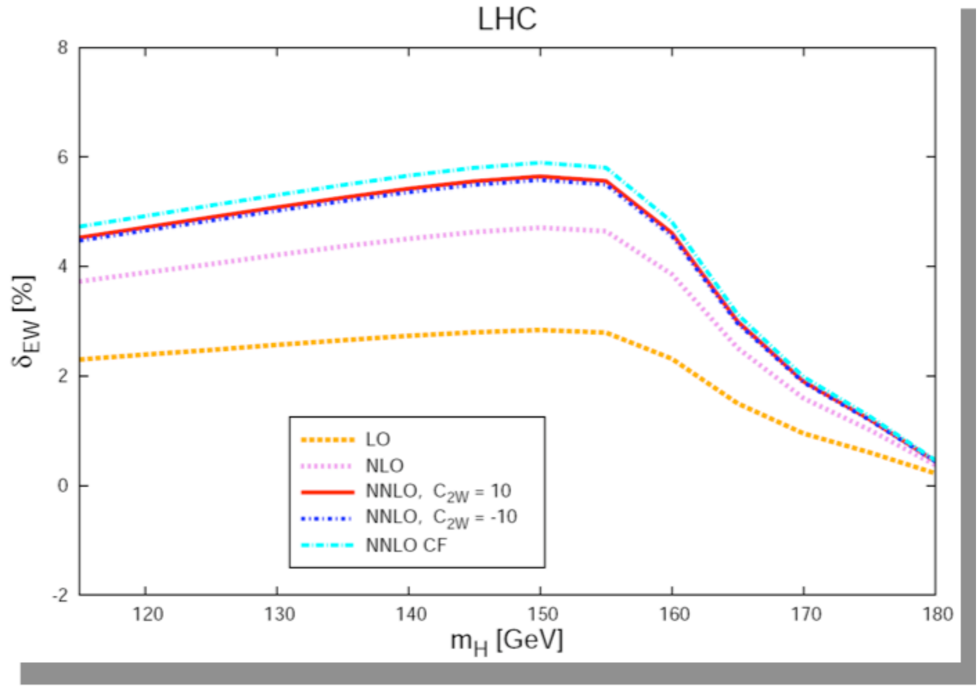
EW corrections to $\sigma(gg \to H)$



Passarino, Higgs Boson 2009, Zurich

Theoretical Work on ggH production is Applicable to both LHC and the Tevatron





Anastasiou, Boughezal, Petriello 2008.

But: Parton Distribution Functions Can be Very Important

Grazzini, Higgs Boson 2009:

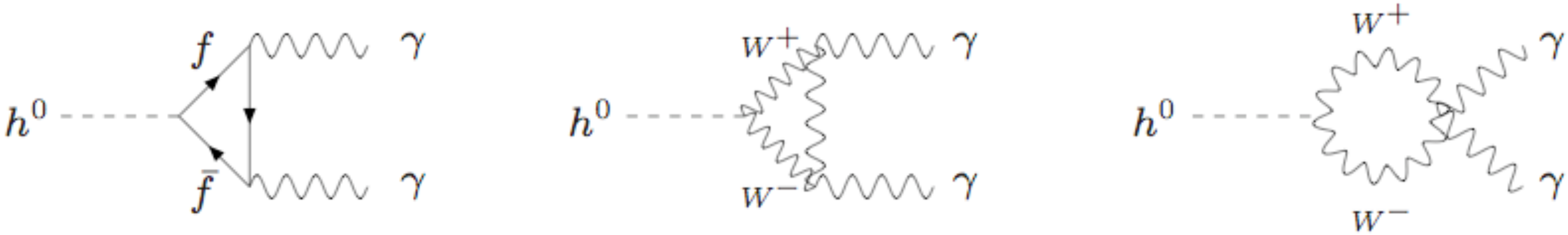
MSTW released a new PDF set on January 5, 2009

Preliminary impact on LHC $gg \rightarrow H$ cross section: ~2%
but on the Tevatron result, big differences -- 6-15%
for $100 < m_H < 200$ GeV

Important concern: Measuring $Br(H \rightarrow WW)$ for m_H~160 GeV relies on theoretical understanding of $\sigma(gg \rightarrow H)$, or non-observation of other modes.

Higgs Boson Couplings to Photons

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



If charged scalars exist, they would contribute as well. These diagrams lead to an effective Lagrangian

$$\mathcal{L}^{\rm eff}_{h\gamma\gamma} = \frac{g\alpha N_\gamma}{12\pi m_W} h^0 F_{\mu\nu}F^{\mu\nu}\,,$$

where

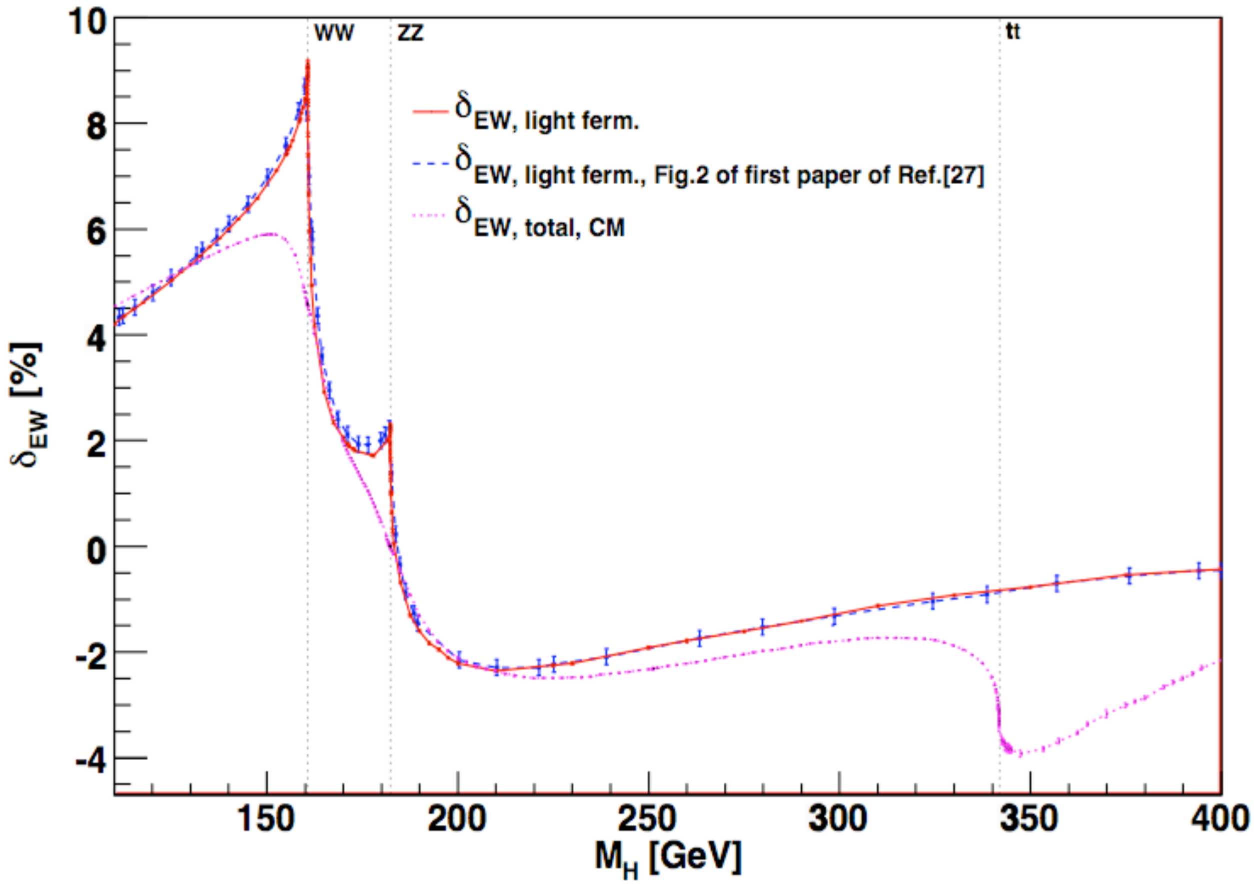
$$N_\gamma = \sum_i N_{ci} e_i^2 F_j(x_i)\,, \qquad x_i \equiv \frac{m_i^2}{m_h^2}\,.$$

In the sum over loop particles i of mass m_i, $N_{ci} = 3$ for quarks and 1 for color singlets, e_i is the electric charge in units of e and $F_j(x_i)$ is the loop function corresponding to ith particle (with spin j). In the limit of $x \gg 1$,

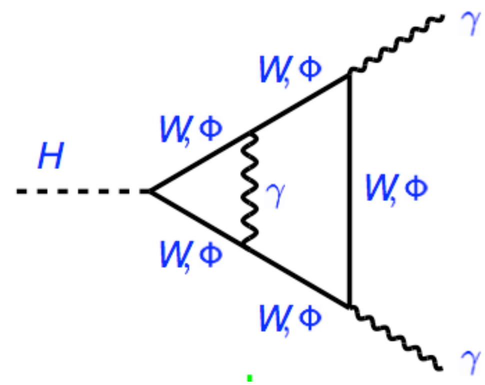
$$F_j(x) \longrightarrow \begin{cases} 1/4\,, & j = 0\,, \\ 1\,, & j = 1/2\,, \\ -21/4\,, & j = 1\,. \end{cases}$$

H. Haber, HCPSS 2008

Comparing H→γγ with gg→H coupling shifts

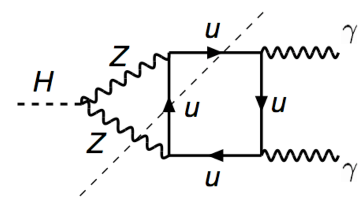


Passarino



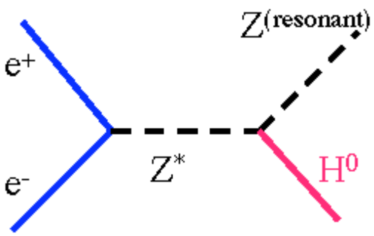
Coulomb singularity
not present in
ggH coupling

Moderated by Γ_W and Γ_Z



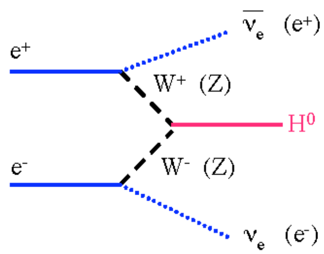
Passarino, Zurich 2009

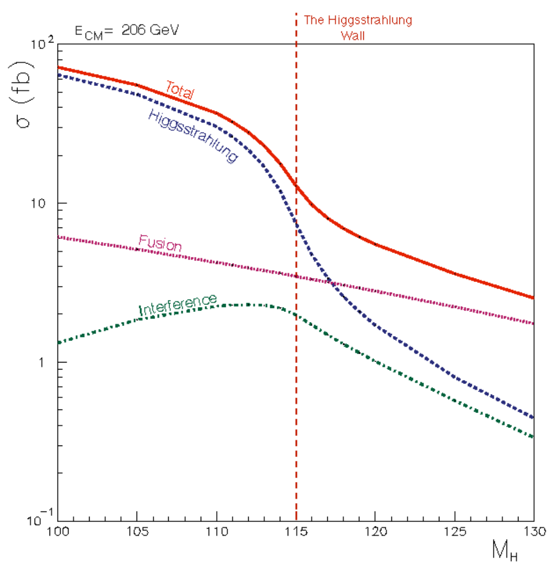
Searches for Higgs Bosons at LEP and LEP2



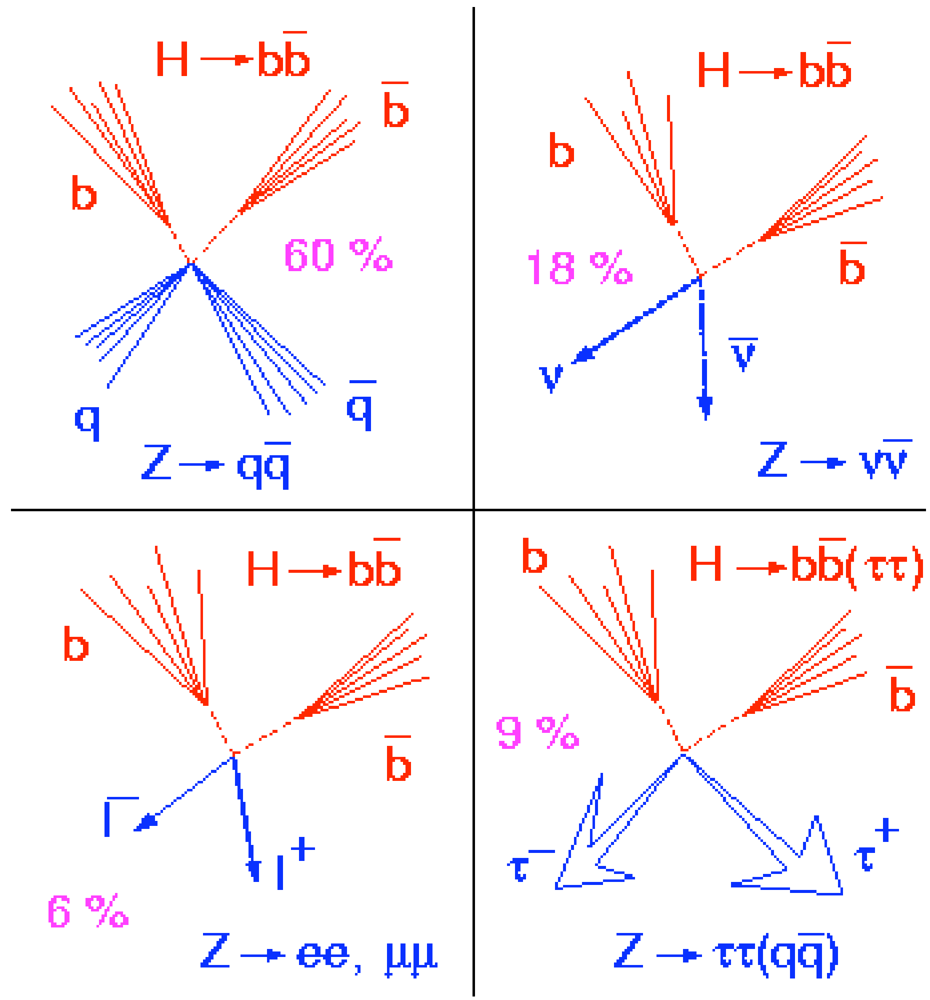
Higgs-strahlung

Vector-
Boson Fusion



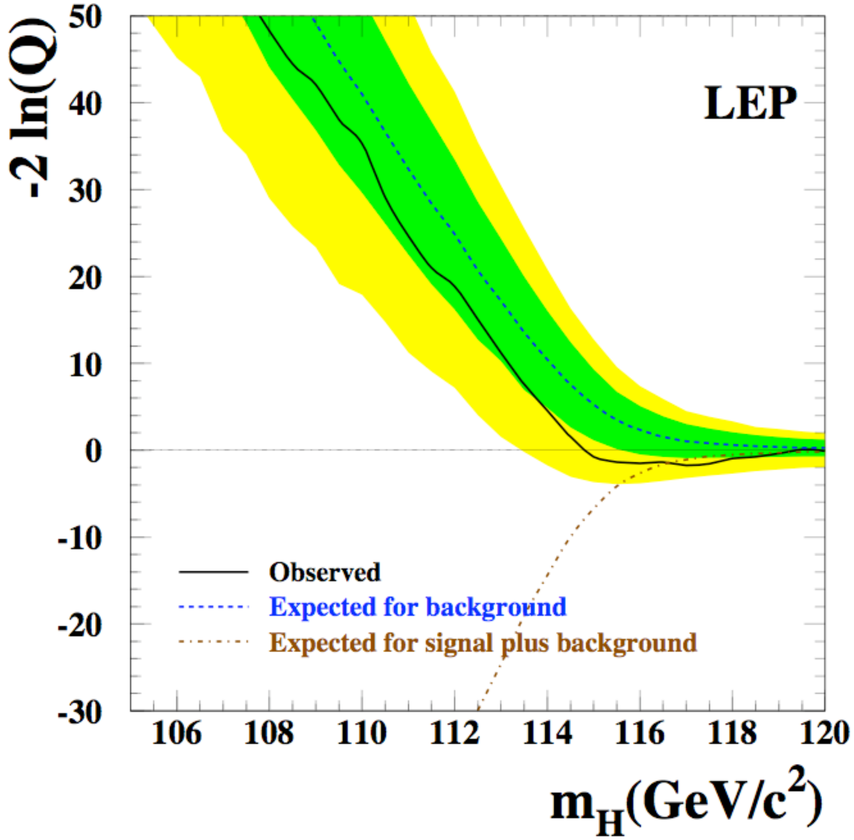


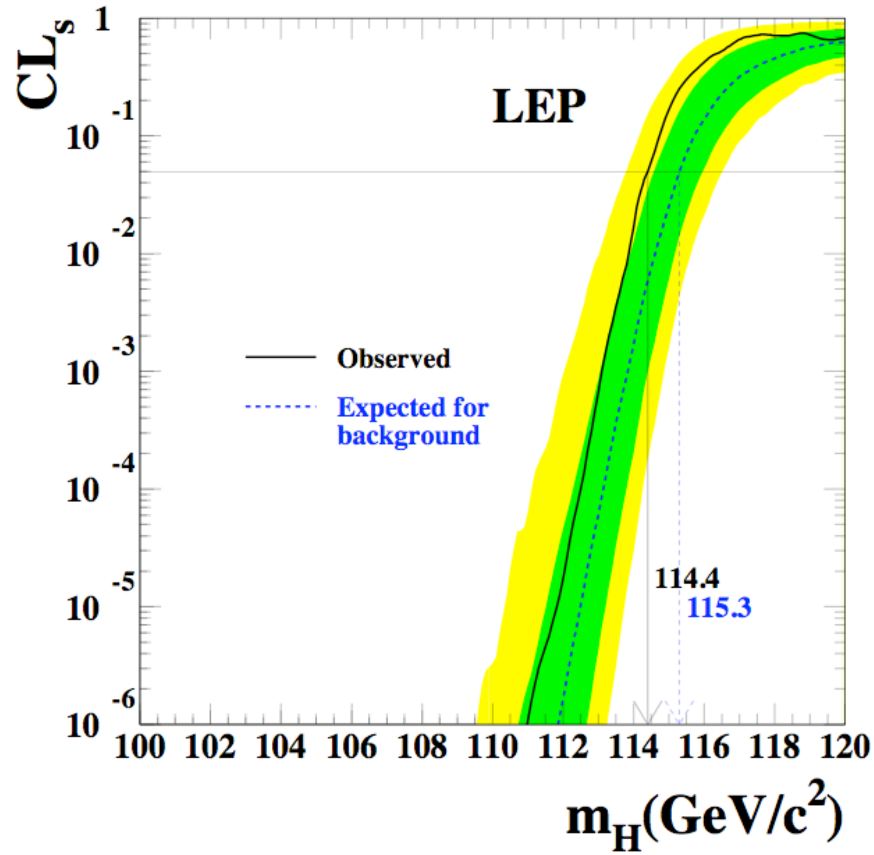
Search channels named after the Z decay mode



LEP2 Direct Search Constraints on SM Higgs

Phys. Lett. B **565** (2003) 61-75

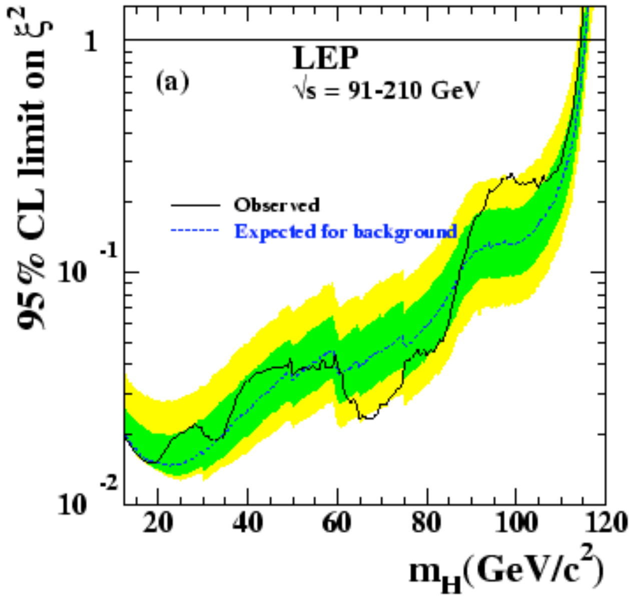


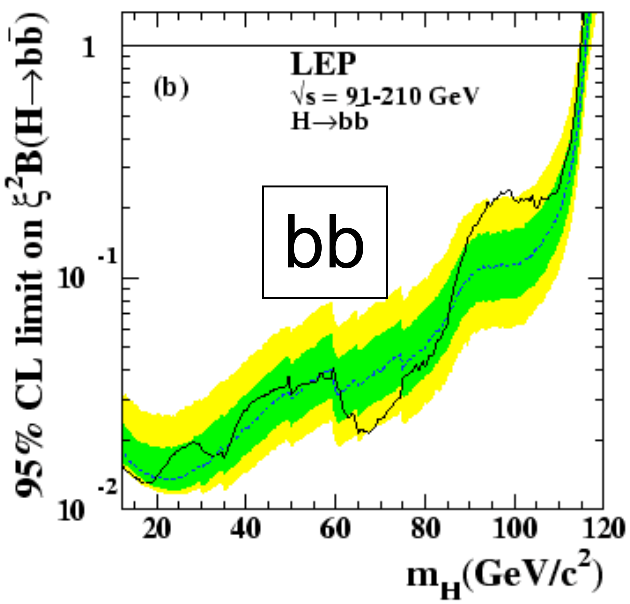


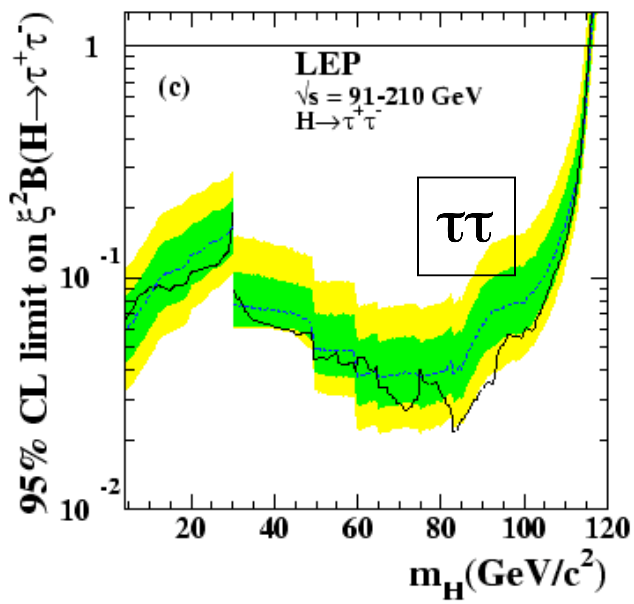
A bit of an excess seen at ~115 GeV,
mostly in ALEPH, mostly in the $e^+e^- \rightarrow qqbb$ channel

LEP Exclusions for Higgsstrahlung with specific Higgs decay modes

SM Decays

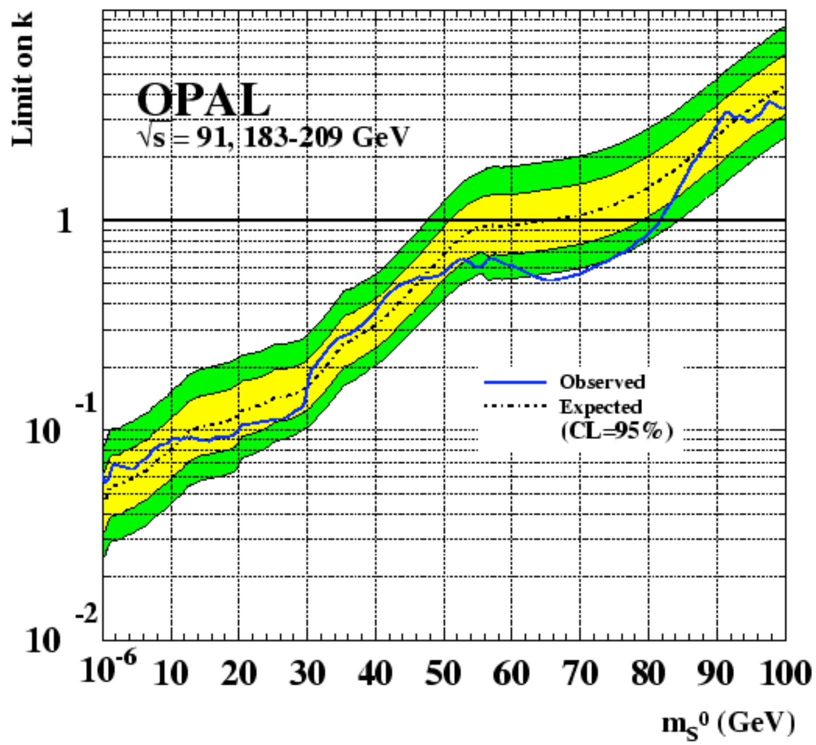






Phys. Lett. B **565** (2003) 61-75

Higgs Coupling to the Z with SM couplings Excluded all the way down to m_H=0



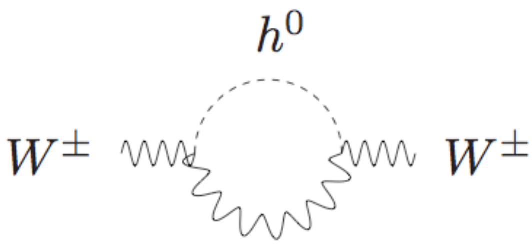
Eur. Phys. J C **27** (2003) 311-329

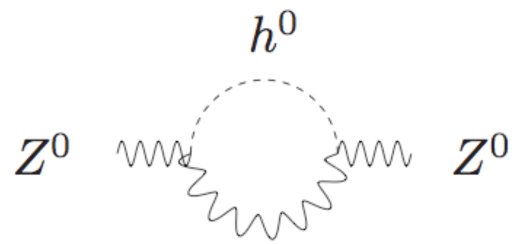
Decay-mode Independent
Search in $e^+e^- \rightarrow$ Z+anything
(CP-even Higgs component!)
Including invisible decay products.

Mass reach extends down to exactly zero.
Many “stealthy Higgs” and continuous-spectrum Higgs models ruled out too.
Assumes Higgsstrahlung production. k=1: SM Higgs production rate.

Separate dedicated searches for CP-even Higgses decaying to
bb, ττ, jets, γγ, invisible
done at LEP2. Limits all ~110 GeV

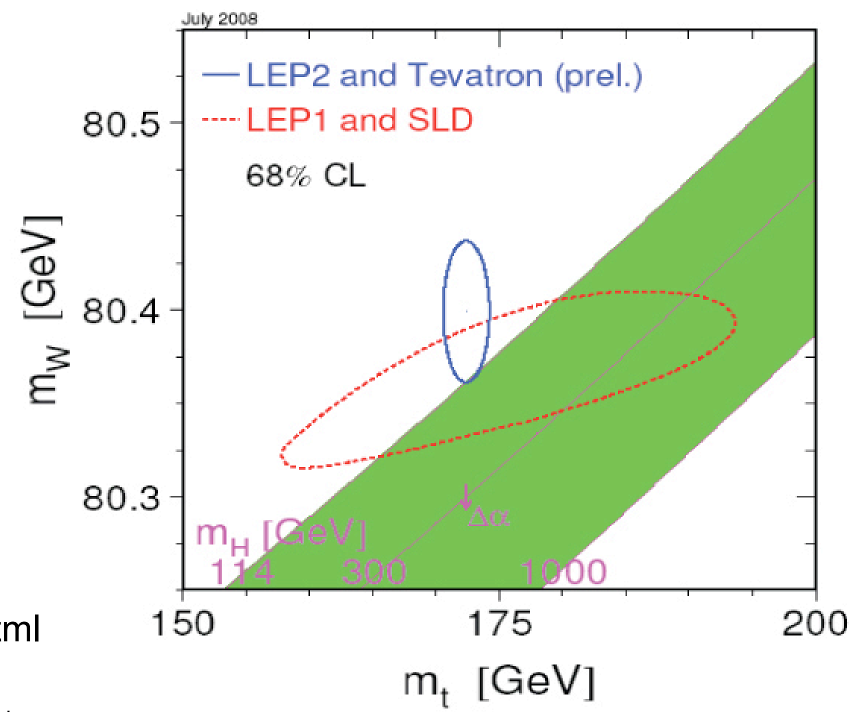
Sensitivity of Precision EW Measurements to m_H in the SM





Small corrections to m_W and m_Z from Higgs loops

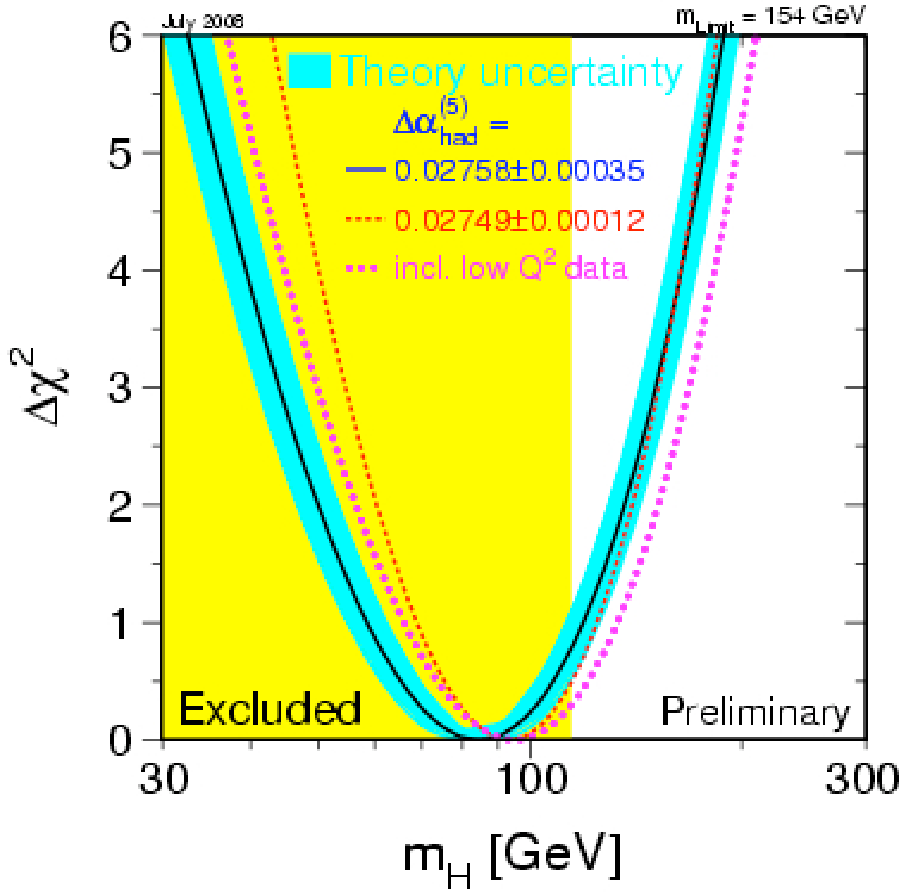
Larger, known contributions from fermion loops
M_Z known to ±2.1 MeV from LEP lineshapes. Approx zero unc.
M_W known to ± 25 MeV
M_t known to ±1.2 GeV.
Left-Right Z-Fermion coupling Asymmetries measured at LEP and SLC also help constrain m_H via $\sin^2\theta_W$

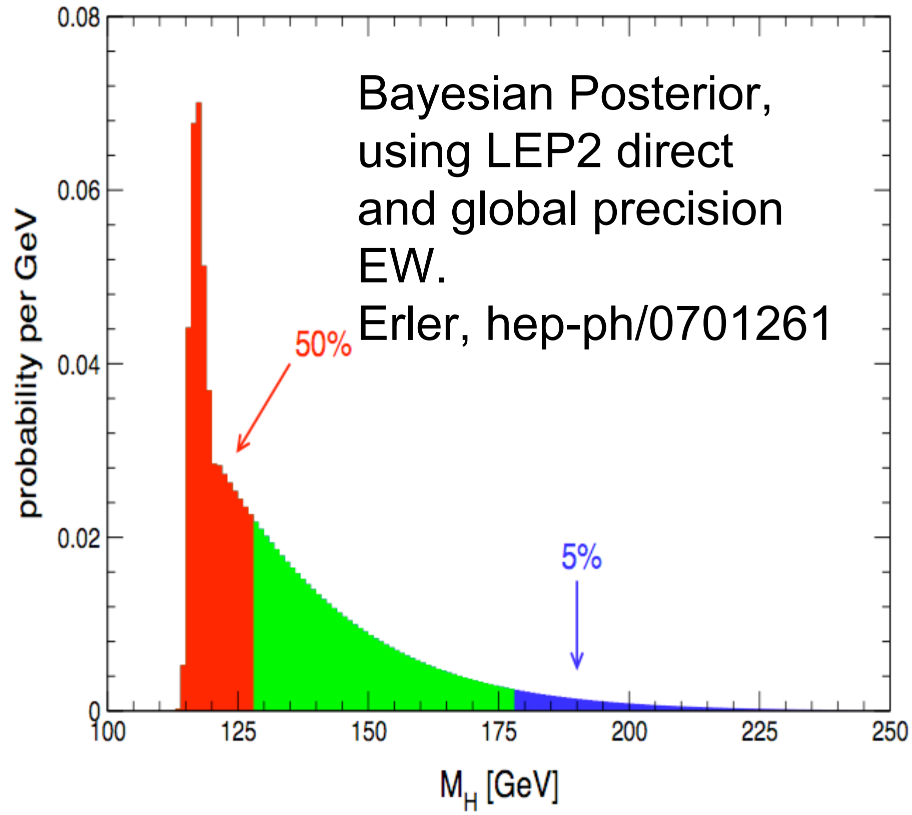


http://www-cdf.fnal.gov/physics/new/top/public_mass.html

Precision Electroweak Constraints on m_H

http://www.cern.ch/lepewwg/





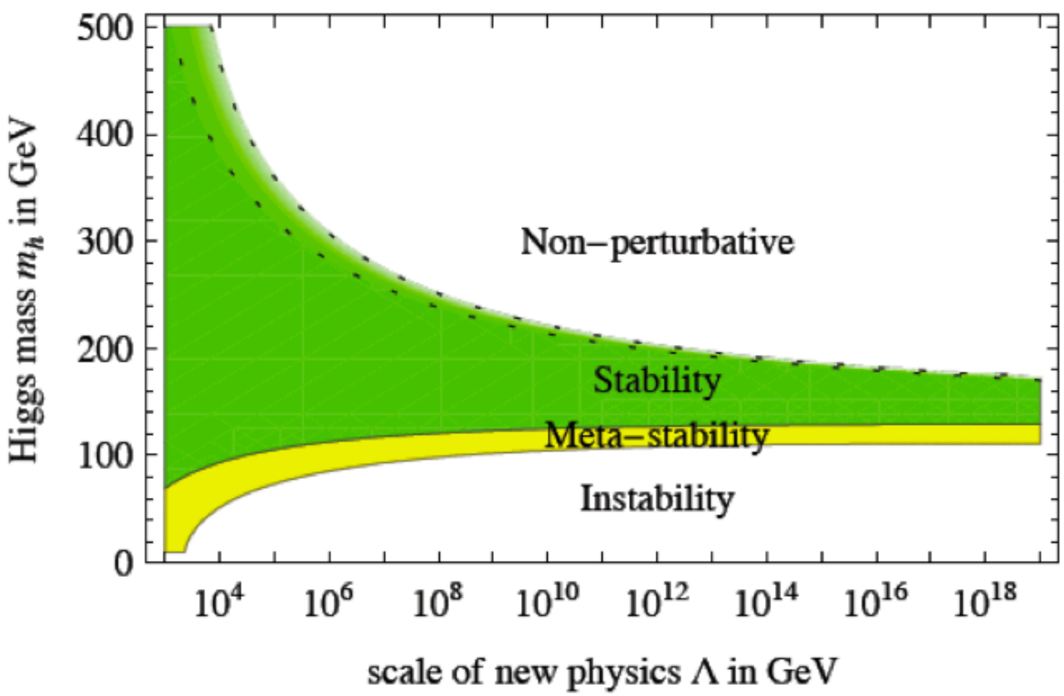
$$m_H^{fit} = 84^{+34}_{-26} \text{ GeV}$$

m_H<154 GeV (95% CL), but with m_H>114.4 GeV, this changes to m_H<185 GeV

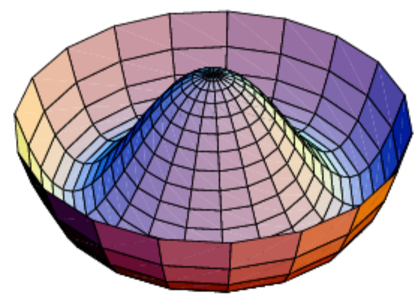
Vacuum Stability and Triviality Bounds on SM m_H

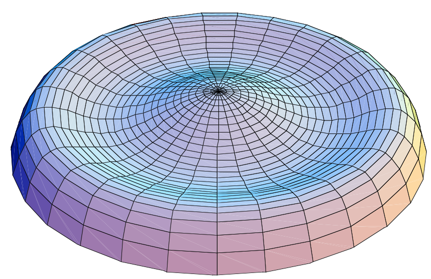
Loops with SM particles modify the effective Higgs potential.

Isidori, Rychkov, Strumia, Tetradis '08



Finding a Higgs boson with m_H "too low" or "too high" is suggestive of new physics.





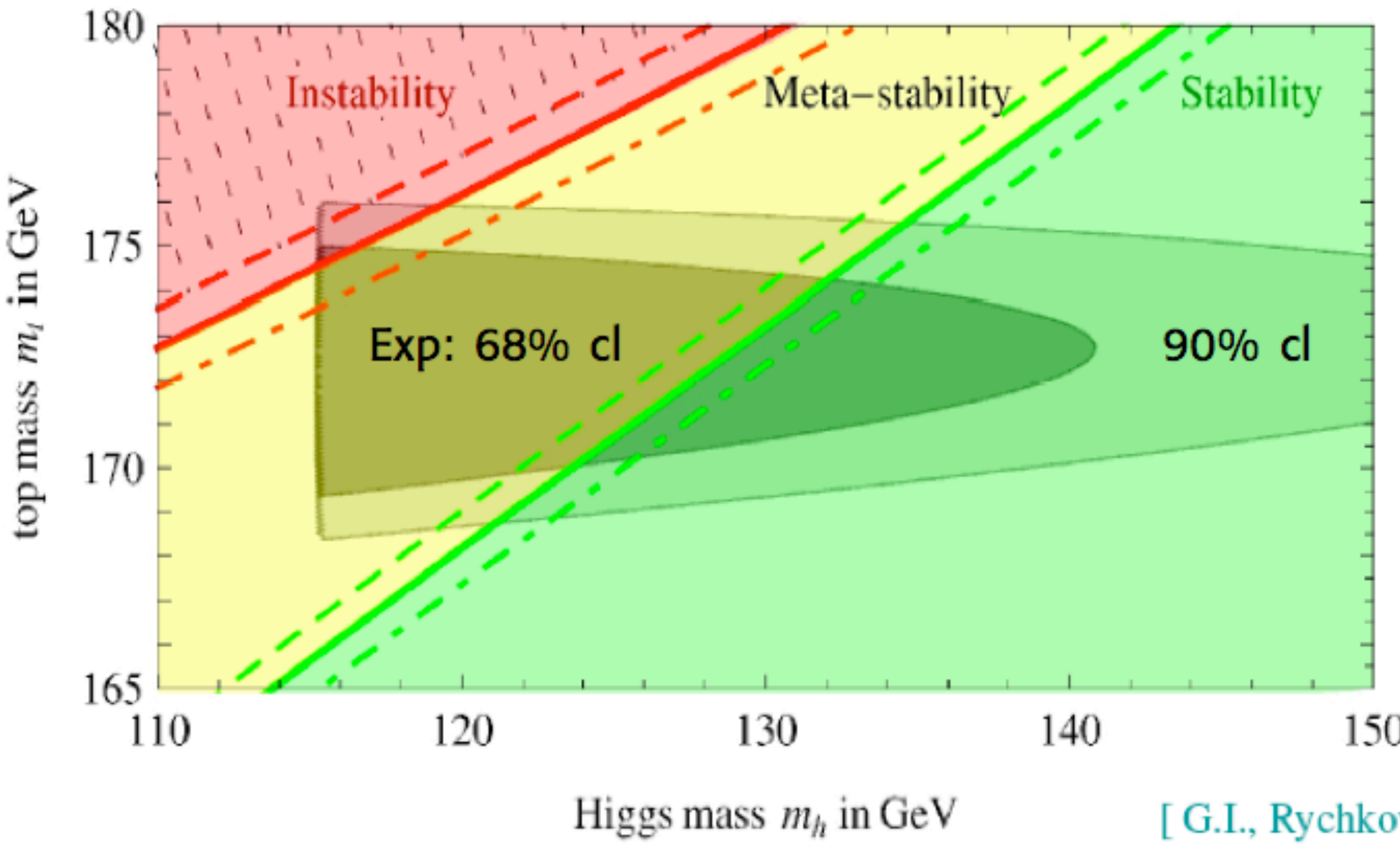
m_H too light!

See also hep-ph/9708416

Hambye and Riesselman

Adding the metastable possibility:

Isidori, Ridolfi, Strumia '01

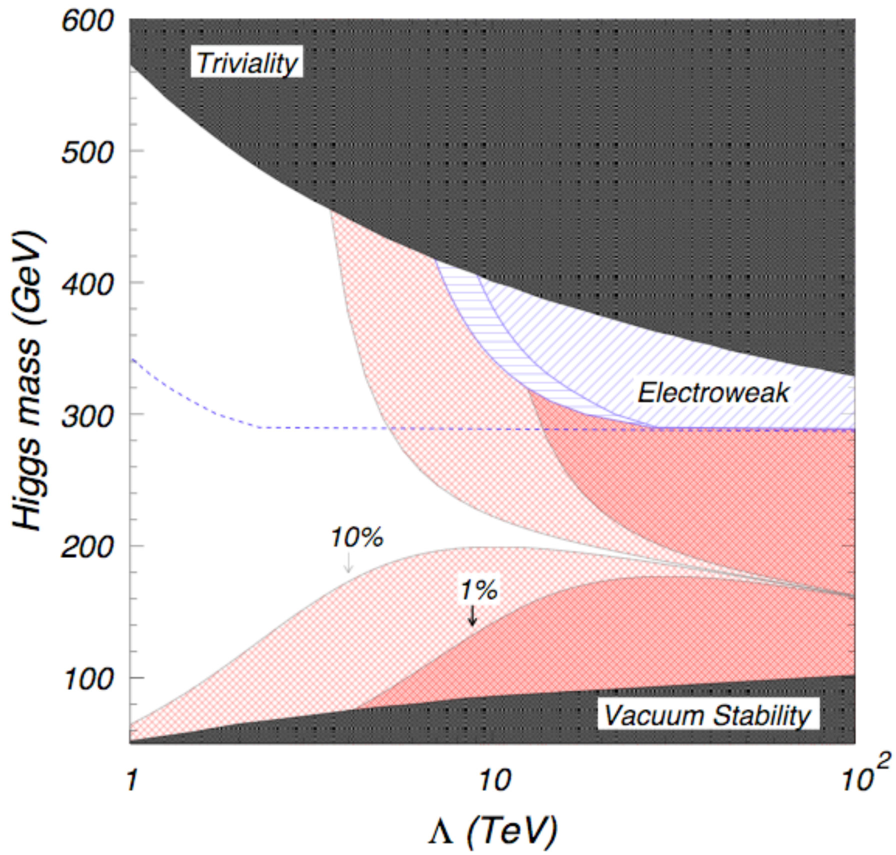


[G.I., Rychkov, Strumia, Tetradis '08]

- The unstable region is almost ruled out

a slide from G. Altarelli's HCPSS 2008 talk

How Much Fine-Tuning Can We Tolerate?



$$m_h^2 = 2\mu^2 = 4\lambda v^2$$

At one loop,

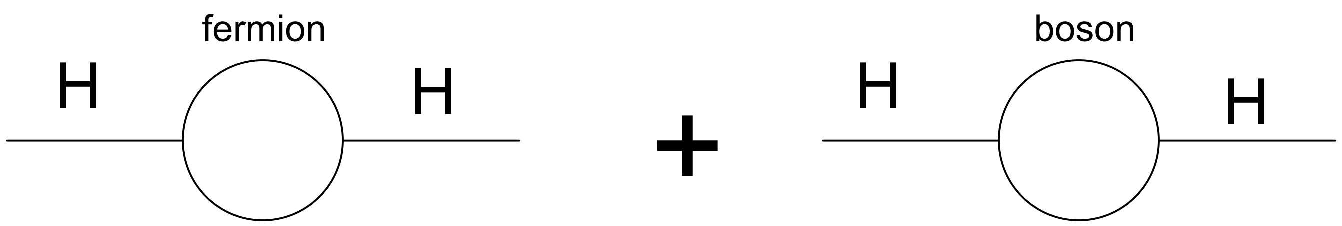
$$\mu^2 \to \mu^2 + \frac{\Lambda^2}{32\pi^2 v^2}\left(2M_W^2 + M_Z^2 + m_h^2 - 4m_t^2\right)$$

If the radiative corrections to m_h are not >> m_h, we get much stronger constraints. "Veltman Condition": termi in parentheses vanishes.

C. Kolda and H. Murayama, JHEP **0007**, 035 (2000)

m_t=175 GeV

A Natural Answer to the Hierarchy Problem



Fermion and Boson loops add with opposite signs. If there is a Boson degree of freedom of equal mass for each Fermion degree of freedom and vice versa, these would cancel exactly.

No direct evidence for superpartners yet, but the cancellation doesn't have to be exact.

The Higgs Bosons of the MSSM

- Two Complex Higgs Doublets! Needed to avoid anomalies.
- Type II 2HDM: One doublet couples to up-type fermions, the other to down-type fermions to prevent tree-level FCNC's
- Five Degrees of Freedom plus $W^{+,-}$, Z^0 longitudinal polarization states
- Five scalars predicted: h, H, A, H^+, H^-
- CP-conserving models: **h^0, H^0 are CP-even, A^0 is CP-odd**
- Independent Parameters: ("Constrained" MSSM)
  - m_A
  - $\tan\beta$ = ratio of VEV's of the two doublets
  - μ
  - M_0, $M_{1/2}$ (parameterizes squark, gaugino masses in CMSSM)
  - Trilinear couplings *A* (mostly through stop mixing)

- And a real prediction: $m_h < 135\ \mathrm{GeV}$ Let's test it!

  $m_h < m_Z$ at tree level! Radiative corrections raise m_h.

Tree-level MSSM Higgs masses

H. Haber, HCPSS 2008

The charged Higgs mass is given by

$$m^2_{H^\pm} = m^2_A + m^2_W \,,$$

and the CP-even Higgs bosons h^0 and H^0 are eigenstates of the squared-mass matrix

$$\mathcal{M}_0^2 = \begin{pmatrix} m_A^2 \sin^2\beta + m_Z^2 \cos^2\beta & -(m_A^2 + m_Z^2)\sin\beta\cos\beta \\ -(m_A^2 + m_Z^2)\sin\beta\cos\beta & m_A^2\cos^2\beta + m_Z^2 \sin^2\beta \end{pmatrix} .$$

The eigenvalues of $\mathcal{M}_0^2$ are the squared-masses of the two CP-even Higgs scalars

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

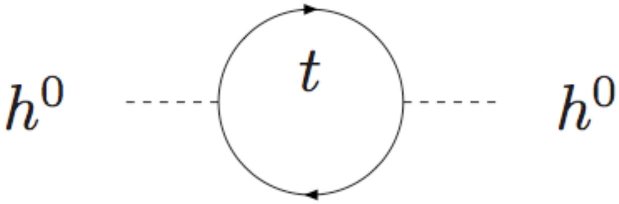
and α is the angle that diagonalizes the CP-even Higgs squared-mass matrix. It follows that

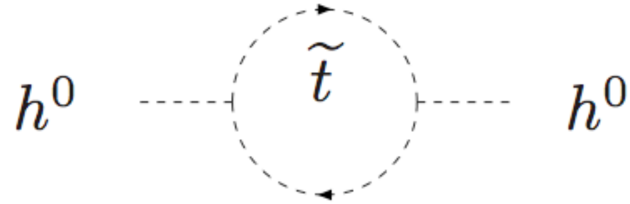
$$\boxed{m_h \le m_Z |\cos 2\beta| \le m_Z \,.}$$

Note the contrast with the SM where the Higgs mass is a free parameter, $m_h^2 = \frac{1}{2}\lambda v^2$. In the MSSM, all Higgs self-coupling parameters of the MSSM are related to the squares of the electroweak gauge couplings.

Higgs Boson Masses in the MSSM

m_h receives potentially large upwards radiative corrections from top and stop loops.





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

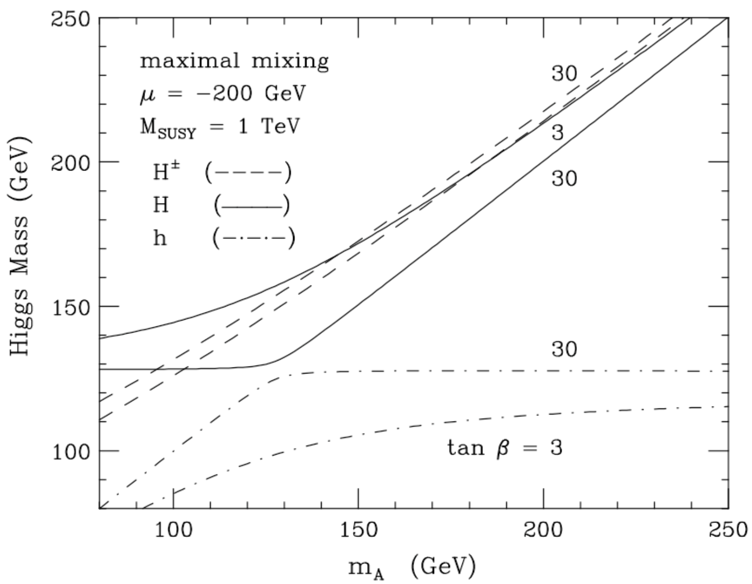
$$X_t \equiv A_t - \mu \cot\beta$$

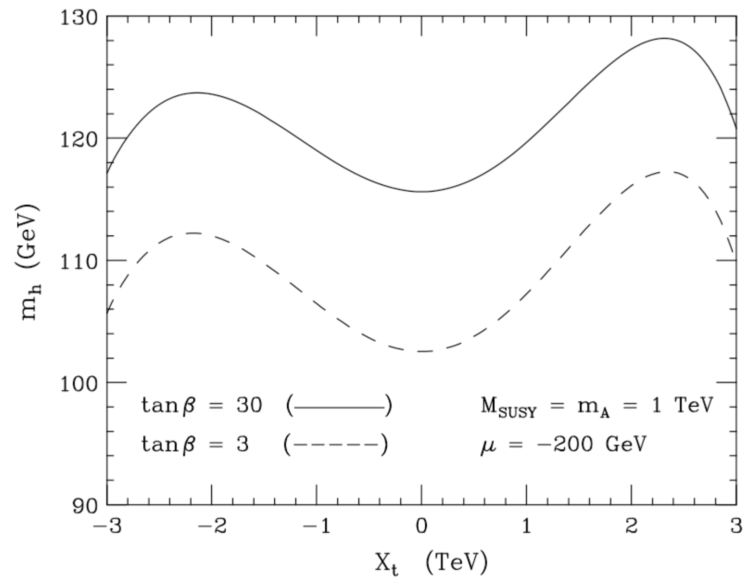
controls stop-quark mixing (two stop quarks, “L” and “R” mix to form two mass eigenstates)
A_t=trilinear Higgs coupling.

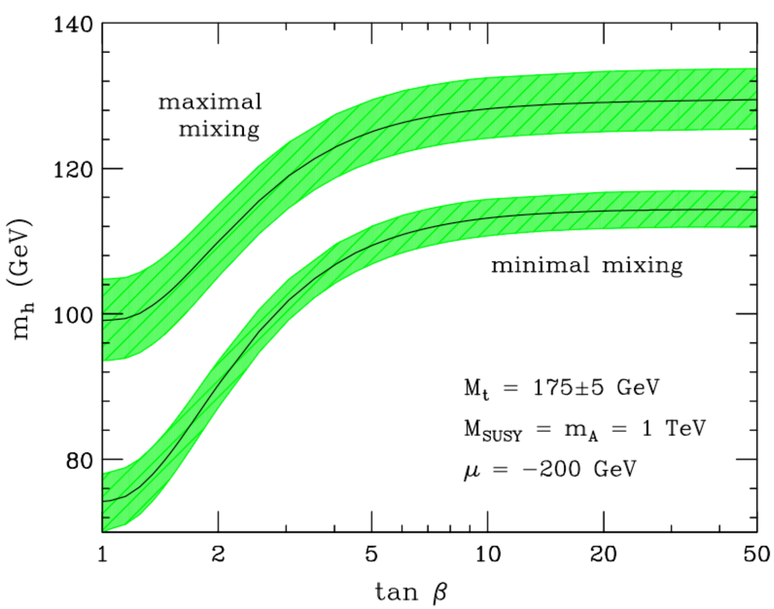
H. Haber, HCPSS08

M_S^2 is the average mass squared of the two stop quarks

Dependence of Lightest m_h on Stop Quark Mixing M_A, and tanβ



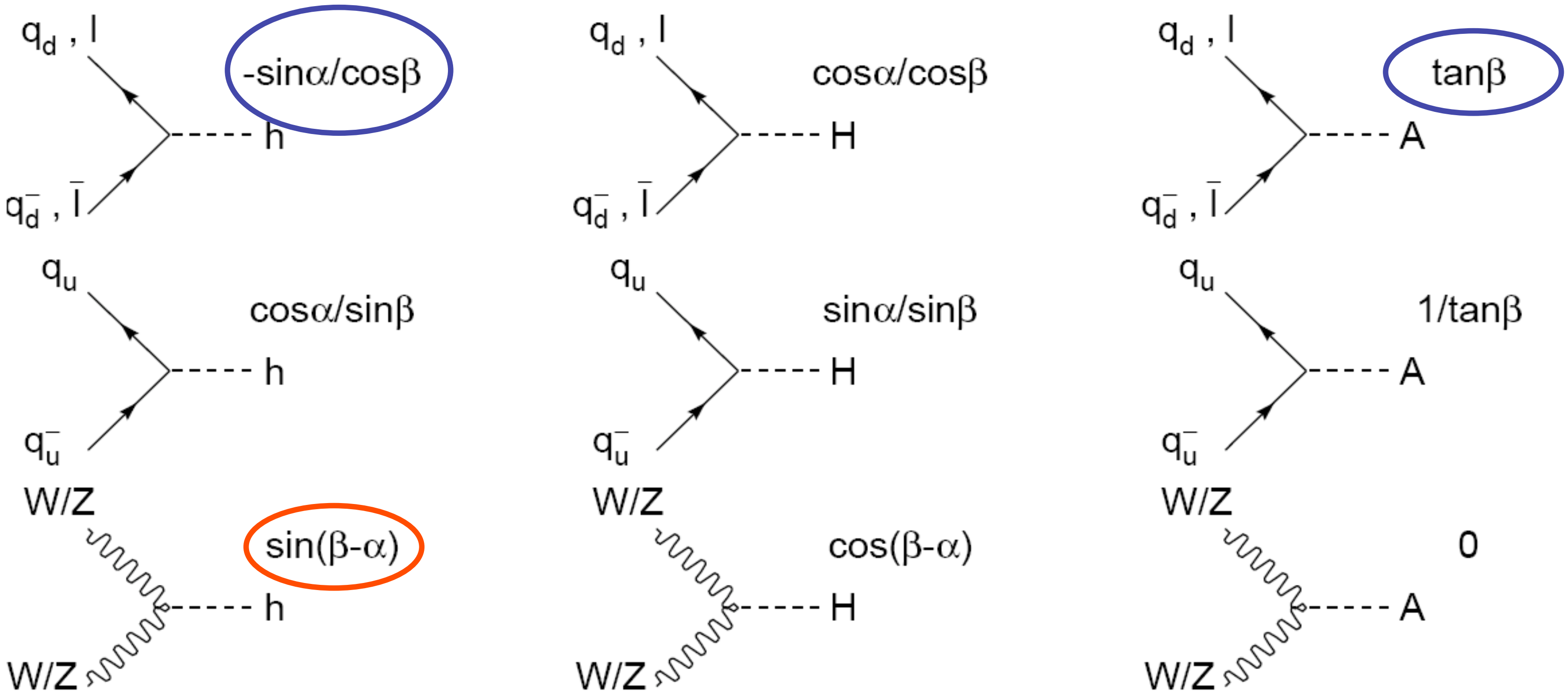




State of the art: Full one-loop plus main two-loop calculations with RG improvement. Many contributors: Carena, Quirós, Wagner, Mrenna, Heinemeyer, Hollik, Weiglein, Haber, Hempfling, Espinosa, and many others.

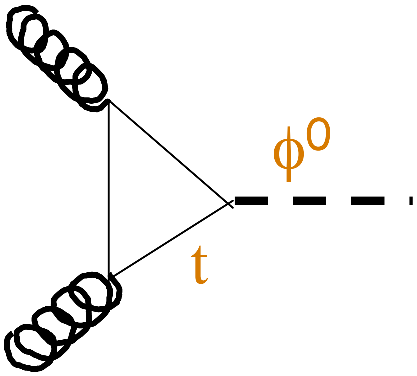
A useful program: FeynHiggs
http://www.feynhiggs.de

Couplings of MSSM Higgs Bosons Relative to SM



- W and Z couplings to H, h are **suppressed** relative to SM
- but the sum of squares of h^0, H^0 couplings are the SM coupling).
- Yukawa couplings (scalar-fermion) **can be enhanced by tanβ**
  b and tau couplings scale with each other.
- Radiative corrections modify couplings too! Can choose scenarios which zero out your favorite decay mode and enhance others.

Higgs Boson Production Mechanisms



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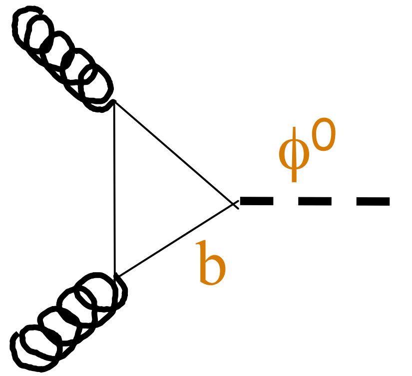
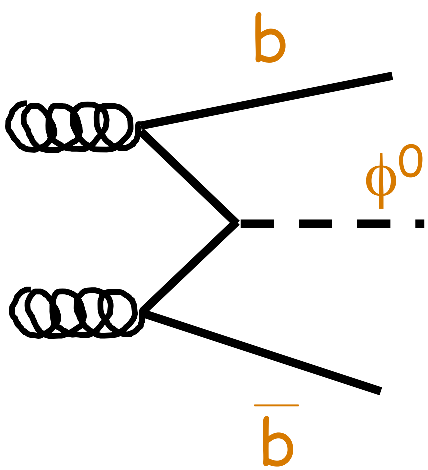


Amplitude $\propto$ 1/tanβ
suppressed!

Amplitude $\propto$ tanβ
enhanced!



Amplitude $\propto$ tanβ
enhanced!

And many other diagrams

At high tanβ, σ(h,A+X) $\propto$ tan$^2\beta$

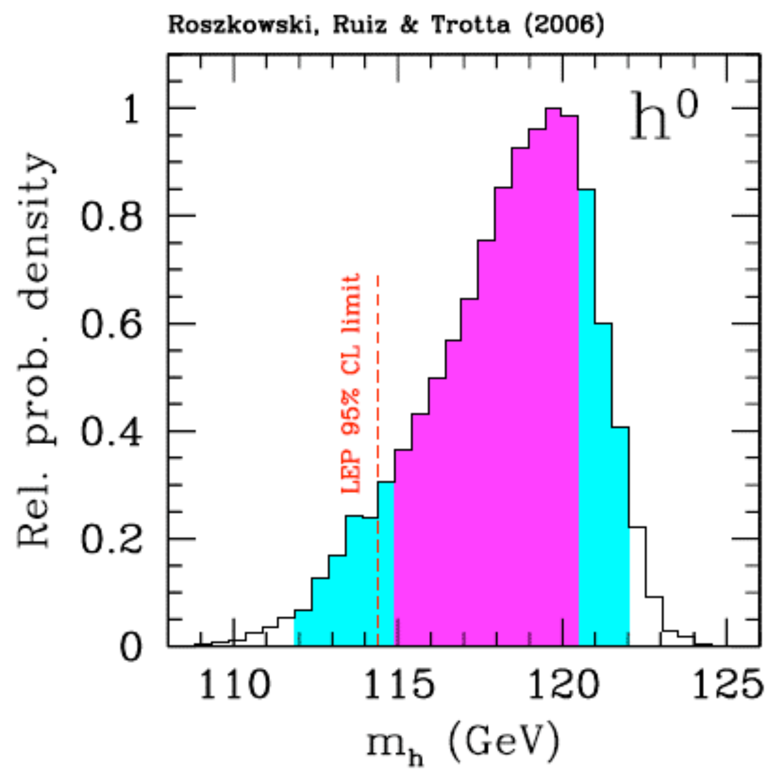
(low tanβ and SM case: cross-sections too small to test with current data.)

CMSSM Favors m_H <120 GeV

- Bayesian scan over CMSSM parameter space.
- Inputs
  - Direct LEP2 Higgs searches
  - Precision EW
  - Muon g-2
  - WMAP assuming CDM=neutralinos: $\Omega_\chi h^2$
  - B_s Mixing Rate: ΔM_{B_s}
  - $Br(B \rightarrow s\gamma)$
  - $Br(B_s \rightarrow \mu^+\mu^-)$
- Sophisticated MCMC guided search for high-posterior-probability parameter values
- CMSSM parameters (flat prior)
  50 GeV < m_0 < 4 TeV
  50 GeV < $m_{1/2}$ < 4 TEV
  $|A_0|$ < 7 TeV 2 < $\tan\beta$ < 62

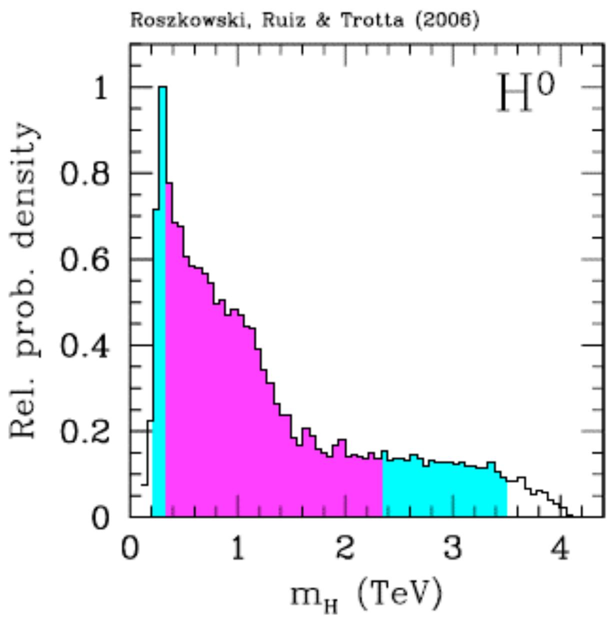
MSSM h is SM-like for these models (production, decay)

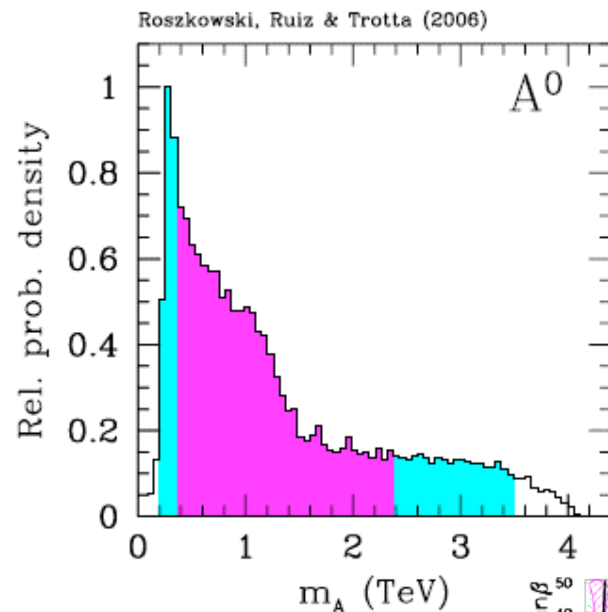
hep-ph/0611173
JHEP 0704:084 (2007)



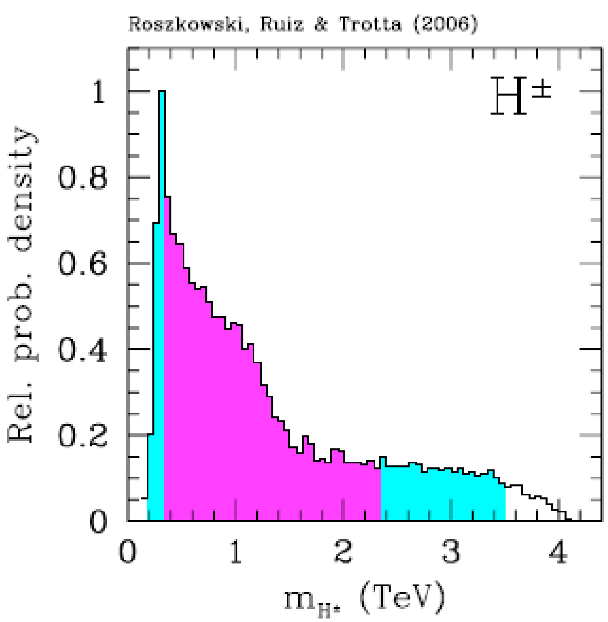
Update: R. Trotta et al., arXiv:0809.3792 [hep-ph] -- similar constraints

Heavier Higgs Bosons are, Well, Heavier

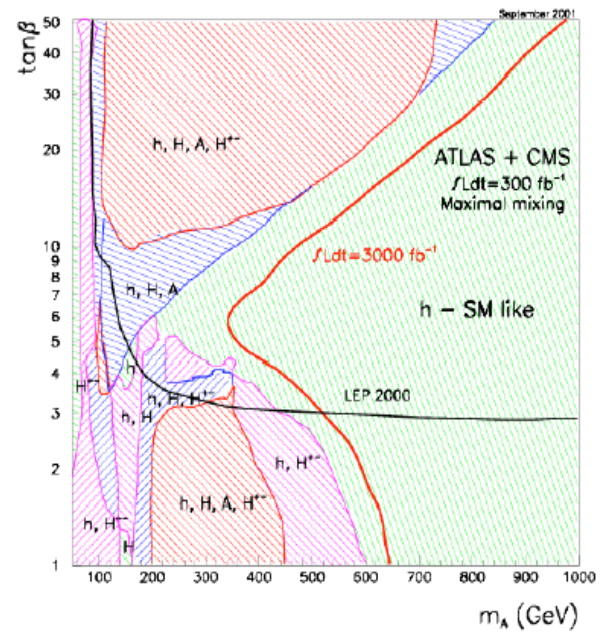




hep-ph/0611173



They could be out of
reach at the LHC
New estimations of SM
br($b \to s\gamma$)
lowered these predictions.

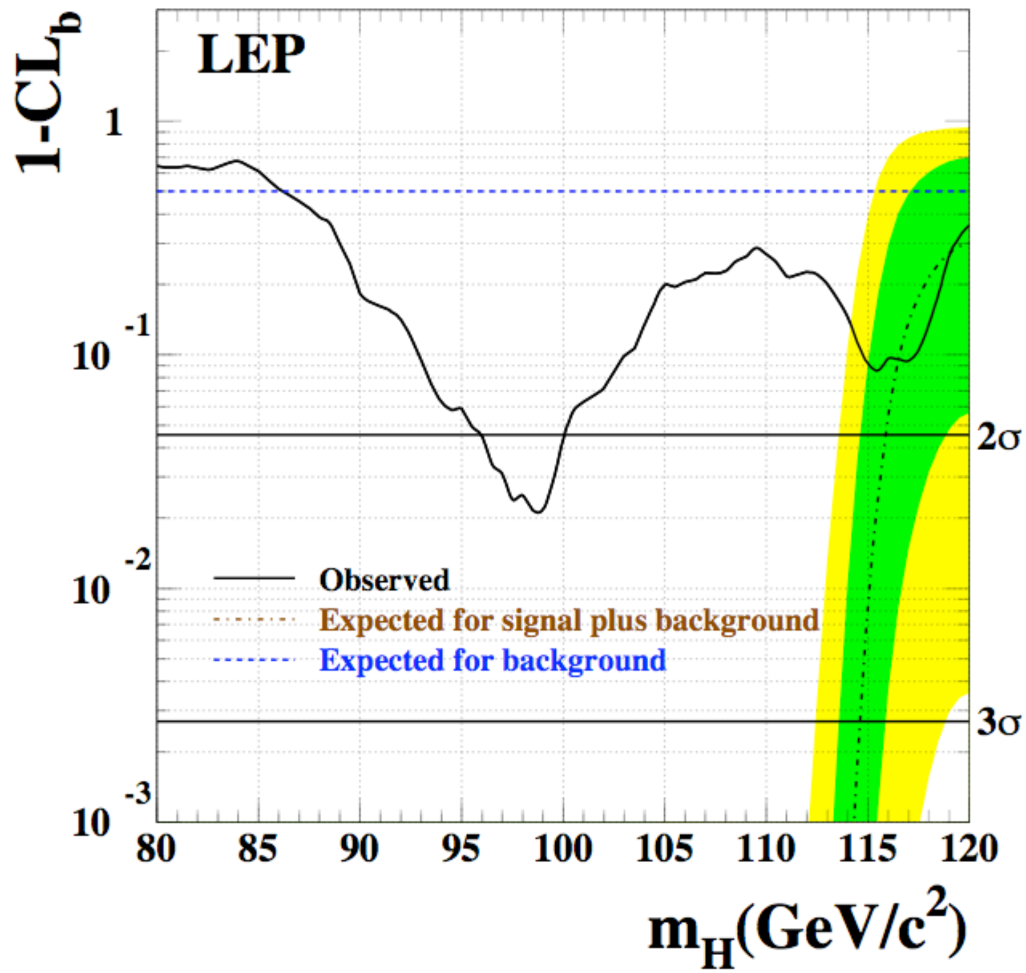


Two Excesses in SM Higgs Searches at LEP2

Phys. Lett. B **565** (2003) 61-75

Lower excess too small to be SM Higgs by far -- $e^+e^- \rightarrow ZH$ cross section is much bigger by far than allowed by experiment.

Could be a Higgs boson with a suppressed cross section? MSSM allows this.



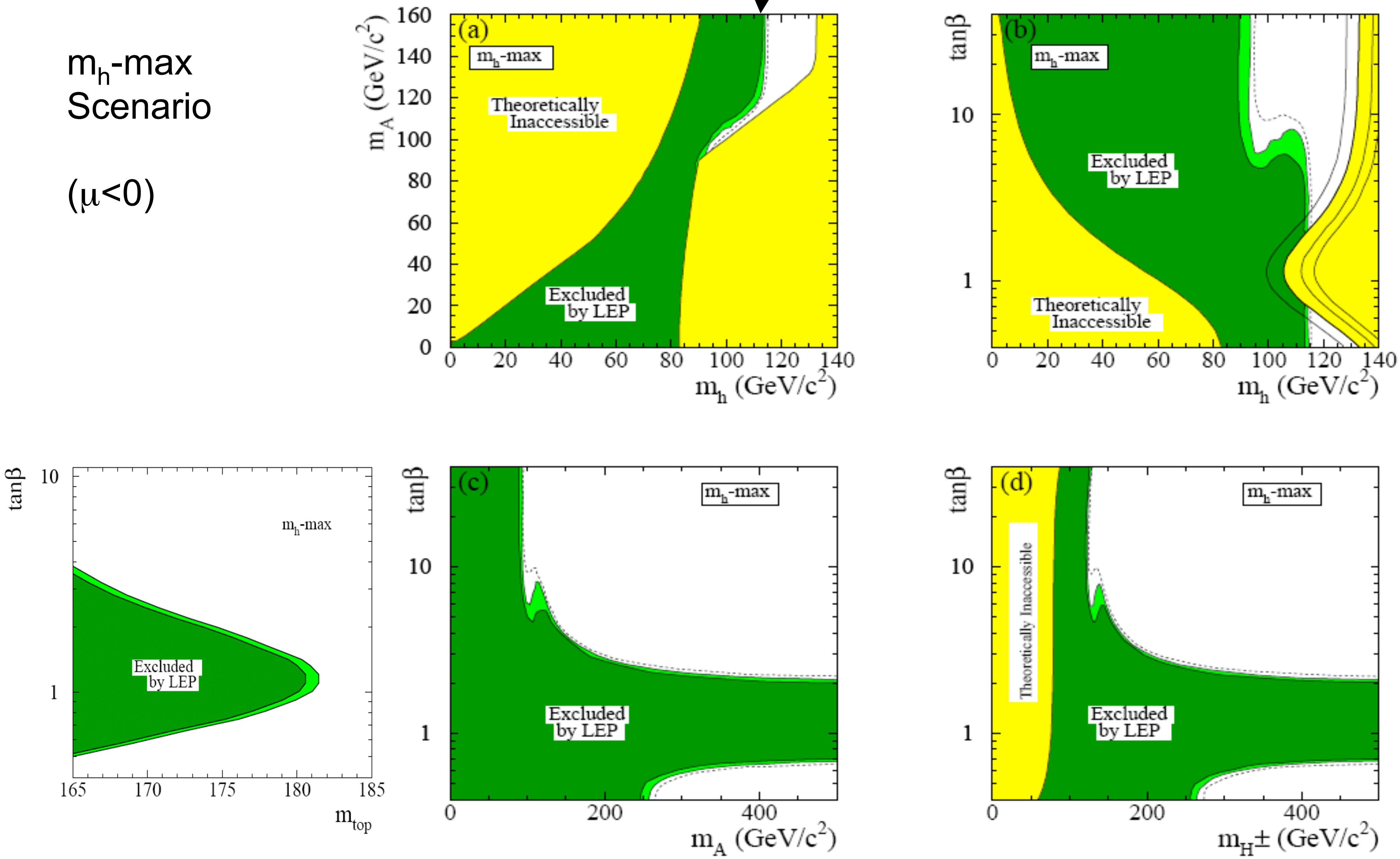
An old cottage industry to stack these atop each other:
G. Kane et al., Phys. Rev. D **71**, 035006 (2005)
(hep-ph/0407001)

LEP Exclusions for MSSM Higgs bosons

~114.4 GeV "Decoupling Limit"

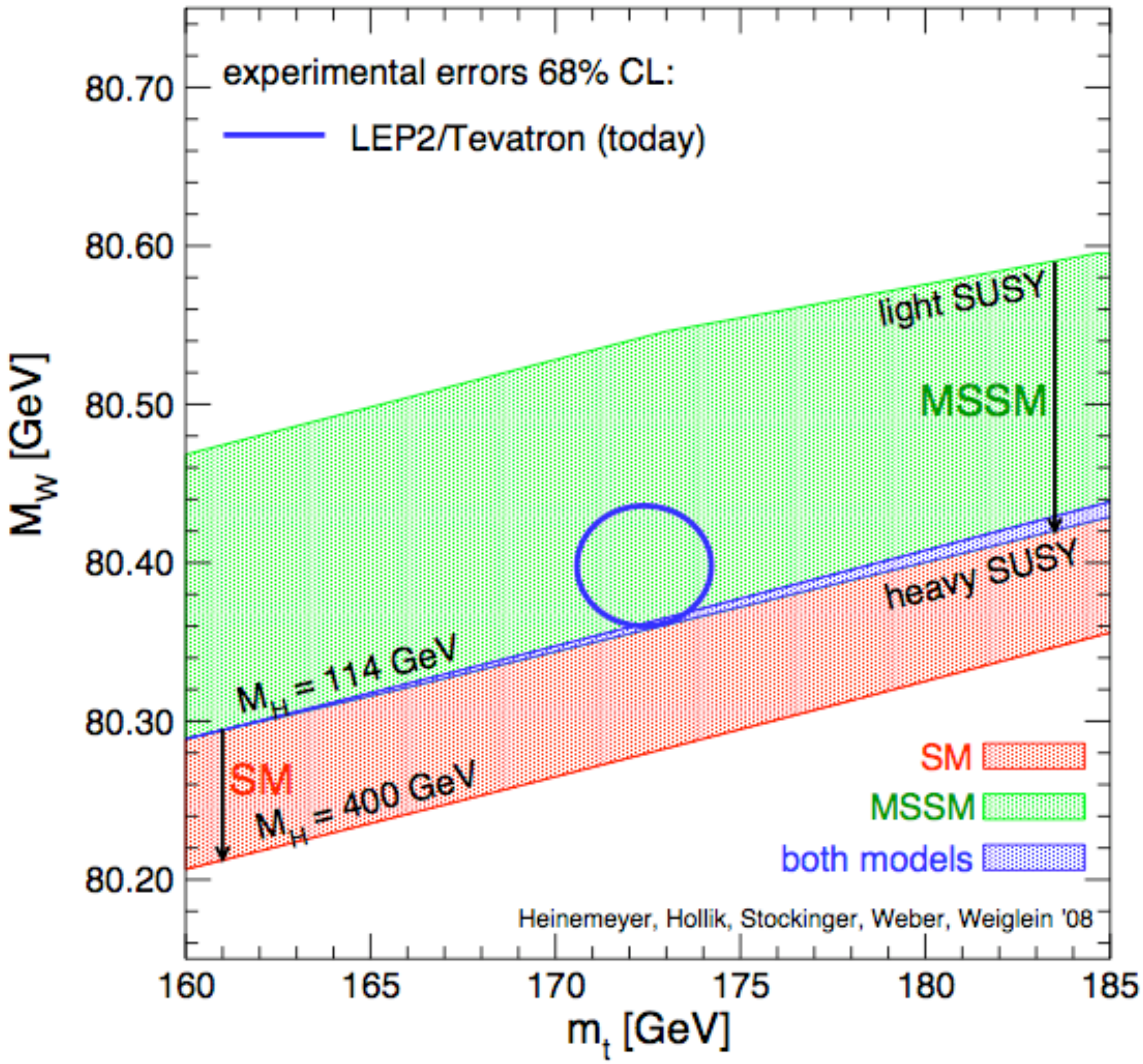
m_h-max
Scenario

(μ<0)



Eur.Phys.J.C47:547-587,2006 (and many more scenarios)

Lightest Higgs Boson and Precision EW constraints



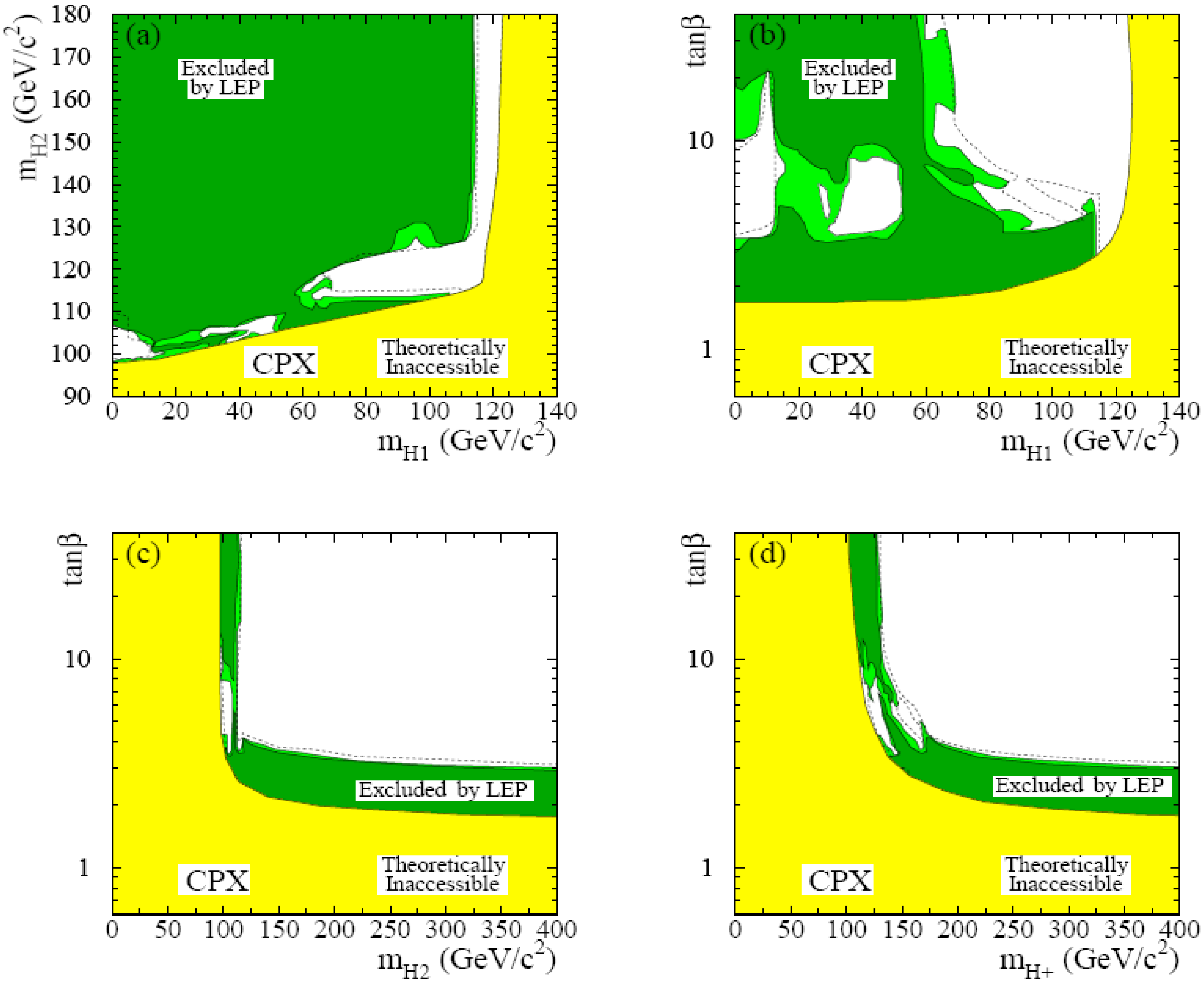
An Interesting Possibility -- CP Violation in the Higgs Sector

- MSSM Higgs sector CP conserving at tree level -- neutral Higgs bosons are CP eigenstates.
- Radiative corrections from CP-violating quarks and squarks, gauginos and higgsinos can spoil this.

Instead of h^0,H^0, and A^0, have neutral eigenstates H_1, H_2, H_3.

- Sums of squares of couplings to vector bosons remains constant. But -- it need not be the lowest-mass Higgs boson which couples well to the W and Z, and even in the MSSM, when the A^0 is light, often have h or H within reach. No longer true!

LEP Exclusions are Weaker in CP-Violating Scenarios



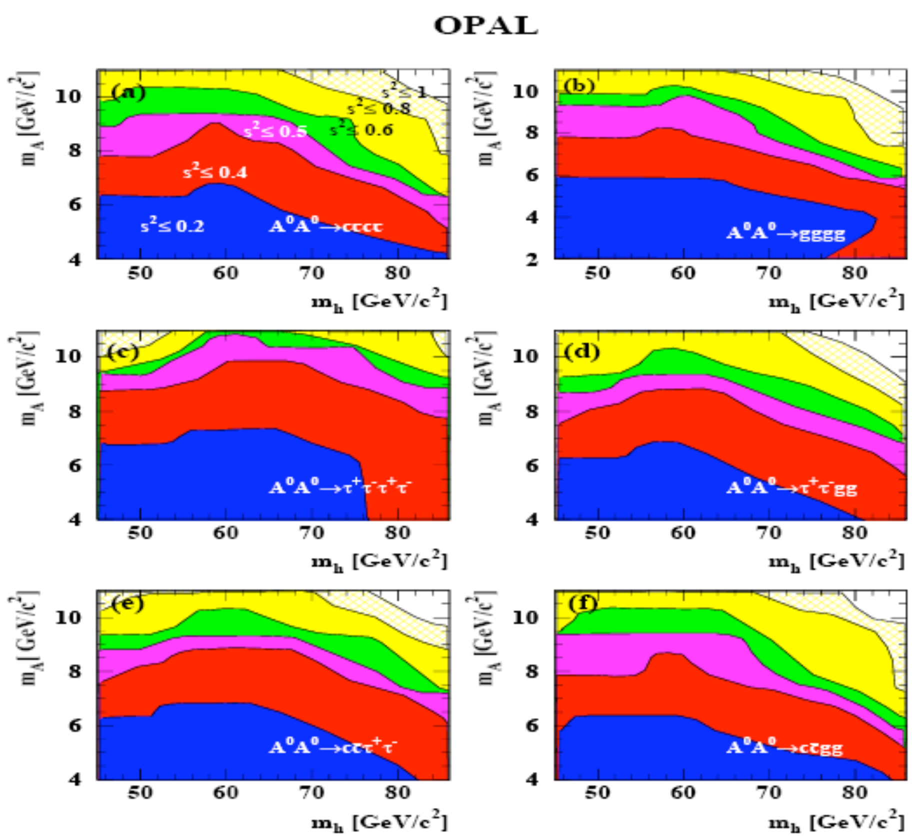
ALEPH, DELPHI, L3 and OPAL Collaborations and the LHWG, Eur.Phys.J.C47:547-587,2006

An Additional Loophole -- h→AA only Partially Plugged

$$m_h \geq 86\text{GeV},\ \text{if}\, m_a \lesssim 12\text{GeV}$$

$h^0 \to A^0A^0 \to \tau\tau\tau\tau$,
$\tau\tau cc$, $\tau\tau gg$,
$ggcc$, $\tau\tau ss$, ...

$h^0 \to A^0A^0$ could be the dominant h decay mode, but the A^0 decay modes are many and vary strongly with m_A as thresholds are crossed. A light A^0 could even mix with bb resonances.



[*Eur. Phys. J.* **C27** (2003) 483-495; hep-ex/0209068]

(low-mass A^0 not ruled out since ZZA coupling = 0)

Summary

- The Higgs Mechanism (or something like it) is needed to reconcile SU(2)xU(1) gauge symmetry with particle mass -- and make scattering unitary.

- The SM Higgs Mechanism has clumsy features and lots of arbitrariness
  - Hierarchy problem
  - Yukawa couplings

- Supersymmetry offers a natural solution to the Hierarchy problem, but at the expense of more arbitrary parameters

- Supersymmetry predicts at least one light Higgs boson, which behaves a lot like H_{SM} in the decoupling limit (large m_A)

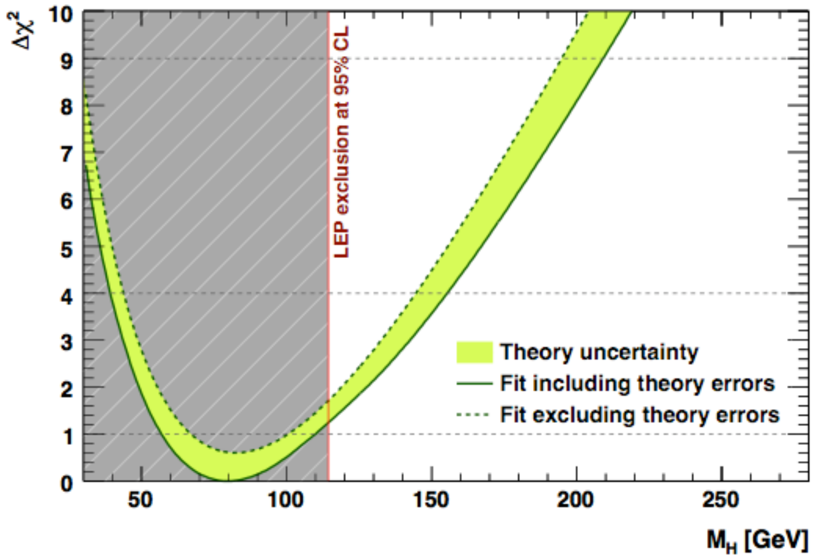
- Higgs bosons are exquisitely sensitive to heavy, unseen particles. Let's measure them precisely (but let's find them first).

- Finding more than one Higgs boson would be spectacular.

- Finding no Higgs boson would also be spectacular. Warning: Theorists are good at finding loopholes!

Backup Slides

GFitter results including Direct Searches at the Tevatron



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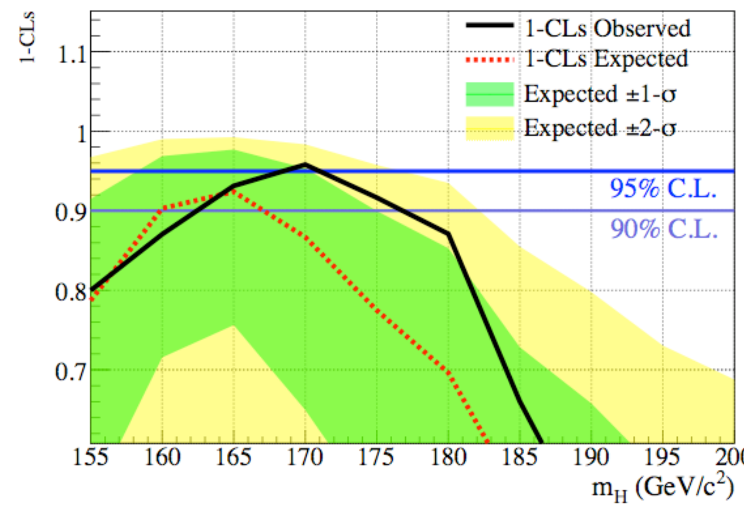

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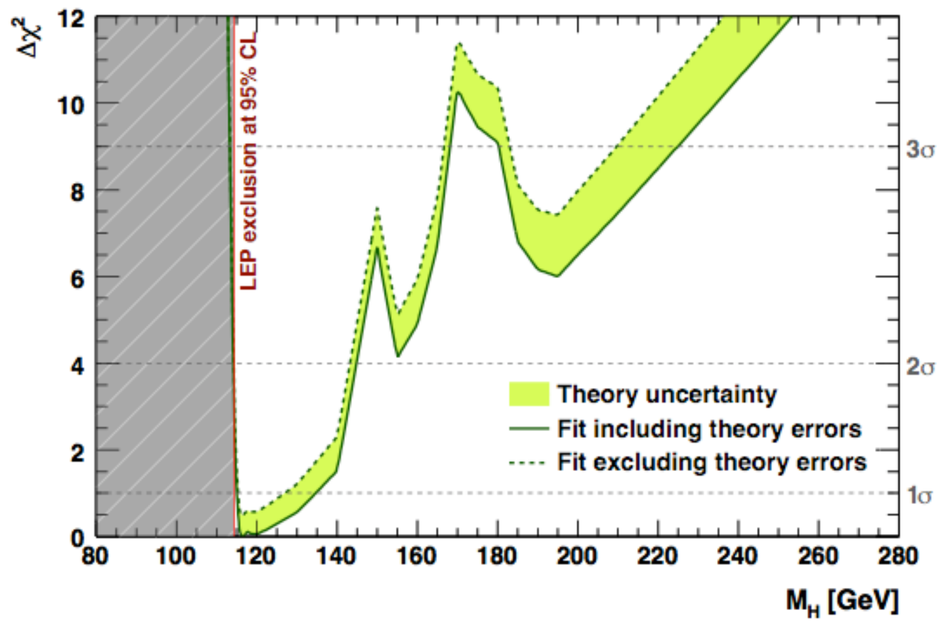
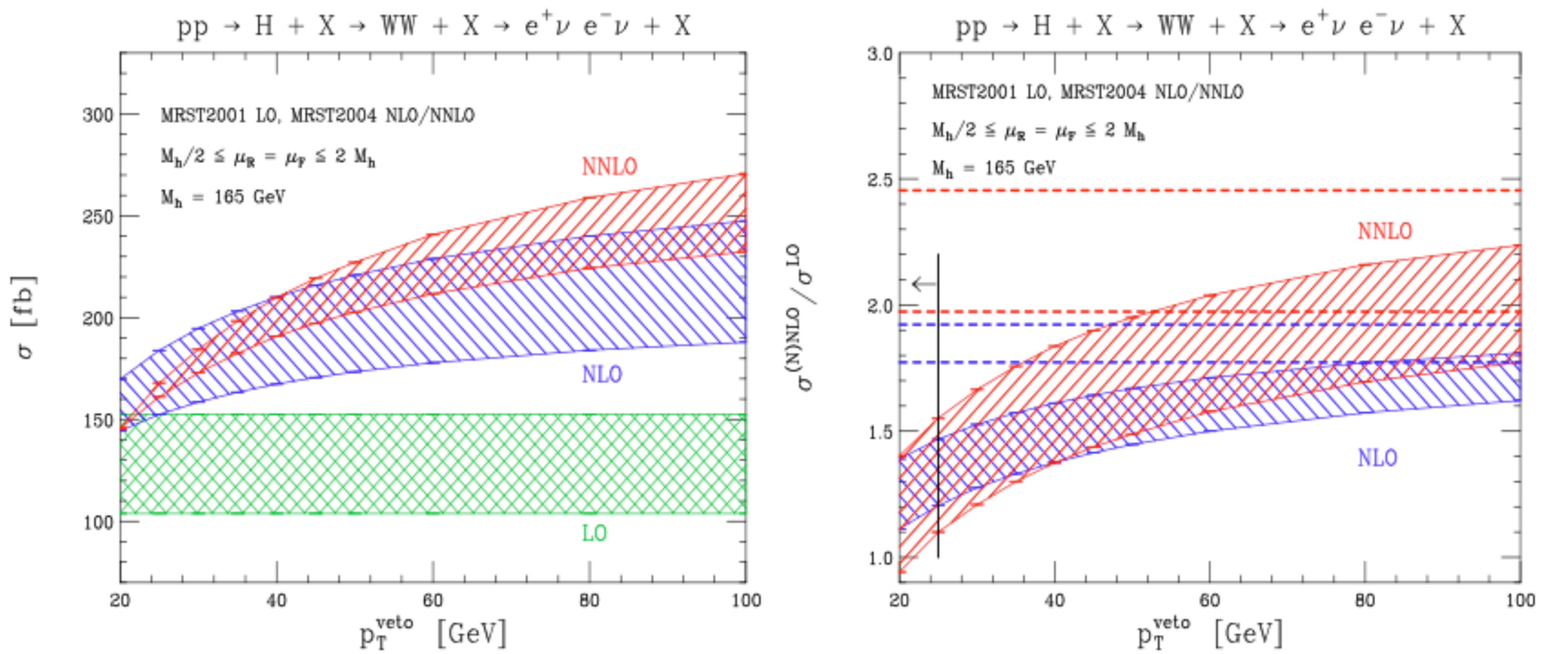


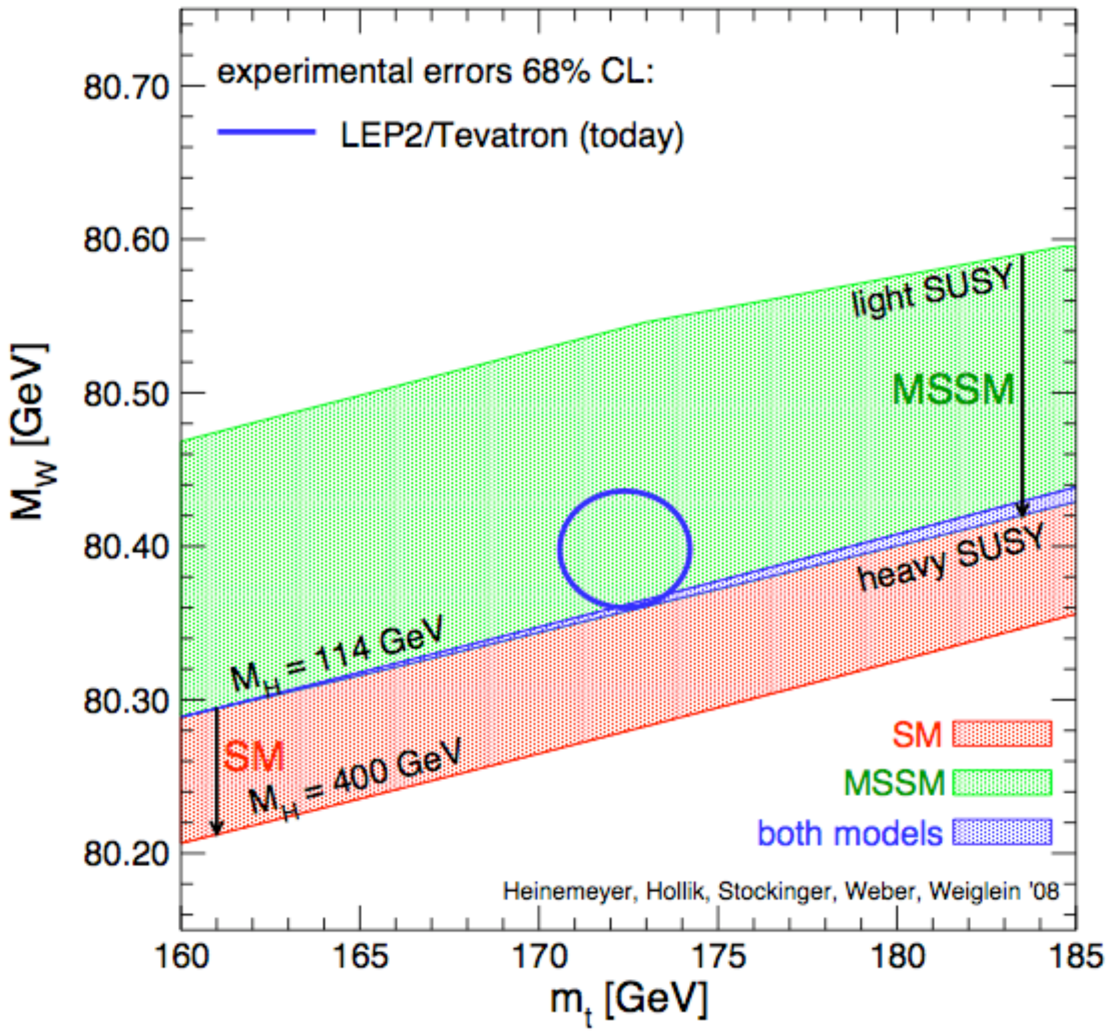
http://www.gfitter.de

Jet veto



$$|\eta| < 2.5 \text{ and } p_T^{\text{jet}} > p_T^{\text{veto}}$$

Anastasiou, Dissertori, Stöckli 2007


experimental errors 68% CL:
LEP2/Tevatron (today)
light SUSY
MSSM
heavy SUSY
M_H = 114 GeV
SM
M_H = 400 GeV
SM
MSSM
both models
Heinemeyer, Hollik, Stockinger, Weber, Weiglein '08
80.70
80.60
80.50
80.40
80.30
80.20
M_W [GeV]
160
165
170
175
180
185
m_t [GeV]