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Testing the Standard Model

- Gauge boson masses and couplings
- The Higgs boson

The line-shape of the Z

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Close to the Z **peak** the cross section for $e^+e^- \to f\bar{f}$ is completely dominated by the resonance, **photon exchange** diagrams and **box diagrams** can be **neglected**.

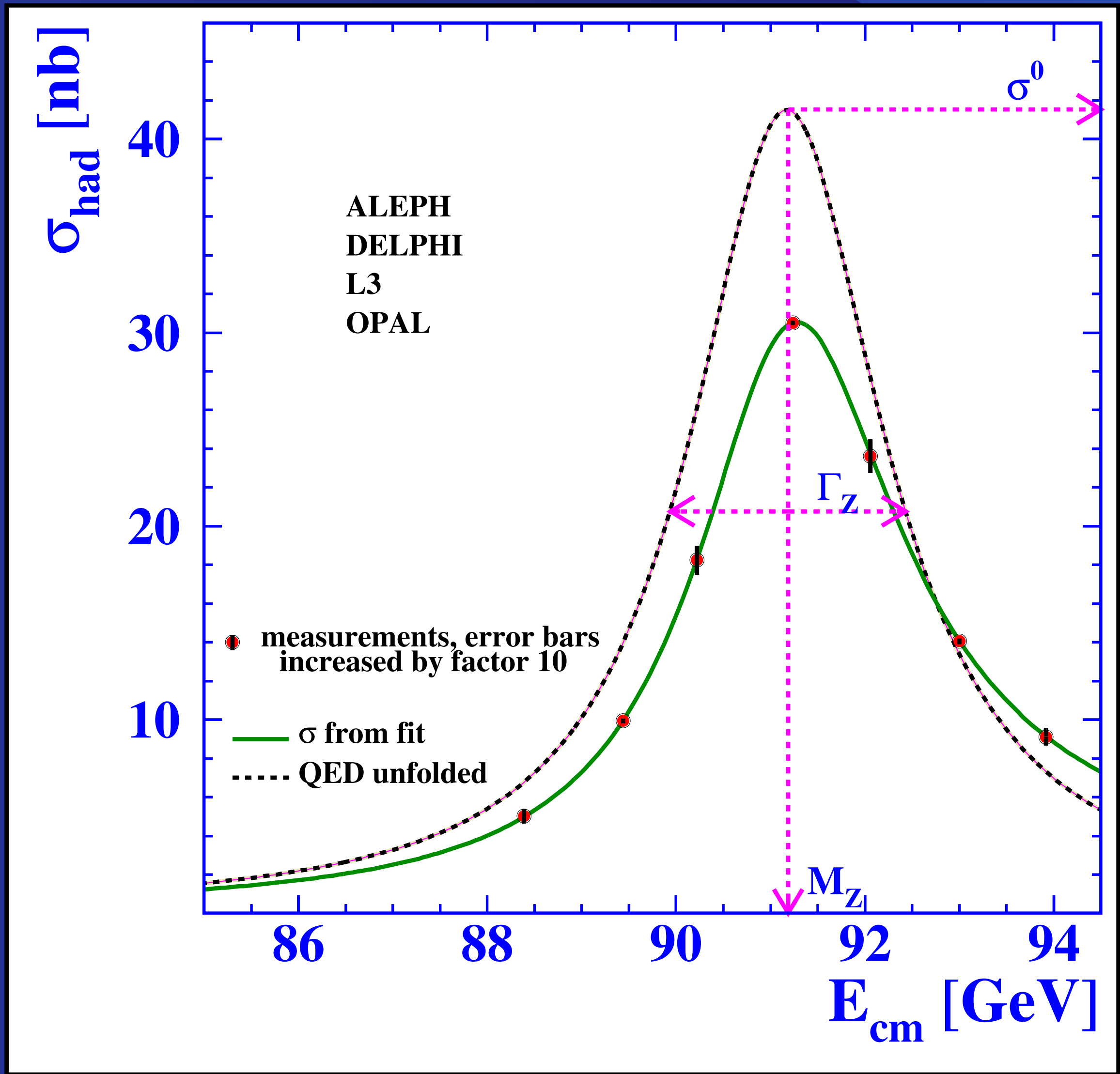
$$\sigma^0(e^+e^- \to f\bar{f}) \approx \frac{12\pi\Gamma_e\Gamma_f}{m_Z^2}\,\frac{s}{(s-m_Z^2)^2+s^2\,\Gamma_Z^2/m_Z^2}$$

where Γ_f,Γ_e,Γ_Z include the appropriate radiative corrections.
Including ISR as commented before one obtains

$$\sigma_{ISR}(s) \approx \left(1+\frac{3}{4}\beta\right)\left(\frac{(s-m_Z^2)^2+s^2\,\Gamma_Z^2/m_Z^2}{s^2}\right)^{\beta/2}\sigma^0(s)$$

with $\beta = \dfrac{4\alpha}{\pi}\ln\dfrac{m_Z}{m_e}$. This amounts to 26% **on the peak**.

LEP gives:


σ_{had} [nb]
40
30
20
10
86
88
90
92
94
E_{cm} [GeV]
σ^0
Γ_Z
M_Z
ALEPH
DELPHI
L3
OPAL
measurements, error bars increased by factor 10
σ from fit
QED unfolded

Decay widths of gauge bosons

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The decay widths of the weak gauge bosons can be easily computed:

$$\Gamma\left(Z \to \bar{f} f\right) = \frac{\hat{\alpha}}{12 s_Z^2 c_Z^2} C_f \left(|v_f|^2 + |a_f|^2\right)$$

C_f takes into account the color of quarks, QCD corrections and final state QED corrections

$$C_f = \begin{cases} \delta_{f\mathrm{QED}} & \text{leptons} \\ 3\left(1 + \alpha_s(m_Z)/\pi + \cdots\right)\delta_{f\mathrm{QED}} & \text{quarks} \end{cases}$$

$\delta_{f\mathrm{QED}} = 1 + Q_f^2 3\alpha/(4\pi)$ and v_f and a_f are the tree-level neutral-current couplings written in terms of s_Z. For the b-quark additional corrections needed.
Similar expressions obtained for the W **decay widths**

Asymmetries

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Since **parity violation** comes comes from the **axial-vector couplings** it is customary to define the combination of the vector and axial couplings of the fermions as

$$\mathcal{A}_f = \frac{2 v_f a_f}{v_f^2 + a_f^2}$$

In $e^+e^- \to f^+f^-$ collisions one can define the **forward-backward asymmetry**

$$\mathcal{A}_{FB} \equiv \frac{N_F - N_B}{N_F + N_B}$$

with N_F (N_B) denote the number of f emerging in the **forward** (**backward**) directions.

At the Z pole, it is given by

$$\mathcal{A}_{FB}^{0,f} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f$$

The measurement of $\mathcal{A}_{FB}^{0,f}$ for charged leptons, and c and b quarks give us information only on the **product of A_e and A_f**.
On the other hand, the measurement of the τ lepton polarization is able to determine the values of A_e and A_τ **separately**. The **longitudinal τ polarization** is defined as

$$\mathcal{P}_\tau \equiv \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

where $\sigma_{R(L)}$ is the cross section for tau-lepton pair production of a right (left) handed τ^-. At the Z pole, $\mathcal{P}_\tau$ can be written in terms of scattering (e^-, τ^-) angle θ as,

$$\mathcal{P}_\tau = -\frac{\mathcal{A}_\tau(1+\cos^2\theta) + 2\mathcal{A}_e\cos\theta}{1+\cos^2\theta + 2\mathcal{A}_e\mathcal{A}_\tau\cos\theta}$$

Another interesting asymmetry that can be measured by using **polarized beams** (in SLD) is the **left-right cross section asymmetry**,

$$\mathcal{A}_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = -\mathcal{P}_e$$

where $\sigma_{L(R)}$ is the cross section for (left-) right-handed incident electron with the positron kept unpolarized.

The Global Fit

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Observables can be expressed in terms of a few parameters G_F, $\hat{\alpha}(m_Z)$, m_Z, m_t, m_H, $\alpha_s(m_Z)$. G_F **well known** from muon decay. The hadronic contributions to $\hat{\alpha}(m_Z)$ are not so well known and one leaves them also free in the global fit. Thus

$$\chi^2(\text{parameters}) = \sum_i \left(\frac{\mathcal{O}^i_{\text{th}}(\text{parameters}) - \mathcal{O}^i_{\text{exp}}}{\Delta \mathcal{O}^i} \right)^2$$

by **minimizing** χ^2 one **determines the parameters** and gives **predictions** for the rest of the observables which can be compared back with measured values using the "Pull"

$$\text{Pull}_\text{i} = \frac{\mathcal{O}^i_{\text{th}}(\text{fitted} - \text{parameters}) - \mathcal{O}^i_{\text{exp}}}{\Delta \mathcal{O}^i}$$

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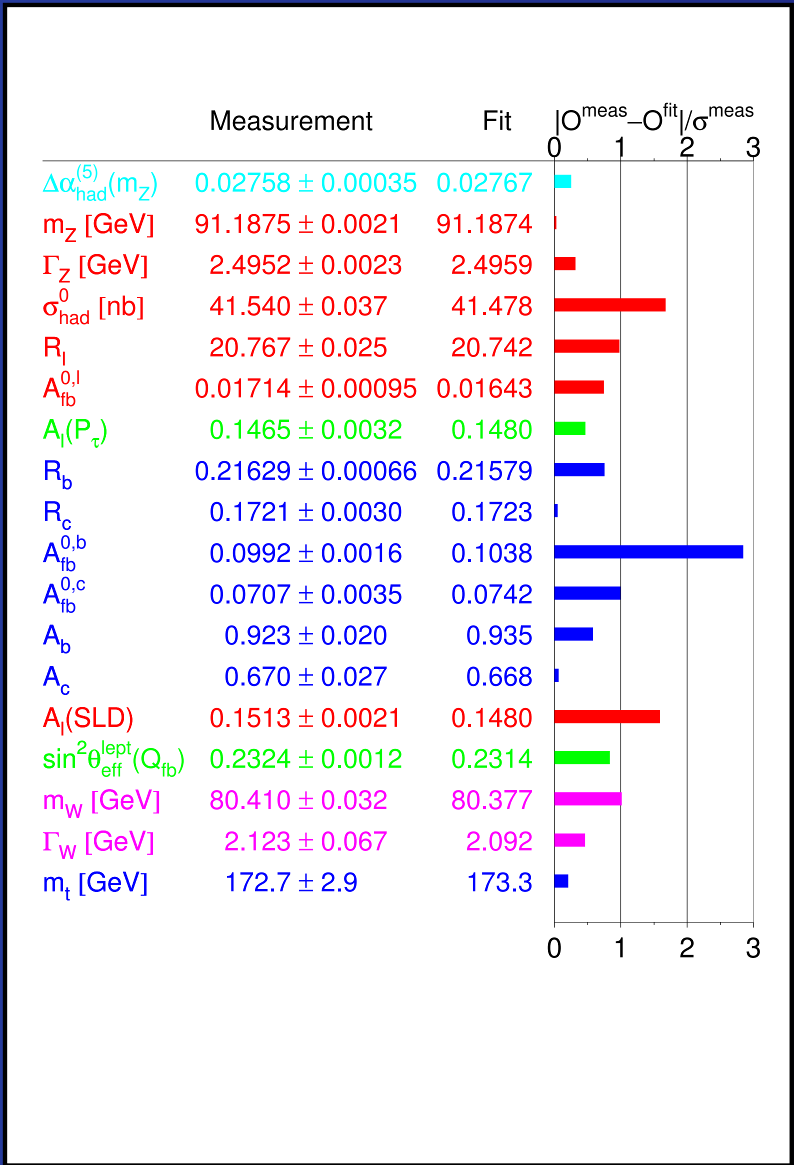

	Z-pole fit
m_Z	$91.1874 \pm 0.0021\,\mathrm{GeV}$
m_H	$111\, \pm^{190}_{60}\ \mathrm{GeV}$
m_t	$173\, \pm^{13}_{10}\ \mathrm{GeV}$
$\alpha_s(m_Z)$	0.1190 ± 0.0028
$1/\hat{\alpha}(m_Z)$	127.918 ± 0.018

To be compared with the recent measurement of m_t at Fermilab

$$172.7 \pm 2.9\,\mathrm{GeV}$$

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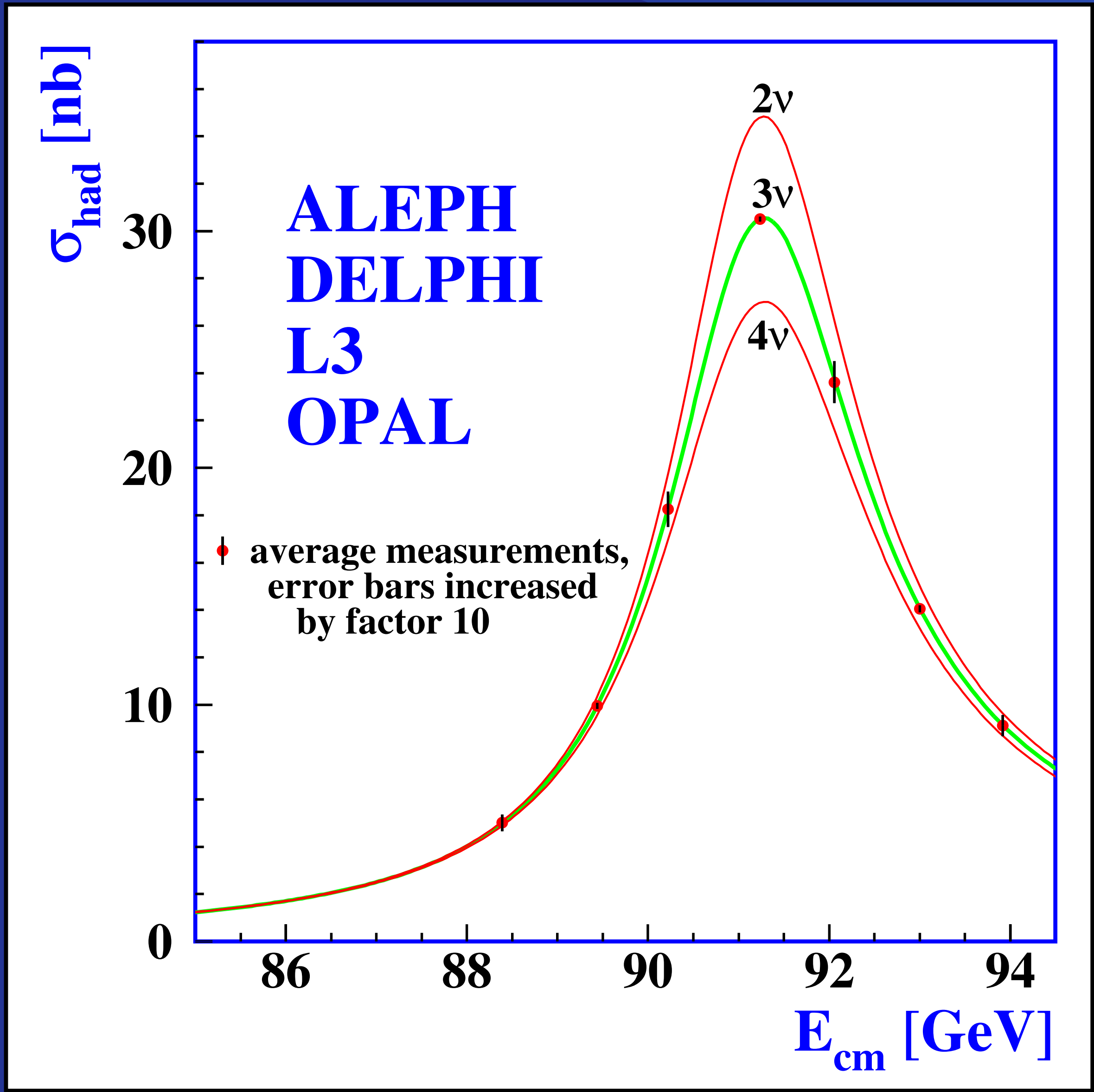
Number of Neutrino Species



We can extract information on the number of light neutrino species by assuming that they are the **only** particles **responsible for the invisible width**, i.e. $\Gamma_{inv} = N_\nu \Gamma_\nu$. The LEP data gives the ratio of the invisible and leptonic Z partial widths, $\Gamma_{inv}/\Gamma_\ell = 5.941 \pm 0.016$ and the SM predicts $(\Gamma_\nu/\Gamma_\ell)_{SM} = 1.9912 \pm 0.0008$. Γ_ℓ cancels out and then

$$N_\nu = 2.984 \pm 0.008$$

N_ν is the number of neutrino flavors that are **accessible kinematically to the Z**. This result indicates that there exist **only three families of fermions**.
If we assume $N_\nu = 3$ we can put bounds on additional contributions to $\Gamma_{\rm inv}$.

$$\Delta\Gamma_{\rm inv} = -2.7 \pm 1.7\,{\rm MeV} \;\rightarrow\; \Delta\Gamma_{\rm inv} < 2\,{\rm MeV} \quad 95\%\,{\rm CL}$$

The couplings of leptons and universality

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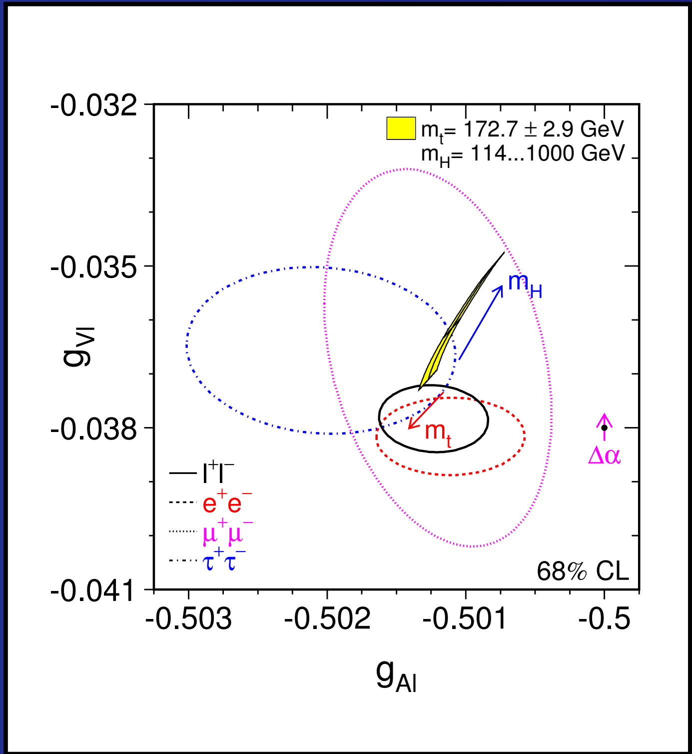
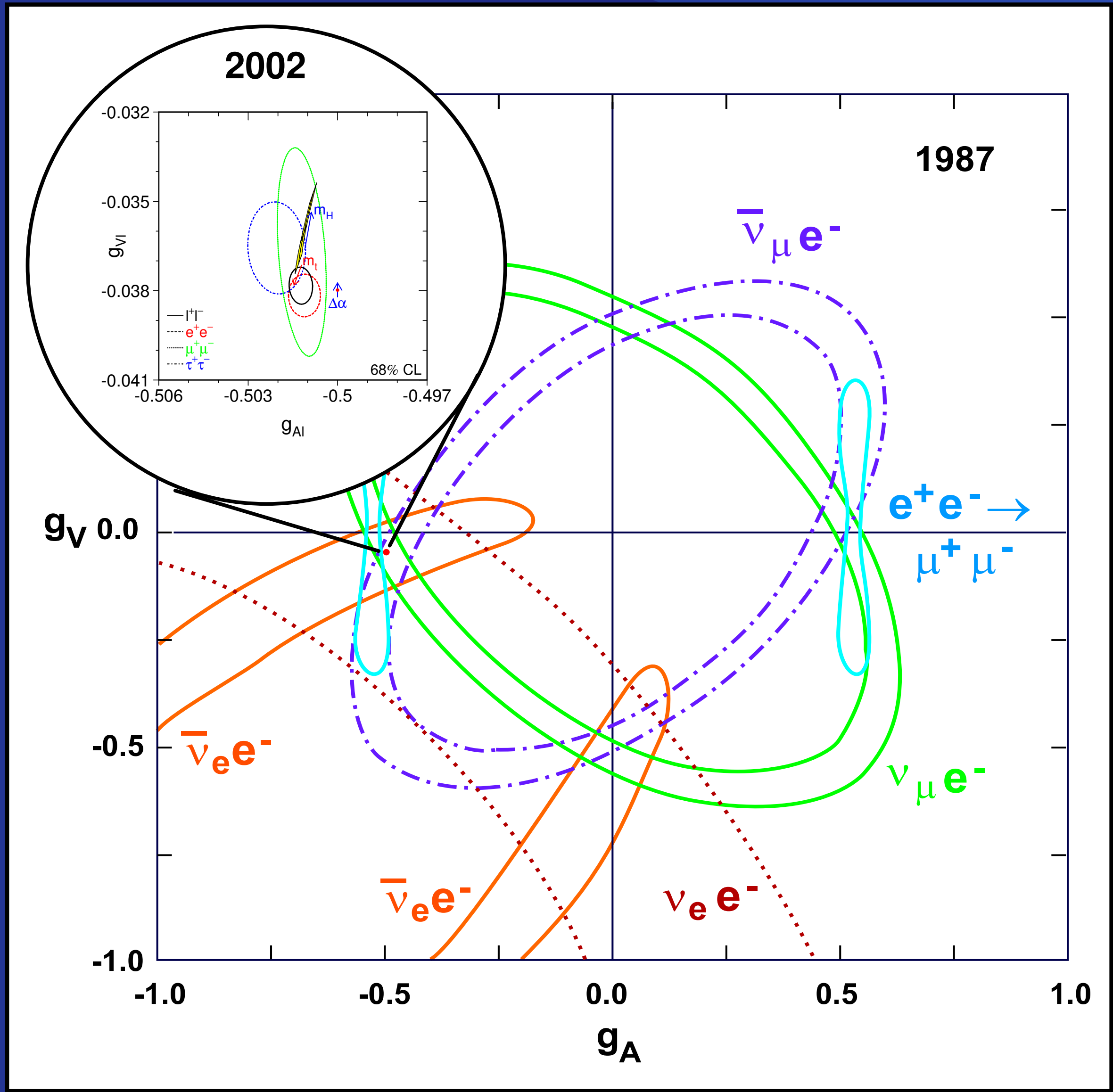
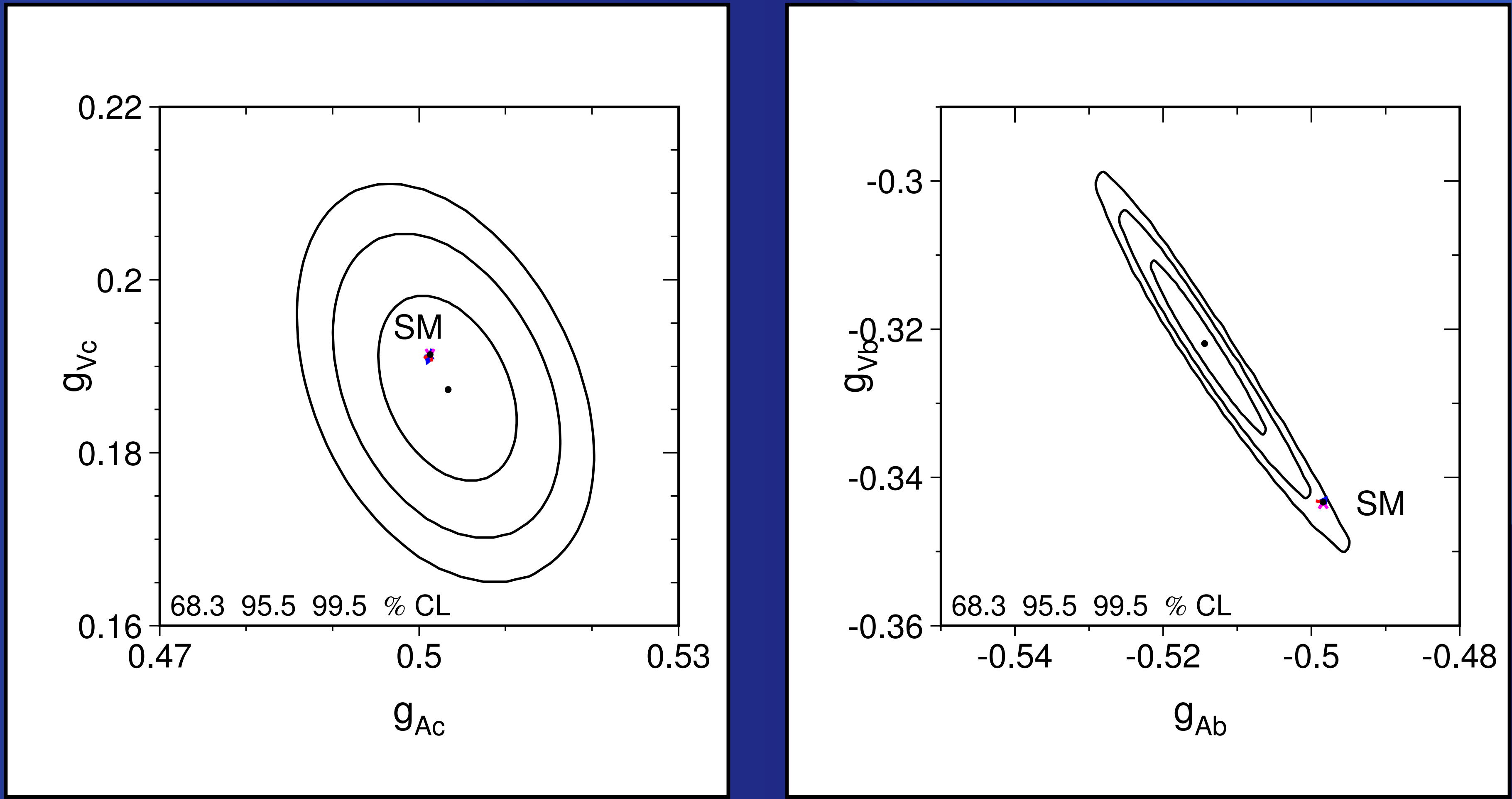
The **partial Z widths** in the different lepton flavors together with the **asymmetries** allows for a determination of all **lepton neutral-current couplings**, $v_\ell \equiv g_{V\ell}$ and $a_\ell \equiv g_{A\ell}$. The values of $g_{V\ell}$ and $g_{A\ell}$ can be plotted for $\ell = e$, μ, τ.




2002
-0.032
-0.035
-0.038
-0.041
-0.506
-0.503
-0.5
-0.497
68% CL
1987
gV 0.0
-0.5
-1.0
-1.0
-0.5
0.0
0.5
1.0
gA

The couplings of heavy quarks



top-quark, W, and Higgs masses

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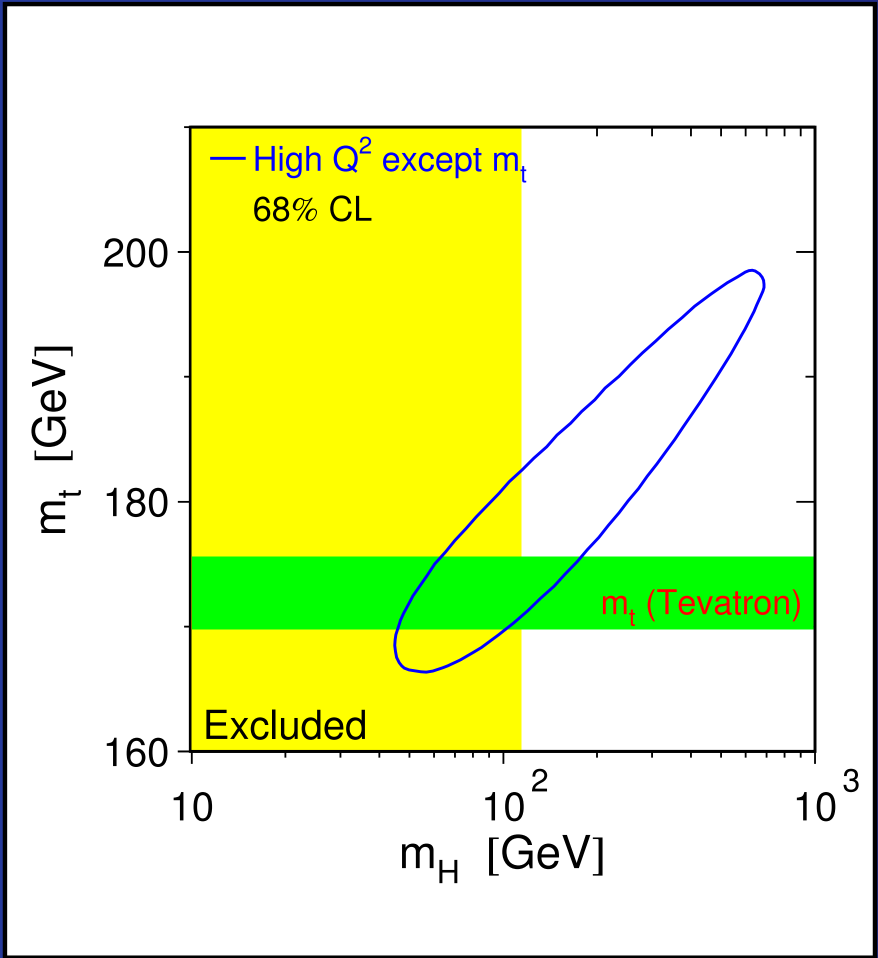

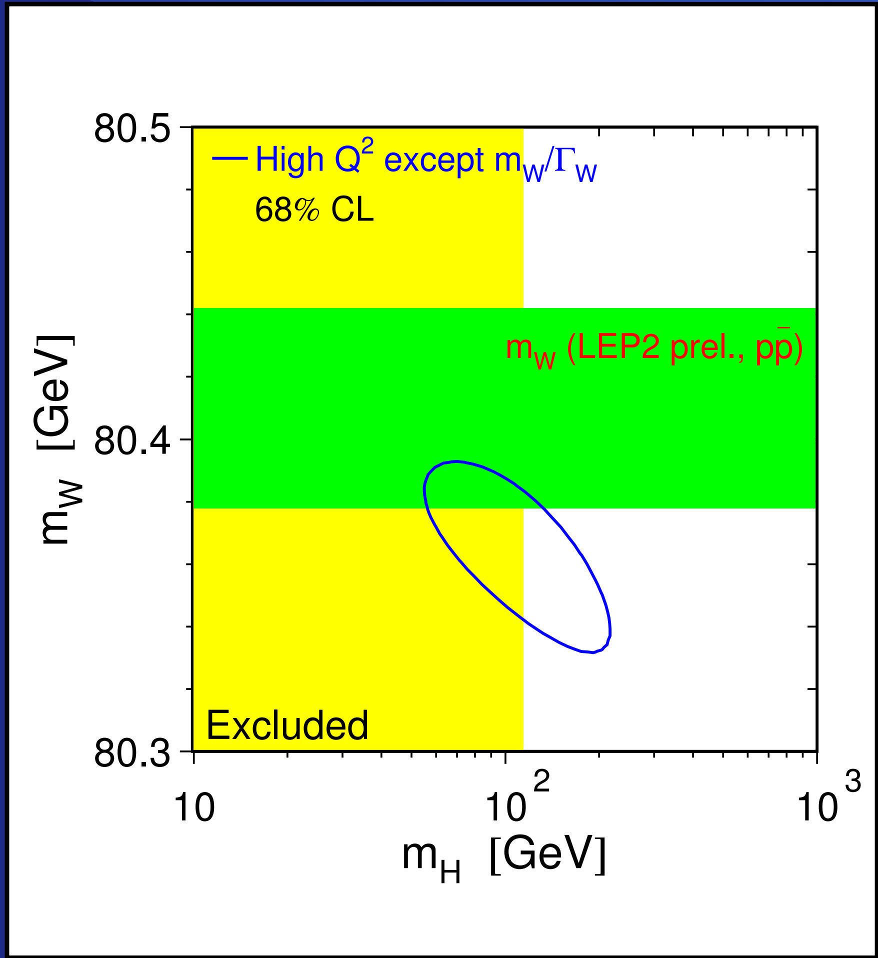

LEP2 and the non-Abelian couplings

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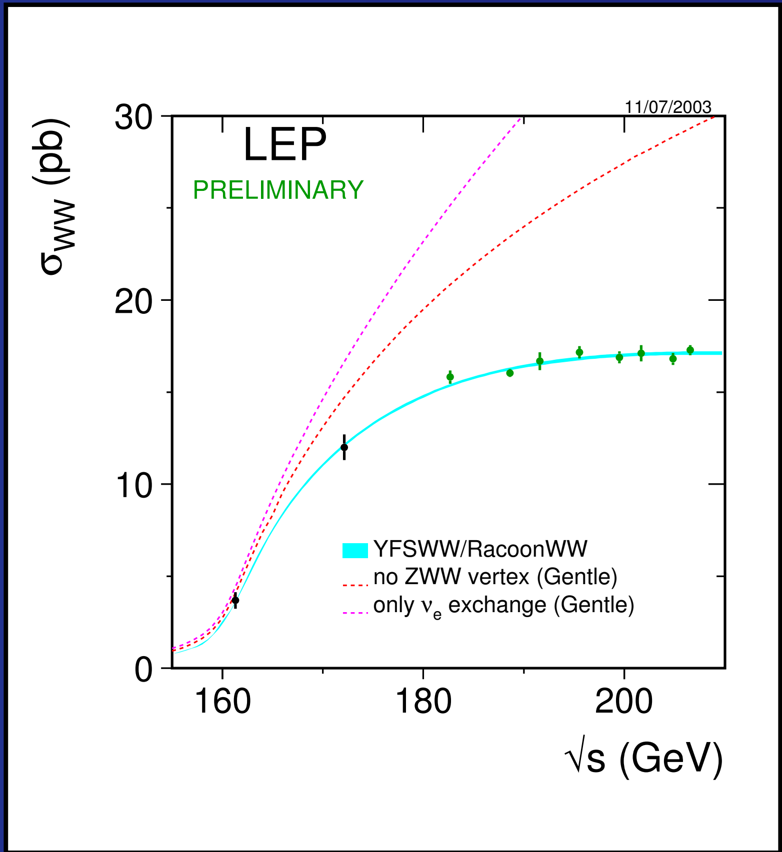
The **unitarity problems of the IVB** and the need for non-Abelian couplings were one of the main points that triggered the development of the SM. These have been **tested at LEP2**



The Higgs Couplings

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Coupling	Intensity
$H f \bar{f}$	M_f / v
$H W^+ W^-$	$2 M_W^2 / v$
$H Z^0 Z^0$	M_Z^2 / v
$H H W^+ W^-$	M_W^2 / v^2
$H H Z^0 Z^0$	$M_Z^2 / 2v^2$
$H H H$	$M_H^2 / 2v$
$H H H H$	$M_H^2 / 8v^2$

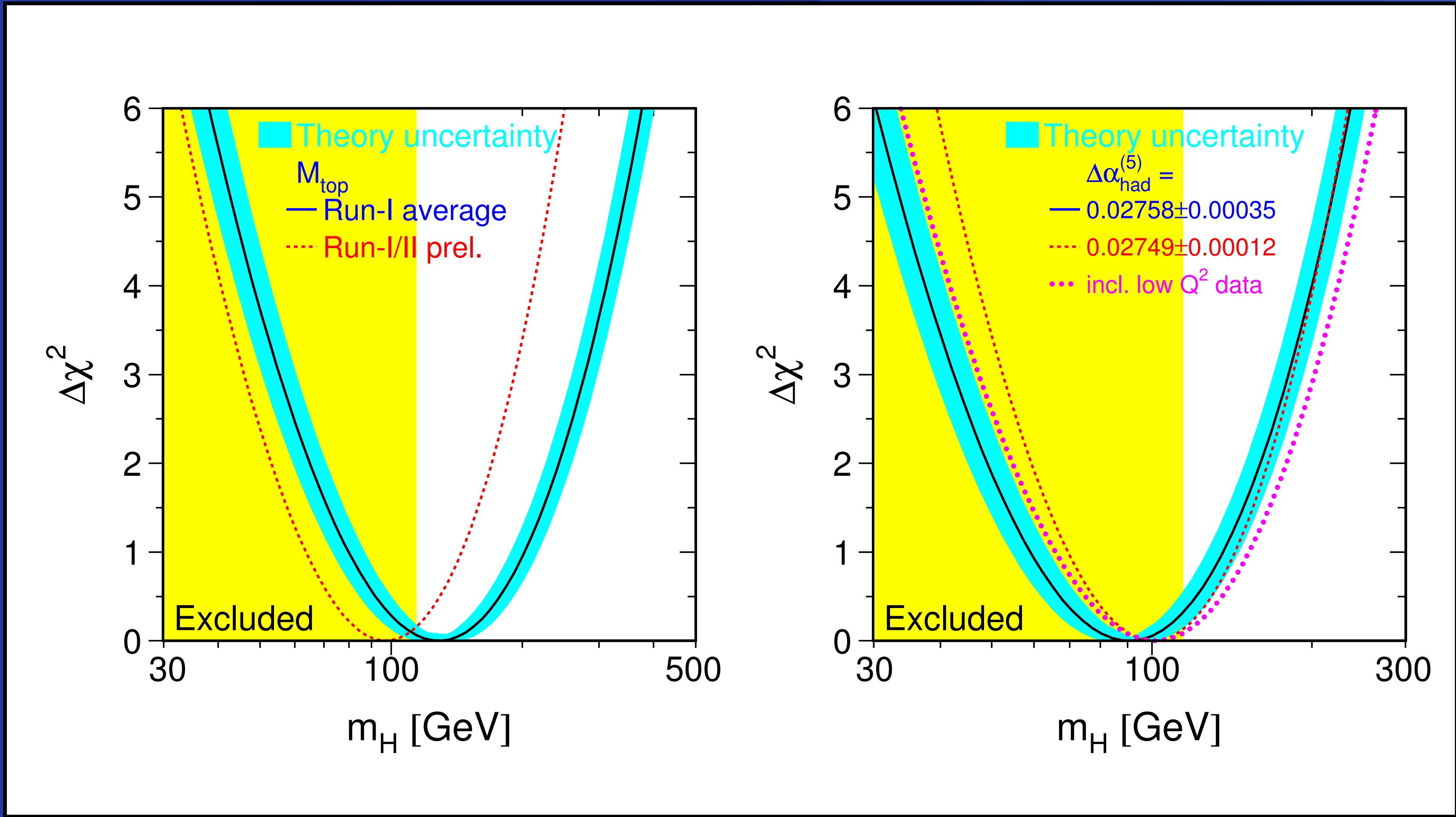
The Higgs also couples at **higher orders** with other gauge bosons

$$H\gamma\gamma\,,\ HZ\gamma\,,\ Hgg$$

Higgs coupling proportional to particle masses:

- **Produced in** association with **heavy particles**
- **Decay** into the **heaviest** accessible **particles**

Direct searches and global fit



$$114 < M_H < 285\,\mathrm{GeV} \quad 95\%\,\mathrm{CL}$$

Unitarity and perturbativity bounds

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Decay widths of the Higgs into gauge bosons grow like the Higgs mass

$$\Gamma(H \to W^+W^-) = \frac{G_F m_H^3}{8\pi\sqrt{2}}\,, \quad \Gamma(H \to Z\,Z) = \frac{G_F m_H^3}{16\pi\sqrt{2}}$$

Requiring $\Gamma_{\rm tot}(H) \leq m_H$ gives

$$m_H \leq 1.6\,\mathrm{TeV}$$

Requiring that tree-level unitarity is not violated in $W^+W^- \to W^+W^-$ leads to a slightly better bound

$$m_H \leq 1.2\,\mathrm{TeV}$$

These are **not strict bounds,** just say that for larger m_H one should **not trust perturbation theory**.

Triviality

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The λ coupling in the scalar potential grows with energy

$$\frac{d\lambda}{d\ln q^2} = \frac{3\lambda^2}{4\pi^2} + \cdots$$

then, λ diverges at some scale Λ, unless it is strictly zero.
Taking $\lambda(\Lambda) = \infty$ (the theory only makes sense up to $q^2 \sim \Lambda^2$) one finds

$$\lambda(q^2) = \frac{4\pi^2}{3\log(\Lambda^2/q^2)} \qquad m_H^2 = 2\lambda(v^2)v^2 \approx \frac{4\pi^2}{3\log(\Lambda^2/v^2)}$$

Since Λ should be larger than m_H one finds

$$m_H \leq \frac{4\pi^2}{3\sqrt{2}G_F\log(m_H^2/v^2)} \approx 850\,\mathrm{GeV}$$

Stability of the Higgs Potential

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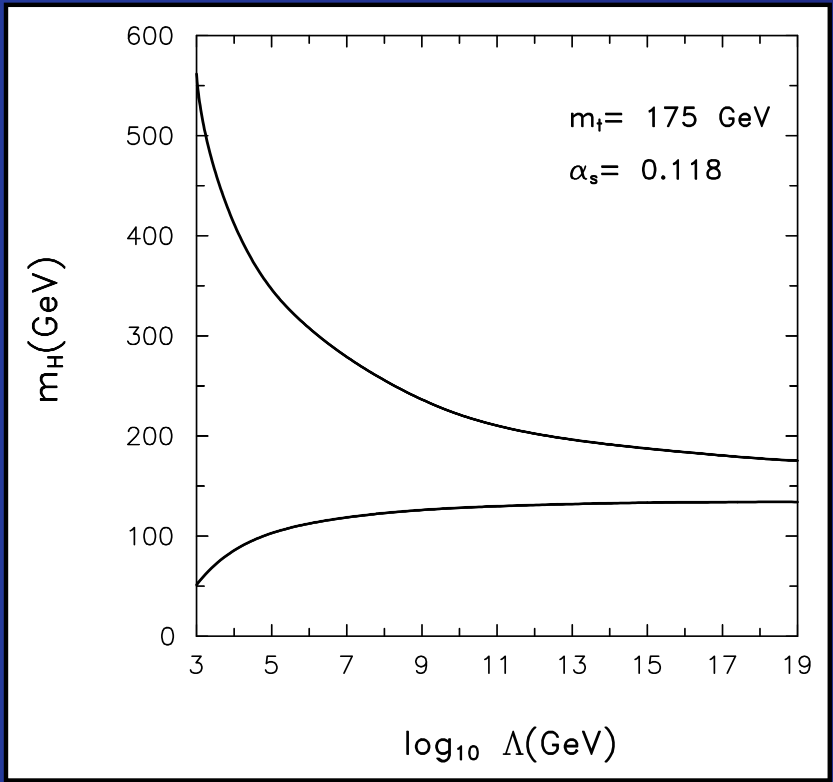
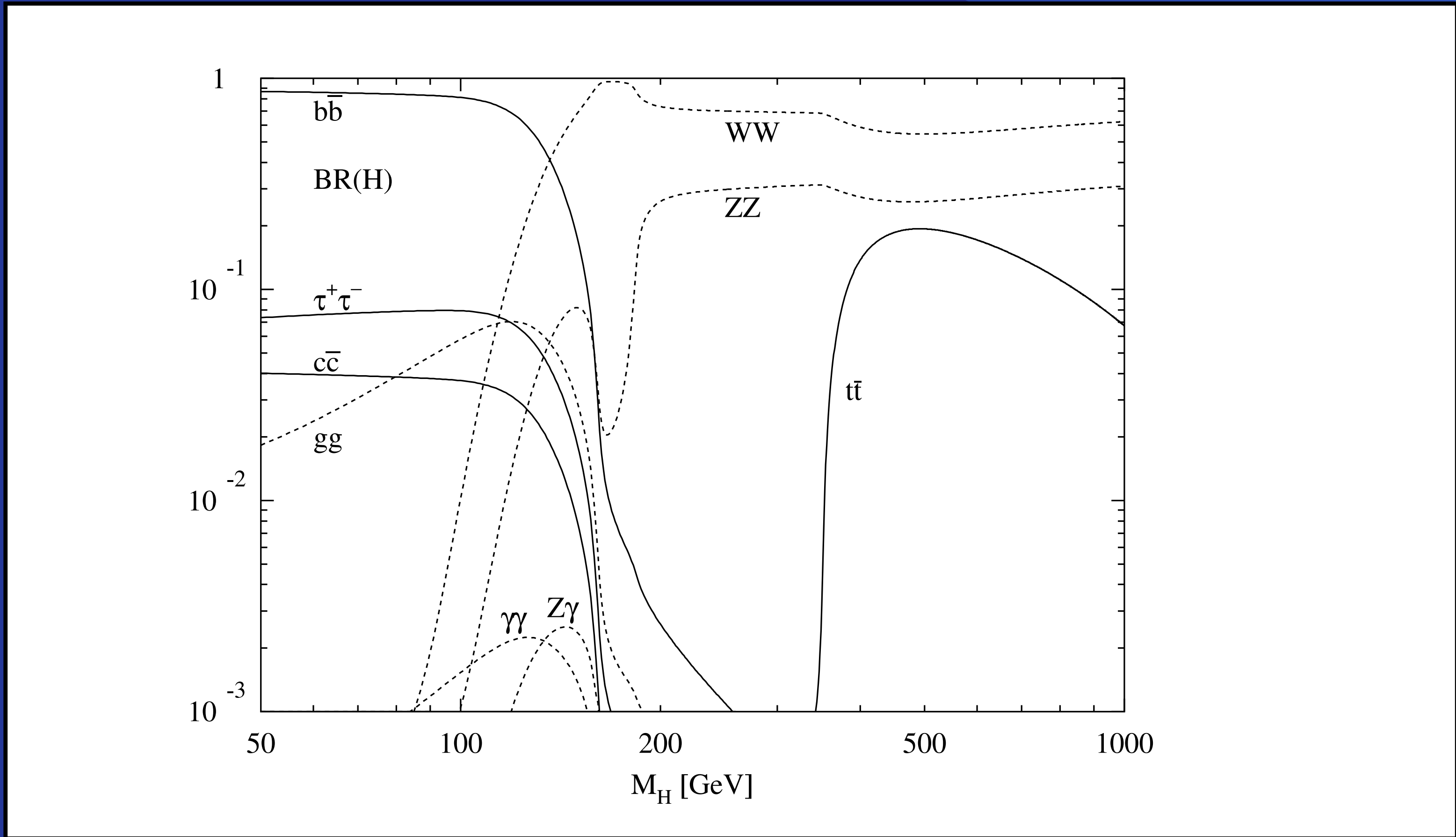
Radiative corrections modify the shape of the Higgs potential and could destabilize it. Requiring this does not happen gives a lower bounds on the Higgs mass (at one loop).



$$m_H > 100\,\mathrm{GeV} \qquad \text{(Stability)}$$

$$m_H < 850\,\mathrm{GeV} \qquad \text{(Triviality)}$$

The Decay Modes of the Higgs Boson



95 **GeV** $< m_H < 130$ **GeV**, $\Gamma_H < 10$ **MeV**

$$\begin{aligned} BR(H \to b\bar{b}) &\sim 90\% \,, \\ BR(H \to c\bar{c}) &\simeq BR(H \to \tau^+\tau^-) \sim 5\% \\ BR(H \to gg) &\sim 5\% \quad \text{for}\, m_H \sim 120\,\text{GeV} \end{aligned}$$

$m_H > 130$ **GeV**

$$BR(H \to W^+W^-) \sim 65\% \,, \; BR(H \to Z^0Z^0) \sim 35\%$$

$m_H \simeq 500$ **GeV** $\qquad BR(H \to t\bar{t}) \sim 20\%$

Production at e^+-e^- Colliders

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- **Bjorken:** $e^+e^- \to Z \to Z\,H$
- WW **fusion:** $e^+e^- \to \nu\bar{\nu}(WW) \to \nu\bar{\nu}H$
- ZZ **fusion:** $e^+e^- \to e^+e^-(ZZ) \to e^+e^-H$

At **LEP1 and 2**, where $\sqrt{s} \simeq M_Z$ or $2\,M_W$ the Higgs production is dominated by the **Bjorken mechanism**. Present bounds come from the analysis of LEP2 results. At the future e^+e^- accelerators, like the **Next Linear Collider**, where $\sqrt{s} = 500$ GeV, the production of a Higgs with $100 < M_H < 200$ GeV will be dominated by the WW **fusion**. One expects $M_H \sim 350$ GeV.

Production at Hadron Colliders

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At proton-(anti)proton collisions

- **Gluon fusion:** $p\,p \longrightarrow g\,g \longrightarrow H$
- VV **fusion:** $pp \longrightarrow VV \longrightarrow H$
- **Association with** V**:** $pp \longrightarrow qq' \longrightarrow VH$

Fermilab Tevatron , with $\sqrt{s} = 1.8$ (2) TeV: better produced in **association with vector bosons**, look for the $VH(\rightarrow b\bar{b})$ signature. Will be able to explore to explore up to $M_H \sim 100$ GeV.

CERN Large Hadron Collider (LHC), with $\sqrt{s} = 14$ TeV: the dominant mechanism is **gluon fusion** and the best signature $H \rightarrow ZZ \rightarrow 4\,\ell^{\pm}$ for $M_H > 130$ GeV. For $M_H < 130$ GeV rely on the small $BR(H \rightarrow \gamma\gamma) \sim 10^{-3}$. Will explore up to $M_H \sim 700$ GeV.