

# Particle Physics II

## Winter Semester 2011/2012

### Albert-Ludwigs-Universität Freiburg



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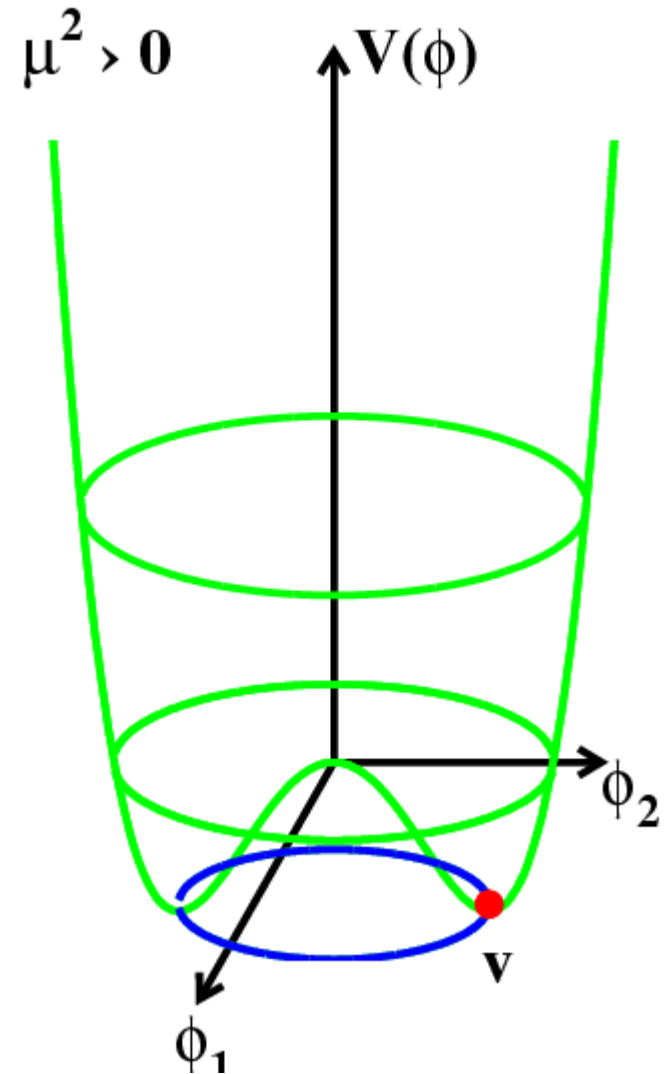
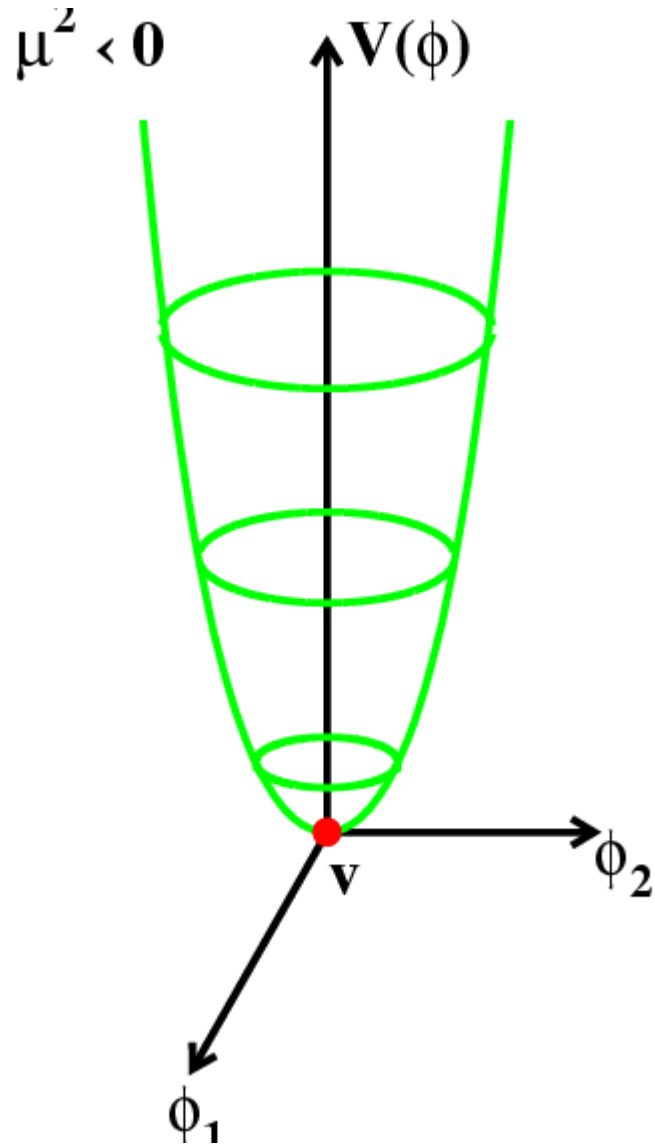
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# Kapitel 7

## Der Englert-Brout-Higgs-Guralnik-Hagen-Kibble-Mechanismus und die Phänomenologie des Higgs-Bosons

# Skalares Potential für 2FG



# Massen der Eichbosonen und HVV-WW

Higgs-Beitrag zur Lagrangedichte:  $\mathcal{L}_S = (D^\mu \Phi)^\dagger (D_\mu \Phi) - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$

Betrachte zunächst „kinetischen“ Term  $T$  ( $L=T-V$ )

$$\begin{aligned} |D_\mu \Phi|^2 &= \left| \left( \partial_\mu - ig_2 \frac{\tau_a}{2} W_\mu^a - ig_1 \frac{1}{2} B_\mu \right) \Phi \right|^2 \\ &= \frac{1}{2} \left| \begin{pmatrix} \partial_\mu - \frac{i}{2}(g_2 W_\mu^3 + g_1 B_\mu) & -\frac{ig_2}{2}(W_\mu^1 - iW_\mu^2) \\ -\frac{ig_2}{2}(W_\mu^1 + iW_\mu^2) & \partial_\mu + \frac{i}{2}(g_2 W_\mu^3 - g_1 B_\mu) \end{pmatrix} \begin{pmatrix} 0 \\ v + H \end{pmatrix} \right|^2 \\ &= \frac{1}{2} (\partial_\mu H)^2 + \frac{1}{8} g_2^2 (v + H)^2 |W_\mu^1 + iW_\mu^2|^2 + \frac{1}{8} (v + H)^2 |g_2 W_\mu^3 - g_1 B_\mu|^2 \end{aligned}$$

Definiere folgende Linearkombinationen

$$W^\pm = \frac{1}{\sqrt{2}} (W_\mu^1 \mp iW_\mu^2), \quad Z_\mu = \frac{g_2 W_\mu^3 - g_1 B_\mu}{\sqrt{g_2^2 + g_1^2}}, \quad A_\mu = \frac{g_2 W_\mu^3 + g_1 B_\mu}{\sqrt{g_2^2 + g_1^2}}$$

a) für  $W^{1,2} \rightarrow W^\pm$  um Ladungseigenzustände zu erhalten

b) für  $W^3$  und  $B \rightarrow Z$  und  $A$  um Masseneigenzustände zu erhalten

Die Terme bilinear in den Vektorfelder und dem Vakuumerwartungswert  $v$  lauten dann

$$M_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu + \frac{1}{2} M_A^2 A_\mu A^\mu \quad M_W = \frac{1}{2} v g_2, \quad M_Z = \frac{1}{2} v \sqrt{g_2^2 + g_1^2}, \quad M_A = 0$$

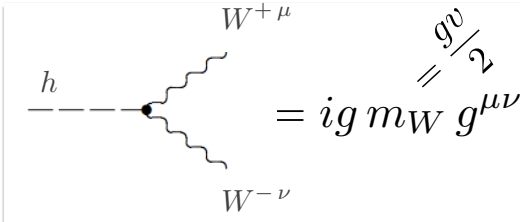


# HHV- und HHVV-Wechselwirkungen

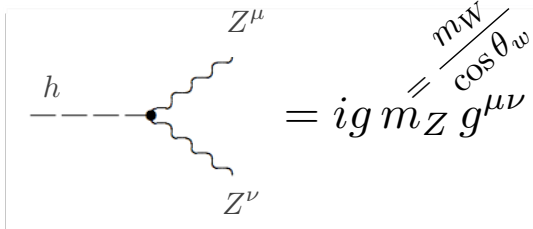
$$|D_\mu \Phi|^2 = \frac{1}{2}(\partial_\mu H)^2 + \frac{1}{8}g_2^2(v+H)^2|W_\mu^1 + iW_\mu^2|^2 + \frac{1}{8}(v+H)^2|g_2W_\mu^3 - g_1B_\mu|^2$$

$$W^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp iW_\mu^2), \quad Z_\mu = \frac{g_2W_\mu^3 - g_1B_\mu}{\sqrt{g_2^2 + g_1^2}}, \quad A_\mu = \frac{g_2W_\mu^3 + g_1B_\mu}{\sqrt{g_2^2 + g_1^2}}$$

Terme linear in H und v und bilinear in  $W^\pm, Z$ :



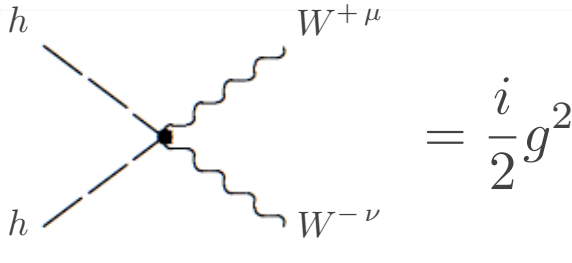
A Feynman diagram showing a Higgs boson (h) interacting with a W boson pair (W<sup>+</sup> and W<sup>-</sup>). The vertex is represented by a black dot. The diagram is equated to the expression  $= ig m_W g^{\mu\nu}$ . A handwritten note above the diagram indicates  $= \frac{gv}{2}$ .



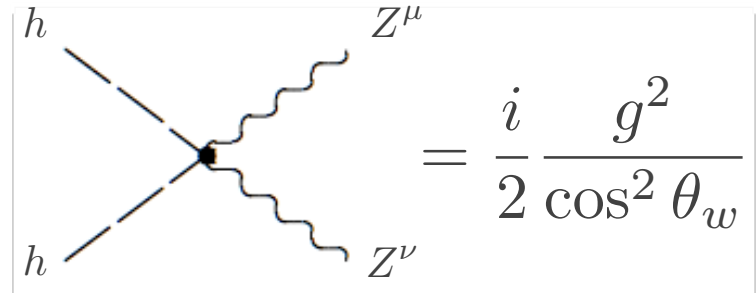
A Feynman diagram showing a Higgs boson (h) interacting with a Z boson pair (Z<sup>+</sup> and Z<sup>-</sup>). The vertex is represented by a black dot. The diagram is equated to the expression  $= ig m_Z g^{\mu\nu}$ . A handwritten note above the diagram indicates  $= \frac{m_W}{\cos\theta_w}$ .

Kopplungsstärke  $\sim$  Eichkopplung  $\times$  Masse  $\rightarrow$  Unitarität

Terme bilinear in H und bilinear in  $W^\pm, Z$ :



A Feynman diagram showing a Higgs boson (h) interacting with a W boson pair (W<sup>+</sup> and W<sup>-</sup>) at a vertex, and another Higgs boson (h) interacting with the same W boson pair at a second vertex. The two vertices are connected by a dashed line representing the Higgs boson. The diagram is equated to the expression  $= \frac{i}{2}g^2$ .



A Feynman diagram showing a Higgs boson (h) interacting with a Z boson pair (Z<sup>+</sup> and Z<sup>-</sup>) at a vertex, and another Higgs boson (h) interacting with the same Z boson pair at a second vertex. The two vertices are connected by a dashed line representing the Higgs boson. The diagram is equated to the expression  $= \frac{i}{2} \frac{g^2}{\cos^2 \theta_w}$ .

# Masse und Selbstwechselwirkung des Higgs

Betrachte nun den Potentialterm:  $V = \frac{\mu^2}{2}(0, v+H) \begin{pmatrix} 0 \\ v+H \end{pmatrix} + \frac{\lambda}{4} \left| (0, v+H) \begin{pmatrix} 0 \\ v+H \end{pmatrix} \right|^2$

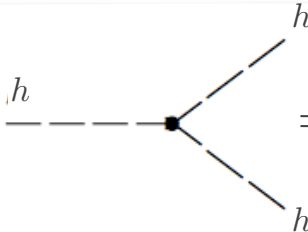
$$v^2 = -\mu^2/\lambda \quad V = -\frac{1}{2}\lambda v^2 (v+H)^2 + \frac{1}{4}\lambda(v+H)^4$$

Ergibt:

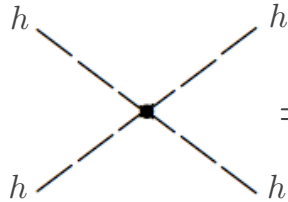
$$\begin{aligned} \mathcal{L}_H &= \frac{1}{2}(\partial_\mu H)(\partial^\mu H) - V \\ &= \frac{1}{2}(\partial^\mu H)^2 - \lambda v^2 H^2 - \lambda v H^3 - \frac{\lambda}{4} H^4 + \lambda/4 v^4 \end{aligned}$$

Bilinear in H  $\rightarrow$  Massenterm mit korrektem Vorzeichen:  $M_H^2 = 2\lambda v^2 = -2\mu^2$

Tril- und Quadrolinear in H  $\rightarrow$  Selbst-WW:  $g_{H^3} = (3!)i\lambda v = 3i \frac{M_H^2}{v}$ ,  $g_{H^4} = (4!)i \frac{\lambda}{4} = 3i \frac{M_H^2}{v^2}$



$$= -i \frac{3 g m_h^2}{2 m_W}$$



$$= -i \frac{3 g^2 m_h^2}{4 m_W^2}$$

Beitrag zur dunklen Energie:  $V_{DE} = -\lambda/4 v^4$  ca  $-10^{60}$  mal beobachteten Wert

# Massen der Fermionen

Neue Terme in Langrangedichte:

$$\tilde{\Phi} = i\tau_2 \Phi^*$$

sogenannte Yukawakopplungen zwischen Higgs-Feld und Fermionen

$$\mathcal{L}_Y = -c_1 (\bar{u}, \bar{d})_L \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} d_R - c_2 (\bar{u}, \bar{d})_L \begin{pmatrix} \phi^{(0)*} \\ -\phi^{(-)} \end{pmatrix} u_R - c_3 (\bar{\nu}_e, \bar{e})_L \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} e_R + \text{h.c.}$$

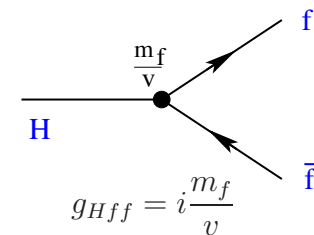
Einsetzen des Higgs-Feldes nach SSB

$$\mathcal{L}_Y = -\frac{1}{\sqrt{2}} (v + H) \{c_1 \bar{d}d + c_2 \bar{u}u + c_3 \bar{e}e\}$$

Massenterme für Fermionen:  $m_d = c_1 \frac{v}{\sqrt{2}}$ ,  $m_u = c_2 \frac{v}{\sqrt{2}}$ ,  $m_e = c_3 \frac{v}{\sqrt{2}}$

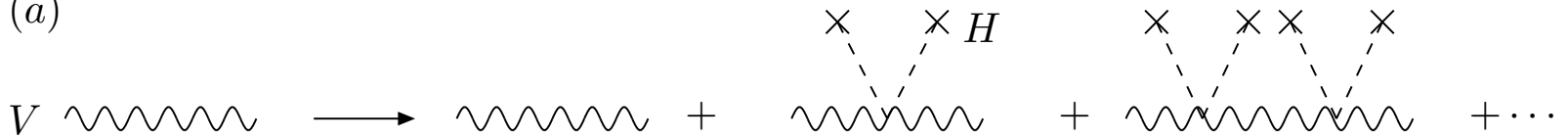
Wechselwirkungsterme: Kopplung  $\sim$  Masse des Fermions  $\rightarrow$  Unitarität

$$\mathcal{L}_Y = -\left(1 + \frac{H}{v}\right) \{m_d \bar{d}d + m_u \bar{u}u + m_e \bar{e}e\}$$



# Massen durch WW mit Vakuum: "Anschaulich"

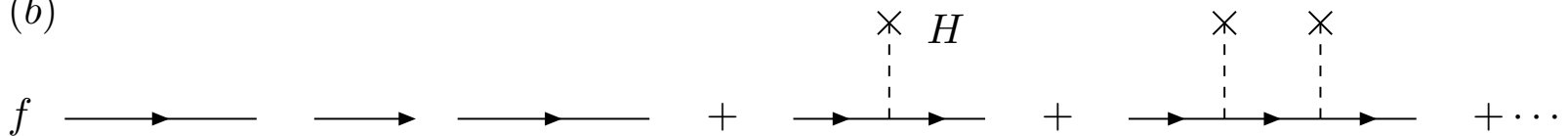
(a)



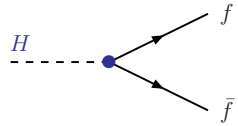
$$\frac{1}{q^2} \rightarrow \frac{1}{q^2} + \sum_j \frac{1}{q^2} \left[ \left( \frac{gv}{2} \right)^2 \frac{1}{q^2} \right]^j = \frac{1}{q^2 - M^2} \quad : \quad M^2 = g^2 \frac{v^2}{4}$$

$$\frac{1}{\not{q}} \rightarrow \frac{1}{\not{q}} + \sum_j \frac{1}{\not{q}} \left[ \frac{g_f v}{\sqrt{2}} \frac{1}{\not{q}} \right]^j = \frac{1}{\not{q} - m_f} \quad : \quad m_f = g_f \frac{v}{\sqrt{2}}$$

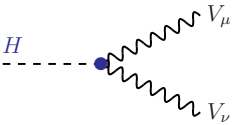
(b)



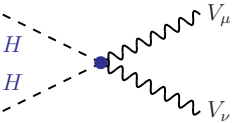
# Higgs-Kopplungen und freie Parameter



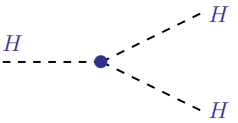
$$g_{Hff} = m_f/v = (\sqrt{2}G_\mu)^{1/2} m_f \quad \times (i)$$



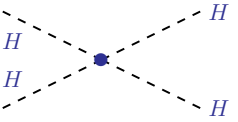
$$g_{HVV} = 2M_V^2/v = 2(\sqrt{2}G_\mu)^{1/2} M_V^2 \quad \times (-ig_{\mu\nu})$$



$$g_{HHVV} = 2M_V^2/v^2 = 2\sqrt{2}G_\mu M_V^2 \quad \times (-ig_{\mu\nu})$$



$$g_{HHH} = 3M_H^2/v = 3(\sqrt{2}G_\mu)^{1/2} M_H^2 \quad \times (i)$$



$$g_{HHHH} = 3M_H^2/v^2 = 3\sqrt{2}G_\mu M_H^2 \quad \times (i)$$

Alle Kopplungen bekannt

$$g_{Hff} = i\frac{m_f}{v}, \quad g_{HVV} = -2i\frac{M_V^2}{v}, \quad g_{HHVV} = -2i\frac{M_V^2}{v^2}$$

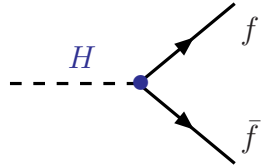
Vakuumerwartungswert  $v$   
aus  $G_F$  bekannt

$$M_W = \frac{1}{2}g_2v = \left(\frac{\sqrt{2}g^2}{8G_\mu}\right)^{1/2} \Rightarrow v = \frac{1}{(\sqrt{2}G_\mu)^{1/2}} \simeq 246 \text{ GeV}$$

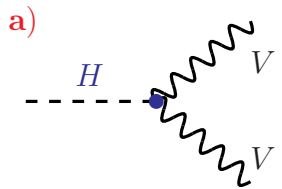
nur ein freier und unbekannter Parameter im Standardmodell:  $M_H$  oder  $\lambda$

$$M_H^2 = 2\lambda v^2 = -2\mu^2$$

# Partialbreiten und Verzweigungsverhältnisse

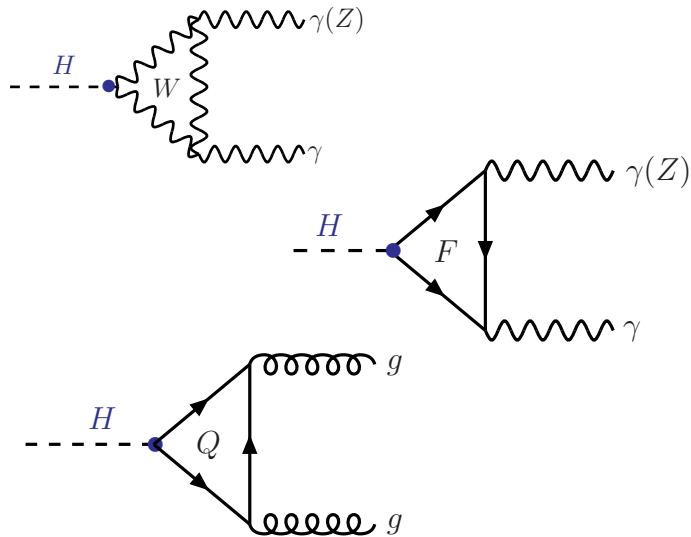


$$\Gamma(H \rightarrow f\bar{f}) = n_c \frac{G_F}{4\sqrt{2}\pi} m_f^2(M_H^2) M_H \beta_f^3 \quad \beta_f = \sqrt{1 - 4m_f^2/M_H^2}$$



$$\Gamma(H \rightarrow VV) = \delta_V \frac{G_F}{16\sqrt{2}\pi} M_H^3 (1 - 4x + 12x^2) \beta_V$$

$$x = M_V^2/M_H^2 \quad \delta_V = 2 \text{ and } 1 \text{ for } V = W \text{ and } Z$$

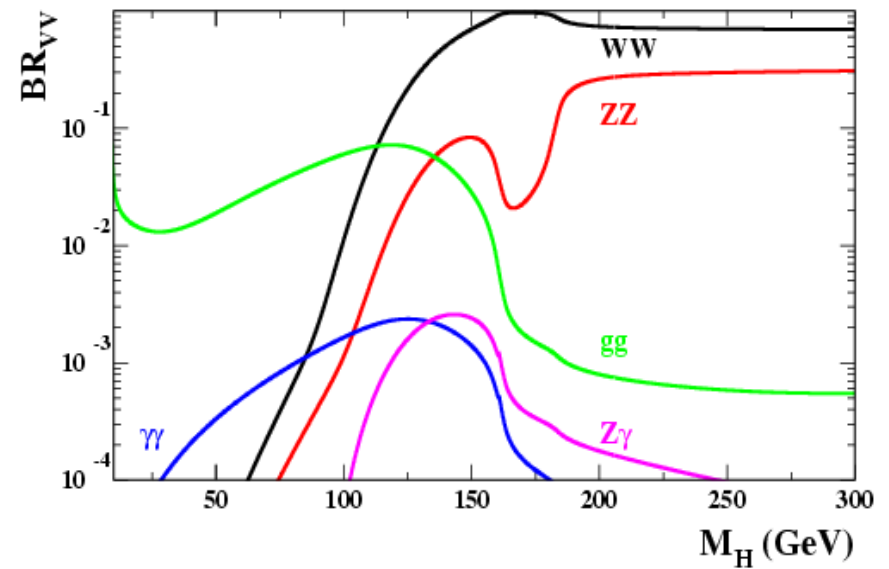
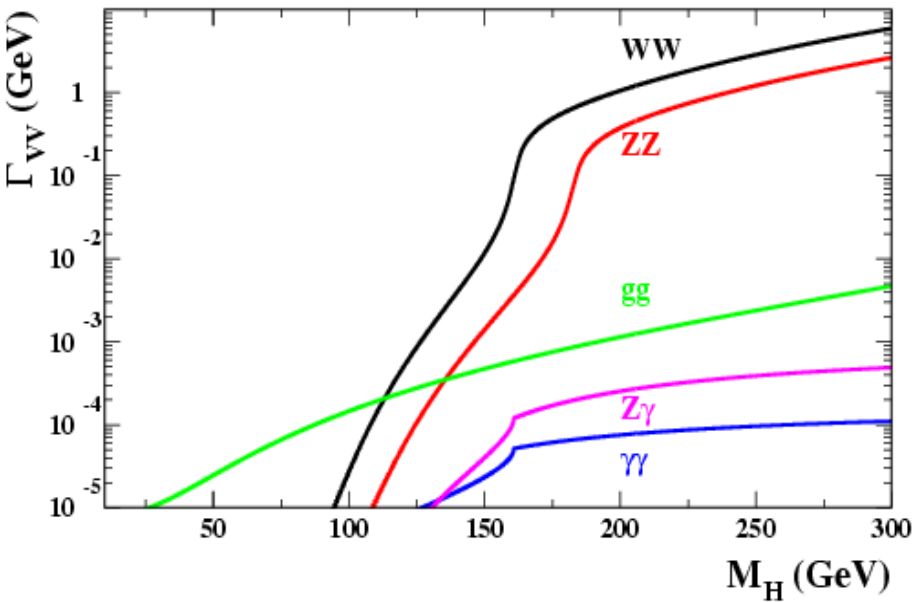
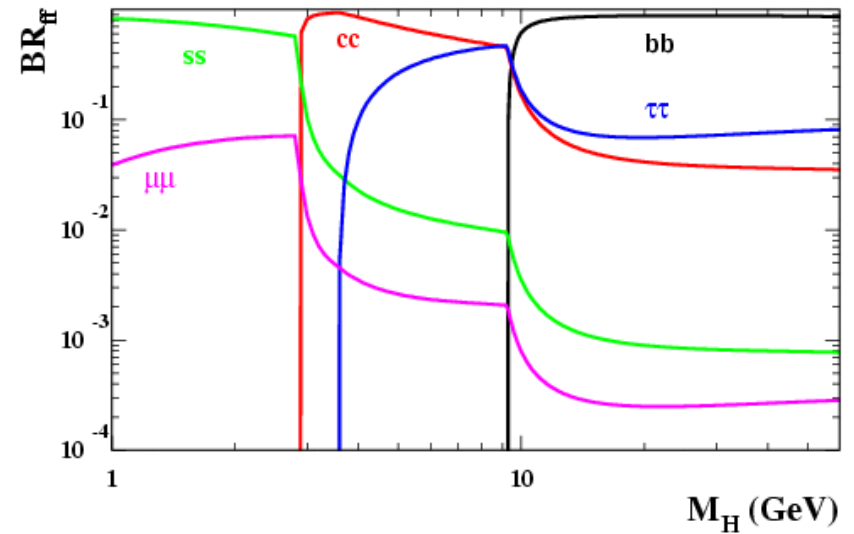
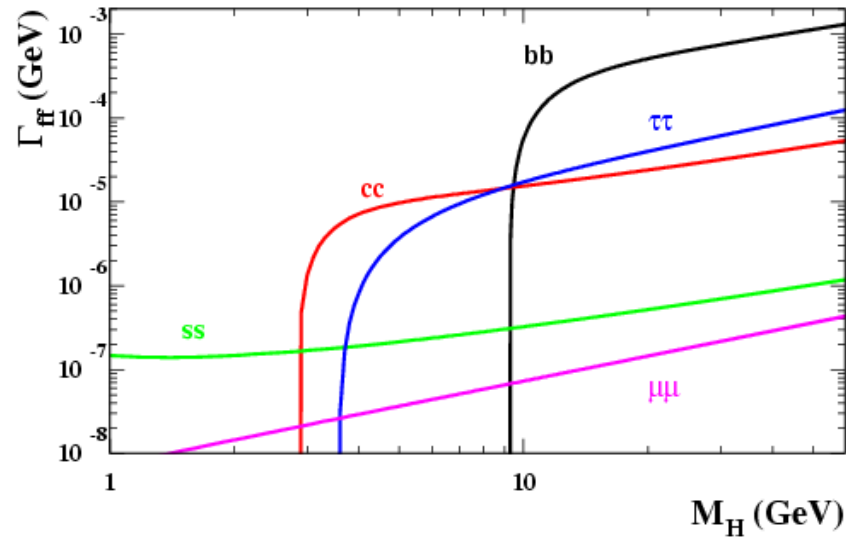


$$\Gamma(H \rightarrow gg) = \frac{G_F \alpha_s^2(M_H^2)}{36\sqrt{2}\pi^3} M_H^3 \left[ 1 + \left( \frac{95}{4} - \frac{7n_F}{6} \right) \frac{\alpha_s}{\pi} \right],$$

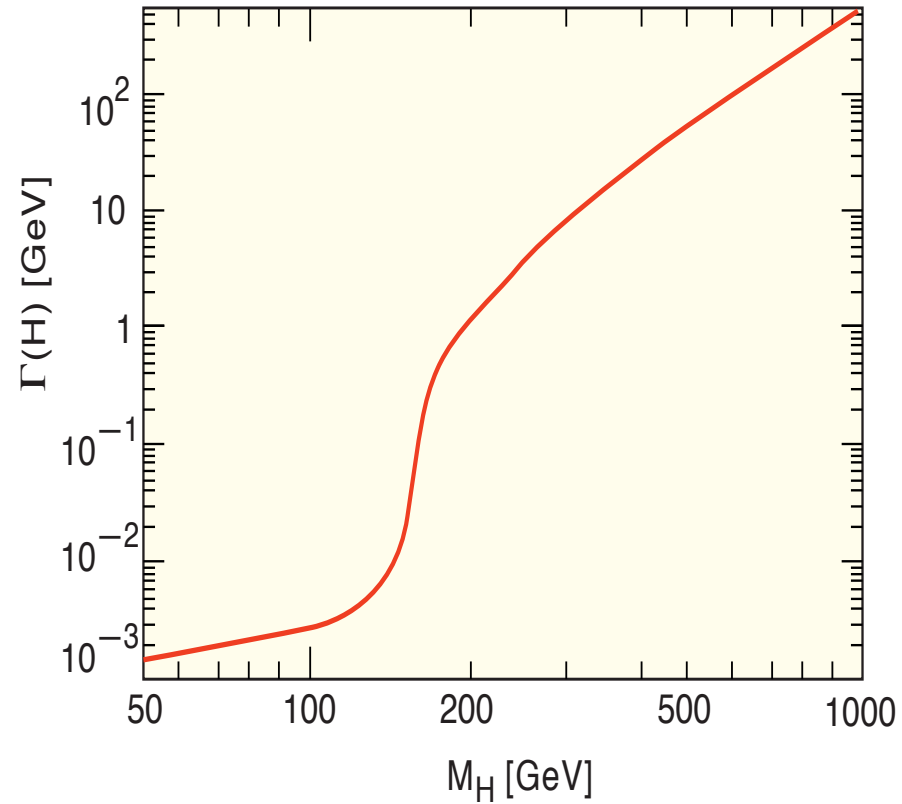
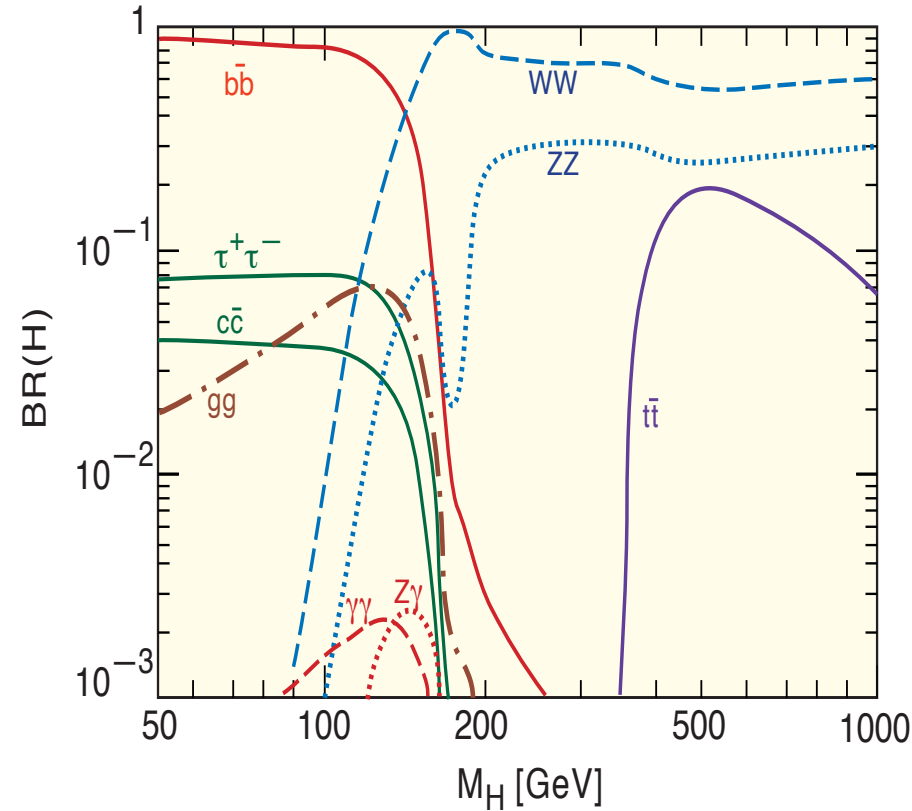
$$\Gamma(H \rightarrow \gamma\gamma) = \frac{G_F \alpha^2}{128\sqrt{2}\pi^3} M_H^3 \left[ \frac{4}{3} n_c e_t^2 - 7 \right]^2,$$

$$M_H^2 \ll 4M_W^2, 4m_t^2.$$

# Partialbreiten und Verzweigungsverhältnisse



# Verzweigungsverhältnisse und totale Breite



$Q$	$m_Q$	$\bar{m}_Q(m_Q)$	$\bar{m}_Q(100 \text{ GeV})$
$c$	1.64 GeV	1.23 GeV	0.63 GeV
$b$	4.88 GeV	4.25 GeV	2.95 GeV
$t$	178 GeV	170.3 GeV	178.3 GeV



# 7.5 Grenzen auf die Higgs-Boson-Masse im SM

Grenze aus der Theorie:

- Unitaritätsgrenze
- Trivialitätsgrenze, kein Landau-Pol
- Vakuumstabilität

Indirekte Vorhersage im SM

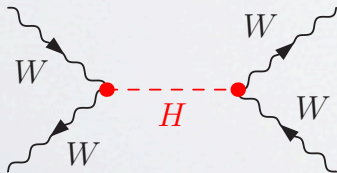
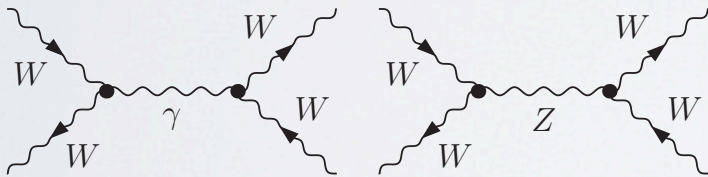
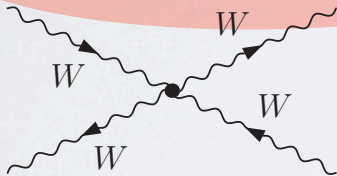
Direkte Suche an

- LEP
- TEVATRON
- LHC

# Unitaritätsgrenze für Masse des Higgs

$$S^\dagger S = \mathbb{1} \implies a_\ell = \frac{1}{32\pi} \int_{-1}^1 d\cos\theta \mathcal{M}(\cos\theta) P_\ell(\cos\theta), \quad |a_\ell| \leq 1$$

$$\varepsilon_L^\mu = k^\mu/m_W + \mathcal{O}(m_W/E)$$



+ crossed  $s \leftrightarrow t$

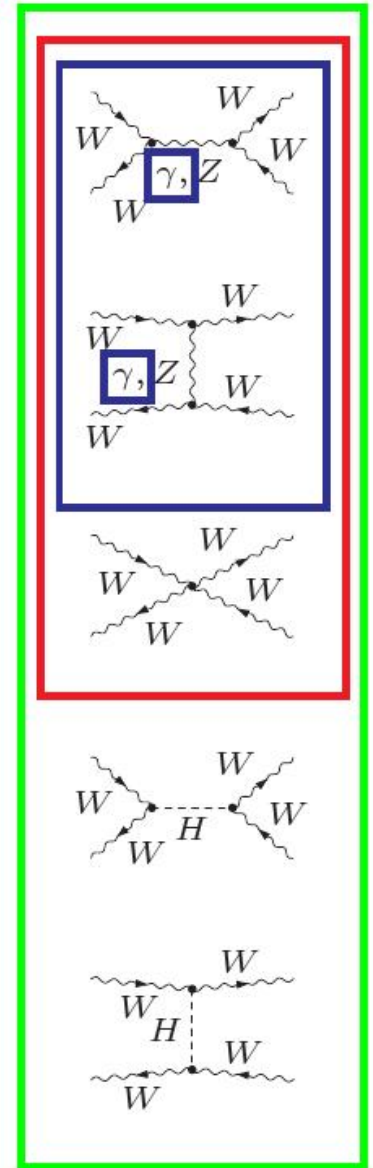
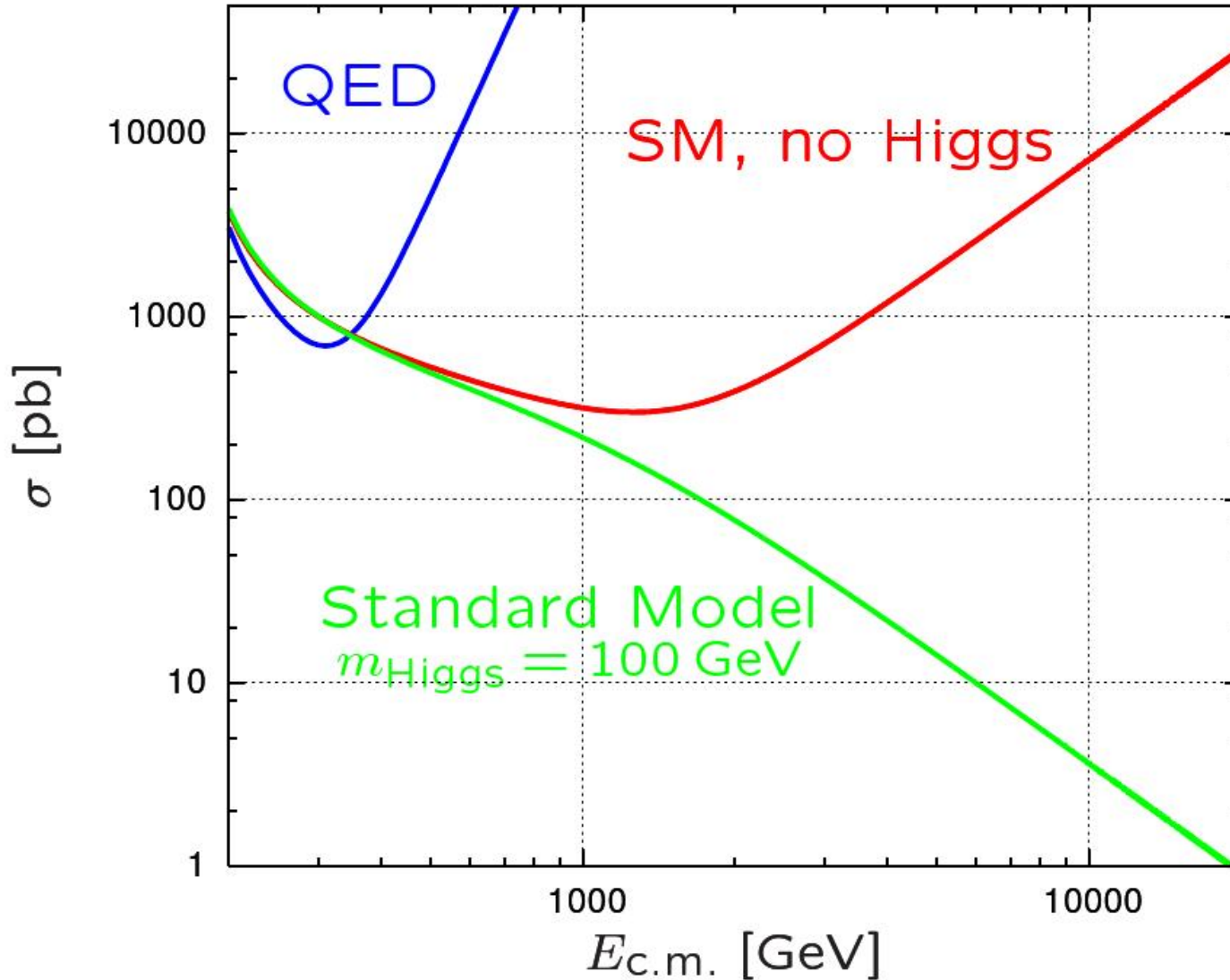
$$a_0 = \frac{1}{16\pi s} \int_s^0 dt |A| = -\frac{M_H^2}{16\pi v^2} \left[ 2 + \frac{M_H^2}{s - M_H^2} - \frac{M_H^2}{s} \log\left(1 + \frac{s}{M_H^2}\right) \right]$$

$$a_0 \xrightarrow{s \gg M_H^2} -\frac{M_H^2}{8\pi v^2}$$

$$m_h \lesssim 700 \text{ GeV}$$

# Unitaritätsgrenze für Masse des Higgs

$\sigma(W_L W_L \rightarrow W_L W_L)$  at tree-level

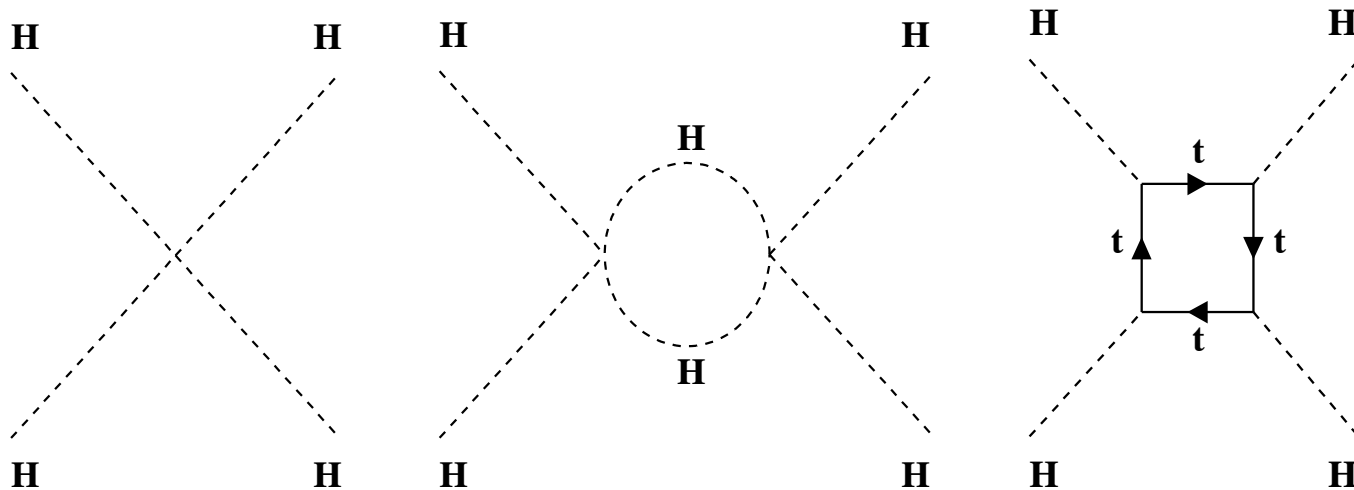


# Grenzen auf $M_H$ aus Störungstheorie für $\lambda$

Quartische Higgs-Selbstkopplung  $\lambda$  ist energieabhängig

$\lambda < \infty$  oder  $1$  für Störungstheorie     $\lambda > 0$  Stabiles Vakuum

$$\frac{d\lambda}{dt} = \frac{3}{8\pi^2}(\lambda^2 + \lambda\lambda_t^2 - \lambda_t^4) \quad \text{mit} \quad \lambda(v^2) = \frac{M_H^2}{2v^2} \quad \text{und} \quad t = \ln \frac{Q^2}{v^2}$$
$$\frac{d\lambda_t}{dt} = \frac{1}{32\pi^2} \left( \frac{9}{2}\lambda_t^3 - 8\lambda_t g_s^2 \right) \quad \text{mit} \quad \lambda_t(v^2) = \frac{\sqrt{2}m_t}{v}$$

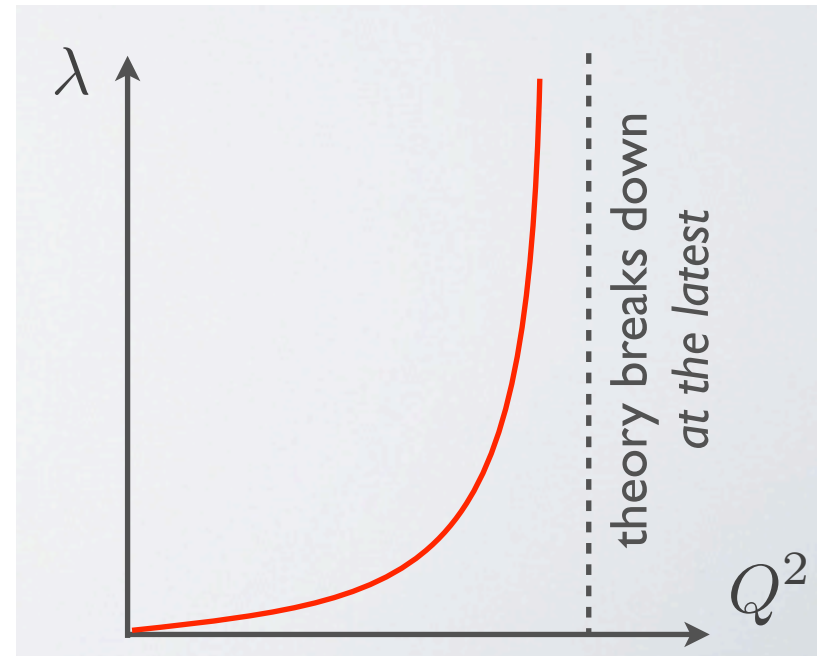


# Grenzen auf $M_H$ aus Störungstheorie für $\lambda$

$$V(\Phi^\dagger \Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \quad m_h^2 = \frac{\lambda v^2}{2}$$

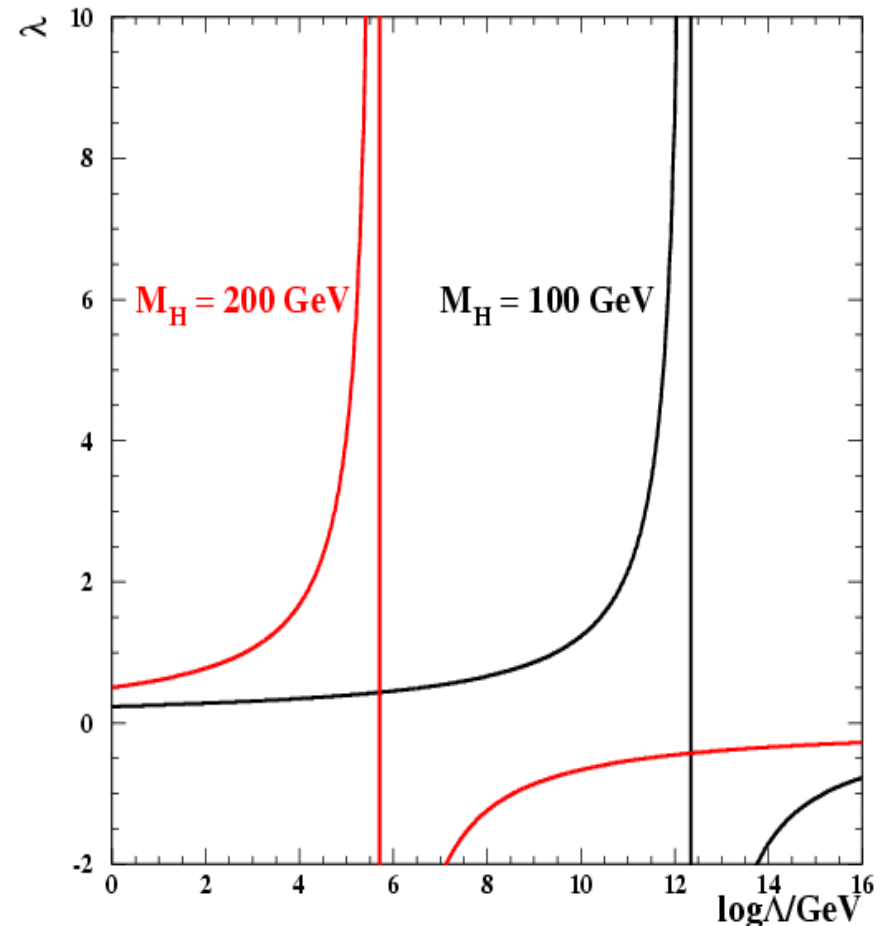
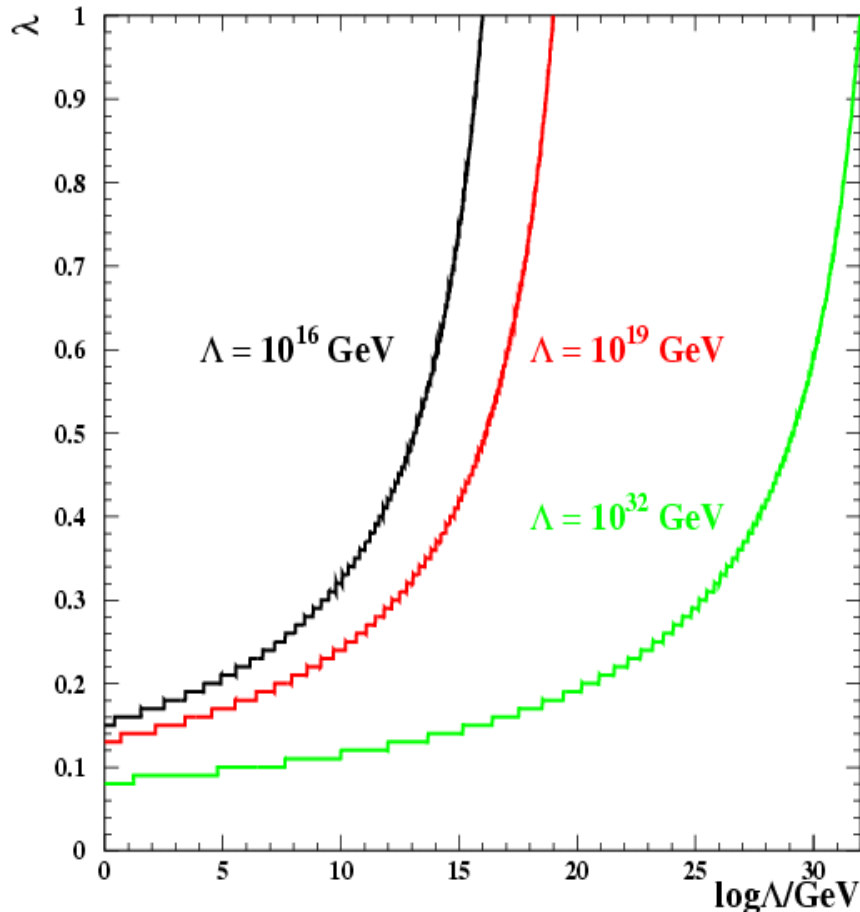
$$\frac{d\lambda}{d \log Q^2} = \frac{1}{16\pi^2} \left[ 12\lambda^2 + 6\lambda\lambda_t^2 - 3\lambda_t^4 - \frac{3}{2}\lambda(3g_2^2 + g_1^2) + \frac{3}{16}(2g_2^4 + (g_2^2 + g_1^2)^2) \right]$$

$$\frac{d\lambda}{d \log Q^2} = \frac{12\lambda^2}{16\pi^2} + \text{gauge \& fermion terms}$$
$$\rightarrow \lambda = \lambda(v^2) \left[ 1 - \frac{3}{4\pi^2} \lambda(v^2) \log \frac{Q^2}{v^2} \right]^{-1}$$



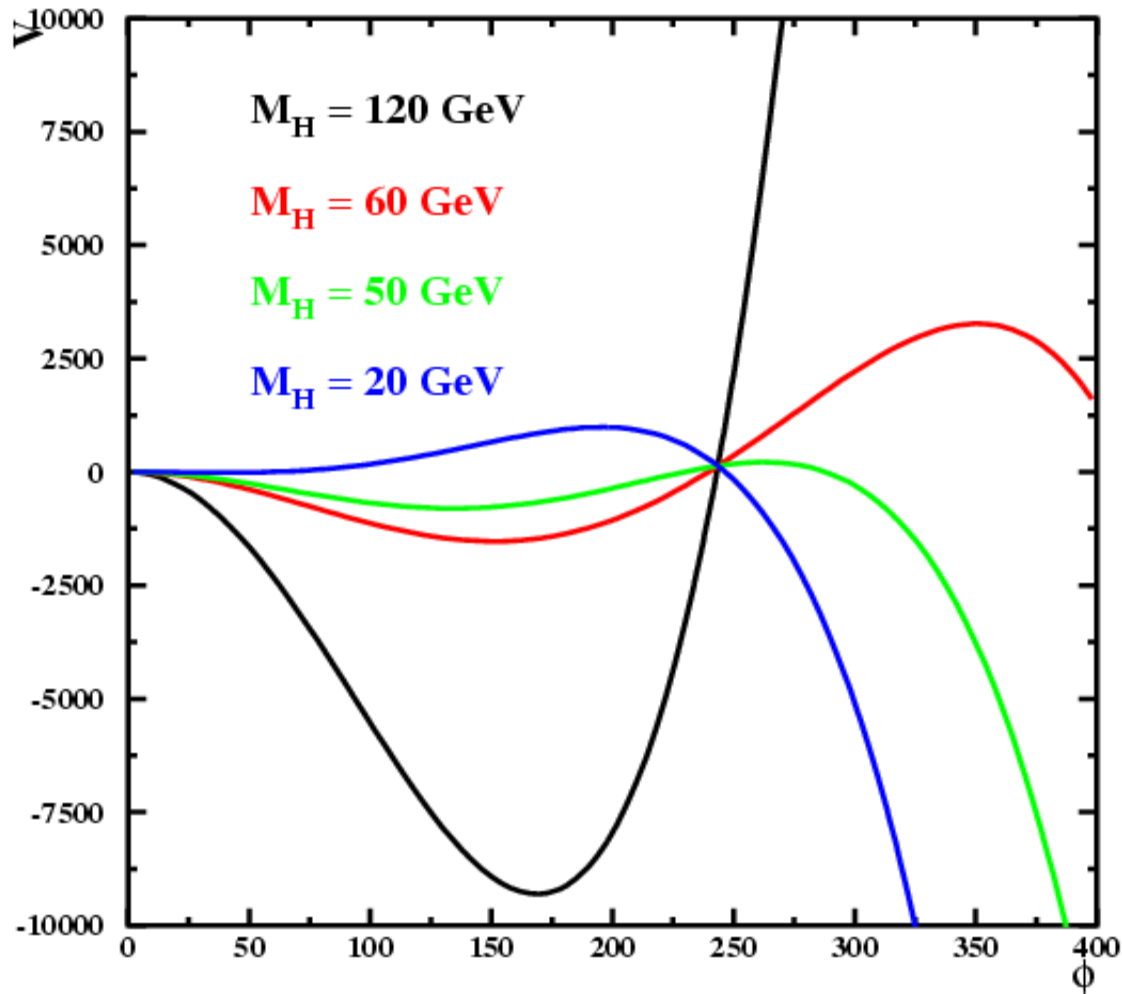
# Trivialitätsgrenze / kein Landau-Pol

- $\lambda < \infty$  oder 1 bis Energiskala  $\Lambda$  für Störungstheorie
- $\lambda < 1$  für  $\Lambda$  unendlich  $\rightarrow \lambda = 0$  bei kleinen Energien  $\rightarrow$  kein SSB (trivial)
- $\lambda < 1$  für „Cut off“  $\Lambda \rightarrow$  obere Grenze auf  $M_H$



# Stabiles Vakuum

$\lambda > 0$  bis Energieskala  $\Lambda$  für Vakuumstabilität  
→ untere Grenze auf  $M_H$   
 $\times 10^4$



# Grenzen aus Bedingungen an Selbstkopplung

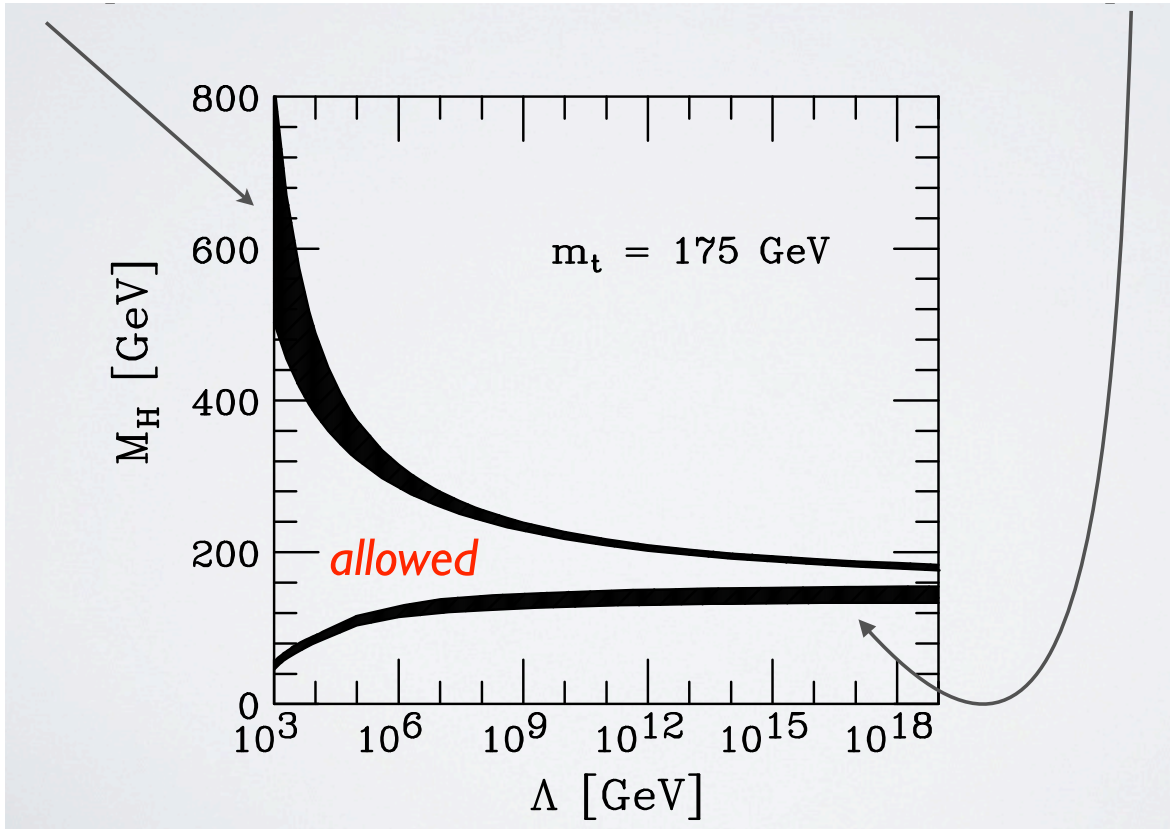
$$\frac{d\lambda}{d \log Q^2} = \frac{1}{16\pi^2} \left[ 12\lambda^2 + 6\lambda\lambda_t^2 - 3\lambda_t^4 - \frac{3}{2}\lambda(3g_2^2 + g_1^2) + \frac{3}{16}(2g_2^4 + (g_2^2 + g_1^2)^2) \right]$$

triviality bound

vacuum stability bound

$$\lambda(Q^2) = \frac{\lambda(v^2)}{1 - \frac{3\lambda(v^2)}{8\pi^2} \ln \frac{Q^2}{v^2}}$$

$$M_H^2 < \frac{8\pi^2 v^2}{3 \ln \Lambda^2 / v^2}$$

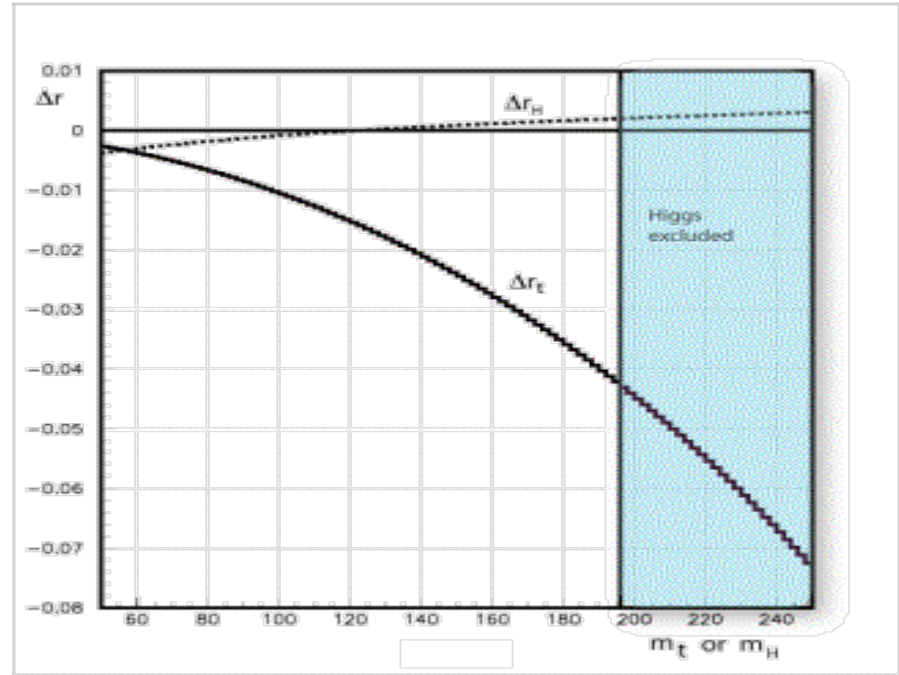
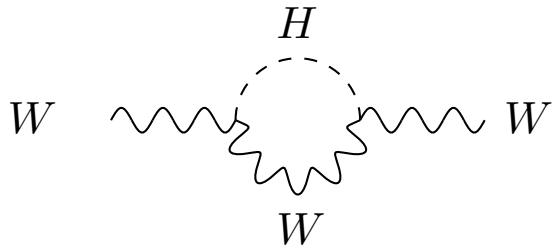
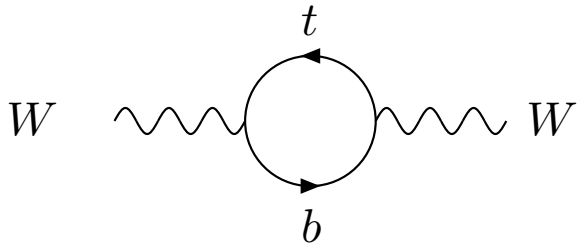


$$M_H^2 > \frac{v^2}{8\pi^2} \left[ -12 \frac{m_t^4}{v^4} + \frac{3}{16} (2g_2^4 + (g_2^2 + g_1^2)^2) \right] \log \frac{Q^2}{v^2}$$



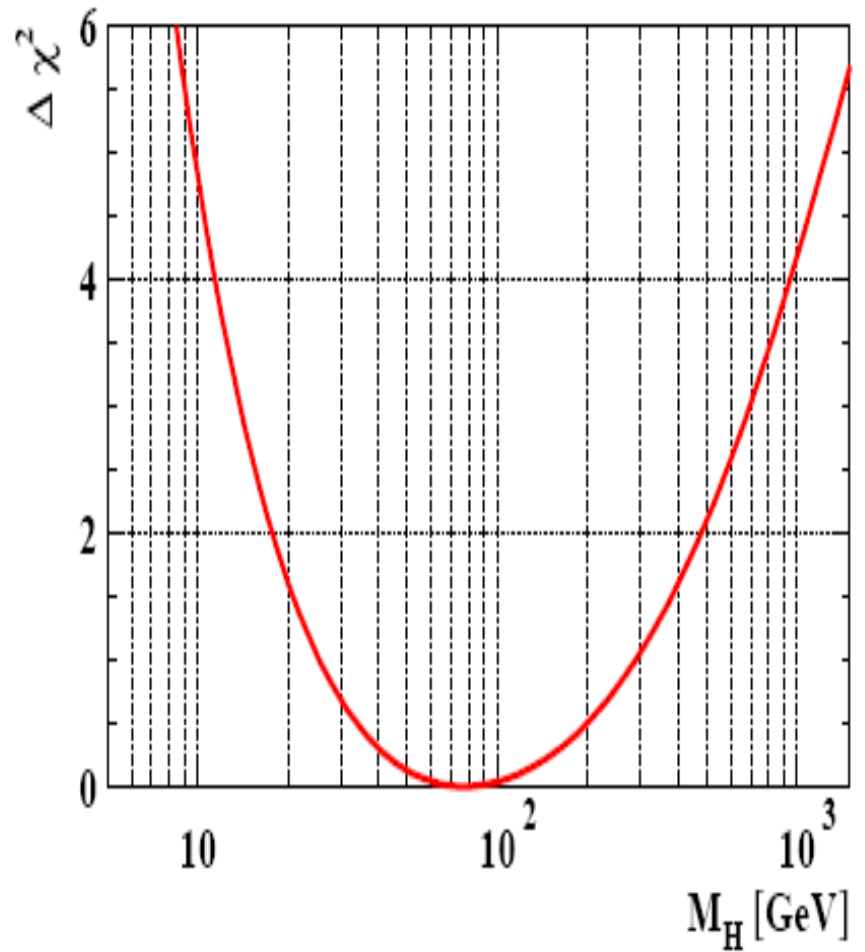
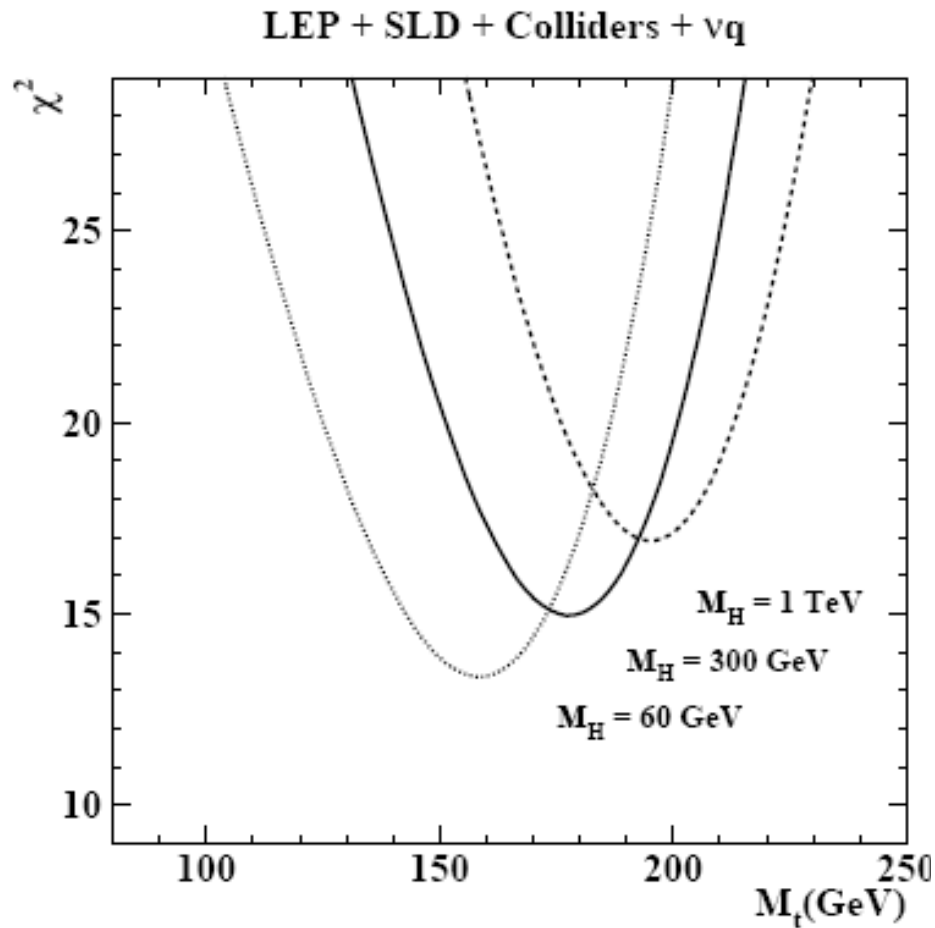
# $M_H$ aus Präzisionsmessungen: Bsp. $M_W$

$$\frac{G_F}{\sqrt{2}} = \frac{2\pi\alpha}{\sin^2 2\theta_W M_Z^2} [1 + \Delta r_\alpha + \Delta r_t + \Delta r_H].$$

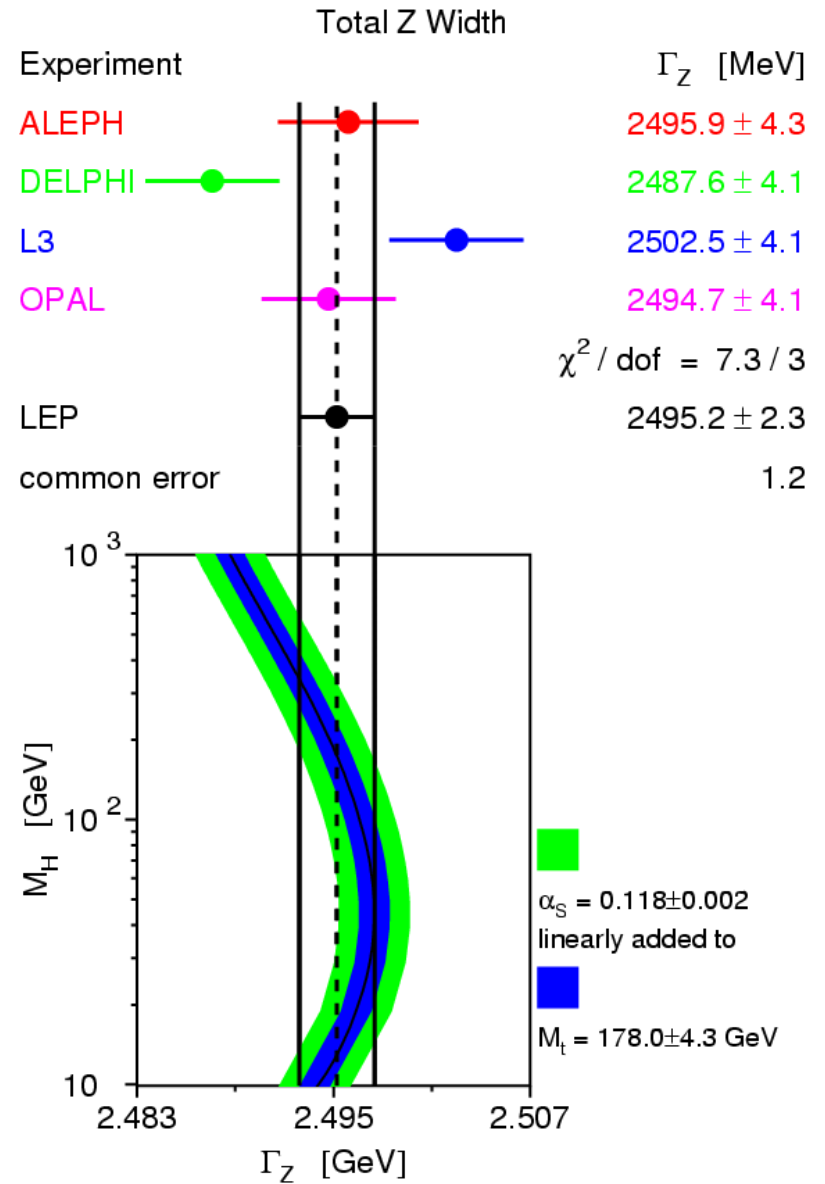
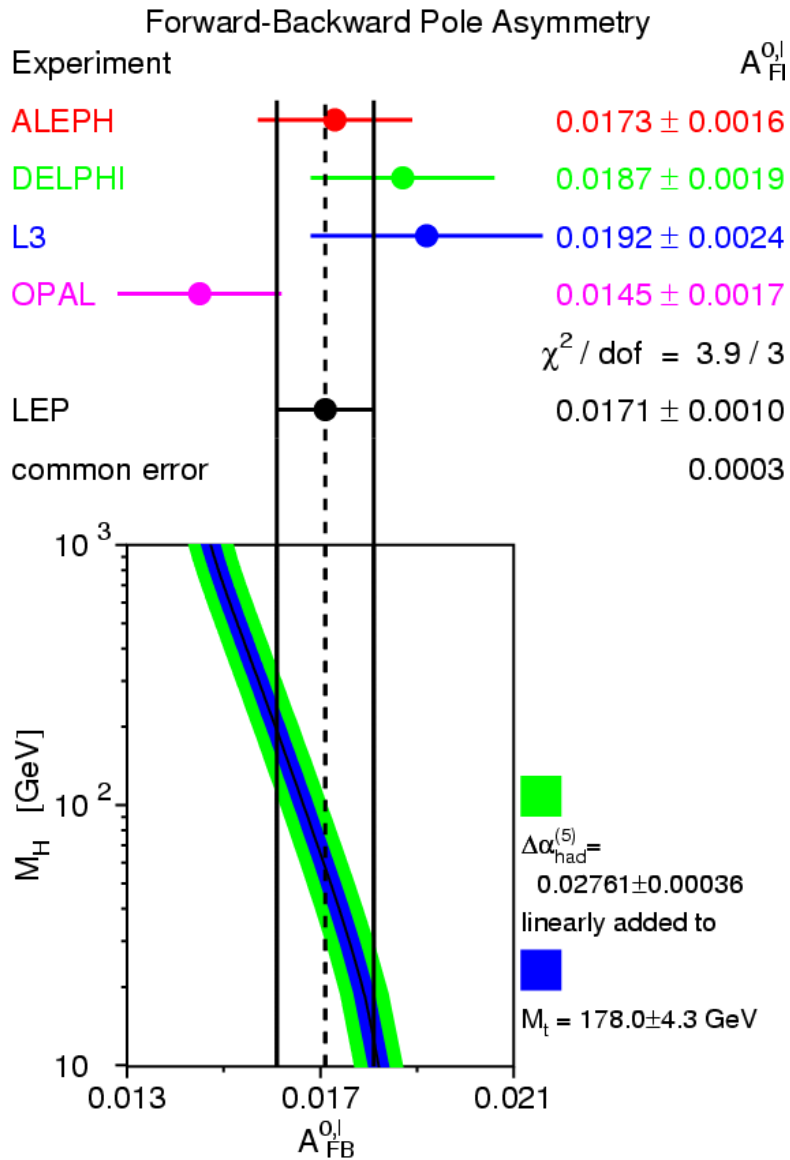


$$\Delta r_H = \frac{G_F M_Z^2 (1 + 9 \sin^2 \theta_W)}{24\sqrt{2}\pi^2} \log \frac{M_H^2}{M_W^2} + \dots \quad (M_H^2 \gg M_W^2)$$

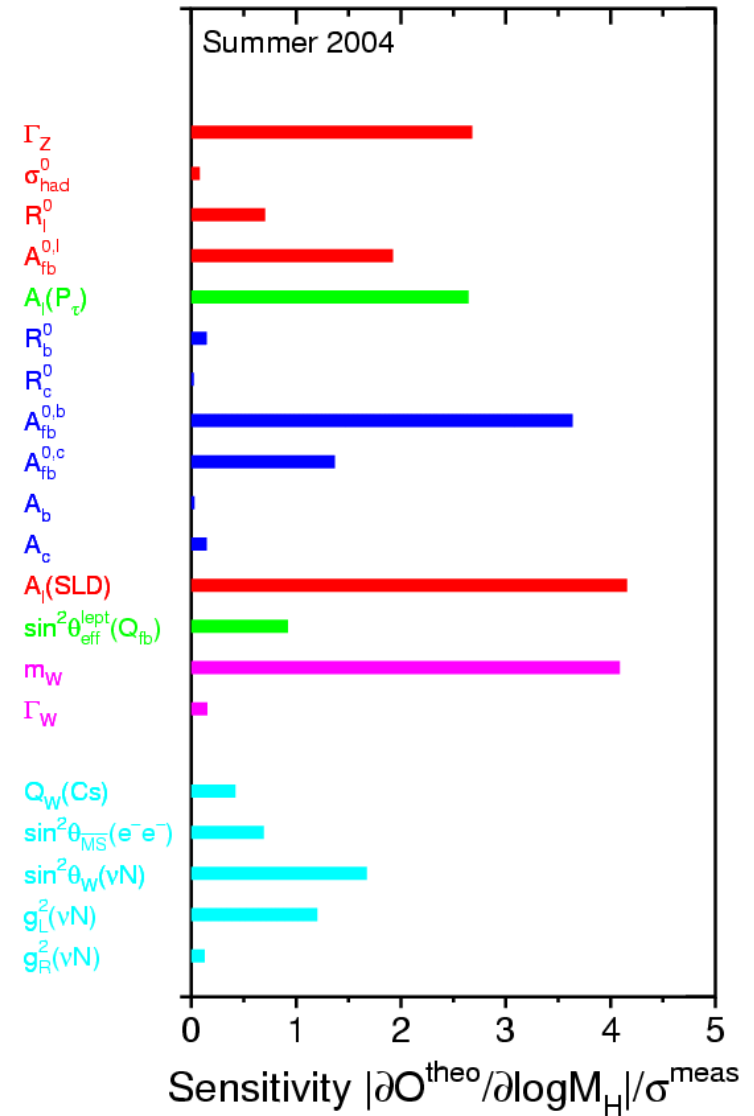
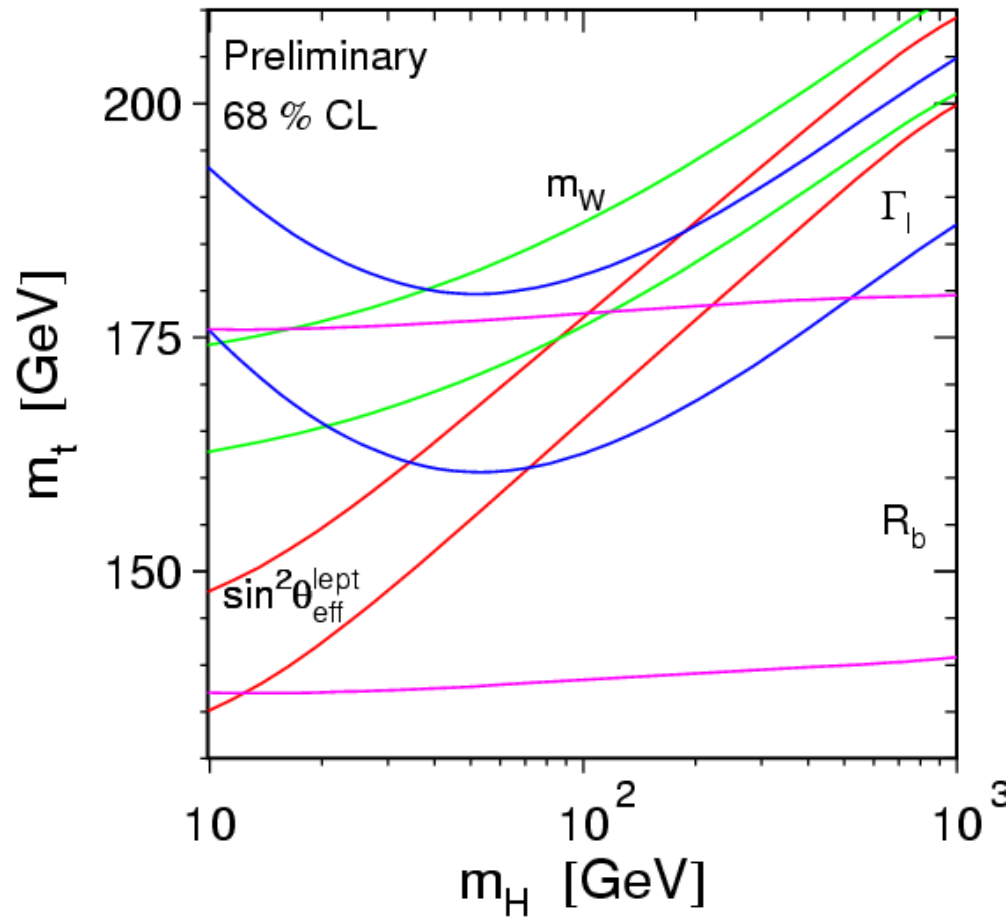
# Vorhersage vor u. nach Entdeckung des Top-Quarks



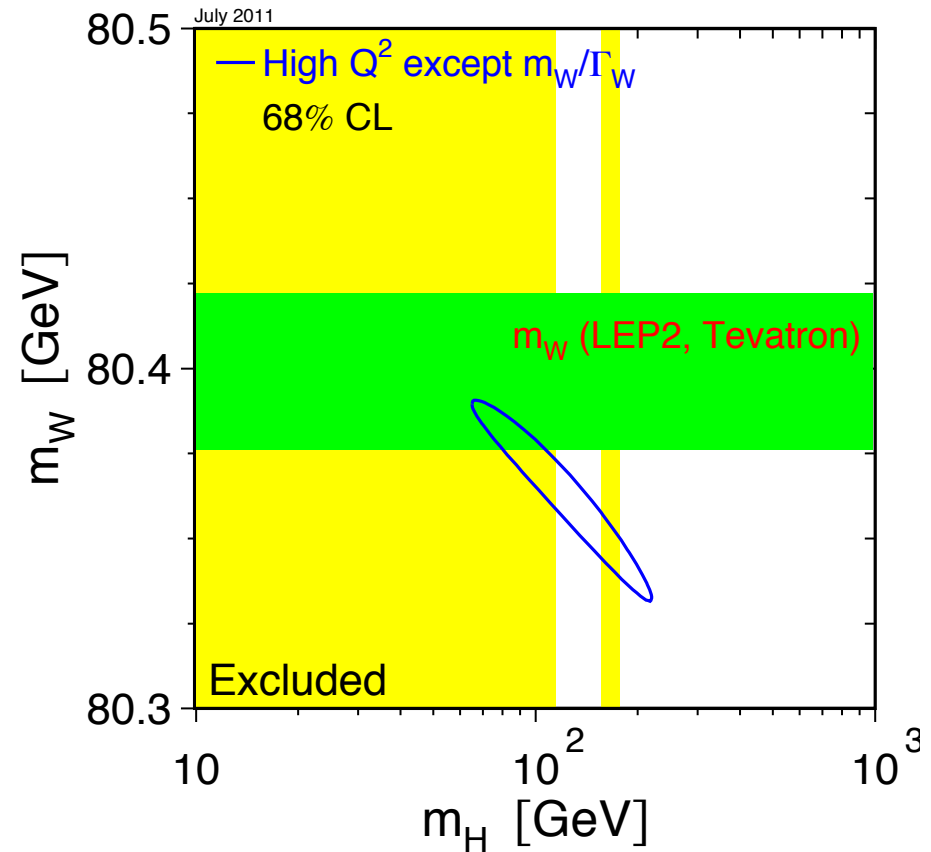
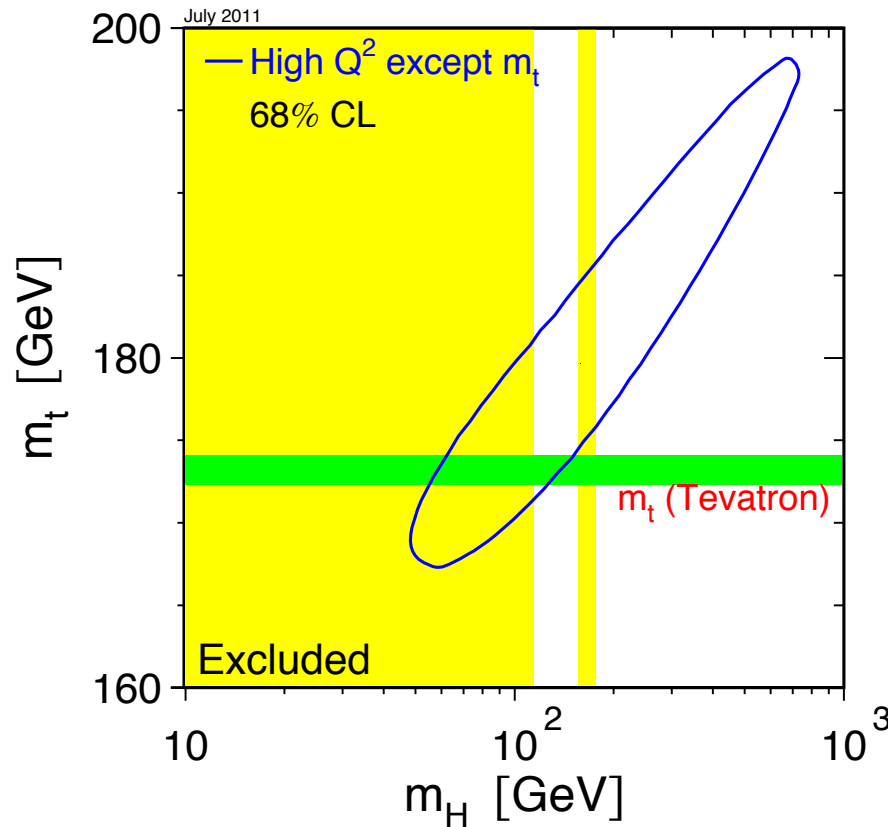
# Sensitivität auf die Higgs-Masse



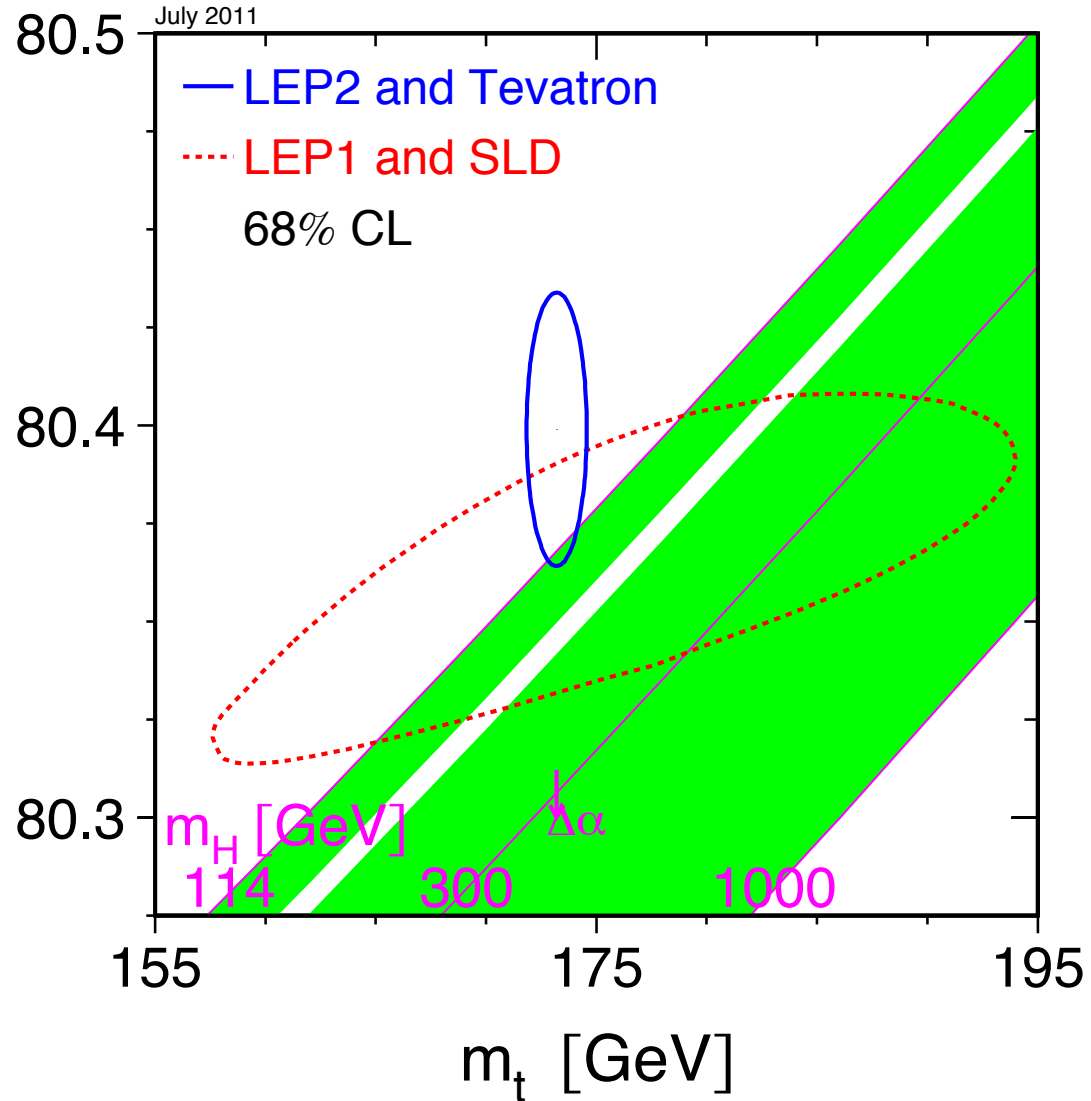
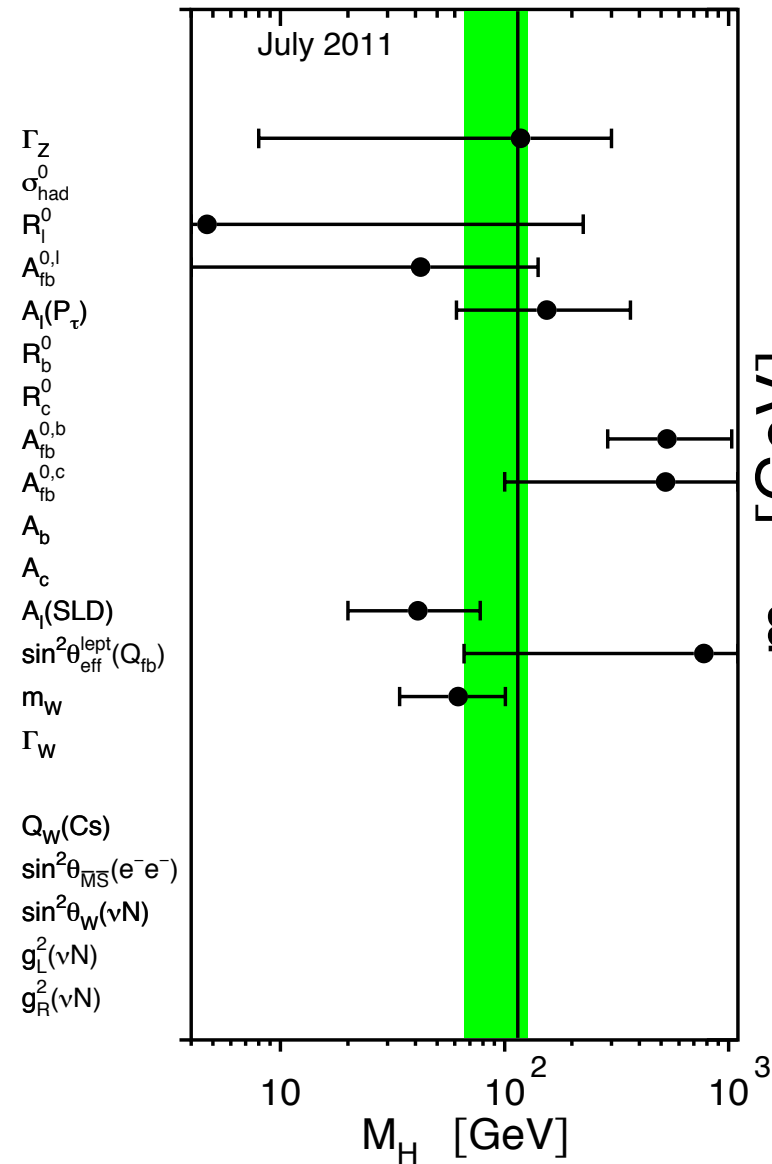
# Sensitivität auf die Higgs-Masse



# Sensitivität auf die Higgs-Masse

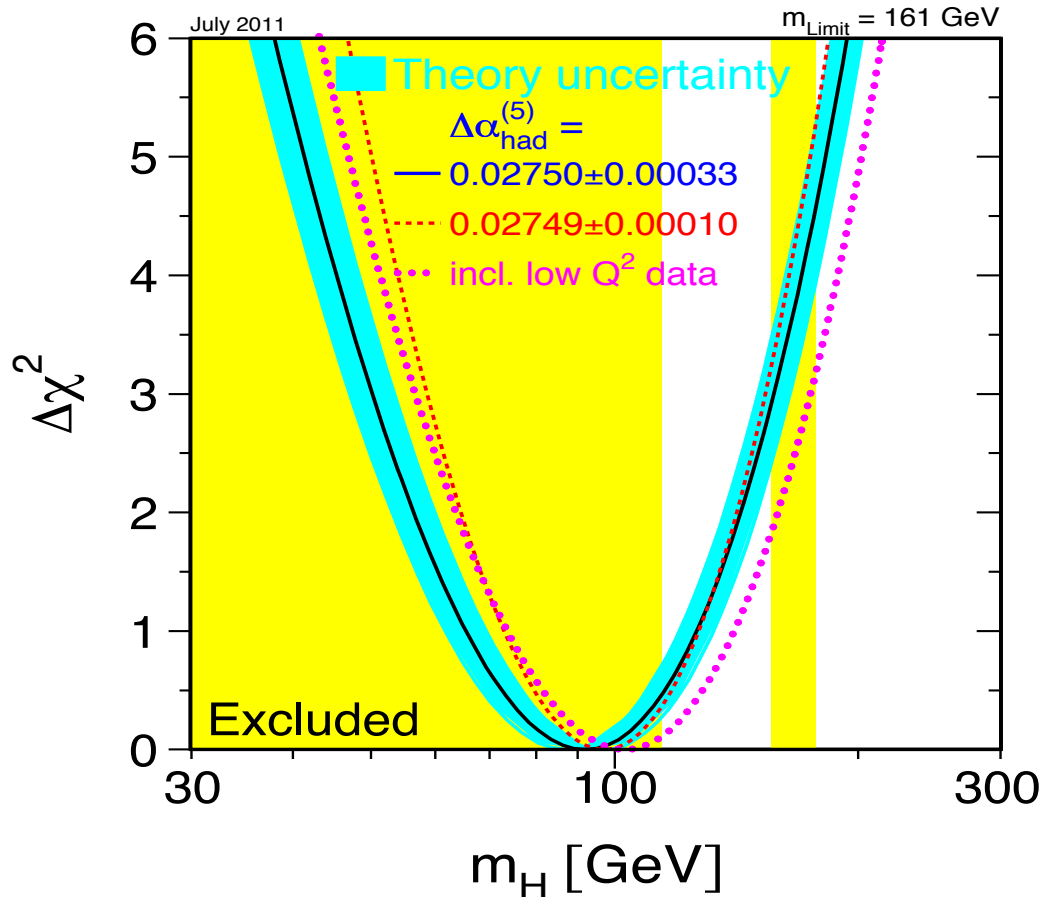


# Sensitivität auf die Higgs-Masse



# Vorhersage von $M_H$ im SM Sommer 2011

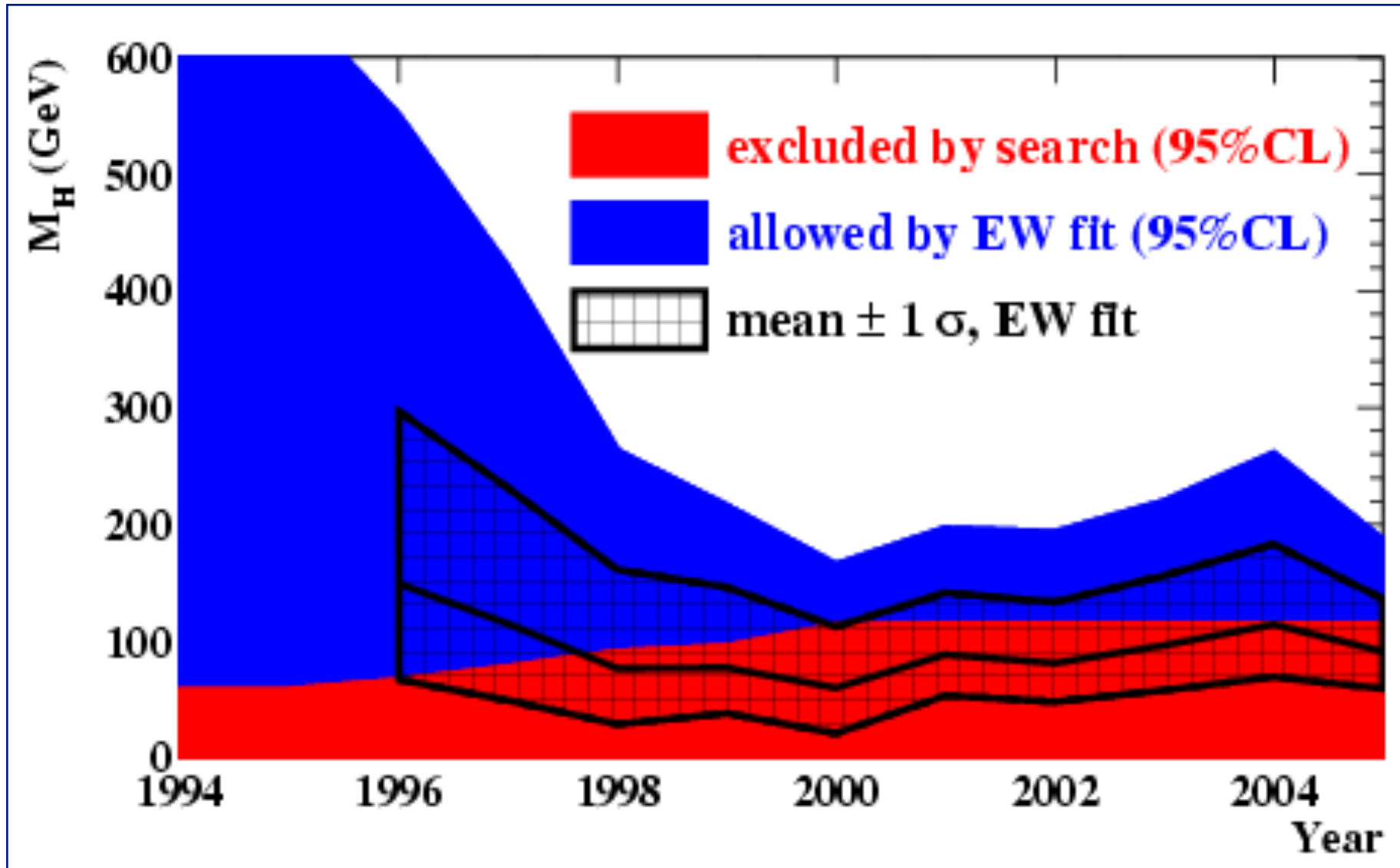
Angepasste SM-Parameter:  $M_H, M_Z, G_F, \alpha(M_Z), m_t$



	Measurement	Fit	$10^{meas} - O^{fit} / \sigma^{meas}$
$\Delta\alpha_{had}^{(5)}(m_Z)$	$0.02750 \pm 0.00033$	0.02759	0.00009
$m_Z [\text{GeV}]$	$91.1875 \pm 0.0021$	91.1874	-0.0001
$\Gamma_Z [\text{GeV}]$	$2.4952 \pm 0.0023$	2.4959	0.0007
$\sigma_{had}^0 [\text{nb}]$	$41.540 \pm 0.037$	41.478	-0.062
$R_l$	$20.767 \pm 0.025$	20.742	-0.025
$A_{fb}^{0,l}$	$0.01714 \pm 0.00095$	0.01646	-0.00068
$A_l(P_{\bar{\nu}})$	$0.1465 \pm 0.0032$	0.1482	0.0017
$R_b$	$0.21629 \pm 0.00066$	0.21579	-0.0005
$R_c$	$0.1721 \pm 0.0030$	0.1722	0.0001
$A_{fb}^{0,b}$	$0.0992 \pm 0.0016$	0.1039	0.0047
$A_{fb}^{0,c}$	$0.0707 \pm 0.0035$	0.0743	0.0036
$A_b$	$0.923 \pm 0.020$	0.935	0.012
$A_c$	$0.670 \pm 0.027$	0.668	-0.002
$A_l(\text{SLD})$	$0.1513 \pm 0.0021$	0.1482	-0.0031
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	$0.2324 \pm 0.0012$	0.2314	-0.0010
$m_W [\text{GeV}]$	$80.399 \pm 0.023$	80.378	-0.021
$\Gamma_W [\text{GeV}]$	$2.085 \pm 0.042$	2.092	0.007
$m_t [\text{GeV}]$	$173.20 \pm 0.90$	173.27	0.07

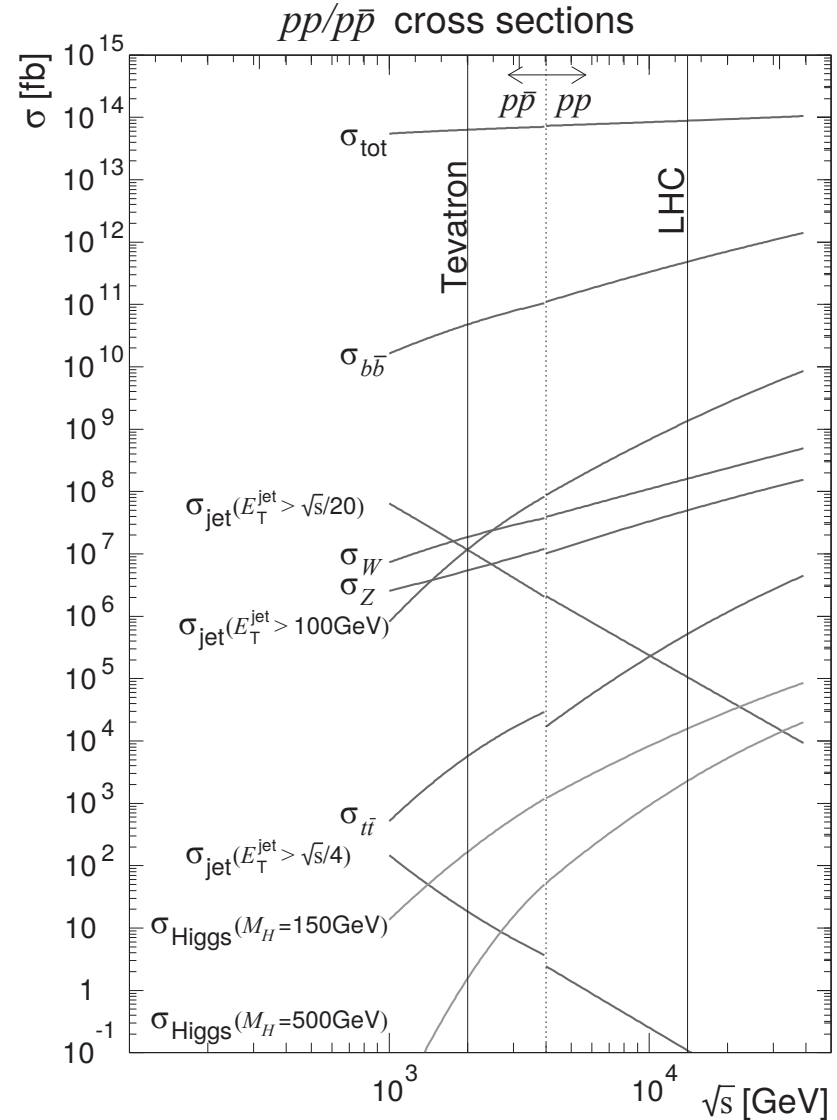
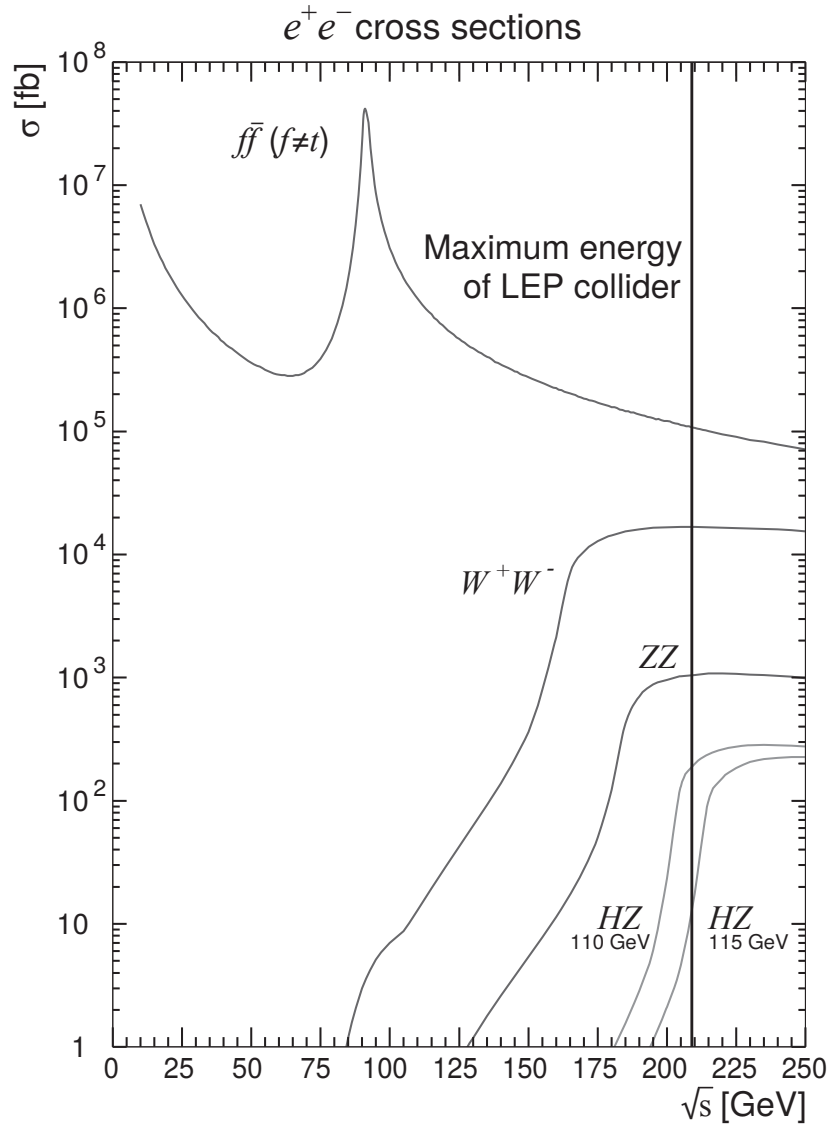
July 2011

# Zeitliche Entwicklung bis 2004

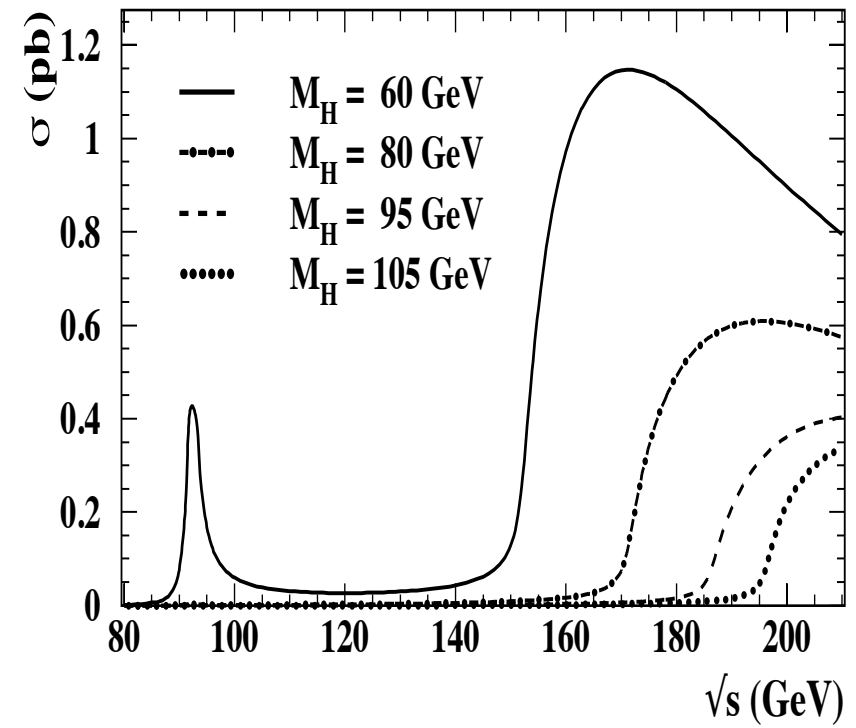
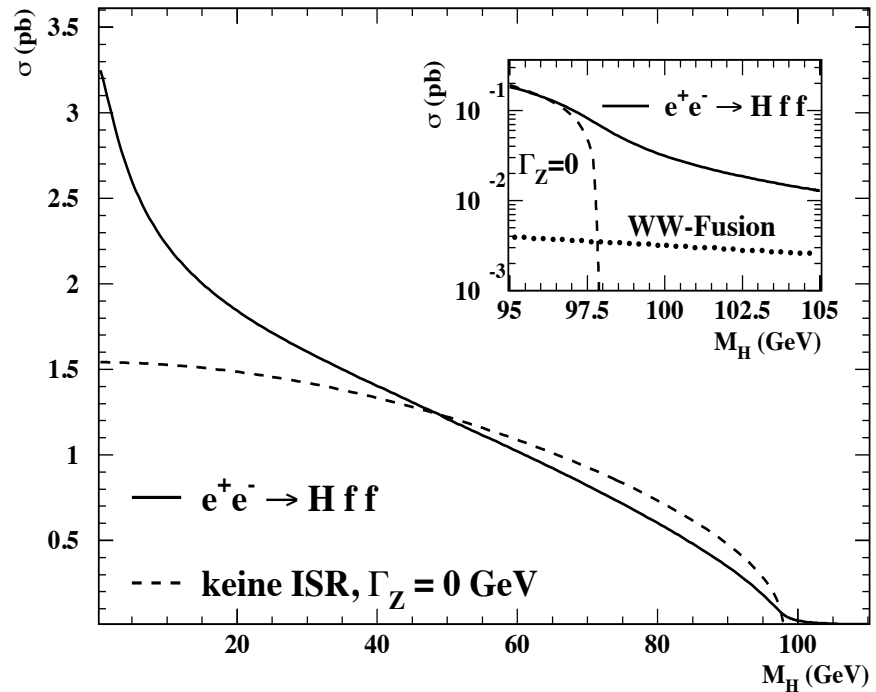
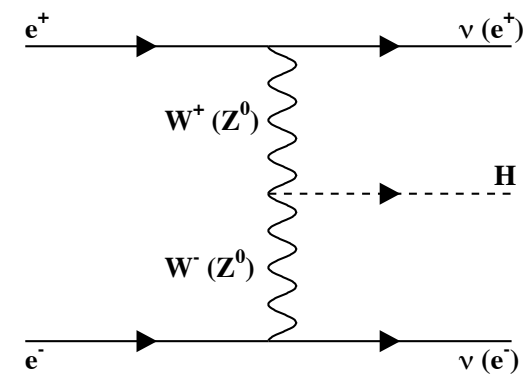
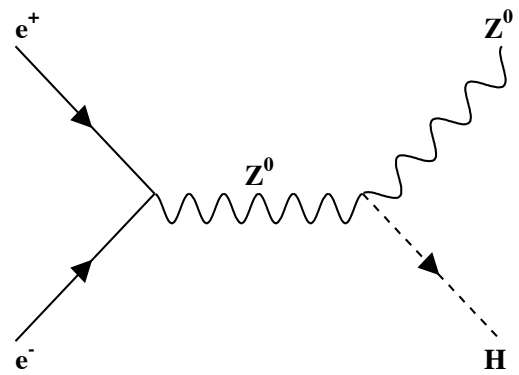




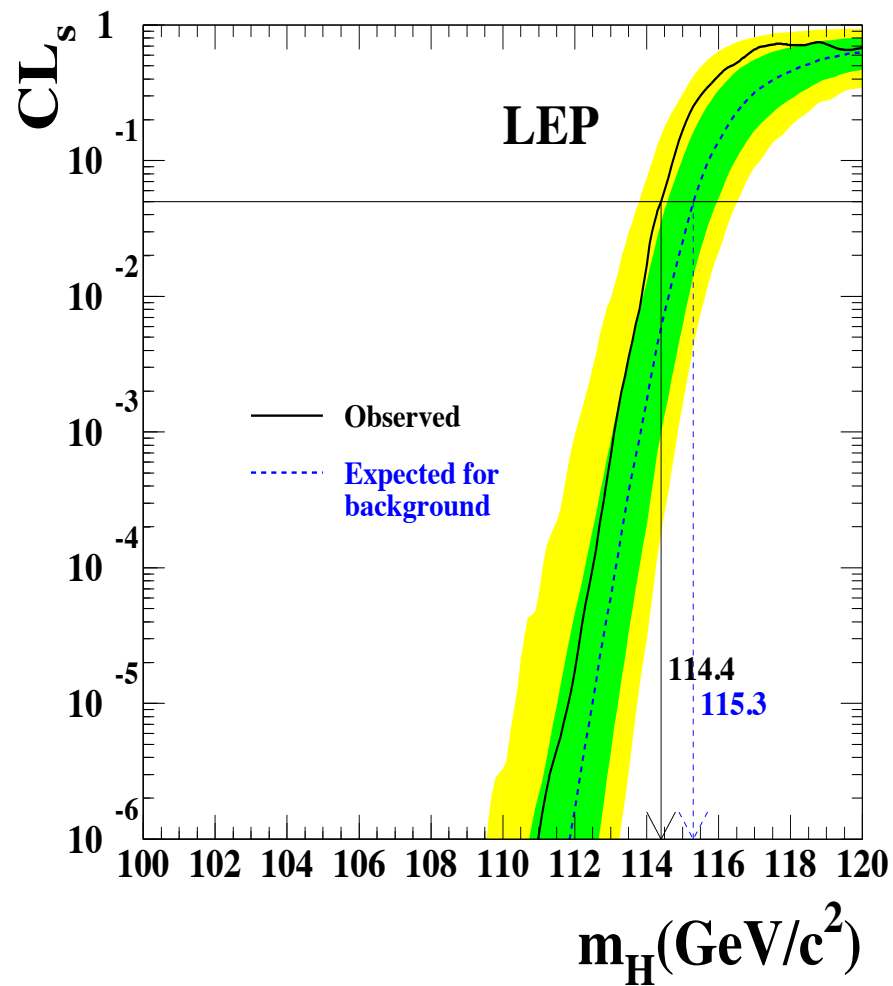
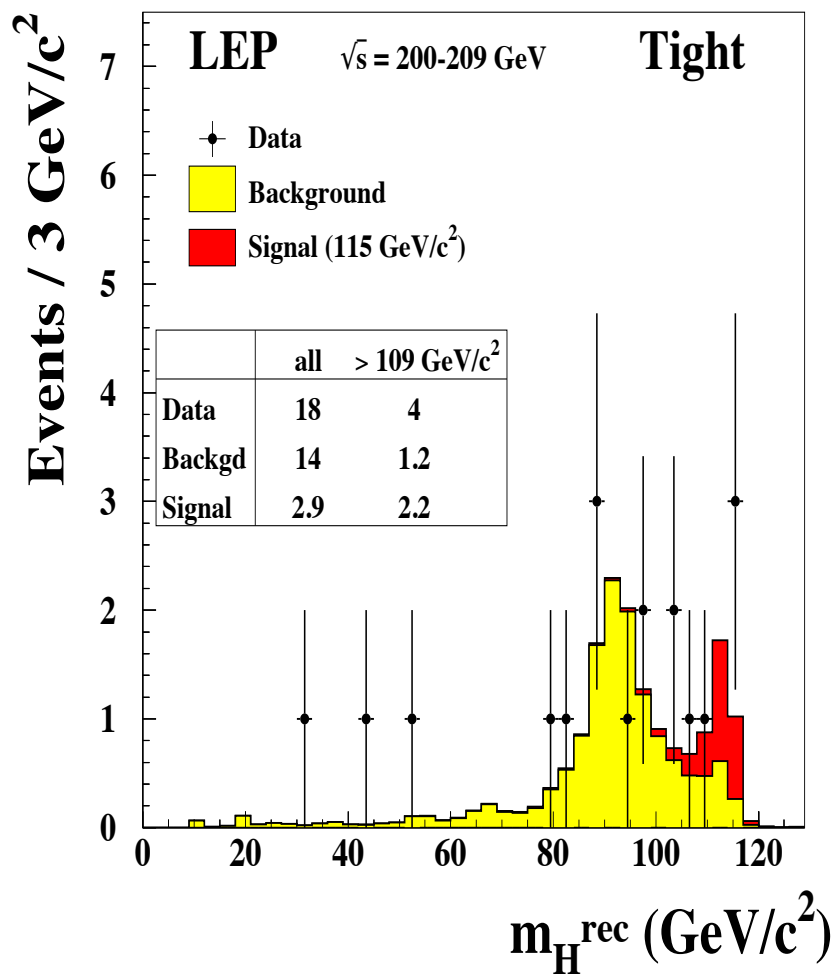
# Die Herausforderung bei LEP, TEVATRON und LHC



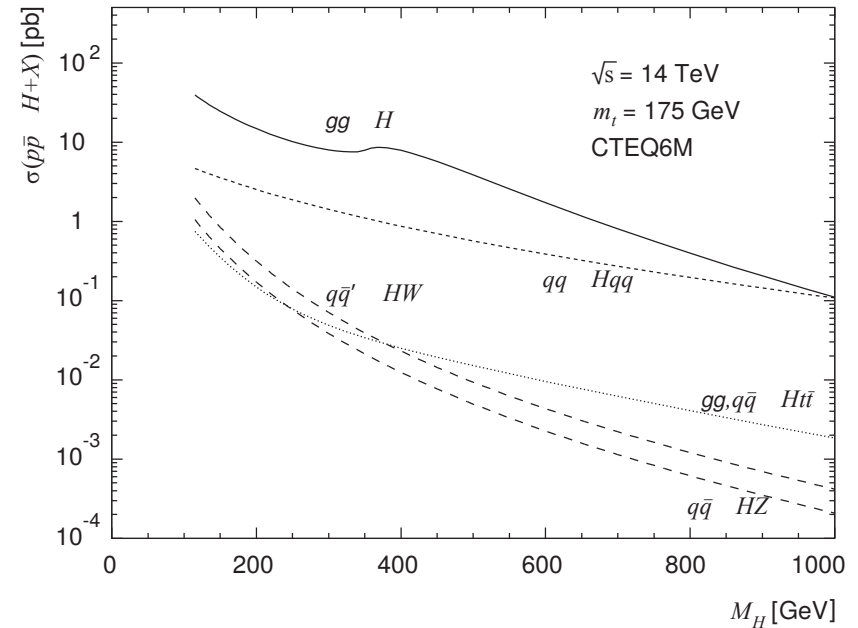
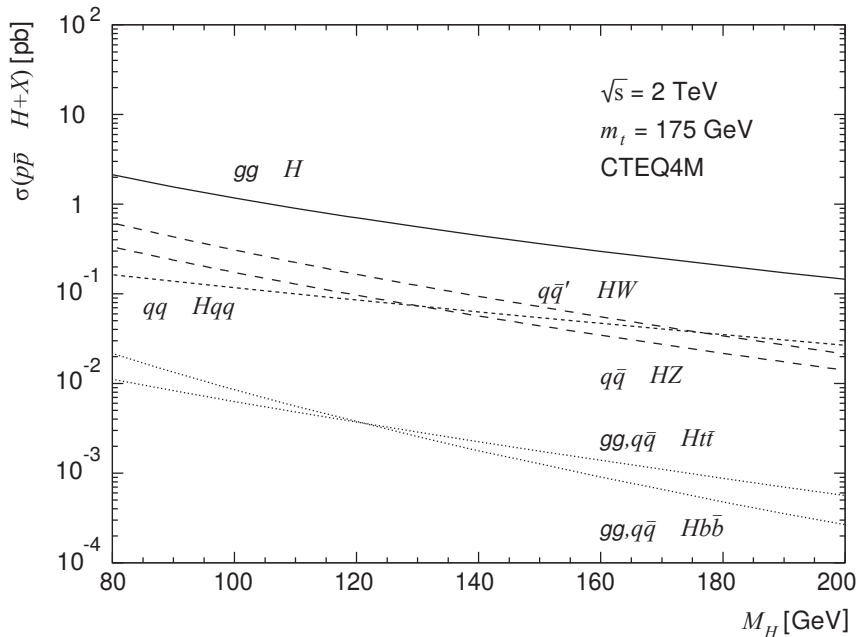
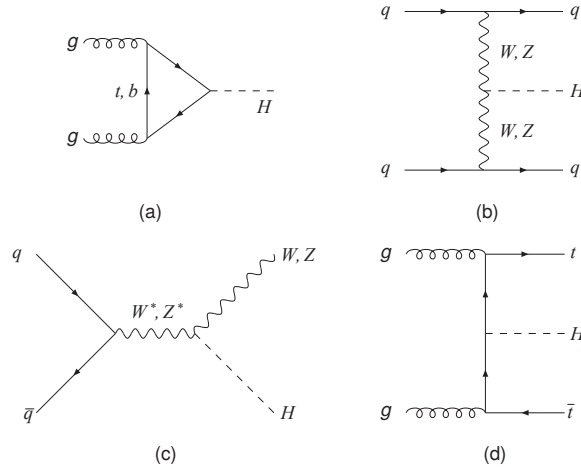
# Higgsproduktion bei LEP: $E_{CM} < 209 \text{ GeV}$



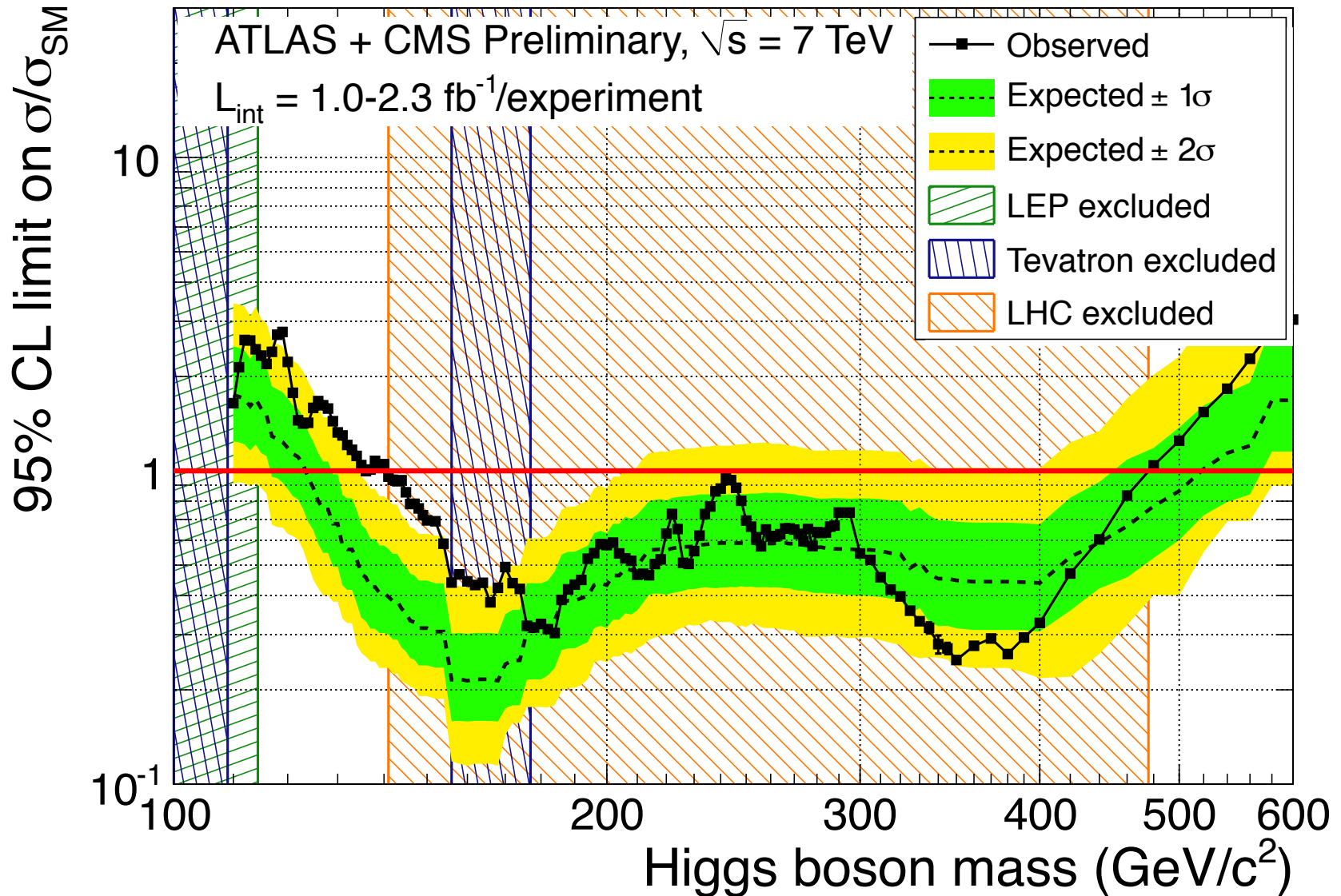
# Ergebnis der Higgs-Suche bei LEP



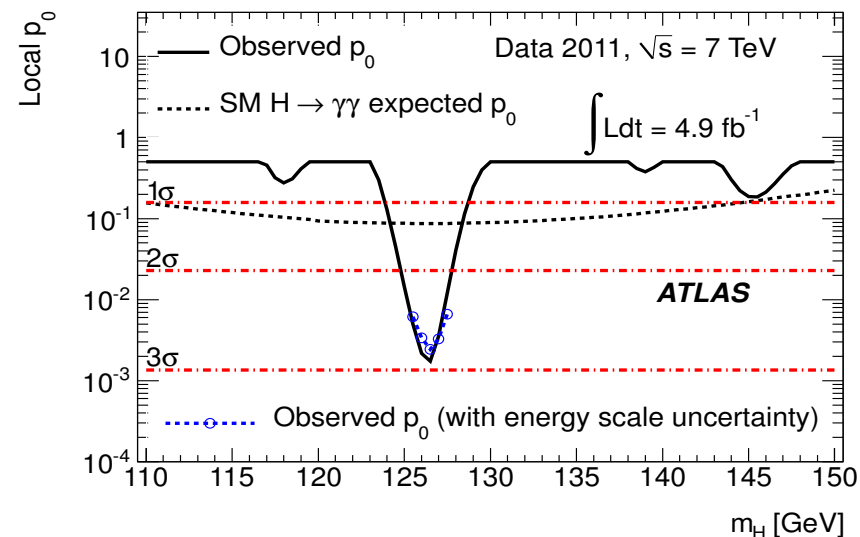
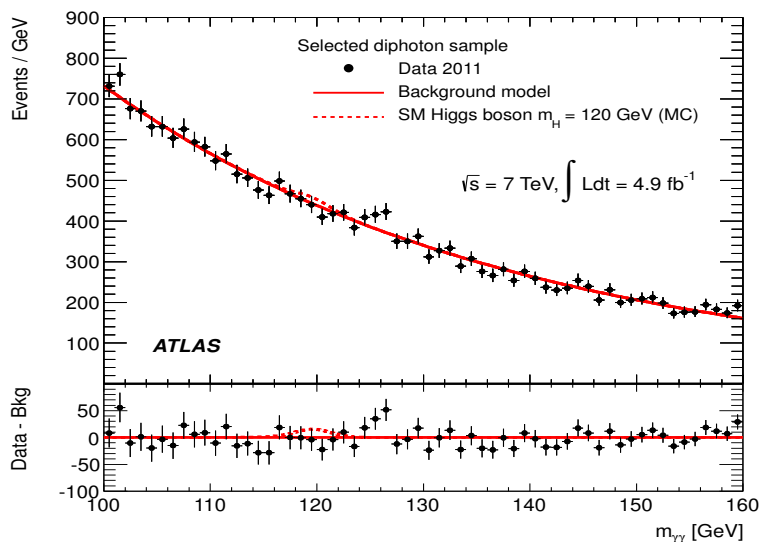
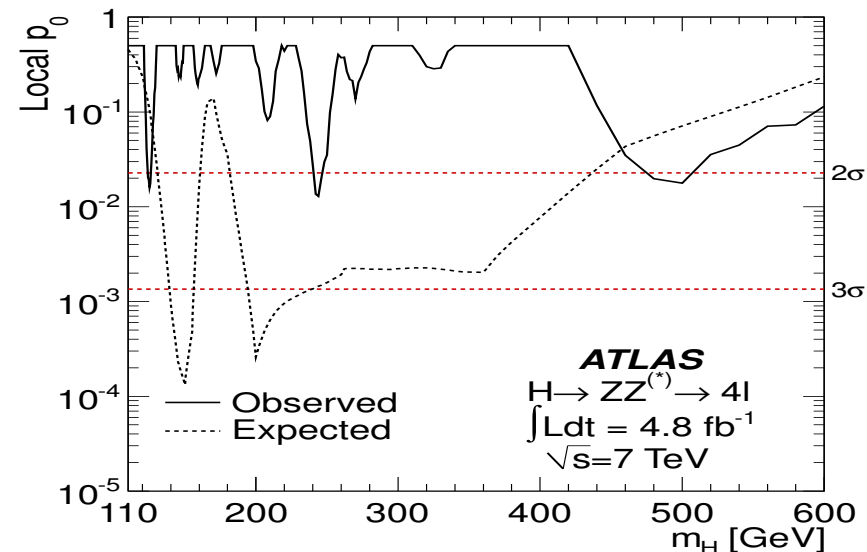
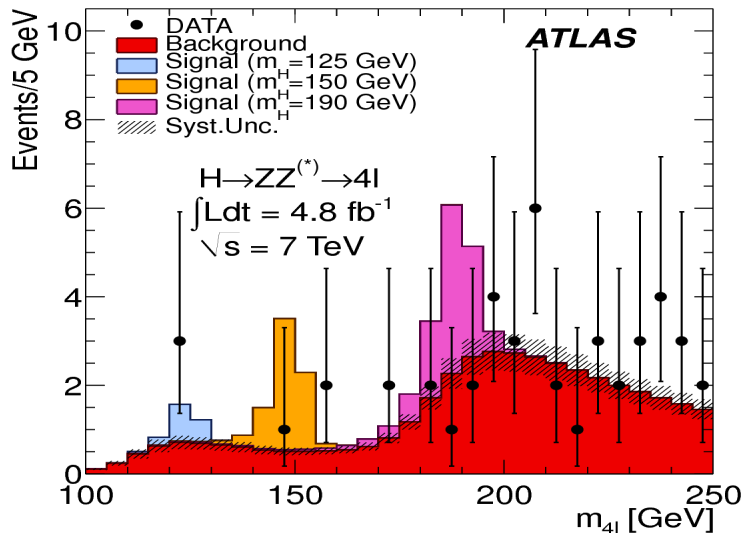
# Produktion am TEVTARON und LHC



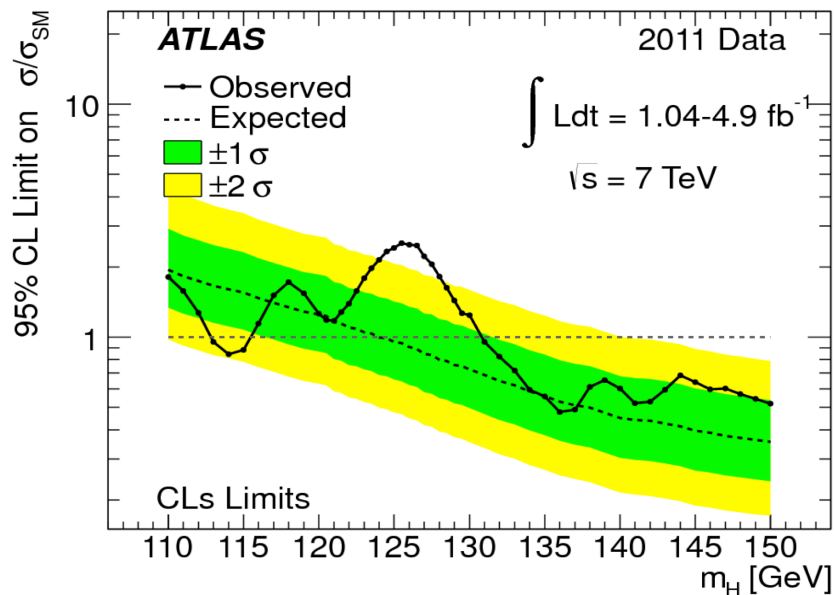
# Status der Suchen am Tevatron und LHC Nov 2011



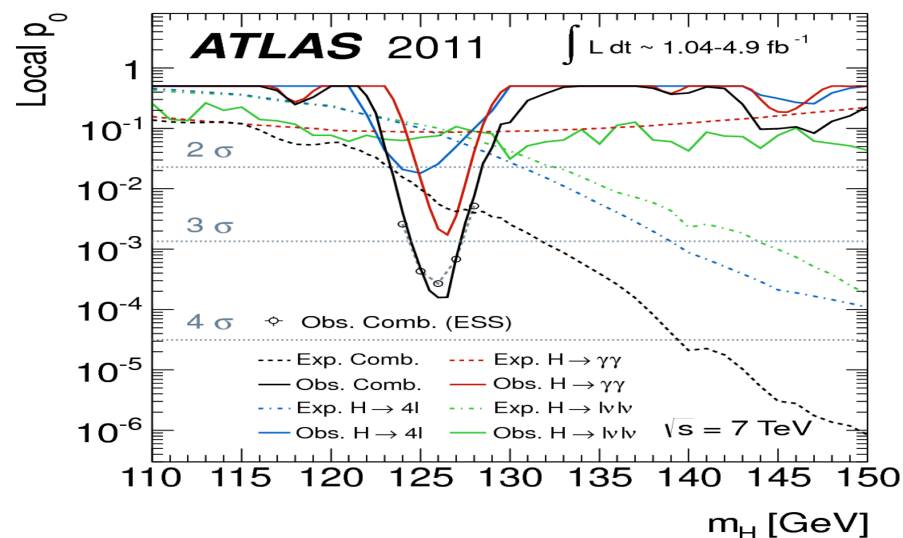
# Status der Suche bei ATLAS: heute



# Status der Suche bei ATLAS: heute



nur ein kleines  
 Massenfenster noch  
 nicht ausgeschlossen:  
 115.5 GeV bis 131 GeV



schon Hinweise auf ein  
 Higgs bei 125 GeV?

bisher nur  
 lokal  $3.5 \sigma$   
 global  $2.2 \sigma$