Electroweak Physics: Preparing for TESLA

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DESY Academic Training Lectures

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Lecture 1:

- The Higgs boson of the electroweak Standard Model
- Higgs search at present and future colliders
- Quantum corrections, renormalization and running couplings
- Precision tests of the electroweak theory

Further reading

Standard Model phenomenology:

- M. Böhm, A. Denner and H. Joos
  Gauge theories of the strong and electroweak interaction (Teubner, 2001)

- D. Bardin and G. Passarino
  The Standard Model in the Making : Precision Study of the Electroweak Interactions (Oxford University Press, 1999)

Higgs physics:

- J.F. Gunion, H.E. Haber, G. Kane, S. Dawson
  The Higgs Hunter's Guide (Perseus Books, 2000)

Supersymmetry:

- D. Bailin and A. Love
  Supersymmetric Gauge Field Theory and String Theory (Inst. of Physics, 1994)

- S.P. Martin
  A Supersymmetry Primer (In: Perspectives on Supersymmetry, ed. G. Kane, World Sci., 1998)

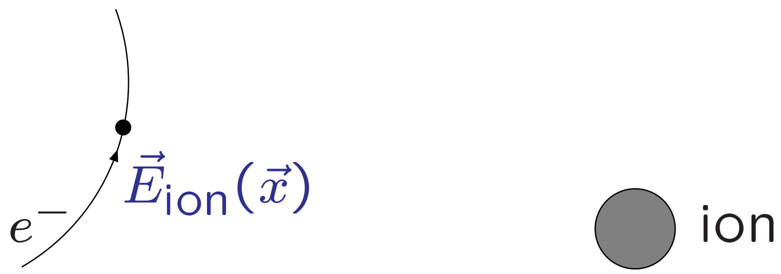
- S. Weinberg
  The Quantum Theory of Fields, Vol. III: Supersymmetry (Cambridge University Press, 2000)

The Standard Model (SM) of the electroweak and strong interactions

Standard Model: quantum field theory

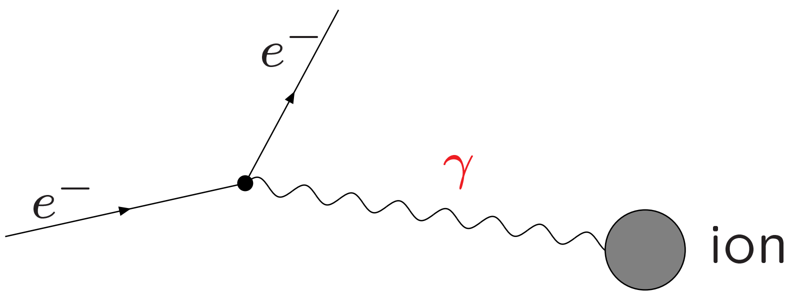
Classical field theory:

Classical Electrodynamics (Maxwell theory, unification of electrostatics and magnetism)



Quantum field theory:

QED; field is quantized, field quantum: photon



Interaction: exchange of field quanta

Electroweak interaction:

Fermion fields:

quarks: $\begin{pmatrix} u_L \\ d_L \end{pmatrix}, u_R, d_R,$ leptons: $\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, e_R$

3 generations: $\begin{matrix} u, d, & s, c & t, b \\ \nu_e, e & \nu_\mu, \mu & \nu_\tau, \tau \end{matrix}$

gauge bosons: γ, Z, W^+, W^-

Gauge group: $\mathrm{SU(2)_I \times U(1)_Y \supset U(1)_{em}}$

Strong interaction: QCD

quarks: q_r, q_g, q_b

gauge bosons: $g_1, \ldots g_8$: gluons, $\mathrm{SU(3)_C}$

All postulated fermions and gauge bosons experimentally verified

Construction principle of SM: gauge invariance

Example: Quantum electrodynamics (QED)

free electron field: $\mathcal{L}_{\text{Dirac}} = i\overline{\Psi}\gamma_\mu\partial^\mu\Psi - m\overline{\Psi}\Psi$

invariant under global gauge transform.: $\Psi \to e^{i\theta}\Psi$

Requirement of local gauge invariance:

gauge field A_μ introduced, $\partial_\mu \to D_\mu = \partial_\mu - ieA_\mu$

gauge transform.: $\Psi \to e^{ie\lambda(x)}\Psi$, $A_\mu \to A_\mu + \partial_\mu\lambda(x)$

⇒ Lagrangian with interaction term:

$$\mathcal{L}_{\text{QED}} = \underbrace{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{free photon field}} + \underbrace{\overline{\Psi}(i\gamma_\mu\partial^\mu - m)\Psi}_{\text{free electron field}} + \underbrace{e\overline{\Psi}\gamma_\mu\Psi A^\mu}_{\text{interaction}}$$

invariant under local gauge transformation

mass term, $m^2A^\mu A_\mu$: not gauge-invariant

⇒ A_μ: massless gauge field

Problem:

gauge fields Z, W^+, W^- are massive

explicit mass terms $\Leftrightarrow$ gauge invariance broken

$\Rightarrow$ **Higgs mechanism**

scalar field postulated, gauge-invariant mass terms from coupling to Higgs field

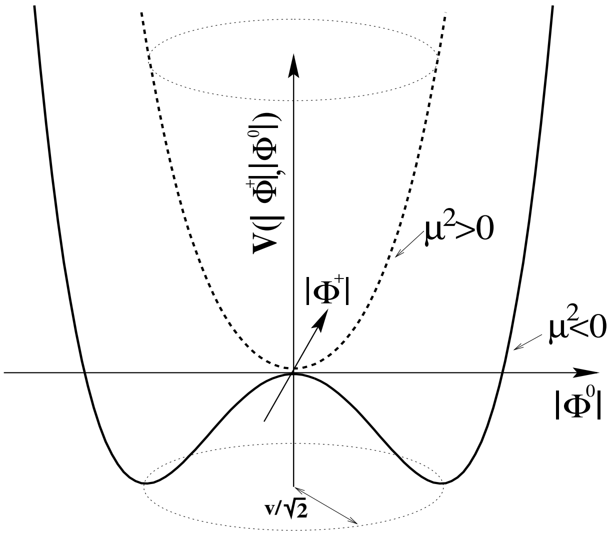
Higgs sector of the Standard Model:

scalar SU(2) doublet: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

Higgs potential:

$$V(\phi) = \mu^2 \left|\Phi^\dagger \Phi\right| + \lambda \left|\Phi^\dagger \Phi\right|^2, \quad \lambda > 0$$

$\mu^2 < 0$: spontaneous symmetry breaking



minimum of the potential at $\langle \Phi \rangle = \frac{1}{\sqrt{2}}\sqrt{\frac{-\mu^2}{\lambda}} \equiv \frac{v}{\sqrt{2}}$

Gauge-invariant interaction with gauge fields:

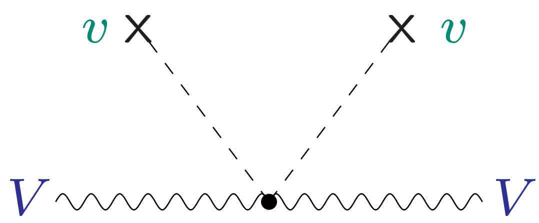
$$\mathcal{L}_{\mathsf{Higgs}} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi)$$

$\Rightarrow$ mass terms

Unitary gauge:

$$\Phi = \begin{pmatrix} 0 \\ v + H \end{pmatrix}$$

$VV\Phi\Phi$ coupling:



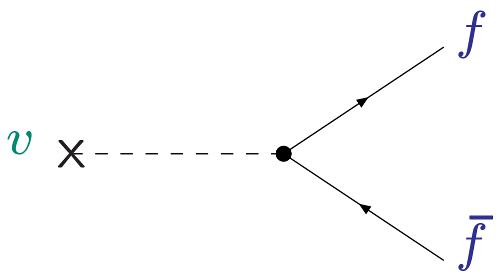
$\Rightarrow$ VV mass terms

$$\frac{1}{2} g_2^2 v^2 \equiv M_{\mathsf{W}}^2, \quad \frac{1}{2}(g_1^2 + g_2^2) v^2 \equiv M_{\mathsf{Z}}^2$$

3 components of Higgs doublet $\longrightarrow$ longitudinal components of $W^\pm$, Z

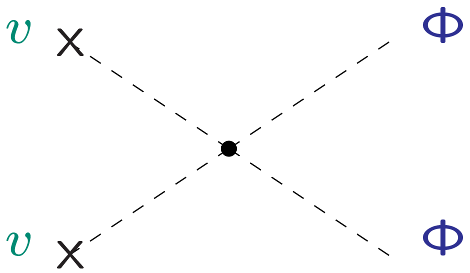
H: elementary scalar field, Higgs boson

Fermion mass terms: Yukawa couplings



$m_f = v\, g_f$ free parameters

Mass of the Higgs boson: self-interaction



$M_{\mathrm{H}} = v\sqrt{\lambda}$ free parameter

$\Rightarrow$ Higgs couplings proportional to masses of the particles

Gauge-invariant Lagrangian:

$$\mathcal{L}_{\mathrm{EW}}(\underbrace{g_2, g_1, v}_{M_{\mathrm{W}},\, M_{\mathrm{Z}},\, \alpha}, \quad \underbrace{\lambda}_{M_{\mathrm{H}}}, \ \underbrace{g_f}_{m_f}) + \mathcal{L}_{\mathrm{QCD}}(\alpha_{\mathrm{s}})$$

gauge invariance $\Rightarrow$ **theory is renormalizable**

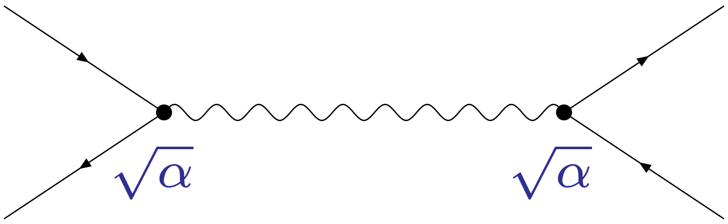
[*G. 't Hooft '71*] *Nobel price '99*

[*G. 't Hooft, M. Veltman '72*]

$\Rightarrow$ quantum field theory: quantum effects calculable

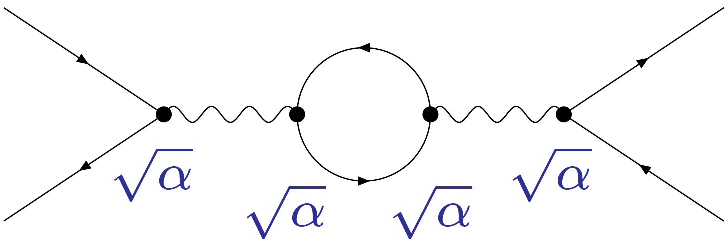
expansion in coupling constant:

lowest order, classical limit



$\alpha \approx \frac{1}{137}$

quantum corrections: loop diagrams



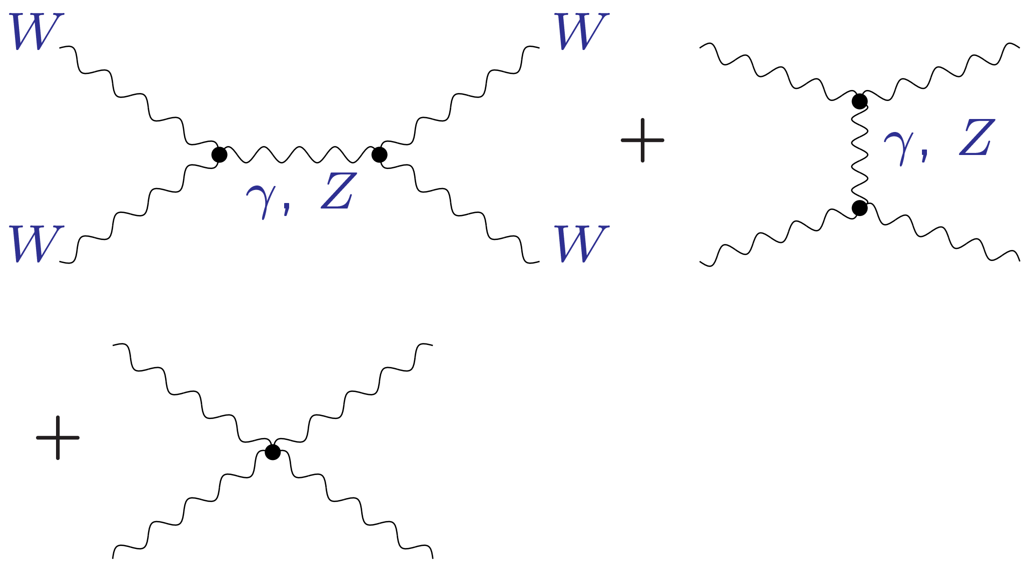
via loop corrections: all particles of the model enter

Further effect of the Higgs field:

scattering of longitudinally polarized W bosons:

$$W_L W_L \to W_L W_L$$

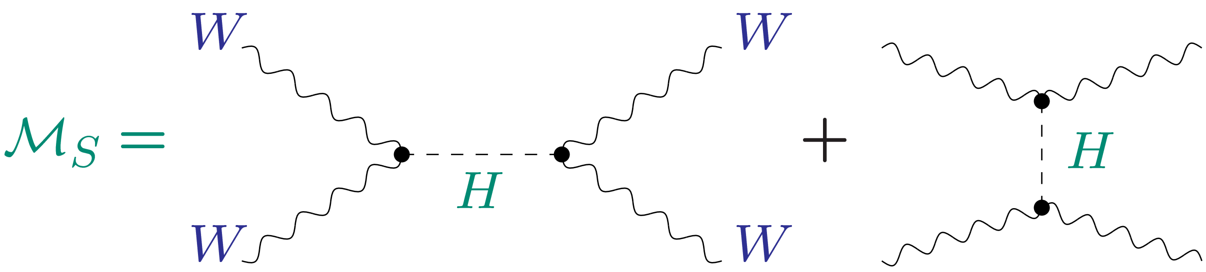
$\mathcal{M}_V =$



$$= -g^2 \frac{E^2}{M_{\mathrm{W}}^2} + \mathcal{O}(1) \qquad \text{for } E \to \infty$$

$\Rightarrow$ violation of probability conservation

Extra contribution from scalar particle:



$$= g^2_{WWH} \frac{E^2}{M_\mathrm{W}^4} + \mathcal{O}(1) \qquad \text{for } E \to \infty$$

$$\mathcal{M}_\mathrm{tot} = \mathcal{M}_V + \mathcal{M}_S$$

$\Rightarrow$ terms with bad high-energy behavior cancel for

$$g_{WWH} = g\, M_\mathrm{W}$$

$\Rightarrow$ Upper limit on M_H: $M_\mathrm{H} \lesssim 1$ TeV

If no fundamental Higgs field exists:

strong interaction in gauge-boson sector for $E \gtrsim 1$ TeV

probability conservation via non-perturbative effects:

dynamical symmetry breaking, "Technicolor", . . .
[*S. Weinberg '79*] [*L. Susskind '79*]

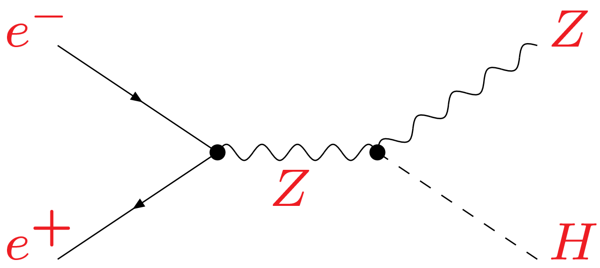
$\Rightarrow$ Higgs boson is last missing ingredient of ew SM

M_{H}: free parameter of SM

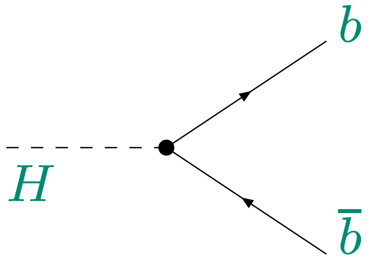
Theoretical arguments (unitarity, ...): $M_{\mathrm{H}} \lesssim 1$ TeV

Search for the Standard Model Higgs at LEP

Dominant production process: $e^+e^- \to ZH$



Dominant decay process: $H \to b\bar{b}$

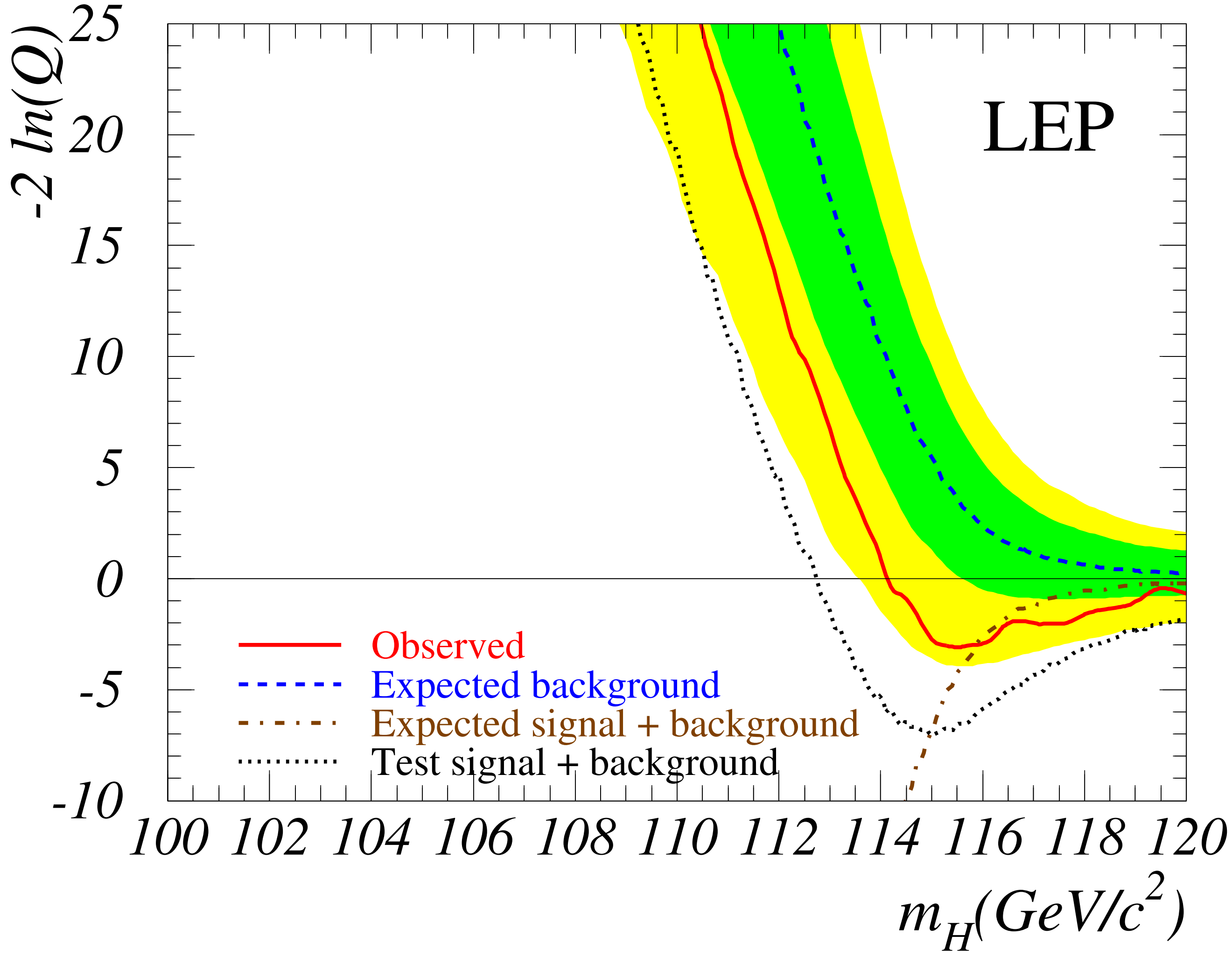


Highest energy: $E_{\mathrm{CM}} \approx 206$ GeV

Exclusion limit, 95% C.L.:

$M_{\mathrm{H}} > 114.1$ GeV (expected: 115.4 GeV)

Comparison of observed signal with expected background, expected signal + background and expected signal + background for $M_{\mathrm{H}} = 115$ GeV:
[*LEP Higgs Working Group '01*]



⇒ 2.1σ excess over background expectation

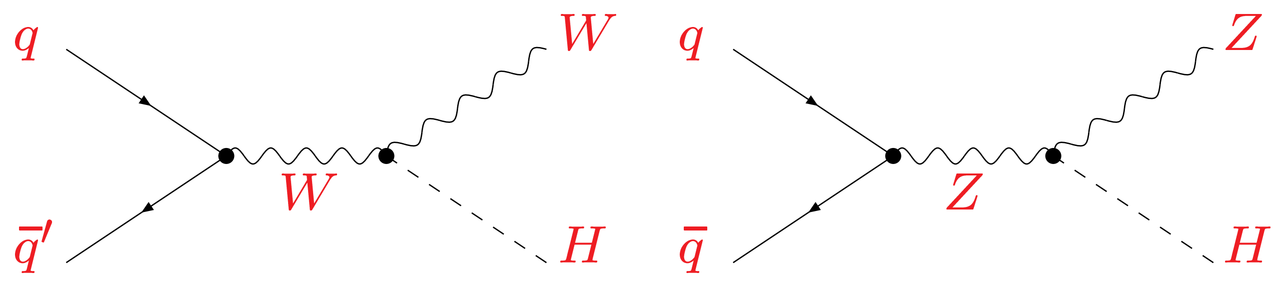
probability of background fluctuation: 3.4%

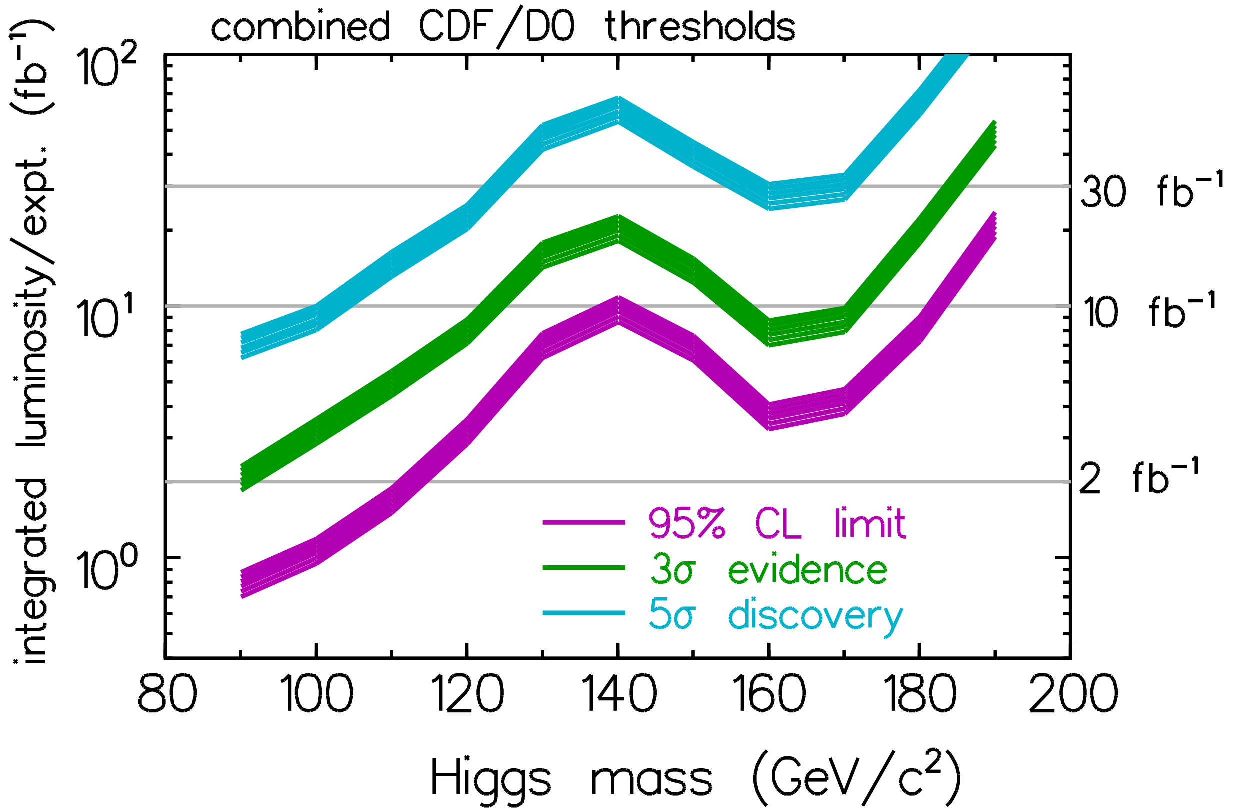
consistent with production of SM Higgs
with $M_{\mathrm{H}} \approx 115.6$ GeV

Search for SM Higgs at Tevatron, Run II:

$p\bar{p}$ collider with $E_{\text{CM}} \approx 2$ TeV

Dominant production processes:





For SM Higgs with $M_{\text{H}} \approx 115$ GeV:

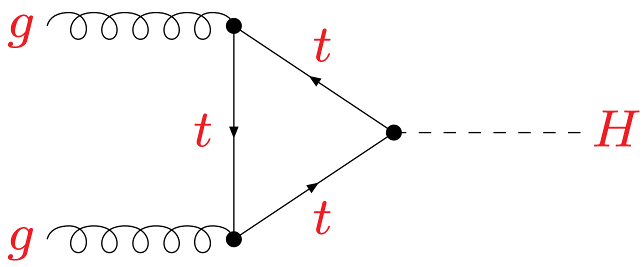
$\approx$ 2003: sensitivity for 95% C.L. exclusion

$\approx$ 2007: sensitivity for 5σ discovery

Search for the SM Higgs at the LHC ($\geq$ 2007):

pp collider with $E_{\mathrm{CM}} \approx 14$ TeV
covers whole range $M_{\mathrm{H}} \lesssim 1$ TeV

Dominant production process:



SM Higgs with $M_{\mathrm{H}} \approx 115$ GeV:
$\approx$ 2008: sensitivity for 5σ discovery
$\delta m_{\mathrm{h}}^{\mathrm{exp}} \approx 0.2$ GeV

Higgs physics at an e^+e^- LC ($\gtrsim$ 2010?):

LC with $E_{\mathrm{CM}} \approx 500$–$1000$ GeV

$\delta m_{\mathrm{h}}^{\mathrm{exp}} \approx 0.05$ GeV

Precise measurement of Higgs mass and couplings
determination of quantum numbers, . . .

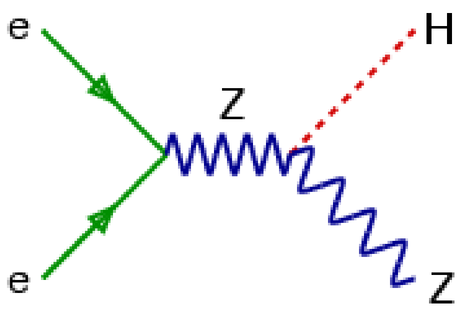
Verification of Higgs mechanism

Precision measurements at
Z resonance / WW threshold (GigaZ), tt threshold:
$\delta M_{\mathrm{W}} \approx 6$ MeV, $\delta \sin^2\theta_{\mathrm{eff}} \approx 1 \times 10^{-5}$, $\delta m_{\mathrm{t}} \approx 0.2$ GeV

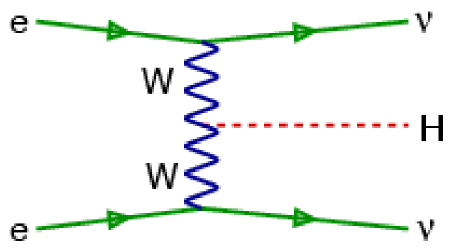
The LC is a Higgs factory !

The Profile of the Higgs Boson

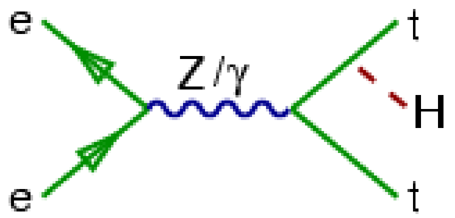
Production Processes



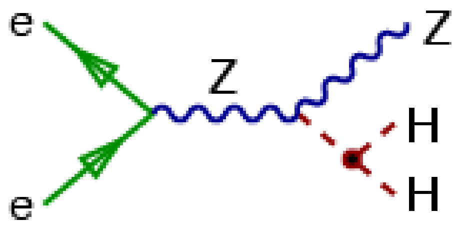
	500 fb^{-1}	500 fb^{-1}	1000 fb^{-1}
	350 GeV	500 GeV	800 GeV
m_H = 120	74000	35000	27000
m_H = 160	52000	29000	24000
m_H = 250	5500	16500	19000



	500 fb^{-1}	500 fb^{-1}	1000 fb^{-1}
	350 GeV	500 GeV	800 GeV
m_H = 120	15500	37500	158000
m_H = 160	7500	25000	126000
m_H = 250	6500	8000	71000



	500 fb^{-1}	500 fb^{-1}	1000 fb^{-1}
	350 GeV	500 GeV	800 GeV
m_H = 120	–	90	2600
m_H = 160	–	–	1500
m_H = 250	–	–	390

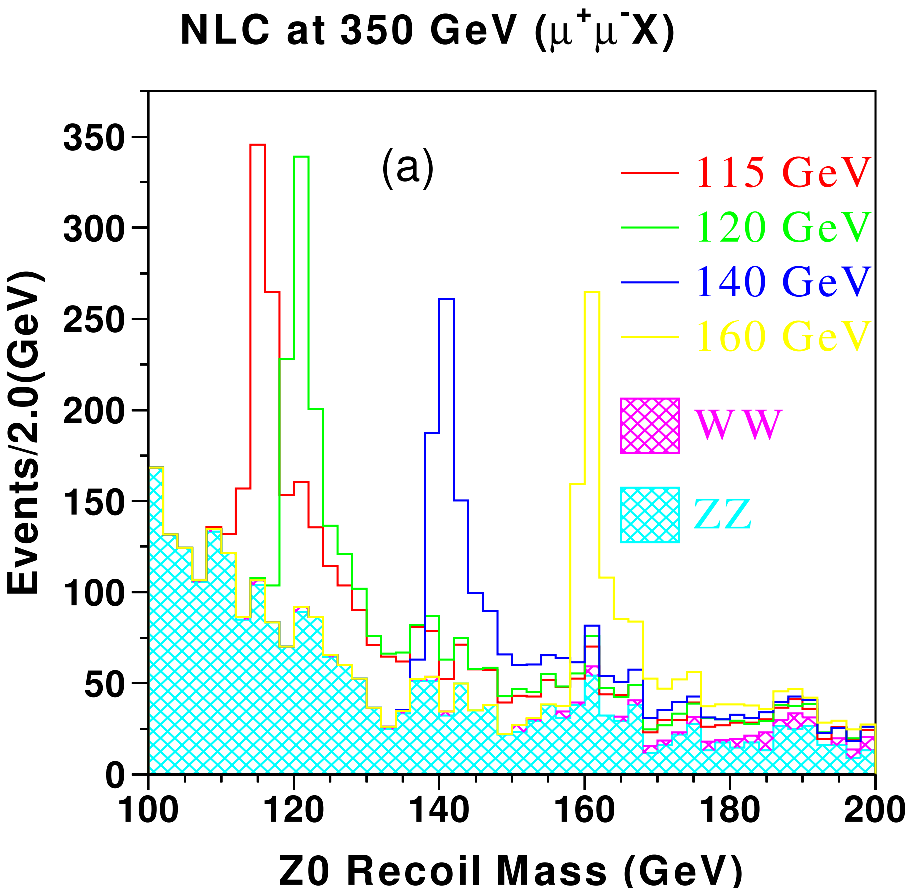


	500 fb^{-1}	500 fb^{-1}	1000 fb^{-1}
	350 GeV	500 GeV	800 GeV
m_H = 120	–	80	160
m_H = 160	–	20	120
m_H = 250	–	–	30

Observation

Gold plated channel:

$e^+e^- \to ZH$ **with** $Z \to e^+e^-, \mu^+\mu^-$



Use recoil mass against $\ell^+\ell^-$ pair:

$\Rightarrow$ **independent of Higgs decay**

$\Rightarrow$ **direct probe of Higgs coupliung to the Z**

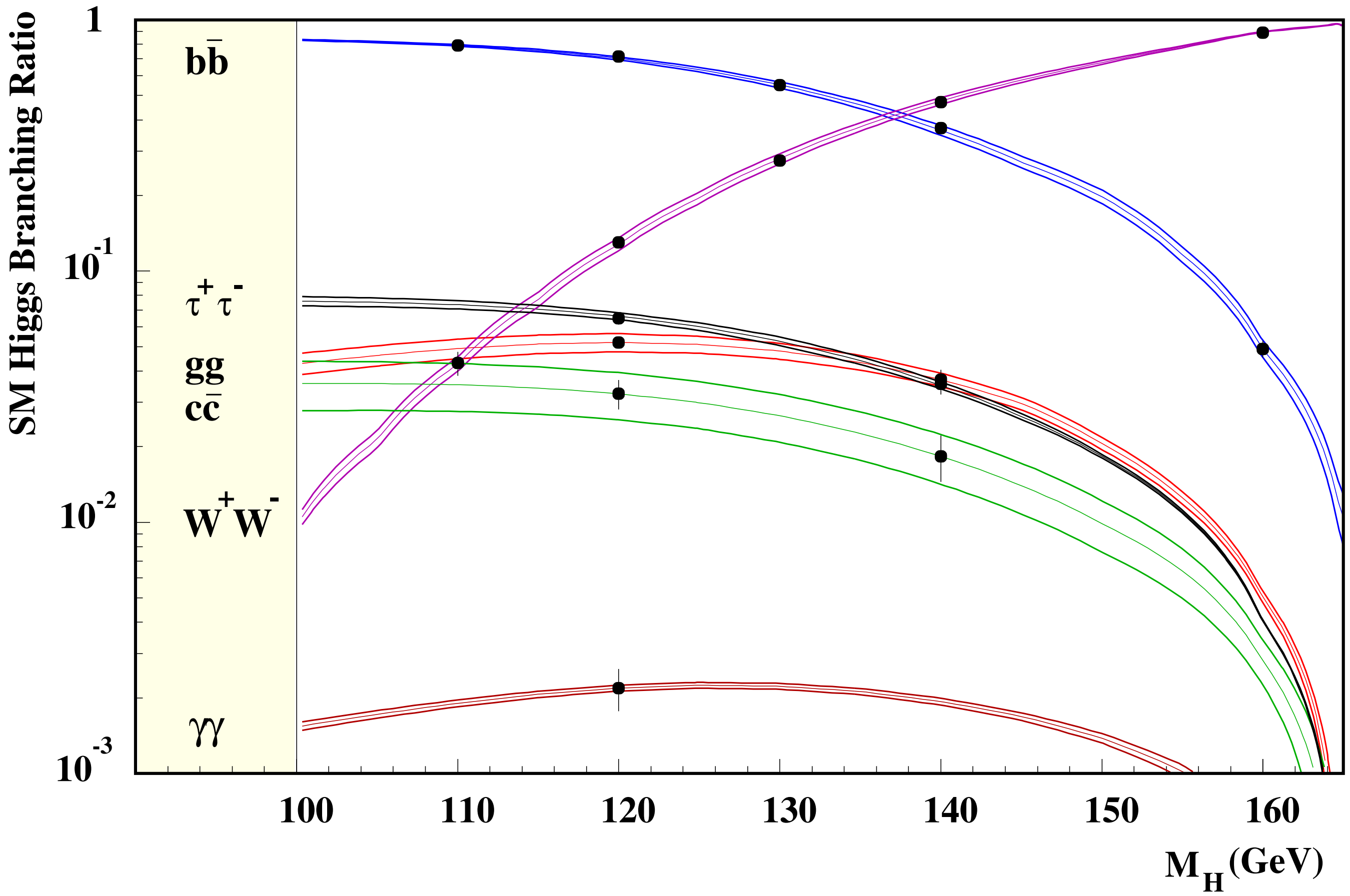
$\Delta\sigma_{HZ}/\sigma_{HZ} \approx$ **2%**

(350 GeV/ 500 fb^{-1})

Very precise measurement of

Higgs mass: $\Delta M_{\mathsf{H}}/M_{\mathsf{H}} \approx 3-5\times10^{-4}$

Higgs branching ratios, $H \to f\bar{f}, VV$: % level
[*TESLA TDR '01*]



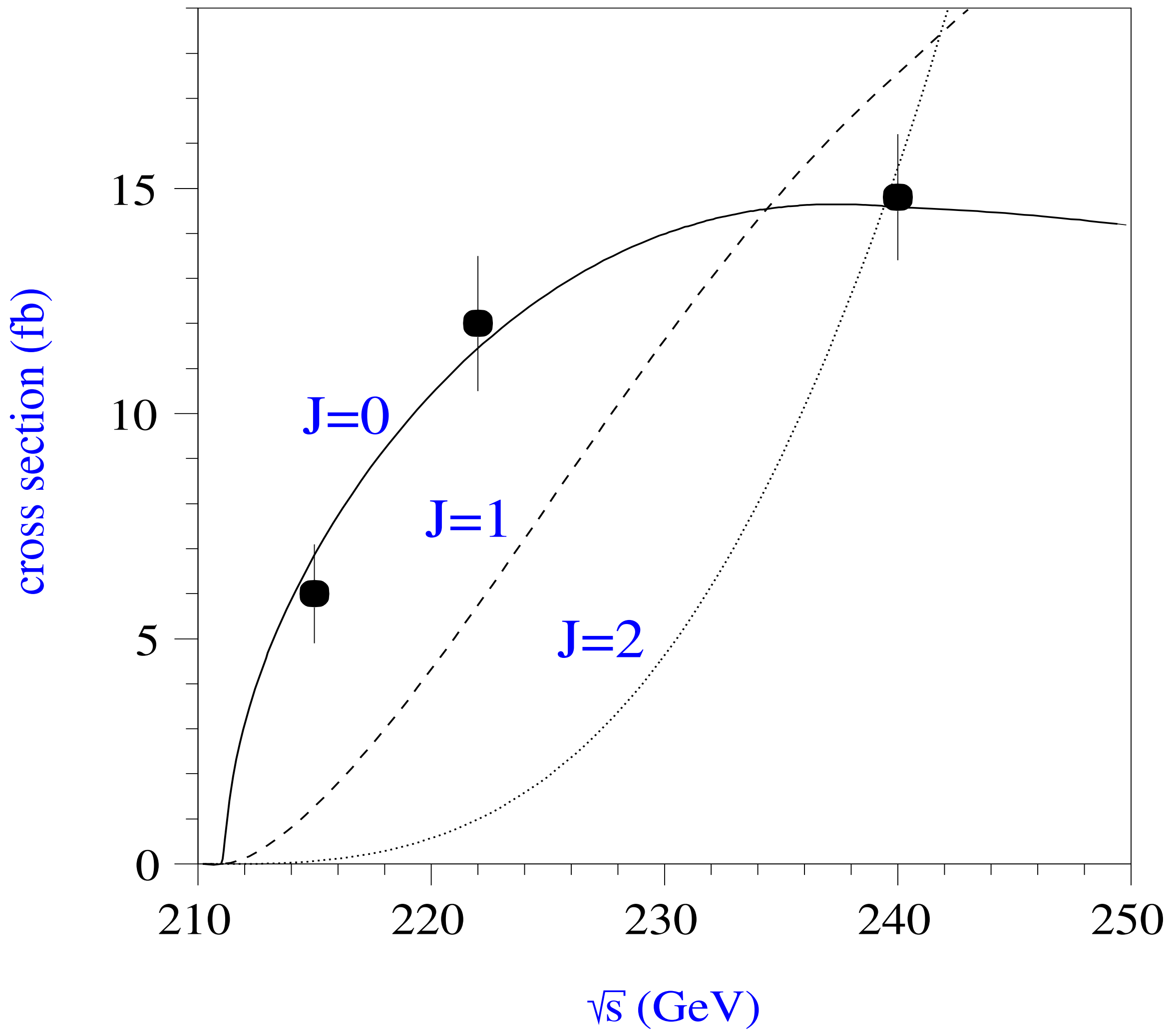
Coupling to gauge bosons: % level

Higgs width: % level

. . .

Determination of spin and $\mathcal{CP}$ quantum numbers:

Energy dependence of σ_{HZ} near threshold:
[*TESLA TDR '01*]



⇒ Spin

Angular distributions of fermions in $ZH \to f\bar{f}H$

⇒ $\mathcal{CP}$ quantum numbers

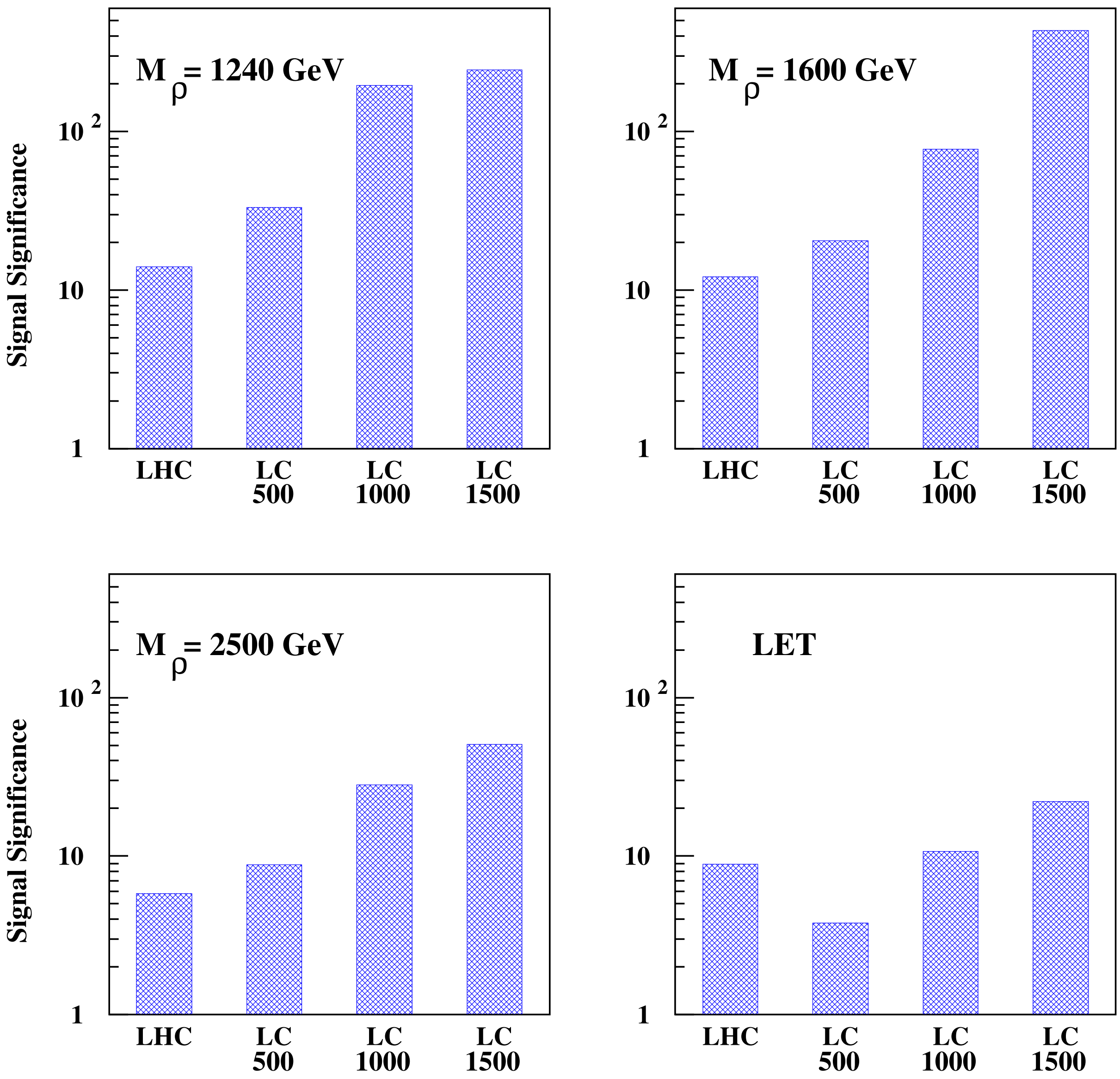
Higgs self coupling: $\Delta\lambda_{HHH}/\lambda_{HHH} \approx 20\%$

⇒ Reconstruction of Higgs potential

Sensitivity to signals of strong electroweak symmetry breaking:

Signal significance in σ for various masses M_ρ of vector resonance in $W_L W_L$ scattering

[American LC Working Group '01]



⇒ Strong electroweak symmetry breaking scenarios can be probed in detail

Constraints on the Standard Model Higgs from electroweak precision tests

Precision measurements

$\Rightarrow$ test quantum effects of the theory

Electroweak precision measurements:

M_Z [GeV]	$=$	91.1875 ± 0.0021	0.002%
Γ_Z [GeV]	$=$	2.4952 ± 0.0023	0.09%
$\sin^2\theta_{\text{eff}}^{\text{lept}}$	$=$	0.23149 ± 0.00017	0.07%
M_W [GeV]	$=$	80.451 ± 0.033	0.04%
m_t [GeV]	$=$	174.3 ± 5.1	2.9%
G_μ [GeV^{-2}]	$=$	$1.16637(1)\,10^{-5}$	0.0009%
$\ldots$			

Quantum effects of the theory:

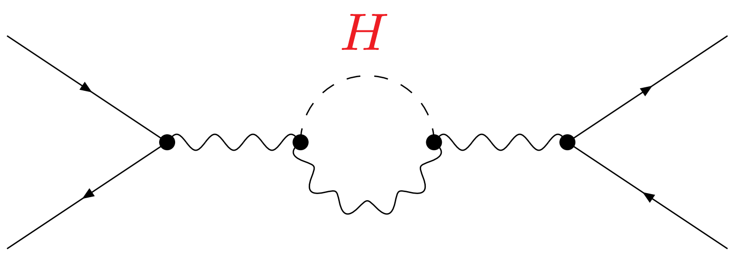
Loop corrections: $\sim \mathcal{O}(1\%)$

Indirect constraints on M_H from comparison of electroweak precision data with theory:

EW precision data:	Theory:
$M_\mathrm{Z}, M_\mathrm{W}, \sin^2\theta_\mathrm{eff}^\mathrm{lept}, \ldots$	SM, MSSM, . . .

$$\Downarrow$$

Test of theory at quantum level:



$$\Downarrow$$

Indirect constraints on M_H, . . .

Leading corrections to precision observables:

$$\sim m_\mathrm{t}^2, \ \sim \ln M_\mathrm{H}$$

$\Rightarrow$ Very high accuracy of measurements and theoretical predictions needed

Theoretical uncertainties:

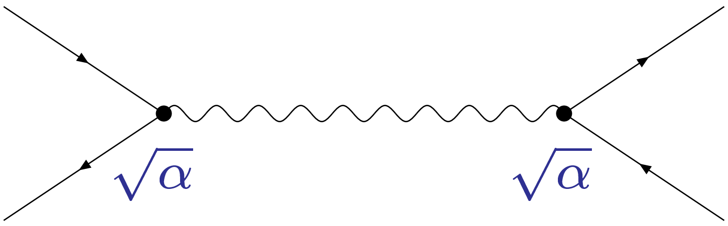
– unknown higher-order corrections

– exp. error of input parameters: m_t, $\Delta\alpha_\mathrm{had}$, . . .

Perturbative evaluation of QFTs based on Feynman diagrams:

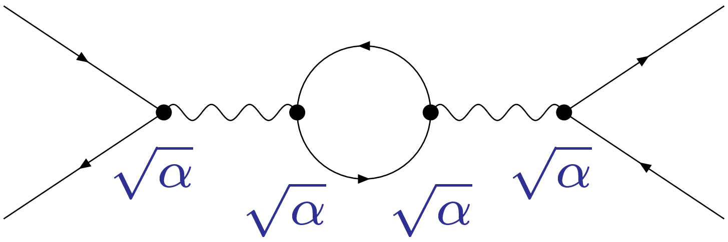
Example: $2 \to 2$ process

Lowest order (tree level):



$\alpha \approx \frac{1}{137}$

One-loop diagrams:



$+ \quad \ldots$

$\mathcal{O}(\alpha)$ relative to lowest order

...

Feynman rules of specific model (SM, MSSM, ...) for propagators and vertices

$\Rightarrow$ mathematical expression

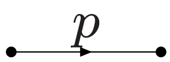
Example: Feynman rules of QED

- photon propagator (Feynman gauge):

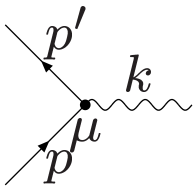
$$\Delta_{\mu\nu}(k) = \frac{-ig_{\mu\nu}}{k^2 + i\varepsilon} = $$

- electron/positron propagator:

$$S_F(p) = \frac{i(\not{p} + m)}{p^2 - m^2 + i\varepsilon} = $$



- electron–positron–photon vertex:



$$= (2\pi)^4 \delta^4(p - p' - k)(ie\gamma_\mu)$$

- ingoing and outgoing lines:

electron: $= u(p,\sigma)$ $= \overline{u}(p,\sigma)$

Positron: $= \overline{v}(p,\sigma)$ $= v(p,\sigma)$

Photon: $= \epsilon_\mu(p,\lambda)$ $= \epsilon^*_\mu(p,\lambda)$

- integration over momenta of internal particles

  δ-distr. $\Rightarrow$ momentum conservation

  for loop diagrams $\Rightarrow \int \frac{d^4q}{(2\pi)^4}$ for each loop

- minus sign for fermion loops, combinat. factor

Dirac algebra, Dirac traces:

$$\{\gamma_\mu, \gamma_\nu\} = 2g_{\mu\nu} \quad \Rightarrow \mathrm{Tr}\,\{\gamma_\mu \gamma_\nu\} = 4g_{\mu\nu}$$

Tensor-integral decomposition:

$$\int \frac{d^D q}{(2\pi)^D} \frac{q_\mu}{(q^2 - m^2)\,[(q+k)^2 - m^2]} = a\; k_\mu$$

$\Rightarrow$ scalar integrals:

$$\begin{aligned} A_0(m^2) &= \frac{1}{i\pi^2} \int \frac{d^D q}{(2\pi)^D} \frac{1}{q^2 - m^2} \\ B_0(p^2, m_1^2, m_2^2) &= \frac{1}{i\pi^2} \int \frac{d^D q}{(2\pi)^D} \frac{1}{(q^2 - m_1^2)\left[(q+k)^2 - m_2^2\right]} \\ \ldots & \end{aligned}$$

Evaluation of standard scalar integrals:

One-loop: reducible to A_0, B_0, C_0, D_0:

$$A_0, B_0 : \log(\sqrt{\ldots}); \quad C_0, D_0 : \log,\ \ \mathrm{Li}_2(x) = \int_0^1 dt \frac{\ln t}{t - 1/x}$$

Two-loop: in general not expressible in terms of polylogarithmic functions [*R. Scharf '91*]

$\Rightarrow$ numerical evaluation, asymptotic expansions, . . .

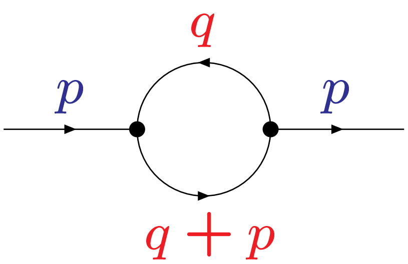
On-shell conditions for external legs

$\Rightarrow$ S-Matrix elements

$|\mathcal{M}^2|$, phase-space integration

$\Rightarrow$ cross sections, life times

Example of loop integral:



$$\sim \int d^4q \frac{1}{(q^2 - m_1^2)\left[(q+k)^2 - m_2^2\right]}$$

$$q \to \infty : \quad \sim \int_0^\infty \frac{q^3 dq}{q^4} = \int_0^\infty \frac{dq}{q} \quad \to \infty$$

$\Rightarrow$ integral diverges for large q!

$\Rightarrow$ theory in this form not physically meaningful

$\Rightarrow$ further concept needed: renormalization

Renormalizable theories: infinities can consistently be absorbed into parameters of theory

Two step procedure:

Regularization:

theory modified such that expressions become mathematically meaningful

$\Rightarrow$ “regulator” introduced, removed at the end

e.g. cut-off in loop integral

$$\int_0^\infty d^4q \;\to \int_0^\Lambda d^4q; \quad \Lambda \to \infty \text{ at the end}$$

technically more convenient: dimensional regularization

$$\int d^4q \;\to \int d^Dq, \quad D = 4 - \varepsilon; \quad D \to 4 \text{ at the end}$$

Renormalization:

original “bare” parameters replaced by renormalized parameters + counterterms

reparameterization:

$$\underbrace{g_0}_{\substack{\text{bare}\\\text{parameter}}} = \underbrace{g}_{\substack{\text{renormalized}\\\text{parameter}}} + \underbrace{\delta g}_{\text{counterterm}}$$

Renormalizable theory:
divergencies compensated by counterterms

Renormalization:

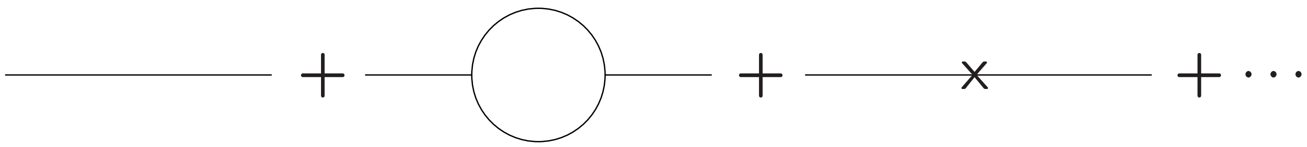
- absorption of divergencies
- determination of physical meaning of parameters order by order in perturbation theory

Example:

mass renormalization, $m_0^2 = m^2 + \delta m^2$

Physical mass: pole of propagator

inverse propagator up to 1-loop order:



$p^2 - m^2$ $\qquad \Sigma(p^2)$ $\qquad - \delta m^2$

pole of the propagator:

$$p^2 - m^2 + \Sigma(p^2) - \delta m^2 = 0$$

If renormalization such that

$$\delta m^2 = \Sigma(p^2)\Big|_{p^2=m^2} \qquad \text{"on-shell renormalization"}$$

$\Rightarrow$ pole of propagator for $p^2 = m^2$

$\Rightarrow$ m corresponds to physical mass

Counterterm contains divergence:

expansion in $\varepsilon \equiv 4 - D$, 1-loop:

$$\delta m^2 \quad = \quad \underbrace{a\frac{1}{\varepsilon}}_{\substack{\text{divergent} \\ \text{for } D \to 4}} \quad + \quad \underbrace{b\varepsilon^0}_{\text{finite}} \quad + \quad \underbrace{c\varepsilon}_{\substack{\to 0 \\ \text{for } D \to 4}} \quad + \quad \ldots$$

Other renormalization prescription:

$$\delta m^2 = a\frac{1}{\varepsilon} \qquad \text{"minimal subtraction" (MS)}$$

Different renormalization prescriptions $\Leftrightarrow$ different parameterizations of the result

Physical result must be independent of renormalization prescription, e.g.

$$\Sigma^{\text{ren}}(p^2 = \underbrace{\mu^2}_{\text{renormalization scale}}) \equiv \Sigma(p^2 = \mu^2) - \delta m^2 = 0$$

$\Rightarrow$ for physical observable σ:

$$\mu \frac{d}{d\mu} \sigma\left(p_i, g(\mu), m(\mu), \mu\right) = 0$$

"renormalization group equation"

$\Rightarrow$ explicit dependence of σ on μ compensated by μ-dependence of $g(\mu)$, $m(\mu)$

$$\frac{1}{g^2(\mu^2)} = \frac{1}{g^2(\mu_0^2)} + \beta \ln\left(\frac{\mu^2}{\mu_0^2}\right), \quad \beta = \text{const.}$$

$g(\mu)$: "running coupling"

$m(\mu)$: "running mass"

Example:

Theoretical prediction for M_W in the SM:

Definition of Fermi constant G_μ via muon lifetime:

$$\tau_\mu^{-1} = \frac{G_\mu^2 m_\mu^5}{192\pi^3} F\left(\frac{m_e^2}{m_\mu^2}\right) \left(1 + \frac{3}{5}\frac{m_\mu^2}{M_W^2}\right) (1 + \Delta q)$$

Δq: QED corrections in Fermi Model,
included in definition

[*R. Behrends, R. Finkelstein, A. Sirlin '56*]

[*T. van Ritbergen, R. Stuart '99*]

Comparison with SM prediction for muon decay:

$$\Rightarrow \quad M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{\pi\alpha}{\sqrt{2}G_\mu} (1 + \Delta r)\,,$$

$\Updownarrow$

loop corrections

$\Rightarrow$ Theoretical prediction for M_W in terms of M_Z, α, G_μ

SM prediction for Δr, one-loop:

[A. Sirlin '80], [W. Marciano, A. Sirlin '80]

$$\Delta r_{1-\mathrm{loop}} = \Delta\alpha - \frac{c_W^2}{s_W^2}\Delta\rho + \Delta r_{\mathrm{rem}}(M_H)$$

$$\sim \log\frac{M_Z}{m_f} \qquad \sim m_t^2$$

$$\sim 6\% \qquad \sim 3.3\% \qquad \sim 1\%$$

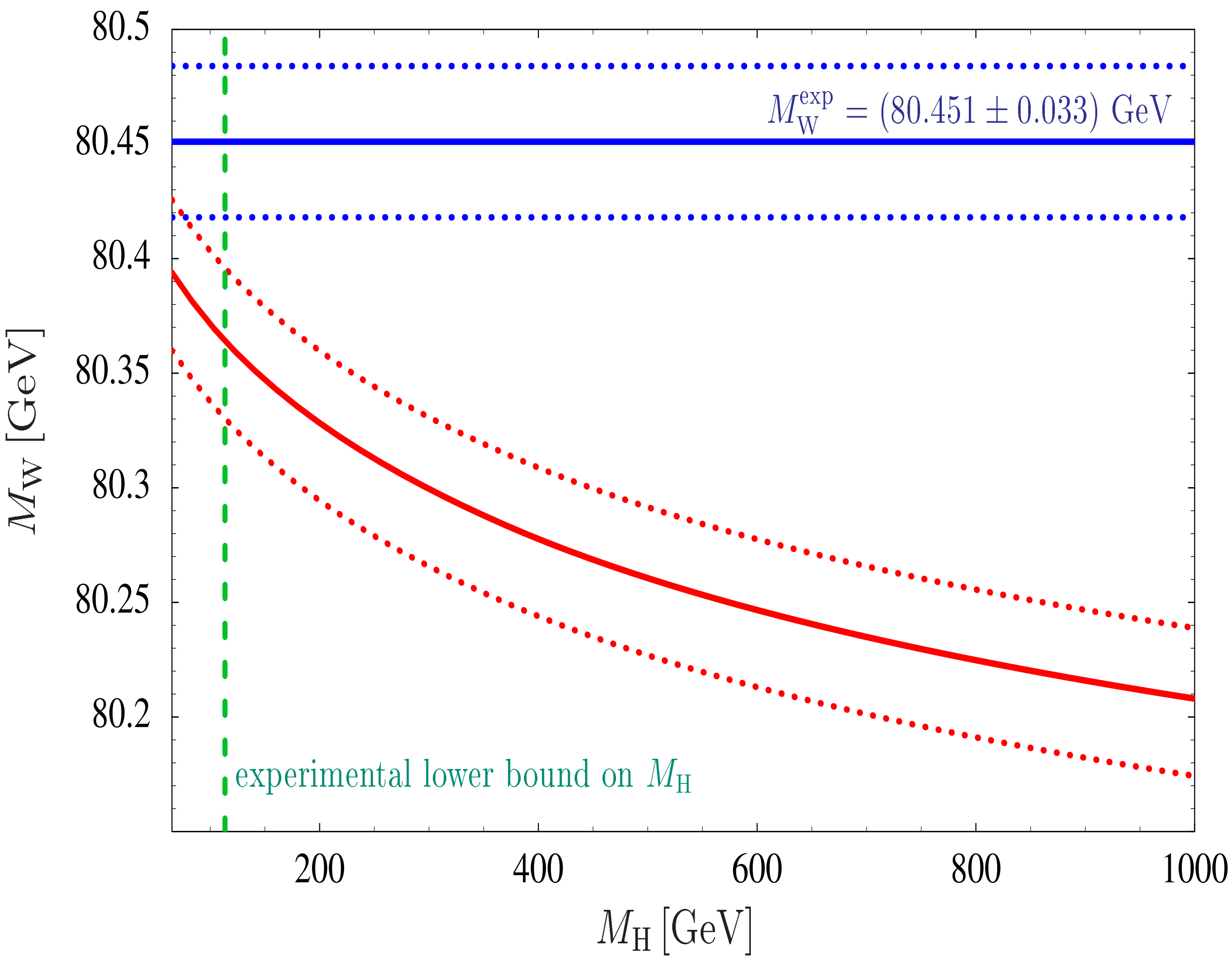
$\Delta\alpha$: running of α, $\alpha(M_Z^2) = \alpha(0)/(1 - \Delta\alpha)$

$\Delta\rho$: leading m_t contributions to precision observables enter quadratically

$\Delta r_{\mathrm{rem}}(M_H)$: leading M_H dependence is logarithmic

SM prediction for M_{W} vs. experimental result:

[*A. Freitas, W. Hollik, W. Walter, G.W. '00, '02*]



$\Rightarrow$ Light Higgs preferred

$M_{\mathrm{W}}^{\mathrm{exp}} = 80.451 \pm 0.033$ GeV, $m_{\mathrm{t}}^{\mathrm{exp}} = 174.3 \pm 5.1$ GeV

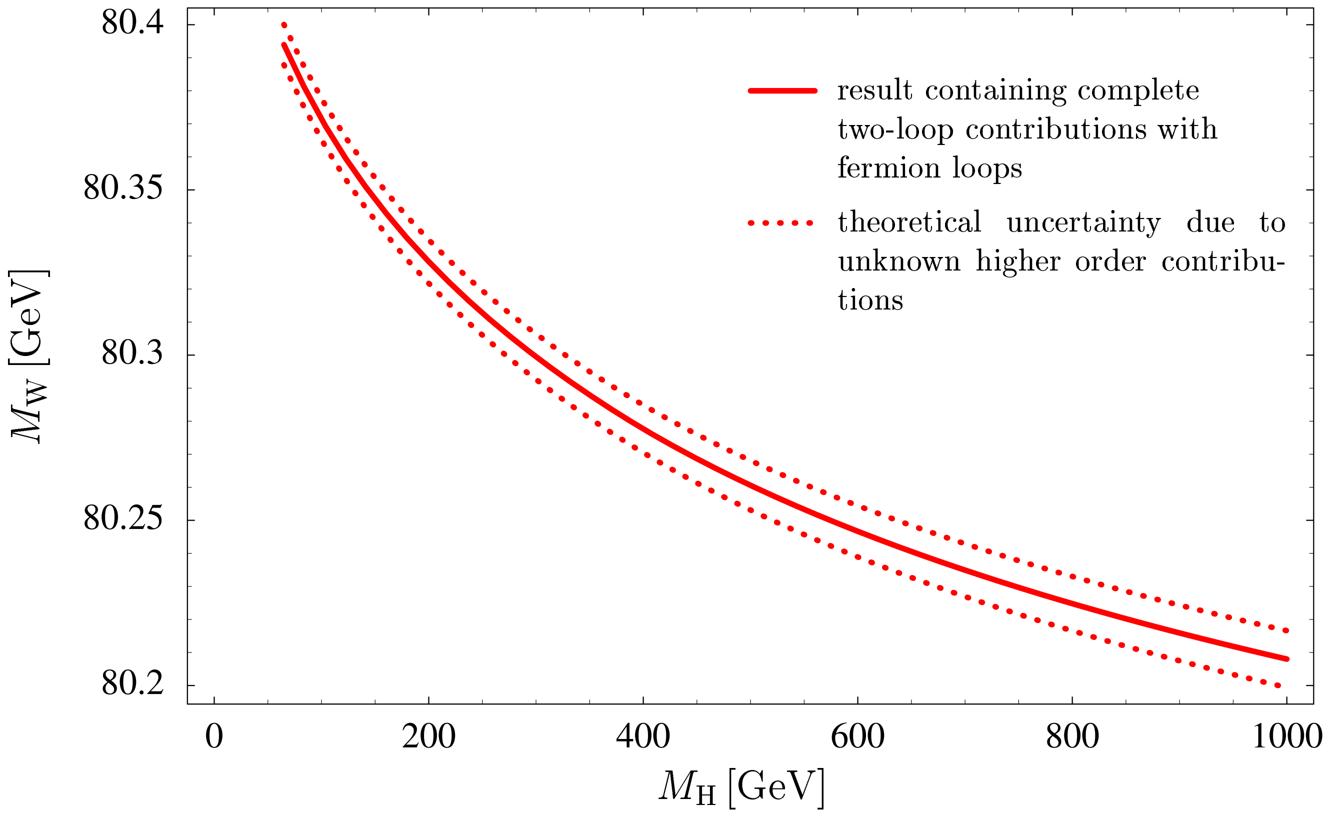
$M_{\mathrm{H}} > 114.1$ GeV, 95% C.L.

$\Rightarrow$ 1σ regions do not overlap

Uncertainty from experimental error of input parameters: $\delta m_{\mathrm{t}} = \pm 5.1$ GeV $\Rightarrow$ $\delta M_{\mathrm{W}} \approx \pm 31$ MeV

Estimate of theoretical uncertainty from unknown higher-order corrections:

- Purely bosonic $\mathcal{O}(\alpha^2)$ electroweak corrections
- Higher-order electroweak corrections: $\mathcal{O}(\alpha^3)$
- Higher-order QCD corrections: $\mathcal{O}(\alpha\alpha_{\mathrm{s}}^3)$, $\mathcal{O}(\alpha^2\alpha_{\mathrm{s}})$

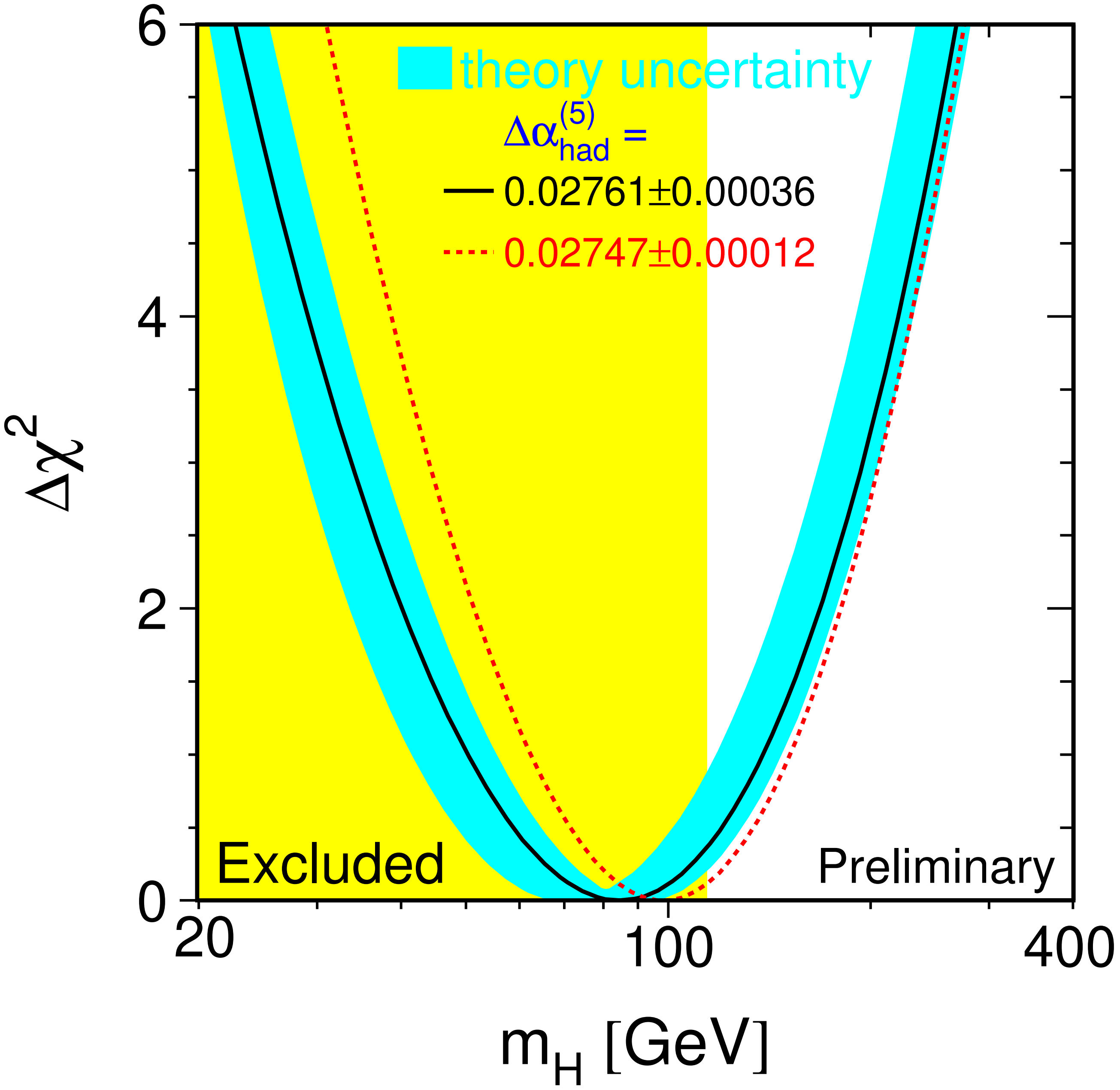


For light Higgs masses:

$$\Delta M_{\mathrm{W}}^{\mathrm{theo}} \approx \pm 6\,\mathrm{MeV}$$

Global fit to all data in the SM:

[*LEPEWWG '02*]



$\Rightarrow$ $M_{\rm H} = 85^{+54}_{-34}$ GeV

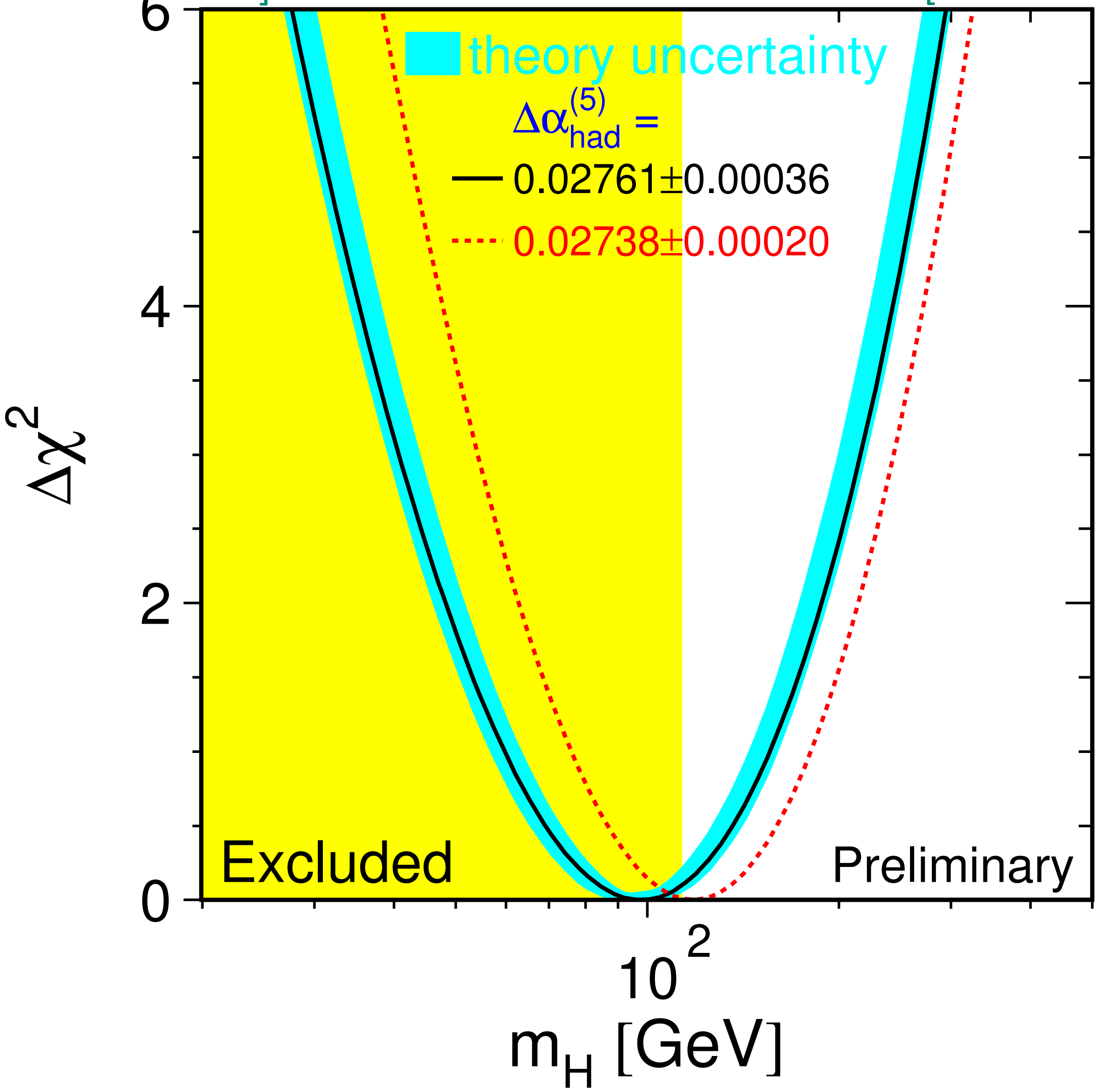
$M_{\rm H} < 196$ GeV, 95% C.L.

$\Rightarrow$ Preference for light Higgs

Uncertainties from unknown higher-order corrections:

Comparison: global fit results one year ago

[LEPEWWG '01] *[Moriond '01]*



$\Rightarrow M_H = 98^{+58}_{-38}$ GeV, $M_H < 212$ GeV, 95% C.L.

"Blue band" has widened w.r.t. one year ago

Old estimate (up to Moriond '01):

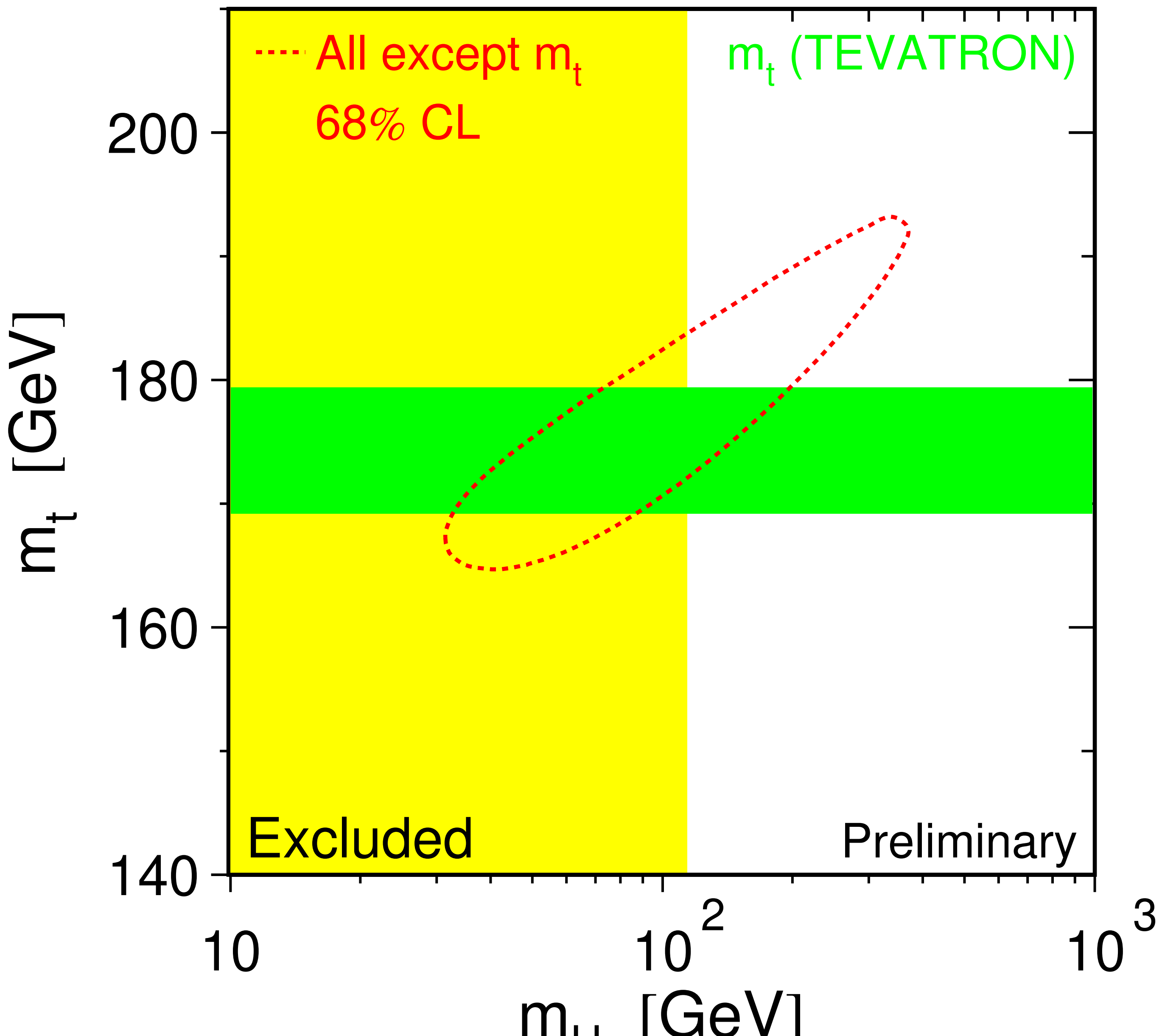
$\Delta \sin^2\theta_{\mathrm{eff}}^{\mathrm{theo}} \approx \pm 3 \times 10^{-5}$, $\quad \Delta M_W^{\mathrm{theo}} \approx \pm 3$ MeV

New estimate of higher-order uncertainties:

$\Delta \sin^2\theta_{\mathrm{eff}}^{\mathrm{theo}} \approx \pm 7 \times 10^{-5}$, $\quad \Delta M_W^{\mathrm{theo}} \approx \pm 6$ MeV

Interpretation of fit result:

Strong correlation between M_H and m_t in the fit:
[*LEPEWWG '02*]



$\Rightarrow$ Upward shift of m_t by 1σ would have significant effect on M_H bound

Basic assumption in global fit:

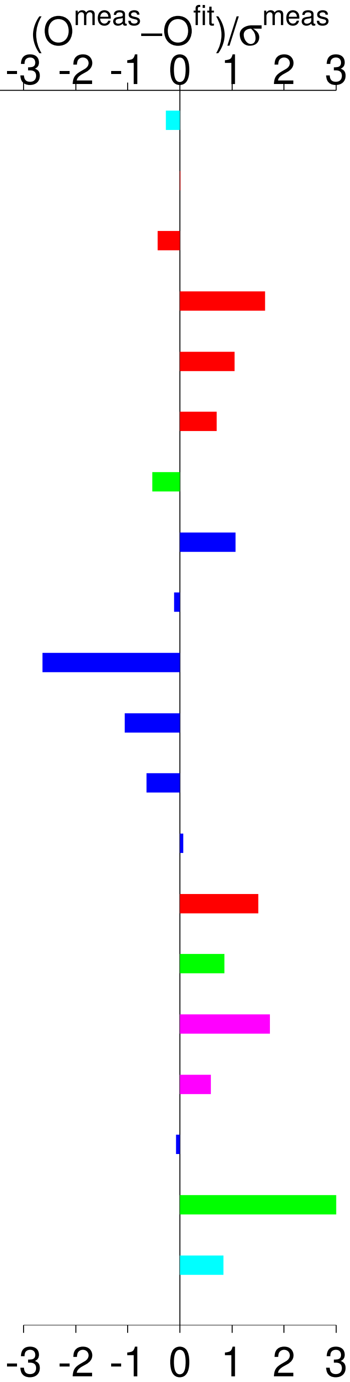
SM provides correct description of experimental data

Comparison of SM prediction with the data:

[*LEPEWWG '02*]

Winter 2002

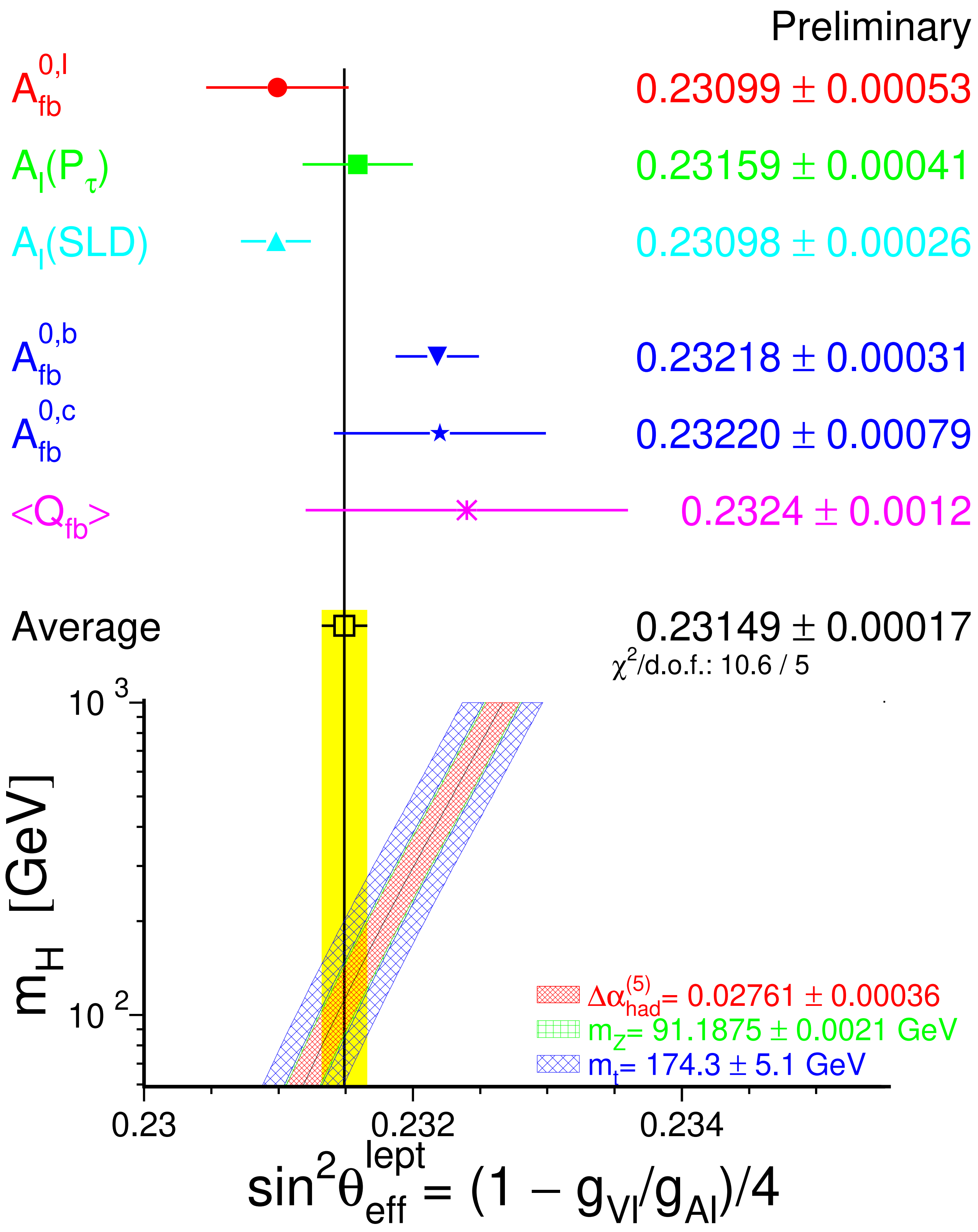
	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-.27
m_Z [GeV]	91.1875 ± 0.0021	.01
Γ_Z [GeV]	2.4952 ± 0.0023	-.42
σ^0_{had} [nb]	41.540 ± 0.037	1.63
R_l	20.767 ± 0.025	1.05
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.70
$A_l(P_\tau)$	0.1465 ± 0.0033	-.53
R_b	0.21646 ± 0.00065	1.06
R_c	0.1719 ± 0.0031	-.11
$A^{0,b}_{fb}$	0.0994 ± 0.0017	-2.64
$A^{0,c}_{fb}$	0.0707 ± 0.0034	-1.05
A_b	0.922 ± 0.020	-.64
A_c	0.670 ± 0.026	.06
A_l(SLD)	0.1513 ± 0.0021	1.50
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	.86
m_W [GeV]	80.451 ± 0.033	1.73
Γ_W [GeV]	2.134 ± 0.069	.59
m_t [GeV]	174.3 ± 5.1	-.08
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	3.00
$Q_W(Cs)$	-72.39 ± 0.59	.84



Overall fit probability (quality of the fit): 1.7%

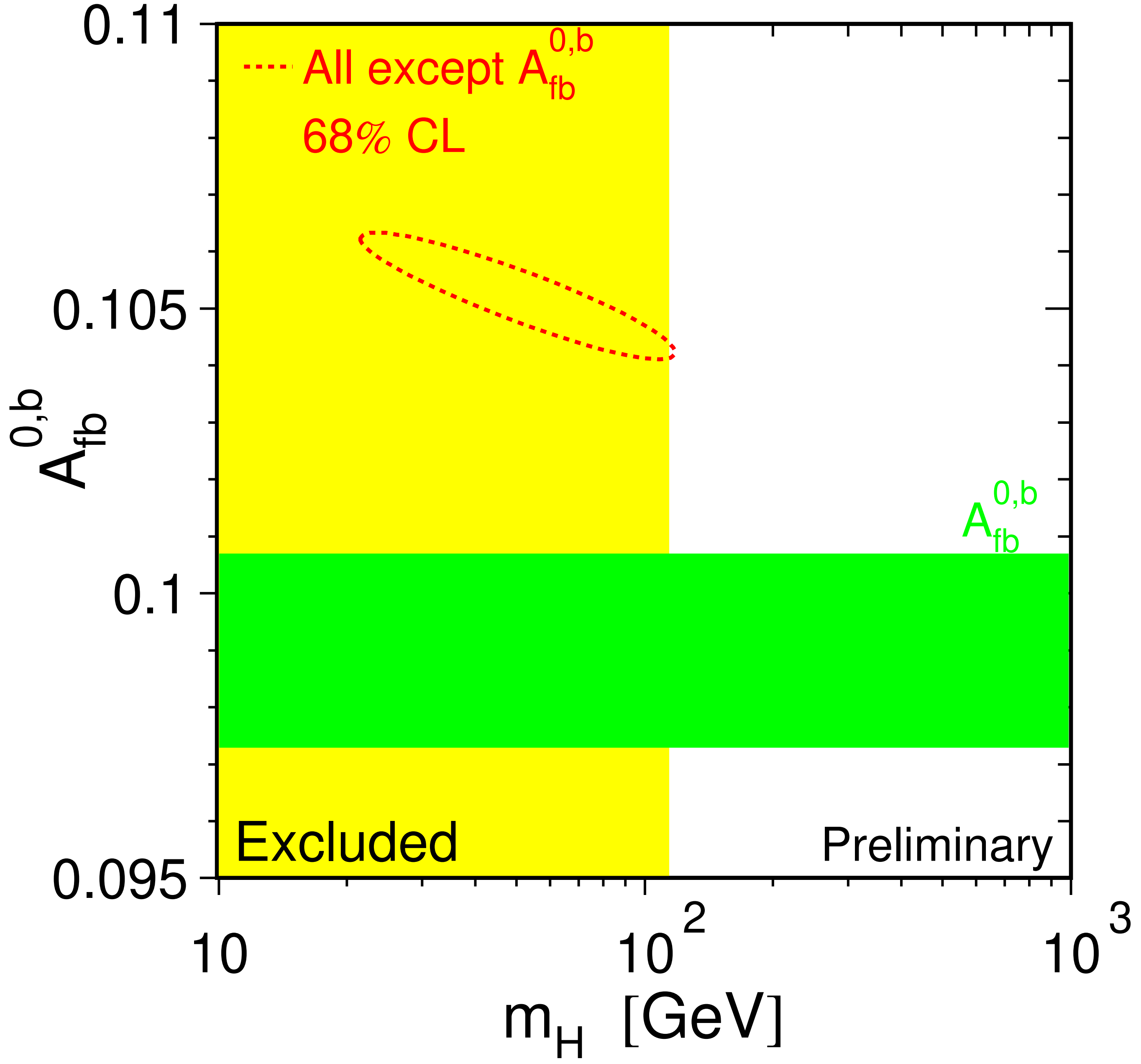
The effective weak mixing angle $\sin^2\theta_{\text{eff}}$:

[LEPEWWG '02]



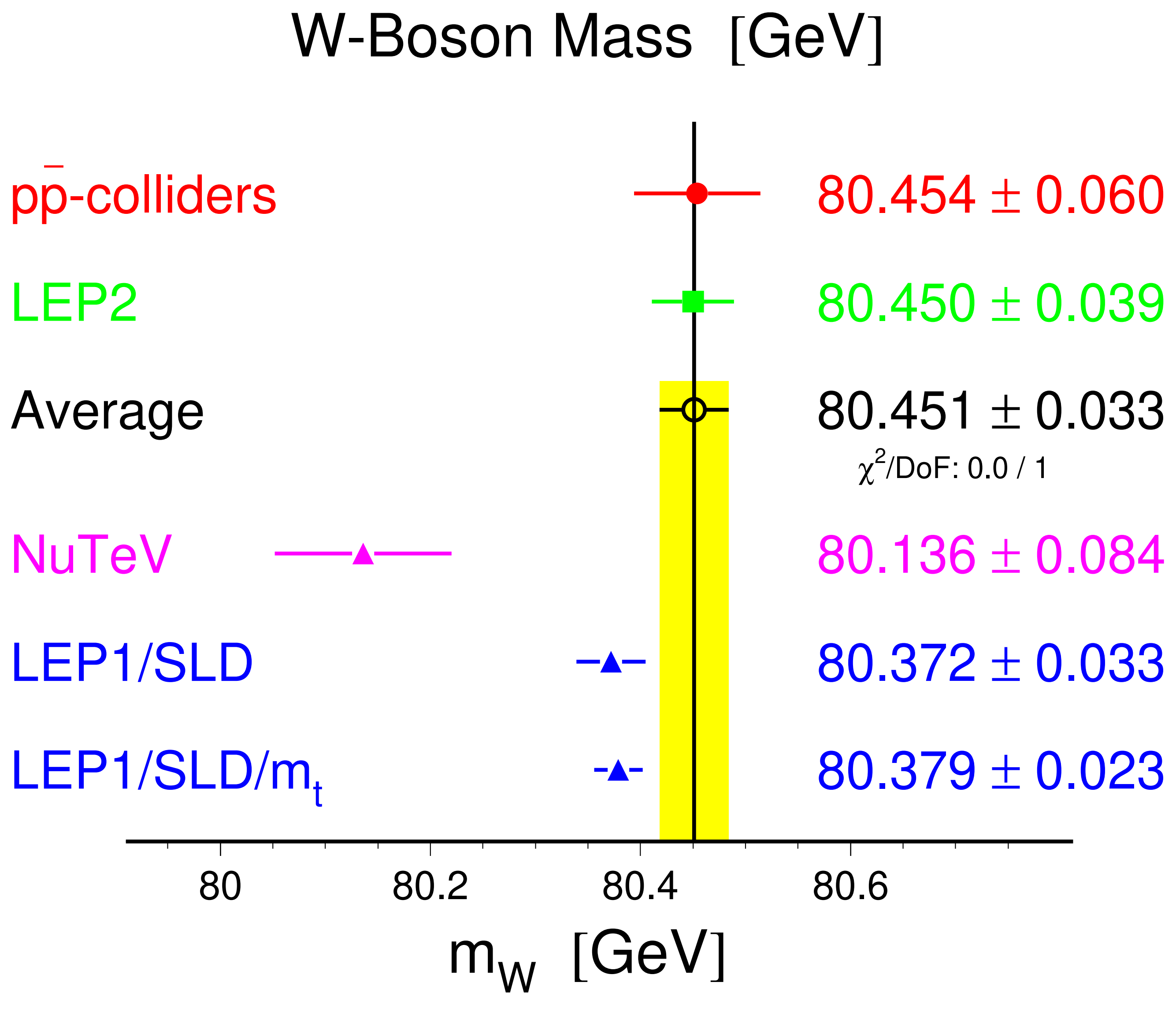
Forward–backward asymmetry of b quarks:

[*LEPEWWG '01*]



$\Rightarrow$ the "$A_{\mathrm{fb}}^{0,b}$ crisis"

Direct measurement of M_{W} at LEP2, Tevatron vs. indirect determinations from LEP1, SLD, NuTeV: [*LEPEWWG '02*]



No convincing new physics model for "explaining" deviations from SM

Note, however:

if NuTeV result interpreted as deviation in $Z\nu\bar{\nu}$ coupling:

(ν neutral current rate)/prediction:

0.995 ± 0.003	LEP1 lineshape (invisible Z width)
0.988 ± 0.004	NuTeV

Need some patience until experimental clarification:

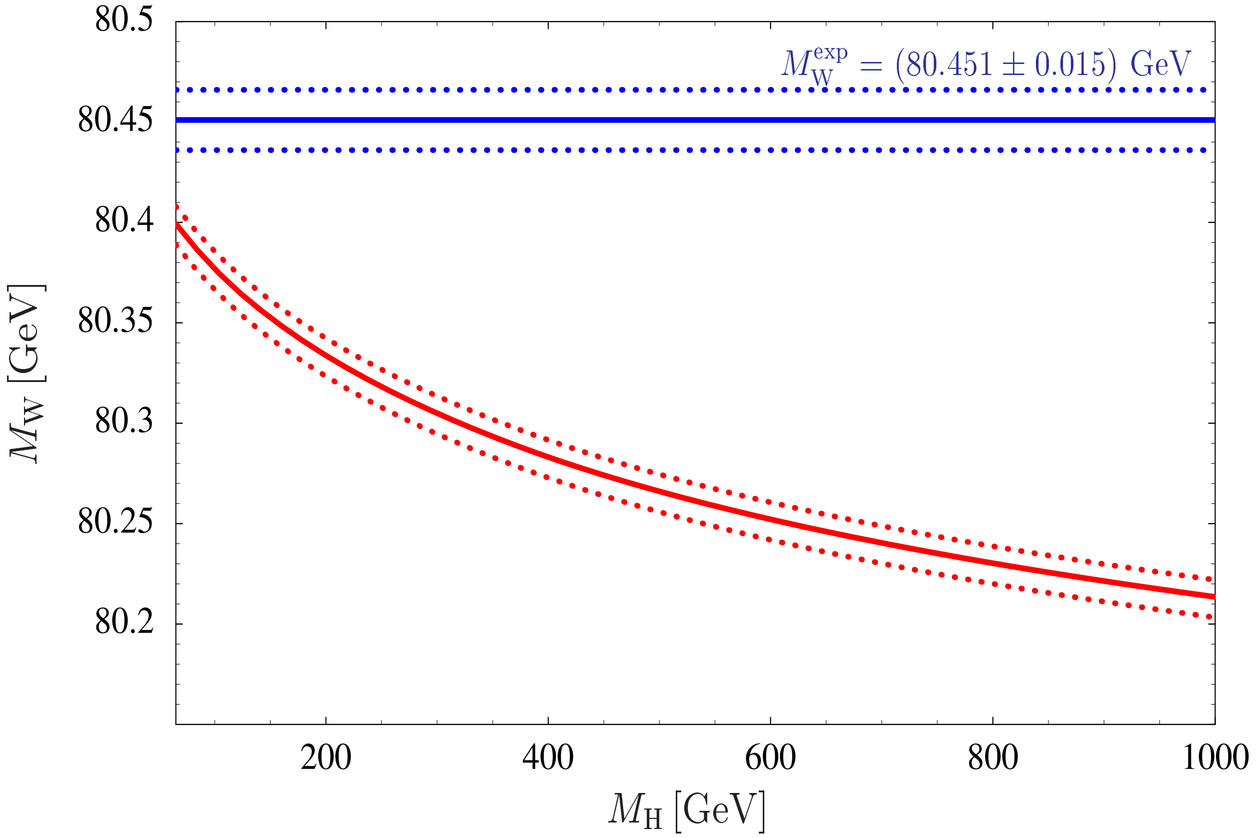
A_{LR}, A_{FB}:	LC with GigaZ option?
ν–nucleon scatt.:	ν factory?

If hadronic data on A_{FB} and NuTeV data on ν–nucleon scattering were removed from fit:

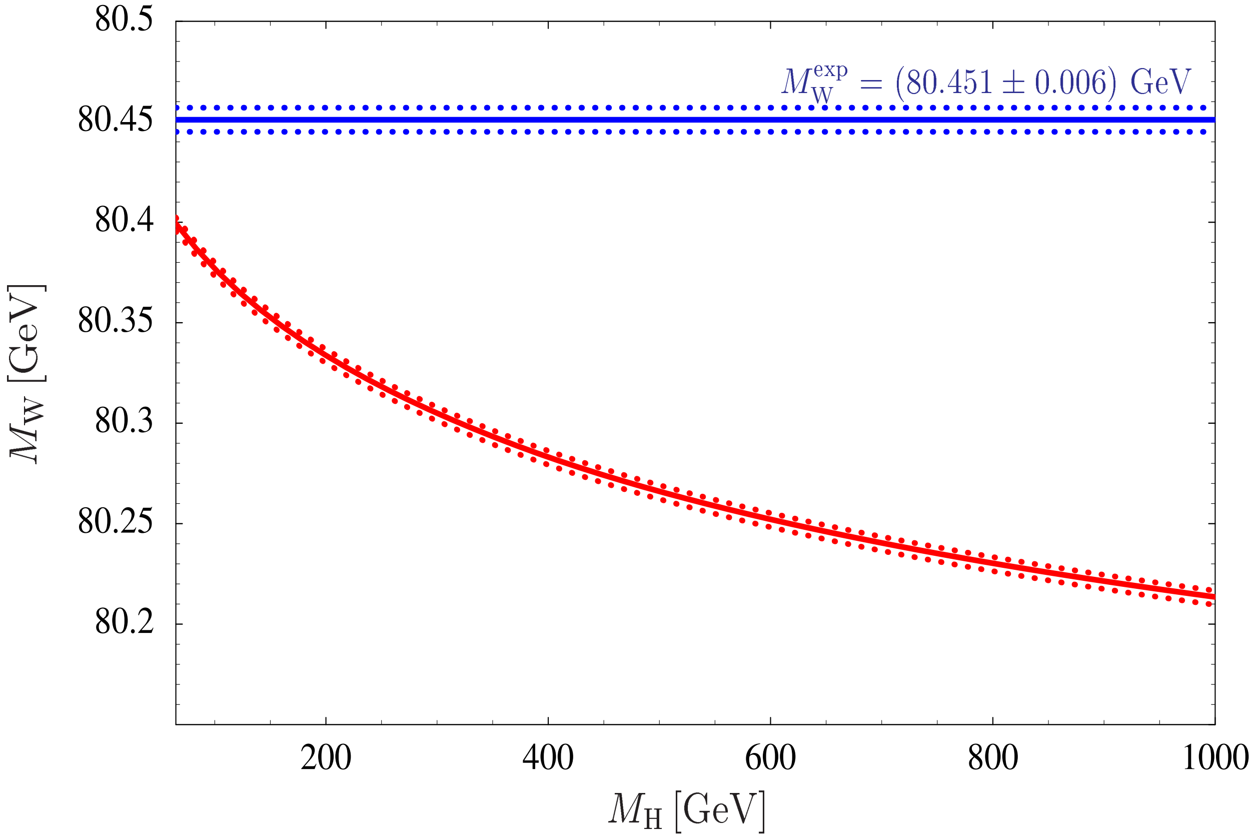
much better fit quality, probability $\approx 70\%$

stronger preference for light Higgs:
$M_{\mathrm{H}} \lesssim 110$ GeV, 95% C.L.

Prospects for Tevatron Run II, LHC:

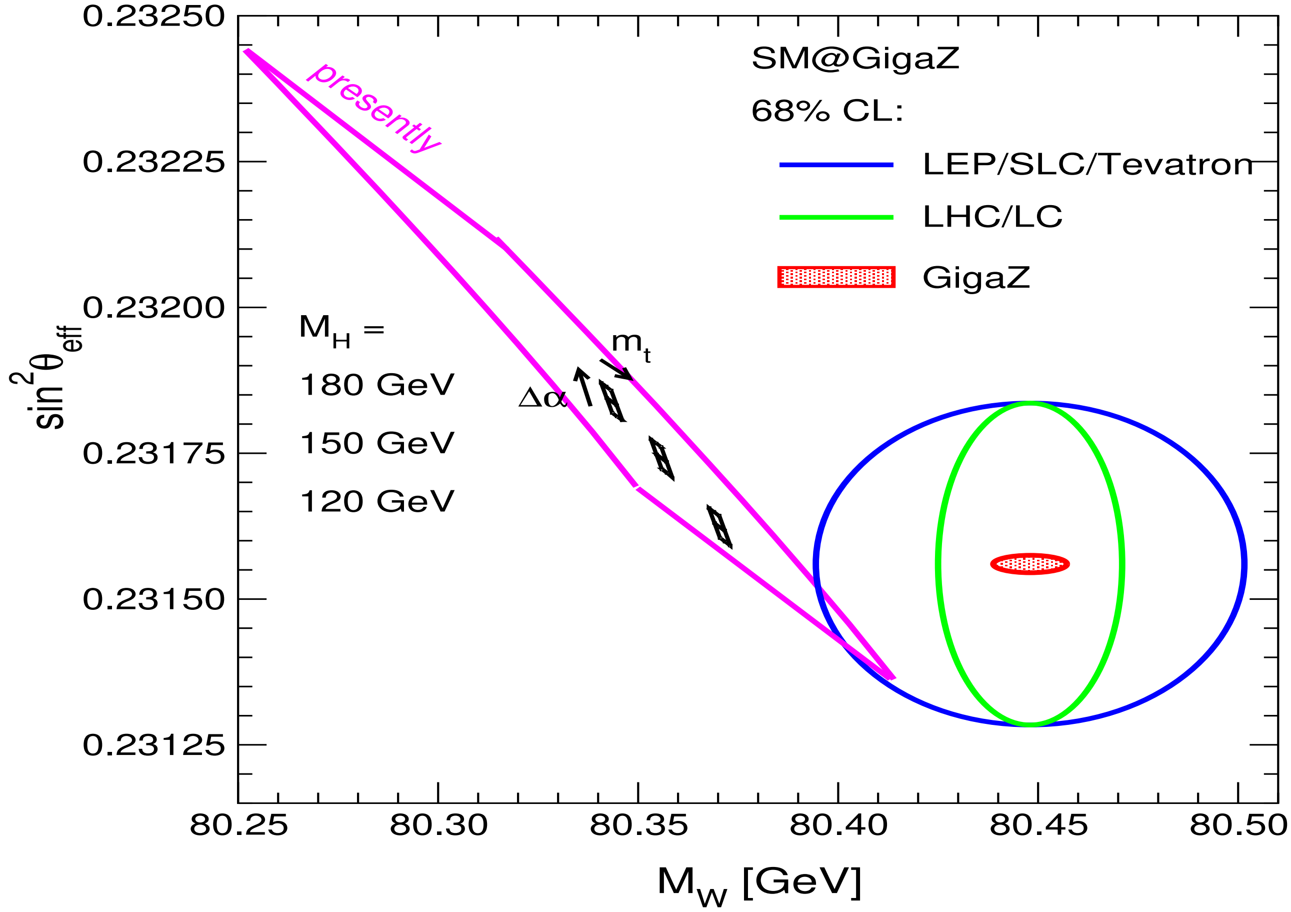


LC with high luminosity in low-energy mode: GigaZ

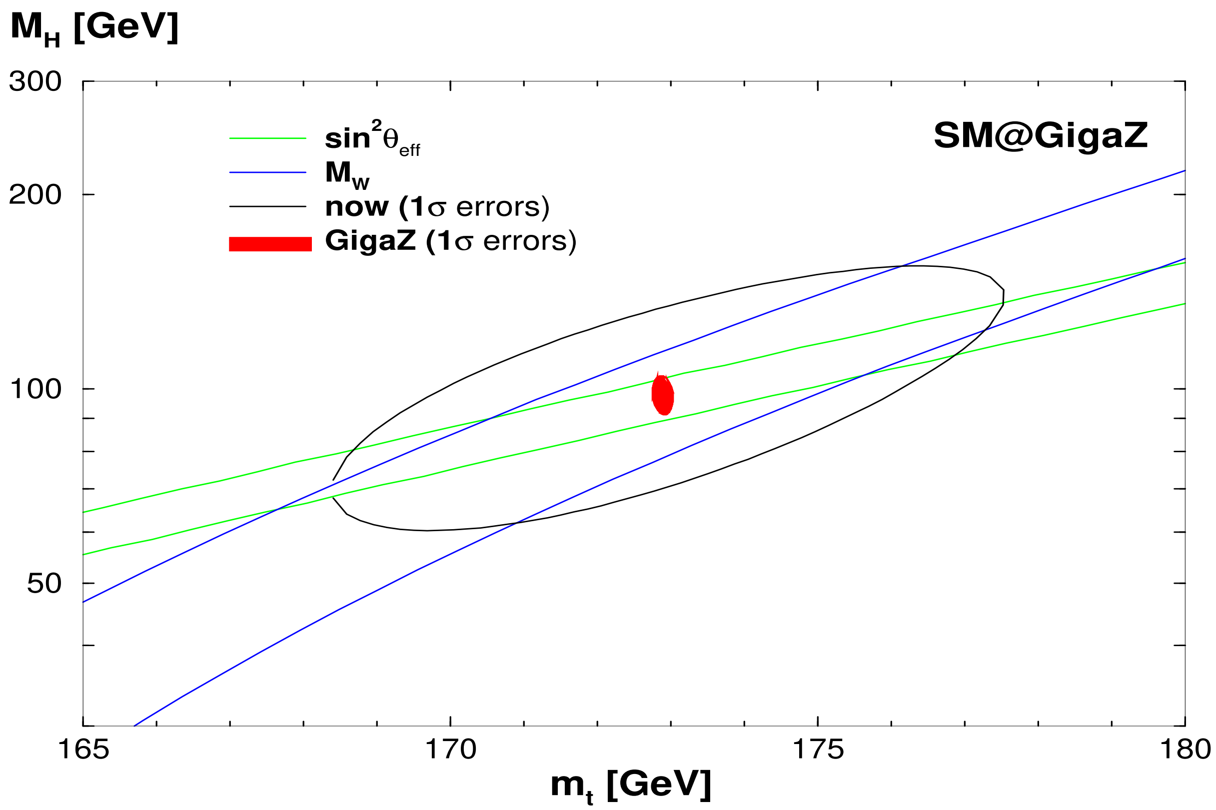


SM prediction for M_W and $\sin^2\theta_{eff}$ vs. prospective accuracies at LEP2/Tevatron, Tev./LHC/LC, GigaZ:

[*J. Erler, S. Heinemeyer, W. Hollik, G.W., P. Zerwas '00*]



Indirect determination of m_t, M_H at GigaZ:



Summary of Lecture 1:

- Standard Model:

  Higgs boson is last missing ingredient

- LEP: $M_{\mathrm{H}} > 114.1$ GeV, 95% C.L.

  $\approx 2\sigma$ excess at $M_{\mathrm{H}} \approx 115$ GeV

- Precision tests of the SM $\Rightarrow$ light Higgs preferred

- At TESLA:

  m_{h}, Higgs couplings as precision observables

  improved accuracy of precision observables
  m_{h}, M_{W}, $\sin^2\theta_{\mathrm{eff}}$, . . . and
  input parameters m_{t}, . . .

  $\Rightarrow$ Highly sensitive test of electroweak theory