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SUMMER SCHOOL ON PARTICLE PHYSICS

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The Standard Model and Higgs Physics - Part 2

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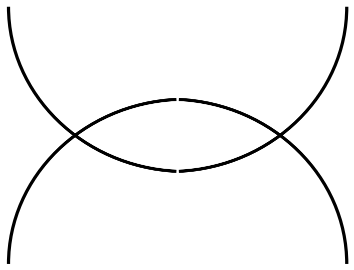
▷ Triviality of scalar field theory

Only *noninteracting* scalar field theories make sense on all energy scales

Quantum field theory vacuum is a dielectric medium that screens charge ⇒ *effective charge* is a function of the distance or, equivalently, of the energy scale

running coupling constant

In $\lambda\phi^4$ theory, it is easy to calculate the variation of the coupling constant λ in perturbation theory by summing bubble graphs



$\lambda(\mu)$ is related to a higher scale Λ by

$$\frac{1}{\lambda(\mu)} = \frac{1}{\lambda(\Lambda)} + \frac{3}{2\pi^2} \log\left(\Lambda/\mu\right)$$

(Perturbation theory reliable only when λ is small, lattice field theory treats strong-coupling regime)

For stable Higgs potential (*i.e.*, for vacuum energy not to race off to $-\infty$), *require* $\lambda(\Lambda) \geq 0$

Rewrite RGE as an inequality

$$\frac{1}{\lambda(\mu)} \geq \frac{3}{2\pi^2} \log\left(\Lambda/\mu\right) \quad .$$

implies an *upper bound*

$$\boxed{\lambda(\mu) \leq 2\pi^2/3\log\left(\Lambda/\mu\right)}$$

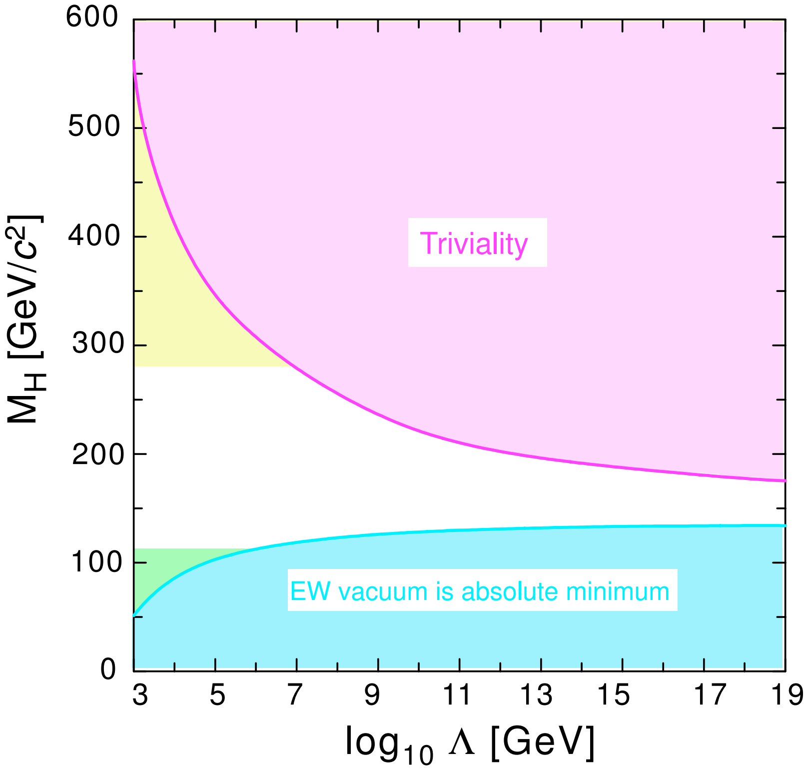
If we require the theory to make sense to arbitrarily high energies—or short distances—then we must take the limit $\Lambda \to \infty$ while holding μ fixed at some reasonable physical scale. In this limit, the bound forces $\lambda(\mu)$ to zero. $\longrightarrow$ free field theory "trivial"

Rewrite as bound on M_H:

$$\Lambda \leq \mu \exp\left(\frac{2\pi^2}{3\lambda(\mu)}\right)$$

Choose $\mu = M_H$, and recall $M_H^2 = 2\lambda(M_H)v^2$

$$\boxed{\Lambda \leq M_H \exp\left(4\pi^2 v^2/3M_H^2\right)}$$



Moral: For any M_H, there is a *maximum energy scale* $\Lambda^\star$ at which the theory ceases to make sense.

The description of the Higgs boson as an elementary scalar is at best an effective theory, valid over a finite range of energies

Perturbative analysis breaks down when $M_H \to 1$ TeV/c^2 and interactions become strong

Lattice analyses $\Longrightarrow$ $M_H \lesssim 710 \pm 60$ GeV/c^2 if theory describes physics to a few percent up to a few TeV

If $M_H \to 1$ TeV EW theory lives on brink of instability

$\triangleright$ *Lower bound* by requiring EWSB vacuum $V(v) < V(0)$

Requiring that $\langle\phi\rangle_0 \neq 0$ be an absolute minimum of the one-loop potential up to a scale Λ yields the vacuum-stability condition

$$M_H^2 > \frac{3G_F\sqrt{2}}{8\pi^2}(2M_W^4 + M_Z^4 - 4m_t^4)\log(\Lambda^2/v^2)$$

…for $m_t \lesssim M_W$

(No illuminating analytic form for heavy m_t)

If the Higgs boson is relatively light—which would itself require explanation—then the theory can be self-consistent up to very high energies

If EW theory is to make sense all the way up to a unification scale $\Lambda^\star = 10^{16}$ GeV, then

$$134 \text{ GeV}/c^2 \lesssim M_H \lesssim 177 \text{ GeV}/c^2$$

Higgs-Boson Properties

$$\Gamma(H \to f\bar{f}) = \frac{G_F m_f^2 M_H}{4\pi\sqrt{2}} \cdot N_c \cdot \left(1 - \frac{4m_f^2}{M_H^2}\right)^{3/2}$$

$\propto M_H$ in the limit of large Higgs mass

$$\Gamma(H \to W^+W^-) = \frac{G_F M_H^3}{32\pi\sqrt{2}}(1-x)^{1/2}(4-4x+3x^2)$$

$$x \equiv 4M_W^2/M_H^2$$

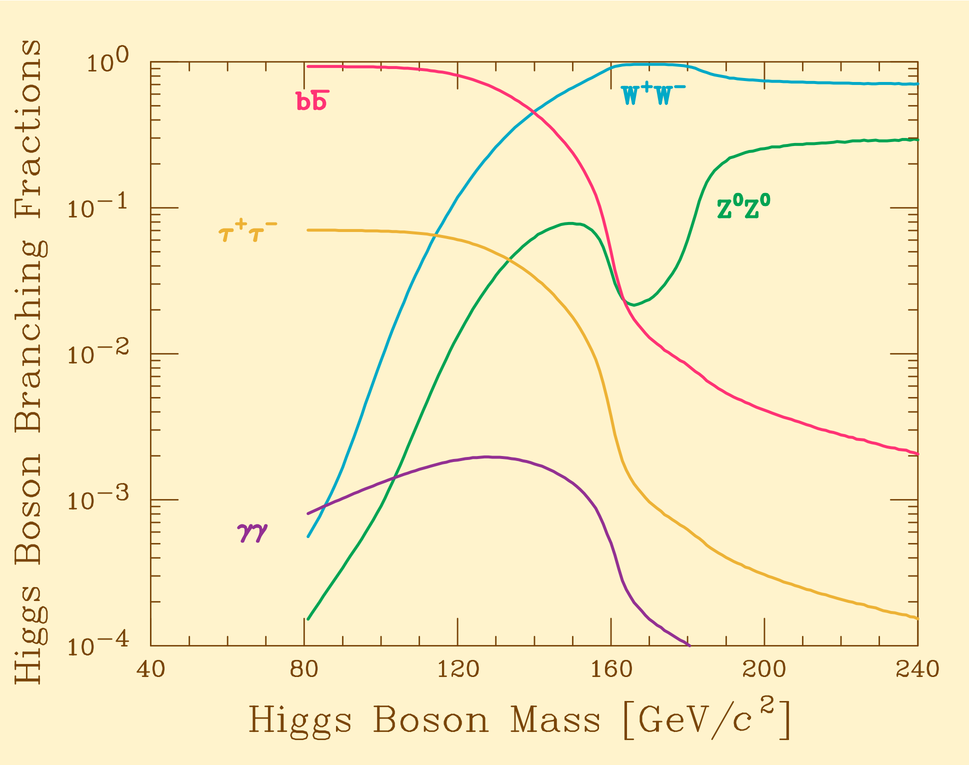
$$\Gamma(H \to Z^0Z^0) = \frac{G_F M_H^3}{64\pi\sqrt{2}}(1-x')^{1/2}(4-4x'+3x'^2)$$

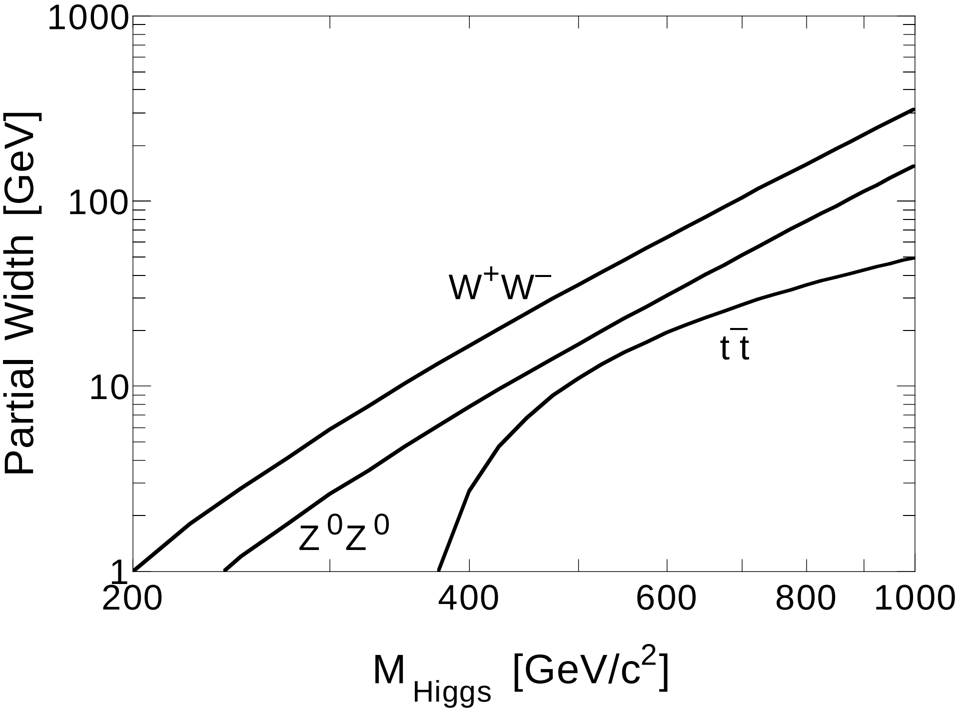
$$x' \equiv 4M_Z^2/M_H^2$$

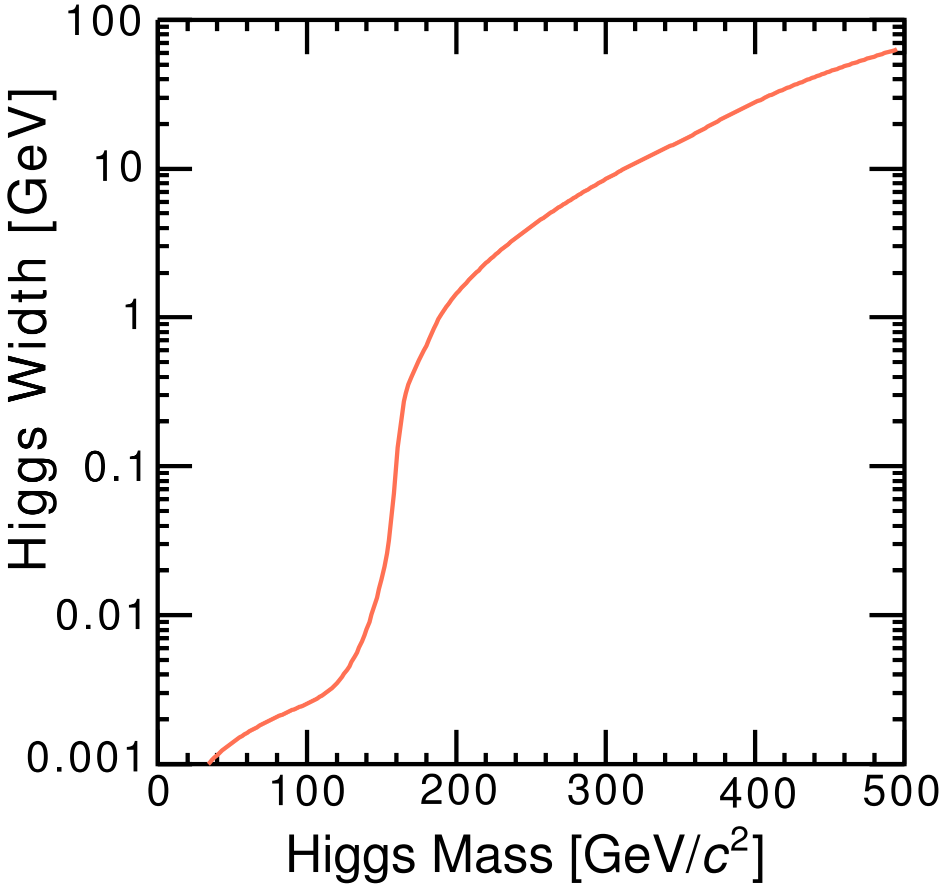
asymptotically $\propto M_H^3$ and $\frac{1}{2}M_H^3$, respectively
($\frac{1}{2}$ from weak isospin)

$2x^2$ and $2x'^2$ terms ⇔ decays into transversely polarized gauge bosons

Dominant decays for large M_H into pairs of longitudinally polarized weak bosons


Higgs Boson Branching Fractions
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$b\bar{b}$
W^+W^-
Z^0Z^0
$\tau^+\tau^-$
$\gamma\gamma$
40
80
120
160
200
240
Higgs Boson Mass [GeV/c^2]


Partial Width [GeV]
1000
100
10
1
W^+W^-
Z^0Z^0
$t\bar{t}$
200
400
600
800
1000
M_{Higgs} [GeV/c^2]



Below W^+W^- threshold, $\Gamma_H \lesssim 1$ GeV

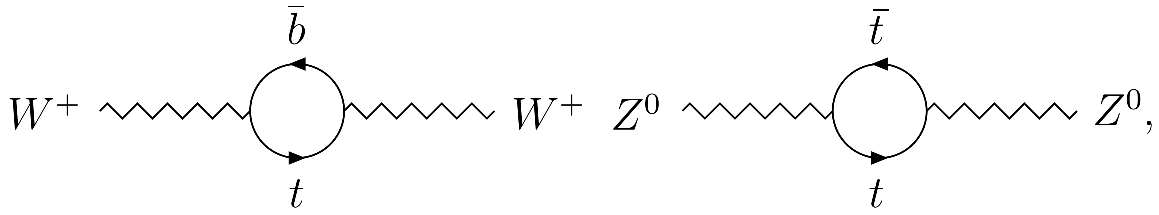
Far above W^+W^- threshold, $\Gamma_H \propto M_H^3$

For $M_H \to 1$ TeV/c^2, Higgs boson is an *ephemeron*, with a perturbative width approaching its mass.

Clues to the Higgs-boson mass

Sensitivity of EW observables to m_t gave early indications for massive top

quantum corrections to SM predictions for M_W and M_Z arise from different quark loops



…alter link between the M_W and M_Z:

$$M_W^2 = M_Z^2 \left(1 - \sin^2\theta_W\right)(1 + \Delta\rho)$$

where $\Delta\rho \approx \Delta\rho^{(\text{quarks})} = 3G_F m_t^2 / 8\pi^2\sqrt{2}$

strong dependence on m_t^2 accounts for precision of m_t estimates derived from EW observables

m_t known to $\pm 3\%$ from Tevatron …

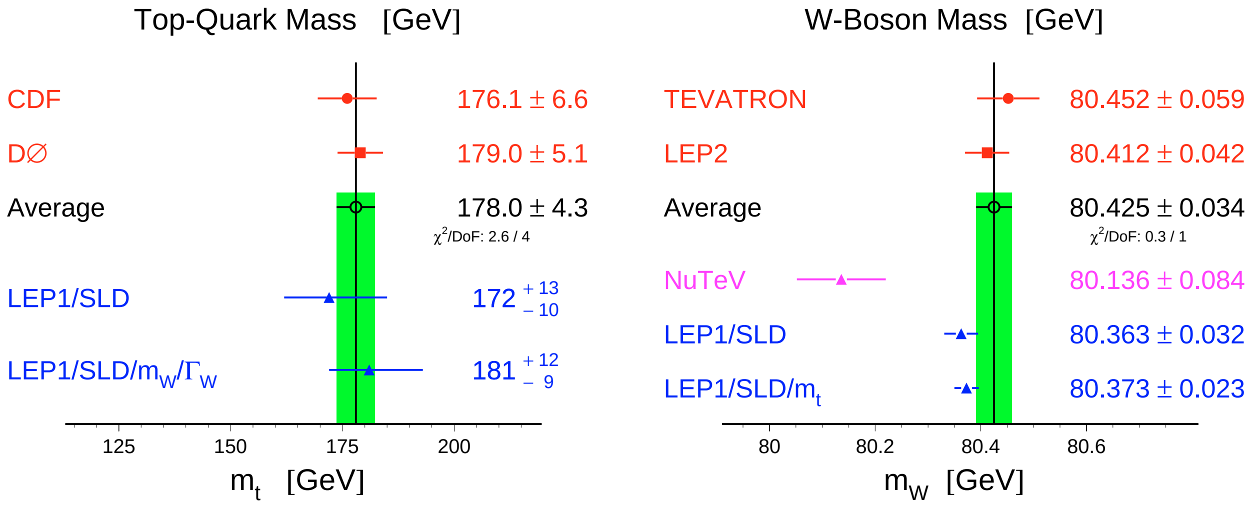
$\Longrightarrow$ look beyond the quark loops to next most important quantum corrections:

Higgs-boson effects

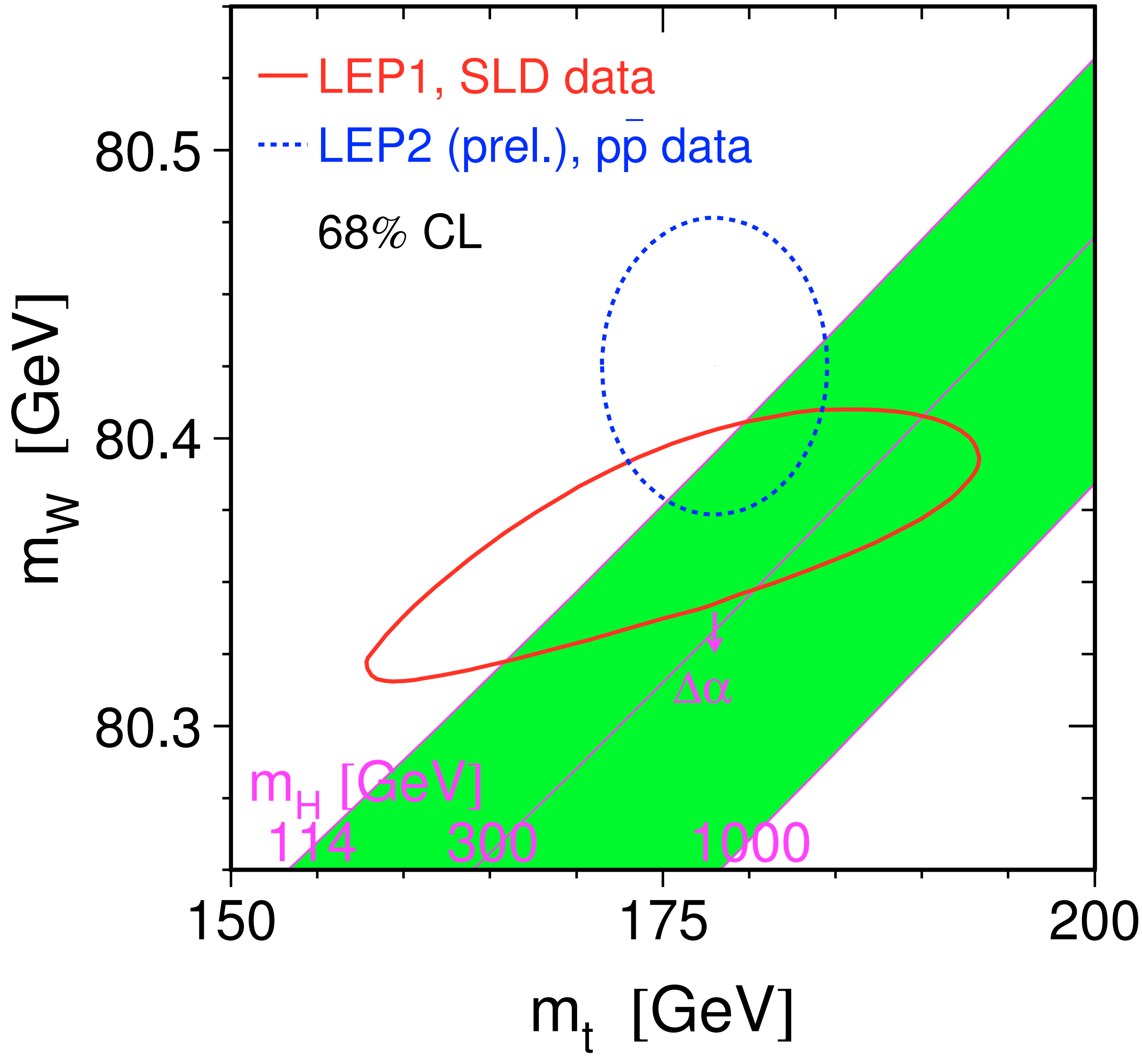
H quantum corrections smaller than t corrections, exhibit more subtle dependence on M_H than the m_t^2 dependence of the top-quark corrections

$$\Delta\rho^{(\mathrm{Higgs})} = \mathcal{C} \cdot \ln\left(\frac{M_H}{v}\right)$$

M_Z known to 23 ppm, m_t and M_W well measured



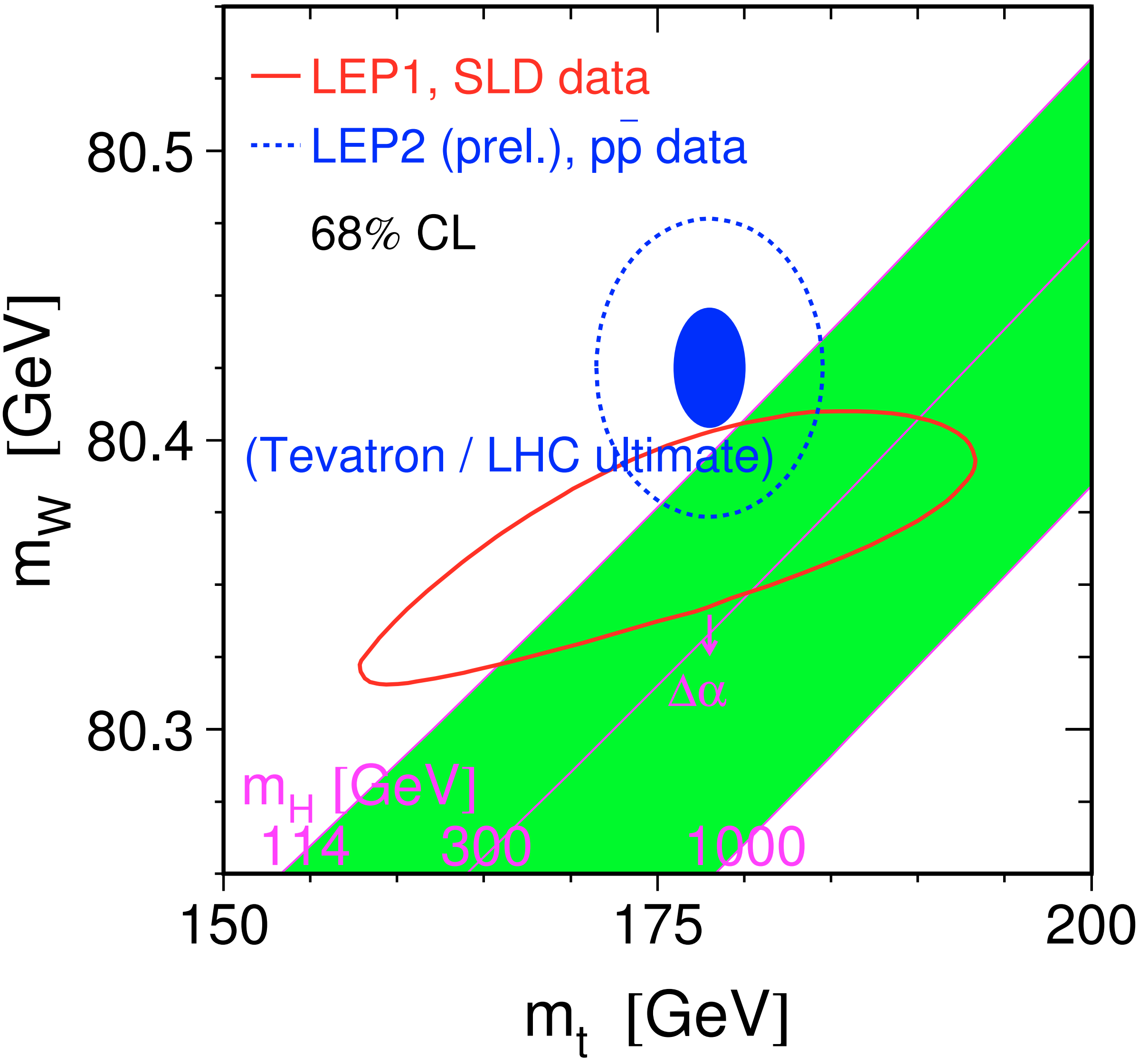
so examine dependence of M_W upon m_t and M_H



Direct, indirect determinations agree reasonably

Both favor a light Higgs boson,

within framework of SM analysis.



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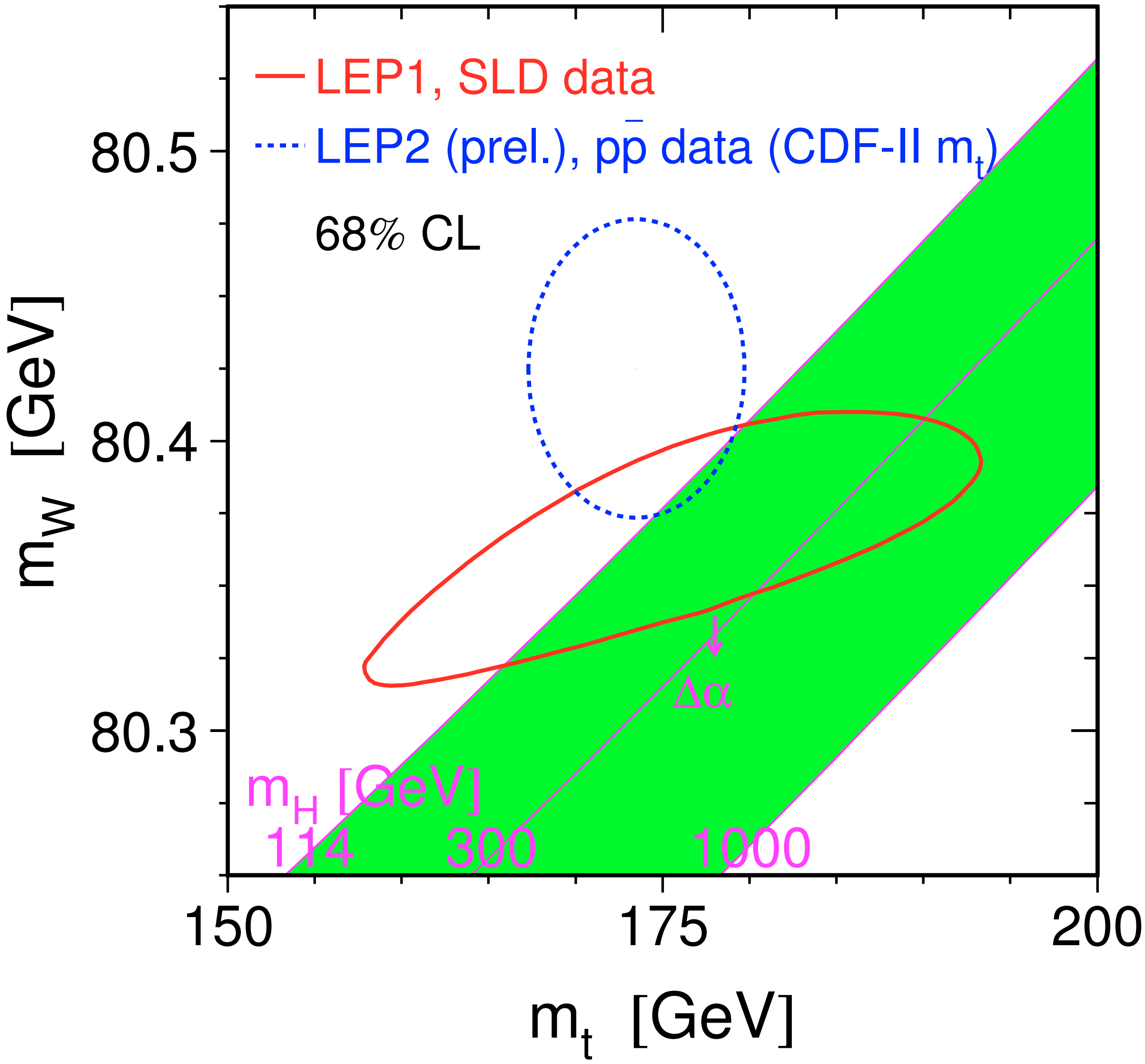

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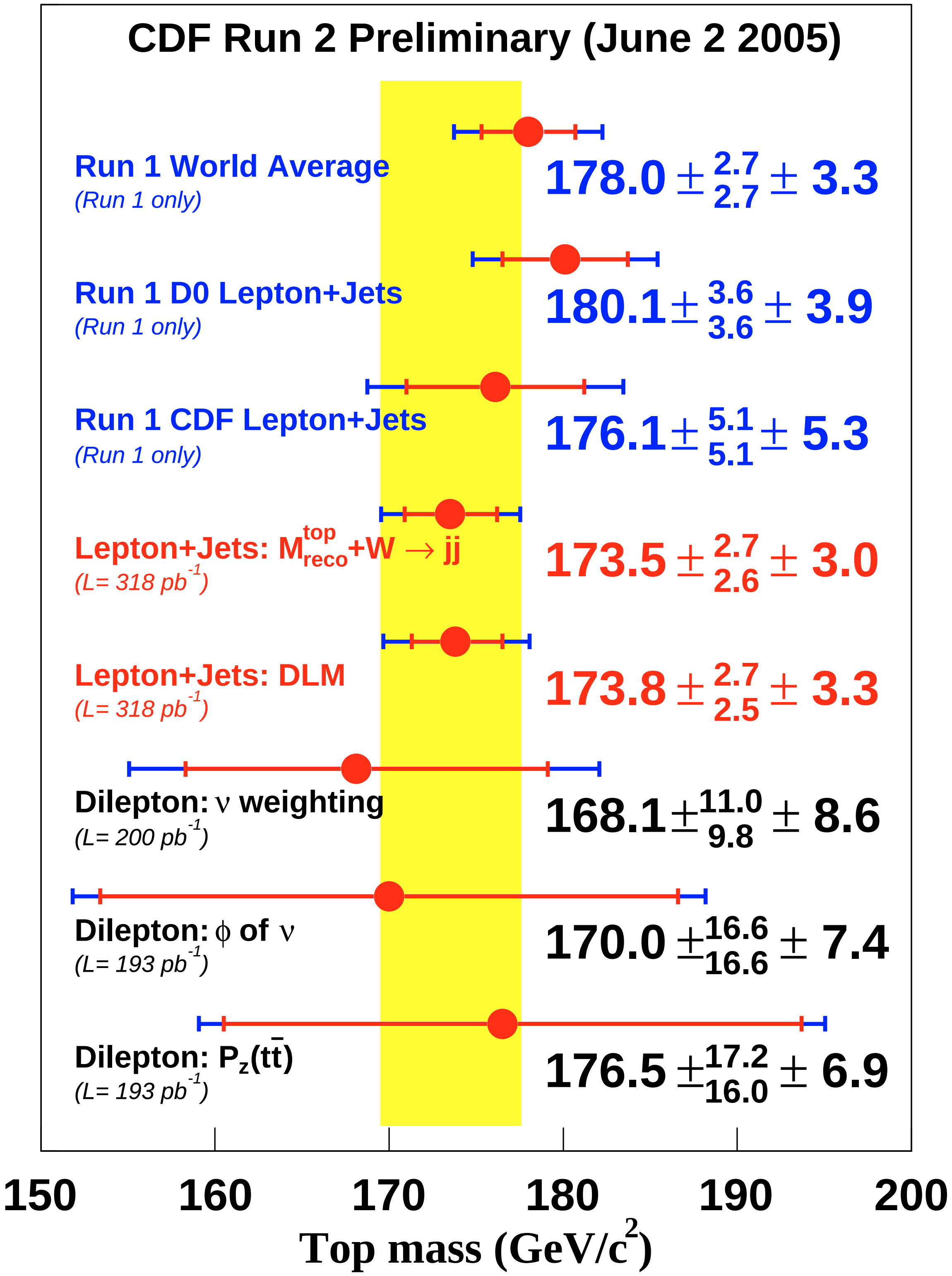
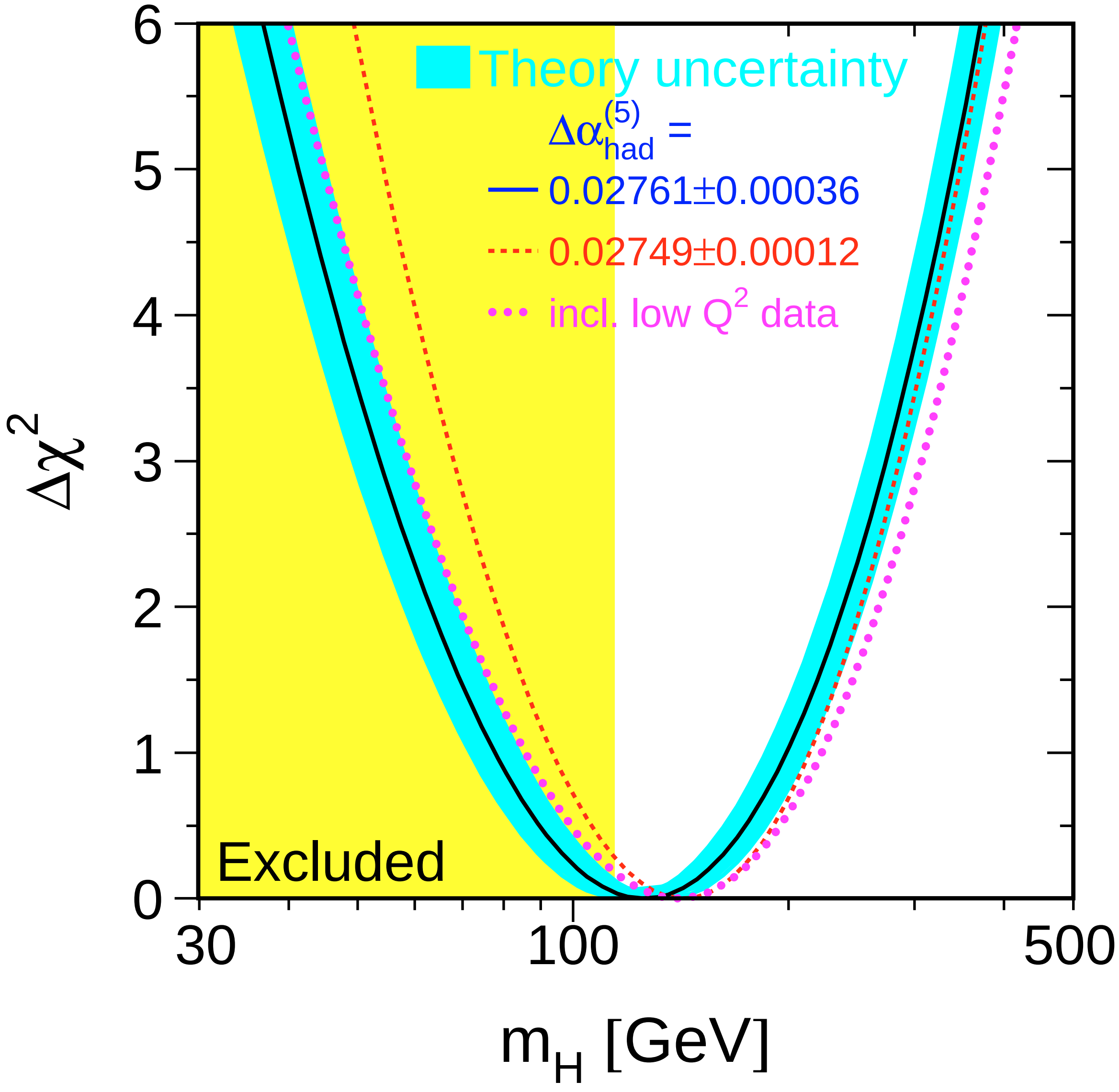
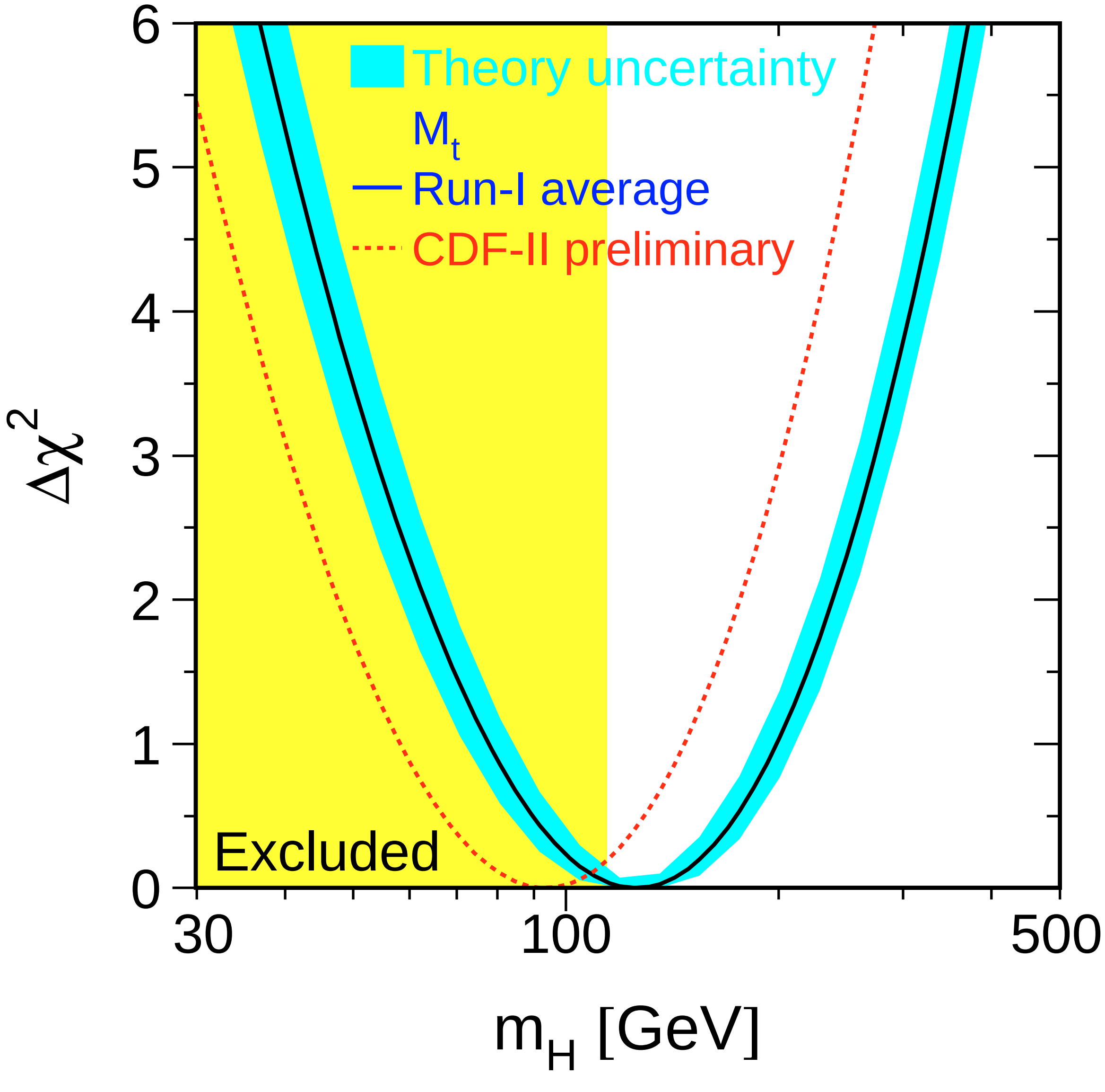

CDF Run 2 Preliminary (June 2 2005)
Run 1 World Average
(Run 1 only)
178.0 ± $^{2.7}_{2.7}$ ± 3.3
Run 1 D0 Lepton+Jets
(Run 1 only)
180.1 ± $^{3.6}_{3.6}$ ± 3.9
Run 1 CDF Lepton+Jets
(Run 1 only)
176.1 ± $^{5.1}_{5.1}$ ± 5.3
Lepton+Jets: M^{top}_{reco}+W → jj
(L= 318 pb^{-1})
173.5 ± $^{2.7}_{2.6}$ ± 3.0
Lepton+Jets: DLM
(L= 318 pb^{-1})
173.8 ± $^{2.7}_{2.5}$ ± 3.3
Dilepton: ν weighting
(L= 200 pb^{-1})
168.1 ± $^{11.0}_{9.8}$ ± 8.6
Dilepton: φ of ν
(L= 193 pb^{-1})
170.0 ± $^{16.6}_{16.6}$ ± 7.4
Dilepton: $P_z(t\bar{t})$
(L= 193 pb^{-1})
176.5 ± $^{17.2}_{16.0}$ ± 6.9
150
160
170
180
190
200
Top mass (GeV/c^2)

Fit to a universe of data



Fit to a universe of data



Within SM, LEPEWWG deduce a 95% CL upper limit, $M_H \lesssim 280$ GeV/c^2.

Direct searches at LEP $\Rightarrow M_H > 114.4$ GeV/c^2, excluding much of the favored region

either the Higgs boson is just around the corner, or SM analysis is misleading

Things will soon be popping!

Expect progress from M_W-m_t-M_H correlation

- ▷ Tevatron and LHC measurements will determine m_t within 1 or 2 GeV/c^2
- ▷ . . . and improve δM_W to about 15 MeV/c^2
- ▷ As the Tevatron's integrated luminosity approaches 10 fb^{-1}, CDF and DØ will begin to explore the region of M_H not excluded by LEP
- ▷ ATLAS and CMS will carry on the exploration of the Higgs sector at the LHC

Assessment

25 YEARS OF CONFIRMATIONS OF $SU(2)_L \otimes U(1)_Y$

- ⋆ neutral currents
- ⋆ $W^{\pm}$, Z^0
- ⋆ charm

(+ experimental guidance)

- ⋆ τ, ν_τ
- ⋆ b, t

+ experimental surprises

- ⋆ narrowness of ψ, ψ'
- ⋆ long B lifetime
- ⋆ large B^0–$\bar{B}^0$ mixing
- ⋆ heavy top
- ⋆ neutrino oscillations

10 YEARS OF PRECISION MEASUREMENTS. . .
. . . FIND NO SIGNIFICANT DEVIATIONS

QUANTUM CORRECTIONS TESTED AT $\pm 10^{-3}$

NO “NEW” PHYSICS . . . YET!

Theory tested at distances
from 10^{-17} cm
to $\sim 10^{22}$ cm

origin Coulomb's law (tabletop experiments)

smaller $\left\{ \begin{array}{l} \text{Atomic physics} \to \text{QED} \\ \text{high-energy experiments} \to \text{EW theory} \end{array} \right.$

larger $M_\gamma \approx 0$ in planetary . . . measurements

IS EW THEORY TRUE ?
COMPLETE ??

EWSB: another path?

Modeled EWSB on Ginzburg–Landau description of SC phase transition

had to introduce new, elementary scalars

GL is not the last word on superconductivity: *dynamical* Bardeen–Cooper–Schrieffer theory

The elementary fermions—electrons—and gauge interactions—QED—needed to generate the scalar bound states are already present in the case of superconductivity. Could a scheme of similar economy account for EWSB?

$\boxed{SU(3)_c \otimes SU(2)_L \otimes U(1)_Y + \text{massless } u \text{ and } d}$

Treat $SU(2)_L \otimes U(1)_Y$ as perturbation

$m_u = m_d = 0$: QCD has exact $SU(2)_L \otimes SU(2)_R$ chiral symmetry. At an energy scale $\sim \Lambda_{\text{QCD}}$, strong interactions become strong, fermion condensates appear, and $SU(2)_L \otimes SU(2)_R \to SU(2)_V$

$\Longrightarrow$ 3 Goldstone bosons, one for each broken generator: 3 massless pions (Nambu)

Broken generators: 3 axial currents; couplings to π measured by pion decay constant f_π

Turn on $SU(2)_L \otimes U(1)_Y$: EW gauge bosons couple to axial currents, acquire masses of order $\sim gf_\pi$

$$\mathcal{M}^2 = \begin{pmatrix} g^2 & 0 & 0 & 0 \\ 0 & g^2 & 0 & 0 \\ 0 & 0 & g^2 & gg' \\ 0 & 0 & gg' & g'^2 \end{pmatrix} \frac{f_\pi^2}{4} \; ,$$

$(W^+, W^-, W_3, \mathcal{A})$

same structure as standard EW theory. Diagonalize: $M_W^2 = g^2 f_\pi^2/4$, $M_Z^2 = (g^2 + g'^2) f_\pi^2/4$, $M_A^2 = 0$, so

$$\frac{M_Z^2}{M_W^2} = \frac{(g^2 + g'^2)}{g^2} = \frac{1}{\cos^2 \theta_W}$$

Massless pions disappear from physical spectrum, to become longitudinal components of weak bosons

$$\boxed{M_W \approx 30 \text{ MeV}/c^2}$$

With no Higgs mechanism . . .

▷ Quarks and leptons would remain massless

▷ QCD would confine them in color-singlet hadrons

▷ *Nucleon mass would be little changed,* but proton outweighs neutron

▷ QCD breaks EW symmetry, gives $(1/2500\times$observed) masses to W, Z, so weak-isospin force doesn't confine

▷ Rapid! β-decay ⇒ lightest nucleus is one neutron; no hydrogen atom

▷ Probably some light elements in BBN, but ∞ Bohr radius

▷ No atoms (as we know them) means no chemistry, no stable composite structures like the solids and liquids we know

. . . the character of the physical world would be profoundly changed

In a decade or two, we can hope to . . .

Understand electroweak symmetry breaking

Observe the Higgs boson

Measure neutrino masses and mixings

Establish Majorana neutrinos ($\beta\beta_{0\nu}$)

Thoroughly explore CP violation in B decays

Exploit rare decays (K, D, . . .)

Observe neutron EDM, pursue electron EDM

Use top as a tool

Observe new phases of matter

Understand hadron structure quantitatively

Uncover QCD's full implications

Observe proton decay

Understand the baryon excess

Catalogue matter and energy of the universe

Measure dark energy equation of state

Search for new macroscopic forces

Determine GUT symmetry

Detect neutrinos from the universe

Learn how to quantize gravity

Learn why empty space is nearly weightless

Test the inflation hypothesis

Understand discrete symmetry violation

Resolve the hierarchy problem

Discover new gauge forces

Directly detect dark-matter particles

Explore extra spatial dimensions

Understand the origin of large-scale structure

Observe gravitational radiation

Solve the strong CP problem

Learn whether supersymmetry is TeV-scale

Seek TeV-scale dynamical symmetry breaking

Search for new strong dynamics

Explain the highest-energy cosmic rays

Formulate problem of identity

. . .

. . . and learn to ask the right questions

Appendix: The EW scale and beyond

EWSB scale, $v = (G_F\sqrt{2})^{-\frac{1}{2}} \approx 246$ GeV, sets

$$M_W^2 = g^2 v^2/2 \qquad M_Z^2 = M_W^2/\cos^2\theta_W$$

But it is not the only scale of physical interest

quasi-certain: $M_{\text{Planck}} = 1.22 \times 10^{19}$ GeV

probable: $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ unification scale $\sim 10^{15-16}$ GeV

somewhere: flavor scale

How to keep the distant scales from mixing in the face of quantum corrections?

OR

How to stabilize the mass of the Higgs boson on the electroweak scale?

OR

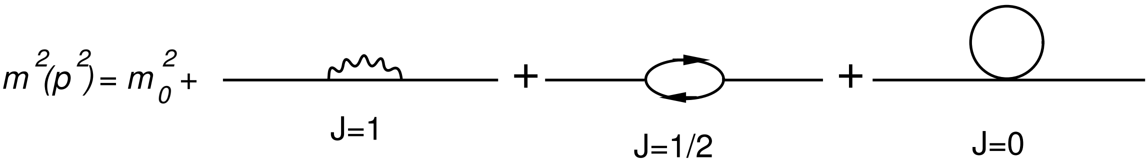
Why is the electroweak scale small?

Higgs potential $V(\phi^\dagger\phi) = \mu^2(\phi^\dagger\phi) + |\lambda|\,(\phi^\dagger\phi)^2$

$\mu^2 < 0$: $SU(2)_L \otimes U(1)_Y \to U(1)_{\text{em}}$, as

$$\langle\phi\rangle_0 = \begin{pmatrix} 0 \\ \sqrt{-\mu^2/2|\lambda|} \end{pmatrix} \equiv \begin{pmatrix} 0 \\ \underbrace{(G_F\sqrt{8})^{-1/2}}_{175\ \text{GeV}} \end{pmatrix}$$

Beyond classical approximation, quantum corrections to scalar mass parameters:



Loop integrals are potentially divergent.

$$m^2(p^2) = m^2(\Lambda^2) + Cg^2 \int_{p^2}^{\Lambda^2} dk^2 + \cdots$$

Λ: reference scale at which m^2 is known

g: coupling constant of the theory

C: coefficient calculable in specific theory

$$m^2(p^2) = m^2(\Lambda^2) + Cg^2 \int_{p^2}^{\Lambda^2} dk^2 + \cdots$$

For the mass shifts induced by radiative corrections to remain under control (not greatly exceed the value measured on the laboratory scale), *either*

- ▷ Λ must be small, *or*
- ▷ new physics must intervene to cut off the integral

BUT natural reference scale for Λ is

$$\Lambda \sim M_{\text{Planck}} = \left(\frac{\hbar c}{G_{\text{Newton}}}\right)^{1/2} \approx 1.22 \times 10^{19}\ \text{GeV}$$

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

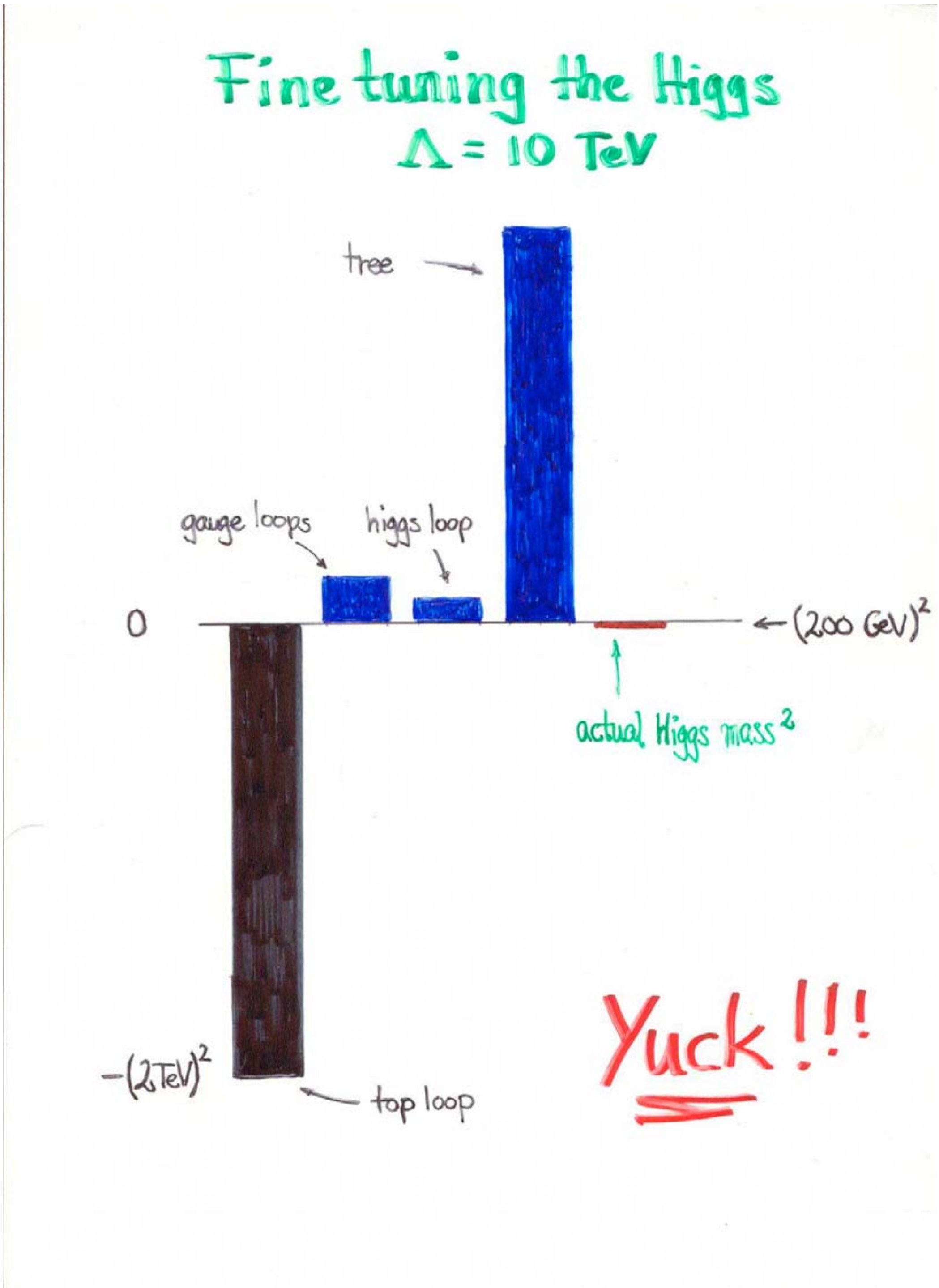
OR

$$\Lambda \sim M_U \approx 10^{15}\text{-}10^{16}\ \text{GeV}$$

for unified theory

Both $\gg v/\sqrt{2} \approx 175$ GeV $\Longrightarrow$

$\boxed{\text{New Physics at } E \lesssim 1 \text{ TeV}}$



Martin Schmaltz, ICHEP02

Only a few distinct scenarios . . .

▷ Supersymmetry: balance contributions of fermion loops (-1) and boson loops $(+1)$

Exact supersymmetry,

$$\sum_{i=\substack{\text{fermions}\\+\text{bosons}}} C_i \int dk^2 = 0$$

Broken supersymmetry, shifts acceptably small if superpartner mass splittings are not too large

$g^2 \Delta M^2$ "small enough" $\Rightarrow \widetilde{M} \lesssim 1$ TeV/c^2

▷ Composite scalars (technicolor): New physics arises on scale of composite Higgs-boson binding,

$$\Lambda_{\mathrm{TC}} \simeq O(1\ \text{TeV})$$

"Form factor" cuts effective range of integration

▷ Strongly interacting gauge sector: WW resonances, multiple W production, probably scalar bound state "quasiHiggs" with $M < 1$ TeV

▷ Extra spacetime dimensions: pseudo-Nambu–Goldstone bosons, extra particles to cancel integrand, . . .