Phenomenology

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LPTHE, Universities of Paris VI and VII and CNRS

BUSSTEPP
Ambleside, August 2005

What is phenomenology?

Google `define: phenomenology`

- a philosophy that puts experience above conceptualizations about it
- the branch of existentialism which deals with phenomena with no attempt at explanation.
- a philosophical doctrine [...] in which considerations of objective reality are not taken into account

Google: phenomenology

Phenomenologists tend to oppose the acceptance of unobservable matters and grand systems erected in speculative thinking;

[Center for advanced research in phenomenology]

WIKIPEDIA:

Phenomenology is a current in philosophy that takes intuitive experience of phenomena (what presents itself to us in conscious experience) as its starting point and tries to extract the essential features of experiences and the essence of what we experience.

[early 20th century philosophers: Husserl, Merleau-Ponty, Heidegger]

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Stop Press

BUSSTEPP 2005

Particle physics phenomenology makes it to 10^{th} place on google search!

(Madison phenomenology institute
`www.pheno.info`)

'Phenomenology' Nobel Prizes

Theorists:

- 2005: David Gross, David Politzer, Frank Wilczek *for the discovery of asymptotic freedom in the theory of the strong interaction.*
- 1999: Gerardus 't Hooft, Martinus Veltman *for elucidating the quantum structure of electroweak interactions in physics.*
- 1979 Sheldon Glashow, Abdus Salam and Steven Weinberg *for their contributions to the theory of the unified weak and electromagnetic interaction...*

Experimenters

- 1995: Martin Perl, Frederick Reines *for pioneering experimental contributions to lepton physics.*
- 1988: Leon Lederman, Melvin Schwartz and Jack Steinberger *for the [...] demonstration of the doublet structure of the leptons through discovery of the muon ν.*
- 1984: Carlo Rubbia and Simon van der Meer *for their decisive contributions to the project which led to the discovery of the [W & Z].*
- 1980: James Cronin and Val Fitch *for the discovery of violations of fundamental symmetry principles in the decay of neutral K-mesons.*
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Our definition of phenomenology

Approach to high-energy physics that seeks to further our knowledge by

- exploiting the hints and clues available from observable phenomena (experimental data), as well as consistency arguments;
- working around / parametrizing those aspects of our theories for which we as yet have no fundamental understanding.

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Do it in context of Standard Model

Two gauge sectors:

- Electroweak ($U(1) \otimes SU(2)$, $\gamma, Z, W^{\pm}$)
- Strong ($SU(3)$ colour, 8 gluons).

Two matter sectors:

- leptons (just EW interactions)
- quarks (EW and Strong)
- mass and interaction matrices different (CKM)

Higgs sector:

- breaks $U(1) \otimes SU(2)$ symmetry
- gives masses to gauge and matter sectors
- without breaking gauge invariance

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H NOT YET DISCOVERED!

Overview of these lectures

- Refresh/explain some basic aspects of the standard model.
  - Lecture 1 (1st half)
- Acquaint you with one of the main phenomenological 'activities' in the EW sector, Higgs physics
  - Lecture 1 (2nd half): indirect knowledge of the Higgs
  - Lecture 2: Higgs hunting at today's colliders

Illustrate prinicple components of any search for new physics

- Discuss common QCD issues that arise repeatedly in such studies and provide a QCD 'sampler'.
  - Lecture 3: basic concepts of QCD (running coupling, infrared safety), jets
  - Lecture 4: processes with incoming hadrons

Tevatron, HERA, LHC are all hadronic colliders; QCD unavoidable

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Recall QED

Lagrangian

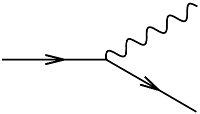
$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{\psi}(i\not{D} - m_e)\psi\,, \quad F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu\,, \quad D_\mu = \partial_\mu + ieA_\mu$$

$$\not{D} = \gamma^\mu D_\mu$$

Gauge invariance:

$$\psi(x) \to \psi'(x) = e^{i\theta(x)}\psi(x) \qquad A_\mu(x) \to A'_\mu(x) = A_\mu(x) - \frac{1}{e}\partial_\mu\theta(x)$$

Feynman rules (interactions)



$ie\gamma^\mu$

SU(2)⊗U(1)

SU(2) fields: W^i_μ $(i = 1 \ldots 3)$; U(1) field: B_μ

$$\mathcal{L}_{gauge} = -\frac{1}{4} W^{i\,\mu\nu} W^i_{\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu}$$

$$W^i_{\mu\nu} = \partial_\mu W^i_\nu - \partial_\nu W^i_\mu - g_W \epsilon^{ijk} W^j_\mu W^k_\nu \,, \quad B^{\mu\nu} = \partial^\mu B^\nu - \partial^\nu B^\mu$$

Covariant derivative:

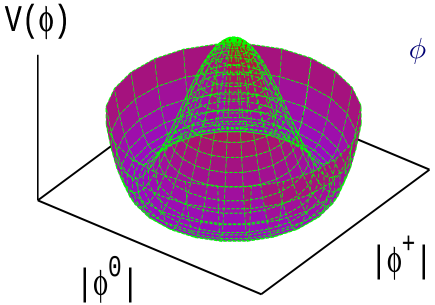
$$D^\mu = \delta_{ij} \partial^\mu + i g_W (T \cdot W^\mu)_{ij} + i Y \delta_{ij} g'_W B^\mu$$

- matrices T_{ij} depend on representation for weak isospin;

$$[T^i, T^j] = i\epsilon^{ijk} T^k \,; W^\pm_\mu = (W^1_\mu \mp i W^2_\mu)/\sqrt{2} \,, \; T^\pm = T^1 \pm i T^2;$$

  Doublet representation: T^i are the Pauli matrices.
- Y = weak hypercharge;
- two coupling constants g_W and g'_W.

Higgs mechanism



Higgs fields: complex scalar doublet

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \ \mathcal{L}_H = (D^\mu \phi)^\dagger (D_\mu \phi) - V(\phi)$$

Potential has form

$$V(\phi) = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

which leads to a *Vacuum Expectation Value (VEV): $|\phi| = \sqrt{\mu^2/2\lambda} = v/\sqrt{2}$.*

SU(2) symmetry of configurations with $|\phi| = v/\sqrt{2}$. Choose gauge transformation (unitary gauge) to map

$$\phi \to \begin{pmatrix} 0 \\ (v+H)/\sqrt{2} \end{pmatrix}$$

Higgs Mechanism (cont.)

Higgs sector of Lagrangian becomes:

$$\mathcal{L}_H = \frac{1}{2}\partial_\mu H \partial^\mu H - V((v+H)/\sqrt{2}) +$$
$$\frac{(v+H)^2}{8}\left[(g_W W^3_\mu - g'_W B_\mu)(g_W W^{3\,\mu} - g'_W B^\mu) + 2g_W^2 W^-_\mu W^{+\mu}\right]$$

Diagonalise W^3, B:

$$\begin{pmatrix} W^3_\mu \\ B_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix}, \quad \sin^2\theta_W = \frac{{g'_W}^2}{g_W^2 + {g'_W}^2} \simeq 0.23$$

See mass terms for $W^\pm$ and Z:

$$\mathcal{L}_M = \frac{g_W^2 v^2}{4} W^+_\mu W^{-\,\mu} + \frac{(g_W^2 + {g'_W}^2)v^2}{8} Z_\mu Z^\mu \,,$$

$$\Rightarrow M_W = \frac{1}{2} v g_W \,, \quad M_Z = \frac{M_W}{\cos\theta_W}, \quad \frac{g_W^2}{8m_W^2} \equiv \frac{1}{2v^2} = \frac{G_F}{\sqrt{2}}, \quad v = 246 \text{ GeV}$$

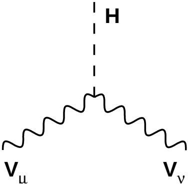
Boson Couplings

Higgs couplings

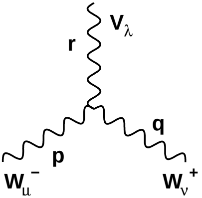
$$\mathcal{L}_{Higgs} = \frac{1}{2}\partial_\mu H \partial^\mu H - \mu^2 H^2 - \lambda v H^3 - \frac{1}{4}\lambda H^4 , \quad M_H = \sqrt{2}\mu \equiv \sqrt{2\lambda} v$$

VEV (v) is known from G_F. Higgs mass is unpredicted.

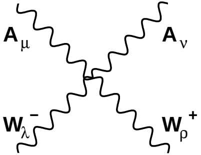
Also have a range of couplings between bosons, *e.g.*



$+g_{VH} M_W g_{\mu\nu}$
$(g_{WH} = g_W,$
$g_{ZH} = \frac{g_W}{\cos^2\theta_W})$



$ig_V[(p-q)_\lambda g_{\mu\nu} + \text{cycl.}]$
$(g_A = e = g_W \sin\theta_W,$
$g_Z = g_W \cos\theta_W)$



$-ie^2[2g_{\mu\nu}g_{\lambda\rho} -$
$g_{\mu\lambda}g_{\nu\rho} - g_{\mu\rho}g_{\lambda\nu}]$

Fermion Sector

$$\mathcal{L}_F = \bar{\psi}_R i(\partial\!\!\!/ + i g'_W Y_R \; B\!\!\!/)\psi_R + \bar{\Psi}_L i(\partial\!\!\!/ + i g_W T \, W\!\!\!\!/ + i g'_W Y_L \; B\!\!\!/)\Psi_L$$
$$- y_u \bar{\Psi}_L \psi_{u,R} \tilde{\phi} - y_d \bar{\Psi}_L \psi_{d,R} \phi - \text{h.c.}$$

$$\psi_{L/R} = \frac{1 \mp \gamma_5}{2}\psi \,, \qquad \Psi = \begin{pmatrix} \psi_u \\ \psi_d \end{pmatrix} \qquad \tilde{\phi} = \begin{pmatrix} \phi^{0*} \\ \phi^{+*} \end{pmatrix}$$

Fermion			T_L^3	Y_L	T_R^3	Y_R	q_i
u	c	t	$+\frac{1}{2}$	$+\frac{1}{6}$	0	$+\frac{2}{3}$	$+\frac{2}{3}$
d	s	b	$-\frac{1}{2}$	$+\frac{1}{6}$	0	$-\frac{1}{3}$	$+\frac{1}{3}$
ν_e	ν_μ	ν_τ	$+\frac{1}{2}$	$-\frac{1}{2}$	0	-	-
e^-	μ^-	τ^-	$-\frac{1}{2}$	$-\frac{1}{2}$	0	-1	-1

i	y_i	i	y_i
u	$2 \cdot 10^{-5}$	d	$3 \cdot 10^{-5}$
c	$8 \cdot 10^{-3}$	s	$6 \cdot 10^{-4}$
b	$3 \cdot 10^{-2}$	t	1

ν_e	$\sim 10^{-13}$	e	$3 \cdot 10^{-6}$
ν_μ		μ	$6 \cdot 10^{-4}$
ν_τ		τ	$1 \cdot 10^{-2}$

Fermion Sector (symm. broken)

$$\mathcal{L}_F = \sum_i \bar{\psi}_i \left(i \not\partial - m_i - g_W \frac{m_i H}{2 M_W} \right) \psi_i \qquad \left[m_i = y_i \frac{v}{\sqrt{2}} \right]$$

$$- \frac{g_W}{2\sqrt{2}} \sum_f \bar{\Psi}_f \, \gamma^\mu \, (1 - \gamma^5)(T^+ \, W_\mu^+ + T^- \, W_\mu^-) \, \Psi_f$$

$$- e \sum_i q_i \, \bar{\psi}_i \, \gamma^\mu \, \psi_i \, A_\mu$$

$$- \frac{g_W}{2 \cos\theta_W} \sum_i \bar{\psi}_i \, \gamma^\mu (g_V^i - g_A^i \gamma^5) \, \psi_i \, Z_\mu$$

$$\psi_i = u, d, e, \nu_e, \ldots \qquad \Psi_f = \binom{u}{d'}, \binom{e}{\nu_e}, \ldots$$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}, \qquad g_V^i \equiv T_i^3 - 2 q_i \sin^2\theta_W, \quad g_A^i \equiv T_i^3$$

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Current EW issues

- Find the Higgs
- Pin down elements of CKM matrix
- Establish neutrino masses and mixing angles
- Check overall consistency of whole framework
  - Consistency of different measurements of $\sin^2\theta_W$
  - Unitarity of CKM matrix
  - Vector boson self couplings (*e.g.* WWZ)
  - Check Higgs really is *the* Higgs (*e.g.* self couplings)
  - ...
- OR: find hints of new physics
  - Supersymmetry
  - Large extra dimensions

$\rightarrow$ understanding of EW model parameters

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Concentrate on Higgs and consistency tests

If electroweak symmetry were not hidden . . .

▷ Quarks and leptons would remain massless

▷ QCD would confine them into 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

▷ Rapid! β-decay $\Rightarrow$ 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

C. Quigg, colloquium: 'The coming revolutions in particle physics'

Higgs Hunting

LHC collider ($\gtrsim$ £1bn) 'being built to find the Higgs'. Can this be a priori justified?

➥ Only if we 'know' that Higgs is within reach of the LHC.

But Higgs mass is unknown parameter of standard model:

$$M_H = \sqrt{2\lambda}v \qquad\qquad (v = 246\text{ GeV})$$

HOWEVER: λ is a coupling constant (of ϕ^4).

- If it's too large, theory is non-perturbative.
  - How big is too large?
  - What are the consequences if it is too large?
- If it's negative, Higgs model stops making sense (unstable vacuum)
  - Didn't we just make it positive by definition?

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Upper bound on M_H (rough guide)

λ satisfies a renormalisation group evolution equation:

$$32\pi^2 \frac{d\lambda}{dt} = 24\lambda^2 - (3g'^2 + 9g^2 - 12y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2 g^2 + \frac{9}{8}g^4 - 6y_t^4 + \dots$$

$$t = \ln(Q^2/Q_0^2)$$

For large λ, first term dominates; 1-loop evolution gives

$$\lambda(Q) = \frac{\lambda(Q_0)}{1 - \frac{3}{4\pi^2}\lambda(Q_0)\ln\left(\frac{Q^2}{Q_0^2}\right)}$$

If we fix value of λ at $Q_0^2 = v^2$, theory should remain perturbative at least up to $Q^2 = M_H^2 = 2\lambda v^2$:

$$M_H^2 \lesssim \frac{8\pi^2 v^2}{3\ln(M_H^2/v^2)}$$

Correct determination based on scattering of longitudinal $W^\pm, Z$ + unitarity constraints:

$M_H \lesssim 800$ GeV

(Alternative: interesting non-perturbative dynamics at TeV scale)

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For small λ (light Higgs), last term dominates:

$$\lambda(Q^2) = \lambda(Q_0^2) - \frac{3}{16\pi^2} y_t^4 \ln \frac{Q^2}{Q_0^2}$$

Take $Q_0^2 \sim M_H^2 \sim 2\lambda(Q_0^2)v^2$ and $Q^2 \sim m_t^2$ and require $\lambda(Q^2) > 0$:

$$M_H \gtrsim v\sqrt{\frac{3}{8\pi^2} \ln \frac{m_t^2}{M_H^2}} \quad \Longrightarrow \quad \boxed{M_H \gtrsim 70 \text{ GeV}}$$

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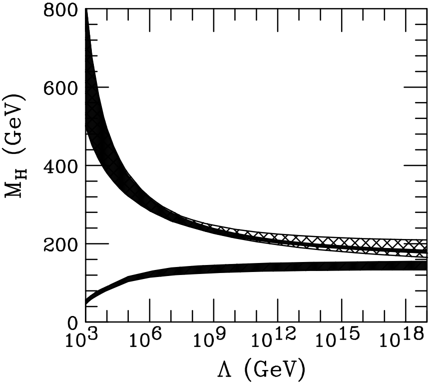
Putting it together



Hambye & Riesselmann, '96

Combined bounds for Higgs mass as a function of scale Λ up to which theory is perturbative and vaccum is stable.

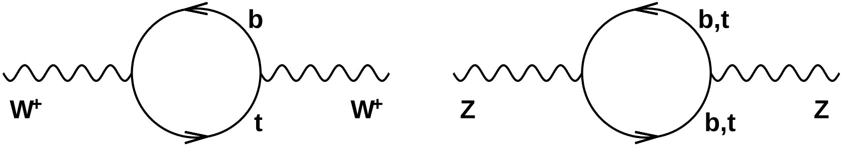
➥ Some degree of certainty (within SM) that if an experiment has a mass reach up to $\sim$ 1 TeV then it will either see the Higgs, or else something else.

Short of seeing the Higgs, can we do any better?

Indirect Higgs mass constraints

So far, presentation of standard model has been at tree level.

Relations between parameters are affected by loop corrections. E.g. relation between W, Z masses



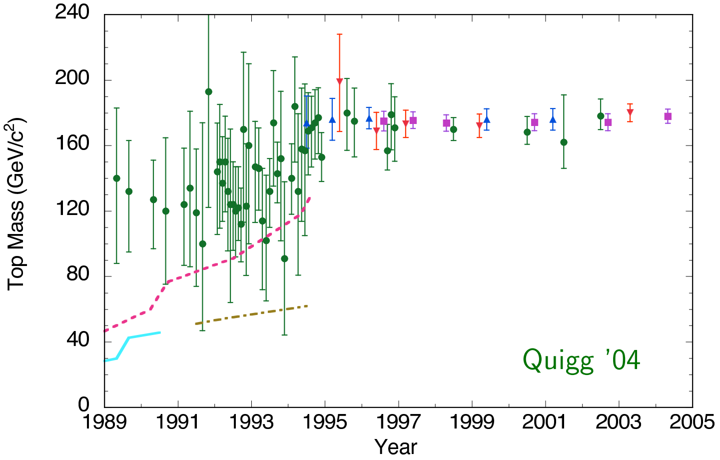
$$M_W^2 = M_Z^2(1 - \sin^2\theta_W)(1 + \Delta\rho) \qquad \Delta\rho \sim \Delta\rho_{quarks} \sim \frac{3 G_F m_t^2}{8\pi^2\sqrt{2}}$$

This correction (and others) dominated by top-quark mass

➥Precision electroweak measurements used to predict top mass before its discovery & check EW consistency since.

Top mass (excursion)

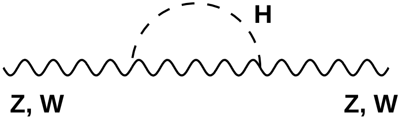
Indirect top-mass predictions & direct measurements v. time:



Try your hand at EW precision fits: see question on problem sheet!

Precision Indirect Higgs Mass

Try same trick to find Higgs mass:



$$\delta M_W^2 \sim \ln \frac{M_H}{M_W}$$

Much weaker dependence on M_H than on m_t.

➥Task is harder and requires as much EW precision data as you can get your hands on...

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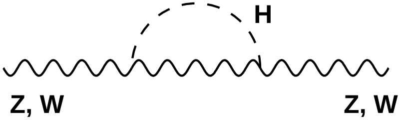

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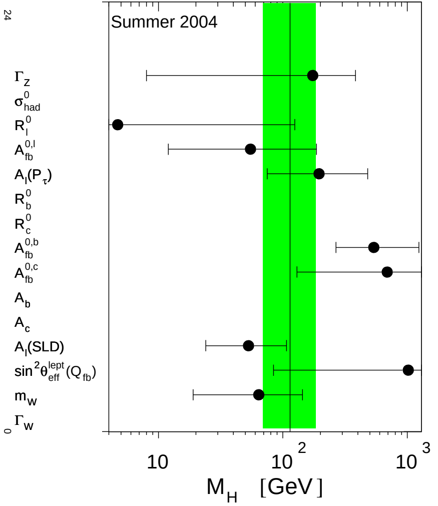
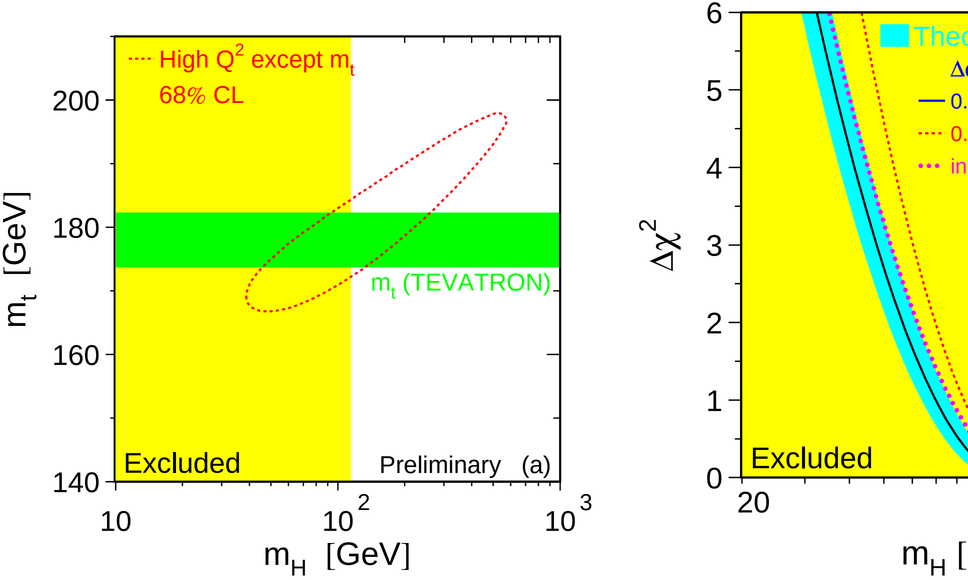


LEP+SLD EW Working Group '04 (adapted)

Precision Indirect Higgs Mass (cont.)



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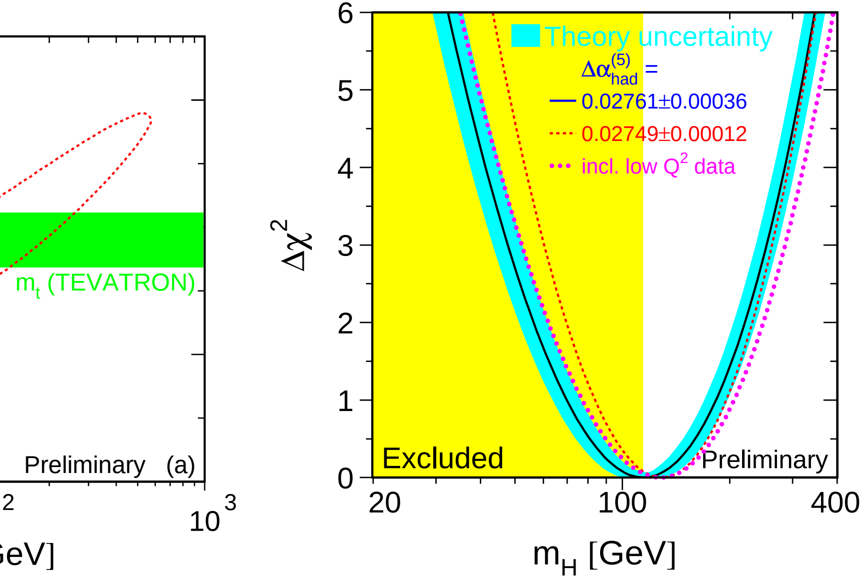

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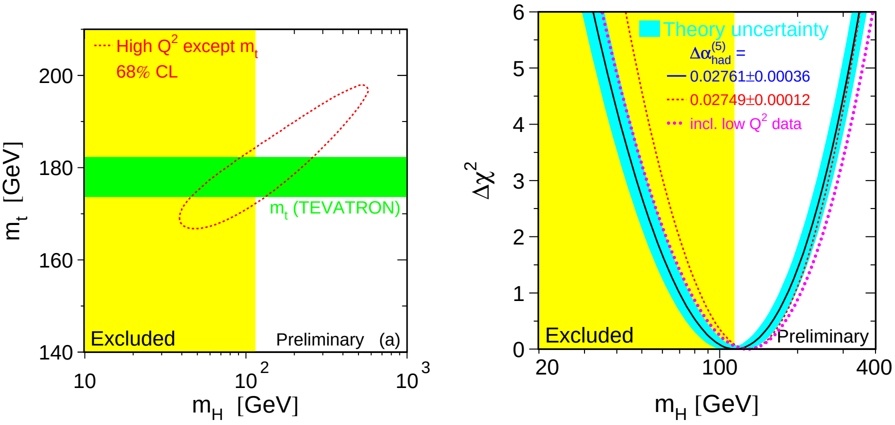
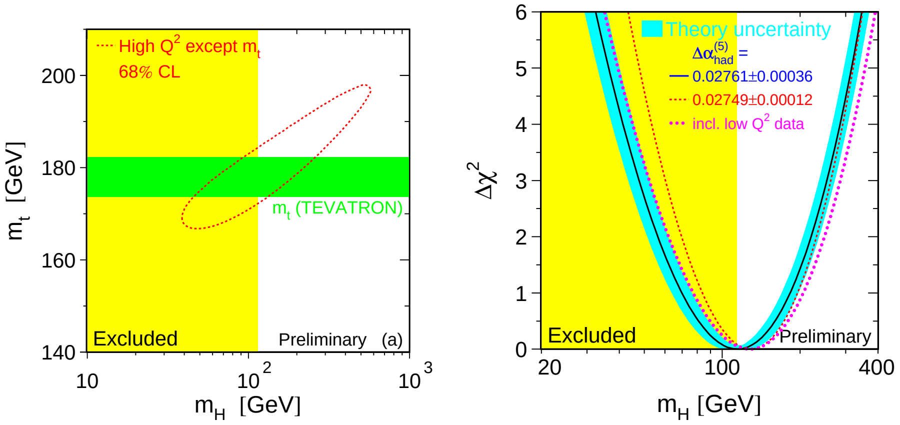


$M_H = 114^{+69}_{-45}$ GeV, $M_H < 260$ GeV @ 95% confidence level

LEP+SLD EWWG, summer '04 ($m_t \simeq 178.0 \pm 4.3$)

Precision Indirect Higgs Mass (cont.)



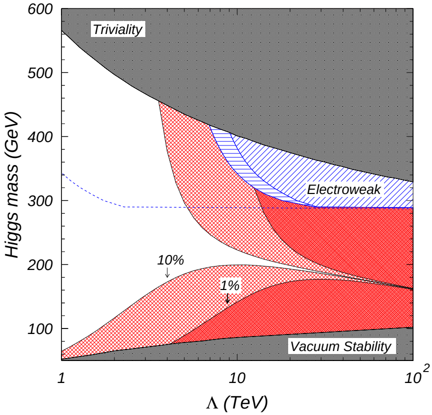
$M_H = 91^{+45}_{-32}$ GeV, $M_H < 186$ GeV @ 95% confidence level

LEP+SLD EWWG, summer '05 ($m_t = 172.7 \pm 2.9$)

Next lecture

Direct searches for the Higgs

Higgs Extras



Kolda & Murayama, '00

Renormalisation gives quadratically divergent corrections to Higgs mass:

$$M_H^2(M_H^2) = M_H^2(\Lambda^2) + \frac{g^2}{16\pi^2}\Lambda^2 \cdot \text{const.} + \text{H.O.}$$

If effective cutoff ($\equiv$ new physics) $\Lambda \gg M_H$, then there must be fine tuning.

This is basics of a main argument for new physics 'within reach'.