HIGGSOLOGY IN THE LHC ADVENT TIME

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A PRELUDE

A Big Question: Mechanism of ESB

- minimal SM Higgs sector → scalar Higgs boson
- alternative theories

Higgs: "To be or not to be..."

- LHC

OUTLINE

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1. ESSENTIALS OF THE STANDARD MODEL
2. Experimental Limits on the Minimal Higgs
3. If a Higgs is discovered
4. Summary

GAUGE PRINCIPLE

SM Lagrangian gauge symmetry:

$$\underset{\text{gluon octet}}{SU(3)} \times \underset{W\text{-triplet}}{SU(2)} \times \underset{B\text{-singlet}}{U(1)}$$

$$\downarrow \qquad\qquad \downarrow$$

$$\boxed{W^{\pm}, Z^{0}, A}$$

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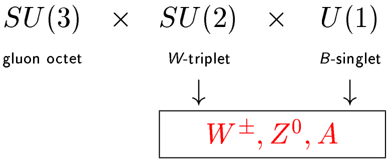

$SU(3) \quad \times \quad SU(2) \quad \times \quad U(1)$

gluon octet — W-triplet — B-singlet

$$\boxed{W^{\pm}, Z^0, A}$$

⇒ only massless gauge bosons

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EW part of SM Lagrangian is chiral:

- PARITY: left fermion ↔ right fermion
- left fermions:

  $SU(2)$-doublets, $U(1)$-singlets

  interact to W and B
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$\Rightarrow$ parity violation, only massless fermions

REALITY

massles SM particles:

- gauge bosons:
  photon, gluons
- fermions:
  e-neutrino(?)
  PDG 2007 world average:
  $m_{\nu_e}^2 = (-1.1 \pm 2.4)\text{eV}^2$ (^{3}H β-decay)

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remaining masses > 0 !!!

SPONTANEOUS SYMMETRY BREAKING (PRIME TIME)

if

the symmetry of Lagrangian (Hamiltonian) > the symmetry of the ground state (vacuum)

Spontaneous Symmetry Breaking (prime time)

if

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then

particle spectrum does not reflect the symmetry of the Lagrangian

SPONTANEOUS SYMMETRY BREAKING (LATE NIGHT)

$\hat{H}$ - Hamiltonian, G - symmetry Lie group:

$$|\psi\rangle \to \hat{U}|\psi\rangle, \qquad \hat{O} \to \hat{U}\hat{O}\hat{U}^\dagger$$

$$[\hat{H}, \hat{U}] = 0$$

G-invariant subspaces

$$|2\rangle = \hat{U}|1\rangle$$

are degenerated

$$\hat{H}|1\rangle = E|1\rangle, \qquad \hat{H}|2\rangle = E|2\rangle$$

SPONTANEOUS SYMMETRY BREAKING (LATE NIGHT)

QFT: $\hat{H} = \hat{H}(\hat{\phi}_1, \hat{\phi}_2)$

internal trafo $\hat{U} : \hat{\phi}_1 \to \hat{\phi}_2$

$$[\hat{H}, \hat{U}] = 0$$

$$\hat{a}_2^\dagger(\vec{p}) = \hat{U}\hat{a}_1^\dagger(\vec{p})\hat{U}^\dagger$$

$|1\rangle$, $|2\rangle$ = 1-particle states: $|i\rangle = \hat{a}_i^\dagger|0\rangle \ldots (\vec{p}, m_i), \quad i = 1, 2$

$$\hat{H}|i\rangle = E(\vec{p}, m_i)|i\rangle$$

$|1\rangle, |2\rangle \in G$-invariant subspace only if $\hat{U}|0\rangle = |0\rangle$:

$$\hat{U}|1\rangle = \hat{a}_2^\dagger\hat{U}|0\rangle$$

$$\boxed{\hat{U}|0\rangle = |0\rangle \quad \Rightarrow \quad m_1 = m_2}$$

SSB IN THE HIGGS LAGRANGIAN

$SO(4)$ Higgs Lagrangian:

$$\mathcal{L}_H = \mathcal{L}_H(\mu, \lambda | \underbrace{\pi_1, \pi_2, \pi_3, \sigma}_{\Phi})$$

the lowest energy configuration:

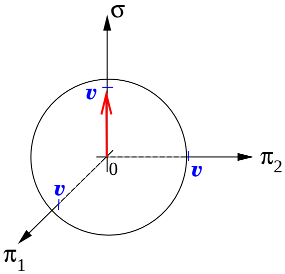
$$\pi_1^2 + \pi_2^2 + \pi_3^2 + \sigma^2 = \mu^2/\lambda \equiv v^2$$

the vacuum choice not unique:

$$\Phi_{vac} \equiv (0, 0, 0, v)$$

reparameterization:

$$\sigma(x) = v + h(x)$$



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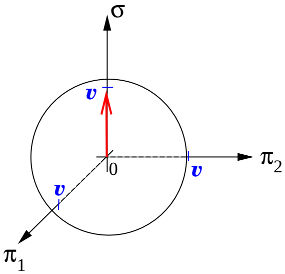

$SO(3)_\sigma$ ... symmetry of Φ_{vac} and $\mathcal{L}_H$
(π_1, π_2, π_3) ... $SO(3)_\sigma$-inv. subspace
$\Rightarrow \quad m_{\pi_1} = m_{\pi_2} = m_{\pi_3}$

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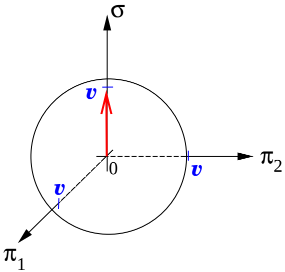

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$$\boxed{m_{\pi_1} = m_{\pi_2} = m_{\pi_3} = 0, \qquad m_h = \sqrt{2}\mu}$$

HIGGS LAGRANGIAN

$SO(4)$ Higgs Lagrangian:

$$\boxed{\mathcal{L}_H = \frac{1}{2}(\partial_\mu \Phi)^\dagger(\partial^\mu \Phi) + \frac{1}{2}\mu^2 \Phi^\dagger \Phi - \frac{1}{4}\lambda(\Phi^\dagger \Phi)^2}$$

$$\Phi(x) = \sqrt{2}\begin{pmatrix} \phi^+(x) \\ \phi^0(x) \end{pmatrix} = \begin{pmatrix} \pi_2 + i\pi_1 \\ \sigma - i\pi_3 \end{pmatrix}$$

the lowest energy configuration:

$$\Phi^\dagger \Phi = \mu^2/\lambda \equiv v^2$$

the vacuum choice and reparameterization:

$$\Phi(x) \propto \begin{pmatrix} 0 \\ v \end{pmatrix} + \begin{pmatrix} \pi_2(x) + i\pi_1(x) \\ h(x) - i\pi_3(x) \end{pmatrix}$$

MASSES FOR THE SM

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π's are gone; $W^\pm$, Z^0 and fermions have masses!

SM INVENTORY

- fundamental fields: 1 scalar , 24 L-fermions, 24 R-fermions, 12 gauge bosons; Total $= 61$
- free parameters: g_C, g_L, g_Y, μ, λ , 9 (12) fermion masses, 4 CKM angles, Θ_3^{QCD}; Total $= 18\ (21)$
- alternative parameters: $\tan\Theta_W = g_Y/g_L$, $e = g_L \sin\Theta_W$, $v = \mu/\sqrt{\lambda}$, $m_h = v\sqrt{2\lambda}$, $M_W = g_L v/2$, $M_Z = M_W/\cos\Theta_W$, $G_F = v^2/\sqrt{2}$, …

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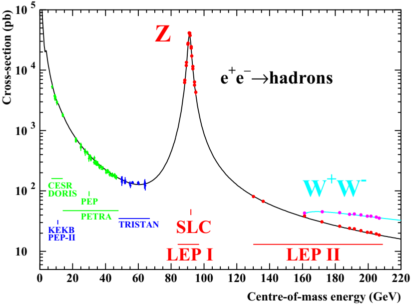
TESTING THE SM: MILESTONES

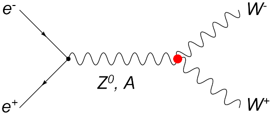
- neutral current interactions, 1973, neutrino-nucleon scattering
- W, Z discovery, 1983, $p\bar{p}$-collisions at CERN
- Z-peak high-precision measurements, the 90s, e^+e^- LEP(89-95), SLC
- top quark discovery, 1995, Tevatron, Fermilab, $p\bar{p}$ at 2 TeV
- LEP2 $\leq$ 208 GeV, 1996-2000, W^+W^- production
- LHC, 2008?, pp at 14 TeV

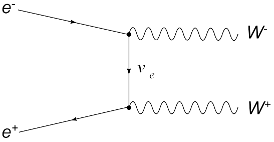


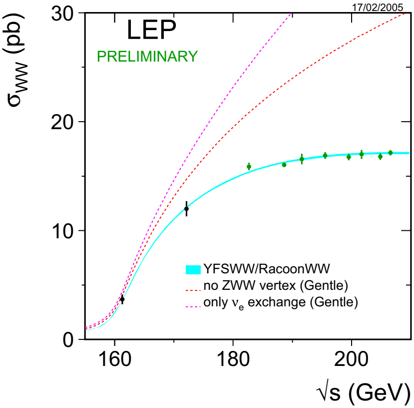
- $\nu_{e/\mu} N \overset{CC}{\to} (e/\mu)X$, $\nu_\mu N \overset{NC}{\to} \nu_\mu X$
- $e^-_{L,R}\, {}^2D \to e^- X$
- $p\bar{p}$: $u\bar{d}/\bar{u}d \to W^{+/-}$, $u\bar{u}/d\bar{d} \to Z^0$
- $e^+e^- \to f\bar{f}, W^+W^-$

TESTING THE SM: GAUGE INVARIANCE

$e^+e^- \to W^+W^-$ in $m_e = 0$ limit:

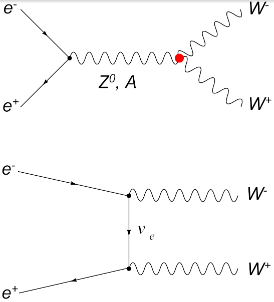






$m_e \neq 0$ effect undistinguishable

HIGGS BOSON AND VALIDITY OF THE SM



$m_e > 0$:

- not a full gauge-invariant set
- amp's violate unitarity at $\mathcal{O}(1\ \text{TeV})$

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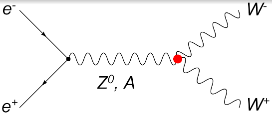

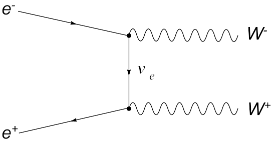

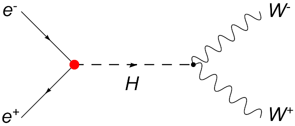

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- unitarity holds → $\mathcal{O}(M_{Planck})$

FITTING THE SM

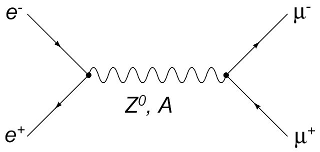
Observables:

- cross-sections, distributions
- $A_{LR} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$, $A_{FB} = \frac{F-B}{F+B}$
- M_Z, Γ_Z^{tot}, $B.R.$'s, line shape
- W^+W^- threshold

Fitting:

1. choose a set of parameters directly measured or calculated without uncertainty
2. make a fit to all data to check the validity of the model
3. find the remaining unknowns

CONSTRAINTS FROM RADIATIVE CORRECTIONS



$$\sigma_{th}^{(2)} = \sigma_{th}^{(2)}(\alpha, G_F, m_e, m_\mu, M_Z)$$

theory testing:

$$\sigma_{th}^{(2)} \overset{?}{=} \sigma_{exp}$$

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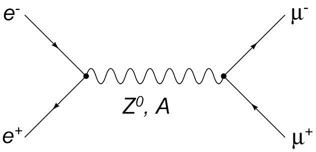
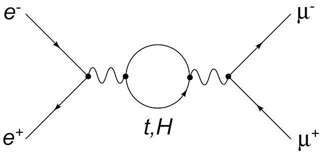




$$\sigma_{th}^{(2)} = \sigma_{th}^{(2)}(\alpha, G_F, m_e, m_\mu, M_Z)$$

$$\sigma_{th}^{(4)} = \sigma_{th}^{(2)} + \underbrace{\delta\sigma(\ldots, {\color{red}m_t}, {\color{red}m_H}, \ldots)}_{\mathcal{O}(1\%)}$$

theory testing:

$$\sigma_{th}^{(2)} \overset{?}{=} \sigma_{exp}$$

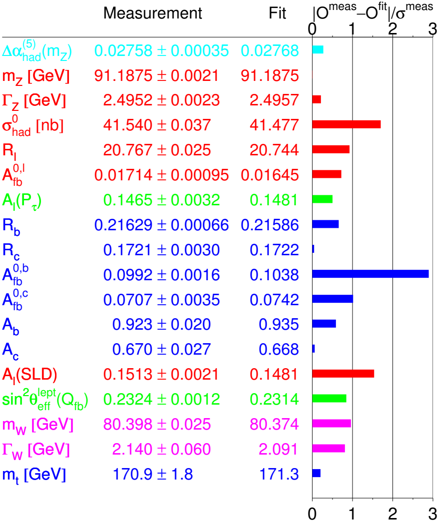
parameter fitting (constraining):

$$\sigma_{th}^{(4)} = \sigma_{exp} \quad \Rightarrow \quad {\color{red}m_t, m_H}$$

SM FITTING 2007

Constraints on the SM (winter 2007)

Tevatron results also included.



	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ^0_{had} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3

LEP Electroweak Working Group,

http://lepewwg.web.cern.ch/LEPEWWG/plots/winter2007/

OUTLINE

WORLD LIMITS

direct lower limit:

$$M_H > 114 \text{ GeV} \qquad (1)$$

EW precision data:

$$\begin{aligned} M_H &= 76^{+33}_{-24} \text{ GeV} && (2) \\ M_H &< 144 \text{ GeV} \;\; 95\%_{\text{C.L.}} && (3) \end{aligned}$$

(1),(2),(3) $\Rightarrow$

$$M_H < 182 \text{ GeV} \;\; 95\%_{\text{C.L.}}$$

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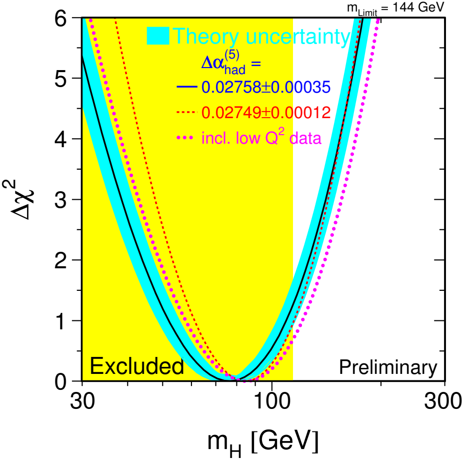

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MASS OF TOP QUARK

EW precision data (w/o direct Tevatron measurements):

$$m_t = 178.9^{+11.7}_{-8.6}\ \text{GeV}$$

direct CDF/D0 measurement:

$$m_t = 170.9 \pm 1.8\ \text{GeV}$$

the overall SM fit down to 15% (χ^2/dof $= 18/13$)

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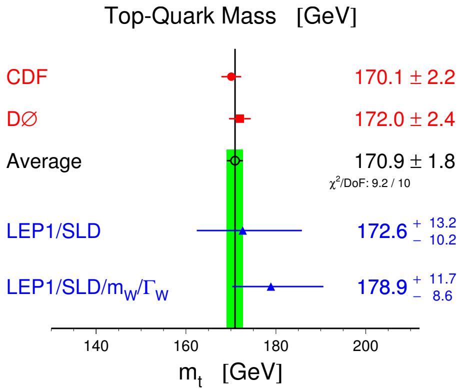

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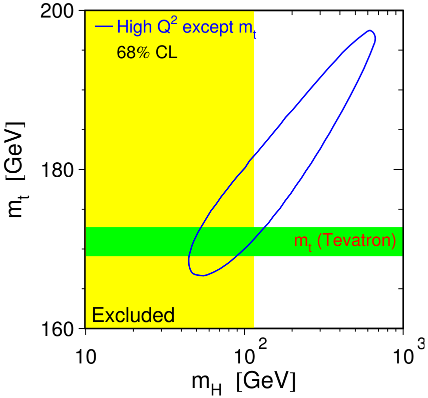

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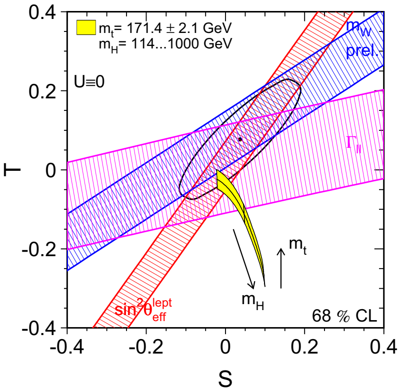
MASS OF TOP QUARK AGAINST LIMITS FROM EW OBSERVABLES

68% contours from different EW observables and from combined data. Yellow area is the SM prediction.



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$\sin^2\theta_W$

2 most precise measurements of $\sin^2\theta_W$ differ by more than 3σ:

- $A_{fb}^{LEP}(b\bar{b}) \rightarrow$ large $\sin^2\theta_W \rightarrow$ heavy Higgs:

$$M_H = 420^{+420}_{-190}\ \text{GeV}$$

- $A_{LR}^{SLD}(lepton) \approx A_{LR}^{LEP}(lepton) \rightarrow$low $\sin^2\theta_W \rightarrow$ light Higgs:

$$M_H = 31^{+33}_{-19}\ \text{GeV}$$

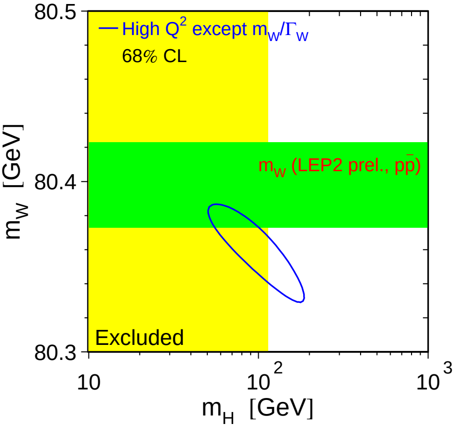
MASS OF W BOSON

$$M_W^{world} = 80.392 \pm 0.029 \text{ GeV}$$

$$M_W^{world} \quad > \quad M_W(\text{SM fit})$$

$$\Downarrow$$

$$M_H \quad < \quad M_H(\text{direct limit})$$



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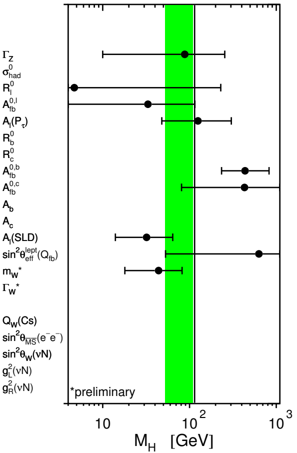
LIMITS FROM VARIOUS OBSERVABLES

Higgs mass values extracted from different EW observables. The average is shown as a green band.



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A Fit of SM Observables

- fit of all SM observables: 15%
- fit of the SM observables most sensitive to M_H: $< \ 2\%$

[P.Gambino, Proceedings of the EPS 2007 Conference at Manchester]

OUTLINE

1. Essentials of the Standard Model
2. Experimental Limits on the Minimal Higgs
3. IF A HIGGS IS DISCOVERED
4. Summary

THE DAY AFTER ...

if a Higgs is discovered ...

$\boxed{M_H} \quad \Rightarrow$

- the Higgs quartic coupling λ $\big($the last unknown param. of the SM$\big)$
- indirect info on ext's of SM

THEORY LIMITS

theory limits (SM valid up to $\Lambda_{GUT} \approx 10^{16} GeV$):

$$125 \text{ GeV} < M_H < 175 \text{ GeV}$$

EW vacuum $>$ Universe

no Landau pole in λ

exp. limits: 114 GeV $< M_H <$ 182 GeV

if

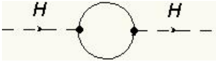
- M_H/GeV $\in (125, 175)$ $\Rightarrow$ no new physics up to Λ_{GUT}
- M_H/GeV< 125 $\Rightarrow$ EW vacuum metastable, new physics modifies the Higgs potential, constraints on cosmology
- M_H/GeV> 182 $\Rightarrow$ new physics at the Fermi scale, modifies interpr. of EW data, affects evolution of λ

HIERARCHY PROBLEM

$$G_F/G_N \approx 10^{33} \Rightarrow M_{Planck} \approx 10^{17} M_W$$

higher-order corrections to Higgs mass, $m^2 = 2\mu^2$:

$$m^2 = m_0^2 + \delta m^2 \approx (10^2 \text{GeV})^2$$



$$\delta m^2 \sim \frac{gM^2}{8\pi^2}$$

if $M \approx M_{Planck}$:

$$\left|\frac{m_0^2}{\delta m^2}\right| \approx 1 - \mathcal{O}(10^{-32})$$

→ fine-tuning problem

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- Symmetry-driven cancellations:
  Higgs is elementary, NP contributions to μ cancel each other: SUSY

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- composite Higgs, no Higgs: QCD-like theories (Technicolor)
- the Little Higgs: "collective breaking" at two/higher loops
- gauge-Higgs unification: higher-dim theories
- holographic Higgs: as above, 4-dim interpretation through duality with theories with warped extra dims

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$\Rightarrow$ new states at LHC (much better precision ILC)

THE VACUUM ENERGY

particle physics:

- vacuum energy contrib. from a particle of a mass m:

$$\delta\rho_0 \sim \mathcal{O}\left(\frac{m^4}{16\pi^2}\right)$$

- in particle physics vacuum energy not measurable

gravity:

- gravity couples to all energies
- vacuum energy density = Einstein's cosmological constant
- measurable effects in the expansion of the universe:

$$\rho_{cc} \sim (2.4 \times 10^{-3}\text{eV})^4$$

THE COSMOLOGICAL CONSTANT PROBLEM

$$\frac{\delta\rho_0}{\rho_{cc}} \sim \quad \underset{\substack{\uparrow \\ \boxed{\text{electron}}}}{10^{40}}, \quad \dots, \quad \underset{\substack{\uparrow \\ \boxed{\text{t-quark}}}}{10^{54}}, \quad \dots, \quad \underset{\substack{\uparrow \\ \boxed{\text{Planck}}}}{10^{122}}$$

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more fine tunings needed?

- particles below EW scale do not cancel their contrib's!
- how to modify the low-energy physics and remain consistent with experiments
- The CC problem → the most severe theoretical problem in HEP today!

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SUMMARY

- the minimal Higgs → discovery is overdue
- SM still consistent with the minimal Higgs but not perfect
- theoretical arguments for alternative scenarios
- a Higgs found or not → LHC will attack BIG questions (ESB, QG, CC)

OUTLINE

5 APPENDIX
- Peskin-Takeuchi Parameters
- Anecdotes

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INTRODUCTION

S, T, U - parameterize potential new physics (NP) contributions to elweak radiative corrections (M. Peskin and T. Takeuchi, 1990)

- at a reference point in the SM, with a particular value chosen for the (as yet unmeasured) M_H:

$$S = T = U = 0$$

- they are only sensitive to new physics that contributes to the oblique corrections (the vacuum polarization corrections to four-fermion scattering processes)
- their values are extracted from a global fit to the high-precision elweak data from particle collider experiments (mostly the Z pole data from the CERN LEP collider) and atomic parity violation
- the measured values of S, T, U agree with the SM
- S, T, U can be used to constrain models of NP beyond the SM

DEFINITION

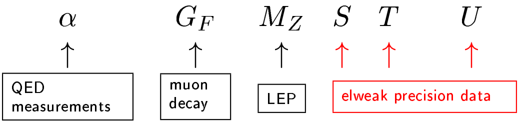
ASSUMPTIONS:

- no additional elweak gauge bosons beyond $W^{\pm}$, Z^0, A
- NP couplings to light fermions are suppressed $\Rightarrow$ nonoblique corr's can be neglected
- $\Lambda_{NP} \gg v$

$\Rightarrow$ oblique corr's expressed through 4 vacuum polar. functions

$$\Pi_{\gamma\gamma}(q^2),\ \Pi_{ZZ}(q^2),\ \Pi_{WW}(q^2),\ \Pi_{Z\gamma}(q^2)$$

$\Rightarrow$ 6 param's:



α ↑ QED measurements

G_F ↑ muon decay

M_Z ↑ LEP

S T U ↑ ↑ ↑ elweak precision data

DEFINITION

- $$\alpha S = 4 s_W^2 c_W^2 \left[\Pi'_{ZZ}(0) - \frac{c_W^2 - s_W^2}{s_W c_W} \Pi'_{Z\gamma}(0) - \Pi'_{\gamma\gamma}(0) \right]$$
- $$\alpha T = \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2}$$
- $$\alpha U = 4 s_W^2 \left[\Pi'_{WW}(0) - c_W^2 \Pi'_{ZZ}(0) - 2 s_W c_W \Pi'_{Z\gamma}(0) - s_W^2 \Pi'_{\gamma\gamma}(0) \right]$$

USES

- $S \sim N(\Psi_L^{T\neq 0}) - N(\Psi_R^{T\neq 0})$, T - weak isospin
  constrains the allowable number of new fourth-generation chiral fermions
- T measures the weak isospin violation
  isospin symmetry $\Rightarrow$ $m_f(T_3 = +1/2) = m_f(T_3 = -1/2)$
- S, T affected by varying M_H from its $S = T = U = 0$ reference value
- contributions to U from most NP models are very small
  $S, T \sim$ coeff. of dim-6 operators, $U \sim$ dim-8 operators

PDG07 EXCERPTS

The data allow a simultaneous determination of $\hat{s}^2_Z$ (from the Z-pole asymmetries), S (from M_Z), U (from M_W), T (mainly from Γ_Z), α_s (from R_ℓ, σ_{had}, and τ_τ), and m_t (from CDF and D0), with little correlation among the SM parameters:

$$S = -0.13 \pm 0.10(-0.08), \quad T = -0.13 \pm 0.11(+0.09), \quad U = 0.20 \pm 0.12(+0.01), \qquad (10.66)$$

and $\hat{s}^2_Z = 0.23124 \pm 0.00016$, $\alpha_s(M_Z) = 0.1223 \pm 0.0018$, $m_t = 172.6 \pm 2.9 GeV$, where the uncertainties are from the inputs. The central values assume $M_H = 117 GeV$, and in parentheses we show the change for $M_H = 300 GeV$. As can be seen, the SM parameters (U) can be determined with no (little) M_H dependence. On the other hand, S, T, and M_H cannot be obtained simultaneously, because the Higgs boson loops themselves are resembled approximately by oblique effects. Eqs. (10.66) show that negative (positive) contributions to the S (T) parameter can weaken or entirely remove the strong constraints on M_H from the SM fits.

The parameters in Eqs. (10.66), which by definition are due to new physics only, all deviate by more than one standard deviation from the SM values of zero. However, these deviations are correlated. Fixing $U = 0$ (as is done in Fig. 10.4) will also move S and T to values compatible with zero within errors,

$$S = -0.07 \pm 0.09(-0.07), \quad T = -0:03 \pm 0.09(+0.09) \qquad (10.67)$$

There is no simple parametrization that is powerful enough to describe the effects of every type of new physics on every possible observable. The S, T, and U formalism describes many types of heavy physics which affect only the gauge self-energies, and it can be applied to all precision observables. However, new physics which couples directly to ordinary fermions, such as heavy Z' bosons [192] or mixing with exotic fermions [209] cannot be fully parametrized in the S, T, and U framework.

⏩ Fig. 10.4

PDG07 EXCERPTS: FIG.10.4

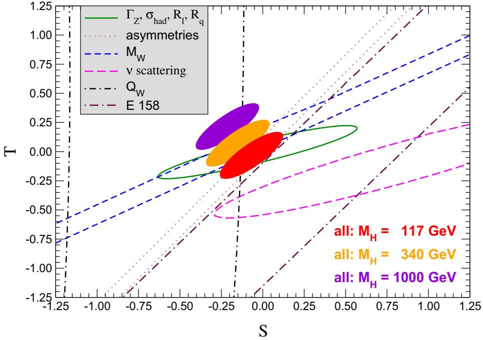


FIGURE: Figure 10.4: 1σ constraints (39.35%) on S and T from various inputs combined with M_Z. S and T represent the contributions of new physics only. (Uncertainties from m_t are included in the errors.) The contours assume $M_H = 117 GeV$ except for the central and upper 90% CL contours allowed by all data, which are for $M_H = 340 GeV$ and $1000 GeV$, respectively. Data sets not involving M_W are insensitive to U. Due to higher order effects, however, $U = 0$ has to be assumed in all fits. α_s is constrained using the τ lifetime as additional input in all fits. See full-color version on color pages at end of book.

OBLIQUE CORRECTIONS

oblique corrections are the vacuum polarization corrections to the elweak sector of the SM in four-fermion scattering processes

- they only affect the mixing and propagation of the gauge bosons and they do not depend on which type of fermions appear in the initial or final states
- any new particles charged under the electroweak gauge groups can contribute to oblique corrections
- they can be used to constrain possible NP beyond the SM
- to affect the nonoblique corrections the new particles must couple directly to the external fermions
- they are usually parameterized in terms of the Peskin-Takeuchi parameters S, T, and U

JONATHAN BAGGER'S STORY:

Dr. Bagger on precision and the mass of the Z boson at CERN: "The experimenters found that the Z boson got heavier at certain times of the day. This was a very high-precision experiment. They discovered that the patterns of the particle getting heavier corresponded to the tides. The gravitational adjustments due to tides slightly changed the shape of the collider over the course of the day. After adjusting for tidal effects, they found that the Z boson was heavier in spring and lighter in fall. This was because there's a lake in Geneva near the detector, that is drained in Fall to make room for the spring snow-melt. So the bigger lake in the Spring was making the particle heavier. After correcting for both of these factors, they found that the particle got suddenly heavier multiple times during the day, at the same times. This was because a train runs near the detector whose electromagnetic fields were disturbing the experiment. This is how precise the experiment was."

HEINEKEN BOTTLES

LEP2 1996: two Heineken bottles left in the vacuum chamber

LEP2 HIGGS DISCOVERY?

June 2000: Aleph observed a high signal-to-background four jet Higgs candidate with a mass around 115 GeV. As the year progressed the strength of their signal at this mass continued to grow, and the excess reported by Aleph in Sept 2000 motivated the demand for a 2 month extension by the LEP experiments. In the end a total 6 weeks extension was granted, and subsequently Higgs candidates were also seen by other experiments in other channels. A combined excess of 2.9 sigma with respect to the background hypothesis was reported at the end of the 2000 run.