Particle Physics around 1990
Summary of the Standard Model

- Particles and SU(3) × SU(2) × U(1) quantum numbers:

<table>
<thead>
<tr>
<th>$L_L$</th>
<th>$(\nu_e)<em>{e^-}^L, (\nu</em>{\mu}^\mu)<em>{\mu^-}^L, (\nu</em>{\tau}^\tau)_{\tau^-}^L$</th>
<th>(1,2,-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_R$</td>
<td>$(e^{-})<em>{e^-}^R, (\mu^-)</em>{\mu^-}^R, (\tau^-)_{\tau^-}^R$</td>
<td>(1,1,-2)</td>
</tr>
</tbody>
</table>

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<tr>
<th>$Q_L$</th>
<th>$(u)<em>{u}^L, (c)</em>{s}^L, (t)_{b}^L$</th>
<th>(3,2,+1/3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_R$</td>
<td>$(d)<em>{u}^R, (s)</em>{c}^R, (t)_{b}^R$</td>
<td>(3,1,+4/3)</td>
</tr>
<tr>
<td>$D_R$</td>
<td>$(d)<em>{d}^R, (s)</em>{s}^R, (b)_{b}^R$</td>
<td>(3,1,-2/3)</td>
</tr>
</tbody>
</table>

- Lagrangian:

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu}^a F_a^{\mu\nu}$$

- gauge interactions
- matter fermions
- Yukawa interactions
- Higgs potential

1967/8

No direct evidence until 2012

Ignored for several years
Gauge Theories taken Seriously

1971/2
- `t Hooft and Veltman: renormalizable

1973
- Kobayashi and Maskawa show how to include CP violation in the Standard Model
- Neutral currents in Gargamelle

1974
- J/Ψ discovered

1975/6
- Tau lepton and charmed particles discovered
What about the Higgs boson?

**Higgs Boson Couplings**

\[ g_2 M_W, \quad g_2 \frac{M_Z}{c_W} \]

\[ \frac{m_f}{v} = \frac{g_2 m_f}{2 M_W} \]

\[
\Gamma(H \rightarrow f \bar{f}) = N_e \frac{G_F M_H}{4\pi \sqrt{2}} m_f^2, \quad N_C = 3 \ (1) \text{ for quarks (leptons)}
\]

\[
\Gamma(H \rightarrow VV) = \frac{G_F M_H^3}{8\pi \sqrt{2}} F(r) \left( \frac{1}{2} \right)_Z, \quad r = \frac{M_V}{M_H}
\]
A Phenomenological Profile of the Higgs Boson

• First attempt at systematic survey

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPoulos **
CERN, Geneva

Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.
1983

Discovery of the W and Z

- The top quark still undiscovered
- The search for the Higgs moved up the agenda

How did it get so heavy?
Theoretical worries about the Higgs boson

Elementary Higgs or Composite?

- Higgs field: 
  \[ \langle 0 | H | 0 \rangle \neq 0 \]

- Quantum loop problems

  - Fermion-antifermion condensate
  - Just like \( \pi \) in QCD, BCS superconductivity
  - New ‘technicolour’ force?
  - Heavy scalar resonance?
  - (Problems with precision electroweak data)
  - Pseudo-Nambu-Goldstone boson?

Cut-off \( \Lambda \sim 1 \) TeV with Supersymmetry?

Cutoff
\[ \Lambda = 10 \text{ TeV} \]
(Theoretical) Discovery of Supersymmetry @ CERN

1973/4

![Diagram of Standard and SUSY particles]

- Quarks: u, d, s, b
- Leptons: e, μ, τ
- Force particles: γ, Z, W
- Higgs
- SUSY particles: ~u, ~d, ~s, ~b, ~γ, ~Z, ~W, ~H
- Squarks, Sleptons, SUSY force particles

Standard particles

SUSY particles
Minimal Supersymmetric Extension of Standard Model (MSSM)

- Double up the known particles:
  \[
  \begin{pmatrix}
  \frac{1}{2} \\
  0
  \end{pmatrix}
  \text{ e.g., } \begin{pmatrix}
  \ell \text{ (lepton)} \\
  \tilde{\ell} \text{ (slepton)}
  \end{pmatrix}
  \text{ or } \begin{pmatrix}
  q \text{ (quark)} \\
  \tilde{q} \text{ (squark)}
  \end{pmatrix}
  \begin{pmatrix}
  1 \\
  \frac{1}{2}
  \end{pmatrix}
  \text{ e.g., } \begin{pmatrix}
  \gamma \text{ (photon)} \\
  \tilde{\gamma} \text{ (photino)}
  \end{pmatrix}
  \text{ or } \begin{pmatrix}
  g \text{ (gluon)} \\
  \tilde{g} \text{ (gluino)}
  \end{pmatrix}
  \]

- Two Higgs doublets
  - 5 physical Higgs bosons:
  - 3 neutral, 2 charged

- Lightest neutral supersymmetric Higgs looks like the single Higgs in the Standard Model
Lightest Supersymmetric Particle

- Stable in many models because of conservation of R parity:
  \[ R = (-1)^{2S - L + 3B} \]
  where \( S = \) spin, \( L = \) lepton \#, \( B = \) baryon \#
- Particles have \( R = +1 \), sparticles \( R = -1 \):
  Sparticles produced in pairs
  Heavier sparticles \( \rightarrow \) lighter sparticles
- Lightest supersymmetric particle (LSP) stable
Lightest Sparticle as Dark Matter?

- No strong or electromagnetic interactions
  
  Otherwise would bind to matter
  Detectable as anomalous heavy nucleus
- Possible weakly-interacting scandidates
  
  Sneutrino
  (Excluded by LEP, direct searches)
  
  Lightest neutralino $\chi$ (partner of Z, H, $\gamma$)
  
  Gravitino
  (nightmare for detection)
SUPERSYMMETRIC RELICS FROM THE BIG BANG*

John ELLIS and J. S. HAGELIN

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, USA

D. V. NANOPoulos, K. OLIVE†, and M. SREDNICKI‡

CERN, CH-1211 Geneva 23, Switzerland

Received 16 September 1983
(Revised 15 December 1983)

We consider the cosmological constraints on supersymmetric theories with a new, stable particle. Circumstantial evidence points to a neutral gauge/Higgs fermion as the best candidate for this particle, and we derive bounds on the parameters in the lagrangian which govern its mass and couplings. One favored possibility is that the lightest neutral supersymmetric particle is predominantly a photino $\tilde{\gamma}$ with mass above $\frac{1}{2}$ GeV, while another is that the lightest neutral supersymmetric particle is a Higgs fermion with mass above 5 GeV or less than $O(100)$ eV. We also point out that a gravitino mass of 10 to 100 GeV implies that the temperature after completion of an inflationary phase cannot be above $10^{14}$ GeV, and probably not above $3 \times 10^{12}$ GeV. This imposes constraints on mechanisms for generating the baryon number of the universe.
Physics case

What is the deep origin of mass and what are the relations between Higgs and symmetry breaking processes, such as those which are at work in the Higgs mechanism?

Why is there a repetition of the quark and lepton families which our present theory can merely only accommodate but not explain? The origin of the different flavours is still a riddle. So is the origin of CP violation.

Is gravitation and how does it relate to the other interactions as presently described in the framework of the standard model?...
A Preview of the Higgs Boson @ LHC

• Prepared for LHC Lausanne workshop 1984
A Preview of Supersymmetry @ LHC

Gluinos

Squarks

JE, Gelmini & Kowalski, 1984
Estimating Masses with Electroweak Data

- High-precision electroweak measurements are sensitive to quantum corrections

\[ m_W^2 \sin^2 \theta_W = m_Z^2 \cos^2 \theta_W \sin^2 \theta_W = \frac{\pi \alpha}{\sqrt{2} G_F} (1 + \Delta r) \]

- Sensitivity to top mass is quadratic:

\[ \frac{3 G_F}{8 \pi^2 \sqrt{2}} m_t^2 \]

- Sensitivity to Higgs mass is logarithmic:

\[ \frac{\sqrt{2} G_F}{16 \pi^2} m_W^2 \left( \frac{11}{3} \ln \frac{M_H^2}{m_Z^2} + \ldots \right), \ M_H >> m_W \]

- Measurements at LEP et al. gave indications first on top mass, then on Higgs mass

\[ \Delta \rho = 0.0026 \frac{M_t^2}{M_Z^2} - 0.0015 \ln \left( \frac{M_H}{M_W} \right) \]
Estimating the Top Quark Mass

- Needed as a partner of the bottom quark
- Not discovered in 1975 or 1984
- Many speculations about its mass
- Indication of large mass from B physics
- Estimate from radiative corrections in neutral currents

“In the minimal standard model with $\rho = 1$ and equal Higgs and Z masses we find that $m_t < 168$ GeV at 90% confidence level”

- Not so bad!

1987
7 Conclusions

In this report we have analyzed the general structure of the higher order electroweak effects relevant for LEP/SLC experiments. We have discussed in detail the on-shell renormalization scheme but also compared our results with those obtained by different authors. The set of formulae includes all vector boson self energy parts, the relevant vertex functions, and box contributions. Some approximate analytical expressions for various quantities (asymmetries, Z decay widths), incorporating the leading terms, have also been presented. Together with the QED corrections, generally dominant but theoretically under control, the discussed weak corrections provide the basic ingredients for precision tests of the Standard Model. If the "minimal" model is correct the calculations of the various observables have to reproduce the experimental results with a choice of the unknown parameters $m_t$ and $M_H$ within a reasonable range (50 GeV < $m_t$ < 200 GeV as favored by present experimental data, 10 GeV < $M_H$ < 1 TeV as required for a consistent weak coupling interpretation of the theory). If agreement is found the high precision measurements will considerably restrict the allowed area in the space of the unknown parameters. In this sense the inclusion of radiative corrections is not only a necessity but also a benefit: providing a unique chance to test the quantum structure of the Standard Model and its empirically unknown part.
The Top Mass after First Precise $m_Z$

- In combination with low-energy measurements
  
  \[ m_t = 132^{+31}_{-37} \text{ GeV} \]

- A first discussion of $m_H$

\[ m_H^2/m_Z^2 = 100, 1, 0.01 \]

Low energies

Vector boson masses
Estimating the Higgs mass

- Early attempts

1990

1991

- Difficult before the discovery of the top quark

JE, Fogli & Lisii
At present, the increase in $\chi^2$ when $M_H$ is changed between the two extreme values is about 2.0, which does not allow the derivation of any meaningful constraints on $M_H$. In addition, an increase of 1.4 out of 2.0 is traced back to the contribution of the $\Gamma_{bb}/\Gamma_{had}$ measurement. As stated above, the measurement of $\Gamma_{bb}/\Gamma_{had}$ ‘artificially’ constrains $M_t$. The rest of the data give a determination of $M_t$ which is strongly correlated with the assumed value of $M_H$ used as input to the fit. Therefore, the inclusion of the $\Gamma_{bb}/\Gamma_{had}$ measurement also artificially constrains $M_H$. Our conclusion is that the present increase in $\chi^2$ with $M_H$ is ‘artificial’ and hence its interpretation has to be taken with care.
Combining Information from Previous Direct Searches and Indirect Data

$M_H = 125 \pm 10$ GeV
Higgs Hunter’s Guide

- Production at the LHC, SSC and Eloisatron (~FCC)
The Higgs Hunter’s Guide

Previous searches and prospects in $e^+e^-$ collisions

Prospects at the SSC

Experimental Probes of $\phi^0$ (SSC)

- $\phi^0 \rightarrow Z(\ell^+\ell^-)Z(\ell^+\ell^-)$
- $\phi^0 \rightarrow W(W\rightarrow q\bar{q})$

Experimental Probes of $\phi^0$ (SSC)

- $\phi^0 \rightarrow Z(\ell^+\ell^-)Z(\ell^+\ell^-)$
- $\phi^0 \rightarrow Z(W\rightarrow q\bar{q})$

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- $\phi^0 \rightarrow Z(W\rightarrow q\bar{q})$
- $\phi^0 \rightarrow Z(W\rightarrow q\bar{q})$
1990

Supersymmetry via Missing $E_T$

Aachen meeting
Higgs Mass in Supersymmetry

Pushed beyond reach of LEP2 by radiative corrections?
Could be 125 GeV!
Circumstantial Evidence for Supersymmetric Grand Unification

1991 Amaldi, de Boer & Furstenau

JE, Kelley & Nanopoulos
Abstract

The theoretical attempts to understand the scalar states of the standard model are reviewed. Top quark condensates and technicolour theories give calculational schemes for non-perturbative extensions of the standard model and lead to composite Higgs bosons. The perturbative alternative invokes supersymmetry and extends the standard model to include superpartners of the standard model states. The implications of unification for the mass of these new states are discussed and the expectation for supersymmetric phenomenology are briefly reviewed. The suggestion of structure beyond the standard model following from neutrino masses is also discussed paying particular regard to the possibility of a 17 keV state and the solar neutrino deficit. Finally we consider “smoking guns”, the experimental signatures signalling departures from the standard model.

Technical obstacles

Technical obstacles lie in the path of the construction and exploitation of LHC. It requires novel two-in-one magnets operating at nearly ten tesla. Can reliable and robust magnets be industrially produced at reasonable cost? The physics reach of the LHC is extended by exchanging a compromised collision energy for a more intense luminosity, but can appropriate detectors be designed and built to make use of such luminosities?

Operational difficulties

Operational difficulties may hamper the construction of LHC. LEP has made a glorious start in its ambitious and exciting program. It has both a higher-luminosity and a higher-energy phase to look forward to. It would be tragic for physics if LHC deployment would hamper, delay or constrain these essential projects.

The serious scientific risk

The serious scientific risk associated with LHC must not be swept under the rug. Its collision energy is severely constrained by its need to fit within the LEP tunnel. There is a distinct possibility that the new physics will accessible at 40 TeV but not at 20 TeV or less.
Mainstream New Physics

Outline

- Progress since Lausanne
- Possible discoveries pre LHC
- Arguments ⇒ physics beyond std. model
- Constraints from LEP
- The problem of mass
- Phenomenology
  - Higgs < minimal SUSY
  - Strong VvV scattering?
  - SUSY
  - Top
- Conclusions

Since Lausanne (1984)

- Unchanged
  - Status of big issues - mass
  - flavony
  - CP
  - unification
  - Case for new physics < 1 TeV

- Decreased
  - Scope for discoveries pre-LHC
  - but only slightly

- Increased
  - Confidence in SM
  - Understanding of phenomenology
1992

Mainstream New Physics

[Graph and diagrams related to particle physics, showing various processes and cross-sections.]
Flavour Physics

Unitarity Triangle @ Aachen

LHC B physics experiment

<table>
<thead>
<tr>
<th></th>
<th>LHC Collider</th>
<th>e⁺e⁻ (e.g. SLAC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Luminosity</td>
<td>4•10^{31}</td>
<td>3•10^{33}</td>
</tr>
<tr>
<td>σ_{b\bar{b}}</td>
<td>3•10^{-28}</td>
<td>1.2•10^{-33}</td>
</tr>
<tr>
<td>2-Arm Geom. Accept.</td>
<td>.55</td>
<td>1.0</td>
</tr>
<tr>
<td>Trigger Efficiency</td>
<td>.20</td>
<td>1.0</td>
</tr>
<tr>
<td>Reconstruction Eff.</td>
<td>.20</td>
<td>.58</td>
</tr>
<tr>
<td>Tagging Efficiency</td>
<td>.36</td>
<td>.45</td>
</tr>
<tr>
<td>D² = I₀D²</td>
<td>.077</td>
<td>.25</td>
</tr>
<tr>
<td>Rate = D²N (Hz)</td>
<td>35•10^{-5}</td>
<td>1.4•10^{-5}</td>
</tr>
<tr>
<td>δ[ sin(2β) ] t=2•10^7</td>
<td>[0.012]</td>
<td>[0.060]</td>
</tr>
</tbody>
</table>
**Everything Else**

---

**WEAK PHASE TRANSITION**

\[ T > \phi_0 \ (246 \text{ GeV}) \]

\[ \downarrow \quad T < \phi_0 \]

\[ \text{WHERE IS } 0? \quad \phi_0 \quad \phi \]

\[ \Lambda_{\text{EMPIR}} \lesssim \frac{g H_0^2}{c^2} \sim 3 \times 10^{-33} \text{ GeV}^2 \]

\[ \Delta \Lambda_{\text{WEAK TRANS.}} = 2 n \lambda G_{\text{MW}} \phi_0^4 = 2 n \lambda 3 \times 10^{-29} \text{ GeV}^2 \]

\[ \Lambda_{\text{WEAK}} \sim 10^{54} \Lambda_{\text{EMPIR}} \]

---

**SEARCH FOR MASSIVE STABLE PARTICLES AT, e.g., LHC**

\[ \text{C} = 1 \ (\text{in hardware units} \sim 1 \text{ foot/nanosec.}) \]

\[ \text{ONE BUNCH CROSSING} /15 \text{ nanosec} \]

\[ \text{LIGHT TRAVELS} 5 \text{m in that time} \]

\[ n_{\text{CH}} \sim 500/\text{INTER} \quad n_{\text{INTS}} \sim 15 \quad (L = 10^3 \text{ cm}) \]

---

**EVENT HORIZONS**

\[ O(10) \]

**HORIZONS SIMULTANEOUS IN DETECTOR**
• « Empty » space is unstable
• Dark matter
• Origin of matter
• Sizes of masses
• Masses of neutrinos
• Inflation
• Quantum gravity
• ...

The **Standard Model**
Into the LEP Era

1980s

• Yellow Reports: several groups calculated radiative corrections to LEP observables
• Including effects of top and Higgs loops
• Estimated accuracy of $m_Z$ measurement ~ 50 MeV
• No calculation of accuracy on $m_t$, $m_H$

1989

Potential implication for $m_t$ of $m_Z$ measurement

$$m_t = 95 \text{ GeV} + 66(91.6 \text{ GeV} - M_Z)$$

• First LEP measurement

$$m_t = 132^{+31}_{-37} \text{ GeV}$$

NEUTRAL CURRENTS, $M_{Z}$ AND $m_{t}$
John ELLIS
CERN, CH-1211 Geneva 23, Switzerland

and

G.L. FOGLI
Dipartimento di Fisica, Università di Bari, I-70126 Bari, Italy
and Istituto Nazionale di Fisica Nucleare, Sezione di Bari, I-70126 Bari, Italy

Received 17 July 1989

We summarize and update constraints on $m_t$ from present neutral current data. Soon precision measurements of $M_Z$ will give a tight correlation between sin$^2\theta_W$ and $m_t$. Combining this information with low-energy neutral current data will pin down sin$^2\theta_W$ and hence fix $m_t$ with an error of ~ ± 35 GeV. The central value of the top quark mass will be $m_t = 95 \text{ GeV} + 66(91.6 \text{ GeV} - M_Z)$. 
Refined Estimate from Electroweak Radiative Corrections

THE MASS OF THE TOP QUARK FROM ELECTROWEAK RADIATIVE CORRECTIONS

John ELLIS
CERN, CH-1211 Geneva 23, Switzerland

and

Gianluigi FOGLI
Dipartimento di Fisica, Università di Bari, I-70126 Bari, Italy
and Istituto Nazionale di Fisica Nucleare, Sezione di Bari, I-70126 Bari, Italy

Received 29 July 1988

Measurements of low-energy neutral current parameters and vector boson masses are sensitive to the top quark mass $m_t$ via one-loop radiative corrections in the standard model. Assuming the Higgs mass $M_H = M_Z$, the combination of present data imposes $m_t < 153$ GeV at the 68.3% CL if the charm quark mass $m_c = 1.45$ GeV, or $m_t < 185$ GeV if $m_c$ is left free. The upper limit on $m_t$ is only weakly sensitive to $M_H$. The overall $\chi^2$ increases slightly with $M_H$, but there is no significant upper bound on $M_H$.

- $m_t < 185$ GeV
- Indication on $\sin^2 \theta_W$
- Comments on $m_H$