PHY521 – Elementary Particle Physics

What is the physical world made of ?
or
“So that no more with bitter sweat
I need to talk of what I don’t know yet,
So that I may perceive whatever holds
The world together in its inmost folds, ...”
Faust, Johann Wolfgang von Goethe

We learnt a lot about fundamental particles and interactions but we are still “sweating” ...

6. Summary and Outlook

In particle physics, our understanding of physical phenomena is based on identifying a few fundamental constituents and a few fundamental interactions.

The forces/interactions among the constituents of matter are interpreted in terms of the exchange of gauge bosons.

Matter particles: quarks and leptons

Forces: strong, weak $\otimes$ electromagnetic, (gravity)

Gauge bosons: gluons, $W^{\pm}$ and Z bosons, photon, (graviton)

The ultimate goal of elementary particle physics is to find the fundamental law(s) of nature, the final underlying theory, that determines the dynamics of matter.

S.Weinberg: “*... to look for a simple set of physical principles, which have about them the greatest possible sense of inevitability and from which everything we know about physics can, in principle, be derived.*” Elementary Particles and the Laws of Physics, The 1986 Dirac Memorial Lectures. Steven Weinberg, Sheldon L. Glashow, Abdus Salam, won the Nobel prize in Physics in 1979 ”for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including inter alia the prediction of the weak neutral current”.

The Standard Model (SM) of particle physics successfully describes the strong and electroweak interactions of leptons and quarks down to distances of $\mathcal{O}(10^{-17})$ cm.

The underlying theory is a local relativistic Quantum Field Theory (QFT), subject to symmetry principles and a principle of renormalizability.

S.Weinberg:
One could imagine "... *that specifying the symmetry group of nature may be all we need to say about the physical world, beyond the principles of Quantum Mechanics.*"

Elementary Particles and the Laws of Physics, The 1986 Dirac Memorial Lectures

6.1 The SM of Particle Physics in a Nutshell

The electroweak and strong interactions of quarks and leptons are described by renormalizable quantum gauge theories.

The principle of invariance of the theory under the transformation of a local gauge symmetry group fixes the dynamics.

The particles that transmit the forces are thus called gauge bosons. They have spin 1 and have to be quantized according to Bose-Einstein spin statistics (*bosons*).

The matter particles, the quarks and leptons, have spin $\frac{1}{2}$ and have to be quantized according to Fermi-Dirac spin statistics (*fermions*).

Force	acts on	transmitted by
electromagnetic	all electrically charged particles	photon (massless, spin 1)
weak	quarks, leptons, $W^\pm$, Z	$W^\pm$, Z (massive, spin 1)
strong	all colored particles (quarks and gluons)	8 gluons (massless, spin 1)

Symmetries are mathematically formulated using group theoretical methods:

The transformations of local gauge symmetries are described by unitary $n \times n$ matrices, $U = e^{iH}$ (H: hermitian, quadratic $n \times n$ matrix), with real, space-time dependent elements.

The matrices U form a group called U(n), SU(n) (det(U)=1).

U(n) has n^2 and SU(n) $n^2 - 1$ parameters, $\alpha_j(x)$, and generators, λ_j, and can be written in terms of infinitesimal transformations as follows ($x = (t, \vec{x})$):

U(n): $U(\alpha_j) = 1 + i \sum_{j=1}^{n^2} \delta\alpha_j(x)\lambda_j$

SU(n): $U(\alpha_j) = 1 + i \sum_{j=1}^{n^2-1} \delta\alpha_j(x)\lambda_j$

Example:

Gauge group of the electromagnetic interaction: U(1) with $U(\alpha) = 1 + iQ\delta\alpha(x)$. Q is the electric charge.

Requiring the Dirac equation, which describes free electrons, to be invariant under these transformations leads to electron-photon interaction and the existence of massless photons.

Interaction	symmetry group	gauge theory
electromagnetic	unbroken local U(1): invariance under space-time dep. phase transitions generated by the electric charge	QED
strong	unbroken local SU(3): invariance under space-time dep. rotations in the 8-dimensional color space	QCD
electroweak	(spontaneously broken) SU(2)⊗U(1): invariance under space-time dep. rotations in the 3-dim. (weak) isospin space and under phase transitions generated by the (weak) hypercharge, Y ($Q = I_3 + Y/2$)	SM of electroweak interactions

Leptons and quarks are arranged in three families (generations) of left-handed doublets of the symmetry group of the weak isospin, SU(2) ($I_3 = \pm 1/2$):

$\Psi_L = (1 - \gamma_5)\Psi$	I_3	Q	L	B
Leptons				
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$+\frac{1}{2}$ $-\frac{1}{2}$	0 -1	$+1$ $+1$	0 0
Quarks				
$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L$	$+\frac{1}{2}$ $-\frac{1}{2}$	$+\frac{2}{3}$ $-\frac{1}{3}$	0 0	$+\frac{1}{3}$ $+\frac{1}{3}$

Right-handed quarks and leptons ($\Psi_R = (1 + \gamma_5)\Psi$) form singlets under SU(2) ($I_3 = 0$).

I_3: third component of the weak isospin

Q: electric charge in units of e, $e = \sqrt{4\pi\alpha}$ (α is the Sommerfeld fine structure constant).

L, $L_{i=e,\mu,\tau}$: Lepton number is separately conserved for each family (with, e.g., $L_e = 0$ for ν_μ, μ, ν_τ, τ) and $L = L_e + L_\mu + L_\tau$. B: Baryon number is observed experimentally to be conserved.

The antiparticles of the quarks and leptons have the same mass and spin as the particles but the quantum numbers Q, L, B are reversed in sign.

In the SM the neutrinos (ν_e, ν_μ, ν_τ) are considered to be massless. However, recently, strong experimental evidence has been found that this might not be the case. This could be the first signal of physics beyond the SM.

Leptons do not carry color charge and thus do not feel the strong force. Quarks carry color charge and each quark flavor comes in three colors.

Colored particles are permanently bound in colorless hadrons ("confinement") (mesons: $q\bar{q}$ bound states, baryons: qqq bound states).

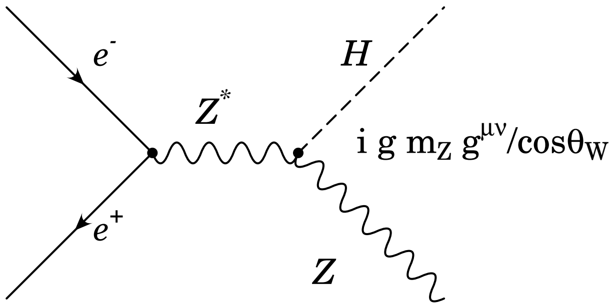
As a consequence of QCD, quarks are asymptotically free, i.e. the strength of the coupling decreases with increasing momentum transfer of the interaction discussed (term paper).

As a consequence of the mechanism which generates mass for the electroweak gauge bosons, $W^\pm$, Z, (Higgs-Kibble mechanism), the SM predicts the existence of a massive, neutral, spin 0 particle, the Higgs boson.

The Higgs boson is the only SM particle that has not been experimentally observed (yet).

The direct search for the Higgs boson is extremely challenging:

LEP-II and the Tevatron mainly look for the Higgs boson produced in association with a electroweak gauge boson, e.g., $e^+e^- \to Z \to HZ$:



and $H \to b\bar{b}$, $Z \to q\bar{q}$

Signature in the detector: 2 b-quark jets (identified via b-tagging) and two light quark jets.

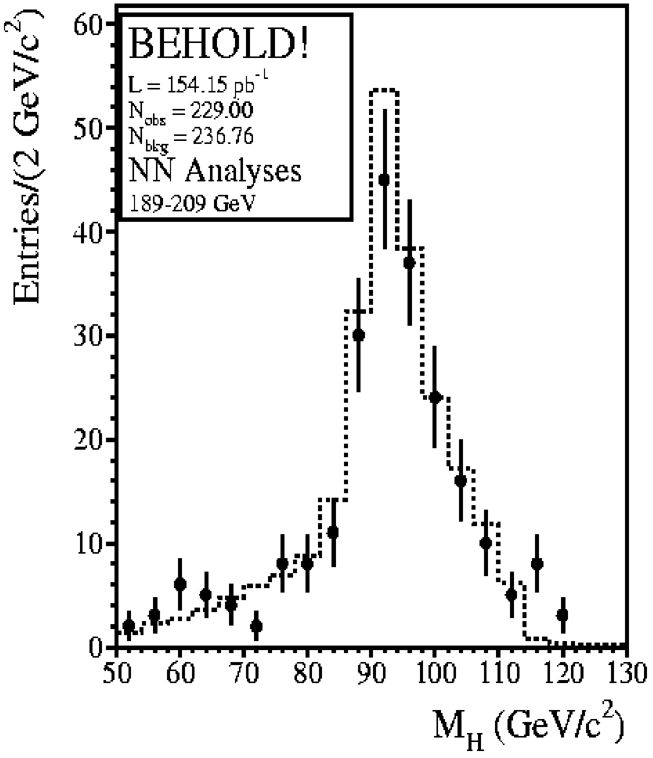
These events are extremely rare:

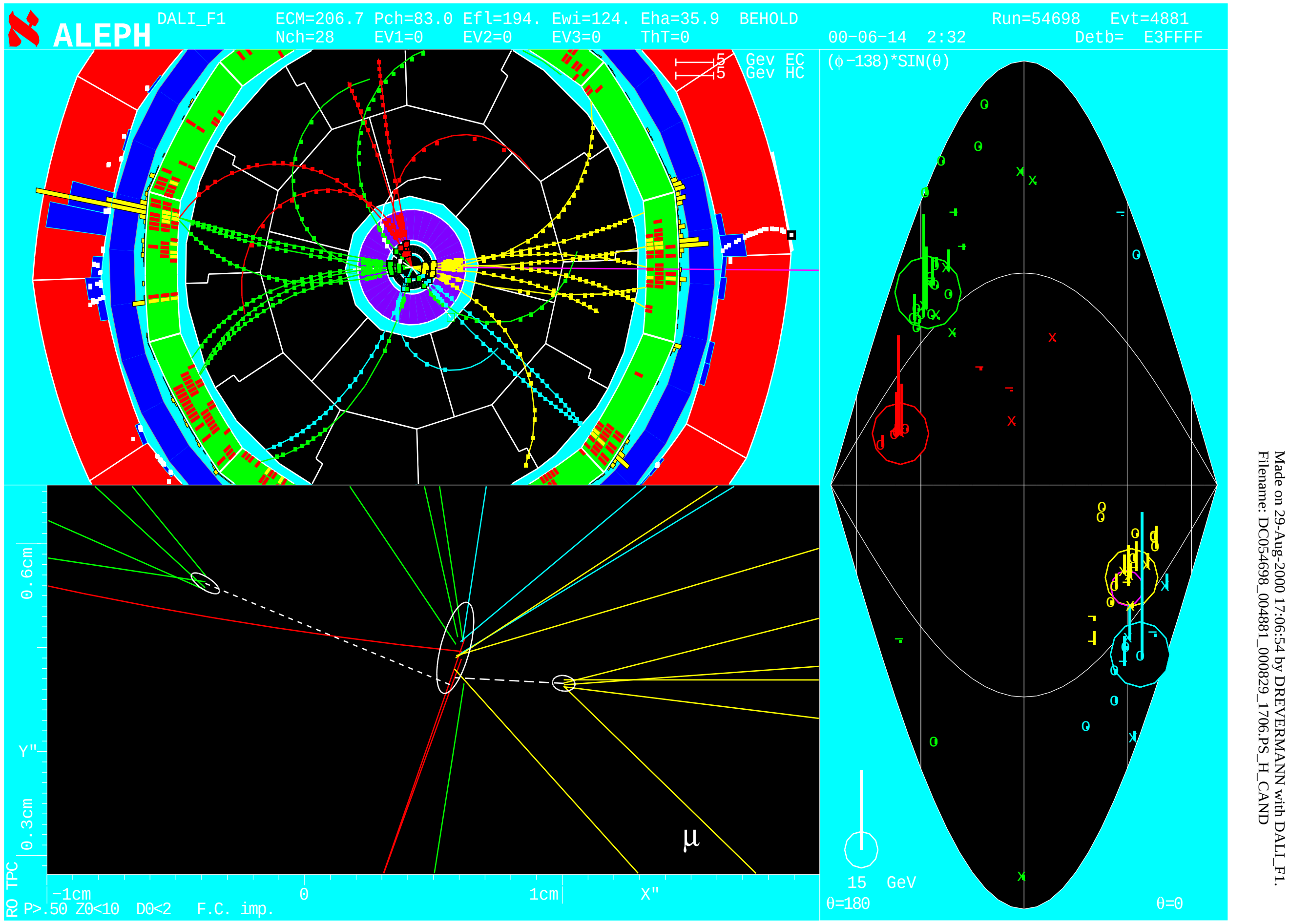
At LEP-II the background (=same signature in the detector but contains no Higgs) is up to two orders of magnitude larger than the Higgs signal.

At the Tevatron $\sigma(p\bar{p})/\sigma(p\bar{p} \to H) \approx 10^{10}$.

At the LHC, the background for the light Higgs search ($H \to b\bar{b}$) is of the order 10^7 times larger than the Higgs signal.

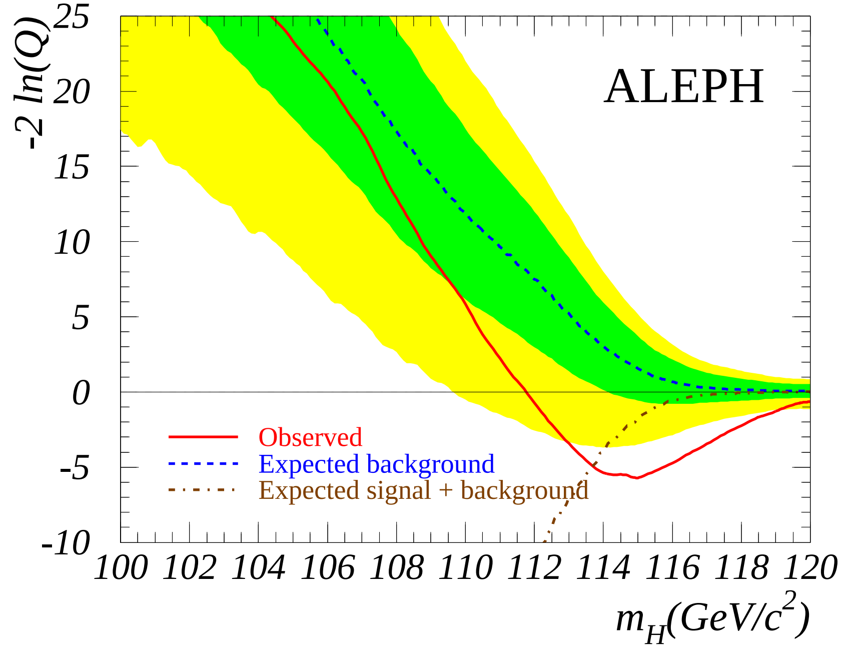
At LEP-II, a few spectacular SM Higgs candidates have been recorded (ALEPH, 4-jet events, > 206 GeV) consistent with M_H around 116 GeV, but no discovery could be claimed.



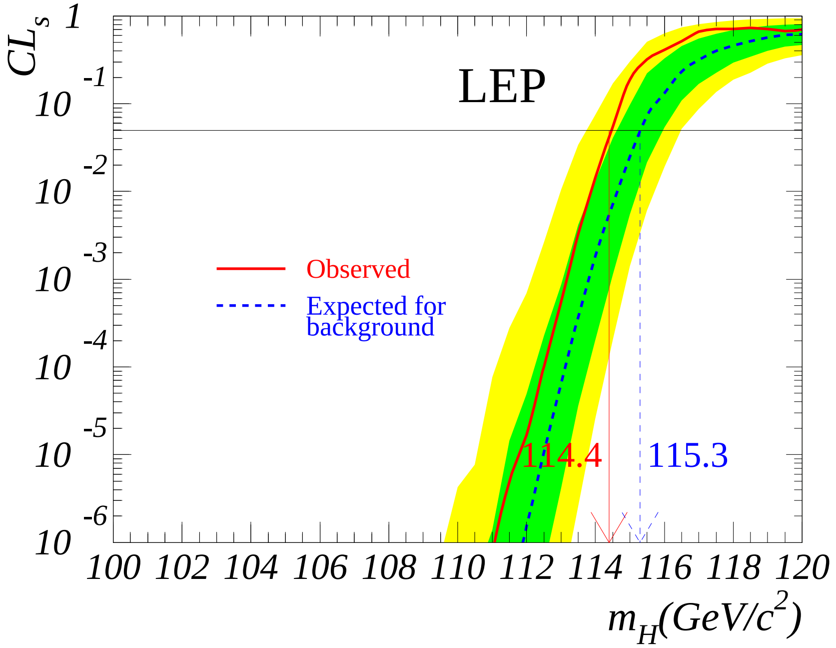


from the ALEPH webpage at CERN

$Q(M_H) = \mathcal{L}(s+b)/\mathcal{L}(b)$



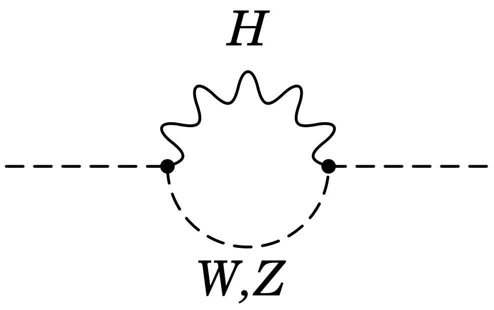
CL for s+b hypothesis



from the LEP Higgs WG, LHWG Note/2002-01

The LEP-II Higgs search resulted in a lower bound on the Higgs boson mass of $M_H = 114.4$ GeV (95 % C.L.). The LEP Higgs WG, LHWG Note/2002-01

The indirect search for the Higgs boson:
the Higgs boson leaves a “trace” in measurements of W and Z boson properties through its virtual presence in quantum loops, e.g.,

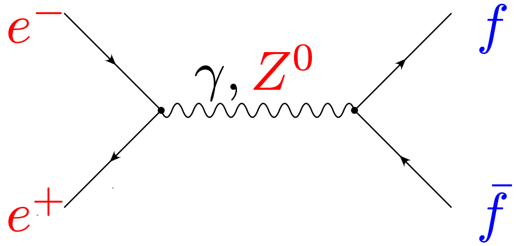


When comparing precise predictions with at least equally precise measurements information about unknown parameters of the SM such as the Higgs mass can be extracted.

How to make precise predictions for high-energy collider experiments ?

We rely on perturbation theory, e.g., a Feynman graph expansion in the coupling constant of the scattering amplitude:

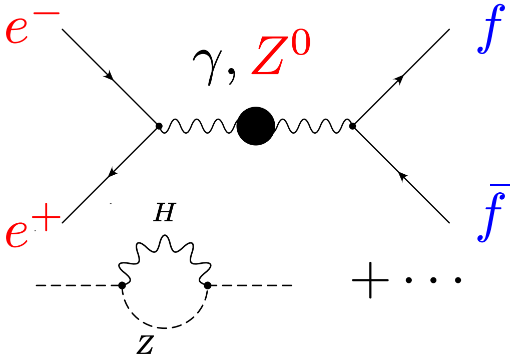
lowest order: Born approximation, e.g., Z boson production at LEP/SLC



$f = e, \mu, \tau, \nu_l, q$

: $\mathrm{d}\sigma^{\mathrm{Born}}_{e^+e^- \to f\bar{f}}(q^2, \alpha, m_f, m_e)$ is of $\mathcal{O}(\alpha^2)$

1-loop: in the 'quantum world' the photon and Z boson feel the virtual presence of all particles:



$f = e, \mu, \tau, \nu_l, q$

: $\delta\mathrm{d}\sigma(q^2, \alpha, m_f, m_e, m_{top}, M_H, \ldots)$ is of $\mathcal{O}(\alpha^3)$

$$\Rightarrow \mathrm{d}\sigma^{theory}_{e^+e^- \to f\bar{f}} = \mathrm{d}\sigma^{Born}_{e^+e^- \to f\bar{f}} + \delta\mathrm{d}\sigma(m_{top}, M_H) + \mathcal{O}(\alpha^4)$$

$\delta\mathrm{d}\sigma$ are the quantum corrections (radiative corrections) of the theory.

By comparing predictions for electroweak observables including radiative corrections with measurements

- the electroweak sector of the SM is probed at the quantum-loop level,
- the consistency of the SM is checked by comparing direct with indirect determinations of input parameters, e.g., m_t, M_W,
- the SM Higgs boson mass can be predicted, and
- the parameters of models beyond the SM can be constrained.

The SM is successfully tested as a Quantum Field Theory at the permille level – no deviations found.

Note: We need to extend the SM to incorporate the experimental fact that neutrinos have mass.

Moreover: Small descrepancies $(2-3\sigma)$ observed in the measurement of the weak mixing angle at NuTeV and the anomalous magnetic moment of the muon at BNL.

The global SM fit to all electroweak data:

A few ∼ 3σ “anomalies”:

e.g., $A_{FB}^{0,b}$

Possible sources:

statistical fluctuation

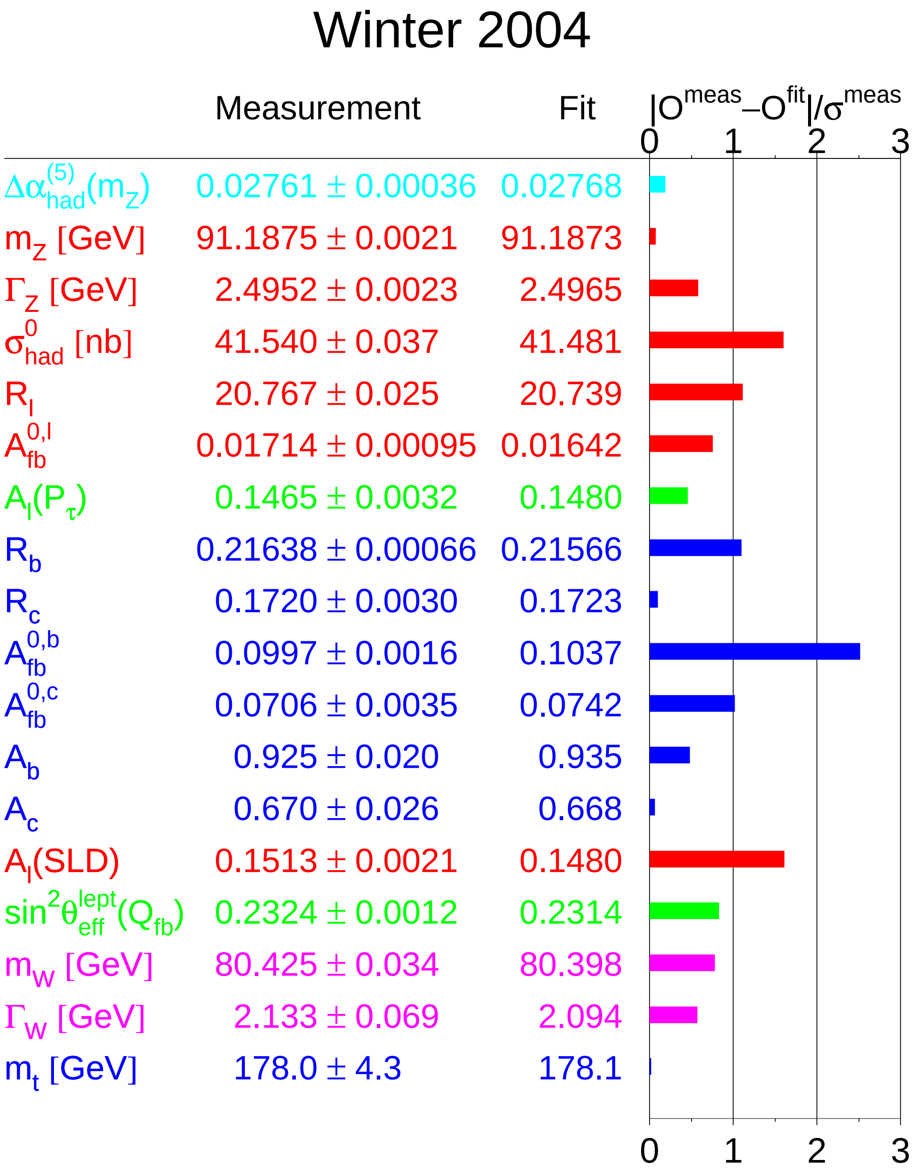
experimental systematics

theoretical uncertainties

non-standard physics (“tough”,

e.g., the MSSM does not help)

2 more anomalies: NuTeV, muon g-2



Winter 2004

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1873
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ_{had}^{0} [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21638 ± 0.00066	0.21566
R_c	0.1720 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0997 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0706 ± 0.0035	0.0742
A_b	0.925 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.398
Γ_W [GeV]	2.133 ± 0.069	2.094
m_t [GeV]	178.0 ± 4.3	178.1

“New physics” ?

No compelling evidence for new physics has been found (apart from ν flavor oscillations).

But:

- the minimal supersymmetric SM (MSSM) fits the electroweak precision data as well as the SM see, e.g. W.de Boer, C.Sander, and
- the present high central value of M_W is in better agreement with the MSSM prediction of M_W.

However, the MSSM does not help to reduce the exp.-theo. discrepancy in $A_{fb}^{0,b}$.

Searches include: MSSM, LeptoQuarks, exotic Higgs, H^{++}, extra gauge bosons Z', extra dimensions, ...

For constraints on parameters of models beyond the SM from LEP/SLC data, please visit lepsusy.web.cern.ch/lepsusy/, lepexotica.web.cern.ch/LEPEXOTICA/.

Supersymmetry: one of the most attractive extensions of the SM

Supersymmetry (SUSY) introduces a higher symmetry into the SM. SUSY relates fermions (spin 1/2) and bosons (spin 0,1) and predicts new SUSY particles: Every SM particle gets a partner which only differs in spin.

- Nature has shown that it likes gauge theories - SUSY is the next logical gauge theory to try.

  Locally supersymmetric transformations are intimately tied up with space-time ones: possible path to unification of gravity with strong and electroweak forces

- *fine tuning* or the problem of fundamental scalars: In the SM the Higgs boson can be arbitrarily heavy due to the occurrence of quadratic divergences $\Rightarrow$ fine tuning is needed so that $M_H < 1$ TeV - not natural in a theory of everything

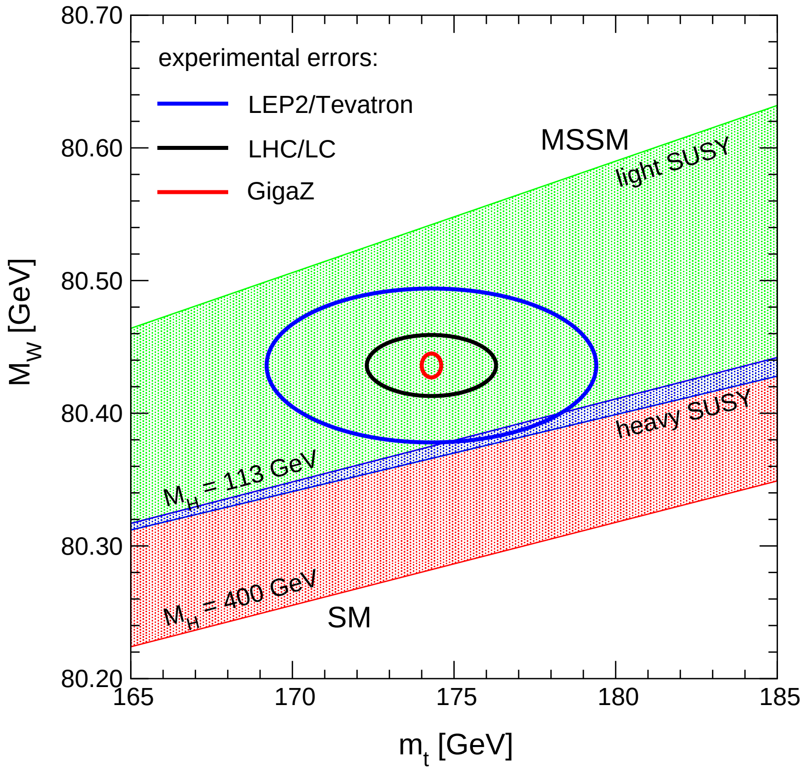
  SUSY partners cancel divergences - no fine tuning needed.

The Minimal Supersymmetric SM (MSSM) predicts the existence of 5 Higgs bosons, one of them (h^0) with a mass smaller than about 130 GeV.

The M_W - M_Z correlation within the MSSM:

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha(0)}{\sqrt{2}G_\mu(1-\Delta r(M_W,m_t,M_{SUSY},\ldots))}$$

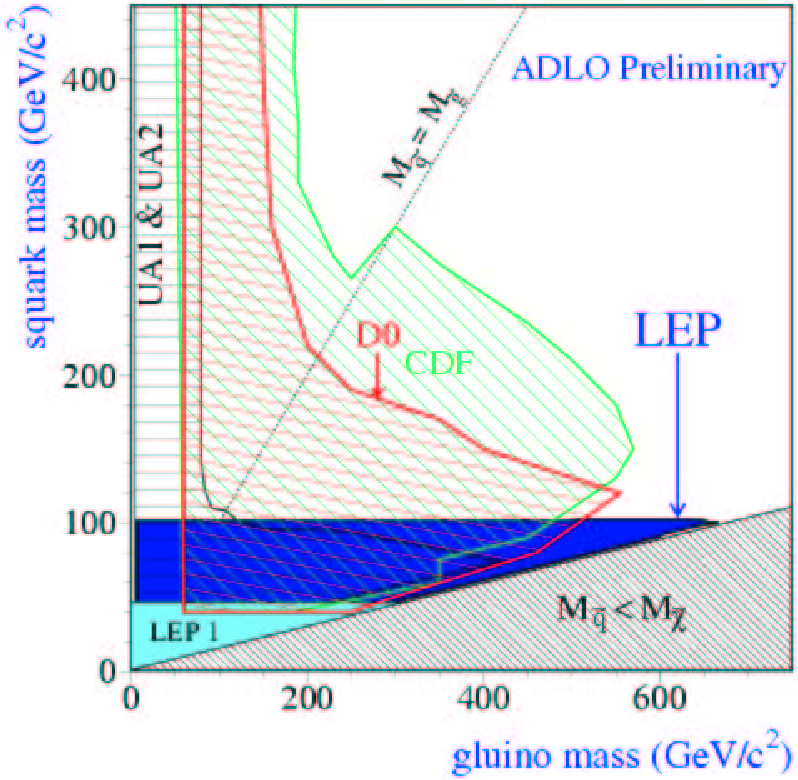
courtesy of S.Heinemeyer, W.Hollik and G.Weiglein:



An example:

LEP-II with $\sqrt{s} = 183 - 208$ GeV data

LEPSUSYWG, lepsusy.web.cern.ch, Summer 2002



CDF Collaboration, hep-ex/0106001, D0 Collaboration,hep-ex/9902013

The Future:

Hadron colliders (Tevatron Run II, LHC, VLHC), Lepton colliders (e^+e^- colliders (B-factories, high-energy linear colliders), muon collider), Neutrino experiments (study of solar, atmospheric and accelerator generated neutrinos), Astro-particle physics (dark matter search, study of high-energetic cosmic rays etc.).

We are seeking answers to many open questions, such as

- Are the weak gauge boson masses generated by the Higgs-Kibble mechanism or Where is the Higgs boson ?
- Why are there so many copies of the first generation of leptons and quarks ? What determines their mass hierarchy ? What is the origin of CP violation and how do neutrinos mix ?
- At what energy scale does the Standard Model break down and new physics emerges ? Which of the principles we believe to be fundamental will survive and what new ones will emerge to shape the new theory ?
- Is there another symmetry of nature that connects fermions and bosons called Supersymmetry ?
- How does gravity fit in the picture ?

Expect the Unexpected

and

Stay tuned !