SM Parameters and Tests

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Standard model parameters

- Quark masses, 6
- Lepton masses, 6
- Neutrino mixing angles, 3+1+(2) dimensionless
- Gauge coupling, 3, dimensionless
- CKM matrices, 4, dimensionless
- θ −vacuum, 1, dimensionless

A total of 12+6+4+1 = 24 (6) parameters.

If neutrinos were massless, there are 17 parameters.

A natural theory?

- If SM is a natural effective theory, then all dimensionless parameters shall be of order 1.
- However, this is not the case !
- SM is unnatural in many ways.
- For mass parameters, SM has two scales:

One is the EW SSB scale, v, which determines the masses of quarks and leptons.

The other is the QCD scale, Λ_{QCD}, which determines the scale of the strong-interaction dynamics.

QCD scale Λ_{QCD}

- QCD scale is determined by the scale-dependence of the strong interaction parameter α_s.

$$\alpha_s(Q^2) = \frac{4\pi}{\beta_0 \log\left(\frac{Q^2}{\Lambda_{QCD}^2}\right)} \; , \; \beta_0 = \frac{11}{3} - \frac{n_f}{2}$$

- $\Lambda_{QCD} \sim 200\ \mathrm{MeV}$, proton mass is about (3-4) Λ_{QCD}
- QCD scale determines the mass of the protons and neutrons and glueballs.
- QCD scale is in some sense arbitrary. It can be for example on the scale of GeV, 10 GeV, 100 GeV… It is determined by physics beyond SM model.

EWSB scale *v*

- EWSB scale is determined by the vacuum expectation value
$$\langle 0|\phi_0|0\rangle = v/\sqrt{2}.$$
- This sets the scale for lepton and quark masses, and, also the masses for W and Z boson, and higgs particle.
- $v = 246\ GeV$!
- This scale is also determined by physics beyond SM.
- This scale not stable, as the higgs particle mass gets quantum corrections,
$$\delta m^2 = \alpha \Lambda_{\mathrm{cutoff}}^2$$

what is the $\Lambda_{\mathrm{cutoff}}$? Generally it shall be the Planck scale, $10^{19} GeV$, thus
$$m_H^2(126\ GeV^2) = m_{H0}^2(10^{19} GeV^2) + \alpha\Lambda^2(10^{19}\ GeV^2)$$
fine-tuned by 17 orders of magnitude! Motivation for supersymmetry !

Quark mass and QCD dynamics

- Quark masses are generated through SSB
  - $m_i = \lambda_i v/\sqrt{2}$
- Ideally, the λ_i shall be of order 1, and quark masses shall be on the order of v. however, the reality is strongly deviated from that

  $\mathrm{m}_u = 1.7 - 3.1\ \mathrm{MeV},\ m_d = 4.1 - 5.7\ \mathrm{MeV}$

  $\mathrm{m}_\mathrm{s} = 100\ \mathrm{MeV},\ m_c = 1.3\ \mathrm{GeV}$

  $\mathrm{m}_\mathrm{b} = 4.2\ \mathrm{GeV},\ m_t = 173\ \mathrm{GeV}\ (this\ is\ the\ most\ natural)$
- For light flavors, QCD has approximate chiral symmetry, which is spontaneously broken

  $$SU(2)_L \times SU(2)_R \to SU(2)_{\mathrm{isospin}}$$

  The Goldstone bosons are pions.
- Heavy quarks ($m_Q \gg \Lambda_{QCD}$) lead heavy-quark symmetry.

Lepton masses

- Lepton masses are generally smaller than the quark masses.
- However, the neutrino mass is even smaller.

$$|\Delta m_{21}^2| \cong 7.6 \times 10^{-5} \ \text{eV}^2 ,$$
$$|\Delta m_{31}^2| \cong 2.4 \times 10^{-3} \ \text{eV}^2 ,$$
$$|\Delta m_{21}^2|/|\Delta m_{31}^2| \cong 0.032 .$$

The neutrino mass is in general meV! Which differs from the top quark mass and the Higgs condensate by 11 orders of magnitude.
This raises the question that why $\lambda_v \sim 10^{-11}$!!
It is not know yet that what is the lightest neutrino mass is!
However, the origin of the neutrino mass is not clear. It could come from the Majorana origin: seesaw mechanism.

Flavor mixing

- Flavor mixing is determined by CKM matrix.

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} .$$

- The most natural guess for all the matrix elements is order of one.
- However, CKM matrix has a hierarchical structure such that it is very close to unit matrix.
- Wolfenstein parametrization (small $\lambda = 0.22$ expansion)

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix} .$$

CP violation

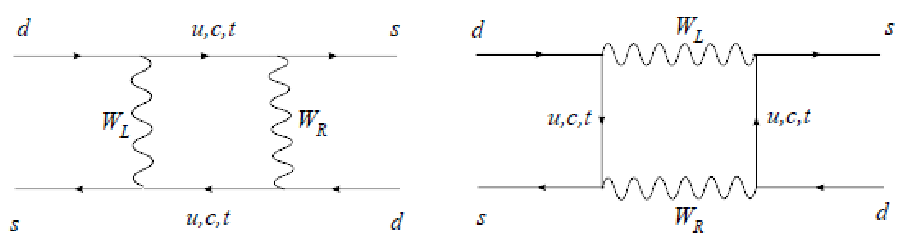
- In SM, the CP violation manifests only in the CKM matrix. All other terms do not admit complex coupling due to hermiticity of the theory.
- However, due to flavor mixing, this effects is reduced by a factor of $\lambda^3 \sim 10^{-3}$, and also when the third generation is involved.
- First observation of CP violation happens in the neutral kaon decay, (Cronin and Fitch, 1980)

$$K_L \to \pi\pi,$$

- B-factory has produced more CP violations consistent with the CKM mechanism -> Nobel prize to Kobayashi and Moskawa (2008)
- This small CP violation will generate a too small neutron EDM and cannot explain the Baryon number asymmetry in the Universe.

Fine tuning in flavor mixing and CP

- Consider $K_0(d\bar{s})\overline{K}_0(\bar{d}s)$ mixing



All three generations contribute to the mixing.

- For the mass difference, $m_{K_L} - m_{K_S}$,the dominate contribution comes from the intermediate charm quark, after considering the quark masses and CKM matrix!
- However, for the indirect CP violation parameter, ϵ, its contribution is mainly from imaginary part of the diagram, which is dominated by top quark!

Graveyard for New Models

- Flavor structure and CP violation is very difficult to describe in new models!
  - No flavor-changing neutral current
  - Flavor changing structure is highly organized (eg, $\mu \to e\gamma$)
  - CP violation is small.
- This is no natural starting point for any new model. As such, most of the new models will generate
  - A democratic flavor process
  - Flavor-changing neutral current process
  - Large CP violation

Theta angle

- Theta-angle is a new term is the QCD lagrangian,
  $$L = \theta \frac{g^2}{32\pi^2} F^{\mu\nu} \tilde{F}_{\mu\nu}$$
- It is a total derivative term which is important only when the gluon fields have non-trivial topology (instanton)
- It is correlated with the overall phase of the quark mass matrix.
- It violates T and P
- It will generate neutron electric dipole moment (EDM). The current limit on the neutron EDM moment $(10^{-26} e\ cm)$ thus, we have the constraint
  $$\theta < 10^{-10}$$

Why it is so small? How to relax this? Peccei-Quinn symmetry?

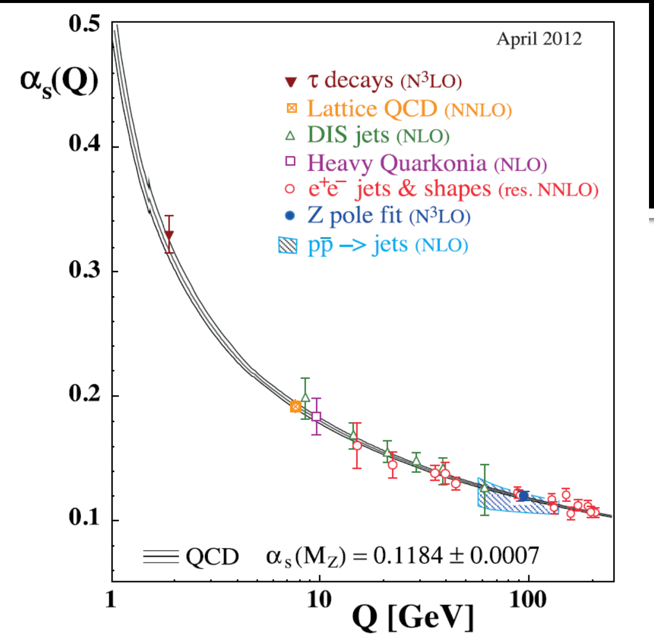
SM question summary

- Why the electroweak scale is so small compared with Planck scale?
- Why the quark and lepton masses have such large differences?
- Why flavor structure and CP violation are so peculiar?
- Why the theta parameter is so small?
- Why there are 3 generations?
- Why there appears a coupling constant unification?
- Why the baryon number violation is so small?

……

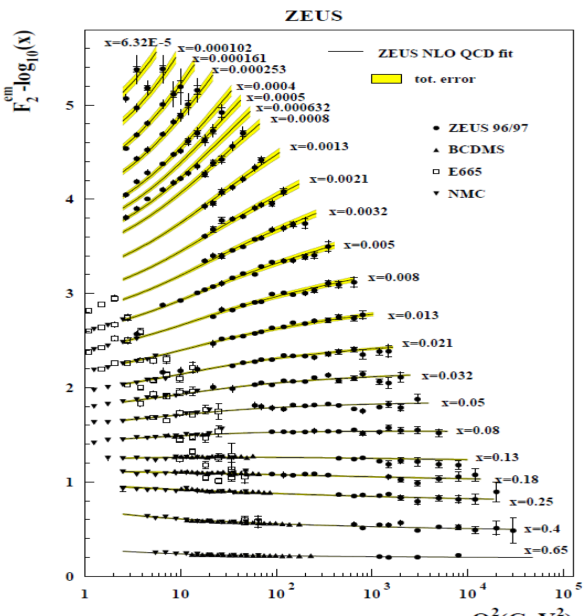
- However, the SM has been tested so precisely….

Perturbative QCD

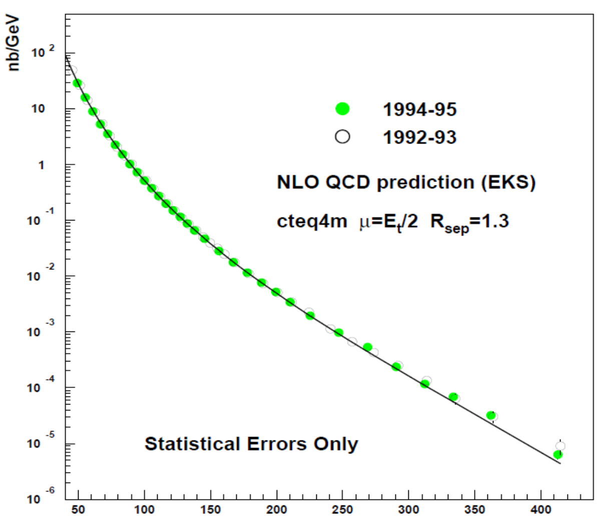


- At high-energy, the QCD coupling is small. Therefore, one can use perturbation theory to calculate high-energy scattering process.
- Factorization theorems

$F_2(x, Q^2)$ in ℓN interactions (ZEUS

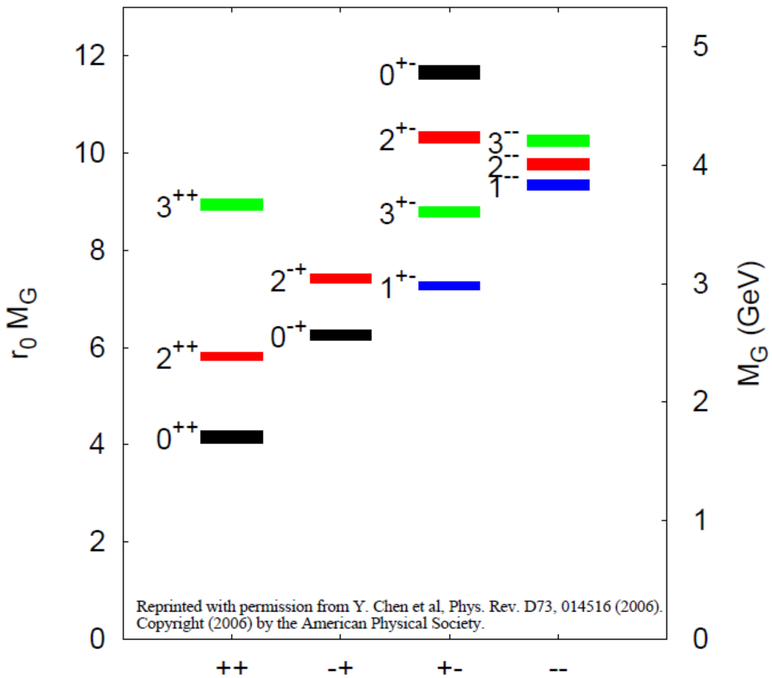


Inclusive jet cross section at $\sqrt{s} = 1.8$ TeV (CDF)



Non-perturbative QCD

- Non-perturbative QCD dynamics includes the structure of the proton and neutron.
- The only way to solve the QCD non-perturbatively is on a Euclidean lattice QCD. High precision calculations.



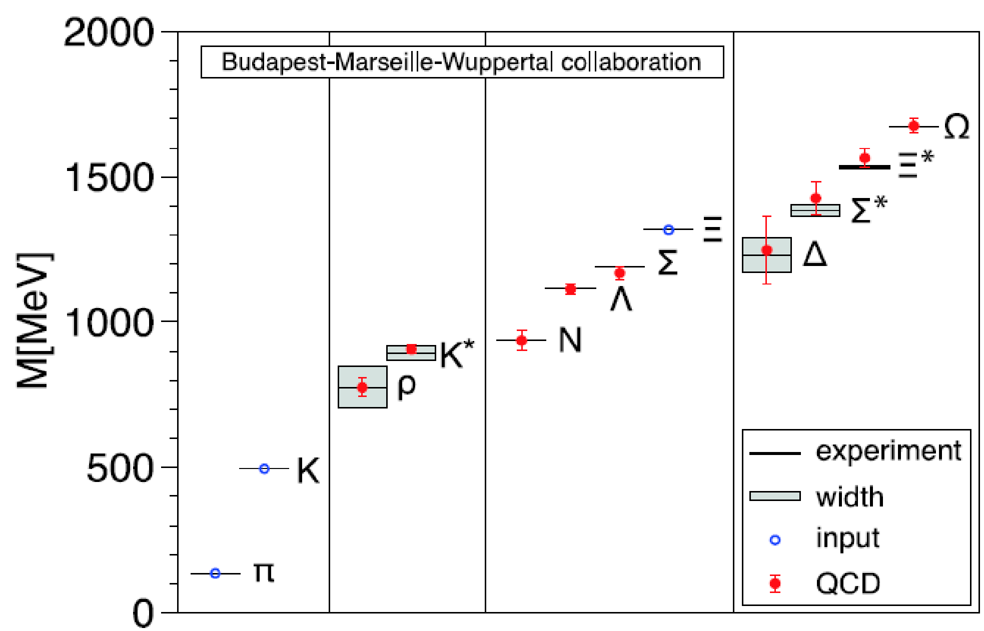


Figure 14.7: Light hadron spectroscopy from Ref. 40.

SM (EW theory) tests

- Assuming the quark masses, Higgs masses and QCD coupling, we have three parameters related to electroweak theory
  - Couplings g and g’
  - Higgs vev, v
- Better parameters to use is the
  - Fine structure constant α_{em}
  - Fermi decay constant G_F
  - Mass of Z particle, M_Z

Precision electroweak observables

- Mostly involving leptons and inclusive quarks. (excluding almost all weak interaction processes involving hadrons)
- Low-energy observables
- Precision flavor physics
- Z-pole (LEP-I and LEP-II)

electron-positron collisions at the Z-mass and above

LEP I and LEP II:

When the LEP collider started operation in August 1989 it accelerated the electrons and positrons to a total energy of 45 GeV each to enable production of the Z boson, which has a mass of 91 GeV.[1] The accelerator was upgraded later to enable production of a pair of W bosons, each having a mass of 80 GeV. LEP collider energy eventually topped at 209 GeV at the end in 2000. At a Lorentz factor (γ= particle energy/rest mass = [104.5 GeV/0.511 MeV]) of over 200,000, LEP still holds the particle accelerator speed record, extremely close to the limiting speed of light. At the end of 2000, LEP was shut down and then dismantled in order to make room in the tunnel for the construction of the Large Hadron Collider (LHC)

Low-energy EW observables

- Effective Interactions to one-loop accuracy

$$
\begin{aligned}
-\mathscr{L}^{\nu h} = & \frac{G_F}{\sqrt{2}} \, \overline{\nu} \, \gamma^\mu (1-\gamma^5) \nu \\
& \times \sum_i [\epsilon_L(i) \overline{q}_i \, \gamma_\mu (1-\gamma^5) q_i + \epsilon_R(i) \overline{q}_i \, \gamma_\mu (1+\gamma^5) q_i],
\end{aligned}
$$

$$
-\mathscr{L}^{\nu e} = \frac{G_F}{\sqrt{2}} \, \overline{\nu}_\mu \gamma^\mu (1-\gamma^5) \nu_\mu \, \overline{e} \, \gamma_\mu (g_V^{\nu e} - g_A^{\nu e} \gamma^5) e,
$$

$$
-\mathscr{L}^{eh} = - \frac{G_F}{\sqrt{2}} \sum_i \left[C_{1i} \, \overline{e} \, \gamma_\mu \gamma^5 e \, \overline{q}_i \, \gamma^\mu q_i + C_{2i} \, \overline{e} \, \gamma_\mu e \, \overline{q}_i \, \gamma^\mu \gamma^5 q_i \right],
$$

$$
-\mathscr{L}^{ee} = - \frac{G_F}{\sqrt{2}} \, C_{2e} \, \overline{e} \, \gamma_\mu \gamma^5 e \, \overline{e} \, \gamma^\mu e,
$$

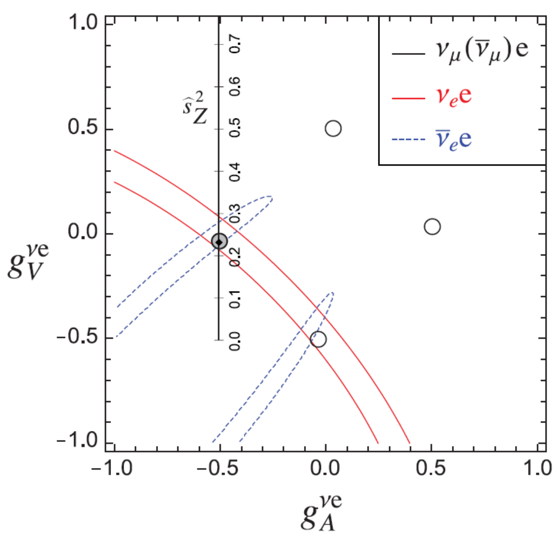
Couplings including one-loop corrections

Quantity	Standard Model Expression
$\epsilon_L(u)$	$\rho_{\nu N}\left(\frac{1}{2}-\frac{2}{3}\,\hat{\kappa}_{\nu N}\,\hat{s}_Z^2\right)+\lambda_{uL}$
$\epsilon_L(d)$	$\rho_{\nu N}\left(-\frac{1}{2}+\frac{1}{3}\,\hat{\kappa}_{\nu N}\,\hat{s}_Z^2\right)+\lambda_{dL}$
$\epsilon_R(u)$	$\rho_{\nu N}\left(-\frac{2}{3}\,\hat{\kappa}_{\nu N}\,\hat{s}_Z^2\right)+\lambda_R$
$\epsilon_R(d)$	$\rho_{\nu N}\left(\frac{1}{3}\,\hat{\kappa}_{\nu N}\,\hat{s}_Z^2\right)+2\,\lambda_R$
$g_V^{\nu e}$	$\rho_{\nu e}\left(-\frac{1}{2}+2\,\hat{\kappa}_{\nu e}\,\hat{s}_Z^2\right)$
$g_A^{\nu e}$	$\rho_{\nu e}\left(-\frac{1}{2}\right)$
C_{1u}	$\rho'_e\left(-\frac{1}{2}+\frac{4}{3}\,\hat{\kappa}'_e\,\hat{s}_Z^2\right)+\lambda'$
C_{1d}	$\rho'_e\left(\frac{1}{2}-\frac{2}{3}\,\hat{\kappa}'_e\,\hat{s}_Z^2\right)-2\,\lambda'$
C_{2u}	$\rho_e\left(-\frac{1}{2}+2\,\hat{\kappa}_e\,\hat{s}_Z^2\right)+\lambda_u$
C_{2d}	$\rho_e\left(\frac{1}{2}-2\,\hat{\kappa}_e\,\hat{s}_Z^2\right)+\lambda_d$
C_{2e}	$\rho_e\left(\frac{1}{2}-2\,\hat{\kappa}_e\,\hat{s}_Z^2\right)+\lambda_e$

Neutrino electron scattering

$$\frac{d\sigma_{\nu,\bar{\nu}}}{dy} = \frac{G_F^2 m_e E_\nu}{2\pi}\left[(g_V^{\nu e} \pm g_A^{\nu e})^2 + (g_V^{\nu e} \mp g_A^{\nu e})^2(1-y)^2 - (g_V^{\nu e 2} - g_A^{\nu e 2})\frac{y\, m_e}{E_\nu}\right],$$

The most accurate measurements [95–100] of $\sin^2\theta_W$ from ν-lepton scattering (see Sec. 10.6) are from the ratio $R \equiv \sigma_{\nu_\mu e}/\sigma_{\bar{\nu}_\mu e}$ in which many of the systematic uncertaint cancel. Radiative corrections (other than m_t effects) are small compared to the precisi of present experiments and have negligible effect on the extracted $\sin^2\theta_W$. The mos precise experiment (CHARM II) [98] determined not only $\sin^2\theta_W$ but $g_{V,A}^{\nu e}$ as well



Neutrino nucleus scattering

- CDHS and CHARM at CERN
- CCFR and NuTeV at Fermilab
- Deep-inelastic neutrino scattering on isoscalar target

Consider various ratios to minimize the uncertainty

$$R_\nu \equiv \sigma^{NC}_{\nu N} / \sigma^{CC}_{\nu N} \qquad R_{\bar\nu} \equiv \sigma^{NC}_{\bar\nu N} / \sigma^{CC}_{\bar\nu N}$$

$$R^- = \frac{\sigma^{NC}_{\nu N} - \sigma^{NC}_{\bar\nu N}}{\sigma^{CC}_{\nu N} - \sigma^{CC}_{\bar\nu N}} \qquad R_\nu = g_L^2 + g_R^2 r, \quad R_{\bar\nu} = g_L^2 + \frac{g_R^2}{r}, \quad R^- = g_L^2 - g_R^2$$

$$g_L^2 \equiv \epsilon_L(u)^2 + \epsilon_L(d)^2 \approx \frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W,$$

$$g_R^2 \equiv \epsilon_R(u)^2 + \epsilon_R(d)^2 \approx \frac{5}{9}\sin^4\theta_W,$$

The NuTeV final result

$\sin^2\theta_W = 0.2277 \pm 0.0016$

Which is 3σ higher than SM prediction.

Parity-violating electron scattering

- Polarized electron-D DIS,

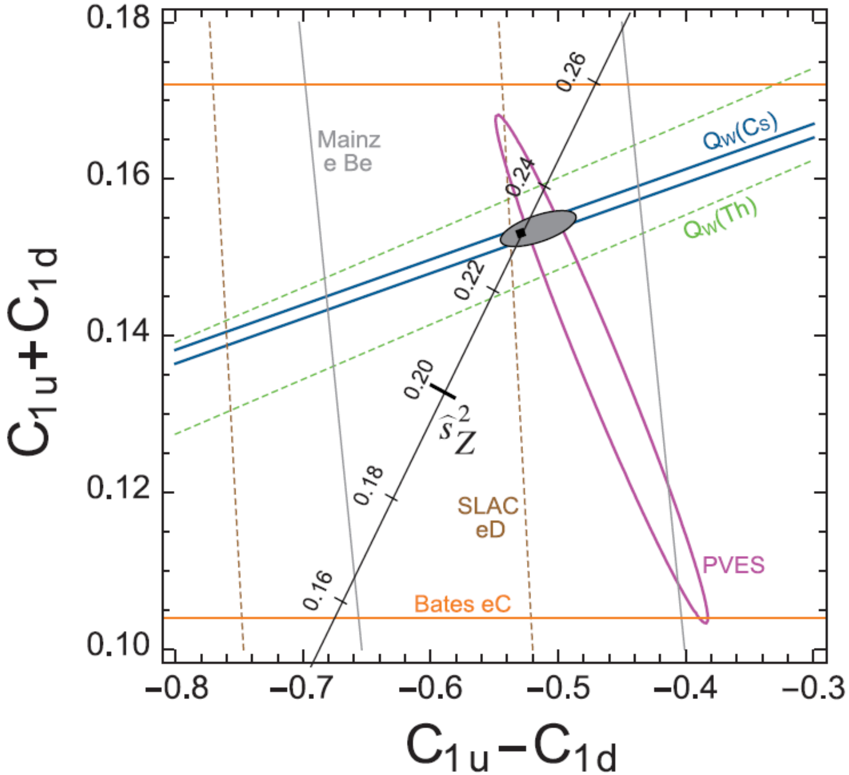
$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \,, \qquad \frac{A}{Q^2} = a_1 + a_2 \frac{1-(1-y)^2}{1+(1-y)^2} \,,$$

$$a_1 = \frac{3G_F}{5\sqrt{2}\pi\alpha}\left(C_{1u} - \frac{1}{2}C_{1d}\right) \approx \frac{3G_F}{5\sqrt{2}\pi\alpha}\left(-\frac{3}{4} + \frac{5}{3}\sin^2\theta_W\right),$$

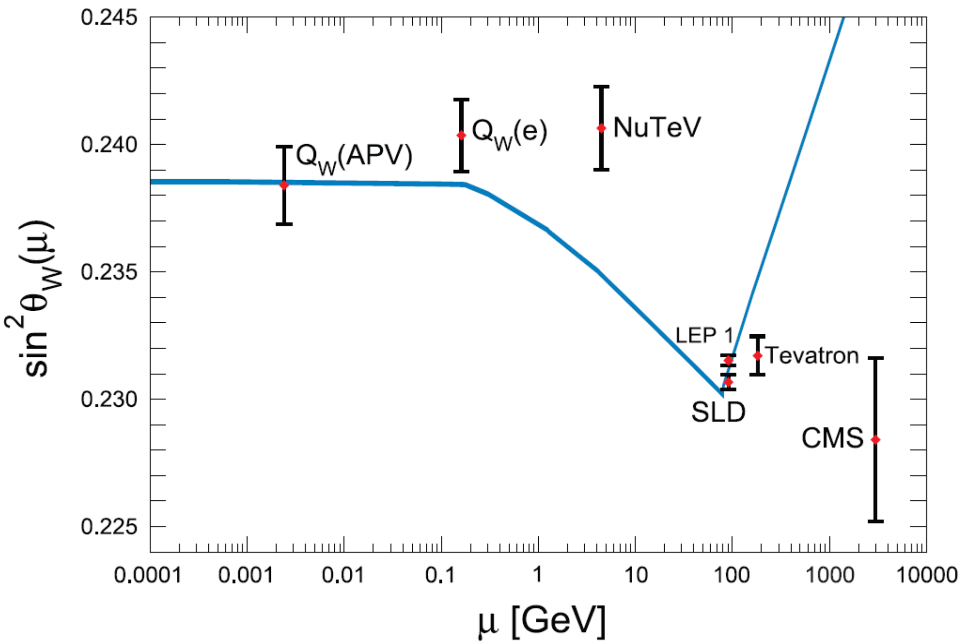
$$a_2 = \frac{3G_F}{5\sqrt{2}\pi\alpha}\left(C_{2u} - \frac{1}{2}C_{2d}\right) \approx \frac{9G_F}{5\sqrt{2}\pi\alpha}\left(\sin^2\theta_W - \frac{1}{4}\right).$$

- Parity-violating quasi-elastic scattering on D (C_{2u}-C_{2d})
- Weak charges
  - Electrons, PV moller scattering, $Q_W(e) = -2C_{2e}$
  - Proton, PV scattering on proton, $Q_W(p) = -2[2C_{1u} + C_{1d}]$
  - Nucleus, Atomic PV, $Q_W(Z, N) = -2[(2Z+N)C_{1u} + (Z+2N)C_{1d}]$

Results



0.18
0.16
0.14
0.12
0.10
−0.8
−0.7
−0.6
−0.5
−0.4
−0.3
$C_{1u}+C_{1d}$
$C_{1u}-C_{1d}$
Mainz e Be
$Q_W(Cs)$
$Q_W(Th)$
SLAC eD
PVES
Bates eC
$\hat{s}^2_Z$
0.16
0.18
0.20
0.22
0.24
0.26



0.245
0.240
0.235
0.230
0.225
$\sin^2\theta_W(\mu)$
μ [GeV]
0.0001
0.001
0.01
0.1
1
10
100
1000
10000
$Q_W(APV)$
$Q_W(e)$
NuTeV
LEP 1
SLD
Tevatron
CMS

Precision flavor physics

- $b \to s\gamma$ very sensitive to new physics.
- τ lepton decay, extraction of α_s from the lifetime and leptonic decay width. $\alpha_s(M_Z) = 0.1193^{+0.0022}_{-0.0020}$,
- Muon g-2:

$$a_\mu^{\rm exp} = \frac{g_\mu - 2}{2} = (1165920.80 \pm 0.63) \times 10^{-9},$$

is dominated by the final result of the E821 collaboration at BNL [194]. The QED contribution has been calculated to four loops [195] (fully analytically to three loops [196,197]) , and the leading logarithms are included to five loops [198,199]. The estimated SM EW contribution [200–202], $a_\mu^{\rm EW} = (1.52 \pm 0.03) \times 10^{-9}$, which includes leading two-loop [201] and three-loop [202] corrections, is at the level of twice the current uncertainty.

$$a_\mu^{\rm theory} = (1165918.41 \pm 0.48) \times 10^{-9} \ ,$$

- There is a 3σ discrepancy

Fits 1

Quantity	Value	Standard Model	Pull	Dev.
m_t [GeV]	173.4 ± 1.0	173.5 ± 1.0	-0.1	-0.3
M_W [GeV]	80.420 ± 0.031	80.381 ± 0.014	1.2	1.6
	80.376 ± 0.033		-0.2	0.2
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0398 ± 0.0003	0.0	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064 ± 0.0001	0.0	0.0
$Q_W(e)$	-0.0403 ± 0.0053	-0.0474 ± 0.0005	1.3	1.3
$Q_W(\mathrm{Cs})$	-73.20 ± 0.35	-73.23 ± 0.02	0.1	0.1
$Q_W(\mathrm{Tl})$	-116.4 ± 3.6	-116.88 ± 0.03	0.1	0.1
τ_τ [fs]	291.13 ± 0.43	290.75 ± 2.51	0.1	0.1
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	$(4511.07 \pm 0.77) \times 10^{-9}$	$(4508.70 \pm 0.09) \times 10^{-9}$	3.0	3.0

Z pole physics

- Total Width, Γ_Z
- Partial Widths, $\Gamma(l\bar{l})$, $\Gamma(hadron)$,
- $\Gamma(inv) = \Gamma_Z - 3\Gamma(l\bar{l}) - \Gamma(hadron)$
- $R_\ell = \Gamma(hadron)/\Gamma(l\bar{l})$ $(\ell = e, \mu, \tau)$
- $R_{b,c} = \Gamma(b\bar{b}, c\bar{c})/\Gamma(hadron)$

$$\sigma_{\mathrm{had}} \equiv 12\pi\,\Gamma(e^+e^-)\,\Gamma(\mathrm{had})/M_Z^2\,\Gamma_Z^2$$

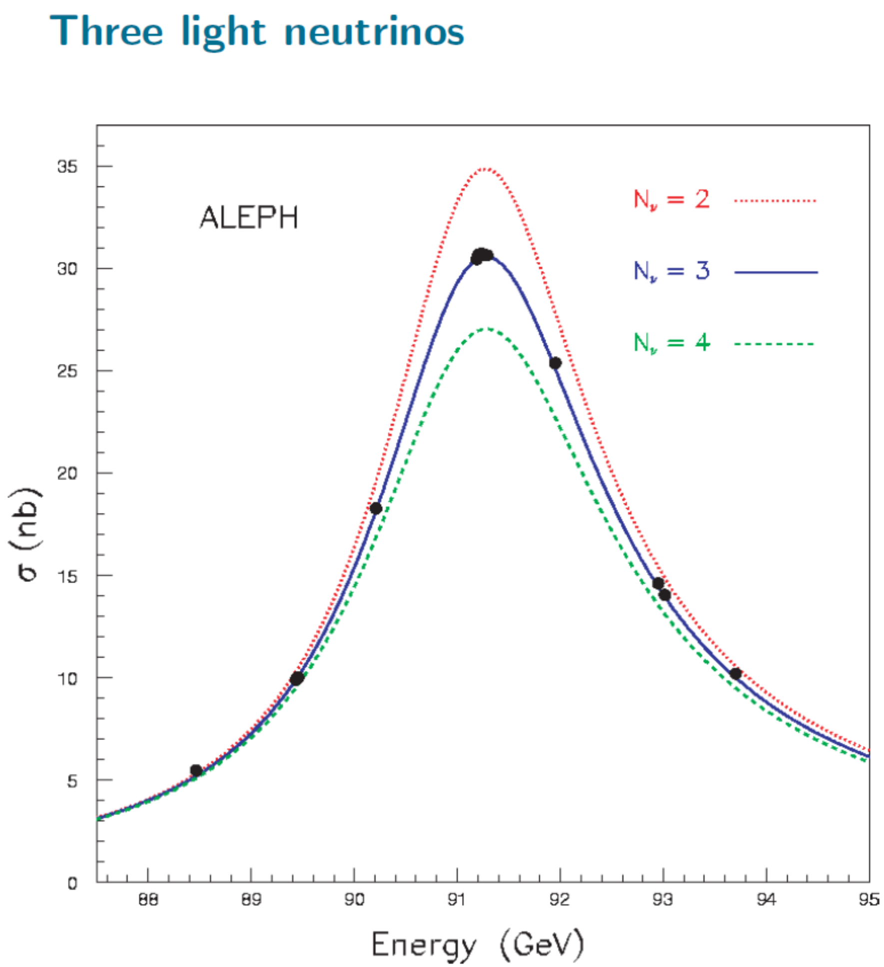
- Polarization asymmetry (net polarization of fermion in decay)

$$A_f \equiv \frac{2\bar{g}_V^f\,\bar{g}_A^f}{\bar{g}_V^{f2} + \bar{g}_A^{f2}} .$$

- Forward and backward asymmetry with and without Pol.

$$A_{FB} = \frac{3}{4} A_f \frac{A_e + P_e}{1 + P_e A_e} , \qquad A_{FB}^{(0,f)} = \frac{3}{4} A_e A_f$$

Three light neutrinos!



Z-pole measurement for leptons

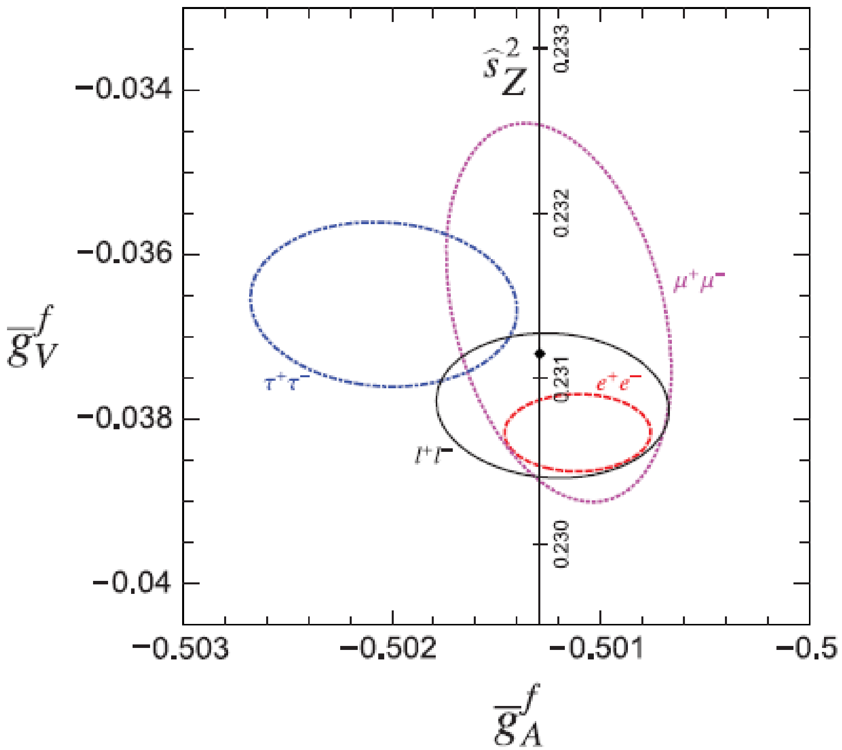


Figure 10.4: 1 σ (39.35% C.L.) contours for the Z-pole observables $\bar{g}_A^f$ and $\bar{g}_V^f$, $f = e, \mu, \tau$ obtained at LEP and SLC [11], compared to the SM expectation as a function of $\hat{s}_Z^2$. (The SM best fit value $\hat{s}_Z^2 = 0.23116$ is also indicated.) Also shown is the 90% CL allowed region in $\bar{g}_{A,V}^\ell$ obtained assuming lepton universality.

Z-pole Fit 1

Quantity	Value	Standard Model	Pull	Dev.
M_Z [GeV]	91.1876 ± 0.0021	91.1874 ± 0.0021	0.1	0.0
Γ_Z [GeV]	2.4952 ± 0.0023	2.4961 ± 0.0010	-0.4	-0.2
$\Gamma(\mathrm{had})$ [GeV]	1.7444 ± 0.0020	1.7426 ± 0.0010	—	—
$\Gamma(\mathrm{inv})$ [MeV]	499.0 ± 1.5	501.69 ± 0.06	—	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	84.005 ± 0.015	—	—
σ_{had}[nb]	41.541 ± 0.037	41.477 ± 0.009	1.7	1.7
R_e	20.804 ± 0.050	20.744 ± 0.011	1.2	1.3
R_μ	20.785 ± 0.033	20.744 ± 0.011	1.2	1.3
R_τ	20.764 ± 0.045	20.789 ± 0.011	-0.6	-0.5
R_b	0.21629 ± 0.00066	0.21576 ± 0.00004	0.8	0.8
R_c	0.1721 ± 0.0030	0.17227 ± 0.00004	-0.1	-0.1
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01633 ± 0.00021	-0.7	-0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.4	0.6
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.5	1.6

Z-pole Fit 2

$A_{FB}^{(0,b)}$	0.0992 ± 0.0016	0.1034 ± 0.0007	-2.6	-2.3
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0739 ± 0.0005	-0.9	-0.8
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1035 ± 0.0007	-0.5	-0.5
$\bar{s}_\ell^2(A_{FB}^{(0,q)})$	0.2324 ± 0.0012	0.23146 ± 0.00012	0.8	0.7
	0.23200 ± 0.00076		0.7	0.6
	0.2287 ± 0.0032		-0.9	-0.9
A_e	0.15138 ± 0.00216	0.1475 ± 0.0010	1.8	2.1
	0.1544 ± 0.0060		1.1	1.3
	0.1498 ± 0.0049		0.5	0.6
A_μ	0.142 ± 0.015		-0.4	-0.3
A_τ	0.136 ± 0.015		-0.8	-0.7
	0.1439 ± 0.0043		-0.8	-0.7
A_b	0.923 ± 0.020	0.9348 ± 0.0001	-0.6	-0.6
A_c	0.670 ± 0.027	0.6680 ± 0.0004	0.1	0.1
A_s	0.895 ± 0.091	0.9357 ± 0.0001	-0.4	-0.4

Higgs from radiative corrections: Power of QFT!

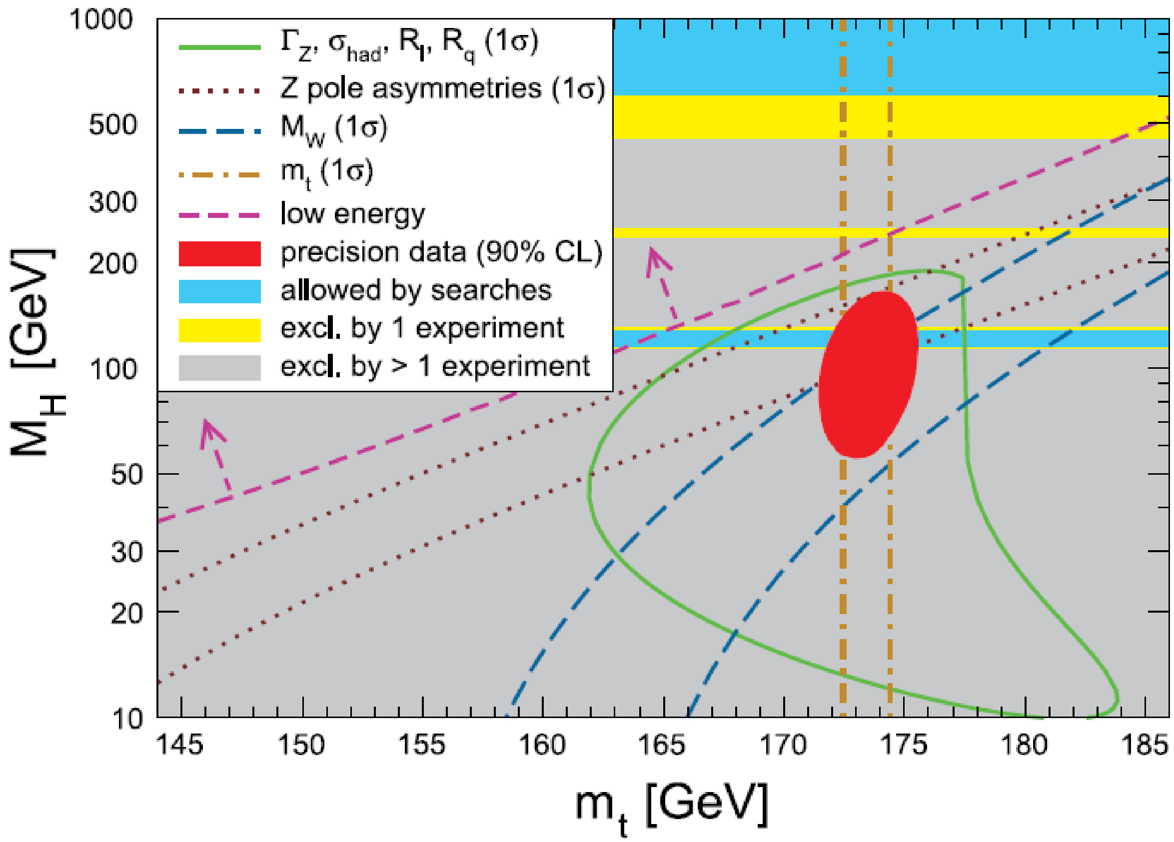


Table 10.4, Table 10.5, and Table 10.7. A combination of all available data yields (at the 68% CL) [215]

$$M_H = 124.5 \pm 0.8 \text{ GeV}. \tag{10.51}$$

Neutral current parameters

Quantity	Experimental Value	SM	Correlation		
$\epsilon_L(u)$	0.328 ± 0.016	$0.3461(1)$			
$\epsilon_L(d)$	-0.440 ± 0.011	$-0.4292(1)$	non-		
$\epsilon_R(u)$	-0.179 ± 0.013	$-0.1549(1)$	Gaussian		
$\epsilon_R(d)$	$-0.027\,^{+0.077}_{-0.048}$	0.0775			
g_L^2	0.3009 ± 0.0028	$0.3040(2)$			
g_R^2	0.0328 ± 0.0030	0.0300		small	
θ_L	2.50 ± 0.035	$2.4630(1)$			
θ_R	$4.56\,^{+0.42}_{-0.27}$	5.1765			
$g_V^{\nu e}$	-0.040 ± 0.015	$-0.0399(2)$			-0.05
$g_A^{\nu e}$	-0.507 ± 0.014	$-0.5064(1)$			
$C_{1u} + C_{1d}$	0.1537 ± 0.0011	$0.1530(1)$	0.64	-0.18	-0.01
$C_{1u} - C_{1d}$	-0.516 ± 0.014	$-0.5300(3)$		-0.27	-0.02
$C_{2u} + C_{2d}$	-0.21 ± 0.57	-0.0089			-0.30
$C_{2u} - C_{2d}$	-0.077 ± 0.044	$-0.0627(5)$			
$Q_W(e) = -2C_{2e}$	-0.0403 ± 0.0053	$-0.0474(5)$			

Sign for New Physics

- Rho –parameter:

$$\rho_0 \equiv \frac{M_W^2}{M_Z^2\,\widehat{c}_Z^{\,2}\,\widehat{\rho}}\ ,$$

- S, T, U parameters.

$$\widehat{\alpha}(M_Z)T \equiv \frac{\Pi_{WW}^{\rm new}(0)}{M_W^2} - \frac{\Pi_{ZZ}^{\rm new}(0)}{M_Z^2}\ ,$$

$$\frac{\widehat{\alpha}(M_Z)}{4\,\widehat{s}_Z^{\,2}\widehat{c}_Z^{\,2}}S \equiv \frac{\Pi_{ZZ}^{\rm new}(M_Z^2) - \Pi_{ZZ}^{\rm new}(0)}{M_Z^2} - \frac{\widehat{c}_Z^{\,2} - \widehat{s}_Z^{\,2}}{\widehat{c}_Z\widehat{s}_Z}\frac{\Pi_{Z\gamma}^{\rm new}(M_Z^2)}{M_Z^2} - \frac{\Pi_{\gamma\gamma}^{\rm new}(M_Z^2)}{M_Z^2}\ ,$$

$$\frac{\widehat{\alpha}(M_Z)}{4\,\widehat{s}_Z^{\,2}}(S+U) \equiv \frac{\Pi_{WW}^{\rm new}(M_W^2) - \Pi_{WW}^{\rm new}(0)}{M_W^2} - \frac{\widehat{c}_Z}{\widehat{s}_Z}\frac{\Pi_{Z\gamma}^{\rm new}(M_Z^2)}{M_Z^2} - \frac{\Pi_{\gamma\gamma}^{\rm new}(M_Z^2)}{M_Z^2}\ .$$

- Z’ particles

Rho parameter

- Multiple Higgs fields,

For a general (charge-conserving) Higgs structure,

$$\rho_0 = \frac{\sum_i [t(i)(t(i)+1) - t_3(i)^2]|v_i|^2}{2\sum_i t_3(i)^2 |v_i|^2},$$

- Non-degenerate SU(2) multiplets

$$\rho_0 = 1 + \frac{3\,G_F}{8\sqrt{2}\pi^2} \sum_i \frac{C_i}{3}\,\Delta m_i^2\ ,$$

$$\Delta m^2 \equiv m_1^2 + m_2^2 - \frac{4m_1^2 m_2^2}{m_1^2 - m_2^2} \ln \frac{m_1}{m_2} \geq (m_1 - m_2)^2,$$

- Global fits:

$$\rho_0 = 1.0004^{+0.0003}_{-0.0004}\ ,$$

STU parameters

A multiplet of heavy degenerate chiral fermions yields

$$S = \frac{C}{3\pi} \sum_i \Big(t_{3L}(i) - t_{3R}(i) \Big)^2,$$

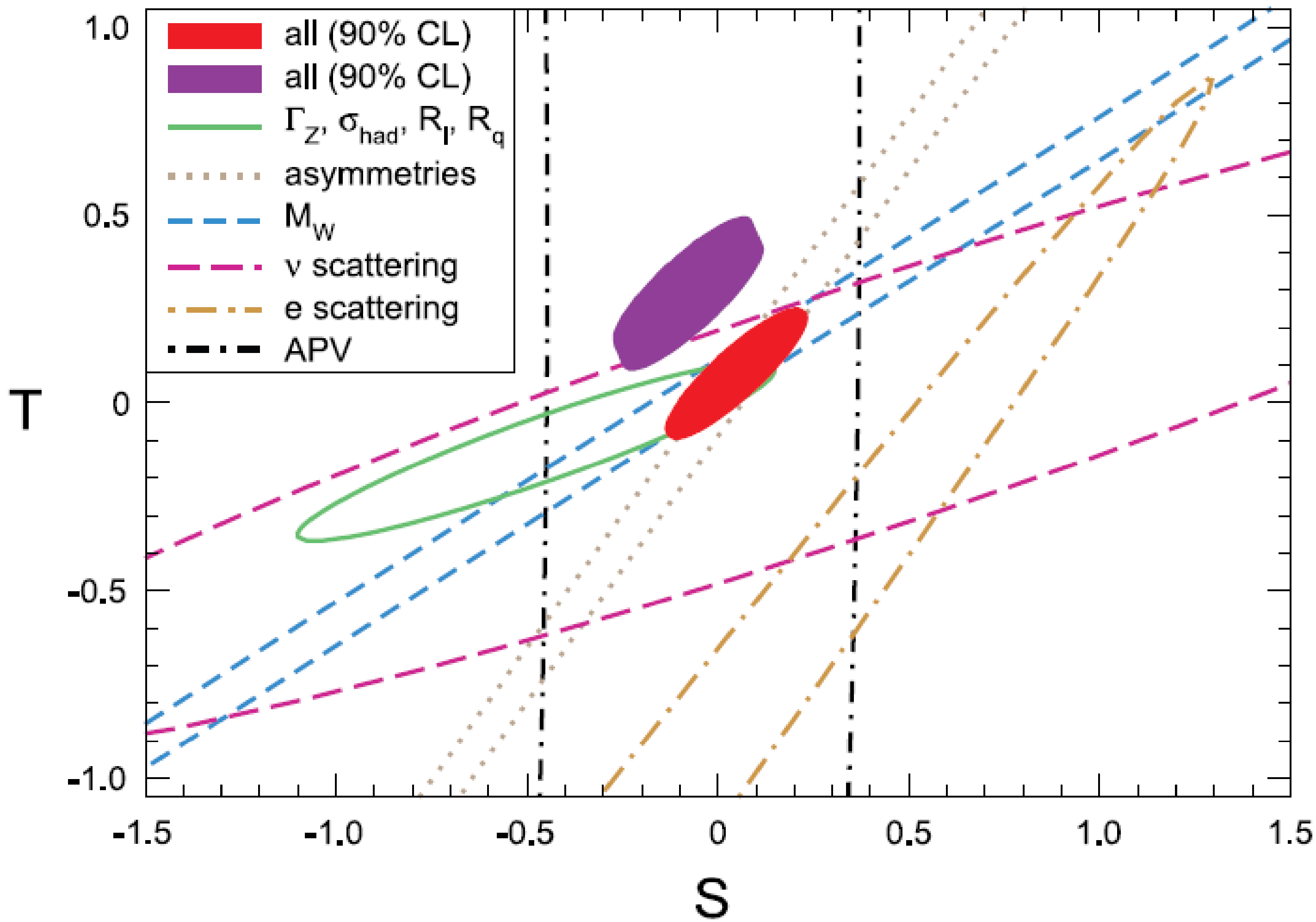
where $t_{3L,R}(i)$ is the third component of weak isospin of the left-(right-)handed component of fermion i and C is the number of colors. For example, a heavy degenerate ordinary or mirror family would contribute $2/3\pi$ to S. In Technicolor models with QCD-like dynamics, one expects [232] $S \sim 0.45$ for an iso-doublet of techni-fermions, assuming $N_{TC} = 4$ techni-colors, while $S \sim 1.62$ for a full techni-generation with $N_{TC} = 4$; T is harder to estimate because it is model-dependent. In these examples one has $S \geq 0$. However, the QCD-like models are excluded on other grounds (flavor changing neutral-currents, and too-light quarks and pseudo-Goldstone bosons [240]) . In particular, these estimates do not apply to models of walking Technicolor [240], for which S can be smaller or even negative [241]. Other situations in which $S < 0$, such as loops involving scalars or Majorana particles, are also possible [242]. The simplest origin of $S < 0$ would probably be an additional heavy Z' boson [229], which could mimic $S < 0$. Supersymmetric extensions of the SM generally give very small effects. See

Global fits

$$S = 0.00^{+0.11}_{-0.10},$$

$$T = 0.02^{+0.11}_{-0.12},$$

$$U = 0.08 \pm 0.11,$$



Sources of Z'

Higgs models [259]. For example, the SO(10) GUT contains an extra U(1) as can be seen from its maximal subgroup, $SU(5) \times U(1)_\chi$. Similarly, the E_6 GUT contains the subgroup $SO(10) \times U(1)_\psi$. The Z_ψ possesses only axial-vector couplings to the ordinary fermions, and its mass is generally less constrained. The Z_η boson is the linea combination $\sqrt{3/8}\,Z_\chi - \sqrt{5/8}\,Z_\psi$. The Z_{LR} boson occurs in left-right models with gau group $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \subset SO(10)$, and the secluded Z_S emerge in a supersymmetric bottom-up scenario [269]. The sequential Z_{SM} boson is defined t have the same couplings to fermions as the SM Z boson. Such a boson is not expecte in the context of gauge theories unless it has different couplings to exotic fermions tha the ordinary Z boson. However, it serves as a useful reference case when comparing constraints from various sources. It could also play the role of an excited state of th ordinary Z boson in models with extra dimensions at the weak scale [258]. Finally we consider a Superstring motivated Z_{string} boson appearing in a specific model [270

Various Searches!

Z'	EW	ATLAS	CMS	CDF	DØ	LEP 2	M_H
Z_χ	$1,141$	$1,640$	–	930	903	673	$171^{+493}_{-\ 89}$
Z_ψ	147	$1,490$	$1,620$	917	891	481	$97^{+\ 31}_{-\ 25}$
Z_η	427	$1,540$	–	938	923	434	423^{+577}_{-350}
Z_{LR}	998	–	–	–	–	804	$804^{+174}_{-\ 35}$
Z_S	$1,257$	$1,600$	–	858	822	–	$149^{+353}_{-\ 68}$
Z_{SM}	$1,403$	$1,830$	$1,940$	$1,071$	$1,023$	$1,787$	331^{+669}_{-246}
Z_{string}	$1,362$	–	–	–	–	–	$134^{+209}_{-\ 58}$

Conclusions

- SM parameters show strong fine-tuning.
- Agreement between SM and date is impressive.
- New physics from precision electroweak physics shows little sign!