Introduction to the Standard Model

- Origins of the Electroweak Theory
- Gauge Theories
- The Standard Model Lagrangian
- Spontaneous Symmetry Breaking
- The Gauge Interactions
- Problems With the Standard Model

("Structure Of The Standard Model," hep-ph/0304186)

Spontaneous Symmetry Breaking

Gauge invariance implies massless gauge bosons and fermions

Weak interactions short ranged $\Rightarrow$ spontaneous symmetry breaking for mass; also for fermions

Color confinement for QCD $\Rightarrow$ gluons remain massless

Allow classical (ground state) expectation value for Higgs field

$$v = \langle 0|\varphi|0\rangle = \text{constant}$$

$\partial_\mu v \neq 0$ increases energy, but important for monopoles, strings, domain walls, phase transitions (e.g., EWPT, baryogenesis)

Minimize $V(v)$ to find v and quantize $\varphi' = \varphi - v$

$SU(2)\times U(1)$: introduce Hermitian basis

$$\varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{2}}(\varphi_1 - i\varphi_2) \\ \frac{1}{\sqrt{2}}(\varphi_3 - i\varphi_4 \end{pmatrix},$$

where $\varphi_i = \varphi_i^\dagger$.

$$V(\varphi) = \frac{1}{2}\mu^2 \left(\sum_{i=1}^{4} \varphi_i^2\right) + \frac{1}{4}\lambda \left(\sum_{i=1}^{4} \varphi_i^2\right)^2$$

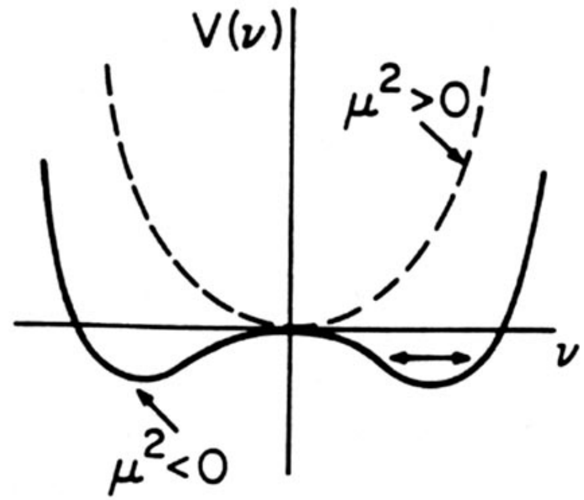
is $O(4)$ invariant.

w.l.o.g. choose $\langle 0|\varphi_i|0\rangle = 0, \quad i = 1, 2, 4$ and $\langle 0|\varphi_3|0\rangle = \nu$

$$V(\varphi) \rightarrow V(v) = \frac{1}{2}\mu^2\nu^2 + \frac{1}{4}\lambda\nu^4$$

For $\mu^2 < 0$, minimum at

$$V'(\nu) = \nu(\mu^2 + \lambda\nu^2) = 0$$
$$\Rightarrow \nu = \left(-\mu^2/\lambda\right)^{1/2}$$



SSB for $\mu^2 = 0$ also; must consider loop corrections

$\varphi \rightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu \end{pmatrix} \equiv v \Rightarrow$ the generators L^1, L^2, and $L^3 - Y$ spontaneously broken, $L^1 v \neq 0$, etc $(L^i = \frac{\tau^i}{2},\ Y = \frac{1}{2} I)$

$Qv = (L^3 + Y)v = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} v = 0 \Rightarrow U(1)_Q$ unbroken $\Rightarrow$ $SU(2) \times U(1)_Y \rightarrow U(1)_Q$

Quantize around classical vacuum

- Kibble transformation: introduce new variables ξ^i for rolling modes

$$\varphi = \frac{1}{\sqrt{2}} e^{i \sum \xi^i L^i} \begin{pmatrix} 0 \\ \nu + H \end{pmatrix}$$

- $H = H^\dagger$ is the Higgs scalar
- No potential for $\xi^i \Rightarrow$ massless Goldstone bosons for global symmetry
- Disappear from spectrum for gauge theory ("eaten")
- Display particle content in unitary gauge

$$\varphi \rightarrow \varphi' = e^{-i \sum \xi^i L^i} \varphi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu + H \end{pmatrix}$$

$+$ corresponding transformation on gauge fields

Rewrite Lagrangian in New Vacuum

Higgs covariant kinetic energy terms

$$
\begin{aligned}
(D_\mu \varphi)^\dagger D^\mu \varphi &= \frac{1}{2}(0\ \nu)\left[\frac{g}{2}\tau^i W^i_\mu + \frac{g'}{2}B_\mu\right]^2 \begin{pmatrix} 0 \\ \nu \end{pmatrix} + H \text{ terms} \\
&\rightarrow M_W^2 W^{+\mu} W^-_\mu + \frac{M_Z^2}{2} Z^\mu Z_\mu \\
&+ H \text{ kinetic energy and gauge interaction terms}
\end{aligned}
$$

Mass eigenstate bosons: W, Z, and A (photon)

$$
\begin{aligned}
W^\pm &= \frac{1}{\sqrt{2}}(W^1 \mp i W^2) \\
Z &= -\sin\theta_W B + \cos\theta_W W^3 \\
A &= \cos\theta_W B + \sin\theta_W W^3
\end{aligned}
$$

Masses

$$M_W = \frac{g\nu}{2}, \quad M_Z = \sqrt{g^2 + g'^2}\frac{\nu}{2} = \frac{M_W}{\cos\theta_W}, \quad M_A = 0$$

(Goldstone scalar transformed into longitudinal components of $W^\pm$, Z)

Weak angle: $\tan\theta_W \equiv g'/g$

Will show: Fermi constant $G_F/\sqrt{2} \sim g^2/8M_W^2$, **where** $G_F = 1.16637(1)\times 10^{-5}\ GeV^{-2}$ **from muon lifetime**

Electroweak scale

$$\nu = 2M_W/g \simeq (\sqrt{2}G_F)^{-1/2} \simeq 246\ GeV$$

Will show: $g = e/\sin\theta_W$, **where** $\alpha = e^2/4\pi \sim 1/137.036 \Rightarrow$

$$M_W = M_Z \cos\theta_W \sim \frac{(\pi\alpha/\sqrt{2}G_F)^{1/2}}{\sin\theta_W}$$

Weak neutral current: $\sin^2\theta_W \sim 0.23 \Rightarrow M_W \sim 78\ GeV$, **and** $M_Z \sim 89\ GeV$ **(increased by** $\sim 2\ GeV$ **by loop corrections)**

Discovered at CERN: UA1 and UA2, 1983

Current:

$$\begin{aligned} M_Z &= 91.1876 \pm 0.0021 \\ M_W &= 80.403 \pm 0.029 \end{aligned}$$

The Higgs Scalar H

Gauge interactions: $ZZH, ZZH^2, W^+W^-H, W^+W^-H^2$

$$\varphi \rightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu + H \end{pmatrix}$$

$$\begin{aligned} \mathcal{L}_\varphi &= (D^\mu \varphi)^\dagger D_\mu \varphi - V(\varphi) \\ &= \tfrac{1}{2} (\partial_\mu H)^2 + M_W^2 W^{\mu +} W_\mu^- \left(1 + \frac{H}{\nu}\right)^2 \\ &+ \tfrac{1}{2} M_Z^2 Z^\mu Z_\mu \left(1 + \frac{H}{\nu}\right)^2 - V(\varphi) \end{aligned}$$

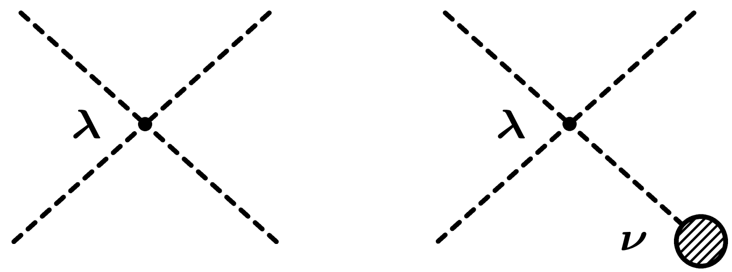
Higgs potential:

$$V(\varphi) = +\mu^2\varphi^\dagger\varphi + \lambda(\varphi^\dagger\varphi)^2$$
$$\rightarrow -\frac{\mu^4}{4\lambda} - \mu^2 H^2 + \lambda\nu H^3 + \frac{\lambda}{4}H^4$$

Fourth term: Quartic self-interaction

Third: Induced cubic self-interaction

Second: (Tree level) H mass-squared, $M_H = \sqrt{-2\mu^2} = \sqrt{2\lambda}\nu$

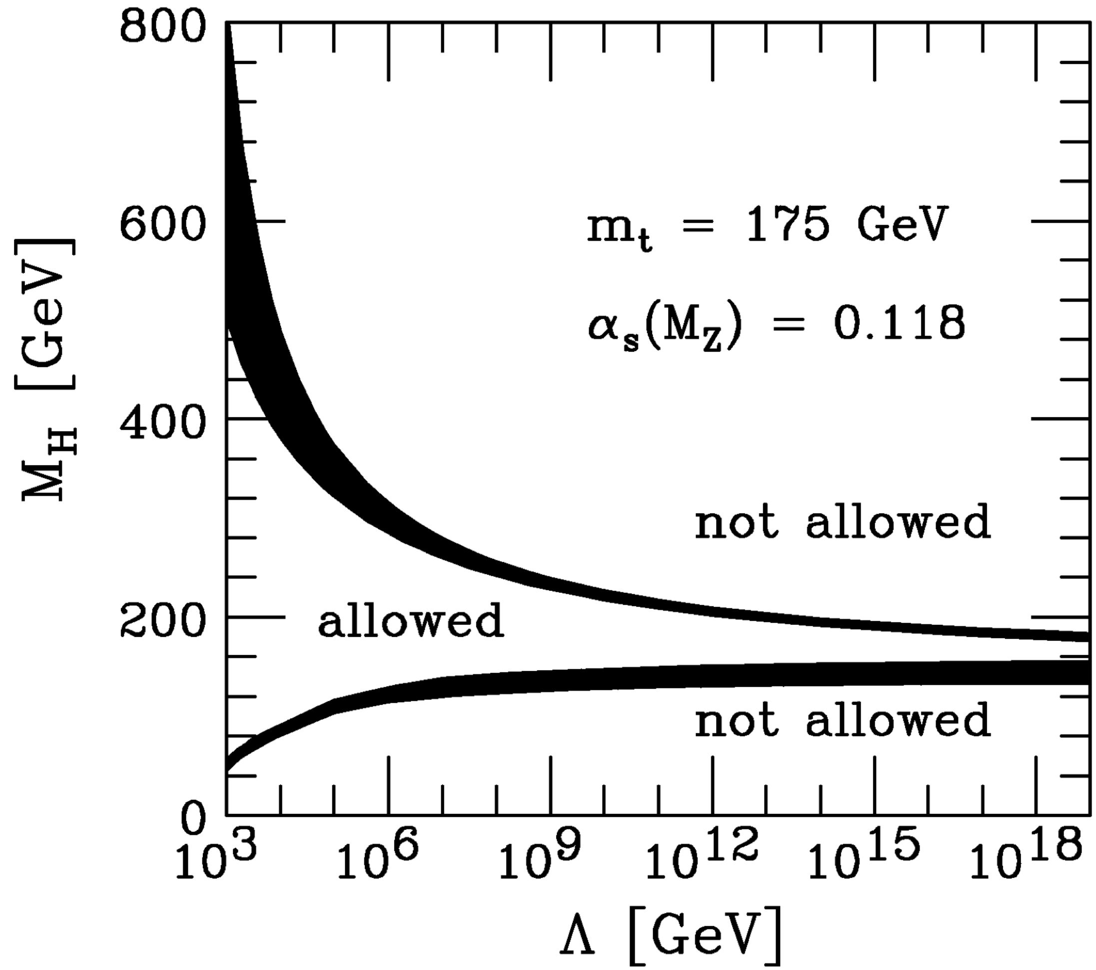


No a priori constraint on λ except vacuum stability ($\lambda > 0 \Rightarrow 0 < M_H < \infty$), but

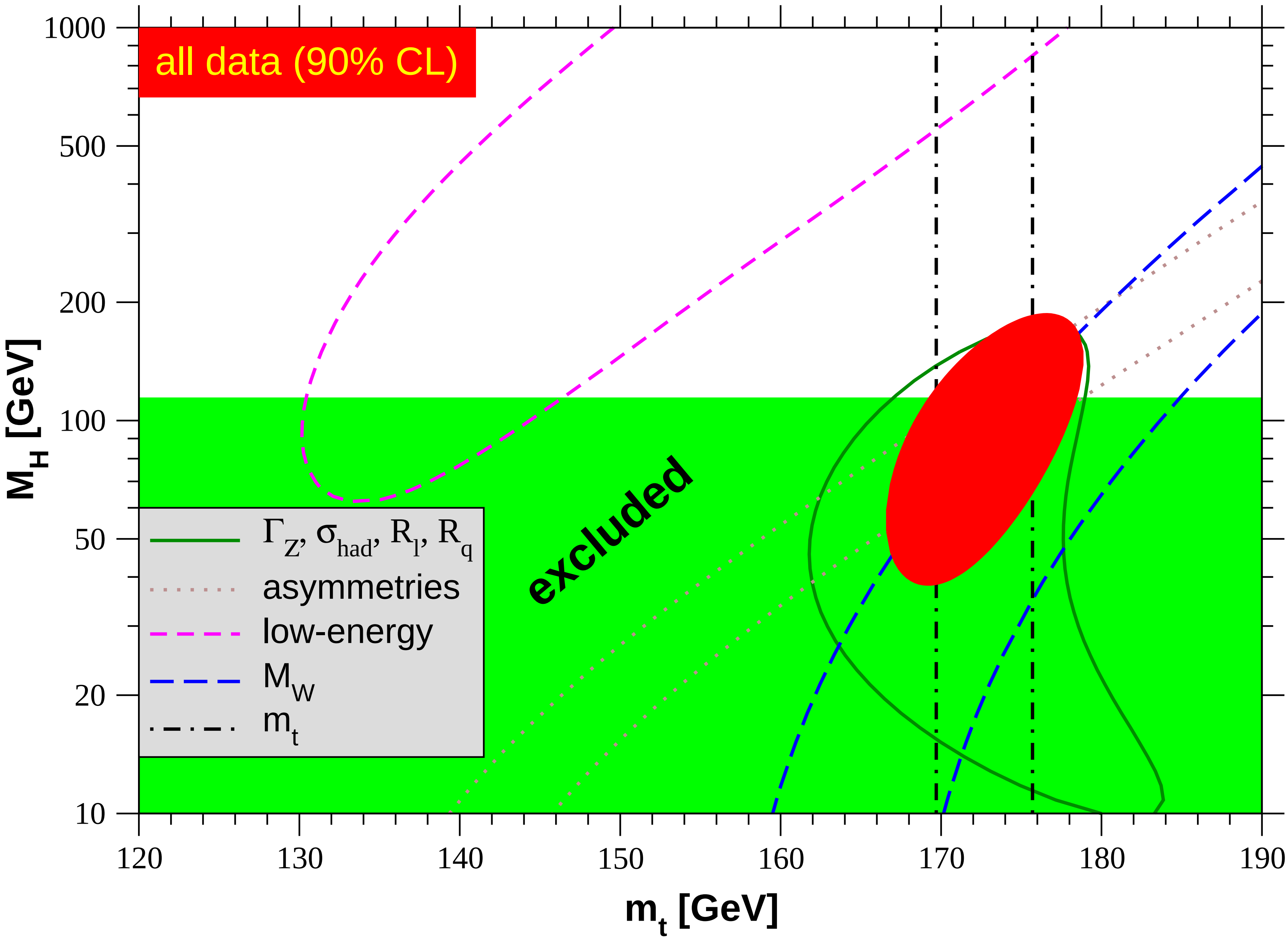
- t quark loops destabilize vacuum unless $M_H \gtrsim 130$ GeV
  (Depends on Λ. Doesn't hold in supersymmetry)
- Strong coupling for $\lambda \gtrsim 1 \Leftrightarrow M_H \gtrsim 1$ TeV
- Triviality: running λ should not diverge below scale Λ at which theory breaks down $\Rightarrow$

$$M_H < \begin{cases} O(200)\ \text{GeV}, & \Lambda \sim M_P = G_N^{-1/2} \sim 10^{19}\ \text{GeV} \\ O(750)\ \text{GeV}, & \Lambda \sim 2M_H \end{cases}$$

- Experimental bound (LEP 2), $e^+e^- \rightarrow Z^* \rightarrow ZH \Rightarrow M_H \gtrsim 114.5$ GeV at 95% cl (can evade with singlet or in MSSM)
- Hint of signal at 115 GeV
- Indirect (precision tests): $M_H < 189$ GeV, 95% cl
- MSSM: much of parameter space has standard-like Higgs with $M_H < 130$ GeV



Theoretical M_H limits, Hambye and Riesselmann, hep-ph/9708416


all data (90% CL)
1000
500
200
100
50
20
10
M_H [GeV]
120
130
140
150
160
170
180
190
m_t [GeV]
excluded
Γ_Z, σ_{had}, R_l, R_q
asymmetries
low-energy
M_W
m_t

Decays: $H \rightarrow \bar{b}b$ dominates for $M_H \lesssim 2M_W$ ($H \rightarrow W^+W^-$, ZZ dominate when allowed because of larger gauge coupling)

Production:

LEP: Higgstrahlung ($e^+e^- \rightarrow Z^* \rightarrow ZH$)

Tevatron, LHC: GG-fusion ($GG \rightarrow H$ via top loop), WW fusion ($WW \rightarrow H$), or associated production ($\bar{q}q \rightarrow WH,\ ZH$)

First term in V: vacuum energy

$$\langle 0|V|0\rangle = -\mu^4/4\lambda$$

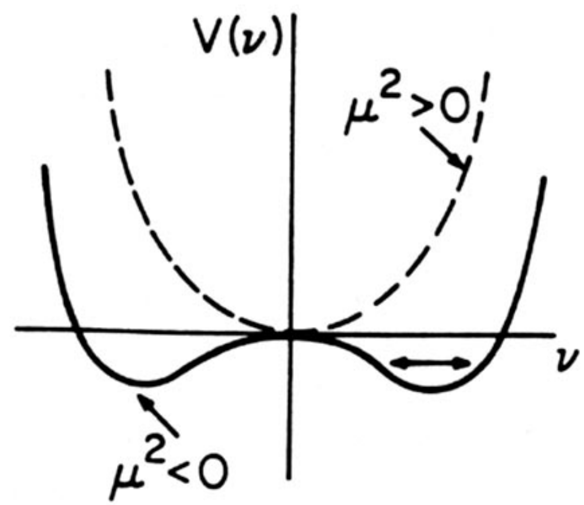
No effect on microscopic interactions, but gives *negative* contribution to cosmological constant

$$|\Lambda_{\rm SSB}| = 8\pi G_N |\langle 0|V|0$$

Require fine-tuned cancellation

$$\Lambda_{\rm cosm} = \Lambda_{\rm bare} + \Lambda_{\rm SSB}$$

Also, QCD contribution from SSB of global chiral symmetry



Yukawa Interactions

$$-\mathcal{L}_{\text{Yukawa}} \rightarrow \sum_{m,n=1}^{F} \bar{u}^0_{mL} \Gamma^u_{mn} \left(\frac{\nu + H}{\sqrt{2}} \right) u^0_{mR} + (d, e) \text{ terms} \quad + \quad \text{H.C.}$$

$$= \quad \bar{u}^0_L \left(M^u + h^u H \right) u^0_R + (d, e, \nu) \text{ terms} \quad + \text{H.C.}$$

$u^0_L = \left(u^0_{1L} u^0_{2L} \cdots u^0_{FL} \right)^T$ is F-component column vector

M^u is $F \times F$ fermion mass matrix $M^u_{mn} = \Gamma^u_{mn} \nu / \sqrt{2}$ (need not be Hermitian, diagonal, symmetric, or even square)

$h^u = M^u / \nu = g M^u / 2 M_W$ is the Yukawa coupling matrix

Diagonalize M by separate unitary transformations A_L and A_R (($A_L = A_R$) for Hermitian M)

$$A_L^{u\dagger} M^u A_R^u = M_D^u = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix}$$

is diagonal matrix of physical masses of the charge $\frac{2}{3}$ quarks. Similarly

$$\begin{aligned} A_L^{d\dagger} M^d A_R^d &= M_D^d \\ A_L^{e\dagger} M^e A_R^e &= M_D^e \\ (A_L^{\nu\dagger} M^\nu A_R^\nu &= M_D^\nu) \end{aligned}$$

(may also be Majorana masses for ν_R)

Find A_L and A_R by diagonalizing Hermitian matrices $MM^\dagger$ and $M^\dagger M$, e.g., $A_L^\dagger M M^\dagger A_L = M_D^2$

Mass eigenstate fields

$$
\begin{aligned}
u_L &= A_L^{u\dagger} u_L^0 = (u_L \; c_L \; t_L)^T \\
u_R &= A_R^{u\dagger} u_R^0 = (u_R \; c_R \; t_R)^T \\
d_{L,R} &= A_{L,R}^{d\dagger} d_{L,R}^0 = (d_{L,R} \;\; s_{L,R} \;\; b_{L,R})^T \\
e_{L,R} &= A_{L,R}^{e\dagger} e_{L,R}^0 = (e_{L,R} \;\; \mu_{L,R} \;\; \tau_{L,R})^T \\
\nu_{L,R} &= A_{L,R}^{\nu\dagger} \nu_{L,R}^0 = (\nu_{1L,R} \;\; \nu_{2L,R} \;\; \nu_{3L,R})^T
\end{aligned}
$$

(For $m_\nu = 0$ or negligible, define $\nu_L = A_L^{e\dagger} \nu_L^0$, so that $\nu_i \equiv \nu_e, \; \nu_\mu, \; \nu_\tau$ are the weak interaction partners of the $e, \; \mu$, and τ.)

Typical estimates: $m_u = 1.5 - 4$ MeV, $m_d = 4 - 8$ MeV, $m_s = 80 - 130$ MeV, $m_c \sim 1.3$ GeV, $m_b \sim 4.2$ GeV, $m_t = 170.9 \pm 1.8$ GeV

Implications for global $SU(3)_L \times SU(3)_R$ **of QCD**

These are current quark masses. $M_i = m_i + M_{dyn}$, $M_{dyn} \sim \Lambda_{\overline{MS}} \sim 300$ **MeV from chiral condensate** $\langle 0|\bar{q}q|0\rangle \neq 0$

m_t **is pole mass; others, running masses at** m **or at 2 GeV**^{2}

Yukawa couplings of Higgs to fermions

$$L_{\text{Yukawa}} = \sum_i \bar{\psi}_i \left(-m_i - \frac{g m_i}{2M_W} H \right) \psi_i$$

- Coupling $g m_i / 2M_W$ is flavor diagonal and small except t quark
- $H \rightarrow \bar{b}b$ dominates for $M_H \lesssim 2M_W$ ($H \rightarrow W^+W^-$, ZZ dominate when allowed because of larger gauge coupling)
- Flavor diagonal because only one doublet couples to fermions $\Rightarrow$ fermion mass and Yukawa matrices proportional
- Often flavor changing Higgs couplings in extended models with two doublets coupling to same kind of fermion (*not* MSSM)
  - Stringent limits, e.g., tree-level Higgs contribution to $K_L - K_S$ mixing (loop in standard model) $\Rightarrow h_{\bar{d}s}/M_H < 10^{-6}$ GeV^{-1}

The Weak Charged Current

Fermi Theory incorporated in SM and made renormalizable

W-fermion interaction

$$\mathcal{L} = -\frac{g}{2\sqrt{2}}\left(J_W^\mu W_\mu^- + J_W^{\mu\dagger} W_\mu^+\right)$$

Charge-raising current

$$\begin{aligned} J_W^{\mu\dagger} &= \sum_{m=1}^{F}\left[\bar{\nu}_m^0 \gamma^\mu (1-\gamma^5) e_m^0 + \bar{u}_m^0 \gamma^\mu (1-\gamma^5) d_m^0\right] \\ &= (\bar{\nu}_e \bar{\nu}_\mu \bar{\nu}_\tau)\gamma^\mu (1-\gamma^5)\begin{pmatrix} e^- \\ \mu^- \\ \tau^- \end{pmatrix} + (\bar{u}\ \bar{c}\ \bar{t})\gamma^\mu (1-\gamma^5) V \begin{pmatrix} d \\ s \\ b \end{pmatrix}. \end{aligned}$$

Ignore ν masses for now

Pure $V - A \Rightarrow$ maximal P and C violation; CP conserved except for phases in V

$V = A_L^{u\dagger} A_L^d$ is $F \times F$ unitary Cabibbo-Kobayashi-Maskawa (CKM) matrix from mismatch between weak and Yukawa interactions

Cabibbo matrix for $F = 2$

$$V = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix}$$

$\sin\theta_c \simeq 0.22 \equiv$ Cabibbo angle

Good zeroth-order description since third family almost decouples

CKM matrix for $F = 3$ involves 3 angles and 1 CP-violating phase (after removing unobservable q_L phases) (new interations involving q_R could make observable)

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{td} & V_{td} \end{pmatrix}$$

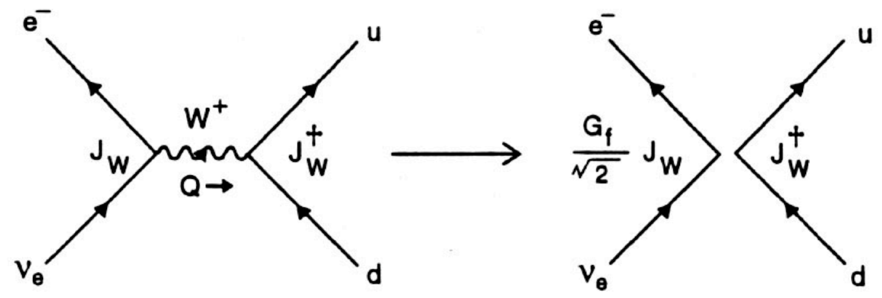
Extensive studies, especially in B decays, to test unitarity of V as probe of new physics and test origin of CP violation

Need additional source of CP breaking for baryogenesis

Effective zero- range 4-fermi interaction (Fermi theory)

For $|Q| \ll M_W$, neglect Q^2 in W propagator

$$-L^{cc}_{\rm eff} = \frac{G_F}{\sqrt{2}} J^{\mu}_W J^{\dagger}_{W\mu}$$



Fermi constant

$$\frac{G_F}{\sqrt{2}} \simeq \frac{g^2}{8M_W^2} = \frac{1}{2\nu^2}$$

Muon lifetime $\tau^{-1} = \frac{G_F^2 m_\mu^5}{192\pi^3} \Rightarrow G_F = 1.16639(2)\times 10^{-5}$ **GeV**$^{-2}$

Weak scale $\nu = \sqrt{2}\langle 0|\varphi^0|0\rangle \simeq 246$ **GeV**

Excellent description of β, K, hyperon, heavy quark, μ, and τ decays, $\nu_\mu e \to \mu^- \nu_e$, $\nu_\mu n \to \mu^- p$, $\nu_\mu N \to \mu^- X$

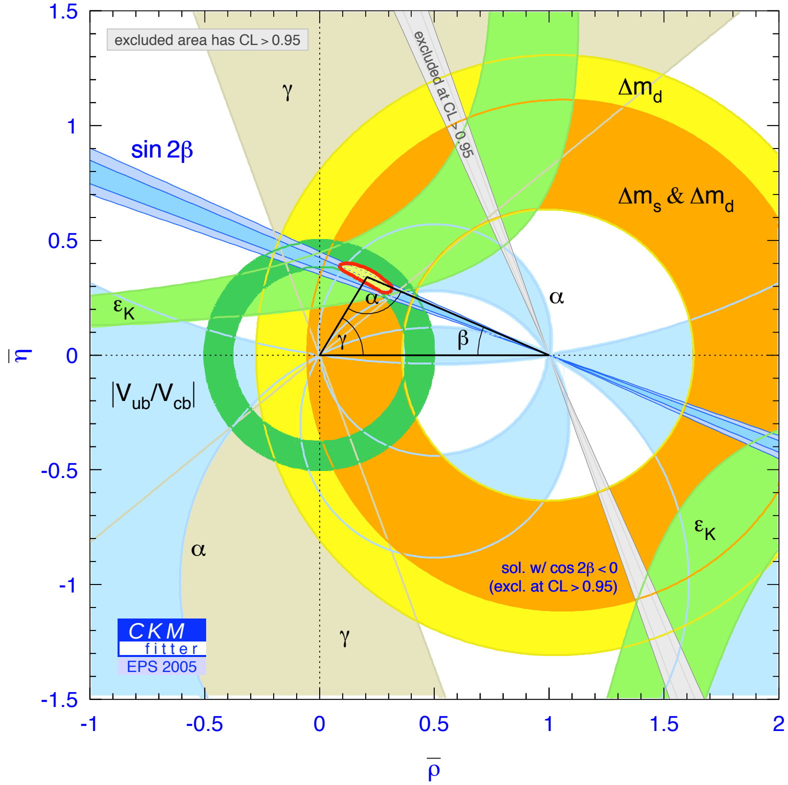
Full theory probed:

$e^{\pm}p \rightarrow \overset{(-)}{\nu}_e X$ **at high energy (HERA)**

Electroweak radiative corrections (loop level)

(Very important. Only calculable in full theory.)

$M_{K_S} - M_{K_L}$, **kaon** CP **violation,** $B \leftrightarrow \bar{B}$ **mixing (loop level)**



(CKMFITTER group:

`http://ckmfitter.in2p3.fr/)`

Quantum Electrodynamics (QED)

Incorporated into standard model

Lagrangian:

$$\mathcal{L} = -\frac{gg'}{\sqrt{g^2 + g'^2}} J_Q^\mu (\cos\theta_W B_\mu + \sin\theta_W W_\mu^3)$$

Photon field:

$$A_\mu = \cos\theta_W B_\mu + \sin\theta_W W_\mu^3$$

Positron electric charge: $e = g\sin\theta_W$, **where** $\tan\theta_W \equiv g'/g$

Electromagnetic current:

$$J_Q^\mu = \sum_{m=1}^{F} \left[\frac{2}{3} \bar{u}_m^0 \gamma^\mu u_m^0 - \frac{1}{3} \bar{d}_m^0 \gamma^\mu d_m^0 - \bar{e}_m^0 \gamma^\mu e_m^0 \right]$$

$$= \sum_{m=1}^{F} \left[\frac{2}{3} \bar{u}_m \gamma^\mu u_m - \frac{1}{3} \bar{d}_m \gamma^\mu d_m - \bar{e}_m \gamma^\mu e_m \right]$$

Flavor diagonal: Same form in weak and mass bases because fields which mix have same charge

Purely vector (parity conserving): L and R fields have same charge

Experiment	Value of α^{-1}		Difference from $\alpha^{-1}(a_e)$
Deviation from gyromagnetic ratio, $a_e = (g-2)/2$ for e^-	137.035 999 58 (52)	$[3.8 \times 10^{-9}]$	–
ac Josephson effect	137.035 988 0 (51)	$[3.7 \times 10^{-8}]$	$(0.116 \pm 0.051) \times 10^{-4}$
h/m_n (m_n is the neutron mass) from n beam	137.036 011 9 (51)	$[3.7 \times 10^{-8}]$	$(-0.123 \pm 0.051) \times 10^{-4}$
Hyperfine structure in muonium, μ^+e^-	137.035 993 2 (83)	$[6.0 \times 10^{-8}]$	$(0.064 \pm 0.083) \times 10^{-4}$
Cesium D_1 line	137.035 992 4 (41)	$[3.0 \times 10^{-8}]$	$(0.072 \pm 0.041) \times 10^{-4}$

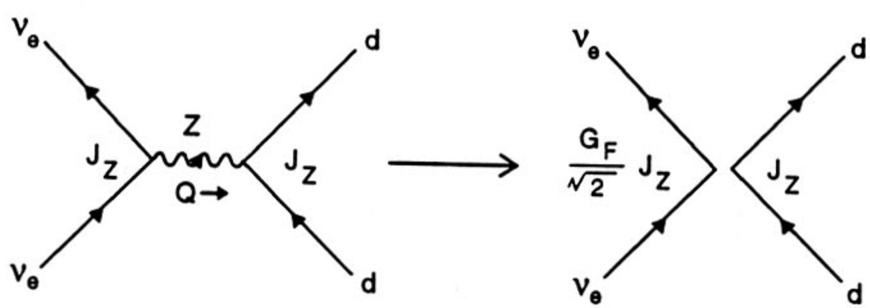
Spectacularly successful:

- Most precise: e anomalous magnetic moment $\rightarrow \alpha$
- Many low energy tests to few $\times 10^{-8}$
- $m_\gamma < 6 \times 10^{-17}$ eV
- $q_\gamma < 5 \times 10^{-30} |e|$
- Running $\alpha(Q^2)$ observed
- High energy well-measured (PEP, PETRA, TRISTAN, LEP)
- Muon $g-2$ sensitive to new physics. Anomaly?

The Weak Neutral Current

Prediction of $SU(2) \times U(1)$

$$\begin{aligned} \mathcal{L} &= -\frac{\sqrt{g^2 + g'^2}}{2} J_Z^\mu \left(-\sin\theta_W B_\mu + \cos\theta_W W_\mu^3 \right) \\ &= -\frac{g}{2\cos\theta_W} J_Z^\mu Z_\mu \end{aligned}$$



Neutral current process and effective 4-fermi interaction for $|Q| \ll M_Z$

Neutral current:

$$
\begin{aligned}
J_Z^\mu &= \sum_m \left[\bar{u}^0_{mL}\gamma^\mu u^0_{mL} - \bar{d}^0_{mL}\gamma^\mu d^0_{mL} + \bar{\nu}^0_{mL}\gamma^\mu \nu^0_{mL} - \bar{e}^0_{mL}\gamma^\mu e^0_{mL}\right] \\
&- 2\sin^2\theta_W J_Q^\mu \\
&= \sum_m \left[\bar{u}_{mL}\gamma^\mu u_{mL} - \bar{d}_{mL}\gamma^\mu d_{mL} + \bar{\nu}_{mL}\gamma^\mu \nu_{mL} - \bar{e}_{mL}\gamma^\mu e_{mL}\right] \\
&- 2\sin^2\theta_W J_Q^\mu
\end{aligned}
$$

Flavor diagonal: Same form in weak and mass bases because fields which mix have same charge

- GIM mechanism: c quark predicted so that s_L could be in doublet to avoid unwanted flavor changing neutral currents (FCNC) at tree and loop level
- Parity and charge conjugation violated but not maximally: first term is pure $V - A$, second is V

Effective 4-fermi interaction for $|Q^2| \ll M_Z^2$:

$$-\mathcal{L}_{\text{eff}}^{NC} = \frac{G_F}{\sqrt{2}} J_Z^\mu J_{Z\mu}$$

Coefficient same as WCC because

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} = \frac{g^2 + g'^2}{8M_Z^2}$$

The Z, the W, and the Weak Neutral Current

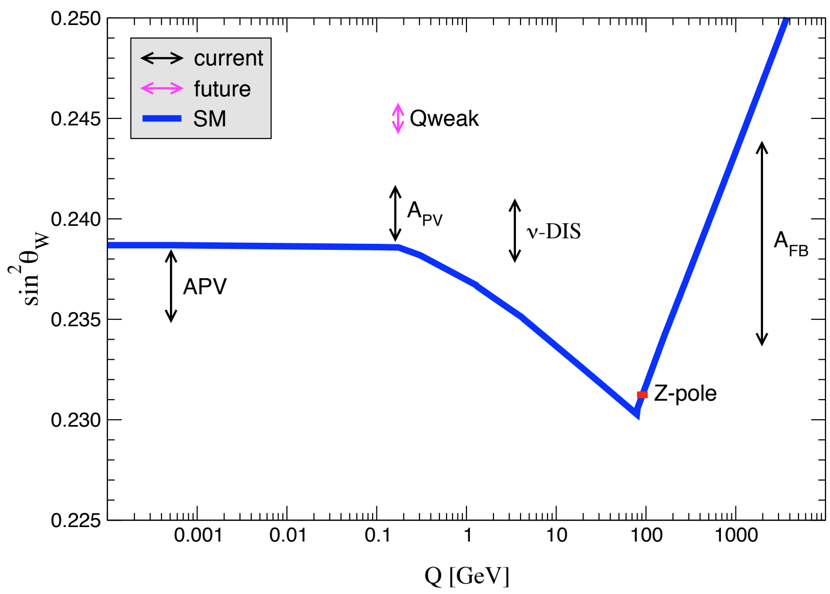
- Primary prediction and test of electroweak unification
- WNC discovered 1973 (Gargamelle at CERN, HPW at FNAL)
- 70's, 80's: weak neutral current experiments (few %)
  - Pure weak: νN, νe scattering
  - Weak-elm interference in eD, e^+e^-, atomic parity violation
  - $SU(2)\times U(1)$ group/representations; t and ν_τ exist; hint for SUSY unification; limits on TeV scale physics
- W, Z discovered directly 1983 (UA1, UA2)

- **90's: Z pole (LEP, SLD), 0.1%; lineshape, modes, asymmetries**

- **LEP 2: M_W, Higgs search , gauge self-interactions**

- **Tevatron: m_t, M_W, M_H search**

- **4th generation weak neutral current experiments (atomic parity (Boulder); νe; νN (NuTeV); polarized Møller asymmetry (SLAC))**

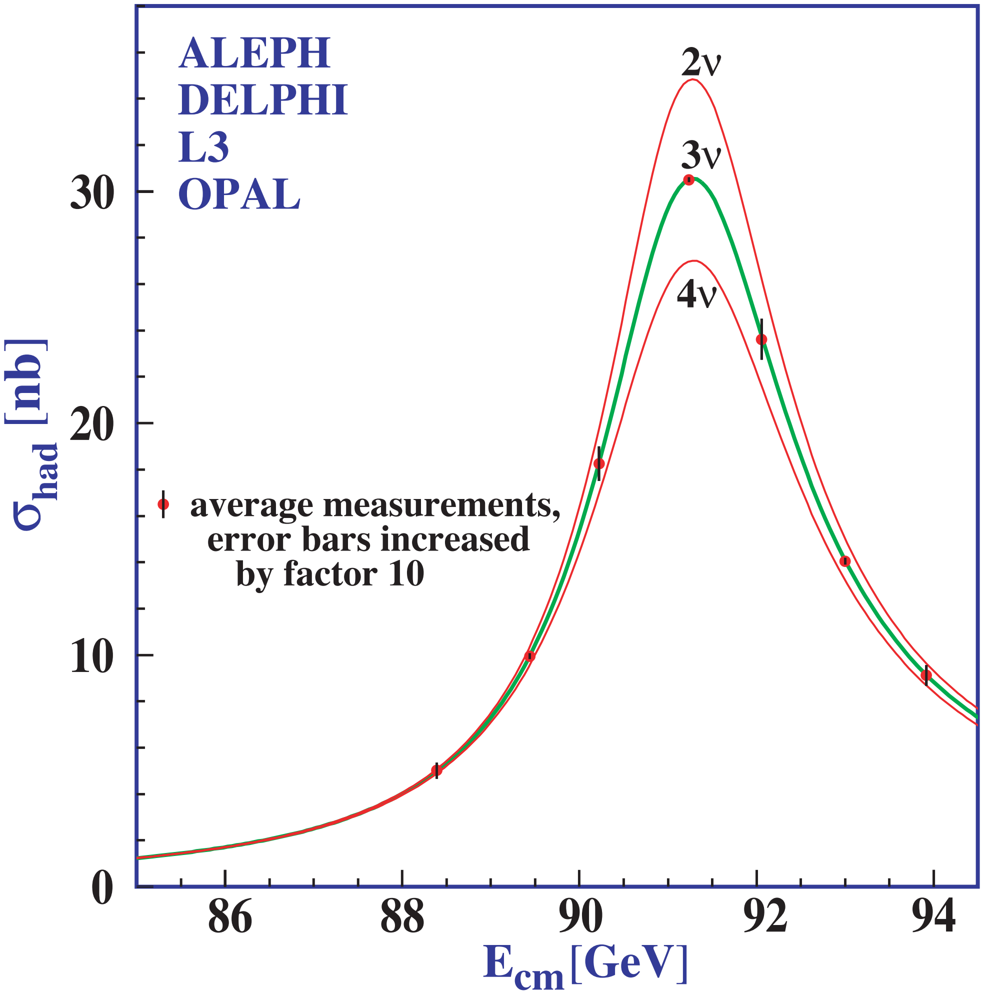


Running $\hat{s}^2_Z$ in $\overline{\mathrm{MS}}$ scheme

The LEP/SLC Era

- Z Pole: $e^+e^- \to Z \to \ell^+\ell^-, \quad q\bar{q}, \quad \nu\bar{\nu}$
  - LEP (CERN), 2×10^7 $Z's$, unpolarized (ALEPH, DELPHI, L3, OPAL); SLC (SLAC), 5×10^5, $P_{e^-} \sim$ 75 % (SLD)

- Z pole observables
  - lineshape: M_Z, Γ_Z, σ
  - branching ratios
    * $e^+e^-, \mu^+\mu^-, \tau^+\tau^-$
    * $q\bar{q}, c\bar{c}, b\bar{b}, s\bar{s}$
    * $\nu\bar{\nu} \Rightarrow N_\nu = 2.984 \pm 0.009$ if $m_\nu < M_Z/2$
  - asymmetries: FB, polarization, P_τ, mixed
  - lepton family universality



- $N_\nu = 3 + \Delta N_\nu = 2.984 \pm 0.009$
- $\Delta N_\nu = 1$ for fourth family ν with $m_\nu \lesssim M_Z/2$
- $\Delta N_\nu = \frac{1}{2}$, light $\tilde{\nu}$ in supersymmetry
- $\Delta N_\nu = 2$, Majoron + scalar in triplet model of m_ν with spontaneous L violation

The Z Pole Observables: LEP and SLC (09/05)

Quantity	Group(s)	Value	Standard Model	pull
M_Z [GeV]	LEP	91.1876 ± 0.0021	91.1874 ± 0.0021	0.1
Γ_Z [GeV]	LEP	2.4952 ± 0.0023	2.4968 ± 0.0011	-0.7
$\Gamma(\text{had})$ [GeV]	LEP	1.7444 ± 0.0020	1.7434 ± 0.0010	—
$\Gamma(\text{inv})$ [MeV]	LEP	499.0 ± 1.5	501.65 ± 0.11	—
$\Gamma(\ell^+\ell^-)$ [MeV]	LEP	83.984 ± 0.086	83.996 ± 0.021	—
σ_{had} [nb]	LEP	41.541 ± 0.037	41.467 ± 0.009	2.0
R_e	LEP	20.804 ± 0.050	20.756 ± 0.011	1.0
R_μ	LEP	20.785 ± 0.033	20.756 ± 0.011	0.9
R_τ	LEP	20.764 ± 0.045	20.801 ± 0.011	-0.8
$A_{FB}(e)$	LEP	0.0145 ± 0.0025	0.01622 ± 0.00025	-0.7
$A_{FB}(\mu)$	LEP	0.0169 ± 0.0013		0.5
$A_{FB}(\tau)$	LEP	0.0188 ± 0.0017		1.5

Quantity	Group(s)	Value	Standard Model	pull
R_b	LEP/SLD	0.21629 ± 0.00066	0.21578 ± 0.00010	0.8
R_c	LEP/SLD	0.1721 ± 0.0030	0.17230 ± 0.00004	-0.1
$A_{FB}(b)$	LEP	0.0992 ± 0.0016	0.1031 ± 0.0008	-2.4
$A_{FB}(c)$	LEP	0.0707 ± 0.0035	0.0737 ± 0.0006	-0.8
$A_{FB}(s)$	DELPHI/OPAL	0.0976 ± 0.0114	0.1032 ± 0.0008	-0.5
A_b	SLD	0.923 ± 0.020	0.9347 ± 0.0001	-0.6
A_c	SLD	0.670 ± 0.027	0.6678 ± 0.0005	0.1
A_s	SLD	0.895 ± 0.091	0.9356 ± 0.0001	-0.4
A_{LR} (hadrons)	SLD	0.15138 ± 0.00216	0.1471 ± 0.0011	2.0
A_{LR} (leptons)	SLD	0.1544 ± 0.0060		1.2
A_μ	SLD	0.142 ± 0.015		-0.3
A_τ	SLD	0.136 ± 0.015		-0.7
$A_\tau(\mathcal{P}_\tau)$	LEP	0.1439 ± 0.0043		-0.7
$A_e(\mathcal{P}_\tau)$	LEP	0.1498 ± 0.0049		0.6
$\bar{s}_\ell^2(Q_{FB})$	LEP	0.2324 ± 0.0012	0.23152 ± 0.00014	0.7
$\bar{s}_\ell^2(A_{FB}(q))$	CDF	0.2238 ± 0.0050		-1.5

- **LEP 2**
  - M_W, Γ_W, B **(also hadron colliders)**
  - M_H **limits (hint?)**
  - WW **production (triple gauge vertex)**
  - **Quartic vertex**
  - **SUSY/exotics searches**

Global Standard Model Fit Results

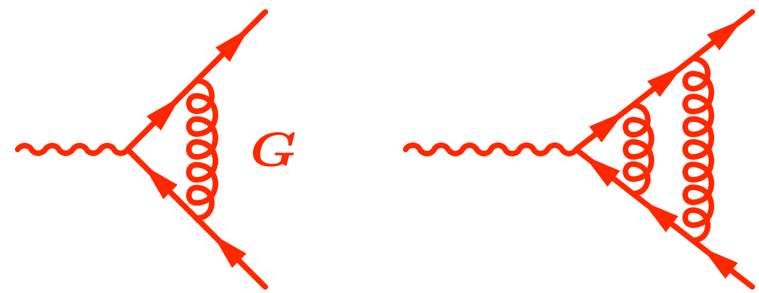
- PDG 2006 (9/05) (Erler, PL)
  - $\chi^2/df = 47.5/42$
  - Fully $\overline{MS}$
  - Good agreement with LEPEWWG up to known effects

$$
\begin{aligned}
M_H &= 89^{+38}_{-28} \text{ GeV}, \\
m_t &= 172.7 \pm 2.8 \text{ GeV} \\
\alpha_s &= 0.1216 \pm 0.0017 \\
\hat{\alpha}(M_Z)^{-1} &= 127.904 \pm 0.019 \\
\hat{s}^2_Z &= 0.23122 \pm 0.00015 \\
\bar{s}^2_\ell &= 0.23152 \pm 0.00014 \\
s^2_W &= 0.22306 \pm 0.00033 \\
\Delta\alpha^{(5)}_{\rm had}(M_Z) &= 0.02802 \pm 0.00015
\end{aligned}
$$

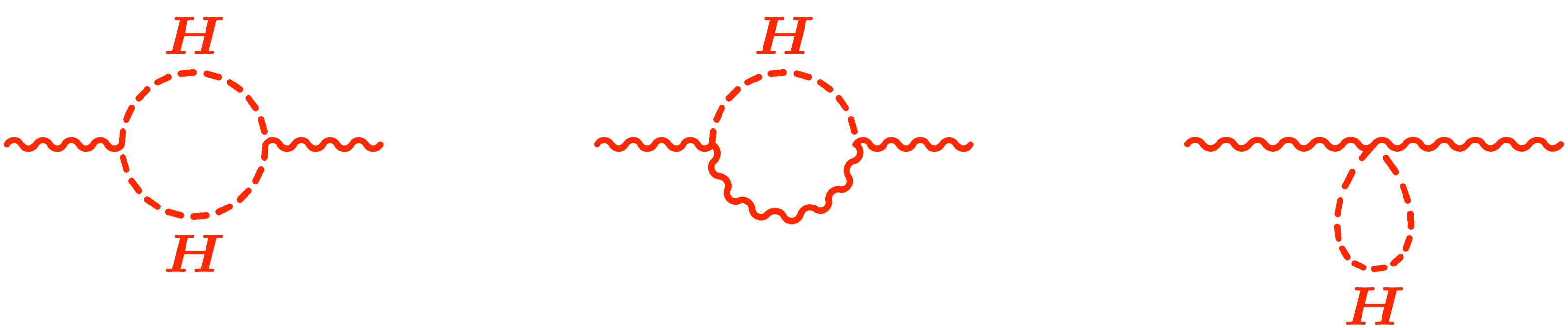
- $m_t = 172.7 \pm 2.8$ GeV
  - $172.3^{+10.2}_{-7.6}$ GeV from indirect (loops) only (direct: $172.7 \pm 2.9 \pm 0.6$)

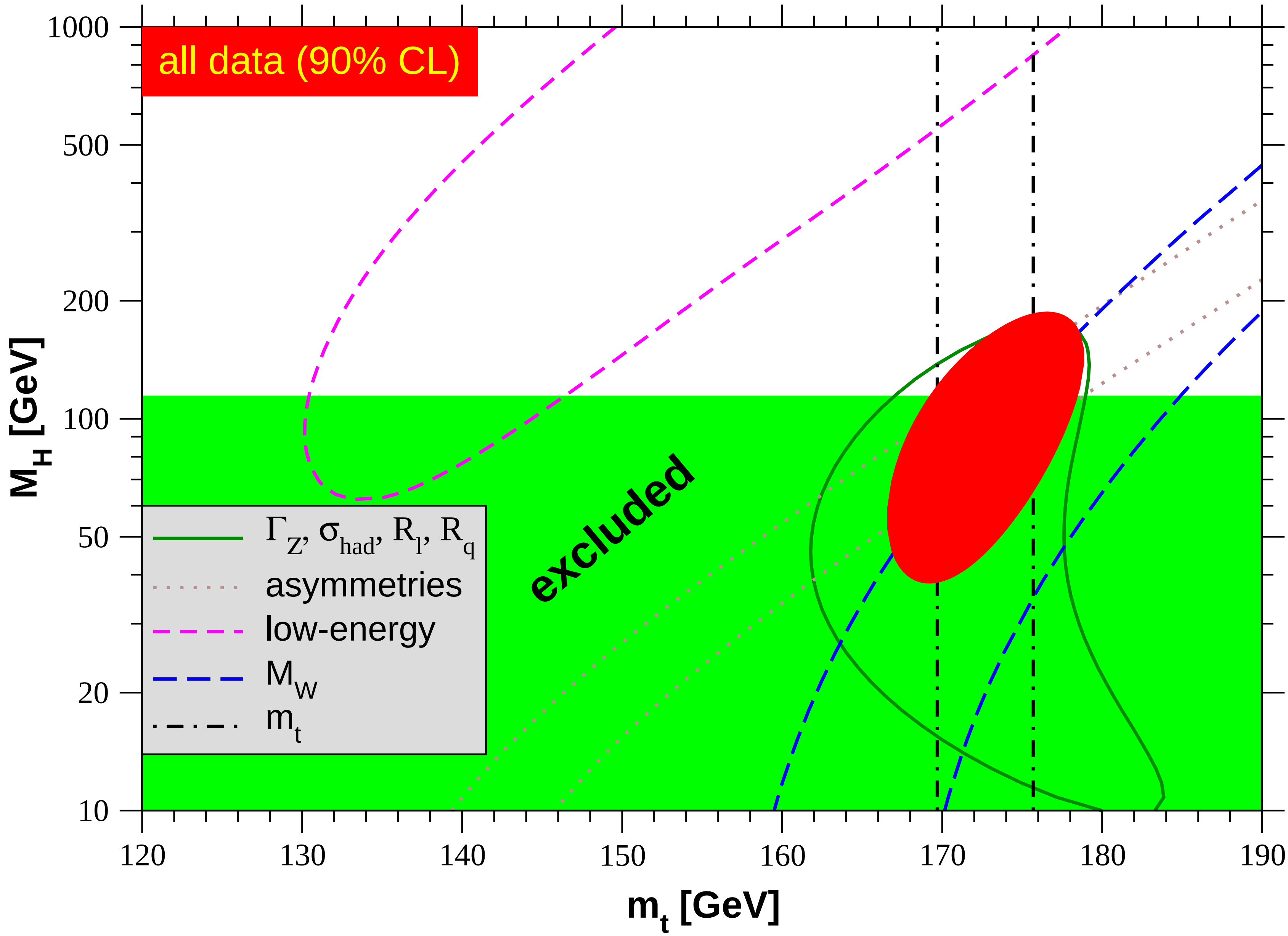
  - Fit actually uses $\overline{\mathrm{MS}}$ mass $\hat{m}_t(\hat{m}_t)$ ($\sim$ 10 GeV lower) and converts to pole mass at end
  - Significant change from previous analysis due to lower m_t from Run II

- $\alpha_s = 0.1216 \pm 0.0017$
  - Higher than $\alpha_s = 0.1187(20)$ (PDG: 2004), because of τ lifetime
  - Z-pole alone: $\alpha_s = 0.1198(28)$
  - insensitive to oblique new physics
  - very sensitive to non-universal new physics (e.g., $Zb\bar{b}$ vertex)

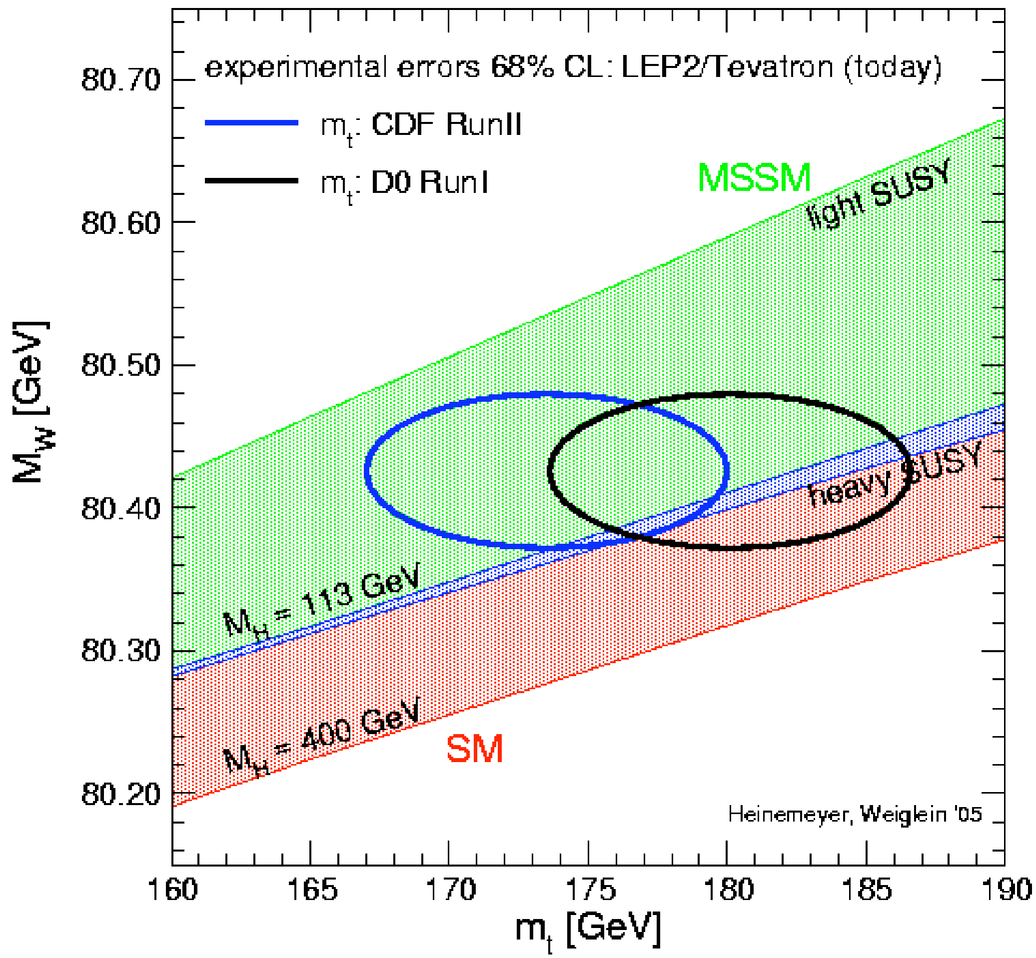


- **Higgs mass $M_H = 89^{+38}_{-28}$ GeV**
  - **LEPEWWG: 91^{+45}_{-32}**
  - **direct limit (LEP 2): $M_H \gtrsim 114.4\ (95\%)$ GeV**
  - **SM: 115 (vac. stab.) $\lesssim M_H \lesssim$ 750 (triviality)**
  - **MSSM: $M_H \lesssim 130$ GeV (150 in extensions)**
  - **indirect: $\ln M_H$ but significant**
    - **affected by new physics ($S < 0$, $T > 0$)**
    - **strong $A_{FB}(b)$ effect**
    - **$M_H < 189$ GeV at 95%, including direct**




all data (90% CL)
1000
500
200
100
50
20
10
M_H [GeV]
120
130
140
150
160
170
180
190
m_t [GeV]
excluded
Γ_Z, σ_{had}, R_l, R_q
asymmetries
low-energy
M_W
m_t

- **Supersymmetry**
  - **decoupling limit ($M_{new} \gtrsim 200-300$ GeV): only precision effect is light SM-like Higgs**
  - **little improvement on SM fit**
  - **Supersymmetry parameters constrained**

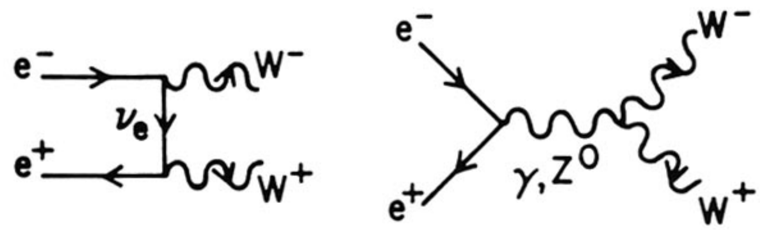


Gauge Self-Interactions

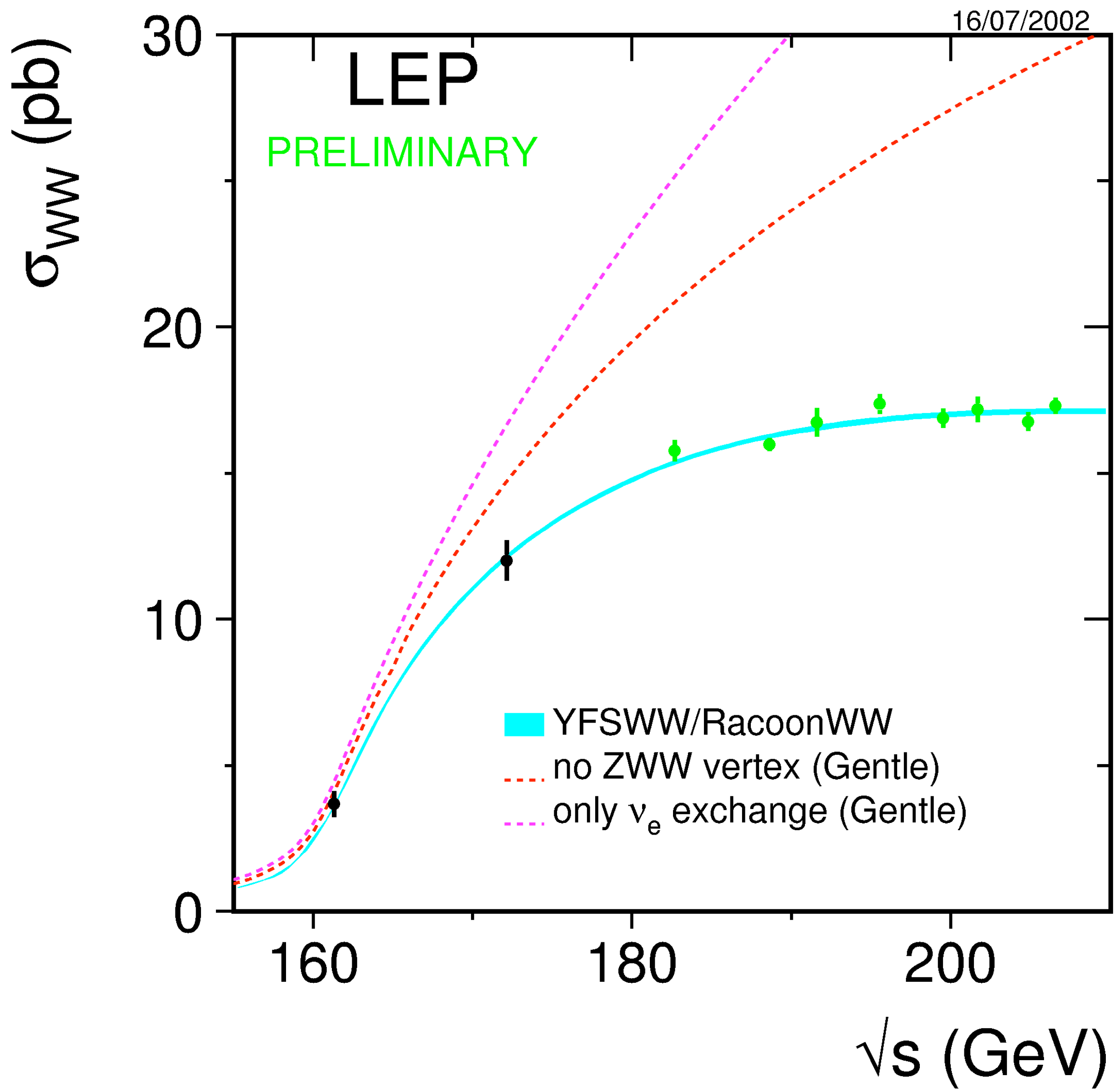
Three and four-point interactions predicted by gauge invariance

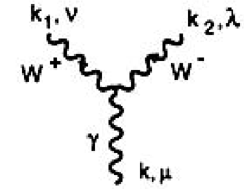
Indirectly verified by radiative corrections, α_s running in QCD, etc.

Strong cancellations in high energy amplitudes would be upset by anomalous couplings



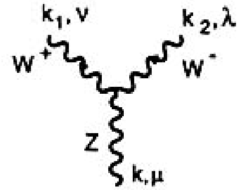
Tree-level diagrams contributing to $e^+e^- \rightarrow W^+W^-$


16/07/2002
LEP
PRELIMINARY
σ_{WW} (pb)
30
20
10
0
160
180
200
$\sqrt{s}$ (GeV)
YFSWW/RacoonWW
no ZWW vertex (Gentle)
only ν_e exchange (Gentle)

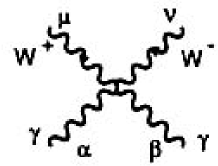


$$ieF_{\nu\lambda\mu}$$

$$F_{\nu\lambda\mu} = g_{\nu\lambda}(k_1 - k_2)_\mu + g_{\lambda\mu}(k_2 - k)_\nu + g_{\mu\nu}(k - k_1)_\lambda$$

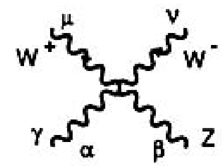


$$\frac{ie}{\tan\theta_W} F_{\nu\lambda\mu}$$

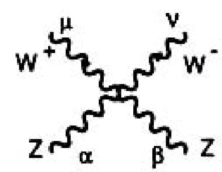


$$-ie^2 G_{\alpha\beta\mu\nu}$$

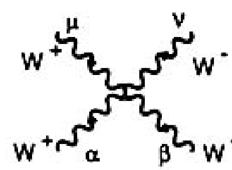
$$G_{\alpha\beta\mu\nu} = 2g_{\alpha\beta}g_{\mu\nu} - g_{\alpha\mu}g_{\beta\nu} - g_{\alpha\nu}g_{\beta\mu}$$



$$\frac{-ie^2}{\tan\theta_W} G_{\alpha\beta\mu\nu}$$

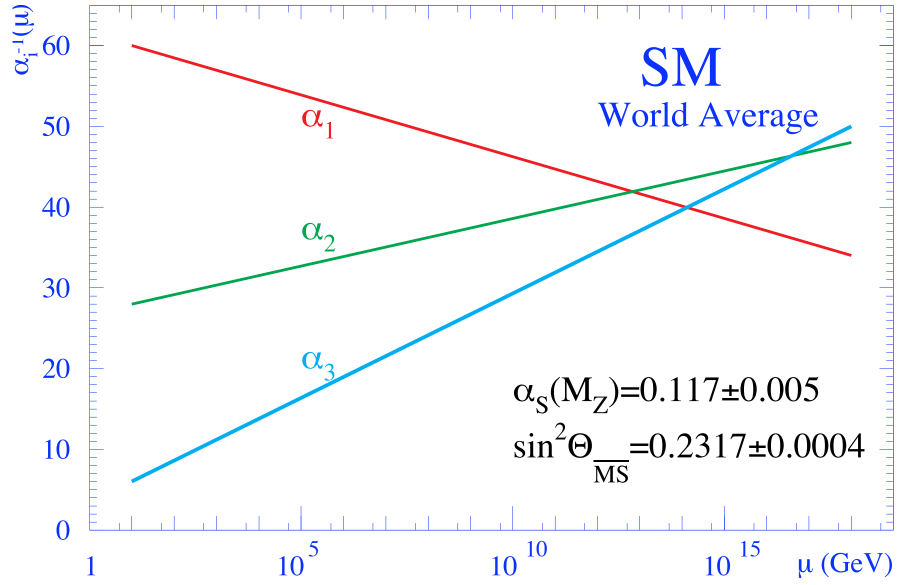


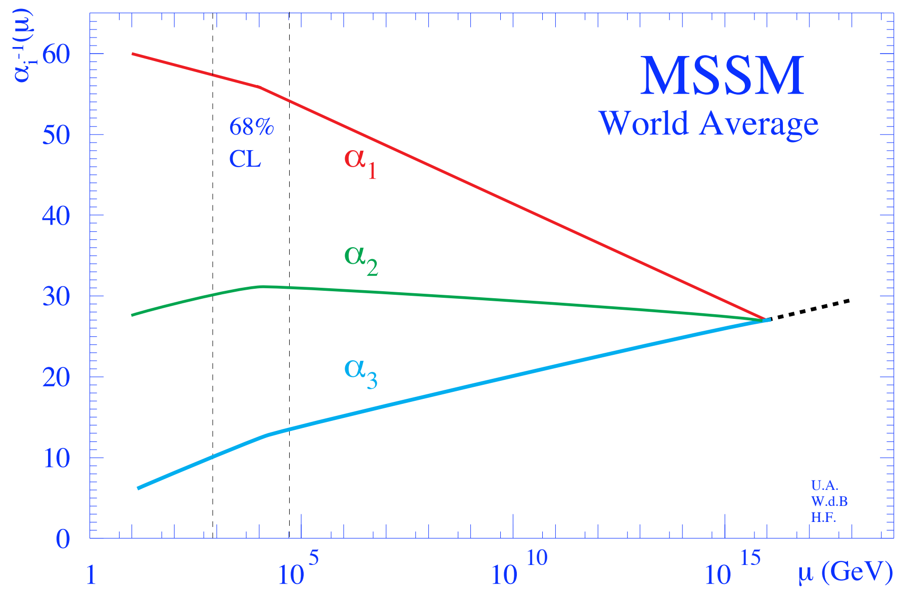
$$\frac{-ie^2}{\tan^2\theta_W} G_{\alpha\beta\mu\nu}$$



$$\frac{ie^2}{\sin^2\theta_W} G_{\alpha\beta\mu\nu}$$

- **Gauge unification: GUTs, string theories**
  - $\alpha + \hat{s}^2_Z \rightarrow \alpha_s = 0.130 \pm 0.010$ **(MSSM)** (non-SUSY: 0.073(1))
  - $M_G \sim 3 \times 10^{16}$ **GeV**
  - **Perturbative string:** $\sim 5 \times 10^{17}$ **GeV (10% in** $\ln M_G$**). Exotics:** $O(1)$ **corrections.**





Implications of Precision Electroweak

- WNC, Z, W are primary predictions and test of electroweak unification

- SM correct and unique to first approx. (gauge principle, group, representations)

- SM correct at loop level (renorm gauge theory; m_t, α_s, M_H)

- Watershed: TeV physics severely constrained (unification vs compositeness)
  - unification (decoupling): expect 0.1%
  - TeV compositeness/dynamics: several % unless decoupling
  - Z',W_R; 4-Fermi; exotic fermions/mixings; extended Higgs; $\cdots$

- Precise gauge couplings (gauge unification)

Problems with the Standard Model

Lagrangian after symmetry breaking:

$$\mathcal{L} = L_{\rm gauge} + L_{\rm Higgs} + \sum_i \bar{\psi}_i \left(i \not{\partial} - m_i - \frac{m_i H}{\nu} \right) \psi_i$$
$$- \frac{g}{2\sqrt{2}} \left(J_W^\mu W_\mu^- + J_W^{\mu\dagger} W_\mu^+ \right) - e J_Q^\mu A_\mu - \frac{g}{2\cos\theta_W} J_Z^\mu Z_\mu$$

Standard model: $SU(2) \times U(1)$ **(extended to include** ν **masses) + QCD + general relativity**

Mathematically consistent, renormalizable theory

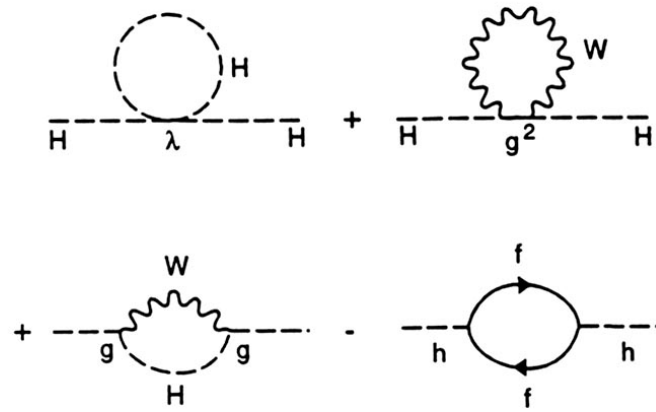
Correct to 10^{-16} **cm**

However, too much arbitrariness and fine-tuning: $O(27)$ parameters (+ 2 for Majorana ν) *and* electric charges

- **Gauge Problem**
  - complicated gauge group with 3 couplings
  - charge quantization ($|q_e| = |q_p|$) unexplained
  - Possible solutions: strings; grand unification; magnetic monopoles (partial); anomaly constraints (partial)

- **Fermion problem**
  - Fermion masses, mixings, families unexplained
  - Neutrino masses, nature? Probe of Planck/GUT scale?
  - CP violation inadequate to explain baryon asymmetry
  - Possible solutions: strings; brane worlds; family symmetries; compositeness; radiative hierarchies. New sources of CP violation.

- Higgs/hierarchy problem
  - Expect $M_H^2 = O(M_W^2)$
  - higher order corrections: $\delta M_H^2/M_W^2 \sim 10^{34}$



Possible solutions: supersymmetry; dynamical symmetry breaking; large extra dimensions; Little Higgs; anthropically motivated fine-tuning (split supersymmetry) (landscape)

- Strong CP problem
  - Can add $\frac{\theta}{32\pi^2} g_s^2 F\tilde{F}$ to QCD (breaks, P, T, CP)
  - $d_N \Rightarrow \theta < 10^{-9}$, but $\delta\theta|_{\text{weak}} \sim 10^{-3}$
  - Possible solutions: spontaneously broken global $U(1)$ (Peccei-Quinn) $\Rightarrow$ axion; unbroken global $U(1)$ (massless u quark); spontaneously broken CP + other symmetries

- **Graviton problem**
  - gravity not unified
  - quantum gravity not renormalizable
  - cosmological constant: $\Lambda_{\rm SSB} = 8\pi G_N \langle V \rangle > 10^{50} \Lambda_{\rm obs}$ (10^{124} for GUTs, strings)

  Possible solutions:

  - supergravity and Kaluza Klein unify
  - strings yield finite gravity
  - Λ? Anthropically motivated fine-tuning (landscape)?

- Necessary new ingredients
  - Mechanism for small neutrino masses
    - Planck/GUT scale? Small Dirac (intermediate scale)?
  - Mechanism for baryon asymmetry?
    - Electroweak transition (Z' or extended Higgs?)
    - Heavy Majorana neutrino decay (seesaw)?
    - Decay of coherent field? CPT violation?
  - What is the dark energy?
    - Cosmological Constant? Quintessence?
    - Related to inflation? Time variation of couplings?
  - What is the dark matter?
    - Lightest supersymmetric particle? Axion?
  - Suppression of flavor changing neutral currents? Proton decay? Electric dipole moments?
    - *Automatic* in standard model, but not in extensions

Conclusions

- **The standard model is spectacularly successful, but is incomplete**
- **Promising theoretical ideas at Planck and TeV scale**
- **Eagerly anticipate guidance from LHC**