STANDARD MODEL PHENOMENOLOGY

- Review of the SM
- SM: where are we?
- Higgs search
- Radiative corrections
- Flavoured SM
- Open problems of the SM

3. Higgs search

- Interaction ∝ mass (M_Z^2, M_W^2, m_f) ➔ Higgs couples to heavy particles

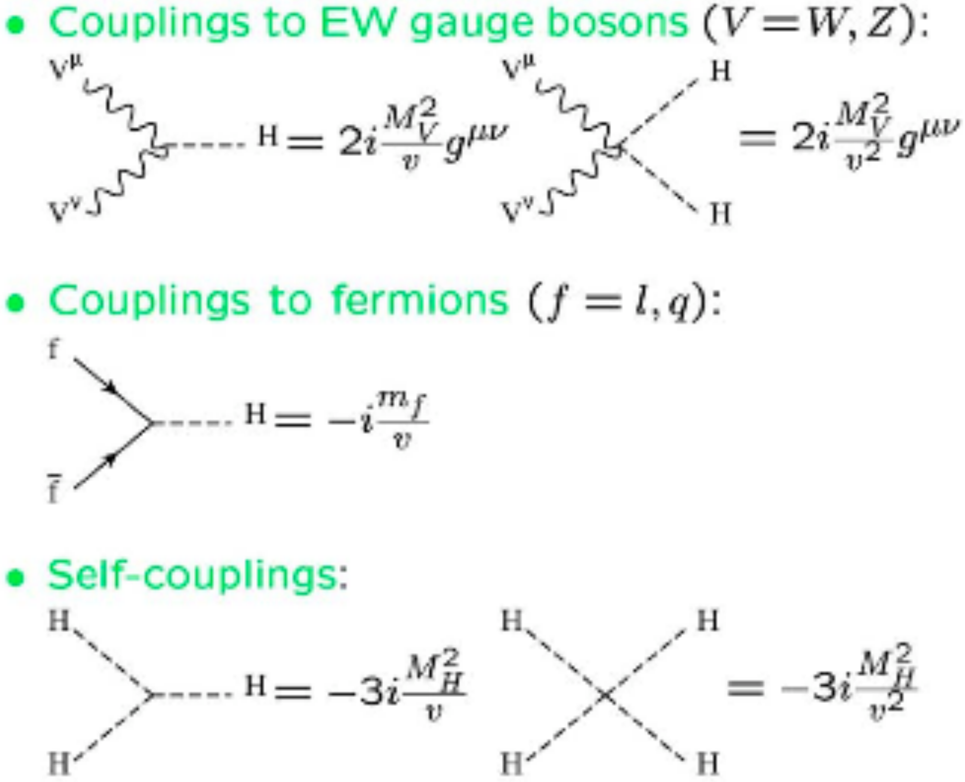
  - Top-Higgs coupling plays special role?

  - No Higgs coupling to neutrinos

- No tree level couplings to photons (γ) nor gluons (g)

-$M_H^2 = 2\lambda v^2$ ➔ large M_H is strong coupling regime

-M_H is parameter which separates perturbative/non-perturbative regimes



- Couplings to EW gauge bosons ($V=W,Z$):

$$= 2i\frac{M_V^2}{v}g^{\mu\nu} \qquad = 2i\frac{M_V^2}{v^2}g^{\mu\nu}$$

- Couplings to fermions ($f=l,q$):

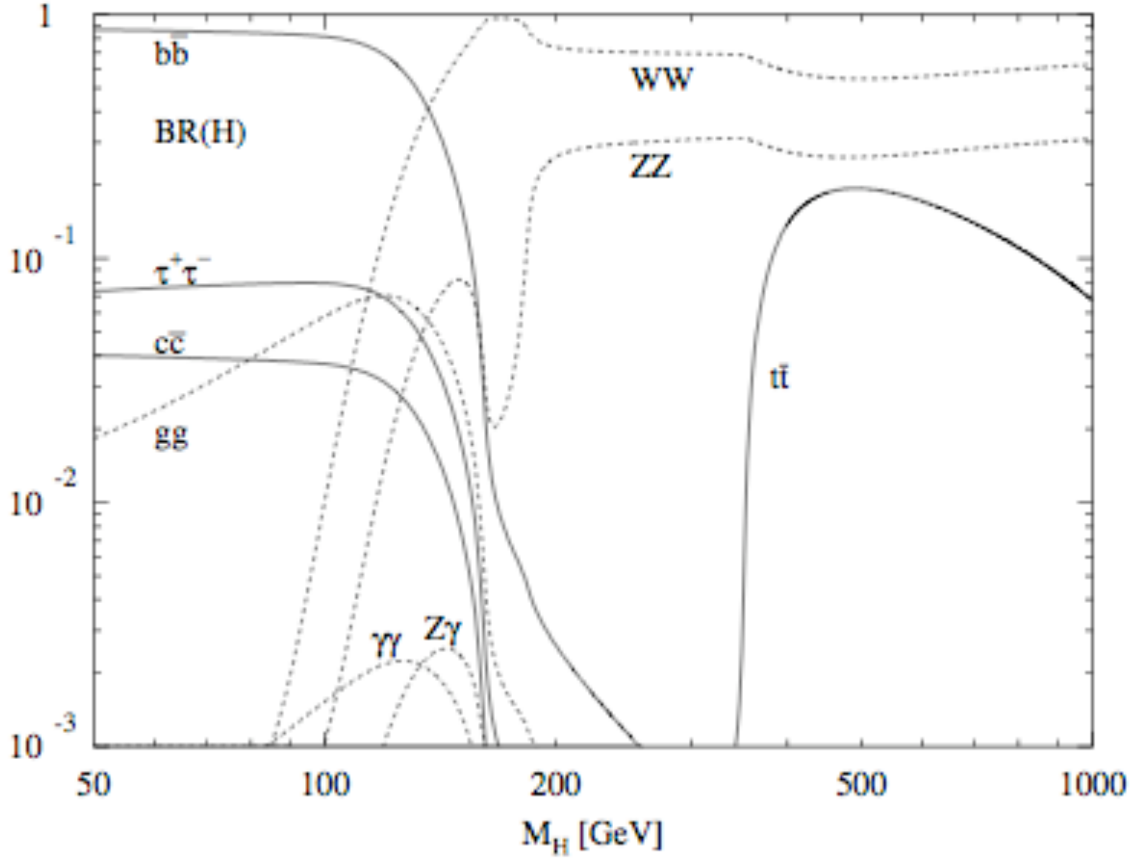
$$= -i\frac{m_f}{v}$$

- Self-couplings:

$$= -3i\frac{M_H^2}{v} \qquad = -3i\frac{M_H^2}{v^2}$$

Higgs decay modes

- The Higgs also couples at higher orders with other gauge bosons: $H\gamma\gamma$, $HZ\gamma$, Hgg



Higgs branching ratios

- 95 GeV < M_H < 130 GeV , Γ_H < 10 MeV

$$\begin{aligned} BR(H \to bb) &\sim 90\% \\ BR(H \to c\bar{c}) &\simeq BR(H \to \tau^+\tau^-) \sim 5\% \\ BR(H \to gg) &\sim 5\% \text{ for } \mathrm{M_H} \sim 120\mathrm{GeV} \end{aligned}$$

- M_H > 130 GeV

$$BR(H \to W^+W^-) \sim 65\% \; , \; BR(H \to ZZ) \sim 35\%$$

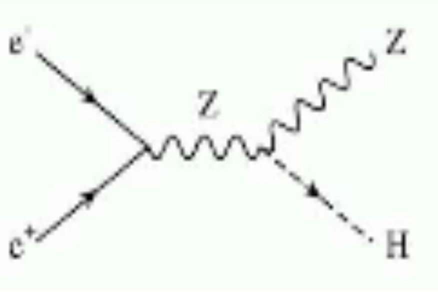
- $M_H \approx$ 500 GeV

$$BR(H \to tt) \sim 20\%$$

Higgs searches at LEP2

- LEP2 searched for $e^+e^- \to Z \to Z\,H$
- Rate turns on rapidly after threshold, peaks just above threshold
- Measure recoil mass of Higgs; result independent of Higgs decay pattern
- Momentum conservation:

$$(P_{e^-} + P_{e^+} - P_Z)^2 = P_H^2 = M_H^2$$
$$s - 2\sqrt{s}E_Z + M_Z^2 = M_H^2$$



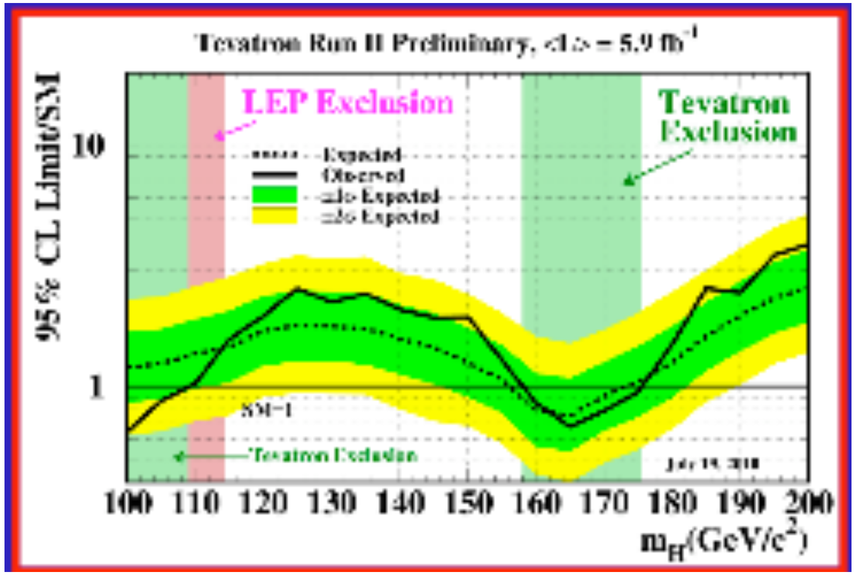
- LEP2 limit: $M_H > 114.4$ GeV

Higgs searches at hadron colliders

- At proton - (anti)proton collisions, the Higgs is produced via:
  - Gluon fusion: p p → g g → H
  - VV fusion: p p → V V → H
- Tevatron direct limit: $M_H \in [158, 173]$ GeV excluded (95% CL)

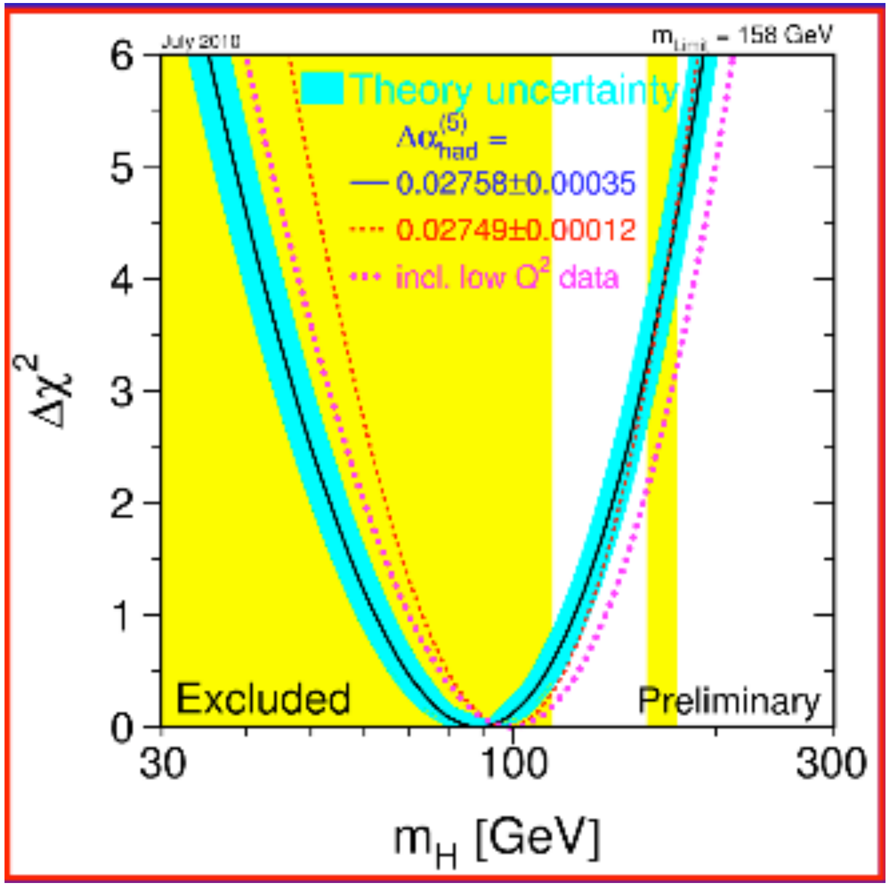
$H \to W^+ W^-$

CDF + DO
(July 2010)



But precision data prefer light Higgs:

LEP EWWG (July 2010)

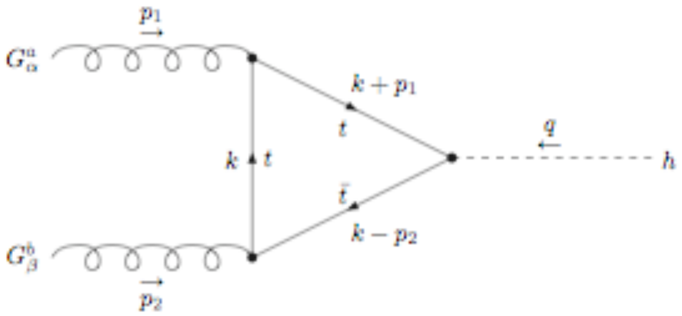


114.4 GeV $< M_H < 158$ GeV

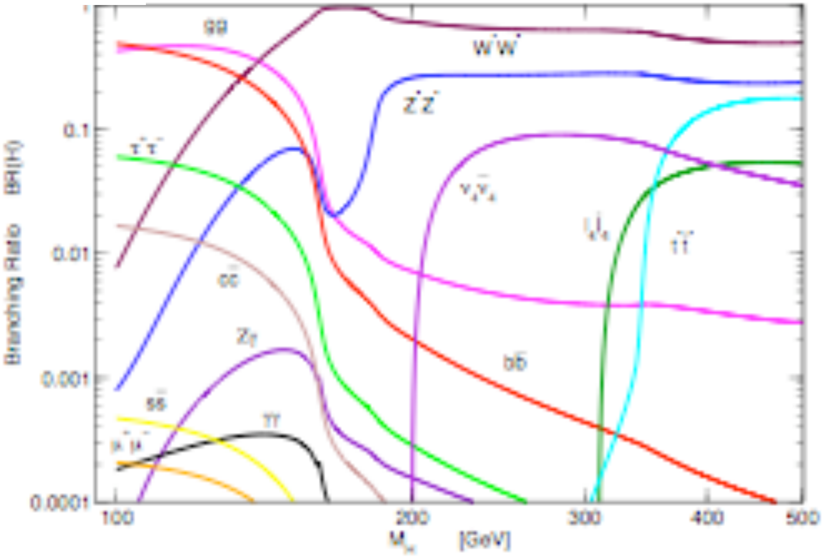
$M_H > 185$ GeV excluded by precision ew data (95% CL)

LHC?

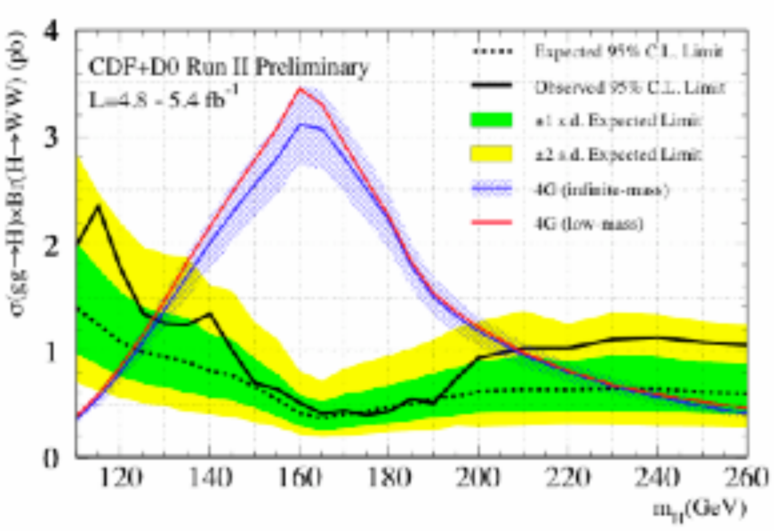
- No limits for 3 generations, yet …
- In the SM with 4 generations, Higgs-gluon-gluon vertex enhanced a factor 3 (2 extra heavy quarks running in the loop)

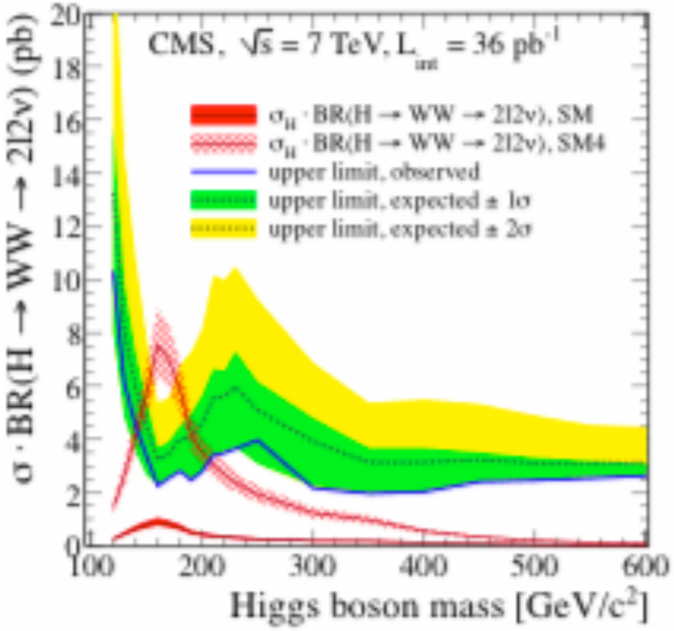


- Higgs branching ratios modified:



Limits from Tevatron and LHC





- 131 GeV < M_H < 204 GeV at 95% CL Tevatron
- 144 GeV < M_H < 207 GeV at 95% CL LHC

4. Radiative corrections

- ρ parameter
- Oblique corrections: S,T,U formalism

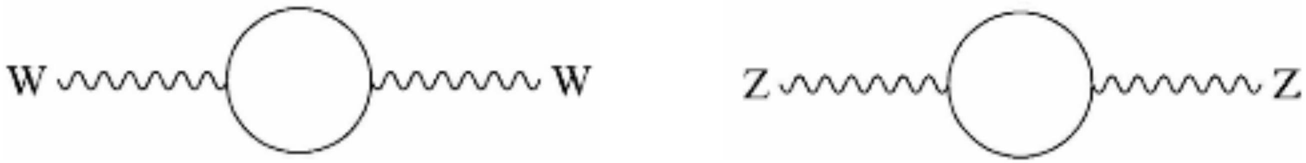
$$\rho = \frac{M_W^2}{c_W^2 M_Z^2}$$

- $\rho = 1$ at tree level ➔ consequence of an unbroken global SU(2) symmetry of the Higgs sector, custodial SU(2) symmetry

- Higgs doublet (complex) = 4 real scalars
  $V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$ ➔ O(4) global symmetry

The vev of ϕ breaks this symmetry down to O(3), that is, SU(2)

- At one loop: $\rho = \frac{M_W^2}{c_W^2 M_Z^2} = 1 - \delta\rho$
- Top quark contributes to W and Z 2-point functions:



$$\delta\rho = \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2}$$

- $q^\mu q^\nu$ piece connects to light (massless) fermions, and doesn't contribute here

$$\delta\rho = \frac{G_F}{\sqrt{2}} \frac{N_c}{8\pi^2} \left(\frac{m_t^2}{M_W^2} \right)$$

➔ top quark doesn't decouple

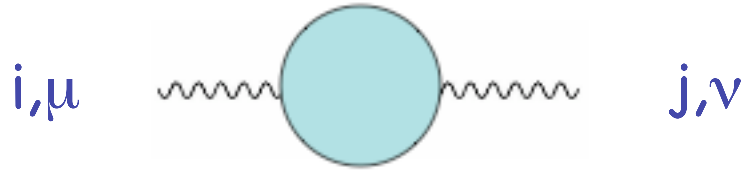
- In QED, running of α at scale μ not affected by heavy virtual particles with $M \gg \mu$

- Decoupling theorem doesn't apply to particles which couple to mass (longitudinal modes of gauge bosons in the SM)

Oblique corrections: S,T,U formalism

[Peskin & Takeuchi, PRD46 (1992) 381]

- Suppose "new physics" contributes primarily to gauge boson two point functions
  - cf Δr where vertex and box corrections are small



- Also assume new physics is at scale $M \gg M_Z$
- Two point functions for γγ, WW, ZZ, γZ

$$\Pi_{ij}^{\mu\nu}(q) = \Pi_{ij}(q^2) g^{\mu\nu} - \Delta(q^2) q^\mu q^\nu$$

- $q^\mu q^\nu$ piece connects to light (massless) fermions, and doesn't contribute

- Taylor expand 2-point functions:

$$\Pi_{ij}(q^2) = \Pi_{ij}(0) + q^2 \Pi'_{ij}(0) + \ldots$$

- Keep first two terms

- **QED** Ward identity requires any amplitude involving EM current vanish at $q^2=0$

$$\Pi_{\gamma\gamma}(0) = 0$$

- Recall that $J_Z \propto J_3 - s_W^2 J_Q$

$$\begin{aligned}
\Pi_{\gamma\gamma} &= e^2 \Pi_{QQ} \\
\Pi_{WW} &= \frac{e^2}{s_W^2} \Pi_{11} \\
\Pi_{ZZ} &= \frac{e^2}{c_W^2 s_W^2} \left(\Pi_{33} - 2 s_W^2 \Pi_{3Q} + s_W^4 \Pi_{QQ} \right) \\
\Pi_{\gamma Z} &= \frac{e^2}{c_W s_W} \left(\Pi_{3Q} - s_W^2 \Pi_{QQ} \right)
\end{aligned}$$

- To order q^2 there are 6 coefficients:

$$\begin{aligned}
\Pi_{QQ} &= q^2 \Pi'_{QQ}(0) + \ldots \\
\Pi_{3Q} &= q^2 \Pi'_{3Q}(0) + \ldots \\
\Pi_{ii} &= \Pi_{ii}(0) + q^2 \Pi'_{ii}(0) + \ldots \quad i = 1, 3
\end{aligned}$$

- Three combinations of parameters absorbed in α, G_F, M_Z
- Three independent coefficients that can be extracted from data:

$$\begin{aligned}
\alpha T &= \frac{\Pi^{new}_{WW}(0)}{M_W^2} - \frac{\Pi^{new}_{ZZ}(0)}{M_Z^2} \\
\frac{\alpha}{c_W^2 s_W^2} S &= \frac{\Pi^{new}_{ZZ}(M_Z^2)}{M_Z^2} - \frac{\Pi^{new}_{ZZ}(0)}{M_Z^2} \\
\frac{\alpha}{4 s_W^2}(S+U) &= \frac{\Pi^{new}_{WW}(M_W^2)}{M_W^2} - \frac{\Pi^{new}_{WW}(0)}{M_W^2}
\end{aligned}$$

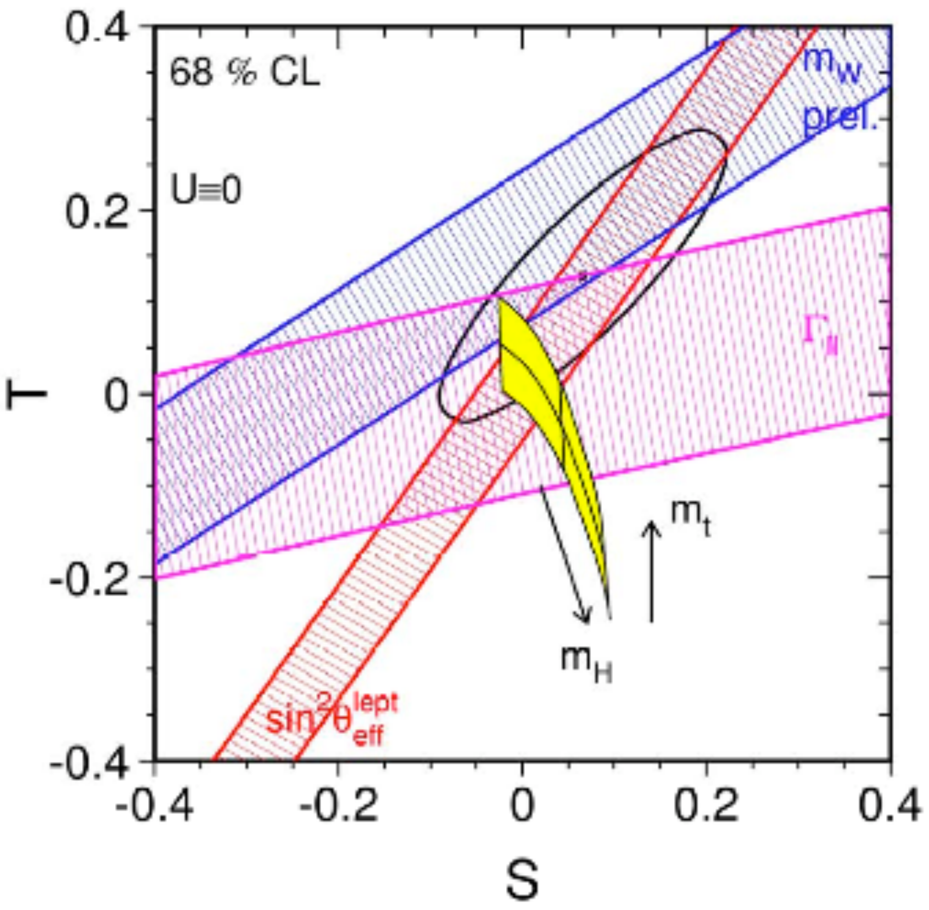
SM contributions in α, G_F and M_Z

- Advantages:
  - Easy to calculate
  - Valid for many models
  - Experimentalists can provide model independent fits

Limits on S & T

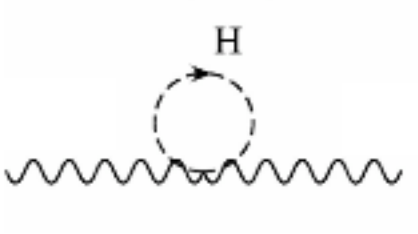
- A model with a heavy Higgs requires a source of large (positive) ΔT

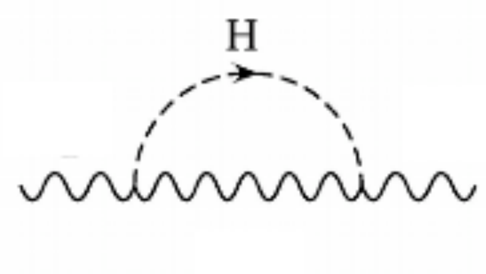
- Fit assumes M_H = 150 GeV



- SM values of S, T, U are defined for a reference M_{H0}

$$
\begin{aligned}
S &= \frac{1}{12\pi}\log\left(\frac{M_H^2}{M_{H0}^2})\right) \\
T &= -\frac{3}{12\pi c_W^2}\log\left(\frac{M_H^2}{M_{H0}^2}\right) \\
U &= 0
\end{aligned}
$$





- $\alpha T = \delta\rho$

- Radiative corrections necessary to fit LEP and Tevatron data
- Radiative corrections strongly limit new physics:
- Allowed quark mass splitting of a fourth generation

$$m_{t'} - m_{b'} \simeq \left[1 + \frac{1}{5}\log\left(\frac{M_H}{115\mathrm{GeV}}\right)\right] \times 50\,\mathrm{GeV}$$

From Tevatron: $m_{t'} > 335\,\mathrm{GeV}$, $m_{b'} > 385\,\mathrm{GeV}$

- Large and negative S in technicolor models

4. Flavoured SM

Fermions come in generations:

N_G= 3 identical copies

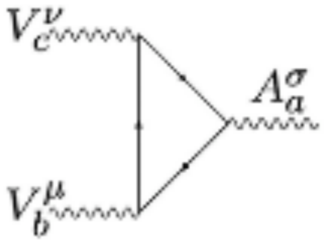
Why ?

$$\left.\begin{array}{l}
\begin{pmatrix}u\\ d\end{pmatrix}_L \quad u_R, \quad d_{R,} \begin{pmatrix}\nu\\ e\end{pmatrix}_L, \quad e_R \\[2em]
\begin{pmatrix}c\\ s\end{pmatrix}_L \quad c_R, \quad s_{R,} \begin{pmatrix}\nu\\ \mu\end{pmatrix}_L, \quad \mu_R \\[2em]
\begin{pmatrix}t\\ b\end{pmatrix}_L \quad t_R, \quad b_{R,} \begin{pmatrix}\nu\\ \tau\end{pmatrix}_L, \quad \tau_R
\end{array}\right\}$$

Except for masses, the generations look identical

Need complete generations

- Sensible gauge theories can't have anomalies
  (see M.A. Vázquez-Mozo lectures)



- Triangle diverges; grows with energy

$$T^{\mu\nu\sigma} \approx \int \frac{d^n k}{(2\pi)^n} \frac{1}{k^3}$$

- Anomaly independent of mass; depends only on gauge properties

$$T^{\mu\nu\sigma} \approx \mathrm{Tr}\left[\{T^a, T^b\} T^c\right]_L - \mathrm{Tr}\left[\{T^a, T^b\} T^c\right]_R$$

$T^a \Rightarrow$ group generator

- Complete generations needed for anomaly cancellation

Anomalies, 2

- Standard Model generators: $T^a = \sigma^a/2,\ Y$
- Three W's or one W and two B's cancel because Tr(σ^a) = 0
- Contributions only from two W's and one B or three B's:

$$[SU(2)]^2\, U(1) \quad : \quad \mathrm{Tr}\left[\{\sigma^a, \sigma^b\} Y\right] = 2\delta^{ab} \sum_{doublets} Y \propto -1 + N_C\,\frac{1}{3}$$

$$[U(1)]^3 \quad : \quad \mathrm{Tr}\left(Y^3\right) \propto \sum_{doublets} Y^3 - \sum_{singlets} Y^3$$

$$= \ 2\left(-\frac{1}{2}\right)^3 + 2N_C\left(\frac{1}{6}\right)^3 - \left[(-1)^3 + N_C\left(\frac{2}{3}\right)^3 + N_C\left(-\frac{1}{3}\right)^3\right]$$

$$= \ -\frac{3}{4}\left(-1 + N_C\,\frac{1}{3}\right)$$

Fermion masses

- For 3 generations, α,β=1,2,3 (flavour indices):

$$\mathcal{L}_Y = -\mathbf{Y}'^{\alpha\beta}_{\ell}\,\vec{\bar{\ell}}'^{\alpha}_{L}\,\phi\,\ell'^{\beta}_{R} - \mathbf{Y}'^{\alpha\beta}_{d}\,\bar{Q}'^{\alpha}_{L}\,\phi\,d'^{\beta}_{R} - \mathbf{Y}'^{\alpha\beta}_{u}\,\bar{Q}'^{\alpha}_{L}\,\phi_c\,u'^{\beta}_{R} + h.c.$$

- After SSB:

$$\mathcal{L}_Y = -\left(1+\frac{H}{v}\right)\{\bar{\ell}'\cdot\mathbf{M}'_{\ell}\cdot\ell' + \bar{q}'_d\cdot\mathbf{M}'_d\cdot q'_d + \bar{q}'_u\cdot\mathbf{M}'_u\cdot q'_u\}$$

- Arbitrary non-diagonal complex mass matrices:

$$[\mathbf{M}'_f]_{\alpha\beta} = [\mathbf{Y}'_f]_{\alpha\beta}\frac{v}{\sqrt{2}}$$

- Unitary matrices diagonalize mass matrices:

$$\mathbf{M}'_f = H_f S_f = U^{\dagger}_f M_f U_f S_f \equiv U^{\dagger}_f M_f V_f$$

M_f diagonal

$$H_f = H^{\dagger}_f \qquad U_f,\ S_f\ ,V_f \text{ unitary}$$

$$\ell_L = U_\ell \ell'_L \qquad d_L = U_d d'_L \qquad u_L = U_u u'_L$$

$$\ell_R = V_\ell \ell'_R \qquad d_R = V_d d'_R \qquad u_R = V_u u'_R$$

- Mass eigenstates ≠ weak eigenstates
- Yukawa couplings are diagonal in mass basis:

$$\mathcal{L}_Y = -\left(1 + \frac{H}{v}\right)\{\bar{\ell} \cdot \mathbf{M}_\ell \cdot \ell + \bar{q}_d \cdot \mathbf{M}_d \cdot q_d + \bar{q}_u \cdot \mathbf{M}_u \cdot q_u\}$$

$$\mathbf{M}_\ell = \mathrm{diag}[m_e, m_\mu, m_\tau], \ \mathbf{M}_d = \mathrm{diag}[m_d, m_s, m_b], \ \mathbf{M}_u = \mathrm{diag}[m_u, m_c, m_t]$$

- Neutral currents remain flavour diagonal
- Not necessarily true in models with extended Higgs sector

- **Neutral current:** $\bar{f}'_L f'_L = \bar{f}_L f_L \qquad \bar{f}'_R f'_R = \bar{f}_R f_R$

$$\mathcal{L}^{Z}_{NC} = -\frac{g}{2\cos\theta_W} Z_\mu \sum_f \bar{f}\gamma^\mu \left[v_f - a_f\gamma_5\right] f$$

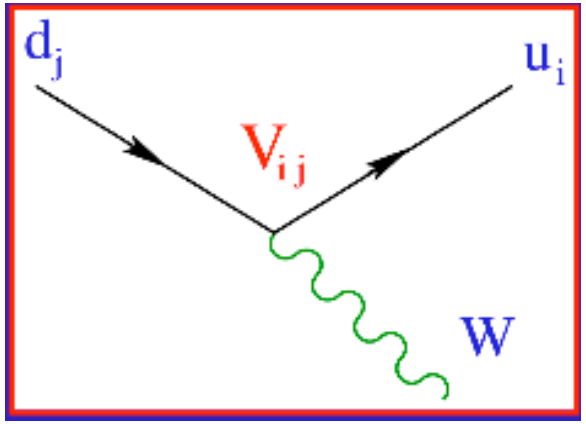
  - Flavour conserving neutral currents (GIM)

- **Charged current:** $\bar{u}'_L d'_L = \bar{u}_L V d_L$

$V \equiv U_u U_d^\dagger$ ➔ CKM matrix

$$\mathcal{L}_{CC} = -\frac{g}{2\sqrt{2}} W^\dagger_\mu \left[\sum_{i,j} \bar{u}_i \gamma^\mu (1-\gamma_5) V_{ij} d_j + \sum_\ell \bar{\nu}_\ell \gamma^\mu (1-\gamma_5)\ell\right] + h.c.$$

- Flavour changing charged currents



Lepton mixing

$$\mathcal{L}_{CC}^{\ell} = -\frac{g}{2\sqrt{2}} W_{\mu}^{\dagger} \sum_{i,j} \bar{\nu}_i \gamma^{\mu} (1-\gamma_5) V_{ij}^{\ell} \ell_j + + h.c.$$

- Minimal SM without ν$_R$ ➔ $m_{\nu_i} = 0$

$$\bar{\nu}_{\ell_j} \equiv \bar{\nu}_{\ell_i} V_{ij}^{\ell} \ \Rightarrow\ \mathcal{L}_{CC}^{\ell} = -\frac{g}{2\sqrt{2}} W_{\mu}^{\dagger} \sum_{\ell} \bar{\nu}_{\ell} \gamma^{\mu} (1-\gamma_5) \ell + h.c.$$

  - Separate lepton number conservation

- If ν$_R$ exists and $m_{\nu_i} \neq 0$ ➔ lepton flavour violation, $L = L_e + L_{\mu} + L_{\tau}$ conserved
- If neutrinos are Majorana ➔ lepton flavour and total lepton number L violation
- Present bounds:

$$BR(\mu \to e\gamma) < 1.2 \times 10^{-11} \ ; \ BR(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$$

Quark mixing

- Unitary N_G x N_G matrix ➔ N_G^2 parameters

$$V^\dagger V = V V^\dagger = 1$$

- 2 N_G - 1 arbitary phases:

$$u_i \to e^{i\phi_i} \; ; \; d_j \to e^{i\theta_j} \Rightarrow V_{ij} \to e^{i\theta_j - \phi_i} V_{ij}$$

- V_{ij} physical parameters:

Moduli: $\frac{1}{2} N_G(N_G - 1)$ Phases: $\frac{1}{2}(N_G - 1)(N_G - 2)$

- **NG=2:** 1 angle (Cabibbo), 0 phases

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

No CP violation

- **NG=3:** 3 angles, 1 phase (CKM)

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$c_{ij} \equiv \cos\theta_{ij} \ , \ s_{ij} \equiv \sin\theta_{ij}$$

CP violation

- **NG=4:** 6 angles, 3 phases

$$\Gamma(d_j \to u_i \ell^- \bar{\nu}_\ell) \propto |V_{ij}|^2$$

- We measure decays of hadrons (no free quarks) ➔ important **QCD** uncertainties
- Also data from hadronic decays of W

$$|V_{ij}| = \left[\begin{array}{ccc} 0.9739 - 0.9751 & 0.221 - 0.227 & 0.0029 - 0.0045 \\ 0.221 - 0.227 & 0.9730 - 0.9744 & 0.039 - 0.044 \\ 0.0048 - 0.014 & 0.037 - 0.043 & 0.9990 - 0.9992 \end{array} \right)$$

- Hierarchical pattern ➔ Wolfenstein parametrization

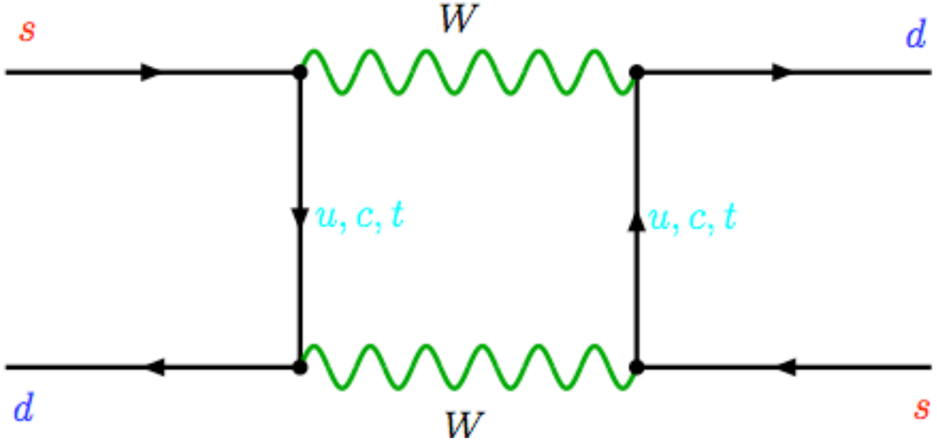
$$V \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$\lambda = \sin\theta_c \approx 0.225 \; ; \; A \approx 0.81 \; ; \; \sqrt{\rho^2+\eta^2} \approx 0.37$$

$\eta \neq 0$ ➔ CP violation

- C, P : violated maximally in weak interactions
- CP : symmetry of nearly all observed phenomena
- CP violation in meson – antimeson systems
  - 0.2 % CP violation in K^0 decays (1964)
  - Sizeable CP violation in B^0 decays (2001)
  - Hope we don't need to wait other 30 years …
- Huge Matter-Antimatter asymmetry in our Universe → Baryogenesis
- CPT theorem: CP violation ⇔ T violation

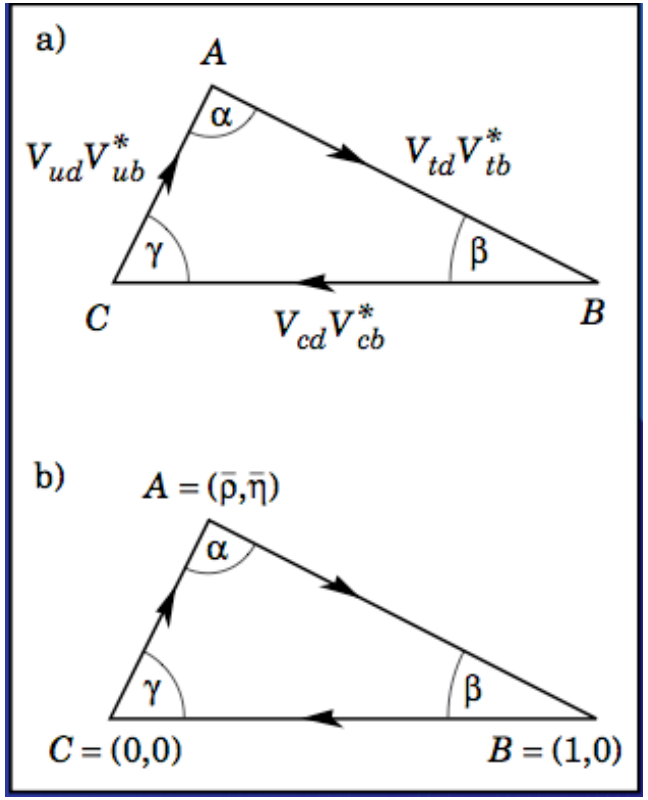
- In the SM, meson - antimeson mixing and CP violation generated by diagramas like ➔ phases + interferences



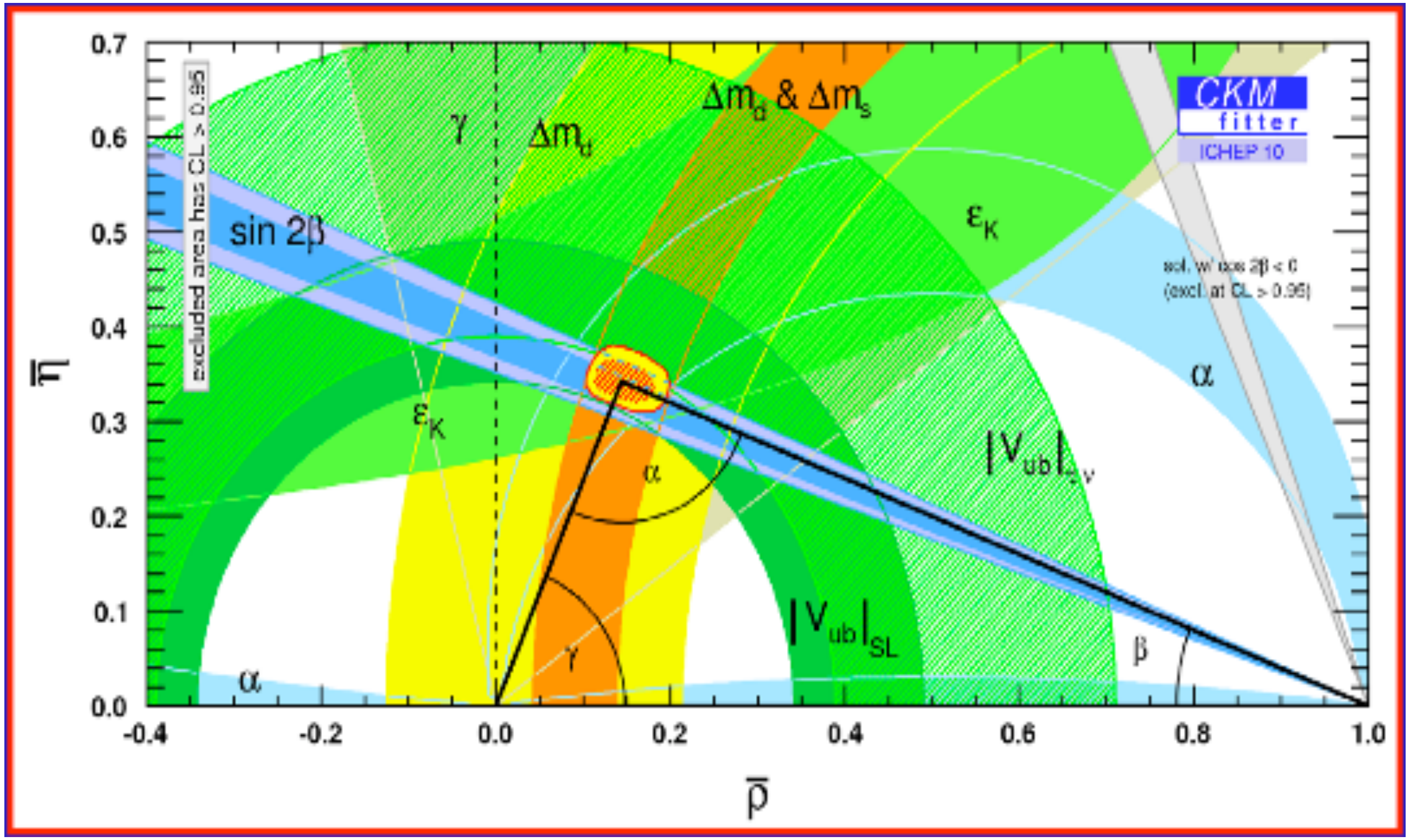
- Unitarity triangle

$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$

- An area ≠ 0 means CP violation



$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$



Standard Model CP violation

- Complex phases only in Yukawa couplings

- After SSB and diagonalization of quark's mass matrix:

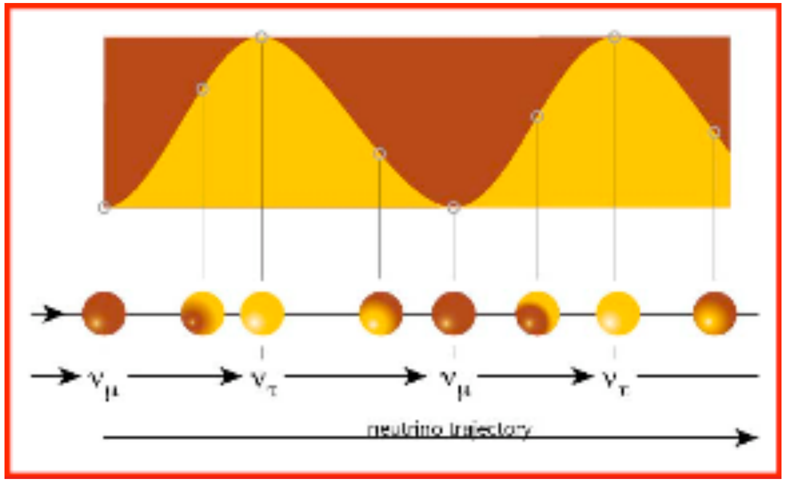
$$\mathcal{L}_{CC} = -\frac{g}{2\sqrt{2}} W_\mu^\dagger \sum_{i,j} \bar{u}_i \gamma^\mu (1-\gamma_5) V_{ij} d_j + h.c.$$

- The CKM matrix V_{ij} is the only source of CP violation

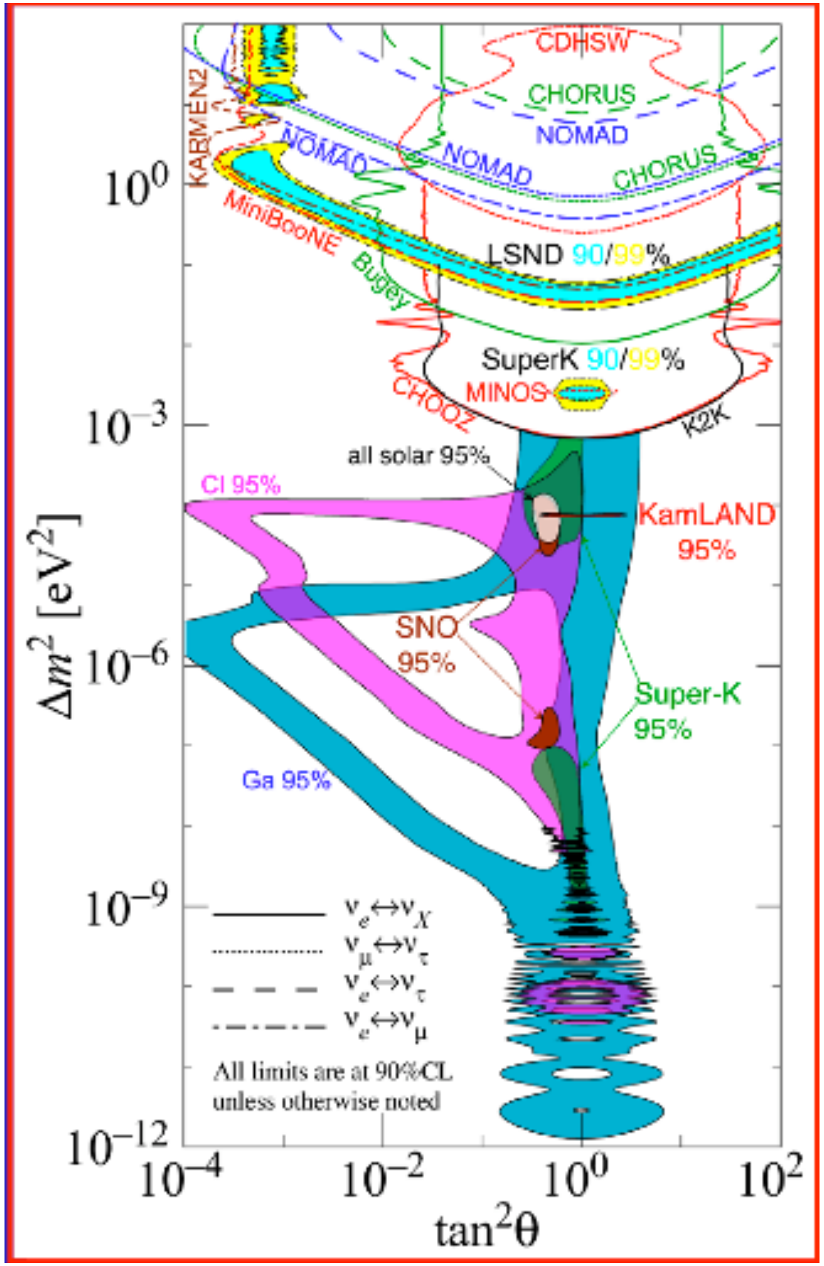
  ➔ not sufficient to explain the baryon asymmety of the Universe

Neutrino oscillations

http://hitoshi.berkeley.edu/neutrino



- Lepton mixing
- Neutrino masses
- ν_R ?
- New physics!



- Evidence for lepton flavour change from:
  - Solar neutrino oscillations, confirmed by reactor experiment (KamLAND)
  - Atmospheric neutrino oscillations, confirmed by accelerator experiment (K2K)
  - LSND and MiniBOONE ?

- If ν's are massive, mass eigenstates are not flavour eigenstates, $W^+ \to \ell_\alpha^+ \nu_\alpha \; , \; \alpha = e, \mu, \tau$

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle$$

U ➔ PMNS mixing matrix, unitary

- After traveling a distance L, time evolution gives ($p \gg m_i$)

$$|\nu_\alpha(L)\rangle = \sum_i U_{\alpha i}^* e^{-i m_i^2 L/2E} |\nu_i\rangle$$

- Then, $P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu_\alpha(L) \rangle|^2$
- For only 2 flavours: $P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2 \left(1.27 \frac{\Delta m^2 L}{E} \right)$

  Δm^2 in eV, L in Km, E in GeV

- Sizeable transition probability if $E/L \approx \Delta m^2$
- Tiny neutrino masses lead to unobservable flavour changing in charged lepton decays

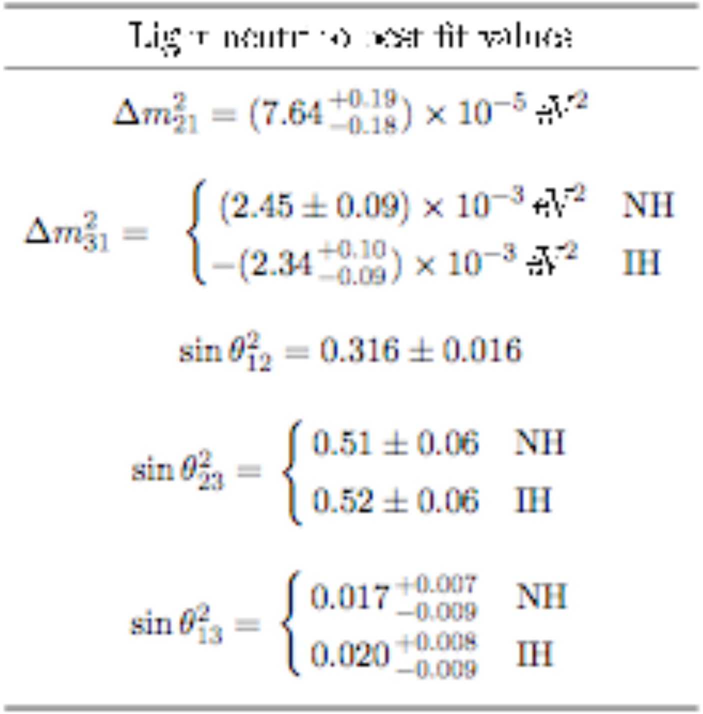
- **PMNS mixing matrix:**

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} e^{i\phi_1} & & \\ & e^{i\phi_2} & \\ & & 1 \end{pmatrix}$$

- Dirac phase δ
- 2 physical phases ϕ_i if neutrinos are Majorana particles
- CP violating phase δ may be observable only if s_{13} big
- Upper limit from CHOOZ (reactor experiment, no evidence of $\bar{\nu}_e$ disappearance): $\sin^2(2\theta_{13}) < 0.2$ at 90% CL
- DOUBLE CHOOZ underway: limit down to 0.03

Global fit to neutrino oscillation data

March, 2011 (new reactor fluxes)



Light neutrino best fit values

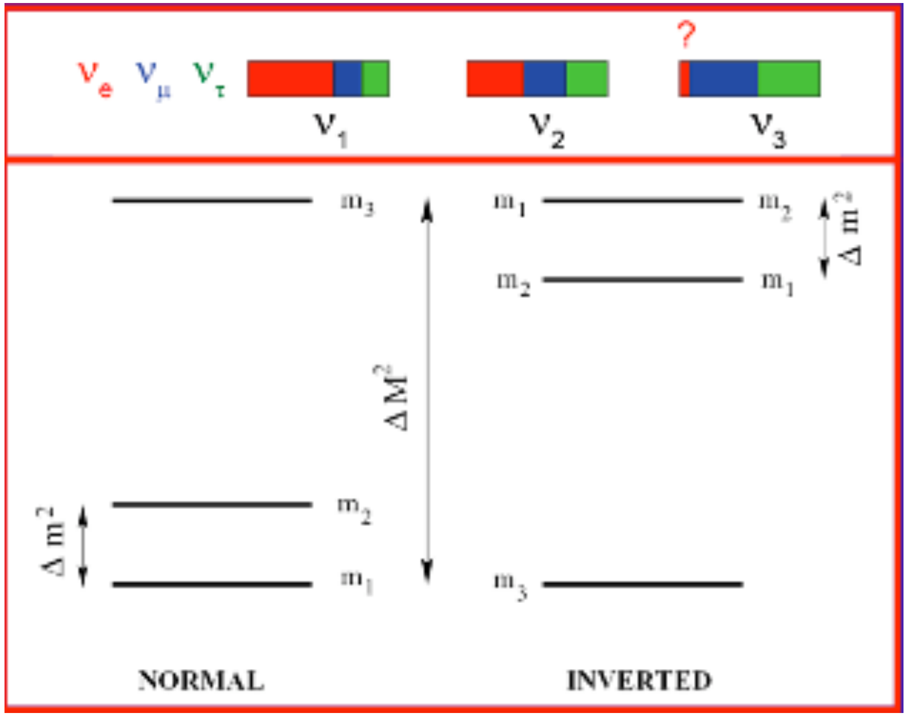
$$\Delta m^2_{21} = (7.64^{+0.19}_{-0.18}) \times 10^{-5}\ \mathrm{eV}^2$$

$$\Delta m^2_{31} = \begin{cases} (2.45 \pm 0.09) \times 10^{-3}\ \mathrm{eV}^2 & \mathrm{NH} \\ -(2.34^{+0.10}_{-0.09}) \times 10^{-3}\ \mathrm{eV}^2 & \mathrm{IH} \end{cases}$$

$$\sin\theta^2_{12} = 0.316 \pm 0.016$$

$$\sin\theta^2_{23} = \begin{cases} 0.51 \pm 0.06 & \mathrm{NH} \\ 0.52 \pm 0.06 & \mathrm{IH} \end{cases}$$

$$\sin\theta^2_{13} = \begin{cases} 0.017^{+0.007}_{-0.009} & \mathrm{NH} \\ 0.020^{+0.008}_{-0.009} & \mathrm{IH} \end{cases}$$



Recent indications of $\nu_\mu \rightarrow \nu_e$ appearance in T2K and MINOS long-baseline accelerator experiments ➔

non zero θ_{13} ?

- Mixing pattern close to tribimaximal, very different from quarks:

$$U \approx \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

- Only mass differences $\Delta m_{ij}^2 = m_i^2 - m_j^2$ can be determined from oscillations

- Absolute neutrino mass scale unkown; best bound from cosmology $m_\nu < 1$ eV

Neutrino masses

- Two types of mass terms:

$$\begin{aligned}\mathcal{L}_{Dirac} &= \bar{\nu}_R M_\nu \nu_L + h.c. \\ \mathcal{L}_{Majorana} &= -\frac{1}{2}\bar{\nu_L^c} M_\nu \nu_L + h.c.\end{aligned}$$

- Indistinguishable in oscillations
- Majorana ν's violate lepton number (accidental symmetry of the SM) ➔ neutrinoless double beta decay
- If ν_R exists, and lepton number is conserved

$$\mathcal{L}_N = -\bar{\ell}_L \mathbf{Y}_\nu \phi_c \nu_R + h.c.$$

➔ $Y_\nu \approx 10^{-12}$

Seesaw mechanism

- But ν_R can have a Majorana mass term (not forbiden by gauge symmetry, because it is a SM singlet)

$$\mathcal{L}_N = -\bar{\ell}_L \mathbf{Y}_\nu \phi_c \nu_R - \frac{1}{2}\bar{\nu^c}_R M_\nu \nu_R + h.c.$$

- After SSB, neutrino mass matrix in (ν_L, ν_R^c) basis is

$$M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M \end{pmatrix}$$

- If $M \gg M_D$:

N_G heavy Majorana neutrinos, ~ ν_R with masses ~ M

N_G light Majorana neutrinos, ~ ν_L with masses ~ M_D^2/M

- If there is CP violation in the leptonic sector

➔ Generation of the matter - antimatter asymmetry of the Universe via Leptogenesis : CP-violating out of equilibrium decay of the heavy neutrino in the Early Universe

5. Open problems of the SM

- Theoretical:
  - Hierarchy problem (SUSY, Xdim, composite Higgs)
  - Flavour structure

- Experimental:
  - Neutrinos
  - Dark matter
  - Dark energy
  - Baryon asymmetry of the Universe
  - Find the Higgs ?

Stay tuned: Exciting times ahead !