Standard Model

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Issues concerning the Standard Model of particle physics:

Even though we call it a model it is actually the candidate for **the** 'theory' of the fundamental particles and interactions among them!

Built, brick by brick, over the last 50-60 years, combining information from a lot of different types of experiments and many many innovative theoretical ideas.

The basic mathematical framework is that of quantum field theories (QFT) which possess some special properties (symmetries). Some aspects of these will be covered in lectures by Prof. Deredinger.

Using this information I intend then to cover the following :

• How did we find out about the fundamental constituents and interactions among them.

• How did we arrive at an understanding of the symmetries and hence a gauge theory description of the same: how was the SM built?

• What is the significance of the different families of quarks and leptons: flavour physics.

• What is the piece of the SM still left to be checked and how does the theory guide us about how and where to look for the missing piece.

SM - III

Electroweak Theory.

1. $SU(2)_L \times U(1)_Y$ model , prediction of a new interaction (weak neutral currents) and masses of the weak gauge bosons in terms of Neutral Current (NC) couplings of quarks and leptons.

2. First observation of W/Z and what did it test for the Standard Model?

3. Why does the SM need the charm quark? Glashow-Iliopoulos-Maiani(GIM) mechanism. Predicting m_c? Absence of flavour changing Neutral Currents.

4. Quark and Lepton families and mixing among quarks (CKM) matrix.

Glashow:

(Two) Doublets of quarks $\mathcal{Q}_i$ and leptons $\mathcal{L}_i$:

Postulated that Left handed quarks and lepton form a doublet of a $SU(2)_L$ the L implying that only the left handed fermions have a nonzero charge, i.e. interactions with the $W^{\pm}$

Glashow's observation:

$Q = I_W^3 + Y/2$ (Q is the electromagnetic charge in units of $|e|$, where e is electron charge.)

where $Y = 1/3$ for quark doublets and $Y = -1$ for lepton doublet. Thus Y is the hyper charge of the $U(1)$ symmetry group.

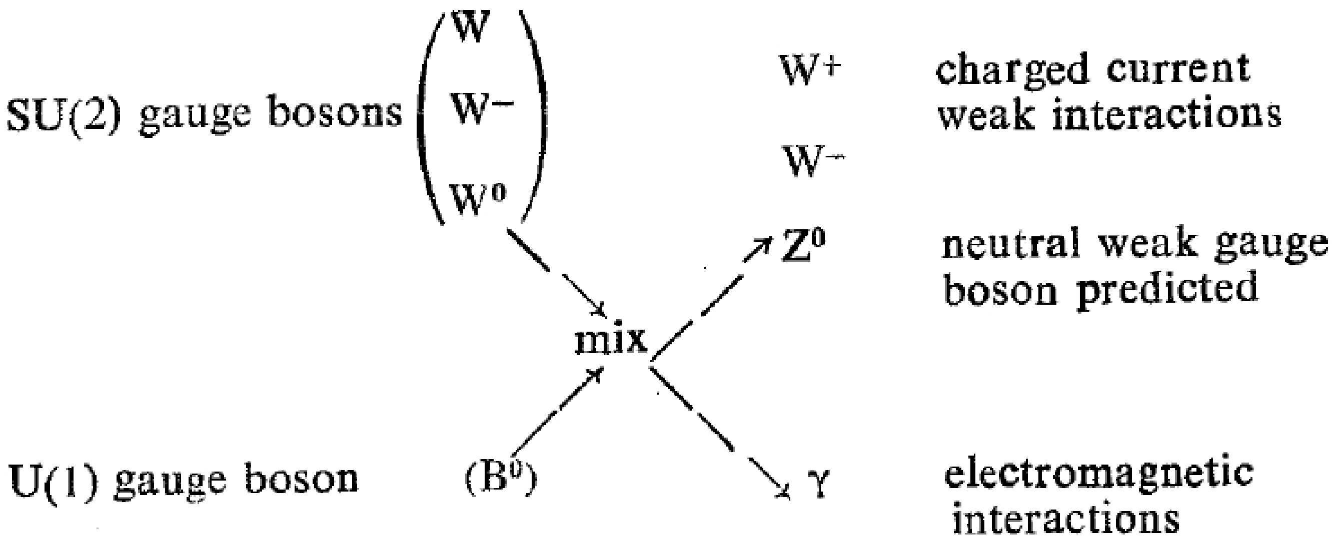
Right handed fermions will have $I_W^3 = 0$ and hence a different Y value than the left handed fermions.

Thus the net symmetry is $SU(2)_L \times U(1)_Y$ g_2 coupling constant for $SU(2)$ and g_1 for $U(1)_Y$.

$SU(2)_L$: Three gauge bosons W^1, W^2, W^3 : all couple only to left handed fermions.

$U(1)_Y$: B couples to all fermions (LH and RH).

B and W^3 mix, giving one zero mass eigenstate γ. Identify other with a new Neutral vector boson called Z.



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

$$Z_\mu = -\sin\theta_W B_\mu + \cos\theta_W W^3_\mu$$

$$e = g_2 \sin\theta_W = g_1 \cos\theta_W$$

$$\frac{G_F}{\sqrt{2}} = \frac{g_2^2}{M_W^2} = \frac{e^2}{8M_W^2 \sin^2\theta_W}$$

$SU(2)_L \times U(1)$ model predicts

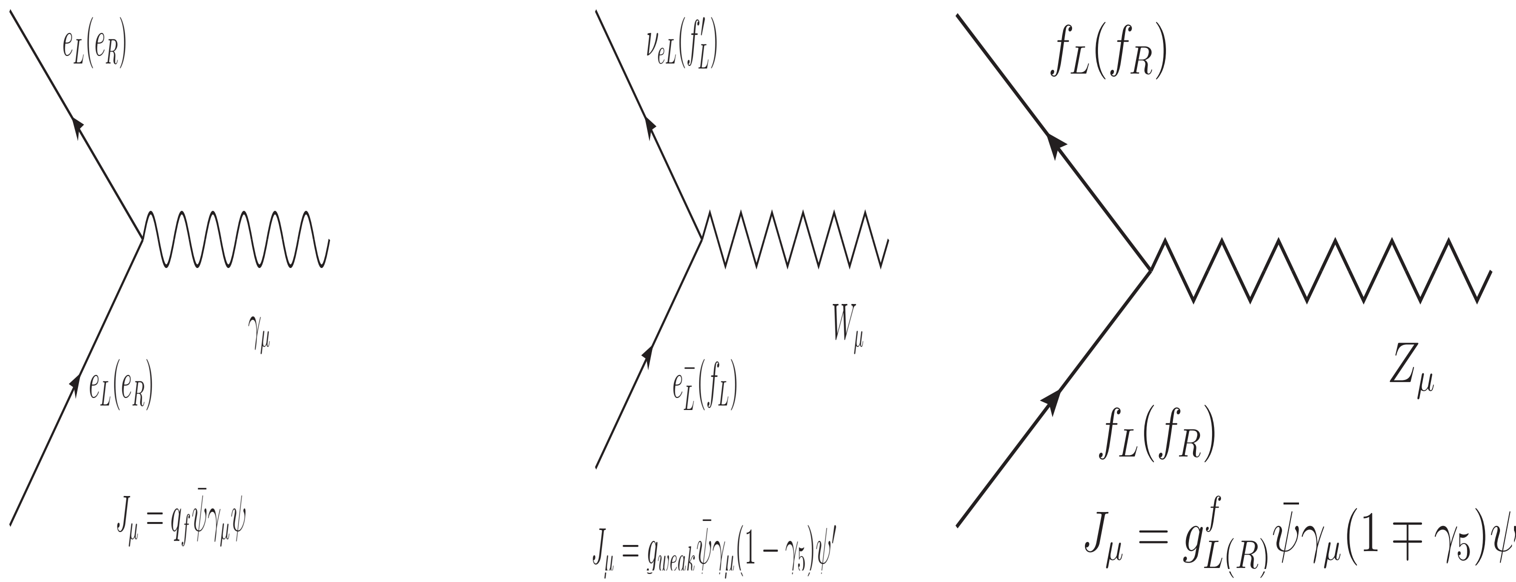
1)New particles: Z, charm quark c.

2)Weak Neutral current mediated by Z analogous to Weak Charged Current mediated by the W.

3)Mass predicted in terms of one parameter θ_W, which will decide the couplings of the various particles to the Z.

4)WWZ coupling possible and predicted.

5)A sort of unification: Unless $\sin\theta_W$ unnaturally small (then the whole idea is not sensible) e, g_1, g_2 all of similar order. The difference in strengths of interactions only apparent due to large M_W.



Like the photon the Z couples f to f and NOT f to f'. No flavour change.

Unlike the photon Z couples differently to the left and right handed fermions.

Like the W, Z coupling too violates parity, but unlike the W not necessarily maximally.

An aside:

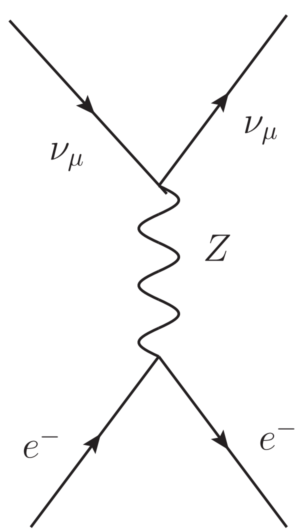
Massive gauge bosons have a problem. Amplitudes like $\nu_e \bar{\nu}_e \to W^+ W^-$ grow with energy and can violate unitarity.

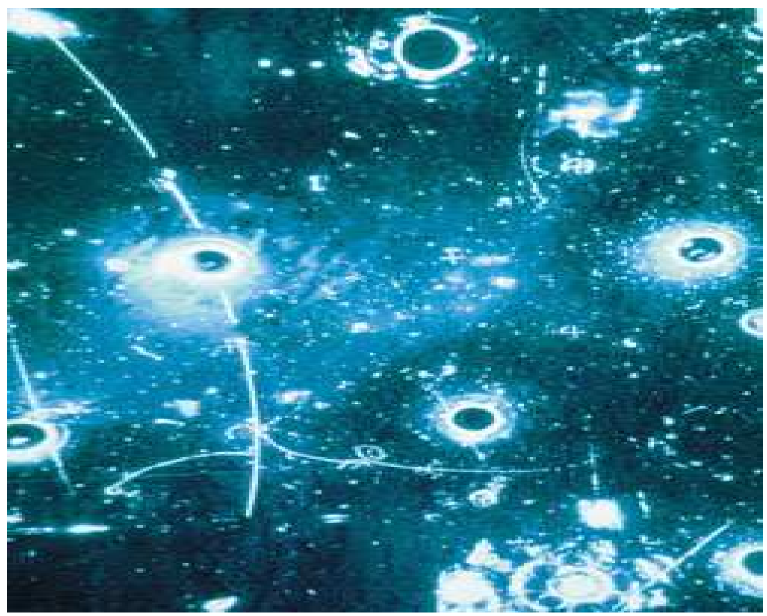
One can show that this violation of unitarity can be tamed by adding a neutral spin 1 boson which ZW^+W^- couplings as expected in the $SU(2)_L \times U(1)_Y$ model!

Cornwall, Tiktopolous (1974, 1975); Llewellyn Smith (1973), S.D. Joglekar (1973)

First attempt to see weak neutral current : D. H. Perkins, Veltman. Failed.

Discovery of neutral currents: In an experiment at CERN with a Bubble Chamber. (Photograph Courtesy CERN). Experiments with ν_μ beams obtained from π decays.





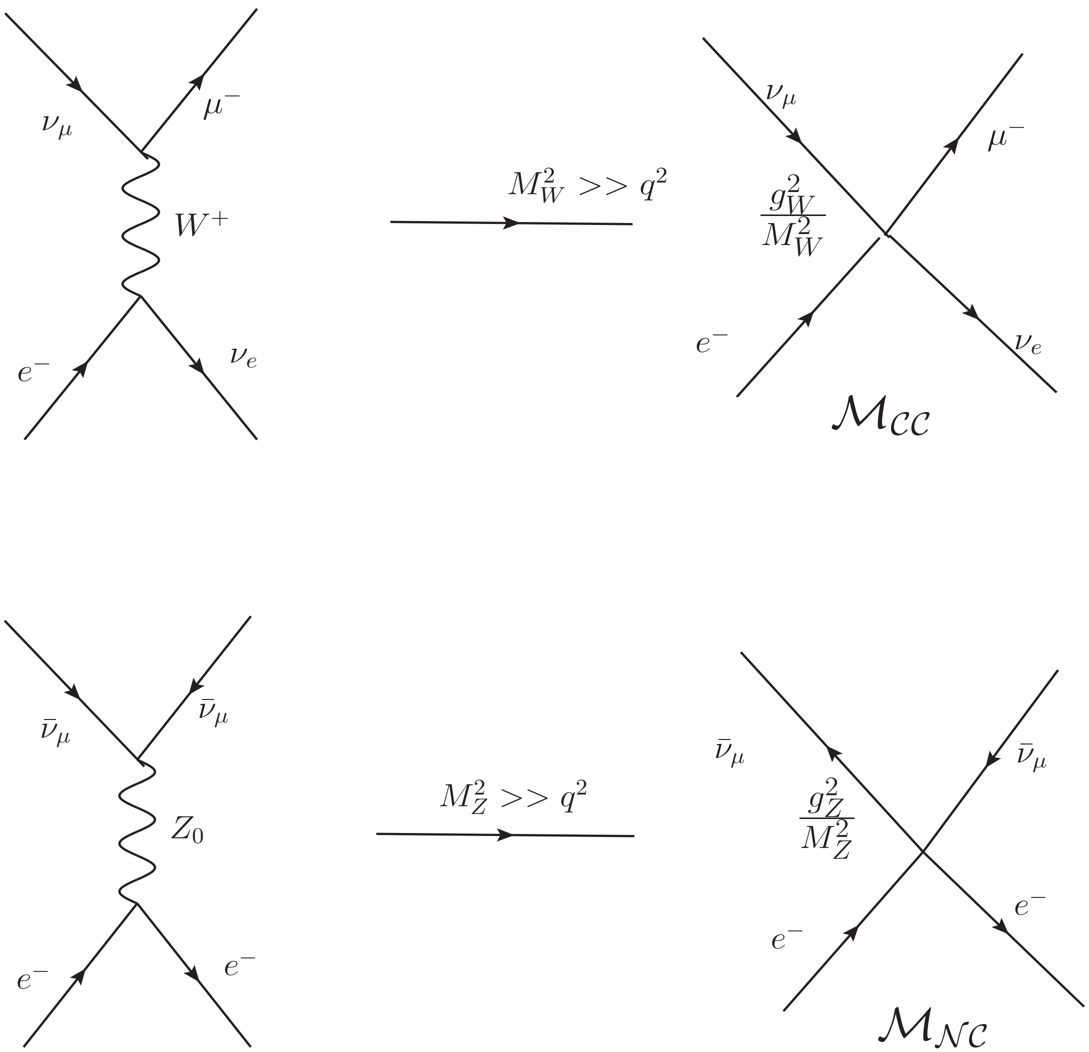
Glashow did not attempt to generate M_W, M_Z, in a gauge invariant manner.

Glashow's model did fix the problem with $\nu_e \bar{\nu}_e \to W^+ W^-$ process violating unitarity.

Alternative mechansims to do that without neutral currents had existed eg. Georgi model which predict a new heavy neutral lepton. This is ruled out by Gargamelle data.

Neutral current discovery means that between the two solutions to restore unitarity to weak processes, the one with new massive neutral gauge boson seems to be called for.

Weinberg and Salam made use of Higgs mechanism to generate masses in a gauge invariant manner AND could predict M_Z in terms of M_W and θ_W as a bonus!



$$\rho = \frac{g_Z^2}{2g_W^2}\frac{M_W^2}{M_Z^2}$$
$$= \frac{M_W^2}{M_Z^2 \cos^2\theta_W}$$

ρ measures the ratio of strengths of the coupling in $\mathcal{M}_{\mathcal{CC}}$ and $\mathcal{M}_{\mathcal{NC}}$.

For the WS model $\rho = 1$ and Only if we choose doublet for the Higgs representation.

Study of Neutral current processes confirming model predictions for couplings, including $\rho \simeq 1$, fetched Nobel prize for Glashow, Salam and Weinberg in 1979.

Non zero M_W, M_Z break gauge invariance.

Mass terms for fermions contains $\bar{\psi}_L\psi_R$, Left handed and Right handed fields have diff rent $SU(2)_L$, $U(1)_Y$ charges. So clearly a fermion mass term breaks gauge invariance too!

Weinberg and Salam, separately, used the Higgs mechanism to generate masses for fermions and gauge bosons in a gauge invariant way. Prediction for both M_W, M_Z in terms of g_1, g_2 and $\sin\theta_W$.

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

gets nonzero vacuum expectation value

$$\langle\phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}$$

Symmetry spontaneously broken. Vac cum not symmetric but the Lagrangian still is. Scattering amplitudes are gauge invariant. (The Nambu Jona Lasinio mechanism at the heart of this: Nobel prize 2008)

Predictions: M_W, M_Z

$$M_W = \left(g_2^2\sqrt{2}/8G_F\right)^{1/2} = \frac{37.4}{\sin\theta_W},\ \ M_Z = \frac{M_W}{\cos\theta_W}; \rho = 1$$

(Weinberg paper Phys. Rev. Lett. 19, 1264,1967) How to determine $\sin\theta_W$?. Couplings g_Z, g_W of W, Z to all fermions predicted in terms of $\sin\theta_W$ and G_F.

Determine $\sin^2\theta_W$ using data from 1) $\bar{\nu}_\mu e^- \to \bar{\nu}_\mu e^-$; 2)$\nu_\mu e^- \to \nu_\mu e^-$; 3)$\bar{\nu}_e e^- \to \bar{\nu}_e e^-$; 4) $e^+e^- \to \mu^+\mu^-$.

Using this $\sin^2\theta_W$ predict M_W, M_Z.

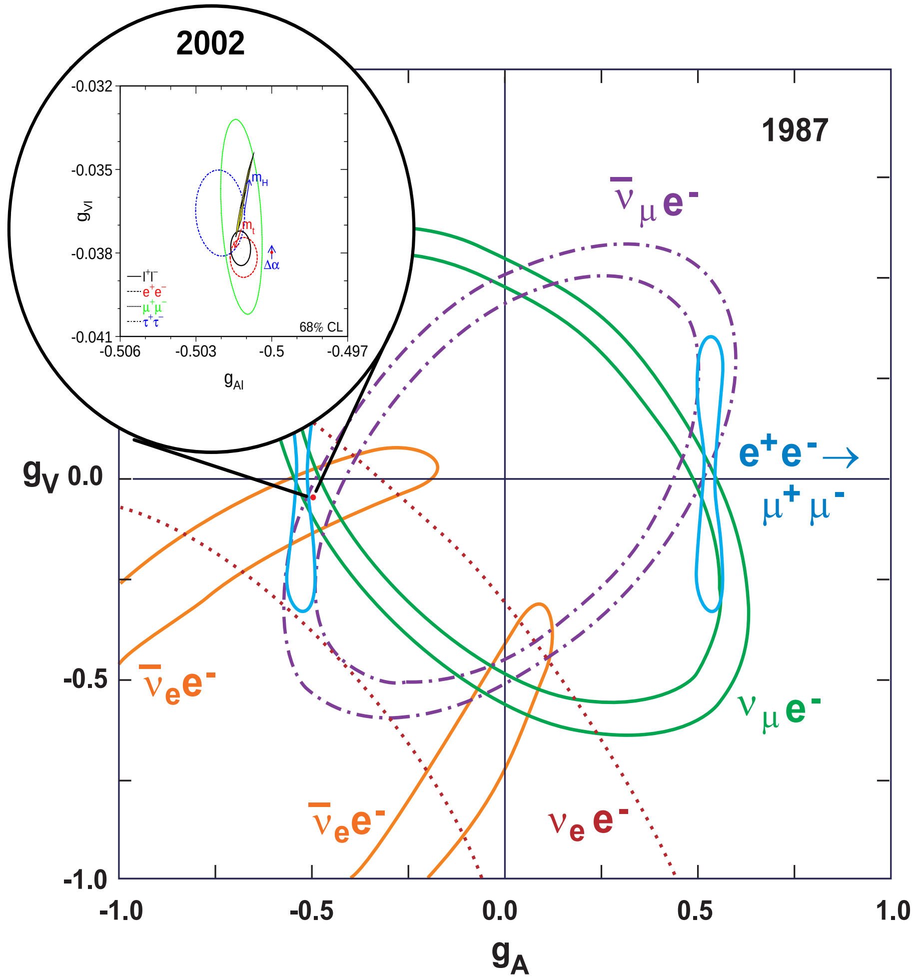
$M_W = 82 \pm 2$ GeV$/c^2$

$M_Z = 92 \pm 2$GeV$/c^2$

UA-1 and UA-2 experiments found W/Z with these masses, thus consistent with $\rho \sim 1$.

(Carlo Rubbia + Van der Meer Nobel Prize) (1984)

Proof of Weinberg Salam Glashow model!



Current eigenstates that couple to the W are two doublets:

$$\begin{pmatrix} u \\ d\cos\theta_c + s\sin\theta_c \end{pmatrix} \qquad \begin{pmatrix} c \\ -d\sin\theta_c + s\cos\theta_c \end{pmatrix}$$

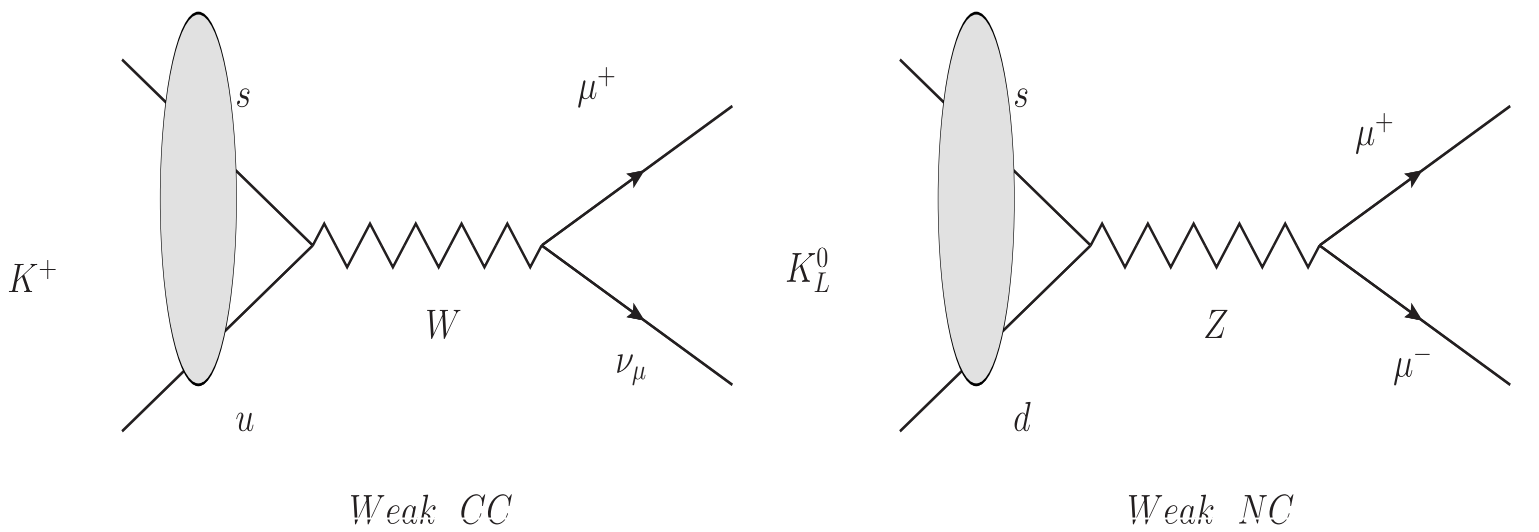
Quark mixing in two generations can then be represented by

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

$$J_\mu^{CC} = \bar{d}'\gamma_\mu(1-\gamma_5)u + \bar{s}'\gamma_\mu(1-\gamma_5)c$$

(recall the $f\bar{f}'W$ vertices we saw yesterday)

Charm is postulated. This does the trick of making Flavor Changing Neutral Current vanish at least by making sure that a vertex $d\bar{s}Z$ does not exist. Can more complicated diagrams produce FCNC?



K^+, $\bar{s}u$ bound state. $K^+ \to \mu^+\nu_\mu$: weak charged current decay, $\Delta S = 1$

K^0 is a $\bar{s}d$ bound state. If a weak neutral current with $\Delta S \neq 0$ (Flavor Changing Neutral Current: FCNC) were to exist with the same strength as the weak charged current it would cause problems.

$K^0_L \to \mu^+\mu^-$ happens very rarely (one part in 10^8 among all K_L decays)

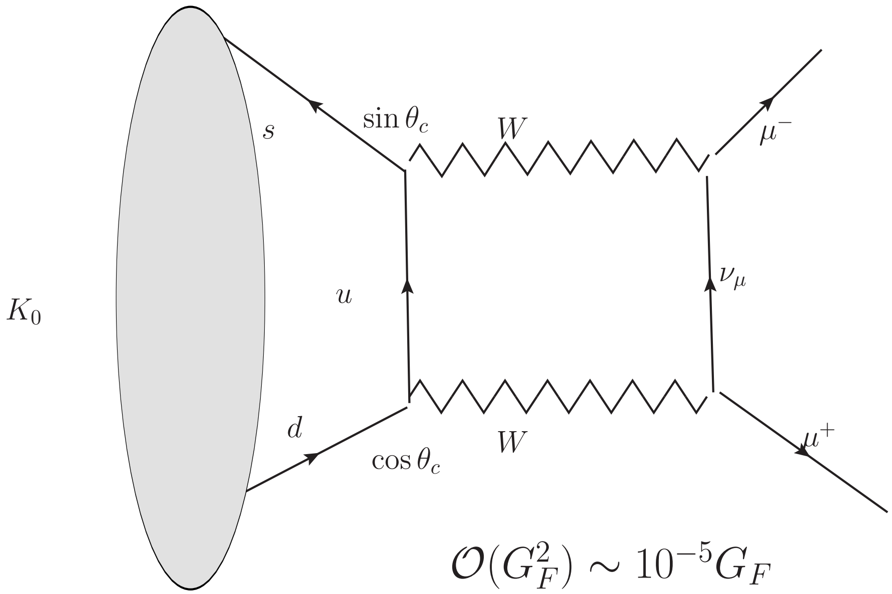
Once we have two quark doublets, tree level FCNC vanishes automatically.☺

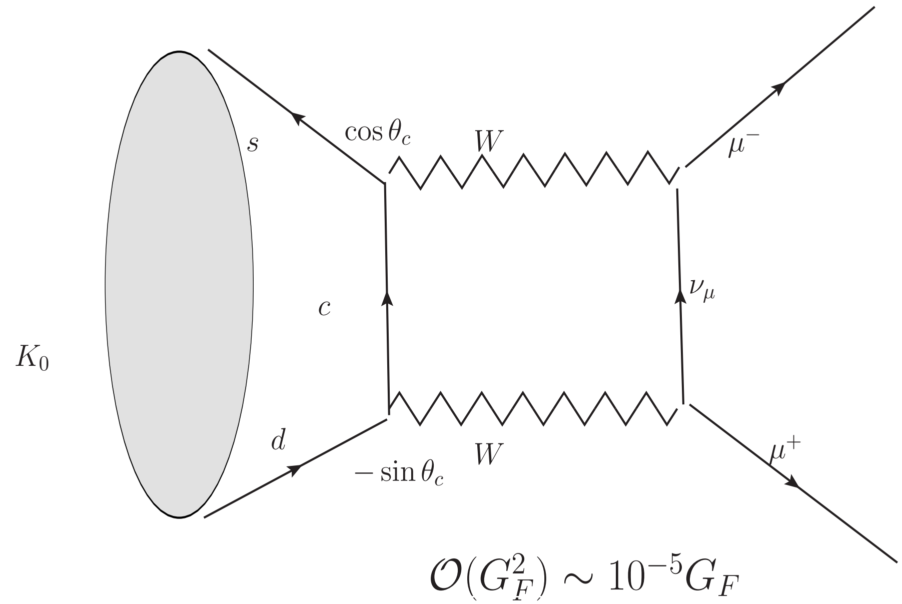
Is Rabi's question answered? We somehow show that we need a new quark. Can we say FCNC ordered a new quark?

Still no answer to Rabi's question 'who ordered the μ

But what this tells is that the left handed fermions have to appear as doublets.

Second point : Quantum properties of the $SU(2)_L \times U(1)$ gauge theory imply that the number of generations should be equal for quarks and leptons.





What happens with loops?

If charm contribution is absent the prediction for this flavour changing decay will be much too big compared to data.

Absence of Flavour Changing Neutral Currents is granted in the EW theory ONLY IF CHARM exists. Will be exactly zero if $m_c = m_u$.

For any physics beyond SM this is always a constraint that HAS to be satisfied.

This cancellation is an example of the Glashow-Iliopoulos-Maiani (GIM) cancellation mechanism.

A very simplistic presentation given here.

Neutral meson oscillations:

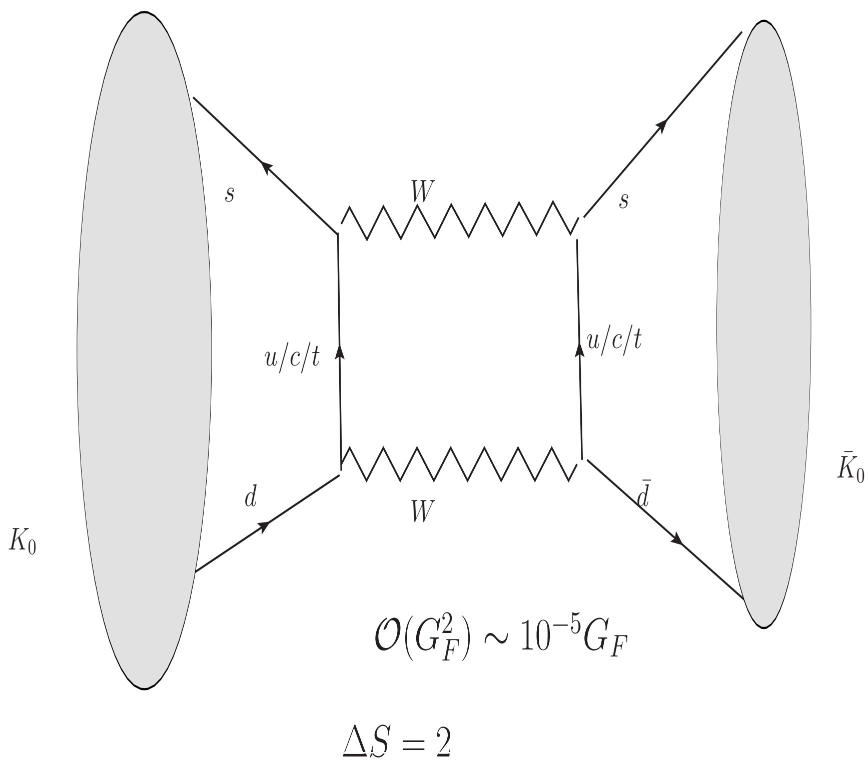
Weak interactions cause mixing between K_0 and $\bar{K}_0$ Two states with $S = \pm 1$. Strong interaction eigenstates, the weak interactions are a perturbation, cause these to mix.

$\Delta S = 2$ effect, higher order in Weak Interactions.

Mass difference measured experimentally through oscillations:

$$\Delta M_K = M_{K_L} - M_{K_S} = 7 \times 10^{-15} \times M_K \sim 3.5 \times 10^{-12} MeV$$

Can be computed in EW theory. Can be CP violating, but ONLY if we have three generations (Kobayashi-Masakawa)



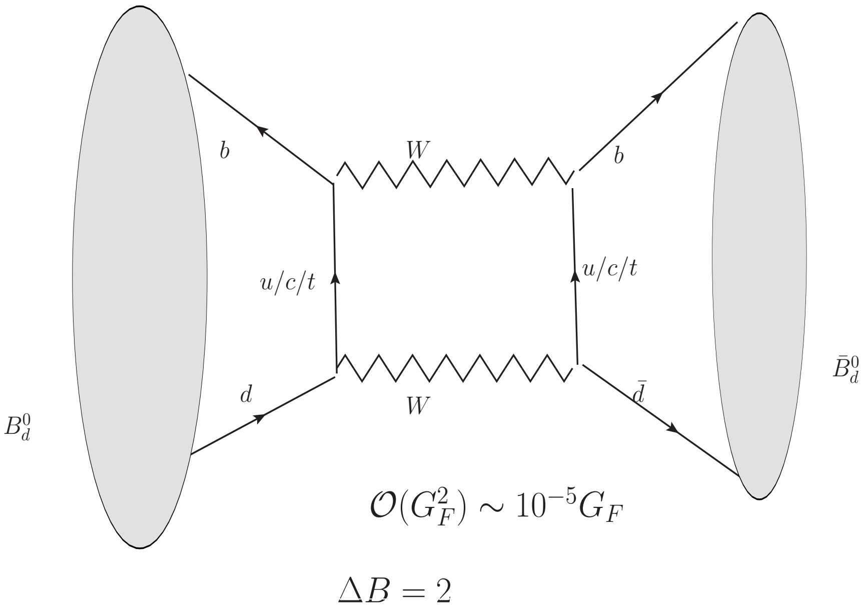
In this diagram I have included now the top too!

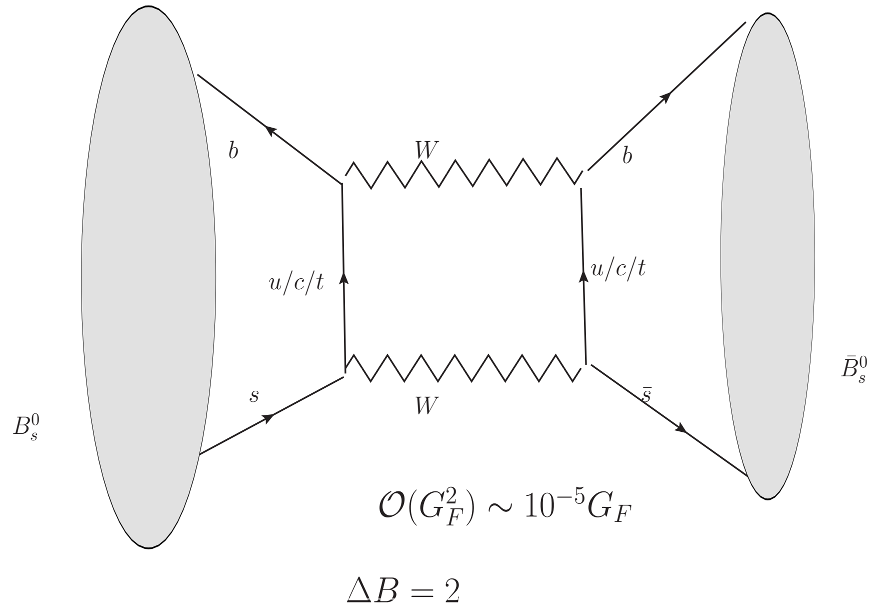
In a four quark picture the result of the calculation is:

$$\frac{\Delta M_K}{M_K} = \frac{G_F^2}{4\pi} m_c^2 \cos^2\theta_c \sin^2\theta_c f_K^2$$

f_K Kaon decay constant measured experimentally.

Gaillard and Lee (Phys. Rev 10, 1974, 897) used the experimentally measured value of this mass difference to calculate m_c before Charmonium ($c\bar{c}$) bound state was found in 1974.





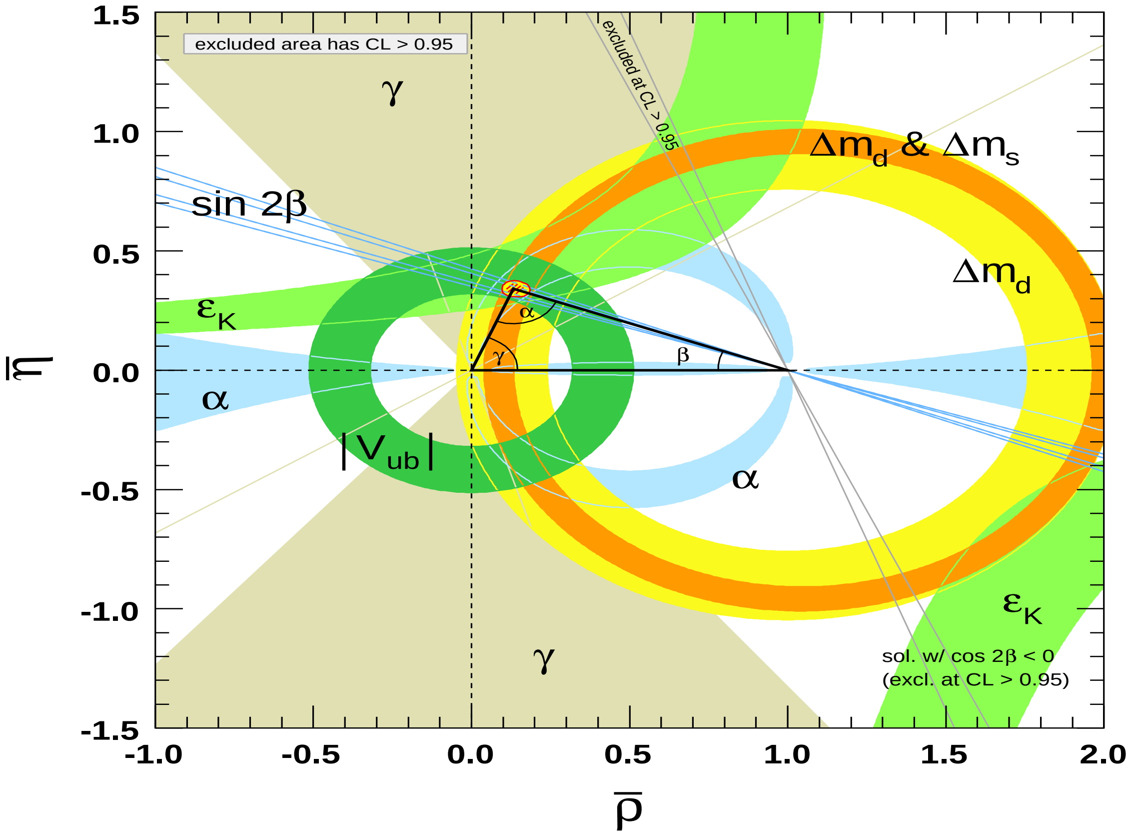
Heavier mesons B_0 and $\bar{B}_0$ mix too! Mixing is dominated by the top quark and was measured by ARGUS at DESY in Hamburg at an e^+e^- collider. Phys.Lett. B192 (1987) 24, CDF for B^0_S system Phys.Rev.Lett. 97 (2006) 242003

On theoretical grounds expected B–$\bar{B}$ mixing is large, because the quark which can contribute most is heavy!

In 1987 this observation was taken as an indirect proof of the existence of the top quark before its actual discovery and gave some information on the mass. (just like for m_c earlier)

The measurements of meson mixing and CP violation in this system, gives constraints on elements of mixing among quark states (CKM)

CKM matrix is the 3×3 version of the mixing matrix we wrote before. This matrix should be unitary. Testing the unitarity is an achievement of the last decade.



Current status of measurement of the CKM matrix.

Constituents we covered here are W, Z and c. τ was discovered accidentally, then was b. But then t and ν_τ were hunted for! Last lecture will cover t and Higgs.