

How the Standard Model was built

Historical Aspects

J.O.Eeg. , Phys. Dept., Univ. Oslo

February 4, 2025

How I experienced it 1967-2012

Important years:

1949-1954 ..1956-1964...1967...1974...2012

Updated version after seminar 29/1-2025

Important events

- 1949 Feynman's version of QED. Feynman diagrams !
- 1954 Yang Mills theory was published
- 1956 Parity (P) was found to be broken. But CP -sym good ?
- 1956: Neutrinos detected
- 1961-1962: Ne'eman and Gell-Mann introduced $SU(3)$ -symmetry, ("8-fold way") for baryons and mesons.
- 1964: Higgs mechanism for mass of gauge bosons published
- 1964 Combined Charge-Parity (CP) -symmetry : Broken!
———1967
- 1969 SLAC experiments to look for "partons" (quarks?)
- The 1974 revolution: Charm quark found and Quarks (finally) accepted....
- 1977 b-quark found....top-quark expected "around the corner" ??
- In 1984 almost announced (!) at 45GeV...but "disappeared"
- 1983 W and Z finally found
- 1995 Finally the top-quark found
- 2012 Finally the Higgs boson found

The books I read to learn

- (Standard books of Bjorken and Drell. Mc Graw Hill)
- David Lurie: “Particles and Fields” (1967)
Publisher: Interscience publ.
Content: QED, some properties of strong and weak interactions
- Stephen Gasiorowicz: “Elementary particles” (1966)
John Wiley and Sons
Content: QED, some properties of strong and weak interactions, some phenomenology
- Later I read:
J. C. Taylor: “Gauge theories of weak interactions” (1976)
Cambridge University Press

Quantum electrodynamics (QED)

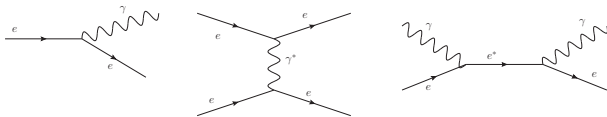


Figure: QED illustrated in terms of Feynman diagrams

- Ca. 1967 QED was the only successful QFT
Verified to many orders in perturbation theory
- Examples: Basic interaction, ee -scattering, γe -scattering
- QED is a *gauge theory*. Not so hard stressed in my youth
- Problem: In QED was “everything” already done !
- I worked on an generalized Dirac eq. for higher spin

Weak interact. : Up to 1956 “ $\theta - \tau$ -puzzle” :

- Apparently one observed the decays $(\theta, \tau) \rightarrow 2\pi$
and $(\theta, \tau) \rightarrow 3\pi$

Because parity was thought to be conserved, it was thought that θ and τ were two different particles with the same mass, one decaying to 2 pions and the other to 3 pions.

- Actually: θ and τ turned out to be the *same particle*, the K -meson (kaon), and π and K are pseudo-scalar particles (spin-parity 0^-).

K -mesons can decay both to two and three pions because parity is a broken symmetry.

- Big shock: (Lee and Yang 1956 : Explained experiments !)

Parity symmetry is broken in weak interaction

- Most known weak process (C-14): β -decay:

$$n \rightarrow p e^- \bar{\nu}_e$$

also breaks parity-symmetry. (C.-S. Wu , 1957)

- For massive fermions and anti-fermions: In total four degrees of freedom. BUT: For massless fermions/anti-fermions: Two degrees of freedom. Are neutrinos massless? (Up to 1998?)
- Choice: Lefthanded particles and righthanded antiparticles, i.e $(\nu_e)_L$ and $(\bar{\nu}_e)_R$.

Conservation of lepton numbers built into the theory !

- Lepton number L_e conserved: $L(e^-) = L(\nu_e) = +1$ for the particles, and -1 for anti-leptons (similar for μ and later for τ)
Then $L_e(e^- \bar{\nu}_e) = 0$

Fermi "theory"

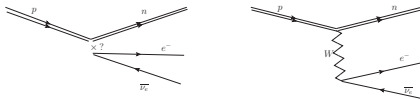


Figure: Fermi-Theory" for beta-decay. Hypothetical extension with W .
Current for $\nu_e \rightarrow e^-$ automatically left-handed for $m_\nu = 0$.

Books: Interaction product of two left-handed currents. Feynman and Gell-Mann 1958: Current for $n \rightarrow p$ is also *left-handed* !

$$\mathcal{L}_F = 4 \frac{G_F}{\sqrt{2}} j_L(N)^\mu j_L(l)_\mu, \quad j_{L\mu} = \frac{1}{2} (j_\mu^V - j_\mu^A)$$

If the two currents were mediated by a heavy weak boson W , then

$$\frac{g_W^2}{q^2 - M_W^2} = -4 \frac{G_F}{\sqrt{2}} \quad ; \quad |q^2| \ll M_W^2, \quad G_F \simeq \frac{10^{-5}}{m_p^2}$$

Then (Gasiorowicz): $M_W > 2 \text{ GeV} !!$ (and $(g_W/M_W) \sim 5 \times 10^{-3}/m_p$)

CP -symmetry believed to be true !

- Simplest decays of pions: $\pi^+ \rightarrow \mu^+ \nu_\mu$ and $\pi^- \rightarrow \mu^- \bar{\nu}_\mu$
- No P or C symmetry because $\nu = (\nu)_L$ and $\bar{\nu} = (\bar{\nu})_R$
- But: $CP [\pi^+ \rightarrow \mu^+ (\nu_\mu)_L] = [\pi^- \rightarrow \mu^- (\bar{\nu}_\mu)_R]$.
- Conclusion :In these processes CP -symmetry (combined C and P) is apparently satisfied ? - Or ?
- If so:

Symmetry between $(matter)_L$ and $(anti - matter)_R$!

- supported by Landau and others
- Second shock 1964 (experiments by Fitch and Cronin):
 CP -symmetry broken in decays of neutral K -mesons

CP-symm. broken in weak decays of neutral K 's

- K^0 and $\overline{K}^0$ are degenerate in mass, - in strong interact. but with different hypercharges. In weak interact, $K^0 \rightarrow 2\pi \rightarrow \overline{K}^0$ is possible, which lift degeneracy (Gell-Mann and Pais 1955)
- CP eigenstates: $|K_{\pm}\rangle \equiv (|K^0\rangle \mp |\overline{K}^0\rangle)/\sqrt{2}$ and $CP|K_{\pm}\rangle = \pm|K_{\pm}\rangle$.
- Physical states $K_S = K_+$ (shortlived) and $K_L = K_-$ (longlived)
Exp. mass difference of these two: 3.5×10^{-12} MeV.
If CP -symmetry were fulfilled, then we should see $K_S \rightarrow 2\pi$ and $K_L \rightarrow 3\pi$. (2 π has CP -sym = + ; while 3 π may have CP -sym = -) But this was not exact:
some 2 to 3 permille of K_L decayed to 2π !
- Explanation. $K_L \simeq K_- + \epsilon K_+$, with $|\epsilon| \simeq 2.6 \times 10^{-3}$.
- Mystery: What was the mechanism for CP -violation ?
(Wolfenstein, Weinberg)

Trying to build a theory for strong interactions

Phenomenological models, Regge poles, $\pi - N$ - interactions

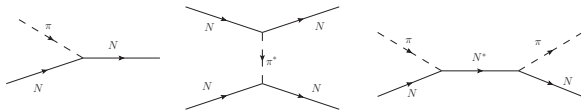


Figure: Some π -Nucleon Feynman diagrams

Interaction Lagrangian for strong interactions? Isospin invariant, described in books! “Mathematically OK”

$$\mathcal{L}_{\pi N} = G_{\pi N} \bar{N} (\tau_i \Phi_i) \gamma_5 N, \quad N = \begin{pmatrix} p \\ n \end{pmatrix}$$

where N is the nucleon doublet, Φ the pion triplet and τ the Pauli matrices which here represents isospin.

$G_{\pi N}$ too big to make perturbative theory(expansion) valid!

Yang-Mills *gauge theory* : C.N. Yang and R.Mills, 1954 ! : Inspired by QED with conserved charge. Now: Isospin conserved.

$$\mathcal{L}_{YM} = \bar{N} \gamma^\mu (iD_\mu - m_N) N - \frac{1}{2} \text{Tr}(F^{\mu\nu} F_{\mu\nu})$$

$$iD_\mu \equiv i\partial_\mu - g B_\mu ; B_\mu = t^a B_\mu^a ; [iD_\mu, iD_\nu] = -igF_{\mu\nu}$$

The unknown (*massless*) gauge fields B_μ are self-interacting:

$$F_{\mu\nu}^a = (\partial_\mu B_\nu^a - \partial_\nu B_\mu^a) + gf^{abc} B_\nu^b B_\mu^c$$

- Could $B = \rho$?? -Massive ρ discovered in 1961
- YM-theory mentioned by Lurie and Gasiorowicz. But “ YM put on ice” At that time unsuccessful (in physics)
- Strong int: Analytical S-matrix in complex plane, Phenomenological models, for inst. Chiral perturbation theory.

Ne'eman 1961, Gell-Mann 1962 :

“The eightfold way”

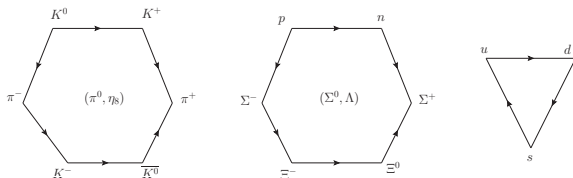


Figure: Pseudoscalars (0^-) and baryons ($\frac{1}{2}^-$) put in *octet* (8-plet) representation of $SU(3)$. including strange particles

- Pseudoscalars: $\pi^+ = (u\bar{d})$, $K^+ = (u\bar{s})$, etc
- Baryons : $p = (uud)$, $\Lambda = (uds)$, $\Xi^- = (dss)$, etc
- Making order 1 hadronic particles. BUT elementary triplet (3-plet) representation (“quarks”) *apparently* not realized ??

$SU(3)_F$ Spin 3/2 Decuplett

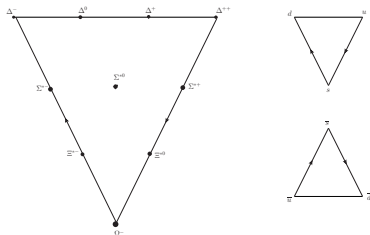


Figure: Decuplett containing $\Omega^- (sss)$ not observed from beginning

Ω^- found in 1964, “proven by group theory”

$$\mathbf{3} \times \mathbf{3} = \mathbf{6} + \mathbf{\bar{3}} ; \mathbf{6} \times \mathbf{3} = \mathbf{10} + \mathbf{8} ; \mathbf{\bar{3}} \times \mathbf{3} = \mathbf{8} + \mathbf{1} \quad (1)$$

Question: Are quarks real?

BUT: Three quarks with spin component in same direction would break the Pauli principle,- so what to do ?

What did my books tell me in 1967 ?

- In Lurie: $SU(3)$ (flavor-) symmetry was mentioned, but not quarks explicitly
- In Gasiorowicz about quarks: If such quark particles existed, at least one of them would have to be stable, because baryon conservation would forbid the decay into “ordinary” particles. A search for new particles of this type has so far proved unsuccessful, In view of this failure and the difficulty of inventing a mechanism which would bind a quark and an antiquark, or three quarks, but not two quarks , for example, we will not discuss the quark model further.
- Gasiorowicz: If the (hypothetical) W -boson exists its mass must be bigger than 2 GeV (-which was still a heavy particle in the 1960's)

Do quarks exist ???

- In 1967 we knew two charged leptons e^- and μ^- and their neutral partners, the neutrinos ν_e and ν_μ . We knew that the known baryons and mesons could be explained by three entities called “quark’s” types (“flavors”) u , d and s .
- Were quarks real or just a practical auxiliary concept? Some people liked the idea about quarks as real particles (Zweig....), some did definitely not. There was a joke: Those who believed in quarks were like a bunch of frogs sitting around a pond saying “quark, quark, quark”
- Noted: Pauli principle satisfied with existence of new quantum number (3 values) called “Color”. (Gell-Mann and Fritzsche 1971) NB! Then three quarks (and quark-antiquark) could make color singlets!

An elektron-proton collision

“Parton Model”. Is the proton *composite* ?. Could one shoot it to pieces?

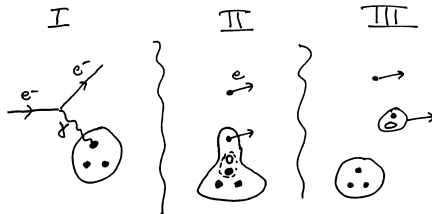


Figure: Elektron-proton collision at high energy at Stanford Linear Accelerator Center (SLAC), California, in 1969 $e p \rightarrow e N \pi$

What is seen: The elektron cannot shoot loose a quark, but some times a *meson* ($q - \bar{q}$ -pair). Dogma(?)/Explanation: A quark cannot be free! The “color”-charge is confined ! (bound to a baryon or a meson.)

Quantum Chromodynamics QCD (YM theory), Gell-Mann and Fritzsche 1972. With quarks as color triplets an octet of gluons

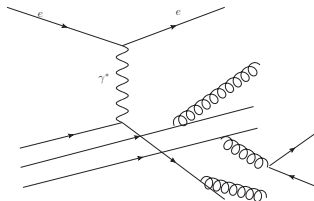


Figure: Collision $ep \rightarrow eX$ with quarks and gluons

The cross section contains the structure functions $f_p(x)$, and depend only on the momentum fraction of the scattered parton, - called *Scaling* $x \equiv p_{part}/p_{proton} = (-q^2)/(2M_p\nu)$, where $\nu = E_e - E'_e$.
Interpretation of data: At high energies, the proton consists of “sea-quarks” = *quarks* and *anti-quarks* and *gluons* in addition to the *valence quarks* (uud).

The 1974-revolution

- Even after the SLAC experiments there was resistance: “OK,- The parton model gives scaling. But there are also other models giving scaling”
- Then came *the 1974- revolution...* The Ψ -particles. They had a decay spectrum similar to positronium- they were a particle-antiparticle system- with masses 3 to 4 GeV/ c^2 .
- Now the resistance against quarks collapsed.... (!?). The “charm”-quark c was found
- These experiments were extremely important. I think it is fair to say that they indicated the way to go- both in *weak* interactions ($SU(2)$ -doublets) and in *strong interactions*- with the existence of quarks -as color triplets, -and *QCD of YM-type*.

Weinberg 1967, inspired by QED and Yang-Mills theory
 “A model of leptons” -ONLY- (Similar ideas by Glashow and Salam
 $\Rightarrow$ Nobel price in 1979).

$SU(2)_L \times U(1)_Y$ gauge theory for first lepton doublet

$\chi_L \equiv \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$ and e_R , Four gauge bosons $W_\mu^i, i = 1, 2, 3$ with coupling g , and B_μ with coupling g' (the Y 's are weak hypercharges):

$$\begin{aligned} \mathcal{L}_{EW11} = & \overline{\chi_L} \gamma^\mu \left(i\partial_\mu - g \frac{1}{2} \tau^i W_\mu^i - \frac{1}{2} g' Y_L B_\mu \right) \chi_L \\ & + \overline{e_R} \gamma^\mu \left(i\partial_\mu - \frac{1}{2} g' Y_R B_\mu \right) e_R - \frac{1}{4} W^{i,\mu\nu} W_{\mu\nu}^i - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} \\ & + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa} \end{aligned}$$

- Assuming the existence of $W^\pm, Z, \gamma$!- and Higgs-field (1964)
- All particles are apriori massless- to have *gauge invariance* !
- Masses from $\mathcal{L}_{Higgs}$ and $\mathcal{L}_{Yukawa}$

Adding the Higgs sector

$$\mathcal{L}_{Higgs} = \left(iD_{\alpha}^{(\phi)} \phi \right)^{\dagger} \left(iD_{(\phi)}^{\alpha} \phi \right) - V(\phi)$$

$$V(\phi) \equiv \mu^2 \left(\phi^{\dagger} \phi \right) + \lambda \left(\phi^{\dagger} \phi \right)^2$$

$$iD_{\alpha}^{(\phi)} = i\partial_{\mu} - g \frac{1}{2} \tau^i W_{\mu}^i - \frac{1}{2} g' Y_{\phi} B_{\mu}$$

$$\mathcal{L}_{Yukawa} = -G_e \left(\overline{\chi}_L \phi e_R + \overline{e}_R \phi^{\dagger} \chi_L \right) + \dots$$

For $\mu^2 < 0$ the potential $V(\phi)$ has a minimum for nonzero value of ϕ ,
 i.e. $\langle 0|\phi|0 \rangle \sim v \neq 0$ Giving the *Spontaneous symmetry breaking*
 (SSB)

$$\phi = \begin{pmatrix} \phi_+ \\ \phi_0 \end{pmatrix} ; \text{ Physical gauge: } \Rightarrow \phi' = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix}$$

Masses $\sim gv$ for 3 linear comb of B_{α} and W_{α}^j . $m_e \sim G_e v$, $m_{\nu} = 0$.

Photon A_μ and Z-boson field Z_μ from rotation θ_W in (B, W^3) plane:

$$A_\mu = c_W B_\mu + s_W (W_\mu^3) ; Z_\mu = -s_W B_\mu + c_W (W_\mu^3)$$

$s_W \equiv \sin\theta_W$ and $c_W \equiv \cos\theta_W$, and θ_W = weak mixing angle.

- To obtain the correct electromagnetic current. Force on Lagr. some *requirements* ! (-mathematically Y is arbitrary)

$$Q = I_3^W + \frac{1}{2}Y \quad (2)$$

analogous to $SU(3)_F$. For lepton doublet(s)

$$Y_L = -1, Y_R = -2, \tan\theta_W = \frac{g'}{g}$$

The couplings for the physical bosons $\gamma, Z, W^\pm$ will be

$$e \equiv g_\gamma = g \sin\theta_W, g_Z = \frac{g}{\cos\theta_W}, g_W = \frac{g}{\sqrt{2}},$$

Partial Unification: Three couplings has become two !

From processes involving the Z-boson : $\sin^2\theta_W \simeq 0.23$.

From knowing α_{em} and G_F , find $v \simeq 246$ GeV.

$$M_W = \frac{1}{2} g v = \frac{37 \text{ GeV}}{\sin\theta_W}, \Rightarrow \frac{M_Z}{M_W} = \frac{1}{\cos\theta_W}$$

This relation must hold experimentally!!! (-up to higher correct.)

Gauge inv. $\Rightarrow$ relations between couplings, masses

Worry: Was the Higgs-mech a “dirty trick” An Effective theory only ?

- (Speculation: “Technicolor”)
- Same for μ^- , ν_μ BUT: Before 1974 ONLY for 2 lepton doublets !
Only 3 known types of quarks ! ?
- Problem in 1967-1974: How to include the *three* quarks u, d, s ?
Alternative $O(3)$ Georgi-Glashow 1972: Lepton triplet with
Heavy lepton ? -and *no* Z-boson.

Decaying Cabibbo-rotated d -quark in Beta-decay

- Discovered (before quarks accepted) beta decay of strange particles, for inst. : $\Lambda \rightarrow p e^- \bar{\nu}_e$ and $\Sigma^- \rightarrow n e^- \bar{\nu}_e$ which was explained in 1963 by the italian physicist Nicola Cabibbo. Later, at quark level, it could be explained as a rotation in (d, s) plane:
- The decaying quark is the Cabibbo-rotated d -quark:
 $d \rightarrow d_\theta = d \cos\theta + s \sin\theta$, where $\theta = \theta_C$, the Cabibbo angle.
- (Similar decays of Ξ particles) Ratio of Σ^- and n beta decay amplitudes = $\tan\theta_C$. Exper.: $\sin\theta_C \simeq 0.225$ NB! $\theta_C \neq \theta_W$
- Orthogonal to d_θ : $s \rightarrow s_\theta = s \cos\theta - d \sin\theta$. Where to put that?

The GIM- mechanism

- In 1970 Glashow, Iliopoulos and Maiani postulated a fourth quark c ($=charm$) to solve problems in K -decays. Two doublets
 $\begin{pmatrix} u \\ d_\theta \end{pmatrix}$, $\begin{pmatrix} c \\ s_\theta \end{pmatrix}$ (Without c -quark $\rightarrow s\bar{d}$ Z -coupling)
- $K^+ \rightarrow \mu^+ \nu_\mu$ is the most common decay of K^+ - (Sim. for K^-).
 Why is decays of K^0 almost absent (10^{-7})

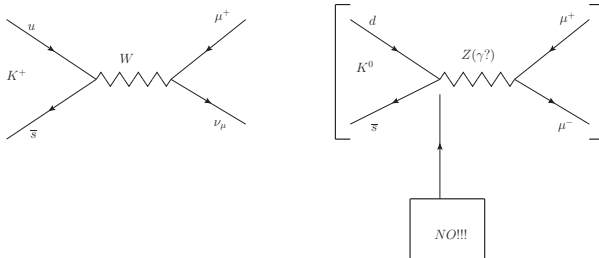


Figure: Decay of charged $K^\pm$. What about neutral K^0 ?

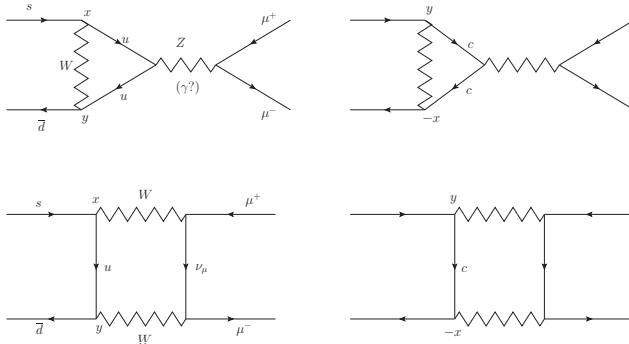


Figure: K^0 decay = 0 if $m_c = m_u$. Here $x = \cos\theta_C$ and $y = \sin\theta_C$

- Decays of K -mesons has played an important role in understanding of weak interactions
- Now two full quark doublets: $\begin{pmatrix} u \\ d_\theta \end{pmatrix}_L$, $\begin{pmatrix} c \\ s_\theta \end{pmatrix}_L$ and four quark singlets $u_R, (d_\theta)_R, (s_\theta)_R, c_R$ solve the problem!

Six quark types imply CP-violation

- In 1977 the fifth quark - named b was discovered, and also the τ -lepton.
- Expected(?): Discovery of the sixth quark t *soon*. Then we would have three full quark doublets including $\begin{pmatrix} t \\ b \end{pmatrix}_L$
- Some people insisted in the names *truth* and *beauty*, but it became *top* and *bottom*
- Already in 1973 Kabayashi and Maskawa had found that with three quark doublets there will be three rotations - and NB! : *one complex phase factor* - *CKM*-matrix -implying *CP-violation* !
- We had a mechanism for CP-violation !!!
- BUT found later: Not enough CP-violation in *CKM* to explain assymetry between matter and anti-matter in the universe!

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L, \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

$$\begin{pmatrix} u \\ d_{CKM} \end{pmatrix}_L, \begin{pmatrix} c \\ s_{CKM} \end{pmatrix}_L, \begin{pmatrix} t \\ b_{CKM} \end{pmatrix}_L$$

-plus right-handed singlets for quarks and charged leptonss

$$d_{CKM} = V_{ud} d + V_{us} s + V_{ub} b$$

$$s_{CKM} = V_{cd} d + V_{cs} s + V_{cb} b$$

$$b_{CKM} = V_{td} d + V_{ts} s + V_{tb} b$$

where (d, s, b) are the physical quarks (with definite mass).

- In 1977 : SM theory established(?) BUT: The top quark, W, Z and the Higgs-boson not found experimentally! Assuming $SU(2)_L \times U(1)_Y$, the W and Z masses pinned down. Top and Higgs masses completely unknown ! And quark mixings V_{ij} relatively unknown.(-measured via decays of K, D -and B .)

The long way to verify the SM

- The seminar 29/1-2025 stopped here.
- It turns out that in 1977 we had identified all the particles in the SM- and had the correct Lagrangian.- But even if we had “everything” (except for the neutrino masses) -we did not know if it was-or was not- more...more Higgses, a new fourth generation of fermions, extremely heavy new neutral Z-bosons, New heavy leptons, technicolor, supersymmetry(SUSY), Grand Unified Theories (GUTs).... We had to do calculations within the SM, to see if it was complete.
- I worked on K -decays (see next slides) with I. Picek (and Kr. Kumericki) in Zagreb, with S. Bertolini and M. Fabbrichesi in Trieste, with decays of heavier (B -)mesons with S.Fajfer in Ljubljana.
I should also mention other working groups including for instance: J.Bijnens, A.Buras, G.Ecker, L.Oliver, A.Pich....

Theoretical Laboratory : K -decays

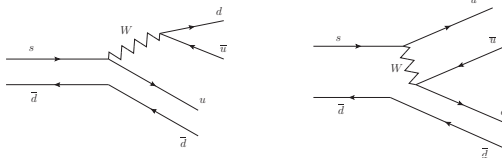


Figure: Quark diagrams for $K \rightarrow 2\pi$. (Strong int. not shown. Quark lines “bathing” in gluon field.) Use: Basic Non-leptonic interaction below.

Decays of kaons (K -mesons) have played an important role in understanding of the SM. (J.O.E. with I. Picek, Zagreb)

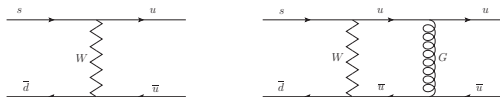


Figure: Basic non-leptonic interaction- and perturbative QCD correction. No CP -violation so far. (Need also the “Penguin diagram”. See later)

CP-violation

within the SM needs the top-quark in play.

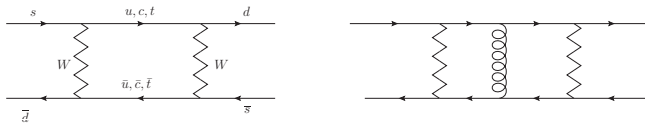


Figure: Basic quark diagram for $\bar{K}^0 \rightarrow K^0$ determining mass difference $(M_L - M_S)$ and the (“indirect”) CP -violating parameter ϵ . Gluon correction also shown. (Similar diagrams also for neutral B -mesons)

Found from diagrams that $m_c < 2 \text{ GeV}$ (GIM 1970). CP -violating part depending on m_t . ($m_t = 10, 20, 45 \text{ GeV}, \rightarrow \dots 174 \text{ GeV}$). Decays of K -mesons have played an important role in understanding of the SM. Non-diagonal elements of V_{CKM} are complex! $\Rightarrow CP$ -violation! To be used in “Box-diagrams” above!

CP-violation in the “Penguin-diagram”

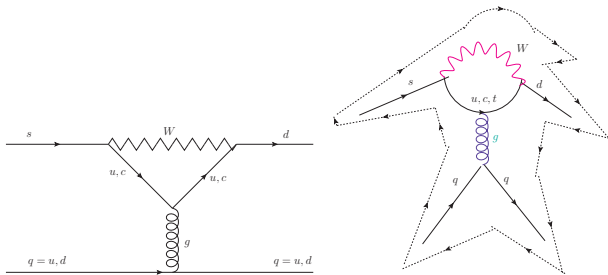


Figure: Penguin-diagram. ITEP group (SVZ, M.Shifman et al. Moscow) 1975. Later given the fancy name by J. Ellis. Left: The original version. Right: Drawing of penguin convoluting a penguin diagram. Also with t -quark in loop. To be included in Basic non-lept int. shown before. (-Also include gluon(g) $\rightarrow \gamma, Z$)

$V_{CKM}^\dagger V_{CKM} = 1 \Rightarrow GIM\text{-cancellation, for Amp}(sq \rightarrow dq)$ (Here $q = u, d$ at lower line):

$$\text{Amp} = [F(m_c) - F(m_u)] (V_{cd})^\dagger V_{cs} + [F(m_t) - F(m_u)] (V_{td})^\dagger V_{ts}$$

“Double-penguin-diagram” for $\overline{K^0} \rightarrow K^0$

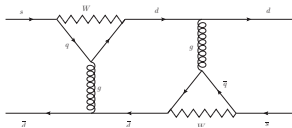


Figure: Double-penguin-diagram for $(M_L - M_S)$ and the CP -violating parameter ϵ . Here $q = u, c, t$ are running in the two penguin loops. Included together with Box-loops shown before

Calculating these in ca. 1985 the top quark value was not known (rumors: $m_t = 45$ GeV). Rough estimate in lit. $\sim (m_t)^2$ (false !).

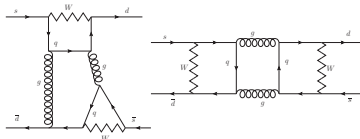


Figure: Sim. diagrams for $\overline{K^0} \rightarrow K^0$. In total 36 such diagrams. Reduction of ϵ an amount $\sim -25\%$ for $m_t \sim 45$ GeV (JOE with I.Picek)

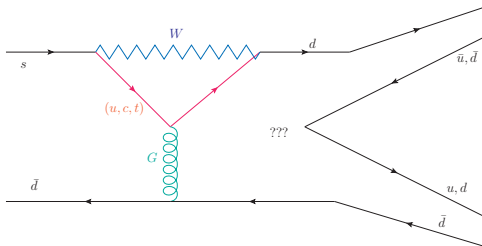


Figure: Example: “Penguin diagram”. Perturbative weak and strong interactions in play. AND *Non-perturbative QCD*- at “???” in fig.

Diagram for $K_L \rightarrow \pi^+ \pi^-$ - or $2\pi^0$. CP -violation (“direct”) is different for charged and neutral pions. The ϵ' -effect !! (Exp. 1998: $\epsilon'/\epsilon \sim 1.7 \times 10^{-3}$) The non-perturbative QCD part difficult... Some claimed “New Physics?” Attacked by many groups (1990’s including Bertolini, Fabbrichesi, JOE). Should be calculated by *Lattice gauge theory* (Finally ca. 2017). Confirming exp. result from 1998.

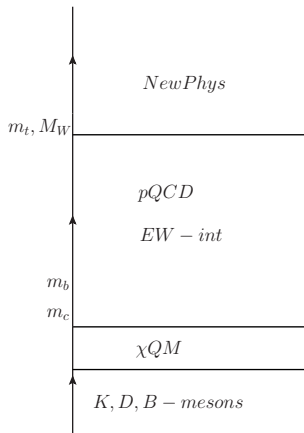


Figure: Energy scales. At bottom : Hadron scales below ca. 1 GeV

From K -decays (Picek, Trieste group) to B -decays (with S. Fajfer)
 Always hard part: Non-perturbative QCD. Used Chiral quark models (χQM), Chiral perturbation th. (Finally $\rightarrow$ Lattice gauge th.)

J.O.E. with I.Picek(1984) and S. Fajfer(2014), calculated *Electric dipole moments*, very small *CP*-violating quantity sensitive to various models with “New physics”.

Speculations ...”New Physics” ?..

- The SM is now robust, but there has been speculations
- Technicolor (alternative to Higgs mech?)
- Origin of neutrino masses (Majorana particles?)
- Left-right sym. $SU(2)_L \times SU(2)_R$ (restore parity at high energies?)
- GUTs : $SU(5)$, $SO(10)$, E_6 ,...
- SUSY,..Strings,....