Broken Symmetries – Nobel Prize in Physics 2008

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① Nobel Prize in Physics 2008 as announced

② Symmetries in fundamental physics laws

③ Spontaneously broken symmetries and Nambu-Goldstone bosons

④ CP violation from 3 family mixing

⑤ All basic ingredients of the Standard Model confirmed, except Higgs!

⑥ Outlook

The Nobel Prize in Physics 2008

"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

Photo: SCANPIX

Yoichiro Nambu

1/2 of the prize

USA

Enrico Fermi Institute, University of Chicago Chicago, IL, USA

b. 1921

Photo: Universtity of Chicago

Makoto Kobayashi

1/4 of the prize

Japan

High Energy Accelerator Research Organization (KEK) Tsukuba, Japan

b. 1944

Photo: Kyoto University

Toshihide Maskawa

1/4 of the prize

Japan

Kyoto Sangyo University; Yukawa Institute for Theoretical Physics (YITP), Kyoto University

Kyoto, Japan

b. 1940

② Symmetries in fundamental physics laws

Symmetry = invariance under change of frames

$\Updownarrow$

Lie Groups of transformations

Key insight about symmetries by E. Noether 1918: **Noether theorem**

Symmetry transformations generated by generators = generalized charges, which are space - integrals

$$Q_i = \int \mathrm{d}^3x \, j_i^0(t, \vec{x})$$

of the j_i^0 component of conserved currents

$$j_i^\mu(x) = (\rho_i(t,\vec{x}), \vec{j}_i(t,\vec{x}))$$

satisfying the continuity equation

$$\partial_\mu j_i^\mu(x) = 0 \quad \Leftrightarrow \quad \frac{\mathrm{d}Q_i}{\mathrm{d}t} = 0$$

In QFT prototype current: flavor diagonal electromagnetic current

$$j^\mu(x) = \bar{\psi}(x)\,\gamma^\mu \psi(x)$$

with $\psi(x)$ a charge 1 Dirac field [γ^μ=Dirac matrices]; by the Dirac equation

$$\partial_\mu j^\mu(x) = 0 \quad \text{conserved}$$

In weak processes flavor off–diagonal current play a role: because of parity violation vector– and axialvector–currents: (fields of different mass and charges)

$$V^\mu_{12} = \bar{\psi}_1(x)\,\gamma^\mu \psi_2(x)\;;\quad A^\mu_{12} = \bar{\psi}_1(x)\,\gamma^\mu \gamma_5 \psi_2(x)\,.$$

In this cases the Dirac equation yields

$$\partial_\mu V^\mu_{12}(x) = \mathrm{i}\,(m_1 - m_2)\,\bar{\psi}\psi(x)\;;\quad \partial_\mu A^\mu_{12}(x) = \mathrm{i}\,(m_1 + m_2)\,\bar{\psi}\gamma_5\psi(x)\,.$$

These are the basic relations needed to understand chiral symmetry the basis of Nambu's work.

- V^μ_{12} is conserved $\Leftrightarrow$ $m_1 = m_2$
- A^μ_{12} is conserved $\Leftrightarrow$ $m_1 = m_2 = 0$ what is called the chiral limit

❑ Space-time symmetries = symmetries of the dynamics

Quantum Mechanics

Galilei invariance, unitary symmetry, Hilbert space
Schrödinger [NP 1933] equation
Heisenberg uncertainty relation[NP 1932]
Pauli [NP 1933] equation ($SU(2)$-spin), exclusion principle

Quantum Field Theory

Newton Mechanics

rotations, space-translations
Galilei invariance

Special Relativity

Maxwell Electromagnetism

+ Lorentz [NP 1902] boosts
+ time-translations
Lorentz/Poincaré invariance

Einstein 1905 [NP 1921]
relativistic kinematics
$\mathcal{P}_+^\uparrow$ invariance

Dirac 1928 [NP 1933]
$SL(2,C)$ invariance
Wigner states
etc. (see next)
$\left[SL(2,C)' \sim \mathcal{P}_+^{\uparrow\,\prime} \right]$

❑ Quantum Field Theory: som general properties

- **Particle-antiparticle crossing symmetry:**

ANTIMATTER predicted 1928 by Dirac [NP 1933]

to each particle an antiparticle must exist charge conjugation C new symmetry !

electron $\longrightarrow$ positron [discovered 1932 by C. Anderson [NP 1936]]

- **Spin-statistics theorem:** (Fierz 1939, Pauli 1940)

fermions $=\frac{1}{2}$ odd integer, bosons=integer spin (consequence of Einstein causality)

- **CPT theorem:** (Schwinger 1951, Lüders, Pauli, Bell 1954)

product of C, P and T in any order universal symmetry of any local relativistic QFT

1948: Tomonaga, Schwinger and Feynman [NP 1965] QED renormalizable QFT

to all orders in perturbation theory mathematically well-defined

charge and mass as only free parameters [the ones in the Lagrangian],

very predictive [Lambshift, $g-2$, etc.] 20 years after Dirac!

❑ Discrete space-time symmetries

P parity=space-reflections Wigner 1927 QED is P invariant,

explains Laporta rule for transitions in atomic spectra

Note: Dirac field = P doubled pair of Weyl fields

T time-reflections Wigner 1932 QED is T invariant

Note, in classical physics: macroscopic systems do not behave time-reversal invariant

- Thermodynamics: 2nd law $dS > 0$ (time irreversibility !)
  (e.g. a piece of sugar dissolves in hot tee)
- Electrodynamics: retardation of waves
  (e.g. a radio signal is received after having been emitted)
- Cosmology: universal expansion of the universe (vastly out of equilibrium!)

For along time it was believed: microphysics is T, P and C invariant (prototype QED)

❑ Global internal symmetries

Discovery of the neutron by J. Chadwick 1932 [NP 1935]

- Heisenberg 1932: proton-neutron ($M_p \simeq M_n$) as a $SU(2)$–duplet $\Rightarrow$ isospin I
- Wigner 1934: strong interactions binds protons and neutrons in atomic nuclei,
  weak interactions are responsible for radioactive decays like β–decay
- Fermi 1934: weak current–current interaction model $\mathcal{L}^{\mathrm{Fermi}} = \frac{G_F}{\sqrt{2}} J_{\mathrm{V}}^{+}(x)\, J_{\mathrm{V}}^{-}(x)$,
- Gell-Mann, Feynman and others 1957 true J_{weak}=V-A strict [after discovery of P̸],
- Gell-Mann, Nishijima 1962 introduce strangeness S to classify Kaons and Hyperons

[$K^0 [K_S \to \pi^+ \pi^-]$ ("V" tracks) Rochester & Butler 1946 , Λ 1947 in cosmic rays]

(strange particles), Hypercharge $Y = B + S$, $Q = I_3 + \frac{Y}{2}$

- Cabibbo 1962 Unitary Symmetry, Cabibbo mixing, Cabibbo universality

[one G_F up to mixing], $G_F = G_\mu$, $G_{\pi,n} = G_F \cos\theta_c$, $G_{K,\Lambda} = G_F \sin\theta_c$,

$F_K / F_\pi = 1$ in $SU(3)$ limit etc.

- Gell-Mann, Zweig 1964 $SU(2)$ extension to $SU(3)$: singlets, octets, decuplets etc.

built from quarks (u,d,s) $\longrightarrow$ birth of quark model! $\Rightarrow$ composite hadrons

[first attempts Sakata 1956 (p, n, Λ) as constituents model]

❑ P̸ a new paradigm: the key role of discrete symmetries. Puzzling weak interaction processes (weak radioactive decays): Lee, Yang 1956, Madame Wu et al. 1957 parity violation of weak interaction $\Rightarrow$ V-A theory (V=vector, A=axialvector), thus P maximally violated (equal strength V and A, absence of right–handed neutrinos!), but also C violated maximally such that CP and hence

T is still a symmetry

by CPT. CP–violation below.

Chiral Symmetry

$$U(N_f)_{\rm V} \otimes U(N_f)_{\rm A}$$

key role of Left–handed and Right–handed massless fields

Nambu 1960

chiral symmetry of strong interaction must be broken spontaneously!

only $SU(N_f)_V$ hadrons exist [parity partners missing]

$\Longrightarrow$ pions as Nambu-Goldstone bosons!

(see below)

if unbroken: nucleons must be massless, parity doubling! contradicting observation!

❑ Local internal symmetries = gauge symmetries

Weyl 1929, Yang, Mills 1954

global $\psi(x) \to U(\omega)\,\psi(x) \Rightarrow$ local $\psi(x) \to U(\omega(x))\,\psi(x)$

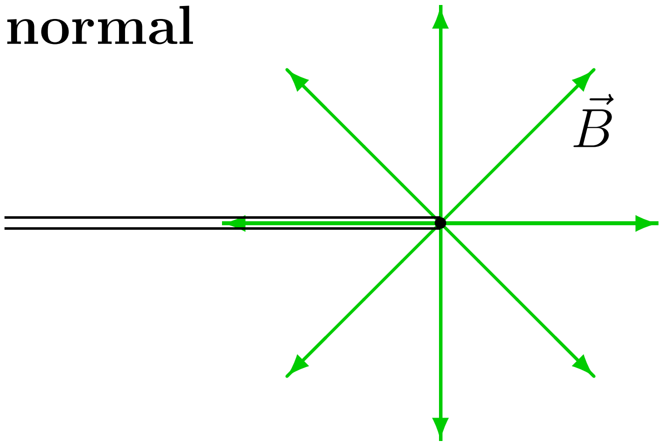
turns out to fix the dynamics

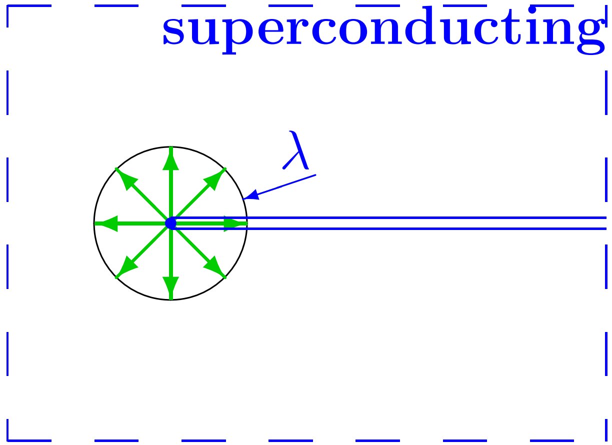
(a dynamical principle rather than a symmetry)

all known interactions derive from local gauge symmetry

$$SU(3)_c \otimes SU(2)_L \otimes U(1_Y)$$

“Spontaneously” broken gauge invariance: the Meissner effect in superconductivity





$$\varphi_{magn} \propto \frac{1}{r} \; ; \; m_\gamma = 0$$

Weyl,Yang-Mills

$$\varphi_{magn} \propto \frac{e^{-r/\lambda}}{r} \; ; \; m_\gamma = \frac{\hbar}{\lambda e} \propto \sqrt{n_s}$$
$$n_s \propto |\psi|^2 \neq 0$$

Yukawa

Microscopic model based electron-phonon interaction (bound Cooper-pairs):

Bardeen, Cooper and Schrieffer 1957 (BCS theory) [NP 1972], P. Anderson [NP 1977], N. Bogoliubov 1958 refined BCS, quasi-particle excitations, degenerate vacua (=spontaneous SB). In fact Ginzburg-Landau theory 1950 is appropriate effective theory!

BCS in Bogoliubov's refinement inspired Nambu 1960 to discover spontaneous symmetry breaking in a relativistic quantum field theoretic formulation! in an attempt to understand the low lying hadron spectrum in strong interactions.

Paradigm at that time: in a QFT there must exist a unique (empty) vacuum! 2

In magnetism or in superconductivity the "vacuum" is really a ground state, in first case of atoms and in the second case of electrons and atoms. In such systems it looks natural to get a non-vanishing vacuum expectation value for a physical quantity like a spin. Nambu's superconductor correspondence:

Superconductivity	Strong Interactions
free electrons	bare fermions (zero or small mass)
phonon interaction	some unknown interaction
energy gap	observed mass (nucleon)
collective excitations	mesons bound nucleon pair
charge	chirality
gauge invariance	γ_5-invariance (rigorous or approximate)

③ Spontaneously broken symmetries and Nambu-Goldstone bosons

Broken Symmetries in Particle Physics. Toy model: $U(1)_{\rm V} \otimes U(1)_{\rm A}$

[discards ABJ anomaly; strictly: consider $SU(N_f)_{\rm V} \otimes SU(N_f)_{\rm A}$ ($N_f \geq 2$)]

Global symmetry: chiral invariance [$x^\mu = (t, \vec{x})$, $\psi \equiv \psi(x)$, γ^μ Dirac matrices, $\partial_\mu \equiv \frac{\partial}{\partial x^\mu}$]

$$\mathcal{L}(x) = -\bar{\psi}\gamma^\mu\partial_\mu\psi - g\left[\bar{\psi}\psi\bar{\psi}\psi - \bar{\psi}\gamma_5\psi\bar{\psi}\gamma_5\psi\right]$$

invariant under

$$\text{(a)} \quad \psi \to \exp[\mathrm{i}\alpha]\,\psi\;; \qquad \bar{\psi} \to \bar{\psi}\,\exp[-\mathrm{i}\alpha]$$

$$\text{(b)} \quad \psi \to \exp[\mathrm{i}\beta\gamma_5]\,\psi\;; \qquad \bar{\psi} \to \bar{\psi}\,\exp[+\mathrm{i}\beta\gamma_5]$$

where α and β are constants. Is a non-renormalizable model, requires a cut-off [low energy effective theory].

(a) Baryon number conservation

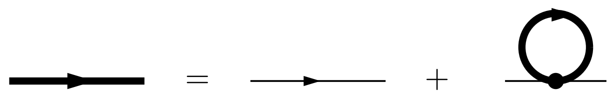
(b) Chirality conservation (γ_5 invariance); preserves $N_R - N_L$

N_R number of right–handed, N_L number of left–handed bare particles (massless)

Point is: currents are conserved (axial current anomaly ignored here, was unknown in 1960)

$$\partial_\mu\bar{\psi}\gamma^\mu\psi = 0\;; \quad \partial_\mu\bar{\psi}\gamma^\mu\gamma_5\psi = 0$$

Consider fermion self–energy at zero momentum via Schwinger-Dyson equation:



Schwinger-Dyson equation $\Rightarrow$ gap-equation

Gap equation:

$$
\begin{aligned}
m &= 2g \left[\boxed{\langle \bar{\psi}\psi \rangle} - \gamma_5 \boxed{\langle \bar{\psi}\gamma_5\psi \rangle} \right] \\
&= -2g \left[\mathrm{Tr}\, S^{(m)}(0) - \gamma_5 \, \mathrm{Tr}\, \gamma_5 S^{(m)}(0) \right]
\end{aligned}
$$

with $S^{(m)}$ the dressed fermion (nucleon) propagator; in momentum space

$$
m = -\frac{g}{(2\pi)^3} \int_0^\Lambda \frac{m \, \mathrm{d}^3 p}{\sqrt{p^2 + m^2}}
$$

Solutions: m=0 trivial and provided $g < 0$ and $\pi^2 < |g| \, \Lambda^2$ also

$$
\frac{\pi^2}{|g|\Lambda^2} = \sqrt{1+x^2} - x^2 \, \sinh^{-1} \frac{1}{x}
$$

with $x = |m/\Lambda|$. Creates a mass out of “nothing”!

Now look at the current conservation taking $\langle p_2 | \cdots | p_1 \rangle$

$$
\begin{aligned}
\langle p_2 | \partial_\mu \bar{\psi} \gamma^\mu \psi | p_1 \rangle &= 0 \\
\langle p_2 | \partial_\mu \bar{\psi} \gamma^\mu \gamma_5 \psi | p_1 \rangle &= -2m \langle p_2 | \bar{\psi} \gamma_5 \psi | p_1 \rangle \neq 0
\end{aligned}
$$

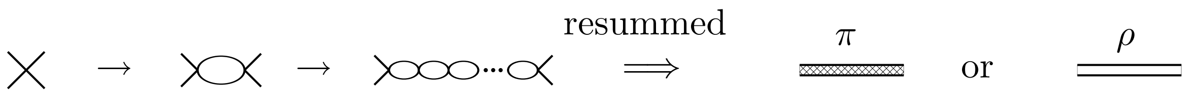
means $\gamma^\mu \gamma_5$ cannot be the correct vertex operator of the conserved current, radiative corrections must be included! General form of vertex:

$$
\Gamma_5^\mu(p_2, p_1) = \left(\gamma^\mu \gamma_5 + \frac{2 \mathrm{i} m \gamma_5 q^\mu}{q^2} \right) F(q^2) \,, \;\; q = p_2 - p_1
$$

where $F(q^2)$ is a forms factor and must satisfy a (subtracted) dispersion relation

$$F(q^2) = F(0) - \frac{q^2}{\pi} \int_{k_1^2}^{\infty} \frac{\mathrm{Im}\, F(-k^2)}{(q^2+k^2)\, k^2}\, \mathrm{d}k^2 \,.$$

If $F(0) \neq 0$ then there exists a pole at $q^2 = 0$ and thus the spontaneous breakdown of the chiral symmetry requires the existence of a massless pseudoscalar boson contribution to the axial vertex form factor!



meson formation $\Rightarrow$ as $\bar{\psi}\psi$ bound states

Furthermore the degeneracy of the vacuum and its meaning is analyzed [vacuum not anymore annihilated by the chiral charge, Hilbert spaces built upon different vacua totally orthogonal (super selection rule) etc.]. Later these ideas were worked out in collaboration with Jona-Lasinio to a fairly realistic phenomenological model, with all the proper isospin ingredients: the famous NJL model (which however as we know today is not the true low energy effective field theory of QCD, although it describes the main pattern of the low lying hadron spectrum correctly).

Highlights:

- **chiral symmetry and its spontaneous breakdown; chiral symmetry requires massless "primary" fermions [bare nucleons?] to start with**
- **implication of massless pseudoscalar bosons, to be understood as bound states of the primary fermion pairs**
- **existence of primary fermion–pair condensates and non-triviality and degeneracy of the ground state [buries dogma of an empty vacuum]**
- **primary fermions must have a small mass [few MeV] to explain mass of the pions**
- **nucleon masses "out of nothing", i.e. generated by some interaction [in chiral limit pure binding energy]**

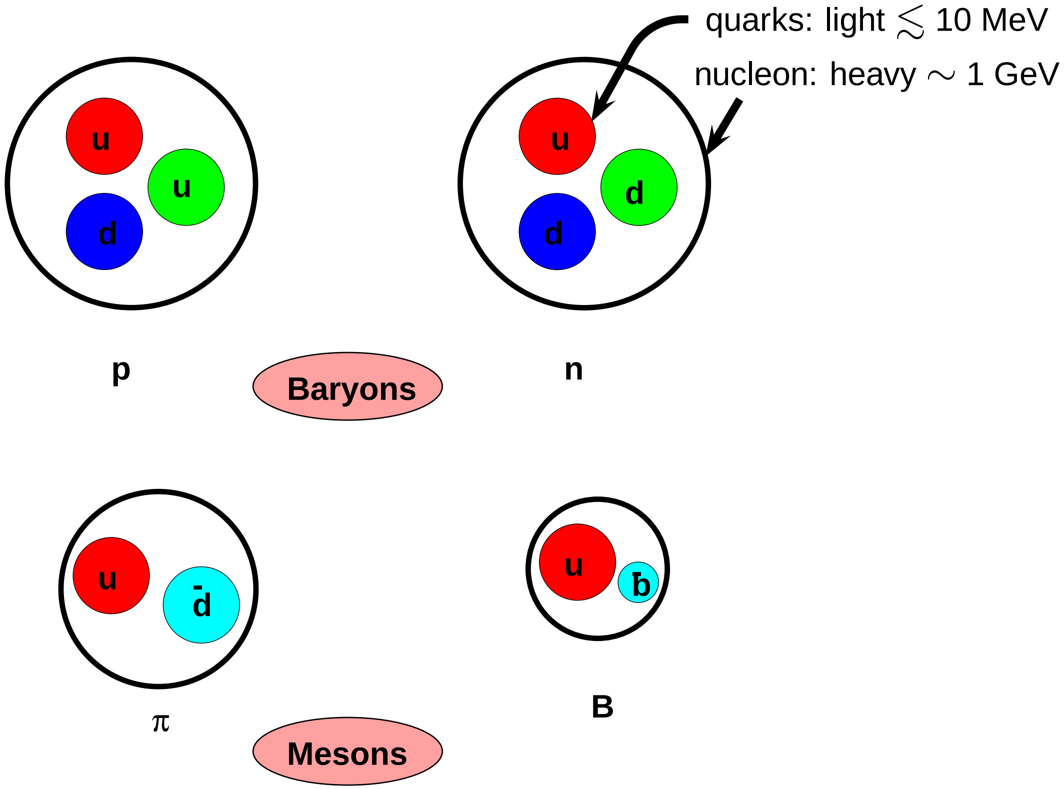
Looks really visionary: "bare" nucleons we know are the light quarks u and d [which however do not interact among themselves but only via gluon exchange] and truly not proton and neutron, which were the only known strongly interacting spin 1/2 hadrons in the isospin sector at that time. In abstract of NJL-II [1961]: "On the basis of numerical mass relations, it is suggested that the bare nucleon field is similar to the electron-neutrino field." i.e. "light quarks" required. Via DIS, Scaling,$\cdots \longrightarrow$ QCD 1973

Hadrons are made of Quarks and Gluons

QUARKS are permanently confined in HADRONS

QCD: u, d quarks must be very light $\sim$ few MeV [Leutwyler 1974]

Nucleon mass: 97% energy (as Nambu claimed in 1960) **M=E/c^2 !**



Hadrons are elementary composite systems [Wigner state]

Visualizing the Nambu-Goldstone phenomenon

Goldstone Model $O(2)$ equivalently $U(1)$:

$\hat{\varphi} = (\varphi_1, \varphi_2)$ **with φ_i two real scalar fields**

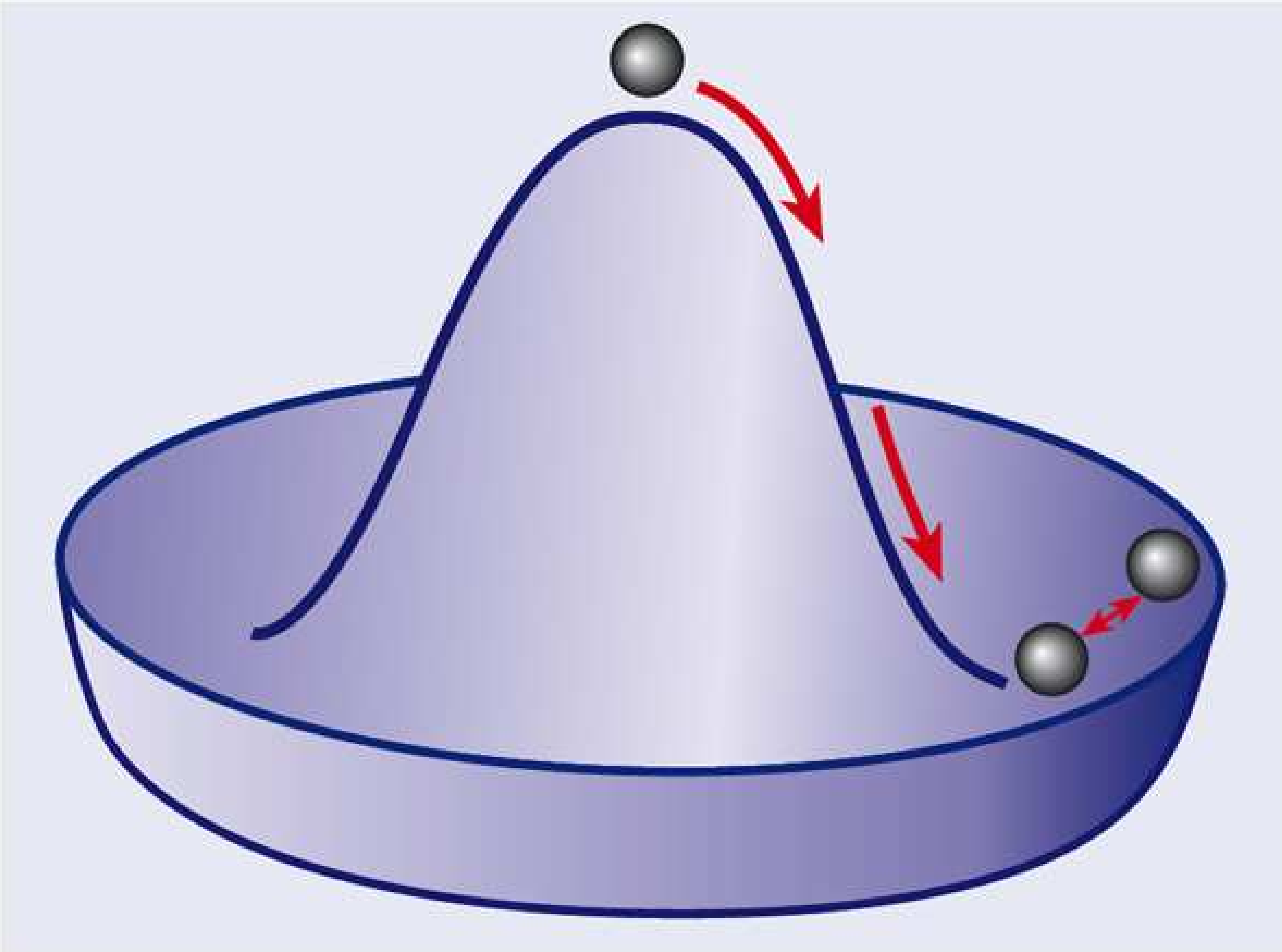
$$\mathcal{L} = \frac{1}{2}\partial^\mu \hat{\varphi}^+ \partial_\mu \hat{\varphi} - V(\hat{\varphi}^+ \hat{\varphi}) \;\; ; \quad V(x) = \frac{\mu^2}{2} x - \frac{\lambda}{4!} x^2$$

If $\mu^2 < 0$ symmetric phase, unique ground state; two equal mass fields $m_1 = m_2 = \mu$

if $\mu^2 > 0$ spontaneous SB, minimum of potential at $\hat{\varphi} = \hat{\varphi}_0 = (0, v)$ where $v = \sqrt{6\mu^2/\lambda}$. Rewrite Lagrangian by shift of field $\hat{\varphi} = \hat{\varphi}' + \hat{\varphi}_0 \Rightarrow$
field φ_1 has mass $m^2_{1\mathrm{eff}} = 0$! = Nambu-Goldstone boson while
field φ_2 has mass $m^2_{2\mathrm{eff}} = 2\mu^2/\lambda > 0$.

- **vacuum continuously degenerate [$O(2)$ orbit] and not invariant**
- **field acquiring vacuum expectation value is massive (radial mode)**
- **other fields must be Nambu-Goldstone bosons (massless spin 0 particles)**

The “Mexican Hat” Potential



Goldstone theorem: spontaneous breaking of global continuous symmetry requires the existence of spin zero massless bosons. Essentially: Provided $|p\rangle$ is spin 0 state, relativistic covariance says

$$\langle 0|j_i^\mu(x)|p\rangle = F_P\, p^\mu\, \mathrm{e}^{\mathrm{i}px}$$

$$\partial_\mu j_i^\mu(x) = 0 \Leftrightarrow \langle 0|\partial_\mu j_i^\mu(x)|p\rangle = \mathrm{i}\, F_P\, p_\mu p^\mu\, \mathrm{e}^{\mathrm{i}px} = 0$$

SSB $\Leftrightarrow F_P \neq 0$

as $Q_i\,|0\rangle = \int \mathrm{d}^3x\, j^0(t,\vec{x})|0\rangle \neq 0$ does not annihilate the vacuum

[as it must in case of true symmetry: $Q_i\,|0\rangle = 0$]

hence: only possibility is $p_\mu p^\mu = p^2 = 0$; state $|p\rangle$ must exhibit

massless spin 0 particle = Nambu-Goldstone boson.

(as a theorem conjectured: Goldstone 1961; proven: Goldstone, Salam, Weinberg 1962)

Note: other than spin 0 “Nambu-Goldstone” particles would require to break Lorentz invariance spontaneously (in contradiction with observations)

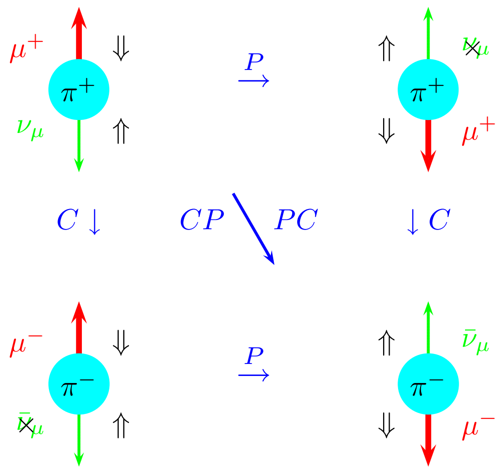
④ CP violation

Events:

- **CP at work: CP conservation while P and C are violated**

Example: the weak leptonic decays

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu \text{ versus } \pi^- \longrightarrow \mu^- + \bar{\nu}_\mu$$



Starting from the observed π^+ decay P and C map this decay into decays which do not exist. CP or PC however relate the observed π^+ and π^- decays.

- CP violation by $K^0 \leftrightarrow \bar{K}^0$ oscillations [Gell-Mann, Pais 1955] : overview K–decays

Channel	K^+	K_S	K_L
		Branching fractions in %	
$\mu^+\nu_\mu$	63.51	–	–
$e^+\nu_e$	1.55×10^{-5}	–	–
$\pi^+\pi^0$	21.16	–	–
$\pi^+\pi^-$	–	68.61	2.03×10^{-3}
$\pi^0\pi^0$	–	31.39	9.14×10^{-4}
$\pi^+\pi^-\pi^+$	5.59	–	–
$\pi^+\pi^-\pi^0$	–	$< 8.5 \times 10^{-5}$	12.38
$\pi^+\pi^0\pi^0$	1.73	–	–
$\pi^0\pi^0\pi^0$	–	$< 3.7 \times 10^{-5}$	21.60
$\mu\nu_\mu\pi$	3.18	4.66×10^{-4}	27.00
$e\nu_e\pi$	4.82	6.68×10^{-4}	38.70

- **1964** Christensen, Cronin, Fitch, Turlay observation of the decay $K_L \to \pi^+\pi^-$ nearly 30 years ago Cronin, Fitch [NP 1980]. Since, probe of direct CP–violation in the $K^0 - \bar{K}^0$ complex, only u, d and s quark sector involved [isospin + strangeness]

- **1972** SM known (Glashow, Weinberg, Salam 1968), 2 families needed (quark–lepton duality, GIM mechanism) charm c yet missing but expected to be there, renormalizability ('t Hooft, Veltman 1972) $\Rightarrow$ for the 1st time a consistent theory of weak interactions

- **1973** Kobayashi and Maskawa note that CP–violation cannot be accommodated in a 2 family SM (without adding at least one specific interaction term by hand: Wolfenstein's superweak theory), and they observe that in contrast a 3 family SM automatically incorporates a CP violating phase in the 3 family quark mixing matrix! Given the tiny 0.2 % CP violation in the K–system, the CKM scheme predicts a $O(1)$ CP violation in the at that time hypothetical B–system, because the CKM matrix must be unitary!

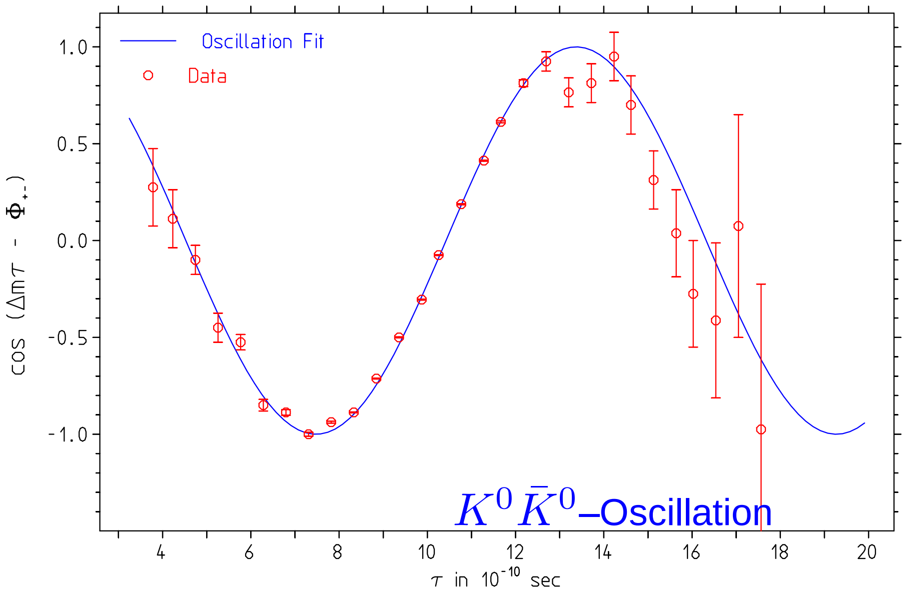
- as we know: the 3rd family exists, all members found, surprisingly with a very heavy top [which is crucial for large CP violating $B^0 - \bar{B}^0$ oscillations, observed first 1987 by ARGUS at DESY], and in **2001** the B–factories BaBar/SLAC and Belle/KEK were able to precisely confirm the SM prediction based on the CKM quark mixing scheme.

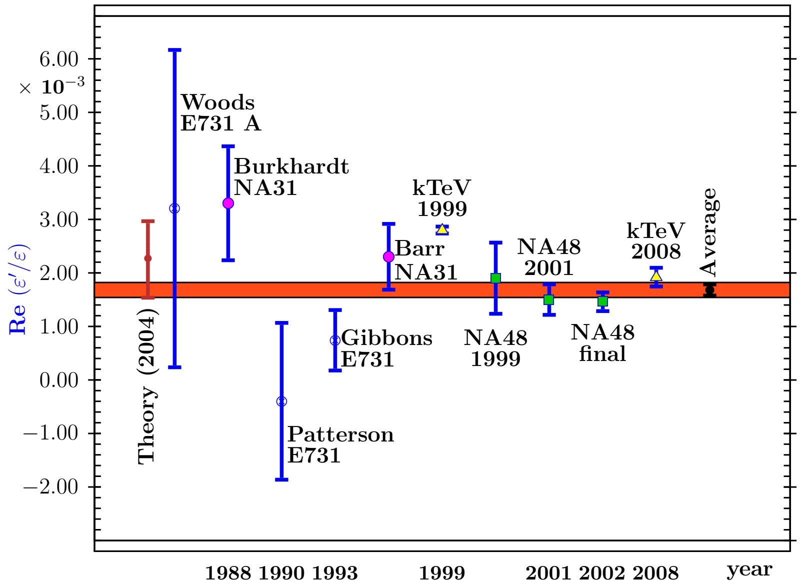
- Direct CP-violation in K system [CP-LEAR/CERN, kTEV/FNL]: also a consequence of KM–mixing

$$\eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} = \frac{L^{+-}}{S^{+-}} = \epsilon + \epsilon'$$

$$\eta_{00} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} = \frac{L^{00}}{S^{00}} = \epsilon - 2\epsilon'$$

$$\mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right) = (1-R)/6\;;\quad R = \left|\frac{L^{00}}{S^{00}} \cdot \frac{L^{+-}}{S^{+-}}\right| = (1.68 \pm 0.14) \cdot 10^{-3} \quad \text{[NA48 (2002), kTeV (2008)]}$$

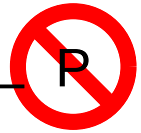




❑ SM Yukawa couplings, quark masses and mixings

Transformation properties of the fields:

$$
\begin{array}{llll}
\Psi_{Lf} \doteq L_f & \rightarrow & U(x) L_f & \text{fermion doublet} \\
\Phi_{b,t} & \rightarrow & U(x) \Phi_{b,t} & \text{Higgs doublet} \\
f_R & \rightarrow & f_R & \text{fermion singlet ;}
\end{array}
$$



fix most general renormalizable invariant Yukawa Lagrangian for the quark interactions with the Higgs field

$$\mathcal{L}^q_{\rm Yukawa} \;=\; -\sum_{i,j=1}^{3} \left[G^u_{ij} \bar{L}_{qi} \Phi_t u_{jR} + G^d_{ij} \bar{L}_{qi} \Phi_b d_{jR} + \text{h.c.} \right]$$

with G^u_{ij} and G^d_{ij} arbitrary complex 3 x 3 matrices.

Fields with identical $SU(2)_L \otimes U(1)_Y$ quantum numbers form *horizontal vectors*. For the quarks there are the 4 horizontal vectors $q_{uL}, q_{dL}, q_{uR}, q_{dR}$ where $q_u = (u, c, t)$ and $q_d = (d, s, b)$.

In order to transform the fermion mass matrix (obtained by replacing $\phi_0^* = \phi_0 = v/\sqrt{2}$, $\phi^+ = \phi^- = 0$) to diagonal form we must perform independent global unitary transformations of the 4 horizontal vectors. Whereas,

- unitary transformations of $(q_u, q_d)_L$ as a doublet, q_{uR} and q_{dR} do *not* change the matter field Lagrangian,
- an independent transformation of q_{dL} leads to **"mismatch"** $\tilde{q}_{dL} = U_{\rm CKM}\, q_{dL}$ of the quark fields in the charged current.

This leads us to the following form of the hadronic charged current

$$J_\mu^{CC} = (\bar{u}, \bar{c}, \bar{t})\, \gamma_\mu (1-\gamma_5)\, U_{\rm CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \qquad U_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

[X (green) =Cabibbo, X (yellow) =Glashow, Iliopoulos, Maiani, X (violet) =Kobayashi-Maskawa],

which may be parametrized in terms of 3 rotation angles and 1 phase which is CP violating [9-5=4=3+1]:

$$U_{\rm CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} .$$

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$ with i and j being the family labels.

- may assume all $c_{ij}, s_{ij} > 0$ and $0 \leq \delta_{13} < 2\pi$. If $\delta_{13} > 0 \Rightarrow$ CP violation
- condition: 4 independent unitary transformations required to diagonalize mass matrix $\Rightarrow$ particles of same

charge must have different masses, is true for quarks.

Note: any degeneracy of the CKM and/or the mass matrix would spoil the CP violation!!!

Due to unitarity, there is no mixing effect in the neutral current, since

$$\bar{\tilde{q}}_{dL} \tilde{q}_{dL} \equiv \bar{q}_{dL} q_{dL} \; .$$

This is called the GIM-mechanism explaining the absence of flavor-changing neutral currents (FCNC).

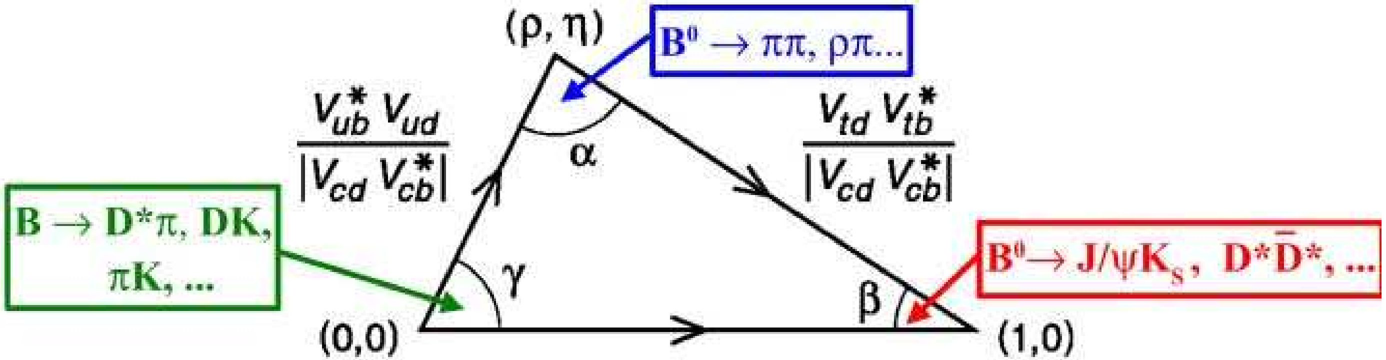
CP Violation in the Standard Model

CP violation arises in Standard Model through a single phase in the CKM matrix

$$\mathbf{V} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

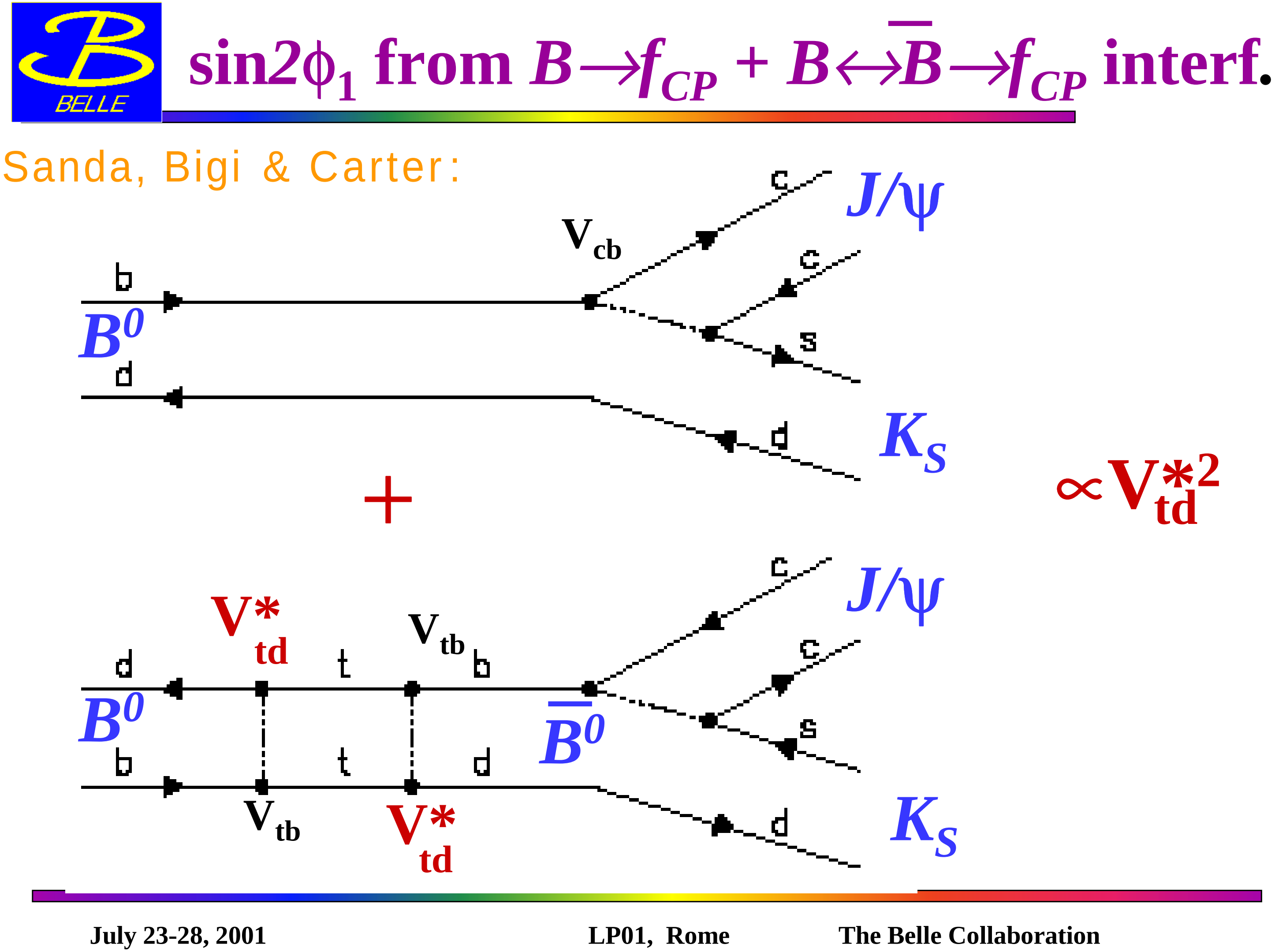
Unitarity of V requires e.g. $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$

Can be represented as "unitarity" triangle in the complex plane



CP violating asymmetries A(Δt) in B^0 decays measure α, β, γ

07/23/2001 Lepton Photon 2001



CP violation in interference of mixing and decay

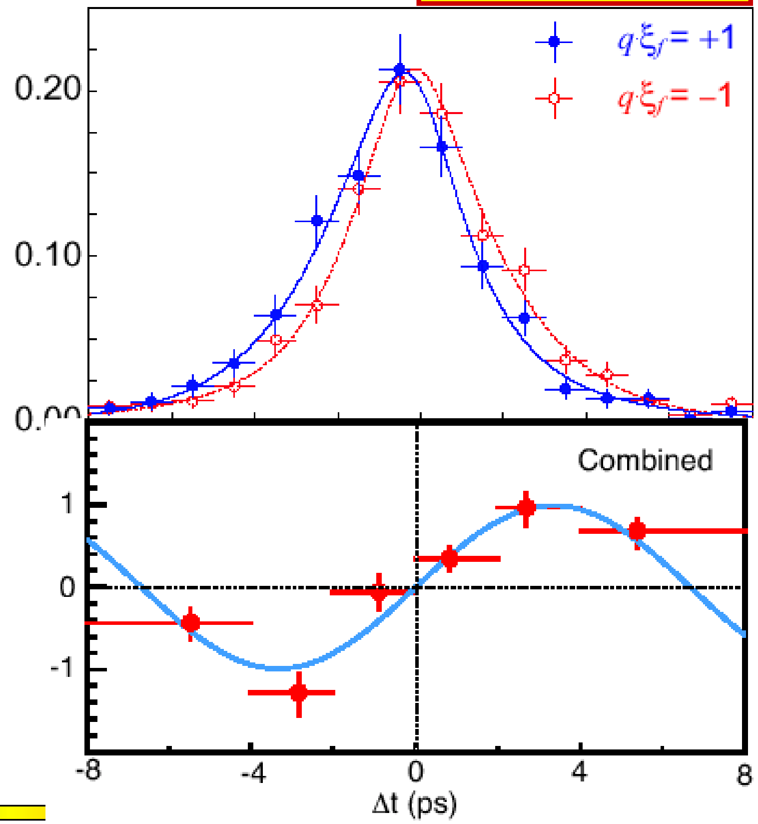
Conclusions

- CP is violated in B decay **>6σ!!**

- sin $2\phi_1$ is large:

$0.99 \pm 0.14 \pm 0.06$

>0.7 @ 95%CL

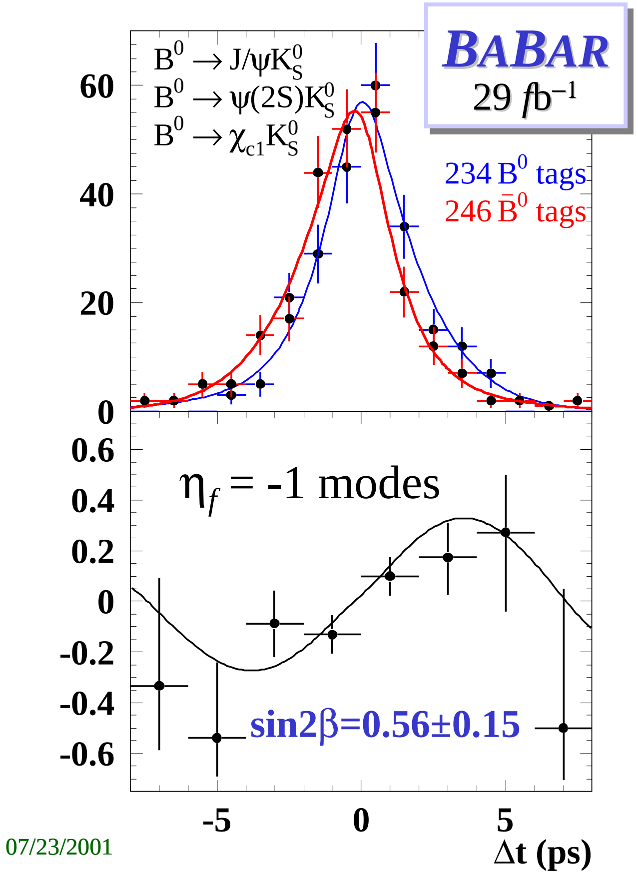


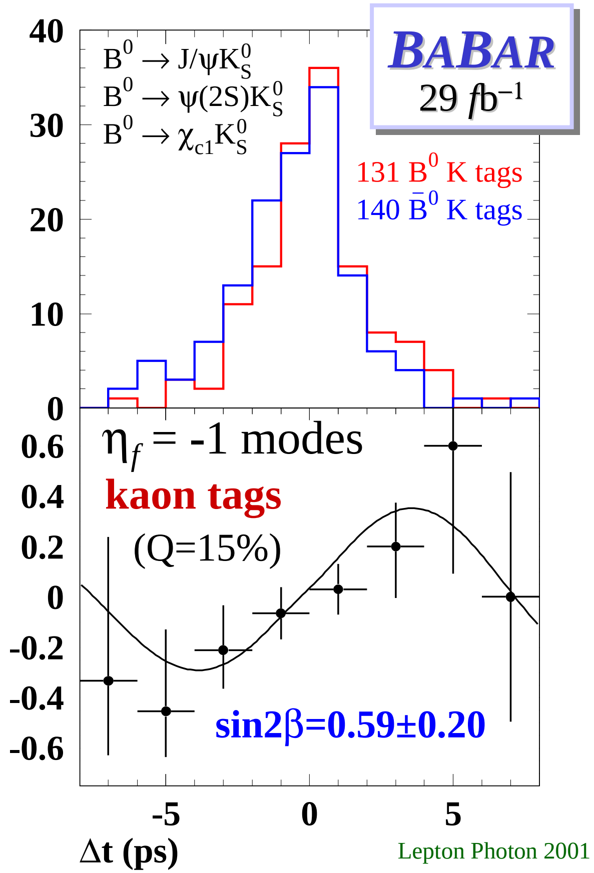
July 23-28, 2001 LP01, Rome The Belle Collaboration

Experimental results I

Raw Asymmetries

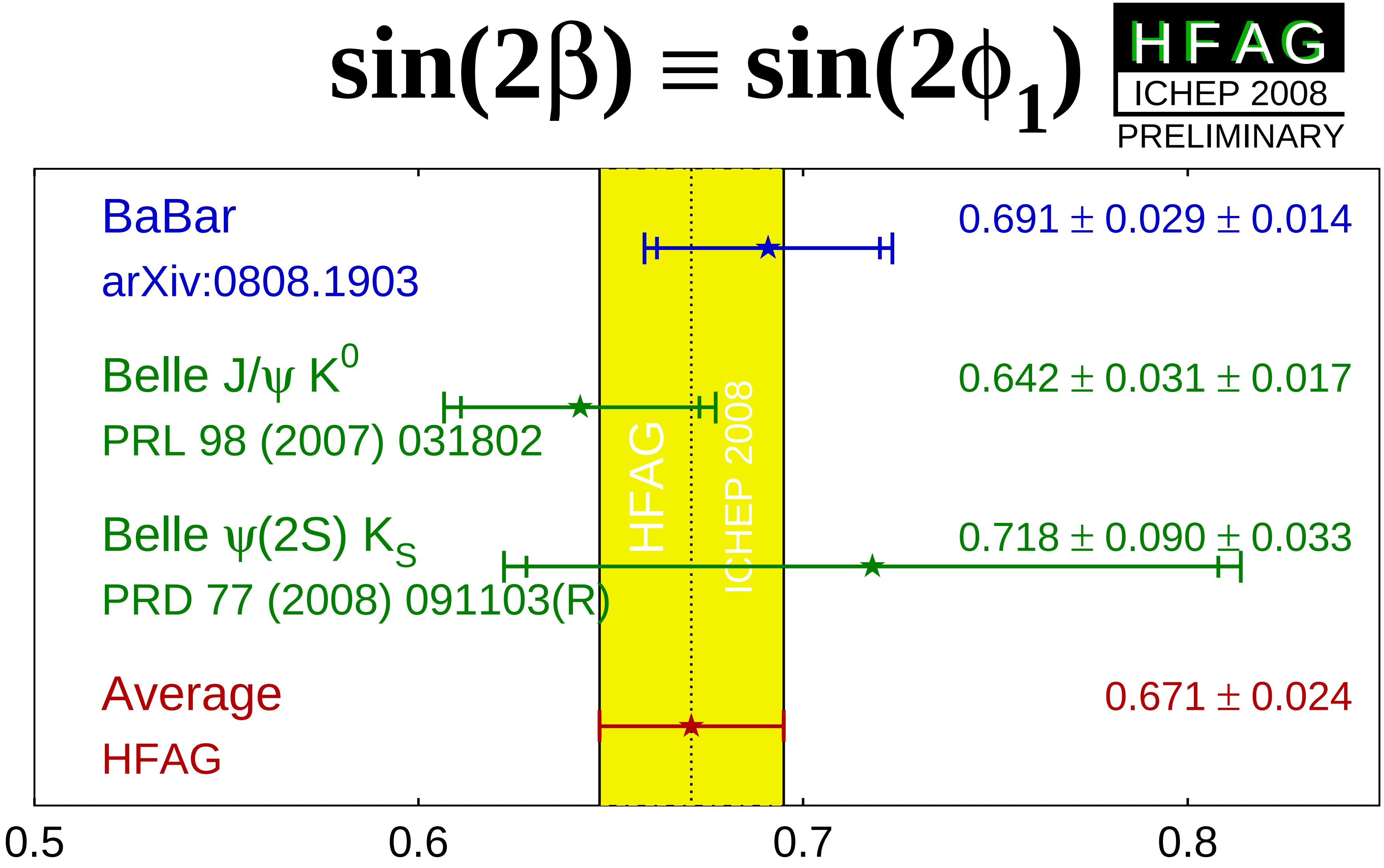
$$A_{CP}(\Delta t) \approx (1-2w)\,\sin 2\beta\,\sin(\Delta m_d\,\Delta t)$$



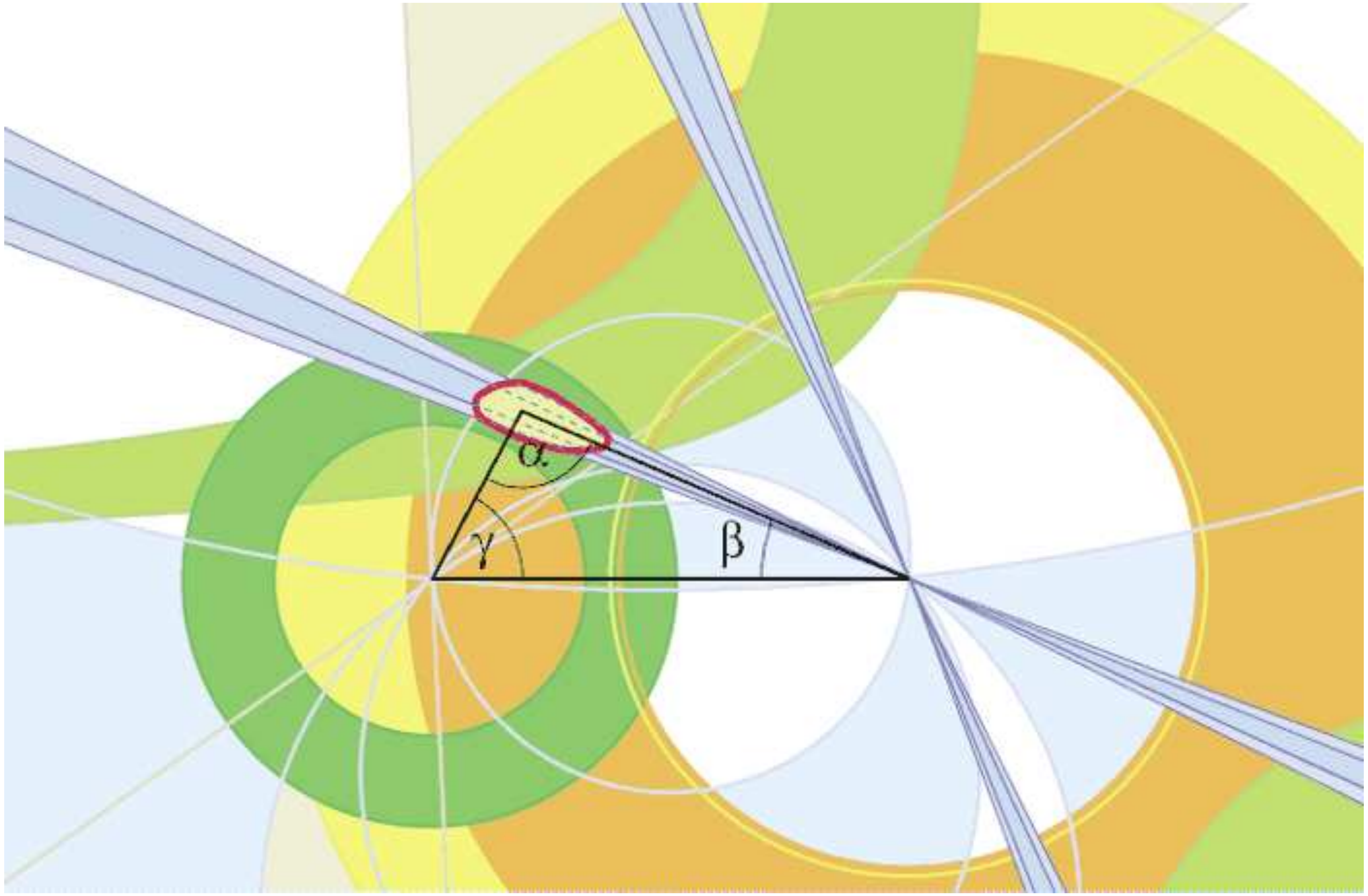


Experimental results II

$\sin(2\beta) \equiv \sin(2\phi_1)$



CP violation parameter $\sin(2\beta)$ in B decays



Unitarity Triangle for the B system

Area of triangle direct measure for CP violation in B system

[CP conservation = Area of triangle =0]

⑤ All basic ingredients of the Standard Model confirmed, except Higgs!

Three lepton-quark families

Leptons and neutrinos from direct detection. In 1973: e, ν_e, μ, ν_μ known

Quarks until end 1973: all normal and "strange" hadrons are built from u, d and s

1964 M. Gell-Mann [NP 1969]: introduced $SU(3)$ and quarks as a hadron classification scheme [hadron singlets, octets, decaplets etc]

Theory requires: fermions in families only!

quark-lepton duality required for anomaly [Adler, Bell, Jackiw 1969] cancellation [Bouchiat and others 1972] $\Rightarrow$ quark-lepton families!

1. Family: e^-, ν_e, u(up), d(down)

2. Family: μ^-, ν_μ, ?c(charm)? , s(strange)

3. Family: τ^- discovered 1975 by Perl at SLAC, ν_τ, ?t(top)? , b(bottom)

Charmed quark: c (charm) J/ψ–particle 1974 B. Richter (SLAC), S. Ting (BNL)

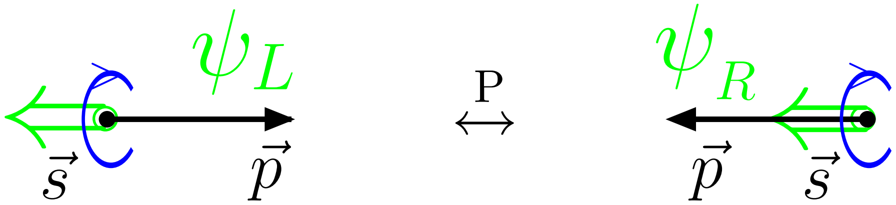
Bottom quark: b (bottom) Υ–particle: 1978 L. Ledermann (BNL), DORIS(DESY)

Top quark: t (top) 1996 CDF, D0, Tevatron Fermilab USA

Fundamental constituents of matter: QUARKS & LEPTONS

Dirac particles (spin 1/2, Pauli principle), “in first place” massless

left or right handed: (helicity, chirality)

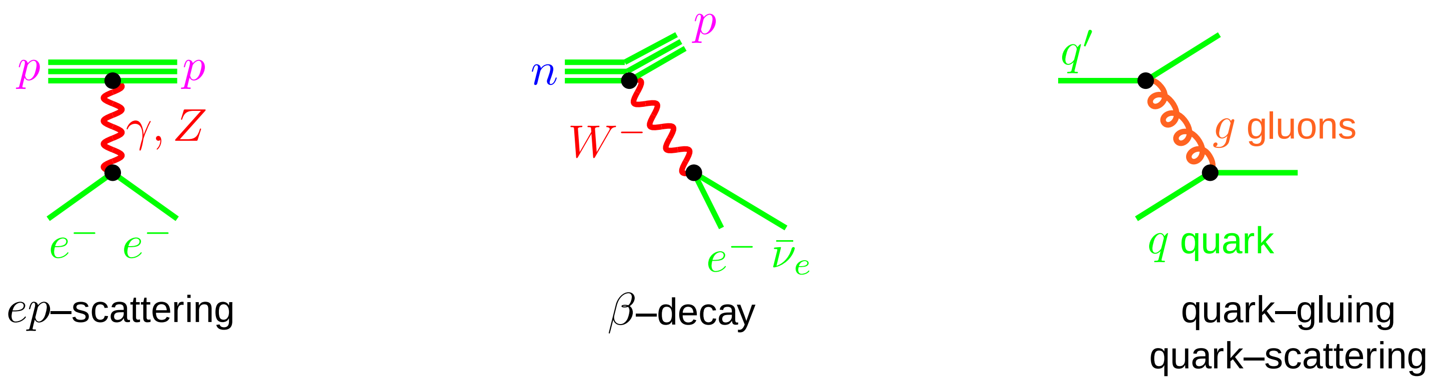


Forces are exchange forces of a particular type: gauge forces

which derive from an equivalence principle

Weyl 1918,1929, Yang & Mills 1954

Constituents of matter only communicate via spin 1 gauge bosons



Gauge bosons: γ^+, $\underbrace{Z,\ W^{\pm *}}_{\text{heavy!}}$, $g^\bullet$ $[\ SU(3)_c \otimes SU(2)_L \otimes U(1)_Y\ ]$

$+$ **Hertz 1888** $*$ **CERN $p\bar{p}$ 1983** $\bullet$ **DESY 1978**

Gauge principle ony allows for massless particles

- **Gauge bosons must be massless by gauge invariance!**
- **Fermions must be massless (chiral invariance)**

Reason: weak interactions are different for L field and R fields vector and axial-vector currents participate which must be conserved non-conserved fermion currents would spoil gauge invariance!

What is the origin of masses? $\Rightarrow$

“Spontaneous Symmetry Breaking” via Higgs Mechanism

(Higgs, Englert, Brout, Guralnik, Hagen, Kibble 1964)

There must exist a Higgs particle (neutral, spin 0)!

$\Rightarrow$ System in superconducting phase w.r.t. weak force

not the γ (as in normal superconductors)

but W^+,W^-, Z [$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \to SU(3)_c \otimes U(1)_{\rm em}$]

as well as quarks, leptons and neutrinos

aquire a mass via non-vanishing Higgs condensate $v = \langle 0|H|0\rangle \neq 0$!

Non-trivial vacuum!!!

“Spontaneously” broken local symmetry: no Nambu-Goldstone bosons

[like in normal superconductor]

Note: massless photon automatic, CP-violation $\geq$ 3 families automatic!!!

Basic idea: Ginzburg-Landau[a] theory of superconductivity [1950]. A massless particle (the photon) moving in a Bose condensate ground state (sea of Cooper-pairs) behaves like a massive particle (Meissner-effect)

[a](Landau [NP 1962] liquid Helium, Ginzburg [NP 2003] superconductors and superfluids)

⑥ Outlook

Symmetries play a key role in physics. Often symmetries are a fiction, e.g. if we don't look close enough, a ball of metal may seem to have perfect rotation symmetry in spite of the fact that it consists of a lattice of atoms. Symmetries are almost without exception broken at some point. We have learned about two important patterns of breaking symmetries the discovery of which are awarded with the Nobel Prize 2008.

The first is spontaneous symmetry breaking as a non-perturbative phenomenon of the fundamental interactions. This allows us to understand the low lying spectrum of hadrons with the pions as quasi–Nambu-Goldstone bosons of spontaneously broken chiral symmetry [$SU(2)_{\rm V} \otimes SU(2)_{\rm A} \to SU(2)_{\rm V}$]. At the same time Fermion masses where generated "out of nothing" via a gap-equation. Lattice QCD confirms this!

The solution of the problem with axial currents in strong interaction physics [Goldberger-Treiman] was only possible by questioning truly holly principles like the emptiness of the vacuum on which fundamental physics was supposed to be built. Fermion pair operators $\langle \bar{\psi}\psi \rangle$ suddenly turned into an order parameter with non-vanishing vacuum expectation value. Nambu had to cope with the contradiction that the fermions where required to be massless, while when identified with the only known strongly interacting fermions, the proton and the neutron (in the isospin sector), had huge masses near 1 GeV. In addition, the predicted pions rather than being massless have masses of about 140 MeV and do not perfectly look like Nambu-Goldstone bosons. As a first Nambu explained why parity partners are absent in spite of chiral symmetry.

Nambu's "bare" Fermions, we know today, are the light u and d quarks, and the condensates are the quark condensates. The primary unbroken chiral symmetry would be there if not the Higgs mechanism (spontaneously broken local $SU(2)_L$ gauge symmetry) would give masses to the quarks [as well as to the weak gauge bosons, leptons and neutrinos]. From the point of view of QCD (local $SU(3)_c$ quark–gluon gauge theories) chiral symmetry is explicitely broken by the quark masses and quark mass differences and the pion masses are given by (Gell-Mann, Oakes, Renner)

$$m^2_{\pi^+} = B\,(m_u + m_d)\ ;\quad B \equiv -\frac{1}{F_\pi^2}\,\langle 0|\bar{u}u + \bar{d}d|0\rangle\ ;\quad B > 0\ \ .$$

Note that perturbative QCD does not allow us to understand the emergence of the pions in the bound state spectrum as they are a result of a non-perturbative phenomenon of spontaneous chiral symmetry breaking. QCD intrinsically non-perturbative

$\Rightarrow$ **Lattice QCD!** * * * **What is the correct low energy effective QCD?**

Non–linear chiral σ–model*

The pseudoscalars are encoded in a unitary 2×2 matrix field (in the isospin sector)

$$U(\phi) = \exp\left(-\mathrm{i}\sqrt{2}\,\frac{\phi(x)}{F}\right)$$

with (T_i the $SU(2)$ generators)

$$\phi(x) \;=\; \sum_i T_i \phi_i = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} & \pi^+ \\ \pi^- & \frac{-\pi^0}{\sqrt{2}} \end{pmatrix} \quad .$$

The leading order Lagrangian at $O(p^2)$ is then given by

$$\mathcal{L}_2 \;=\; \frac{F^2}{4} \mathrm{Tr}\left\{\partial^\mu U \partial_\mu U^\dagger + M^2 \left(U + U^\dagger\right)\right\}$$

where $M^2 = 2B\hat{m}$ with B is proportional to the quark condensate $\langle 0|\bar{u}u|0\rangle$ and $\hat{m} = \frac{1}{2}(m_u + m_d)$. Extend to $SU(3)$,

- **plus corrections $\Rightarrow$ chiral perturbation theory (Weinberg, Gasser, Leutwyler, $\cdots$)**

*Gürsey 1960's

- Beyond QCD, kind of spontaneous symmetry breaking is the key mechanism of breaking the electroweak gauge symmetry $SU(2)_L \otimes U(1)_Y \to U(1)_{\rm em}$: the Higgs mechanism, the key mechanism to generate the masses of all the elementary particles (but the Higgs itself, which is a problem (=hierarchy problem)).

Big hope that the LHC will find the Higgs and helps to establish that the masses of all SM particles are generated by spontaneous symmetry breaking by the Higgs condensate, as assumed by the SM?

If so, all particles have their mass because they are propagating in a non-empty ground state, the Higgs vacuum expectation value in fact is one of the most precisely known SM parameters:

$$v = 1/\sqrt{(\sqrt{2}G_F)} = 246.22 \text{ GeV}$$

the electroweak symmetry breaking scale.

- Key question: **New Physics beyond the SM ?** SM accounts only for the 4% of normal (baryonic) matter in the universe. What about the 73% of dark energy, the 23% of cold dark matter floating around? Bayogenesis: need B, L–violation and more CP–violation!

The second is generating CP violation by 3 family mixing $\Rightarrow$ CP is a property of normal CC weak interaction! Here are relatively trivial hypothetical extension of the 2 family SM to 3 families in fact generated a new mechanism to understand how ~~CP~~ may be understood. Not only that a tiny CP breaking of about 0.2% in the $K^0/\bar{K}^0$ system found its natural incorporation into the SM, the generalization turned out to be very predictive and made out of a small effect and $O(1)$ phenomenon! Namely, given that the effect was small in the known two–family subsystem, it predicted a large effect in the complementary 3rd family sector (by unitarity of the CKM matrix), specifically in the hypothetical B-system, which about 30 years later found its perfect experimental confirmation.

The crucial point about this discovery is its existential importance for the reality of life. CP violation means the absence of time-reversal invariance of the fundamental interactions [$\Rightarrow$ electric dipole moments]. Most importantly ~~T~~ is vital for the

"Matter – Antimatter Asymmetry in the Universe"

Early in the evolution of the universe almost perfect Matter – Antimatter symmetry: On 1 antiparticle (antiproton/positron) there was 1.000000001 particle (proton/electron), after matter-antimatter annihilation by cooling down of the universe there survived a relict of 0.000000001 matter particles while antimatter completely disappeared.

Baryogenesis: how come $n_{\bar{p}}/n_p \simeq 0$; $n_p/n_\gamma \simeq 10^{-9}$?

Conditions for possibility of baryogenesis: (A. Sacharov 1967)

① Baryon-number violating processes (B–L violation !)

② CP violation ! Cronin, Fitch 1964 (NP 1980) violation of time-reversal symmetry in basic laws of nature ! for a long time seen only in K^0 system as a 0.2% effect
origin and type of CP violation in SM predicted by Kobayashi and Maskawa in 1973
confirmed experimentally by the B–factories Belle and BaBar 2001

③ Thermic non-equilibrium (non stationary time evolution)
a fact satisfied by the expansion of the universe

Standard Model of elementary particles cannot explain this fact: ➜ There must be NEW PHYSICS supposedly at energies not yet explored

waiting for answers from the LHC!!! and from our young researchers!!!

What we know today: the vacuum of our universe in not empty, and Nambu was the first who had the idea that this indeed must be real.

similar ideas: Schwinger 1957, Heisenbeg et.al. 1959 but in different context

Another puzzle: the cosmological constant. Is empty space not flat as originally taken for granted by Einstein as a natural boundary condition? Condensates like $\langle 0|H|0\rangle$ are a true unsloved problem here!

Epilogue on broken symmetries:

Which "symmetries" are really exact? To present knowledge QCD is an asymptotically free unbroken non-Abelian gauge field theory. This exact symmetry however is hidden since color is not observable. The proper low energy effective theory of QCD is not the Nambu–Jona-Lasinio model! and not the Gell-Mann–Levy linear σ–model but a chiral non-linear σ–model (framework of chiral perturbation theory)! The other unbroken fundamental theory is QED, an unbroken Abelian gauge theory. This symmetry implies a strictly massless photon [in SM with 1 Higgs doublet automatic!]. All other local, global and discrete symmetries seem to be broken, either spontaneous, like chiral symmetry in the chiral limit of massless quarks, or explicitely, like isospin by the quark mass splitting, or local weak isospin by the Higgs mechanism. Poincaré invariance is broken by gravity and only a good symmetry if gravitational fields are weak. CP is an example of a vitally important phenomenon, without which we would not exist. The same with isospin splitting by the u and d quarks. The inverted hierarchy $m_d > m_u$

(while $m_c > m_s$ and $m_t > m_b$) implies $M_{\rm neutron} > M_{\rm proton}$, which causes the neutron to decay ($n \to p + e^- + \bar{\nu}_e$) and the proton to be stable. This prevents matter to end up all in cold neutron stars.

Note: 3 family unitarity is in good shape! In nature minimalist? Just the 3 families required to be alive? If there exists a 4th or more families we know they only leak very little to what we understand by the 3 family SM. Still dark matter and baryogenesis definitely require physics beyond the SM: need new forms of matter, more B and L violation and likely more CP violation too. More symmetry breaking Nobel Prizes to come!

∞∞∞∞∞∞

We congratulate this years Nobel Prize winners

Yoichiro Nambu, Makoto Kobayashi and Toshihide Maskawa

for their outstanding contributions to an exciting field of physics. In particular, Nambu's work based on his enthusiasm for condensed matter physics payed off in big progress in field theory and particle physics. An excellent example for the unity of science.

Backup Slides

❑ Selection of Relevant Publications

Spontaneous symmetry breaking in elementary particle physics:

Gell-Mann, Levy 1960 [19 Feb 1960], The axial vector current in beta decay [1139 cit]

propose PCAC and model it by the linear and the non-linear σ-model in the spontaneously broken phase [basic symmetry feature not recognized]

Nambu 1960 [23 Feb 1960], Axial vector current conservation in weak interactions [481 cit]

proposes chiral symmetry and its spontaneous breakdown by analogy to BCS

Nambu 1960, talk at Purdue University [presented actually by Jona-Lasinio]

A 'superconductor' model of elementary particles and its consequences

Note: all basic ideas on SSB and the chiral structure of low energy strong interaction are presented here with textbook clarity, quotes Gell-Mann, Levy

Goldstone1961[08 Sep 1960], Field Theories with Superconductor Solutions [788 cit]

Goldstone model [=scalar $O(2)$ toy–model], conjectures "Goldstone theorem" without any proof, quotes Nambu's model mimicking BCS

Nambu, Jona-Lasinio 1961[27 Oct 1960]

Dynamical Model of Elementary Particles Based on an Analogy with Superconductivity I [2969 cit]

Nambu, Jona-Lasinio 1961[10 May 1961]

Dynamical Model of Elementary Particles Based on an Analogy with Superconductivity II [1337 cit]

Goldstone, Salam, Weinberg 1962 [16 Mar 1962]

Broken Symmetries [673 cit], prove of the Goldstone theorem

Older relevant related papers:

Feynman, Gell-Mann 1958 [Sep 16, 1957]

Theory of Fermi interaction [859 cit], V-A theory of weak interactions

Goldberger, Treiman 1958 [Apr 25, 1958]

Conserved Currents in the Theory of Fermi Interactions [61 cit], Axial current conservation vs. observation clash

Flavor Mixing the source of CP Violation:

Three family mixing:

Kobayashi and Maskawa 1973 [1 Sep 1972], CP Violation in the Renormalizable Theory of Weak Interactions [5481 cit]

no natural way to incorporate CP violation in a 2 family SM, extension to 3 families automatically yield CP violation

Related topics:

Quark flavor mixing:

Cabibbo 1962, Unitary Symmetry and Leptonic Decays, [2707 cit]

[projected] rotation in flavor space [isospin $\leftrightarrow$ strangeness] explains $F_K/F_\pi \simeq 1$ as expected from flavor $SU(3)$, universality of CC weak interaction

Quark-Lepton Duality or from “Cabibbo mixing” to “two–family mixing”:

Glashow, Iliopoulos and Maiani 1970, Weak Interactions with Lepton-Hadron Symmetry, [3727 cit]

extends “Cabibbo rotation” to a true rotation in 4 quark space by adding new hypothetical charm quark c = 2 family–mixing; natural explanation of absence of flavor changing neutral currents [FCNC]; GIM mechanism

Mixing of neutrinos:

Maki, Nakagawa, Sakata 1962,

Remarks on the unified model of elementary particles, [1386 cit]

is anybody able to see in this paper 3 neutrino mixing and/or CP violation considered?

❑ Flavor mixing pattern

Historically flavor mixing was "observed" first by a comparison of the decays $K \to \mu\nu$ and $\pi \to \mu\nu$. Only u, d and s flavors (isospin and strangeness) were known at that time and the approximate $SU(3)_{flavor}$ symmetry was established. This symmetry is substantially broken by mass splittings within $SU(3)$ multiplets like for the pseudoscalar mesons with $m_K \simeq 494$ MeV and $m_\pi \simeq 140$ MeV. Hadronic transition matrix-elements however satisfy $SU(3)$ relations quite well. Denoting the matrix element between the pseudoscalar meson P and the weak hadronic current $h^\mu(x)$ by

$$< 0|h^\mu(0)|P(p) >= ip^\mu f_P$$

one obtains for the ratio of the decay widths

$$\frac{\Gamma(K \to \mu\nu)}{\Gamma(\pi \to \mu\nu)} = \frac{m_K}{m_\pi} \left(\frac{1 - m_\mu^2/m_K^2}{1 - m_\mu^2/m_\pi^2} \right)^2 \left(\frac{f_K}{f_\pi} \right)^2 \simeq 1.3$$

and thus

$$\left(\frac{f_K}{f_\pi} \right)^2 \simeq 0.075$$

and not $O(1)$ as suggested by approximate $SU(3)$ symmetry! Cabibbo solved this puzzle by noting that the strangeness conserving $\Delta S = 0$ part and the strangeness changing $\Delta S = 1$ part of the hadronic current mix in a specific way, described by a rotation:

$$h^\mu = h^\mu_{\Delta S=0} \cos\theta_c + h^\mu_{\Delta S=1} \sin\theta_c$$

such that the effective couplings for the two processes are

$$K \to \mu\nu \quad : \quad G_F \sin\theta_c$$
$$\pi \to \mu\nu \quad : \quad G_F \cos\theta_c$$

with $\sin\theta_c \simeq 0.22$ and thus

$$\left(\frac{f_K}{f_\pi}\right)^2 \to \tan^2\theta_c \left(\frac{f_K}{f_\pi}\right)^2 \simeq 0.0795 \left(\frac{f_K}{f_\pi}\right)^2$$

such that the $SU(3)$ relation $f_K = f_\pi$ is satisfied quite well. Of course if one uses the above ratio to fix the Cabibbo angle one has to consider other processes in order to see whether the above hypothesis makes sense or not.

Baryons: β–decay: $G_n = G_F \cos\theta_c$, Λ–decay: $G_\Lambda = G_F \sin\theta_c$.

In addition, as a result of CVC, μ–decay: $G_\mu = G_F$!

All weak processes **one** coupling G_F up to mixing!

Cabibbo universality works for $\Delta S = 0$ and $\Delta S = 1$ not for $\Delta S = 2$ transitions $\Rightarrow$ requires c–quark!

In SM even NC coupling = CC coupling: $\rho = G_{\rm NC}/G_{\rm CC} = 1$ at tree level! (custodial symmetry)

As a next step Glashow, Iliopoulos and Maiani introduces the c quark in order to explain the absence of FCNC's and thus for the first time considered a 2 family world:

$$\mathcal{L}^{CC} = \frac{g}{2\sqrt{2}} (\bar{u}, \bar{c})\, \gamma_\mu\, (1 - \gamma_5)\, U_{\mathrm{CKM}} \begin{pmatrix} d \\ s \end{pmatrix} W^\mu$$

with the unitary 2×2 matrix

$$U = \begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix} .$$

For N=2 the quark mixing matrix is automatically real and given by a simple rotation, the Cabibbo rotation matrix

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

In the 2 family world the hadronic currents are:

$$
\begin{aligned}
\text{CC:}\quad J_\mu^+ &= \bar{u}\gamma_\mu\,(1-\gamma_5)\,\underbrace{(\;d\cos\theta_c + s\sin\theta_c)}_{\tilde{d}} && \text{Cabibbo}\\
&+ \bar{c}\gamma_\mu\,(1-\gamma_5)\,\underbrace{(-d\sin\theta_c + s\cos\theta_c)}_{\tilde{s}} && \text{GIM piece}\\
\text{NC:}\quad J_\mu^Z &= \bar{u}\gamma_\mu\,(v_u - a_u\gamma_5)\,u + \underbrace{\bar{\tilde{d}}\gamma_\mu\,(v_d - a_d\gamma_5)\,\tilde{d}}_{\text{FCNC}} &&\\
&+ \bar{c}\gamma_\mu\,(v_u - a_u\gamma_5)\,c + \bar{\tilde{s}}\gamma_\mu\,(v_d - a_d\gamma_5)\,\tilde{s} && \text{GIM piece}\\
&= \bar{u}\gamma_\mu\,(v_u - a_u\gamma_5)\,u + \bar{d}\gamma_\mu\,(v_d - a_d\gamma_5)\,d &&\\
&+ \bar{c}\gamma_\mu\,(v_u - a_u\gamma_5)\,c + \bar{s}\gamma_\mu\,(v_d - a_d\gamma_5)\,s\;\;. &&
\end{aligned}
$$

Without the c quark $\tilde{s}$ would be absent in the CC and if one assumes that in the NC only the fields already present in the CC enter one ends up with a flavor changing NC. Although NC's had not been observed at all (before 1973) such FCNC's would have had observable consequences. The N=2 mixing scheme sometimes is called *Cabibbo universality*. Due to the existence of a third family Cabibbo universality is violated, because the 2 by 2 sub-matrix of the CKM-matrix is not unitary. A comparison of the N=2 and the N=3 mixing schemes in the 2 family world yields:

U	N=2	N=3
V_{ud}	$\cos\theta_c$	c_{12}
V_{us}	$\sin\theta_c$	s_{12}
V_{cd}	$-\sin\theta_c$	$-s_{12}c_{23}$
V_{cs}	$\cos\theta_c$	$c_{12}c_{23}$

where we used the excellent approximation $c_{13} = 1$, as c_{13} is known to deviate from unity only in the fifth decimal place.

The N=2 mixing scheme was extended to N=3 by Kobayashi and Maskawa in 1973 in order to incorporate CP-violation in a natural way.

Empirically the CKM matrix elements may be expanded in $\lambda = \sin\theta_{\rm Cabibbo} \simeq 0.22$ with the following approximate sizes of the elements

$$|V| \sim \left(\begin{array}{ccc} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{array} \right) .$$

with $\lambda \simeq \sin\theta_c \simeq 0.22$ given by the sine of the Cabibbo angle. This suggests the Wolfenstein parametrization

(by unitarization up to higher order terms)

$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3\,(\rho - \mathrm{i}\,\boxed{\eta}) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3\,(1-\rho-\mathrm{i}\,\boxed{\eta})) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

where $A \sim 1$ and $\rho^2 + \eta^2 < 1$. The corresponding quark decay pattern is illustrated in the following diagram:

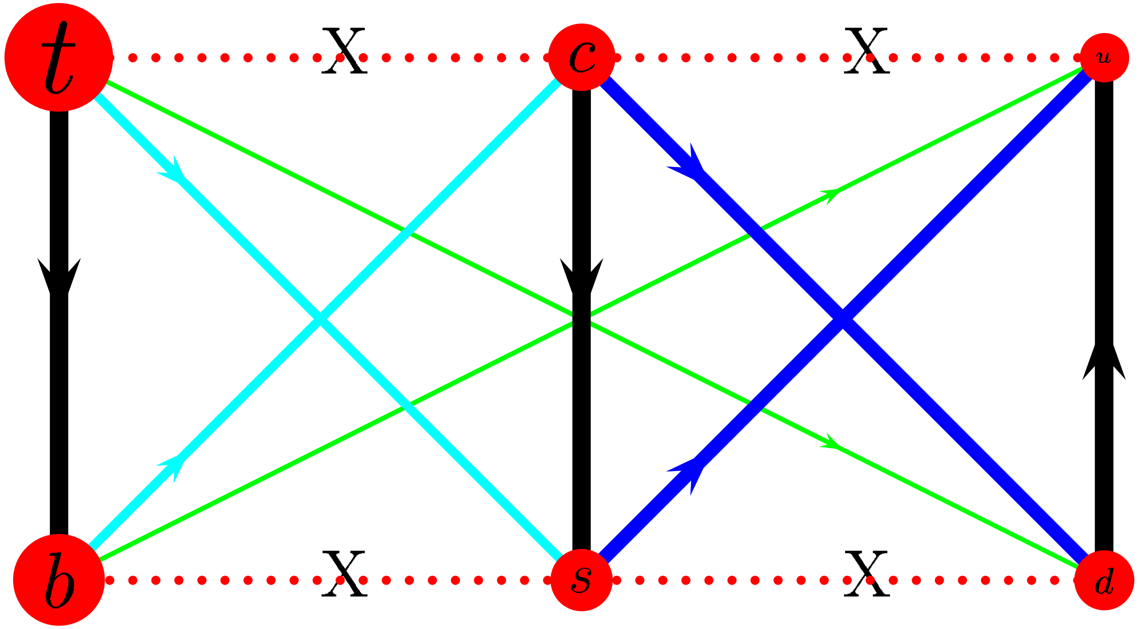
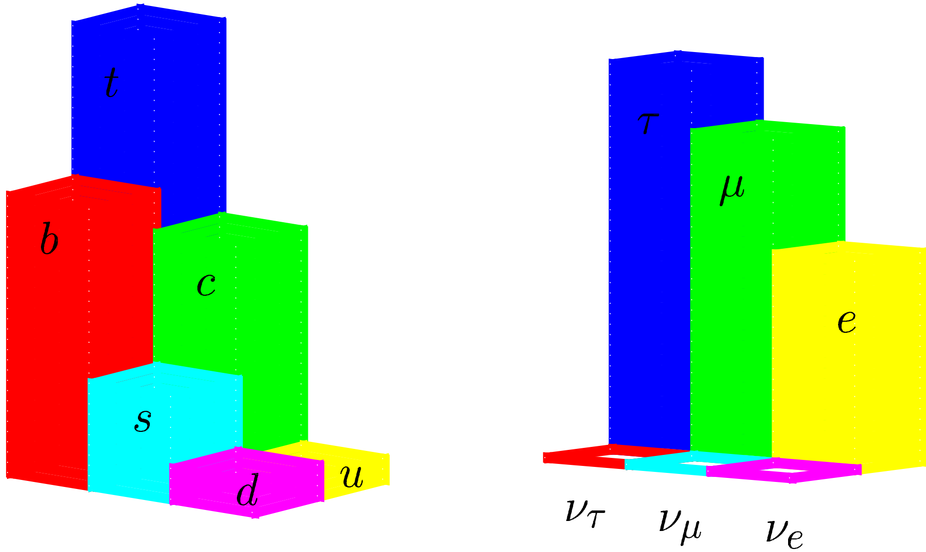


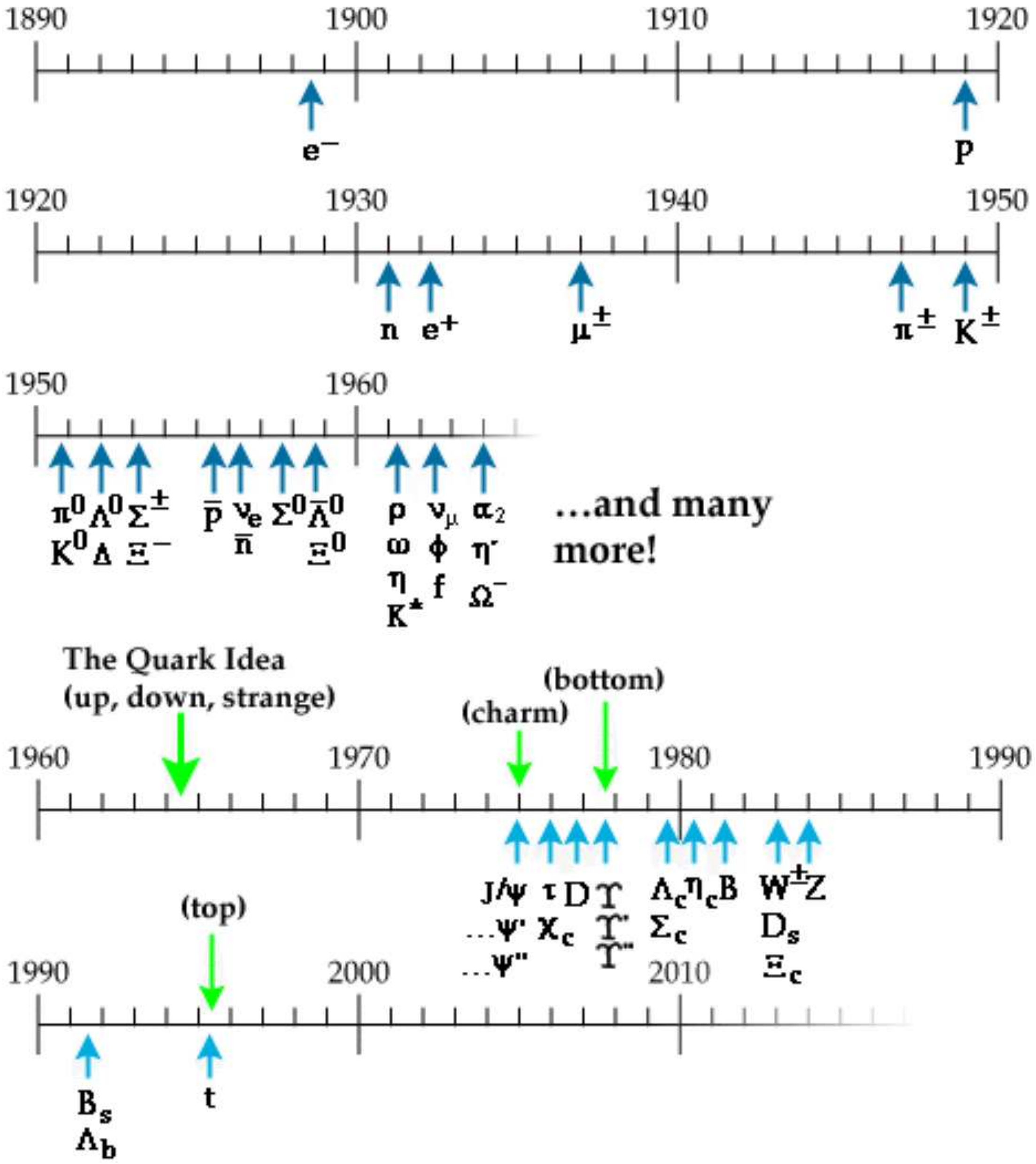
Figure 1: The CKM mixing hierarchy (**??**). FCNCs at tree level are forbidden [X].

Note: the u quark is stable, the s and b quarks are metastable. Flavor changing neutral current transitions are allowed only as second (or higher) order transitions: e.g. $b \longrightarrow s$ is in fact $b \longrightarrow (t^*, c^*, u^*) \longrightarrow s$, where the asterisks indicates “virtual transition”.



Hierarchy of quark (right top) and lepton masses (right bottom)
[$\sim \log m_f$ in arbitrary units]

The Zoo of Elementary Particles



Another History: the basic building blocks of matter

- Family Nr. 1:

e^- [J.J. Thomson 1897],

p [E. Rutherford 1911],

n [J. Chadwick 1932],

ν_e [Pauli's explanation of β–decay 1930/34, Reines [NP 1995], Cowan 1956]

- Family Nr. 2:

μ^- [1937 in cosmic rays],

s Kaons (tiny CP-violation!), Hyperons [1947] strangeness [Gell-Mann, Nishijima 1962],

ν_μ existence of 2nd lepton doublet, Lederman, Schwartz, Steinberger 1962 [NP 1988]

c discovery of Charm 1974, 2nd family complete! Richter, Ting [NP 1976]

Glashow, Iliopoulos, Maiani required c to forbid flavor changing NC's 1970

- Family Nr. 3:

Kobayashi and Maskawa propose 3rd family as a natural (automatic) framework for CP violation in the SM in 1973,

τ^- discovery of tau lepton 1975 by Perl et al. [NP1995],

b discovery of Bottom 1977 (Υ resonances) E288 experiment at Fermilab

t top quark discovery by CDF/D0 at Tevatron 1995,

ν_τ tau neutrino established by DONUT experiment at Tevatron 2000.

GROUP	MULTIPLET	REPRESENTATION	
$SU(3)_c$:	LEPTONS	1	color singlet
	QUARKS	3	color triplet
	ANTIQUARKS	3^*	anticolor triplet
$SU(2)_L$:	$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L , \begin{pmatrix} u \\ \tilde{d} \end{pmatrix}_L$		
	$\begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L , \begin{pmatrix} c \\ \tilde{s} \end{pmatrix}_L$	$2=2^*$	weak iso-spin doublets
	$\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L , \begin{pmatrix} t \\ \tilde{b} \end{pmatrix}_L$		
	$\nu_{eR}, e^-_R, u_R, d_R$		
	$\nu_{\mu R}, \mu^-_R, c_R, s_R$	1	weak iso-spin singlets
	$\nu_{\tau R}, \tau^-_R, t_R, b_R$		
$U(1)_Y$:	$Y = 2(Q - T_3)$	Abelian	weak hypercharge

By $\tilde{q}$ we denoted the Cabibbo-Kobayashi-Maskawa (CKM) rotated quarks $\tilde{q}_d = U_{CKM} q_d$ where $q_d = (d, s, b)$ is a horizontal vector (in family space) of quark mass eigen-fields.

Constituents of matter:

Spin 1/2 fermions

SU(3)$_c$

singlets | color triplets ↓ | anti-triplets

← SU(2)$_L$ weak iso-spin doublets

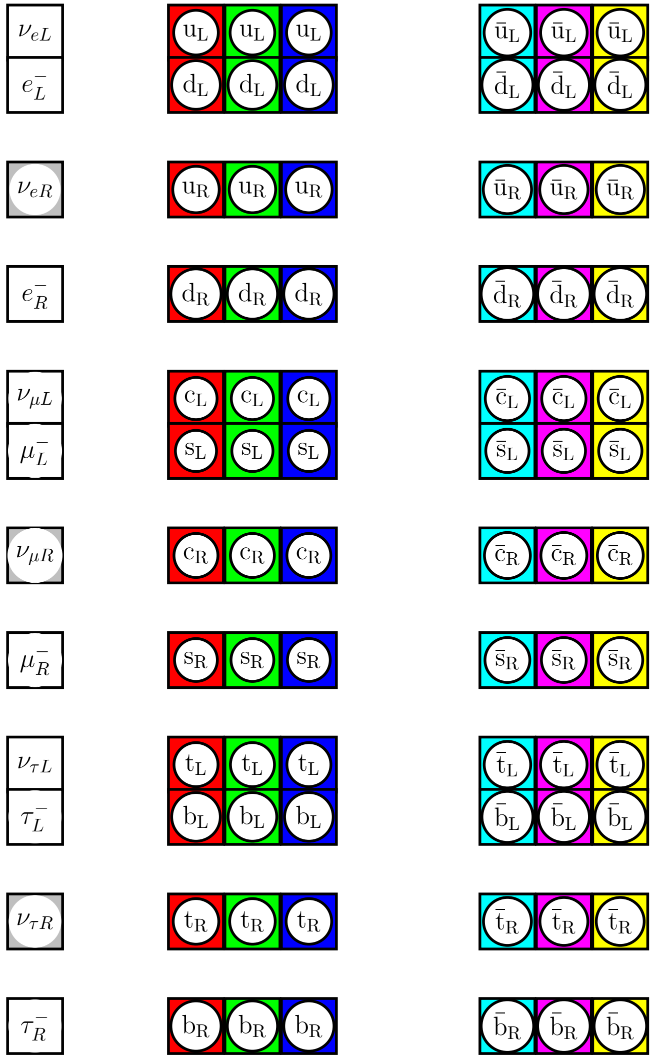
weak iso-spin singlets

sterile ν_s ⇨

1st family

2nd family

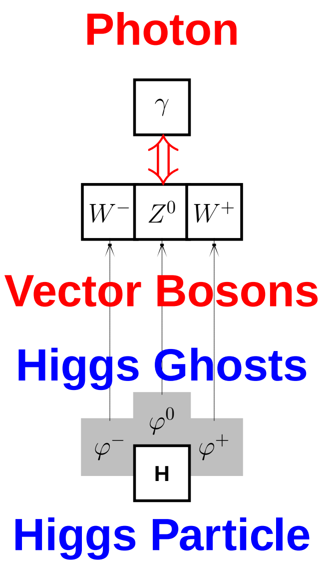
3rd family

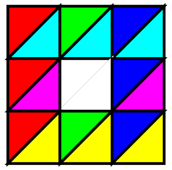


Leptons Quarks

Carrier of Forces:

Spin 1 Gauge Bosons





Octet of Gluons

“Cooper Pairs”:

Spin 0 Higgs Boson

❑ Particle Physics as a low energy effective theory:

We know nature has one unique fundamental dimensionfull parameter: the Planck length of $l_{\rm Planck} \sim 10^{-33}$ cm, which reads $M_{\rm Planck} \sim 10^{19}$ GeV in energy units, all laboratory physics even at the LHC reaching several TeV is all a long distance phenomenon, and what e see looks to us as a quasi-critical system in the sense of critical phenomena in condensed matter physics. But if our universe is like a condensed matter system [the ether], we naturally expect the world to be in a non-trivial ground state and an empty vacuum would look very unlikely anyway. Maybe particle physicists are doing just condensed matter physics, investigating a system with a tremendously large gap between the scales we are able to access and the “atomic” scale which is the Planck scale.

Condensed Matter Physics

Van der Waals 1873 [NP 1910]
· · · Ken Wilson 1971 [NP 1982]
Phase Transitions
Universality near Criticallity
Symmetries at large scales
QFT as a long range phenomenon

Elementay Particle Physics

QFT as the basic structure
gauge interactions
non-triviality of the ground state
massless particles [critical modes]
aquire mass via vacuum condensate

"Gaussian Extended SM"

"Ether": condensed matter state at Planck scale
Critical Effective Field Theory far below Planck scale
"Selforganizing" long distance "stuff"
Emergent structures at long distances [long range Darwinism]
???

❑ The emergence of Yang-Mills structure as a low energy effective theory

"Ether" at Planck scale (some condensed matter state), intrinsic scale (cut-off)

$M_{\rm Planck} = \Lambda_{\rm Pl}$: low energy expansion

$$\mathcal{L}^{\rm eff} \simeq \sum_{i_4} g_{i_4}^{(4)} \Delta\mathcal{L}_{i_4}^{(4)} + \sum_{i_5} g_{i_5}^{(5)} \Delta\mathcal{L}_{i_5}^{(5)} + \sum_{i_6} g_{i_6}^{(6)} \Delta\mathcal{L}_{i_6}^{(6)} + \cdots$$

where upper index is the dimension $n = \dim \Delta\mathcal{L}^{(n)}$. Operators with $n > 4$ are irrelevant in low energy expansion: suppressed by $(E/\Lambda_{\rm Pl})^{n-4}$!

For simplicity consider only 3 particle species:

Scalars: ϕ_a, Fermions: ψ_α, Vector bosons: $W_{i\mu}$ with covariant propagators.

Because of IR power–counting we need consider only terms which are not manifestly irrelevant:

$$\begin{aligned}
\mathcal{L}_1 &= \bar{\psi}_\alpha \left\{ L^i_{\alpha\beta} P_- + R^i_{\alpha\beta} P_+ \right\} \gamma^\mu \psi_\beta W_{\mu i} \\
\mathcal{L}_2 &= \tfrac{1}{2} D_{ijk} W^k_\mu \left(W^j_\alpha \partial_\mu W^{\alpha i} - W^i_\alpha \partial_\mu W^{\alpha j} \right) \\
\mathcal{L}_3 &= \bar{\psi}_\alpha \left\{ C^{+b}_{\alpha\beta} P_+ + C^{-b}_{\alpha\beta} P_- \right\} \psi_\beta \phi^b + \tfrac{1}{2} K^b_{ij} W^i_\mu W^j_\mu \phi_b \\
&\quad + \tfrac{1}{2} T^i_{ba} W^i_\mu \left(\phi_a \partial_\mu \phi_b - \phi_b \partial_\mu \phi_a \right) + \tfrac{1}{4} M^{ij}_{ab} W_{\mu i} W_{\mu j} \phi_a \phi_b
\end{aligned}$$

Predictions: leading low energy effective structure

- **Non-Abelian gauge structure automatic [non-renormalizable terms suppresed by E/Λ_{Pl}]! Conspiracy in small multiplets doublets, triplets $\to SU(2)$, $SU(3)$, $\cdots$ natural [E_6 and other GUT's unnatural!]**

- **Asymptotic freedom must be lost at higher energies: Requires $N \geq$ 9 families!?**

- **Relationship between bare and renormalized parameters must be physical (positivity of counter terms etc.)**

- **Basic QFT features like Einstein causality etc. may be lost lost once $E/\Lambda_P, \;\; (E/\Lambda_P)^2, \cdots$ terms come into play: say at 0.1% level, i.e., above $E \simeq 10^{16}$ GeV**

Other condensed matter physics concept: naturalness G. 't Hooft 1979 "criticallity condition" i.e., existence of long range modes requires relevant operators $n < 4$ to be protected by symmetry [gauge symmetry (spin 1 bosons), chiral symmetry (fermions), supersymmetry (scalars)]!