Highlights in High-Energy Physics
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Review

From Charm to CP Violation

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How To Cite: Maiani, L. From Charm to CP Violation. *Highlights in High-Energy Physics* **2025**, *1*(1), 6. https://doi.org/10.53941/hihep.2025.100006.

Received: 5 April 2025
Revised: 13 June 2025
Accepted: 18 June 2025
Published: 30 June 2025

Abstract: The paper provides a personal recollection of key developments in high-energy physics, from the quark model to CP violation and the November revolution. It highlights how pivotal theoretical breakthroughs, as the GIM mechanism and the formulation of the Standard Model, have been deeply intertwined with experimental discoveries shaping modern particle physics. Lastly a few suggestions are given to orient the search for a more fundamental theory beyond the Standard Model.

Keywords: quark model; charm; GIM; standard model; CP violation

1. Late 1960: Hopes to a Get a Fundamental Theory of Particle Interactions

The years 1960's saw an impressive progress of the theoretical understanding of particle physics, that led to the hope to arrive at a fundamental theory of all particle interactions.

- Abundant spectroscopic data supported the Gell-Mann-Zweig hypothesis [1,2] that hadrons are all composite states of elementary quarks in three flavours ($u,\ d,\ s$): baryons made by three quarks, e.g., $p = (uud)$, $n = (udd)$, etc. and mesons by quark antiquark pairs, e.g., $\pi^+ = u\bar{d},\ \pi^0 = (u\bar{u} - d\bar{d})/\sqrt{2}$, etc.;
- The Cabibbo Theory [3] described in a simple and elegant way the Weak Interactions of hadrons and leptons, in agreement with the $V - A$ [4–6], current $\times$ current Fermi theory and the universality principle. In quark language:

$$\begin{aligned} \mathcal{L}_F &= \frac{G}{\sqrt{2}} J^\lambda J_\lambda \\ J^\lambda &= \bar{\nu}_e \gamma^\lambda (1-\gamma_5) e + \bar{\nu}_\mu \gamma^\lambda (1-\gamma_5)\mu + \bar{u}\gamma^\lambda (1-\gamma_5) d_C \\ d_C &= (\cos\theta_C\ d + \sin\theta_C\ s) \end{aligned} \tag{1}$$

with G the Fermi constant and θ_C a new universal constant known as the Cabibbo angle.

There were clouds, however, pointing out that something was missing:

- Do quark clash with Fermi-Dirac statistics? with first ideas about color by Han and Nambu [7];
- The structure of basic strong interactions was not clear: mediated by *abelian gluons*? determined by *Veneziano duality* [8]?
- Fermi theory is not renormalizable. Is it mediated by a $W^\pm$ boson? Are divergences for hadron weak decays cured by form-factors?

A new line of investigations was opened by J. Schwinger [9], suggesting the unification of Weak and Electromagnetic interactions in a Yang-Mills, non-abelian, gauge theory. The idea was followed by a sequence of bright papers:

- the theory of Glashow (1961) [10], based on the gauge group: $SU(2)_L \otimes U(1)_Y$;
- the Brout-Englert-Higgs Mechanism [11,12], proposing spontaneous symmetry breaking of the gauge symmetry to give a mass to the W boson(1965);
- the model by Weinberg [13] and Salam[14], incorporating the Brout-Englert-Higgs idea in Glashow's model (1967).

The unified theories, however, could be applied to lepton interactions only: embedding the Cabibbo Theory in $SU(2)_L \otimes U(1)_Y$ would produce flavour-changing neutral currents to first order in the Fermi constant, in blatant contradiction with data. Does unification work for leptons only? Or, are flavour-changing neutral currents suppressed by form factors ?

2. The $G\Lambda^2$ Puzzle, 1968

The discussion on higher order weak interactions was opened in 1968 by a calculation by Boris Ioffe and Evgeny Shabalin [15], indicating that $\Delta S = \pm 1$ neutral currents and $\Delta S = 2$ amplitudes would result from higher order weak interactions, even in a theory with one charged W boson only. Amplitudes, see Figure 1, were found to be divergent, of order $G(G\Lambda^2)$, and in disagreement with experiments, unless limited by an ultraviolet cut-off $\Lambda = 3$–4 GeV (from Δm_K);

The result was based on current algebra commutators: it shows that hadron form factors are irrelevant. Current commutators imply hard constituents.

Similar results were found by R. Marshak and collaborators [16] and by F. Low [17] and the exceedingly small value of the cut-off raised a wide discussion.

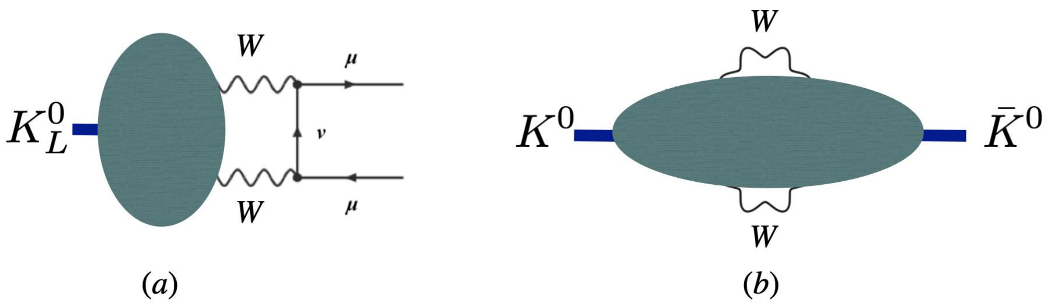

Figure 1. Decays and mixing in the Ko system resulting from higher order weak corrections.

Attempts were made during 1968-69 to make the amplitude more convergent:

- Introducing more than one Intermediate Vector Boson(Gell-Mann, Low, Kroll, Ruderman) [18]: far too many were needed;
- Introducing negative metrics (ghost) states (T.D.Lee and G.C. Wick), of mass $= \Lambda$ [19];
- Another line was to cancel the quadratic divergence, in correspondence to a specific value of the Cabibbo angle, i.e., "computing" the Cabibbo angle (Gatto, Sartori, Tonin,Cabibbo, Maiani) [20,21];
- In this context, it was realised that quadratic divergent amplitudes at order $G\Lambda^2$ would also arise, in the intermediate vector boson theory, with potential violations of strong interaction symmetries (parity, isospin, SU(3) and strangeness). However, with chiral $SU(3)_L \otimes SU(3)_R$ breaking described by a $\mathbf{3} \otimes \bar{\mathbf{3}}$.

...but the small cutoff in the $G(G\Lambda^2)$ terms still called for an explanation.

3. A Personal Recollection

The Ioffe-Shabalin problem was still on the table in November 1969, when I moved to Harvard and met with John Iliopoulos, at work with Shelly Glashow on the $G(G\Lambda^2)$ corrections [22]. We discussed for long, usually two of us arguing against the one at the blackboard, apparently getting nowhere. But during our discussions a change in paradigm occurred. Previous works had been done in the framework of the algebra of currents, Figure 1, but slowly we began to phrase more and more our discussion in terms of quarks.

In quark language, the Ioffe-Shabalin problem is represented by the box diagram in Figure 2a. The divergent amplitude is proportional to the product of the couplings of quarks d and s to the u quark, as required by the Cabibbo theory. By January 1970 we got convinced that we had to modify the weak interaction theory. Once we realised that, the solution was just under our eyes. A fourth quark of charge $+2/3$, called the charm quark, had been introduced by Bjorken and Glashow (and others), for entirely different reasons. In the weak interaction, the charm quark is coupled to s_C, the quark left out in the Cabibbo theory, represented by the orthogonal combination to d_C of Equation (1). The exchange of a c-quark, Figure 2b, cancels the singularity and produces an amplitude of order $G[G(m_c^2 - m_u^2)]$, the GIM mechanism [23].

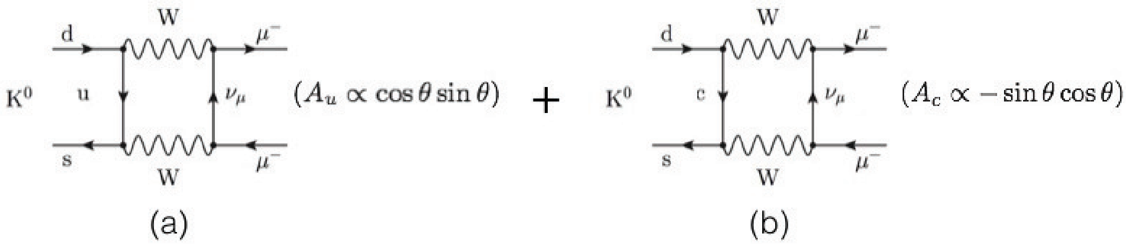

Figure 2. GIM mechanism for $K^0 \to \mu^+\mu^-$.

With two quark generations, Cabibbo weak mixing $d_C = (\cos\theta\; d + \sin\theta\; s)$ is replaced by a unitary 2×2 matrix U

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \tag{2}$$

Charged currents in four-flavor space (u, c, d, s) are given by the matrices C and $C^\dagger$:

$$C = \begin{pmatrix} 0 & U \\ 0 & 0 \end{pmatrix};\; C_3 = [C, C^\dagger] = \begin{pmatrix} UU^\dagger & 0 \\ 0 & -U^\dagger U \end{pmatrix} = \begin{pmatrix} \mathbf{1} & 0 \\ 0 & -\mathbf{1} \end{pmatrix} \tag{3}$$

The neutral current generator, C_3, is flavour diagonal. Thus, a unified gauge theory including charged and neutral vector bosons, as in Refs. [10,13,14], with flavour conserving neutral currents is possible [23].

The observed strangeness changing processes appear to one loop (the first weak interaction loop ever computed), are finite and determined by the mass difference $m_c - m_u$. Ioffe's cutoff becomes the prediction: m_c~1.5 GeV.

A detailed study made later by B. W. Lee and M. K. Gaillard, in the Glashow-Weinberg-Salam theory with two generations of quark and leptons, confirmed the charm quark mass prediction [24].

4. Predictions and Facts Following GIM

Quark-Lepton Symmetry. The fourth quark restores a full quark-lepton symmetry. In fact, quark-lepton symmetry is mandatory for the cancellation of the Adler-Bell-Jackiw anomalies.

Charm is needed, fractionally charged, color triplet quarks are necessary, as shown by Bouchiat, Iliopulos and Meyer in [25], removing the last obstacle towards a renormalizable $SU(2)_L \otimes U(1)_Y$ theory,

Neutrino neutral current processes. Flavor diagonal, neutral current processes are predicted in Yang-Mills theory, to order $G[C, C^\dagger]$; in the unified theory, they appear in lowest order, mediated by Z^0.

1973. The Gargamelle Collaboration led by the French physicist Andrè Lagarrigue, operating the heavy liquid, large bubble chamber exposed to the high energy CERN beam, observes muonless neutrino events: events in which a hadronic jet is produced without an energetic muon track, interpreted as the neutral current process:

$$\nu_\mu + N \to \nu_\mu + \text{hadrons} \tag{4}$$

The Collaboration observed also events with an isolated electron track, interpreted as:

$$\nu_\mu + e \to \nu_\mu + e. \tag{5}$$

1974. The neutrino experiment in Fermilab led by Carlo Rubbia announced the observation of two-muon neutrino events. It was the first positive indication, at least in the Western countries, of the existence of a new quark flavour produced off the nucleons in the $\nu_\mu \to \mu$ transition (the first muon in the final state) and stable enough to decay semileptonically (the second muon). In quark language:

$$\nu + d \to\; c + \mu^- \;\to\; s + \nu_\mu + \mu^+ \;+ \mu^- \tag{6}$$

(Cabibbo suppressed, rate $\propto \sin^2\theta_C$).

The Search for Charmed Particles. In 1970 there was no experimental evidence of weakly decaying hadrons beyond the lowest lying strange baryons and mesons. GIM explanation: ... *Suppose they are all relatively heavy, say 2 GeV. ..will decay rapidly* (10^{-13} *sec) by weak interactions....into a very wide variety of uncharmed final states ?..are copiously produced only in associated production, such events will necessarily be of very complex topology...Charmed mesons could easily have escaped notice* [23].

In fact, in 1971, K. Niu and collaborators observed kinks in cosmic ray emulsion events, indicating unstable particles with lifetimes of order of 10^{-12} to 10^{-13} sec [26], values that were in the right ballpark for charmed particles. They were indeed identified, in Japan, with the weakly decaying p' particle of the extended Sakata model. Following the discovery of two neutrino flavours at Brookhaven (Lederman, Schwarz ad Steinberger, 1962), the Sakata model, with elementary constituents the observed baryons $(p,\ n,\ \Lambda)$, had been extended to $(p,\ n,\ p',\ \Lambda)$, to restore hadron-lepton symmetry. In the Sakata model translation of the Cabibbo theory, p' was coupled weakly to $n' = -\sin\theta_C\ n + \cos\theta_C\ \Lambda$.). Cosmic rays event, unfortunately, were not paid much attention at the time and the Niu events went essentially unnoticed in western countries.

5. The November Revolution

The November Revolution was opened by the simultaneous and independent discovery of a new mesonic particle, at Brookhaven (November 12) and SLAC [27,28] (13 November), with mass 3.098 GeV and width 93 keV, decaying into $e^+e^-,\ \mu^+\mu^-$ and hadrons. The authors named this particle J and Ψ respectively, hence the name J/Ψ adopted since then.

A week later, a Frascati collaboration at the electron-positron collider Adone confirmed the J/Ψ particle [29].

Remarkably, the three papers followed each other so closely that they could appear in the same issue of the Physical Review Letters.

The news arrived in our group in Roma precisely in the day fixed by Nicola Cabibbo for a briefing in Frascati to convince them to search for a narrow width, charm-anticharm vector meson in the Adone energy range(A more detailed account of the events in Roma following J/Ψ discovery are found in [22].).

Already in Harvard we had guessed that this resonance was probably below threshold for decay into a pair of charmed mesons, indeed the ϕ meson is almost in this condition with respect to the $K\bar{K}$ pair. However, the ϕ example led to guess a J/Ψ width in the order of 1 MeV, 10 times the observed value.

In Roma, we noted that a Z^0 of 3 GeV mass coupled with the Fermi constant would decay with about the observed rate. Also, in the form of a confidential rumour, we got from Frascati that the $\mu^+\mu^-$ events could exhibit a backward-forward asymmetry (The initially found asymmetry has very slowly disappeared with the increase of statistics.), a signal of parity violation. All that convinced us to write a quick paper with the proposal of a light Z^0 [30].

Unfortunately for us, the Harvard group was light years ahead. Following previous work by Applequist and Politzer [31], De Rujula and Glashow could explain the large difference of ϕ and J/Ψ widths as due to the strong dependence of the QCD constant from the difference in momentum scale of the two decays and use the smallness of the width to support the charm-anticharm interpretation of the J/Ψ [32] (see Alvaro De Rujula's talk at this Conference).

In these days, things were moving fast. Our paper was received (by Nuovo Cimento Letters) on November 20, De Rujula and Glashow (by Phys. Rev. Letters) on November 27. Few days later, I was reached in Trieste by a phone call by Nicola Cabibbo with the news of the discovery of ψ' at SLAC (November 25), which definitely supported the hadronic nature of the J/Ψ.

In the same days, Greco and Dominguez [33] advanced the proposal of a $c\bar{c}$ resonance, based on an estimate of the rise of the $e^+e^- \to$ hadrons cross section above the J/Ψ mass, based on duality arguments (see Mario Greco's talk at this Conference). This interpretation was questionable due to the presence of problematic $e-\mu$ events. Only in 1977 M. Perl and coll. could prove that these events are due to a new sequential lepton, the τ lepton [34], whose contribution has to be subtracted to obtain the correct $c\bar{c}$ contribution.

In 1976, the D^0 meson, the lightest weakly decaying charmed meson, was discovered by the Mark I detector (SLAC).

In the same year L. Lederman and coll. discovered $\Upsilon = b\bar{b}$ evidence of the 3rd generation together with the τ lepton.

The observation of the top quark at Fermilab (1994) completed the third generation. Since then we have seen no evidence for any further elementary constituent.

6. CP Violation in K Decays

With 4 quarks in 2 doublets (N=2 quark generations with 2N, up and down, lefthanded flavours) it was shown in the GIM paper that the weak coupling matrix U can always be made real [23]. Already commited to a new quark, we did not investigate what would happen with additional quark generations.

In 1973, Kobayashi and Maskawa, explored the possibility of CP violation with more quark generations and discovered that one complex phase is allowed with three quark generations, offering a possible Weak Interaction source of the observed CP violation [35]. In general, for N generations and 2N left-handed fields, one may have a number of irreducible phases given by:

$$N_{\text{phases}} = \frac{(N-1)(N-2)}{2} \tag{7}$$

vanishing in the cases of Cabibbo Theory and GIM. The consequences of KM observation have been studied in 1976 by myself and by Pakvasa and Sugawara, after discovery of the τ lepton and of the b quark [36,37].

A few formulae. CP violation in K decays is well described by the *milliweak interaction* based on the Cabibbo-Kobayash-Maskawa mixing matrix (Closely related parameters $\bar{\rho}$ and $\bar{\eta}$ are frequently used in the literature, with:

$$\rho + i\eta = \frac{(\bar{\rho}+i\bar{\eta})\sqrt{1-A^2\lambda^4}}{\sqrt{1-\lambda^2}[1-A^2\lambda^4(\bar{\rho}+i\bar{\eta})]} = (\bar{\rho}+i\bar{\eta})(1+\mathcal{O}(\lambda^2)) \tag{8}$$

In the Wolfenstein parametrisation [38], valid to order $(\sin\theta_C)^3$:

$$U_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3[1-(\rho+i\eta)] & -A\lambda^2 & 1 \end{pmatrix} \tag{9}$$

with:

$$\lambda = \sin\theta_C = 0.2253 \pm 0.0007; \text{A} = 0.808^{+0.022}_{-0.015}; \rho = 0.132 \pm 0.018,\ \eta = 0.341 \pm 0.013 \tag{10}$$

CP violating $K^0 \to 2\pi$ decays are determined by two different mechanisms: $K_1 - K_2$ mixing (parameter ϵ) and CP-violation in non-leptonic Hamiltonian (parameter ϵ'). One defines:

$$K_1 = \frac{K^0 - \bar{K}^0}{\sqrt{2}}\ (CP=+1);\ K_2 = \frac{K^0+\bar{K}^0}{\sqrt{2}}\ (CP=-1) \tag{11}$$

and the mass eigenstates are (CPT symmetry assumed):

$$K_S = N(K_1 + \epsilon K_2),\ K_L = N(K_2 + \epsilon K_1) \tag{12}$$

- ϵ arises from the $K^0 - \bar{K}^0$ mixing amplitude, which is 2^{nd} order in the Weak Interactions, and it could receive a CP-violating contribution from a Superweak Interaction.
- ϵ' competes with non leptonic interactions of order G. In the Superweak theory $\epsilon' = 0$, and $\epsilon'/\epsilon \neq 0$ indicates a milliweak nature of CP violation.

One defines two CP violating parameters

$$\eta_{+-} = \tfrac{A(K_L\to\pi^+\pi^-)}{A(K_S\to\pi^+\pi^-)};\ \ \eta_{+-} = \epsilon + \tfrac{<K_2|H_{NL}|\pi^+\pi^->}{<K_1|H_{NL}|\pi^+\pi^->} = \epsilon + \epsilon'$$
$$\eta_{00} = \tfrac{A(K_L\to\pi^0\pi^0)}{A(K_S\to\pi^0\pi^0)};\ \ \eta_{00} = \epsilon + \tfrac{<K_2|H_{NL}|\pi^0\pi^0>}{<K_1|H_{NL}|\pi^0\pi^0>} = \epsilon - 2\epsilon'$$

and the ratio ϵ'/ϵ can be obtained experimentally from the ratio

$$R = |\frac{\eta_{00}}{\eta_{+-}}|^2 = 1 - 6\,\mathcal{R}e(\epsilon'/\epsilon) \tag{13}$$

CKM and ϵ. In the Standard Theory ϵ arises from the familiar box diagrams Figure 3, via $d-t$ and $s-t$ couplings in the KM matrix, expected to be small: a milliweak effect, even with a not-so-small CP violating phase.

ϵ'/ϵl: Theory. CP violation is in the operator $\mathcal{O}_t$, the $t-\bar{t}$ penguin, Figure 4, which gives an imaginary contribution to the decay amplitude (with respect to the CP conserving amplitude of order λ):

$$Im(\mathcal{O}_t)/\lambda = (-\eta A^2\lambda^4)\ (\bar{s}_L\gamma_\mu t^A d_L)(\bar{q}_R\gamma^\mu t^A q_R) \tag{14}$$
$$\eta A^2\lambda^4 \sim 0.5\cdot 10^{-3} \tag{15}$$

leading to a theoretical prediction $\epsilon'/\epsilon = \mathcal{O}(10^{-3})$.

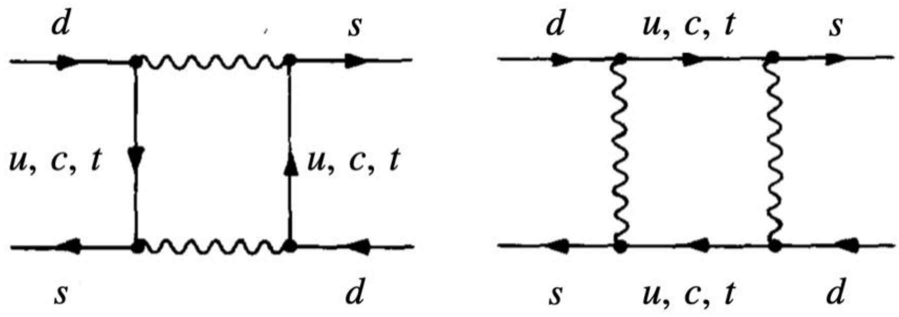

Figure 3. GIM mechanism for $K^0 - \bar{K}^0$ mixing.

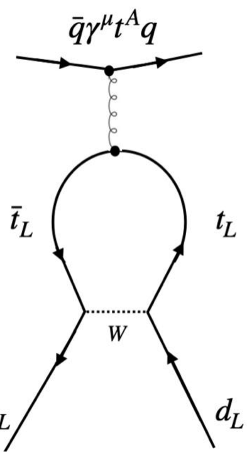

Figure 4. Penguin diagram yielding an imaginary contribution to the decay amplitude.

After several controversial results, a non vanishing value of ϵ'/ϵ was established in 2001 by the NA48 (CERN) and KTeV (FermiLab) Collaborations, with the observation of the double ratio Equation (13):

$$\begin{gathered}\epsilon'/\epsilon \cdot 10^3 = 1.53 \pm 0.26\ (\text{NA48});\ \ 2.07 \pm 0.28\ (\text{KTeV}) \\ [\text{PdG}(2024) : 1.66 \pm 0.23]\end{gathered} \tag{16}$$

7. The Electric Dipole Moment of the Neutron

Milliweak theories of CP violation are in danger to contradict the existing experimental limits to the electric dipole moment (e.d.m.) of the neutron, a T and P violating, $\Delta S = 0$, effect.

In a milliweak theory, we would expect a neutron e.d.m. of the order: $d_e(\mathrm{n}) < 0.18\ 10^{-25}\ e \cdot \mathrm{cm}$

$$d_e(\mathrm{n}) = e \cdot r_P \cdot (GM_P^2)|\epsilon| \sim 10^{-21}\ e \cdot \mathrm{cm} \tag{17}$$

(r_P and M_P the nucleon's radius and mass), vs. the present PdG upper limit: $d_e(\mathrm{n}) < 0.18\ 10^{-25}\ e \cdot \mathrm{cm}$.

The Standard Theory evades the limit at one loop level, since, e.g., for the d-quark, the correction is determined by the real product $V_{dq}(V_{qd})^*$, which brings the previous estimate to $\sim 10^{-24}\ e \cdot \mathrm{cm}$ [36].

Further investigations [39] led to further reductions of the estimate and later to the conclusion that the two loop contribution to $d_e(\mathrm{n})$ vanishes also to two loop order [40], bringing the estimate below $\sim 10^{-30}\ e \cdot \mathrm{cm}$.

8. CP Violation in B Decays

- 1986. I. Bigi and A. Sanda predict direct CP violation in B decay [41].
- 2001, Belle and BaBar discover CP violating mixing effects in B-decays.
- New impetus in theory calculations of $V_{ub},\ V_{cb},\ f_B, \ldots$ from particle phenomenology and Lattice QCD.

We report in Figure 5 examples of lattice QCD determination of the CKM parameter V_{ub} and V_{cb} by the UT_{fit} Lattice Collaboration [42] from electroweak effects, including CP violation in K and B decays.

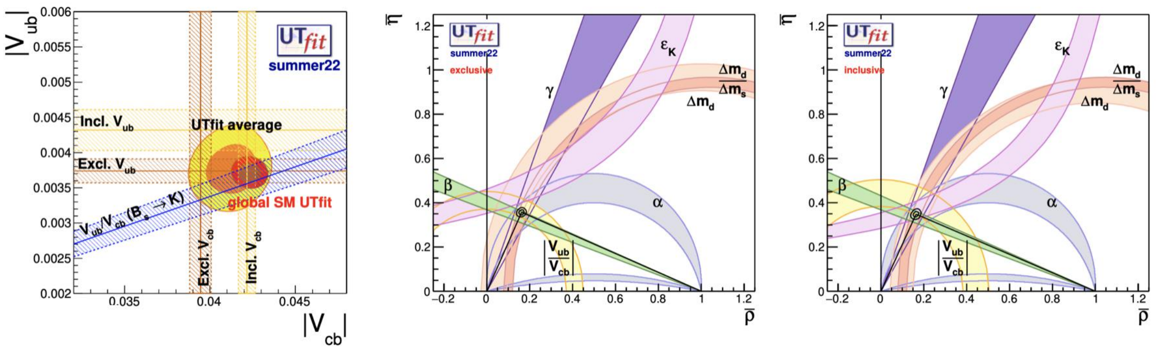

Figure 5. Examples of lattice QCD determination of the CKM parameter $V_{ub},\ V_{cb}$.

9. The Special Role of Massive Quarks in QCD

- QCD is asymptotically free. Quarks carry color, associated to $SU(3)_{col}$ and flavour, associated to $S(3)_{flavour}$, and are confined inside color singlet hadrons. The momentum scale which marks the transition from non-perturbative to perturbative QCD is called Λ_{QCD}. Numerically: $\Lambda_{QCD} \simeq 250$ MeV.
- The decrease of the colour coupling $\alpha_S(q^2)$ has been observed at LEP and LHC and is consistent with the value $\alpha_S(q^2 = M_Z^2) = 0.1185$.
- Quarks u and d have small masses, $m_q \simeq \Lambda_{QCD}$, and fall in the color strong interaction regime. The strange quark is marginal, but from charm onward we are in the heavy quark region ($m_Q >> \Lambda_{QCD}$). Inclusive semileptonic decays are calculable like deep inelastic processes.
- Bound states involve short distance forces, implying a calculable spectrum of charmonia and bottomonia, as first observed by Politzer and Appelquist [31].
- Heavy quark $c\bar{c}$ or $b\bar{b}$ pairs inside hadrons are not easily created or destroyed. A hadron decaying into J/Ψ or $\Upsilon+$ light hadrons, most likely contains a valence $c\bar{c}$ or $b\bar{b}$ pair: heavy-quark counting is possible.

Parton model and perturbative QCD have been used in the years 1980s to compute inclusive semileptonic widths and the energy spectra of the charged lepton in charmed and beauty quarks, see e.g., [43–46] and have provided a valuable method to determine the CKM couplings $V_{ub},\ V_{cb}$ from inclusive semileptonic decays of charm and beauty.

The special role of heavy quarks as indicators of multiquark structures, mentioned in the last bullet, was recognised in the years 2000, in connection with the observation of so-called *unanticipated charmonia* discussed in the next Section.

10. Unanticipated Charmonia: X, Y, Z and More

Unanticipated, hidden charm/beauty resonances not fitting in predicted charmonium/bottomonium spectra have been observed, classified initially as $\mathbf{X},\ \mathbf{Y}$ and $\mathbf{Z}$ particles.

- X, e.g., $X(3872)$ (BELLE, BaBar, 2003): neutral, typically seen in $\Psi + 2\pi$, positive parity: $J^{PC} = 0^{++},\ 1^{++},\ 2^{++}$.
- Y, e.g., $Y(4260)$ (BaBar, 2005): neutral, seen in e^+e^- annihilation with Initial State Radiation (ISR): $e^+e^- \to e^+e^- + \gamma_{ISR} \to Y + \gamma_{ISR}$, therefore $J^{PC} = 1^{--}$.
- Z, e.g., $Z(4430)$ (BELLE, 2007; confirmed by LHCB, 2014): typically $J^{PC} = 1^{+-}$, charged or neutral; mostly seen to decay in $\Psi + \pi$ ($Z(3900)$, (BESIII 2013), and $h_c(1P) + \pi$ ($Z(4020)$, (BESIII, 2013). 4 valence quarks manifest in the charged Z: ($c\bar{c}u\bar{d}$). Z_b observed ($b\bar{b}u\bar{d}$).

Figure 6 reports, in black, a recent determination of the spectrum of charmonia, Ref. [47,48], using the Cornell potential [49–51], see also [52]. In red, the lowest lying unexpected charmonia.

Unexpected, electrically neutral states differ from charmonia also by their decay modes, e.g., $X(3872) \to J/\Psi + \rho^0/\omega^0$ with a substantial violation of isospin symmetry, not expected for a pure $c\bar{c}$ bound state.

We know by now about one hundred meson resonances that contain two quark pairs, tetraquarks ($c\bar{c}q\bar{q}$ or $cc\bar{q}\bar{q}$), and a few baryons with ($c\bar{c}qqq$) composition, pentaquarks: an entire family of new states is showing up.

Multiquark hidden charm hadrons, in hadron colliders, originate mostly from the decays of mesons and baryons containing b-quark, via the weak decay $b \to c + (\bar{c}s)$. For B^+ decay see Figure 7, taken from [53]. A similar diagram for Λ_b gives rise to pentaquark production: $\Lambda_b \to K + \mathcal{P} \to K + J/\Psi + p$.

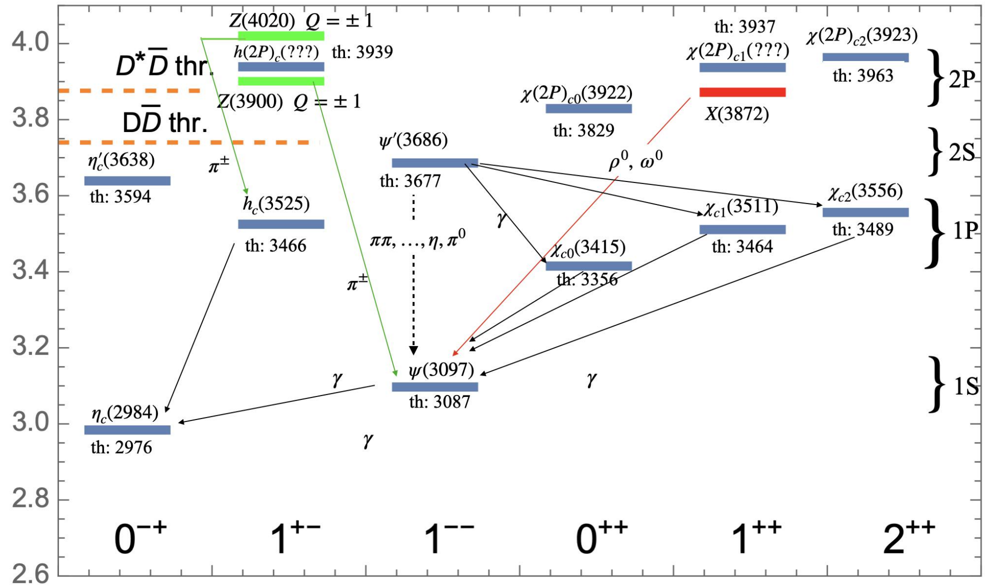

Figure 6. Predicted and observed charmonia, $S1,2$ and $P1,2$ states in (black). In red the first discovered unanticipated charmonia. Figure from Ref. [47] .

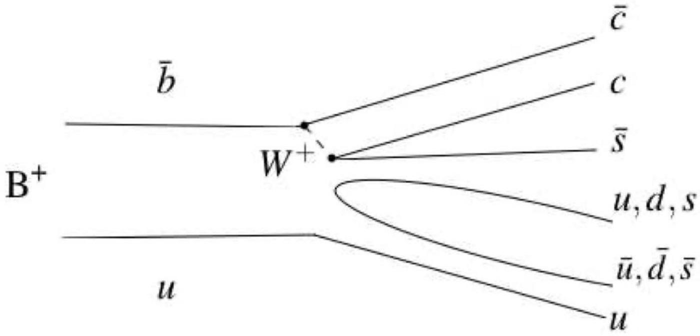

Figure 7. Quark diagram for $B^+ \to K^+ + X$, with $X = (c\bar{c}q\bar{q}')$. Figure from [53].

The challenge, after X, Y and Z particle discovery, is to reconcile their structure with what we know about the binding of the classical mesons ($q\bar{q}$) and baryons (qqq) by QCD interactions.

There is no consensus yet. A few alternatives still under discussion can be described as follows, see also [54].

- The first guess advanced for $X(3872)$ was that of a *hadron molecule*, pioneered by E. Braaten [55]: a ($D\bar{D}^*$ + C-conjugate) meson pair bound by the same nuclear forces that bind nucleons in atomic nuclei. The rationale was the closeness of X mass to the $D\bar{D}^*$ threshold, reminding the deuteron pn bound state, see [56] for a more recent review. In the first papers, pion exchange was considered to provide the binding force, but this is incompatible with exotic mesons such as $J/\Psi - \phi$ or Z_{cs}, which cannot be bound by pion exchange. A recently advanced hypothesis [57] to connect exotic hadrons to the known mesons is that *contact interactions*, described by a chiral Effective Field Theory, produce exotic hadrons as real or virtual poles in the scattering amplitude of meson pairs.
- A different scheme is provided by the *compact diquark-antidiquark* picture proposed in 2005 and further specified in 2014 [58,59]. It describes the exotic hadrons as multiquark states bound by QCD forces, in addition to but independent from $q\bar{q}$ mesons or qqq baryons. Closeness to meson pair thresholds of the lowest lying exotic hadron masses would be the obvious consequence of the fact that these exotic hadrons are made of the same quarks as Gell-Mann Zweig mesons and baryons.
- Models based on pure QCD interactions and specific to hidden charm or hidden beauty exotic hadron, called Hadrocharmonia, have been considered by Voloshin and coll [60] and by Braaten and coll [61], in which a color octet, heavy quark pair is formed by QCD forces, with color being shielded by a cloud of light quarks and antiquarks. They are dominated by QCD interactions, and are, in fact, simple variations of the last mentioned scheme.

Exotic $SU(3)$ flavour multiplets, with a characteristic scale of symmetry breaking is a distinctive prediction of compact tetraquarks. The newly found $J-\phi$ and $J-K$ exotics, Figure 8, fit into nonets with $X(3872)$, $Z_c(3900)$, $Z_c(4020)$.

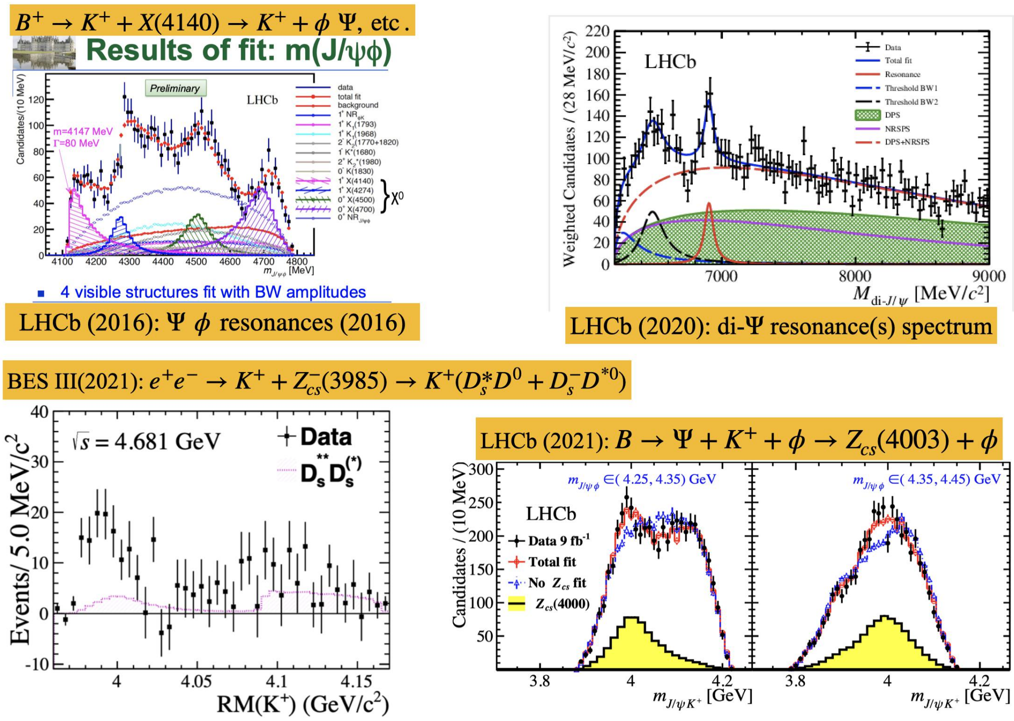

Figure 8. The new wave of multiquark states discovered by LHCb and BES III, 2016-2021. All can be described as multiquark states bound by QCD forces, $J/\Psi-\phi$ and $J/\Psi K$ states fit into SU(3) flavour nonets with $X(3872)$, $Z_C(3900)$ and $Z_c(4020)$.

Much remains to be done, to produce more precise data and to search for still missing particles, to complete the flavour multiples required by QCD bound, multiquark Exotics.

Many questions still remain unanswered. Among the missing particles:

- $X(3872)^+$: the I=1 partner of X(3872), with decays into: $X^+ \to J/\psi\,\rho^\pm \to J/\psi\,\pi^+\pi^0$. X^+ is expected to be produced in B non leptonic decays within the bounds [62]

$$0.057 < \frac{\Gamma(B^0 \to K^+X^- \to K^+\psi\,\pi^0\pi^-)}{\Gamma(B^0 \to K^0X(3872) \to K^0\psi\,\pi^+\pi^-)} < 0.50 \tag{18}$$

- Is $X(3872)$ split into two lines?
- Double charm or beauty spectrum to be explored: can we find $\mathcal{T}_{cc}^{++}(?)$, $\mathcal{T}_{bb}^{-}$?;
- For several missing states, we have predicted mass and decay modes, see e.g., [63];
- Are Exotic hadrons produced in hadron collisions at large p_T, besides $X(3872)$?.

These questions will require more luminosity, better energy definition, detectors with exceptional qualities. . . a lot of work. . . and will keep us busy for quite a while.

Conflicts of Interest

The author declares no conflict of interest.

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