Fundamental Dynamics & Symmetries and for the future – like CP Violation & EDMs

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Abstract

Working with Kolya Uraltsev was a real ‘marvel’ for me in general, but in particular about CP & T violation, QCD & its impact on transitions in heavy flavor hadrons and EDMs. The goal was – and still is – to define fundamental parameters for dynamics, how to measure them and compare SM forces with New Dynamics using the best tools. The correlations of them with accurate data were crucial for Kolya. Here is a review of CP asymmetries in $B$, $D$ and $\tau$ decays, the impact of perturbative and non-perturbative QCD, about EDMs till 2013 – and for the future.

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1 About my collaboration with Kolya

In 1988 Kolya, V.A. Khoze, A.I. Sanda and I have produced the article ”The Question of CP Noninvariance – as seen through the Eyes of Neutral Beauty” that was published in the World Scientific book ”CP Violation” edited by C. Jarlskog [1]. I am proud of that article. Here are two of the best reasons for me:

- After long discussions about this article with the Nobel prize winner Jack Steinberger at the ARCS2000 in the French alps, he smiled and said: ‘Very good work.’
- It discussed CP violation predicted with quarks and how they are affected by ‘hard’ and ‘soft’ re-scattering; I will come back to that.

Kolya and I had not met in person in 1988; that happened first in 1990 when he visited me at Notre Dame and produced your second paper, namely ”Induced Multi-Gluon Couplings and The Neutron Electric Dipole Moment” [2]. A few months later when Kolya was back in the Leningrad Institute of Nuclear Physics, he sent me a Russian paper with a very similar title about this item and asked me, if I agree with that content. I did – so that he put my name as an author and submitted to Zh.Eksp.Teor.Fiz. At that time I could read in Russian. I was very impressed by his work that he had done to add to the previous paper and was honored (and still are) that Kolya put my name on [3]. Now you can read it in English.

Kolya and I spent long times at Notre Dame and at CERN, in particular in the year of 1993/94, when we could work most of the night (and even in the week from Christmas to New Year, when the CERN rooms were cold) 1. Vivek Sharma allowed us to use the rooms, computers and printers there 2. It was a fruitfull year. We had worked with Vainshtein and Shifman by email and phones about establishing Heavy Quark Symmetry (HQS) and its expansion (HQE) not only in principle, but also ‘practical’. Kolya had produced new theoretical tools for non-perturbative QCD. He knew that hard theoretical working is needed to produce trustworthy predictions – and it often takes a lot of time. Finally we have to check correlations with other data. He also said that in the end data

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1Kolya's wife Lilya knew how to deal with Russian theorists; Kolya could not find a better wife, and he knew it. Kolya followed Lilya's expeditions to Kola Peninsula in the summers to produce food by fishing.
2Vivek should get fair credit for that.
are the supreme judges. There is a basic difference between pre- and post-diction. One of the obvious examples is the history about the ratio of the lifetimes of beauty baryons vs. mesons. Kolya & his collaborators stated many times that HQE gives a ratio of around 0.9 - 1.0 (and also by Voloshin) – and were steadfast about their prediction when it was in obvious disagreement with the data given during a decade or more. Kolya had spent thinking and working on this item before leading to [4]:

\[
\frac{\tau(\Lambda_b)}{\tau(B_d)} \simeq 1 - \Delta_b, \quad \Delta_b \simeq 0.03 - 0.12.
\]  

(1)

It is important to remember that the limit of HQE is unity here. Therefore our control (or lack) of nonperturbative QCD depends on \(\Delta_b\), which shows large theoretical uncertainties, in particular about non-leptonic dynamics\(^3\). The most accurate data come from the LHCb collab.\(^4\):

\[
\frac{\tau(\Lambda_b)}{\tau(B_d)} = 0.974 \pm 0.006 \pm 0.004.
\]  

(2)

Both Kolya (et al.)\(^4\) and Voloshin\(^5\) were very happy about it – but not surprized at all. This was a true prediction when it was very, very different from data ‘then’ for a long time. It is not obvious how much working and deep understanding of dynamics were needed to give these predictions – but it is true.

Before I write about dynamics in some details, I want to say: Kolya was a wonderful person. I know he was very interested about art and history obviously for a person who was born in Russia, worked in Italy, France, Japan and Siegen (the painter P.P. Rubens was born in Siegen, not in Holland!). Kolya with his family and I spent a day in the small city in Arezzo in Italy to see paintings, churches and architectures there. He liked long discussions about fundamental physics with passion and honesty. He was a true wonderful friend. He often asked me about my family’s health situation (including my mother’s one) and how he could help, when he was in a bad situation himself. I miss him so much.

Here I give a review mostly of CP symmetry and its asymmetries, impact of QCD, some subtle points about EDMs and write about the future for the next ten years.

2 CP symmetry and its violations

In 1964 – fifty years ago – CP violation has been found due to the existence of \(K_L \to \pi^+\pi^-\). Okun explicitly listed the search for it as a priority for the future in his 1963 text book\(^7\) – a true prophet, since he was the only one. It has been predicted in 1981\(^8\) that sizable or even large CP violation should be found in \(B^0 \to \psi K_S\) transitions when the CKM model of flavor dynamics is a least the leading source of it. The existence of \(B\) mesons has not been established then, never mind top quarks. After 1981 Sanda & I and Uraltsev & collaborators had worked about CP asymmetries in \(B\) and \(D\) mesons in parallel by refining theoretical tools, but without communications between Russia on one

\(^3\)Voloshin preferred to say \(\Delta_b \simeq 0.0 - 0.1\)\(^5\).
side and Westeurope/USA on the other side due to ‘iron curtain’. It was predicted that CKM dynamics produce sizable or even large indirect CP violation in $B_d$ oscillation, but small one in $B_s^0$ ones.

2.1 Landscape of CP & T violation 1986 till 2013

It was known that two neutral $B^0$ and $B^0_s$ mesons oscillate, but in different landscapes of $x = \Delta M_B/\Gamma_B$ due to SM dynamics. As pointed out by Azimov, Uraltsev & Khoze [9], indirect CP violation is small in $B_s^0$ oscillations. However those can produce sizable CP asymmetries in CKM suppressed $B^0_s$ decays, and therefore one has to look for them. They emphasized the hierarchy of neutral $B$ decays. Their quantitative predictions are based on the experimental claim that top quarks have been found with $M_t = 40 \pm 10$ GeV. It has been found that this claim was wrong, as history shows. Still Azimov, Uraltsev & Khoze have good reasons to be proud of this paper, since the basic idea is correct.

By 1987 $B$ mesons had been found with $|V_{ub}| \ll |V_{cb}|$ and sizable $B_d$ oscillations [10]; indirectly they gave reasons about existence of top quarks with $50 \text{ GeV} < m_t < 200 \text{ GeV}$. The long article [11] by Khoze, Sanda, Uraltsev and me discussed both indirect and direct CP violation in $B_d$, $B_s$ and $D^0$. The collaboration of these theorists happened by phones, emails and exchanging files between West Coast in the USA and Russia.

The 1988 article consisted of five Acts plus Prologue & Epilogue: Act I. The Plots: CP Asymmetries in $B$ Decays; Act II. The Likely Hero: $B_d$ & its Decays; Act III. The Dark Horse: $B_s$ & its Decays; Act IV. The Dark Side – Search Scenarios; Act V. Conclusions and Outlook.

It focused on crucial points: (i) Three sides of ‘the’ CKM triangle are all of the order of $\lambda^3$; it gives CP asymmetries between $\sim 10\%$ and $\sim 80\%$ for $B_d$ and $B^+$ transitions due to large angles [14]. (ii) Another triangle allows to probe $B_s$ transitions. It gives one small angle that leads to indirect CP violation due to $\lambda^2$ around $5\%$ in $B_s$ oscillations, but allows large direct CP asymmetries. (iii) CP violation in $D$ decays are given by the order of $\lambda^4$ – i.e. a few $\times 10^{-3}$ in the SM. (iv) There are ‘good’ and ‘bad’ signs; I will come back to that later. (v) We have to look for the impact from New Dynamics (ND) with more accuracy and/or in rare decays. (vi) For direct CP violation in two- and three-body final states (FS) one need final state interactions (FSI), and strong forces can do it. (vii) Penguin diagrams [12] can affect or even produce direct CP asymmetries in $B_{u,d,s}$ decays. However there are several subtle points: penguin diagrams are formulated for quark states; to compare those predictions with measured data with hadrons one has to use the concept of ‘duality’.

Penguin diagrams emphasize their connections with local operators; first it was introduced for kaon nonleptonic decays. For $B$ decays it affects inclusive final state with hard re-scattering. For CP asymmetry in exclusive ones one has to deal with soft re-scattering. Based on rough models (although it needed a lot of work about strong forces and checked

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4When I found the statement from CERN outside our offices in the theoretical HEP group in Aachen, I looked at it and said: ”They found it!” Peter Zerwas look at it, read it, thought for a few minutes and said: ”It must be wrong, and I give you my reasons.” Peter was correct as usual.
it with other observables) it had predicted $A_{\text{CP}}(B_d \to K^- \pi^+) \sim 0.1$. It is a decent prediction so early one about subtle features of $B$ dynamics. Actually this article gave good predictions in general, namely:

- $B_d$ transitions are the ‘hero’ of true large CP violation in the SM as predicted in Act II. It was stated that in the future the angles $\phi_1$ in $B_d \to \psi K_S$ and $\phi_2$ in $B_d \to \pi^+ \pi^-$ will be measured with sizable or even large ones; the latter one will also show sizable direct CP asymmetry.

It was established only in 2001 about $B_d \to \psi K_S$; later PDG 2013 gives:

$$S_{\text{CP}}(B_d \to \psi K_S) = \sin \phi_1 = +0.676 \pm 0.021$$

Very recent Belle data show [13]:

$$S_{\text{CP}}(B_d \to \pi^+ \pi^-) = -0.64 \pm 0.08_{\text{stat.}} \pm 0.03_{\text{syst.}}$$
$$A_{\text{CP}}(B_d \to \pi^+ \pi^-) = +0.64 \pm 0.33_{\text{stat.}} \pm 0.03_{\text{syst.}}$$

- Indeed $B_s$ decays are ‘Dark Horse(s)’ in Act III: (i) The SM gives CP asymmetries in semi-leptonic decays significantly less than $10^{-4}$, while ND could produce it ‘closer’ to 0.01. (ii) Indirect CP violation in $B_s \to \psi \phi$ could be seen around a few percent due to SM, while ND would reach the 10 - 20 % level as Sanda & I had said it before 2000. (iii) Direct CP asymmetries in CKM suppressed decays could be large.

Very recent LHCb data confirm these 1988 predictions in subtle ways [14]; first:

$$\frac{\Delta \Gamma(B_s)}{\text{ps}} = 0.106 \pm 0.011 \pm 0.007, \quad \frac{\Gamma(B_s)}{\text{ps}} = 0.661 \pm 0.004 \pm 0.006, \quad y_s \simeq 0.08 \quad (6)$$

Kolya & I was not sure (and I am still) about the small theoretical uncertainty about $\Delta \Gamma(B_s)$; Alex Lenz will discuss it in his article. I focus on indirect CP violation:

$$\phi_{\text{C\bar{C}}s}^{\text{C\bar{C}s}} = (0.01 \pm 0.07 \pm 0.01) \text{ rad vs. } \phi_{\text{C\bar{C}}s}^{\text{C\bar{C}s}} = (-0.0363_{+0.0016}^{+0.0016}) \text{ rad (SM)} \quad (7)$$

These data are close to expected SM values – but also consistent with ND’s contributions to be sizable or even leading source there. Furthermore I disagree with the uncertainty from the SM usually claimed in the literature; below I will explain why.

- Search scenarios for CP violation in neutral heavy mesons are discussed indeed in Act IV about the ‘Dark Side’ of neutral beauty and charm mesons: (i) It had been emphasized that CP violation in inclusive decays are much smaller than found in exclusive ones. (ii) It talked about CP asymmetries in $D^0$ decays.

- In Act V it was pointed out that the connection between the observables and the underlying electronweak parameters is ‘obscured’ by the impact of FSI in 1988.
• Epilogue gave important comments: Once detailed data on $B$ decays came to compare with our rather accurate predictions, but failed them – there would be “no plausible denial” that the CKM theory could no longer be maintained as the sole or even dominant source of CP violation – therefore ND had to exist.

Now the landscape has changed: the SM gives at least the leading source of CP violation in $B$ decays; therefore we have to go from ‘accuracy’ to ‘precision’. That is the landscape upon us; it seems to me that ‘young’ people working in HEP (both on the experimental and theoretical side) would like to produce that transfer (I hope). Furthermore we need more deeper understanding of charm decays.

We knew that the impacts of penguin diagrams about hadronic FS and CP asymmetries are very subtle already about $B$ decays, even much more about $D$ ones. It was discussed deeper in 1990 by Dokshitzer & Uraltsev Ref.[15], and at the DPF-92 meeting at Fermilab, where Kolya gave a talk in a short paper about FSI phases [16]. One needs only short time to read it – but only long time to think about the items like inclusive vs. exclusive transitions and ‘hard’ vs. ‘soft’ re-scattering.

From my own direct experience during this long period I know that Kolya was a real leader about probing CP violation in beauty and charm decays and understanding the information given by data then, now – and the future. Furthermore Kolya showed us that the first and second rounds are not enough – one has to go further.

2.2 Duality – the connection of quark & hadronic diagrams

The item of ‘duality’ between quarks and hadronic forces has been used in very different situations. Some are straightforward like for ‘jets’, while others are subtle: flavor forces depend crucially about non-perturbative impact of QCD. Kolya & collaborators have worked about duality as a tool in HQE mostly for beauty hadrons decays. It is not enough to give hand-waving statements there – we can defend them with some accuracy to measure CKM triangles and compare inclusive vs. exclusive rates. It is not enough at all to compare sums of measured hadronic FS rates vs. parton model ones with quarks. One of the first papers to deal with this subtle item was given in 1986 [17]. It gives us insight into inner structure of strong forces. We had discussed local vs. semi-local duality and how close one has to go to thresholds as discussed in Ref.[18]. It will be discussed in other articles in this Memorial Book. For heavy quarks the ratios of lifetimes of baryons and mesons go to unity by $\sim (m_c/m_b)^2$ in HQE and higher order; thus the theoretical uncertainty is ‘sizable’. The next steps are to measure $\tau(\Xi_b^0)$ and $\tau(\Xi_b^-)$ with some accuracy. It was predicted [5]: $\tau(\Xi_b^0) \simeq \tau(\Lambda_b) < \tau(B_d) < \tau(\Xi_b^-)$. It shows how much we can control the impact of non-perturbative QCD in a semi-quantitative way on inclusive decays of beauty hadrons. Data told us we can reproduce the lifetimes of charm ones semi-quantitatively – just luck?
2.2.1 Re-scattering & CP violation & CPT constraints

It is important to think about the connections between quark diagrams and measured (or measurable) rates with hadrons. There are important, but subtle points:

- In the quark world we use weak dynamics with $b\bar{q} \rightarrow q_1 \bar{q}_2 q_3 \bar{q}_4$ (even with including ‘Weak Annihilation/Scattering’). Using SM we deal with inclusive FS with $q_i = u, d, s$. Including QCD forces we use $m_u < m_d \ll m_s < \Lambda$. The predictions are different due to iso-spin and $SU(3)_{fl}$ violations, however differences are small compared to $\Lambda$ for inclusive rates. Measured inclusive FS consist of sums of hadrons; those show little effect of $SU(3)$ $fl$ violation.

- The landscapes for exclusive non-leptonic decays are quite different. Two-, three- and four-body etc. FS can easily show sizable $SU(3)$ $fl$ violation and therefore about CP asymmetries. The impact are due to re-scattering with QCD dynamics, in particular soft re-scattering with non-perturbative forces. It can be calibrated by $M_K$ vs. $M_\pi$, the impact of chiral symmetry and its violations.

The connection between the strength of re-scattering, CP asymmetries and CPT invariance has been discussed in Ref. [1]; it is given in Sect. 4.10 in Ref. [19] with much more details including CPT invariance following the history sketched above:

\[ T(P \rightarrow a) = e^{i\delta_a} \left[ T_a + \sum_{a \neq a_j} T_{a_j}^{\text{resc}} \right] \]

\[ T(\bar{P} \rightarrow \bar{a}) = e^{i\delta_a} \left[ T^*_a + \sum_{a \neq a_j} T^*_a \left. T_{a_j}^{\text{resc}} \right] \]

where amplitudes $T_{a_j a}^{\text{resc}}$ describe FSI between $a$ and intermediate states $a_j$ that connect with this FS. Thus one gets for regional CP asymmetries:

\[ \Delta \gamma(a) = |T(P \rightarrow \bar{a})|^2 - |T(P \rightarrow a)|^2 = 4 \sum_{a \neq a_j} T_{a_j a}^{\text{resc}} \text{Im} T^*_a T_{a_j} \]

For the near future one can focus on strong FSI. For this work I apply these amplitudes for FS with hadrons and resonances: $P \rightarrow h_1 [h_2 h_3] + h_2 [h_1 h_3] + h_3 [h_1 h_2] \Rightarrow h_1 h_2 h_3$. This CP asymmetry has to vanish upon summing over all such states $a$:

\[ \sum_a \Delta \gamma(a) = 4 \sum_a \sum_{a \neq a_j} T_{a_j a}^{\text{resc}} \text{Im} T^*_a T_{a_j} = 0 \]

since $T_{a_j a}^{\text{resc}}$ & $\text{Im} T^*_a T_{a_j}$ are symmetric & antisymmetric, respectively, in the indices $a$ & $a_j$. It shows that CPT symmetry imposes equality also between subclasses of partial widths.

These equations apply for amplitudes of hadrons or quarks and also for boundstates of $\bar{q}_i q_j$ (or $q_i q_j q_k$). The crucial point is how to connect ‘measurable’ hadronic amplitudes with quark (& gluon) ones. One can show that connection with diagram; however in
quantitative ways it is subtle due to non-perturbative forces. To make it short: in the world of quarks our tools mostly focus on inclusive transitions, unless one can use other theoretical tools; it depends on our ‘judgement’. I will discuss it separately in $B$ & $D$ decays.

2.2.2 Comments about ‘hard’ vs. ‘soft’ re-scattering

There is a large difference between computing penguin diagrams and what they mean for beauty and charm decays (for different reasons) – unlike for kaon transitions. In beauty decays one can calculate inclusive CKM suppressed FS with CP asymmetries based on ‘hard’ re-scattering between FS with local operators. Penguin diagrams can give us the direction about correlations between hadrons in exclusive FS, but not in a quantitative way. About charm decays we have penguin diagrams about CP asymmetries, but less control over ‘soft’ re-scattering as discussed in Ref.\textsuperscript{[20]} in some details.

2.3 CP violation via Higgs dynamics

We have known for a long time that non-minimal Higgs models could not contribute sizably to $\epsilon$ and/or $\epsilon'$ unless ‘our’ world lives in very tiny corners of Higgs forces. In the 1997 book ”Perspectives on Higgs Physics II”\textsuperscript{[21]} there is an article by Sanda, Uraltsev and me about ”Addressing the Mysterious with the Obscure – CP Violation via Higgs Dynamics”. It focused on EDMs of neutron & electrons & atoms, $T$ odd electron-nucleon interaction & $K \to \mu\nu\pi$ and CP violation in $B$ & $D$ & top transitions. One neutral Higgs boson has been found in 2012, but no charged one (yet).

Probing the impact of ND in $K \to \mu\nu\pi$ will not happen at J-PARC, since other projects have higher priority. On the other hand non-minimal Higgs models are one of leading candidates for ND: they give us the road to SUSY (and thus string theory) directly and indirectly. I will discuss it in the next subsection; however I will first comment about the measurable status of the real Higgs.

The SM neutral Higgs state is 100 % scalar. ATLAS and CMS have established the existence of a neutral spin 0 boson $\Phi$ with a mass combined $125.8 \pm 0.4(\text{stat.}) \pm 0.4(\text{syst.})$ GeV in the FS of $2\gamma$, $l^+l^-$, $\bar{b}b$ quarks, $ZZ^*$ and $WW^*$\textsuperscript{[22]}. We know that $\Phi$ is at least mostly a scalar one, and pseudo-scalar contribution are at best non-leading one. Small pseudo-scalar amplitudes cannot produce sizable rates by themselves, but can sizably contribute to interferences with scalar SM ones – i.e., $\Phi$ state is mixing in leading even and small odd CP states\textsuperscript{[23]}. It is an important project for very high runs at LHC and also ILC.

Another comment about production & decays of established neutral Higgs boson: usually ATLAS and CMS base their analyses about the Higgs width predicted by the SM; however the impact of ND and Dark Matter can hide there. A new idea has appeared, namely to probe $pp \to H + X_1 \to ZZ' + X_2 \to e^+e^-\mu^+\mu^- + X_3$ with $M(e^+e^-\mu^+\mu^-) > 130$ GeV that hardly depend on $\Gamma_H$; then one can compare the data from 126 GeV\textsuperscript{[24]}.
2.4 Probing CP asymmetries in the future

We have predicted in the last 24 years that the SM gives at least the leading source of CP violation in $\Delta B \neq 0$ dynamics. Furthermore the neutral Higgs boson has been found now as expected with $M(H^0) \simeq 125$ GeV. On the other hand the usual reasons for ND exist, namely:

- We need ND to produce ‘us’, namely huge matter vs. antimatter asymmetry now; forces based on the CKM matrix cannot do it.
- Theorists tell us tiny, tiny fine tuning of electric-weak symmetry is a bad idea to get it around 1 TeV instead $10^{10}$ or $10^{15}$ or $10^{19}$ GeV.

The data and our experimental colleagues tell us:

- The three neutrinos have different masses to give oscillations as measured.
- Working about ‘known’ matter (and ‘us’) is a sideshow in ‘our’ universe, since it produces only around 4% part of our universe.
- Dark matter produces around 23%; there are several candidates like SUSY, but none is established (yet).
- Dark energy produce around 73% – but what is it or them?

A very, very lot of work has to be done about ‘our’ universe – but we need even more. CP asymmetries can be based on the interferences between SM amplitude and ND one. It can or might reach higher scales that are not allowed (or close to it) by the SM.

ND can produce at best non-leading source of CP violation in $B$ mesons. Therefore one needs more data with better experimental and theoretical accuracies. First one focus on (quasi-)two-body FS. However I think we have to measure three- and four-body non-leptonic FS and their ‘topologies’ like the two-dimensional Dalitz plots and the correlations between narrow and broad resonances. We need even more data and more tools, but the data give us much more information about the underlying forces. People who work in Hadro-Dynamics have produced and checked their technologies about $h_1h_2 \rightarrow h_3h_4$ scattering; now we can apply them about deeper understanding of fundamental physics. Also we know now that the usual Wolfenstein parameterization is very usable for leading sources of CP violation, but not for non-leading ones.

The situation is different for charm decays. The SM produce only small asymmetries in singly Cabibbo suppressed (SCS) decays and close to zero in doubly Cabibbo (DCS) ones. The limits from the data tell us that ND can produce only small asymmetries in SCS decays. For DCS decays we have little limits about CP asymmetries. However we need much larger productions of $D_{(s)}$ and $\Lambda_c$ states. Again we have to probe FS with three- and four-body FS; CPT invariance is usable there.
The SM cannot produce measurable CP asymmetry in $\tau$ decays beyond the well measured CP violation in $K^0 - \bar{K}^0$ oscillations. BaBar data show CP asymmetry in $\tau^- \rightarrow \nu \bar{K}_S \pi^- [+\pi^0]'s$ that is opposite to predicted one – but only with 2.9 sigma:

$$A_{\text{CP}}(\tau^+ \rightarrow \bar{\nu} \bar{K}_S \pi^+)/|_{\text{SM}} = +(0.36 \pm 0.01)\%$$  \hfill (12)

$$A_{\text{CP}}(\tau^+ \rightarrow \bar{\nu} \bar{K}_S \pi^+ [+\pi^0]'s)/|_{\text{BaBar2012}} = -(0.36 \pm 0.23 \pm 0.11)\%$$  \hfill (13)

Now available data probe only integrated CP asymmetries. It is important to probe regional CP asymmetries in $\tau^- \rightarrow \nu [S = -1]$ FS; we had to wait for Belle II (and Super-Tau-Charm Factory if & when it exists). It is important as pointed out last year to measure the correlations with $D^+ \rightarrow K^+ \pi^+ \pi^- / K^+ K^+ K^-$ etc. \hfill (27).

Finally we have to probe correlations between known matter and candidates of dark matter in CP asymmetries and rare $B$ and $D$ decays – if we get even more data with precision and understand underlying dynamics with better theoretical tools.

The Wolfenstein parametrization for CKM matrix is very obvious about its pattern and therefore very usable. Now we know that the SM produces at least the leading source of CP violation in $B$ transitions. It is true in the real world there is ND in neutrino oscillations, very different rates of matter vs. antimatter and the existence of Dark Matter and Dark Energy.

### 2.4.1 Better parameterization of the CKM matrix

With three quark families one constructs six triangles with different shapes, but also the same area. Obviously one can construct them in several ways. One can do it by their three sides (or the ratios); crucial contributions come from $|V_{ub}|$, $|V_{td}|$, $|V_{ts}|$ etc. In particular vivid discussions are still happen about compare $|V_{ub}|_{\text{excl}}$ vs. $|V_{ub}|_{\text{incl}}$ and $|V_{ub}|_{\text{excl}}$ vs. $|V_{ub}|_{\text{incl}}$. Kolya was a true leader in predicting these four classes of transitions and understanding the informations the data tell us about the underlying dynamics with accuracy; it is discussed in other articles in this Memorial Book.

PDG and HFAG show also the ‘exact’ CKM matrix with three families of quarks. However experimenters and theorists do not use exact CKM matrix as you can see in their papers and talks.

In Wolfenstein parameterization one gets six triangles that are combined into three classes with four parameters $\lambda$, $A$, $\bar{\eta}$ and $\bar{\rho}$ with $\lambda \simeq 0.223$. Those are probed and measured in $K$, $B$, $B_s$ and $D$ transitions: $A \sim 1$, but the two ones are not of $O(1)$: $\bar{\eta} \simeq 0.34$ and $\bar{\rho} \simeq 0.13$. It is assumed – usually without mentioning – that one applies them without expansion of $\bar{\eta}$ and $\bar{\rho}$. Obviously it is a ‘smart’ parameterization with a clear hierarchy.

Now we need a parameterization of the CKM matrix with more precision for non-leading sources in $B$ decays and very small one for CP asymmetries in $D$ decays with little ‘background’ from SM. Several ‘technologies’ was given like in Ref.\hfill [28] with $\lambda$ as before, but $f \sim 0.75$, $\bar{h} \sim 1.35$ and $\delta_{\text{QM}} \sim 90^\circ$. Now we get somewhat different six classes,
and it is more subtle for CP violation:

\[
\begin{align*}
1 - \frac{\lambda^2}{2} &- \frac{\lambda^4}{8} - \frac{\lambda^6}{16}, \\
-\lambda + \frac{\lambda^2}{2} f^2, &-\lambda + \frac{\lambda^2}{2} f, \\
\lambda, &\lambda^3, \\
-\lambda^2 - \frac{\lambda^4}{8} i\delta_{\text{QM}}, &f\lambda^3 - \frac{\lambda^6}{8} i\delta_{\text{QM}}, \\
\frac{f\lambda^2 + \lambda^3 e^{-i\delta_{\text{QM}}}}{2}, &-\frac{\lambda^2}{2} + \lambda^3 e^{-i\delta_{\text{QM}}},
\end{align*}
\]

\( + \mathcal{O}(\lambda^7) \) (14)

Class I.1: \( V_{ud}V_{us}^* [\mathcal{O}(\lambda)] + V_{cd}V_{cs}^* [\mathcal{O}(\lambda)] + V_{td}V_{ts}^* [\mathcal{O}(\lambda^5\lambda^6)] = 0 \) (15)
Class I.2: \( V_{ud}V_{cd} [\mathcal{O}(\lambda)] + V_{us}V_{cs}^* [\mathcal{O}(\lambda)] + V_{ub}V_{cb}^* [\mathcal{O}(\lambda^6\lambda^7)] = 0 \) (16)
Class II.1: \( V_{us}V_{ub}^* [\mathcal{O}(\lambda^5)] + V_{cd}V_{cb}^* [\mathcal{O}(\lambda^2\lambda^3)] + V_{ts}V_{tb}^* [\mathcal{O}(\lambda^2)] = 0 \) (17)
Class II.2: \( V_{cd}V_{ub}^* [\mathcal{O}(\lambda^3)] + V_{cs}V_{ts}^* [\mathcal{O}(\lambda^2\lambda^3)] + V_{cb}V_{tb}^* [\mathcal{O}(\lambda^2\lambda^3)] = 0 \) (18)
Class III.1: \( V_{ud}V_{ub}^* [\mathcal{O}(\lambda^3)] + V_{cd}V_{cb}^* [\mathcal{O}(\lambda^3\lambda^4)] + V_{td}V_{tb}^* [\mathcal{O}(\lambda^3)] = 0 \) (19)
Class III.2: \( V_{ud}V_{td} [\mathcal{O}(\lambda^3)] + V_{us}V_{ts}^* [\mathcal{O}(\lambda^3\lambda^4)] + V_{ub}V_{ub}^* [\mathcal{O}(\lambda^4)] = 0 \) (20)

One finds the same pattern as from Wolfenstein parametrization, namely ‘large’ CP asymmetries in Class III.1, sizable ones in Class II.1 and ‘small’ one in Class I.1. However, the pattern is not so obvious, and it is similar only in a semi-quantitative way:

(i) In Class III.1 triangle one usually calls the two angles \( \phi_1/\beta \) & \( \phi_3/\gamma \). They are measured in CP asymmetries in \( B_d \rightarrow \psi K_S \) & \( B^+ \rightarrow D_s K^+ \) decays due to interference between two contributions one gets from CKM dynamics. Adapting the refined parametrization one finds that CKM dynamics produce \( S(B_d \rightarrow \psi K_S) \) \( \sim 0.72 \) as largest possible value for CP asymmetry with \( \delta_{\text{QM}} \sim 100^\circ - 120^\circ \) to compare with the measured

\[ S(B_d \rightarrow \psi K_S) \sim 0.676 \pm 0.021. \] (21)

When correlations with \( \phi_2/\alpha \) and \( \phi_3/\gamma \) point to \( \phi_1/\beta \approx 75^\circ - 90^\circ \) one gets \( S(B_d \rightarrow \psi K_S) = \sin 2\phi_1 \approx 0.62 - 0.68 \). Therefore it seems that CKM dynamics give very close to ‘maximal’ SM CP violation possible. However the situation is more subtle as mentioned next.

(ii) We are searching for non-leading source of CP violation in \( B \) transitions, in particular in \( B^0 - \bar{B}^0 \) oscillations. ND’s impact could ‘hide’ there in “SM predicted” CP asymmetries. ‘Data’ given by HFAG, for example, are averaged over values of \( |V_{ub}/V_{cb}| \) from \( B \rightarrow l\nu\pi \) and \( B \rightarrow l\nu X_c \); actually the ‘central’ value is closer to \( |V_{ub}|_{\text{excl}} \) rather than the larger \( |V_{ub}|_{\text{incl}} \). It is quite possible that the theoretical uncertainties about extracting \( |V_{cb}|, |V_{ub}| \) and \( |V_{ub}/V_{cb}| \) from \( B \rightarrow l\nu\pi \) vs. \( B \rightarrow l\nu D^* \) are sizably larger than claimed; some details are told about it in Refs. [29]. A new idea using more work and tool like dispersion relations and chiral symmetry (in a smart way) came up very recently, namely to extract \( |V(ub)| \) from data on \( B \rightarrow l\nu\pi^+\pi^- \) [30]; it probes the impact of broad scalar resonances. It gives us more roads to understand the underlying dynamics. One can think also about measuring \( B \rightarrow l\nu K\bar{K} \) and how much you can use chiral symmetry.

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(iii) The information from the data now and in the future about ND has to be based on accuracies and its correlations with different FS in several B, D and K transitions and rare decays.

(iv) It gives more deeper insight into flavour dynamics and QCD’s impact, but also about inner structures for non-perturbative forces.

(v) We have to probe correlations with different FS based on CPT invariance. The best fitting of the data do not give us the best information about the underlying dynamics.

2.5 ‘Catholic’ road to ND – three-body final states

For $D/B \rightarrow P_1P_2P_3$ or $\tau \rightarrow \nu P_1P_2$ decays there is a single path to the ‘heaven’, namely asymmetries in the Dalitz plots. One can rely on relative rather than absolute CP violation; thus it is much less dependent on production asymmetries. However one needs a lot of statistics – and robust pattern recognition.

2.5.1 CP asymmetries in $B^{\pm}$ decays

Data of CKM suppressed $B^+$ decays to charged three-body FS show not surprising rates

$$\text{BR}(B^+ \rightarrow K^+\pi^-\pi^+) = (5.10 \pm 0.29) \cdot 10^{-5}$$

$$\text{BR}(B^+ \rightarrow K^+K^-K^+) = (3.37 \pm 0.22) \cdot 10^{-5}.$$  

LHCb data show sizable CP asymmetries averaged over the FS with correlations $^{[31]}$:

$$\Delta A_{CP}(B^\pm \rightarrow K^\pm\pi^+\pi^-) = +0.032 \pm 0.008_{\text{stat}} \pm 0.004_{\text{syst}}[\pm 0.007_{\psi K^\pm}]$$

$$\Delta A_{CP}(B^\pm \rightarrow K^\pm K^-K^+) = -0.043 \pm 0.009_{\text{stat}} \pm 0.003_{\text{syst}}[\pm 0.007_{\psi K^\pm}].$$  

It is not surprising that these CP asymmetries come with opposite signs (due to the road to CPT invariance). Furthermore it shows ‘regional’ CP asymmetries:

$$A_{CP}(B^\pm \rightarrow K^\pm\pi^+\pi^-)_{\text{regional}} = +0.678 \pm 0.078_{\text{stat}} \pm 0.032_{\text{syst}}[\pm 0.007_{\psi K^\pm}]$$

$$A_{CP}(B^\pm \rightarrow K^\pm K^-K^+)_{\text{regional}} = -0.226 \pm 0.020_{\text{stat}} \pm 0.004_{\text{syst}}[\pm 0.007_{\psi K^\pm}].$$  

‘Regional’ CP asymmetries mean here: (i) positive asymmetry at low $m_{\pi^+\pi^-}$ below $m_{\rho^0}$; (ii) negative asymmetry both at low and high $m_{K^+K^-}$ values. One has to remember that scalar resonances (like $f_0(500)/\sigma$ & $\kappa$) produce broad ones that are not described by Breit-Wigner parametrization; instead they can be described by dispersion relations (or other ways). At the qualitative level one should not be surprised. Probing the topologies of Dalitz plots with accuracy one might find the existence of ND. Most of the data come along the frontiers, while the centers are practically empty. Therefore interferences happen on few places, and regional asymmetries are much larger than averaged ones – but so much?

One looks at even more CKM suppressed three-body FS:

$$\text{BR}(B^+ \rightarrow \pi^+\pi^-\pi^+) = (1.52 \pm 0.14) \cdot 10^{-5}$$

$$\text{BR}(B^+ \rightarrow \pi^+K^-K^+) = (0.52 \pm 0.07) \cdot 10^{-5}.$$  

LHCb has shown these averaged and ‘regional’ CP asymmetries [32]:

\[
A_{CP}(B^\pm \rightarrow \pi^\pm \pi^+\pi^-) = +0.117 \pm 0.021_{\text{stat}} \pm 0.009_{\text{syst}}[\pm 0.007_{\psiK^\pm}]
\]

\[
A_{CP}(B^\pm \rightarrow \pi^\pm K^+K^-) = -0.141 \pm 0.040_{\text{stat}} \pm 0.018_{\text{syst}}[\pm 0.007_{\psiK^\pm}]
\]

\[
\Delta A_{CP}(B^\pm \rightarrow \pi^\pm \pi^+\pi^-)|_{\text{regional}} = +0.584 \pm 0.082_{\text{stat}} \pm 0.027_{\text{syst}}[\pm 0.007_{\psiK^\pm}]
\]

\[
\Delta A_{CP}(B^\pm \rightarrow \pi^\pm K^+K^-)|_{\text{regional}} = -0.648 \pm 0.070_{\text{stat}} \pm 0.013_{\text{syst}}[\pm 0.007_{\psiK^\pm}].
\]

Again it is not surprizing that these asymmetries come with opposite signs. However there are two very interesting statements about the data shown [32]:

- \(B^\pm \rightarrow \pi^\pm \pi^-\pi^+\) decays show CP asymmetries both positive signs with \(m^2_{\pi^+\pi^-} > 15 \text{ GeV}^2\) and \(m^2_{\pi^+\pi^-} < 0.4 \text{ GeV}^2\).

- On the other hand we find negative CP asymmetry in \(m^2_{K^+K^-} < 1.5 \text{ GeV}^2\).

We need more data (those will appear ‘soon’), find other regional asymmetries and work on correlations with other FS. Importantly we need more thinking to understand what the data tell us about the underlying dynamics including the impact of non-perturbative QCD. It seems that the landscape is even more complex as said before and show the impact of really broad resonances.

There will be ‘active’ discussions about the impact of CPT invariance, namely the duality – averaged and regional transitions – between the worlds of hadrons and quarks. There are several reasons that the impact of penguin diagrams are large. However there is a quantitative question now: How can CP asymmetries in Eqs. [29] larger by a factor of three than in Eqs. [24]? Also there are subtle questions, namely the definition of ‘regional’ transitions: The best-fit result does not give us the best information about underlying dynamics, in particular about non-leading sources; we have to think deeper and use several theoretical tools. At first we need some good judgment to define ‘regional’ asymmetry with finite data. Later we can test our judgment with even more – but still finite – data and correlations with other data. Still we need thinking – model independent analyses are not always an excellent idea.

We have to think about the impact of penguins diagrams on exclusive rates and CP asymmetries. It shows the impact of penguins/re-scattering diagrams, since the FS with \(\Delta S \neq 0\) are larger than with \(\Delta S = 0\). However one can remember that penguins operators show only hard re-scattering and focus on inclusive decays. First one probes averaged CP asymmetries, but later regional ones in the Dalitz plots and probe the correlations with different FS as shown above. Such procedures have been suggested and simulated about three-body FS in \(B^\pm\) decays [33] as second steps – but not the final step in my view. The meaning of the analysis ‘being model independent techniques’ is very complex with finite data with non-perturbative QCD about non-leading source of CP violation. It is not enough to trust only LQCD ‘data’; one needs more other theoretical tools with chiral symmetry like dispersion relations based on data with low energy collisions.
2.5.2 CP asymmetries in $D_{(s)}^{\pm}$ ($\tau^{\pm}$) decays

No CP violation has been established in charm hadron decays so far. CPV can well be probed with two-body FS, but also in three- & four-body ones with more data like $D \rightarrow K_S \pi\pi$. Visionary paper by Azimov & Iogansen was published in 1981 about direct CPV in two-body FS [34].

Probing three-body SCS & DCS gives more information about fundamental forces. It was pointed in 1989 [35] in general. One can disagree on several details, however it is important to think about our tools. $D_{(s)}^{\pm}$ has two all charged three-body FS on the SCS level – namely $D_{(s)}^{\pm} \rightarrow \pi^\pm \pi^+ \pi^- / \pi^\pm K^+ K^-$ [36] – and also on the DCS one – $D_{(s)}^{\pm} \rightarrow K^\pm \pi^+ \pi^- / K^\pm K^+ K^-$. $D_{(s)}^{\pm}$ has two ones on the SCS level – $D_{(s)}^{\pm} \rightarrow K^\pm \pi^+ \pi^- / K^\pm K^+ K^-$ – however only one for DCS level – $D_{(s)}^{\pm} \rightarrow K^\pm K^\pm \pi^\mp$.

As stated above, for SCS FS SM gives small ‘background’ for CPV and very close to zero about DCS ones. We have to probe FS with broad resonances – in particular scalar ones like $f_0(500)/\sigma$ and $\kappa$ – and their interferences. The ‘landscapes’ of Dalitz plots in charm decays are different from $B$ decays, when centers are not empty.

There may be a sign – may be – of ND in $\tau$ decays about averaged CP asymmetries, see Eqs. (12,13). It is crucial to probe regional ones. Furthermore one has to measure correlations with $D_{(s)}^{\pm}$ decays [27].

2.6 ‘Protestant’ road to ND – four-body final states

There are several ways to probe CPV in four-body FS and to differentiate the impact of SM vs. ND: the landscapes are even more complex, while our theoretical tool box is smaller so far. On the hand, when we have more data on charm & beauty decays, it will enhance – I hope – the interests of young theorist (maybe from hadrodynamics) to produce new tools for probe four-body FS.

In this article I focus on charm decays. One can compare T odd moments or correlations in $D$ vs. $\bar{D}$. For example one has to measure the angle $\phi$ between the planes of $\pi^+ - \pi^-$ and $K - \bar{K}$ and described its dependence [19,27]:

$$\frac{d\Gamma}{d\phi}(D \rightarrow K\bar{K}\pi^+\pi^-) = \Gamma_1\cos^2\phi + \Gamma_2\sin^2\phi + \Gamma_3\cos\phi\sin\phi$$

$$\frac{d\bar{\Gamma}}{d\phi}(\bar{D} \rightarrow K\bar{K}\pi^+\pi^-) = \bar{\Gamma}_1\cos^2\phi + \bar{\Gamma}_2\sin^2\phi - \bar{\Gamma}_3\cos\phi\sin\phi$$

The partial width for $D[\bar{D}] \rightarrow K\bar{K}\pi^+\pi^-$ is given by $\Gamma_{1,2}[\bar{\Gamma}_{1,2}]$: $\Gamma_1 \neq \bar{\Gamma}_1$ and/or $\Gamma_2 \neq \bar{\Gamma}_2$ represents direct CPV in the partial width. $\Gamma_3$ and $\bar{\Gamma}_3$ represent T odd correlations; by themselves they do not necessarily indicate CPV, since they can be induced by strong FSI; however [37,19]:

$$\Gamma_3 \neq \bar{\Gamma}_3 \rightarrow \text{CPV}$$

Integrated rates give $\Gamma_1 + \Gamma_2$ vs. $\bar{\Gamma}_1 + \bar{\Gamma}_2$; integrated forward-backward asymmetry

$$\langle A \rangle = \frac{\Gamma_3 - \bar{\Gamma}_3}{\pi/2(\Gamma_1 + \Gamma_2 + \bar{\Gamma}_1 + \bar{\Gamma}_2)}$$
gives full information about CPV. One could disentangle $\Gamma_1$ vs. $\bar{\Gamma}_1$ and $\Gamma_2$ vs. $\bar{\Gamma}_2$ by tracking the distribution in $\phi$. If there is a production asymmetry, it gives global $\Gamma_1 = c\bar{\Gamma}_1$, $\Gamma_s = c\bar{\Gamma}_2$ and $\Gamma_3 = -c\bar{\Gamma}_3$ with global $c \neq 1$.

Furthermore one can applying these observables to $D[\bar{D}] \to 4\pi$ (with CPT invariance) and later for $D^+ \to K^+\pi^-\pi^+\pi^-$ vs. $D^- \to K^-\pi^+\pi^-\pi^+$.

Of course, there are other roads to probe CP asymmetries in four-body FS [38]. I want to emphasize that multi-body FS give us more information about the underlying dynamics. However we have not yet the best tools to get it quantitatively. More data will attract theorists to think about it.

2.7 Dealing with final states interactions

Tools about FSI in three-body FS have been produced in the last 15 years, namely dispersion relations (& others) based on low energy collisions with strong forces [39]. Chiral symmetry is a good tool for probing FS for pions. However their impact and the connections of CPT are subtle for $\pi K \Leftrightarrow \pi K$ and $K \bar{K} \Leftrightarrow K \bar{K}$. For four-body FS we need more thinking – but it is very important both on the theoretical and experimental side.

3 Intermezzo: QCD & the strong CP problem

Very shortly I comment about extraction of $V_{cb}$ and $V_{ub}$ and their correlations about CP asymmetries as discussed above and with EDM below.

Comparing $|V_{cb}|$ and $|V_{ub}|$ from inclusive and exclusive semi-leptonic $B$ decays is a very ‘hot’ item – in particular, since the SM produces at least the leading source of semi-leptonic transitions. It is crucial to produce ‘golden’ CKM triangle (and the ‘second triangle’ for $B_s$ transitions) with at least one side of it with accuracy or even precision. As Kolya stated in his last conference talk in November 2012 (using refined theoretical technologies like BPS and non-local correlations), he sees no different values of $|V_{cb}|_{incl}$ vs. $|V_{cb}|_{excl}$; however it does not mean that the angles might not show signs of ND in CP asymmetries.

There is no local ‘competitor’ with QCD to describe strong forces. However, the landscape of QCD forces is more complex and its connection with global symmetries & their violations. Usually we use QCD as a tool to find CP and T violation in $B$, $K$, $D$, top quarks, $\tau$ and neutron & leptons decays due to weak or superweak forces. Of course, there are very good reasons to probe the features of the strong forces in details; there is an expected challenge to our understanding of QCD.

It was pointed out in 1976 by ‘t Hooft [40] that the dimension four operator $G \cdot \tilde{G}$ – with $G$ gluon field strength tensor – can be added to the QCD lagrangian. If one ‘decides’ that this coefficient for this operator is zero, then quantum corrections will come back with non-zero value $\tilde{\theta}$. Thus strong forces violate both P and T invariance called ‘quantum anomaly’: chiral invariance for massless quarks are no longer conserved in quantum field
theory. Strong CP\textsuperscript{5} and chiral problems are furthermore intertwined by including also weak dynamics. The neutron EDM is described by an operator with dimension five. Thus its dimensionful coefficient $d_N$ can be calculated as finite quantity, in particular for $d_N \sim \mathcal{O}((e/M_N)(m_q/M_N)\bar{\theta}) \sim \mathcal{O}(10^{-16}\bar{\theta})$ e-cm \textsuperscript{11}. Data give limits about $d_N$ leading to $\bar{\theta} < 10^{-9}$ or less – an ‘un-natural’ limit seen by most in HEP. Peccei-Quinn symmetry can make it ‘natural’ \textsuperscript{12}. It has been discussed the differences between ‘global’ and ‘local’ symmetry and their limits like for chiral symmetry, whether they were given by symmetry or dynamic mechanism. No axion has been found – yet, however I am still a fan of it for several reasons.

4 Subtle working for EDMs

So far CP & T violations have been established in $\Delta S & \Delta B \neq 0$ transitions, but not in flavor diagonal ones (except ‘our’ existence). There are excellent reasons to probe EDM deeper and deeper in many different states: few are elementary leptons ($e$, $\mu$ & $\tau$), most are very complex (heavy atoms & nuclei) and neutron, proton & deuteron in between. It tells us that the ratio of ND vs. SM effects can be huge. However one goes after tiny effects in subtle environments. It needs long time commitments on the experimental groups (and the funding agencies). If an EDM has been found and established, it would be a wonderful achievement. Then we have to understand the features of the underlying ND. It would be a golden mine for theorists. We have not found them yet. However theorists might help experimenters to continue their hard work with good ideas to find other systems with non-zero EDMs and later about correlations with other ones.

It shows again Kolya’s broad horizon: he had worked about EDMs, Higgs dynamics in the 1980’s, then for CP asymmetries in heavy quark transitions, next for the impact of perturbative and non-perturbative QCD and then about EDMs again. I know he had thought many times, as you had seen during and afterwards discussions about talks given by other people. You knew whether Kolya was attending a seminar or not – it was obvious.

4.1 Early era

Kolya had worked about neutron EDM with A.A. Anselm in 1984 \textsuperscript{13}. I had my first meeting with Anselm at SLAC around 1986; he came to my office after a talk I had given about CP violation in $B_d$ decays and just mentioned a paper about neutron EDM due to Higgs exchanges. He told me politely that most people neglected quark interaction with neutral Higgs bosons. It was claimed that these contributions should be proportional to the third power of light current quarks. However nucleon coupling with neutral Higgs bosons depends on nucleon mass at low momenta and does not vanish in the chiral limit. Higgs exchange could not give sizable contribution to CP violation in kaons transitions, but still could produce neutron EDM around $10^{-22}$ e-cm – i.e., that prediction exceeds $5^{\text{Old problems (like old soldiers) never die – they just fade away!}}$

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experimental limit at least around two orders magnitude. There were very subtle statements to understand that; I had never heard that before. Therefore I read that paper right away and was very impressed by it. Later I had met Anselm at least twice at Winter Schools close to Moscow and always enjoyed talking and discussing with him. Kolya was a graduate student with Anselm and co-autor of 1984 paper.

Kolya and I had produced the first paper in ‘person’ when Kolya was invited to the physics department at Notre Dame in 1990 with the title "Induced Multi-Gluon Couplings and the Neutron EDM". Let us assume that in the future this or another idea will be established ‘natural’ to make \( \theta < 10^{-9} \) or less. Then we can deal with a challenge that on the surface hardly connected with the \( G \cdot \tilde{G} \) problem. Non-minimal Higgs models can produce neutron EDM close to the experimental limit while contribute very little about to \( K_L \to \pi\pi \) due producing \( G^2\tilde{G} \) operator. In 1990 Kolya generalized and refined these arguments:

(a) \( G^2\tilde{G} \) operator is induced in different classes of models for CP violation. It had also been noted by several authors that typically ‘sizable’ effects arise there. The CKM dynamics produces a coefficient of the \( G^2\tilde{G} \) operator that is utterly tiny.

(b) We had discussed a new method for estimating of the relevant matrix element, namely \( \langle N|\bar{q}\gamma_\mu qF_{\mu\nu}|N \rangle \) as induced by \( G^2\tilde{G} \): it yields a result that is considerably smaller than Weinberg’s estimate.

(c) It refined the findings from other authors that QCD radiative corrections suppress rather than enhance of the impact the operator \( G^2\tilde{G} \).

We discussed the one-, two- and three-loop situations including QCD radiative corrections. It was non-trival work to get three conclusions: (i) We found strong evidence that contribution from \( G^2\tilde{G} \) operator is quite unlikely to be cancelled by additional Peccei-Quinn term. (ii) Finding neutron EDM larger than \( 10^{-31} \) e-cm is a clear sign of the existence of ND in T violation – but not of its features. (iii) There are even more (theoretical & experimental) reasons to probe EDM for electrons, atoms, nuclei, \( \mu, \tau \) etc. coming forward.

An excellent 1991 article "The electric dipole moment of the electron" was given already by Bernreuther & Suzuki. It focused on electron EDM and how probing it in atoms and molecules; however it discussed the connection with neutron EDM including Kolya’s work.

### 4.2 Around 2000 - 2013

The era of probing EDMs as a direct sign of T violation came even more wonderful around 2000 with new ideas and more tools & technologies (and also for sociology reasons, since experimental collaborations are relatively small). One can see it about conferences and workshops – in particular about "Flavor in the Era of the LHC Reports of the CERN Workshop, November 2005 - March 2007; it produced a long and very good proceedings with five meetings published in Eur.Phys.J. C (2008) with three sections. I have enjoyed and learnt from them, in particular EDM and g-2 miniworkshop on Oct. 9 - 11, 2006. Many discussions happened in ‘public’ or ‘private’ – and Kolya liked that also.
We need more data, more technologies – and more thinking for leptons, quarks and gluon dynamics.

No EDM has been found yet anywhere in this (relatively) huge landscape in different ‘dimensions’, namely to probe EDMs in neutron, protons, nucleis, atoms, molecules, charged leptons etc. The ACME collaboration has given limit on electron EDM: $|d_e| < 8.7 \cdot 10^{-29} \, e \cdot cm$ [49]. I find it exciting to read how experimental physicists did it. Furthermore it attracts more theorists to think about probing EDMs in different directions (and some of them come back as before including connections about axions) [50, 51]. We need new ideas as before.

As said before Kolya was a true leader in discussions for talks about the importance of probing EDMs more and more in very different situations. Kolya had produced two papers together with Th. Mannel published in 2012/13. In Ref. [52] they pointed out that the neutron EDM can be generated in the SM already by tree diagrams due to boundstate effects without short-distance penguin diagrams. It produces non-zero chiral limit and does not depend on the difference $m_s - m_d$; they estimated around $d_N \sim 10^{-31} \, e \cdot cm$ – a value similar to hand-waving arguments given in [2]. In the longer paper [53] they gave more details how they came to two statements: (i) The landscape of neutron EDM is described not by effective CP-odd operators of lowest dimension, but by non-trivial interplay of different amplitudes at low energy scales like 1 GeV for two $\Delta C = 1 \& \Delta S = 0$ four-quark operators. (ii) Those operators can be probed in $D$ decays.

Kolya & Thomas and many physicists (like me) were excited to find CPV in charm transitions for the first time in $D^0 \to K^+K^-$ vs. $D^0 \to \pi^+\pi^-$; furthermore those data seem for many theorists to be beyond what the SM can generate. However more LHCb data did not confirmed the sign of CPV in charm decays. Even so I think in the future CPV will be established in $\Delta C \neq 0$ transitions. My main point is: even non-established data can give us to think deeper about fundamental forces. These two papers are good examples: tree diagrams can produce TV/CPV in boundstates of quarks and come back to an old, but still not mature question, namely the impact of penguin diagrams [12] in general and in particular about nucleon EDMs how they depend on long-distance strong forces.

Again they dealt with subtle points that most people prefer to forget about them:
(i) We have to ‘understand’ dynamics with measurable parameters, in particular ‘complex’ impact on baryons transitions.
(ii) We have to talk about the connection with ‘constituent’ vs. ‘current’ quarks as discussed before [43], but with more tools.
(iii) We have to understand why several chiral suppression of light quarks can be vitiated in composite hadrons like nucleons.
(iv) It is possible that the impact ‘heavy’ quarks loops are sizable or even important for nucleon EDMs and for boundstate effects.
(v) It is even more subtle to discuss the connection between neutron EDM and direct CP asymmetries in $B$, $D$ and $\mu \& \tau$ decays – and their connections with Dark Matter.
(vi) It is important to think about boundstate effects without short-distance dynamics from penguins.
I had worked on that item in the past, the present and also in the future – and have learnt so much from Kolya about fundamental dynamics.

4.3 Future era

As mentioned before here (and other many places like in Ref. [48]) we have to find non-zero EDMs in leptons, neutron, deuteron, atoms, molecules etc. for several reasons:

- The SM produces tiny ‘backgrounds’ in all these situations.
- EDMs affect many landscapes and with different correlations.
- Factors of two or three of different predictions produce no problem for ‘friends’ a.k.a. theorists in this world.
- It is a wonderful challenge for experimenters to apply their tools in a new situation or produce a new technology. It helps ‘inventiveness’. ‘Young’ experimenters will enjoy much more working in groups that are small compared to the very huge collaborations.

Neither charged Higgs or a second neutral Higgs have been found, and the known one is at least mostly a scalar. Fans of SUSY like me do not give up that theory will exists in our world – but not in the mass region which LHC can probe directly.

Obviously SUSY cannot solve all problems for fundamental forces together. However I do not think that our world prefers someway minimal versions of SUSY. Non-minimal versions can produce EDMs that can be measured in the future. Probing EDMs can be competitive with the reach of $\epsilon_K$ [54].

In the future experiments at FNAL will measure $(g - 2)_\mu$ with more data (& I hope about muon EDM later) and at the J-PARC Hadron Experimental Facility (Japan) that combine measurements of $(g - 2)_\mu$ & $d_\mu$ using very new tools. Even if the second experiment fails to reach its goals, the community would learn so much and will come up new ideas and new technologies that can be applied in the ‘real’ world. That way some of ‘us’ respond well known Beckett’s skepticism. In one way one can compare $d_e < 105 \times 10^{-29}$ e-cm (from PDG) or recent value $d_e < 8.7 \times 10^{-29}$ e-cm [49] vs. $\delta F_2(0)/2m_e \sim 2 \times 10^{-22}$ e-cm derived from $\delta[(g - 2)/2] \sim 10^{-11}$ or $d_\mu = (-0.1 \pm 0.9) \times 10^{-19}$ e-cm.

I have been thinking and working about EDMs and leptonic dynamics as signs of the features of ND and correlations with CP asymmetries in particular in charm hadrons and top quarks. The last two published 2012/2013 papers from Kolya give me and others new ‘directions’. Three very recent papers [51, 23, 55] points out that partners of SUSY or general about ND might ‘easily’ exist at mass scales of ten of TeV and above. The best way to probe that mass scales one can measure EDMs. I am not saying that LHC cannot find ND – but we have to think about it.
5 Kolya’s impact in the past, presence and for the future

Kolya has worked for around 35 years about fundamental dynamics in many landscapes and showed his broad horizon: impact of Higgs state(s), CP & T violation, perturbative & non-perturbative QCD and the correlations between landscapes (in particular the subtle ones). He always showed that first and second wins are not enough – one has to get deeper. He always liked connection with experimental colleagues, explain why theoretical predictions are good or bad and where more theoretical works are needed. He also showed that real theorists do not act as ‘slaves’ of the data of that time. Sometimes predictions are correct based on good theoretical tools (and a lot of thinking and working), while data were quite different ‘then’; however the data are moving closer and closer to good real predictions – like the ratio of $\tau(\Lambda_b)/\tau(B^0)$ as mentioned above.

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