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THE DYNAMICS OF BEAUTY & CHARM HADRONS AND TOP QUARKS IN THE ERA OF THE LHCb & BELLE II AND ATLAS & CMS — MOTTO: NON-PERTURBATIVE QCD & MANY-BODY FINAL STATES*

Ikaros I. Bigi

Department of Physics, University of Notre Dame du Lac
Notre Dame, IN 46556, USA

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This article is dedicated to Timothy O'Meara, mathematician and first lay Provost of the University of Notre Dame du Lac

Our community has to apply *non*-perturbative QCD on different levels of flavor dynamics in strange, charm and beauty hadrons and even for top quarks. We need *consistent* parameterization of the CKM matrix and describe weak decays of beauty hadrons with *many-body* final states. It is crucial to use the *Wilsonian* OPE and discuss "duality" in the worlds of quarks *vs.* hadrons. The pole mass of heavy quarks is *not* well-defined on the *non*-perturbative level: it is *not* Borel summable in total QCD. We need a novel team to combine the strengths of our tools from MEP and HEP.

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1. Prologue

I have truly enjoyed the 2018 Epiphany Conference in Kraków, learnt about fundamental dynamics — and the 'landscapes' of history and art on the true European scale. A very special event happened on January 6 long time ago (see Fig. 1): three 'sages' came to meet with the Christ child. The old center of the city of Kraków is an amazing part of the European culture. I try to show that by pictures I took on January 13, 2018:

(a) The Barbican in Kraków is just outside of one of the gates on the north wall and very close to the Jagiellonian University Guesthouse. The Barbican was built to protect the city against the 'barbarians',

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Fig. 1. Painting of ‘Epiphany’ in a museum in Kraków (picture taken by I.I.B.).

see Fig. 2. An analogy one can think about using Dalitz plots to probe impact of New Dynamics and protect oneself from ‘barbaric’ perturbative QCD.

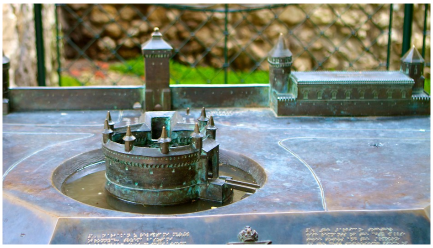

Fig. 2. Model of Barbican in Kraków.

(b) Copericus was a student at the Jagiellonian University of Kraków, see Fig. 3. He had large impact on our understanding of the Universe then.

Fig. 3. Solar system (picture taken by I.I.B.).

(c) Just south of the Main Market Square, one can see a wonderful connection of Renaissance architecture and modern sculpture, see Fig. 4 — if one can find it inside a building.

Fig. 4. Renaissance architecture and modern sculpture (picture taken by I.I.B.).

2. Introduction to the 'roads'

The Greek word 'Epiphany' means: 'manifestation of a divine being an intuitive grasp of reality through something both simple and striking'! I have always been a fan of local Super-symmetry and still am; however, we are in a different situation: it is *neither* simple *nor* striking. As I will discuss here in some details: best 'fitted' analyses of the data do *not* give us the best information about the underlying dynamics — it is crucial to use correlations with other data and judgments! Furthermore, I can admire the courage of the young physicists to deal with the challenges in our world on different levels, while listen also to the talks of 'mature' colleagues like Danish Buras and Swiss Jegerlehner. To make progress, we have to discuss the disagreements. Fashion does *not* help us to go closer to our goals as my Italian colleague Augusto said at the conference.

Firstly, I will present comments that include disagreements I have with some speakers at this conference; some are obvious, while others are more subtle. If a reader finds it interesting (I hope), she/he can look at the details in [1, 2]. Is it 'old stuff'? In my view, it is still up-to-data of our understanding of fundamental forces.

One might think the choice of words is in the details: HQE *vs.* HQET. The titles are: HQE = "Heavy Quark Expansion" *vs.* HQET = "Heavy Quark Effective Theory"; in the latter item I want to mention that the applications of HQET in local QCD *vs.* Lattice QCD are different, and I have less problems with the second than the first one. The differences go much deeper in their 'meaning'.

The usual HQET papers claim to show the impact of non-perturbative physics

$$\text{“observable”} = \text{perturbative forces} + \text{non-perturbative forces}\,. \tag{1}$$

Instead Kolya Uraltsev (and collaborators like Shifman and me [3]) pointed out that is much deeper to describe the situations by

$$\text{“observable”} = \text{short-distance dynamics} + \text{long-distance dynamics}\,. \tag{2}$$

Crucial statements in my view:

(1) It is not enough to say that OPE is an important theoretical tool: it is the *Wilsonian* OPE. The separation of short- *vs.* long-distances dynamics is scale-*dependent* around 1 GeV for QCD. One might think it is a bad idea and gives more work without better understanding of the underlying dynamics. However, I will explain why I disagree with such a ‘feeling’.

(2) What the left hand does, does not matter what the right hand does? No — perturbative and non-perturbative QCD effects have to be treated *simultaneously* with accuracy; furthermore, we have to think about the correlations with experimental analyses.

These will be discussed with some details or some examples.

General comments:

— Anomalies — “deep” or not so far;
— Wilsonian Operator Product Expansion;
— Infrared renomalon with non-perturbative QCD.

Items with some details:

1. Consistent parameterization of the CKM matrix;
2. Definition of quark masses: “$\overline{\text{MS}}$”, “kinetic”, “PS”, ‘1S’, ‘pole mass’;
3. V_{qb} $[q = c, u]$: exclusive *vs.* inclusive rates and duality;
4. Broken U- and V-spin symmetries;
5. 3- and 4-body final states in beauty and charm mesons;
6. Challenges for understanding weak decays of beauty and charm *baryons*;
7. The stage of top quarks — in a search for New Dynamics;
8. Collaboration of HEP and MEP/Hadrodynamics.

For some of these points I have very short comments, while for others I give some discussions with more references. In a talk at a conference like this, one can only ‘paint the landscape’, but not beyond. For that, one has to go to summer (or winter) schools.

3. Anomalies: "deep" or not so

The word 'anomaly' is often used in the literature, in particular, when one looks for the impact of New Dynamics (ND). It is easier to discuss exclusive semi-leptonic transitions. However, the situation is more complex.

There is a "quantum anomaly": a classical symmetry is no longer conserved, once one-loop corrections are included. In this well-known case of chiral invariance: for massless quarks, we have a "triangle anomaly", since it is produced by a diagram with a triangular fermion loop — or called the "Adler–Bardeen–Bell–Jackiw anomaly"

$$\partial_\mu J_\mu^{(5)} = \frac{\alpha_{\rm S}}{8\pi}\,\tilde{G}\cdot G\left(+m_q\,\bar{\psi}\gamma_5\psi\right)\;; \tag{3}$$

that is not renormalizable in $4-\epsilon$ dimensions. The SM 'deals' with that by connecting the world of quarks and charged leptons (*i.e.*, 3 colors of quarks)[1].

Our community has found 'anomalies' in previous and present data, namely the differences between expectations from the SM *vs.* measured data as a sign of the impact of ND. Even in my view, it is not just a fashionable one; we have to work and think about semi-leptonic transitions in beauty hadrons with several examples like $B \to K^* l^+ l^-$ and $\Lambda_b^0 \to \Lambda l^+ l^-$. One discusses (tiny) rates and the landscape in $M_{l^+l^-}$. Present data show *more* events than expected with 3σ uncertainties. Of course, I am not surprised that our colleagues are waiting impatiently to reach 5σ uncertainties or more.

Allow me to give another lesson in the history: after losing the 1811 battle of Albuera in Spain, Marechal Soult said: 'I had beaten the British — it was just they did not know when they were beaten.' He was right on both counts. To 'battle with the British' there is an analogue to probe the SM and its limitations: HEP theorists start with a penguin operator $b \to s$ to describe the transitions of $B \to l^+ l^- X_s$ as $[b\bar{q}] \to l^+ l^- s \ldots \bar{q}$. In the worlds of hadrons, one can measure the final states with $K\pi's$, $2K\bar{K}$ *etc.* It makes it in steps: K, K^*, broad resonance κ, in general, $K\pi$'s, $2K\bar{K}$ *etc.* The question is: with which certainties can one describe the connection in the world of quarks and gluons with that of hadrons, namely the "duality". I want to pointed out that duality is *not* an additional assumption. Duality is well-defined in the deep Euclidean region thus avoiding proximity to singularities, cuts induced by hadronic thresholds *etc.*; then one analytically continues it into the Minkowskian domain. There is a price to be paid for this 'prize': in general, one cannot apply local duality, but averaged one over an energy interval of around 1–1.5 GeV. Furthermore, it is not a mathematical statement: we understand the source of the underlying dynamics;

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[1] There must be a deep reason for that.

it needs some judgment where and how to apply duality in the world of current quarks and gluons

$$[b\bar{q}] \to l^+l^- s \dots \bar{q} \Rightarrow l^+l^- K/K\pi' s/2K\bar{K} \dots \tag{4}$$

Except that, the branching ratios are tiny, the situations are simpler for these transitions: the underlying dynamics can be probed with $M_{l^+l^-}$. The situations are much more 'complex', when I discuss non-leptonic weak decays below. In the future, one can probe $b \to d$. The good side is that the SM penguin amplitudes suppressed; unfortunately, the landscape has much background.

4. Wilsonian OPE and renormalons

Almost all authors invoke OPE — but mostly with*out* "Wilsonian" prescription. One might think it is about bragging right. However, Shifman and collaborators [4] have a long record to emphasize that applying OPE is subtle: the Wilsonian OPE has to stop around 1 GeV, not lower. It is one thing to draw diagrams, while another thing is to understand the underlying dynamics, in particular about non-perturbative QCD with some accuracy. I will come back in the next section about infrared renormalon and later also about the definition of quark masses. Mostly, I follow the 'road' described by Shifman in Ref. [4] with more details now and for the future.

4.1. First step to deal with renormalons

Dyson pointed out in his famous 1952 paper "Divergences of Perturbation Theory in QED" [5] that amplitudes can*not* be convergent. Later, it was realized perturbative series in a QFT are *factorially divergent* like $Z = \sum_k C_k \alpha^k k^{b-1} A^{-k} k!$ with $k \gg 1$ is the number of loops, C_k's are numerical coefficients of order one, and b and A are numbers. It is traced back to the factorially large number of multi-loop Feynman diagrams. The features responsible for the renormalon factorial divergence is the logarithmic running of the effective coupling constant.

Instead of *asymptotic* series, one can introduce a Borel transform

$$B_Z = \sum_k C_k \alpha^k k^{b-1} A^{-k}; \tag{5}$$

the singularity of $B_Z(\alpha)$ closest to the origin of the α plain is at a distance A, and thus $B_Z(\alpha)$ is *convergent*. One recovers the original function Z by

$$Z(\alpha) = \int_0^\infty \mathrm{d}t\, e^{-t} B_Z(\alpha t)\,. \tag{6}$$

The integral representation is well-defined provided that $B_Z(\alpha)$ has *no* singularities on the real positive semi-axis in the complex α plane. That is not a problem for QED. For other weak couplings, it is not trivial, but one can deal with that.

If $B_Z(\alpha)$ has a singularity on the real positive semi-axis — like coefficients C_k are all positive or all negative — the integrated in the Eq. (6) become *ambiguous*. This ambiguity is of the order of $e^{-A/\alpha}$; more information is needed from the underlying dynamics. The question comes from QCD with

$$\begin{aligned} \alpha_S\left(Q^2\right) &\simeq \frac{\alpha_S\left(\mu^2\right)}{1-\frac{\beta_0\alpha_S(\mu^2)}{4\pi}\log\left(\mu^2/Q^2\right)} = \frac{\alpha_S\left(\mu^2\right)}{1+\frac{\beta_0\alpha_S(\mu^2)}{4\pi}\log\left(Q^2/\mu^2\right)}\,, \\ \beta_0 &= 11-\frac{2}{3}N_f\,; \end{aligned} \tag{7}$$

the energy scale μ is used to calibrate $\alpha_S(Q^2)$. The good side is: at large scales the strong couplings go down to zero with Q^2/μ^2 (on the log scale) — *i.e.* “asymptotic freedom”.

On the other hand, there is a true challenge. With $\mu^2 \gg Q^2$, $\alpha_S(Q^2)$ gets larger and larger; thus QCD gives us true strong forces at low scales. First, one might say it goes to infinite, but that is too naive. One has to stop at $\mu \sim 1$ GeV based on perturbative QCD.

4.2. Non-perturbative renormalons

It was pointed out first in 1994 that the pole mass is *not* well-defined at the non-perturbative level [6, 7]. Furthermore, a rather powerful renormalon-based tool was suggested for evaluating the corresponding non-perturbative contribution [4]. Pole mass is sensitive to large distance dynamics, although this fact is not obvious in perturbative calculations. IR contributions lead to an *intrinsic uncertainty* in the pole mass of the order of Λ — *i.e.*, a Λ/m_Q power correction. It comes from the factorial growth of the high order terms in the α_S expansion corresponding to a singularity residing at the $2\pi/\beta_0$ in the Borel plane. Thus, one cannot say it is a correction.

Actually, there are two renormalon-based tools, namely ultraviolate (UV) and infrared (IR) dynamics. One has to include non-perturbative QCD with IR one. Those give contribution to b-quark mass numerically [3], see Fig. 5: $m_b^{\rm pole} = m_b(1\,{\rm GeV}) + \delta m_{\rm pert}(\leq 1\,{\rm GeV}) \simeq 4.55\,{\rm GeV} + 0.25\,{\rm GeV} + 0.22\,{\rm GeV} + 0.38\,{\rm GeV} + 1\,{\rm GeV} + 3.3$ GeV $\ldots$, where $\delta m_{\rm pert}(\leq 1\,{\rm GeV})$ is the perturbative series taking account of the loop momenta down to zero.

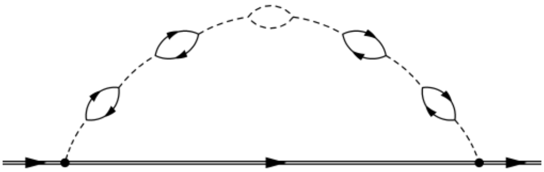

Fig. 5. Perturbative diagrams leading to the IR renormalon uncertainty in m_Q^{pole} of the order of $\bar{\Lambda}$. The number of bubble insertions in the gluon propagator is arbitrary. The horizontal line at the bottom is the heavy quark Green's function.

Top quarks decays before they have produced top hadrons. Still they carry unbroken color symmetry and thus find partners with color to produce hadrons with color zero in the final states. I will come back to that below.

5. Describing the CKM matrix consistently

Wolfenstein's parameterization was very smart, easily usable and well-known. The SM with three families of quarks describes the CKM matrix with four parameters, namely λ, A, $\bar{\rho}$ and $\bar{\eta}$. One uses expansion of the Cabibbo angle $\lambda = \sin\theta_{\mathrm{C}} \simeq 0.223$, while A, $\bar{\rho}$ and $\bar{\eta}$ should be of the order of unity [8]. It is an important item (in particular about finding the impact of ND), but a subtle one: what does one mean by 'maximal' CP violation? In principle, 100% asymmetry is possible: I give just three examples: $\bar{\rho} \sim 1$ and $\bar{\eta} \sim -1$; $\bar{\rho} \sim -1$ and $\bar{\eta} \sim -0.5$; $\bar{\rho} \sim -0.5$ and $\bar{\eta} \sim -0.3$.

Measured values are $A \simeq 0.82$ as assumed. However, *measured* $\bar{\eta} \sim 0.35$ and $\bar{\rho} \simeq 0.14$, which are not close to unity; thus we have not real control over systematic uncertainties here.

The SM produces at least the leading source of CP violation in $K_{\mathrm{L}} \to 2\pi$ and B decays with good accuracy. Searching for ND, we need even precision and to measure the correlations with other FS's. The landscape of the CKM matrix is more subtle as pointed out through $\mathcal{O}(\lambda^6)$ consistently [9]

$$V_{\mathrm{CKM}} \simeq \begin{pmatrix} 1 - \frac{\lambda^2}{2} - \frac{\lambda^4}{8} - \frac{\lambda^6}{16}, & \lambda, & \bar{h}\lambda^4 e^{-i\delta_{\mathrm{QM}}}, \\ -\lambda + \frac{\lambda^5}{2} f^2, & \begin{matrix} 1 - \frac{\lambda^2}{2} - \frac{\lambda^4}{8}(1+4f^2) - f\bar{h}\lambda^5 e^{i\delta_{\mathrm{QM}}} \\ +\frac{\lambda^6}{16}(4f^2 - 4\bar{h}^2 - 1), \end{matrix} & \begin{matrix} f\lambda^2 + \bar{h}\lambda^3 e^{-i\delta_{\mathrm{QM}}} \\ -\frac{\lambda^5}{2}\bar{h}e^{-i\delta_{\mathrm{QM}}}, \end{matrix} \\ f\lambda^3, & \begin{matrix} -f\lambda^2 - \bar{h}\lambda^3 e^{i\delta_{\mathrm{QM}}} \\ +\frac{\lambda^4}{2} f + \frac{\lambda^6}{8} f, \end{matrix} & \begin{matrix} 1 - \frac{\lambda^4}{2} f^2 - f\bar{h}\lambda^5 e^{-i\delta_{\mathrm{QM}}} \\ -\frac{\lambda^6}{2}\bar{h}^2 \end{matrix} \end{pmatrix}$$

with $\bar{h} \simeq 1.35$, $f \simeq 0.75$ and $\delta_{\mathrm{QM}} \sim 90°$ and only expansion in $\lambda \simeq 0.223$. The pattern in flavor dynamics is less obvious for CP violation in hadron decays as stated before [10]; the situation has changed: we have to measure the correlations between four CKM triangles, not focus only on the 'golden triangle'. Some of the important points are emphasized:

(a) The maximal SM value of $S(B^0 \to J/\psi K_{\rm S})$ for indirect CP violation is ~ 0.74.
(b) For $S(B_s^0 \to J/\psi\phi)$ is ~ 0.03–0.05.
(c) The SM gives basically zero CP value for doubly Cabibbo suppressed transitions.

One has to measure accurately the correlations with several triangles.

6. Schemes of quark masses

Quark masses are in general *not* observables. Therefore, I use the word of 'Schemes'.

6.1. "$\overline{\rm MS}$", "kinetic", "PS"

$\overline{\rm MS}$ mass $\bar{m}_Q(m_Q)$ stands for 'modified minimal subtraction scheme'. It represents a quantity of computational convenience, in particular when calculating perturbative contributions in "dimensional regularization"[2]. For $\mu \geq m_Q$, it basically coincides with the running mass in the Lagrangian and is best normalized at $\mu \sim m_Q$. It is appropriate for describing heavy-flavor *production* like $Z^0 \to \bar{b}b$ and now also $H \to \bar{b}b$. However, it diverges logarithmically for $\mu \to 0$.

The "kinetic" mass of the heavy quark is regular in the infrared regime including a non-leading source [7, 11–13]: $\frac{{\rm d}m_Q^{\rm kin}(\mu)}{{\rm d}\mu} = -\frac{16}{9}\frac{\alpha_{\rm S}}{\pi} - \frac{4}{3}\frac{\alpha_{\rm S}}{\pi}\frac{\mu}{m_Q} + \mathcal{O}(\alpha_{\rm S}^2)$. For b quarks, $\mu \sim 1$ GeV is the best scale to describe their weak decays[3]. Using $\mu \sim m_b$ instead, it leads to higher-order perturbative corrections that are artificially large, for which one has *no* control [12].

"PS" = "potential-subtracted": the schemes "kinetic" and "PS" are quite different already on the conception level; technical problems of "PS" arise at $\mathcal{O}(\alpha_{\rm S}^4)$. Still they are in the same 'division' of fundamental physics. I will come back to this point below about top quarks.

6.2. 'Pole mass', '1S'

A pole mass for quarks is gauge-independent and infrared stable in perturbative QCD; furthermore, it is easy to apply pole mass in Feynman graphs. However, it is *not* infrared stable non-perturbatively. Make the same statement with different words: pole mass depends on long-distance dynamics, for what we have little control.

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[2] It does not necessarily mean we understand the underlying dynamics.

[3] A reader might think, my judgment is 'biased'; however, I stay by my statement.

Recent PDG reviews basically ignore the "kinetic" scheme, while focus on the $1S$ scheme based on $m_b^{1S} \simeq M_{\Upsilon(1S)}/2$ [4]. It claims these schemes give us the same information about underlying dynamics. However, it is incorrect, as Uraltsev pointed out [14]: $m_b^{1S} = m_b^{\rm pole}[1 - C_F^2(\alpha_{\rm S}^2/8) + \mathcal{O}(\alpha_{\rm S}^3, \beta_0\alpha_{\rm S}^3 \log\alpha_{\rm S})]$ — *i.e.*, also m_b^{1S} is *not* well-defined at the *non*-perturbative level.

6.3. Short comments

Flavor dynamics is 'complex'. At a conference, the goal is to 'paint' the landscape, but not to discuss the details. However, it is important to give short, but subtle comments. I give a reference to an important (and large) 2001 paper [15]. My main disagreements with Pineda: his Abstract does not mention some of his important results. However, a careful reader can find it on page 16: (a) "...it is achieved by the threshold scheme, *i.e.* the *kinetic*, the PS-like, the $1S$ ...". I would say, the meaning of 'threshold' is not obvious. When one talks about $b \to c$ $[W^-_{\rm off-shell}]$, it means to get one or two charm quarks. However, the situations are quite different for $b \to u$ $[W^-_{\rm off-shell}]$. (b) "Note also that the $1S$ and PS schemes depend on ν_{us}." At three-loops diagrams, the ultrasoft scale appears in the static potential and the heavy quarkonium mass. Again, the situations are quite different for the impact of perturbative QCD *vs.* non-perturbative one.

7. Duality: Measuring $|V_{qb}|$ with $q = c, u$

The item of "duality" is referred to very complex situations, namely the connections of the worlds of hadrons *vs.* quark and gluons. In this section, I give short comments at the very specific case: compare the values of $|V_{cb}|$ and $|V_{ub}|$ from inclusive *vs.* exclusive semi-leptonic amplitudes.

It seems the difference between the $|V_{cb}|_{\rm incl}$ *vs.* $|V_{cb}|_{\rm excl}$ has become smaller now based on realistic theoretical uncertainties, mostly due to LQCD analyses.

On the other hand, the difference between $|V_{ub}|_{\rm incl}$ *vs.* $|V_{ub}|_{\rm excl}$ has not changed. It has been pointed out that the values of $|V_{ub}|_{\rm incl}$ based on the data from $B \to l\nu\pi$'s, while assuming that $B \to l\nu\bar{K}K\ldots$ are irrelevant due to a traditional understand duality. It is a good assumption — but *local* duality does not work close to thresholds. Maybe the real $|V_{ub}|_{\rm incl}$ are smaller and thus solve that challenge. The LHCb experiment cannot measure inclusive rates. However, it might be able to go after the rates of $B^+ \to l^+\nu K^+K^-$ and $B^0 \to l^+\nu K^+K^-\pi^-$ with non-zero values. Furthermore, Belle II should measure values there or limits.

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[4] Due to 'par ordre du Mufti' (= no right of appeal).

8. Many-body final states for $\Delta B \neq 0 \neq \Delta C$ hadrons

Indirect CP violation has been established in $K_{\rm L} \to 2\pi$ and $B^0 \to J/\psi K_{\rm S}$. On the other hand, the landscapes are much more 'complex' as expected, since direct CP asymmetries depend on final-state interactions

$$\left|T\left(\bar{P} \to \bar{a}\right)\right|^2 - |T(P \to a)|^2 = 4 \sum_{a_j, a} T^{\rm resc}_{a_j, a}\, {\rm Im} T^*_a T_{a_j}\,; \tag{8}$$

with*out* non-zero re-scattering direct CP asymmetries cannot happen, even if there are weak phases [16–19]. One expects large impact of strong re-scattering, and the LHCb data of suppressed $B \to 3$ mesons have shown that; I will discuss it below. It is obvious that the crucial information about the underlying dynamics cannot be found in two-body FS. Even so, it is a very good hunting region for the impact of ND, since they can depend only on ND amplitude.

8.1. Tools

One has to think which tool can be best applied here. Not surprisingly, it comes to your mind, at least for theorists, namely symmetries of different kinds; I discuss one example below.

One can apply ${\rm SU(3)}_{\text{light flavor}}$ symmetry (not ${\rm SU(3)}_{\rm color}$) which is induced by *local* operators and FS with only one and two pions. The global ${\rm SU(3)}_{\text{light flavor}}$ is broken. It was pointed out by Lipkin, it helps the thinking by using three SU(2) subgroups: one combines (u, d) quarks for I-spin, while $s \rightleftharpoons d$ for U-spin and $s \rightleftharpoons u$ for V-spin symmetries.

Broken U-spin symmetry with*out* V-spin is usable for spectroscopy with a good record. Yet the situation is quite different for weak transitions. I give one example from the PDG2017 data CP asymmetry

$$A_{\rm CP}\left(B^0 \to K^+\pi^-\right) = -0.082 \pm 0.006\,. \tag{9}$$

(In 1987 Sanda and I had given a prediction: $A_{\rm CP}(B^0 \to K^+\pi^-) \sim -0.1$.) It shows the impact of penguin diagrams — but (semi-)quantitatively. Then looks at the PDG2017 data

$$A_{\rm CP}\left(B^0_s \to \pi^+ K^-\right) = +0.26 \pm 0.04\,. \tag{10}$$

Can we predict this connection?

It had been suggested by Lipkin in 2005 [20] to use U-spin symmetry[5]

$$\Delta = \frac{A_{\rm CP}\left(B^0 \to K^+\pi^-\right)}{A_{\rm CP}\left(B^0_s \to \pi^+ K^-\right)} + \frac{\Gamma\left(B^0_s \to \pi^+ K^-\right)}{\Gamma\left(B^0 \to K^+\pi^-\right)} = 0\,. \tag{11}$$

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[5] The positive sign in Eq. (11) is not surprizing in the SM.

The LHCb Collaboration had published in 2013 a short paper [21]

$$\Delta_{\mathrm{LHCb}} = -0.02 \pm 0.05 \pm 0.04 \tag{12}$$

saying: "These results allow a stringent test of the validity of the …". I disagree with this statement for several reasons! First examples from two-body FS:

— Indeed, the value of Δ_{LHCb} is consistent with zero.

— Yet, it is also consistent with a value ∼ 0.1 expected for direct CP asymmetry for two-body FS.

— One has to think about correlations of U-spin symmetry with V-spin one due to re-scattering. What about $B^0 \to K^0\pi^0/K^0\eta$ and $B_s^0 \to \pi^0K^0/\eta K^0$? One has to remember that these transitions are affected by oscillations and indirect CP violation.

— One can look at the situation with two-body FS of B^+ decays

$$A_{\mathrm{CP}}\left(B^+ \to K_{\mathrm{S}}\pi^+\right) = -0.017 \pm 0.016\,, \tag{13}$$

$$A_{\mathrm{CP}}\left(B^+ \to K^+\pi^0\right) = +0.037 \pm 0.021\,, \tag{14}$$

$$A_{\mathrm{CP}}\left(B^+ \to K^+\eta'\right) = +0.004 \pm 0.011 \tag{15}$$

with no sign of CP asymmetry, while it was found in

$$A_{\mathrm{CP}}\left(B^+ \to K^+\eta\right) = -0.37 \pm 0.08\,. \tag{16}$$

It shows the impact of the strong re-scattering. There are two lessons: difference between U- and V-spin is 'fuzzy' due to re-scattering — and we have to go beyond two-body FS.

Probing FS in non-leptonic decays with two hadrons (including narrow resonances) is not trivial to measure CP violations, if one has enough data for suppressed transitions; theorists can 'predict' those and analyze the data. On the other hand, one gets 'just' numbers. We have to remember that two-body FS of suppressed non-leptonic weak decays are a small part of charm mesons and tiny ones for beauty mesons; data show that it is not surprising. Three- and four-body FS are described by two and more dimensional plots. There is a price: lots of work for experimenters and theorists. There is also a prize: to find the existence of ND and also its features.

The situations are very different for strange hadrons with $\Delta S = 1$ *and* 2 as you listened to my Danish colleague Buras (member of the Bavarian Academy!): it is produced by *local* operators and FS with only one and two pions.

8.2. Probing Dalitz plot for $B^\pm$

The data of CKM suppressed B^+ decays show no surprising rates for $B^+ \to K^+\pi^-\pi^+/K^+K^-K^+$ and $B^+ \to \pi^+\pi^-\pi^+/\pi^+K^-K^+$ [6].

LHCb data from Run 1 show averaged direct CP asymmetries [22]

$$\begin{aligned} A_{\rm CP}\left(B^\pm \to K^\pm\pi^+\pi^-\right) &= +0.032 \pm 0.008_{\rm stat} \pm 0.004_{\rm syst}\,, \\ A_{\rm CP}\left(B^\pm \to K^\pm K^+K^-\right) &= -0.043 \pm 0.009_{\rm stat} \pm 0.003_{\rm syst} \end{aligned} \tag{17}$$

with 2.8σ and 3.7σ from zero. Based on our experience with the impact of penguin diagrams on the best measured $B^0 \to K^+\pi^-$, the sizes of these averaged asymmetries are not surprising; however, it does not mean that we could really predict them. It is very interesting that they come with opposite signs due to **CPT** invariance.

LHCb data show *regional* CP asymmetries [22]

$$\begin{aligned} A_{\rm CP}\left(B^\pm \to K^\pm\pi^+\pi^-\right)_{\rm region} &= +0.678 \pm 0.078_{\rm stat} \pm 0.032_{\rm syst}\,, \\ A_{\rm CP}\left(B^\pm \to K^\pm K^+K^-\right)_{\rm region} &= -0.226 \pm 0.020_{\rm stat} \pm 0.004_{\rm syst}\,. \end{aligned} \tag{18}$$

"Regional" CP asymmetries are defined by the LHCb Collaboration: positive asymmetry at low $m_{\pi^+\pi^-}$ just below m_{ρ^0}; negative asymmetry both at low and high $m_{K^+K^-}$ values. One should note again the opposite signs in Eqs. (18). It is not surprising that "regional" asymmetries are very different from averaged ones. Even when one uses states only from the SM — $SU(3)_C \times SU(2)_L \times U(1)$ — one expects that; it shows the *impact of re-scattering* due to $SU(3)_C$ (actually $SU(3)_C \times$QED) in general. Of course, our community needs more data, but that is not enough. There are important questions and/or statements:

- How do we *define* regional asymmetries and probe them on the experimental and theoretical sides?
- Can it show the impact of broad resonances like $f_0(500)$ and $K^*(800)$?
- Again, the best fitted analyses often do not give us the best understanding of the underlying fundamental dynamics.

LHCb data from the Run 1 show *larger* averaged CP asymmetries as discussed above in Eqs. (17) (again, with the opposite signs)

$$\begin{aligned} A_{\rm CP}\left(B^\pm \to \pi^\pm\pi^+\pi^-\right) &= +0.117 \pm 0.021_{\rm stat} \pm 0.009_{\rm syst}\,, \\ A_{\rm CP}\left(B^\pm \to \pi^\pm K^+K^-\right) &= -0.141 \pm 0.040_{\rm stat} \pm 0.018_{\rm syst}\,. \end{aligned} \tag{19}$$

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[6] The four Dalitz plots have been measured with additional systematic uncertainty of 0.007 in $B^\pm \to \psi K^\pm$.

It is interesting already with the averaged ones, since $b \Longrightarrow d$ penguin diagrams are more suppressed than $b \Longrightarrow s$ ones. Again, CP asymmetries focus on small regions in the Dalitz plots [22]

$$\begin{aligned} A_{\rm CP}\left(B^\pm \to \pi^\pm\pi^+\pi^-\right)_{\rm region} &= +0.584 \pm 0.082_{\rm stat} \pm 0.027_{\rm syst}\,, \\ A_{\rm CP}\left(B^\pm \to \pi^\pm K^+K^-\right)_{\rm region} &= -0.648 \pm 0.070_{\rm stat} \pm 0.013_{\rm syst}\,. \end{aligned} \tag{20}$$

Again, there should also be noted the signs in Eqs. (19) and (20). Do they show the impact of broad scalar resonances like $f_0(500)$ and/or $K^*(800)$?

First one analyzes the data using model-independent techniques [23], compares them and discuss the results — but that is not the end of our 'traveling'. Well-known tools like dispersion relations are 'waiting' to apply — but we have to do it with some 'judgement'. I had visited a museum in the north Wall of Kraków and looked at this painting, see Fig. 6.

Fig. 6. 'Lady with an Ermine' by Leonardo da Vinci (picture taken by I.I.B.).

I was very happy to see it again — but after looking at that closely, I realized I did *not* see the 'real' painting. It has colors, but *pale* ones. The real painting with wonderful colors is still in its original part of the museum just a very steps behind this Wall, but it is closed for a year. It gives us an idea about the painting of Leonardo da Vinci, but not beyond.

Coming back to fundamental physics: one has to be prepared for analyses of Dalitz plots (and beyond); first, one has to produce simulations to see both the strong and weak features for hardware and software of a detector. Yet that is *not* the final step. The best fitted analyses often do not give us the best information about the underlying dynamics. Final steps need judgment based on correlations with other data applying resonances, threshold enhancements *etc.* with dispersion relations and other refined tools.

8.3. CP asymmetries in the decays of beauty baryons

I had suggested to probe Dalitz plots of $\Lambda_b^0 \to \Lambda \pi^+ \pi^- / \Lambda K^+ K^- / \Lambda D^- \pi^+$ and $\Xi_b^0 \to \Lambda \pi^+ \pi^- / \Lambda K^+ K^-$ that do not depend on production asymmetries [19]. However, at the ICHEP2016 conference in Chicago, the LHCb Collaboration showed data with evidence for CP asymmetry in $\Lambda_b^0 \to p \pi^- \pi^+ \pi^-$ with a novel idea. It is discussed in [24] with details. In *pp* collisions, one gets different numbers of Λ_b^0 *vs.* $\bar{\Lambda}_b^0$ due to production asymmetries. Therefore, one focuses on T-odd moments. LHCb measured the angle between two planes: in the rest frame of Λ_b^0 one plane defined by $[\vec{p} \times \vec{\pi}^-_{\text{fast}}]$, while the other one by $[\vec{\pi}^+ \times \vec{\pi}^-_{\text{slow}}]$; likewise for $\bar{\Lambda}_b^0$. They found evidence for CP asymmetry on the level of 3.3σ based on its Run 1 of 3 fb^{-1}. Actually, they found *regional* CP asymmetry $\sim 20\%$ without saying that clearly. In principle, it is not surprising due to strong dynamics with $\Delta(1232)[\Delta(1600)/\Delta(1620)] \Rightarrow p\pi^-$. We should keep in mind the situations should be affected by different broad resonances, thresholds *etc.*

Are we lucky to find this effect and its size? Of course, we need more data. Yet, the *present* data can give us more information about the underlying dynamics by measuring the angle between two different planes: one is defined by $[\vec{p} \times \vec{\pi}^-_{\text{slow}}]$, while the other one $[\vec{\pi}^+ \times \vec{\pi}^-_{\text{fast}}]$. Can we find CP asymmetries, too? *Regional* ones, where and what is their size?

The data are very interesting for several reasons:

— Maybe CP asymmetry was found in a decay of a baryon for the first time (except 'our existence'); it is for a beauty baryon.

— It is another example that many-body FS are *not* a background for the information our community got from two-body FS.

— The plot given at the ICHEP2016 shows the strength of regional T asymmetry around 20 $\times 10^{-2}$. Very interesting, but we cannot claim to understand the underlying dynamics — yet! Furthermore, in the world of quarks and gluons one looks at CKM penguin of $b \to d$, where one expects less than for $b \to s$. LHCb data already shown similar lessons for CP asymmetries in $B^+ \to \pi^+\pi^+\pi^- / \pi^+ K^+ K^-$ *vs.* $B^+ \to K^+\pi^+\pi^- / K^+ K^+ K^-$, see Eqs. (17)–(20) just above.

— The LHCb Collaboration did not get enough data from Run 1 to probe $\Lambda_b^0 \to p\pi^- K^+ K^-$ and $\bar{\Lambda}_b^0 \to \bar{p}\pi^- K^+ K^-$. It will change very 'soon'.

— Furthermore, the LHCb Collaboration can measure rates and CP "regional" asymmetries in $\Lambda_b^0 \to p K^- \pi^+ \pi^-$ and $\Lambda_b^0 \to p K^- K^+ K^-$ 'soon' — and has no competition from other experiments. First, we have to discuss $\Lambda_b^0 \to p \pi^- \pi^+ \pi^-$ and $\Lambda_b^0 \to p \pi^- K^+ K^-$, and $\Lambda_b^0 \to p K^- \pi^+ \pi^-$

and $\Lambda_b^0 \to pK^-K^+K^-$. Will they follow the same 'landscape' for $B^+ \to \pi^+\pi^+\pi^-/\pi^+K^+K^-$ *vs.* $B^+ \to K^+\pi^+\pi^-/K^+K^+K^-$ as discussed above qualitatively or not? So say it with different words: will they show the strengths of 'penguin diagrams' in Λ_b^0 decays or not? Are the situations similar for beauty mesons and beauty baryons or only on the qualitative way?

9. Top quark in the search for ND

The landscape of top-quark dynamics is very different from $\Delta B \neq 0 \neq \Delta C$, as I had 'painted' it, see Fig. 6 above. To find its direct impact, power is not enough — we have to think, see Fig. 7.

Fig. 7. Greek goddess Athena.

My suggestion is that the 2020 Epiphany Conference in Kraków can mostly focus on describing the landscape of top-quark dynamics, namely the productions of a pair and single top quarks and forward *vs.* center regions of pp collisions; furthermore, one discusses CP asymmetries together $W^\pm$ and Z^0 and H^0, where one hardly gets background from the SM. Finally, one discusses the future with new technologies for collisions and detectors. The 'future' is defined for the time schedule of ~ 30 years, which is beyond my personal 'horizon'. I give you only three references coming from the 10th International Workshop on Top Quark Physics, Braga, Portugal, 2017. Unfortunately (for me) I did not attend this Workshop. I disagree with several statements given in these papers I found on the Internet; maybe our real disagreements are smaller, since I am unable to follow the discussions there. It will make progress, but it will need a lot of time. My statements below make my point.

Now the ‘top-quark community’ is hitting the ‘Systematics Wall’ in different ways, see the ‘Experimental Summary’ [25][7]:

— Take ratios — go differential — stop and think.

— Production rates of $\bar{t}t$ pairs are powerful handles to constraint the parton distribution functions (PDF). It has been suggested that $\bar{t}t$ rates may be the relative luminometer of the future for LHC and possible future hadron colliders.

— The landscapes for the cross sections of $\bar{t}tV$ with $V = W, Z$ have changed with the 2016 data, where statistical uncertainties are smaller than the systematic ones; likewise for $\bar{t}t\bar{t}t$: there are possible hunting regions for ND — and even more for *single* (anti-)top quarks [26].

First I make general statements and later give examples for special situations. There is a comment about the use of the ‘words’: Nason said in the abstract in his paper [27]: ‘shower generators (NLO + PS) of increasing accuracy, interfaced to both Pythia8 and Herwig7 Monte Carlo generators’. The first statement: obviously the meaning of his ‘PS’ is quite different from Beneke’s ‘word’ as I had discussed in Sect. 6.1.

The second statement is not so short: Nason and I talk about different worlds.

(a) He focuses on the perturbative impact of QCD if only with a short comment claimed ‘the renormalon ambiguity’ is safely below the current experimental errors’, namely the ‘ambiguity’ of 110 MeV or 250 MeV. I quite disagree. One can*not* ignore the works of Shifman [4], who has an excellent record[8]. There is an important difference between perturbative renormalon *vs.* non-perturbative one. Furthermore, how ‘safe’ we are to depend on Montre Carlo generators?

(b) As I have said above, the ‘pole mass’ is *not* well-defined. Using simulations and modeling is one thing (see Fig. 6 above), while understanding the underlying dynamics is quite another thing. Of course, using pole masses is popular — in particular in experimental papers and analyses — but it is only the first step, as I had said above. So far, we are not close to ‘precision’ or even ‘accuracy’.

It was said top quarks decay before they can produce top hadrons [28]. Still they carry “color” based on a local unbroken QFT; thus, they can evolve with other “color” states in connection to produce hadrons without “color” states in the end. It means that the ‘world’ of simulations is *less* complex than the FS in the real word.

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[7] He gave a reference to: V.I. Lenin: ‘What Is To Be Done?’

[8] Of course, I am ‘biased’.

9.1. CP asymmetries without Higgs dynamics

One can measure pp collisions with a pair of $[\bar{b}W^-]_t[bW^+]_t \ldots$ in the center region with gg or forward(backward) region $q\bar{t}tg$ with $q = u, d$. It is unlikely to find CP asymmetries there; on the other hand, we might learn new lessons about very heavy resonances.

Another road: $pp \to [\bar{b}W^-]_t \ldots [q'W^+]_t/[\bar{q}'W^-]_t \ldots [bW^+]_t$ with $q' = s, d$. One might find CP asymmetries there: a possible source is an asymmetric dark matter. Maybe probe CP asymmetry with a *single* top: $bg \to W^-tg \to W^-[bW^+]_tg$ *vs.* $\bar{b}g \to W^+\bar{t}g \to W^+[\bar{b}W^-]_tg$. Again, a possible source is an asymmetric dark matter.

9.2. CP asymmetries with on-shell Higgs dynamics

Collisions at the LHC have enough energies to produce very often $pp \to H^0\bar{t}tX$. To use different words to talk about short distance forces like $gg \to \bar{t}H^0t$. However, can one find these events with a huge background? While I disagree with some statements in these articles, I have to say first I admire the courage of these experimenters that enter this challenge.

10. Summary and a new alliance for the future

The ruler of a Greek city in southern Italy once approached the resident sage (Pythagoras) with the request to be educated in mathematics, but in a 'royal way', since he was busy with many obligations. Whereupon Pythagoras replied with admirable candor: 'There is no royal way to mathematics.'

Likewise there is *no* 'royal insights' into the inner working of 'our' Nature as I try to show first with pictures: power is not enough — we have to think as Fig. 7 shows.

The painting of Piero della Francesca shows the dream before the crucial battle outside of Rome between Constantine and Maxentius on different dimensions, see Fig. 8[9]. Kolya Uraltsev and I had looked at this painting in person and realized that it is symbol of a true collaboration.

Our community proceeds in steps: first one uses models to describe the data and then model-independent analyses. However, those should not be the final step(s). Often best fitted analyses do not give us the best information about the underlying dynamics. How to do that? We have theoretical tools with a good record like dispersion relations and other refined tools. They are 'waiting' — it 'only' needs to work with *judgements* and test it with correlations with other data! Yes, the data are the referees, but in the end — theorists should not be the slaves of the data.

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[9] Another example of divine manifestation in the old history?

Fig. 8. The dream in the night *before* the battle by the bridge over the Tiber.

In the previous century, we had talked about fundamental physics: Nuclear Physics at low energies, while HEP at high energies; flavor dynamics are part of HEP. In this century, one thinks (or should) about Nuclear Physics and MEP and HEP. Probing jets, Higgs and top-quarks dynamics and direct SUSY is the 'job' for HEP still again. However, the landscape is more complex with many interconnected parts: decays of strange/beauty/charm hadrons, where tools applied to Dalitz plots with dispersion relations *etc.* We have to go for accuracy and even precision to find the impact of ND. To make progress, it is crucial to connect the world of hadrons, where MEP applies — or with a better choice of word, namely "hadro-dynamics" — with the world of quarks and gluons, where HEP works; it is highly non-trivial.

11. Personal epilogue from my week in Kraków

In a museum of Kraków that is inside of the north Wall of the old center I have seen a very good Roman sculpture to show the goddess 'Minerva/Athena'. I saw a group of pairs of ladies, where one was blind and the other was a guide: the blind one was allowed to *touch* this sculpture in some details — a wonderful experience!

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