Impact of Non-perturbative QCD on CP Violation in Many-Body Final States of Flavor Transitions

I.I. Bigi
Department of Physics, University of Notre Dame du Lac, Notre Dame, IN 46556, USA
email address: ibigi@nd.edu

The title of my talk pointed out central statements: the impact of non-perturbative QCD on **CP** asymmetries in many-body FS in charm & beauty hadrons. For practical reasons one measures first **CP** violation in two-body final states of heavy flavor hadrons. However, those are small parts of charm hadrons and tiny ones for beauty hadrons; therefore one has to probe **CP** asymmetries in three- & four-body final states. Thus the transitions to the many-body FS basically give information about the underlying dynamics. The impact of non-perturbative QCD on **CP** asymmetries in many-body FS shows that – in principle; it is a true challenge even in a semi-quantitative way. One needs correlations with other transitions. That is my strategy; however, I have to discuss the tactics on the same level like using consistent parameterization of the CKM matrix. Our community has entered a novel era: direct **CP** violation has been found in $D^0 \to h^+h^-$ decays [1]. Finally I give short comments about the possible impact of New Dynamics on direct **CP** violation in $K_L \to 2\pi$ and probe **CP** asymmetry in $J/\psi \to \bar{\Lambda}\Lambda$ transitions.

I. GODS = SYMMETRIES SPEAK IN RIDDLES

I see a connection of the 'Gods' with symmetries: not all symmetries are the same; 'local' vs. 'global', 'broken' vs. 'unbroken'. To describe data one first use models and then model-independent analyses – indeed true progress. However, the best fitted analyses often do not give the best information about the underlying dynamics. Of course, data are the referees – in the end! We need true collaborations of experimenters and theorists with correlations with other transitions – and 'judgments'. The goal for the first quarter of this century (& this conference): establish the existence of New Dynamics (ND) and their features. The tools are: (a) probe many-body non-leptonic final states and (b) use collaboration with members of HEP vs. Hadrodynamics from different 'cultures'.

II. SHORT COMMENTS

Due to the limit of four pages I give only short comments.

- For weak decays of H_Q one can use "kinetic scheme" or "potential-subtracted scheme". However, the PDG2018 review basically ignores these schemes, while focus on '1S scheme' claiming it gives the same information about the underlying dynamics. However, I quite disagree; the '1S scheme' is not well defined on the non-perturbative level!
- Wolfenstein's parameterization was very smart & used all the time. The SM with 3 families of quarks describes the CKM matrix with 4 parameters: $\lambda \simeq 0.223$ plus A, ρ & $\eta \sim \mathcal{O}(1)$. Fitting the data one gets $A \simeq 0.84$, but also $\eta \simeq 0.35$ & $\rho \simeq 0.14$; there is no real control over systematic uncertainties. Furthermore reviews show uncertainties $\mathcal{O}(\lambda^4)$. Now we have gotten a *consistent* parameterization [2].
- Drawing diagrams is easy, but understanding the underlying dynamics is another thing. One example: re-scattering of $\pi\pi \rightleftharpoons \bar{K}K$ due to non-perturbative QCD.
- It is crucial to probe **CP** asymmetries in Λ_b^0, Λ_c^+ & Λ decays.

Basically I have said before – like at the FPCP2013.

III. BROKEN U- & V-SPIN SYMMETRIES

$SU(3)_{\rm flav}$ can be described by 3 $SU(2)$ with I-, U- & V-spin symmetries. Broken U-spin symmetry without V-spin is okay for strong spectroscopy, where (s,d) are combined. What about weak decays? In 2005 Lipkin had suggested to subtly use U-spin symmetry [3]:

$$\Delta = \frac{A_{\rm CP}(B^0 \to K^+\pi^-)}{A_{\rm CP}(B^0_s \to \pi^+K^-)} + \frac{\Gamma(B^0_s \to \pi^+K^-)}{\Gamma(B^0 \to K^+\pi^-)} = 0 \quad (1)$$

while the LHCb collaboration found in 2018 based on the run-1 [4]:

$$\Delta_{\rm LHCb} = -\,0.11 \pm 0.04 \pm 0.03\ . \quad (2)$$

While $\Delta_{\rm LHCb}$ is still consistent with zero, it is also consistent with ~ -0.1 as expected for direct **CP** violation for two-body final states.

Correlations of U-spin with V-spin due to re-scattering? PDG2018 shows: $A_{\rm CP}(B^+ \to K^+\eta) = -0.37 \pm 0.08$. One should learnt two lessons:
(1) The difference between U- & V-spins is 'fuzzy' in weak transitions.
(2) We have to go *well beyond* two-body final states to probe **CP** asymmetries!

IV. CP VIOLATION IN D^0 DECAYS

We have entered a 'novel era': (direct) **CP** violation has been found by LHCb [5]:

$$\begin{aligned}\Delta A_{\mathbf{CP}} &\equiv A_{\mathbf{CP}}(D^0 \to K^+K^-) - A_{\mathbf{CP}}(D^0 \to \pi^+\pi^-) \\ &= (-15.4 \pm 2.9) \cdot 10^{-4} \; ; \end{aligned} \tag{3}$$

it is an important achievement! The next question is: where the LHCb collaboration has to 'go' now? To establish indirect **CP** violation in $D^0 \to K^+K^-$ (& $D^0 \to K_S\pi^+\pi^-$) or direct **CP** asymmetries in other final states, like to probe Dalitz plots $D^\pm \to \pi^\pm\pi^+\pi^-/\pi^\pm K^+K^-$ or $D_s^+ \to K^+\pi^+\pi^-/K^+K^+K^-$. Which lesson can one learn from that? Obviously we need more data.

What about double Cabibbo suppressed (DCS) ones? Two very short comments about the LHCb paper JHEP **04**(2019)063:

(a) The 'Figure 9(a)' there cannot be the leading source; it is misleading to connect the WA diagram with re-scattering.

(b) Re-scattering gives connections of $D^+ \to K^+K^+K^-$ with $D^+ \to K^+\pi^+\pi^-$. We have to wait for run-3 of LHCb to find **CP** asymmetry there. Non-zero values would show there the impact of ND.

It is crucial to probe **CP** asymmetries in three- & four-body final states both of charm & beauty hadrons; I talk about it in the next Section we have examples with non-zero values.

V. CP ASYMMETRIES FOR THREE- & FOUR-BODY FINAL STATES

Two-body final states of suppressed non-leptonic weak decays are a small part of charm mesons & tiny ones for beauty mesons. It means one need much more information about the underlying dynamics. There is a price for working on the 3- & 4-body final states, but also a prize for the underlying dynamics, namely the existence of ND & its features. The situations are very different for $\Delta S = 1\,\&\,2$ transitions: the final states are two pions, and they are produced by local operators. In particular, when one talks about direct **CP** violation, one needs a weak phase, but also strong re-scattering:

$$\begin{aligned}&|T(\bar{H}_Q \to \bar{a})|^2 - |T(H_Q \to a)|^2 \propto \\ &\propto \sum_{a_j \neq a} T^{\rm resc}_{a_j,a} \, {\rm Im}\, T^*_a \, T_{a_j} \neq 0 \; . \end{aligned} \tag{4}$$

To understand the information from the data, one needs several tools like chiral symmetry, dispersion relations & etc. Dalitz plots with π, K, η & η' probe the underlying dynamics with two observables: without angular correlations a plot is flat, while resonances & thresholds show their impact. We have also broad resonances in the 0.5 - 3 GeV; scalar ones like $f_0(500)$, $K_0^*(700)$ etc. can*not* described with a Breit-Wigner parameterization.

A. Regional CP asymmetries in $B^\pm \to K^\pm h^+h^-$ & $B^\pm \to \pi^\pm h^+h^-$

LHCb data from run-1 of CKM suppressed B^+ decays show no surprising rates:

$$\begin{aligned}{\rm BR}(B^+ \to K^+\pi^-\pi^+) &= (5.10 \pm 0.29) \cdot 10^{-5} \\ {\rm BR}(B^+ \to K^+K^-K^+) &= (3.40 \pm 0.14) \cdot 10^{-5} \; . \end{aligned}$$

Averaged **CP** asymmetries are not surprising [6]:

$$\begin{aligned}\Delta A_{\rm CP}(B^+ \to K^+\pi^+\pi^-) &= +0.032 \pm 0.008 \pm 0.004 \\ \Delta A_{\rm CP}(B^+ \to K^+K^+K^-) &= -0.043 \pm 0.009 \pm 0.003 \end{aligned}$$

(I ignore production asymmetry of ± 0.007 with $B^\pm \to J/\psi K^\pm$ as reference mode.). 'Regional' ones [6]:

$$\begin{aligned}&\Delta A_{\rm CP}(B^+ \to K^+\pi^+\pi^-)|_{\rm `regional'} = \\ &= +0.678 \pm 0.078 \pm 0.032 \end{aligned} \tag{5}$$

$$\begin{aligned}&\Delta A_{\rm CP}(B^+ \to K^+K^+K^-)|_{\rm `regional'} = \\ &= -0.226 \pm 0.020 \pm 0.004 \; . \end{aligned} \tag{6}$$

The data of even more CKM suppressed B^+ decays show no surprising rates:

$$\begin{aligned}{\rm BR}(B^+ \to \pi^+\pi^-\pi^+) &= (1.52 \pm 0.14) \cdot 10^{-5} \\ {\rm BR}(B^+ \to \pi^+K^-K^+) &= (0.50 \pm 0.07) \cdot 10^{-5} \; . \end{aligned}$$

However, both averaged **CP** asymmetries

$$\begin{aligned}\Delta A_{\rm CP}(B^+ \to \pi^+\pi^+\pi^-) &= +0.117 \pm 0.021 \pm 0.009 \\ \Delta A_{\rm CP}(B^+ \to \pi^+K^+K^-) &= -0.141 \pm 0.040 \pm 0.018 \end{aligned}$$

and 'regional' ones [6]:

$$\begin{aligned}&\Delta A_{\rm CP}(B^+ \to \pi^+\pi^+\pi^-)|_{\rm `regional'} = \\ &= +0.584 \pm 0.082 \pm 0.027 \end{aligned} \tag{7}$$

$$\begin{aligned}&\Delta A_{\rm CP}(B^+ \to \pi^+K^+K^-)|_{\rm `regional'} = \\ &= -0.648 \pm 0.070 \pm 0.013 \end{aligned} \tag{8}$$

Of course, re-scattering has large impact. One can describe it in the world of hadrons – like $\pi\pi \rightleftharpoons \bar{K}K$ – or in the world of quarks – $\bar{u}u/\bar{d}d \rightleftharpoons \bar{s}s$. Furthermore they are connected using the word of 'duality'. Can one predict that semi-quantitatively? It depends on the situations. In particular, one needs 'judgment' for the definition of 'regional' **CP** asymmetries and best connected with other transitions. There is a good chance that the LHCb collaboration will change its definition of 'regional' **CP** asymmetries after the analyses the data from run-2. Anyway, it is not easy for theorists to wait for the results of these analyses.

VI. CP ASYMMETRIES IN BEAUTY & CHARM BARYONS

CP asymmetries have been established in strange, beauty and charm mesons, but so far not in the decays of baryons. Of course, one looks for direct **CP** violation.

A. Weak decays of beauty baryons

At the ICHEP2016 conference the LHCb collaboration had shown the data based on run-1 evidence for **CP** asymmetry in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$. In pp collisions one gets different numbers of Λ_b^0 vs. $\bar{\Lambda}_b^0$ due to *production* asymmetries. Therefore one focuses first on **T**-odd moments. The LHCb experiment has measured the angle between two planes: one is formed by the momenta of p & $\pi^-_{\rm fast}$, while the other one with the momenta of π^+ & $\pi^-_{\rm slow}$. It has found evidence for **CP** asymmetry on the level of 3.3 σ [7]. Furthermore, the plot given at the ICHEP2016 and the Ref.[7] shows the strength of 'regional' **T** asymmetry around $20 \cdot 10^{-2}$. On the other hand, no evidence has been found in $\Lambda_b^0 \to p\pi^-K^+K^-/pK^-\pi^+\pi^-/pK^-K^+K^-$. One can try to 'paint' these situations with tree & penguin diagram. However, one cannot claim to understand the underlying dynamics – yet. Our community has to wait for the data from run-2 based on pp collisions at $\sqrt{s} = 13$ TeV.

B. Weak decays of charm baryons

For singly Cabibbo suppressed decays PDG2018 gives $\mathrm{BR}(\Lambda_c^+ \to p\pi^+\pi^-) = (4.2 \pm 0.4) \cdot 10^{-3}$ & $\mathrm{BR}(\Lambda_c^+ \to pK^+K^-) = (1.0 \pm 0.4) \cdot 10^{-3}$. These values will be updated from the run-2 of the LHCb experiment 'soon' and later by Belle II. Averaged **CP** asymmetries in these Dalitz plots can be on the order of 10^{-3} similar to D^0 decays as discussed above, see Eq.(3), and larger for 'regional' ones with run-2.

VII. IMPACT OF NEW DYNAMICS ON STRANGE HADRONS?

Indirect & direct **CP** violation has been established in the neutral kaon with $\mathrm{Re}(\epsilon'/\epsilon_K) = (1.66 \pm 0.23) \cdot 10^{-3}$. The 'Buras team' has argued that the SM can produce only a sizably smaller value like with a factor of two [8, 9]. Present LQCD result is somewhat close to that [10]. One can hope that future results will clean out the possible impact of ND on direct **CP** asymmetry. While I am 'biased' about this situation, I have to mention the words of my other colleague Pich [11].

The next step is to probe **CP** asymmetry in strange *baryons* as suggested by my colleague G. Punzi from Pisa: LHCb can measure $J/\psi \to \bar{\Lambda}\Lambda \to [\bar{p}\pi^+][p\pi^-]$ in the run-3 with a dedicated trigger & probe **CP** asymmetry below 10^{-4}. One would get new lessons about the impact of non-perturbative QCD. The real goal is to find **CP** asymmetry in Λ decays and even to connect the results of K_L & Λ decays. Of course, it is a tough order.

VIII. LESSONS FOR THE FUTURE

I said it in the beginning: 'Gods speak in riddles: tragic oracles and tragic misunderstanding', see FIG.1. In quantum field theories one can see a connection between 'Gods' and symmetries where I gave examples: some symmetries are perfect, while other are broken. I see an analogy in FIG.1, namely HEP experimenters and HEP & MEP theorists have to work as a 'team'.

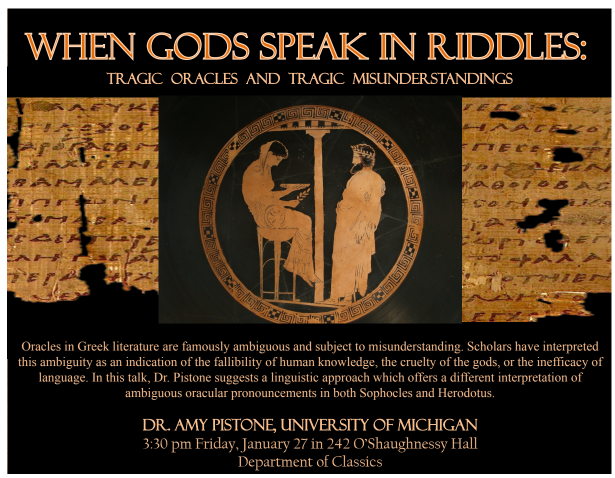

FIG. 1: When Gods speak in Riddles

BaBar (& Belle) were pioneers about weak dynamics & non-perturbative QCD and now LHCb & soon Belle II in a new era. We need more data, but that is not enough: thinking & 'judgment' about the impact of long-distance QCD from different 'cultures': 'observables = perturb. forces + non-perturb. ones' vs. "observable = long-distance forces + short-distance ones" [12]: best fitted analyses do not give the best information about the underlying dynamics; **CP** asymmetries in 3- & 4-body final states is crucial to make progress about ND. Challenges between 'cultures' of HEP vs. Hadrodynamics like the 'masses of current quarks' vs. 'pole masses of hadrons' as discussed with details in Ref.[13] and 'soon' in Ref.[14].

Going back to old history: seeing a missile shot by a catapult which had been brought then for the first time, a king from Sparta in the 4th century B.C. cried out: 'By Heracles, this is the end of man's valor.' Can a theorist see an analogy with computers?

IX. SHORT COMMENT ABOUT V_{ub}

While I had talked about **CP** violation and the impact of non-perturbative QCD, I give very short comments about the situations of $|V_{qb}|$ with $q = c, u$. In the present literature the difference between exclusive vs. inclusive data of $|V_{cb}|$ is around $\sim 2\sigma$ [15]. However, the discussions about the values $|V_{ub}|$ are $(3-4)\,\sigma$ between exclusive vs. inclusive rates with different theoretical tools including LQCD. I had suggested before, there could another way to solve this challenge; of course, these loads will go down on the shoulders of our experimenter colleagues. Present data about $|V_{ub}|$ could be incomplete in a sizable way: PDG2019 lists branching ratios of $B^+ \to l^+\nu\pi^0/\eta/\eta'$ on the level of several$\cdot 10^{-5}$, while $B^+ \to l^+\nu\rho^0/\omega$ for $\sim 10^{-4}$ and even for $\mathrm{BR}(B^+ \to l^+\nu\bar{p}p) = (5.8^{+2.6}_{-2.3}) \cdot 10^{-6}$. Yet PDG2019 has not listed even limits for $B^+ \to l^+\nu\phi$ or $B^+ \to l^+\nu K^+K^-$! Feynman diagrams give (suppressed) transition $B^+ = [\bar{b}u] \to l^+\nu[\bar{u}s][\bar{s}u]$; furthermore this could be enhanced close to a threshold, which is a subtle item about hadron-quark duality. We have the tools to give semi-quantitatively predictions like dispersion relations; 'soon' I will work on that.

Acknowledgments: This work was supported by the NSF PHY-1820860.

[1] 'Charm' is to ward off 'evil spirits' = infinity.
[2] Y.H. Ahn, H-Y Cheng, S. Oh, *Phys.Lett.* **B 703** (2011) 571.
[3] H. Lipkin: *Phys.Lett.* **B621** (2005) 126 [arXiv:hep-ph/0503022].
[4] R. Aaij *et al.*, *Phys.Rev.* **D98** (2018) 032004.
[5] LHCb collaboration: "Observation of **CP** violation in charm decays", *Phys.Rev.Lett.* **122** (2019) 211803 [arXiv: 1903.08726 [hep-ex]].
[6] R. Aaij *et al.*, *Phys.Rev.Lett.* **111** (2013) 101801; *Phys.Rev.Lett.* **112** (2014) 101801.
[7] R. Aaij *et al.*, LHCb collaboration: Nature Physics, **13** (2017) 391 [arXiv: 1609.05216 [hep-ex]].
[8] A.J. Buras: "The Return of Kaon Flavor Physics", *Acta Phys.Polon.* **B49** (2018) 1043 [arXiv: 1805.11096 [hep-ph]]; it makes it clearly the connection with the impact of LQCD.
[9] A.J. Buras, J.-M. Gerard: *Eur.Phys.J.* **C77** (2017) 10 [arXiv:1603.05686[hep-ph]].
[10] N. Garron: [arXiv:1512.02440 [hep-lat]]; R.J. Hudspith, N. Garron, A.T. Lytle: [arXiv:1512.05398 [hep-lat]].
[11] H. Gisbert, A. Pich: "Direct **CP** violation in $K^0 \to \pi\pi$: Standard Model Status", *Rept.Prog.Phys.* **81** (2018) 076201 [arXiv:1712.06147 [hep-ph]].
[12] A reader can see that I am biased about the 'cultures'.
[13] I.I. Bigi, A.I. Sanda: "CP Violation, Second Edition" (Cambridge University Press) 2009.
[14] A new book will be published by the World Scientific Publ.Co. in the Fall 2019: I.I. Bigi, M. Pallavicini & G. Ricciardi, "New Era for CP Asymmetries, Axions and Rare Decays of Hadrons and Leptons", dedicated to L. Okun.
[15] It was said at FPCP2019 it could be $\sim 3\sigma$.