V3.0

CP asymmetries in the decays of charm hadrons with many-body Final States & short comments about strange hadrons -- Impact of Non-perturbative QCD on CP Violation

Ikaros Islam Bigi, Notre Dame du Lac

LHCb WS, October 2019

When Gods speak in Riddles

? Tragic Oracles & Tragic Mis-understanding ?

Delphi ⟷

(old Delphi detector is still close to the LHCb experiment)

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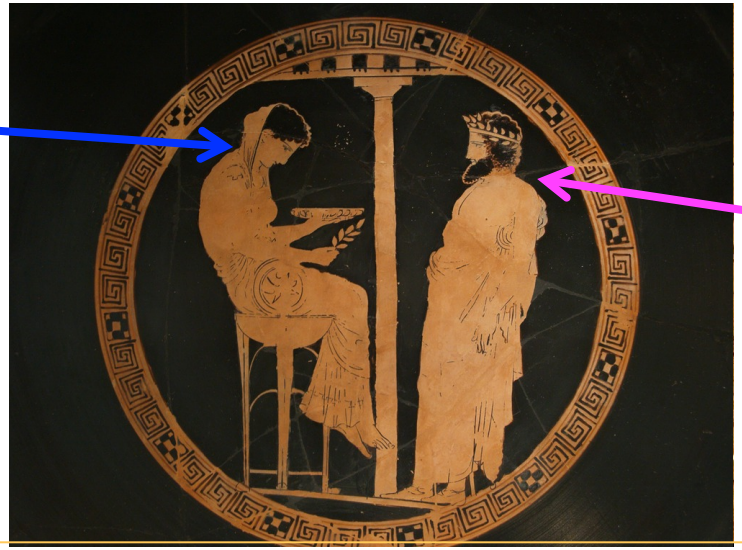
When `Gods' (=` Symmetries') speak in Riddles

? Tragic Oracles & Tragic Mis-understanding ?

LHCb & Belle II both as a pioneer about non-pert. QCD & weak dynamics – as a team of experimenters and HEP theorists [as before BaBar & Belle]



On seeing the missile shot by a catapult which had been brought then for the first time from Sicily, the king from Sparta in the fourth century B.C. cried out:
`By Heracles, this is the end of man's valor.'

Analogy of physicists with computers?

Manifestation of a *divine* being through something both simple & striking:
symmetries & their tools !

Fitting the data vs. *Information* inside the data

1st step: models

2nd step: model-independent analyses – indeed, true progress

3rd step: best fitted analyses often do *not* give the best information about the underlying dynamics;
data are the referees – in the end !

crucial: *collaborations* of experimenters & theorists with *correlations* & judgments !

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The *goals* for my talk here:

-- *Direct CP asymmetry* in D^0 -> K+K-/π+π- is a wonderful 1st step for a long traveling for fundamental dynamics !
Next one measures *indirect* CP violation in D^0 -> K+K-.

-- *Probes many-body* non-leptonic FS of charm hadrons.

-- Short comments about possible impact of ND on *strange* hadrons.

-- collaboration of HEP & Hadrodynamics from different `cultures'

(I) Introduct: *Wilsonian* OPE, *broken* U- & V-spin symmetries

(II) *Consistent* Parameterization of the CKM Matrix

(III) Intermezzo: *CP asymmetry* in D^0 -> K+K-/π+π-

(IV) CP asymmetries with $\Delta C \neq 0$ (& lifetimes of charm *baryons*)

(V) Direct CP asymmetries for *Strange* Hadrons

Epilogue for the future: *Collaboration* of HEP & Hadrodynamics

(VI) Summary: Impact of *non*-perturbative QCD on CP Violation

The slides I think are very important see the symbol *

I had produced this picture; later I will explain why it is *not* about bragging rights.

(I) Introduction: *Wilsonian* OPE, *broken* U- & V-spin symmetries

(I.1) *Wilsonian* Operator Product Expansion (OPE)

Almost all invoke OPE -- often *without* using *Wilsonian* prescription!
However: "*not* all OPE's are created equality"!
Shifman & collaborators had emphasized applying OPE is subtle:

the *Wilsonian* OPE *stops* at ~ 1 GeV, not sizably lower *

(I.2) *broken* U- & V-spin symmetries

Does `Lipkin rule' work for B decays? Hardly.

1st lesson: difference between U- & V-spin is `fuzzy'
2nd lesson: we have to go *well beyond 2-body* FS *

(II) Parameterization of the CKM Matrix

(II.1) Wolfenstein's parameterization

Wolfenstein's parameterization was very smart, easily usable, well-known & used all the time. The SM with 3 families of quarks describes the CKM matrix with 4 parameters: λ, A, ρ, η;
expansion of $\lambda = 0.223$, while A, ρ, η are $O(1)$.
Fitted values give $A \approx 0.82$ -- but $\eta \approx 0.35$, $\rho \approx 0.14$ not close to unity;
-- thus not real control over *systematic* uncertainties.

(II.2) *Consistent* parameterization

Consistent parameterization of CKM matrix with more precision [Y.H. Ahn, H-Y. Cheng, S. Oh (2011)] *through* $O(\lambda^6)$!
Pattern is not so obvious as before:

- *correlations between 4 triangles*, not focus `golden one'
- -- maximal SM value for $S(B^0 \to \psi K_S) \sim 0.74$ for indirect CPV
- -- SM value $S(B_s^0 \to \psi\phi) \sim 0.03 - 0.05$
- -- basically *zero* CPV for *double Cabibbo suppressed (DCS)* decays
  - *hunting region for ND*!
- -- ...

(III) Intermezzo – *Direct CP asymmetry* in $D^0 \to K^+K^-/\pi^+\pi^-$!

Now we are just entering a new era:
for the first time CP violation has been established in $\Delta C \neq 0$!
LHCb collaboration has shown its data from the run-1 & run-2 --
but an achievement:

$$\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-) = (-1.54 \pm 0.29) \times 10^{-3}$$

indirect CPV was found first in $\Delta S \neq 0 \neq \Delta B$, but not yet for $\Delta C \neq 0$;
SM `paints' the `landscape' for indirect CPV ~ 10^{-4} – 10^{-3}.
Here talk about SCS rates [below will discuss DCS ones]:
-- $BR(D^0 \to K^+K^-) \sim 4 \times 10^{-3}$ vs. $BR(D^0 \to \pi^+\pi^-) \sim 1.4 \times 10^{-3}$;
-- $BR(D^+ \to K^+K_S) \sim 2.8 \times 10^{-3}$ vs. $BR(D^+ \to \pi^+\pi^0/\eta\,/\eta') \sim (1.2/3.8/5.0) \times 10^{-3}$;
-- $BR(D_s^+ \to \pi^+K_S) \sim 1.2 \times 10^{-3}$ vs. $BR(D_s^0 \to K^+\pi^0/\eta\,/\eta') \sim (0.6/1.8/1.8) \times 10^{-3}$.

three comments:
- first one probes direct CP asymmetries in 2-body FS ;
- present data show the impact of FSI ;
- it is crucial to probe *3- & 4-body* FS; I will discuss next. *

[Suggestion: LHCb → LHCbc]

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(IV) CP asymmetries with $\Delta C \neq 0$

March 2019: LHCb Collaboration has established *direct* CP asymmetry
Next steps:
-- Indirect CP violation

-- *SCS* decays direct CP asymmetries:
$D^0 \to 2\pi^+2\pi^-/K^+K^-\pi^+\pi^-$; $D^+ \to \pi^+\pi^+\pi^-/\pi^+K^+K^-$; $D_s^+ \to K^+\pi^+\pi^-/K^+K^+K^-$
- *Averaged* CPV: SM ~ 0.001
- *Regional* CPV: large impact of re-scattering like ~ 0.01 or more

-- *DCS* decays direct CP asymmetries:
$D^0 \to K^+\pi^-\pi^+\pi^-/2K^+K^-\pi^-$; $D^+ \to K^+\pi^+\pi^-/K^+K^+K^-$; $D_s^+ \to K^+K^+\pi^-$
- *Averaged* CPV: basically zero for the SM
- *Regional* CPV: hunting region for ND with no SM background when one has large data plus refined tools plus novel lessons about non-perturb. QCD
- Maybe the main challenge: confused by true CF transitions

(IV.1) CP asymmetries with singly Cabibbo suppressed (SCS) ones

BR($D^+ \to \pi^+\pi^+\pi^-$) =$(3.27\pm0.18)\times10^{-3}$, BR($D^+ \to \pi^+K^+K^-$)=$(9.93\pm0.24)\times10^{-3}$;

BR($D_s^+ \to K^+\pi^+\pi^-$)=$(6.6\pm0.4)\times10^{-3}$, BR($D_s^+ \to K^+K^+K^-$)=$(0.218\pm0.021)\times10^{-3}$;

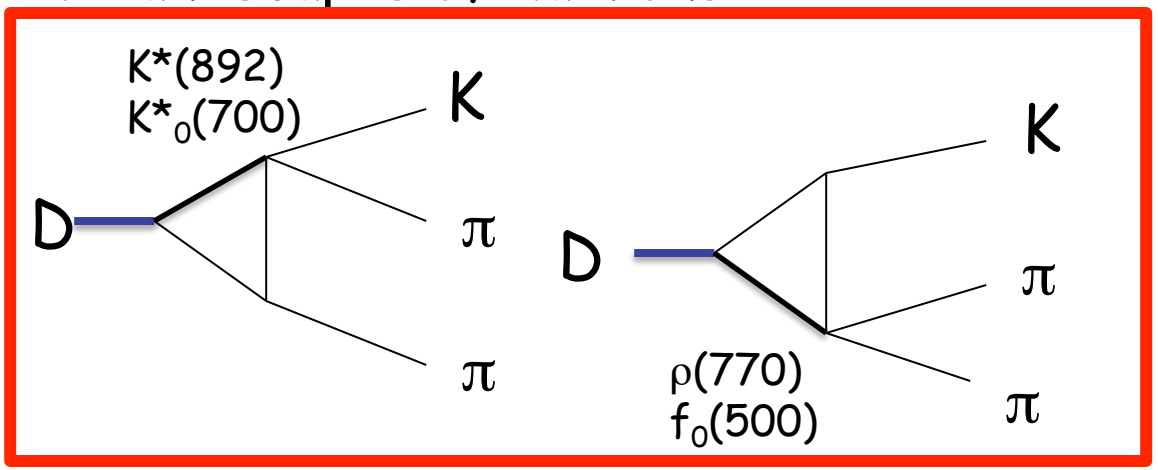
BR($D^0 \to 2\pi^+2\pi^-$) = $(7.56\pm0.20)\times10^{-3}$, BR($D^0 \to K^+K^-\pi^+\pi^-$) =$(2.47\pm0.11)\times10^{-3}$;

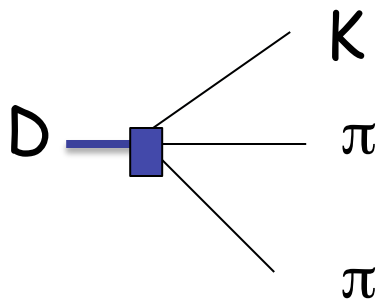
LHCb collaboration is probing CPV in many-body FS `now' !

Remember:
do *not* ignore the impact of broad (scalar) resonances
like *$f_0(500)$/sigma, $K^*_0(700)$/kappa etc. etc.*

Furthermore, broad resonances in the region ~ 0.5 – 1.5 GeV can*not* been described with Breit-Wigner parameterization.

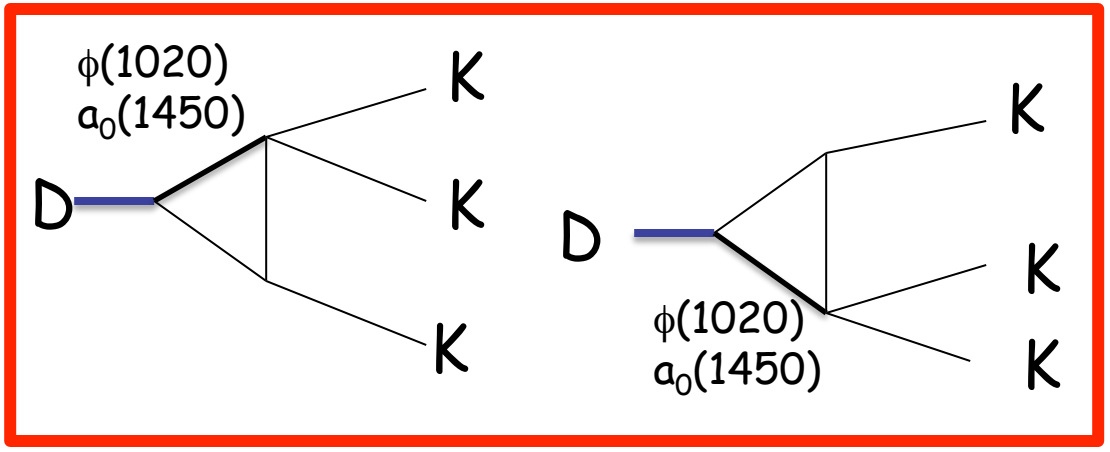
The landscapes of hadrons

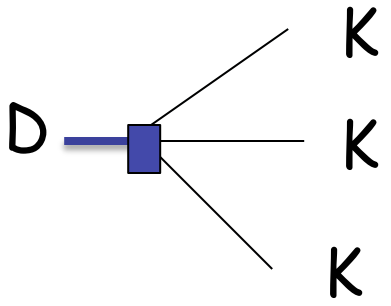




`effective' (?!) operator

Re-scattering is crucial to understand the underlying dynamics !





`effective' (?!) operator

need `judgment' about applying resonances, *threshold enhancements* etc. with tools like *dispersion relations*

(IV.1) CP asymmetries with singly Cabibbo suppressed (SCS) ones

Analyses with *dispersion relations* !

The idea came from theorists.
However, it pointed out one needs `good' data to analyze with a team of experimenters & theorists;

amplitude $f(s) = (1/\pi)\int ds'\ \mathrm{Im}\ f(s')/(s'-s-i\varepsilon)$

amplitude $f(s) = f(0) + (s/\pi)\int ds'\ \mathrm{Im}\ f(s')/s'(s'-s-i\varepsilon)$

Dispersion relations are above models, but below QFT;
both experimenters & theorists need judgments to apply –
i.e. dispersion relations are `Protestant', not `Catholic'.

(IV.2) CP asymmetries with doubly Cabibbo suppressed ones

PDG2018 for *DCS* decays:

$BR(D^+ \to K^+K^+K^-)/BR(D^+ \to K^-\pi^+\pi^+) = (0.95 \pm 0.22) \times 10^{-3}$
$BR(D^+ \to K^+\pi^+\pi^-)/BR(D^+ \to K^-\pi^+\pi^+) = (5.77 \pm 0.22) \times 10^{-3}$
$BR(D_s^+ \to K^+\pi^-K^+)/BR(D_s^+ \to K^-K^+\pi^+) = (2.33 \pm 0.23) \times 10^{-3}$

LHCb for *DCS* decays, arXiv:1810.03138 [hep-ex] about 8 TeV (not run-2)
published in JHEP 03 (2019) 176

$BR(D^+ \to K^+K^+K^-)/BR(D^+ \to K^-\pi^+\pi^+) = (0.6541 \pm 0.0025 \pm 0.0042) \times 10^{-3}$

$BR(D^+ \to K^+\pi^+\pi^-)/BR(D^+ \to K^-\pi^+\pi^+) = (5.231 \pm 0.009 \pm 0.023) \times 10^{-3}$

$BR(D_s^+ \to K^+\pi^-K^+)/BR(D_s^+ \to K^-K^+\pi^+) = (2.372 \pm 0.024 \pm 0.025) \times 10^{-3}$

what a progress in this experiment !

(IV.2) CP asymmetries with doubly Cabibbo suppressed ones

PDG2018 for *DCS* decays:

BR(D+ -> K+K+K-)/BR(D+ -> K-π+π+) = (0.95 ± 0.22) x 10^{-3}

BR(D+ -> K+π+π-)/BR(D+ -> K-π+π+) = (5.77 ± 0.22) x 10^{-3}

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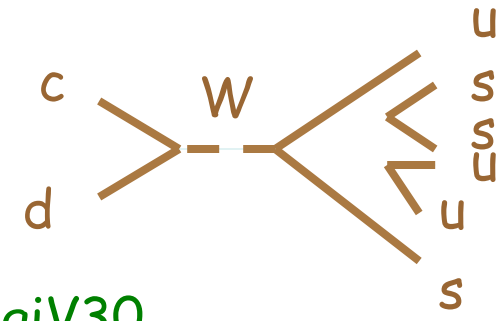
what a progress in this experiment!

However, look at Feynman diagrams in Figs. 1(a), 1(b) & 1(c) on page 1 of this article:

-- Figs. 1(b) & 1(c) are okay, but incomplete.

-- however, my main problem comes from Fig. 1(a):



-- `WA' no chance to be the leading source !

-- `WA' <-> re-scattering (FSI) is *misleading* !

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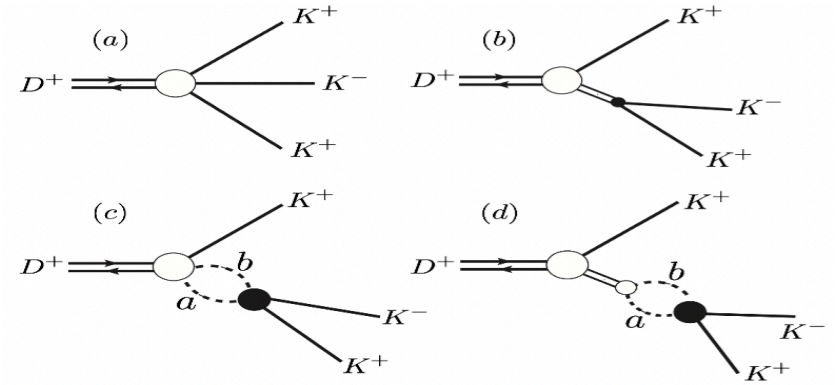
Connections of HEP & Hadrodynamics

One example in arXiv:1902.05884v3 [hep-ex] published in JHEP 04 (2019) 063

The world of hadrons



Nice `painting' !

Figure 10. Diagrams contributing to the amplitude T for the decay D+ → K– K+ K+: (a) the final state kaons are produced directly from the weak vertex; (b) a bare resonance is produced directly from the weak vertex; (c) particles produced at the weak vertex undergo final state interactions; (d) final state interactions endow finite widths to the resonances. The full circle represents the unitary ab → K+K– scattering amplitude with angular momentum J and isospin I, and ab = KK, ππ, ηπ and ηη.

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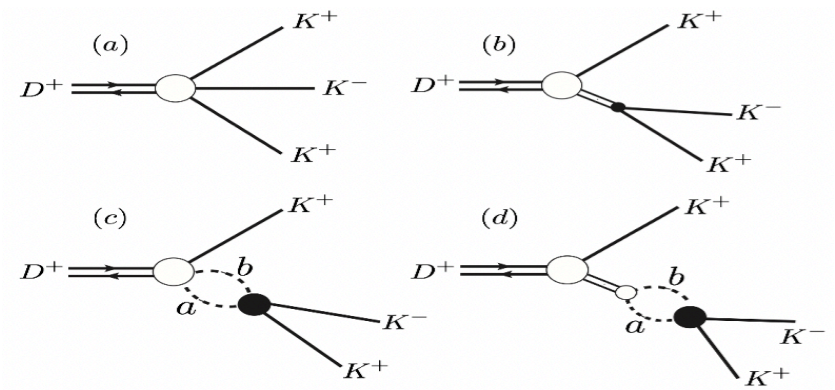

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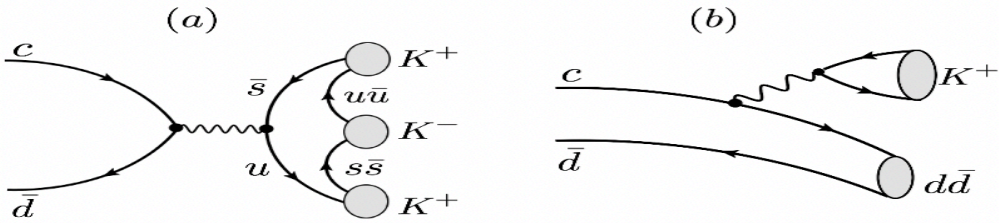
The world of quarks & gluons



`WA' <-> re-scattering (FSI) is *misleading* !

Figure 9. Diagrams representing the two quark-level topologies for the D+ → K–K+K+ decay. In the Triple-M [3], diagram (a) is assumed to be the dominant mechanism of the decay, whereas diagram (b) is suppressed since the production of a K+K– pair from a $d\bar{d}$ pair requires rescattering.

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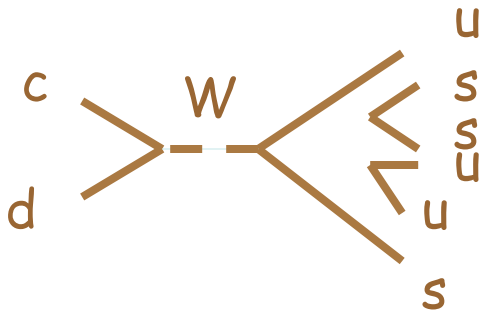
(IV.2) $\Delta C \neq 0$ with 3-body FS

LHCb for *DCS* decays,arXiv:1902.05884v3[hep-ex] about 8 TeV (not run-2)
published in JHEP 04 (2019) 063
`Dalitz plot analysis of the D+ -> K-K+K+ decay'
p. 12, `Figure 9 (a) is assumed to be the dominant mechanism ⋯'

again



-- `WA' no chance to be the leading source !
-- `WA' <-> re-scattering (FSI) is *misleading* !

-- *cannot* ignore D+ -> K+π+π- !

(IV.2) Δ C ≠ 0 with 3-body FS

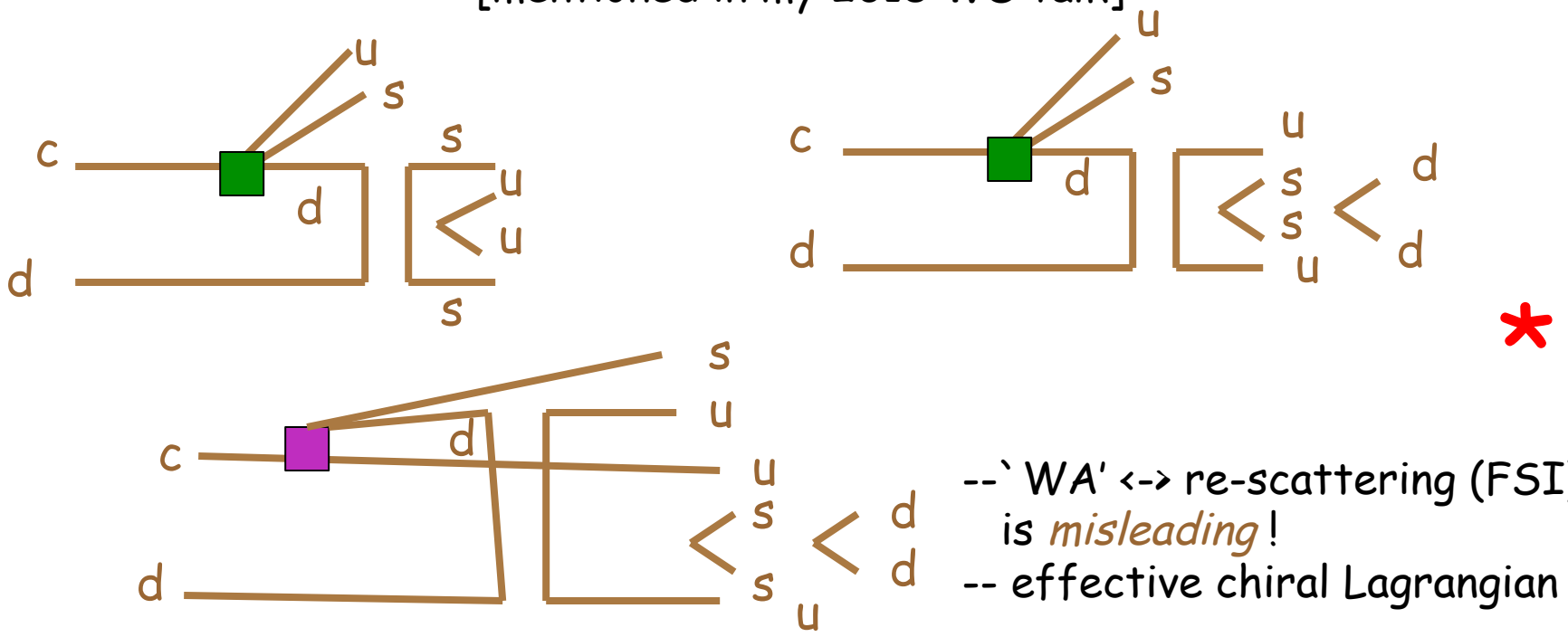
LHCb for *DCS* decays, arXiv:1810.03138 [hep-ex] from 8 TeV;
arXiv:1902.05884v3 [hep-ex] from 8 TeV:

BR(D+ -> K+K+K-) = (0.587 ± 0.002 ± 0.004 ± 0.018) x 10^{-4}

BR(D+ -> K+π+π-) = (4.70 ± 0.01 ± 0.02 ± 0.15) x 10^{-4}

[BR(D_s^+ -> K+π-K+) = (1.293 ± 0.013 ± 0.014 ± 0.040) x 10^{-4}]

My `painting' of the amplitudes for D+ -> K+K+K-/K+π+π-
[mentioned in my 2018 WS talk]



*

--` WA' <-> re-scattering (FSI)
is *misleading* !
-- effective chiral Lagrangian ! ?

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(IV.3) Lifetimes & SL widths of charm baryons

-- PDG2018: $\tau(\Omega^0_c) < \tau(\Xi^0_c) < \tau(\Lambda^+_c) < \tau(\Xi^+_c)$

in previous century one had expected this pattern based on HQE in a *simple* qualitative way.

-- PDG2019: $\tau(\Xi^0_c) < \tau(\Lambda^+_c) < \tau(\Omega^0_c) < \tau(\Xi^+_c)$

the `landscape' has changed:
while the *pattern* of $\tau(\Xi^0_c) < \tau(\Lambda^+_c) < \tau(\Xi^+_c)$ is the same,
it has changed sizably for $\tau(\Omega^0_c)$;
predictions depend on quark *models*, not QFT.
Compare $\Lambda^+_c = [c(ud)_{j=0}]$ vs. $\Omega^0_c = [c(ss)_{j=1}]$

-- The goal is to measure `soon' SL widths of Ξ^0_c, Ξ^+_c, Ω^0_c.
They are connected based on *non-perturb.* QCD.

(IV.4) CP asymmetries in weak decays of charm *baryons*

-- When one goes for CPV, one can*not* stop at 2-body FS: crucial to probe 3- & 4-body FS including regional CPV.

-- On first & second steps one goes after SCS ones where the SM predicts small CPV on the order of $O(10^{-3})$.

-- For DCS decays the SM predicts basically zero; hunting regions for ND.

-- One has to probe CPV in charm baryons with Dalitz plots
- SCS: Λ^+_c -> p π+π- / p K+K-
- DCS: Λ^+_c -> p K+π-
  - tiny rates are not the only challenge: compare DCS Λ^+_c -> p K+π- vs. CF Λ^+_c -> p K-π+

(V) Present and future lessons of $\Delta S \neq 0$

-- We know that CP asymmetries has been found & established in the transitions of neutral strange mesons:

- *indirect* CPV in $K^0 \to 2\pi$ with the scale ~ 2.23×10^{-3} data
- *direct* CPV in $K^0 \to 2\pi$ with
  - ~ 3.6×10^{-6} data
  - < 2.2×10^{-6} SM ?!?
  - ~ 1.1×10^{-6} "Buras team" ["LQCD"]

  *
- amazing established data & analyses
- it *might be beyond* the SM: "Buras team" ["LQCD"].

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- amazing established data & analyses
- it *might be beyond* the SM: "Buras team" ["LQCD"].

-- Next step for direct CP asymmetry in strange *baryons*

$e^+e^- \to J/\psi \to \Lambda\,\Lambda \to [p\,\pi^+][p\,\pi^-]$

- maybe BESIII could probe CPV by 2019 with below 10^{-3}

- duality violation enhanced close to thresholds ! ?

It is a novel `road':

Giovanni Punzi: LHCb can do better with *run-3/4 below* 10^{-4} !

$J/\psi \to \Lambda\,\Lambda \to [p\,\pi^+][p\,\pi^-]$

-- Some details:

$J/\psi \to Y\,Y \to [X\,\pi]\,[X\,\pi]$ with a *dedicated trigger*

- Measure T-odd moments

$\alpha_y^X = \langle \sigma_y \cdot (\sigma_X \times \pi_X) \rangle$, $\alpha_y^X = \langle \sigma_y \cdot (\sigma_X \times \pi_X) \rangle$,

based on CPT invariance

probe direct CP asymmetry $\langle A_{CP}^X \rangle = (\alpha_y^X + \alpha_y^X)/(\alpha_y^X - \alpha_y^X)$

with*out* polarized Y & Y due to very narrow resonance J/ψ !

"Imagination created reality" – Richard Wagner

Epilogue for the future: *Collaboration* of HEP & Hadrodynamics

Need to connect the worlds of quarks & gluons with hadrons !

Back to the history outside

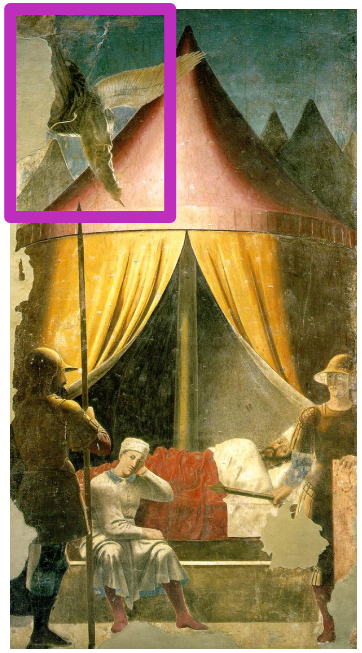
San Francesco, Arezzo (Italy)

Epilogue for the future: *Collaboration* of HEP & Hadrodynamics

Need to connect the worlds of quarks & gluons with hadrons !

Back to the history outside -- & inside

San Francesco, Arezzo (Italy)



`The Dream of Constantine'
by Piero della Francesca,
painter of Early Renaissance,
mathematician/geometer

`dreaming in more dimensions'
Kolya Uraltsev & I had looked at this painting *in person* & realized that it is symbol of collaboration.

Final steps need `judgment' about applying resonances, threshold enhancements etc. with dispersion relations

-- 1st step: models;

-- 2nd step: model-independent

-- 3rd step: best fitted analyses often do *not* give us the best information about the underlying dynamics – *correlations* & judgments

Future lessons for LHCb/Belle II

Yes, the data are the referees, but in the end - theorists should not be the slaves of the data !

One example:

IIB&collab.: bragging rights? It goes beyond -- the power of HQE !

$\tau(\Lambda_b)/\tau(B_d) > 0.9$ 1993; ~ 0.94 & > 0.88 1996

Data: $\tau(\Lambda_b)/\tau(B_d) = 0.77 \pm 0.05$ 1996; 0.81 ± 0.05 2004; 0.94 ± 0.09 2005

I had produced this picture – correlations & judgments are not always obvious!

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Short comments in one slide just before the Summary,
namely about V(qb) about exclusive *vs.* inclusive ones:

V(cb): $B \to l\,\nu\,D/D^*$ *vs.* $B \to l\,\nu\,X_c$

- (a) difference ~ 2 σ
- (b) *data landscape* is not clear about FS: D, D*, D**, D***, ···

V(ub): $B \to l\,\nu\,\pi/\rho$ *vs.* $B \to l\,\nu\,X_u$;

(a) difference ~ 3 – 4 σ ;

(b) probe $B \to l\nu\, f_0(500)/\text{sigma} \to l\nu\, 2\pi$ as a *bridge*
between exclusive & inclusive ones using *dispersion relations*

(c) X_u vs. only π's ?

(d) probe $B^- \to l^-\nu K^+K^-$ & $B^0 \to l^-\nu\, K^+K^-\,\pi^+$ to help to solve this problem

(e) in general "duality" is *not local* close to thresholds

(VI) Summary: Impact of *non*-perturbative QCD on *CP Violation*

about fundamental dynamics:

(a) Two-body FS do not give `royal insights' in general;

(b) diagrams give no `royal ones';

(c) Wolfenstein's parameterization of the CKM matrix is well-known & used all the time, but it is *not* `royal ones' for *this* century;

(d) even more: pole masses give no `royal insights' !

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(d) even more: pole masses give no `royal insights' !

"Goals for *flavor dynamics* of quarks":

- Probing CP asymmetries in 3- & 4-body FS of charm & beauty hadrons is crucial to find both existence & features of ND.
  [At least it shows the impact of non-perturbative QCD.]
- Theorists do not like waiting: *results from run-2* !
- Waiting for run-3 & run-4: that is life.
- Worlds of quarks & gluons and for hadrons are connected, but often they are not obvious (` duality' is more subtle than just looking at diagrams)!

Short summary:

-- `We' need more data, but that is not enough –
thinking & judgments about the impact of *long distance* QCD!

[-- HQET [with $\mu = 0$] ≠ HQE [$\mu \sim 1$ GeV]

HQET: `observables'= perturb. forces + non-perturb. forces

HQE: "observables" = "long-distance" forces +"short-distance "ones]

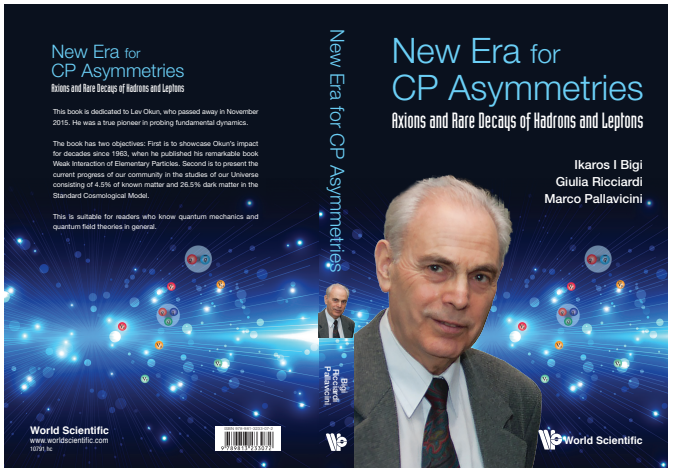
-- best fitted analyses do *not* give the best information about the underlying dynamics

-- CP asymmetries in 3- & 4-FS is crucial to make progress about ND

$$\Delta\gamma(a) = |T(P \to a)|^2 - |T(P \to a)|^2 = 4 \sum_{aj \neq a} T_{aj,a}^{resc} \; \mathrm{Im} T^*_a T_{aj}$$

-- `Challenges between Cultures' of HEP vs. Hadrodynamics
like "current quarks" vs. `pole masses of hadrons'

-- My new book will be published in the Winter 2019/20:
dedicated to L. Okun



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