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`Bridge between Hadrodynamics & HEP' -- Regional CP Asymmetries in Many-Body Final States

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Central points:

-- *consistent* parameterization of the CKM matrix
-- probe *many-body* final states (FS)
-- *connections* between U- vs. V-spin (broken) symmetries
-- Penguin *diagrams* vs. Penguin *operators*

crucial:

collaborations of experimenters & theorists with judgments

I do *not* give you solutions – I `paint' the progress

ibi: "Mature ND"

We are *not* close to the end of the "road" probing heavy flavor dynamics: we need *much more* than `just' *more data*:

-- We have to apply more refined tools & more thinking to make progress.

-- There are two different cultures at work between
Hadrodynamics & HEP

-- accuracy → precision on different levels

-- subtle theoretical tools are `waiting', we have to learn how to apply them

-- Quark-hadrons duality – a subtle tool & its limits/violation.
"Duality" is *not* an additional assumption, although often it is `subtle'.

The main points are:

- 3- & 4-body final states of charm & beauty hadrons *not* back-up for information from 2-body ones – the landscapes are very different !

- The best fitted analyses often do *not* give us the best information about the underlying dynamics i.e., theorists should not be the slaves of the data. Of course, data are the referees – in the end !

I. Parameterization of CKM Matrix *through* $O(\lambda^6)$

(A) In smart Wolfenstein parameterization with
$\lambda \approx 0.225$ with A, η & $\rho \sim O(1)$; $A \sim 0.81 = O(1)$
however:

- $\eta \approx 0.34$, $\rho \approx 0.13 \ll O(1)$
- $V_{CKM,Wolf} = \ldots + O(\lambda^{4,5,6})$

(B) Needs *consistent* parameteriz. of CKM matrix with more precision ! Y.H. Ahn, H-Y. Cheng, S. Oh (2011)

-- $V_{CKM} = \ldots + O(\lambda^7)$
-- basically zero CP asymmetries in DCS decays of charm hadrons
-- the *maximal* value of $\sin\phi_1 \sim 0.74$ in the SM
-- correlations etc.

II. Re-scattering & Impact of CPT Invariance

The goal is: measuring CP asymmetries probes existence & even features of New Dynamics (ND), since they can depend only an amplitude.

$$T(P \to a) = \exp(i\delta_a)\,[T_a + \sum_{aj \neq a} T_{aj}\; i\, T_{aj,a}^{resc}]$$

$$T(P \to a) = \exp(i\delta_a)\,[T^*_a + \sum_{aj \neq a} T^*_{aj}\; i\, T_{aj,a}^{resc}]$$

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

Without *out* re-scattering direct CP asymmetries cannot happen, even if there are weak phases.

Shifman & Voloshin & collab.; Wolfenstein

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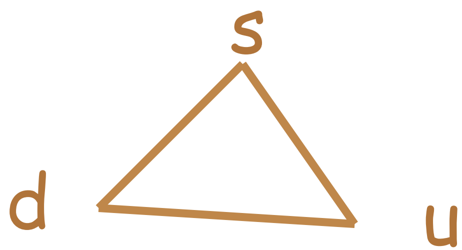
(II.1) Connections between U- vs. V-spin symmetries

U- vs.V-spin symmetries were introduced to describe *spectroscopies* of hadrons as subgroups of global SU(3) (by Lipkin …),
before quarks were seen as real physical states.



The situation changes much with *weak* transition

Lipkin suggested based on U-spin symmetry:

$\Delta = A_{CP}(B_d \to K+\pi-)/A_{CP}(B_s \to K+\pi-) + BR(B_s \to K-\pi+)/BR(B_d \to K+\pi-)(\tau_d/\tau_s) = 0$

LHCb, PRL 110 (2013) 221601:

$A_{CP}(B_s \to K^-\pi^+) = 0.27 \pm 0.04 \pm 0.01$, $A_{CP}(B_d \to K^+\pi^-) = -0.080 \pm 0.007 \pm 0.03$

$$\Delta_{LHCb} = -\,0.02 \pm 0.05 \pm 0.04$$

"These results allow a *stringent* test of the validity of the …"

to get opposite signs in the SM is obvious

? Your job was done by probing *2-body* FS ?

I disagree with two important reasons in different dimensions!

(a) $\Delta_{LHCb} = -\,0.02 \pm 0.05 \pm 0.04$

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(b) $A_{CP}(B_s \to K_S K^+ K^-)$? $A_{CP}(B_d \to K_S K^+ K^-)$? $A_{CP}(B^+ \to K^+\pi^+\pi^- / K^+K^+K^-)$?

$A_{CP}(B_s \to K^+\pi^-\pi^+\pi^- / K^+K^-K^+\pi^-)$? $A_{CP}(B_d \to K^-\pi^+\pi^-\pi^+ / K^-K^+K^-\pi^+)$? etc.

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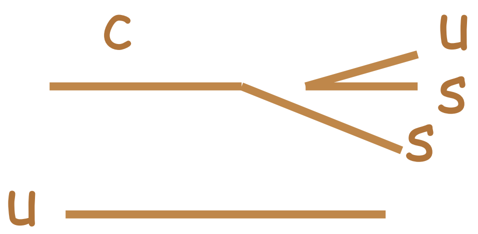
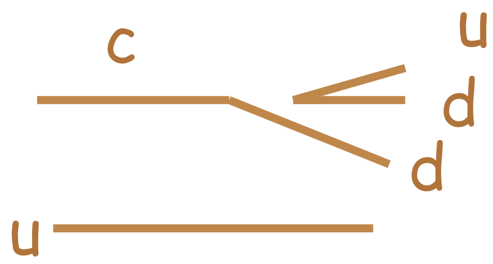
Well-known examples:

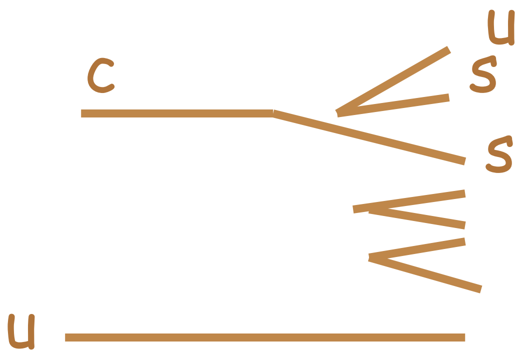
-- $BR(D^0 \to K^+K^-)/BR(D^0 \to \pi^+\pi^-) \sim 3$



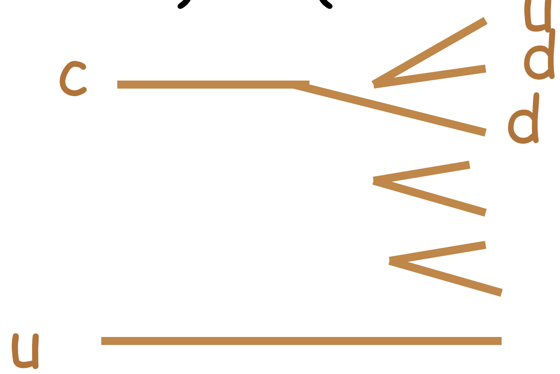
vs.



-- on the other hand: $BR(D^0 \to K^+K^-\pi^+\pi^-)/BR(D^0 \to 2\pi^+2\pi^-) \sim 1/3$



vs.

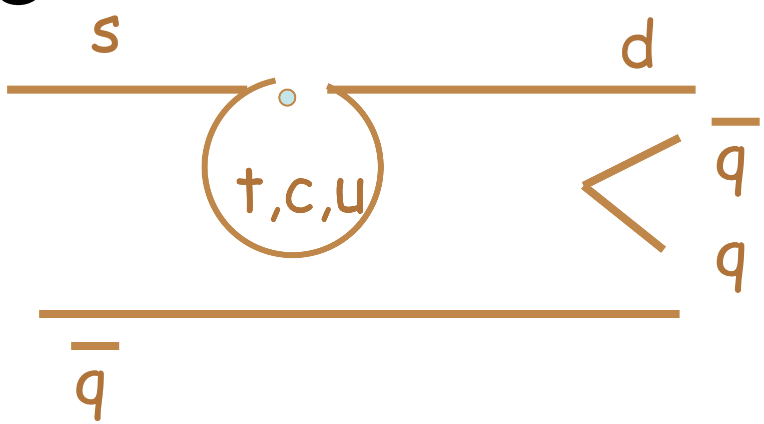


-- next: $BR(D^0 \to K^+K^-/K^+K^-\pi^+\pi^-)/BR(D^0 \to \pi^+\pi^-/2\pi^+2\pi^-) \sim 0.8$

-- impact of many-body FS

(II.2) Impact of Penguin *diagrams* on CPV?

-- the impact of `penguin' was an important pioneering work of Shifman, Vainshtein, Zakharow 1975; it is based on *local* operators for kaons with mostly two-body FS



-- explain $\Delta I=1/2 \gg \Delta I=3/2$ & direct CPV ϵ'/ϵ in $\Delta S=1$ (semi-)quantitatively

-- easy part !

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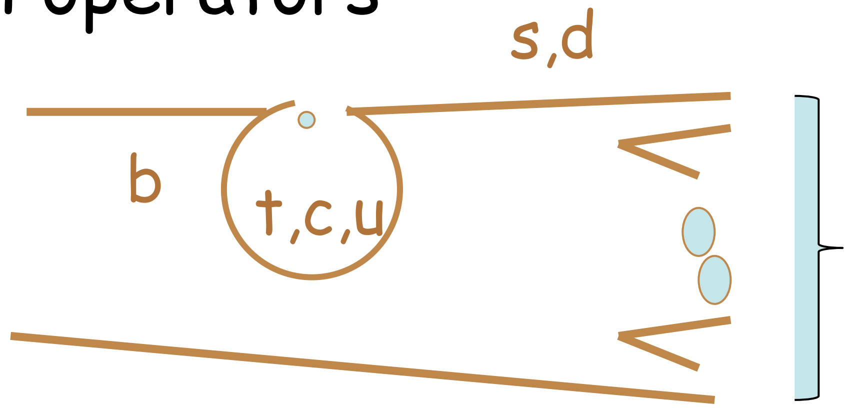
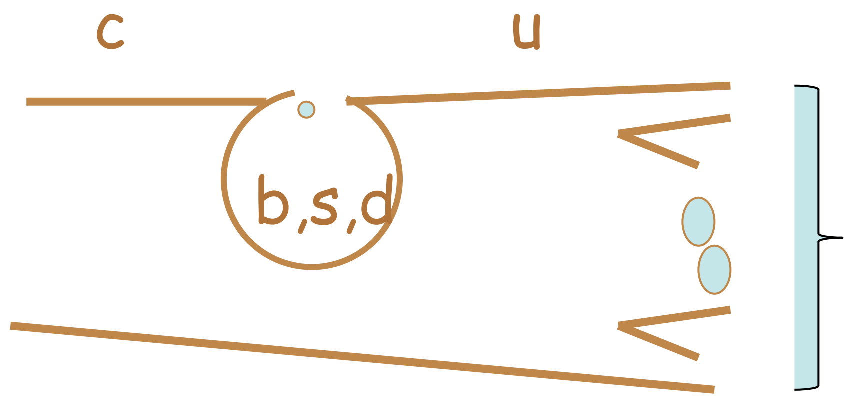
-- Penguin diagrams are fine for suppressed B decays about inclusive CPV with hard FSI to describe with local operators



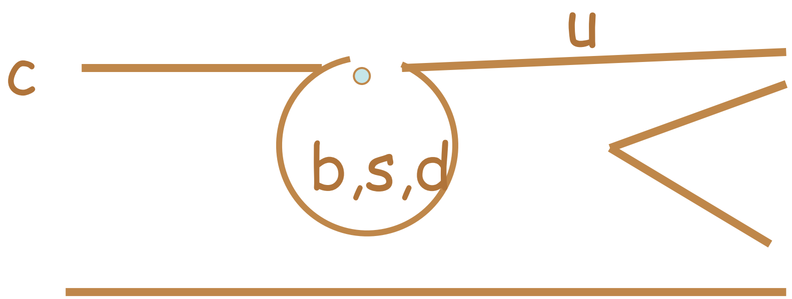
However, *not* about exclusive rates & soft FSI with hadrons in a quantitative way!

In special situations we can use other tools like HQE, LQCD, chiral symmetry, dispersion relations etc. etc.

-- one can *draw* Penguin diagrams for SCS transitions:



but one can hardly describe D decays (semi-)quantitatively
for inclusive CPV with local operators,
even less about exclusive rates & soft FSI with hadrons!



'We' have little control over the impact of penguin diagrams in *2*-body FS for $\Delta C \neq 0 \neq \Delta B$.

III. 3- & 4-Body FS of CP Asymmetries in B & D

Probing final states with 2 hadrons (including narrow resonances) is not trivial to measure CPV;
on the other hand one gets `just' numbers.
However 3- & 4-body FS are described in general by two-& more dimensional plots.

☹ Price:

lots of work both for experimenters & theorists

☺ Prize:

find *existence* & *features* of New Dynamics (ND)!

(III.1) $B^{+/-} \to K^{+/-}\pi^+\pi^-$ vs. B+/- -> K+/-K+K-

Data about rates:

$BR(B^+ \to K^+\pi^+\pi^-) = (5.10 \pm 0.29) \times 10^{-5}$;

$BR(B^+ \to K^+K^+K^-) = (3.37 \pm 0.22) \times 10^{-5}$;

not surprising at all

averaged CP asymmetries for direct ones

$\Delta A_{CP}(B^+ \to K^+\pi^+\pi^-) = + 0.032 \pm 0.008 \pm 0.004 \pm 0.007$;

$\Delta A_{CP}(B^+ \to K^+K^+K^-) = - 0.043 \pm 0.009 \pm 0.003 \pm 0.007$;

it is okay

regional CP asymmetries

$\Delta A_{CP}(B^+ \to K^+\pi^+\pi^-)|_{regional} = + 0.678 \pm 0.078 \pm 0.032 \pm 0.007$;

$\Delta A_{CP}(B^+ \to K^+K^+K^-)|_{regional} = - 0.226 \pm 0.020 \pm 0.004 \pm 0.007$;

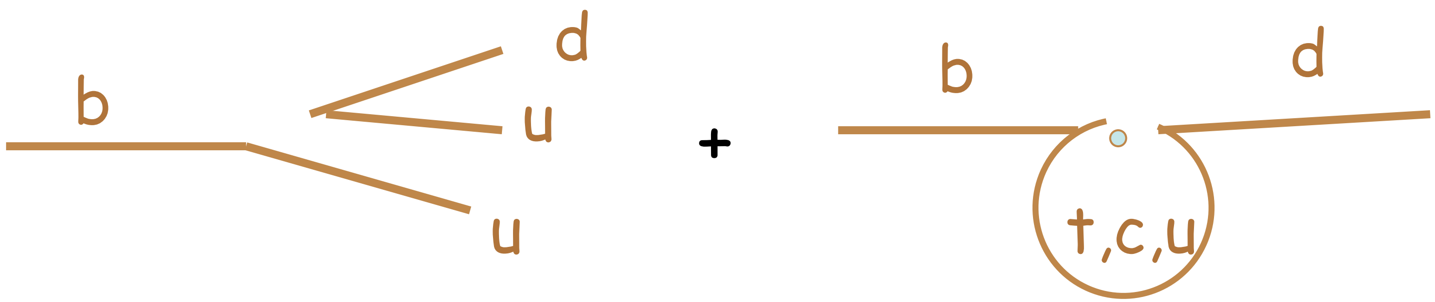
Very surprising to me due to two connected points:

-- the centers of the Dalitz plots are mostly empty

-- the differences are so huge!

(III.2) $B^{+/-} \to \pi^{+/-}\pi^+\pi^-$ vs. $B^{+/-} \to \pi^{+/-}K^+K^-$

Data about rates:
$BR(B^+ \to \pi^+\pi^+\pi^-) = (1.52 \pm 0.14) \times 10^{-5}$;
$BR(B^+ \to \pi^+K^+K^-) = (0.50 \pm 0.07) \times 10^{-5}$;
not surprising
averaged CP asymmetries
$\Delta A_{CP}(B^+ \to \pi^+\pi^+\pi^-) = +\ 0.117 \pm 0.021 \pm 0.009 \pm 0.007$;
$\Delta A_{CP}(B^+ \to \pi^+K^+K^-) = -\ 0.141 \pm 0.040 \pm 0.018 \pm 0.007$;
surprising: impact of more suppressed penguin diagrams?



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(III.2) $B^{+/-} \to \pi^{+/-}\pi^+\pi^-$ vs. $B^{+/-} \to \pi^{+/-}K^+K^-$

Data about rates:

$BR(B^+ \to \pi^+\pi^+\pi^-) = (1.52 \pm 0.14) \times 10^{-5}$;

$BR(B^+ \to \pi^+K^+K^-) = (0.50 \pm 0.07) \times 10^{-5}$;

not surprising

averaged CP asymmetries

$\Delta A_{CP}(B^+ \to \pi^+\pi^+\pi^-) = +\ 0.117 \pm 0.021 \pm 0.009 \pm 0.007$;

$\Delta A_{CP}(B^+ \to \pi^+K^+K^-) = -\ 0.141 \pm 0.040 \pm 0.018 \pm 0.007$;

surprising: impact of more suppressed penguin diagrams?

regional CP asymmetries

$\Delta A_{CP}(B^+ \to \pi^+\pi^+\pi^-)|_{regional} = +\ 0.584 \pm 0.082 \pm 0.027 \pm 0.007$;

$\Delta A_{CP}(B^+ \to \pi^+K^+K^-)\ |_{regional} = -\ 0.648 \pm 0.070 \pm 0.013 \pm 0.007$;

Very surprising for me due to two connected points:

-- the centers of the Dalitz plots are mostly empty

-- the differences are so huge!

(III.4) Outside CPV: $|V_{ub}|_{incl.}$ vs. $|V_{ub}|_{excl.}$

I mention $|V_{ub}|_{incl.}$ vs. $|V_{ub}|_{excl.}$ in an unusual way:
usually one measures $B \to l\, \nu\, \pi$'s to extract the value of
$|V_{ub}|_{incl.}$, but *not*
$B^- \to l^- \nu\; K^+K^-$, $l^- \nu\; K^0\bar{K}^0$, $l^- \nu\, K\, \bar{K}\, \pi$
$B^0_d \to l^+ \nu\; K_S K^-$, $l^- \nu\; K\, \bar{K}\, \pi$
based on the item of "duality"

However, "duality" is often subtle:
Local duality does not work, in particular close to thresholds
(it does not work for $|V_{cb}|_{incl.}$ vs. $|V_{cb}|_{excl.}$)

Real $|V_{ub}|_{incl.}$ might be smaller than thought before due re-scattering!

Test it!

(III.5) 3-body FS of $D^+_{(s)}$

-- CPT invariance in D (& τ) decays is `practical', since `few' channels can be combined.

SCS:

$D^+ \to \pi^+\pi^-\pi^+$ / $\pi^+K^-K^+$

$D^0 \to \pi^+\pi^-\pi^0$, $K^+K^-\pi^0$, $K_SK^+\pi^-$, $K_SK^-\pi^+$

$D_s^+ \to K^+\pi^-\pi^+$, $K^+K^-K^+$

- no CPV has been found (yet)
- one has to deal with re-scattering; it is not trivial, but crucial; `paintings diagrams' are not enough.

DCS:

$D^+ \to K^+\pi^-\pi^+$ / $K^+K^-K^+$ SM ~zero CPV

$D^0 \to K^+\pi^-\pi^0$ (the situation with $D^0 \to K_S\pi^+\pi^-$, $K_S K^+K^-$ is subtle)

$D_s^+ \to K^+K^+\pi^-$ SM ~zero CPV

(III.6) 4-body FS of $D^+_{(s)}$

(III.6.1) General comments

-- obviously one first measures T-odd moments of
$D \to h_1 h_2 h_3 h_4$ vs. $\bar{D} \to \bar{h}_1 \bar{h}_2 \bar{h}_3 \bar{h}_4$, namely *moments*
$A_T = \langle p_1 \cdot (p_2 \times p_3) \rangle$ and $\bar{A}_T = \langle \bar{p}_1 \cdot (\bar{p}_2 \times \bar{p}_3) \rangle$

FSI can produce $A_T, \bar{A}_T \neq 0$ with*out* CPV - but
$a_{CPV}^{T\text{-odd}} = (1/2)(A_T - \bar{A}_T)$ establishes CP asymmetry
they give us only numbers

-- we cannot stop there, namely to probe
semi-regional CP asymmetries like
- measure the angle ϕ between the planes of $h_1 h_2$ and $h_3 h_4$:

$$d/d\phi\, \Gamma(D \to h_1 h_2 h_3 h_4) = \Gamma_1 \cos^2\phi + \Gamma_2 \sin^2\phi + \Gamma_3 \cos\phi \sin\phi$$

$$d/d\phi\, \Gamma(\bar{D} \to \bar{h}_1 \bar{h}_2 \bar{h}_3 \bar{h}_4) = \bar{\Gamma}_1 \cos^2\phi + \bar{\Gamma}_2 \sin^2\phi - \bar{\Gamma}_3 \cos\phi \sin\phi$$

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(III.6.2) Specific comments *beyond* moments

-- SCS: $D^0 \to K^+K^-\pi^+\pi^-/2\pi^+2\pi^-$

-- DCS: $D^0 \to K^+\pi^-\pi^+\pi^-/K^+K^-K^+\pi^-$

-- DCS: $D_s^+ \to K^+K^+\pi^-\pi^0/K^+K^+\pi^-\eta$

IV. CPV in the decays of charm & beauty baryons

In principle CPV has been found in `our existence';

Back to real world:

-- No CPV has been found in the decays of charm & beauty *baryons* !

-- It seems there are huge `hunting regions' for LHCb, when one `thinks' about it.

SCS decays:

-- CPV in $\Lambda_c^+ \to \Lambda K^+$; its production rate can be calibrated with $\Lambda_c^+ \to \Lambda \pi^+$.

-- $\Lambda_c^+ \to p \pi^+\pi^-$, pK^+K^-;

DCS decays:

-- CPV in $\Lambda_c^+ \to pK^+\pi^-$.

CPV in $\Delta B=1$: probe Dalitz plots independent of production

-- $\Lambda_b^0 \to p \pi^-$, $\Lambda K^+\pi^-$;

-- $\Lambda_b^0 \to p K^-$, $\Lambda\pi^+\pi^-$, ΛK^+K^- ;

-- $\Lambda_b^0 \to p \pi^-\pi^+\pi^-$, $p \pi^- K^+K^-$;

V. Summary of Indirect Searching for New Dynamics (ND) in 3- & 4-Body Final States

the goal is to find ND – like a criminal case where you did *not* see two witnesses at the crime.

-- accuracy -> precision !

-- No golden test of flavor dynamics you have to rely on a series of several arguments with *correlations* !

➢ Need detailed analyses of 3- & 4-body final states including CPV – despite the large start-up work!

-- The best fitted analyses often do *not* give us the best information about the underlying dynamics
i.e., theorists should not be the slaves of the data
Of course, data are the referees – in the end !

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Quote of Marinus

(~468 AD student of Proklos, known Neoplatonist Philosopher):

" Only *being* good is one thing –

but good *doing* it is the other one! "

One example of different cultures to get a `team':
"dispersion relations"

"Bridge between Hadrodynamics & HEP"
or
"Lot of Water still Passing under the Bridge"

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