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# (Semi-) Regional CP Asymmetries in Many-Body Final States for Beauty & Charm Hadrons

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Central points:

-- *consistent* parameterization of the CKM matrix

-- probe *many-body* final states (FS) *not* as back-up

-- *broad* resonances: `price' to `prize'

-- *connections* between U- vs. V-spin (broken) symmetries

-- Penguin *diagrams* vs. Penguin *operators* crucial



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-- Subtle theoretical tools are `waiting' (*dispersion relations* etc., etc.), 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'.

- 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 judges – in the end !

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

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

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

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

$$\begin{bmatrix} 1-\lambda^2/2-\lambda^4/8-\lambda^6/16 & \lambda & h\lambda^4\exp(-i\delta_{QM}) \\ -\lambda+\lambda^5 f^2/2 & 1-\lambda^2/2-\lambda^4/8(1+4f^2)-fh\lambda^5\exp(-i\delta_{QM})+\dots & f\lambda^2+h\lambda^3\exp(-i\delta_{QM})+\dots \\ f\lambda^3 & -f\lambda^2-h\lambda^3\exp(-i\delta_{QM})+\dots & 1-\lambda^4/2\, f^2 - fh\lambda^5\exp(-i\delta_{QM})+\dots \end{bmatrix}$$

with $f \sim 0.75$, $h \sim 1.35$, $\delta_{QM} \sim 90^o$

*correlations, correlations, correlations*

-- I focus on $H_b$ decays, but mention DCS decays of charm hadrons giving basically zero asymmetries from the SM



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# II. Impactof Re-scattering (based on CPT Invariance)

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

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

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

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

With*out* re-scattering *no* direct CP asymmetries, even if there are weak phases.

Shifman & Voloshin & collab.; Wolfenstein

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With*out* re-scattering *no* direct CP asymmetries, even if there are weak phases.

Shifman & Voloshin & collab.; Wolfenstein

-- However: it is one thing to draw diagrams, while understanding dynamics is quite another thing!



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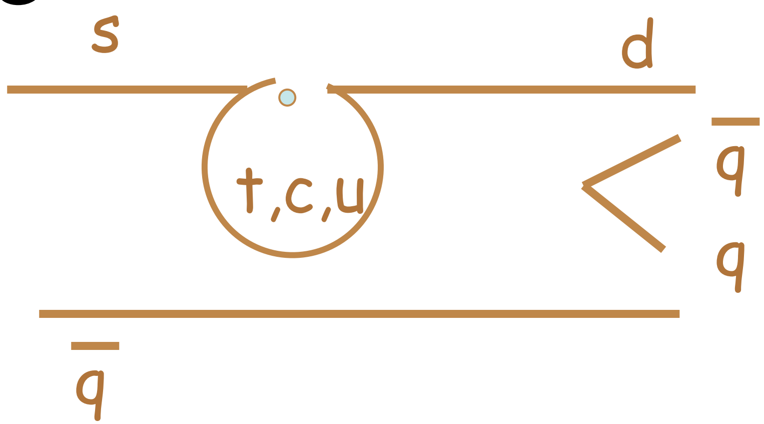
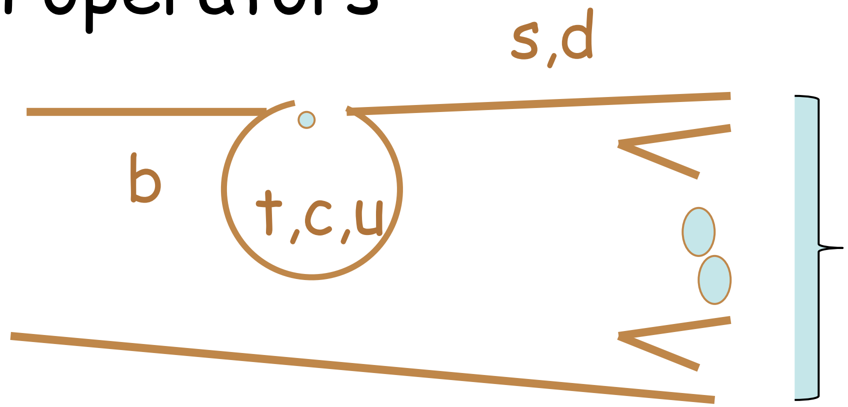
## (II.1) Impact of Penguin *diagrams* on CPV?

-- 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 $\epsilon'/\epsilon$ in $\Delta S=1$ (semi-)quantitatively

-- 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!

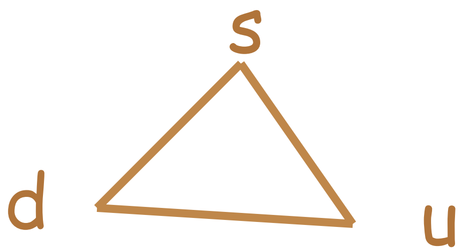
examples: $B^+ \to h_1^+ h_2^+ h_3^-$

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

-- I will focus on beauty hadrons with only a few comments about charm hadrons (& could for strange baryons)

# (II.2) Connections between U- vs. V-spin symmetries

U- vs.V-spin symmetries were introduced for *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:

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

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LHCb, PRL 110 (2013) 221601:

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

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

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

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

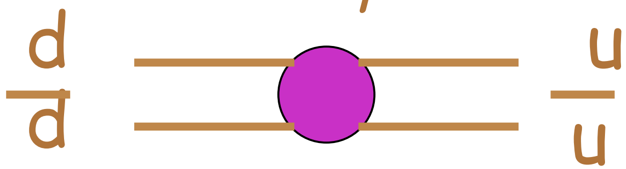
$\Delta_{LHCb} = -\, 0.02 \boxed{\pm 0.05 \pm 0.04}$

(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.

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

-- Landscape is quite different between *masses* & *weak widths*
- re-scattering due to *non-perturb.* QCD



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# 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. $B^{+/-} \to K^{+/-}K^+K^-$

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:

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

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

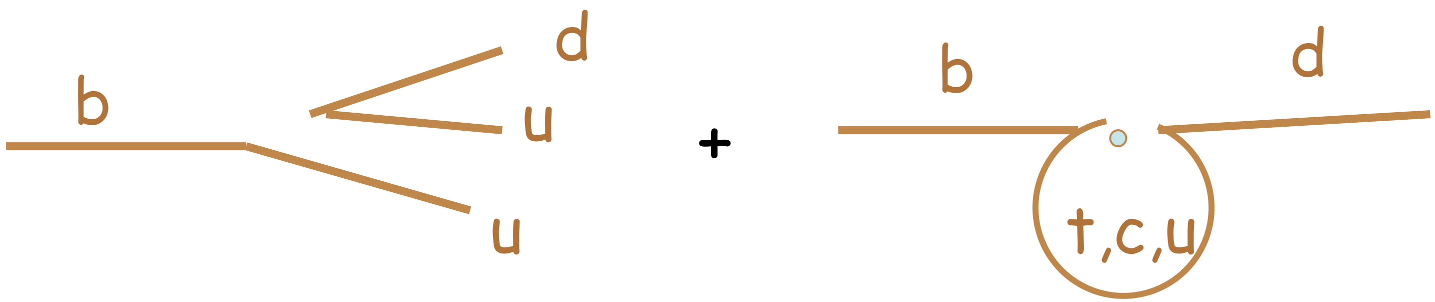
not surprising

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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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.3) Lessons from these Dalitz plots

Obvious lessons:

-- these landscapes are quite different from *rates*, *averaged* CP asymmetries and *regional* ones.
-- landscapes of beauty transitions should be complex, but *not* follow the same `road' – like 4-body FS; I will come back.

Subtle lessons:

-- model-independent analyses are not the final step
-- to get better information of the underlying dynamics we need re-fined tools like *dispersion relations*
-- it needs much more working & thinking; one example of the beginning `road' is: D+ -> K-π+π+ (Kubis etc.)



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# (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!*



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

-- CPT invariance in D (& $\tau$) 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



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## 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 established in the decays of charm & beauty (& strange) *baryons* !

-- It seems there are huge `hunting regions' for LHCb.

pointed out at Pittsburgh WS, LHCb meeting at CERN in June

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 independent of production

-- $\Lambda_b^0 \to p\, \pi^-$, $\Lambda K^+\pi^-$: $\Lambda K^*$ , $\Lambda\kappa$, ...

-- $\Lambda_b^0 \to p\, K^-$, $\Lambda\pi^+\pi^-$, $\Lambda\, K^+K^-$: $\Lambda\rho$ , $\Lambda\sigma$ , …

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

# IV.1 `Hot' item from 2016 LHCb data

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

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

Measured T-odd moments of $\Lambda_b^0 \to p\,\pi^-\pi^+\pi^-$ & $\overline{\Lambda}_b^0 \to \overline{p}\,\pi^+\pi^-\pi^+$;

can be described by the moment of the angle between 2 planes: defined by $[p\,\pi^-_{fast}]$ & $[\pi^+\,\pi^-_{slow}]$ vs. $[p\,\pi^+_{fast}]$ & $[\pi^-\,\pi^+_{slow}]$.

Run-1 LHCb data lead to CP asymmetry with 3.3 $\sigma$ uncertainty,

while no P asymmetry; furthermore it suggests a CPV ~ 20% for a semi-regional asymmetry.

not enough data for $\Lambda_b^0 \to p\,\pi^- K^+ K^-$ ;



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# IV.1 `Hot' item from 2016 LHCb data

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

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

Measured T-odd moments of $\Lambda_b^0 \to p\, \pi^-\pi^+\pi^-$ & $\overline{\Lambda}_b^0 \to \overline{p}\, \pi^+\pi^-\pi^+$;

can be described by the moment of the angle between 2 planes: defined by [$p\, \pi^-_{fast}$] & [$\pi^+\, \pi^-_{slow}$] vs. [$p\, \pi^+_{fast}$] & [$\pi^-\, \pi^+_{slow}$].

Run-1 LHCb data lead to CP asymmetry with 3.3 $\sigma$ uncertainty,

while no P asymmetry; furthermore it suggests a CPV ~ 20% for a semi-regional asymmetry.

not enough data for $\Lambda_b^0 \to p\, \pi^-K^+K^-$ ;

forgive me for a comment about Figure 1 in the LHCb paper: it does not even `paint' the landscape with FSI.

# IV.1.1 Questions for `now' & `soon'

to deal with production asymmetries

-- About different definitions of the moments of 2 planes:

$[p\,\pi^+]$ & $[\pi^-_{fast}\,\pi^-_{slow}]$ vs. $[p\,\pi^-]$ & $[\pi^+_{fast}\,\pi^+_{slow}]$ or

$[p\,\pi^-_{slow}]$ & $[\pi^+\,\pi^-_{fast}]$ vs. $[p\,\pi^+_{slow}]$ & $[\pi^-\,\pi^+_{fast}]$

*in principle* those do not *give* more information

*in reality* it might probe uncertainties in different ways

-- compare CPV $\Lambda_b^0 \to p\,\pi^-$ vs. $\Lambda_b^0 \to p\,K^-$ as discussed by Hsiao & Geng, arXiv:1412.1899; in some details I disagree.

-- measure T-odd moments of $\Lambda_b^0 \to pK^-\pi^+\pi^-$ & later $\Lambda_b^0 \to pK^-K^+K^-$;

remember $B^0 \to K+\pi-$ vs. $B^0 \to \pi+\pi-$ : impact of `penguin' diagrams

-- I guess parts of LHCb collab. work on these items – right?

# IV.1.2 Going beyond for the `future'

*Regional* asymmetries in different ways

-- obviously one first measures T-odd moments of

$H_Q \to h_1h_2h_3h_4$ vs. $\overline{H}_Q \to \overline{h}_1\overline{h}_2\,\overline{h}_3\overline{h}_4$ , namely *moments*

$$A_T = \langle p_1 \cdot (p_2 \times p_3)\rangle \text{ and } \overline{A}_T = \langle \overline{p}_1 \cdot (\overline{p}_2 \times \overline{p}_3)\rangle$$

FSI can produce $A_T$, $\overline{A}_T$ = 0 with*out* CPV - but

$$a_{CPV}^{\text{T-odd}} = (1/2)\,(A_T - \overline{A}_T) \text{ establishes CP asymmetry}$$

they give us only numbers

-- we have to go beyond, namely to probe semi-regional CP asymmetries like

- measure the angle $\phi$ between the planes of $h_1h_2$ and $h_3h_4$:

$$d/d\phi\, \Gamma(H_Q \to h_1h_2h_3h_4) = \Gamma_1 \cos^2\phi + \Gamma_2 \sin^2\phi + \Gamma_3 \cos\phi \sin\phi$$

$$d/d\phi\, \Gamma(\overline{H}_Q \to \overline{h_1h_2}\,\overline{h}_3\,\overline{h}_4) = \overline{\Gamma}_1 \cos^2\phi + \overline{\Gamma}_2 \sin^2\phi - \overline{\Gamma}_3 \cos\phi \sin\phi$$

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

-- 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!

-- accuracy -> precision !

[Remember the SM is *not* the `Trump' !]

-- The best fitted analyses (`binning') 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 judges – in the end !



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