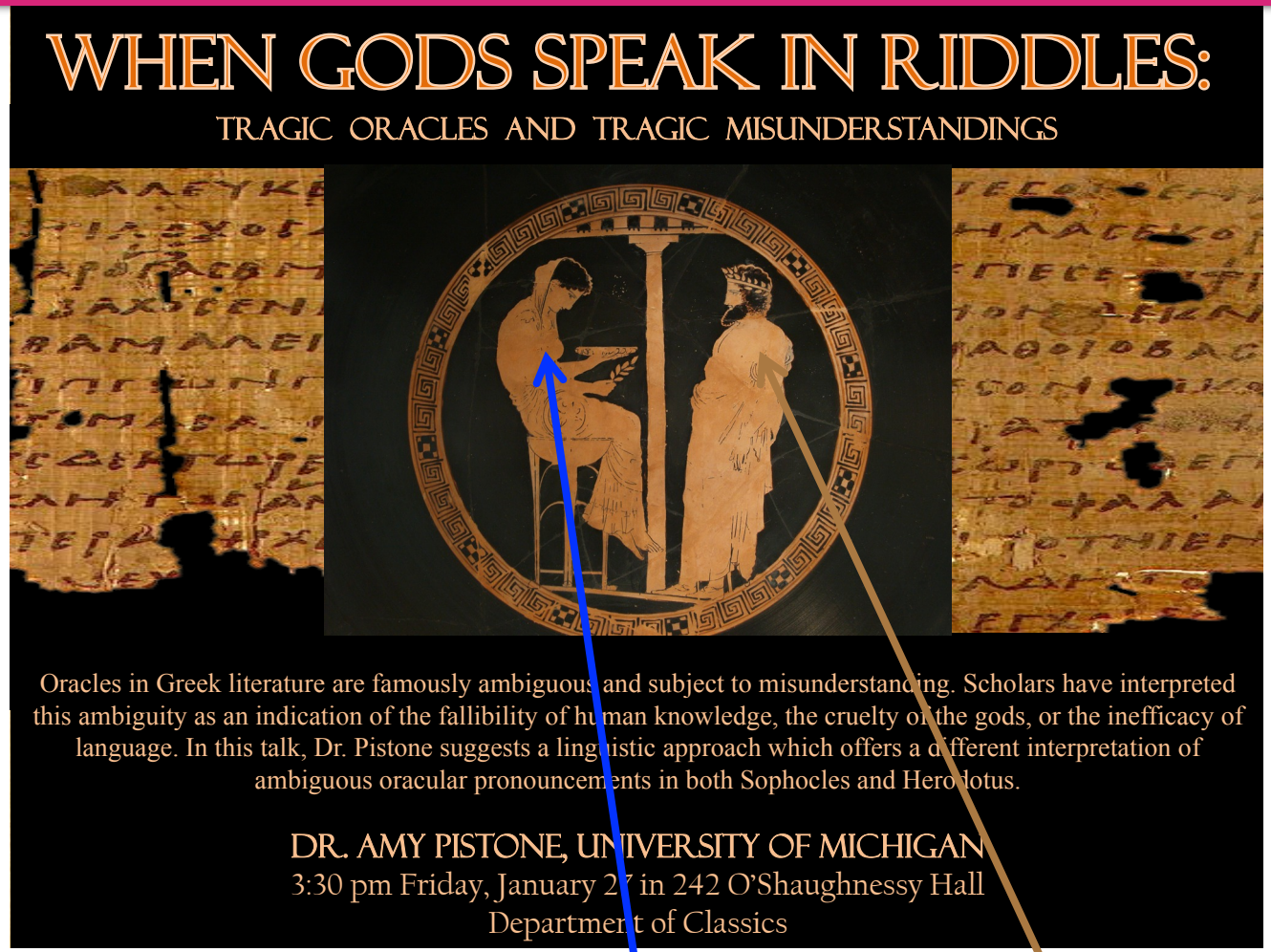
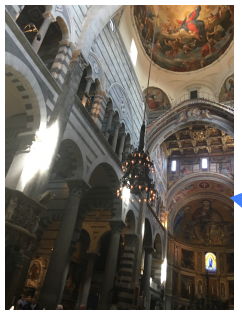
# "The Bridge between HEP & Hadrodynamics
# Motto: Impact of Non-perturbative QCD on CP Violation in Many-Body Final States of Flavor Transitions




"lamp of Galileo"



Picture taken by IIB in Pisa !

experimenters

theorists

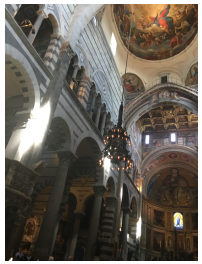
# "The Bridge between HEP & Hadrodynamics
# Motto: Impact of Non-perturbative QCD on CP Violation in Many-Body Final States of Flavor Transitions

Ikaros Bigi, Notre Dame du Lac

CERN, Oct.2018

Manifestation of a divine being through something both simple & striking: local symmetries & their tools !
Best `fitted' analyses of the data ?
Yes, true progress with 2nd step –

but need the 3rd step & … !
*correlations* & judgments !
Prof. Mannelli from Pisa once assured me that he does *not* entertain the illusion that theorists can speak the truth all the time -- speaking in good faith is all he expects from theorists!



Schedule:

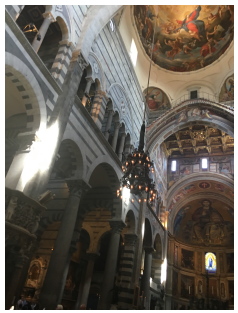
(I) (Consistent) Parameterization of the CKM Matrix

(II) Broken U- & V-spin symmetries

(III) *3- & 4-body* Final States in Beauty & Charm Mesons

(IV) Challenges for Beauty & Charm & Strange *Baryons*

(V) Needed Collaboration of HEP & MEP/Hadrodynamics



# (I) Parameterization of the CKM Matrix

## (I.1) Wolfenstein's parameterization

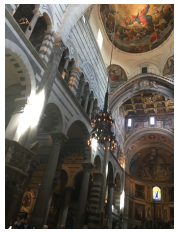
Wolfenstein's parameterization was very smart, easily usable, well-known & used all the time. The SM with 3 families of quarks describes the CKM matrix with 4 parameters: $\lambda$, $A$, $\rho$, $\eta$;
expansion of $\lambda = 0.223$, while $A$, $\rho$, $\eta$ are $O(1)$.

### (I.1.1) Maximal CP asymmetry ?!

It is an important item (in particular about finding the impact of ND), but a subtle one: What does one mean by `maximal CPV'?
Short comments based on an example: Wolfenstein's parameterization:
-- 100 % asymmetry in principle.
-- a few examples in the landscape: $\rho = 1$, $\eta = -1$ ; $\rho = -1$, $\eta \sim 3.5/-0.5$ ;
$\rho = -1/2$, $\eta \sim 2.5/-0.3$. - it would work.

### (I.1.2) `Real' world

*Measured* values: $A \approx 0.82$; however: $\eta \approx 0.35$, $\rho \approx 0.14$ not close to unity;
thus not real control over *systematic* uncertainties.



# (I) Parameterization of the CKM Matrix

## (I.2) *Consistent* parameterization

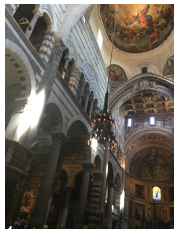
Need *consistent* parameterization of CKM matrix with more precision [Y.H. Ahn, H-Y. Cheng, S. Oh (2011)] through $O(\lambda^6)$ !

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

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

Pattern is not so obvious as before,

- -- needs more accuracy
- -- deeper insights in flavor dynamics & QCD impacts
- -- 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 decays



## (II) *Broken* U- & V-spin symmetries

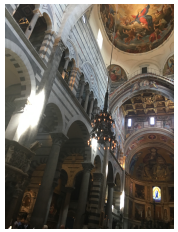
Forgive me to go back again about `our' history:

$SU(3)_{flavor}$ [not $SU(3)_{color}$] in the world of quarks:

-- `constituent' quarks: $m_u \sim 0.33$ GeV $\sim m_d$, $m_s \sim 0.5$ GeV.
It was pointed out by Lipkin that the broken $SU(3)_{flavor}$ can be described by 3 SU(2) with I-, U- & V-spin symmetries

-- (u,d) are obviously combined for I-spin

-- broken U-spin symmetry *without* V-spin is usable for *spectroscopy*, where (s,d) are combined.



-- weak decays?

- $A_{CP}(B^0 \to K^+\pi^-) = -0.082 +/- 0.006$

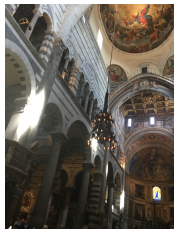
  $[\tau(B^0) = 1.52 \times 10^{-12}$ s, $BR(B^0 \to K^+\pi^-)=(1.96+/-0.05) \times 10^{-5}]$
  our early prediction (1987): $A_{CP}(B^0 \to K^+\pi^-) \sim -0.1$

  it shows the impact of Penguin diagrams,
  but semi-quantitatively ??

- $A_{CP}(B_s^0 \to \pi^+K^-) = +0.26 +/- 0.04$

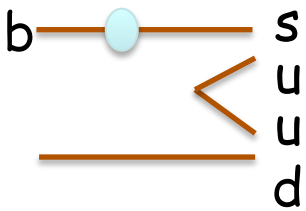
  $[\tau(B_s^0) = 1.51 \times 10^{-12}$ s, $BR(B_s^0 \to \pi^+K^-)=(0.56+/-0.06)\times 10^{-5}]$

- Can we predict this connection?



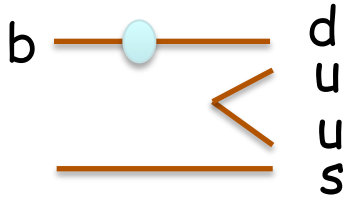
-- it had been suggested by Lipkin in 2005 to use *U-spin sym.*

$B^0 \to K^+\pi^-$




$B_s^0 \to \pi^-K^+$

$d \longleftrightarrow s$




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

- to get opposite signs in the SM is obvious

LHCb Collab. PRL 110 (2013) 221601:

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

2013: $\Delta_{LHCb} = -0.02 \pm 0.05 \pm 0.04$

"These results allow a *stringent* test of the validity of this relation … in the SM given" (`Lipkin rule')

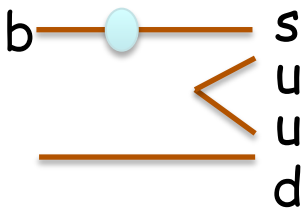
Yet

-- $\Delta_{LHCb}$ is consistent with zero

-- $\Delta_{LHCb}$ is consistent with ~ 0.1 as expected for direct CPV for 2-body FS

-- it had been suggested by Lipkin in 2005 to use *U-spin sym.*

$B^0 \to K^+\pi^-$

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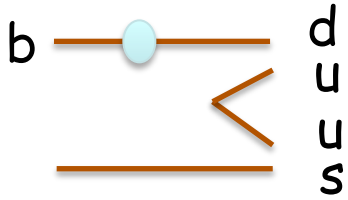


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LHCb Collab. PRD 98 (2018) 032004:

$A_{CP}(B_s \to K^-\pi^+) = 0.213 \pm 0.015 \pm 0.007$, $A_{CP}(B_d \to K^+\pi^-) = -0.084 \pm 0.004 \pm 0.003$

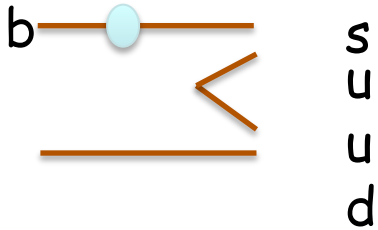
2018: $\Delta_{LHCb} = -0.11 \pm 0.04 \pm 0.03$

-- $\Delta_{LHCb}$ is still consistent with zero

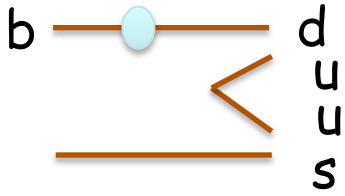
-- $\Delta_{LHCb}$ is consistent with ~ 0.1 as expected for direct CPV for 2-body FS

-- correlations of U-spin with V-spin due to re-scattering

$B^0 \to K^+\pi^-$

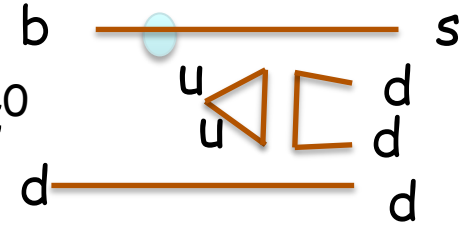



$d \longleftrightarrow s$ $B_s^0 \to \pi^-K^+$

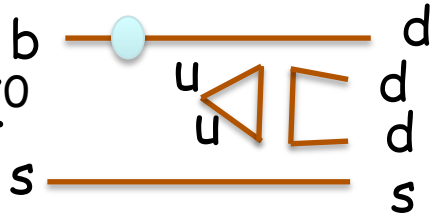



- U-spin is sizable broken
- correlations of U-spin with V-spin due to re-scattering

$B^0 \to K^0\pi^0$

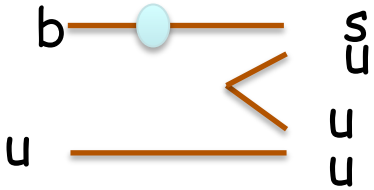


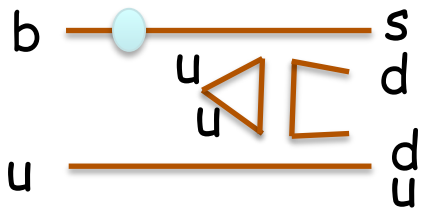

$B_s^0 \to \pi^0K^0/\eta K^0$




$C\,(B \to K^0\pi^0) = -\,0.00 \pm 0.13$ , $S\,(B^0 \to K^0\pi^0) = +\,0.58 \pm 0.17$

$B^+ \to K\pi/K^+\eta/K^+\eta$




$A_{CP}(B^+ \to K_S\pi^+) = -\,0.017 \pm 0.016$ , $A_{CP}(B^+ \to K^+\pi^0) = +\,0.037 \pm 0.021$

$A_{CP}(B^+ \to K^+\eta) = -\,0.37 \pm 0.08$ , $A_{CP}(B^+ \to K^+\eta') = +\,0.004 \pm 0.011$

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

# (III) 3- & 4-body Final States in Beauty & Charm Mesons

-- For experimenters it is easier to measure 2-body FS (including narrow resonances) -- if one has enough data for suppressed transitions -- and for theorists to predict those & analyze the data.

-- 2-body FS of suppressed non-leptonic weak decays are a small part of charm mesons & tiny ones for beauty mesons;

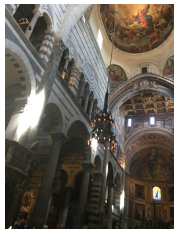
- data show that;
- it is not surprising.

-- However, the final goal is to probe CP asymmetries: it gives only numbers.

-- 3- & 4-body FS are described by two-& more dimensional plots.

☹ Price: lots of work both for experimenters & theorists

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



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-- the situations are very different for $\Delta S = 1$ & 2 [listen Danish colleague Buras (member of the Bavarian Academy!)

- local operators
- FS with only one & two pions

# (III) 3- & 4-body Final States in Beauty & Charm Mesons

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

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

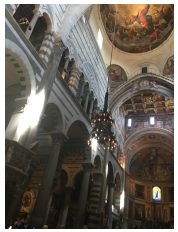
$$\Delta\gamma(a) = |T(\overline{P} \to \overline{a})|^2 - |T(P \to a)|^2 = 4\sum_{aj\neq a} \boxed{T_{aj,a}^{resc}}\; \boxed{\mathrm{Im}\, T^*_a T_{aj}}$$

With*out* strong re-scattering *direct* CP asymmetries can*not* happen, even if there are weak phases.

Misha & Misha & collab.; Wolfenstein

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

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



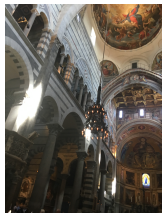
## (III.1) 3-body Final States in general

Dalitz plots (with pions, kaons, $\eta$ & $\eta'$)probe the underlying dynamics with two observables: with*out* angular correlations a plot is flat, while resonances & thresholds show their impact from their deviations; excellent record both about strong forces & weak ones.

Four main statements:

(a) The FS are *not* described only by a sum of (semi-)2-body FS & their interferences; true 3-body FS happen in the weak decays of charm & beauty mesons.

(b) Best fitted analyses often do *not* give us the best information about the underlying dynamics.



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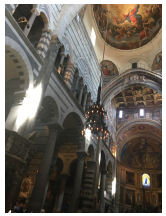
(b) Best fitted analyses often do *not* give us the best information about the underlying dynamics.

(c) We have *broad* resonances in the region of ~ 1 – 3 GeV; scalar ones like $f_0(500)$/*sigma*, $K^*_0(700)$/*kappa* etc. can*not* been described with Breit-Wigner parameterization.

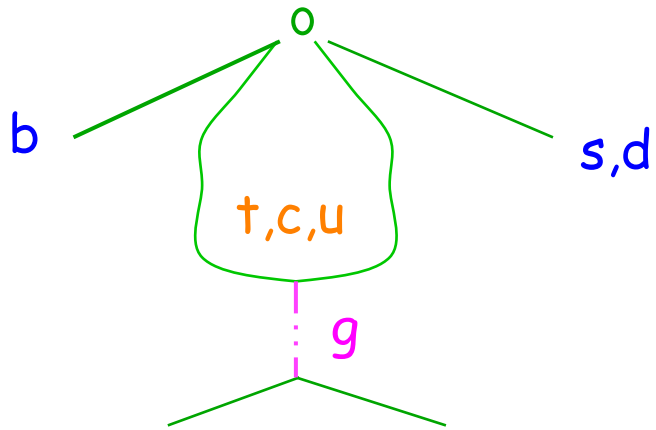
(d) Maybe the centers of the Dalitz plots are far from empty?

*correlations* & judgments !

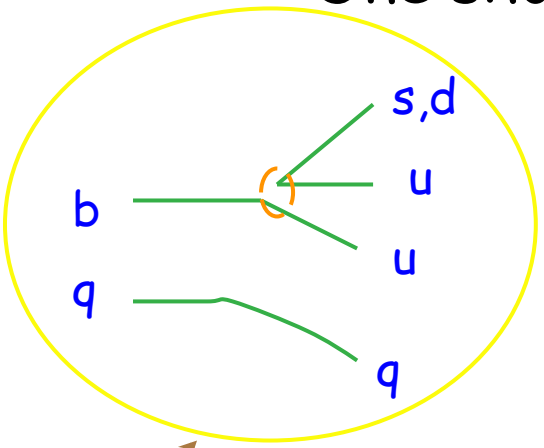


Not trivial to connect the world of hadrons with the diagrams of quarks & gluons. Re-scattering / non-perturbative forces !

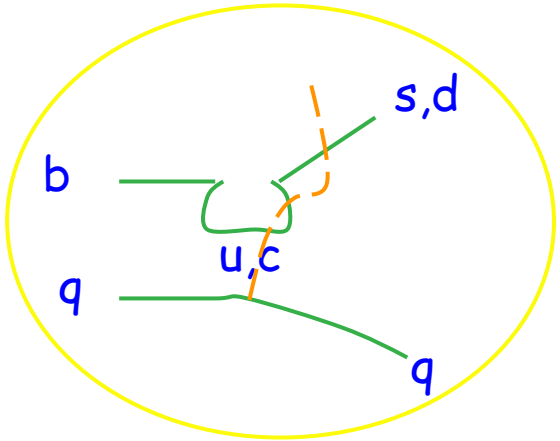
`penguin' diagrams:




One should *not only* look on diagrams




local operator with weak phase

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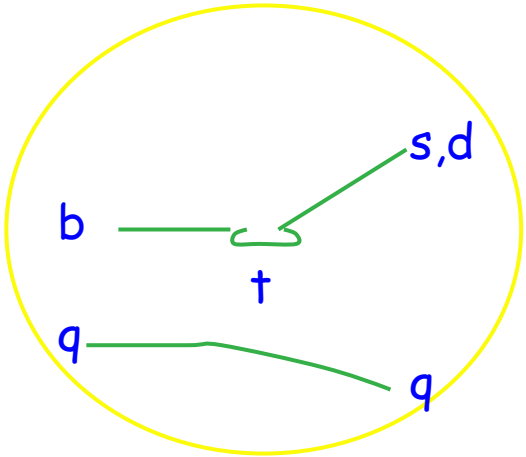
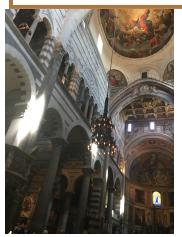


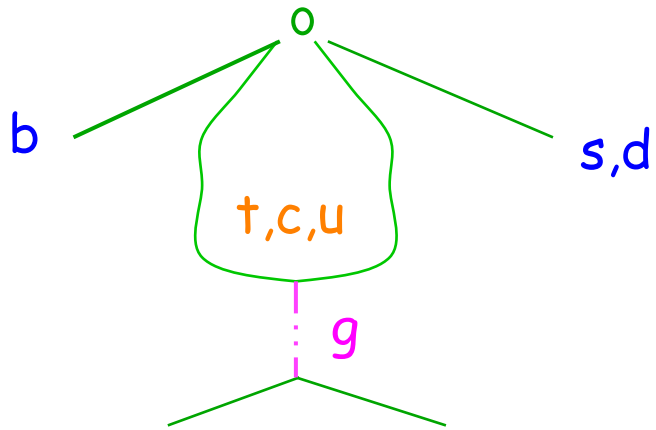

local operator not needed, but it is there



b -> s $\bar{c}$ c & s $\bar{u}$ u `paint' re-scattering

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

`penguin' diagrams: well-known for inclusive one --

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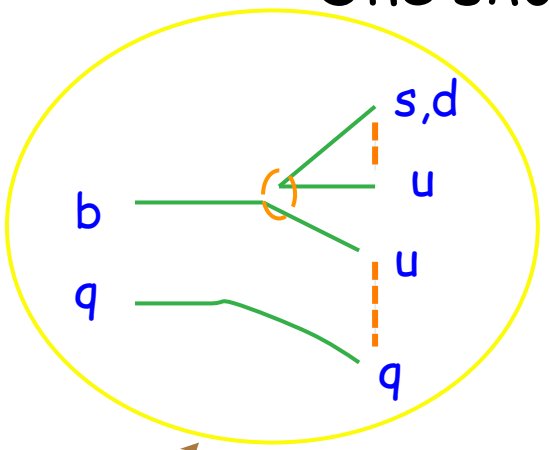
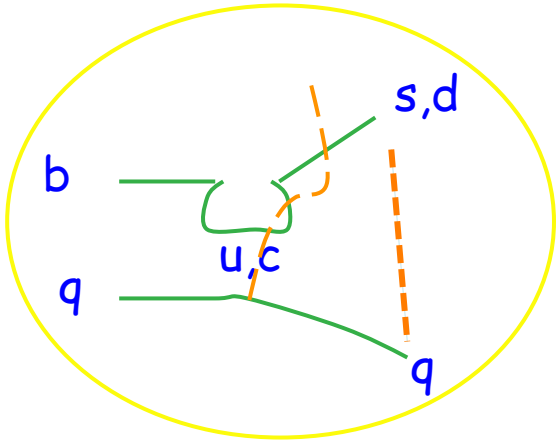
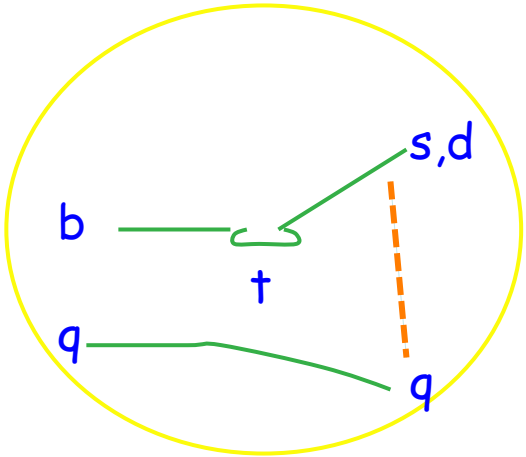


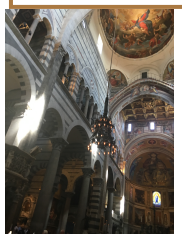

local operator with weak phase




nonlocal operator with strong phase




local operator not needed, but it is there



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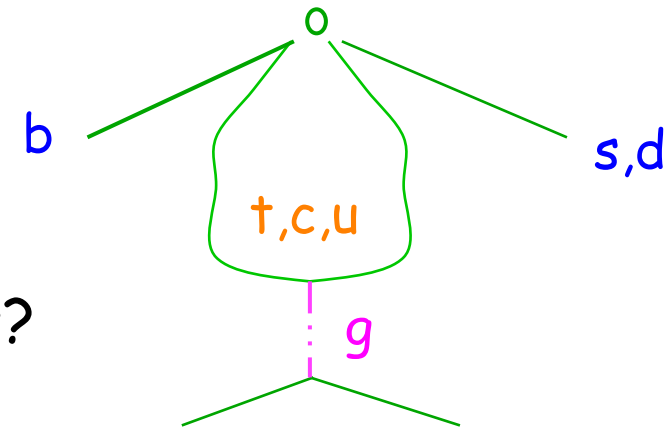
`penguin' diagrams: well-known for inclusive one -- about *exclusive* ones?

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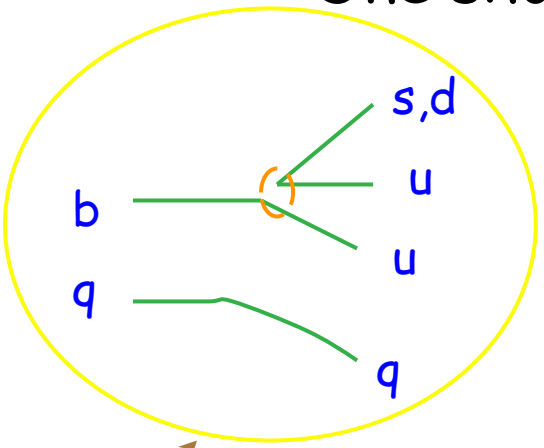
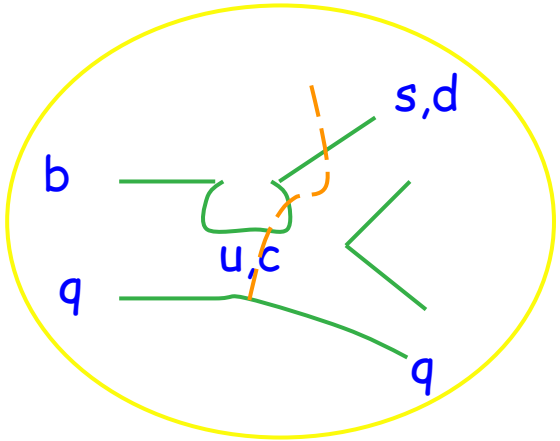
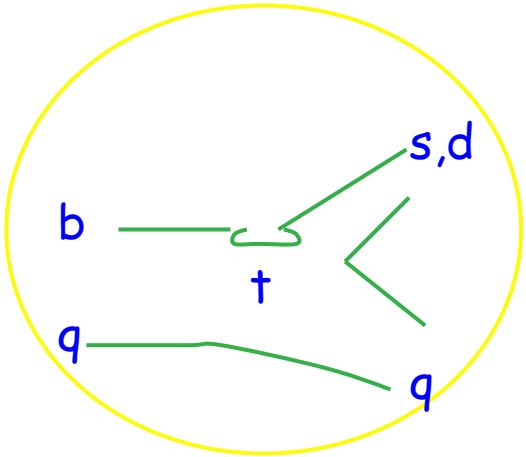


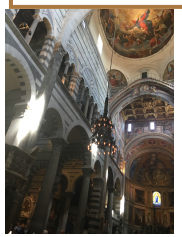




local operator with weak phase

nonlocal operator with strong phase

local operator not needed, but it is there



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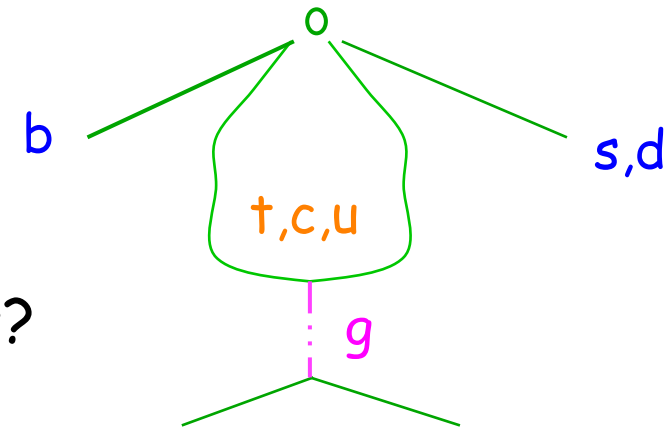


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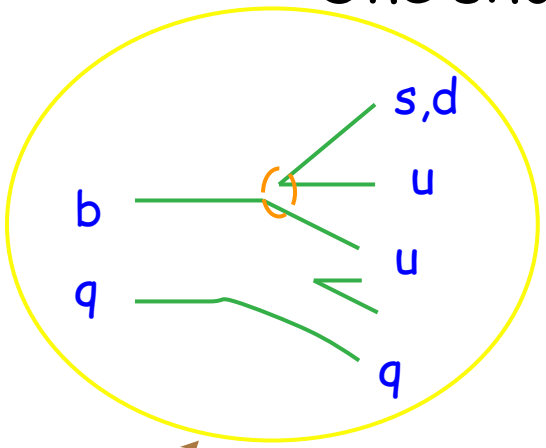


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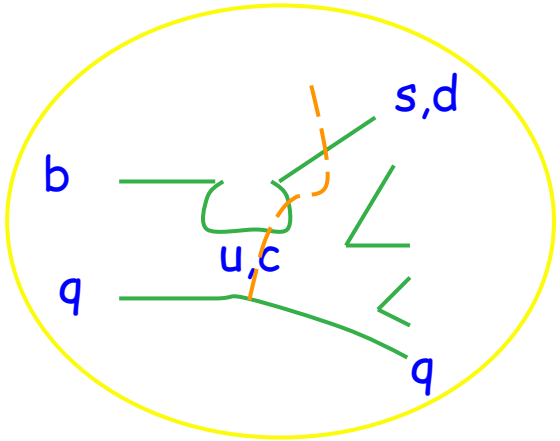


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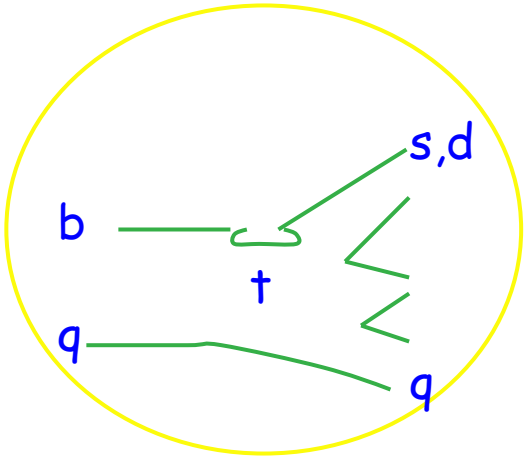


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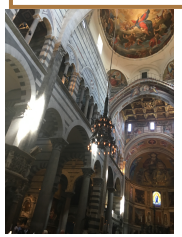

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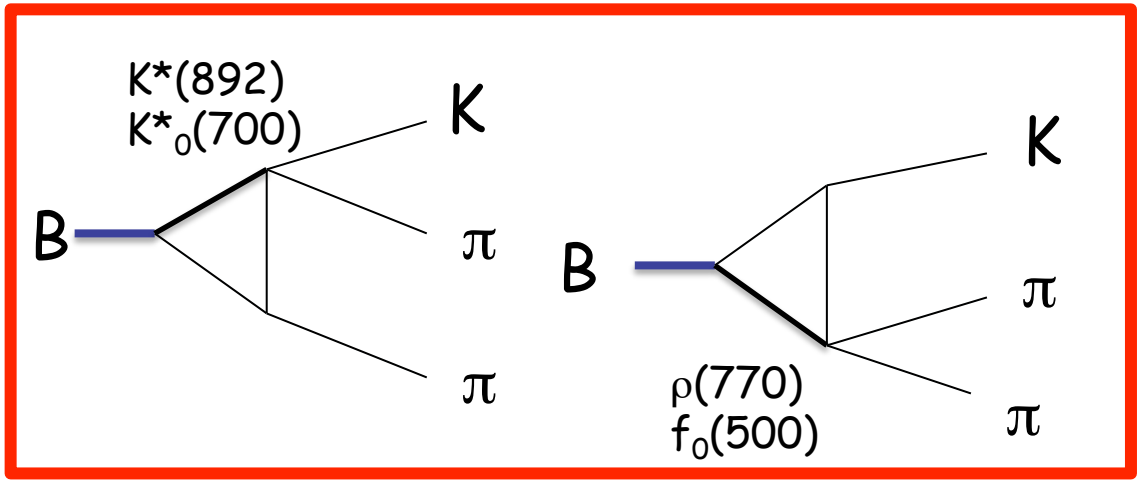
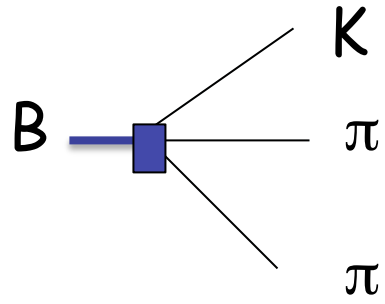
# The landscapes of hadrons

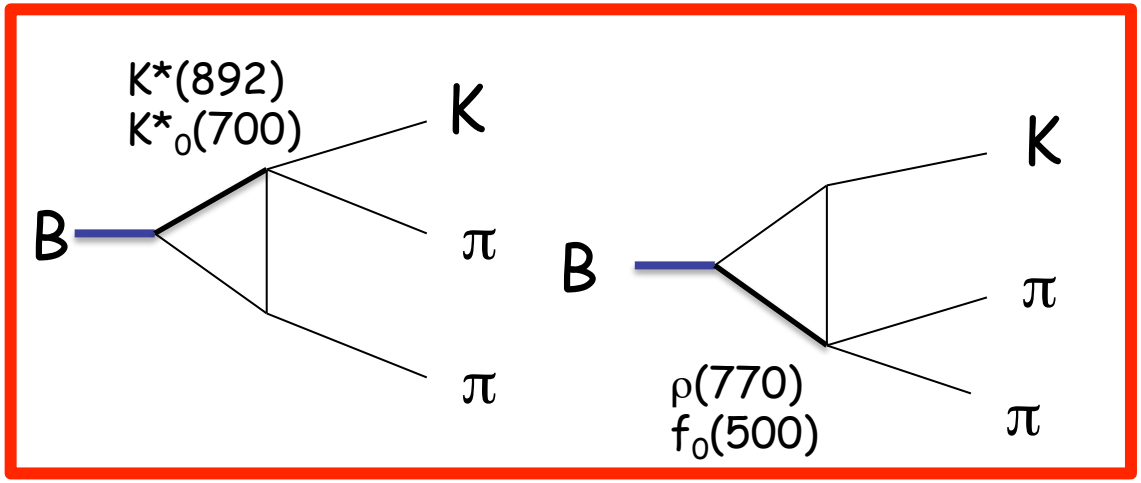


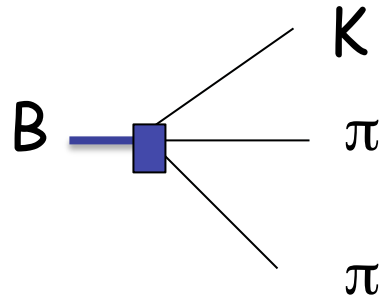




`effective' (?!) operator

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

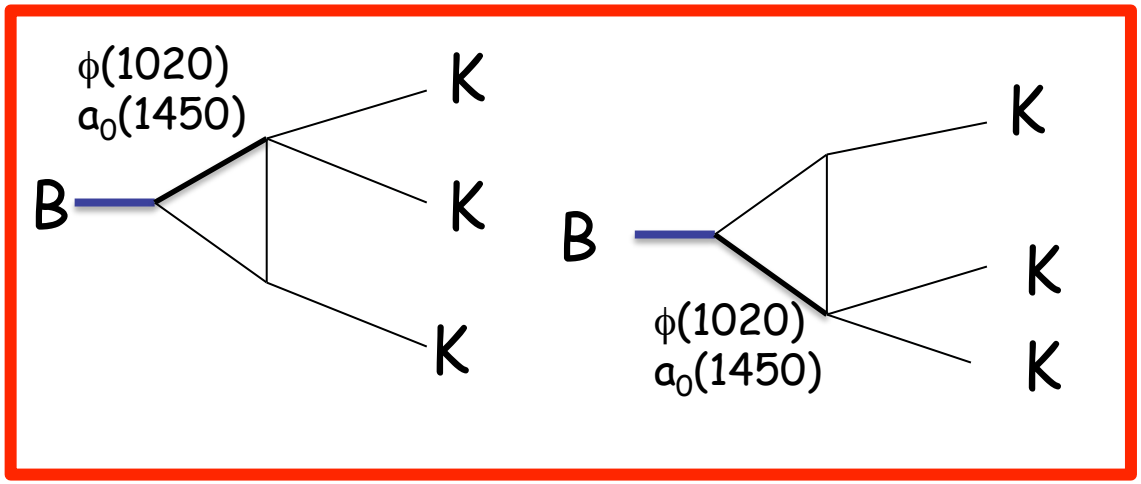
# The landscapes of hadrons

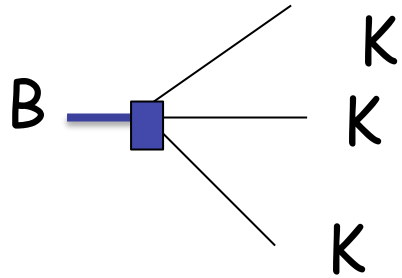



`effective' (?!) operator

Re-scattering is crucial to understand the underlying dynamics !



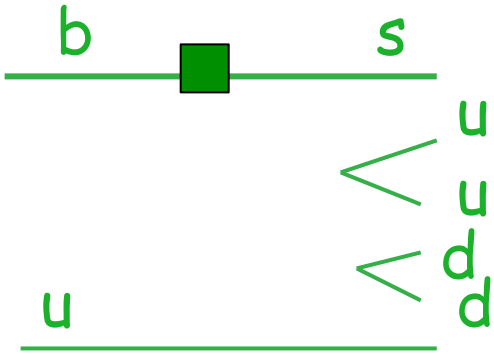




`effective' (?!) operator

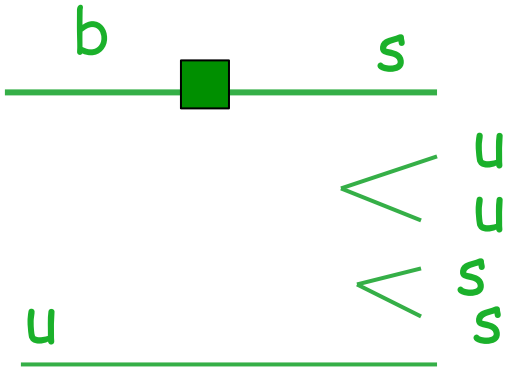
need `judgment' about applying resonances, *threshold enhancements* etc. with tools like *dispersion relations*

Look at quark diagrams:

b -> s – impact of Penguin diagrams in the SM

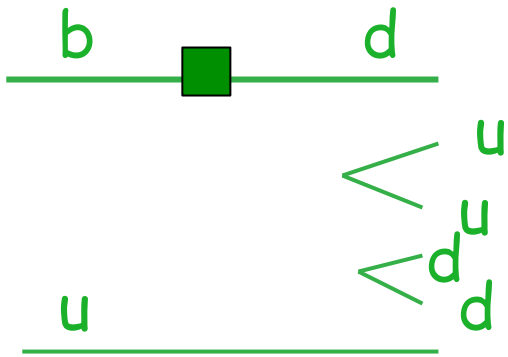



$B^+ \to K^+\pi^+\pi^-$

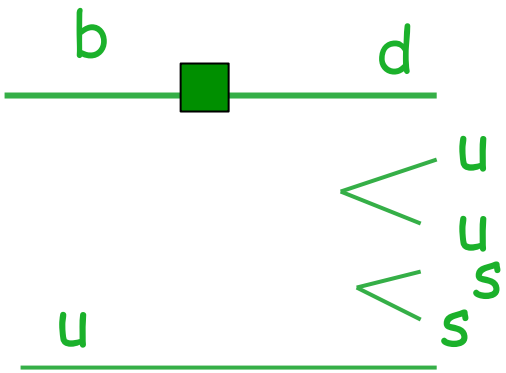



$B^+ \to K^+K^+K^-$

b -> d – less impact of Penguin diagrams in the SM




$B^+ \to \pi^+\pi^+\pi^-$

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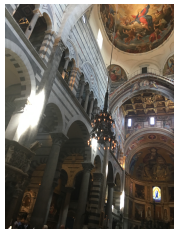
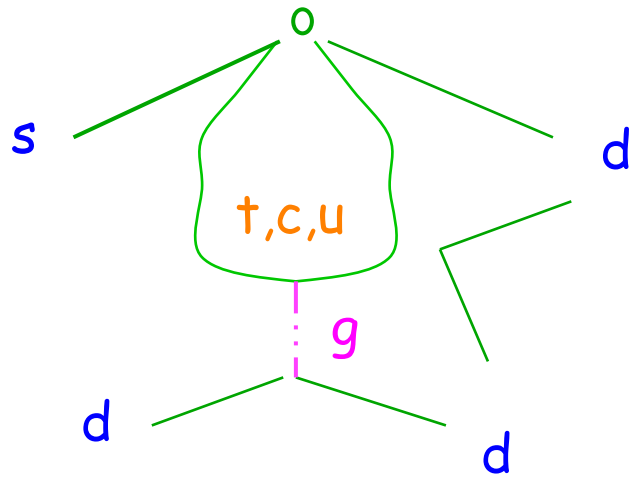


History:
`penguin' diagrams

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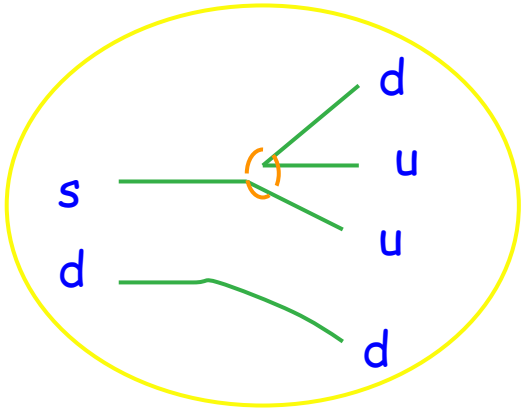
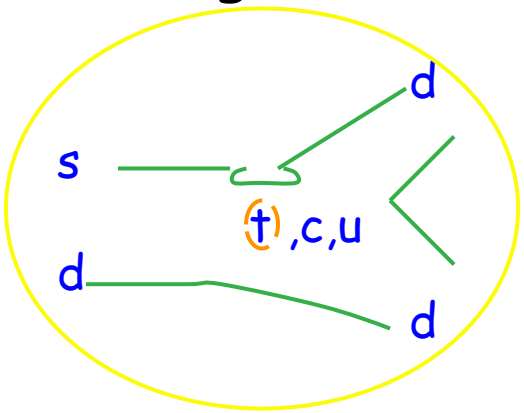
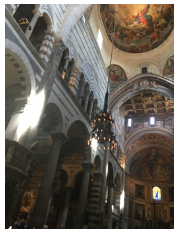



*local* operator




*local* penguin *operator* for $K^0 \to 2\pi$
-- with weak phase



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

LHCb data *run-1* 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

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

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

it is okay

`*regional*' CP asymmetries

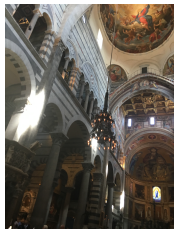
$\Delta A_{CP}(B+ \to K^+\pi^+\pi^-)|_{\text{`regional'}} = +\ 0.678 \pm 0.078 \pm 0.032 \pm 0.007$;

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

Very surprising due to two connected points:

-- the centers of the Dalitz plots are mostly empty

-- the differences are so huge!



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LHCb data *run-1* 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

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

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

maybe surprising

`*regional*' CP asymmetries

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

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

Very surprising due to two connected points:

-- the centers of the Dalitz plots are mostly empty

-- the differences are so huge!

underlying dynamics are not obvious

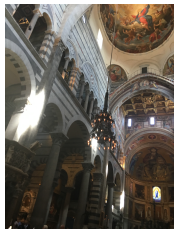
# (III.4) $\Delta C \neq 0$ with 4-body FS

Remember the history: $A_{CPV}(K_L \to \pi^+\pi^- e^+ e^-) = (13.7 +/- 1.5)\%$
so far, no CP asymmetries has been established in charm mesons
-- SCS decays: $D^0 \to 2\pi^+ 2\pi^- / K^+K^-\pi^+\pi^-$:

- Averaged CPV:
  SM ~ 0.001
- Regional CPV:
  large impact of re-scattering like ~ 0.01 or more
  like for decays of $B^+ \to$ light mesons, namely factor of 10

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

- Averaged CPV:
  basically zero for the SM
- Regional CPV:
  hunting region for ND with no SM background
  if one has large data;
  at least novel lessons about non-perturbative QCD



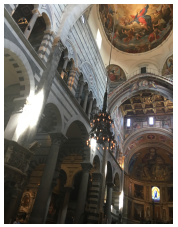
# (III.5) $\Delta C \neq 0$ with 3-body FS

LHCb for DCS decays (arXiv:1810.03138 [hep-ex] about 8 TeV, not run-2)

(1a) BR(D+ -> K+K+K-) = (5.87+/-0.02+/-0.04+/-0.18) x $10^{-5}$
PDG2018: = (8.5 +/-2.0) x $10^{-5}$

(1b) BR(D+ -> K+$\pi$+$\pi$-) = (4.70+/-0.01+/-0.02+/-0.15) x $10^{-4}$
PDG2018: = (5.19 +/-0.26) x $10^{-4}$

(2) BR($D_s^+$ -> K+$\pi$-K+) = (1.293+/-0.013+/-0.014+/-0.040) x $10^{-4}$;
PDG2018: = (1.27 +/-0.13) x $10^{-4}$



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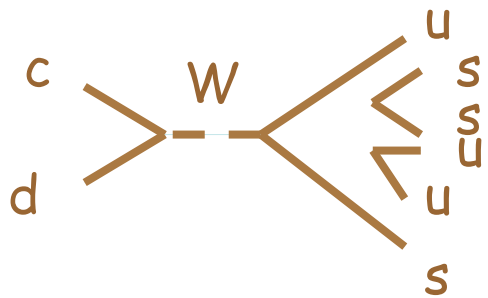
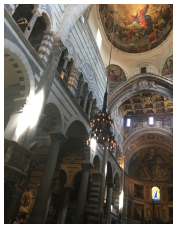
PDG2018: = (1.27 +/-0.13) x $10^{-4}$

I have to disagree with the meaning of these Feynman diagrams:
-- Figs. 1(b) & 1(c) are okay, but incomplete.
-- however, my main problem comes from Fig. 1(a):




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



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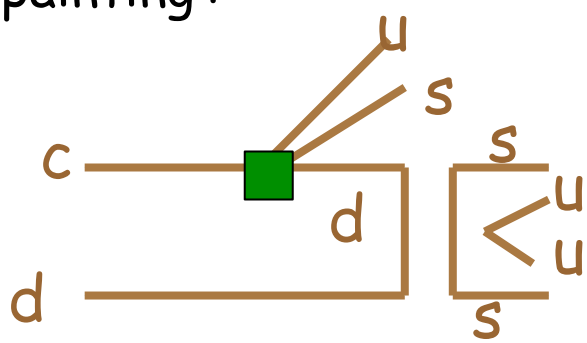
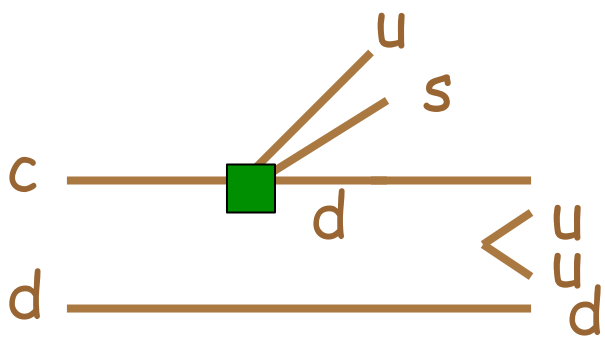
My `painting':

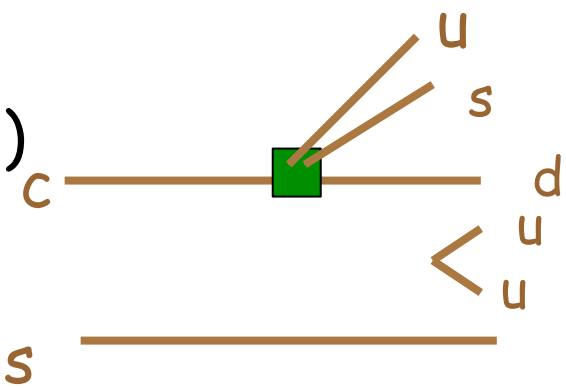
(1a)




(1b)




(2)



# (IV) Challenges for Beauty & Charm & Strange *Baryons*

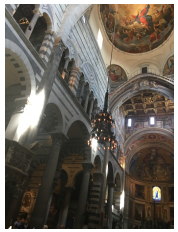
## (IV.1) CP asymmetries in the decays of $\Lambda_b^0$

-- First step: probe $\Lambda_b^0 \to p\,\pi^-/p\,K^-$ ;
no sign, but it is beyond realistic scale

-- I had suggested before to probe Dalitz plots
$\Lambda_b^0 \to \Lambda\pi^+\pi^-/\Lambda K^+K^-$

-- LHCb came by with a novel idea: probe $\Lambda_b^0 \to p\,\pi^-\pi^+\pi^-$
between two planes

- Its result: CPV with 3.3 $\sigma$ uncertainties with
- *regional* asymmetries ~ 20 % due to $[p\,\pi^-_{fast}][\pi^+\pi^-_{slow}]$ !



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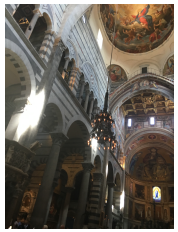
between two planes

- Its result: CPV with 3.3 $\sigma$ uncertainties with
- *regional* asymmetries ~ 20 % due to [p $\pi^-_{fast}$][$\pi^+\pi^-_{slow}$] !
- *Present* data & analyses about [p $\pi^-_{slow}$][$\pi^+\pi^-_{fast}$] ?
  No predictions – we have to learn from the (re-fined) data !

-- probe $\Lambda_b^0$ -> p $\pi$-K+K- where 3 mesons are different

-- likewise $\Lambda_b^0$ -> p K-$\pi+\pi$-[different]/pK-K+K- [complex]

-- application of QFT are subtle due to non-local interferences



-- thus decays of $\Lambda_b^0$ are excellent cases of underlying dynamics

-- no information from *run-2* ?

## (IV.2) Present and future lessons $\Delta C \neq 0$

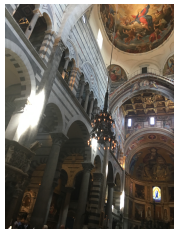
-- When one goes for CPV, one can*not* stop at 2-body FS: crucial to probe 3- & 4-body FS including regional CPV.

-- 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: $\Lambda^+_c \to p\, \pi^+\pi^-$ / $p\, K^+K^-$
- DCS: $\Lambda^+_c \to p\, K^+\pi^-$



## (IV.3) Present and future lessons $\Delta S \neq 0$

-- 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 ~ $2.23 \times 10^{-3}$ data

- *direct* CPV in $K^0 \to 2\pi$ with
  - ~ $3.6 \times 10^{-6}$ data
  - < $2.2 \times 10^{-6}$ SM ?!?
  - ~ $1.1 \times 10^{-6}$ "Buras team/LQCD"
- amazing established of data & analyses
- it *might be beyond* the SM: "Buras team"/"LQCD".

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

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

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

- BESIII will probe CPV by 2018/19 with below $10^{-3}$

-- duality violation enhanced close to thresholds ?

## (IV.3) Present and future lessons $\Delta S \neq 0$

-- It is a novel `road':
Giovanni Punzi said LHCb could do much 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 $J/\psi$ !

## (IV.3) Present and future lessons $\Delta S \neq 0$

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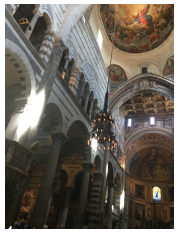
-- `hot' item (in the world of theorists): *direct* CPV in $K^0 \to 2\pi$ !
-- `hot' item in general:
NA62: $K^+ \to \pi^+ \nu\,\nu$ [& for the future $K_L \to \pi^0 \nu\,\nu$]
Landscape: NA48 [KTeV] & NA62 & LHCb !

# (V) Needed Collaboration of HEP & MEP/Hadrodynamics

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 is there no "royal insights" into Nature's inner working.

One example from fundamental dynamics:
*two-body* final states do not give "royal insights"!



-- history

→ NP → HEP

↑

flavor dynamics

-- now

→ NP → MEP/Hadrodynamics → HEP

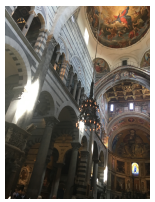
↑ ↑

decays of strange/
beauty/charm mesons & baryons
Dalitz plots
dispersion relations
accuracy/precision

jets,
Higgs, top quarks
direct SUSY

different landscapes & "cultures": it is not easy, but important

- pions, kaons, …, N, … vs. quarks, gluons, gauge bosons, Higgs …
- 3- & 4-body FS and regional CP asymmetries



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 !

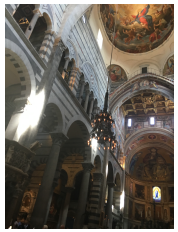
Future lessons for LHCb?

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

"Imagination created reality" – Richard Wagner

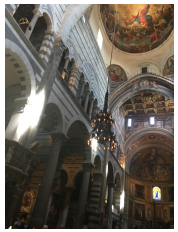
or:

"dedicated trigger"

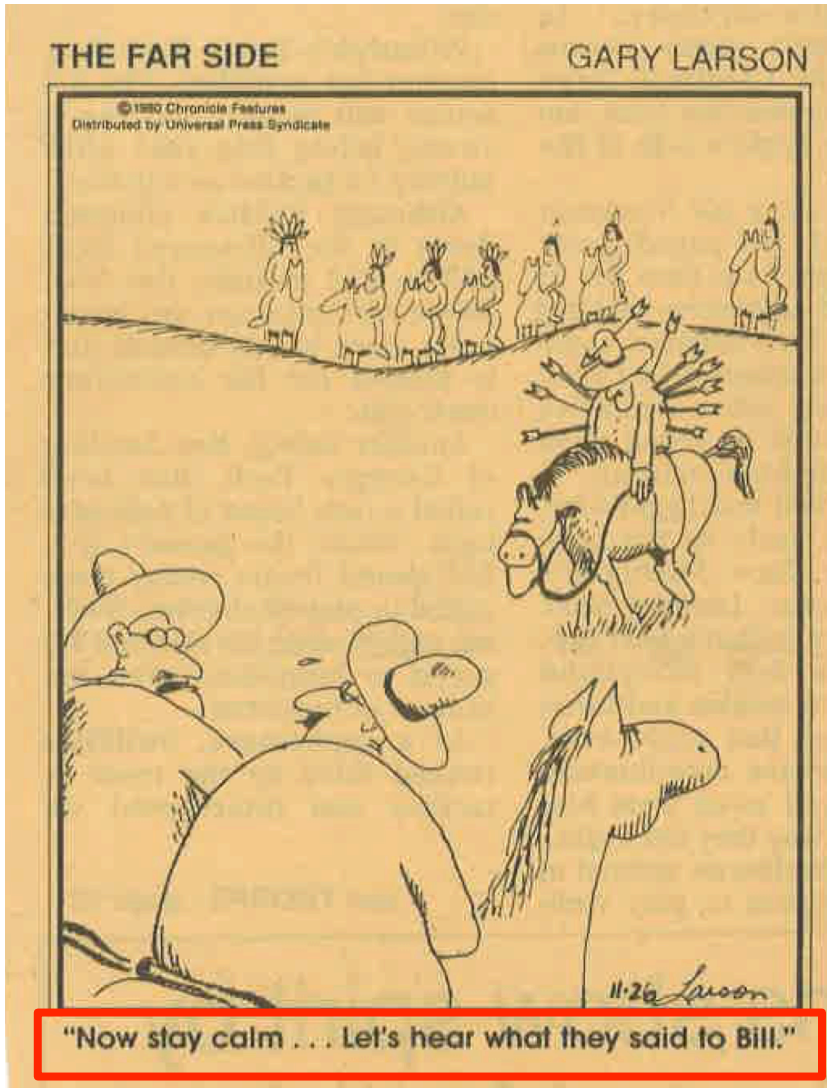


`thinking is better than power'

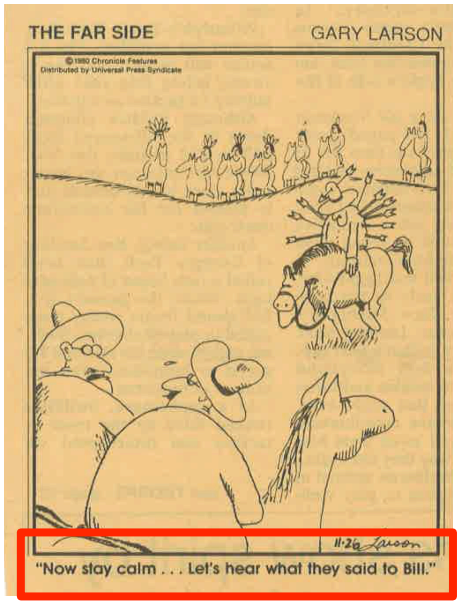
`dreaming in more dimensions'



Kolya Uraltsev & I had looked at this painting in person and realized that it is symbol of collaboration.




"Now stay calm . . . Let's hear what they said to Bill."




"Goals for *flavor dynamics* of quarks":

- ☞ `battle for supremacy' has been decided
  - ✍ goal no longer to find alternatives to CKM – instead to identify corrections to CKM!
- ☞ Probing CP asymmetries in 3- & 4-body FS of charm & beauty hadrons is crucial to find the existence of ND & its features.[At least it shows the impact of non-perturbative QCD.]

- ☞ young & mature theorists do not like waiting (for different reasons):

  results from run-2 !
- ☞ waiting for run-3 & run-4: that is life.

My lesson from the discussions after my talk:

-- `par ordre du mufti '(= no right of appeal):
Wolfenstein's parameterization CKM matrix is well-known & used all the time – it is enough.

-- Looking at diagrams is enough.

# Backup slides