Frascati, June 2011

The CKM Triangle(s) -- a Rosetta Stone for Flavour Dynamics

Ikaros Bigi (Notre Dame du Lac)

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or

"The Achaeans outside Troy"

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The favored candidate was Ajax,
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But the Achaeans elected another hero –
Odysseus
known for his thinking and ideas,
not just for his physical strength!

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Remember what happened:
They built the Trojan Horse (as shown by Tiepolo)

and they took Troy and their prize – Helen, daughter of Zeus!

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- to find the new dynamics we cannot study only high p_T processes
  - we need `low energies' with precision!

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- the Achaeans knew that beauty existed in the form of Helen – they saw Helen from a long distance on the towers of Troy;
- the beauty of New Physics hidden in the SM is implied `only' by theorists!

another lesson from German literature:

"A young man sees Helen in any young woman!"

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3 examples from FNAL 2nd run:

- D0 data on $A_{SL}(B_s)$: ibi comm.: no way!
- CDF data on $p\bar{p} \rightarrow WjjX$: ibi comm.: maybe??
- CDF data on $p\bar{p} \rightarrow t\bar{t}X$: ibi comm.: good chance; CP violation in top prod.?

Yet another lesson from English literature: Marlowe's speech by Faustus in Act V, scene 1

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only true beauty does it!

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Outline after the Prologue

I. Nicola Cabibbo – Pioneer of Our View of Weak Forces

II. Cabibbo-Kobayashi-Maskawa Matrix (and Five more)

III. Status of Cabibbo-Kobayashi-Maskawa Matrix

IV. Rosetta Stone for Understanding Flavour Dynamics

V. The Future – and Memory of Nicola Cabibbo

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➢ Nicola's task has been achieved!

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This is even much more true for New Physics!

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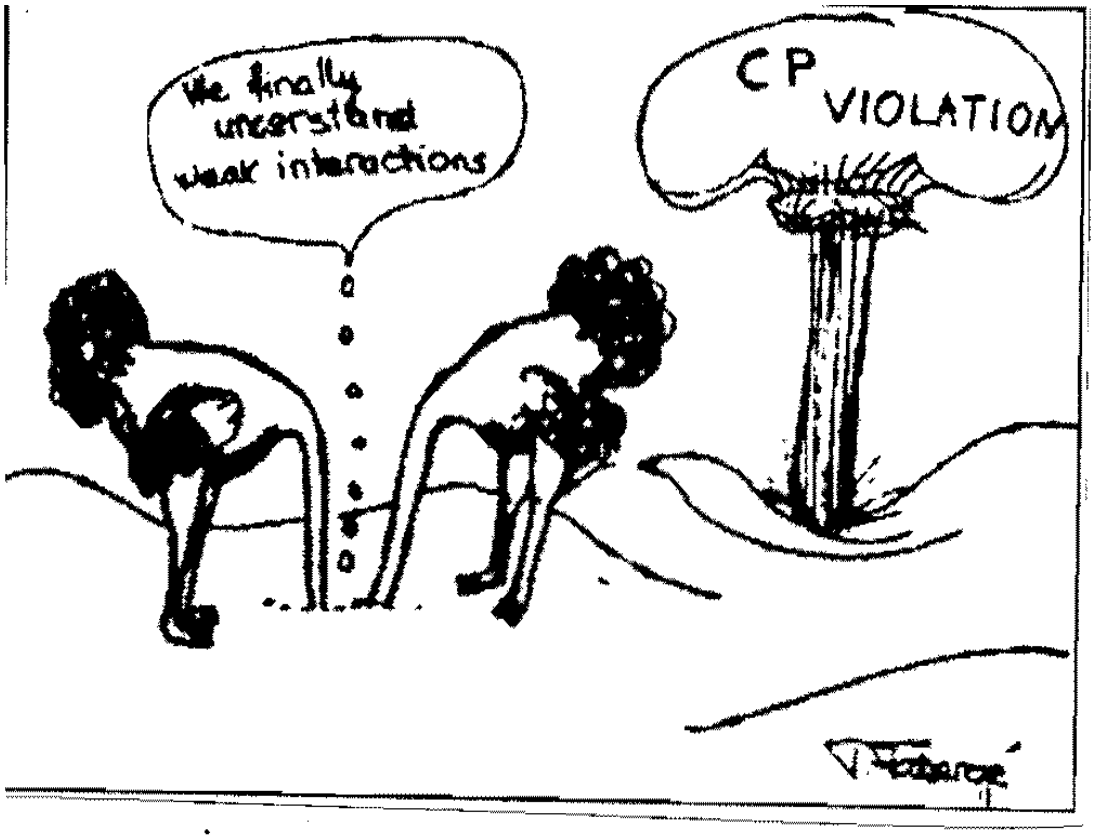

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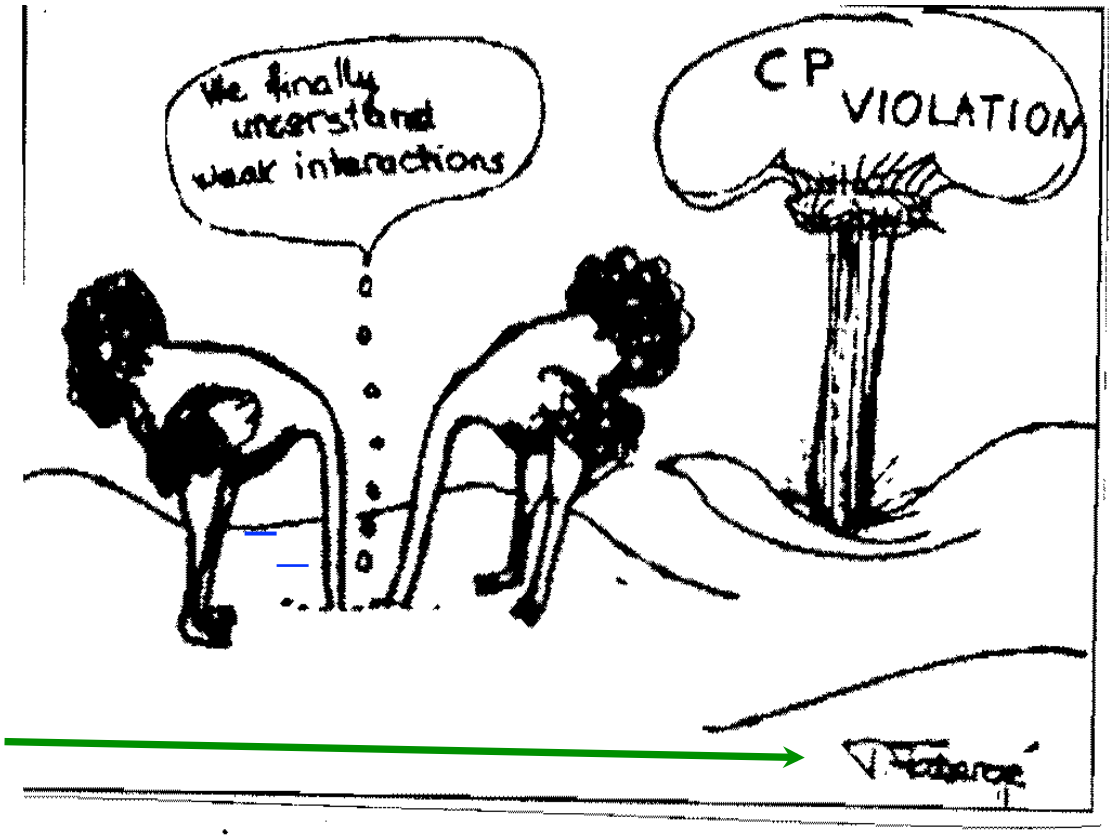

Tatjana Faberge

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`genius loci' of Nagoya University

- home of the Sakata School
  - quarks readily accepted as physical objects
- home of Prof. Niu -- expert in cosmic ray experiments

in '71 Niu reported a candidate for charm seen

- 2 complete families were `known'

$$\begin{pmatrix} u \\ c \\ t \end{pmatrix} \qquad \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

mass eigenstates

≠

interaction eigenstates

➥ weak charged currents couplings affected

$$V_{CKM} = T_{U,L}\, T_{D,L}^{*}$$

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$$\Sigma_{j=1}^{j=3} V^*(ij)V(jk) = 0, \quad i \neq k$$

➥ triangle relations in the complex plane

➥ 6 triangles have equal areas

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weak universality to interpret CP asym

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- the emerging pattern:
  - $|V(us)| = \lambda = \sin\theta_{Cabibbo}$
  - $\tau(B) \sim 1$ psec $\Longrightarrow |V(cb)| \sim O(\lambda^2)$
  - $|V(ub)|/|V(cb)| \sim O(\lambda)$

➥ Wolfenstein representation

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2 & \lambda & A\lambda^3(\rho-i\eta+\eta\lambda^2/2) \\ -\lambda & 1-\lambda^2/2-i\eta A^2\lambda^4 & A\lambda^2(1+\eta\lambda^2) \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

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- I can see the hidden `Helen' on the towers

Ikaros Bigi: "The Achaeans outside Troy"

- 3 classes of 2 triangles
  - $\lambda + \lambda + \lambda^5$

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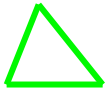

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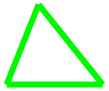

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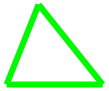

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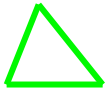

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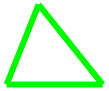

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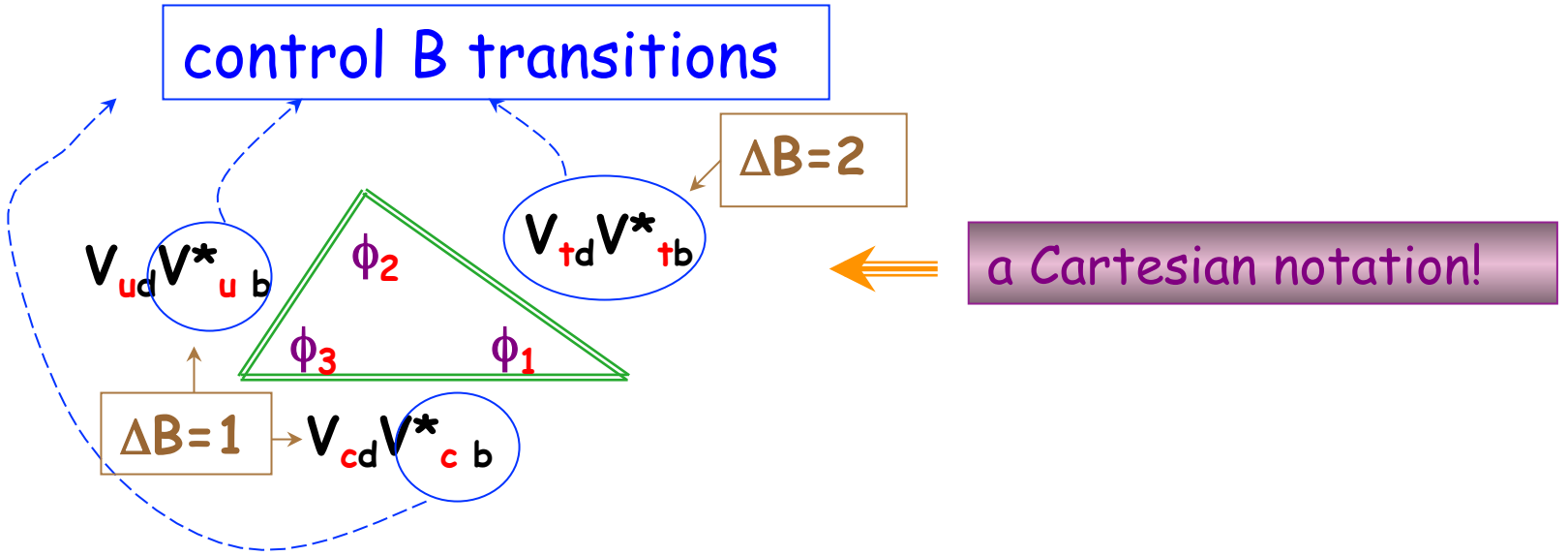

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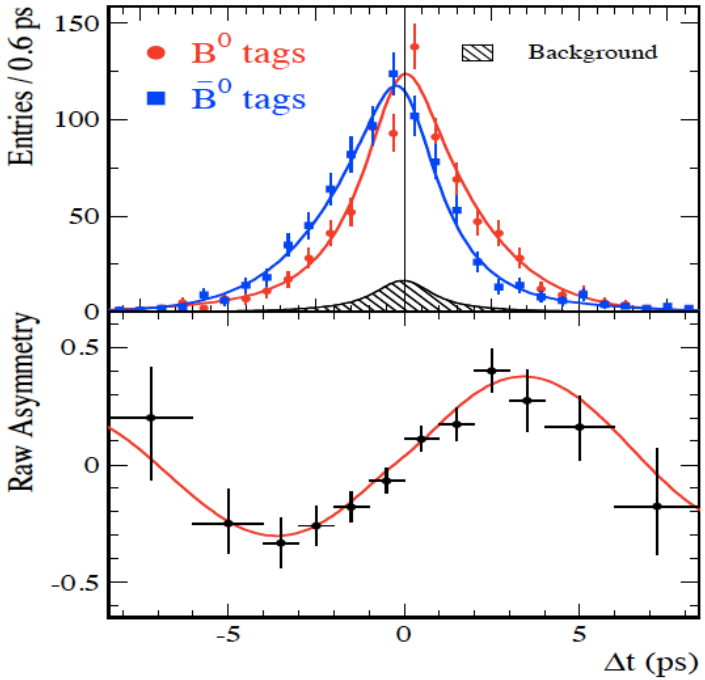

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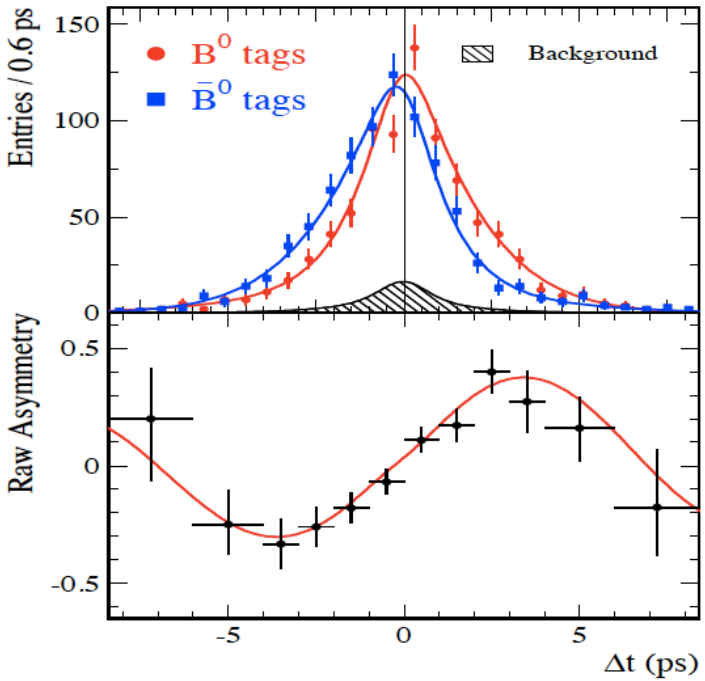
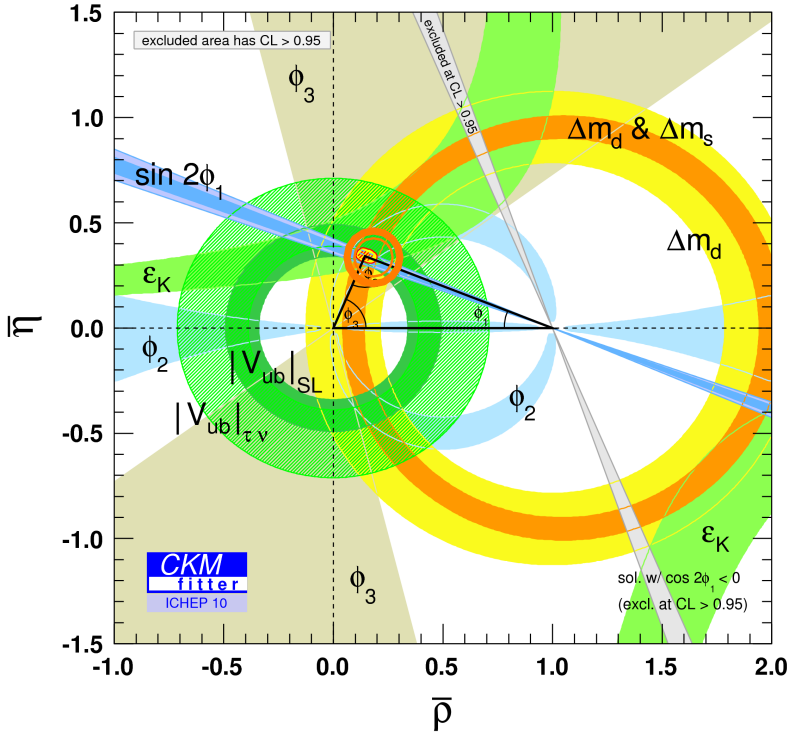
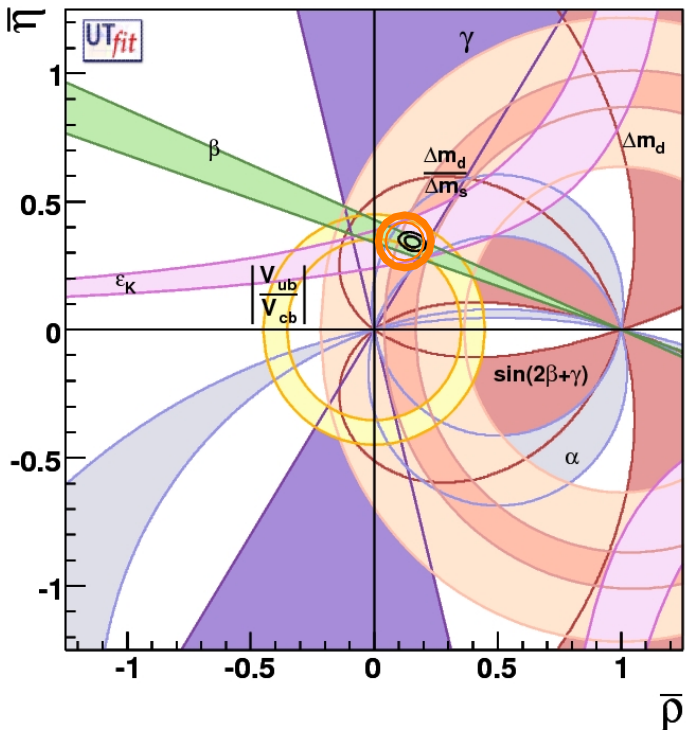
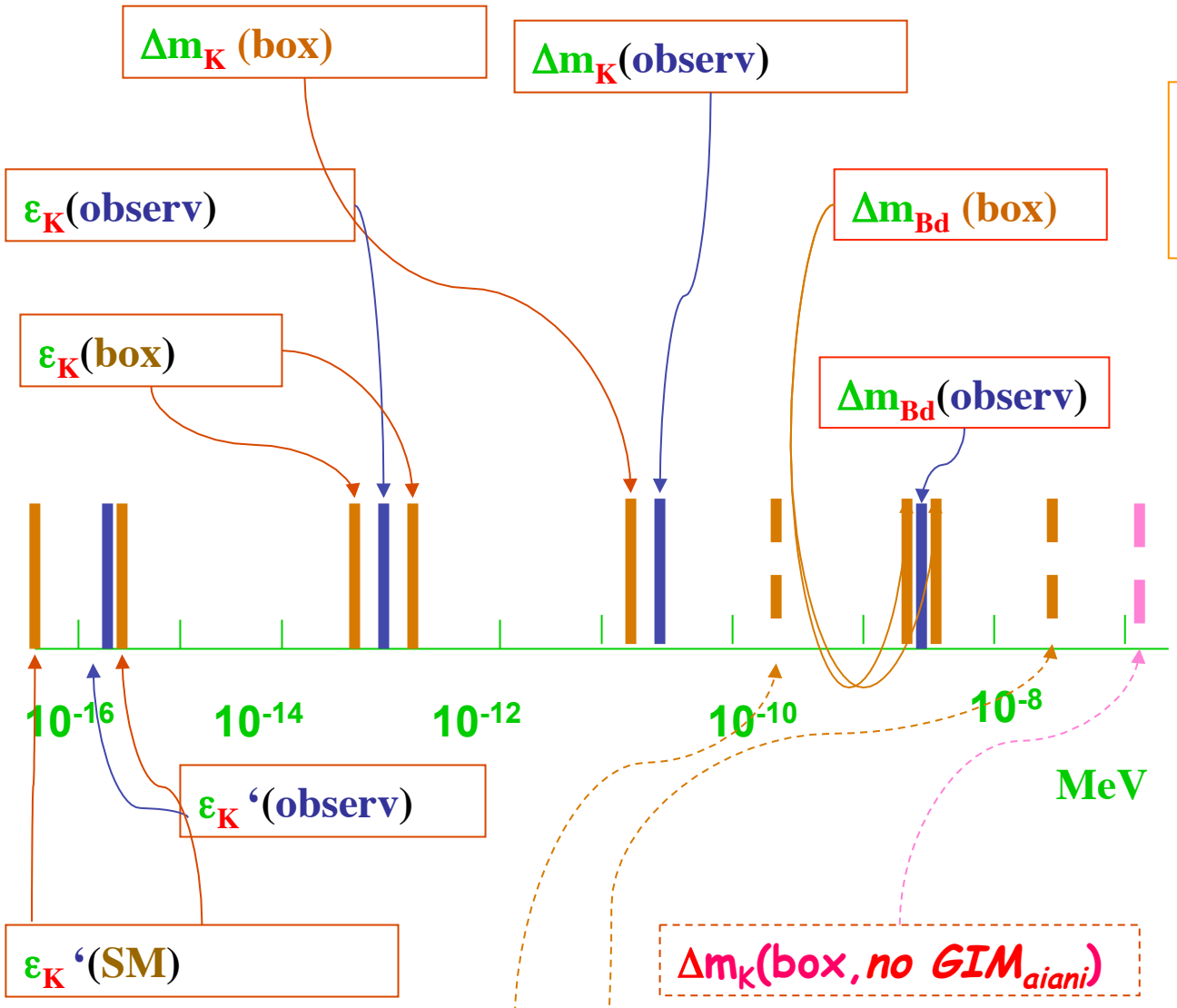


- $\sin 2\phi_2 \sim S(B_d \rightarrow \pi^+ \pi^-) = -0.61 \pm 0.08$



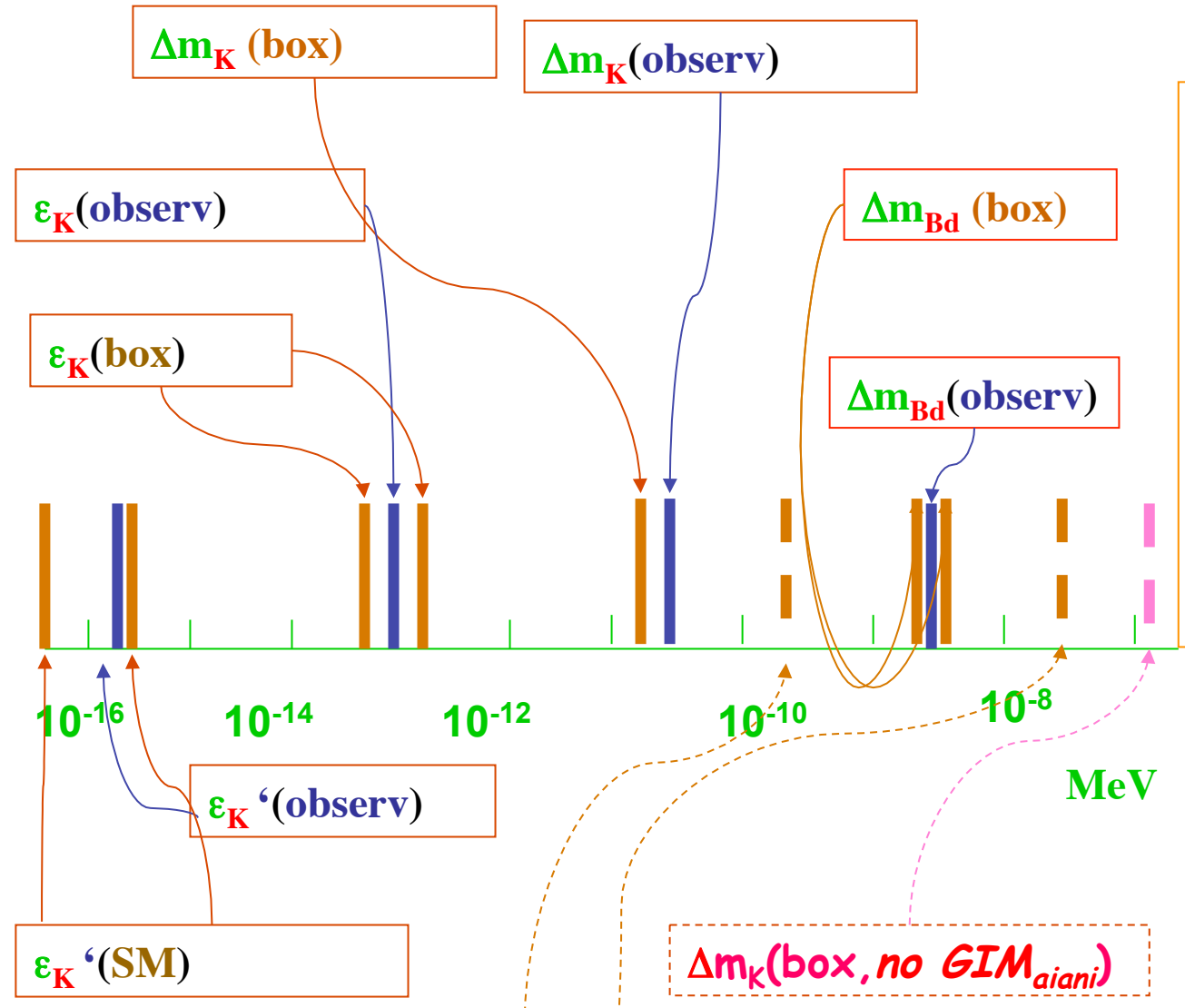


`the' CKM Triangle



reproduced observables spanning several orders of magnitude

small |V(td)| offset by large m_t



reproduced observables spanning several orders of magnitude accommodated with parameter choices

$|V(us)| \sim 0.22, |V(ts)| \sim 0.04$

$|V(td)| \sim 0.004$

$m_u \sim 5$ MeV, $m_c \sim 1.2$ GeV

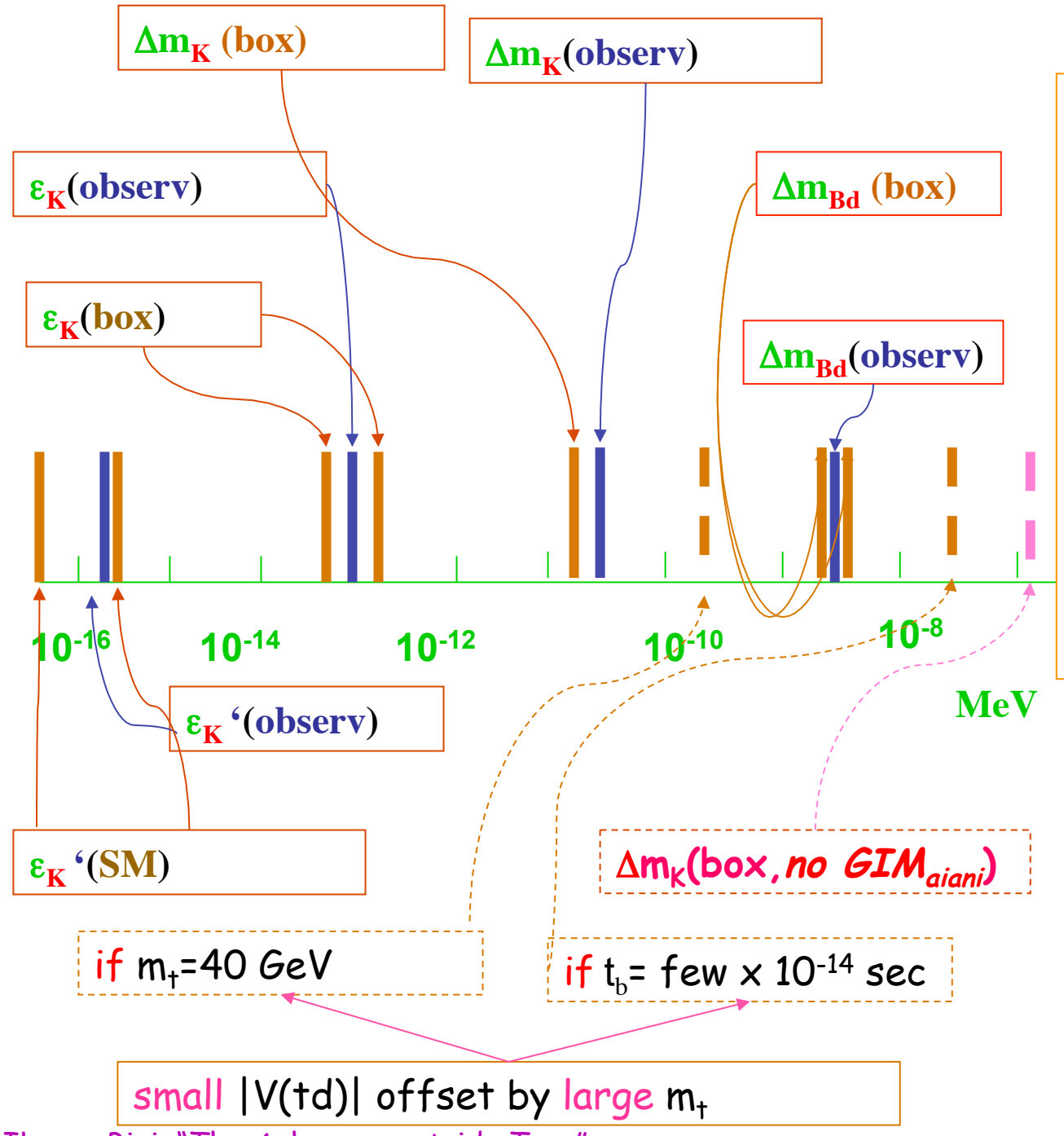
$m_t \sim 180$ GeV, $m_d \sim 10$ MeV

$m_s \sim 0.15$ GeV, $m_b \sim 4.6$ GeV

if m_t=40 GeV

if t_b= few x 10^{-14} sec

small $|V(td)|$ offset by large m_t



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|V(us)|~ 0.22, |V(ts)|~0.04

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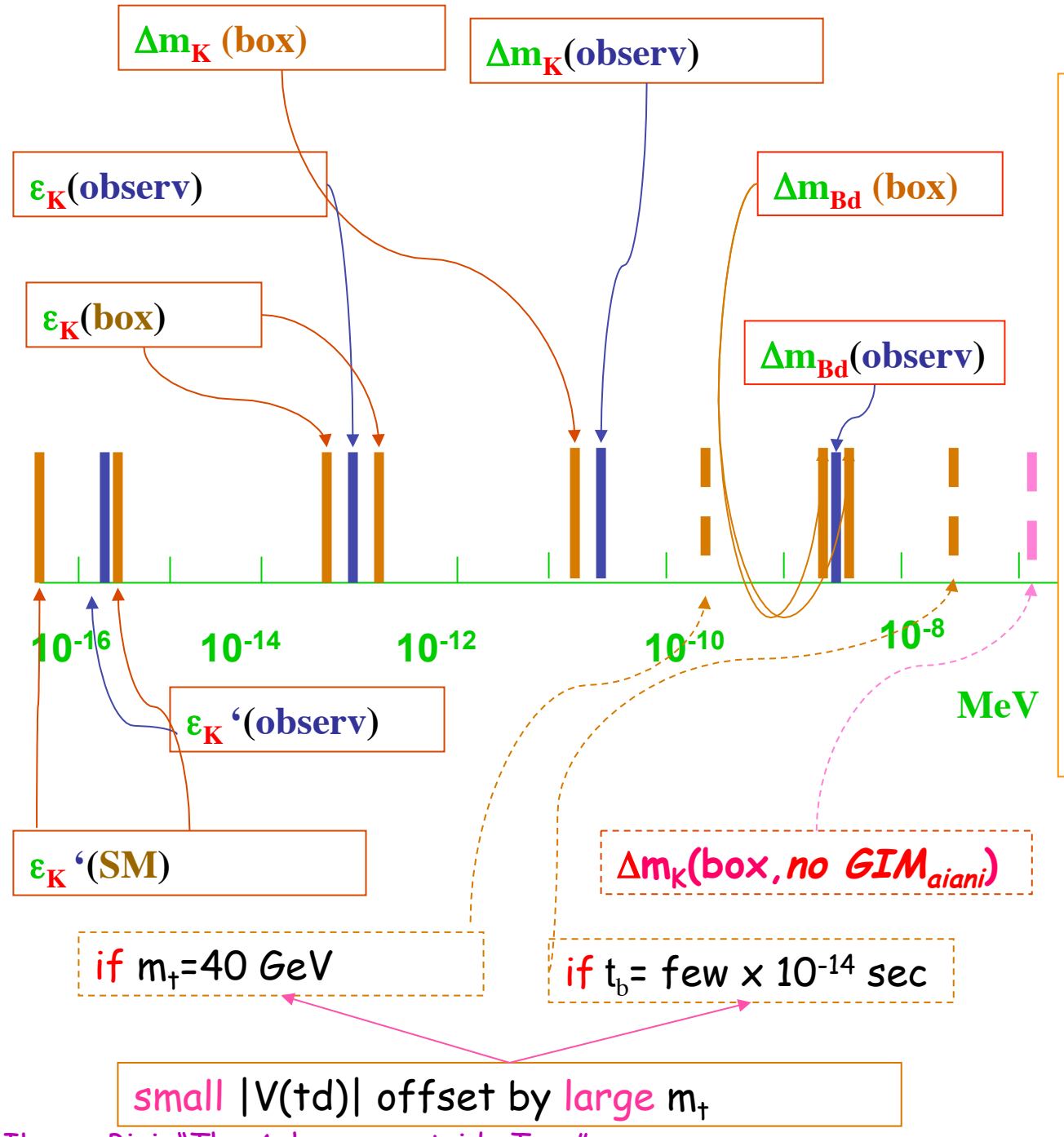
that a priori would seem `frivolous'!

Ikaros Bigi: "The Achaeans outside Troy"



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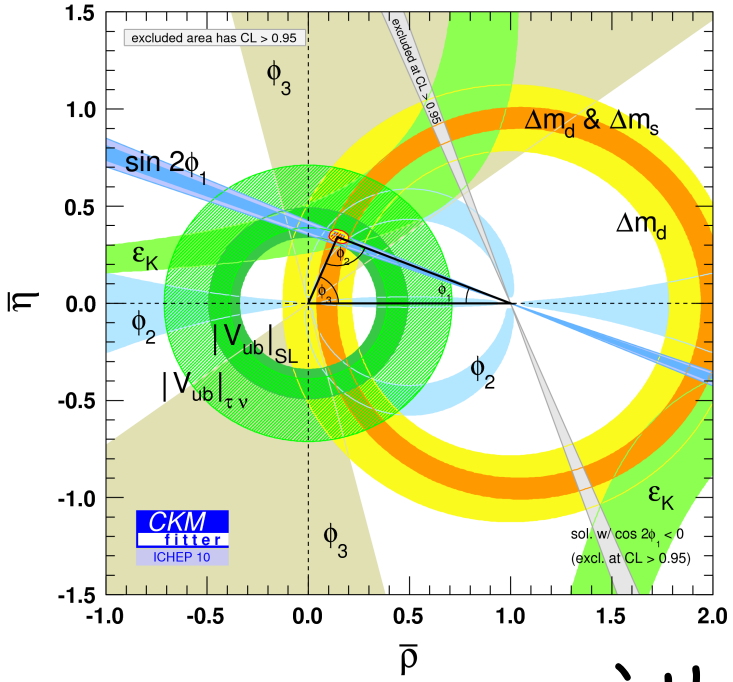
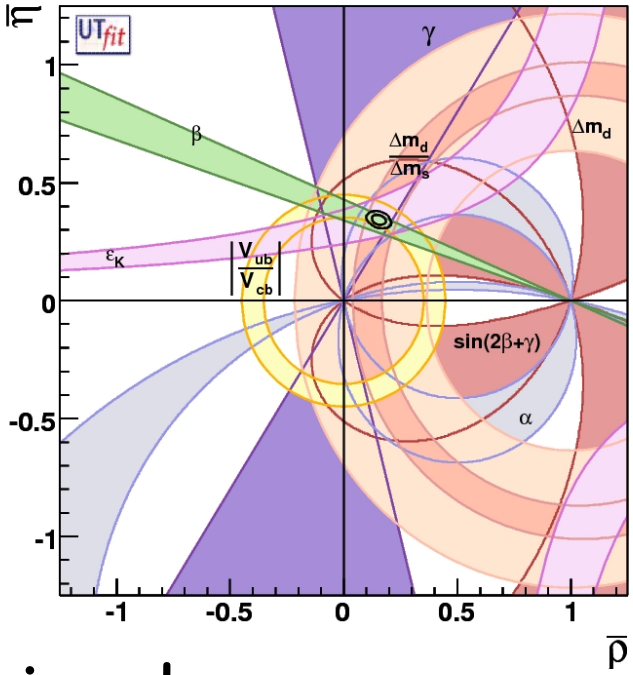
There could easily have been inconsistencies!





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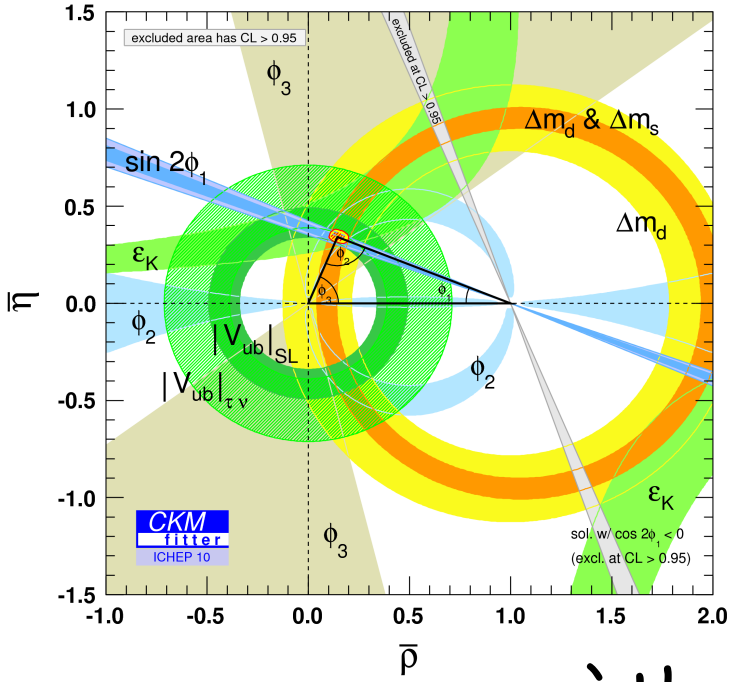
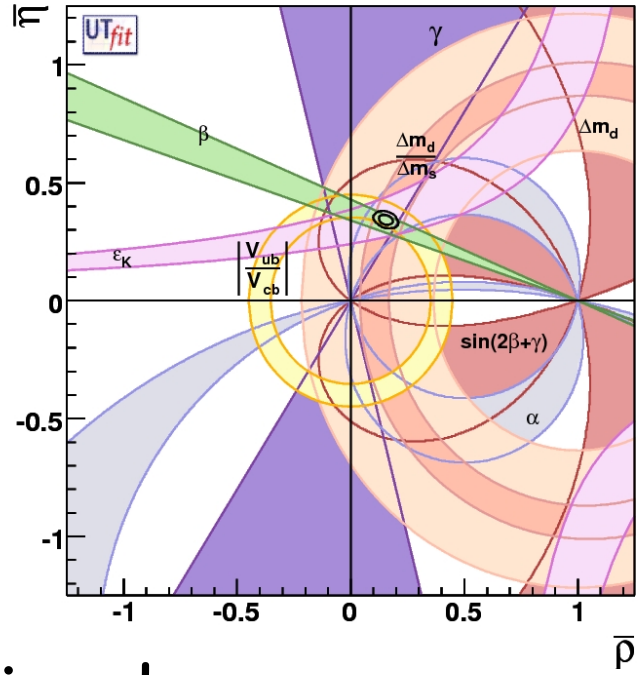
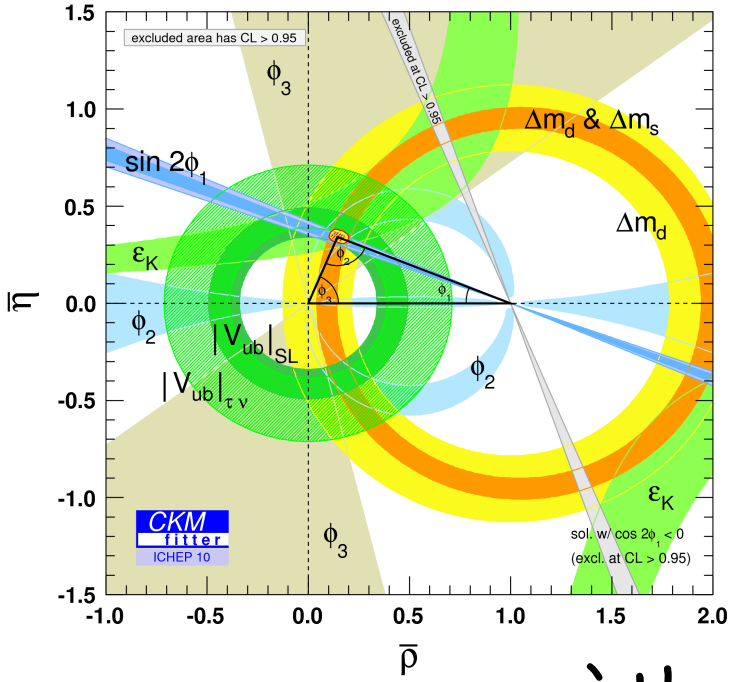
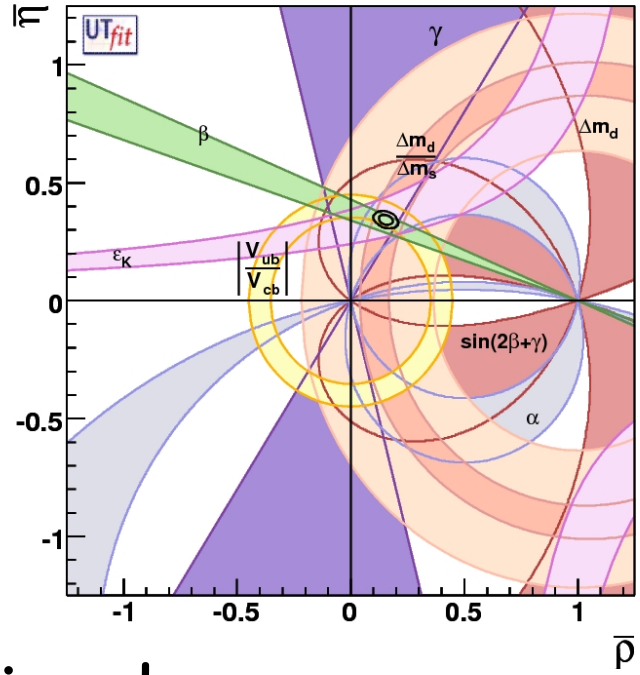




`the' CKM Triangle – Cathedral of Fundamental Science





`the' CKM Triangle – Cathedral of Fundamental Science

Ikaros Bigi: "The Achaeans outside Troy"

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Averages of b-hadron, c-hadron, and τ-lepton Properties

Heavy Flavor Averaging Group (HFAG):

arXiv: 1010.1589 [hep-ex]
lists 601 references

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References

[1] N. Cabibbo, Phys. Rev. Lett. **10**, 531–533 (1963).

[2] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652–657 (1973).

IV. Rosetta Stone for Understanding Flavour Dynamics

Cathedral of Flavour Dynamics has begun

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-- SM = $SU(3)_C \times SU(2)_L \times U(1)$ + CKM + PMNS -

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`only' thing

not even

greatest thing

accidental miracle

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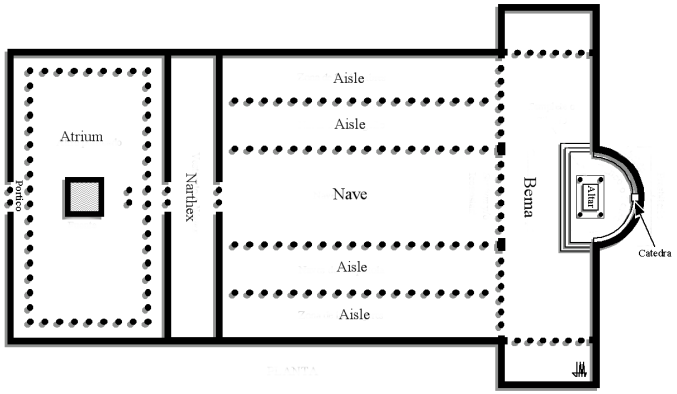

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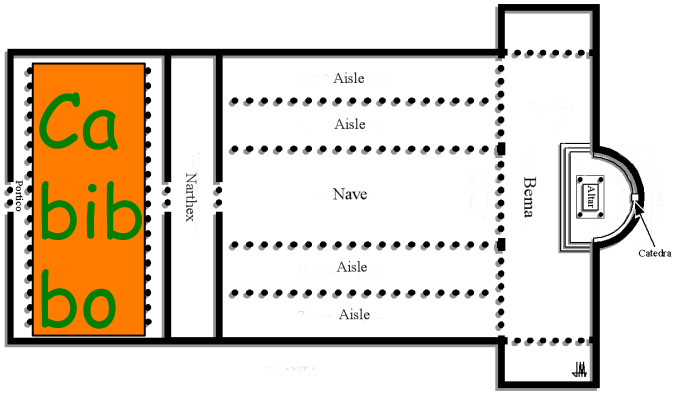

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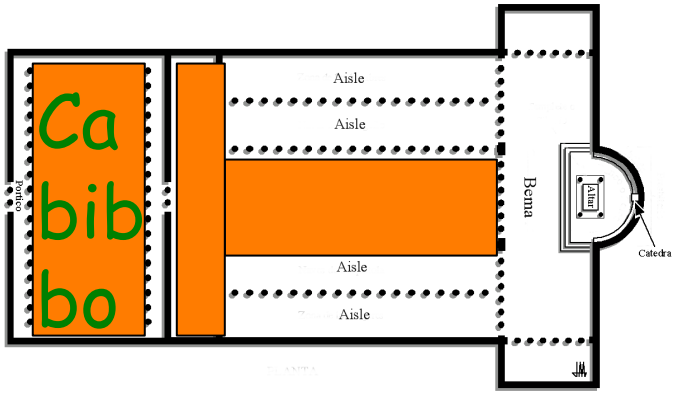
Have the atrium & vestibule & the central nave



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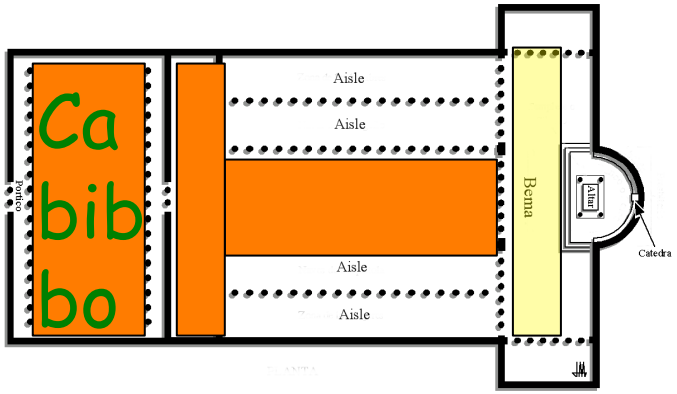
Have the atrium & vestibule & the central nave & an idea about the transept



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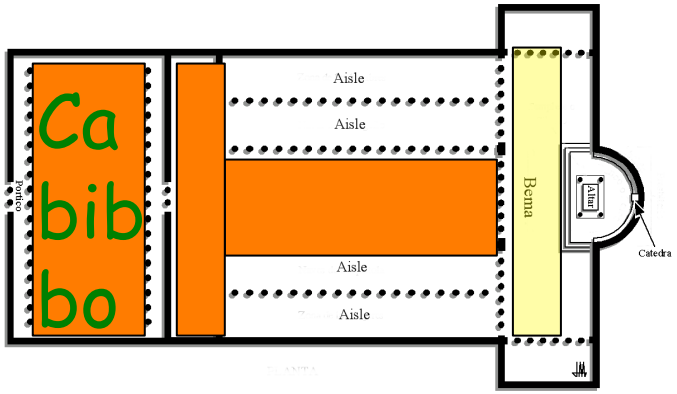

inspired by Kandinsky's several paintings from 1920's

"Composition VIII" 1923
triangles of different shapes

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"Composition VIII" 1923
triangles of different shapes

Kandinsky did not understand that triangles have same area – after all he is not a theorist!

inspired by Kandinsky's several paintings from 1920's

"Composition VIII" 1923
triangles of different shapes

"Black & Violet" 1923
are they triangles,
quadrangle, ???

(1) $\lambda^2 + \lambda^2 + \lambda^4$

bs triangle: $V^*_{us}V_{ub} + V^*_{cs}V_{cb} + V^*_{ts}V_{tb} = \delta_{bs} = 0$ B_s

$S(B_s \to J/\psi\,\phi)|_{CKM} \sim 0.03$

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(2) $\lambda + \lambda + \lambda^5$

cu triangle: $V^*_{ud}V_{cd} + V^*_{us}V_{cs} + V^*_{ub}V_{cb} = \delta_{cu} = 0$ D

$S(D^0 \to K_S\,\phi)|_{CKM} \sim 10^{-5}$, $S(D^0 \to h^+h^-)|_{CKM} \sim 10^{-4}$

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sd triangle: $V^*_{ud}V_{us} + V^*_{cd}V_{cs} + V^*_{td}V_{ts} = \delta_{sd} = 0$ K

$BR(K_L \to \pi^0\nu\nu)|_{CKM} = (8.4 \pm 1.0) \times 10^{-11}$ vs.

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(3) CP violation in top production & decays t

and Electric Dipole Moments (EDM):

neutrons, protons, deuterons, …

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neutrons, protons, deuterons, ...

and for electrons, muons, τ

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a lot to be learnt and done!

V. The Future – and Memory of Nicola Cabibbo

Lagrangian $\Longrightarrow$ $\Longrightarrow$ Observables

V. The Future – and Memory of Nicola Cabibbo

Lagrangian ⟹ ⟹ Observables

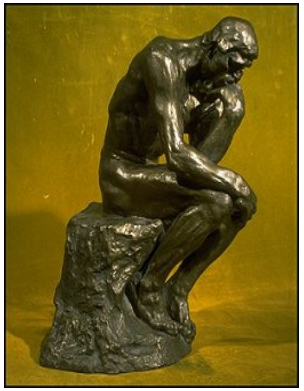
Ikaros Bigi: "The Achaeans outside Troy"

V. The Future – and Memory of Nicola Cabibbo

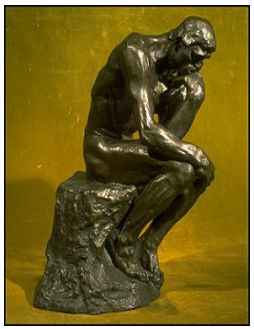
Lagrangian ⇌ ☁ ⇌ Observables

theoretical technology !

"plumbers"



"thinkers"



"thinkers"

Schlaeft ein Lied in allen Dingen,
Die da traeumen fort und fort,
Und die Welt hebt an zu singen,
Findst Du nur das Zauberwort.

There sleeps a song in all things
That dream on and on,
And the world will start to sing,
If only you find the magic word.

J. v. Eichendorff

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symmetry

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Ikaros Bigi: "The Achaeans outside Troy"

beginning of an exciting adventure …

and we are most privileged to participate!

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It is sad that we cannot enjoy it with Cabibbo

-- many of us feel that he should have joined Kobayashi & Maskawa in Stockholm –

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Thank you, Nicola Cabibbo!

to Madame Cabibbo:

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in some years from now on people will not remember which physicists were invited to Stockholm or not –

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Your great(& great)-children can say:

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