Flavor Physics -- A Central Mystery as well as High Sensitivity Probe of Fundamental Dynamics

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6/2006

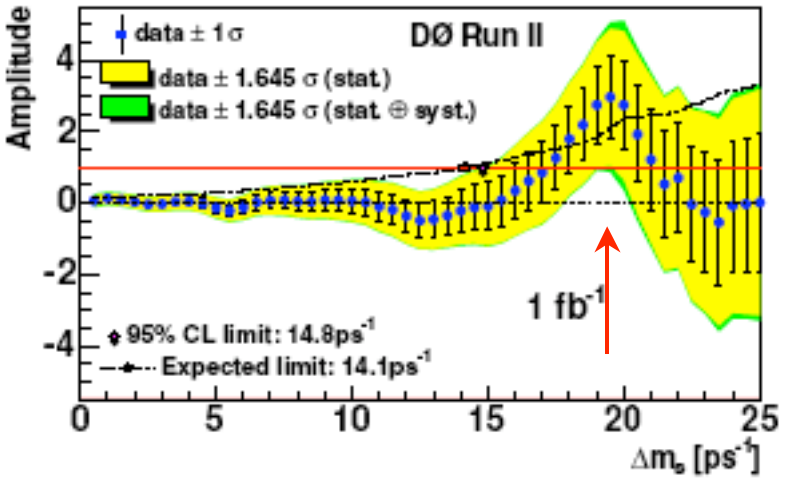
Executive Summary:

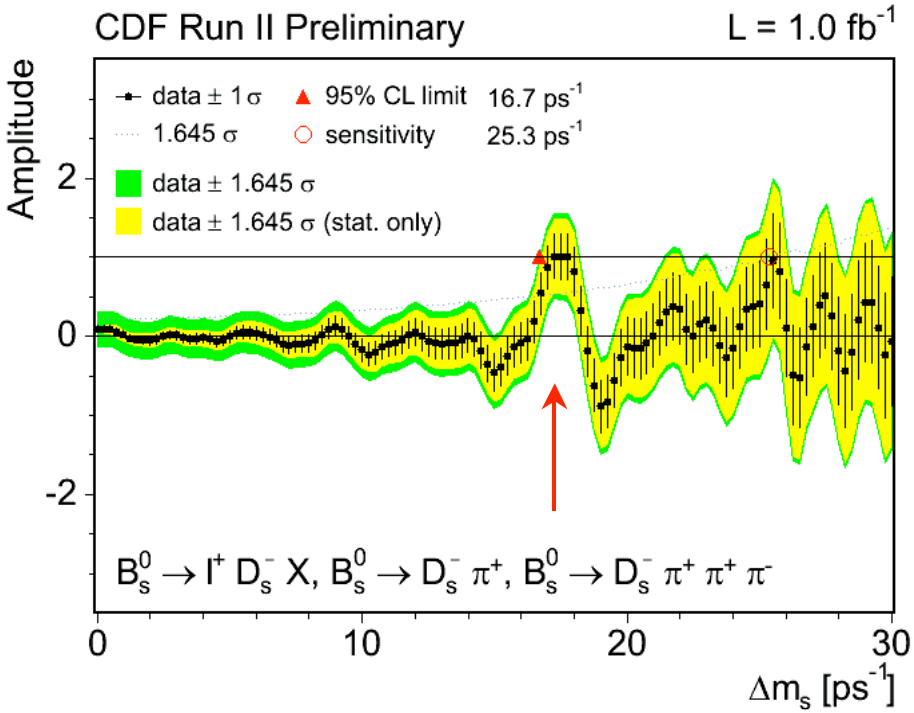
- SM has scored novel success since the turn of the millenium
  - discovery of direct ~~CP~~ in K_L decays
  - validation of its Paradigm of large ~~CP~~ in B decays
    - $B_d \to \psi K_S$, $B_d \to \pi^+\pi^-$, $B_d \to \pi^- K^+$
- interplay theory $\Leftrightarrow$ experiment $\Leftrightarrow$ new technologies
- none of the novel successes of the SM weaken the case for New Physics ~ the TeV scale $\Longrightarrow$ LHC!
- must study its impact on heavy flavour transitions

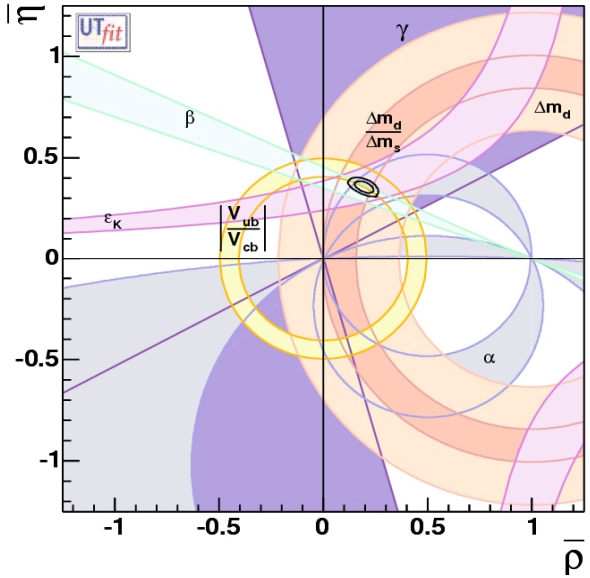
CP studies `instrumentalized' to analyze the New Physics

cannot count on numerically massive impact of the New Physics

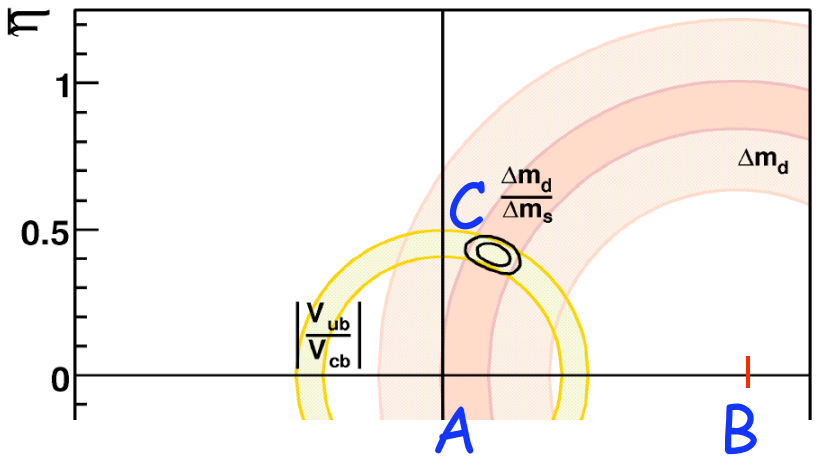
Latest point in case: B_s - B_s oscillations!

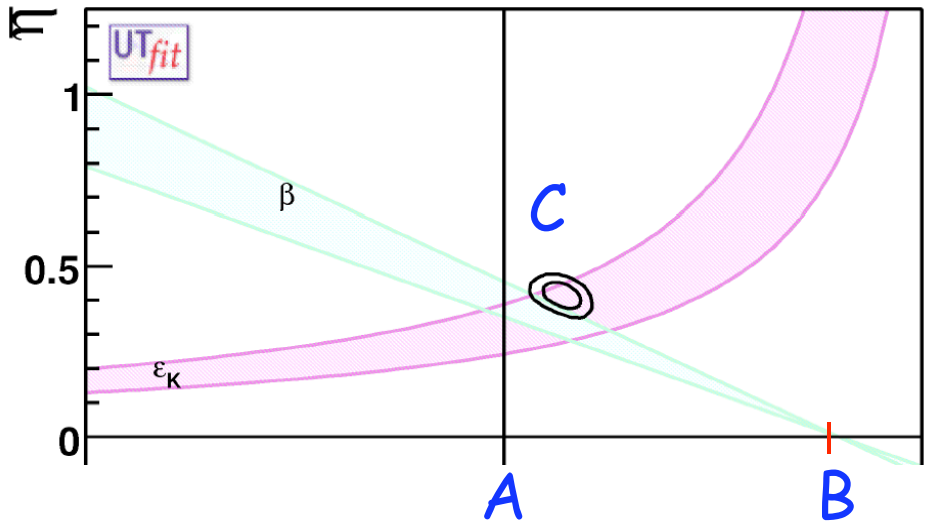






If true, another triumph for CKM theory: CP insensitive observables (V(ub),ΔM_s) imply ~~CP~~!





nevertheless -- B_s transitions able or even likely to exhibit manifestations of New Physics!

- The best from charm studies might still be to come!

- Super-Flavor factory -- an essential element of the HEP landscape in the LHC era -- with precision on the experimental & theoretical side the core task

  - the `Cathedral Paradigm'

Outline

I Status '05

Interludes: on Nature's Gifts -- Quantum Mechanics, Hadronization, Superheavy Top Quarks …

II On the Existence of New Physics -- `From the Heavens to the Earth'

III Indirect Probes for New Physics & Precision Studies

IV On HEP's future landscape -- a Call to Action

I Status '05

1.1 The Completion of a Heroic Era

direct ~~CP~~ established by '99

- WA '04: $\mathrm{Re}\,\epsilon'/\epsilon = (1.67 \pm 0.26) \times 10^{-3}$

$$\frac{\Gamma(K^0 \to \pi^+\pi^-) - \Gamma(\overline{K^0} \to \pi^+\pi^-)}{\Gamma(K^0 \to \pi^+\pi^-) + \Gamma(\overline{K^0} \to \pi^+\pi^-)} = (5.5 \pm 0.9) \times 10^{-6}$$

standard for CPT tests!

- a discovery of the first rank -- irrespective of theory
- experimental groups earned our admiration
- not inconsistent with SM/CKM
  - CKM is not a superweak theory
  - ϵ'/ϵ suppressed by $\Delta I = 1/2$ rule, superheavy top mass, being a loop effect

do not expect quick conclusive reply from theory

1.2 Establishing CKM as a Theory: ~~CP~~ in B Decays

Nature has been extremely kind to us in creating this

`Paradigm of large ~~CP~~ in B decays'

with `no plausible deniability!'

by arranging for

(i) huge top quark mass

(ii) `long' B lifetime

$\Delta M(B_d)/\Gamma(B_d) \sim 1$

and making it observable by arranging for

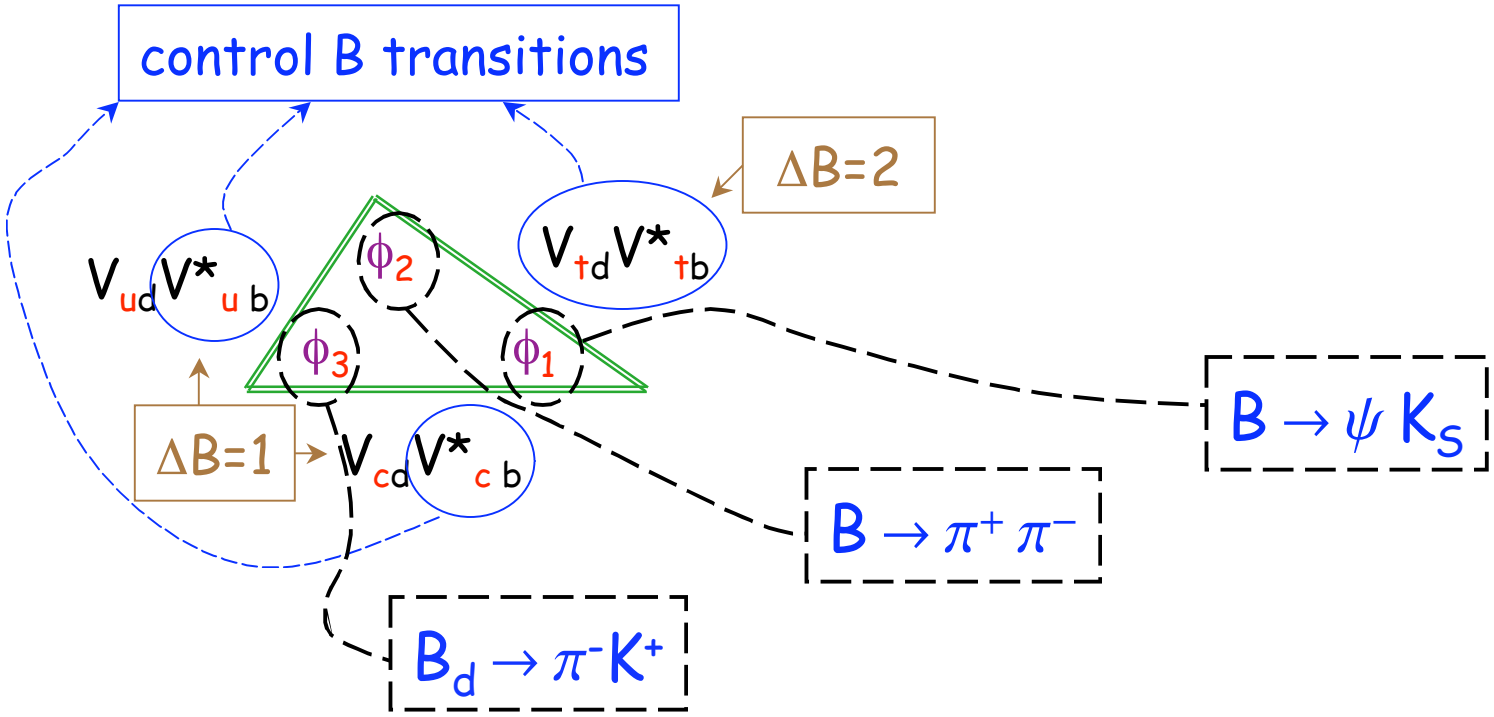
(iii) $\Upsilon(4S)$ being above $B\bar{B}$, yet below BB^* threshold

(iv) charm initiating the development of μvertex detectors

$V_{CKM}\, V_{CKM}^{*} = 1 \Longrightarrow$ 6 unitarity triangles

single $SU(2)_L$

$\tau_B \sim 1$ psec $\Longrightarrow$ `the' CKM triangle with 3 naturally large angles



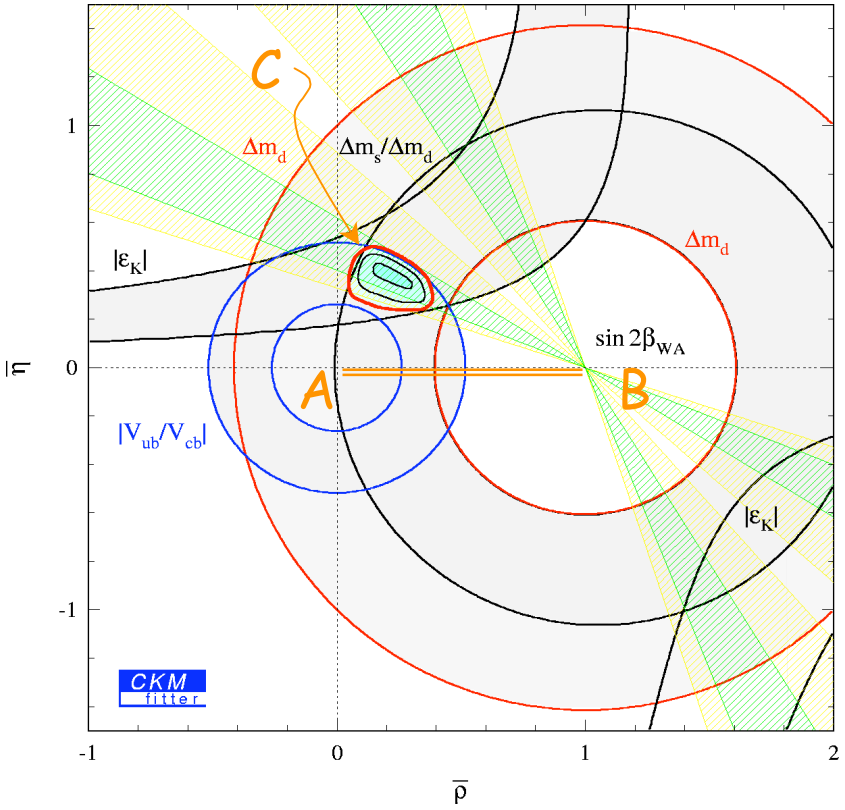
1.2.1 Status of CKM theory end of 2nd millenium

Yes, indeed …

large fraction of Δm_K, ϵ_K, Δm_B } could be due
most of ϵ_K' } to New Physics

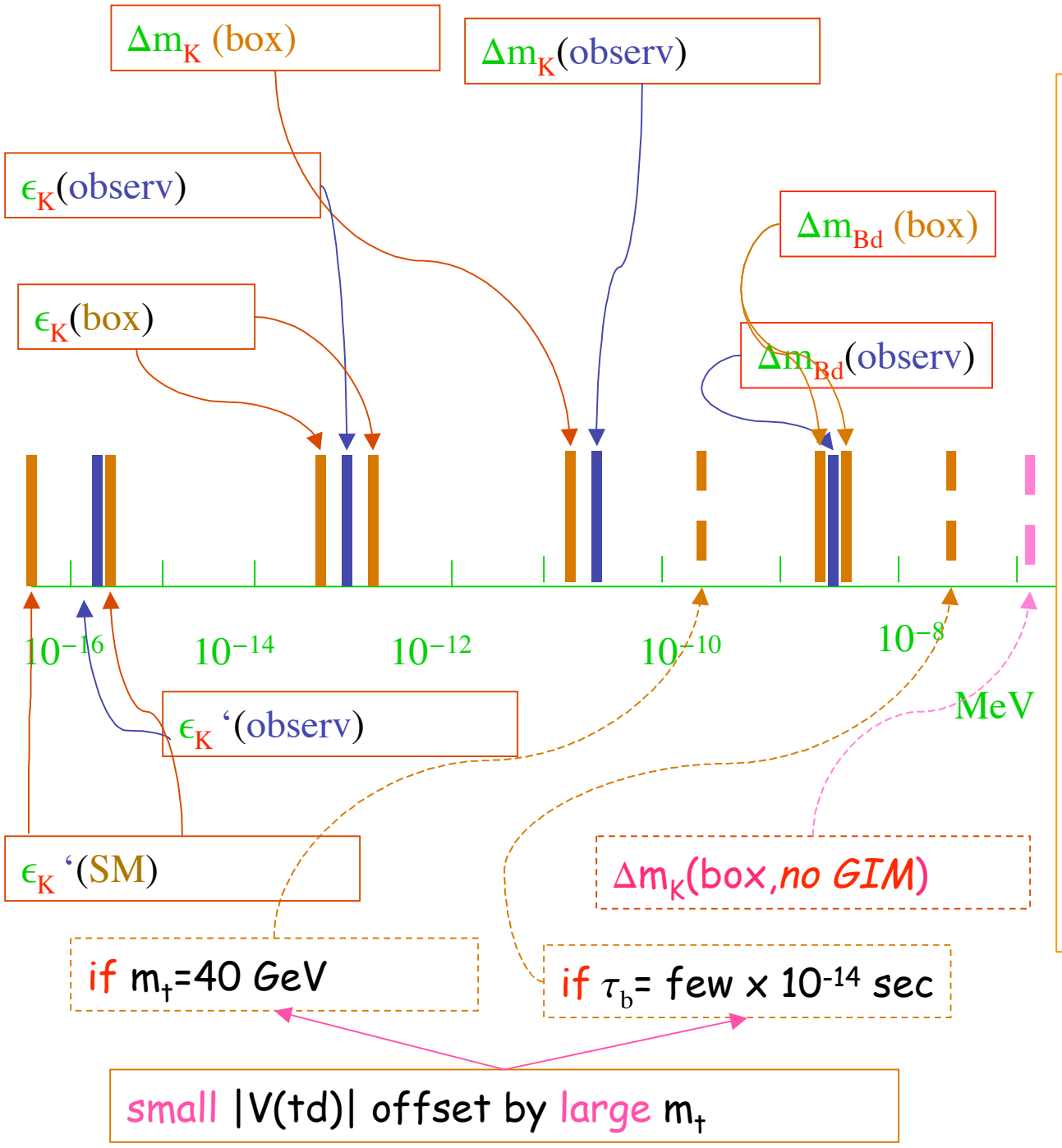
or equivalently

data constraints translate into `broad' bands
in unitarity triangle plots



yet such a statement

misses the real point!



can be reproduced with

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

|V(td)|~ 0.004

m_u~5 MeV,m_c~1.2 GeV

m_t≈180 GeV,m_d ~10 MeV

m_s~0.15 GeV,m_b≈4.6 GeV

observables spanning several orders of magnitude accommodated with parameter choices that a priori would seem frivolous!

There could easily have been inconsistencies!

Interlude A: Singing the Praise of Hadronization

hadronization (& nonperturbative dynamics in general)
usually viewed as unwelcome complication (if not outright nuisance);
case in point:

interpretation of
observed Δm_K, ϵ_K, Δm_B , ϵ_K'
contains sizeable uncertainties

correct --

yet such perspective again misses the deeper truth

without hadronization no formation of bound states

- no K^0-$\overline{K}^0$ oscillations
  - no indirect ~~CP~~: Im M_{12} ~O (10^{-8} eV)!
  - no direct ~~CP~~ a la ϵ'
- no B^0-$\overline{B}^0$ oscillations
  - no ~~CP~~ in $\Delta B=2$: ~O (10^{-4} eV)
  - no New Physics in $\Delta B=2$

hadronization

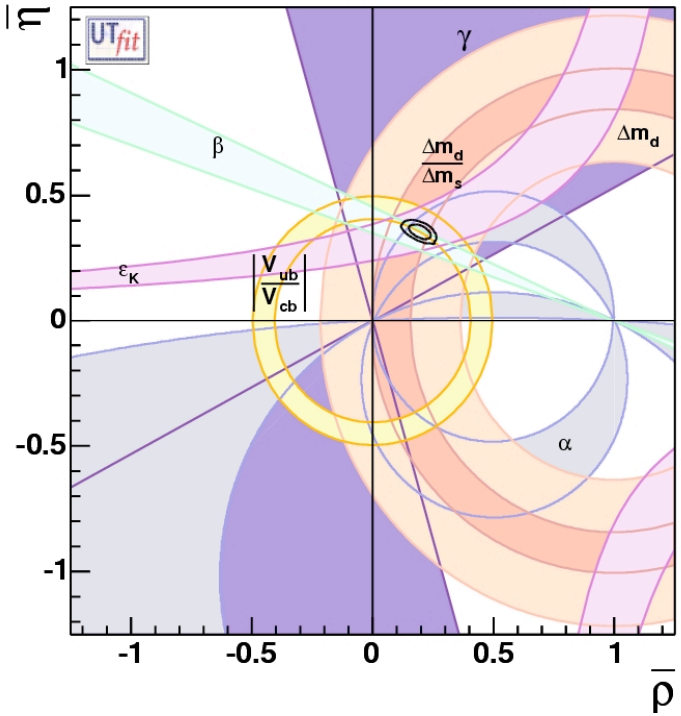
- reduces CP $\surd$ $K_L \to 3\pi$ by ~ 500 due to hadronic PhSp
- awards `patience'; i.e. you can `wait' for pure K_L beam
- generates CP signal in existence rather than asymmetry

- hadronization -- the hero rather than the villain in the tale of ~~CP~~!

Act 1: $B \to \psi K_S$ predicted in 1980

- 2001 BELLE: $\sin 2\phi_1 = 0.99 \pm 0.14 \pm 0.06$
  BABAR: $\sin 2\phi_1 = 0.59 \pm 0.14 \pm 0.05$
- Summer 2005

world average $\sin 2\phi_1 = 0.685 \pm 0.032$



vs. $\sin 2\phi_1|_{CKM} = 0.725 \pm 0.065$

➥ it is there, it is huge -- as expected!

➥ summer '01:

- CKM paradigm has become a ***tested*** theory!
- `demystification of ~~CP~~':

  if dynamics can support ~~CP~~, it can be large!

  i.e., observable phases can be large!

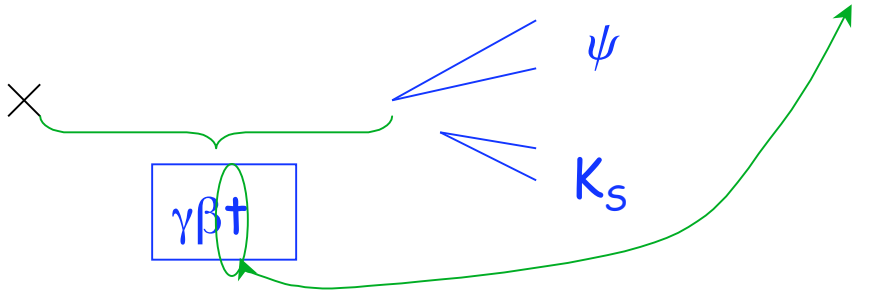
➥ `demystification' **completed**

if find ~~CP~~ **anywhere** in lepton sector

☞ CKM explains naturally why CP invariance is a `near miss' in K_L decays: 1st & 2nd families almost decoupled from 3rd!

Interlude B: "Praise the gods 2x for EPR correlations"

☺ rate(B_d [$\overline{B_d}$](t_{dec}) → ψK_S) ∝ $e^{-\Gamma t}$(1- [+][$A \sin\Delta m_d t$])

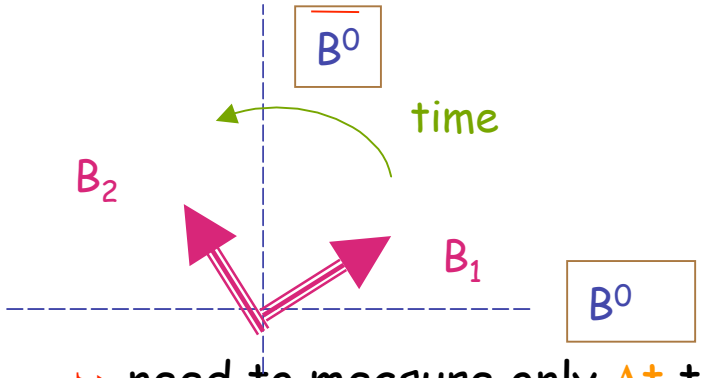


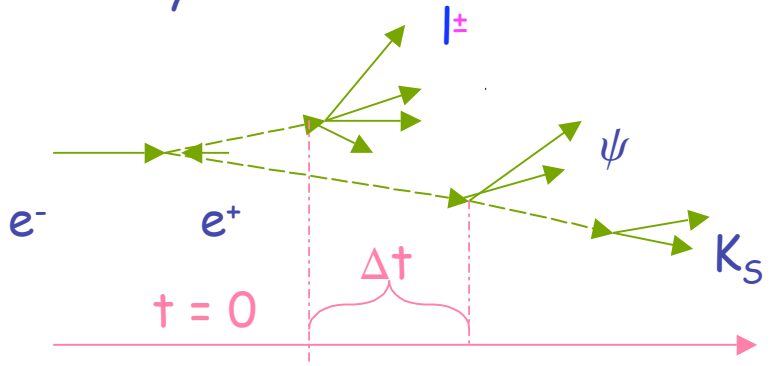
☹ $e^+e^- \to B_d \overline{B_d}$: $c\tau$ ~ 0.45 mm vs. product. region ~ 1 mm

asymmetry washed out?

☺ EPR to the rescue!

$e^+e^- \to B_1 B_2$ in C=- : Bose-Einstein $B_1 \perp B_2$ -- till decay!

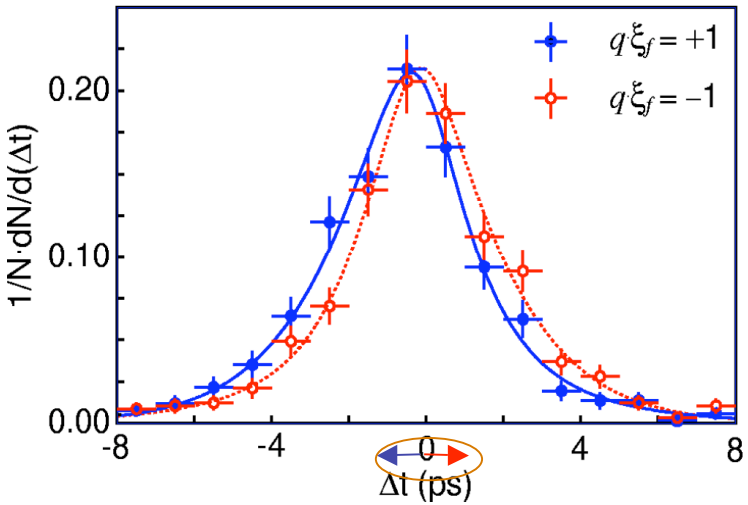




➥ need to measure only Δt time interval between decays

rate($e^+e^- \to B_d B_d \to [l^\pm X]_t [\psi K_S]_{t+\Delta t}$) ~ … (1 ± $A \sin\Delta m_d \Delta t$)

There is even more to it: ~~CP~~ $\Leftrightarrow$ ~~T~~ in B decays



$B \to l^- X$ $\qquad$ $B_d \to \psi K_S$

EPR $\qquad$ EPR

CPT in SL decays

$B_d \to \psi K_S$ $\qquad$ $B \to l^+ X$

➥ ~~CP~~ $\Leftrightarrow$ ~~T~~ in $B \to \psi K_S$

assuming CPT merely in SL B decays

Act 2: $B \to \pi^+ \pi^-$

$$\frac{R_+(\Delta t) - R_-(\Delta t)}{R_+(\Delta t) + R_-(\Delta t)} = S \sin \Delta m_d \Delta t + C \cos \Delta m_d \Delta t,\ S^2 + C^2 \leq 1$$

$$S = \frac{2\,\mathrm{Im}\,(q/p)\rho(f_{CP})}{1 + |(q/p)\rho(f_{CP})|^2},\quad C = \frac{1 - |(q/p)\,\rho(f_{CP})|^2}{1 + |(q/p)\rho(f_{CP})|^2}$$

if $S(f_1) \neq \eta\,(f_1)\,\eta\,(f_2)\,S(f_2)$ or $C(f) \neq 0 \Rightarrow$ direct ~~CP~~!

- Summer 2005

  BELLE: $S = -0.67 \pm 0.16 \pm 0.06,\ C = +0.56 \pm 0.12 \pm 0.06$

- ~~CP~~ with 5.2 σ

  direct ~~CP~~ with 3.3 σ [superweak: $C=0,\ S = -(0.75 - 0.82)$]

  BABAR: $S = -0.30 \pm 0.17 \pm 0.03,\ C = +0.09 \pm 0.15 \pm 0.04$

- guestimate: $90^\circ < \phi_2 < 146^\circ$ consistent with

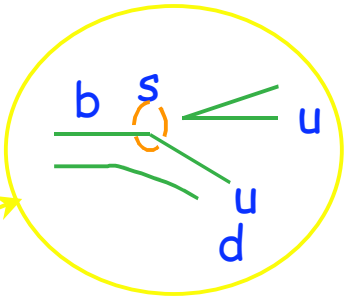
  indirect estimates $77^\circ < \phi_2 < 122^\circ$

Act 3: More on Direct ~~CP~~

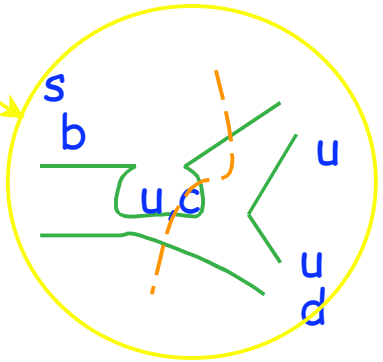
$B_d \to \pi^- K^+$

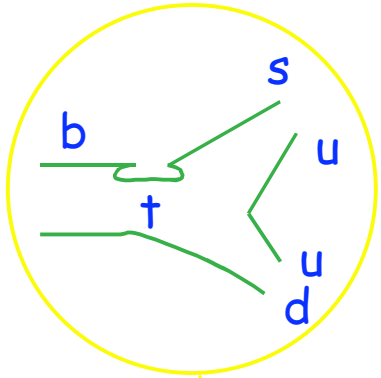
BSS

local operator with weak phase



nonlocal operator with strong phase





local operator not needed, but there

BKSU

1987: $BR(B_d \to \pi^- K^+) \sim 10^{-5}$, $A_{CP} = -0.10$

2004

BABAR *hep-ex/0408057, submitted to PRL*

$A_{CP} = -0.133 \pm 0.030 \pm 0.009$

4.2σ

Belle **Confirmation at ICHEP04**

Signal ($274M$ $B\bar{B}$ pairs): 2140 ± 53

$A_{CP} = -0.101 \pm 0.025 \pm 0.005$

3.9σ

Average $A_{CP} = -0.114 \pm 0.020$

II On the Existence of New Physics -- `From the Heavens to the Earth'

- the Paradigm of large $\not{CP}$ in B decays established in qualitative & quantitative agreement with CKM theory in 3 quite distinct B_d channels
  - commensurate with $\not{T}$ and with
  - large direct $\not{CP}$ in 2 channels
- a novel -- not `merely' a new -- success of the SM

Yet these novel successes do not weaken the arguments for New Physics ~ TeV scale

➥ mandatory to search for New Physics

S. Beckett: "Ever tried? Ever failed?
No matter.
Try again. Fail again. Fail better.

S. Beckett: "Ever tried? Ever failed?
No matter.
Try again. Fail again. Fail better.

Cheer up -- we know there is New Physics -- we will not fail forever!

A. Masiero: "You have to be lucky to find New Physics."

Napoleon:"Being lucky is part of the job description for my generals!"

SM with CKM very successful in describing
(though not necessarily explaining) earthly data, except for:

the `Strong CP Problem' of QCD

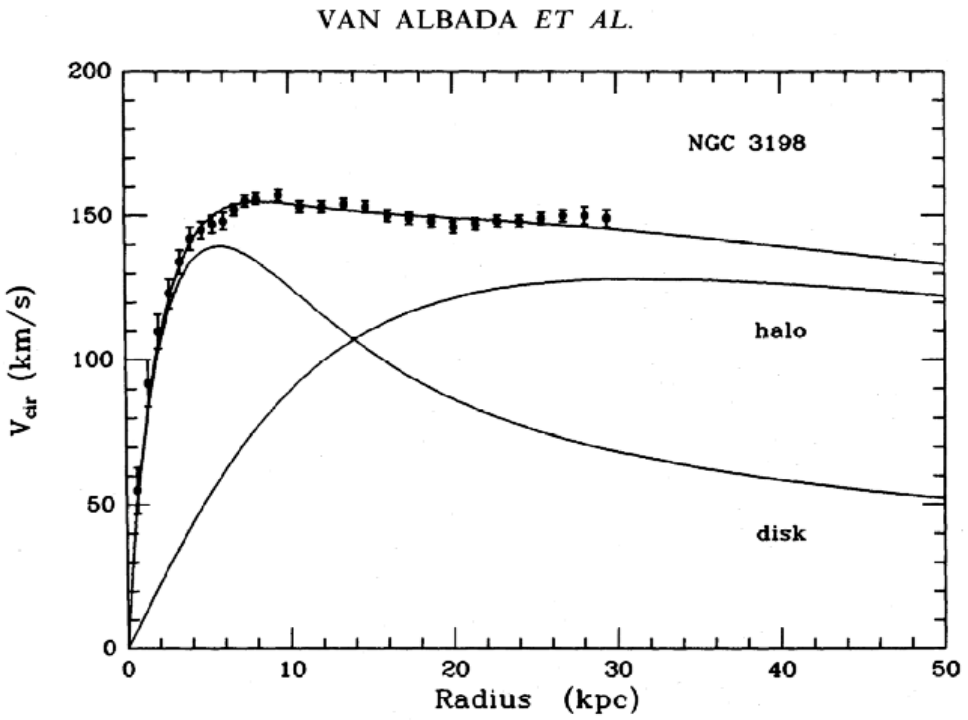
Evidence for ν oscillations from KAMLAND & K2K

Yet `heavenly' evidence is quite unequivocal

compelling evidence from astrophysics & cosmology
that Standard Model is incomplete!

- baryon # of Universe
  - 😐 *standard* CKM irrelevant for baryon number of universe
  - ☺ New Physics exists!
  - ☺ New CP Paradigm: ~~CP~~ phases can be large

Dark Matter

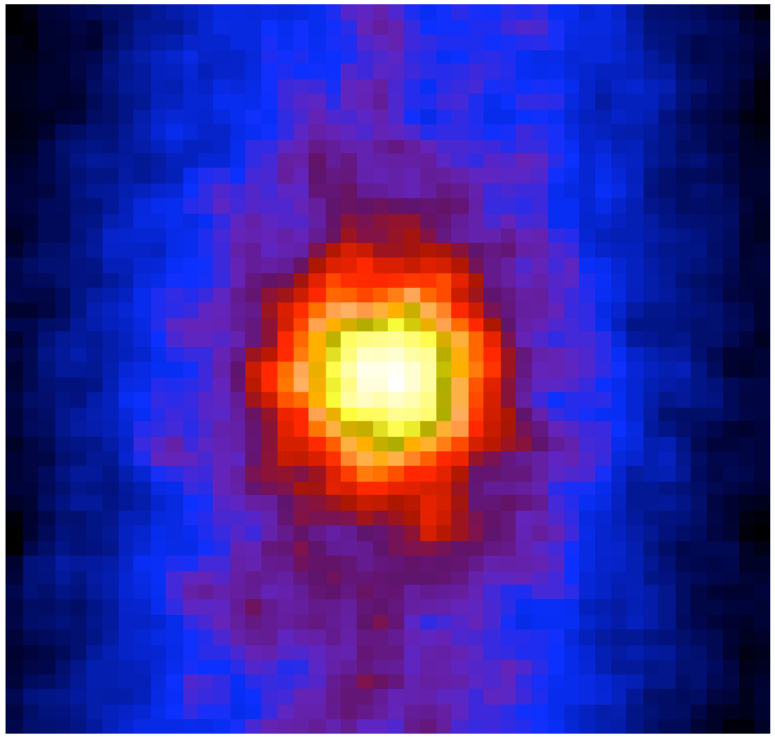


A lot more `stuff' --

i.e. gravitating agents -- out there than meets the eye!

- about 1/4 of gravitating agents in the Universe are `dark matter', mostly non-baryonic
  - ☞ Standard Model has no candidates for it!

- Solar & atmospheric ν `anomalies'



From R. Svoboda

Our sun seen by Super-K in the `light' of neutrinos -- it looks paler than it should: ν_e disappear by changing their identity!

ν_μ produced in the earth's atmosphere `disappear' as well

- Dark Energy

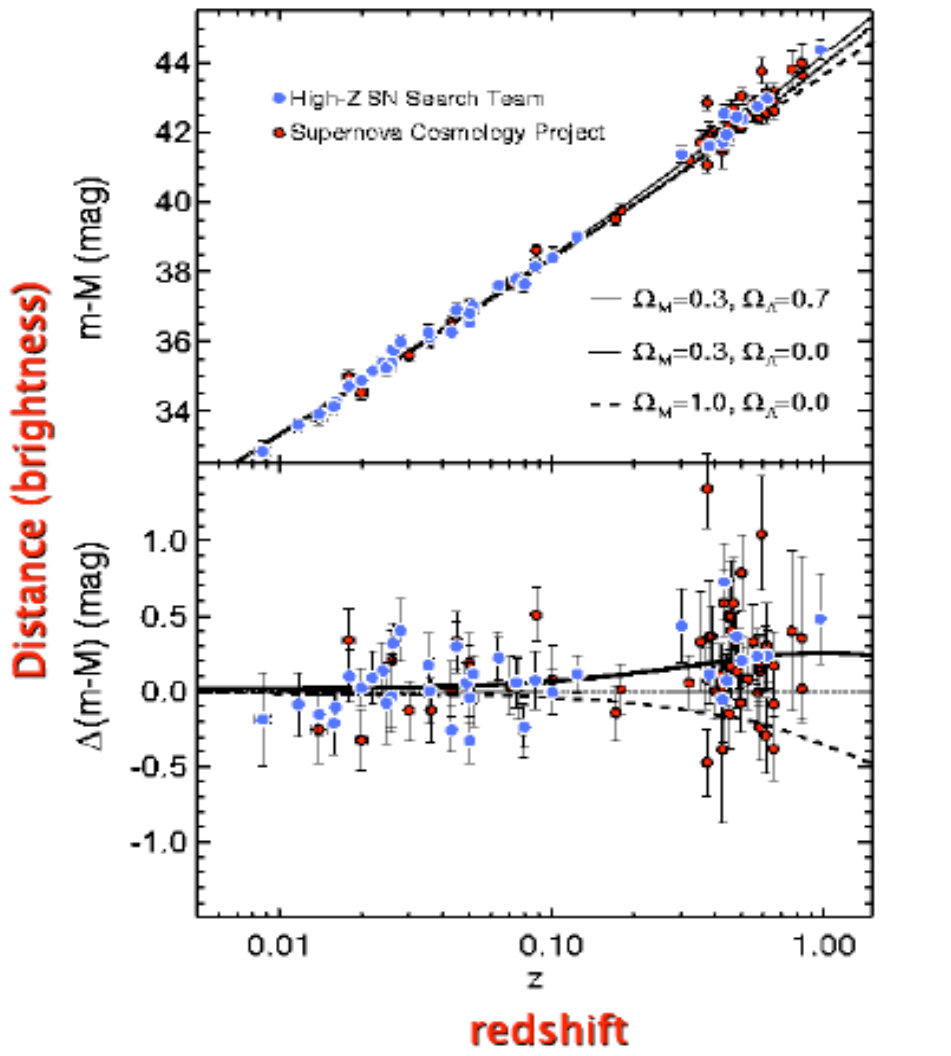
In 1998 2 teams searched for SN 1a (=`standard candles')

~5 billion LY away;

found them fainter than expected from deceleration:

➥ acceleration!

P. Garnavich



novel successes do not illuminate any of the mysterious features of the SM; if anything, they deepen the mysteries:

illuminations/explanations

(i) electroweak symmetry breaking

$SU(2)_L \times U(1) \rightarrow U(1)_{QED}$

`confidently predicted' NP at ~ 1 TeV = *cpNP*; e.g. SUSY

(ii) family structure (charge quantiz.)

$Q_e = 3\, Q_d$

`guaranteed' NP at $O(10^{11})$ TeV = *gNP*; e.g. SO(10)

(iii) finite family replication

$Z^0 \rightarrow 3\, \nu\nu$

CKM pattern most unlikely accidental

➥ `strongly suspected' NP at ??? scale = *ssNP*

e.g., ??? (M theory ??)

heavy flavour studies might provide insights into (iii) & (ii) -- they will be crucial for identifying the *cpNP*

❶ expect confidently LHC will find New Physics at TeV scale

❷ `merely' establishing existence of New Physics not enough

-- goal must be to identify its salient characteristics

SUSY an organizing principle, not a theory!

❸ TeV scale dynamics likely to have some impact on B decays

❹ discovery potential in B,D & τ decays essential to figuring out the New Physics -- not a luxury!

III Indirect Probes for New Physics & Precision Studies

3.1 `King Kong Scenarios for New Physics Searches

"One might be unlikely to encounter King Kong;
yet once it happens there will be no doubt that one has come across something out of the ordinary!"

as with historical precedent of strange hadrons search for a qualitative discrepancy between data & expectation,
i.e. discrepancies by orders of magnitude!

Memento: King Kongs live in far-a-way countries requiring arduous journeys.

3.1.1 ~~CP~~ in leptodynamics

Compelling impetus to search for ~~CP~~ in leptodynamics

- to complete `demystification' of ~~CP~~
- baryogenesis due to primary leptogenesis (?)

ν oscillations

no worry about hadronization, yet … probe ν oscillations

… disentangle matter enhancements …

ancient Greek wisdom:

"If the gods want to really harm you, they fulfill your wishes."

Electric dipole moments

static quantities

energy shift $\Delta\mathcal{E}$ of system inside electric field $\boldsymbol{E}$:

$$\Delta\mathcal{E} = d_i E_i + d_{ij}\, E_i E_j + \ldots$$

linear in E $\quad \mathbf{d} \propto \mathbf{s} \Rightarrow \mathbf{d} \neq 0 \Leftrightarrow$ T violation !

$d_N < 0.63 \times 10^{-25}$ ecm vs. $d_N^{CKM} < 10^{-30}$ ecm (except strong CP)

from ultracold neutrons

$d_e = (0.07 \pm 0.07) \times 10^{-26}$ ecm vs. $d_e^{CKM} < 10^{-36}$ ecm

from atomic EDM

✍ New Physics scenarios can yield ~ 10^{-26} - 10^{-28} ecm

CP in τ Decays -- the Next Hero Candidate

most promising channels: $\tau \to \nu K \pi$

- most sensitive to Higgs dynamics
- CP asymmetries possible also in final state distributions
  rather than integrated rates
- unique opportunity for $e^+e^- \to \tau^+\tau^-$
  pair produced with spins aligned:
  1 τ decays can `tag' the spin of the other
  ➥ can probe spin-dependent CP with unpolarized beams!
- confidently predicted CP: ibi, A.I. Sanda, hep-ph/0506037

0.0033 in $\Gamma(\tau^+ \to \nu K_S \pi^+)$ vs. $\Gamma(\tau^- \to \nu K_S \pi^-)$

-- due to K_S's preference for antimatter

3.1.2 ~~CP~~ in Charm Decays

S. Bianco et al., `A Cicerone for the Physics of Charm', hep-ex/0309021, La Rivista d. N. C.

only up-type quark allowing full range of probes for New Phys.

- top quarks do not hadronize
- up quarks: no π^0-π^0 oscillations possible

CP asymmetries basically ruled out by CPT

basic contention:
charm transitions are a unique portal for obtaining a novel access to the flavour problem with the experimental situation being a priori favourable (apart from absence of Cabibbo suppression)!

only now are entering realistic domain for New Physics

CP Violation

- ☺ baryon # of Universe implies/requires NP in ~~CP~~ dynamics
- ☺ within SM:
  - ☞ highly diluted weak phase in 1x Cabibbo supp. Modes
    $V(cs) = 1 \ldots + i\lambda^4$
  - ☞ no weak phase in Cab. favoured & 2 x Cab. supp. modes
    (except for $D^{\pm} \to K_S h^{\pm}$)
- ☺ CP asymmetry linear in NP amplitude
- ☺ final state interactions large
- ☺ BR's for CP eigenstates large
- ☹ D^0-$\overline{D}^0$ oscillations at best slow

- ✍ B factories can contribute
- ☞ challenge to LHCb: can you?
  $D^{*+} \to D^0(t) \to K^+\pi^-$ vs. $D^{*-} \to \overline{D}^0(t) \to K^-\pi^+$

3.2 Precision CP Studies in B Decays

CKM theory scored a priori very unlikely successes with highly peculiar dynamics, in particular for FlChNC

Generic TeV scale New Physics scenarios should already have manifested themselves in FlChNC --

i.e, we are missing an important message about flavor dynamics

➥ `New Flavour Problem'

✍ therefore cannot count on numerically massive impact of New Physics on B decays

➥ must achieve precision on experim. & theoretical level

Precision an admittedly ambitious, yet not utopian goal

Example: extracting V(cb)

Status '05

Buchmueller,Flaecher: hep-ph/0507253

$m_b(1\ GeV) = (4.59 \pm 0.04)\ GeV$ ⇐ 1.0 %

$m_c(1\ GeV) = (1.14 \pm 0.06)\ GeV$ ⇐ 5.3 %

$m_b(1\ GeV) - 0.74\ m_c(1\ GeV) = (3.74 \pm 0.017)\ GeV$ ⇐ 0.5 %

$|V(cb)| = (41.58 \pm 0.67) \times 10^{-3}$ ⇐ 1.6 %

vs.

$|V(us)|_{KTeV} = 0.2252 \pm 0.0022$ ⇐ 1.1 %

need

- robust theoretical framework:
  - ✔ $1/m_Q$ expansions,Sum Rules, LQCD
- comprehensive & detailed data
  - ✔ SL B decays, lepton spectra, moments …

Pythagoras:"There is no royal way to mathematics!"

Nor is there to fundamental insights into nature's inner working.

Need data that are

- detailed &
- accurate &
- comprehensive &
- can be interpreted with commensurate reliability

e.g.:

high statistics studies of charm decays (Dalitz plots etc.) are essential to saturate discovery potential in B decays

- Even given the SM success in apparently predicting $\Delta M(B_s)$

  $B_s \to \psi\phi/\eta$ have an very good chance to reveal New Physics

- Handful of even perfectly measured processes not enough -- comprehensive body of accurate data essential

Super-B factory = e^+e^- collid. near Y(4S) with $L \sim 10^{36}\ cm^{-2}\ s^{-1}$

- in a clean environment

appears peerlessly able to provide required data base

Super-B factory = Super-Flavor factory can sweep out regime up to ~ 100 TeV >> LHC range

3.3 The `Second Trojan War' (described in the Iliad)

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

theoret. uncertainty [m_c] ~ 7 % (I think can be cut to 4 - 5 %)

- $K_L \to \pi^0 \nu\nu$ = ~~CP~~ !

theoret. uncertainty ~ 2 %

- `standard candles' of SM
- should aim for ~ $O(1000)$ events

IV Future HEP landscape - a Call to ~~Arms~~ well-reasoned Action

❶ We are at the beginning of a most exciting adventure:

LHC, …

What drives the electroweak phase transition?

This has to be our primary goal.

❷ The *gNP* unlikely to shed light on the *ssNP* behind flavour puzzle of SM (though it could);

- ☞ instead studies of flavour transitions might elucidate salient features of the *gNP*
- ☞ New Physics around TeV scale could affect flavour transitions significantly

➥ Heavy flavour decays provide probe for New Physics that is complementary to the TEVATRON, LHC & Linear Collider

i.e., CP studies are instrumentalized

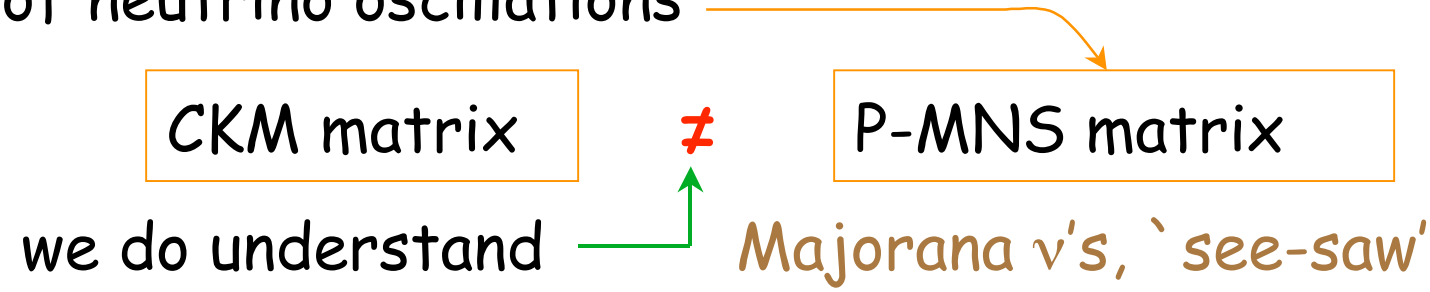
❸ "Know so much, yet understand so little!"

The SM's success in describing flavour transitions not matched by an understanding of the origin of flavour.

☞ heavy flavour studies

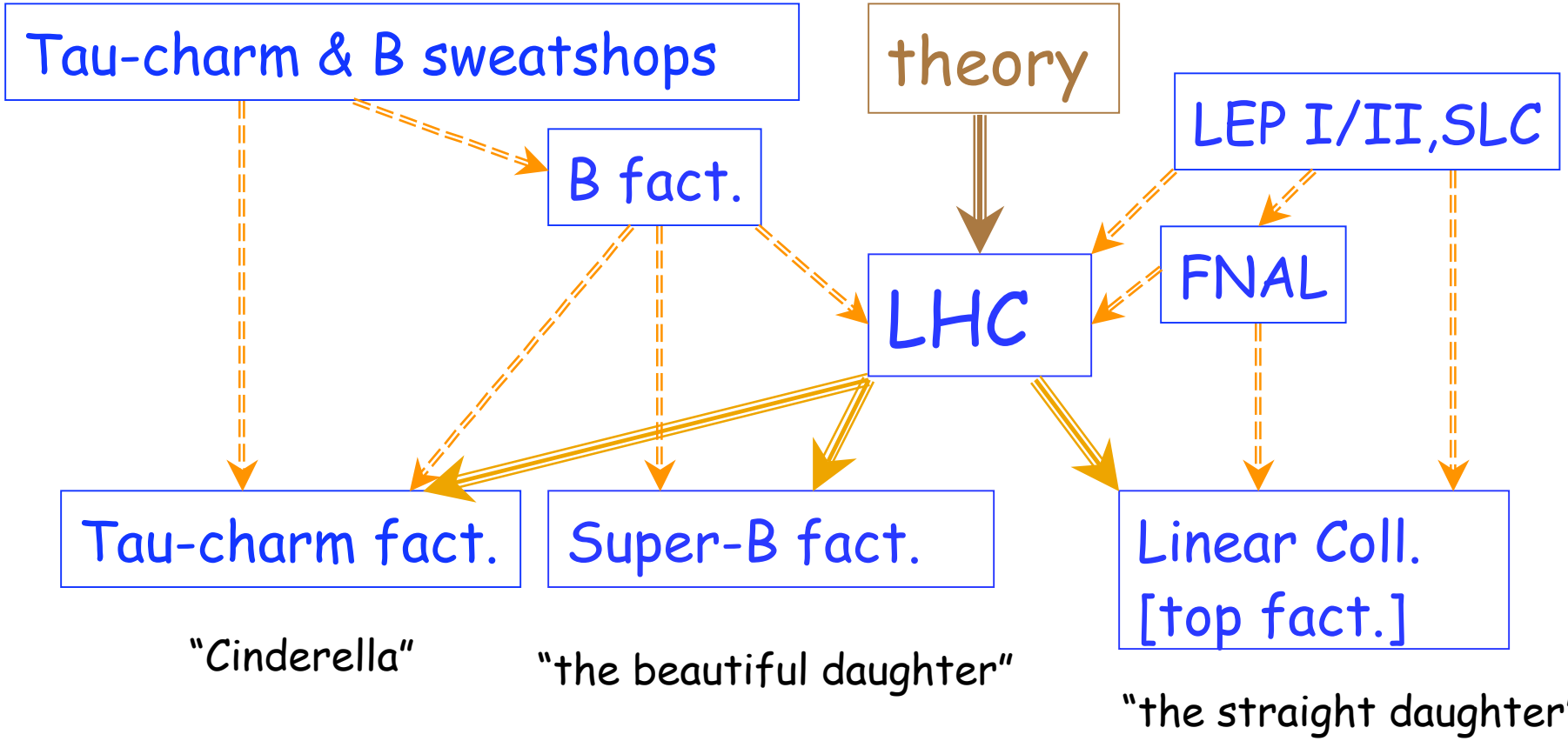
- are of fundamental importance;
- its lessons cannot be obtained any other way;
- cannot become obsolete.

❹ flavour dynamics even more intriguing due to emergence of neutrino oscillations



"exactly the same -- only different!" Austrian saying

[Malreaux & his love for 2 Germanies]



A dedicated Tau-Charm Factory is a crucial step …

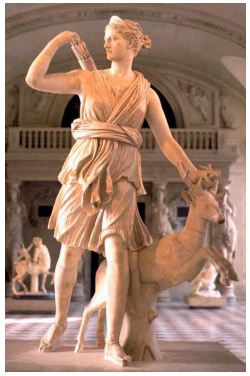
… leading ultimately to a Chinese Super-Beauty Factory using ILC technology

Cathedral Paradigm

Cathedral:

complex, multifaceted structure -- with a coherent theme that

- takes time to build and
- requires comprehensive effort



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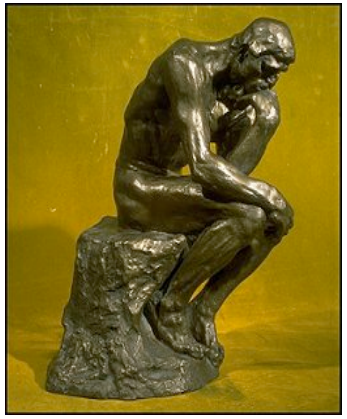

Hall of Central Harmony

"The Way of Heaven is profound & mysterious and the way of mankind is difficult. Only if we make a precise & unified plan and follow the doctrine of the mean, can we rule the country well."

Hall of Central Harmony

"The Way of ~~Heaven~~ Nature is profound & mysterious and the way of ~~mankind~~ research is difficult. Only if we make a precise & unified ~~plan~~ theory and follow the doctrine of ~~the mean~~ experiment, can we ~~rule~~ serve the country well."

beginning of an exciting adventure …

and we are most privileged to participate!