

"The CKM Paradigm -- from an Ansatz to a Tested Theory"

or

~~"CP~~ -- from `Cosmic' to Cosmological"

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Executive Summary:

- ❖ At the turn of the Millenium **2 sectors** of the SM needed **validation** -- the **description** of ~~CP~~ + the Higgs
- ❖ 2001 ff.: the **triumph** of an **a priori very peculiar** theory -- **CKM dynamics**
- ❖ a magnificent tale of the interplay
theory \Leftrightarrow **experiment** \Leftrightarrow **detector** \Leftrightarrow **machine**
- ❖ `dominance' \neq `monopoly'!
 - ☞ the cosmological failure
 - ➔ New Physics with ~~CP~~!
 - ☞ various `chinks in the armour'
- ❖ instrumentalize ~~CP~~ studies to identify New Physics
- ❖ flavour dynamics: "know a lot, yet understand little"
- ❖ *Ceterum Censeo Fabricam Super Saporis Esse Faciendam*

The Format: Periods & their Highlights

I Pre-History: On the Special Role of ~~CP~~

II The Heavy Flavour Sweatshops & CKM Dynamics

Interlude: "The Tale of the 2 Terraces"

III Status at the Turn of the Millenium

IV The Era of the B Factories &
CKM's Triumph (& Cosmological Failure)

V On to the Future --
LHCb and the Need for a Super Flavour Factory

I Pre-History: On the Special Role of ~~CP~~

discovery of ~~P~~ in '57 a great shock, yet theorists quickly recovered

$$\pi^- \rightarrow e_L^- \nu \quad \text{or} \quad \pi^+ \rightarrow e_R^+ \nu$$

"L" = f (" - ")

$$\text{CP: } (\pi^- \rightarrow e_L^- \nu) \iff (\pi^+ \rightarrow e_R^+ \nu)$$

If CP! \implies "L" pure convention!

"the thumb is left on the right hand!"

- ~~CP~~ required to define "matter" vs. "antimatter", "L" vs. "R",
" + " vs. " - " in convention independent way
- ~~CP~~ discovered in '64!

☞ '65: Sakharov conditions for baryogenesis

☞ $\Delta N_{\text{baryon}} \neq 0,$

☞ ~~CP~~

☞ out-of-thermal equilibrium

□ attempts at evasion:

✍️ abandon linear Super Position Principle of QM

$$K_L \rightarrow \pi\pi$$

✍️ repeat Pauli's ν hypothesis: postulate $Q=0$ light particle

`quod licet Jovi, non licet bovi!'

= Pauli

= non-Pauli

➔ both failed

□ smallest observed violation of a symmetry

$$\text{Im } M_{12} \approx 1.1 \times 10^{-8} \text{ eV} \Leftrightarrow \text{Im } M_{12}/m_K \approx 2.2 \times 10^{-17}$$

✍️ ~~P~~ maximal

vs. ~~CP~~

`peccate fortiter' = `sin boldly'
as a `near miss'

➔ ~~CP~~ as a `cosmic' phenomenon??

□ ~~CP~~ discovered in '64 -- yet no theory till '73
(except Mohapatra '72)

II The Heavy Flavour Sweatshops & CKM Dynamics

~~CP~~ discovered in '64 -- yet no theory till '73 (except Moha'72)

K&M had a `competitive edge'/ `insider knowledge' at Nagoya

👉 home of the Sakata School

➔ quarks accepted as physical objects -- in Nagoya

👉 home of Prof. Niu -- an expert in cosmic ray experiments with emulsions:

in '71 Niu reported a candidate for charm seen

➔ 2 complete families were `known' -- in Nagoya

$$U=(u,c,t), \quad D=(d,s,b)$$

Kobayashi & Maskawa extended Cabibbo's idea to distinguish between **mass** & **flavour ES** related by **unitary** transformation:

$$\mathcal{L}_{CC} \propto g_W U_L^{fl} \gamma_\mu D_L^{fl} W_\mu, \quad \mathcal{L}_M \propto U_L^{fl} \mathcal{M}_U U_R^{fl} + D_L^{fl} \mathcal{M}_D D_R^{fl}$$

$\mathcal{M}_{U,D}$ **nondiagonal** in general, diagonalized by **unitary** $T_{U,L/R}, T_{D,L/R}$

👉 $\mathcal{L}_{CC} \implies U_L^m \gamma_\mu V_{CKM} D_L^m W_\mu, \quad \boxed{V_{CKM} = T_{U,L} T_{D,L}^*}$ nontrivial in general

V_{CKM} unitary

➡ 3 weak universality relat.: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$ etc.

➡ 6 orthogonality relations: $V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$ etc.

🔗 **triangles** in the complex plane with **equal** areas

📖 2 families: **no relative** phase and thus **no CP**

"Bigger" Picture

$$\boxed{SU(3)_C \times [SU(2)_L \times U(1)] + \text{Yukawa dynamics}}$$

• Gauge dynamics

• (charged) weak currents with ~~CP~~

👉 remember: Yukawa & family structure

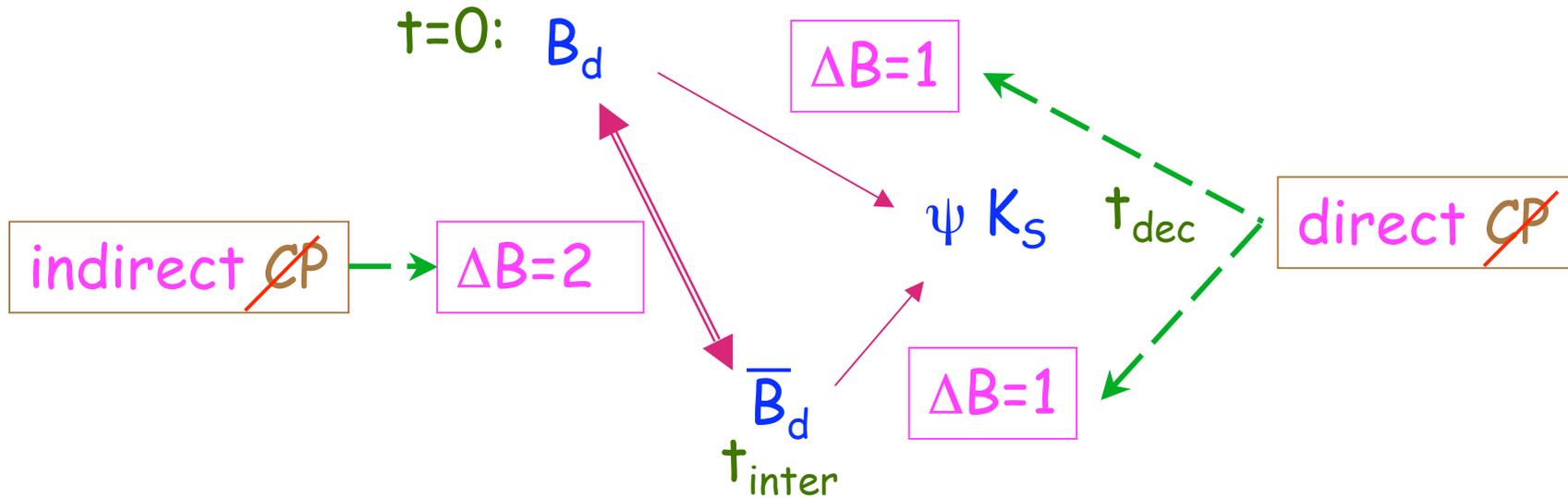
central mysteries of the SM!

Interlude: "The Tale of the 2 Terraces"

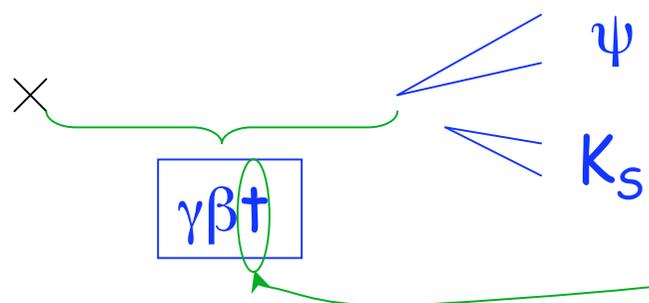
- In 1980 Tony Sanda & I met & talked for the 1st time on the terrace of the *CERN cafeteria* and he told me about his new idea on \cancel{CP} in B decays; it occurred to me quickly that the channel $B_d \rightarrow \psi K_S$ would be particularly suited. Why?
- In 1977 I had heard on the terrace of the *SLAC cafeteria* about the sizable lifetime difference between charm mesons, began working on it & realized that corresponding effects for B mesons could be studied cleanly with

$$B_d \rightarrow \psi K_S \quad \text{vs.} \quad B^- \rightarrow \psi K^-$$

Tony's idea applied to $B_d \rightarrow \psi K_S$:



☺ $\text{rate}(B_d [\bar{B}_d](t_{dec}) \rightarrow \psi K_S) \propto e^{-\Gamma t} (1 - [+] A \sin \Delta m_d t)$



End of Interlude

at that time -- 1980 --

- ❑ lifetime/width of B mesons not known
- ❑ oscillation rate Δm_d not known
- ❑ not a single B meson sighted
- ❑ ...

those were obtained at various sweatshops, chief among them PEP, DORIS, Cornell showing two major surprises:

- ① 1982ff (MAC,...) $\tau(B) \sim 1$ psec $|V(cb)| \sim O(\lambda^2)$
 - ❑ $|V(ub)|/|V(cb)| \sim O(\lambda)$ -- i.e. 'beauty prefers charm'

➔ Wolfenstein representation

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

② '87 (ARGUS) discovery of B^0 oscillations:

$$x(B_d) = \Delta M(B_d) / \Gamma_B = 0.75$$

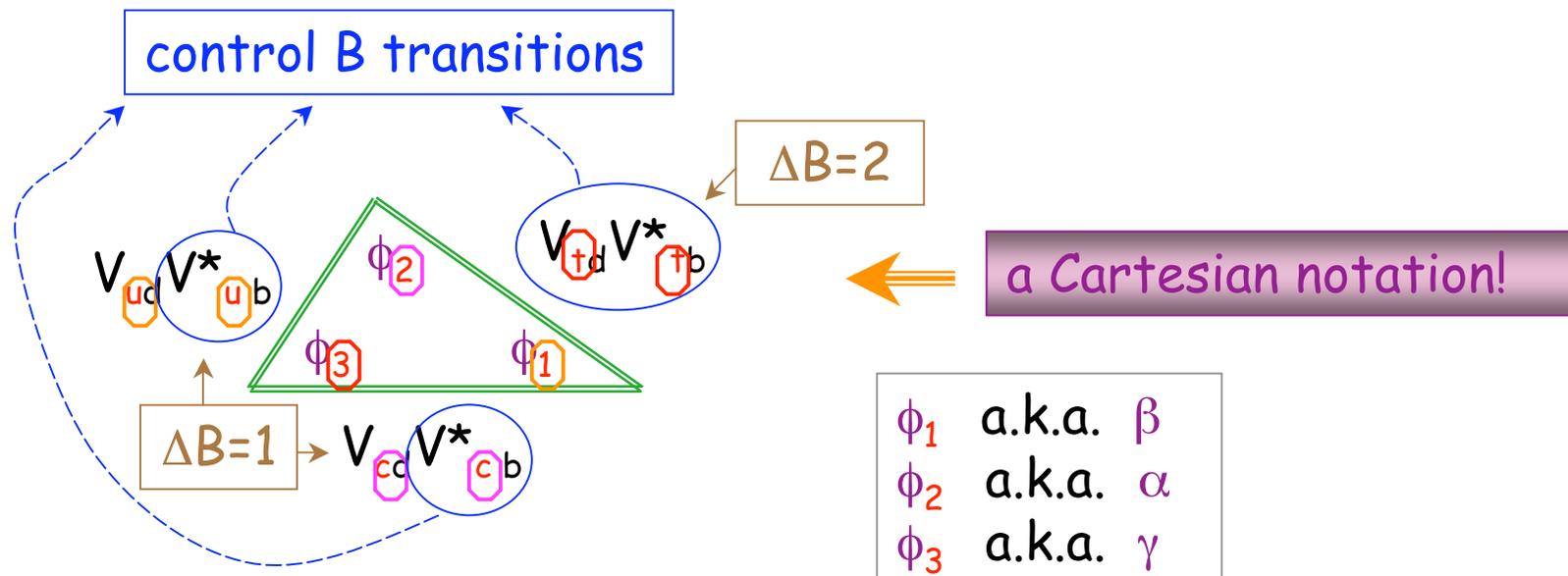
→ indirect bound $m_t > 100 \text{ GeV}$

[similar, though less precise than later LEP I findings]

↔ optimal, since

oscillation rate $\Delta M(B_d) \sim$ decay rate Γ_B

→ one triangle with naturally large angles \Rightarrow large CP !



III Status at the Turn of the Millenium

- ☞ The SM has to produce a host of large CP in B decays -- there is **no** plausible deniability
- ☞ It is not a blind search -- we can predict where effects are expected
- ☞ We can predict correlations among classes of channels
- ☞ In several cases we can make an absolute prediction

$Asym(B_d \rightarrow \psi K_S) = \sin 2\phi_1$ with **no hadronic uncertainty**

$$\sin 2\phi_1 = \begin{cases} \text{up to unity} & \text{our paper (1980)} \\ 0.6 - 0.7 & \text{from } \varepsilon_K/\Delta M_B [=f(m_t)] \text{ (1993,} \\ & \text{i.e. before discovery of top)} \\ 0.72 \pm 0.07 & \text{from CKM fits in 1998} \end{cases}$$

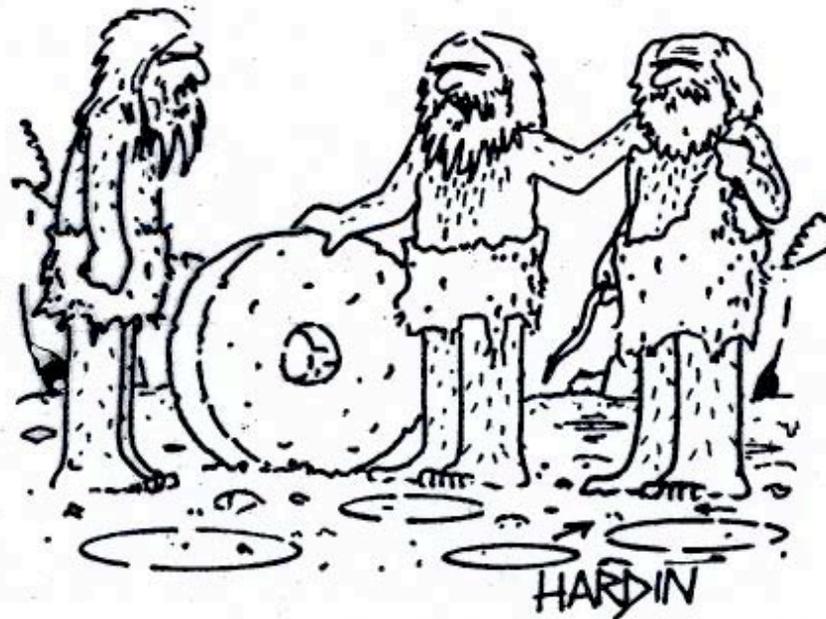
2×10^{-3} in $K^0-\bar{K}^0$ system $\implies \sim 700(!) \times 10^{-3}$ in $B^0-\bar{B}^0$ system

IV The Era of the B Factories & CKM's Triumph (& Cosmological Failure)

The work of the B factories has been marked by a close collaboration between experimentalists and theorists

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"To be honest, I never would have invented the wheel if not for Urg's groundbreaking theoretical work with the circle."

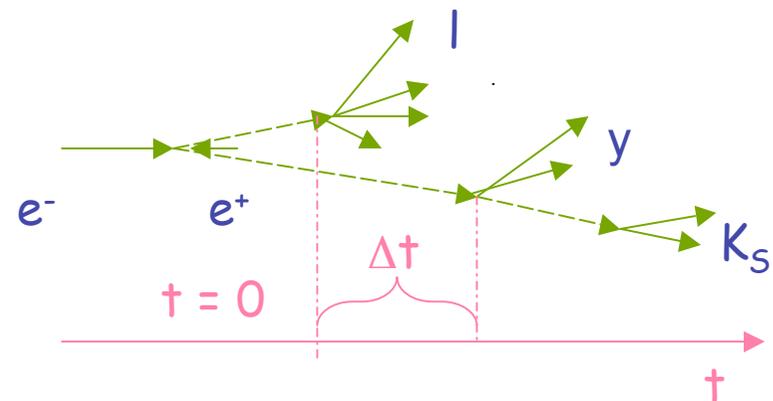
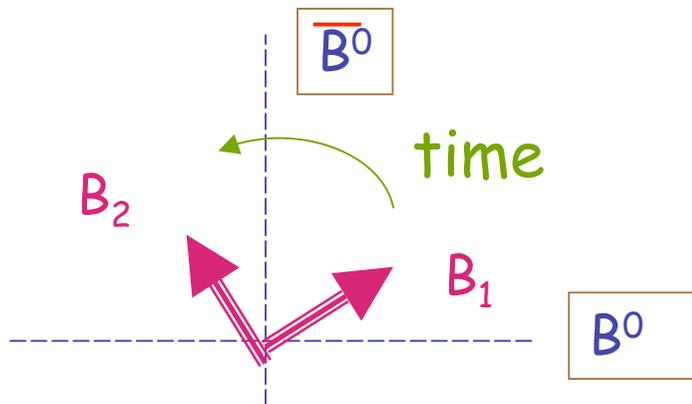
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One example for theory \rightarrow experiment connection

☹ $e^+e^- \rightarrow B_d \bar{B}_d$: $c\tau \sim 0.45$ mm vs. product. region ~ 1 mm
asymmetry washed out?

☺ EPR to the rescue!

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



\rightarrow need to measure only Δt time interval between decays

$$\text{rate}(e^+e^- \rightarrow B_d \bar{B}_d \rightarrow [l^\pm X]_t [y K_S]_{t+\Delta t}) \sim \dots (1 \pm A \sin \Delta m_d \Delta t)$$

☹ symmetric $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$:

cannot resolve B decay vertices & $\int d\Delta t \dots \sin \Delta m_d \Delta t = 0!$

☺ P. Oddone: asymmetric e^+e^- collider to give boost to $B\bar{B}$!

On the dialectic in the name `BaBar`



BABAR

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Collaboration Home Page

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- BaBar (a.k.a. Babur = `Tiger`)

Founder of Mughal Empire in India

descendant of both Tamerlane & Genghis Khan



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- `a man of action rather than of the pen`

On the dialectic in the name `BaBar`



- BaBar (a.k.a. Babur = `Tiger`)



Founder of Mughal Empire in India

descendant of both Tamerlane & Genghis Khan

- `a man of action rather than of the pen`

- **defeated** with a small army & **no** elephants, but with cannons a much larger army with **many** elephants, but no cannons:

thus terminated > 2500 years of using elephants as war machines in battle

$$\sin 2\phi_1(B \rightarrow \psi K_S) = 0.668 \pm 0.026$$

$$\sin 2\phi_1(B \rightarrow \eta' K_S) = 0.61 \pm 0.07$$

$$\sin 2\phi_1(B \rightarrow f_0 K_S) = 0.85 \pm 0.07 \quad (\text{driven by BaBar})$$

$$\sin 2\phi_1(B \rightarrow K^+ K^- K_S \neq \phi K_S) = 0.73 \pm 0.10$$

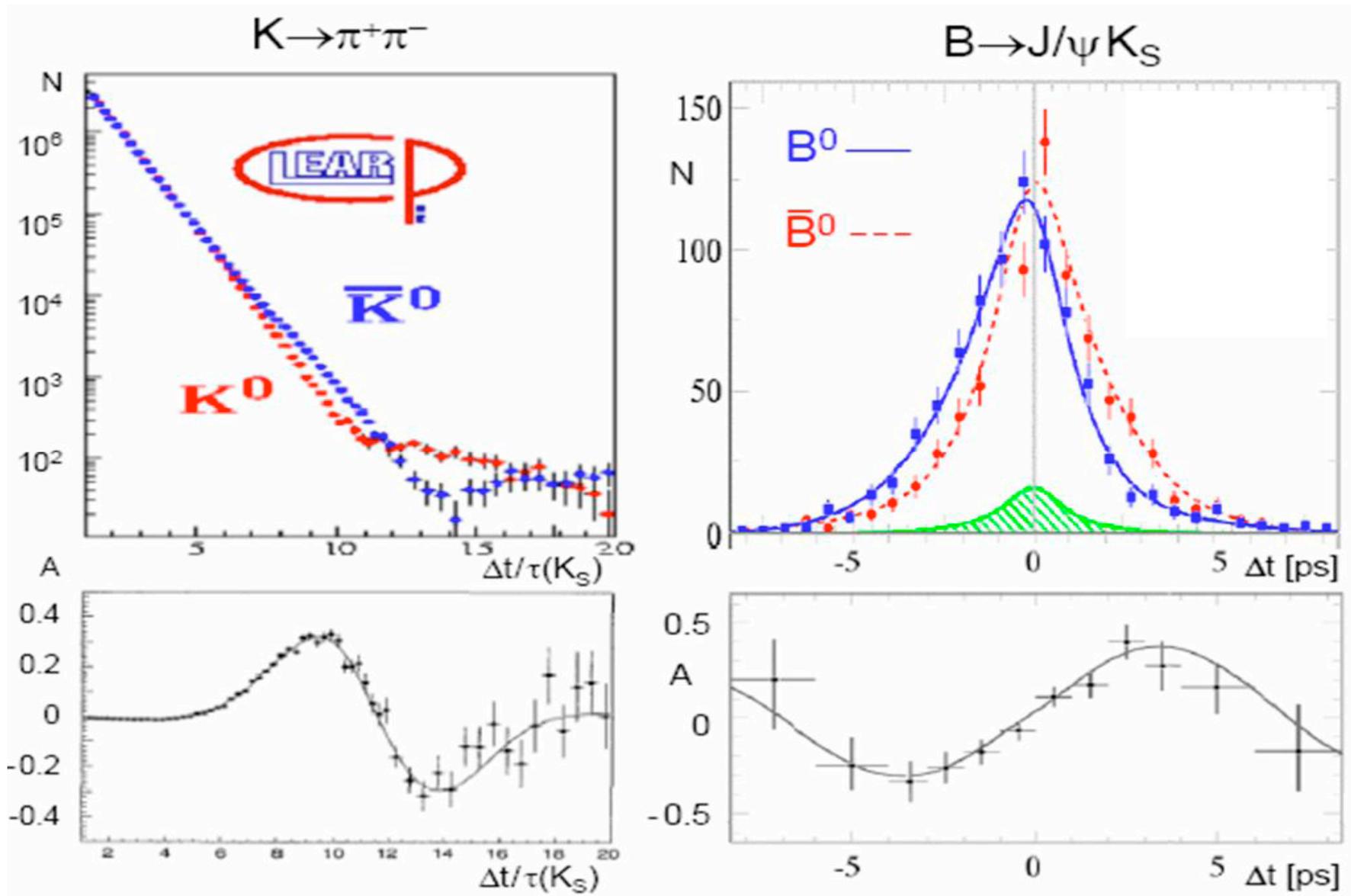
$$S_{CP}(B \rightarrow \pi\pi) = -0.61 \pm 0.08, \quad C_{CP}(B \rightarrow \pi\pi) = -0.38 \pm 0.07$$

$$A_{CP}(B \rightarrow K^+ \pi^-) = -0.097 \pm 0.012$$

the Paradigm of large \cancel{CP} in B decays established in qualitative & quantitative agreement with CKM theory in several distinct B_d channels with

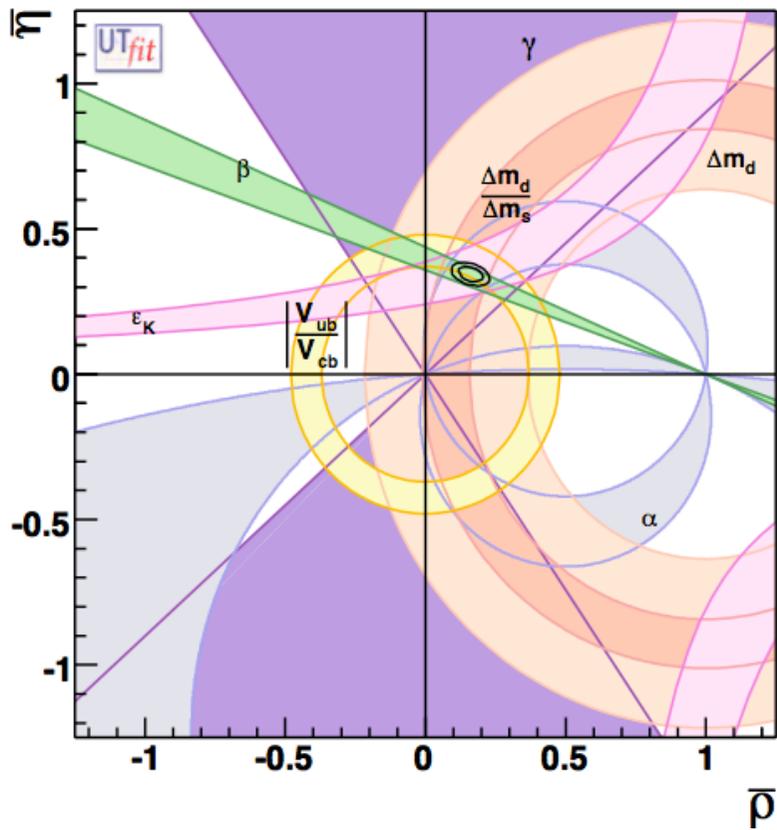
- large direct \cancel{CP} in 2 channels and
- commensurate with \cancel{T}

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



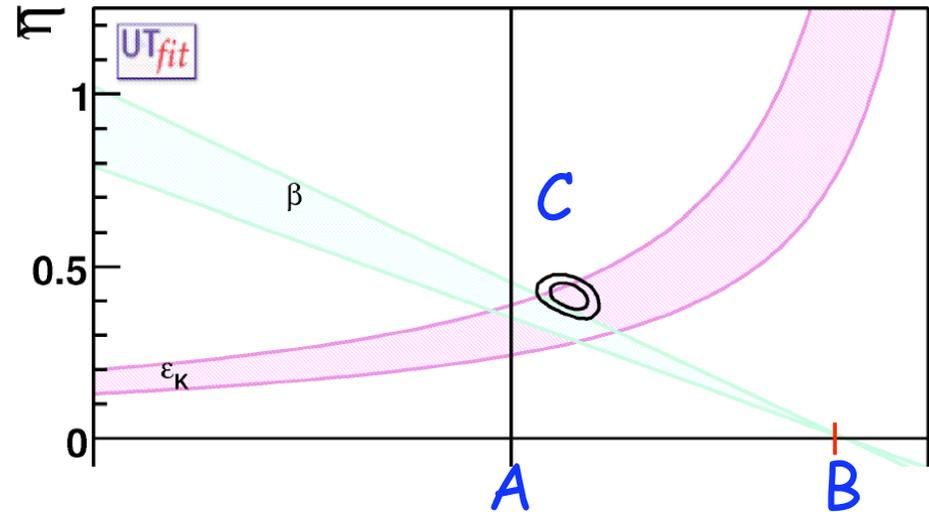
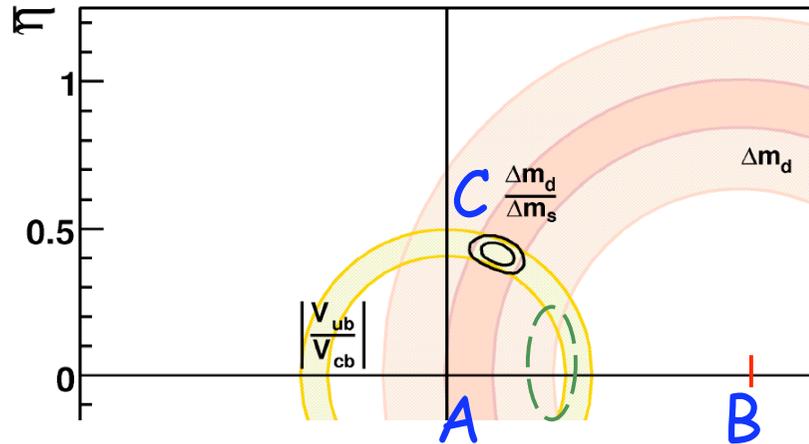
[courtesy of K. Schubert]

→ statement '~~CP~~ in B decays is much larger than in K decays' is an empirically verified fact



Over-abundance of information can obscure its content!

Impact of measurement of $B_s - \bar{B}_s$ oscillations



Another triumph for CKM theory:

CP insensitive observables ($|V_{ub}|, \Delta M_s$) imply ~~CP~~
 qualitatively as well as quantitatively!

- The struggle for supremacy has been decided:
The CKM paradigm has become a *tested* theory!
👉 goal no longer to find alternatives to CKM
- `supremacy' \neq `monopoly'
👉 goal to identify corrections to CKM!
- `demystification of \cancel{CP} ':
if dynamics can support \cancel{CP} , it can be large!
i.e., observable phases can be large!
- ➡ `demystification' completed
if find \cancel{CP} anywhere in lepton sector

This is the triumph -- now to the shortcomings

On CKM's 'Cosmological Failure'

☹ $\Delta N_{\text{baryon}} \neq 0$

☹ ~~CP~~:

☹ out-of-thermal equilibrium

never seen yet

→ ~~CKM CP~~ too weak

2nd order phase transition

$$\det C = -2J(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_u^2 - m_t^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2)(m_d^2 - m_b^2)$$

need $\det C \neq 0$ for ~~CP~~

Another candidate for 'figure of merit':

$$J \log(m_t/m_c)^2 \log(m_t/m_u)^2 \log(m_c/m_u)^2 \log(m_b/m_s)^2 \log(m_b/m_d)^2 \log(m_s/m_d)^2$$

☹ standard CKM irrelevant for baryon number of universe

☺ New Physics with ~~CP~~ exists!

☺ New CP Paradigm: ~~CP~~ phases can be large

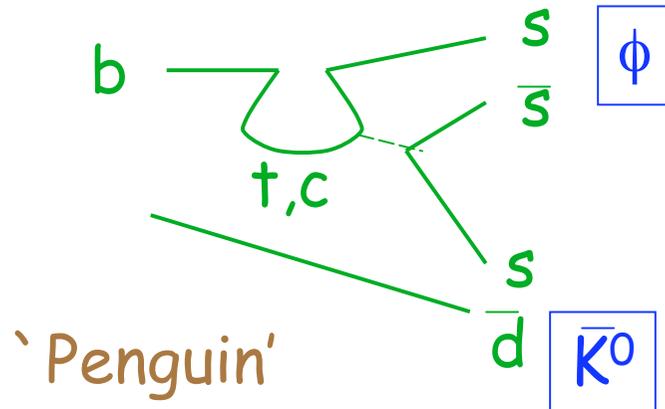
□ non-minimal Higgs sector

□ baryogenesis merely 'shadow' of primary leptogenesis

□ intervention of 4th super-heavy family ?

Other 'chinks' in the armour

□



Summer 2007

$\sin 2\phi_1 = 0.668 \pm 0.026$ from $B_d \rightarrow \psi K_S$

□ BELLE: $\sin 2\phi_1^{\text{eff}} = 0.50 \pm 0.21 \pm 0.06$

□ BaBar: $\sin 2\phi_1^{\text{eff}} = 0.21 \pm 0.26 \pm 0.11$

→ average: $\sin 2\phi_1^{\text{eff}} = 0.39 \pm 0.17$

□ LQCD claims: SM can generate only ~ 80 % of $|\epsilon_K|$!?

V On to the Future --

LHCb and the Need for a Super Flavour Factory

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

📖 case for 'nearby' New Physics as strong as ever!

📖 Like in a modern novel B factories are pointing at next great tale in the decoding of nature:

😊 **strong experimental** evidence for **D^0 oscillations**, albeit with only **$\sim 1/100$ relative** as for B_d oscillations

😞 could be due purely to **SM dynamics** -- or **reveal NP**

😊 dedicated searches for ~~CP~~ can decide --
very tiny SM 'background'

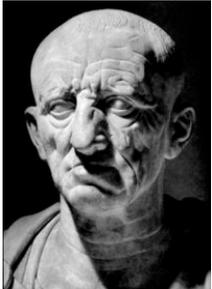
😊 might reveal ~~CP~~ connected with baryogenesis

- ① Studies of CP, oscillations & rare decays instrumentalized to probe & analyze TeV scale New Physics
 - LHCb approved as `first hour' experim. (a credit to the Europ. HEP community recognizing heavy flavour physics as part of the core mission of the LHC)
 - LHCb will make seminal contributions in
 - in B decays -- most notably CP in $B_s(t) \rightarrow \psi\phi/\eta, \phi\phi$
 - & probably in D decays

but it will **not** complete the agenda!
- ② The next great challenge in flavour physics:
find ~~CP~~ in leptodynamics
- ③ The cosmological connection:
We are **still in the dark** about **baryogenesis!**
(and about **family structure** etc. etc.)

LHCb will **not** complete the agenda!

➔ "Ceterum Censeo Fabricam Super Saporis Esse Faciendam"
"Moreover I Advise a Super-Flavour Factory has to be Built"



Super-Flavour Factory:

$$e^+e^- \rightarrow B \bar{B}, D \bar{D} + X, \tau^+\tau^- \text{ at } \sim Y(4S) [\& \sim 4 \text{ GeV}]$$

with $L \sim 10^{36} \text{ cm}^{-1} \text{ s}^{-1}$

Catholic teaching: If it can be stated in Latin, it must be true.

If we lived in a rational world, a Super-Flavour Factory would be built at SLAC, it would work and deliver the goods.

SUMMARY

- ☺ the `harvest' from the B factories is still coming in and/or being processed
- B factories established that
 - ✍ SM describes flavour dynamics with high accuracy even on the quantum level, including ~~CP~~
 - ✍ 1 TeV scale NP is not `generic'
 - ✍ ~~CP~~ phases can be large
- still in the dark on ~~CP~~ driving baryogenesis
- CP studies instrumentalized to identify the 1 TeV scale NP
- CKM dynamics connects ~~CP~~ with central mysteries of the SM: fermion mass generation and family structure
- ➔ "We know so much, yet understand so little!"

Models with extra dimensions have ad-hoc features yet are sufficiently radical to push our thinking out of the comfort zone of a possible dead end into new fruitful directions -- i.e. are a most helpful `imagination stretcher'!

Wind on the Hill

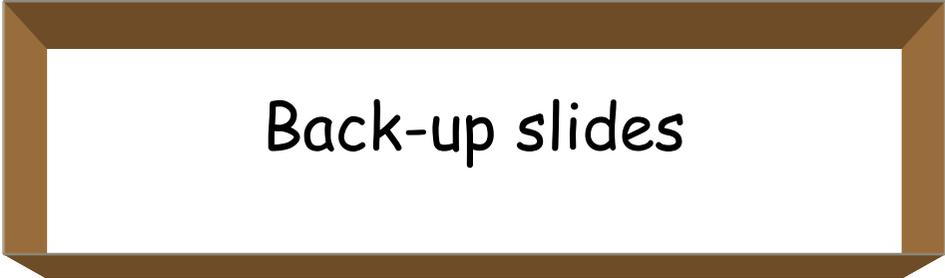
No one can tell me
Nobody knows
Where the wind comes from,
Where the wind goes.

But if I stopped holding
The string of my kite,
It would blow with the wind
For a day and a night.

And then when I found it,
Wherever it blew,
I should know that the wind
Had been going there, too.

So then I could tell them
Where the wind goes ...
But where the wind comes from
Nobody knows.

A.A. Milne
[Winnie-the-Pooh 1926]
(with thanks to T.D. Lee)



Back-up slides

Singing the Praise of Hadronization

hadronization (& nonperturbative dynamics in general)
usually viewed as unwelcome complication:

interpretation of observed $\Delta m_K, \epsilon_K, \Delta m_B, \epsilon_K'$
contains sizeable uncertainties

correct -- yet misses the deeper truth

without hadronization no formation of bound states

→ no $K^0-\bar{K}^0$ oscillations, no $B^0-\bar{B}^0$ oscillations

↔ coupled oscillators = precision instruments

hadronization

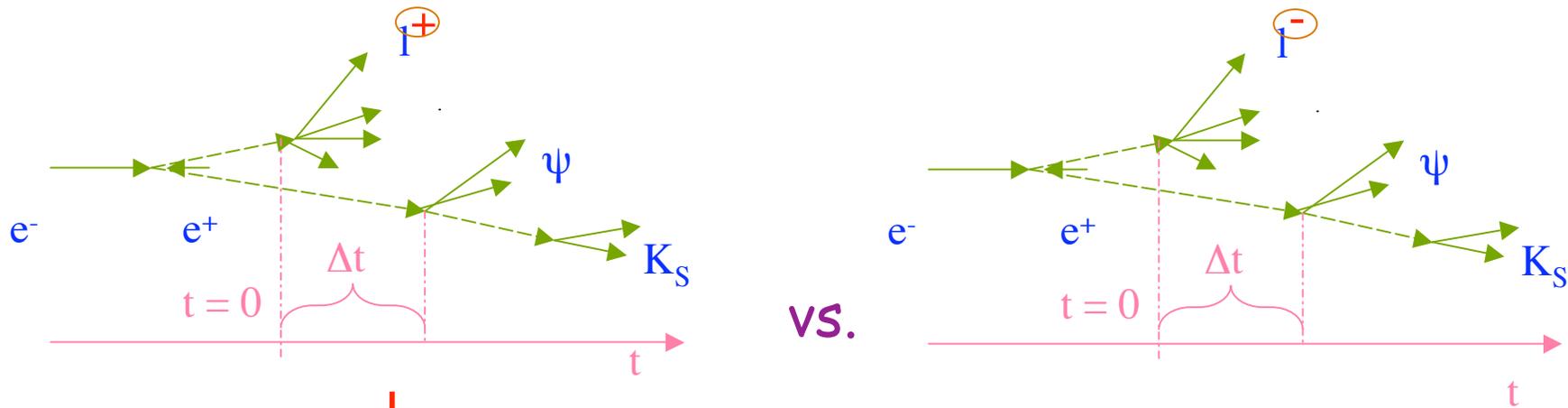
↪ reduces CP! $K_L \rightarrow 3\pi$ by ~ 500 due to hadronic PhSp

↪ awards 'patience'; i.e. you can 'wait' for pure K_L beam

↪ generates ~~CP~~ signal in existence rather than asymmetry

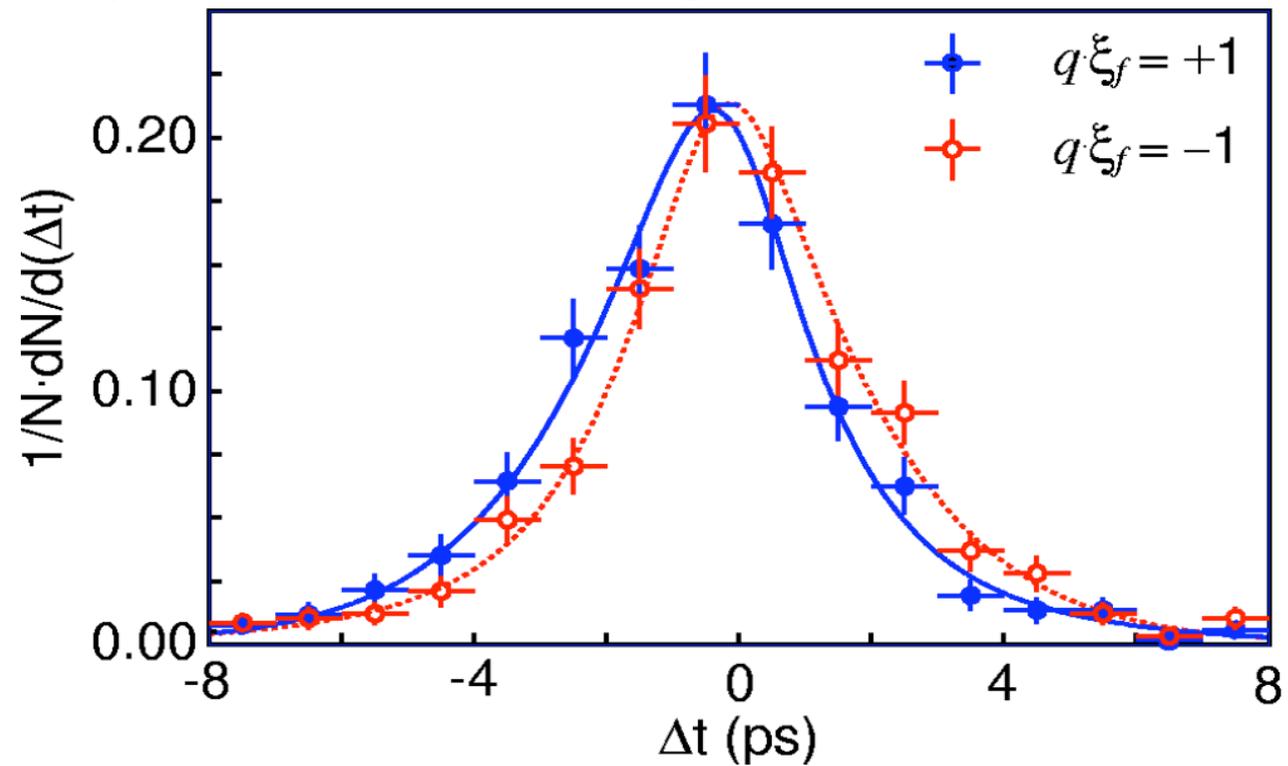
↔ hadronization -- the hero rather than the villain in
the tale of ~~CP~~!

EPR correlations as a routine precision tool

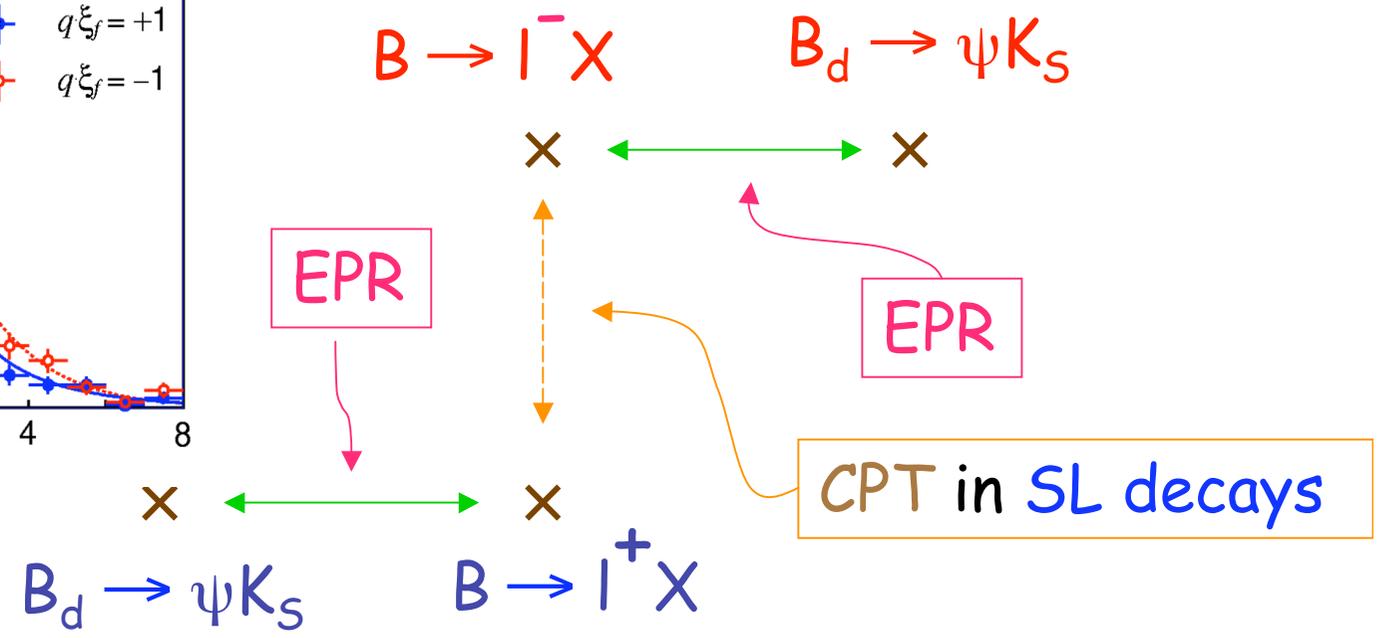
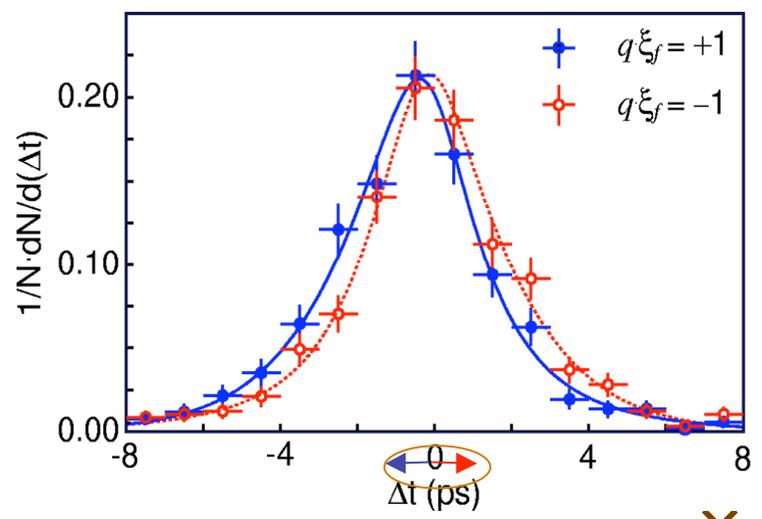


if $e^+e^- \rightarrow l^+ X + \psi K_S \neq e^+e^- \rightarrow l^- X + \psi K_S$

→ ~~CP~~ !



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



- $\Delta t > 0, \Delta t < 0 \implies \cancel{T}$
- $\Delta t \longleftrightarrow -\Delta t \implies \cancel{CP} \cong \cancel{T}$

$\implies \cancel{CP} \cong \cancel{T}$ in $B \rightarrow \psi K_S$

assuming CPT merely in SL B decays

A message from Nature -- encoded or 'cosmic'?

$$|V_{CKM}| \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

👉 the CKM matrix -- with this apparently highly non-accidental pattern -- describes successfully very diverse processes on vastly different scales (see later)

👉 Schlaeft ein Lied in allen Dingen,
Die da traäumen 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

On the signature of ~~CP~~

• time reversal T (or 'reversal of motion')

$$\mathbf{x} \rightarrow \mathbf{x}, t \rightarrow -t \qquad \mathbf{p} \rightarrow -\mathbf{p}, l \rightarrow -l$$

transformation operator T anti-linear & unitary

✎ anti-linear: $T(\alpha|a\rangle + \beta|b\rangle) = \alpha^*T|a\rangle + \beta^*T|b\rangle$

✎ why? Invariance of CCR: $[X,P] = i1$

$$- [X,P] = T[X,P]T^* = T i1 T^* = -i1$$

✎ ~~CP~~ = ~~T~~ \implies ~~CP~~ \iff complex phase