“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, two sectors of the Standard Model (SM) needed validation -- the description of CP and the Higgs
- From 2001 onwards: the triumph of an a priori very peculiar theory -- CKM dynamics
- A magnificent tale of the interplay between theory ⇔ experiment ⇔ detector ⇔ machine
- 'dominance' ≠ '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
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 Millennium

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
discovery of $\pi$ 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 ("-"")

$\text{CP}: (\pi^- \rightarrow e^-_L \nu) \leftrightarrow (\pi^+ \rightarrow e^+_R \nu)$

If CP! $\rightarrow "L"$ 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!'
    \[ = \text{Pauli} \quad = \text{non-Pauli} \]
    ➡ both failed

- smallest observed violation of a symmetry
  \[ \text{Im } M_{12} \approx 1.1 \times 10^{-8} \text{ eV} \iff \text{Im } M_{12}/m_K \approx 2.2 \times 10^{-17} \]
  - P maximal `peccate fortiter' = `sin boldly'
  - CP as a `near miss' vs. CP as a `cosmic' phenomenon??

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

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

$M_{U,D}$ non-diagonal in general, diagonalized by unitary $T_{U,L/R}, T_{D,L/R}$

$$\mathcal{L}_{CC} \rightarrow U_L^{m} \gamma_\mu V_{CKM} D_L^{m} W_\mu, \quad V_{CKM} = T_{U,L} T_{D,L}^*$$

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
\begin{itemize}
  \item \textbf{Gauge dynamics}
  \item (charged) weak currents with CP
  \item \textcolor{orange}{\textbf{remember: Yukawa \& family structure}}
\end{itemize}

\textit{central mysteries of the SM!}
Interlude: “The Tale of the 2 Terraces”

- In 1980 Tony Sanda & I met & talked for the first time on the terrace of the CERN cafeteria and he told me about his new idea on 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 $B_d \rightarrow \psi K_S$:

$t=0$: $B_d$  \hspace{2cm}  $\Delta B=1$

$\Delta B=2$

$\bar{B}_d$  \hspace{2cm}  $\Delta B=1$

$t_{\text{inter}}$  \hspace{2cm}  $t_{\text{dec}}$

$\psi K_S$

indirect $CP$  \hspace{2cm}  direct $CP$

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

End of Interlude
at that time -- 1980 --

- lifetime/width of B mesons not known
- oscillation rate $\Delta m_d$ 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 \quad $|V(cb)| \sim O(\lambda^2)$
   - $|V(ub)|/|V(cb)| \sim O(\lambda)$ -- i.e. `beauty prefers charm'

$\Rightarrow$ Wolfenbstein representation

$V_{_{\text{CKM}}} = \begin{pmatrix}
1-\lambda^2 & \lambda & \lambda(\rho-i\eta+\eta\lambda^2/2) \\
-\lambda & 1-\lambda^2/2-i\eta A^2\lambda^4 & \lambda^2(1+\eta\lambda^2) \\
\lambda(1-\rho-i\eta) & -\lambda^2 & 1
\end{pmatrix}$
"87 (ARGUS) discovery of $B^0$ oscillations:

$$\chi(B_d) = \frac{\Delta M(B_d)}{\Gamma_B} = 0.75$$

- indirect bound $m_t > 100 \text{ GeV}$
  [similar, though less precise than later LEP I findings]

- optimal, since

oscillation rate $\Delta M(B_d) \sim \text{decay rate } \Gamma_B$

- one triangle with naturally large angles $\rightarrow$ large $CP$!
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.

\[ \text{Asym}(B_d \to \psi K_S) = \sin 2\phi_1 \] with no hadronic uncertainty.

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

\[ 2 \times 10^{-3} \text{ in } K^0-\bar{K}^0 \text{ system} \quad \rightarrow \quad \sim 700(!) \times 10^{-3} \text{ in } B^0-\bar{B}^0 \text{ system} \]
The work of the B factories has been marked by a close collaboration between experimentalists and theorists.
IV The Era of the B Factories & CKM’s Triumph (& Cosmological Failure)

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One example for theory $\rightarrow$ experiment connection

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

$\odot$ EPR to the rescue!

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

$\rightarrow$ need to measure only $\Delta \tau$ time interval between decays

rate($e^+e^- \rightarrow B_d\bar{B}_d \rightarrow [l^\pm X]^\uparrow[y K_S]^\uparrow^\tau\Delta \tau)$ $\sim \cdots (1 \pm A\sin\Delta m_d \Delta \tau)$

$\ominus$ symmetric $e^+e^- \rightarrow \Upsilon(4S) \rightarrow BB$:

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

$\odot$ P. Oddone: asymmetric $e^+e^-$ collider to give boost to $B\bar{B}$!
On the dialectic in the name `BaBar'
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- `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
the Paradigm of large CP in B decays established in qualitative & quantitative agreement with CKM theory in several distinct $B_d$ channels with

- large direct CP in 2 channels and
- commensurate with $T$

it is there, it is huge -- as expected!
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!
Another triumph for CKM theory:

\[ |V_{ub}|, \Delta M_s \] 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` ≠ `monopoly`

- goal to identify corrections to CKM!

`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

This is the triumph -- now to the shortcomings
On CKM’s `Cosmological Failure’

😊 $\Delta N_{\text{baryon}} \neq 0$

😊 $\text{CP}$:

😊 out-of-thermal equilibrium $\rightarrow$ 2nd order phase transition

Another candidate for `figure of merit’:

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

need $\det C \neq 0$ for CP

Another candidate for `figure of merit’:

$$J \log(\frac{m_t}{m_c})^2 \log(\frac{m_t}{m_u})^2 \log(\frac{m_c}{m_u})^2 \log(\frac{m_b}{m_s})^2 \log(\frac{m_b}{m_d})^2 \log(\frac{m_s}{m_d})^2$$

😊 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

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

- 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: $\sin 2\phi_1^{\text{eff}} = 0.39 \pm 0.17$
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
Studies of CP, oscillations & rare decays instrumentalyzed 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!

The next great challenge in flavour physics:

find CP in leptodynamics

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 Faciendum”
“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 $\Delta m_K, \varepsilon_K, \Delta m_B, \varepsilon_K'$ contains sizeable uncertainties

correct -- yet misses the deeper truth

without hadronization no formation of bound states

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

$\Rightarrow$ coupled oscillators = precision instruments

hadronization

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

$\Rightarrow$ awards `patience’; i.e. you can `wait’ for pure $K_L$ beam

$\Rightarrow$ generates CP signal in existence rather than asymmetry

$\Rightarrow$ hadronization -- the hero rather than the villain in the tale of CP!
EPR correlations as a routine precision tool

\[ e^- e^+ \rightarrow l^+ X + \psi K_S \neq e^+ e^- \rightarrow l^- X + \psi K_S \]

\[ \text{if } q_{\xi_f} = +1 \]

\[ q_{\xi_f} = -1 \]
There is even more to it: $\mathcal{CP} \cong \mathcal{T}$ in B decays

$B \rightarrow l^- X$  \hspace{1cm} $B_d \rightarrow \psi K_S$

$B_d \rightarrow \psi K_S$  \hspace{1cm} $B \rightarrow l^+ X$

Assuming CPT merely in SL B decays
A message from Nature -- encoded or `cosmic'?

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

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 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
time reversal $T$ (or ‘reversal of motion’)

$x \rightarrow x, \ t \rightarrow -t \quad \quad \quad \ p \rightarrow -p, \ l \rightarrow -l$

transformation operator $T$ anti-linear & unitary

\[
\text{anti-linear: } T(\alpha|a\rangle + \beta|b\rangle) = \alpha^*T|a\rangle + \beta^*T|b\rangle
\]

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

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

$\text{CP} = T \rightarrow \text{CP} \leftrightarrow \text{complex phase}$