Flavour Dynamics & CP in the SM*: A Tale of Great Successes, Little Understanding -- and Promise for the Future!

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Lecture VI (6)

Searching for a New Paradigm 2005 & Beyond
Following Samuel Beckett’s Dictum
Recap from Lectures I -- IV

**CKM** has scored **novel** successes in the last few years that have to be viewed as **amazing** due to its very **peculiar** structure.

`We know a lot -- yet understand so little!``

i.e., these successes do **not** invalidate the general arguments in favour of the **SM** being **incomplete**.

But -- based on these successes -- we cannot **count** on **massive manifestations** of New Physics in **flavour dynamics**.

- must combine **high accuracy** with high **sensitivity** in studies of **flavour dynamics**.
- goal can be achieved combining **robust theory** with **detailed & comprehensive data**.

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 \( \nu \) 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 $\nu$ `anomalies'

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

$\nu_\mu$ 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
Menu for Lecture V

I $\Delta S \neq 0$ -- the `Established Hero'

II The `King Kong Scenario' for New Physics Searches

III $\tau$ Decays -- the Next Hero Candidate

IV Future HEP landscape - a Call to Arms well-reasoned Action
\[ \Delta S \neq 0 \] -- the `Established Hero'

Memento \( \Delta S \neq 0 \) dynamics:

- \( \tau - \theta \) puzzle \( \Rightarrow \) R!
- production >> decay \( \Rightarrow \) families!
  rate rate
- no \( \Delta F_l \neq 0 \) NC \( \Rightarrow \) charm!
- \( K_L \rightarrow \pi \pi \) \( \Rightarrow \) CR, top!

\[ \text{All New Physics at that time} \]

-- yet now pillars of the SM!
the `dark horse'

\[ \text{Pol}_\perp(\mu) \text{ in } K_{\mu3} \text{ decays} \]

\[ K \rightarrow \mu^+ \nu \pi \]

\[ \text{Pol}_\perp(\mu) = \frac{s_\mu \cdot (p_\mu \times p_\pi)}{|p_\mu \times p_\pi|} \quad \text{-- T odd moment} \]

\[ K^+ \rightarrow \mu^+ \nu \pi^0 \]

\[ \text{Pol}_\perp(\mu) = (-1.7 \pm 2.3 \pm 1.1) \times 10^{-3} \quad \text{vs.} \quad \text{Pol}_\perp^{\text{SM}(\mu)} < 10^{-6} \]

a clean search for \( CP \) via Higgs dyn. (need enhanced coupling to leptons to make it viable)

various radiative \( K \) decays -- \( K \rightarrow \pi \gamma \gamma, \pi \pi \gamma \) -- to probe \( \chi_{\text{pert. th.}} \) & possibly get better treatment of long distance contrib. to \( \Delta I=1/2 \) rule, \( \Delta m_K \) & \( \varepsilon' \)
`heresy'

\[ K^+ \rightarrow \pi^+\pi^0 \text{ vs. } K^- \rightarrow \pi^-\pi^0 \quad \text{CPT test on } 10^{-3} \text{ level?} \]

the `Second Trojan War' (described in the Iliad):

- \[ K^+ \rightarrow \pi^+\nu
\]
  theoret. uncertainty \([m_c]\) \sim 7\% (I think can be cut to 4 - 5\%)

- \[ K_L \rightarrow \pi^0\nu \nu = \text{CP}! \]
  theoret. uncertainty \sim 2\%

`standard candles' of SM

should aim for \sim O(1000) events
The `King Kong Scenario' 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!
II.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

energy shift $\Delta \mathcal{E}$ of system inside electric field $\mathbf{E}$:
$$\Delta \mathcal{E} = d_i E_i + d_{ij} E_i E_j + \ldots$$

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

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

d_e = (0.07 \pm 0.07) \times 10^{-26}$ ecm \quad vs. \quad $d_e^{\text{CKM}} < 10^{-32}$ ecm
from atomic EDM

\(\heartsuit\) New Physics scenarios can yield $\sim 10^{-26} - 10^{-28}$ ecm
II.2 Charm Decays

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

Common feeling: charm physics -- great past, no future!

- drove paradigm shift: quarks as *real* entities
  essential support for acceptance of QCD

- electroweak SM phenomenology for $\Delta C \neq 0$ `dull'
  - CKM parameters `known'
  - $D^0 - D^0$ oscillations very slow
  - $CP$ very small
  - loop driven decays extremely rare

`I have come to praise C. -- not to bury it!'
charm dynamics full of challenges -- & promises
triple motivation for further dedicated studies

1. **QCD (\& `beyond`):** understanding nonperturb. dynamics & establishing theoretical control over it
2. **B dynamics:** calibrating theoret. tools for B studies
3. **New Physics:** charm transitions a novel window onto New Physics

1 \& 2 will not be addressed here
New Physics

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

- top quarks do not hadronize
- up quarks: no $\pi^0-\pi^0$ 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)!
D⁰-\overline{D}⁰ oscillations

- case for New Physics based on \( x_D \) uncertain

D⁰-\overline{D}⁰ oscillations `slow' in the SM

How `slow' is `slow'? \( x_D, \quad y_D \sim \text{SU}(3)_F \cdot 2 \sin^2 \theta_C < \text{few} \cdot 0.01 \)

\[
\begin{align*}
x_D &= \frac{\Delta m_D}{\Gamma_D} \\
y_D &= \frac{\Delta \Gamma_D}{2 \Gamma_D}
\end{align*}
\]

- on-shell transitions
- off-shell transitions

\( \Rightarrow \) conservative bound: \( x_D, y_D \sim O(0.01) \)

Data: \( x_D < 0.03, y_D \sim 0.01 \pm 0.005 \)

"game" has just begun!

It is not the quark box diagram, stupid!
sobering lesson: case for New Physics based on $x_D$ uncertain!

- search for $\mathcal{CP}$ in $D^0-\bar{D}^0$ oscillations

Caveat en passant:

- $\Delta \Gamma(B_s)$ vulnerable to violations of local duality!

remember when extracting $|V(td)|$ from $\Delta m(B_d)/\Delta \Gamma(B_s)$

- definitive measurement:
  
  $x_D, y_D$ down to 0.001
**CP Violation**

😊 baryon # of Universe implies/requires **NP in CP dynamics**

😊 within SM:

➡️ highly diluted weak phase in **1x Cabibbo supp. Modes**

\[ V(cs) = 1 + i\lambda^4 \]

➡️ no weak phase in Cab. favoured & **2 x Cab. supp. modes**

(\textit{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-D^0** oscillations at best slow

➡️ B factories can contribute

➡️ **challenge to LHCb**: can you?

\[
D^{*+} \to D^0(t) \to K^+\pi^- \text{ vs. } D^{*-} \to D^0(t) \to K^0\pi^+ 
\]
**time integrated** partial widths

final state interact.

- necessary evil
- cannot fake signal
- \( \sim \) large in charm

- in Cabibbo favoured (CF) modes
  possible only with New Physics (except *)

- in singly Cabibbo supp. modes (SCS)
  possible with KM -- benchmark: \( O(\lambda^4) \sim O(10^{-3}) \)
  New Physics models: \( O(\%) \) conceivable

- in doubly Cabibbo supp. modes (DCS)
  possible only with New Physics (except *)
exception*: \( D^\pm \rightarrow K_{S[L]} \pi^\pm \quad \text{interference between} \quad D^+ \rightarrow K^0\pi^+ \quad \text{and} \quad D^+ \rightarrow K^0\pi^+ \quad \text{DCS} \)

in KM only effect from \( CP \) in \( K^0 - K^0 \)

asymmetry \( A_{S,L} = [+]_{S,L} - [-]_{S,L} = -3.3 \times 10^{-3} \)

with NP in DCS amplitude could reach \( O(1\%) \)
of either sign and \( A_S = - A_L \)

**Final state distributions:** Dalitz plots, T-odd moments

final state interact. \( \begin{cases} \text{😊 not necessary} \\ \text{😢 a nuisance: can fake signal} \\ \text{😀 can be disentangled} \end{cases} \)

very promising -- most effective theoretical tools not developed yet for small asymmetries
\( \text{CP involving } D^0-D^0 \text{ oscillations: 'indirect' CP} \)

\[
\begin{align*}
D^0 & \to K_S \phi/\pi^0 \quad \text{vs.} \quad D^0 \to K_S \phi/\pi^0 \\
D^0 & \to K^+K^-/\pi^+\pi^- \quad \text{vs.} \quad D^0 \to K^+K^-/\pi^+\pi^- \\
D^0 & \to K^+\pi^- \quad \text{vs.} \quad D^0 \to K^-\pi^+ \\
\end{align*}
\]

CP asymmetry given by 
\[ \sin \Delta m_D t \text{ Im}(q/p) \rho(D \to f) \]

small [each \ \sim O(10^{-3})] 

in SM with KM 

\[ \Rightarrow \quad \text{strong case for New Physics!} \]

asymmetry is linear in \( x_D \) whereas \( r_D \) is quadratic 

\[ \Rightarrow \quad \text{could be first signal of oscillations!} \]
Benchmarks for definitive measurements must aim at:

- $x_D, y_D$ down to $\mathcal{O}(10^{-3}) \iff r_D \sim \mathcal{O}(10^{-6} - 10^{-5})$

- Time dependant CP asymmetries in $D^0 \rightarrow K^+K^-, \pi^+\pi^-, K_S\phi$ down to $\mathcal{O}(10^{-4})$;
  $D^0 \rightarrow K^+\pi^-$ down to $\mathcal{O}(10^{-3})$.

- Direct CP in partial widths of $D^\pm \rightarrow K_{S[L]}\pi^\pm$ down to $\mathcal{O}(10^{-3})$;
  in a host of SCS channels down to $\mathcal{O}(10^{-3})$.

- Direct CP in the final state distributions:
  Dalitz plots, T-odd correlations etc. down to $\mathcal{O}(10^{-3})$. 
SM forbidden $\tau$ decays

$\tau \to \mu/e\gamma$

$\tau \to 3\ell$

if New Physics in $b \to sss \approx$ New Physics in $\tau \to \mu\mu\mu$
then $BR(\tau \to \mu\mu\mu) \approx 10^{-8}$
**CP in $\tau$ decays**

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

- most sensitive to Higgs dynamics
- CP asymmetries possible also in final state distributions rather than integrated rates
- unique opportunity for $e^+e^- \rightarrow \tau^+\tau^-$
  - pair produced with spins aligned:
    - 1 $\tau$ decays can `tag' the spin of the other
    - can probe spin-dependent CP with unpolarized beams!
- confidently predicted CP:
  
  $0.0033$ in $\Gamma(\tau^+ \rightarrow \nu K_S \pi^+) \text{ vs. } \Gamma(\tau^- \rightarrow \nu K_S \pi^-)$

-- due to $K_S$'s preference for antimatter
Sketch situation through 7 statements

1. *SM nontrivially consistent with all data* -- except for
   - $\nu$ oscillations
   - probably the Universe’s baryon #, dark energy/matter
   - possibly the strong CP problem
   - maybe -- just maybe CP in $B \to \phi K_S$

2. *New dimension due to findings of 1999-2001*
   first decisive tests of the CKM description of CP --
   - $B \to \psi K_S$: first observation of CP outside $K_L$ decays
   - it is huge -- as predicted!

$\Rightarrow$ CKM a tested theory rather than an ansatz
flavour dynamics even more intriguing due to emergence of neutrino oscillations

- **CKM matrix**
  - do not understand
  - we do understand

- **P-MNS matrix**
  - do not understand

Majorana v's, `see-saw'

F. Mauriac & his love for 2 Germanies

`Grand Challenge' after dynamics behind electro-weak phase transition: CP in lepton sector!
"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. It resolves none of the deep mysteries of the SM in the heavy flavour sector: masses & CKM parameters.

- SM incomplete: `strongly suspected’ NP= ssNP

New Physics driving electroweak phase transition confidently expected ~ TeV scale: \( cpNP \)

- this is the justification for the LHC

SUSY an organizing principle, not a theory!

- LHC (TEVATRON ?) is likely to uncover New Physics

- LHC (TEVATRON) is primarily a discovery machine

- Linear Collid. a surgical probe of the New Physics
The *cpNP* 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 *cpNP*

☞ 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* -- and actually necessary!
heavy flavour studies

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

i.e., no matter what studies of high $p_T$ physics at FNAL & LHC will or will not show -- comprehensive & detailed studies of flavour dynamics will remain crucial in our efforts to reveal Nature’s Grand Design.

7 Crucial manifestations of New Physics likely to be subtle

⇒ precision in interpretation of data essential!
3 scenarios for the next 5 - 8 years out

A -- the optimal one:
   new physics observed at high $p_t$ (FNAL/LHC)
   ➔ must study their impact on flavour dynamics
   ☺ some features -- mass scale etc. known!

B -- the intriguing one
   deviations from SM established in heavy flavour decays

C -- the frustrating one
   no deviation from SM prediction identified

⇴ none of these scenarios weakens the role of flavour studies being essential for coming to grips with nature’s `Grand Design'
handful of even perfectly measured processes not enough
-- comprehensive body of accurate data essential

Super-B factory = asymmetric $e^+e^-$ collider
near $\Upsilon(4S)$ with $L \sim \text{few} \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$

- up to $10^{10}$ B mesons/year

[vs. LHC-b with $20 \times 10^{11}$ beauty hadrons/year]

- in a clean environment

appears peerlessly able to provide required data base
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)
Tau-charm & B sweatshops

B fact.

LHC

Theory

LEP I/II, SLC

Tevatron

Tau-charm fact.

Super-B fact.

"Cinderella"

"the beautiful daughter"

Linear Coll.

[top fact.]

"the straight daughter"
beginning of an exciting adventure ...
and we are most privileged to participate!