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On the Decays of Charm Hadrons & τ Leptons -- The Dark Horses at a Super-B Factory

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Prologue

Dark horses

- charm — 2nd family up-type quark
- τ — 3rd family down-type lepton

`dark': no future states --

everything of fundamental interest known already

-- or so the conventional wisdom goes

Novel successes of SM in heavy flavour sector

- ☞ do not invalidate arguments for SM being incomplete -- only deepen mystery
  - ➥ confidently expect NP at ~ TeV scale
  - ✍ yet need to know NP's impact on heavy flavour transitions to differentiate NP scenarios

SUSY an organizing principle, not a theory!

- ☞ cannot count on numerically massive manifestations of NP
  - ➥ need
    - ✍ precise
    - ✍ reliable
    - ✍ comprehensive (i.e. search in unorthodox places)

    studies experimentally & theoretically
    - ➻ must scrutinize charm & τ

- Charm decays: validate QCD, calibrate tools for B studies
- τ decays: validate QCD, g - 2, ...

very important -- yet will not discuss here

☞ will discuss τ & charm studies as immediate -- albeit indirect -- probes of NP

☞ CP studies `instrumentalized' to analyze this New Physics

- ☺ baryon # of Universe implies/requires NP in ~~CP~~ dynamics
- ☺ CP asymmetry linear in NP amplitude

Interlude: On "Energy Flexibility"

Central target: $\not{CP}$ & LFV → statistics at a premium

❶ $\Upsilon(4S)$

❷ $\Upsilon(5S)$ → B_s

❸ `just below' $\Upsilon(4S)$, i.e. no backgd. for charm, τ

❹ E_{cm} ⇘ : L ⇘, s ⇗, <n> ⇘ } $E_{optimal}$ for charm, τ

❺ E ~ 4 GeV measure strong phases to interprete CP results

One caveat: τ spin effects presumably crucial f. CP studies

- ☞ use EPR spin correl. with unpol. beams
- ☞ have e^- beam polarized

} evaluate & compare efficiencies

easier at lower energies? polar. $\Lambda_c \to \not{CP}$

Outline

I Charm Decays: Uniqueness of Charm

Oscillations

~~CP~~

II τ Decays: LFV

~~CP~~

III Send-Off

Recent Reviews

✍ G. Burdman, E. Golowich, JA. Hewett, S. Pakvasa: "Rare Charm Decays in the SM & Beyond",Phys.Rev.D66,47 pages

✍ S. Bianco,F. Fabbri,D. Benson, I. Bigi: "A Cicerone for the Physics of Charm", La Rivista del Nuovo Cimento, **26**, # 7-8 (2003), ~ 200 pages

✍ G. Burdman, I. Shipsey, "D0 - D0 Mixing and Rare Charm Decays", Ann.Rev.Nucl.Part.Sci. 53(2003), 68 pages

numbers for rare decays!

✍ I. Bigi: "I have come to praise Charm, not bury it", hep-ph/0412041

I New Physics in Charm Decays

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`If baseball teams from Boston & Chicago can win the

World Series in two successive years

-- overcoming curses having lasted > 80 years --

then charm decays can reveal New Physics.'

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(1.1) Uniqueness of Charm

- New Physics scenarios in general induce FlChNC

✍ their couplings could be substantially stronger for Up-type than for Down-type quarks

(actually happens in some models which `brush the dirt of FlChNC in the down-type sector under rug of the up-type sector) up-type quarks: u c t

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

- top quarks do not hadronize ⟶ no T^0 - $\overline{T}^0$ oscillations

  hadronization while hard to force under theor. control

  enhances observability of $\not{C}P$

- 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 flavour dynamics with the experimental situation being a priori favourable (apart from absence of Cabibbo suppression)!

(1.1) `Inconclusive' D^0 - $\bar{D}^0$ Oscillations

- ☺ fascinating quantum mechanical phenomenon
- 😐 ambiguous probe for New Physics (=NP)
- ☺ important ingredient for NP CP asymm. in D^0 decays

$$x_D = \frac{\Delta m_D}{\Gamma_D} \qquad y_D = \frac{\Delta \Gamma_D}{2\Gamma_D}$$

➥ *conservative* bound: x_D, y_D ~ $O(0.01)$

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

"game" has just begun!

Personal comment: the (in)famous `Nelson plot' on theoret. predictions was witty & an appropriate reminder for theorists to use some common sense -- but should be retired now with honour!

systematic analysis based on O$_{\text{perator}}$ P$_{\text{roduct}}$ E$_{\text{xpansion}}$

expansion in powers of $1/m_c$, m_s, KM (Uraltsev,IB,Nucl.Phys.B592('01))

GIM suppression $(m_s/m_c)^4$ of usual quark box diagram un-typically severe!

∃ contributions from higher-dimensional operators with a very gentle GIM factor ~ m_s/μ_{had} … due to condensates in the OPE!

$m_s^2 \mu_{had}^4 / m_c^6$ (vs. m_s^4/m_c^4)

power counting in $1/m_c$ can be quite iffy

- $x_D\,(SM)|_{OPE}$, $y_D\,(SM)|_{OPE}$ ~ $\mathcal{O}(10^{-3})$
- unlikely uncertainties can be reduced

another analysis very different in spirit performed by

A. Falk et al., Phys. Rev. D65 (`02)

✍ yields similar numbers

☛ crucial distinction in question:

"What is the most likely value of x_D & y_D within the SM?"

$\mathcal{O}(10^{-3})$!

vs.

"How large could x_D & y_D conceivably be within the SM?"

Cannot rule out 10^{-2}!

---

sobering lesson: case for New Physics based on x_D uncertain!

➥ search for $\not{C}\!P$ in D^0-$\bar{D}^0$ oscillations

☞ definitive measurement still desirable: x_D, y_D down to 0.001

to (help) { interprete / validate } hoped for $\not{C}\!P$ signal

(1.2) ~~CP~~ with & without D^0 - $\bar{D}^0$ Oscillations

☺ baryon # of Universe implies/requires NP in ~~CP~~ dynamics

☺ existence of three-level Cabibbo hierarchy

☺ within SM:

☞ tiny 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

☺ flavour tagging by $D^{\pm *} \to D\pi^\pm$

☺ many $H_c \to \geq 3$ P, VV... with sizeable BR's

➥ CP observables also in final state distributions

☹ D^0 oscillations at best slow

😐 `Hypothesis-generating' rather than `hypothesis-driven' research:
no compelling NP scenario, yet significant ones exist

☹ Leading SM decays not CKM suppressed:

$$A_{CP}^{NP}(SCS) < \text{few } \%$$

different classes of manifestations:

- D → P P, PV: rate only info:
  - ΔC=1 or ΔC=2: ~~CP~~ independ. of time of decay t
  - ΔC=1 & 2: ~~CP~~ depend. of time of decay t
- D →VV,≥3 P,…: dynamical info also in final state distrib.

  memento: $K_L \to \pi^+\pi^- e^+ e^-$, $K \to 3\pi$
  - ΔC=1 & 2: time depend. Dalitz plots -- `the tool of the future'

-- and all of that on 3 different Cabibbo levels:

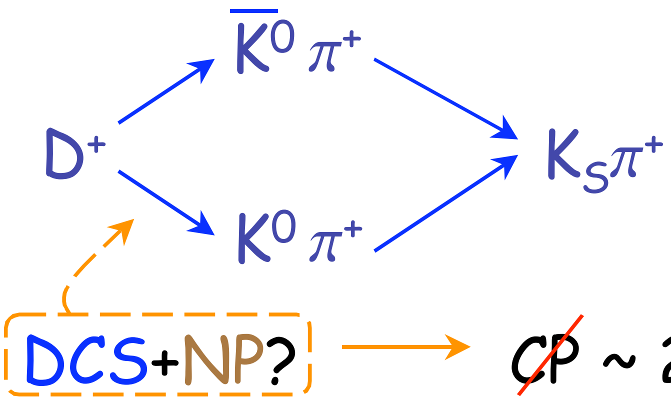
Cabibbo favoured	SM rate ~ 1	CKM ~~CP~~ = 0 **
1x Cabibbo suppr.	SM rate ~ 1/20	CKM ~~CP~~ ~ λ^4
2x Cabibbo suppr.	SM rate ~ 1/400	CKM ~~CP~~= 0

☞ no particular advantage at threshold

** no $\not{CP}$ in CA?

exception: $D^+ \to K_{S[L]}\pi^+$ vs. $D^- \to K_{S[L]}\pi^-$

☞



$\not{CP} \sim 2tg^2\theta_C \sin\alpha_{str}\sin\alpha_W^{NP} \sim O(1\%)$

☞ $\not{CP}$ in $|K_S\rangle$ ⟹ $\not{CP}$ in $D^+ \to K_{S[L]}\pi^+$ vs. $D^- \to K_{S[L]}\pi^-$ = 0.00327

Homework: How to reconcile with CPT?

(1.2.1) A few technicalities on CP asymmetries

Due to CPT ~~CP~~ implemented via complex phase

➥ observable ~~CP~~ requires 2 diff., yet coherent amplitudes

- partial width
  - ☹ need also strong phase -- FSI
  - ☺ FSI cannot fake effect!
- final state distributions: Dalitz plots, T odd moments …
  - ☺ do not need FSI
  - ☹ FSI can fake ~~T~~, since T antilinear; [**X**,**P**] = i
  - ☺ FSI cannot fake ~~CP~~
  - ☺ ~~CP~~ in distributions likely to be significantly larger than when integrated over.

(1.2.2) An example for a T odd distribution

$K_L \to \pi^+\pi^- e^+ e^-$

ϕ = angle between $\pi^+\pi^-$ & e^+e^- planes

forward-backward asymmetry in ϕ: A= 14 % driven by ε=0.002

$D \to K \bar{K} \pi^+\pi^-$

ϕ= angle between $\pi^+\pi^-$ & $K \bar{K}$ planes

$d\Gamma/d\phi\,(D \to K \bar{K} \pi^+\pi^-) = \Gamma_1 \cos^2\phi + \Gamma_2 \sin^2\phi + \Gamma_3 \cos\phi \sin\phi$

$d\Gamma/d\phi\,(\bar{D} \to K \bar{K} \pi^+\pi^-) = \bar{\Gamma}_1 \cos^2\phi + \bar{\Gamma}_2 \sin^2\phi + \bar{\Gamma}_3 \cos\phi \sin\phi$

- Γ_3 drops out after integrating over ϕ
  - Γ_1 vs. $\bar{\Gamma}_1$ & Γ_2 vs. $\bar{\Gamma}_2$: ~~C~~P in partial widths
- T odd moments $\Gamma_3, \bar{\Gamma}_3 \neq 0$ can be faked by FSI
  yet $\Gamma_3 \neq \bar{\Gamma}_3$ ⟹ ~~C~~P!

(1.2.3) CP asymmetries involving D^0 oscillations

$D^0 \to K_S \phi/\pi^0$ vs. $\bar{D}^0 \to K_S \phi/\pi^0$

$D^0 \to K^+K^-/\pi^+\pi^-$ vs. $\bar{D}^0 \to K^+K^-/\pi^+\pi^-$

$D^0 \to K^+\pi^-$ vs. $\bar{D}^0 \to K^-\pi^+$

CP asymmetry given by $\sin\Delta m_D t$ $\mathrm{Im}(q/p)\,\rho(D \to f)$

small [each ~ $O(10^{-3})$] in SM with KM

➥ strong case for New Physics!

asymmetry is linear in x_D whereas r_D is quadratic

➥ could be first signal of oscillations as well!

➻ in general time dependance of C̸P̸ controlled by x_D & y_D

A new chapter

$D^0 \to K_S \pi^+\pi^-$ vs. $\overline{D}^0 \to K_S \pi^+\pi^-$

$D^0 \to K^+K^-\pi^0/\pi^+\pi^-\pi^0$ vs. $\overline{D}^0 \to K^+K^-\pi^0/\pi^+\pi^-\pi^0$

$D^0 \to K^+\pi^-\pi^0$ vs. $\overline{D}^0 \to K^-\pi^+\pi^0$

time dependant Dalitz plot studies require a large amount of initial `overhead' and large statistics -- yet then they are very powerful probes of dynamics

- control systematics
- diagnose findings

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

(1.3) Benchmarks for future searches

for definitive measurements must aim at:

- x_D, y_D down to $O(10^{-3})$ $\Leftrightarrow$ $r_D \sim O(10^{-6} - 10^{-5})$
  important at least as experimental validation

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

    LHCb: ~ $5\text{x}10^7$ $D^* \to D\pi \to KK$ in 10^7 sec

- direct ~~CP~~ in partial widths of
  - $D^\pm \to K_{S[L]}\pi^\pm$ down to $O(10^{-3})$
  - in a host of 1xCS channels down to $O(10^{-3})$
  - in 2xCS channels down to $O(10^{-2})$

- direct ~~CP~~ in the final state distributions:

  Dalitz plots, T-odd correlations etc. down to $O(10^{-3})$

II τ Decays -- LFV & ~~CP~~

(2.1) LFV

SM forbidden τ decays

$\Gamma_{LFV} \sim |A_{NP}|^2$

$\tau \rightarrow \mu/e\ \gamma$ only in e+e-

$\tau \rightarrow 3\ l$ potential competition from LHC

if New Physics in $b \rightarrow sss \approx$ New Physics in $\tau \rightarrow \mu\mu\mu$
then $BR(\tau \rightarrow \mu\mu\mu) \sim 10^{-8}$

(2.2) ~~CP~~ in τ decays

$\Gamma_{CP} \sim A^*_{SM} \, A_{NP}$

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~~:

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

- \`crossed re-incarnation' of $P_t(\mu)$ in $K \to \mu\nu\pi$
- \`fly-in-the-ointment':

Observable $\not{CP}$ requires 2 diff. (& coherent) amplitudes

If $\tau \to \nu K \pi = \tau \to \nu K^*$ ☹

SM: $f_S/f_V \sim 0.05 - 0.1$ (Pich & al.)

+ SUSY large tgβ: + 10 %, yet no phase

non-min. Higgs: interesting range for $\not{CP} \sim 0.1 - 1\%$.

- CP in production: electric dipole moment

compete against electromagnetic forces -- good luck!

III Send-Off

Yes -- SM scored novel success in heavy flavour sector, but:

- `know so much, yet understand so little'
- need to instrumentalize CP studies to probe TEV scale NP
- we need a `New CP Paradigm'

→ charm unique among up-type quarks
  - ☞ non-trivial hadronization
  - ☞ experim. facts in its favour -- except lack of CKM supp.
  - ☞ only now entering `realistic' domain

→ τ unique among leptons
  - ☞ ~~CP~~ for leptogenesis (?)

an exciting adventure -- for the stout-of-heart

➥ Go out and convert the heathens!