Charm Dynamics as a Window onto New Physics

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

- drove paradigm shift: quarks as *real* entities
  essential support for acceptance of QCD
- electroweak SM phenomenolgy for $\Delta C \neq 0$ `dull'
  - CKM parameters `known'
  - D^0 - $\bar{D}^0$ oscillations very slow
  - ~~CP~~ very small
  - loop driven decays extremely rare

Message in a nutshell

- potentially very rich CP phenomenolgy on 3 Cabibbo levels
- study of charm decays not `hypothesis-driven' research
  - ☹ leading charm decays not CKM suppressed unlike for K & B
  - ☹ no special sensitivity to `standard extensions' of the SM
- study of charm decays `hypothesis-generating' research
  - ☺ FlChNC dynamics could be much stronger in up-type quarks
  - ☺ only charm allows full range of probes for New Phys. there
- present absence of any New Physics hint not telling
  - ☺ only now entering realistic search territory
  - ☺ … and a long way to go!
- B factories produce lots of `clean' & `usable' charm

  LHC produces lots of charm -- can LHCb use it?

  Future: Super-B!! Fixed target hadroprod.?

`dullness' of SM phenomenology

- probe (our understanding of) QCD (=LQCD)
  - very relevant near/mid-term: CLEO-c, B fact. & BES III

    (B fact.: $\rightarrow$ '07) (BES III: $\rightarrow$ '10)

  - will hopefully validate & sharpen theoret. tools for establishing and identifying New Physics in B decays

    (crucial -- yet cannot be discussed here)

but long term?? Vis-a-vis New Physics?

"I know she invented fire -- but what has she done lately?"

`fire' = Octobre Revolution of '74

2 kinds of research:

`hypothesis-driven' vs. `hypothesis-generating' research

- first kind very important -- & favoured by funding agencies
- yet `thinking outside the box' crucial

  memento 2005 Nobel Prize in Medicine!

- B physics is `hypothesis-driven'
  - B factories:

    develop & test quantitatively CKM paradigm
  - Super-B factories:

    develop & test quantitatively standard extensions of SM, since all SM B transitions CKM suppressed

- yet charm dynamics:
  - charm spectroscopy led to recent renaissance in
    `hypothesis-generating' QCD
  - best long-term motivation:
    `hypothesis-generating' search for New Physics

Antiquity's paradigm of `hypothesis-generating' analysis:
Delphi & Pythia

`I have come to praise C. -- not to bury it!'

charm transitions a novel window onto New Physics

The Menu

Prologue -- New Physics Scenarios

I Uniqueness of Charm Hadrons Re New Physics

II Inconclusiveness of D^0 - $\bar{D}^0$ Oscillations

III CP with & without D^0 - $\bar{D}^0$ Oscillations

IV Rare Charm Decays

V Conclusions & Outlook

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

✍ BESIII Charm Physics Book, to appear in 2006

Prologue -- New Physics Scenarios

☞ no need to be crazy or contrived -- being innovative will do

➼ New Physics scenarios for charm decays --
`the usual list of suspects' (Captain Renard in "Casablanca"):
nonminimal SUSY with(out) R parity, Higgs dynamics without NatFlCon, technicolour, topcolour, extra dimensions …

➼ no compelling/persuasive New Physics scenario inducing observable & diagnosable effects in D, yet not in B & K decays
`compelling/persuasive': SUSY

➼ yet re-assuring to know New Physics scenarios do exist

✍ memento: "We know so much about flavour structure --
yet understand so little!"

- 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)

`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.'

I Uniqueness of Charm Hadrons Re New Physics

❑ observed suppression of FlChNC implemented in SM through NatFlavCons & GIM mechanism

➻ best bet to search for novel FlChNC in down-type hadrons B & K, since their main decays are CKM suppressed

✍ `think outside the (SM) box':

probe FlChNC dynamics of up-type quarks as

`hypothesis-generating' research

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 - 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)!

II `Inconclusive' D^0 - $\overline{D}^0$ Oscillations

(2.1) Basics

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

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

general expectations

- ❍ $\Delta\Gamma$: on-shell contributions
  - ➥ ~ insensitive to New Physics
- ❍ Δm: virtual intermediate states
  - ➥ sensitive to New Physics

x_D ~O(few %) conceivable in models

☛ central theoretical issue:

duality at the charm scale?

- ➺ more averaging in x_D than in y_D
- ➥ duality better in x_D than in y_D

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

How `slow' is `slow'?

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

x_D, y_D ~ ~~$SU(3)_{Fl}$~~ $\cdot\, 2\sin^2\theta_C$ < few $\cdot$ 0.01

on-shell transitions (y_D)

off-shell transitions (x_D)

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

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

"game" has just begun!

considerable previous literature -- remember the `(in)famous H. Nelson' plot! -- yet with several ad-hoc elements mainly with respect to nonperturbative dynamics

systematic analysis based on Operator **P**roduct **E**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

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

another analysis very different in spirit performed by

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

- ✍ uses dispersion relations & sums up exclusive channels implementing ~~SU(3)~~$_{Fl}$ just by simple phase space
- ✍ 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}!

if $y_D \leq$ fewx10^{-3}
- for $x_D \leq$ fewx10^{-3}: as expect & $1/m_c$ expan.okay
- for $x_D \geq 0.01$: suggestive of New Physics

if $y_D \sim 0.01$
- for $x_D \leq$ few x 10^{-3}: large ~~duality~~ in y_D
- for $x_D \sim 0.01$?? theor. conundrum

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

➥ **search for ~~C~~P in D^0-$\bar{D}^0$ oscillations**

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

Caveat en passant:

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

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

(2.2) Experimental Status & Prospects

$D^0/\bar{D}^0$

change of identity

`birth' → `death'

initial flavour tag

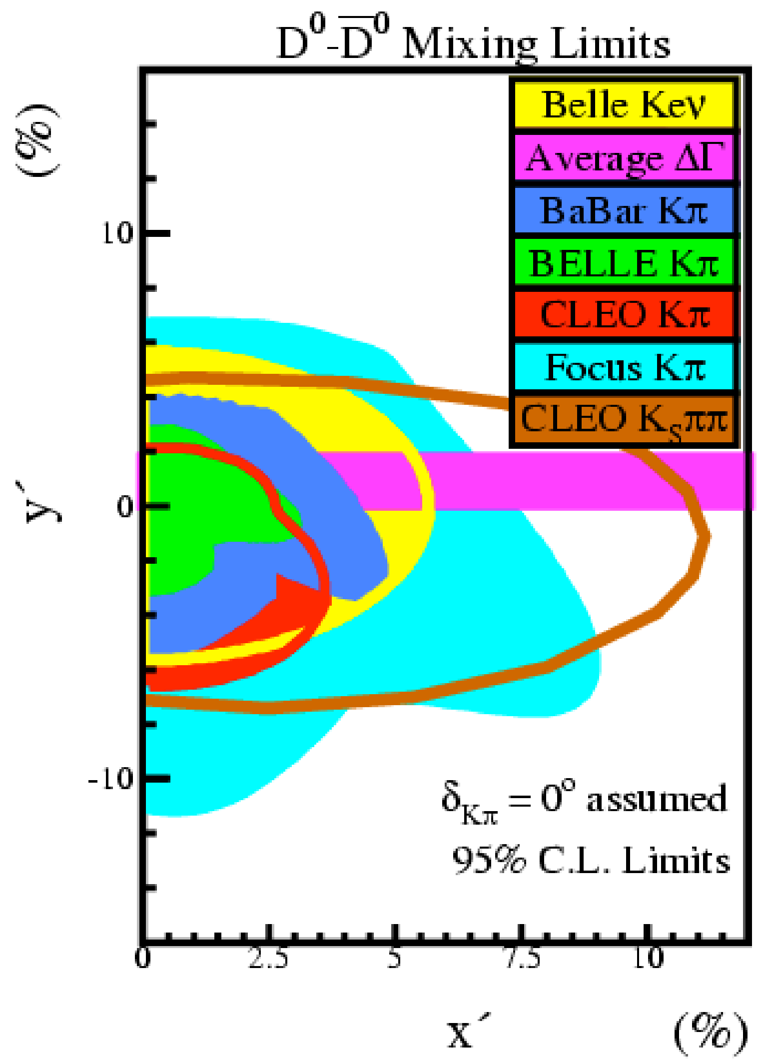
2 classes of setups
(with different flavour tags):

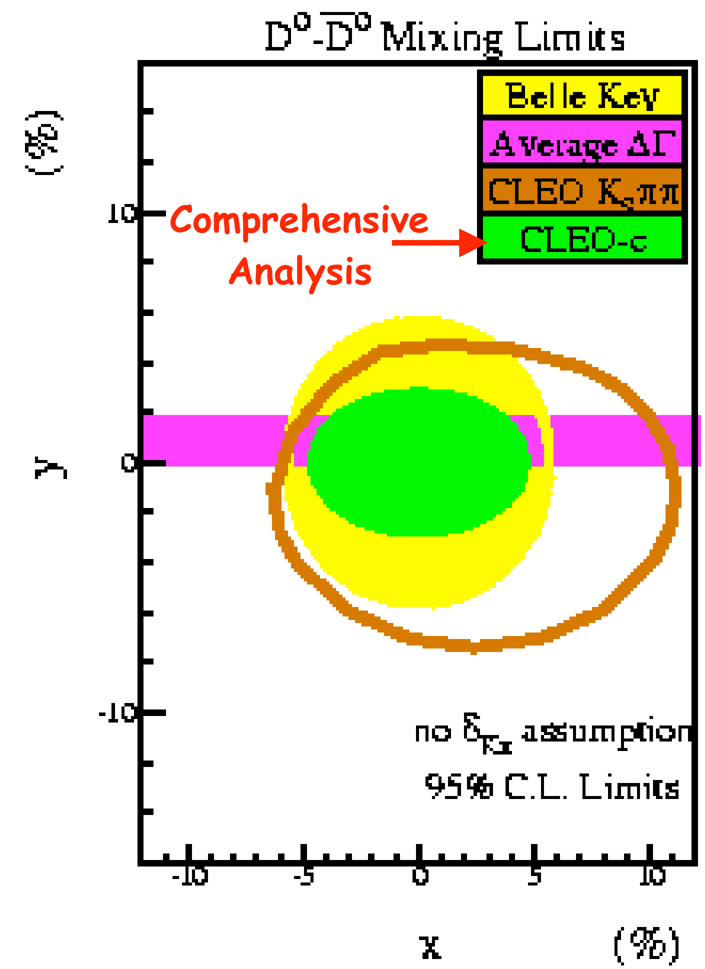
- incoherent production
  γ/h_1+h_2, e^+e^- at $E_{cm} \gg 2M_D$
- coherent production
  $e^+e^- \to D^0\bar{D}^0$, $D^0\bar{D}^0\gamma$

final flavour tag based on selection rules

- `pure' (SM): $l^{\pm}X$
- `mixed': $K^+\pi^-/K^-\pi^+$
  SM: DCSD!

oscillation = change of identity time dependent from D. Asner at Hadron '05





See S. Stone's talk in WG 2

III ~~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

☹ large hadroproduction, yet no efficient triggers

☹ D^0-$\bar{D}^0$ oscillations at best slow

$\not{CP}$ <-> ∃ of complex weak phase

↑ CPT

➥ need 2 different, yet coherent weak amplitudes for $\not{CP}$ to become observable

2 sources of $\not{CP}$

- direct $\not{CP}$: $\Delta C = 1$
- indirect $\not{CP}$: $\Delta C = 2$

different classes of manifestations:

- D → P P, PV: rate only info:
  - $\Delta C=1$ or $\Delta C=2$: $\not{CP}$ independ. of time of decay t
  - $\Delta C=1$ & 2: $\not{CP}$ depend. of time of decay t
- D →VV,≥3 P,…: dynamical info also in final state distrib.

  memento: $K_L \to \pi^+\pi^- e^+ e^-$, $K \to 3\pi$
  - $\Delta C=1$ & 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 $\not{CP}$ = 0
1x Cabibbo suppr.	SM rate ~ 1/20	CKM $\not{CP}$ ~ λ^4
2x Cabibbo suppr.	SM rate ~ 1/400	CKM $\not{CP}$= 0

The SM tells us there is just a desert with hardly an oasis to sustain us on our journey --

yet the ingredients are there for the desert to bloom manyfold!

(3.1) Direct $\not{CP}$

(3.1.1) *time integrated partial widths*

final state interact. {
- ☹ necessary evil
- ☺ cannot fake signal
- ☺ ~ large in charm
}

☺ Cabibbo favour. (CF) modes: need New Physics (except *)

☹ 1x Cabibbo supp. modes (SCS)

possible with KM -- benchmark: $O(\lambda^4) \sim O(10^{-3})$

New Physics models: $O(\%)$ conceivable

if observe direct $\not{CP}$ ~ 1% in SCS decays -- is it New Physics?

must analyze host of channels

☺ 2x Cabibbo supp. modes (DCS):need New Physics (except *)

exception *: $D^{\pm} \to K_{S[L]} \pi^{\pm}$

interference between $D^+ \underset{CF}{\to} K^0\pi^+$ and $D^+ \underset{DCS}{\to} K^0\pi^+$

in KM only effect from $\not{CP}$ in K^0 - $\overline{K}^0$: $A_S=[+]_S-[-]_S=-3.3\times10^{-3}$

(3.1.2) Final state distributions: Dalitz plots, T-odd moments

final state interact.
- 😐 not necessary
- ☹ a nuissance: can fake signal
- ☺ can be disentangled

very promising -- most effective theoretical tools not developed yet for small asymmetries (except Dalitz plot)

Pilot study by Focus (CLEO-c?)

☺ `local' asymmetry likely to be larger than integrated one

☺ angular asymmetry can provide info on chirality of underlying effective operator!

(3.2) $\not{CP}$ involving D^0-$\bar{D}^0$ oscillations: `indirect' $\not{CP}$

$D^0 \to K_S\, \phi/\pi^0$ 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 ~ $\mathcal{O}(10^{-3})$] 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 $\not{CP}$ controlled by x_D & y_D

A new chapter

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

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

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

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

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

(3.3) Experimental status

- So far only time integrated $\not{C}\!P$ analyzed with a sensitivity in
  - D → 2 body (Cab. fav. & 1x supp.) ~ *O*(1%)
  - D → 3 body (Cab. fav. & 1x supp.) ~ *several %*
  - I suspect main limitation is manpower first, statistics only second
- time dependent $\not{C}\!P$ \`terra incognita'
- constraints from CPT will become useful

beyond equality of masses & total widths CPT imposes equality between widths for \`disjoint' sets of final states

\`disjoint' = states that cannot rescatter into each other

(3.4) 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 $O(10^{-3})$

obviously going after $\not{CP}$ below 1 % level not straightforward due to systematics (detectors made from matter!)

possible antidotes:

- time dependance controled by x_D & y_D if oscillations are involved
- Dalitz plot consistency checks
- quantum statistics constraints on distributions, T odd moments etc.

✍ `combined arms' might be essential to reach 10^{-4} level: combining surgical precision of tau-charm data with the long reach of B factory measurements and the statistical muscle of hadroproduction

IV Rare Charm Decays

the usual -- and some unusual -- suspects

- "adagio, ma non troppo"
  - $D_{(s)} \to \gamma X$
  - $D_{(s)} \to \gamma K^* / \rho / \omega / \phi$

  } controlled by long distance dynamics

  - within SM: $BR(D^0 \to \gamma X)|_{SDdyn} \sim$ few x 10^{-8}

    $BR(D^0 \to \gamma K^*) \sim$ few x $(10^{-5} - 10^{-4})$

    $BR(D^0 \to \gamma \rho^0) \sim 10^{-6} - 10^{-5}$, $BR(D^0 \to \gamma \phi) \sim 10^{-6} -$ few x 10^{-5}

  - $BR(D^0 \to \gamma \phi) \sim (2.6 \pm 0.70 \pm 0.17) \times 10^{-5}$

☺ New Physics transition operators local `Penguins'

- "much rarer still" $D^0 \to \mu^+\mu^-$
  - SM: $BR(D^0 \to \mu^+\mu^-) \sim O(10^{-12})$
  - CDF: $BR(D^0 \to \mu^+\mu^-) < 2.4 \times 10^{-6}$

  no cute enhancement in SUSY as for $B_s \to \mu^+\mu^-$
  - SUSY with $\not{R}$: $BR(D^0 \to \mu^+\mu^-)$ up to experim. bound
- forbidden modes: $D^0 \to e^+\mu^-/\mu^+e^-$
  - $BR(D^0 \to \mu^+e^-) < 8.1 \times 10^{-6}$
  - SUSY with R: $BR(D^0 \to \mu^+e^-)$ up to experim. bound
- exotic New Physics: $D^+ \to \pi^+/K^+ f^0$, $\pi^-/K^- l^+ l^+$

familon f^0 searched for in K & B decays, not in D decays

- the likely work horse
  - $D_{(s)} \to l^+l^- X_u$
  - $D_{(s)} \to l^+l^- K/\pi$...

  } shaped to a higher degree by long distance dynamics than in B decays

  - theoret. control helped by analyzing $m(l^+l^-)$
  - within SM: $BR(D^0 \to l^+l^- X)|_{SDdyn} \sim$ few x 10^{-8}

    $BR(D \to l^+l^- \pi/\rho) \sim 10^{-6}$
  - FOCUS: $BR(D^+ \to l^+l^- \pi^+) < 8.8 \times 10^{-6}$

☺ New Physics transition operators local `Penguins'

☺ can/should analyze lepton spectra

V Conclusions & Outlook

Charm -- that provided essential support for acceptance of QCD (and recently seems to teach us novel lessons on QCD) -- might, just might have `its best still to come'. For it could provide essential support for an

emerging New Standard Model:

- (it can calibrate our theoretical tools for B decays)
- exhibits mostly advantages on the experimental side

  ☺ copious production at existing (now & soon) and proposed machines, sizeable BR's for relevant modes, efficient flavour tagging, …

  ☹ yet an efficient trigger for hadronprod. needed

- has mostly advantages also on the phenomenological side
  - ☺ virulent final state interactions for allowing for direct ~~CP~~ in widths
  - ☺ (moderately) complex final states allowing for ~~CP~~ in distributions
  - ☹ yet D^0-$\bar{D}^0$ oscillations not fast
- has some advantages even on the theoretical side
  - ☺ the `dullness' of the SM phenomenology
  - ☺ hadronization could be brought under control due to comprehensive data and future lattice QCD progress
  - ☹ yet no persuasive New Physics Scenario

2 strategic considerations

✍ admission of humility: "We know so much about flavour structure -- yet understand so little!"

✍ we will be unable to diagnose the anticipated New Dynamics at the TeV scale without mapping its impact on flavour dynamics

  ☞ `beggars can't be choosers' -- i.e., only 6 quarks

More specifically:

✍ FlChNC could be considerably stronger for up-type quarks

✍ charm decay provide the most sensitive, though not most direct portal to them

There are measurements `out there' that will put you into the Pantheon (a.k.a. `Valhalla' in Teutonic or `Hall of Fame' in US parlance):

- certainly ~~CP~~
- probably rare decays
- maybe D^0 - $\bar{D}^0$ oscillations

- Only recently have we entered `promising territory'...

- ... and there are 2 - 3 orders of magnitude in sensitivity waiting for `treasure hunters'!

✍ due to `dullness' of SM weak phenomenology will be able to make compelling case for New Physics driving signals…

✍ … and probably more: should be able to identify salient features of that New Physics like the chirality of its effective transition operators.

- CLEO-c/BES III/B fact. will produce a very rich & high quality data base for $D_{(s)}$ decays

(Λ_c/Ξ_c: CLEO-c will not do it, BES III cannot do it -- B fact.?)

- final states sufficiently complex to allow rich phenom., yet maybe simple enough not to be beyond theoret. control

- CPT constraints, chiral dynamics, quasi-2-body unitarity

- lattice QCD approaching charm from above & below

B factories are superb charm factories

Super-B factories even more so

Hadroproduction: to which degree can LHCb do it?
future FT experiments?

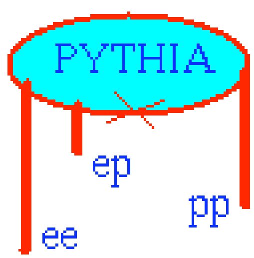
Super-Tau-Charm at 10^{35}??

any NP signal from LHC will be a boost -- morally & substantially

1st hypothesis: more sensitivity in B & K decays -- unless find, e.g., neutral object decaying into single charm

Message has been as specific and clear as can be expected when communicated from this Pythia via an ordinary mortal

not this →



back-up

a few relevant technicalities:

- violation of selection rule = signal for oscillation
  - $\Delta Q = -\,\Delta C$: strict selection rule within SM
  - $\Delta S = \Delta C$: broken selection rule within SM due to DCSD
  - oscillations imply time dependent violation of

    selection rule ⟶ most specific evidence!

- $x_D = \Delta M_D/\Gamma_D$, $y_D = \Delta\Gamma_D/\Gamma_D$ central quantities
  - x_D & y_D directly observable in $D_{neut} \to l^{\pm} X$
  - $x_D' = x_D \cos\delta + y_D \sin\delta$ & $y_D' = y_D \cos\delta - x_D \sin\delta$

    directly observable in $D_{neut} \to K^+\pi^-/K^-\pi^+$

    measurable in $\psi(3770) \to D^0D^0$

$$x_D^2 + y_D^2 = (x_D')^2 + (y_D')^2$$

2 classes of approaches

Class I:

search for a `global' violation of a flavour selection rule,

i.e., integrating over all times of decay

Class II:

search for a time depend. violat. of a flavour selection rule by

- measuring directly times of decay

  important cross check when searching for small effects!

- exploiting EPR correlations (ibi 1987,Asner&Sun hep-ph/0507238)

$$e^+e^- \to D^0\overline{D}^0 \text{ vs. } D^0\overline{D}^0\,\gamma$$