CHARM 2006 Beijing

"I Know She Invented Fire -- but What Has She Done Lately?" -- On the Future of Charm Studies

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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 with huge LD bkg.

Charm a closed chapter?

My intention

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

charm dynamics full of challenges -- & promises

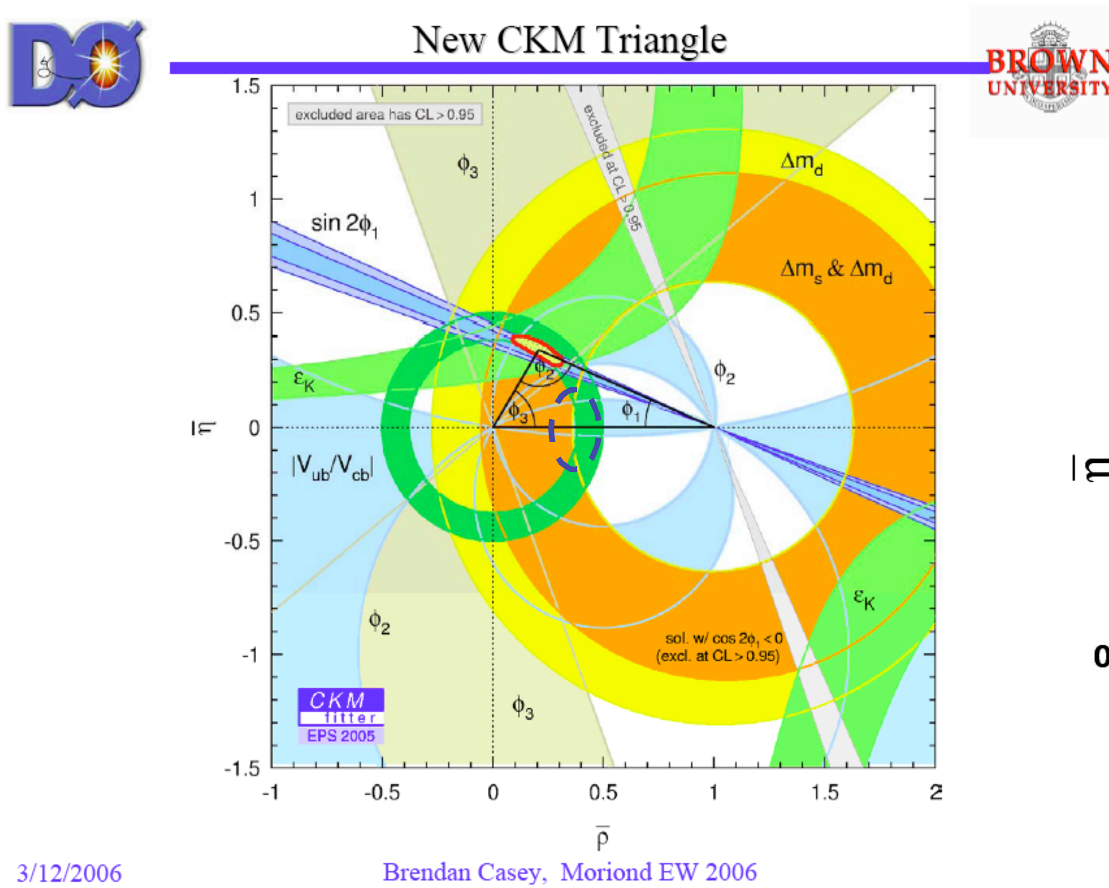
triple motivation for *further dedicated* studies

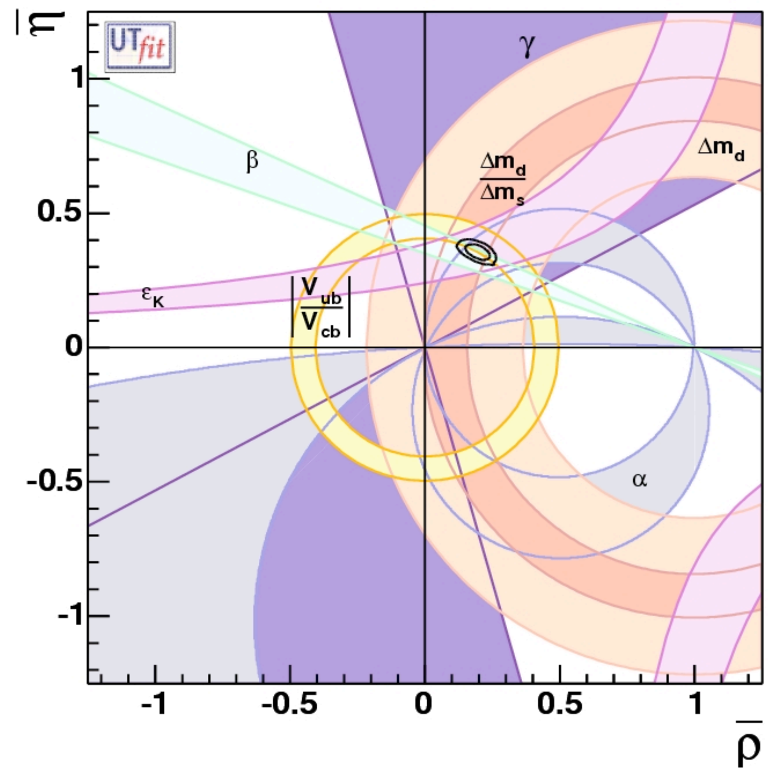
❶ *QCD (& `beyond')*: understanding nonperturb. dynamics & establishing theoretical control over it

❷ *B dynamics*: calibrating theoret. tools for B studies

❸ *New Physics*: charm transitions a novel window onto New Physics

accuracy of theoretical description of essential importance!





If true, another triumph for CKM theory: CP insensitive observables ($V(ub), \Delta M_s$) imply ~~C~~P!

3 basic tenets

- none of the novel successes of the SM weaken the case for New Physics -- presumably around the TeV scale

- to learn the salient features of this New Physics we must study its impact on heavy flavour transitions -- even if there is none observable

  ☞ CP studies `instrumentalized' to analyze this New Physics

- we cannot count on numerically massive impact of this New Physics

  ➥ need

  ✍ precise
  ✍ reliable
  ✍ comprehensive (i.e. search also in unorthodox places)

  studies experimentally & theoretically

The Menu

Short & mid-term

→ '07   → '10

CLEO-c,B fact. & BES III

Mid & long-term

→ '10   → '15('20)

LHCb, Super-B fact. (?)

I The `Guaranteed Profit':

Lessons on QCD

`Tooling up' for B Studies

II `The Best might still be ahead'

Searching for New Physics

Uniqueness of Charm

III 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

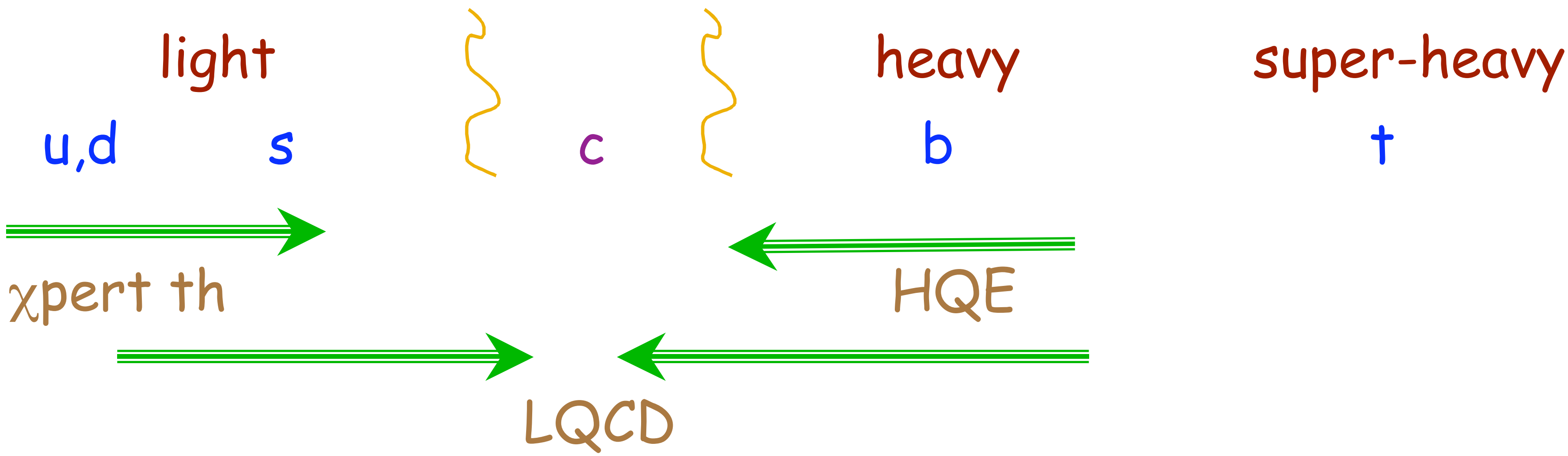
✍ BESIII Charm Physics Book, to appear in 2006

I The `Guaranteed Profit'

(1.1) Lessons on QCD

Issue at stake: *not* QCD as theory of the strong forces, but our ability to perform calculations

`charm: a bridge between bona fide heavy & light flavours'



accumulated evidence: charm `mostly somewhat' heavy

- Non-Rel. Quark Models still useful tool for training intuition & as diagnostics of results from sum rules & LQCD -- but not good enough for final answers
- HQE: expansion in $1/m_Q$
  - ☺ lifetime ratios: a posteriori works!
- Light Cone Sum Rules
  - ☹ $D \to l\nu\ \pi,\rho$: a posteriori fails!
- Lattice QCD: only theoretical technology with promise for truly quantit. treatment of charm hadrons with ability for systematic improvement
  - ☺ only Lattice QCD can approach it from below and above
  - 😐 monopoly of theoretical technology ?

I.B. (Marbella '93):
"A tau-charm factory is *the* QCD machine for the 1990's!"
Yet: threshold for significance much higher in the 2000's!

predictions to be confronted with comprehensive high quality data obtained in a timely fashion from CLEO-c,BELLE/BABAR & BES III

✍ Caveat:

even if $f_D|_{exp} = f_D|_{LQCD} \pm 0.1\ \%$

cannot conclude universal theor. uncertainty $\leq 1\ \%$!

need f_D, $f_{D(s)}$, FF for $D^+/D^0 \to l\,\nu$ [S=-1]/[S=0]

$D_s \to l\,\nu$ [S=0]/[S=+1]

charmonium studies → lessons on quarkonia

not on open flavour hadrons

Is Charm Heavy? -- or: the HQE in Inclusive H_c Decays

- $\overline{m}_c(m_c) = \begin{cases} 1.19 \pm 0.11 \text{ GeV} & \text{charmonium sum rules I} \\ 1.30 \pm 0.03 \text{ GeV} & \text{charmonium sum rules II} \\ 1.18 \pm 0.08 \text{ GeV} & \text{moments of SL B decays} \end{cases}$
  - $\mu_{nonpert.} \approx \Lambda \sim 600 - 800 \text{ MeV} \sim N_C \Lambda_{QCD}$
  - consistent determinations of m_c
    - charm somewhat heavy
- indirect supporting evidence

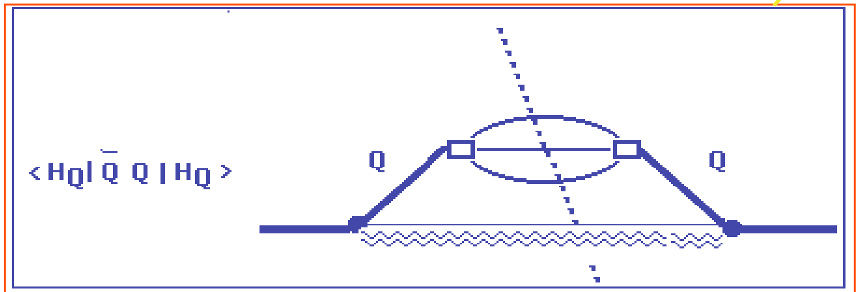
  $B \to l\nu\, D/D^*$ make up ~ 2/3 of $B \to l\nu\, X_c$

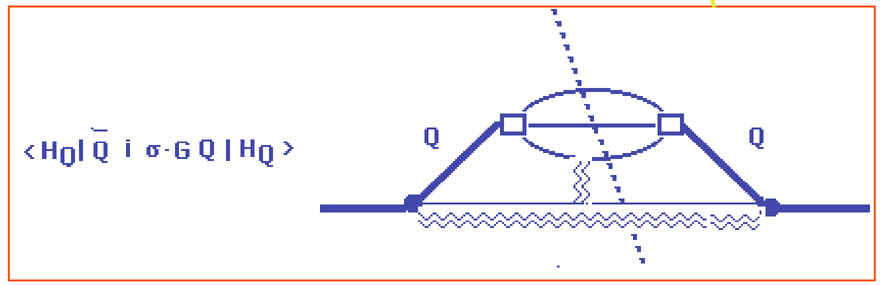
Lifetimes

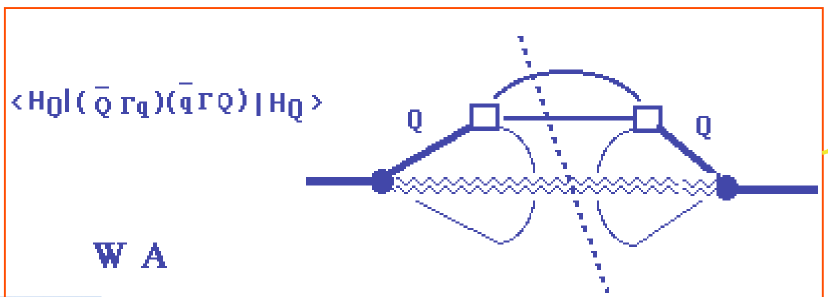
$$\Gamma(H_Q \rightarrow f_{incl}) = \frac{G_F^2 \left|KM\right|^2 m_Q^5}{192\,\pi^3} \times \left\{ c_3(f) \langle H_Q | \bar{Q} Q | H_Q \rangle + c_5(f) \frac{\langle H_Q | \bar{Q} i\sigma \cdot G Q | H_Q \rangle}{m_Q^2} + c_6(f) \frac{\langle H_Q | (\bar{Q}\Gamma q) \cdot (\bar{q}\Gamma Q) | H_Q \rangle}{m_Q^3} + \ldots \right\}$$

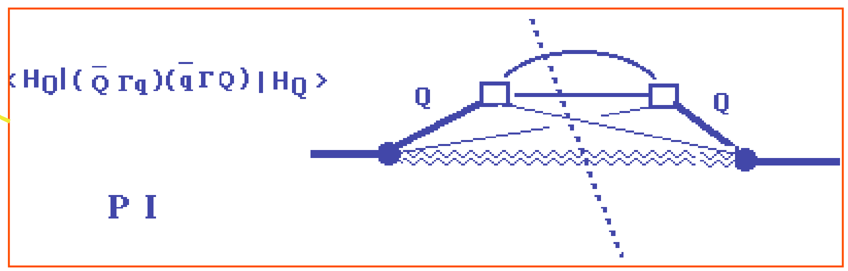
no correction

$\sim 1/m_c$!









➥ $\tau(D^+) > \tau(D^0) \sim \tau(D_s) \geq \tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^0)$

	$1/m_c$ expectations	theory comment	data
$\tau(D^+)/\tau(D^0)$	$\sim 1+(f_D/200\ \text{MeV})^2 \sim 2.4$	PI dominant	2.54 ± 0.01
$\tau(D_s)/\tau(D^0)$	1.0 - 1.07 0.9 - 1.3	without WA with WA	 1.22 ± 0.02
$\tau(\Lambda_c^+)/\tau(D^0)$	~ 0.5	Quark Model ME	0.49 ± 0.01
$\tau(\Xi_c^+)/\tau(\Lambda_c^+)$	$\sim 1.3 - 1.7$	"	2.2 ± 0.1
$\tau(\Lambda_c^+)/\tau(\Xi_c^0)$	$\sim 1.6 - 2.2$	"	2.0 ± 0.4
$\tau(\Xi_c^+)/\tau(\Xi_c^0)$	~ 2.8	"	4.5 ± 0.9
$\tau(\Xi_c^+)/\tau(\Omega_c^0)$	~ 4	"	5.8 ± 0.9
$\tau(\Xi_c^0)/\tau(\Omega_c)$	~ 1.4	"	1.42 ± 0.14

$\tau(D^+)/\tau(\Omega_c^0) \sim 14 >> 1!$

Success in describing observed lifetime ratios one of the best confirmations for charm being a heavy quark whenever leading nonperturb. contributions ~ $O(1/m^2_Q)$

- SELEX has reported candidates for weakly decaying double-charm baryons

  my judgement:

  - lifetimes of candidates too short without expected hierarchy

  If SELEX' interpretation correct, then successful description of single charm lifetimes a misleading accident!

(1.2) `Tooling up' for B Studies

Decay Constants

measure f_D, f_{Ds}

↕ if successful } ↗ f_B, f_{Bs}

calculate f_D, f_{Ds} in LQCD

Spectroscopy of Open Charm Hadrons

general lesson:

we need to understand charm spectroscopy

- to extract a precise value for V(cb) [& V(ub)] and
- search for right-handed charged currents of b quarks

  [if $V(cb)|_{incl}$ & $V(cb)|_{excl}$ inconsistent

  ➥ right-handed currents!]

Semileptonic D Decays

$\not{CP}$ in $B_d \to \phi K_S$ vs. rate of $B \to \gamma X_s$

What if $\gamma = \gamma_R \neq \gamma^{SM} = \gamma_L$?

Can infer γ polarization from $B \to \gamma K\pi\pi$

Yet need to understand $K\pi\pi$ system around 1400 MeV --

can be analyzed in $D \to l\, \nu\, K\pi\pi$!

(Time dependent) Dalitz Plots

$\not{CP}$ in $B_d \to$ 3 kaons

Learn about hadronization effects from

Dalitz analysis of $D \to$ 3 kaons

II Searching for New Physics

2 kinds of research:

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

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

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

- 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.'

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 - $\bar{T}^0$ oscillations

hadronization while hard to force under theor. control

enhances observability of $\not{CP}$

☞ 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)!

(2.1) `Inconclusive' D^0 - 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 ~ $\mathcal{O}(0.01)$

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 $O_{perator}$ 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

- $x_D\,(SM)|_{OPE}$, $y_D\,(SM)|_{OPE}$ ~ $\mathcal{O}(10^{-3})$
- 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 $\not{CP}$ in D^0-$\bar{D}^0$ oscillations

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

(2.2) $\not{CP}$ with & without D^0 - $\bar{D}^0$ Oscillations

☺ baryon # of Universe implies/requires NP in $\not{CP}$ 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

different classes of manifestations:

- D $\rightarrow$ 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 $\rightarrow$VV,$\geq$3 P,...: dynamical info also in final state distrib.

  memento: $K_L \rightarrow \pi^+\pi^-e^+e^-$, $K \rightarrow 3\pi$
  - $\Delta C=1$ & 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

Measuring a large set of nonleptonic $D_{(s)}$ widths with good accuracy provides important info on ME & FSI phases

→ essential input for interpreting CP studies!

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!

(2.3) Benchmarks for future searches

for definitive measurements must aim at:

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

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

    LHCb: $\sim 5\times10^7$ $D^* \to D\pi \to KK$ in 10^7 sec

- direct $\not{CP}$ in partial widths of
  - $D^\pm \to K_{S[L]}\pi^\pm$ down to $\mathcal{O}(10^{-3})$
  - in a host of 1xCS channels down to $\mathcal{O}(10^{-3})$
  - in 2xCS channels down to $\mathcal{O}(10^{-2})$

- direct $\not{CP}$ in the final state distributions:

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

III Conclusions & Outlook

2 very central tasks ahead of us in charm studies

- validate quantit. theoret. control over hadronization
  - ✍ valuable in its own right
  - ✍ sharpen and calibrate tools for B studies
  - ✍ charm baryons?

- unique searches for New Physics with up-type quarks
  - ✍ probing D^0 oscillations important intermediate stage
  - ✍ $\not{CP}$ essential goal -- $\exists$ New $\not{CP}$ Paradigm!
    - experimental situation mostly favourable
    - need as much statistics as possible: (Super-)B, LHCb
    - BESIII will make important start

No effect seen so far -- yet only recently entered realistic domain

… leading ultimately to a Chinese Super-Beauty Factory using ILC technology