Beijing 01/'04

"Quo Vadis, Fascinum?" ("Where do you go, Charm?")
-- 10 Years Later --
or:
On the Motivation for Continuing Studies of Charm Dynamics

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1st Prologue \`The Era of Factories'

Factory more than place where something is produced --

its products *have* to be consumable!

factories

e
+
e
-

heavy flavor

- LEP I: Z^0 factory few $\times 10^6$ Z^0 ***
- CLEO/BELLE/BABAR: B fact. few $\times 10^8$ BB ***
- DAΦNE: φ factory
- CLEO-c: ψ-D factory few $\times 10^7$ DD
- Linear collider: top (& W& H) factory

Super-factories

- DAΦNE II:
- BES III
- Super-B: up to 10^{10} BB
- Giga-Z: 10^9 Z^0
- JLAB: Kaon factory
- neutrino factories

2nd Prologue

Role of Charm in Evolution of SM & its Acceptance

- introduced for specific reasons & with specific properties
- facilitated for KM to come up with KM ansatz
- observation of J/ψ shook up community
- lead to paradigm shift in accepting quarks as real entities
- MARK III established precedent for threshold factory

$$e^+e^- \nearrow J/\psi,\ \psi'$$
$$e^+e^- \searrow \psi'' \rightarrow D\bar{D}$$

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!

The Menu

I Theory

II Lessons on QCD

III `Tooling up' for B Studies

IV QCD Menu for a Super-τ-charm Factory

V Searching for New Physics (mostly in my 2nd talk)

VI Conclusions & Outlook (given in my 2nd talk)

S. Bianco,F. Fabbri,D. Benson, I. Bigi:` A Cicerone for the Physics of Charm', hep-ex/0309021, to appear in Rivista del Nuovo Cimento, ~ 200 pages

I Theory

2 different aspects

(tools for theor. treatment of charm dynamic) | understanding of why charm is the way it is

theory *for* charm $\neq$ theory *of* charm

(1.1) Tools

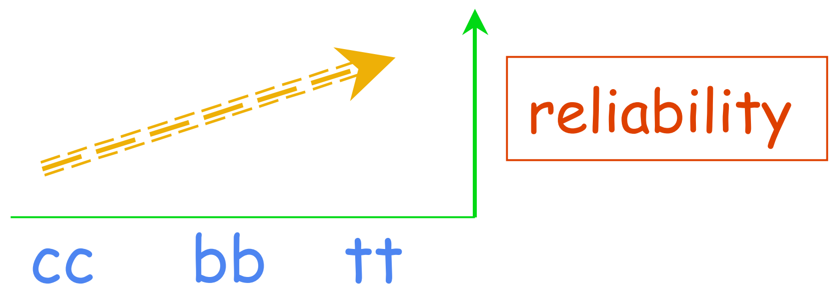
`charm between world of bona fide heavy & light flavours'

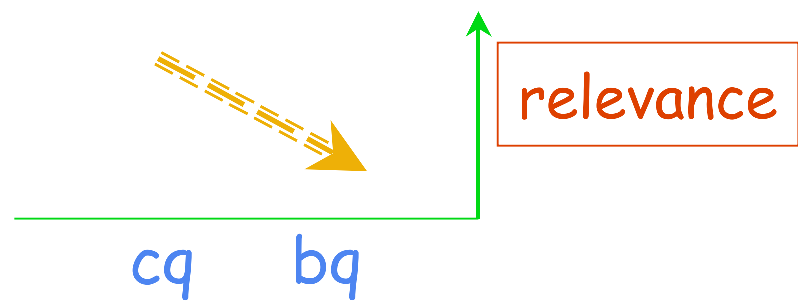
light | | heavy | super-heavy
u,d s | c | b | t

accumulated evidence: charm `mostly somewhat' heavy

a priori semi-quantitative description

- 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
  - ☹ $D \to l\nu$ □,□: a posteriori fails!

- Lattice QCD: only promise for truly quantit. treatment of charm hadrons with ability for systematic improvement
  - ☺ charm as bridge between heavy & light?
  - ☺ needs `just more' time
  - 😐 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!

- ☞ great opportunity for demonstrating theoretical control over strong dynamics: Hashimoto's talk!
- ☞ calibration for B physics
  - engineering input: absolute charm BR's
  - decay constants [not fundamental constants]: f_D, f_{D_s} $\rightarrow f_B$, f_{B_s}
  - 'Cathedral Paradigm': charm spectroscopy & B dynamics

essential QCD info to exhaust discovery potential in B physics!

(1.2) Probes for New Physics

☹ leading transitions Cabibbo favoured (unlike for K & B)

➥ scrutinize Cabibbo once & doubly suppr. modes

☺ SM phenomenology `dull'

➼ D^0-D^0 oscillations `slow'

➼ CP asymmetries `tiny'

How slow is `slow'? -- How tiny is `tiny'?

😐 D^0-D^0 oscillations: within SM Cabibbo & GIM suppr.

not necessarily with New Physics

☺ ~~CP~~: KM phases truly tiny

➥ ~~CP~~ in DCSD -- ***

➥ ~~CP~~ involving D^0-D^0 oscillations -- ***

(1.3) Theory *of* Charm

$\cancel{\square}$

Yet --

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

- ☞ top quarks do not hadronize
- ☞ up quarks: no $\square^0$-$\square^0$ oscillations possible

CP asymmetries basically ruled out by CPT

II Lessons on QCD

- will not cover charmonia $\rightarrow$ Hashimoto-san & Ted Barnes
- will not cover decay constants f_D, f_{D_s} $\rightarrow$ Hashimoto-san
  - f_D, f_{D_s} important parameters -- not constants of nature

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

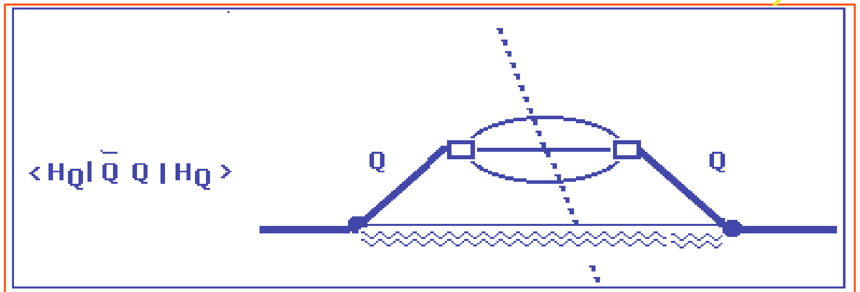
- $$\overline{m}_c(m_c) = \begin{cases} 1.19 \pm 0.11 \ \ \mathrm{GeV} & \text{charmonium sum rules I} \\ 1.30 \pm 0.03 \ \ \mathrm{GeV} & \text{charmonium sum rules II} \\ 1.14 \pm 0.1 \ \ \mathrm{GeV} & \text{moments of SL B decays} \end{cases}$$

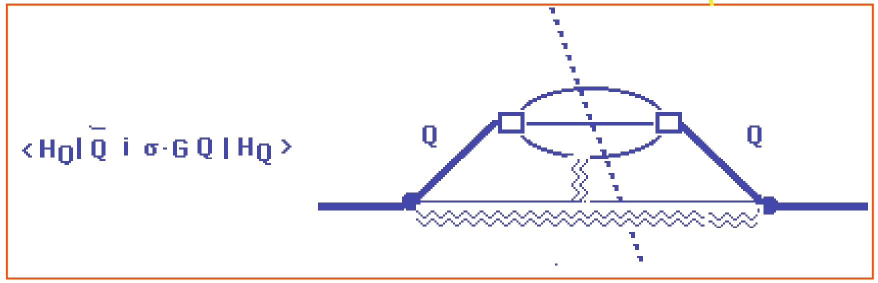
2.1.1 Lifetimes

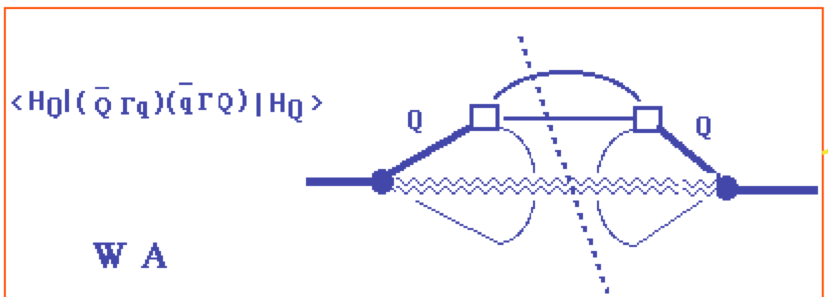
$$\Gamma(H_Q \to f_{incl}) = \frac{G_F^2 \, |KM|^2 \, m_Q^5}{192\,\pi^3} \times \left\{ c_3(f)\,\langle H_Q|\bar{Q}Q|H_Q\rangle + c_5(f)\,\frac{\langle H_Q|\bar{Q}i\sigma\cdot G\,Q|H_Q\rangle}{m_Q^2} + c_6(f)\,\frac{\langle H_Q|(\bar{Q}\Gamma q)\cdot(\bar{q}\Gamma Q)|H_Q\rangle}{m_Q^3} + \ldots \right\}$$

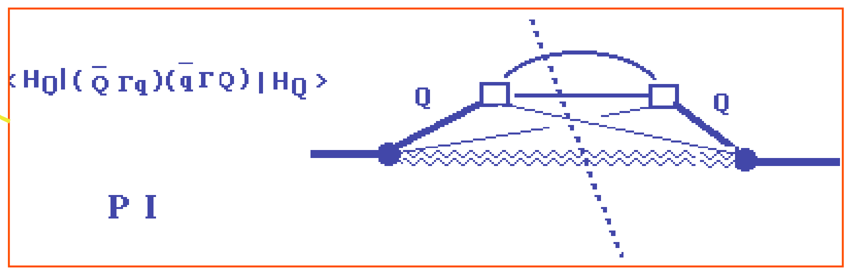
no correction

$\sim 1/m_c$!









➥ $\square(D^+) > \square(D^0) \sim \square(D_s) \geq \square(\square_c^+) > \square(\square_c^+) > \square(\square_c^0) > \square(\square_c^0)$

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

- yes, apply expansion in $1/m_c$ at your own risk, but ...
- saving grace: leading correction of order $1/m_c^2$ rather than $1/m_c$
- observed pattern reproduced/predicted semiquantitatively -- with $□(D^+)/□(\Omega_c^0) \sim 20$!
- destructive PI main engine driving lifetime differences among mesons, yet WA -- while not leading -- still significant in D decays
  - more theoretical work needed on WA in meson decays
  - impact of WA on exclusive final states in meson decays: constructive in D^0 and/or destructive in D_s?
- baryons present complex challenge
- description for baryonic widths helped by generous errors
- sole sign for significant discrepancy emerges in $□(\Xi_c^+)$ -- observed lifetime 50 % longer than predicted !

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

- whatever SELEX has observed -- I do not believe its peculiar events can be double-charm baryons:
  - mass splittings too large
  - lifetimes too short without expected hierarchy

2.1.2 SL Branching Ratios

three issues:

- absolute size of SL BR
- ratios of SL BR's
- absolute size of $\Gamma_{SL}(D)$

new element: contributions of order $1/m^2_Q$

$BR_{SL}(D)$

\`Fly-in-the-ointment':

HQE → PI main engine driving $\Gamma_{NL}(D^+) \searrow$ s.t. < $\Gamma_{NL}(D^0)$

$$\Gamma_{SL}(D^+) = \Gamma_{SL}(D^0) + \mathcal{O}(tg^2\theta_C)$$

➥ $BR_{SL}(D^+)/BR_{SL}(D^0) = \tau(D^+)/\tau(D^0) + \mathcal{O}(tg^2\theta_C)$

➥ $BR_{SL}(D^+)$ > "expected" ~ $BR_{SL}(D^0)$

i.e. \`enhanced' \`normal'

yet: $BR_{SL}(D^+) = (17.2 \pm 1.9)\ \% \sim BR_{SL}(c)$ $BR_{SL}(D^0) = (6.75 \pm 0.29)\ \%$

resolution: μ_G^2/m_c^2 term in HQE lowers $BR_{SL}(D)$

$BR_{SL}(D) \sim 9\ \%$ for $D=D^+, D^0$ in order $1/m_c^2$

Ratios of $BR_{SL}(H_c)$

- isospin invariance $\rightarrow \tau(D^+) / \tau(D^0) = BR_{SL}(D^+) / BR_{SL}(D^0) + \mathcal{O}(tg^2\theta_C)$
- HQE yields $\tau(D_s^+) / \tau(D^0) \approx BR_{SL}(D_s^+) / BR_{SL}(D^0)$
- semileptonic BR's for baryons do not reflect lifetime ratios!

$$\square_{SL}(D) \neq \square_{SL}(\square_c) \neq \square_{SL}(\square_c) \neq \square_{SL}(\square_c)$$

constructive PI in SL $\square_c$ and $\square_c$ decays —>

$BR_{SL}(\square_c^0) \sim BR_{SL}(\square_c)$ vs. $\square(\square_c^0) \sim 0.5 \cdot \square(\square_c)$

$BR_{SL}(\square_c^+) \sim 2.5 \cdot BR_{SL}(\square_c)$ vs. $\square(\square_c^+) \sim 1.3 \cdot \square(\square_c)$

$BR_{SL}(\square_c) < 15\ \%$

➥ SL widths for charm baryons are highly nonuniversal!

important test of HQE in charm transitions

possible only at a tau-charm factory

□$_{SL}$(D)

HQE with factorizable contributios order $1/m_c^3$ yields merely ~ 2/3 of □$_{SL}$(D) -- indications remainder from nonfactorizable contributions

➥ no accurate extraction of V(cb) from □$_{SL}$(D)

2.2 Exclusive H_c Decays

Theor. tools exist only for describing

- SL decays with 1 hadron/resonance
- NL " " 2 hadrons/resonances

in final state

2.2.1 CKM Parameters

$|V(cs)| \gg |V(cd)|$

without imposing 3-family unitarity:

$|V(cd)| = 0.224 \pm 0.016$, mainly from prod. of charm

$|V(cs)| = \boxed{0.97 \pm 0.09 \pm 0.07}, \boxed{0.996 \pm 0.013 \pm ??}$

charm-tagged W decays

lept.vs. had. W decays

☞ should be reclaimed by analysis of SL charm decays
challenge: understand FF $f(q^2)$

normalization & q^2 dependence

hard to evaluate model uncertainty

very limited range → hard to distinguish models experim.

quark models:

☹ no reliable estimate of uncertainty

☹ no systematic improvement

light cone sum rules

☹ underestimate significantly observed $\square(D^0 \to e^+\square\square^-)$

😐 explanation: nonlocal operators & large $1/m_c$ correct. (!?)

LQCD

☺ can be improved systematically

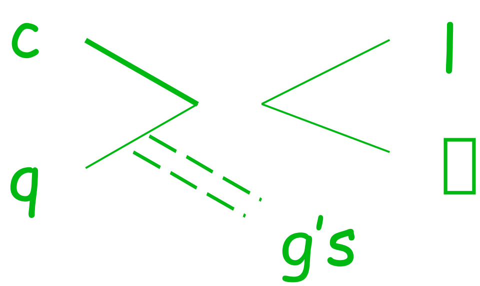
😐 \`our only hope'

➥ essential to extract V(cs) & V(cd) from

SL decays of $D^{0,+}$ & D^+_s

2.2.2 Final States in SL H_c Decays

- $D^+/D^+_s \rightarrow l^+$□ □/□': □/□' wavefunctions
  - ➜ NL D decays & CP asymm.
  - ➜ NL B decays & CP asymm.
- $D^+/D^+_s \rightarrow l^+$□ glueballs



2.2.3 Two-body NL H_c Decays

tool chest:

- pQCD: makes hardly any sense to apply to charm decays
- QCD factorization: could be tried -- yet several reasons why it might fail: contributions ~ $1/m_c$
- QCD sum rules a la Blok-Shifman: should be updated & refined
- quark models: for lack of anything better for the time being
- LQCD: needs to be unquenched!

Driving motivation:

Harnessing CP phenomenology as a probe for New Physics

main road block:

lack of theor. control over final state interactions

☞ need to `map out' whole Cabibbo landscape

-- Cabibbo favoured, once & doubly suppressed --

for D^0,D^+,D^+_s decays including multineutral final states

III `Tooling up' for B Studies

nonperturb. dynamics in exclusive $B \to l\nu D, \to l^+\nu D^* \ldots$

characterized by scale m_c, not m_b!

3.1 Spectra in inclusive SL $D^0, D^+, D_s^+, \Lambda_c$ Decays

challenge:

extract $|V(cd)/V(cs)|$ from

- lepton energy spectra $d\Gamma/dE_l$
- hadronic recoil mass spectra $d\Gamma/dM_X$

in D^0 & D^+ & $D_s^+ \to l^+\nu X$

3.2 Spectroscopy of Open Charm Hadrons

3 motivations for understanding charm spectroscopy

- to extract □$_{SL}$(B) and its error from data
- to extract B → l □ D/D* and their errors
- impact on sum rules for B → l □ D(s_q = 1/2 or 3/2)

☞ $\rho^2(\mu)$ - 1/4 = $\Sigma_n |\tau_{1/2}^{(n)}|^2 + 2\,\Sigma_m |\tau_{3/2}^{(m)}|^2$

☞ $\Lambda(\mu)$ = $2\,(\Sigma_n \epsilon_n |\tau_{1/2}^{(n)}|^2 + 2\,\Sigma_m \epsilon_m |\tau_{3/2}^{(m)}|^2)$

☞ $\mu^2_\pi(\mu)/3$ = $\Sigma_n \epsilon_n^2 |\tau_{1/2}^{(n)}|^2 + 2\,\Sigma_m \epsilon_m^2 |\tau_{3/2}^{(m)}|^2$

where: $\tau_{1/2}$ & $\tau_{3/2}$ denote transition amplitudes for B → l □ D(s_q = 1/2 or 3/2) with excitation energy $\epsilon_k \leq \mu$

$\rho^2(\mu)$, $\Lambda(\mu)$, $\mu^2_\pi(\mu)$ … crucial quantities for describing SL B decays

HQ Sum Rules

- ☞ $\rho^2(\mu) - 1/4 = \Sigma_n |\tau_{1/2}{}^{(n)}|^2 + 2\,\Sigma_m |\tau_{3/2}{}^{(m)}|^2$ Bj 1990
- ☞ $1/2 = -\,2\,\Sigma_n |\tau_{1/2}{}^{(n)}|^2 + \Sigma_m |\tau_{3/2}{}^{(m)}|^2$ U 2000
- ☞ $\overline{\Lambda}(\mu) = 2\,(\,\Sigma_n \epsilon_n |\tau_{1/2}{}^{(n)}|^2 + 2\,\Sigma_m \epsilon_m |\tau_{3/2}{}^{(m)}|^2)$ Vo 1992
- ☞ $\mu^2_\pi(\mu)/3 = \Sigma_n \epsilon_n^2 |\tau_{1/2}{}^{(n)}|^2 + 2\,\Sigma_m \epsilon_m^2 |\tau_{3/2}{}^{(m)}|^2$ BiSUVa 1994
- ☞ $\mu^2_G(\mu)/3 = -2\,\Sigma_n \epsilon_n^2 |\tau_{1/2}{}^{(n)}|^2 + 2\Sigma_m \epsilon_m^2 |\tau_{3/2}{}^{(m)}|^2$ BiSU 1997
- ☞ $\rho^3_D(\mu)/3 = \Sigma_n \epsilon_n^3 |\tau_{1/2}{}^{(n)}|^2 + 2\Sigma_m \epsilon_m^3 |\tau_{3/2}{}^{(m)}|^2$ ChPir 1994
- ☞ $-\rho^3_{LS}(\mu)/3 = -\,\Sigma_n \epsilon_n^3 |\tau_{1/2}{}^{(n)}|^2 + 2\Sigma_m \epsilon_m^3 |\tau_{3/2}{}^{(m)}|^2$ BiSU 1997

where: $\tau_{1/2}$ & $\tau_{3/2}$ denote transition amplitudes for

$B \to l\,\square\,D(s_q = 1/2 \text{ or } 3/2)$ with excitation energy $\epsilon_k \le \mu$

➥ rigorous definitions, inequalities + experim. constraints

Problem: SR barely compatible with broad D resonances above 2400 MeV as 1/2 states (Uraltsev, Orsay group)

Spring '03: BABAR finds $D_s(2317)$

infer $D_{u,d}^{**}(1/2)$ below 2300 MeV

which would be consistent with sum rules

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!]

IV QCD Menu for a Super-τ-charm Factory

key advantage of a τ-charm factory:

☺ extremely clean & model-independent measurements

yet very few things in life come for `free'

☹ run at different energies for different measurements

- ☞ below charm threshold for τ studies
- ☞ $e^+e^- \to \psi(3770) \to DD$
- ☞ $e^+e^- \to DD^*$
- ☞ $e^+e^- \to D_sD_s$ ...

➥ need flexibility and

➥ the highest luminosity possible!

- below charm threshold for □studies
  unique window on lepton dynamics:
  lepton-#, right-handed current, CP ? polarized beams?
- $e^+e^- \rightarrow \psi(3770) \rightarrow DD$: absolute BR's, CKM, full Cabibbo pattern, inclusive SL decays, right-handed currents, rare decays, CP
- $e^+e^- \rightarrow DD^*$: D^0-D^0 oscillations, CP
- $e^+e^- \rightarrow D_sD_s$: absolute BR's, CKM, full Cabibbo pattern, inclusive SL decays, rare decays, CP
- $e^+e^- \rightarrow D_1D_2 + X$: charm spectroscopy
- $e^+e^- \rightarrow □_c□_c$: absolute BR's, inclusive SL decays, CP a must (I.B.)
- $e^+e^- \rightarrow □_c□_c$: absolute BR's, inclusive SL decays desirable (I.B.)

➥ need flexibility, the highest luminosity possible -- and watch the competition!