Prologue: Charm Physics -- like Botticelli in the Sistine Chapel in Rome

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One of the premier tourist destinations in Rome is the Sistine Chapel -- because of Michelangelo's frescoes.

Botticelli's frescoes there get often overlooked; he cannot quite match Michelangelo -- yet is still a world class artist.

Lesson of this comparison: maybe better to do charm physics at a tau-charm than a B factory where it is `second fiddle'

Rare Charm Decays, D^0-$\overline{D}^0$ Oscillations & ~~CP~~ -- Novel Windows onto New Physics

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- SM amazingly successful in describing data --
  - in particular concerning flavour dynamics and
  - the CP phenomenology (except possibly $B_d \to$ □ K_S)

  yet strong circumstantial theor. evidence it is incomplete!

- New Physics confidently expected around TeV scale
  - this is the justification for the LHC

- LHC (TEVATRON ?) is likely to uncover New Physics
  - LHC (TEVATRON) is primarily a discovery machine
  - Linear Collid. a high sensitivity probe of the New Physics
- 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
- If LHC does not uncover New Physics, none of the arguments for the incompleteness of the SM will go away
  - heavy flavour transitions might be only chance to reveal New Physics
- no matter what ... a comprehensive & dedicated heavy flavour program will be essential for fundamental physics!

- The New Physics is not likely to shed light on flavour puzzle of SM (though it could);
  - ☞ instead studies of flavour transitions might elucidate salient features of the New Physics
  - ☞ baryon # of Universe implies New Physics beyond CKM discovery of predicted large asymmetry in $B_d \to$ □ K_S has `demystified' ~~CP~~: if observable weak phases can arise, they can be large!

Prime lab for New Physics: B decays

- ☺ highly KM suppressed
- ☺ speedy (rapid) B^0-B^0 oscillations
- ☺ direct access to large phases

☞ many of QCD lessons learnt in charm applied in B decays

but … charm decays as a direct probe for New Physics?

> 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)!

- ☺ SM weak phenomenology rather dull affair with
  - ➼ \`slow' D^0 - D^0 oscillations,
  - ➼ \`small' CP asymm.
  - ➥ \`zero-background' search for New Physics ?

- ☹ yet … "how slow is \`slow' and how small is \`small' ?"
  - ❑ $x_D < 3$ %; $y_{D,CP} = (1 \pm 0.5)$ %
  - ❑ direct ~~CP~~ < (few to several) %

- ☹ leading charm decays Cabibbo allowed
- ☺ New Physics more likely to surface in 2x[1x] Cabibbo supp.
- ☺ effective weak phase unusually small in CKM description
- ☺ charm only up-type quark allowing full range of probes of flavour couplings, including flavour-changing neutral currents
  - □^{0} decays electromagnetically, no □^{0}- □^{0} oscillations, …
  - top quarks do not hadronize
    - no T^0-T^0 oscillations
    - CP asymm. highly reduced due to lack of coherence

The Menu

I Rare Decays

II D^0-D^0 Oscillations

III CP Violation

IV The Pantheon List

V Conclusions & Outlook

I Rare Decays

(1.1) Unequivocal Signals of New Physics

$D^0 \rightarrow e^+□^-/e^-□^+$

- ☺ clean signature: $BR(D^0 \rightarrow e^-□^+) < 8.1 \times 10^{-6}$
- ☺ must be done
- ☹ helicity suppressed: $(m_□/m_c)^2 \sim 0.007$
- ☹ f_D " : $(f_D/m_c)^2 \sim 0.04$
- ☹ $□ \sim (1/M_X)^4$

$D \rightarrow e□X$

- ☺ must be done
- ☺ no helicity or f_D suppression
- ☹ $□ \sim (1/M_X)^4$

$D^{\pm} \rightarrow h^{\pm}$ + familon/axion

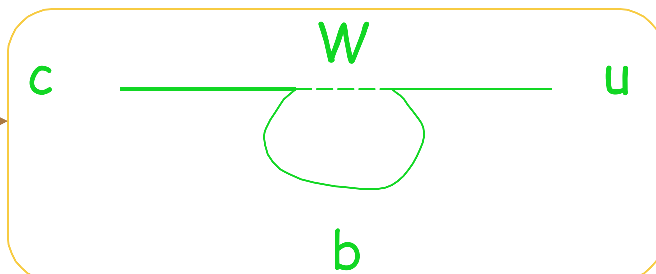
☺ must be done; has been searched for in B & K decays only

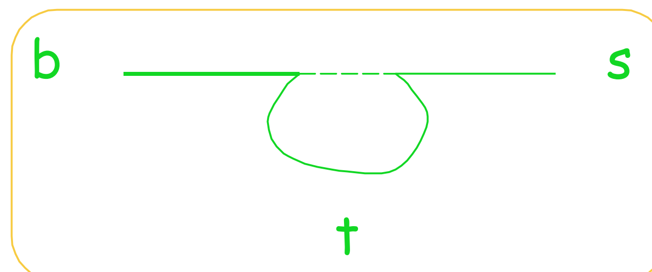
☹ □ ~ $(1/M_X)^4$

(1.2) Potential Signals of New Physics

Caveat: drawing a Feynman diagram does **not** mean one knows how to evaluate it even semiquantitatively!

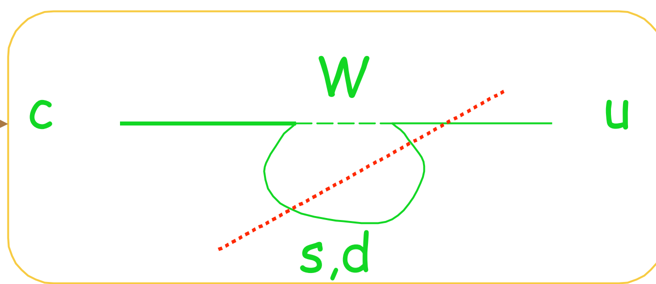
local,but tiny

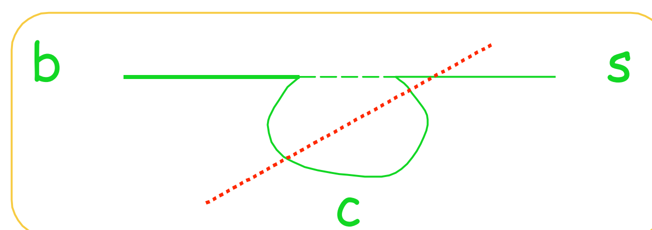




local

nonlocal not SD





SD

(1.2.1) Adagio, ma non troppo

D → □V, V=□,□,□

SM expectations:

BR(D^0→□K^{*0}) = (6-36)×10^{-5}, BR(D^0→□□^{0}) = (0.1-1)×10^{-5}

BR(D^0→□□) = (0.1-0.9)×10^{-5}, BR(D^0→□□) = (0.1-3.4)×10^{-5}

BELLE: BR(D^0→□□) = $(2.6^{+0.70}_{-0.61}\,{}^{+0.15}_{-0.17})\times 10^{-5}$

Motivation

- learning about LD contributions to B → □V
- probing for New Physics (nonminimal SUSY)

  calibrate SM contrib. by D^0→□K^{*0} & D^0→□□

(1.2.2) Rarest of the Rare

$D^0 \to \gamma\gamma$ SM expect.: $BR(D^0 \to \gamma\gamma) = (1\text{-}3.5) \times 10^{-8}$

$D^0 \to \mu^+\mu^-$ SM expect.: $BR(D^0 \to \mu^+\mu^-) = 3.0 \times 10^{-13}$

- ☺ clean signature: $BR(D^0 \to \mu^-\mu^+) < 4.1 \times 10^{-6}$
- ☺ must be done
- ☹ helicity suppressed: $(m_\mu/m_c)^2 \sim 0.007$
- ☹ f_D " : $(f_D/m_c)^2 \sim 0.04$
- 😐 $BR(D^0 \to \mu^-\mu^+)|_{NP} \sim 10^{-11}/8 \times 10^{-8}/3.5 \times 10^{-6}$

II D^0-D^0 Oscillations

- ☺ fascinating quantum mechanical phenomenon
- ☺ can have impact on extracting ϕ_3/γ from $B^{\pm} \to DK^{\pm}$ A.Bondar
- 😐 ambiguous probe for New Physics (=NP)
- ☺ important ingredient for NP CP asymm. in D^0 decays

D^0-D^0 oscillations `slow' in the SM

How `slow' is `slow'?

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

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

on-shell transitions

off-shell transitions

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

Data (see D. Asner): $x_D < 0.03$, $y_D \sim 0.01 \pm 0.005$

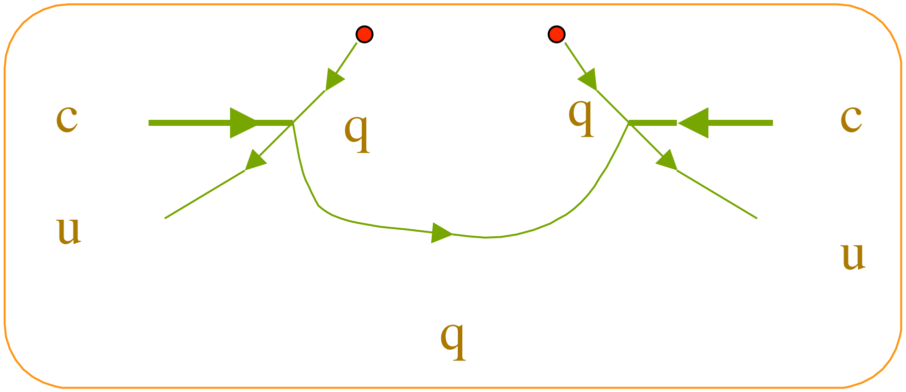
"game" has just begun!

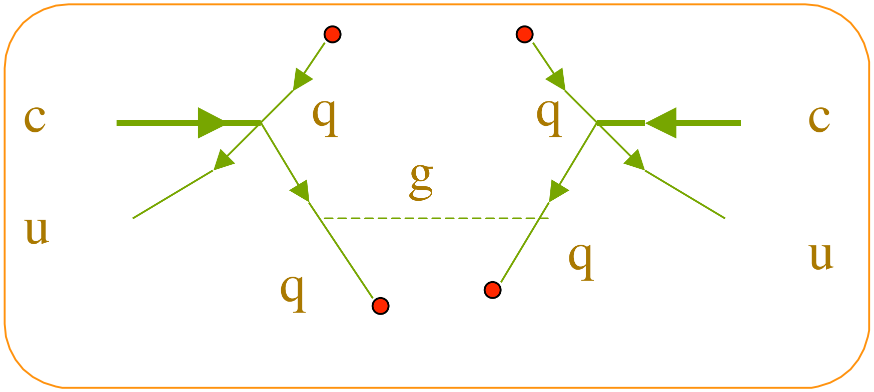
considerable previous literature -- yet with several ad-hoc elements mainly with respect to nonperturbative dynamics

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)

- $x_D(SM)|_{OPE}$, $y_D(SM)|_{OPE} \sim O(10^{-3})$
- unlikely uncertainties can be reduced
- furthermore central theoretical issue:

does quark-hadron duality hold at the charm scale?

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

general expectations

- $\Delta\Gamma$: on-shell contributions
  - ➥ ~ insensitive to New Physics
- Δm: virtual intermediate states
  - ➥ sensitive to New Physics
  - $x_D \sim O$(few %) conceivable in models

if $y_D \sim 0.01$ { for $x_D \leq$ few x 10^{-3}: $1/m_c$ expan. okay!
for $x_D \sim 0.01$: theor. conundrum

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

➥ search for $\not{C}P$ 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

III CP Violation

- ☺ baryon # of Universe implies/requires NP in $\not{C}P$ dynamics
- ☺ within SM:
  - ☞ highly diluted weak phase in 1x Cabibbo supp. Modes
    $V(cs) = 1 \ldots + i\square^4$
  - ☞ 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
- ☹ D^0-D^0 oscillations at best slow

~~CP~~ <-> □ of complex weak phase

CPT

➥ need 2 different, yet coherent weak amplitudes for ~~CP~~ to become observable

(3.1) Direct ~~CP~~ in Widths

(3.1.1) time integrated partial widths

final state interact. { 😐 necessary evil
☺ cannot fake signal
☺ ~ large in charm

☺ in Cabibbo favoured (CF) modes

possible only with New Physics (except *)

😐 in singly Cabibbo supp. modes (SCS)

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

New Physics models: $\mathcal{O}$(%) conceivable

if observe direct $\not{C}P$ ~ 1% in SCS decays

New Physics or hadronic enhancement?

necessary condition: analyze host of channels

☺ in doubly Cabibbo supp. modes (DCS)

possible only with 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 $\not{C}P$ 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 $A_S = -A_L$

(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

(3.2) ~~CP~~ involving D^0-D^0 oscillations: `indirect' ~~CP~~

$D^0 \rightarrow K_S \phi/\pi^0$ vs. $D^0 \rightarrow K_S \phi/\pi^0$

$D^0 \rightarrow K^+K^-/\pi^+\pi^-$ vs. $D^0 \rightarrow K^+K^-/\pi^+\pi^-$

$D^0 \rightarrow K^+\pi^-$ vs. $D^0 \rightarrow K^-\pi^+$

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

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!

3 scenarios for analyzing

- measure $\sin\Delta m_D t$ dependence directly through μ vertex detector

$$\gamma/h\ \ p \to D^{*+}\ X$$

$$\hookrightarrow D^0\ \pi^+$$

$$\hookrightarrow f$$

- \`trading time for space' or \`poor man's picosecond clock'

  measure indirectly exploiting EPR correlations IB 1987 IHEP

- $e^+e^- \to \psi'' \to DD \to (l^\pm X)_D\ f$ vs. $e^+e^- \to D^*D \to DD\ \gamma \to (l^\pm X)_D\ f$

$C = -$ $C = +$

direct ~~CP~~ only

also indirect ~~CP~~

- $e^+e^- \to \psi'' \to DD \to f_1\ f_2$

$CP = +$ $CP = -$

if $CP|\ f_i\rangle = \eta_i |\ f_i\rangle$ & $\eta_1 \eta_2 = +1$

- if $f_1 = f_2$ without being a CP ES
  - indirect ~~CP~~!

homework assignment: how can this be consistent with Bose statistics?

(3.3) Benchmarks

for definitive measurements must aim at:

- x_D, y_D down to $\mathcal{O}(10^{-3})$ $\Leftrightarrow$ $r_D \sim \mathcal{O}(10^{-6} - 10^{-5})$
- 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 $\mathcal{O}(10^{-3})$.
- direct $\not{C}P$ in partial widths of
  $D^\pm \to K_{S[L]}\pi^\pm$ down to $\mathcal{O}(10^{-3})$;
  in a host of SCS channels down to $\mathcal{O}(10^{-3})$.
- direct $\not{C}P$ in the final state distributions:
  Dalitz plots, T-odd correlations etc. down to $\mathcal{O}(10^{-3})$.

IV The Pantheon List

(a.k.a. `Valhalla' in the Teutonic
or `Hall of Fame' in the US language)

(4.1) Sure Bets

Any unequivoal sign of New Physics

☺ Indirect ~~CP~~ or direct ~~CP~~ in Cab. favoured or DCS modes

☺ $D \to e^+\mu^-/e^-\mu^+/e\mu X/\ h^\pm$ + familon/$\mu^-\mu^+$

(4.2) Likely Candidates

☺ Direct ~~CP~~ in SCS modes

☺ If f_D, f_{D_s}, formfactors$|_{exp}$ = f_D, f_{Ds}, formfactors$|_{LQCD}$ ± 1%

(4.3) `On the Bubble'

☺ D^0-D^0 oscillations

☺ Glueballs/hybrids

☺ Quark-Gluon plasma

Windows of opportunity for CLEO-c/BES

V Outlook & Conclusions

Lombardi:"Winning is'n the greatest thing - it's the only thing!"

QCD is the `only' thing -- still

- lessons to learn
- control to establish

`Seth's discriminator': the gluon

1. An experimenter's work starts with the gluon.
2. A phenomenologist's work ends with it.
3. A true theorists asks"What is a gluon?"

$SU(2)\times U(1)$ is not even the greatest thing

➥ New Physics must exist!

LHC

Tau-charm

(Super-)B fact.

Linear Coll.

"the frugal daughter"

"the free-spending daughter"

challenge:

Do many, many things
--excellently!

` The poor sleeper's impatience'
A man wakes up at night,
Sees it is dark outside and falls asleep again.
A short while later he awakes anew,
Notices it still to be dark outside and goes back to sleep.

This sequence repeats itself a few times
- waking up, seeing the dark outside and falling asleep again -
Till he cries out in despair:
"Will there never be daylight?"
A bird starts to sing.