Perugia Super-B, June 2009

No Pain, No Gain -- The Challenges & Opportunities of Charm Studies

Ikaros Bigi (Notre Dame du Lac)

Executive Summary

- Relative `dullness' of SM on FCNC & ~~CP~~ for charm - unique low (yet ≠ 0) background search for NP

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- central challenge: control over systematics
- Double opportunity/double challenge: run ~ 4 GeV.

The Menu

Prologue -- Uniqueness of Charm

I New Physics Scenarios & their CP Footprints

II ~~CP~~ in Final State Distributions

III Rare Decays

IV Outlook

Observables

Prologue -- Uniqueness of Charm

SM:
- FCNC greatly suppressed
- even more so for *up*-type quarks

NP
- FCNC might be less suppressed for *up*-type quarks

➥ SM `background' much smaller for FCNC of *up*-type quarks

➥ cleaner (not larger) signal:

$$\left[\frac{\text{NP signal}}{\text{theor.SM noise}}\right]_{up\text{-type}} > \left[\frac{\text{NP signal}}{\text{theor.SM noise}}\right]_{down\text{-type}}$$

charm only *up*-type quark allowing full range of probes for NP

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)!

I New Physics Scenarios & their CP Footprints

Discovery of D^0 oscillations

-- x_D =(1.00 ± 0.26)%, y_D =(0.76 ± 0.18)% --

a great and essential experimental achievement;

- a scientific rather than `noble' goal to measure precisely
- theoretical interpretation a tactical draw in our battle with SM -- yet it promises a strategic victory in the fields of ~~CP~~

Analogy with another topical case: B_s oscillations

$\Delta M(B_s)|_{obs} \sim \Delta M(B_s)|_{SM}$

yet still possible with NP: $S^{CP}(B_s \to \psi\phi) \sim 0.3$ vs. $0.03|_{SM}$!

(1.1) Generalities

- ☺ baryon # of Universe implies/requires NP in ~~CP~~ dynamics
- ☺ existence of three-level Cabibbo hierarchy

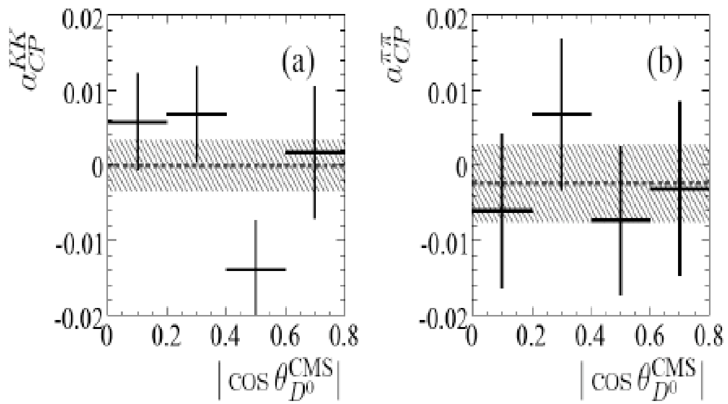
SM rate CF : CS : DCS ~ 1 : 1/20 : 1/400

- ☺ 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
- ☺ ...
- ☺ many $H_c \to \geq 3$ P, VV... with sizeable BR's
  - ➥ CP observables also in final state distributions
- ☺ D^0 oscillations adds a second coherent amplitude needed to make a complex phase observable

oscillations can generate time *dependent* CP asymmetries that survive integrating over time (unless $e^+ e^- \to D^0\bar{D}^0$)

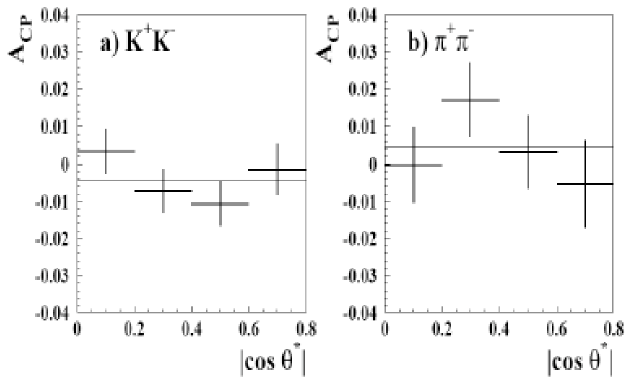
$D^0 \to K^+K^-$ and $\pi^+\pi^-$

Phys.Rev.Lett.100:061803 (2008)



$$A_{CP}^{KK} = [\ 0.00 \pm 0.34(\text{stat.}) \pm 0.13(\text{syst.})]\%$$
$$A_{CP}^{\pi\pi} = [-0.24 \pm 0.52(\text{stat.}) \pm 0.22(\text{syst.})]\%$$

Arxiv:0807.0148v1 (2008) **NEW**



$$A_{CP}^{KK} = [\ 0.43 \pm 0.30(\text{stat.}) \pm 0.11(\text{syst.})]\%$$
$$A_{CP}^{\pi\pi} = [0.43 \pm 0.52(\text{stat.}) \pm 0.12(\text{syst.})]\%$$

- none seen so far down to the 1% ($1\%/tg^2\theta_C$) level --

☞ they are ~ (x_D or y_D) (t/τ_D)sin ϕ_{weak};

- with $x_D, y_D \leq 0.01$ a signal would hardly have been credible
- yet now it is getting interesting!

The `Dark Horse'

SL: $D^0 \to l^- \nu K^+$ vs. $D^0 \to l^+ \nu K^-$

$a_{SL} \sim \mathrm{Min}[\Delta\Gamma/\Delta M, \Delta M/\Delta\Gamma] \sin\phi_{NP}$, $\Delta\Gamma/\Delta M \sim O(1)$

- $a_{SL} \sim 0.1$ conceivable (even few x 0.1)

i.e. relatively few wrong-sign leptons, yet with a large asymmetry!

vs.

- $a_{SL}(K_L) = 3.3 \times 10^{-3}$ with $\Delta\Gamma/\Delta M \sim O(1)$ & $\sin\phi_{CKM,eff} \ll 1$
- $a_{SL}(B_d) \sim 4 \times 10^{-4}$ with $\Delta\Gamma/\Delta M \sim O(\text{few} \times 10^{-3})$
- $a_{SL}(B_s) \sim 2 \times 10^{-5}$ with $\Delta\Gamma/\Delta M \sim O(\text{few} \times 10^{-3})$ & $\sin\phi_{CKM,eff} \sim O(\text{few} \times 10^{-2})$

$a_{SL}(D^0)$ probably cannot be measured by LHCb, yet

$|p/q| \sim |1 - a_{SL}/2|$ affects NL ~~CP~~ observables

(1.2) A New Physics Scenario -- LHT

☞ Baryogenesis requires New Physics with ~~CP~~ !

☞ do *not* need SUSY without R parity to generate observable ~~CP~~ in D decays

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["SUSY without R parity can do anything -- except make coffee!"]

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☞ Baryogenesis requires New Physics with ~~CP~~ !

☞ do *not* need SUSY without R parity to generate observable ~~CP~~ in D decays

["SUSY without R parity can do anything -- except make coffee!"]

can invoke natural scenarios like Littlest Higgs models with T parity

- LHT designed to `delay the day of reckoning' --

i.e. reconcile SM electroweak quantum corrections with NP to emerge directly at the LHC

flavour dynamics not part of the motivation!

✍ even so: LHT ≠ MFV

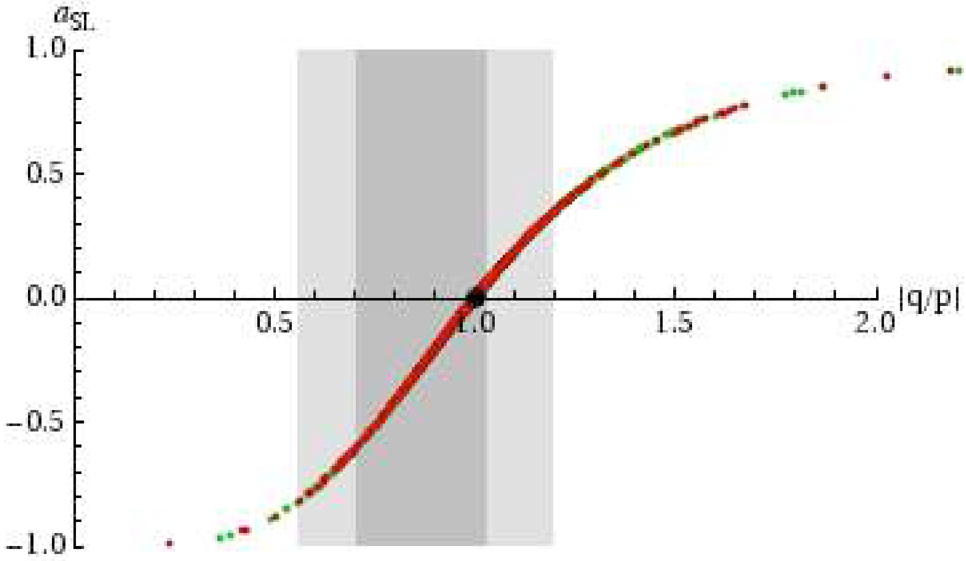
- LHT could
  - generate observed value of x_D without violating other bounds
  - exhibit a weak phase only moderately constrained!

- sizable time dependent CP conceivable!

- presumably also a general feature for *direct* CP (to be worked out soon)

$D^0 \to l^- \nu K^+$ vs. $D^0 \to l^+ \nu K^-$

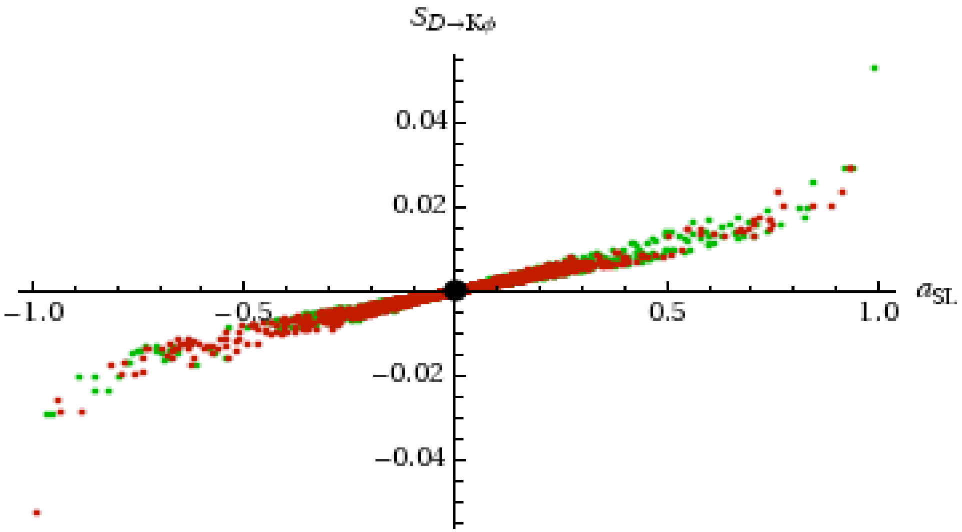
$a_{SL} = [1-|q/p|^4]/[1+|q/p|^4]$



BBBR= IB, M. Blanke, A. Buras, S. Recksiegel: arXiv:0904.1545

$D^0 \to K_S\phi$

$$\frac{\Gamma(D^0(t) \to K_S\phi) - \Gamma(\bar{D}^0(t) \to K_S\phi)}{\Gamma(D^0(t) \to K_S\phi) + \Gamma(\bar{D}^0(t) \to K_S\phi)} \equiv S_{D\to K_S\phi}\frac{t}{2\tau_D}$$



3 points

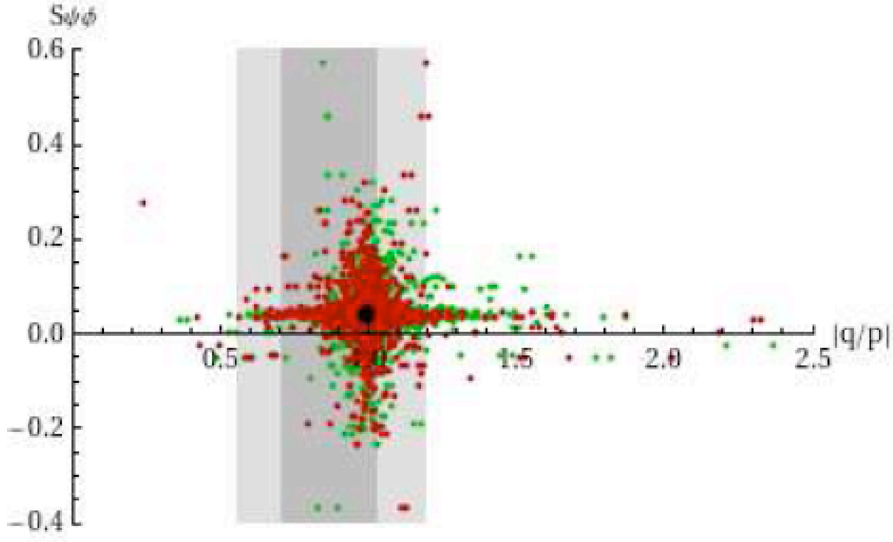
- ☞ with bounds on |q/p|, $S(D^0 \to K_S\phi)$ can hardly be > 1%
- ☞ holds in general in absence of direct ~~C~~P as fction of x,y
- ☞ more intriguing to check for $D^0 \to K^+K^-$

Andrzej Buras has authorized me to make the following statement:

He is willing to bet his beard that LHT models would lead to

observable $\not{CP}$ in D decays!

BBBR



large CP-violating effects in both $B_s - \bar{B}_s$ and $D^0 - \bar{D}^0$ unlikely

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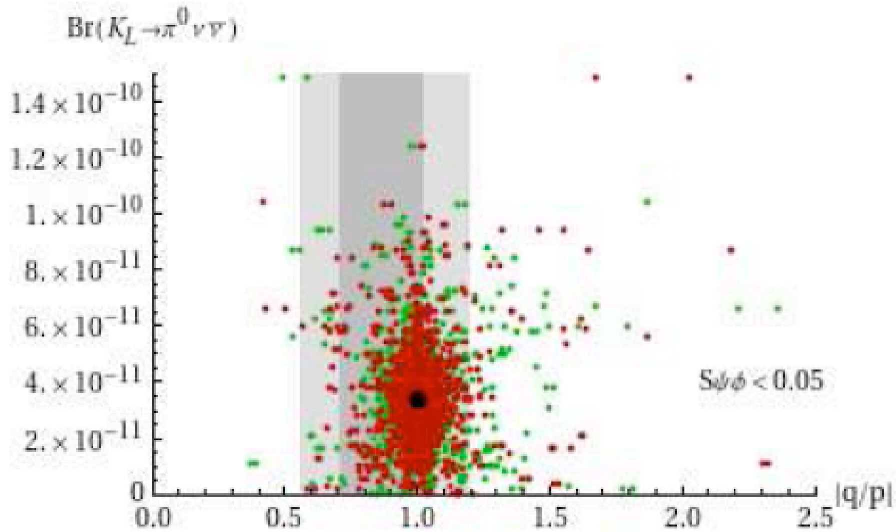
simultaneous large CP-violating effects in both $D^0 - \bar{D}^0$ and rare K_L decays possible



(1.3) ~~CP~~ in partial rates

Well suited channels:

- $D^0(t) \to K^+K^-, \pi^+\pi^-, K^+\pi^-, K_S K^+K^-, K_S\pi^+\pi^-$
- $D^\pm \to K_S\pi^\pm$

Channel possible only at Super-Flavour Factory:

- $D^0 \to l^- \nu K^+$ vs. $D^0 \to l^+ \nu K^-$

~~CP~~ in $L(\Delta C=2) \to \phi_{NP}$ & $\varepsilon_{NP} = 1 - |q/p|$

- CFD: $D^0 \to K_S\phi$ $\quad A_{CP}(t) = (x_D \sin\phi_{NP} - y_D \varepsilon_{NP} \cos\phi_{NP})(t/\tau)$
- SCSD: $D^0 \to K^+K^-, \pi^+\pi^-$ $\quad A_{CP}(t) = (x_D \sin\phi'_{NP} - y_D \varepsilon_{NP} \cos\phi'_{NP})(t/\tau)$
- DCSD: $D^0 \to K^+\pi^-$ -- the SM amplitude suppress. by $tg^2\theta_C$

➥ need to measure x_D & y_D accurately & independently

II ~~CP~~ in Final State Distributions

Four reasons for going beyond 2-body modes

❶ in 2-body modes one probably has to aim for

10^{-3} sensitivity levels -- systematics?

amplitude for $D \to 2P$, VP merely a number

➥ direct ~~CP~~ can be faked by detector biases, production asymmetries etc.

❷ In $D \to 3P$, $4P$, … ~~CP~~ can arise in final state distributions --

- local asymmetries will be larger than integrated ones.
- can rely on relative rather than absolute calibration

❸ Such asymmetries subject to more internal constraints

❹ can give us more info on the NP operator generating them.

➥ ultimate tool for CP studies

$D \rightarrow PPP$

A Catholic Scenario:

single path to heaven: asymmetries in the Dalitz plot

The challenge: search for

- presumably small asymmetries -- ~ 1 % ... 0.1 % --
- in subdomains of the Dalitz plot
- shaped by non-perturb. dynamics
  - ➥ statistical fluctuations !?

How to deal with them?

need

- lots of statistics
- final states with (multi)neutrals
- robust pattern recognition
- some theoretical guidance!

robust pattern recognition

Can learn a lot from astronomers -- typically they have little

a priori knowledge of

where to look for

what kind of sources!

→ `significance' $\sigma = (N_{on} - N_{off})/(N_{on} + N_{off})^{1/2}$

CP signal both in amplitudes and phases!

Intriguing suggestion by J.Miranda, I.Bediaga from CBPF(Rio):

- adopt this procedure for CP asymmetries in Dalitz plot (also adopted by P. Auger Collab.!)

bin-by-bin `significance' $\sigma(i) = (N(i) - \overline{N}(i))/(N(i) + \overline{N}(i))^{1/2}$

A New `Miranda' Procedure for Dalitz CP Studies

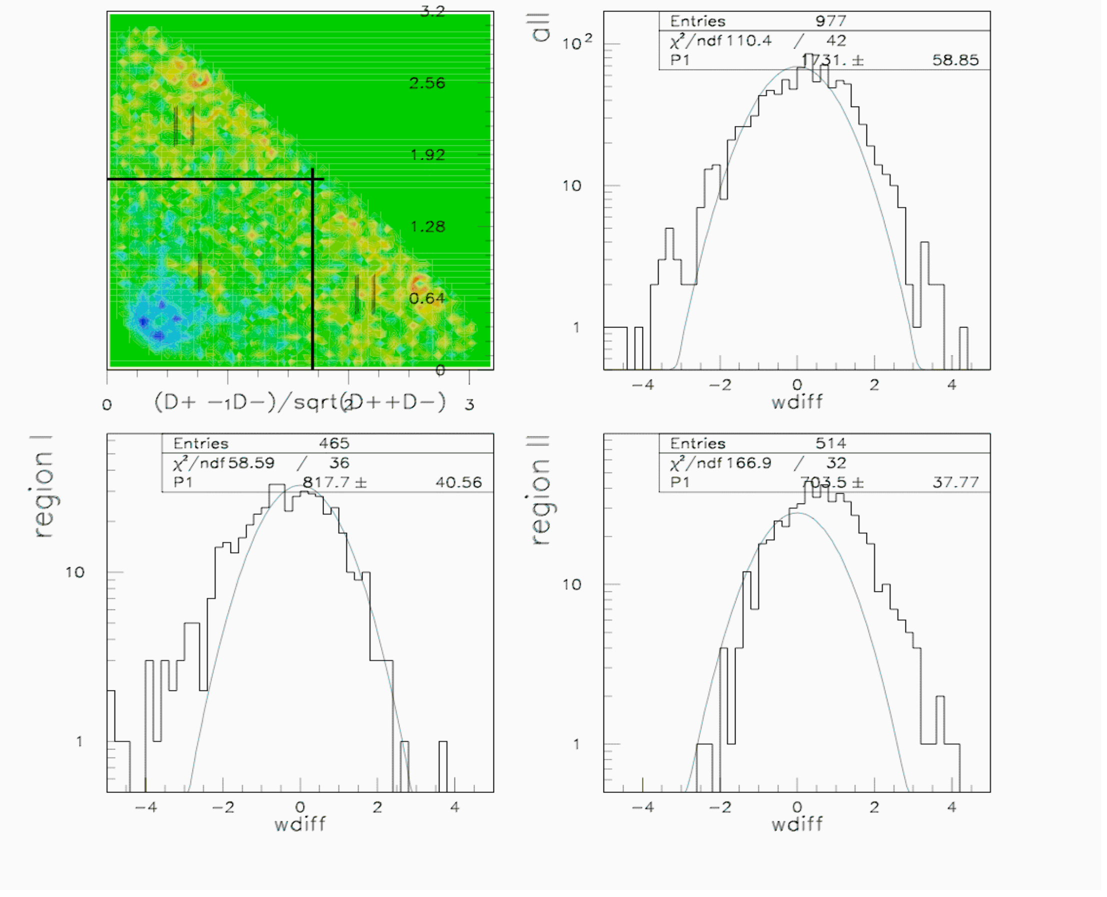
I. Bediaga, ibi, A. Gomes, G. Guerrer, J. Miranda, A. Reis

$D^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$

$\Delta\delta = 3.6^{o}$

$\sigma(i)$ distrib. F. whole DP

$\sigma(i)$ distrib. for subregions



✍ probably more lessons to be learnt from astronomers

"Copying is highest form of flattery!"

$D \to PPPP$

A Calvinist Scenario

many paths to heaven -- success reveals Heaven's blessing

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

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. $\bar{\Gamma}_2$: ~~CP~~ in partial widths
- T odd moments $\Gamma_3, \bar{\Gamma}_3 \neq 0$ can be faked by FSI

  yet $\Gamma_3 \neq \bar{\Gamma}_3 \Longrightarrow$ ~~CP~~!

$D \to K \bar{K} \mu^+\mu^-$ likewise

yet many other ~~CP~~ observables

-- `optimal' one depends on underlying dynamics

III Rare 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'

- 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 $\times 10^{-8}$

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

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☺ New Physics transition operators local `Penguins'

☺ can/should analyze lepton spectra

☹ I am skeptical a convincing case for NP can ever be made from these transitions -- unless

☺ ~~CP~~ emerges!

- $D^0 \to \mu^+\mu^-$ doable at LHCb
  - SM: $BR(D^0 \to \mu^+\mu^-) \sim O(10^{-12})$
  - CDF: $BR(D^0 \to \mu^+\mu^-) < 5.3 \times 10^{-7}$

  no cute enhancement in SUSY as for $B_s \to \mu^+\mu^-$
  - Golowich et al., arXiv:0903.2830: list of NP scenarios
- $D^0 \to \gamma\gamma$ not doable at LHCb
  - NP can generate SD contributions
  - LD contributions here can affect $D^0 \to \mu^+\mu^-$
- 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

IV Outlook

Remember … with the

- beginning of the LHC,
- continuation of flavour factories,
- studies of neutrino oscillations

we could be (I expect we are) at the eve of a

- paradigm shift,
- maybe even a revolution

in our understanding of nature's grand design.

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Let us prove to be worthy of this opportunity!

- Discovery of D^0 oscillations greatly enhances chances for
  - observing $\not{CP}$ in charm decays,
  - establishing it as manifestations of NP
  - differentiating direct vs. indirect $\not{CP}$
  - ➥ important to measure x_D and y_D accurately
- present absence of $\not{CP}$ signal not telling
- \`realistically' can \`expect' small effects only

$$\mathcal{O}(10^{-2}) - \mathcal{O}(10^{-3}) - \mathcal{O}(10^{-4})$$

- NP signal/SM backgr. probably larger than in B decays
- no \`compelling' models, yet viable = *non*-ad-hoc models exist

Areas of top priority

➼ ~~CP~~

experimental tasks

host of promising modes (doable at LHCb)

✍ $D^\pm \to K_S\pi^\pm, \pi^+\pi^-\pi^\pm, K^+K^-\pi^\pm, \dots$

✍ $D^0(t) \to K_SK^+K^-, K_S\pi^+\pi^-, K^+K^-, \pi^+\pi^-, K^+\pi^-, K^+K^-\pi^+\pi^-, K^+K^-\mu^+\mu^-, \dots$

desirable modes (not doable at LHCb?)

✍ $D^0 \to l^- \nu K^+$ vs. $D^0 \to l^+ \nu K^-$ (best at threshold?)

✍ final states with (multi)neutrals

theoretical tasks in interpreting data

☞ dealing with FSI

☞ analyzing Dalitz plots in 3-body modes

☞ treating >3-body modes: T-odd moments etc.

- do not count on miracles from theorists, but can expect a positive learning curve -- *if* faced by accurate data

  - a great deal of expertise exists in the hadronic community that can be applied in CP studies of Dalitz plots etc. with great profit!

  Hanhart, Meissner, ibi trying to create working group

- Rare decays

  - skeptical that $D_{(s)} \to \gamma X$, $l^+l^- X$ can teach us about NP

  - promising modes

    - $D^0 \to \mu^+\mu^-$

    - $D^0 \to \gamma\gamma$ (best at threshold?)

      in its own right and as LD background to $D^0 \to \mu^+\mu^-$

☞ General question:

How useful/efficient/desirable/essential is running at charm threshold?

➼ not `merely' a "Ceterum censeo fascinum esse studiandum"
increased `maturity' ⟹ `phase transition'!

- experimental observation of D^0 oscillations
- theoretical `awakening' concerning NP affecting charm

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So let us jump into action ...

The Few

The Few

The Proud

The Few

The Proud

The Charm Physicists!