Come Botticelli Nella Sistina -- On The Beauty of Charm

Ikaros Bigi (Notre Dame du Lac)

Come Botticelli nella Sistina?

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{Botticelli $\Delta C \neq 0$} cannot match {Michelangelo $\Delta B \neq 0$}

Come Botticelli nella Sistina?

{Botticelli $\Delta C \overline{=} 0$} cannot match {Michelangelo $\Delta B \neq 0$}

yet is still Botticelli, i.e., first-rate!

Study of

$\Delta S \neq 0$ instrumental in creation of SM

- τ - θ puzzle $\Longrightarrow$ ~~P~~ !
- production >> decay $\Longrightarrow$ families !
- no FCNC $\Longrightarrow$ charm !
- $K_L \rightarrow \pi\pi$ $\Longrightarrow$ ~~CP~~ !

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now race is on which one (+Δtop $\neq 0$) will show incompleteness of SM quark flavour dynamics

Emergence of D^0 oscillat. with $x_D, y_D \sim 0.005$ - 0.01 --

$\Delta C \neq 0$ close behind $\Delta B \neq 0$ in this race!

Alternate Title

Could Charm's Third Time Be the Real Charm?

"First Time"

J/ψ Revolution of 1974

Paradigm Shift!

"Second Time"

Observation of D_{sJ}, X, Y, Z … by the B fact. & CDF

Socrates: "Realizing you do not know = *1st step to wisdom!*

Remember -- NP could be from Strong Dynamics

"Third Time"

Since 2007: Compelling evidence has surfaced for D oscillations

A tactical draw in the struggle for gaps in the SM --

x_D & y_D while possibly generated by SM alone,

could contain large contributions from NP --

yet a strategic victory in sight:

CP studies in the future will decide the issue

possibly paving the way for a New SM to emerge!

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No matter.
Try again. Fail again. Fail better.

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☞ baryogenesis requires NP with ~~CP~~!

➥ for me not *if*, but when and what NP

The Plot

I Uniqueness of Charm

II The Present `Draw' on D^0 Oscillations

III $\not{CP}$ as Footprint of NP

IV $\not{CP}$ in Final State Distributions

V Conclusions -- a Plan for Action

Epilogue: Physics a la Bismarck

Truth in advertising: will *not* talk about

- charm data needed/helpful as input for B analysis
- charm baryons and their SL decays
- double charm baryons

I Uniqueness of Charm

SM:

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

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NP:

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

- SM `background' much smaller for FCNC of *Up*-type quarks
  - cleaner (not larger) signal:

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

Up-type quarks: u c t

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

- top quarks do not hadronize $\Longrightarrow$ no T^0 - $\overline{T}^0$ oscillations

  hadronization while hard to force under theor. control

  enhances observability of ~~CP~~

- up quarks: no π^0-π^0 oscillations possible

  CP asymmetries in partial widths basically ruled out by CPT

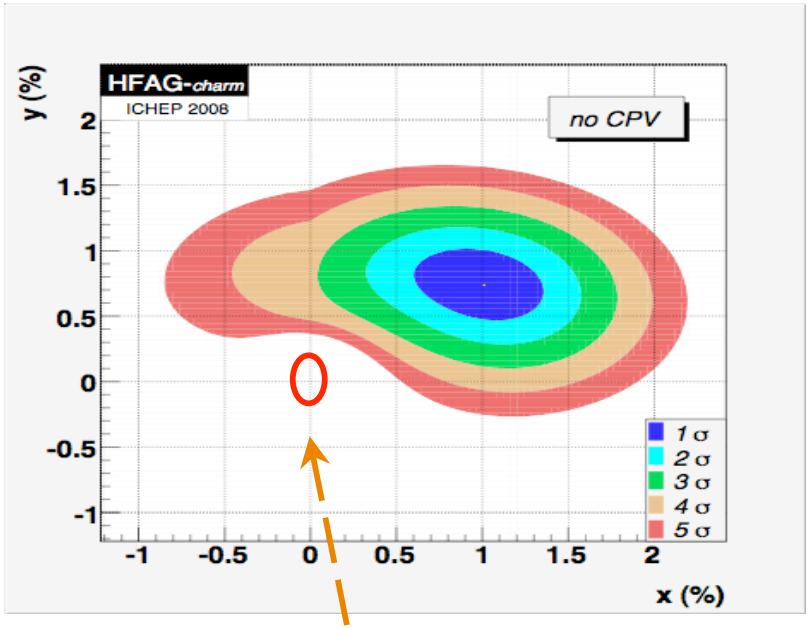
basic contention:
charm transitions are a unique portal for obtaining a novel access to flavour dynamics with the experimental situation being a priori favourable (apart from absence of Cabibbo suppression)!

II The Present `Draw' on D^0 Oscillations

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

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

$x_D = (1.00 \pm 0.26)\ \%$
$y_D = (0.76 \pm 0.18)\ \%$



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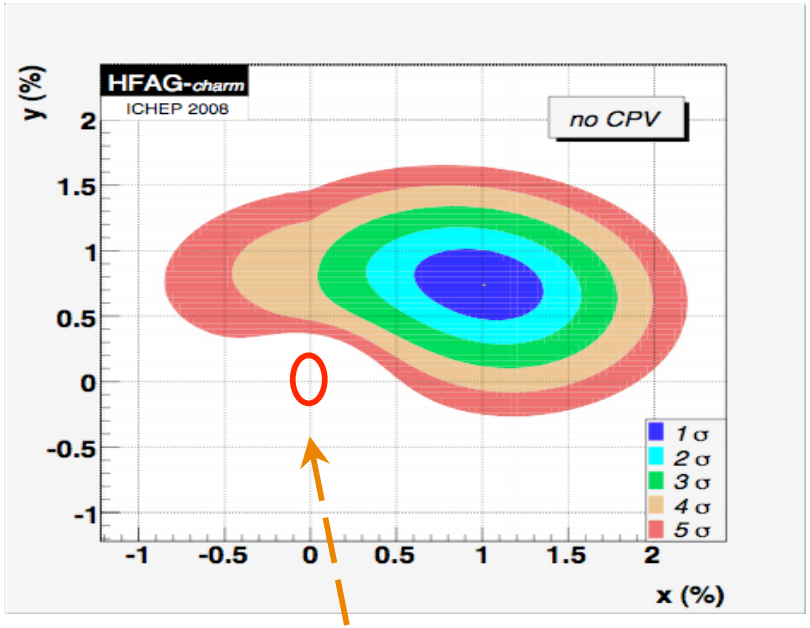

$(x_D, y_D) = (0,0)$

- most likely value in SM?
  x_D (SM), y_D (SM)~ $O(10^{-3})$
- can one rule out 0.01 ? No!

SM: similar numbers for x_D, y_D
-- yet dynamical & theoretical situation quite different!

Interpretation?

☞ *If* $x_D > 1\% \gg y_D$ could be interpreted as manifestation of New Physics -- yet such a scenario has basically been ruled out

☞ data: $x_D, y_D \sim 0.5 - 1\%$

✍ could be due `merely' to SM dynamics --

- still a great discovery & must know x_D vs. y_D irrespective of theory } 'Nobel' goal

Guy W.

✍ yet might also contain large contributions from NP

breakthrough required for more accurate SM prediction

☞ knowing x_D vs. y_D also a practical goal

- important validation of (presumably small) time dep. ~~CP~~
- input for differentiating sources of ~~CP~~ (see later)

➥ D^0 oscillations a `tactical' draw in the `war' between `us' vs. the SM

Knowing x_D & y_D accurately important, albeit intermediate goal

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III $\not{CP}$ as Footprint of NP

Discovery of D^0 oscillations

-- $x_D = (1.00 \pm 0.26)\%$, $y_D = (0.76 \pm 0.18)\%$ --

a great and essential experimental achievement;

Tactically a draw in our battle against the SM --

yet it promises a strategic victory

in the fields of $\not{CP}$

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. $0.03|_{SM}$!

(3.1) 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 at an observable rate!

new situation!

☺ adds a second coherent amplitude needed to make a complex phase observable

☺ within SM its amplitude carries tiny phase ~ $O(\lambda^4)$

➥ even non-leading NP contribution can provide leading CP phase

$$A_{CP}(t) = (x_D \sin\phi_{CP} - y_D \varepsilon_{CP} \cos\phi_{CP})(t/\tau) + \ldots$$

$x_D, y_D = 0.01$, $\sin\phi^{SM}_{CP}$, $\varepsilon^{SM}_{CP} < 0.001$

➥ $A^{SM}_{CP}(t) < 10^{-5}$ vs. $A^{NP}_{CP}(t) < 10^{-2}$

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- lots of statistics
- good time resolution
- efficient & flexible trigger

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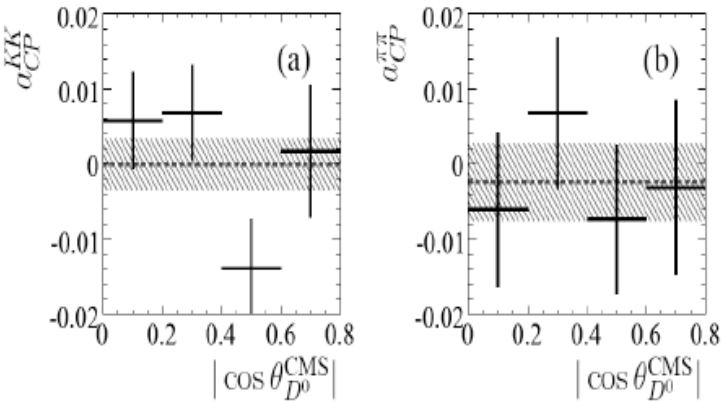
☺ altogether excellent news for LHCb & Experiment X (≠ Project X!) well suited channels for analyzing oscillations & ~~CP~~

$$D^0\,(t) \rightarrow K_S\phi, K^+K^-, \pi^+\pi^-, K^+\pi^-$$

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

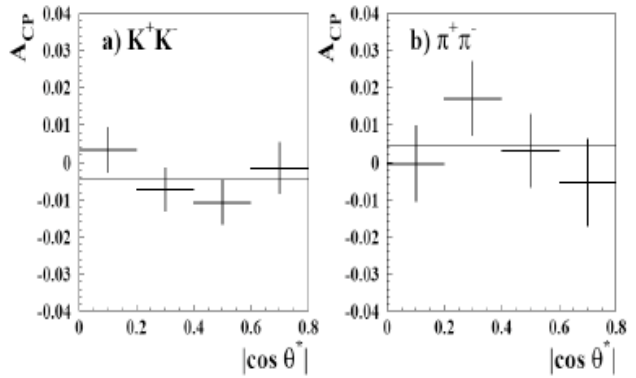
$D^0 \to K^+K^-$ and $\pi^+\pi^-$

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

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

- $a_{SL} \sim 0.1$ 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 $\Delta\Gamma/\Delta M \sim O(1)$ & $\sin\phi_{CKM,eff} << 1$
- $a_{SL}(B_d) \sim 4 \times 10^{-4}$ 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

(3.2) 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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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

- quadratic mass divergence cancelled on 1-loop level with bosons unlike SUSY
  - SM + $(W,Z,A)_H$ + T_H + $\Phi_{I=1}$
- non-SM particles <1 TeV
  - need T parity: T+: SM, T_H^+
    T-: $(W,Z,A)_H^-$, T_H^-, $\Phi_{I=1}^-$ + mirror fermions' q_H

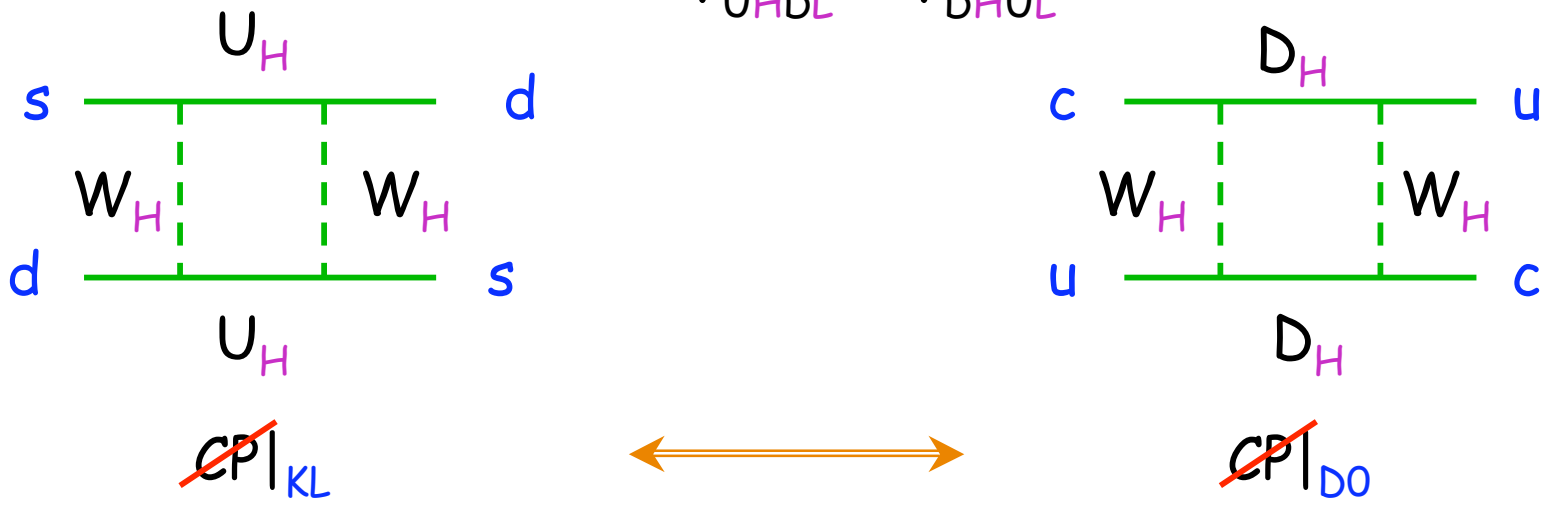
flavour dynamics not part of the motivation!

✍ even so: LHT ≠ MFV

2 new 3x3 mixing matrices for coupling U_H to D_L & D_H to U_L

$$U_H\, V_{UHDL} = V_{DHUL}\, V_{CKM}^*$$

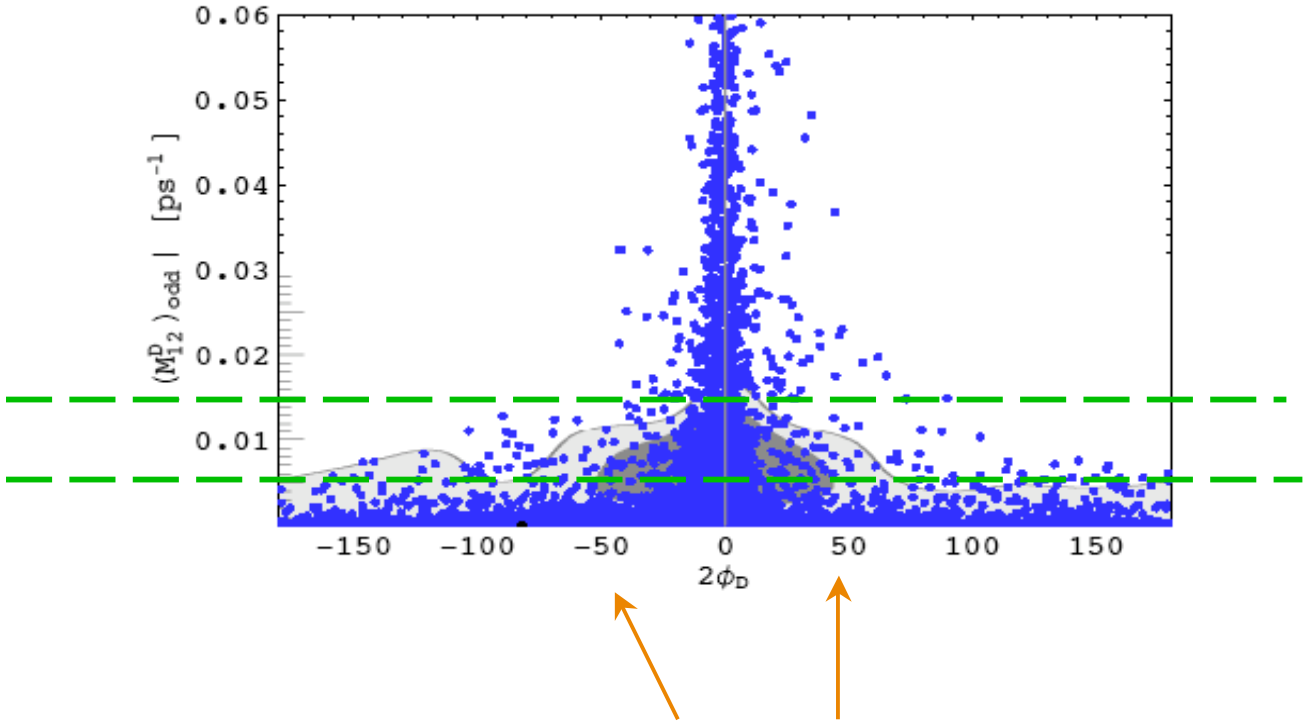
➥ $V_{UHDL} \sim V_{DHUL}$



➥ LHT could

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

Monika Blanke[a,b], Andrzej J. Buras[a], Stefan Recksiegel[a],
Cecilia Tarantino[a] and Selma Uhlig[a]



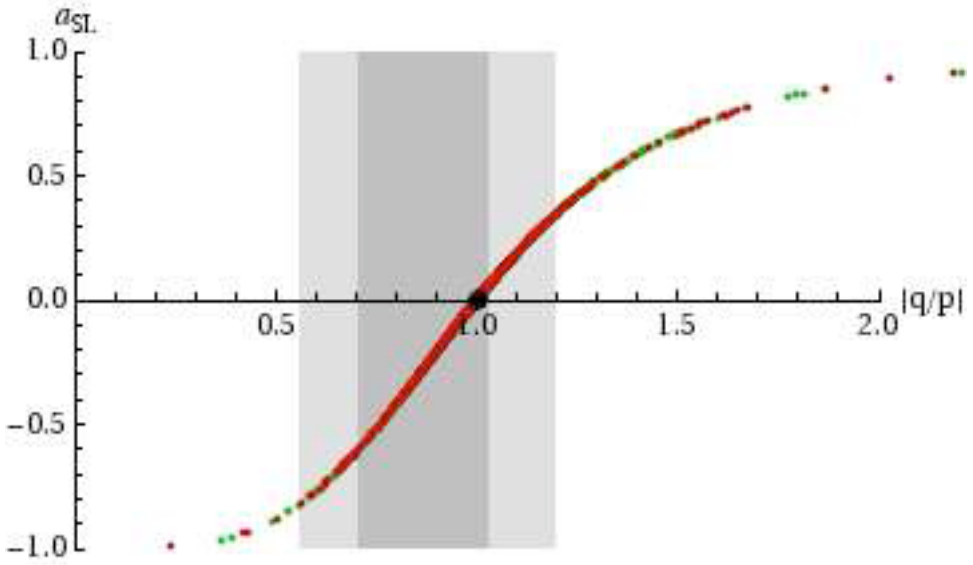
oscillation phase $2\phi_D$ = [-50°,+50°]

➥ 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. $D^0 \to l^+ \nu K^-$

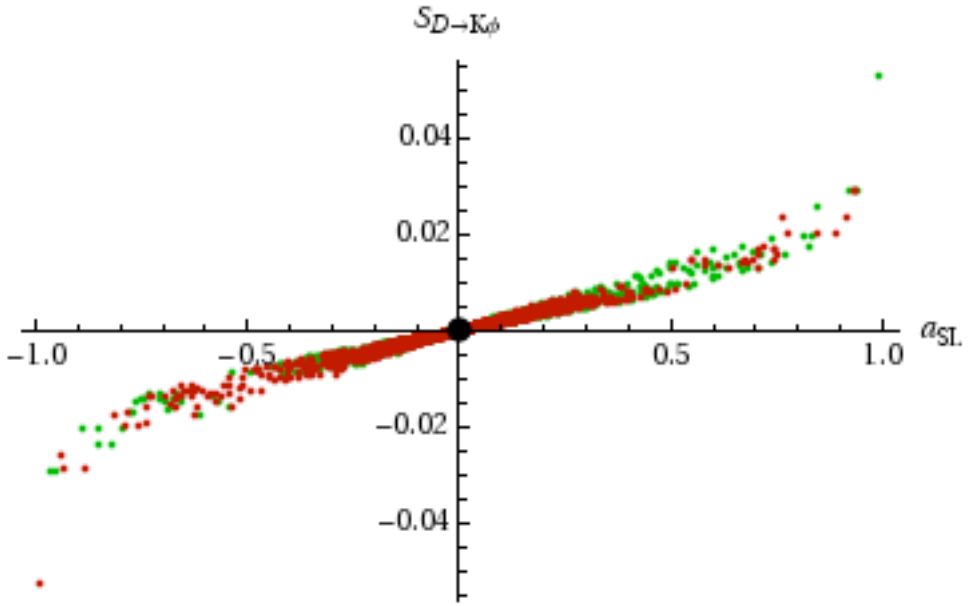
$a_{SL} = [1-|q/p|^4]/[1+|q/p|^4]$



BBBR= IB, M. Blanke, A. Buras, S. Recksiegel:
arXiv:0904.1545; JHEP 07 (2009) 097

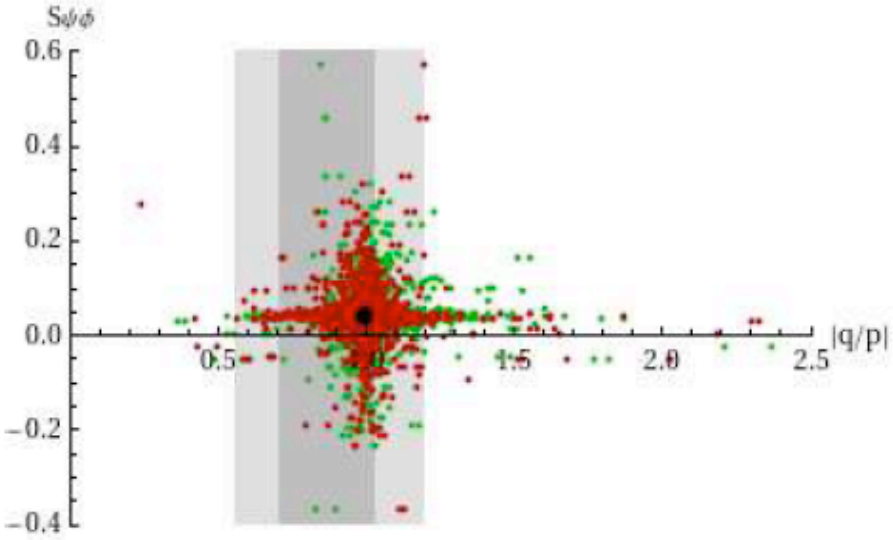
$D^0 \to K_S\phi$

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



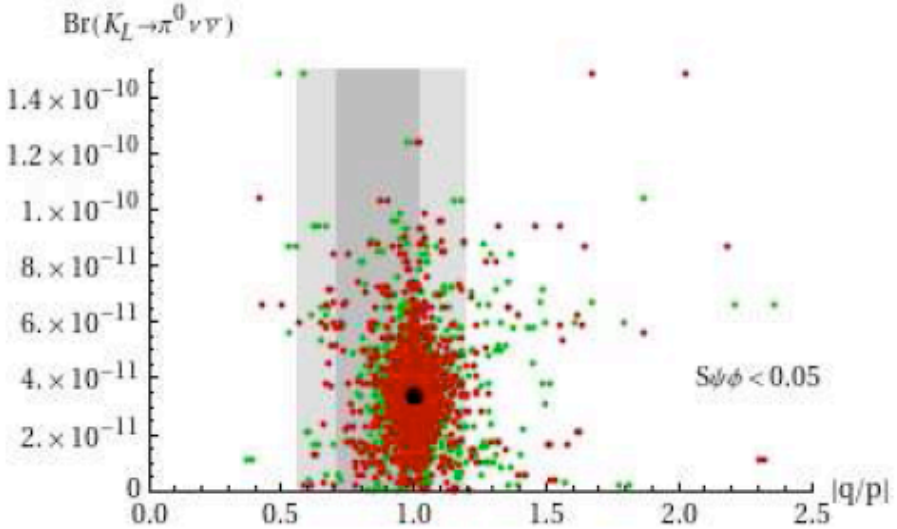
3 points

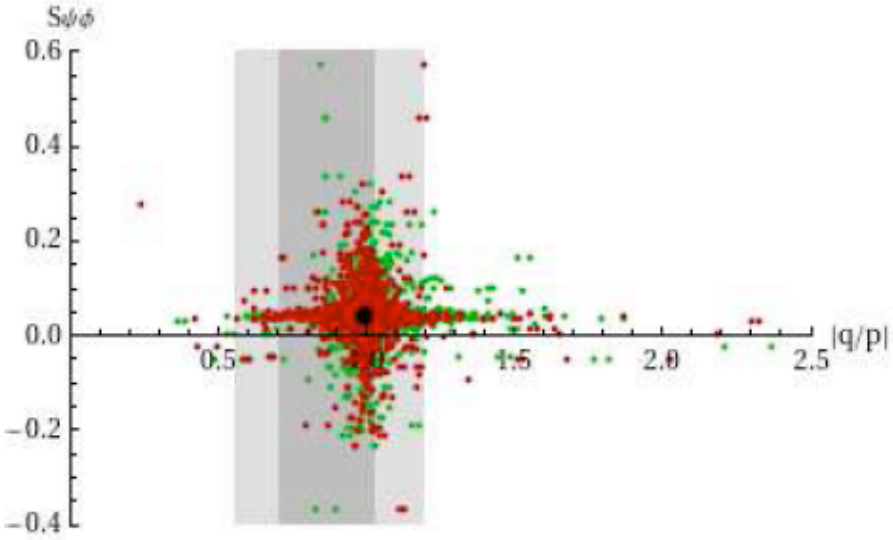
- with bounds on $|q/p|$, $S(D^0 \to K_S\phi)$ can hardly be > 1%
- holds in general in absence of direct CP as fction of x,y
- more intriguing to check for $D^0 \to K^+K^-$



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

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





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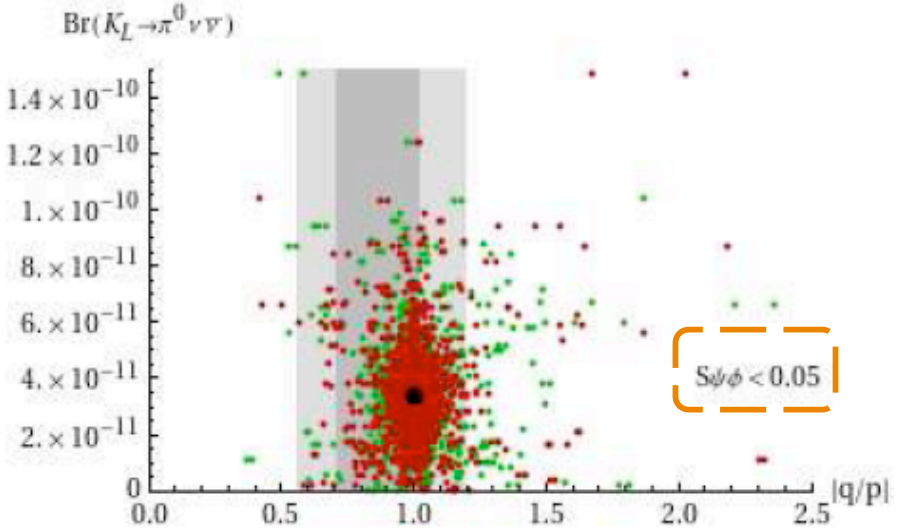

Andrzej Buras has authorized me to make the following statement:

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

observable ~~CP~~ in D decays!

III $\not{CP}$ in Final State Distributions

Four reasons for going beyond 2-body modes

1. 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 $\not{CP}$ can be faked by detector biases, production asymmetries etc.

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   ➥ ultimate tool for CP studies

D → 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!

- ✍ lessons on pattern recognition to be learnt from astronomers

- ☞ working group of theorists & experimentalists founded by Ch. Hanhart, U.-G. Meissner, ibi to deal with

  CPV in Dalitz studies

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a group of post-avantgarde artists who
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$D \to PPPP$

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

V Conclusions -- a Plan for Action

- Discovery of D^0 oscillations greatly enhances chances for
  - observing ~~CP~~ in charm decays,
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$$O(10^{-2}) - O(10^{-3}) - O(10^{-4})$$

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

A general aside:

- Electroweak dynamics: CP studies in charm sector

`hypothesis-generating' rather than `hypothesis-probing' research

-- yet LHT scenarios could provide high p_t-low p_t connection

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

- funding agencies favour `hypothesis-probing' research
- B factories prime examples of `hypothesis-probing' research
- once LHC finds New Physics in high p_t collisions
  - ➥ B & τ program becomes `hypothesis-probing' research

✍ LHT scenarios might achieve same connection for charm

- excellent news for LHCb -- host of promising modes for ~~CP~~
  - ✍ $D^{\pm} \to K_S\pi^{\pm}$, $\pi^+\pi^-\pi^{\pm}$, $K^+K^-\pi^{\pm}$,...
  - ✍ $D^0(\bar{t}) \to K_S K^+K^-, K_S\pi^+\pi^-, K^+K^-, \pi^+\pi^-$, $K^+\pi^-$, $K^+K^-\pi^+\pi^-$, $K^+K^-\mu^+\mu^-$,...
- 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!

- not `merely' a "Ceterum censeo fascinum esse studiandum"

  increased `maturity' ⟹ `phase transition'!

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

BBBR arXiv:0904.1545[hep-ph];
Grossman et al., arXiv:0904.0305, 0903.2118
Golowich et al., arXiv:0903.2830.

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CDF!

$$A_{CP}(t) = (x_D \sin\phi_{CP} - y_D \varepsilon_{CP} \cos\phi_{CP})(t/\tau) + \ldots$$

x_D, y_D given by data, $\sin\phi_{CP}$, ε_{CP} given by theory

(t/τ) under control of experiment

➥ trigger on $t \gg \tau$ to enhance observable asymmetry
(Giovanni Punzi)

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Bismarck:

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➥ it is our duty --

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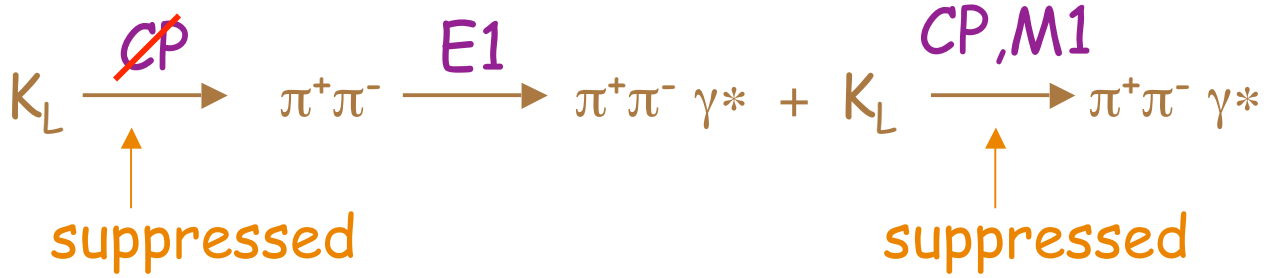
➥ it is our duty -- & there is fame within your grasp!

Back-up Slides

So far all observed ~~CP~~ in partial widths -- except for one:

$K_L \to \pi^+\pi^- e^+ e^-$



ϕ = angle between $\pi^+\pi^-$ & e^+e^- planes analyzes γ^* polarization

interference between CP E1 & CP M1 amplitude

➥ Forw-Backw asymmetry A in ϕ (Sehgal et al.)

A= 14 % driven by ε=0.002

price: BR ~ 3×10^{-7}

} trade BR for size of asymm.!

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

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

    $BR(D^0 \to \gamma\rho^0)$ ~ 10^{-6}- 10^{-5} , $BR(D^0 \to \gamma\phi)$ ~ 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
  - $D_{(s)} \to l^+l^- X_u$
  - $D_{(s)} \to l^+l^- K/\pi\ldots$

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

  - theoret. control helped by analyzing $m(l^+l^-)$
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    $BR(D \to l^+l^-\pi/\rho) \sim 10^{-6}$
  - FOCUS: $BR(D^+ \to l^+l^-\pi^+) < 8.8 \times 10^{-6}$

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

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☺ ~~CP~~ emerges!

- $D^0 \to \mu^+\mu^-$ doable at LHCb
  - SM: BR($D^0 \to \mu^+\mu^-$) ~ O(10^{-12})
  - CDF: BR($D^0 \to \mu^+\mu^-$) < 5.3×10^{-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($D^0 \to \mu^+e^-$) < 8.1×10^{-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