SU(3) anatomy of hadronic charm decays

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Based on works with G.Hiller and St.Schacht,
Phys.Rev. D87 (2013) 014024 (arXiv:1211.3734), arXiv:131x.xxxx

Outline

Why is charm so difficult?

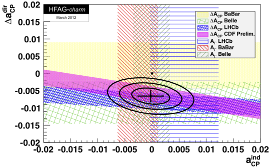
Main problem: missing large hierarchies for m_c

Basically our usual methods don't work here:

- Considering charm as "light" ($m_c \sim m_{u,d,s}$) does not work
- Operator-product expansion (OPE) in $\Lambda_{\rm QCD}/m_c$ questionable
- "Energetic" decay products e.g. in $D \to PP$ have $E < 1$ GeV
- Three-body MEs still extremely hard on the lattice
- Also: SU(3) severely broken

➥Improvement of theoretical description urgently needed!

ΔA_{CP} has been a large motivator...



Moriond 2013

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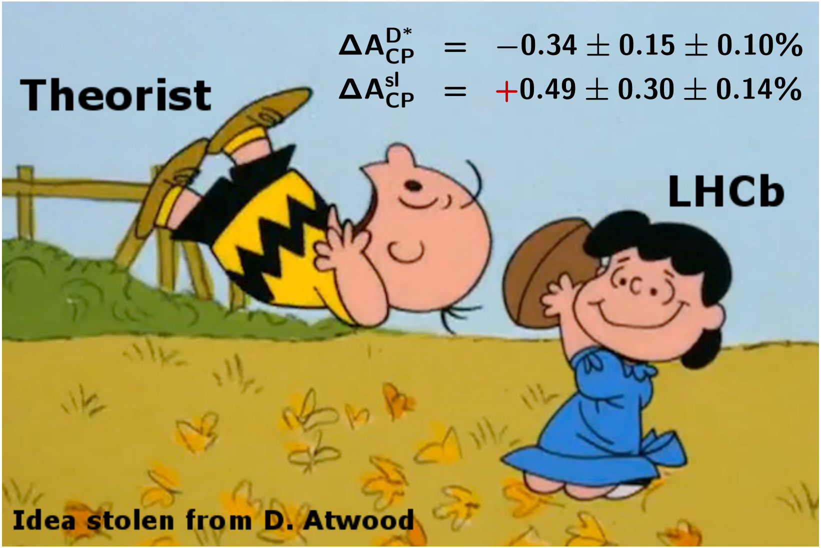
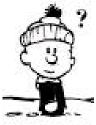


However: WA still about 3σ from zero: $\Delta a_{\rm CP}^{\rm dir} = (-0.33 \pm 0.12)\%$
Independent interest in understanding dynamics at $\mu \sim 1$ GeV

Another Outline

Long discussion whether ΔA_{CP} is NP or not...
➥We need more information!



What are we aiming at?

- NP or enhanced penguins - other modes should be affected
- Independent of enhancement: SM implies pattern in CPV
- Find a description of the full $D \to PP$ data, not just ΔA_{CP}
  ➥Branching ratios and CP asymmetries, $\delta_{K\pi}$
- Find (more) discriminants between NP and SM

How are we doing this?

- Exact limits do not work well
  ➥Include corrections!

Amplitudes for non-leptonic decays

1. Use existing hierarchy $M_W \gg m_c$ to build an effective theory
   ➥Local operators with known coefficients C_i (box to fish)
2. Classification by level of Cabibbo-suppression:
   - $c \to s\bar{d}u$: Cabibbo-favoured (CF), $V_{cs}^* V_{ud} \approx 1$,
   - $c \to s\bar{s}u(\bar{d}du)$: Singly-Cabibbo-suppressed (SCS), $V_{cs}^* V_{us} \approx -V_{cd}^* V_{ud} \approx \lambda$.
   - Additionally in SCS modes: $V_{cb}^* V_{ub} \sim \mathcal{O}(\lambda^5)$, $r_{CKM} = |V_{cb}^* V_{ub} / V_{cs}^* V_{us}| \sim 0.2\%$
3. Find a way to determine matrix elements of the operators
4. Calculate via, e.g.,

$$\mathcal{A}^{CF} = V_{cs}^* V_{ud} \sum_i C_i \langle PP|\mathcal{O}_i|D\rangle$$

These matrix elements main objects of this talk

Flavour SU(3) Symmetry

Wigner-Eckart-Theorem expresses MEs in terms of fewer reduced MEs and Clebsch-Gordan-coefficients

SU(3) flavour symmetry...

- is approximate, for $m_u = m_d = m_s$
- does not allow to calculate MEs, but relates them
- provides a model-independent approach
- includes FSI

The analysis...

- exhibits different structures for SM and NP
- determines reduced MEs from data
  ➥ improves automatically with coming measurements!

Breaking SU(3)

Observation: $BR(D^0 \to K^+K^-)/BR(D^0 \to \pi^+\pi^-)|_{\rm exp} \approx 2.8 \neq 1|_{\rm SU(3)}$

➥ 30% effect on amplitude level possible explanation! [Savage '91]

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The symmetry-breaking term is known: $\mathcal{H}_{\rm mass} = -\sum_q m_q \bar{q} q$

- In principle systematic expansion in $\epsilon = m_s/\Lambda_{\rm QCD} \sim 30\%$ possible [Savage'91,Kwong/Rosen'93,Chau/Cheng'94,Gronau et al.'95,Grinstein/Lebed'96,Hinchliffe/Kaeding'96]
- How large is the SU(3)-expansion parameter?
- Is the number of reduced MEs tractable?

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- Is the number of reduced MEs tractable?

In the remainder of this talk:

➡ Check if expansion works for full $D \to PP$ data (Confirmed for subset $D \to P^+P^-$ e.g. in [Feldmann et al., Brod et al.'12])

➡ Number of MEs large, but possible to handle

➡ Find ways to reduce number of MEs for sharper predictions (See also Yuval's talk for a different idea)

➡ This paves the way to address the question of NP

Some details on the method

Generally:

- Classify initial/final states and Hamiltonian, e.g. $(D) \sim (\bar{\mathbf{3}})$
- For final states and Hamiltonian:
  tensor products $\rightarrow$ irreducible representations (CG coeffs)
- Classify reduced matrix elements (MEs)

SU(3) limit for $D \rightarrow P_8 P_8$:

- 3 MEs w/o CPV
- 2 more $\sim r_{\mathrm{CKM}}$
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SU(3) analysis to first order breaking:
[Pirtskhalava/Uttayarat,Grossman/Robinson,Hiller/MJ/Schacht '12]

- Breaking by quark masses, we leave isospin intact, $\epsilon \sim (\mathbf{8})$
- $\mathcal{H}_\epsilon \sim \mathcal{H}_0 \otimes (\mathbf{8}) \sim 11$ representations (!)
- Lots of new MEs: $(\epsilon \times r_{\mathrm{CKM}} \rightarrow 0!)$
  ➥ $\mathcal{O}(1) + \mathcal{O}(\epsilon) = 3 + 15 \rightarrow 11$, due to linear dependencies

What can we do with 11+2 MEs?

Questions we want to address first: [Hiller/MJ/Schacht'12]

- Can the full dataset $D \to PP$ be described with reasonable $SU(3)$ breaking?
- How large the penguin enhancement has to be?
- What are "minimal scenarios" to explain the data?
- Can we differentiate between NP scenarios?

In this process:

- Include all available data on $D \to PP$
- Avoid prejudices about representations
- ➥ These goals complicate the analysis a lot

Quantifying $SU(3)$ breaking

Quantifying $SU(3)$ breaking non-trivial. Here:

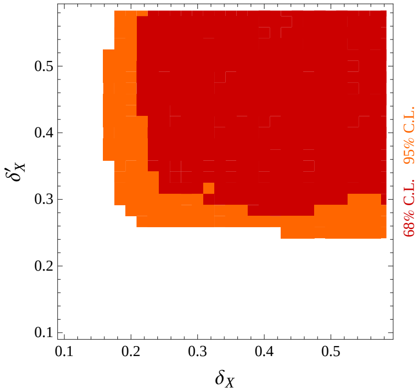
1. Maximum of normalized $SU(3)$-breaking ME (δ_X)
   ➥Ignores suppression by Clebsch-Gordan coefficients
2. Maximum of normalized $SU(3)$-breaking amplitude (δ'_X)
   ➥Ignores possible cancellations

New: Include all MEs(!)
New: Include all data

➥Classify all solutions
➥$SU(3)$ breaking $25 - 40\%$ ok

"Minimal solutions":

- need at least two $\mathcal{O}(\epsilon)$ MEs
- need at least one ME from higher representations

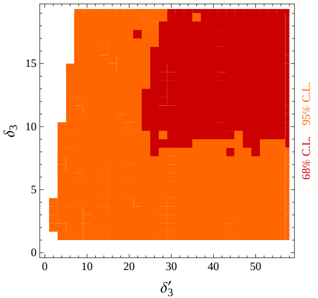


Quantifying "penguin enhancement" (post-Moriond)

For penguins, analogous to SU(3):

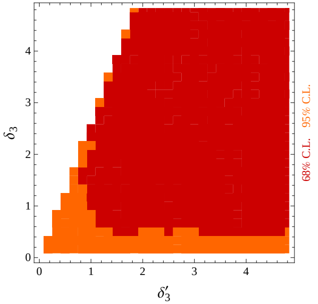
1. δ_3 max. normalized ME $\sim r_{\rm CKM}$
2. δ_3' max. amplitude $\sim r_{\rm CKM}$

➥ $\delta_3^{(\prime)}$ remains huge for 68% CL



Reasons?

- Not only $\Delta a_{\rm CP}$!
- Other CPA's with largish c.v's ($D^0 \to K_S K_S, D_s \to \pi^+ K_S, K^+\pi^0$)
  ➥ Without these, 'nominal' δ_3 ok
  Interest in $A_{CP}(D^0 \to K_S K_S)$: enhancement $\sim 1/\epsilon$ expected (see also [Atwood/Soni '12])



➥ More data necessary (surprise!) to

- check largish asymmetries
- obtain compatible values for ΔA_{CP}

Discriminating NP from SM

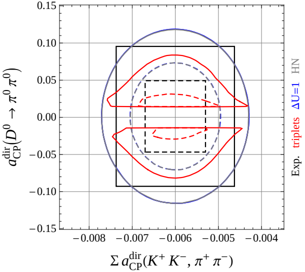
NP sensitivity: different SU(3) structure, $\mathcal{H}^{SCS} = \mathcal{H}^{SCS}_{SM} + \mathcal{H}_{NP}$

- Two options: improve data or theory ($\rightarrow$ less MEs)
- So far, only ΔA_{CP} significant (less so since Moriond)
  ➡2 complex CPV MEs, no predictions with present data

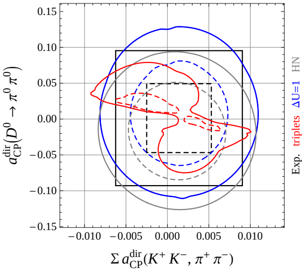
Proof of principle for the future, using pseudo-data:

- Assume LHCb projection for Δa_{CP}, similar precisions for 5 more measurements (LHCb+Belle II+BES III)
- All other uncertainties as today

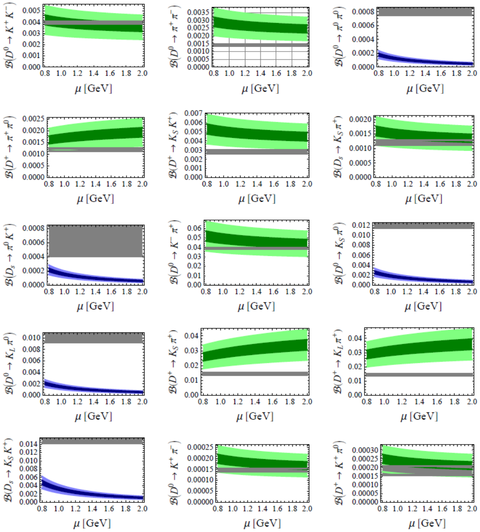
Assume “future” data



Only 3 breaking MEs, present data



Heavy-quark limit in charm decays!?



Heavy-quark limit in charm decays!?

Remember: QCD factorization [BBNS'99,'00,BN'03,Grossman et al.'07]

- MEs for $m_c \to \infty$ in terms of a few universal, non-perturbative objects, e.g. decay constants and form factors
- Corrections of higher orders in α_s are systematically calculable
- Power corrections $\mathcal{O}(\Lambda/m_c)$ are the main problem

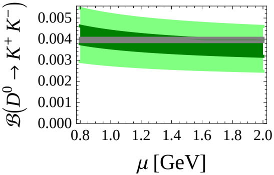
How large are the corrections?

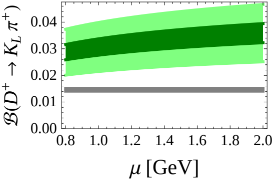
- BR's in heavy-quark limit ($m_c \to \infty$):
  - colour-allowed-tree decays ✔
  - $\mathcal{O}$(colour-suppressed decays) ✔
  - annihilation not included

➥ Reasonable starting point

➥ Assume structure of QCDF to hold

- Power corrections might be large and flavour-dependent





QCDF-structure as SU(3) input I [Hiller/MJ/Schacht '13, in prep.]

QCDF in charm decays is known not to work precisely...

➥ What do we mean by structural input?

1. No constraint in the SU(3) limit
2. No explicit computation of $a_{1,2}^{DM_1M_2}$, $b_{1,2}^{M_1M_2}$
3. No assumption about strong phases
4. No simple $X_{A,H}$ parametrization for annihilation

- ➥ Use relations between amplitudes implied by features of QCDF
- ➥ Match these relations onto SU(3) amplitudes
- ➥ SU(3) constrains general QCDF parametrization

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Starting point universal a_1:

- Pattern of BR's: a_2 has larger corrections than a_1
- SU(3) breaking in a_1: $\mathcal{O}(\alpha_s \times \Lambda/m_c \times m_s/\Lambda \times C_2/C_1 \times 1/N_C^2)$
- QCDF: relative influence in a_2 $C_1^2/C_2^2 \sim 10$ stronger

➡ Assume a_1 flavour-universal, a_2 process-dependent

➡ Yields one relation for MEs in SU(3) approach

QCDF-structure as SU(3) input II

Universal structure of annihilation:

- In QCDF, mainly two annihilation coefficients $b_{1,2}^{M_1 M_2}$
- Both MEs involve identical convolution: $b_2^{M_1 M_2}/b_1^{M_1 M_2} = C_2/C_1$
- However: holds only in one-gluon approximation

➥ allow for $b_2^{M_1 M_2}/b_1^{M_1 M_2} = c$

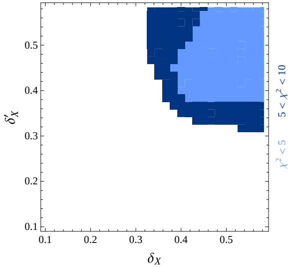
➥ Yields two more relations for MEs in SU(3) approach

➥Third scenario is w.i.p.

QCDF and SU(3) - first results I PRELIMINARY

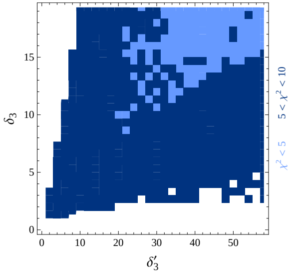
Started analysis in scenarios A and B:

- Sum rules derived ✔
- Minima with $\chi^2/\mathrm{dof} \sim 1$ ✔
- $\delta_{X^{(\prime)}} < 50\%$ ✔



Scenario B ($\chi^2/\mathrm{dof} \sim 5/5$):

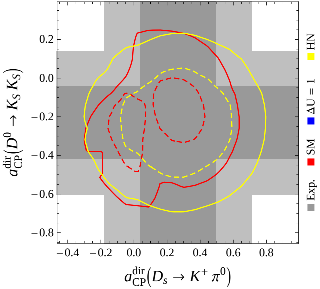
- Sum rules are restrictive
  - but fit works!
- Somewhat larger SU(3) breaking?
  - plots not directly comparable
  - dof not constant over the plot!
- Little change in penguin enhancement



QCDF and SU(3) - first results II PRELIMINARY

Scenario B continued:

- Fit with all remaining MEs
- Structures emerge with present data



➥QCDF yields non-trivial constraints for SU(3) analysis
➥We are exploring further consequences, stay tuned. . .

Conclusions

- Better understanding necessary, independent of Δa_{CP}
- First unbiased, comprehensive analysis of $D \to PP$
- Description possible with reasonable $SU(3)$ breaking
- Direct CP violation in charm (all modes!) remains interesting
- Enhanced asymmetry in $D^0 \to K_S K_S$ expected
- Generally very hard to make quantitative statements

➥ More data will help to improve analysis

- Theory side: idea to use QCDF structure for SU(3) breaking
- Sum rules for decay amplitudes, eliminate SU(3) MEs
- Restricted fits still work

Outlook:

- Complete analysis for QCDF influence (+NP) w.i.p.
- Interesting times! Measurements to come from LHC(b), Belle II, BES III, . . .

Backup slides

Available data for $D \to PP$ I

Observable	Measurement	References
SCS CP asymmetries		
$\Delta a_{CP}^{\rm dir}(K^+K^-, \pi^+\pi^-)$	-0.00333 ± 0.00120	
$\Sigma a_{CP}^{\rm dir}(K^+K^-, \pi^+\pi^-)$	$+0.00008 \pm 0.00228$	†
$a_{CP}^{\rm dir}(D^0 \to K_S K_S)$	-0.23 ± 0.19	
$a_{CP}^{\rm dir}(D^0 \to \pi^0\pi^0)$	$+0.001 \pm 0.048$	
$a_{CP}^{\rm dir}(D^+ \to \pi^0\pi^+)$	$+0.029 \pm 0.029$	
$a_{CP}^{\rm dir}(D^+ \to K_S K^+)$	$+0.0022 \pm 0.0025$	
$a_{CP}^{\rm dir}(D_s \to K_S \pi^+)$	$+0.011 \pm 0.007$	†
$a_{CP}^{\rm dir}(D_s \to K^+\pi^0)$	$+0.266 \pm 0.228$	
Indirect CP Violation		
$a_{CP}^{\rm ind}$	$+0.00015 \pm 0.00052$	
$\delta_L \equiv 2{\rm Re}(\varepsilon)/(1+\lvert\varepsilon\rvert^2)$	$(3.32 \pm 0.06) \cdot 10^{-3}$	
$K^+\pi^-$ strong phase difference		
$\delta_{K\pi}$	$(11.7 \pm 10.2)^\circ$	‡

Table : The observables and the data on indirect CP violation used in this work. We subtract the contribution from indirect CP violation where appropriate. Note that the BESIII result for $\delta_{K\pi}$ cannot be taken into account, as is relies on external non-independent input. †Our average with systematic and statistical error being added quadratically. ‡Our symmetrization of uncertainties.

Available data for $D \to PP$ II

Observable	Measurement	References
SCS branching ratios		
$\mathcal{B}(D^0 \to K^+K^-)$	$(3.96 \pm 0.08) \cdot 10^{-3}$	
$\mathcal{B}(D^0 \to \pi^+\pi^-)$	$(1.401 \pm 0.027) \cdot 10^{-3}$	
$\mathcal{B}(D^0 \to K_S K_S)$	$(0.17 \pm 0.04) \cdot 10^{-3}$	
$\mathcal{B}(D^0 \to \pi^0\pi^0)$	$(0.80 \pm 0.05) \cdot 10^{-3}$	
$\mathcal{B}(D^+ \to \pi^0\pi^+)$	$(1.19 \pm 0.06) \cdot 10^{-3}$	
$\mathcal{B}(D^+ \to K_S K^+)$	$(2.83 \pm 0.16) \cdot 10^{-3}$	
$\mathcal{B}(D_s \to K_S \pi^+)$	$(1.21 \pm 0.08) \cdot 10^{-3}$	
$\mathcal{B}(D_s \to K^+\pi^0)$	$(0.62 \pm 0.21) \cdot 10^{-3}$	
CF* branching ratios		
$\mathcal{B}(D^0 \to K^-\pi^+)$	$(3.88 \pm 0.05) \cdot 10^{-2}$	
$\mathcal{B}(D^0 \to K_S\pi^0)$	$(1.19 \pm 0.04) \cdot 10^{-2}$	
$\mathcal{B}(D^0 \to K_L\pi^0)$	$(1.00 \pm 0.07) \cdot 10^{-2}$	
$\mathcal{B}(D^+ \to K_S\pi^+)$	$(1.47 \pm 0.07) \cdot 10^{-2}$	
$\mathcal{B}(D^+ \to K_L\pi^+)$	$(1.46 \pm 0.05) \cdot 10^{-2}$	
$\mathcal{B}(D_s \to K_S K^+)$	$(1.48 \pm 0.05) \cdot 10^{-2}$	†
DCS branching ratios		
$\mathcal{B}(D^0 \to K^+\pi^-)$	$(1.47 \pm 0.07) \cdot 10^{-4}$	
$\mathcal{B}(D^+ \to K^+\pi^0)$	$(1.83 \pm 0.26) \cdot 10^{-4}$	

Table : The data on the observables used in this work. †Our average with systematic and statistical error being added quadratically. ‡Our symmetrization of uncertainties. *Decays with a $K_{S,L}$ in the final state, *i.e.*, those with a CF and DCS component are assigned to the CF channels.

Further inputs into the analysis

m_{D^0}	(1864.86 ± 0.13) MeV	
m_{D_s}	(1968.49 ± 0.32) MeV	
m_{π^0}	(134.9766 ± 0.0006) MeV	
m_{K^0}	(497.614 ± 0.024) MeV	
f_D	(205.3 ± 5.2) MeV	
f_{D_s}	(257.5 ± 4.5) MeV	
f_π	$(130.41 \pm 0.03 \pm 0.2)$ MeV	
f_K	$(156.1 \pm 0.2 \pm 0.8 \pm 0.2)$ MeV	
$F_0^{DK}(0)$	0.737 ± 0.005	†
$F_0^{D\pi}(0)$	0.638 ± 0.012	†

Table : Numerical input for the heavy quark scenarios. †Our average, with systematic and statistical errors being added quadratically.

Pseudo-data for the future scenario

Observable	"Future" data
SCS CP asymmetries	
$\Delta a_{CP}^{\mathrm{dir}}(K^+K^-, \pi^+\pi^-)$	-0.007 ± 0.0005
$\Sigma a_{CP}^{\mathrm{dir}}(K^+K^-, \pi^+\pi^-)$	-0.006 ± 0.0007
$a_{CP}^{\mathrm{dir}}(D^+ \to K_S K^+)$	-0.003 ± 0.0005
$a_{CP}^{\mathrm{dir}}(D_s \to K_S \pi^+)$	0.0 ± 0.0005
$a_{CP}^{\mathrm{dir}}(D_s \to K^+ \pi^0)$	0.05 ± 0.0005
$K^+\pi^-$ strong phase difference	
$\delta_{K\pi}$	$21.4^\circ \pm 3.8^\circ$

Table : Future pseudo-data, all other values unchanged. The central values of the single CP asymmetries that correspond to $\Delta a_{CP}^{\mathrm{dir}}$ and $\Sigma a_{CP}^{\mathrm{dir}}$ are $a_{CP}^{\mathrm{dir}}(D^0 \to K^+K^-) = -0.0065$ and $a_{CP}^{\mathrm{dir}}(D^0 \to \pi^+\pi^-) = 0.0005$.