Overview of Charm Physics (theory and experiment)

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Back to the roots:
Former CLEO@CESR site under Cornell Soccer Field

Where are we today in Charm?

Why do we love Charm?

Why do we love Charm?

- Because Charm is challenging.
- Physics is about small parameters we expand in.
- In Charm there is none.
- We need to find new ways to make predictions and play the game of QCD.
- That makes life more interesting.

Why is Charm challenging?

- Intermediate mass compared to Λ_{QCD} :
  Not heavy, not light.

- Do methods like Heavy Quark Expansion and Factorization work?

- GIM suppression can be very strong.

Reduced theory toolbox, but lots of data!
$\Rightarrow$ Charm is special.

Why are there $\sim$ 5 anomalies in B decays?

And in Charm: 0 ?

Why are there ~ 5 anomalies in B decays?

And in Charm: 0 ?

- Is it because we have less Charm than B?
  ↳Of course no, we have even more!
- Is it because New Physics is only in down sector?
  ↳Quite unlikely.

Maybe these are some reasons:

- Calculations are harder.
- Rare Charm decays much rarer than rare B decays. For same statistics much less events.

What are the Scientific Goals in Charm?

What are the Scientific Goals in Charm Physics?

1) Discover CP violation in the up sector.

Milestone to complete SM picture of CP violation.

2) Test the SM.

Overconstrain the SM and probe for New Physics.

Different strategies for these goals.

Overview

- 2-body Decays:
  How do we discover CP violation?
  How do we discover New Physics?

- Mixing and Indirect CP violation.

- Baryon Decays.

2-body Decays:

How do we discover CP violation?

How do we detect CP violation in Charm decays?

- Need decay mode with large SM prediction for a_{CP}^{dir}.
- Such a mode is $D^0 \to K_S K_S$.

[Hiller Jung Schacht 1211.3734, Nierste Schacht 1508.00074]

Special Features

- Suppressed $\mathcal{B}(D^0 \to K_S K_S)$
  $\Rightarrow$ enhanced a_{CP}^{dir} due to normalization.

- a_{CP}^{dir} dominated by tree level exchange diagrams.
  $\Rightarrow$ No penguin needed, no loop suppression.

Timeline of $A_{CP}(D^0 \to K_S K_S)$ Measurements

SM prediction [Nierste Schacht 1508.00074]

$$|a_{CP}^{\text{dir}}(D^0 \to K_S K_S)| \leq 1.1\% \quad \text{@95\% CL}$$

including $1/N_c$ color counting hierarchies: $|a_{CP}^{\text{dir}}| \leq 0.6\%$.

Year	Experiment	$A_{CP}(D^0 \to K_S K_S)$	Ref.
2001	CLEO	$(-23 \pm 19)\%$	PRD63, 071101(R) (2001)
2015	LHCb	$(-2.9 \pm 5.2 \pm 2.2)\%$	JHEP 10 055 (2015)
2017	Belle	$(-0.02 \pm 1.53)\%$	PRL119, 171801 (2017)
2018	LHCb	$(4.2 \pm 3.4 \pm 1.0)\%$	1806.01642
2018	LHCb combin.	$(2.0 \pm 2.9 \pm 1.0)\%$	1806.01642

Close to possible observation of SM CP violation.

We are really making progress!

- The experimental error is going down considerably.
- The data is precise enough to perform global fits using SU(3)$_F$.

The approximate SU(3)$_F$ symmetry of QCD

- Because of $m_{u,d,s} \ll \Lambda_{\text{QCD}}$ the hadronic amplitudes are approximately invariant under unitary rotations of (u, d, s) .
- This induces correlations between decay amplitudes.
- Parametrization by topological amplitudes including all-order QCD corrections. [Chau 1980,1982; Zeppenfeld 1981, Gronau Hernandez London Rosner 1995, Buras Silvestrini 1998]

The good news [Hiller Jung Schacht 2012, Müller Nierste Schacht 2015]

- The SU(3)$_F$ limit can be ruled out by more than 5σ .
- This is not an anomaly, it is expected: SU(3)$_F$ is approximate sym.
- Data precise enough for sensitivity to higher order SU(3)$_F$ corrections.
- Data shows at least $\mathcal{O}(30\%)$ SU(3)$_F$ breaking in the decay amplitudes.

Even more special features: $D^0 \to K_S K^{0*}$

Special Features on top of $D^0 \to K_S K_S$

- Prompt decay $K^{0*} \to K^+\pi^-$ with charged tracks.
- Hunt for favorable strong phases in Dalitz plot.
- No flavor tagging needed, essentially undiluted untagged CP asymmetry.

SM prediction

[Nierste Schacht PRL119 251801 (2017)]

$$a_{CP}^{\mathrm{dir}}(\overset{(-)}{D} \to K_S K^{*0}) \approx a_{CP}^{\mathrm{dir}}(D^0 \to K_S K^{0*}) \lesssim 0.3\% \,.$$

[first exp. results: LHCb 1509.06628]

2-body Decays:

How do we discover New Physics?

How do we discover New Physics in Charm decays?

1) Null tests

Need a clean SM prediction.

2) Sum rules between CP asymmetries.

Overconstrain the SM.

Nulltest of the SM: $A_{CP}(D^+ \to \pi^+\pi^0)$

SM prediction

[Buccella et al PLB302, 319 (1993), Grossman et al Phys Rev D85, 114036 (2012)]

$$a_{CP}^{\text{dir}}(D^+ \to \pi^+\pi^0) = 0 \quad \text{(isospin limit)}$$

Higher orders safely below any foreseeable experimental sensitivity.

Violation would be sign of $\Delta I = 3/2$ New Physics.

Year	Experiment	$A_{CP}(D^+ \to \pi^+\pi^0)$	Ref.
2010	CLEO	$(+2.9 \pm 2.9 \pm 0.3)\%$	PRD81 (2010) 052013
2018	Belle	$(+2.31 \pm 1.24 \pm 0.23)\%$	PRD97, 011101(R) (2018)

A_{CP} Sum Rules: Overconstrain the SM

Challenge for predicting CP asymmetries

New hadronic quantities appear.

These cannot be extracted from $\mathcal{B}$ measurements.

Solution

Make up $SU(3)_F$ sum rules in which these cancel.

[Grossman Kagan Nir 2006, Grossman Robinson 2012, Grossman Ligeti Robinson 2014, Müller Nierste Schacht 2015]

- A_{CP} sum rule $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$, $D^0 \to \pi^0\pi^0$.
- A_{CP} sum rule $D^+ \to \overline{K}^0K^+$, $D_s^+ \to K^0\pi^+$, $D_s^+ \to K^+\pi^0$.
- A_{CP} sum rule $D^0 \to \pi^+\pi^0$, $D^0 \to \pi^+\pi^-$, $D^0 \to \pi^0\pi^0$.

Sum Rules need interplay of LHCb and Belle I/II

LHCb Run 1 combination ($3fb^{-1}$) [PLB 767, 177 (2017)]

$$A_{CP}(D^0 \to K^+K^-) = (0.04 \pm 0.12 \pm 0.10)\%$$

$$A_{CP}(D^0 \to \pi^+\pi^-) = (0.07 \pm 0.14 \pm 0.11)\%$$

Run 2 is on tape!

Belle [PRL 112, 211601 (2014)]

$$A_{CP}(D^0 \to \pi^0\pi^0) = (-0.03 \pm 0.64 \pm 0.10)\%$$

We would be very happy if you update:

$$A_{CP}(D_s^+ \to K^+\pi^0) = -0.266 \pm 0.238 \pm 0.009.$$

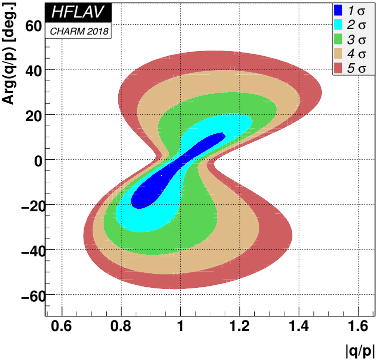
[CLEO, PRD81, 052013 (2010)]

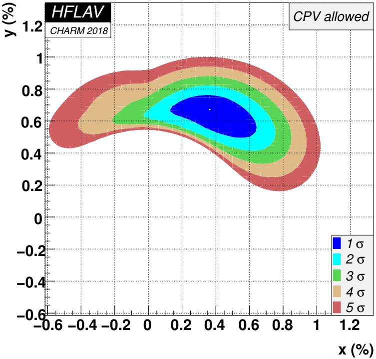
Need even more precision.

⇒ **More results on direct CPV: Tuesday evening**

Mixing and Indirect CP violation

Mixing and Indirect CP violation





- $|q/p| \neq 1$ would indicate CPV in mixing.
- $\mathrm{Arg}(q/p) \neq 0$ would indicate CPV from interference mixing/decay.
- Mixing parameters $x \equiv \Delta m/\Gamma$ and $y \equiv \Delta\Gamma/(2\Gamma)$.
- SM: hard to calculate. Qualitative agreement with SM.
- News on y_{CP}@PIC2018 ⇒ **Talk by Pajero Tuesday morning**
  $y_{CP} \neq y$ would indicate indirect CPV.

Baryon Decays

Baryon Decays

Theory has to learn how to play the game...

- "Baryonic ΔA_{CP}" [LHCb, JHEP 03 (2018) 182]

$$\Delta A_{CP}(\Lambda_c) \equiv A_{CP}(\Lambda_c \to pK^+K^-) - A_{CP}(\Lambda_c \to p\pi^+\pi^-)$$
$$= (0.30 \pm 0.91 \pm 0.61)\%$$

- Similar clever difference as $A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$.
- Quantitative theoretical predictions: None available.
- **But:** Several DCS Λ_c decays usable as CPV null tests. [Bigi 1206.4554]

Lifetimes

- $\tau(\Omega_c)$ 4 times higher than world average. [LHCb, PRL121, 092003 (2018)]
- Heavy Quark Expansion seems to work for meson lifetimes. Confirmation by Lattice desirable. [Kirk Lenz Rauh JHEP 1712 (2017) 068]
- In principle, same approach possible for baryons. [Lenz]

Baryon Decays

Many Highlights, in order of appearance

- First observation of DCS baryon decay: $\Lambda_c^+ \to pK^+\pi^-$.
  [Belle, PRL117, 011801 (2016)]
  $\Rightarrow$ Maybe CPV null test possible in the future? [Bigi 1206.4554]
- Observation of $\Lambda_c \to nK_S\pi^+$. [BESIII, PRL 118, 112001 (2017)]
- First observation of $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$. [BESIII, PLB 772, 388 (2017)]
- First measurement of $\tau(\Xi_{cc}^{++})$. [LHCb, PRL121, 052002 (2018)]
- First observation of $\Xi_{cc}^{++} \to \Xi_c^+\pi^+$. [LHCb, 1807.01919]

More on Baryons: $\Rightarrow$ **Talk by Carla Gobel Tuesday morning**

A rich charming physics program. . .

Life with Charm is hard, but we work harder.

Theory

- Conceptual progress on the lattice. [Hansen Sharpe PRD86 (2012) 016007]
- Lattice results for $\Lambda_c \to \Lambda l \nu$. [Meinel PRL 118(2017) 082001]
- Applying light-cone sum rules. [Khodjamirian Petrov PLB774(2017)235]
- News on CPV in $D^+ \to \pi^+ K_S$. [Wang Yu Li PRL119(2017) 181802]
- NP sensitivity of rare $D \to Pll$ and SM null tests with angular distribution of $D \to PPll$. [de Boer Hiller PRD93 (2016) 074001]
  [Feldmann Müller Seidel JHEP 1708 (2017) 105, de Boer Hiller PRD98 (2018) 035041]

Experiment

- Lepton Flavor Nonuniversality Test with $\mathcal{B}(D^0 \to K^- \pi^+ e^+ e^-)$.
  [Babar@ICHEP2018 and LHCb, PLB 757 (2016) 558]
- First search for $D^0 \to$ invisible. [Belle, PRD95, 011102(R) (2017)]
  SM: $\mathcal{B}(D^0 \to \nu\bar{\nu}) = 1.1 \cdot 10^{-30}$. [Badin Petrov PRD82, 034005 (2010)]

Conclusions

We want to discover CP violation in the up sector

- Key channels: $D^0 \to K_S K_S$ and $D^0 \to K_S K^{0*}$.

We want to falsify the SM and Find New Physics.

- Use null tests or sum rules, eliminating unknown hadronic quantities.

We can do unexpected things with charm

- Search Dark Matter and Lepton-Flavor Nonuniversality.

See you in the parallel sessions.