Introduction to CP-violation in beauty and charm: charm physics

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1. Introduction

- How can CP-violation be observed in charm system?
  - can be observed by comparing CP-conjugated decay rates in various ways, both with and w/out time dependence

$$a_{\mathrm{CP}}(f) = \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \overline{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \overline{f})},$$

  - can manifest itself in charm ΔC=1 transitions (direct CP-violation)

$$\Gamma(D \to f) \neq \Gamma(CP[D] \to CP[f])$$

dCPV

  - or in ΔC=2 transitions (indirect CP-violation): mixing $\left|D_{1,2}\right\rangle = p\left|D^0\right\rangle \pm q\left|\overline{D^0}\right\rangle$

$$R_m^2 = |q/p|^2 = \left|\frac{2M_{12}^* - i\Gamma_{12}^*}{\Delta m - (i/2)\Delta\Gamma}\right|^2 = 1 + A_m \neq 1$$

CPVmix

  - or in the interference b/w decays (ΔC=1) and mixing (ΔC=2)

$$\lambda_f = \frac{q}{p}\frac{\overline{A_f}}{A_f} = R_m e^{i(\phi+\delta)}\left|\frac{\overline{A_f}}{A_f}\right|$$

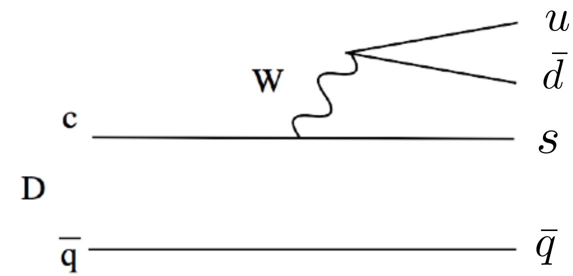
CPVint

★ Can be classified by SM CKM suppression of tree amplitude ($V_{us} \sim \lambda$)

$V_{cs}V_{ud}^*$

★ Cabibbo-favored (CF: λ^0) decay

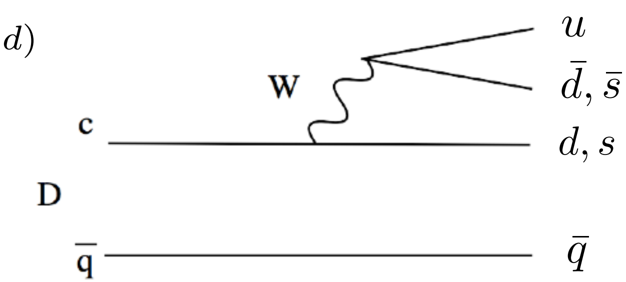
- originates from $c \to s u\bar{d}$
- examples: $D^0 \to K^-\pi^+$



$V_{cs(d)}V_{us(d)}^*$

★ Singly Cabibbo-suppressed (SCS: λ^1) decay

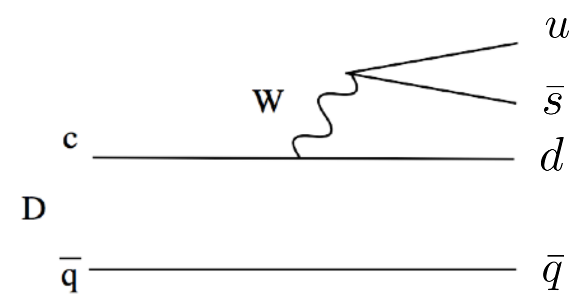
- originates from $c \to q u\bar{q}$
- examples: $D^0 \to \pi\pi$ and $D^0 \to KK$



$V_{cd}V_{us}^*$

★ Doubly Cabibbo-suppressed (DCS: λ^2) decay

- originates from $c \to d u\bar{s}$
- examples: $D^0 \to K^+\pi^-$

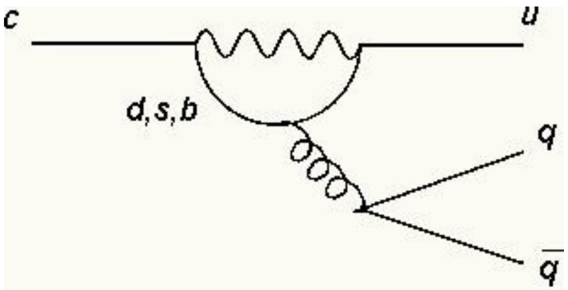


★ We shall concentrate on SCS decays. Why is that?

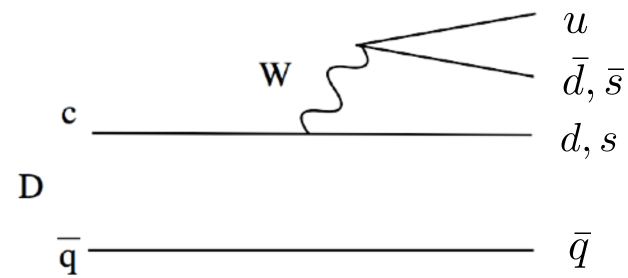
Generic expectations for sizes of CPV effects

★ Generic expectation is that CP-violating observables in the SM are small

$\Delta c = 1$ amplitudes allow to reach third -generation quarks!



"Penguin" amplitude/contraction



"Tree" amplitude

★ The Unitarity Triangle relation for charm:

$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0$$

$$\sim\lambda \qquad \sim\lambda \qquad \sim\lambda^5$$

With b-quark contribution neglected: only **2** generations contribute

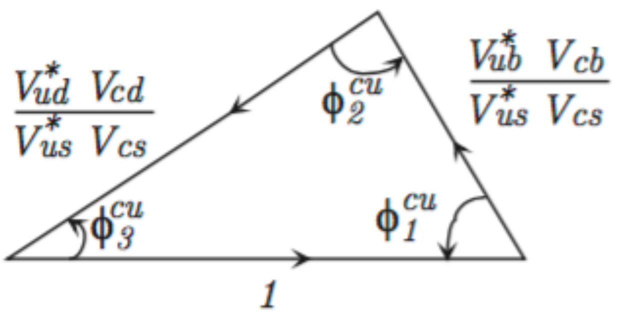
$\Rightarrow$ **real 2x2 Cabibbo matrix**

Any CP-violating signal in the SM will be small, at most $O(V_{ub}V_{cb}^*/V_{us}V_{cs}^*) \sim 10^{-3}$

Thus, O(1%) CP-violating signal can provide a "smoking gun" signature of New Physics

★ Fundamental problem: observation of CP-violation in up-quark sector!

★ "Charmed" CKM triangle is very squashed in the Standard Model



Bigi, Sanda

$$1 + \frac{V_{ub}^* V_{cb}}{V_{us}^* V_{cs}} + \frac{V_{ud}^* V_{cd}}{V_{us}^* V_{cs}} = 0$$

$$\left| \frac{V_{ud}^* V_{cd}}{V_{us}^* V_{cs}} \right| = 1 + \mathcal{O}(\lambda^4) \qquad \left| \frac{V_{ub}^* V_{cb}}{V_{us}^* V_{cs}} \right| \sim \mathcal{O}(\lambda^4)$$

★ … with very small angles, e.g.

$$\chi' = \arg\left(\frac{V_{ud}^* V_{cd}}{V_{us}^* V_{cs}}\right) \simeq A^2 \lambda^4 \eta \simeq 1.6 \cdot 10^{-3} \eta$$

2. Indirect CP-violation

★ Indirect CP-violation manifests itself in $D\overline{D}$-oscillations

★ "Experimental" mass and lifetime differences of mass eigenstates...

$$x_D = \frac{M_2 - M_1}{\Gamma_D}, \quad y_D = \frac{\Gamma_2 - \Gamma_1}{2\Gamma_D}$$

★ ...can be calculated as real and imaginary parts of a correlation function

$$y_{\rm D} = \frac{1}{2M_{\rm D}\Gamma_{\rm D}} \,{\rm Im}\, \langle \overline{D^0}|\, i \int {\rm d}^4x\, T\left\{ \mathcal{H}_w^{|\Delta C|=1}(x)\, \mathcal{H}_w^{|\Delta C|=1}(0) \right\} |D^0\rangle$$

bi-local time-ordered product

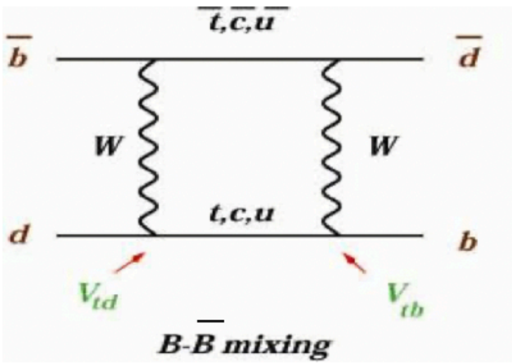
$$x_{\rm D} = \frac{1}{2M_{\rm D}\Gamma_{\rm D}} \,{\rm Re}\, \left[2\langle \overline{D^0}| H^{|\Delta C|=2}\, |D^0\rangle + \langle \overline{D^0}|\, i \int {\rm d}^4x\, T\left\{ \mathcal{H}_w^{|\Delta C|=1}(x)\, \mathcal{H}_w^{|\Delta C|=1}(0) \right\} |D^0\rangle \right]$$

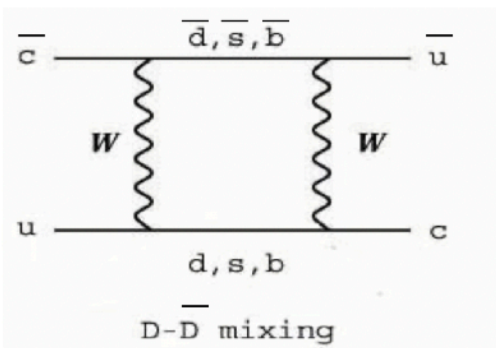
local operator
(b-quark, NP): small?

bi-local time-ordered product

★ Theoretically, y_D is dominated by long-distance SM-dominated effects
★ CP-violating phases can appear from subleading local SM or NP operators

- Why is D-mixing different (from B-mixing)?

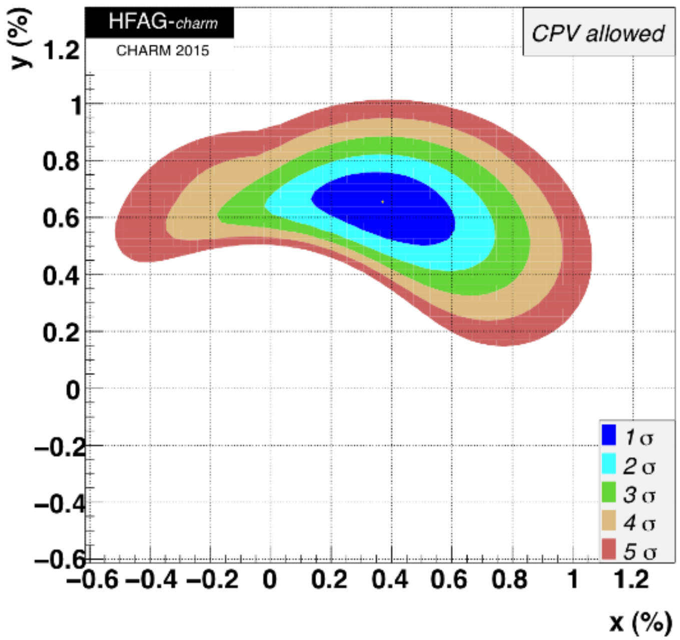


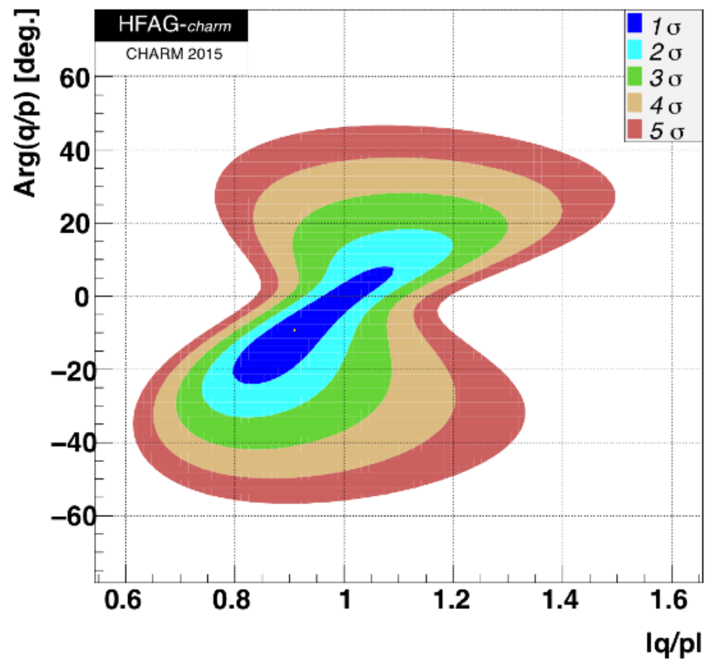


$\overline{D^0} - D^0$ mixing	$\overline{B^0} - B^0$ mixing
• intermediate down-type quarks • SM: b-quark contribution is negligible due to $V_{cd}V_{ub}^*$ • $rate \propto f(m_s) - f(m_d)$ (zero in the SU(3) limit) Falk, Grossman, Ligeti, and A.A.P. Phys.Rev. D65, 054034, 2002 2^{nd} order effect!!!	• intermediate up-type quarks • SM: t-quark contribution is dominant • $rate \propto m_t^2$ (expected to be large)
1. Sensitive to long distance QCD 2. Small in the SM: New Physics! (must know SM x and y)	1. Computable in QCD (*) 2. Large in the SM: CKM!

(*) up to matrix elements of 4-quark operators

Indirect CP-violation





$$y = 0.66^{+0.07}_{-0.10}\%, \quad x = 0.37 \pm 0.16$$

HFAG 2016

Note that if $|M_{12}| < |\Gamma_{12}|$:

$$\begin{aligned} x/y &= 2\,|M_{12}/\Gamma_{12}|\cos\phi_{12}, \\ A_m &= 4\,|M_{12}/\Gamma_{12}|\sin\phi_{12}, \\ \phi &= -2\,|M_{12}/\Gamma_{12}|^2 \sin 2\phi_{12}. \end{aligned}$$

Bergmann, Grossman, Ligeti, Nir, AAP PL B486 (2000) 418

CPV is suppressed even if M_{12} is all NP!!!

Indirect CP-violation

★ Indirect CP-violation manifests itself in $D\bar{D}$-oscillations

- see time development of a D-system:

$$i\frac{d}{dt}|D(t)\rangle = \left(M - \frac{i}{2}\Gamma\right)|D(t)\rangle$$

$$\langle D^0|\mathcal{H}|\overline{D^0}\rangle = M_{12} - \frac{i}{2}\Gamma_{12} \qquad \langle \overline{D^0}|\mathcal{H}|D^0\rangle = M_{12}^* - \frac{i}{2}\Gamma_{12}^*$$

★ Define "theoretical" mixing parameters

$$y_{12} \equiv |\Gamma_{12}|/\Gamma, \quad x_{12} \equiv 2|M_{12}|/\Gamma, \quad \phi_{12} \equiv \arg(M_{12}/\Gamma_{12})$$

★ Assume that direct CP-violation is absent ($\mathrm{Im}\,(\Gamma_{12}^*\bar{A}_f/A_f) = 0,\ |\bar{A}_f/A_f| = 1$)

- can relate x, y, φ, |q/p| to x_{12}, y_{12} and φ_{12}

"superweak limit"

$$xy = x_{12}y_{12}\cos\phi_{12}, \qquad x^2 - y^2 = x_{12}^2 - y_{12}^2,$$
$$(x^2 + y^2)|q/p|^2 = x_{12}^2 + y_{12}^2 + 2x_{12}y_{12}\sin\phi_{12},$$
$$x^2\cos^2\phi - y^2\sin^2\phi = x_{12}^2\cos^2\phi_{12}.$$

★ Four "experimental" parameters related to three "theoretical"

- a "constraint" equation is possible

$$\frac{x}{y} = \frac{1-|q/p|}{\tan\phi} = -\frac{1}{2}\frac{A_m}{\tan\phi}$$

Generic restrictions on NP from DD-mixing

★ Comparing to experimental value of x, obtain constraints on NP models
- assume x is dominated by the New Physics model
- assume no accidental strong cancellations b/w SM and NP

$$\mathcal{H}_{NP}^{\Delta C=2} = \frac{1}{\Lambda_{NP}^2} \sum_{i=1}^{8} z_i(\mu) Q_i'$$

$$\begin{aligned} Q_1^{cu} &= \bar{u}_L^\alpha \gamma_\mu c_L^\alpha \bar{u}_L^\beta \gamma^\mu c_L^\beta, \\ Q_2^{cu} &= \bar{u}_R^\alpha c_L^\alpha \bar{u}_R^\beta c_L^\beta, \\ Q_3^{cu} &= \bar{u}_R^\alpha c_L^\beta \bar{u}_R^\beta c_L^\alpha, \end{aligned} + \left\{ \begin{matrix} L \\ \updownarrow \\ R \end{matrix} \right\} + \begin{aligned} Q_4^{cu} &= \bar{u}_R^\alpha c_L^\alpha \bar{u}_L^\beta c_R^\beta, \\ Q_5^{cu} &= \bar{u}_R^\alpha c_L^\beta \bar{u}_L^\beta c_R^\alpha, \end{aligned}$$

★ ... which are

$$\begin{aligned} |z_1| &\lesssim 5.7 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2, \\ |z_2| &\lesssim 1.6 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2, \\ |z_3| &\lesssim 5.8 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2, \\ |z_4| &\lesssim 5.6 \times 10^{-8} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2, \\ |z_5| &\lesssim 1.6 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2. \end{aligned}$$

New Physics is either at a very high scales

tree level: $\Lambda_{NP} \geq (4-10) \times 10^3\ \mathrm{TeV}$

loop level: $\Lambda_{NP} \geq (1-3) \times 10^2\ \mathrm{TeV}$

or have highly suppressed couplings to charm!

Gedalia, Grossman, Nir, Perez
Phys.Rev.D80, 055024, 2009

E.Golowich, J. Hewett, S. Pakvasa and A.A.P.
Phys. Rev. D76:095009, 2007

★ Constraints on particular NP models available

★ Assume that direct CP-violation is absent $(\text{Im}\,(\Gamma_{12}^* \bar{A}_f / A_f) = 0, \quad |\bar{A}_f / A_f| = 1)$

- experimental constraints on x, y, φ, |q/p| exist
- can obtain generic constraints on Im parts of Wilson coefficients

$$\mathcal{H}_{NP}^{\Delta C=2} = \frac{1}{\Lambda_{NP}^2} \sum_{i=1}^{8} z_i(\mu) Q_i'$$

★ In particular, from $x_{12}^{\rm NP} \sin\phi_{12}^{\rm NP} \lesssim 0.0022$

$$\mathcal{I}m(z_1) \lesssim 1.1 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2,$$

$$\mathcal{I}m(z_2) \lesssim 2.9 \times 10^{-8} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2,$$

$$\mathcal{I}m(z_3) \lesssim 1.1 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2,$$

$$\mathcal{I}m(z_4) \lesssim 1.1 \times 10^{-8} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2,$$

$$\mathcal{I}m(z_5) \lesssim 3.0 \times 10^{-8} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2.$$

New Physics is either at a very high scales

tree level: $\Lambda_{NP} \geq (4-10) \times 10^3$ TeV

loop level: $\Lambda_{NP} \geq (1-3) \times 10^2$ TeV

or have highly suppressed couplings to charm!

Gedalia, Grossman, Nir, Perez
Phys.Rev.D80, 055024, 2009

Bigi, Blanke, Buras, Recksiegel,
JHEP 0907:097, 2009

★ Constraints on particular NP models possible as well

CP-violation I: beyond "superweak"

★ Look at parameterization of CPV phases; separate absorptive and dispersive

$$\lambda_f^2 = \frac{2M_{12}^* - i\Gamma_{12}^*}{2M_{12} - i\Gamma_{12}} \left(\frac{\overline{A}_f}{A_f}\right)^2$$

See A. Kagan's talk

- consider f= CP eigenstate, can generalize later: $\lambda_{CP}^2 = R_m^2 e^{2i\phi}$

$$\phi_{12\,f}^M = \frac{1}{2}\arg\left[\frac{M_{12}}{M_{12}^*}\left(\frac{A_f}{\overline{A}_f}\right)^2\right] \qquad \phi_{12\,f}^\Gamma = \frac{1}{2}\arg\left[\frac{\Gamma_{12}}{\Gamma_{12}^*}\left(\frac{A_f}{\overline{A}_f}\right)^2\right]$$

- CP-violating phase for the final state f is then

$$\phi_{12} = \phi_{12\,f}^M - \phi_{12\,f}^\Gamma$$

★ Can we put a Standard Model theoretical bound on $\phi_{12\,f}^M$ or $\phi_{12\,f}^\Gamma$?

CP-violation I: beyond "superweak"

★ Let us define convention-independent universal CPV phases. First note that

- for the absorptive part: $\Gamma_{12} = \Gamma_{12}^0 + \delta\Gamma_{12}$

$$\Gamma_{12}^0 = -\lambda_s(\Gamma_{ss} + \Gamma_{dd} - 2\Gamma_{sd})$$
$$\delta\Gamma_{12} = 2\lambda_b\lambda_s(\Gamma_{sd} - \Gamma_{ss}) + O(\lambda_b^2)$$

- ... and similarly for the dispersive part: $M_{12} = M_{12}^0 + \delta M_{12}$

★ CP-violating mixing phase can then be written as

$$\phi_{12} = \arg\frac{M_{12}}{\Gamma_{12}} = \mathrm{Im}\left(\frac{\delta M_{12}}{M_{12}^0}\right) - \mathrm{Im}\left(\frac{\delta\Gamma_{12}}{\Gamma_{12}^0}\right) \equiv \phi_{12}^M - \phi_{12}^\Gamma$$

★ These phases can then be constrained; e.g. the absorptive phase

$$|\phi_{12}^\Gamma| = 0.009 \times \frac{|\Gamma_{sd}|}{\Gamma} \times \left|\frac{\Gamma_{sd} - \Gamma_{dd}}{\Gamma_{sd}}\right| < 0.01$$

See A. Kagan's talk!

★ Currently, $\phi_{12} = 0.2 \pm 1.7$ Need improvement!

2. Time-independent (direct) CP-violation

★ Direct CP-violating asymmetries probe CP-violation in ΔC=1 amplitudes

- CP-asymmetries compare partial rates of CP-conjugated decays

$$a_{CP}(f) = \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \overline{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \overline{f})}$$

(both charged and neutral D's)

- a non-vanishing decay asymmetry requires that a decay amplitude
  - contain several components each of which has its own strong and weak phases
  - strong phases: do not change under CP transformation of the decay amplitude
  - weak phases: flip sign under CP transformation of the decay amplitude

$$A(D \to f) \equiv A_f = |A_{f1}| e^{i\delta_1} e^{i\theta_1} + |A_{f2}| e^{i\delta_2} e^{i\theta_2}$$

- Now we can form the CP-asymmetry

$$a_{CP}(f) = 2 r_f \sin(\underbrace{\theta_1 - \theta_2}_{\text{weak}}) \sin(\underbrace{\delta_1 - \delta_2}_{\text{strong}})$$

with $r_f = \left| \frac{A_{f2}}{A_{f1}} \right|$

Direct CP-violation in charm: realities of life

★ IDEA: consider the DIFFERENCE of decay rate asymmetries: $D \to \pi\pi$ vs $D \to KK$!
For each final state the asymmetry

D^0: no neutrals in the final state!

$$a_f = \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \overline{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \overline{f})} \quad \Rightarrow \quad a_f = a_f^d + a_f^m + a_f^i$$

direct mixing interference

★ A reason: $a^m_{KK} = a^m_{\pi\pi}$ and $a^i_{KK} = a^i_{\pi\pi}$ (for CP-eigenstate final states), so, ideally, mixing asymmetries cancel ($r_f = P_f/A_f$)!

$$a_f^d = 2 r_f \sin\phi_f \sin\delta_f$$

★ ... and the resulting DCPV asymmetry is $\boxed{\Delta a_{CP} = a^d_{KK} - a^d_{\pi\pi} \approx 2 a^d_{KK}}$ (double!)

$$A_{KK} = \frac{G_F}{\sqrt{2}} \lambda \left[(T + E + P_{sd}) + a\lambda^4 e^{-i\gamma} P_{bd} \right]$$

$$A_{\pi\pi} = \frac{G_F}{\sqrt{2}} \lambda \left[(-(T + E) + P_{sd}) + a\lambda^4 e^{-i\gamma} P_{bd} \right]$$

★ ... so it is doubled in the limit of $SU(3)_F$ symmetry

SU(3) is badly broken in D-decays

Experimental analysis from LHCb

★ Since we are comparing rates for D^0 and anti-D^0: need to tag the flavor at production

$$D^{*+} \to D^0 \pi_s^+$$

"D*-trick" -- tag the charge of the slow pion (or muon for D's produced in B-decays)

★ The difference Δa_{CP} is also preferable experimentally, as

$$a_f^{\text{raw}} = \underbrace{a_f^{CP}}_{\text{physics}} + \underbrace{a_f^{\text{detect, D}}}_{\text{detection asymmetry of } D^0} + \underbrace{a_D^{\text{detect, } \pi_s}}_{\text{detection asymmetry of soft pion}} + \underbrace{a_{D*}^{\text{prod}}}_{\text{production asymmetry of } D^{*+}}$$

★ D* production asymmetry and soft pion asymmetries are the same for KK and ππ final states-- they cancel in Δa_{CP}!

★ Integrate over time,

$$a_{CP,\ f} = \int_0^\infty a_{CP}(f;t)\underbrace{D(t)}_{\text{distribution of proper decay time}}dt = a_f^d + \frac{\langle t \rangle}{\tau} a_f^{ind}$$

★ Viola! Report observation!

Moriond 2019 announcement

Interpretation

NEW

LHCb-PAPER-2019-006

- For the **interpretation**, $\Delta\langle t\rangle/\tau(D^0)$ and $\overline{\langle t\rangle}/\tau(D^0)$ are needed
- For the full LHCb data set ($\mathbf{9fb^{-1}}$):

$$\boldsymbol{\Delta\langle t\rangle/\tau\left(D^0\right) = 0.115 \pm 0.002,\ \overline{\langle t\rangle}/\tau\left(D^0\right) = 1.71 \pm 0.10}$$

- Using the LHCb averages:
  - $y_{CP} = (5.7 \pm 1.5)\times 10^{-3}$
  - $A_\Gamma = (-2.8 \pm 2.8)\times 10^{-4} \simeq -a_{CP}^{\rm ind}$

$$\Delta A_{CP} \simeq \Delta a_{CP}^{\rm dir}\left(1 + \frac{\overline{\langle t\rangle}}{\tau(D^0)} y_{CP}\right) + \frac{\Delta\langle t\rangle}{\tau(D^0)} a_{CP}^{\rm ind}$$

$$\boxed{\boldsymbol{\Delta a_{CP}^{\rm dir} = (-15.6 \pm 2.9)\times 10^{-4}}}$$

ΔA_{CP} mostly sensitive to direct *CP* violation

F. Betti - INFN Bologna, University of Bologna   Moriond EW 2019 - 21/03/2019   26

Afrtermath

- Experimental results
  - note that while the new result does constitute an observation of CP-violation in the difference…

$$\Delta a_{CP}^{dir} = a_{CP}(K^-K^+) - a_{CP}(\pi^-\pi^+) = (-0.156 \pm 0.029)\%$$

LHCb 2019

  - … it is not yet so for the individual decay asymmetries

$$\begin{aligned} a_{CP}(K^-K^+) &= (0.04 \pm 0.12\ (\mathrm{stat}) \pm 0.10\ (\mathrm{syst}))\%\,, \\ a_{CP}(\pi^-\pi^+) &= (0.07 \pm 0.14\ (\mathrm{stat}) \pm 0.11\ (\mathrm{syst}))\%\,. \end{aligned}$$

LHCb 2017

- Need confirmation from other experiments (Belle II)

- What does this result mean? New Physics? Standard Model?

Theoretical troubles

ΔA_{CP} within the Standard Model and beyond

Mikael Chala, Alexander Lenz, Aleksey V. Rusov and Jakub Scholtz

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Implications on the first observation of charm CPV at LHCb

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The Emergence of the $\Delta U = 0$ Rule in Charm Physics

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Revisiting CP violation in $D \to PP$ and VP decays

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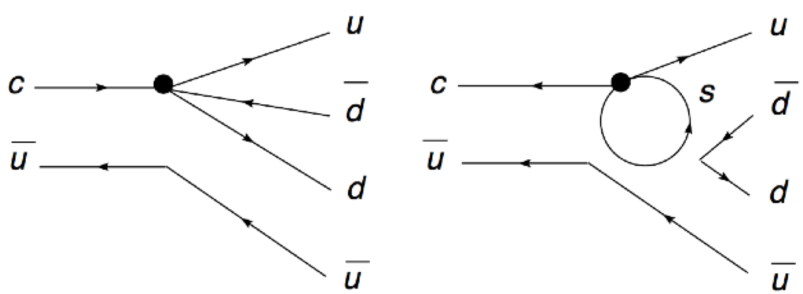
Theoretical troubles

★ These asymmetries are notoriously difficult to compute

★ In the Standard Model

- need to estimate size of penguin/penguin contractions vs. tree



- unknown penguin contributions
  - SU(3) analysis: some ME are enhanced?

    Golden & Grinstein PLB 222 (1989) 501; Pirtshalava & Uttayarat 1112.5451
  - could expect large $1/m_c$ corrections (E/PE/PA/…)

    Isidori et al PLB 711 (2012) 46; Brod et al 1111.5000
  - flavor-flow diagrams

    Broad et al 1203.6659; Bhattacharya et al PRD 85 (2012) 054014; Cheng & Chiang 1205.0580; 1909.03063; Gronau, Rosner

★ General comments on SU(3)/flavor flow — type analyses

- fit both SM and (possible) NP parts of the amplitudes: can one claim SM-only?
- many parameters: can one claim $O(10^{-4})$ precision if rates are known to $O(10^{-2})$?

★ Need direct calculations of amplitudes/CPV-asymmetries

- QCD sum rule calculations of Δa_{CP} Khodjamirian, AAP
- SU(3) breaking analyses of $D \to PV, VV$
- constant (but slow) lattice QCD progress in $D \to \pi\pi, \pi\pi\pi$ Hansen, Sharpe

Calculating CP-asymmetries in QCD

- Effective Hamiltonian for singly Cabibbo-suppressed (SCS) decays
  - drop all "penguin" operators (Q_i for $i \geq 3$) as C_i are small, $\lambda_q = V_{uq} V_{cq}^*$,

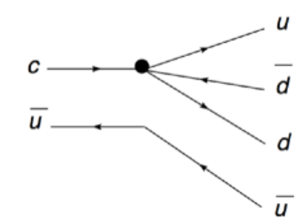
$$\mathcal{H}_{\rm eff} = \frac{G_F}{\sqrt{2}} \left[\sum_{q=d,s} \lambda_q \left(C_1 Q_1^q + C_2 Q_2^q \right) - \lambda_b \cancel{\sum_{i=3,\ldots,6,8g} C_i Q_i} \right]$$

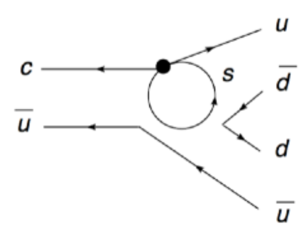
$$Q_1^q = \left(\bar{u} \Gamma_\mu q \right) \left(\bar{q} \Gamma^\mu c \right), \qquad Q_2^q = \left(\bar{q} \Gamma_\mu q \right) \left(\bar{u} \Gamma^\mu c \right)$$

  - recall that $\sum_{q=d,s,b} \lambda_q = 0$ or $\lambda_d = -(\lambda_s + \lambda_b)$ and $\mathcal{O}^q \equiv \frac{G_F}{\sqrt{2}} \sum_{i=1,2} C_i Q_i^q$, with $q = d, s$.

without QCD

with QCD





Amplitude decomposition

- Recipe for calculation of CPV asymmetry
  - prepare decay amplitudes (and using $\lambda_d = -(\lambda_s + \lambda_b)$)

$$
\begin{aligned}
A(D^0 \to \pi^-\pi^+) &= \lambda_d \langle \pi^-\pi^+ | \mathcal{O}^d | D^0 \rangle + \lambda_s \langle \pi^-\pi^+ | \mathcal{O}^s | D^0 \rangle \\
A(D^0 \to K^-K^+) &= \lambda_s \langle K^-K^+ | \mathcal{O}^s | D^0 \rangle + \lambda_d \langle K^-K^+ | \mathcal{O}^d | D^0 \rangle
\end{aligned}
$$

  - add and subtract $\lambda_b \langle \pi^-\pi^+ | \mathcal{O}^s | D^0 \rangle$, put in a new form

$$
\begin{aligned}
A(D^0 \to \pi^-\pi^+) &= -\lambda_s \mathcal{A}_{\pi\pi} \left[1 + \frac{\lambda_b}{\lambda_s} \left(1 + r_\pi \exp(i\delta_\pi) \right) \right] \\
A(D^0 \to K^-K^+) &= \lambda_s \mathcal{A}_{KK} \left[1 - \frac{\lambda_b}{\lambda_s} r_K \exp(i\delta_K) \right]
\end{aligned}
$$

  - define things we cannot compute (extract from branching ratios)

$$
\begin{aligned}
\mathcal{A}_{\pi\pi} &= \langle \pi^-\pi^+ | \mathcal{O}^d | D^0 \rangle - \langle \pi^-\pi^+ | \mathcal{O}^s | D^0 \rangle \\
\mathcal{A}_{KK} &= \langle K^-K^+ | \mathcal{O}^s | D^0 \rangle - \langle K^-K^+ | \mathcal{O}^d | D^0 \rangle
\end{aligned}
$$

  - ... and things we can $\mathcal{P}^s_{\pi\pi} = \langle \pi^-\pi^+ | \mathcal{O}^s | D^0 \rangle$, $\quad \mathcal{P}^d_{KK} = \langle K^-K^+ | \mathcal{O}^d | D^0 \rangle$

$$
r_\pi = \left| \frac{\mathcal{P}^s_{\pi\pi}}{\mathcal{A}_{\pi\pi}} \right|, \quad r_K = \left| \frac{\mathcal{P}^d_{KK}}{\mathcal{A}_{KK}} \right|
$$

Direct CP-violating asymmetries

- QCD-based calculation of direct CPV asymmetry
  - each amplitude has two parts with own weak and strong phases

$$A(D^0 \to \pi^-\pi^+) = -\lambda_s \mathcal{A}_{\pi\pi}\left[1 + \frac{\lambda_b}{\lambda_s}\left(1 + r_\pi \exp(i\delta_\pi)\right)\right]$$
$$A(D^0 \to K^-K^+) = \lambda_s \mathcal{A}_{KK}\left[1 - \frac{\lambda_b}{\lambda_s} r_K \exp(i\delta_K)\right]$$

  - this implies for the direct CP-violating asymmetries ($r_b e^{-i\gamma} = \dfrac{\lambda_b}{\lambda_s}$)

$$a_{CP}^{dir}(K^-K^+) = -2 r_b r_K \sin\delta_K \sin\gamma$$

$$a_{CP}^{dir}(\pi^-\pi^+) = 2 r_b r_\pi \sin\delta_\pi \sin\gamma$$

  - … and for their difference

$$\Delta a_{CP}^{dir} = -2 r_b \sin\gamma (r_K \sin\delta_K + r_\pi \sin\delta_\pi)$$

- We need to compute $r_{\pi(K)}$ and $\delta_{\pi(K)}$

dCPV: amplitude decomposition

- Some things to keep in mind
  - "penguin-type amplitudes" $\mathcal{P}^s_{\pi\pi}$ and $\mathcal{P}^d_{KK}$ denote matrix elements of operators that contain quark-antiquark pair that does not match the valence content of the final state mesons; otherwise no relation to penguin topological amplitudes

$$\mathcal{P}^s_{\pi\pi} = \langle \pi^-\pi^+|\mathcal{O}^s|D^0\rangle\,, \quad \mathcal{P}^d_{KK} = \langle K^-K^+|\mathcal{O}^d|D^0\rangle \; \& \; r_\pi = \left|\frac{\mathcal{P}^s_{\pi\pi}}{\mathcal{A}_{\pi\pi}}\right|\,, \quad r_K = \left|\frac{\mathcal{P}^d_{KK}}{\mathcal{A}_{KK}}\right|$$

  - calculate $\mathcal{P}^s_{\pi\pi}$ and $\mathcal{P}^d_{KK}$ using a modified light-cone QCD sum rules

$$\delta_{\pi(K)} = \arg\left[\mathcal{P}^{s(d)}_{\pi\pi(KK)}\right] - \arg\left[\mathcal{A}_{\pi\pi(KK)}\right]$$

  - extract $\mathcal{A}_{\pi\pi}$ and $\mathcal{A}_{KK}$ amplitudes from measured branch. fractions

$$|\mathcal{A}_{\pi\pi}| \simeq \lambda_s^{-1}\left|A(D\to\pi^-\pi^+)\right| = (2.10\pm0.02)\times10^{-6}\ \mathrm{GeV}\,,$$

$$|\mathcal{A}_{KK}| \simeq \lambda_s^{-1}\left|A(D\to K^-K^+)\right| = (3.80\pm0.03)\times10^{-6}\ \mathrm{GeV}\,.$$

dCPV: calculating matrix elements

Khodjamirian, NPB 605 (2001) 558

- Use modified light-cone QCD Sum Rule (LCSR) method
  - start with the correlation function ($j_5^{(D)} = im_c \bar{c}\gamma_5 u$ and $j_{\alpha 5}^{(\pi)} = \bar{d}\gamma_\alpha\gamma_5 u$)

$$F_\alpha(p,q,k) = i^2 \int d^4x e^{-i(p-q)x} \int d^4y e^{i(p-k)y} \langle 0|\, T\left\{ j_{\alpha 5}^{(\pi)}(y) \mathcal{Q}_1^s(0) j_5^{(D)}(x) \right\} |\pi^+(q)\rangle$$
$$= (p-k)_\alpha F((p-k)^2, (p-q)^2, P^2) + \ldots,$$

  - use dispersion relation in (p-k) and (p-q), perform Borel transform, extract matrix element:

Khodjamirian, Mannel, Melic, PLB571 (2003) 75

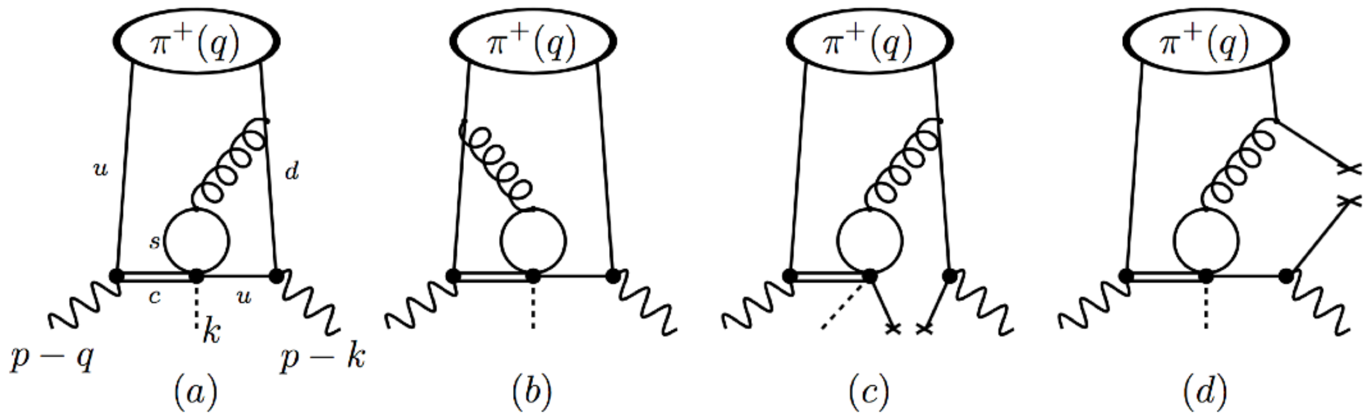
$$\langle \pi^-(-q)\pi^+(p)|\mathcal{Q}_1^s|D^0(p-q)\rangle = \frac{-i}{\pi^2 f_\pi f_D m_D^2} \int_0^{s_0^\pi} ds e^{-s/M_1^2} \int_{m_c^2}^{s_0^D} ds' e^{(m_D^2 - s')/M_2^2} \mathrm{Im}_{s'} \mathrm{Im}_s F(s, s', m_D^2)$$

  - perform LC expansion of F(s, s' m_D^2) to get $\mathcal{P}_{\pi\pi}^s$
  - note that $C_1 \mathcal{Q}_1^s + C_2 \mathcal{Q}_2^s = 2C_1 \widetilde{\mathcal{Q}}_2^s + \left(\frac{C_1}{3} + C_2\right) \mathcal{Q}_2^s$ with $\widetilde{\mathcal{Q}}_2^s = \left(\bar{s}\Gamma_\mu \frac{\lambda^a}{2} s\right)\left(\bar{u}\Gamma^\mu \frac{\lambda^a}{2} c\right)$

thus $\mathcal{P}_{\pi\pi}^s = \frac{2G_F}{\sqrt{2}} C_1 \langle \pi^+\pi^- | \widetilde{\mathcal{Q}}_2^s | D^0 \rangle$

dCPV: calculating matrix elements

- Evaluate (leading) diagrams contributing to the correlation function
  - calculate OPE in terms of known LC DAs **Khodjamirian, AAP: PLB774 (2017) 235**



  - analytically continue from the space-like region of $P^2=(p-k-q)^2$ (with auxiliary 4-momentum $k\neq0$) to $P^2 = m_D^2$, relying on the local quark-hadron duality
  - extract absolute value and the phase of matrix element $\mathcal{P}^s_{\pi\pi}$
  - vary parameters of the calculation to estimate uncertainties

dCPV predictions

- As a result… $\langle \pi^+\pi^-|\widetilde{\mathcal{Q}}_2^s|D^0\rangle = (9.50 \pm 1.13) \times 10^{-3} \exp[i(-97.5^o \pm 11.6)]\,\mathrm{GeV}^3$

$$\langle K^+K^-|\widetilde{\mathcal{Q}}_2^d|D^0\rangle = (13.9 \pm 2.70) \times 10^{-3} \exp[i(-71.6^o \pm 29.5)]\,\mathrm{GeV}^3$$

- Thus, $r_\pi = \dfrac{|\mathcal{P}^s_{\pi\pi}|}{|\mathcal{A}_{\pi\pi}|} = 0.093 \pm 0.011\,, \qquad r_K = \dfrac{|\mathcal{P}^d_{KK}|}{|\mathcal{A}_{KK}|} = 0.075 \pm 0.015$

and with $\Delta a_{CP}^{dir} = -2 r_b \sin\gamma (r_K \sin\delta_K + r_\pi \sin\delta_\pi)$

- Phases of $r_{\pi\pi(KK)}$ are given by the phases of $\mathcal{P}^{s(d)}_{\pi\pi(KK)}$?

No:

$$\left|a_{CP}^{dir}(\pi^-\pi^+)\right| < 0.012 \pm 0.001\%,$$
$$\left|a_{CP}^{dir}(K^-K^+)\right| < 0.009 \pm 0.002\%,$$
$$\left|\Delta a_{CP}^{dir}\right| < 0.020 \pm 0.003\%\,.$$

Yes:

$$a_{CP}^{dir}(\pi^-\pi^+) = -0.011 \pm 0.001\%,$$
$$a_{CP}^{dir}(K^-K^+) = 0.009 \pm 0.002\%.$$
$$\Delta a_{CP}^{dir} = 0.020 \pm 0.003\%\,.$$

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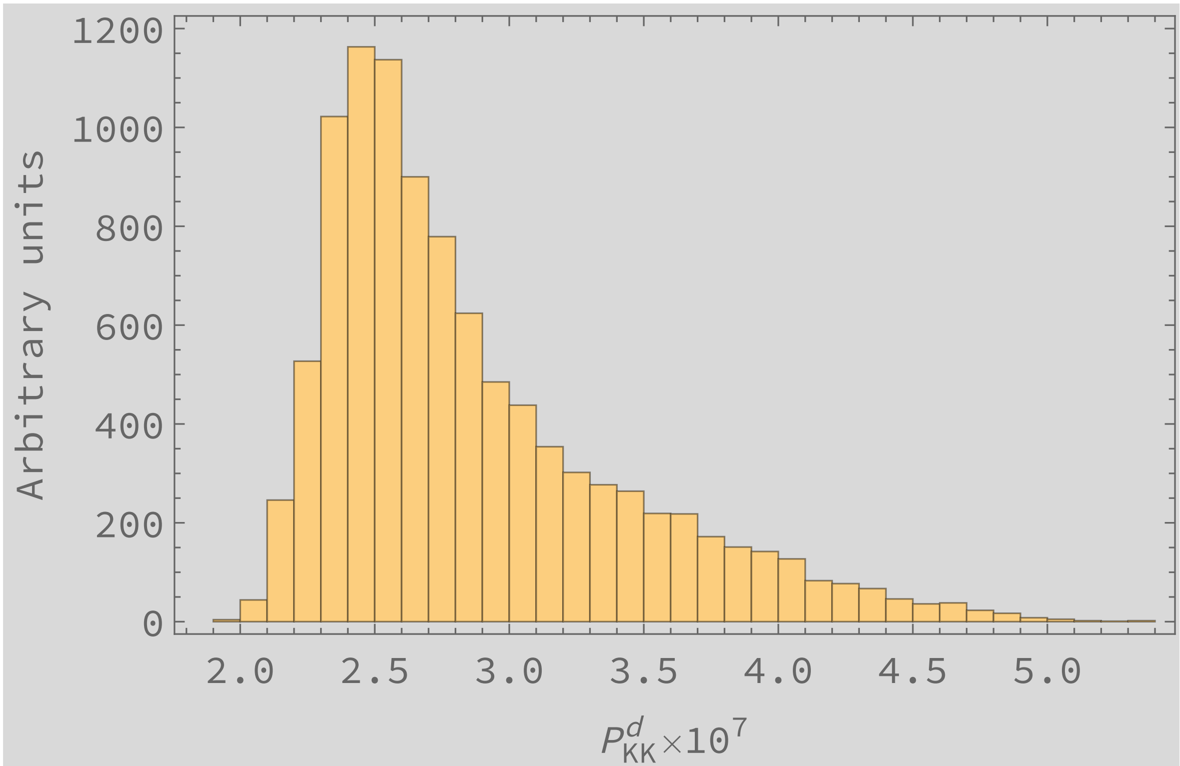
- Again, experiment: $\Delta a_{CP}^{dir} = (-0.156 \pm 0.029)\%$

Error budget: parameter uncertainties

Parameter values and references	Parameter rescaled to $\mu = 1.5$ GeV
$\alpha_s(m_Z) = 0.1181 \pm 0.0011$ [6]	0.351
$\bar{m}_c(\bar{m}_c) = 1.27 \pm 0.03$ GeV [6]	1.19 GeV
$\bar{m}_s(2\,\mathrm{GeV}) = 96^{+8}_{-4}\,\mathrm{MeV}$ [6]	105 MeV
$\langle \bar{q}q \rangle(2\,\mathrm{GeV}) = (-276^{+12}_{-10}\,\mathrm{MeV})^3$ [6]	$(-268\,\mathrm{MeV})^3$
$\langle \bar{s}s \rangle = (0.8 \pm 0.3)\langle \bar{q}q \rangle$ [21]	$(-249\ \mathrm{MeV})^3$
$a_2^\pi(1\,\mathrm{GeV}) = 0.17 \pm 0.08$ [22]	0.14
$a_4^\pi(1\,\mathrm{GeV}) = 0.06 \pm 0.10$ [22]	0.045
$\mu_\pi(2\,\mathrm{GeV}) = 2.48 \pm 0.30\,\mathrm{GeV}$ [6]	2.26 GeV
$f_{3\pi}(1\,\mathrm{GeV}) = 0.0045 \pm 0.015\ \mathrm{GeV}^2$ [19]	$0.0036\,\mathrm{GeV}^2$
$\omega_{3\pi}(1\,\mathrm{GeV}) = -1.5 \pm 0.7$ [19]	-1.1
$a_1^K(1\,\mathrm{GeV}) = 0.10 \pm 0.04$ [23]	0.09
$a_2^K(1\,\mathrm{GeV}) = 0.25 \pm 0.15$ [19]	0.21
$\mu_K(2\,\mathrm{GeV}) = 2.47^{+0.19}_{-0.10}$ GeV [6]	2.25
$f_{3K} = f_{3\pi}$	$0.0036\,\mathrm{GeV}^2$
$\omega_{3K}(1\,\mathrm{GeV}) = -1.2 \pm 0.7$ [19]	-0.99
$\lambda_{3K}(1\,\mathrm{GeV}) = 1.6 \pm 0.4$ [19]	1.5

Error budget: parameter uncertainties

- For example, probability distribution for KK final state:



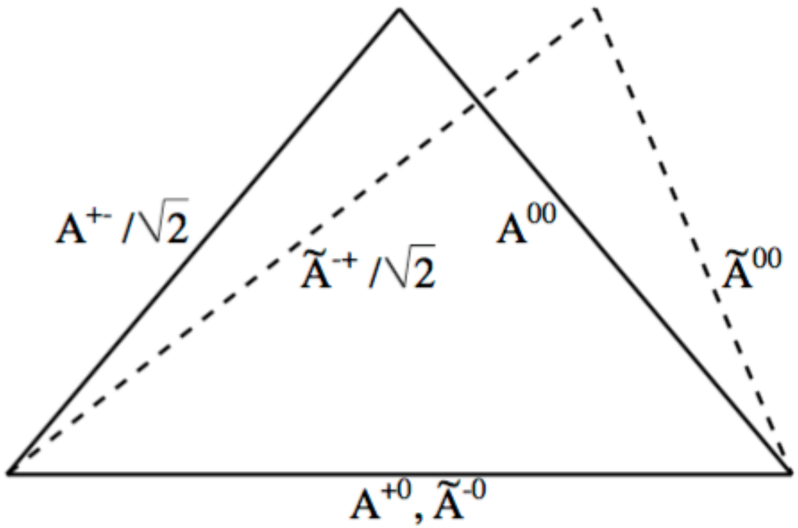
- Analysis of possible higher-order effects (Chala et al):
  - …resulting in $|\Delta A_{CP}| \leq (2.0 \pm 1.0) \times 10^{-4}$

$$\left|\frac{P}{T}\right|_{\pi^+\pi^-} = 0.093 \pm 0.030\,,$$

$$\left|\frac{P}{T}\right|_{K^+K^-} = 0.075 \pm 0.035\,,$$

Charming "triangle analyses"?

★ "Triangle analyses" require a lot of data, but only rely on isospin relations



- several final states possible, for D → $\pi^i\ \pi^k$

$$\frac{1}{\sqrt{2}} A^{+-} = A^{+0} - A^{00},$$
$$\frac{1}{\sqrt{2}} \overline{A}^{-+} = \overline{A}^{-0} - \overline{A}^{00},$$

Gronau, London
Bevan, Meadows

- others include D → $\pi\pi$, $\rho\pi$, $\rho\rho$

▾ Pionic modes

Γ_1	$\pi^+\pi^-$	$(1.420 \pm 0.025) \times 10^{-3}$
Γ_2	$2\,\pi^0$	$(8.25 \pm 0.25) \times 10^{-4}$
Γ_3	$\pi^+\pi^-\pi^0$	$(1.47 \pm 0.09)\%$
Γ_4	$\rho^+\pi^-$	$(1.00 \pm 0.06)\%$
Γ_5	$\rho^0\pi^0$	$(3.82 \pm 0.29) \times 10^{-3}$
Γ_6	$\rho^-\pi^+$	$(5.09 \pm 0.34) \times 10^{-3}$

- Other observables can be constructed for baryons, e.g.

$$A\left(\Lambda_c \to N\pi\right) = \bar{u}_N\left(p,s\right)\left[A_S + A_P\gamma_5\right]u_{\Lambda_c}\left(p_\Lambda, s_\Lambda\right)$$

These amplitudes can be related to "asymmetry parameter" $\alpha_{\Lambda_c} = \frac{2\,\mathrm{Re}\left(A_S^* A_P\right)}{\left|A_S\right|^2 + \left|A_P\right|^2}$

… which can be extracted from $\frac{dW}{d\cos\vartheta} = \frac{1}{2}\left(1 + P\alpha_{\Lambda_c}\cos\vartheta\right)$

Same is true for $\overline{\Lambda}_c$-decay

If CP is conserved $\alpha_{\Lambda_c} \overset{CP}{\Rightarrow} -\bar{\alpha}_{\Lambda_c}$, thus CP-violating observable is

$$\boxed{A_f = \frac{\alpha_{\Lambda_c} + \overline{\alpha}_{\Lambda_c}}{\alpha_{\Lambda_c} - \overline{\alpha}_{\Lambda_c}}}$$

FOCUS[2006]: $A_{\Lambda\pi}$=-0.07±0.19±0.24

Things to take home

- Computation of charm amplitudes is a difficult task
  - no dominant heavy dof, as in beauty decays
  - light dofs give no contribution in the flavor SU(3) limit
  - D-mixing is a second order effect in SU(3) breaking ($x,y \sim 1\%$ in the SM)
- For indirect CP-violation studies
  - constraints on Wilson coefficients of generic operators are possible, point to the scales much higher than those directly probed by LHC
  - consider new parameterizations that go beyond the "superweak" limit
- For direct CP-violation studies
  - unfortunately, large DCPV signal is no more; need more results in individual channels, especially including baryons
  - hit the "brown muck": future observation of DCPV does not give easy interpretation in terms of fundamental parameters
  - need better calculations: lattice?
- Lattice calculations can, in the future, provide a result for a_{CP}!
- Need to give more thought on how large SM CPV can be…

Things to take home

- Theory/Experiment relation:

Theory ✗ **Experiment** ✗ Not a very interesting case…	**Theory** ✗ **Experiment** ✓ SM wins again?
Theory ✓ **Experiment** ✗ SM wins again!	**Theory** ✓ **Experiment** ✓ New Physics!

- Observation of CP-violation in the current round of experiments could have provided a "smoking gun" signals for New Physics
  - But latest LHCb observation seem to be broadly consistent (?) with SM

$$\Delta a_{CP}^{dir} = (-0.156 \pm 0.029)\%$$ **LHCB-PAPER-2019-006**

  - Maybe if we only have a reliable calculation of the SM effects…

$$\left|\Delta a_{CP}^{dir}\right| < 0.020 \pm 0.003\%$$ **Khodjamirian, AAP: PLB774 (2017) 235**

$$|\Delta A_{CP}| \leq (2.0 \pm 1.0) \times 10^{-4}$$ **Chala, Lenz, Rusov, Scholtz: JHEP 1907 (2019) 161**


EXTRA!

Parameters of the dCPV calculation

- Light cone distribution amplitudes

$$\varphi_\pi(u) = 6u\bar{u}\left(1 + a_2^\pi C_2^{3/2}(u-\bar{u}) + a_4^\pi C_4^{3/2}(u-\bar{u})\right)$$

$$\phi_{3\pi}^p(u) \;=\; 1 + 30\frac{f_{3\pi}}{\mu_\pi f_\pi} C_2^{1/2}(u-\bar{u}) - 3\frac{f_{3\pi}\omega_{3\pi}}{\mu_\pi f_\pi} C_4^{1/2}(u-\bar{u}),$$

$$\phi_{3\pi}^\sigma(u) \;=\; 6u(1-u)\left(1 + 5\frac{f_{3\pi}}{\mu_\pi f_\pi}\left(1 - \frac{\omega_{3\pi}}{10}\right) C_2^{3/2}(u-\bar{u})\right)$$

$$\varphi_K(u) = 6u\bar{u}\left(1 + a_1^K C_1^{3/2}(u-\bar{u}) + a_2^K C_2^{3/2}(u-\bar{u})\right)$$