RTG - etc. Nov, Dec 2017 Dominik Mitzel

"Charming Way to probe the Standard Model"

Introduction Basic concepts

I 1. theoretical prediction and experimental discovery

I. 2 Mass generation and flavour transitions in the SM

Charm physics phenomenology

II 1 charm decays

III Neutral meson mixing

CP violation in charm

I. Introduction

Prelude

- Nowadays: the theory that describes fundamental particles and their interactions is the Standard Model.

Matter Content: 3 generations of fundamental particles with same charges under the SU gauge group, but very different masses

	I	II	III	Q [e]	
Quarks	u	c	t	$+2/3$	+ Antiparticles
	d	s	b	$-1/3$	
Leptons	ν_e	ν_μ	ν_τ	0	
	e	μ	τ	-1	

Flavour physics: Study difference between the generations such as masses, flavour transitions and CP violation. Charm physics is flavour physics involving production and decay of hadrons containing c-quarks:

Examples: $J/\psi = |c\bar{c}\rangle$ 'charmonium', 'hidden charm'

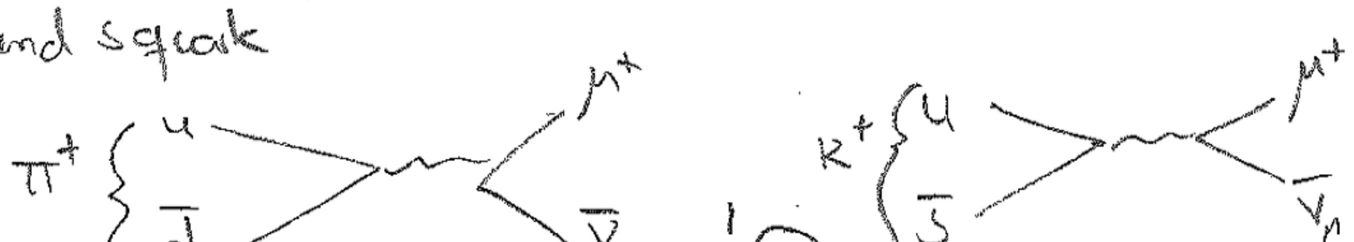
$D^0 = |c\bar{u}\rangle$, $D^+ = |c\bar{d}\rangle$, $D_s^+ = |c\bar{s}\rangle$ 'open charm'

$\Lambda_c = |cud\rangle$ 'charmed baryons'

I.1. Charm prediction and experimental discovery

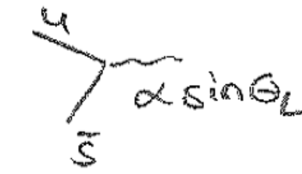
- Let's move back to 1960. Known (quark) matter content: u, d, s

observation of pion and kaon decays showed that the u-quark couples to both the d and s quark



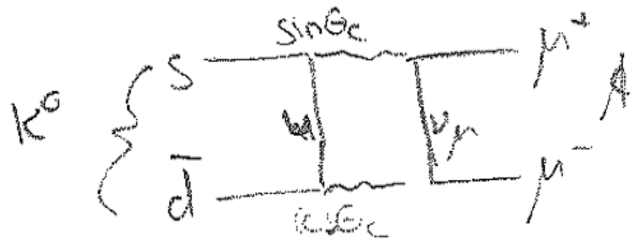
measured ratio: $\frac{\Gamma(K^+\to\mu\nu)}{\Gamma(\pi^+\to\mu\nu)} \sim 1{,}3$ contradictory to 'naive' theoretical prediction of ~ 18 (assuming universal coupling of the weak interaction)

Cabibbo 1963: Weak eigenstates are not pure flavour states: Introduce the doublet

$\begin{pmatrix} u \\ d' \end{pmatrix} = \begin{pmatrix} u \\ d\cos\theta_c + s\sin\theta_c \end{pmatrix}$, with θ_c Cabibbo angle.  $\propto \cos\theta_c$,  $\propto \sin\theta_c$

$\frac{\Gamma(K\to\mu\nu)}{\Gamma(\pi\to\mu\nu)} \propto \tan^2\theta_c \Rightarrow \theta_c \sim 13°$. Cabibbo's idea solved that problem.

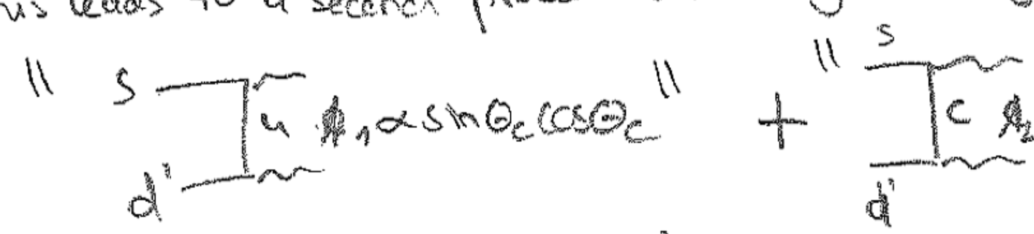
However, this would lead to the following transitions, again contradictory to experimental observations



$A \propto (\sin\theta_c\cos\theta_c)\ (\sim 0.2)$, Exp: $\frac{\Gamma(K^0\to\mu\mu)}{\Gamma(K^0\to\text{anything})} < 10^{-9}$

Glashow, Iliopoulos, Maiani 1970: predict existence of a new fourth quark, ordered in 2 generations: $\begin{pmatrix} u \\ d' \end{pmatrix}, \begin{pmatrix} c \\ s' \end{pmatrix}$ with $\begin{pmatrix} |d'\rangle \\ |s'\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} |d\rangle \\ |s\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta_c |d\rangle + \sin\theta_c |s\rangle \\ -\sin\theta_c |d\rangle + \cos\theta_c |s\rangle \end{pmatrix}$

this leads to a second process with negative sign, explaining the large supression:



$A_1 \propto \sin\theta_c\cos\theta_c$ + $A_2 \propto (-)\sin\theta_c\cos\theta_c$ $= 0$ [if $m_c = m_u$]

→ this is usually called the "GIM mechanism". The charm prediction and completion of the 2nd family was an important step towards nowadays SM.

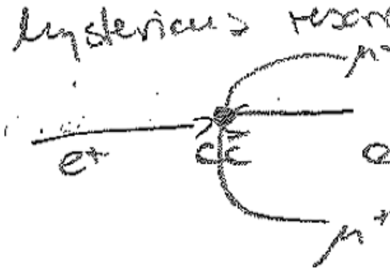
Experimental discovery

1974 two experiments reported observation of a new long lived particle (independently)

Richter et al: SPEAR (Stanford Position Electron Asymmetric Ring) at SLAC (Stanford Linear Accelerator Center)

wanted to measure $R = \frac{\sigma(e^+e^-\to\text{hadrons})}{\sigma(e^+e^-\to\mu\mu)}(\sqrt{s})$

Mysterious resonance @ $\sqrt{s} \approx 3{,}1$ GeV. Inspired by the decay topology SPEAR called it "ψ" and name of experiment



Ting et al: Brookhaven-Experiment: $p + Be \to e^+e^- X$. Peak in the dielectron spectrum at $m_{ee} = 3{,}1$ GeV. Family name Ting ~ Symbol 'J' looks like a "J". Nobel price in 1976, combined name J/ψ ($c\bar{c}$-resonance) ach: Why was the new resonance interpretated as $c\bar{c}$ state? The high mass and long lifetime could not be explained by the existence of 3 quarks (u, d, s). The final confirmation of the charm discovery was given by the measurement of 'open charm' (D^0, D^+) also in 1976! Today's picture was completed by the discovery of the b (1977) and top quark (1995). Theoretically, the third generation was already predicted in 1973 to be able to explain CP violation observed in the kaon system. Let's move back to 2017

2. Mass generation and flavour transitions in the SM

the SM, each generation consists of 3 (quark) fermion multiplets. (We ignore lepton sector in the following)

$$Q_{Li} = \begin{pmatrix} u_{Li} \\ d_{Li} \end{pmatrix} \left(= \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} c_L \\ s_L \end{pmatrix}, \begin{pmatrix} t_L \\ b_L \end{pmatrix} \right)$$ Left handed SU(2) doubletts

generation index

$$u_{Ri} = (u_R, c_R, t_R)$$ right handed SU(2) singlets

$$d_{Ri} = (d_R, s_R, b_R)$$

Let's look at the Yukawa couplings that give mass to the fermions, as 'ordinary' terms such as $\sim m\bar{\psi}\psi$ are not respecting the gauge symmetry.

$$-\mathcal{L}_{Yukawa} = Y_{ij}^d \, \overline{Q}_{Li} \, \phi \, d_{Rj} + Y_{ij}^u \, \overline{Q}_{Li} \, \tilde{\phi} \, u_{Rj} + h.c.$$

Y: Yukawa matrices complex, non-diagonal

ϕ: Higgs, $\langle\phi\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$ after symmetry breaking

$\tilde{\phi} = i\sigma^2 \phi = \frac{1}{\sqrt{2}} \begin{pmatrix} v+h(x) \\ 0 \end{pmatrix}$

$$= \frac{v}{\sqrt{2}} \left(\overline{d}_{Li} Y_{ij}^d d_{Rj} + \overline{u}_{Li} Y_{ij}^u u_{Rj} \right) + h.c.$$

$$= \frac{v}{\sqrt{2}} \Big(\underbrace{\overline{d}_{Li} V_{Ld}^{+}}_{\tilde{\overline{d}}_{Li}} \overbrace{V_{Ld}}^{=\mathbb{1}} \underbrace{V_{LD} Y_{ij}^d V_{Rd}^{+}}_{(M_d)_{ii}} \overbrace{}^{\mathbb{1}} \underbrace{V_{Rd} d_{Rj}}_{\tilde{d}_{Ri}} + \underbrace{\overline{u}_{Li} V_{Lu}^{+}}_{\tilde{\overline{u}}_{Li}} \underbrace{V_{Lu} Y_{ij}^u V_{Ru}^{+}}_{(M_u)_{ii}} \underbrace{V_{Ru} u_{Rj}}_{\tilde{u}_{Ri}} \Big) + h.c.$$

$$= \tilde{\overline{d}}_{Li} \, (M_d)_{ii} \, \tilde{d}_{Ri} + \tilde{\overline{u}}_{Li} \, (M_u)_{ii} \, \tilde{u}_{Ri} + h.c.$$

What happened? We inserted a "$\mathbb{1}$", but the implications are important:

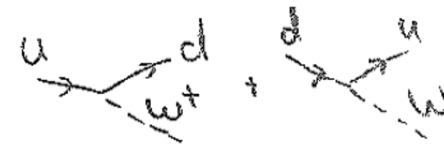
chose V_{Aq} such that: $M_d = \frac{v}{\sqrt{2}} V_{LD} Y^d V_{Rd}^{+} = \mathrm{diag}(m_d, m_s, m_b)$

$M_u = \frac{v}{\sqrt{2}} V_{Lu} Y^u V_{Ru}^{+} = \mathrm{diag}(m_u, m_c, m_t)$

ransform the fields: $\tilde{u}_L = V_{Lu} u_L \quad \tilde{d}_L = V_{Ld} d_L$
$\tilde{u}_R = V_{Ru} u_R \quad \tilde{d}_R = V_{Rd} d_R$

his also has crucial impact on the weak interaction:

$$\mathcal{L}_{cc} = -\frac{g}{\sqrt{2}} \left(\overline{u}_{Li} \gamma^\mu W_\mu^+ d_{Li} + \overline{d}_{Li} \gamma^\mu W_\mu^- u_{Li} \right)$$

[Pictorial: 

$$= -\frac{g}{\sqrt{2}} \left(\overline{\tilde{u}}_{Li} \gamma^\mu W_\mu^+ \underbrace{(V_{Lu} \cdot V_{Ld}^\dagger)_{ij}}_{=V_{CKM}} \tilde{d}_{Lj} + \overline{\tilde{d}}_{Li} \gamma^\mu W_\mu^- \underbrace{(V_{Ld} V_{Lu}^\dagger)_{ij}}_{=V_{CKM}^\dagger} \tilde{u}_{Lj} \right)$$

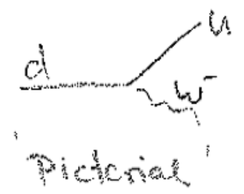
insert transformed fields

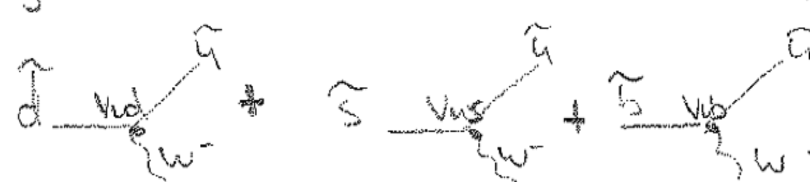
$\left[\begin{array}{l} d_L = V_{Ld}^\dagger \tilde{d}_L, \ \overline{d}_L = \overline{\tilde{d}}_L V_{Ld} \\ \overline{u}_L = \overline{\tilde{u}}_L V_{Lu}, \ u_L = V_{Lu}^\dagger \tilde{u}_L \end{array} \right]$

Note: The neutral current $JA \sim Z_\mu \overline{u} (c_V - c_A \gamma^5) \gamma^\mu u$ is <u>not</u> affected (no FCNC @ tr

Now, let's have a closer look at $d_i = (V_{CKM})_{ij} \tilde{d}_j$: weak states are mixture of mass states!

$$\underset{\text{(interacting states)}}{\begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \underset{\text{(mass states)}}{\begin{pmatrix} \tilde{d}_L \\ \tilde{s}_L \\ \tilde{b}_L \end{pmatrix}}$$

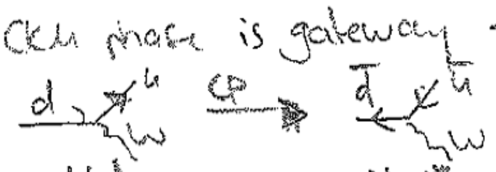


$\Rightarrow$ 

transitions between the generations!

<u>Properties of V_{CKM}</u>:
- unitary (as it is a product of unitary matrices)
- 3 real parameters and 1 phase. [Remark: starting from 18 (9 real + 9 phases); unitary: 9 − (3 real + 6 phases); 5 phases are absent quark phases: 4 (3 real + 1 phase)
- <u>in general</u>: for N generations $\frac{N(N-1)}{2}$ real parameters, $\frac{N}{2}(N-1)(N-2)$ phases

Very important: for $N<3$ no phases left; CKM phase is gateway for CP violation in SM



[we discuss CPV later]

<u>ierarchy of CKM matrix</u>

ctorial: $|V_{CKM}| =$ 

a priori, there is no fundamental reason for the observed magnitude of the CKM elements. The picture is purely based on measurements. But the hierarchy allows to use the 'Wolfenstein parametrization' in $\lambda = |V_{us}| \sim 0.22$

$$V_{CKM} \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

A, ρ, η $\mathcal{O}(1)$, for exact definition see for example PDG review.

<u>mark</u>: unitarity gives rise to 9 equations such as $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$
$\rightsquigarrow$ 6 'triangles' in complex plane

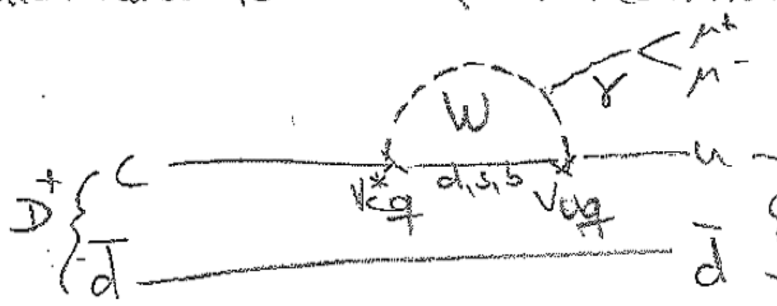
<u>e home message</u>: (I) The charm quark played a major role in the development of the SM
(II) In the SM, mass generation and flavour transitions have a common origin. Transitions are governed by unitary 3×3 CKM matrix.

II Charm physics phenomenology

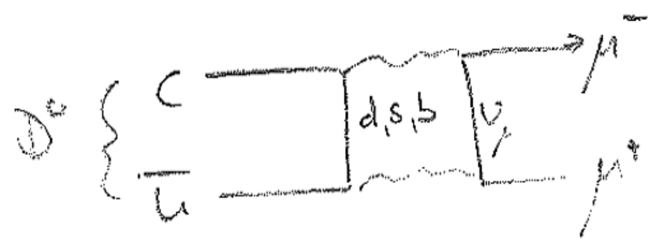
II.1 Rare charm decays

Last week we saw that FCNC are not possible at tree level. However, higher order transitions a[re] possible which allow to search for NP contributions beyond the mass scale accessible in direct search[es].

Examples:



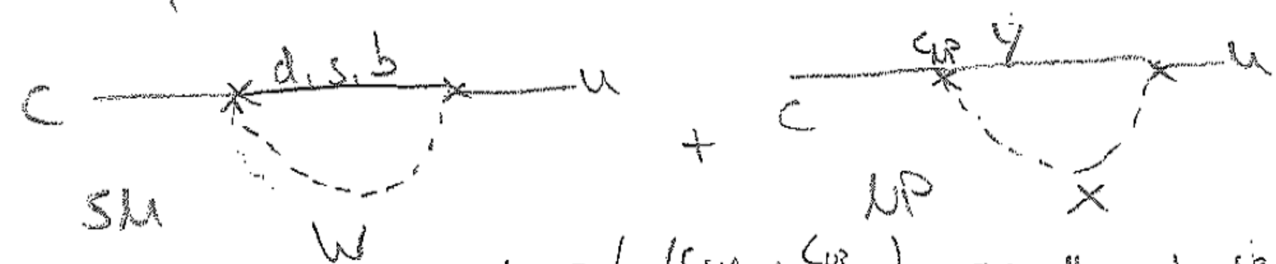
$D^+ \to \pi^+ \mu^+ \mu^-$ via "Penguin diagram"
Quark flavour changes in internal W-loop



$D^0 \to \mu^+ \mu^-$ via "box diagram"

- They all have the FCN $c \to u$ transition in common. As the internal particles are produced 'virtually', potential very heavy and yet unobserved particles can enter the loop and change the rat[e]. Even particles too heavy for direct production can contribute (Indirect approach)

Schematic:



$A_{tot} = A_0 \left(\frac{C_{SM}}{m_W^2} + \frac{C_{NP}}{\Lambda_{NP}^2} \right)$ This allows to set limits on $\frac{C_{NP}}{\Lambda_{NP}^2}$

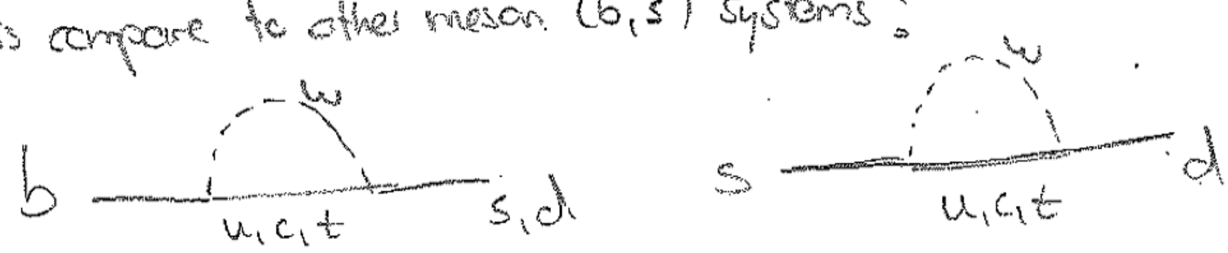
SM contributions:

$$A \propto V_{cd}^* V_{ud}\, f\left(\frac{m_d^2}{m_W^2}\right) + V_{cs}^* V_{us}\, f\left(\frac{m_s^2}{m_W^2}\right) + V_{cb}^* V_{ub}\, f\left(\frac{m_b^2}{m_W^2}\right)$$

$$\underset{\text{unitarity}}{=} V_{cs}^* V_{us} \underbrace{\left(f\left(\frac{m_s^2}{m_W^2}\right) - f\left(\frac{m_d^2}{m_W^2}\right)\right)}_{\substack{\sim 0,\ \text{as } m_s^2 \sim m_d^2 \\ \text{'GIM suppressed'}}} + \underbrace{V_{cb}^* V_{ub}}_{\substack{\sim \lambda^5 (\mathcal{O}(10^{-4})) \\ \text{'CKM suppressed'}}} \left(f\left(\frac{m_b^2}{m_W^2}\right) - f\left(\frac{m_d^2}{m_W^2}\right)\right) \approx 10^{-8}$$

$\left[f\left(\frac{m_q^2}{m_W^2}\right) \sim \frac{1}{16\pi^2} \frac{m_q^2}{m_W^2} \right]$

- Remark: Just a simple estimation. QCD effects enhance the rate and are hard to estimate
  Theory: $BR(c \to u \mu^+ \mu^-) \lesssim 10^{-9}$ [1101.6053], $BR(D^+ \to \pi^+ \mu^+ \mu^-) \leq 3.7 \cdot 10^{-12}$ [1510.00311]
  $BR(D^0 \to \mu^+ \mu^-) \leq 6 \cdot 10^{-11}$ [0112235v2]
- How does this compare to other meson (b, s) systems?



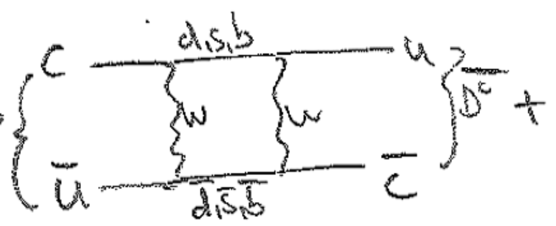
$BR(B \to X_s e^+ e^-) = 7 \cdot 10$
[1312.5364]
$BR(B^+ \to \pi^+ \mu^+ \mu^-) = 2 \cdot 10$
[1509.00414]
$BR(B_s \to \mu^+ \mu^-) = 3 \cdot 10^{-9}$
[1703.05747]

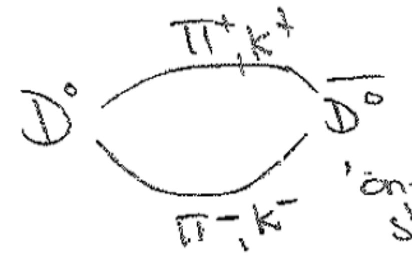
processes are dominated by the t-quark: $f\left(\frac{m_t^2}{m_W^2}\right) \sim \mathcal{O}(1)$

- Charm system: Only system with d-type quarks in the loop (important if NP acts differently). Supression higher ("effectively uncoupled from third generation"). Extremely low SM rate that competes with NP processes.

7.2 Neutral charm mixing

- D^0 ($|c\bar{u}\rangle$) and $\bar{D}^0$ ($|\bar{c}u\rangle$) are accessible though common intermediate states:





"short distance contributions" "Long distance contributions"

- the propagating mass states are therefore a superposition of the flavour states. Describe the system by the following 'effective' Schrödinger equation

$$i\frac{d}{dt}\begin{pmatrix}|D^0(t)\rangle\\|\bar{D}^0(t)\rangle\end{pmatrix} = \left(M - i\Gamma\right)\begin{pmatrix}|D^0(t)\rangle\\|\bar{D}^0(t)\rangle\end{pmatrix} \qquad M, \Gamma \text{ are } 2\times2 \text{ matrices}$$

with eigenstates: $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$, $p^2+q^2=1$

and time evolution $D_{12}(t) = e^{-im_{1,2}t}e^{\frac{1}{2}\Gamma_{1,2}t}|D_{1,2}(0)\rangle$ with different masses $m_{1,2}$ and widths $\Gamma_{1,2}$

usually one defines: $x = \frac{m_1-m_2}{\Gamma}$, $y = \frac{\Gamma_1-\Gamma_2}{2\Gamma}$, $\Gamma = \frac{\Gamma_1+\Gamma_2}{2}$

An initially ($t=0$) produced D^0 ($\bar{D}^0$) meson can oscillate in its antiparticle ! (and vice versa)

$$P(D^0 \to \bar{D}^0)(t) = |\langle \bar{D}^0(t)|D^0(0)\rangle|^2 \propto \left|\frac{q}{p}\right|^2 \frac{e^{-\Gamma t}}{2}\left[\cosh(y\Gamma t) - \cos(x\Gamma t)\right]$$

$$P(\bar{D}^0 \to D^0)(t) = |\langle D^0(t)|\bar{D}^0(0)\rangle|^2 \propto \left|\frac{p}{q}\right|^2 \frac{e^{-\Gamma t}}{2}\left[\cosh(y\Gamma t) - \cos(x\Gamma t)\right]$$

(different, if $\left|\frac{q}{p}\right|^2 \neq \left|\frac{p}{q}\right|^2$)

- Mixing, if either x or y (or both) $\neq 0$!

SM predictions:

- In general, predictions are very hard due to the non-perturbatively calculable long distance contributions. However, due to the small FCNC processes $|x|, |y| \lesssim 10^{-3}$.

How does this compare to b and kaon physics?

	x	y
$K^{0\dagger}$	0.477	1
B_d^0	0.78	0.0015*
B_s^0	26.1	0.06*
D^0	0.003	0.007

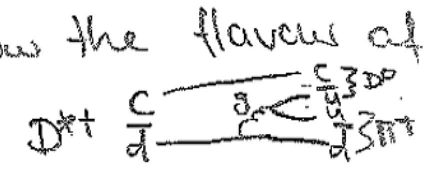
* theoretical values
† fun fact: Kaon mixing dominated by charm quark in the loop

- The observable quantities x and y really depend on the system (i.e. involved quarks and couplings)

- Again, in charm the SM mixing rate (and $\Delta\Gamma$) are really tiny, making charm mixing sensitive for NP contrib

Experimental measurement:

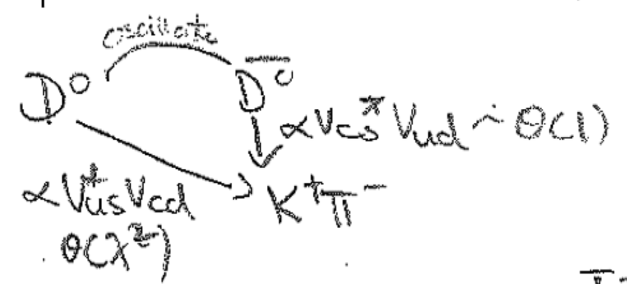
- to measure mixing, one needs to know the flavour at production and moment of deca
(1) at $t=0$: We select a flavour specific decay $D^{*+} \to D^0\pi^+$, $D^{*-} \to \bar{D}^0\pi^-$ i.e. once we know the charge of the $\pi^{+/-}$, we know the flavour of the D^0 (strong decay)



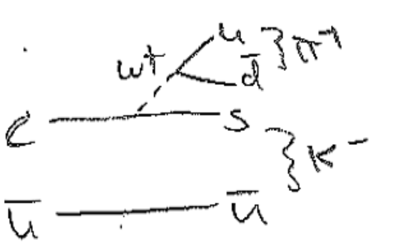
flavour conserved !

) at the moment of decay: It would be very convenient to take also a flavour specific decay such as $D^0 \to K^- \mu^+ \nu$. This is experimentally very challenging

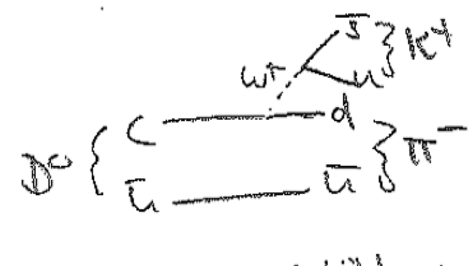
- Easier: Take $D^0 \to K^- \pi^+$, $\bar{D}^0 \to K^+ \pi^-$. However, the D^0 can also directly decay to $K^+ \pi^-$ (very suppressed)



Feynman graphs:



"Cabibbo favoured" (=CF)
$\propto V_{cs}^* V_{ud} \sim \mathcal{O}(1)$



"doubly Cabibbo suppressed" (=DCS)
$\propto V_{cd}^* V_{us} \sim \mathcal{O}(\lambda^2)$

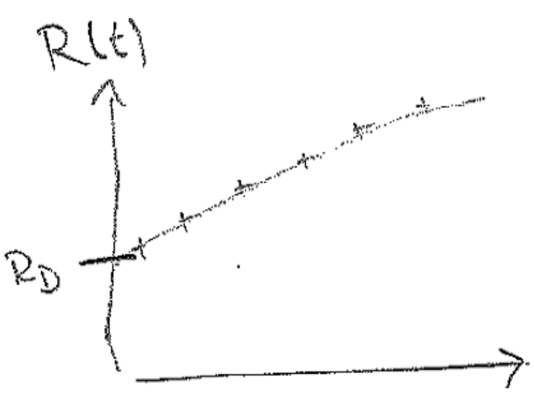
- Measuring the rate $D^0 \to K^+ \pi^-$ ("wrong sign decay") includes both mixing and direct (very) suppressed decay. Comparing with the rate $D^0 \to K^- \pi^+$ ("right side") gives:

$$R(t) = \frac{N^{WS}}{N_{RS}}(t) = R_D + \sqrt{R_D}\, y' \Gamma t + \frac{x'^2 + y'^2}{4} (\Gamma t)^2$$

R_D: Ratio Rates DCS / CF decay; second term $\propto t$; third term $\propto t^2$

$x' = x \sin\delta + y \cos\delta$
$y' = -x \sin\delta + y \cos\delta$
δ = "strong phase difference DCS and CF decay paths"

Schematic



- non trivial dependence on decay time indicates mixing!
- The WS $D \to K\pi$ mixing analysis was the first one showing 5σ significance from a single experiment (arXiv 1211.1230 (2012)). Nowadays more measurements exist.

III.1 CP violation in charm

- What is it and why do we care at all?

CP transformation is the combined charge (C) and parity (P) transformation of a system. CP is violated if the system is not invariant under the transformation

The meta reason to look for CPV: As pointed out by Sakharov, CP violation is a necessary condition for the observed cosmological baryon asymmetry. The CPV in the SM is not sufficient to explain the observed asymmetry

More practical: In the SM, the complex phase of the CKM matrix is the only source of CPV in the SM. Any SM extension (enlarging the particle content) or new interactions with

...mplex couplings" comes with new sources of CPV. This makes CPV <u>very</u> <u>attractive</u> place
to look for NP.

the SM:  , phases of the CKM matrix elements change sign

How to measure CPV?

As all observable quantities are in general obtained by "squaring" the amplitudes, overall phases <u>cannot</u> be observed: $A_1 \rightsquigarrow A_1 e^{i\varphi}$

$$|A_1|^2 \rightsquigarrow |A_1|^2$$

$$|i\rangle \xrightarrow{A_1 = A_1 e^{i\phi_1 + i\delta_1}} |f\rangle \quad \overset{CP}{\Longrightarrow} \quad |\bar{i}\rangle \xrightarrow{A_1 e^{-i\phi_1 + i\delta_1}} |\bar{f}\rangle$$

$$A_2 = A_2 e^{i\phi_2 + i\delta_2} \qquad\qquad A_2 e^{-i\phi_2 + i\delta_2}$$

ϕ changes sign under CP
δ is 'strong phase' not changing sign under CP.

total amplitude $A = A_1 + A_2 = C(1 + R e^{i\Delta\phi + i\Delta\delta})$; $R = \frac{A_2}{A_1}$

$$\bar{A} = \bar{A}_1 + \bar{A}_2 = C(1 + R e^{-i\Delta\phi + i\Delta\delta})$$

define the asymmetry $A_{CP} = \frac{\Gamma(i\to f) - \Gamma(\bar{i}\to\bar{f})}{\Gamma(i\to f) + \Gamma(\bar{i}\to\bar{f})} = 2R\sin(\Delta\phi)\sin(\Delta\delta)$

suppressed if one amplitude dominates!

$$\Gamma \propto |A|^2$$

• Important remark: If there's no strong phase difference, $A_{CP} = 0$!

Why? $\left.\begin{array}{l} |A|^2 \sim \cos(\Delta\phi) \\ |\bar{A}|^2 \sim \cos(-\Delta\phi) \end{array}\right\} |A|^2 - |\bar{A}|^2 = 0$ $[\cos(-\Delta\phi) = \cos(\Delta\phi)]$

• Take home message: CPV is only possible if several amplitudes with different strong and weak phases contribute.

Classification of CPV

neutral + charged D: CPV in the decay: $\frac{|\bar{A}_{\bar{f}}|}{|A_f|} \neq 1$ (i.e. $P(D\to f) \neq P(\bar{D}\to\bar{f})$)

"direct CPV"

only neutral D^0: CPV in mixing: $\left|\frac{q}{p}\right| \neq 1$ (i.e. $P(\bar{D}^0\to D^0) \neq P(D^0\to\bar{D}^0)$)

CPV in interference between mixing and decay (same final state for D^0 and $\bar{D}^0$): $\mathrm{Im}\left(\frac{q\bar{A}_f}{pA_f}\right)$

$$|D^0\rangle \xrightarrow{\phi_D} |f\rangle, \quad |D^0\rangle \xrightarrow{\phi_M} |\bar{D}^0\rangle \xrightarrow{-\phi_D} |f\rangle$$

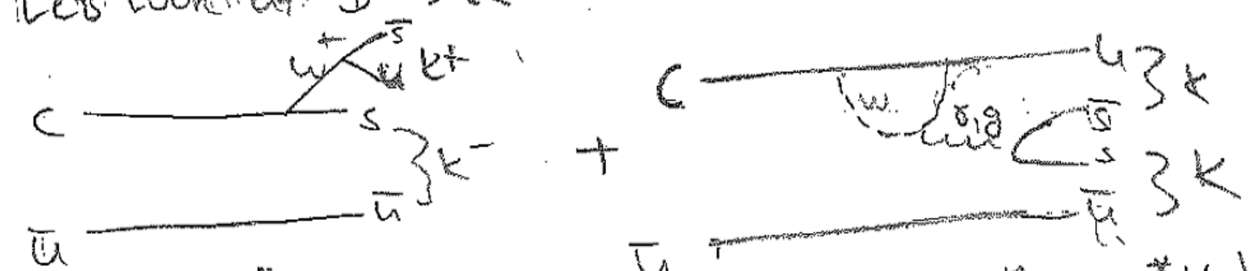
[i.e. $P(D^0\to\bar{D}^0\to f)(t) \neq P(\bar{D}^0\to D^0\to f)$

"indirect CPV"

SM predictions for charm decays

- As we need two competing amplitudes, usually one is very dominant (tree) over a higher order process (often penguin, box..) : $A_{CP} \sim R \cdot \sin(\Delta\phi)\sin(\Delta\delta)$

Let's look at $D^0 \to \bar{K}K^+$



"tree" $\sim V_{cs}^* V_{us}$ "penguin" $\sim V_{cb}^* V_{ub}$

Remark: due to the " $\sim\!\!\sim\!\!<^{\bar{q}}_{q}$ ", only $D \to KK$ and $D \to \pi\pi$ can receive penguin contributions

- We already saw that the $c \to u$ transitions are tiny. In charm, $R \sim \frac{|V_{cb}^* V_{ub}|}{|V_{cs}^* V_{us}|} \sim \frac{\lambda^5}{\lambda} = \lambda^4$
- For indirect CP, the calculations go beyond the scope of this lecture. However, it turns out that $A_{CP}^{mixing} \propto x$, $A_{CP}^{interference} \propto y$. So, as $x, y \lesssim 10^{-3}$, also indirect CPV is expected to be below 10^{-3}. [These are all heuristic arguments, theoretical predictions are really hard]
- Can we do better? It is attractive to look at decays, where R is enhanced, i.e. where the dominant amplitude is also very suppressed, such as $D^0 \to K_S K_S$ (no tree level possible)
- Experimentally: Charm is the only neutral meson system, where CPV has not been measured! (Limits are indeed $\lesssim \mathcal{O}(10^{-3})$)

Take home message: Everything is small in charm!

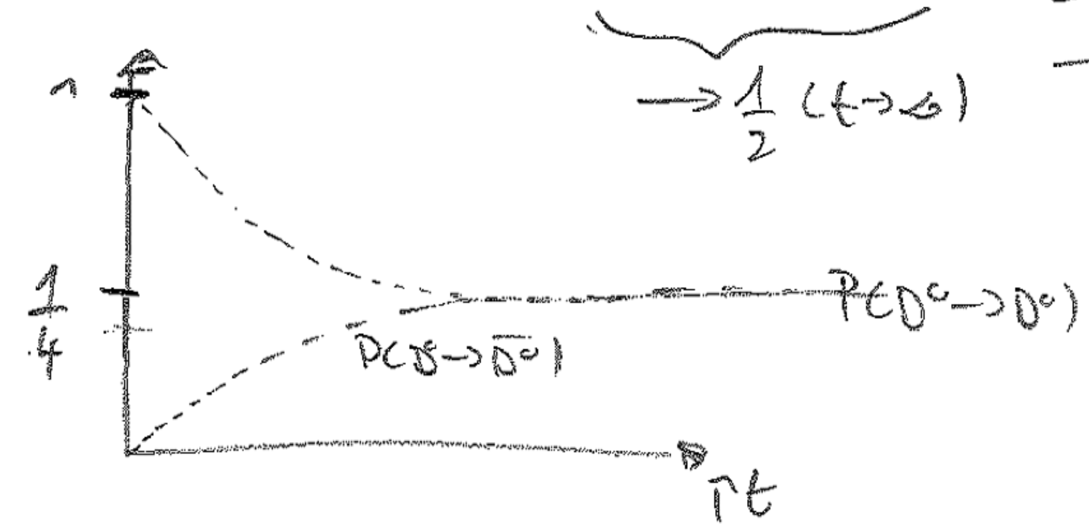
References

- Lecture notes "Quark and Lepton Flavour physics" SS 2015 by Ulrich Uwer
- Lecture notes "Standard Model of Particle physics" SS 2013 by Werner Rodejohann, André Schöning
- Lecture notes "CP violation" by P. Kooijman & N. Tuning April 2011 (Nikhef)
- Talk "Quark Flavour Physics" by Uli Uwer, Neckarzimmern LHCb workshop 2017
- Dissertation by Sascha Stahl 2014: "Measurement of CP violation in muon tagged $D^0 \to KK$ and $D^0 \to \pi\pi$ decays at LHCb"
- Lecture notes "Teilchenphysik II-III - Abteilung IX" WS 2001 by André Rubbia (ETH Zürich)

Case 1.) $x = 0 \quad y = 1$ (one is stable) $\left|\frac{q}{p}\right| = 1$

$$P(D^0 \to \bar{D}^0) = \frac{1}{2} e^{-\Gamma t} \left(\cosh(\Gamma t) - 1 \right)$$

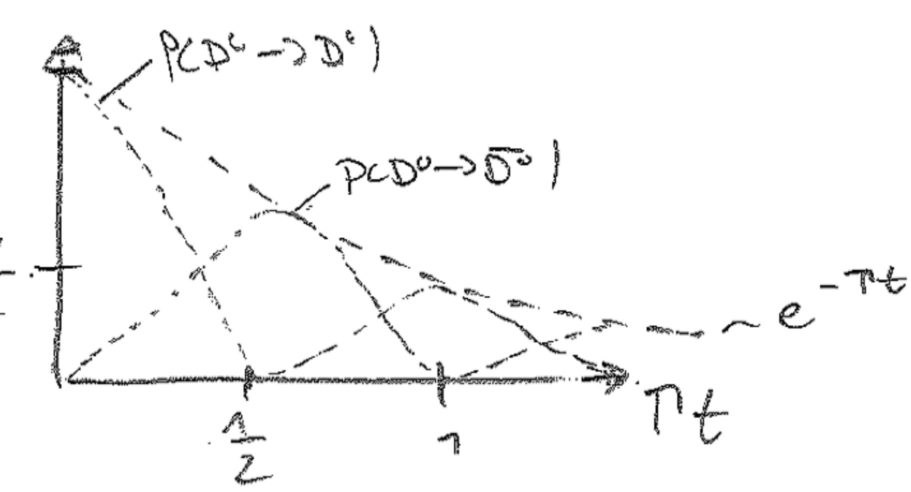
$$P(D^0 \to D^0) = \frac{1}{2} \underbrace{e^{-t\Gamma} \left(\cosh(\Gamma t)\right.}_{\to \frac{1}{2} \, (t \to \infty)} \left. + \underbrace{1}_{\to 0 \, (t \to \infty)} \right)$$



Case 2.) $y = 0 \quad x = 2\pi \quad \left|\frac{q}{p}\right| = 1$

$$P(D^0 \to D^0) = \frac{1}{2} e^{-\Gamma t} \left(1 + \cos(2\pi \Gamma t) \right)$$

$$P(D^0 \to \bar{D}^0) = \frac{1}{2} e^{-\Gamma t} \left(1 - \underbrace{\cos(2\pi \Gamma t)}_{\text{periodic!}} \right)$$



Mixing Kaon: $|V_{ts} V_{td}|^2 \sim \lambda^{10}$

$|V_{cs} V_{cd}|^2 \sim \lambda^2$

[Extra]