Flavour Physics (of quarks)

Part 2: Mixing and CP violation

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Warwick Week Graduate Lectures

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Overview

Lecture 1: Flavour in the SM

- Flavour in the SM
- Quark Model History
- The CKM matrix

Lecture 2: Mixing and CP violation (Today)

- Neutral Meson Mixing (no CPV)
- B-meson production and experiments
- CP violation

Lecture 3: Measuring the CKM parameters

- Measuring CKM elements and phases
- Global CKM fits
- CPT and T-reversal
- Dipole moments

Lecture 4: Flavour Changing Neutral Currents

- Effective Theories
- New Physics in B mixing
- New Physics in rare $b \to s$ processes
- Lepton Flavour Violation

1. Recap

Recap

- Last time we introduced the role of flavour in the SM
- We saw how measurements of meson decays led to the predictions and subsequent discoveries of strange, charm, beauty and top decays
- We saw how various meson and baryon states are built out of the consitituent quarks
- We introduced the CKM matrix (much more on that in the next two lectures)

Homework from last time

Can you explain the 2:1 ratio:

$$\sigma(p + p \to d + \pi^{+}) : \sigma(p + n \to d + \pi^{0}) = 2 : 1?$$

Homework for next time

Why is it that down type neutral mesons contain the anti-quark species but up type contain the quark?

For example:

- $B^0 = (\bar{b}d),\ B_s^0 = (\bar{b}, s),\ K^0 = (\bar{s}d)$
- $\overline{B}^0 = (b\bar{d}),\ \overline{B}_s^0 = (b, \bar{s}),\ \overline{K}^0 = (s\bar{d})$

But:

- $D^0 = (c\bar{u})$
- $\overline{D}^0 = (\bar{c}u)$

Recap

- Recall the CKM matrix which governs quark weak transitions

CKM exhibits a clear hierarchy

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

experimentally determined values

Commonly represented in the Wolfenstein parametrisation

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

4 $\mathcal{O}(1)$ real parameters (A, λ, ρ, η)

Recap

- Wolfenstein parameterisation ensures that

$$\bar{\rho} + i\bar{\eta} = -(V_{ud}V_{ub}^{*})/(V_{cd}V_{cb}^{*}) \quad (1)$$

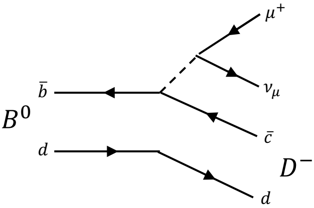
is phase convention independent and CKM matrix written in $(A, \lambda, \bar{\rho}, \bar{\eta})$ is unitary to all orders in λ

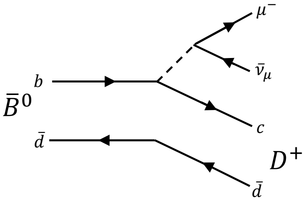
$$\bar{\rho} = \rho(1 - \lambda^2/2 + \dots) \quad \text{and} \quad \bar{\eta} = \eta(1 - \lambda^2/2 + \dots) \quad (2)$$

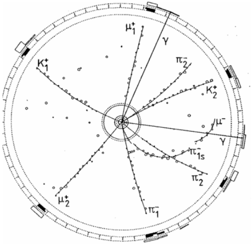
- The amount of CP violation in the SM is equivalent to asking how big is η relative to ρ.

2. Neutral Meson Mixing (no CPV)

- In 1987 the ARGUS experiment observed coherently produced $B^0 - \overline{B}^0$ pairs and observed them decaying to same sign leptons
- How is this possible?
  - Semileptonic decays "tag" the flavour of the initial state



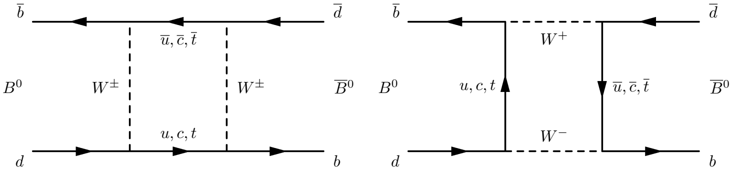




- The only explanation is that B^0–$\overline{B}^0$ can oscillate
- Rate of mixing is large $\rightarrow$ top quark must be heavy

Neutral Meson Mixing

- In the SM occurs via box diagrams involving a charged current ($W^{\pm}$) interaction
- Weak eigenstates are not the same as the physical mass eigenstates
  - The particle and antiparticle flavour states (via CPT theorem) have equal and opposite charge, identical mass and identical lifetimes
  - But the mixed states (*i.e.* the physical B_L^0 and B_H^0) can have $\Delta m, \Delta\Gamma \neq 0$



- In the SM we have four possible neutral meson states
  - K^0, D^0, B^0, B_s^0 (mixing has been observed in all four)
  - Although they all have rather different properties (as we will see in a second)

Coupled meson systems

- A single particle system evolves according to the time-dependent Schrödinger equation

$$i\frac{\partial}{\partial t}|X(t)\rangle = \mathcal{H}|X(t)\rangle = \left(M - i\frac{\Gamma}{2}\right)|M(t)\rangle \tag{3}$$

- For neutral mesons, mixing leads to a coupled system

$$i\frac{\partial}{\partial t}\begin{pmatrix}|B^0\rangle \\ |\overline{B}^0\rangle\end{pmatrix} = \mathcal{H}\begin{pmatrix}|B^0\rangle \\ |\overline{B}^0\rangle\end{pmatrix} = \left(\boldsymbol{M} - i\frac{\boldsymbol{\Gamma}}{2}\right)\begin{pmatrix}|B^0\rangle \\ |\overline{B}^0\rangle\end{pmatrix} \tag{4}$$

$$= \begin{pmatrix}M_{11} - i\Gamma_{11}/2 & M_{12} - i\Gamma_{12}/2 \\ M_{12}^* - i\Gamma_{12}^*/2 & M_{22} - i\Gamma_{22}/2\end{pmatrix}\begin{pmatrix}|B^0\rangle \\ |\overline{B}^0\rangle\end{pmatrix} \tag{5}$$

where

$$M_{12} = \frac{1}{2M}\mathcal{A}(B^0 \to \overline{B}^0) = \langle\overline{B}^0|\mathcal{H}(\Delta B = 2)|B^0\rangle \tag{6}$$

Coupled meson system

- To start with we will neglect CP-violation in mixing (approximately the case for all four neutral meson species)
- Neglecting CP-violation, the physical states are an equal mixture of the flavour states

$$|B_L^0\rangle = \frac{|B^0\rangle + |\overline{B}^0\rangle}{2}, \qquad |B_H^0\rangle = \frac{|B^0\rangle - |\overline{B}^0\rangle}{2}$$

with mass and width differences

$$\Delta\Gamma = \Gamma_H - \Gamma_L = 2|\Gamma_{12}|, \quad \Delta M = M_H - M_L = 2|M_{12}|$$

so that the physical system evolves as

$$i\frac{\partial}{\partial t}\begin{pmatrix}|B_L^0\rangle \\ |B_H^0\rangle\end{pmatrix} = \mathcal{H}\begin{pmatrix}|B_L^0\rangle \\ |B_H^0\rangle\end{pmatrix} = \left(\boldsymbol{M} - i\frac{\boldsymbol{\Gamma}}{2}\right)\begin{pmatrix}|B_L^0\rangle \\ |B_H^0\rangle\end{pmatrix} \tag{7}$$

$$= \begin{pmatrix}M_L - i\Gamma_L/2 & 0 \\ 0 & M_H - i\Gamma_H/2\end{pmatrix}\begin{pmatrix}|B_L^0\rangle \\ |B_H^0\rangle\end{pmatrix} \tag{8}$$

Time evolution

- Solving the Schrödinger equation gives the time evolution of a pure state $|B^0\rangle$ or $|\overline{B}^0\rangle$ at time $t = 0$

$$|B^0(t)\rangle = g_+(t)|B^0\rangle + \frac{q}{p}g_-(t)|\overline{B}^0\rangle$$
$$|\overline{B}^0(t)\rangle = g_+(t)|\overline{B}^0\rangle + \frac{p}{q}g_-(t)|B^0\rangle \quad (9)$$

where

$$g_+(t) = e^{-iMt}e^{-\Gamma t/2}\left[\ \ \cosh\left(\frac{\Delta\Gamma t}{4}\right)\cos\left(\frac{\Delta m t}{2}\right) - i\sinh\left(\frac{\Delta\Gamma t}{4}\right)\sin\left(\frac{\Delta m t}{2}\right)\right]$$
$$g_-(t) = e^{-iMt}e^{-\Gamma t/2}\left[-\sinh\left(\frac{\Delta\Gamma t}{4}\right)\cos\left(\frac{\Delta m t}{2}\right) + i\cosh\left(\frac{\Delta\Gamma t}{4}\right)\sin\left(\frac{\Delta m t}{2}\right)\right] \quad (10)$$

and $M = (M_L + M_H)/2$ and $\Gamma = (\Gamma_L + \Gamma_H)/2$

- No CP-violation in mixing means that $|p/q| = 1$ (and thus we have equal admixtures)

Time evolution

- Using Eq. (10) flavour remains unchanged $(+)$ or will oscillate $(-)$ with probability

$$|g_{\pm}(t)|^2 = \frac{e^{-\Gamma t}}{2}\left[\cosh\left(\frac{\Delta\Gamma t}{2}\right) \pm \cos(\Delta m t)\right] \tag{11}$$

- With no CP violation in the mixing, the time-integrated mixing probability is

$$\frac{\int |g_{-}(t)|^2 dt}{\int |g_{-}(t)|^2 dt + \int |g_{+}(t)|^2 dt} = \frac{x^2 + y^2}{2(x^2+1)} \tag{12}$$

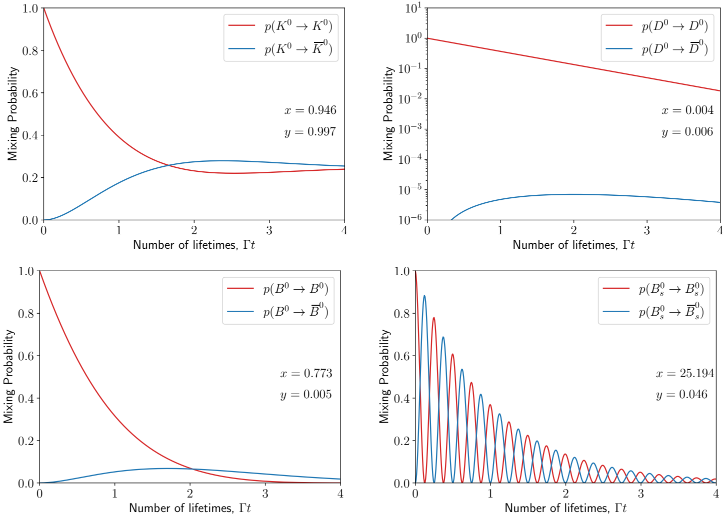
where

$$x = \frac{\Delta m}{\Gamma} \quad \text{and} \quad y = \frac{\Delta\Gamma}{2\Gamma} \tag{13}$$

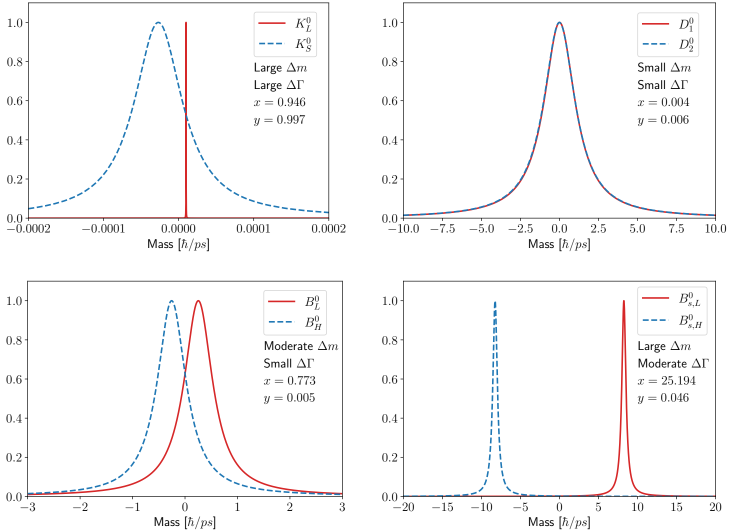
- The four different neutral meson species which mix have very different values of (x, y) and therefore very different looking time evolution properties

Neutral Meson Mixing

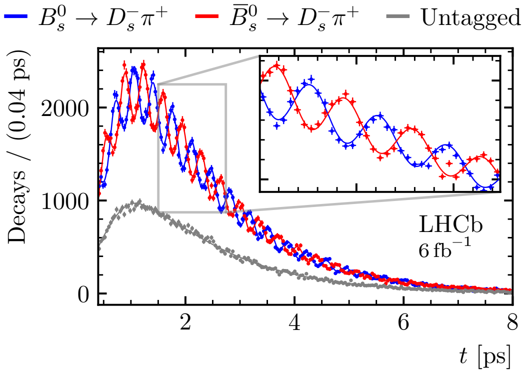
$$|g_{\pm}(t)|^2 = \frac{e^{-\Gamma t}}{2}\left[\cosh\left(\frac{\Delta\Gamma t}{2}\right) \pm \cos(\Delta m t)\right] \tag{14}$$



- Mass and width differences of the neutral meson mixing systems



- Very nice demonstration of the B_s^0 oscillation from the LHCb experiment
- Seen in $B_s^0 \to D_s^- \pi^+$ decays
- Tag the flavour of the initial state at **production** and compare to the flavour at decay (the $D_s^- \pi^+$ final state tags the decaying flavour)
- Why is this so different from the plot on the previous slide (damped oscillation and turn on at low values)?

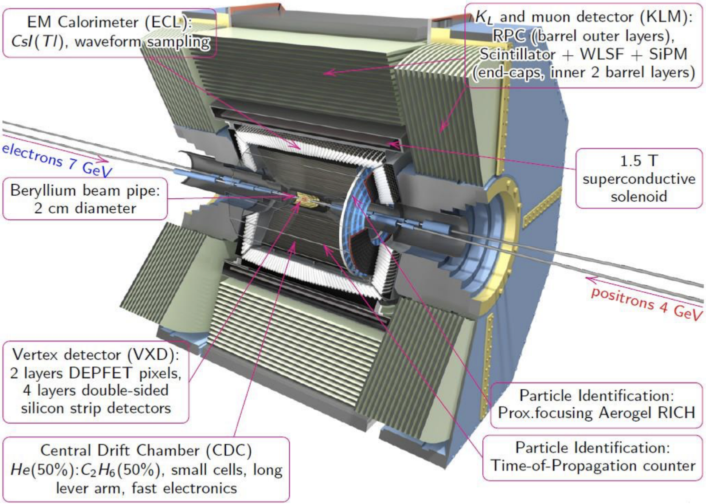


3. B-meson production and experiments

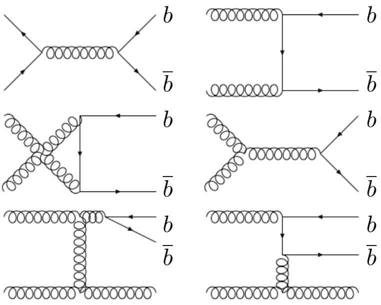
B-factories at the $\Upsilon(4S)$

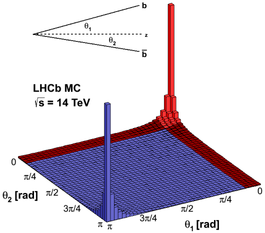
- Asymmetric e^+e^- colliders
- Produce excited $\Upsilon(4S)$ resonance (10.58 GeV) which decays strongly and produces a coherent pair of $B^0\overline{B}^0$ (50%) or B^+B^- pair (50%) moving in the lab frame
  - BaBar produced ~ 500M $B\overline{B}$ pairs in $\sim 530\,\text{fb}^{-1}$ of data from 9 GeV and 3.1 GeV beams at SLAC
  - Belle produced ~ 770M $B\overline{B}$ pairs in $\sim 710\,\text{fb}^{-1}$ of data from 8 GeV and 3.5 GeV beams at KEK
  - Belle-II expected to produce up to ~ 50B $B\overline{B}$ pairs in $\sim 50\,\text{ab}^{-1}$ of data
- Very clean environments but notice that the B_s^0 is not in range of the $\Upsilon(4S)$ resonance. This requires specific running at the $\Upsilon(5S)$.
  - In comparison to LHCb, $B\overline{B}$ pairs are not produced at high boost which makes resolution of B_s^0 oscillations impossible at B-factories
- Because B mesons are produced in pairs from a known resonance you get very high flavour tagging power and very good resolution for missing energy (*i.e.* final state neutrals)
- For Belle-II to acheieve desired luminosity requires incredible squeezing of the beam (target is $8 \times 10^{35}\text{cm}^{-2}\text{s}^{-1}$ which is 40 $\times$ Belle)

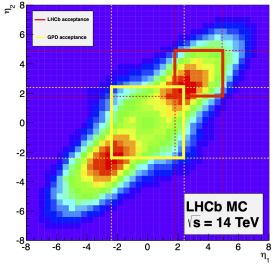
Belle-II Experiment

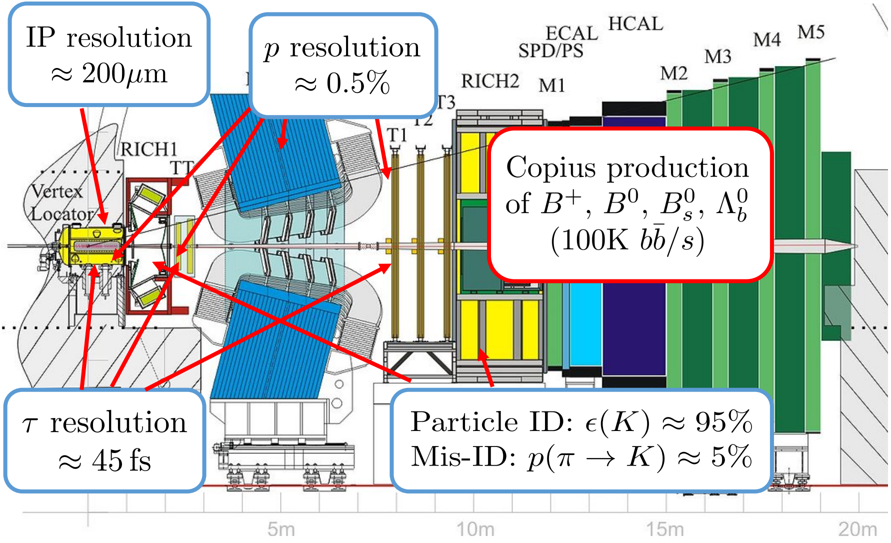


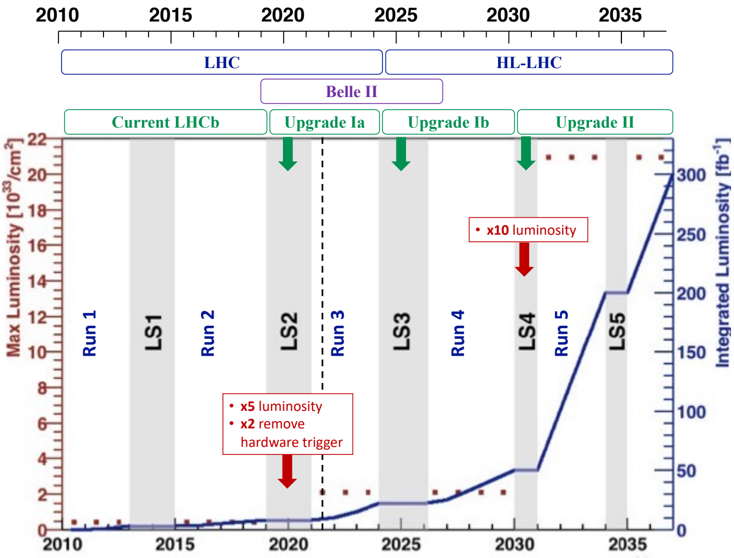
- The LHC is predominantly a gluon collider
- b-quarks are produced in pairs and predominantly in the forward region with a very large boost
  - Hence the very forward geometry of LHCb
- The very large boost and very high quality vertexing makes decay time measurements much easier
  - Can resolve the very rapid B_s^0 oscillations





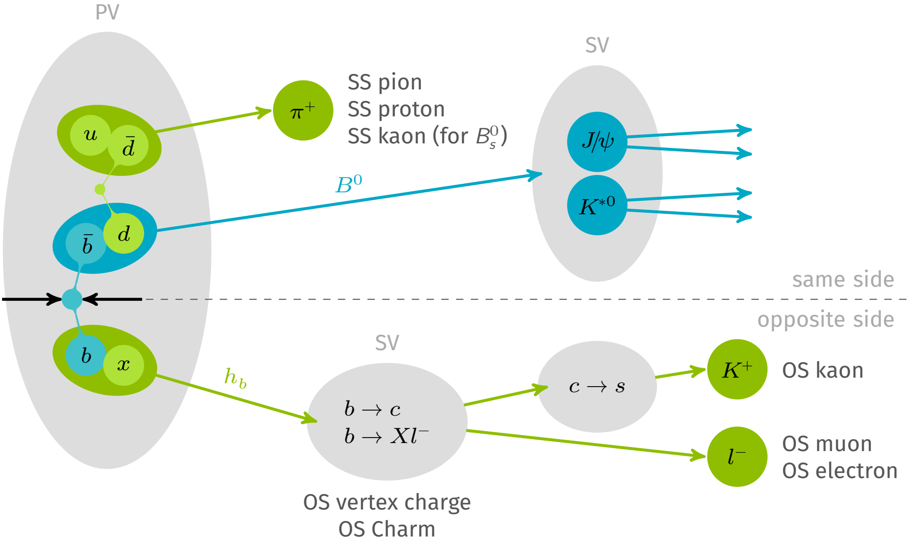



IP resolution $\approx 200\mu$m
p resolution $\approx 0.5\%$
Copius production of B^+, B^0, B^0_s, Λ^0_b (100K $b\bar{b}/s$)
τ resolution ≈ 45 fs
Particle ID: $\epsilon(K) \approx 95\%$
Mis-ID: $p(\pi \to K) \approx 5\%$
Vertex Locator
RICH1
TT
T1
T2
T3
RICH2
M1
SPD/PS
ECAL
HCAL
M2
M3
M4
M5
5m
10m
15m
20m



- COVID has pushed back future schedule by (at least) one year

Flavour Tagging at the LHC



Dalitz plot formalism

- For a nice overview of this, take a look at Sec. 2 of [arXiv:1711.09854]
- Provides a nice method and visualisation of 3-body decays, *e.g.* $B \to XYZ$
- The n-body decay rate is

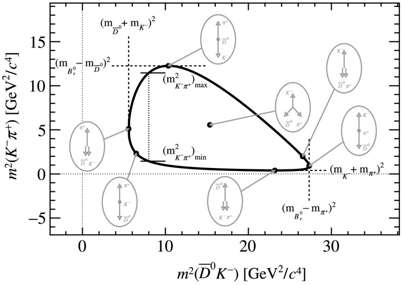
$$d\Gamma = \frac{(2\pi)^4}{2M} |\mathcal{M}|^2 d\phi(p_1, p_2, \ldots, p_n) \tag{15}$$

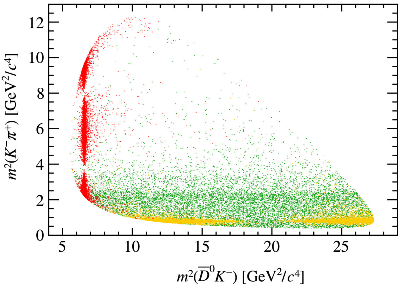
- So for a 3-body decay

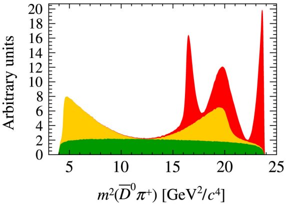
$$d\Gamma = \frac{1}{(2\pi)^3} \frac{1}{32M^3} \overline{|\mathcal{M}|}^2 dm_{12}^2 dm_{23}^2 \tag{16}$$

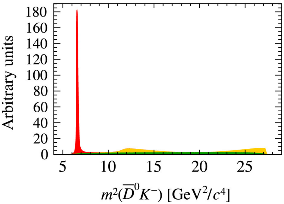
- Note how 3-body phase-space is flat in the Dalitz plot
- Resonances appear as bands in the Dalitz plot where The number of "lobes" in the Dalitz plot is related to the particle spin
  - Spin-0 "scalar" contributions have 1 lobe
  - Spin-1 "vector" contributions have 2 lobes
  - Spin-2 "tensor" contributions have 3 lobes

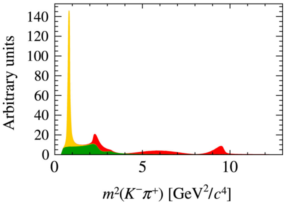
- Example shown for a $B^0 \to \overline{D}^0 K^- \pi^+$ decay











4. CP violation

Measuring CP violation

1. Need at least two interfering amplitudes
2. Need two phase differences between them
   - One CP conserving ("strong") phase difference (δ)
   - One CP violating ("weak") phase difference (ϕ)

- If there is only a single path to a final state, f, then we cannot get direct CP violation
- If there is only one path we can write the amplitudes for decay as

$$\mathcal{A}(B \to f) = A_1 e^{i(\delta_1 + \phi_1)}$$
$$\mathcal{A}(\bar{B} \to \bar{f}) = A_1 e^{i(\delta_1 - \phi_1)}$$

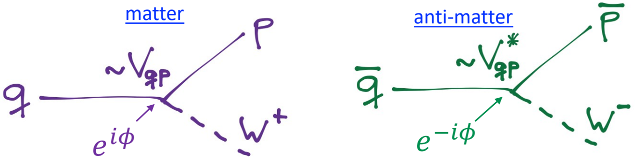
- Which gives an asymmetry of

$$\mathcal{A}_{CP} = \frac{|\mathcal{A}(\overline{B} \to \bar{f})|^2 - |\mathcal{A}(B \to f)|^2}{|\mathcal{A}(\overline{B} \to \bar{f})|^2 + |\mathcal{A}(B \to f)|^2} = 0 \quad (17)$$

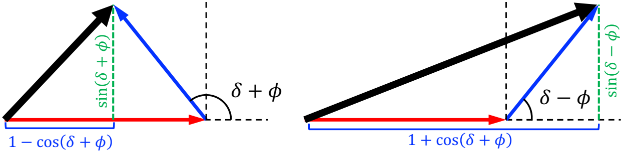
- In order to observe CP-violation we need a second amplitude.
- This is often realised by having interefering tree and penguin amplitudes

Measuring CP-violation

- We measure quark couplings which have a complex phase
- This is only visible when there are two amplitudes



- Below we represent two amplitudes (red and blue) with the same magnitude $= 1$
  - The strong phase difference is, $\delta = \pi/2$
  - The weak phase difference is, $\phi = \pi/4$



$$\Gamma(B \to f) = |A_1 + A_2 e^{i(\delta+\phi)}|^2 \qquad \Gamma(\bar{B} \to \bar{f}) = |A_1 + A_2 e^{i(\delta-\phi)}|^2$$

Measuring (direct) CP-violation

- Introducing the second amplitude we now have

$$\mathcal{A}(B \to f) = A_1 e^{i(\delta_1+\phi_1)} + A_2 e^{i(\delta_2+\phi_2)} \quad (18)$$

$$\mathcal{A}(\bar{B} \to \bar{f}) = A_1 e^{i(\delta_1-\phi_1)} + A_2 e^{i(\delta_2-\phi_2)} \quad (19)$$

- Which gives an asymmetry of

$$\mathcal{A}_{CP} = \frac{|\mathcal{A}(\overline{B} \to \bar{f})|^2 - |\mathcal{A}(B \to f)|^2}{|\mathcal{A}(\overline{B} \to \bar{f})|^2 + |\mathcal{A}(B \to f)|^2} \quad (20)$$

$$= \frac{4A_1A_2\sin(\delta_1-\delta_2)\sin(\phi_1-\phi_2)}{2A_1^2+2A_2^2+4A_1A_2\cos(\delta_1-\delta_2)\cos(\phi_1-\phi_2)} \quad (21)$$

$$= \frac{2r\sin(\delta)\sin(\phi)}{1+r^2+2r\cos(\delta)\cos(\phi)} \quad (22)$$

where $r = A_1/A_2$, $\delta = \delta_1 - \delta_2$ and $\phi = \phi_1 - \phi_2$

- This is only non-zero if the amplitudes have **different** weak **and** strong phases
- This is CP-violation in decay (often called "direct" CP violation).
  - This is the only possible route of CP violation for a charged initial state
  - We will see now that for a neutral initial state there are other ways of realising CP violation

Classification of CP violation

- First let's consider a generalised form of a neutral meson, X^0, decaying to a final state, f
- There are four possible amplitudes to consider

$$A_f = \langle f | X^0 \rangle \qquad \bar{A}_f = \langle f | \bar{X}^0 \rangle$$
$$A_{\bar{f}} = \langle \bar{f} | X^0 \rangle \qquad \bar{A}_{\bar{f}} = \langle \bar{f} | \bar{X}^0 \rangle$$

- Define a complex parameter, λ_f (**not** the Wolfenstein parameter, λ)

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}, \qquad \bar{\lambda}_f = \frac{1}{\lambda_f}, \qquad \lambda_{\bar{f}} = \frac{q}{p}\frac{\bar{A}_{\bar{f}}}{A_{\bar{f}}}, \qquad \bar{\lambda}_{\bar{f}} = \frac{1}{\lambda_{\bar{f}}}$$

Classification of CP violation

Can realise CP violation in three ways:

1. CP violation in decay
   - For a charged initial state this is only the type possible

$$\Gamma(X^0 \to f) \neq \Gamma(\bar{X}^0 \to \bar{f}) \Longrightarrow \boxed{\left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| \neq 1} \tag{23}$$

2. CP violation in mixing

$$\Gamma(X^0 \to \bar{X}^0) \neq \Gamma(\bar{X}^0 \to X^0) \Longrightarrow \boxed{\left|\frac{p}{q}\right| \neq 1} \tag{24}$$

3. CP violation in the interference between mixing and decay

$$\Gamma(X^0 \to f) \neq \Gamma(X^0 \to \bar{X}^0 \to f) \Longrightarrow \arg(\lambda_f) = \boxed{\arg\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \neq 0} \tag{25}$$

- We just saw an example of CP violation in decay
- Let's extend our formalism of neutral mixing, Eqs. (9–13), to include CP violation

Neutral meson mixing with CP violation

- Allowing for CP violation, $M_{12} \neq M_{12}^*$ and $\Gamma_{12} \neq \Gamma_{12}^*$
- The physical states can now be unequal mixtures of the weak states

$$
\begin{aligned}
|B_L^0\rangle &= p|B^0\rangle + q|\overline{B}^0\rangle \\
|B_H^0\rangle &= p|B^0\rangle - q|\overline{B}^0\rangle
\end{aligned}
\tag{26}
$$

where

$$|p|^2 + |q|^2 = 1$$

- The states now have mass and width differences

$$|\Delta\Gamma| \approx 2|\Gamma_{12}|\cos(\phi), \quad |\Delta M| \approx 2|M_{12}|, \quad \phi = \arg(-M_{12}/\Gamma_{12}) \tag{27}$$

- We'll see some examples of this later
- Now to equip ourselves with the formalism for a generalised meson decay

The probability that state X^0 at time t decays to f at time t

- contains terms for CPV in decay, mixing and the interference between the two

$$\Gamma_{X^0\to f}(t) = \boxed{|A_f|^2} \left(\boxed{|g_+(t)|^2} + \boxed{|\lambda_f|^2} \boxed{|g_-(t)|^2} + \boxed{2\mathcal{R}e\left[\lambda_f g_+^*(t) g_-(t)\right]} \right) \quad (28)$$

$$\Gamma_{X^0\to \bar{f}}(t) = \boxed{|\bar{A}_{\bar{f}}|^2} \boxed{\left|\frac{q}{p}\right|^2} \left(\boxed{|g_-(t)|^2} + \boxed{|\lambda_{\bar{f}}|^2} \boxed{|g_+(t)|^2} + \boxed{2\mathcal{R}e\left[\lambda_{\bar{f}} g_+(t) g_-^*(t)\right]} \right) \quad (29)$$

$$\Gamma_{\bar{X}^0\to f}(t) = \boxed{|A_f|^2} \boxed{\left|\frac{p}{q}\right|^2} \left(\boxed{|g_-(t)|^2} + \boxed{|\lambda_f|^2} \boxed{|g_+(t)|^2} + \boxed{2\mathcal{R}e\left[\lambda_f g_+(t) g_-^*(t)\right]} \right) \quad (30)$$

$$\Gamma_{\bar{X}^0\to \bar{f}}(t) = \boxed{|\bar{A}_{\bar{f}}|^2} \left(\boxed{|g_+(t)|^2} + \boxed{|\lambda_{\bar{f}}|^2} \boxed{|g_-(t)|^2} + \boxed{2\mathcal{R}e\left[\lambda_{\bar{f}} g_+^*(t) g_-(t)\right]} \right) \quad (31)$$

where the mixing probabilities are as before

$$|g_\pm(t)|^2 = \frac{e^{-\Gamma t}}{2}\left[\cosh\left(\frac{\Delta\Gamma t}{2}\right) \pm \cos(\Delta m t)\right] \quad (32)$$

$$g_+^* g_-^{(*)} = \frac{e^{-\Gamma t}}{2}\left[\sinh\left(\frac{\Delta\Gamma t}{2}\right) \pm i\sin(\Delta m t)\right] \quad (33)$$

Generalised Meson Decay Formalism

- From the above we get the "master equations" for neutral meson decay

$$\Gamma_{X^0\to f}(t) = |A_f|^2 \quad (1+|\lambda_f|^2)\frac{e^{-\Gamma t}}{2}\Big[\cosh(\tfrac{1}{2}\Delta\Gamma t) + C_f\cos(\Delta m t) + D_f\sinh(\tfrac{1}{2}\Delta\Gamma t) - S_f\sin(\Delta m t)\Big] \quad (34)$$

$$\Gamma_{\overline{X}^0\to f}(t) = |A_f|^2\left|\frac{p}{q}\right|^2(1+|\lambda_f|^2)\frac{e^{-\Gamma t}}{2}\Big[\cosh(\tfrac{1}{2}\Delta\Gamma t) - C_f\cos(\Delta m t) + D_f\sinh(\tfrac{1}{2}\Delta\Gamma t) + S_f\sin(\Delta m t)\Big] \quad (35)$$

where

$$C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2},\quad D_f = \frac{2\mathcal{R}e(\lambda_f)}{1+|\lambda_f|^2},\quad S_f = \frac{2\mathcal{I}m(\lambda_f)}{1+|\lambda_f|^2} \quad (36)$$

- and equivalents for the CP conjugate final state $\bar{f}$
- **The time-dependent CP asymmetry is** (for non-CP-eigenstates there are two)

$$\mathcal{A}_{CP}(t) = \frac{\Gamma_{X^0\to f}(t) - \Gamma_{\overline{X}^0\to f}(t)}{\Gamma_{X^0\to f}(t) + \Gamma_{\overline{X}^0\to f}(t)} = \boxed{\frac{2C_f\cos(\Delta m t) - 2S_f\sin(\Delta m t)}{2\cosh(\frac{1}{2}\Delta\Gamma t) + 2D_f\sinh(\frac{1}{2}\Delta\Gamma t)}} \quad (37)$$

- In the B^0 system $\Delta\Gamma \sim 0$

$$\Gamma_{X^0\to f}(t) = |A_f|^2 \quad (1+|\lambda_f|^2)\frac{e^{-i\Gamma t}}{2}\Big[+ C_f\cos(\Delta m t) - S_f\sin(\Delta m t)\Big] \tag{38}$$

$$\Gamma_{\overline{X}^0\to f}(t) = |A_f|^2 \left|\frac{p}{q}\right|(1+|\lambda_f|^2)\frac{e^{-i\Gamma t}}{2}\Big[- C_f\cos(\Delta m t) + S_f\sin(\Delta m t)\Big] \tag{39}$$

- **The time-dependent CP asymmetry is**

$$\mathcal{A}_{CP}(t) = \frac{\Gamma_{X^0\to f}(t) - \Gamma_{\overline{X}^0\to f}(t)}{\Gamma_{X^0\to f}(t) + \Gamma_{\overline{X}^0\to f}(t)} = \boxed{C_f\cos(\Delta m t) - S_f\sin(\Delta m t)} \tag{40}$$

- In the D^0 system Δm and $\Delta\Gamma$ are both small

$$\Gamma_{X^0\to f}(t) = |A_f|^2 \quad (1+|\lambda_f|^2)\frac{e^{-i\Gamma t}}{2}\Big[1 \quad + C_f \\ + D_f\tfrac{1}{2}\Delta\Gamma t \quad - S_f\Delta m t \Big] \tag{41}$$

$$\Gamma_{\overline{X}^0\to f}(t) = |A_f|^2 \left|\frac{p}{q}\right|(1+|\lambda_f|^2)\frac{e^{-i\Gamma t}}{2}\Big[1 \quad - C_f \\ + D_f\tfrac{1}{2}\Delta\Gamma t \quad + S_f\Delta m t \Big] \tag{42}$$

- **The time-dependent CP asymmetry is**

$$\mathcal{A}_{CP}(t) = \frac{\Gamma_{X^0\to f}(t) - \Gamma_{\overline{X}^0\to f}(t)}{\Gamma_{X^0\to f}(t) + \Gamma_{\overline{X}^0\to f}(t)} = \boxed{\frac{C_f - S_f\Delta m t}{1+\frac{1}{2}D_f\Delta\Gamma t}} \tag{43}$$

Specific Meson Decay Formalism

- With no tagging of flavour we see no asymmetry (just get the sum)

$$\Gamma_{X^0\to f}(t) = |A_f|^2 \quad (1+|\lambda_f|^2)\frac{e^{-i\Gamma t}}{2}\Big[\cosh(\tfrac{1}{2}\Delta\Gamma t) + D_f \sinh(\tfrac{1}{2}\Delta\Gamma t)\Big] \tag{44}$$

$$\Gamma_{\overline{X}^0\to f}(t) = |A_f|^2 \left|\frac{p}{q}\right|(1+|\lambda_f|^2)\frac{e^{-i\Gamma t}}{2}\Big[\cosh(\tfrac{1}{2}\Delta\Gamma t) + D_f \sinh(\tfrac{1}{2}\Delta\Gamma t)\Big] \tag{45}$$

- **The time-dependent CP asymmetry is**

$$\mathcal{A}_{CP}(t) = \frac{\Gamma_{X^0\to f}(t) - \Gamma_{\overline{X}^0\to f}(t)}{\Gamma_{X^0\to f}(t) + \Gamma_{\overline{X}^0\to f}(t)} = \boxed{0} \tag{46}$$

	K^0	K^+	Λ^0	D^0	D^+	D_s^+	Λ_c^+	B^0	B^+	B_s^0	Λ_b^0
CP violation in mixing	✓✓	-	-	✗	-	-	-	✗	-	✗	-
CP violation in interference	✓	-	-	✗	-	-	-	✓✓	-	✓✓	-
CP violation in decay	✓	✗	✗	✓✓	✗	✗	✗	✓✓	✓✓	✓	✓

KEY:

✓✓	Strong evidence ($> 5\sigma$)
✓	Some evidence ($> 3\sigma$)
✗	Not seen
-	Not possible

5. Recap

Recap

In this lecture we have covered

- Neutral Meson Mixing (without CPV)
  - Time evolution of coupled systems
  - Differences in mixing parameters between neutral meson states
- B-meson production and experiments / techniques
  - B-factories and Belle 2
  - LHCb
  - Flavour Tagging
  - Dalitz analysis
- CP violation
  - CP violation types
  - The "master" equations for generalised meson decays

End of Lecture 2