Matter – antimatter asymmetry

Particle Physics
project for FPACS PhD students

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Matter-antimatter asymmetry

Sakharov conditions for matter-antimatter asymmetry of the universe (1967):

1. **There must be a process that violates baryon number conservation.**

   Proton – the lightest baryon should decay, so far this is unobserved, the lifetimes of proton is greater than 10^{35} years.

2. **Both C and CP symmetries should be violated.**

   $$p \neq \overline{p}$$

   This the subject of the following story.

3. **These two conditions must occur in a phase when there was no thermal equilibrium.**

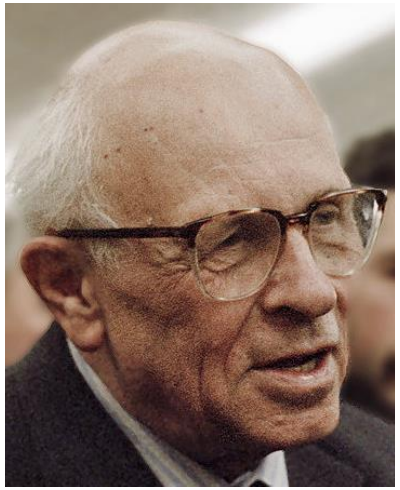
Otherwise $N_{baryons} = N_{\overline{baryons}}$

Из эффекта С. Окубо
при большой температуре
для Вселенной сшита шуба
по ее кривой фигуре

НАРУШЕНИЕ *CP*-ИНВАРИАНТНОСТИ, *C*-АСИММЕТРИЯ
И БАРИОННАЯ АСИММЕТРИЯ ВСЕЛЕННОЙ

А.Д.Сахаров

Теория расширяющейся Вселенной, предполагающая сверхплотное начальное состояние вещества, по-видимому, исключает возможность макроскопического разделения вещества и антивещества; поэтому следует

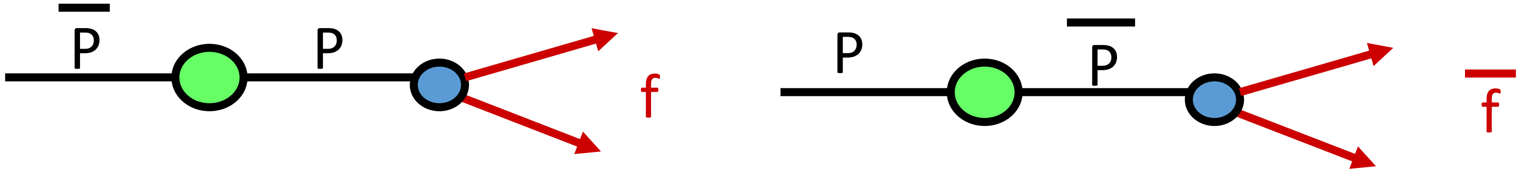


Andrei Sakharov:
- „father” of Soviet hydrogen bomb
- Dissident
- Nobel Peace Prize Winner

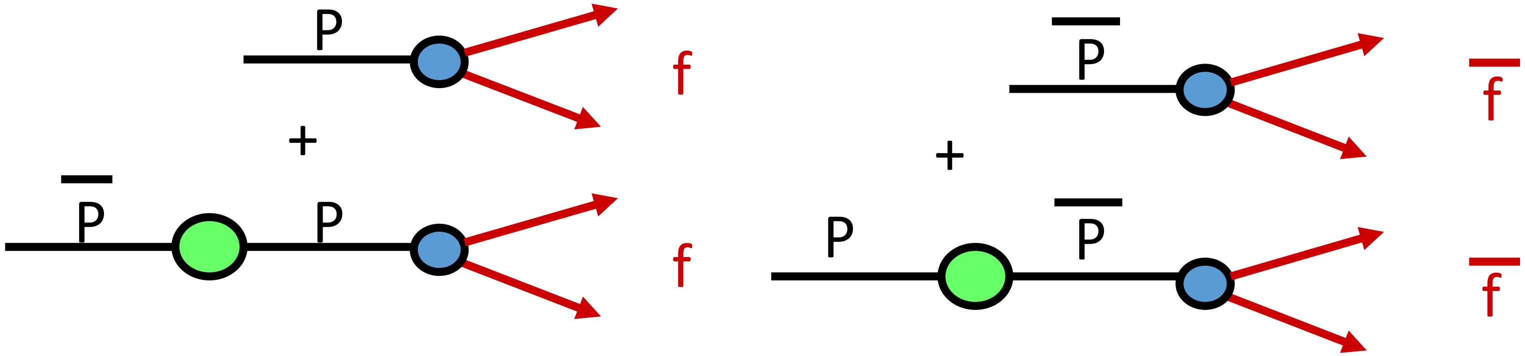
Types of CP Violation

I. CP violation in decay (direct CP Violation)

II. CP violation in mixing (indirect CP Violation)



III. CP violation in interference between mixing and decay



CP Violation in decay (direct)

1. One of the simplest way to discover $\mathcal{CPV}$ is to compare the decay rates $\Gamma(P \to f)$ with $\Gamma(\bar{P}) \to \bar{f}$
2. This is a method for direct $\mathcal{CPV}$ in decay amplitudes, when two amplitudes with diffrent phases interfere.
3. If we define the asymmetry between $\mathcal{CP}$ conjugated decays, for charged and neutral mesons:

$$\boxed{A_{CP,dir} = \frac{\Gamma\{P \to f\} - \Gamma\{\bar{P} \to \bar{f}\}}{\Gamma\{P \to f\} + \Gamma\{\bar{P} \to \bar{f}\}}}$$

where: $\Gamma(P \to f) \propto |A_f|^2$

3. Amplitude A_f:

- is defined as a matrix element that describes the transition between state P and f, such that $P \to f$ depends on:

  $A_f = \langle f|H|P\rangle$ and $\bar{P} \to f$ on: $\overline{A_f} = \langle f|H|\bar{P}\rangle$

- is a complex number that can be written as a value A and phase: $A_f = A\, e^{i\phi}\, e^{i\delta}$

- Usually the amplitude A_f has a strong phase δ that is invariant under CP transformation and weak phase ϕ that changes sign under CP.

CP Violation in decay

4. Final state $\boldsymbol{f}$ can be $\boldsymbol{\mathcal{CP}}$ eigenstate or not $\boldsymbol{\mathcal{CP}}$ eigenstate. In the former additional amplitudes are written: $\overline{\boldsymbol{A}_{\bar{f}}}$ and $\boldsymbol{A}_{\bar{f}}$

5. The phase of the amplitude emerges only if we could find two different amplitudes that lead to the same final state, and:
   - their amplitudes had both different strong and weak phases,
   - then we would see evidence for direct $\boldsymbol{\mathcal{CP}}$ violation (in decay) and decay rates will be different :

$$\boxed{\boldsymbol{\Gamma}(\boldsymbol{P} \to \boldsymbol{f}) \neq \boldsymbol{\Gamma}(\overline{\boldsymbol{P}} \to \bar{\boldsymbol{f}})}$$

   - most general form of asymmetry:

$$\boxed{A = \frac{\left|\overline{A_f}\right|^2 - \left|A_f\right|^2}{\left|\overline{A_f}\right|^2 + \left|A_f\right|^2} = \frac{2|A_1|\,|A_2| sin(\delta_1 - \delta_2)\, sin(\phi_1 - \phi_2)}{|A_1|^2 + |A_2|^2 + \underbrace{|A_1|\,|A_2|\, cos(\delta_1 - \delta_2)\, cos(\phi_1 - \phi_2)}_{\text{amplitude interference!}}}}$$

CP Violation in decay

6. We can also write a couple of asymmetries in a different form, e.g.:

$$A_f \equiv A(B^- \to f) = A_1\, e^{i\phi_1}\, e^{i\delta_1} + A_2\, e^{i\phi_2}\, e^{i\delta_2}$$

$$\bar{A}_{\bar{f}} \equiv \bar{A}\left(B^+ \to \bar{f}\right) = A_1\, e^{-i\phi_1}\, e^{i\delta_1} + A_2\, e^{-i\phi_2}\, e^{i\delta_2}$$

$$|A_f|^2 - |\bar{A}_{\bar{f}}|^2 = 2|A_1|\,|A_2| \sin(\delta_1 - \delta_2)\, \sin(\phi_1 - \phi_2)$$

$$\boxed{\boldsymbol{\Gamma(P \to f) \neq \Gamma(\bar{P} \to \bar{f})}}$$

- or (if there are more amplitudes leading to the state f) we can express this by:

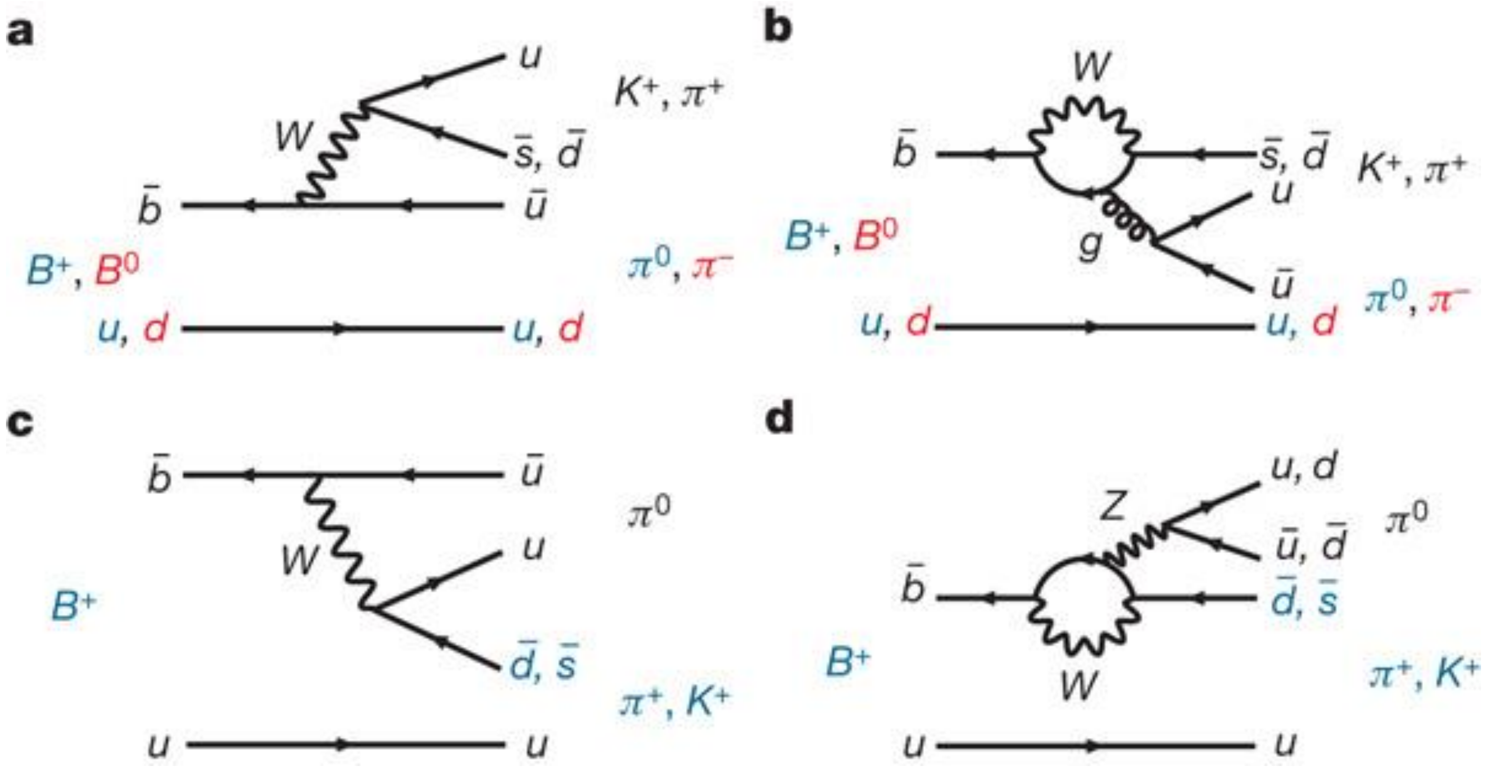
if $\mathcal{CP}$ is **NOT** conserved:

$$\boxed{\left|\frac{A_f}{\overline{A}_{\bar{f}}}\right| = \left|\frac{\sum_i A_i e^{i\varphi_i} e^{i\delta_i}}{\sum_i A_i e^{-i\varphi_i} e^{i\delta_i}}\right| \neq 1}$$

if $\mathcal{CP}$ is conserved:

$$\left|\frac{\boldsymbol{A_f}}{\boldsymbol{\bar{A}_f}}\right| = \mathbf{1}$$

CPV in decay



Think about experimental challenges!

- combinatorics,
- tagging,
- probability….

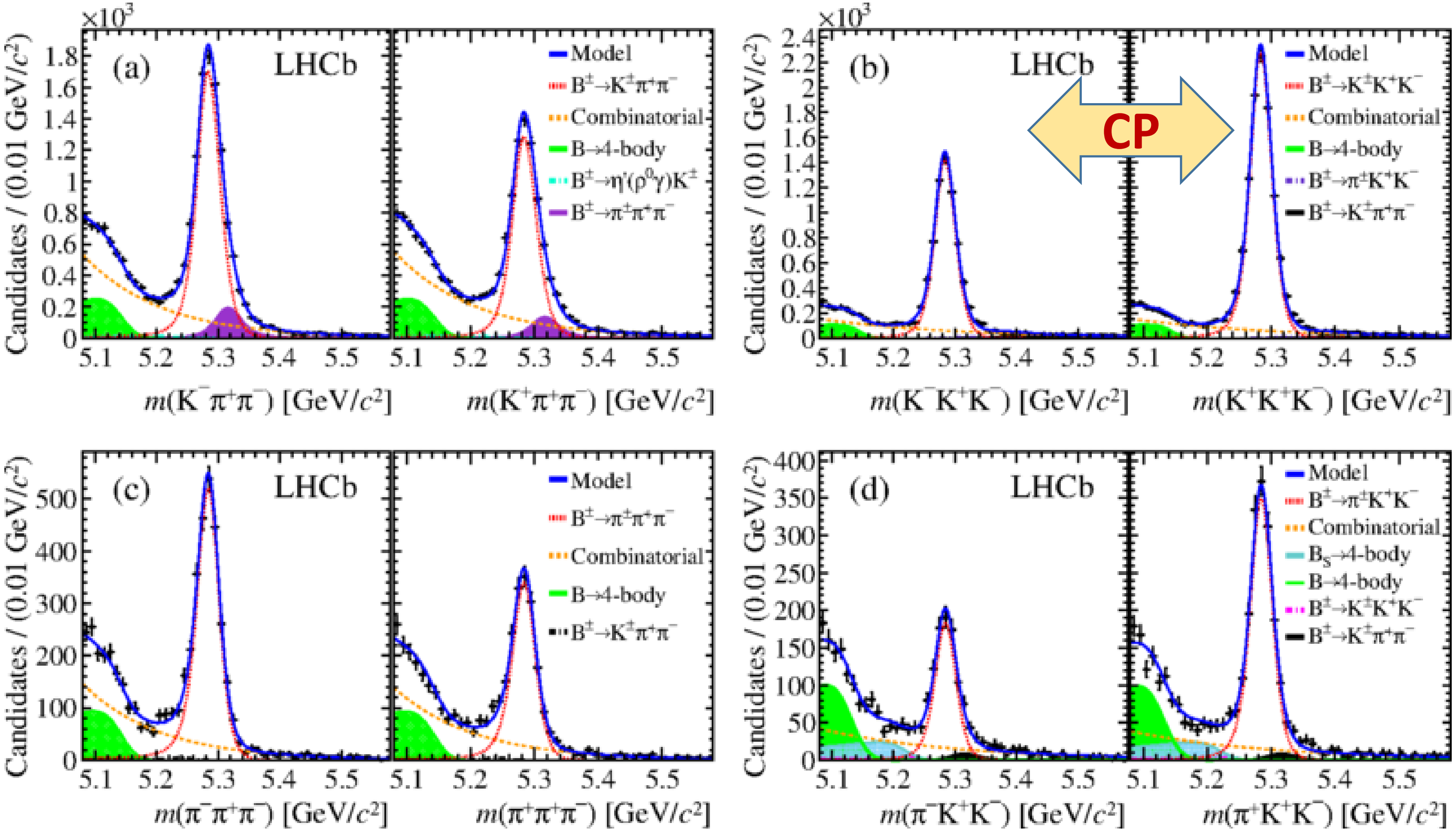
It is very common in flavour physics that simple ideas ($\mathcal{CPV}$ in differences in decay rates) are the most difficult for experiment.

CPV in decay

$B^{+} \rightarrow K^{-}K^{+}K^{+}$

Huge direct **CP** violation in decay amplitudes seen in B^{-}/B^{+} decays

$B^{-} \rightarrow K^{-}K^{+}K^{-}$



Phys.Rev.D90(2014)112004,

3.0 fb^{-1}

Project – observation of direct CPV

- The B^+ and B^- mesons have a short average lifetime (10^{-12} s) and decay via the weak force into other particles..
- The B^+ and B^- mesons are not observed directly in the detector, due to their short lifetime. Even travelling at close to the speed of light, and accounting for the effects of relativity, they only travel for a few mm in the detector before decaying. The charged kaons have long enough lifetimes (10^{-8}s) that do pass through the LHCb detector. We measure the properties of these kaons in the detector, for example determining their momentum and identifying them, and it is the measurements of these kaons we will use for the analysis.

BOTTOM MESONS
(B = ±1)
$B^+ = u\,\bar{b}$, $B^0 = d\,\bar{b}$, $\overline{B}^0 = \bar{d}\,b$, $B^- = \bar{u}\,b$,
similarly for B^*'s

$B^{\pm}$ $\qquad I(J^P) = 1/2(0^-)$

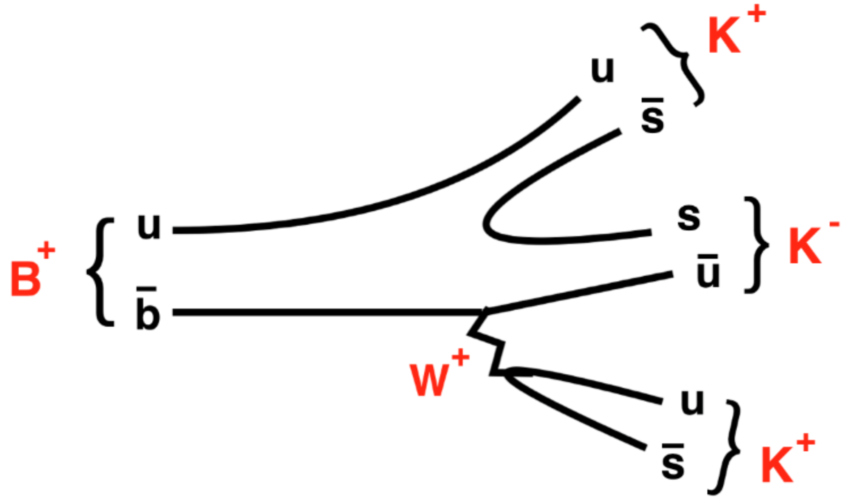
▾ Inclusive modes

		Fraction (Γ_i/Γ)
Γ_{37}	$D^0 X$	$(8.6 \pm 0.7)\%$
Γ_{38}	$\overline{D}^0 X$	$(79 \pm 4)\%$
Γ_{39}	$D^+ X$	$(2.5 \pm 0.5)\%$
Γ_{40}	$D^- X$	$(9.9 \pm 1.2)\%$
Γ_{41}	$D_s^+ X$	$(7.9^{+1.4}_{-1.3})\%$
Γ_{42}	$D_s^- X$	$(1.10^{+0.40}_{-0.32})\%$
Γ_{43}	$\Lambda_c^+ X$	$(2.1^{+0.9}_{-0.6})\%$
Γ_{44}	$\overline{\Lambda}_c^- X$	$(2.8^{+1.1}_{-0.9})\%$
Γ_{45}	$\bar{c} X$	$(97 \pm 4)\%$
Γ_{46}	$c X$	$(23.4^{+2.2}_{-1.8})\%$
Γ_{47}	$c\,\bar{c} X$	$(120 \pm 6)\%$

Project – observation of direct CPV

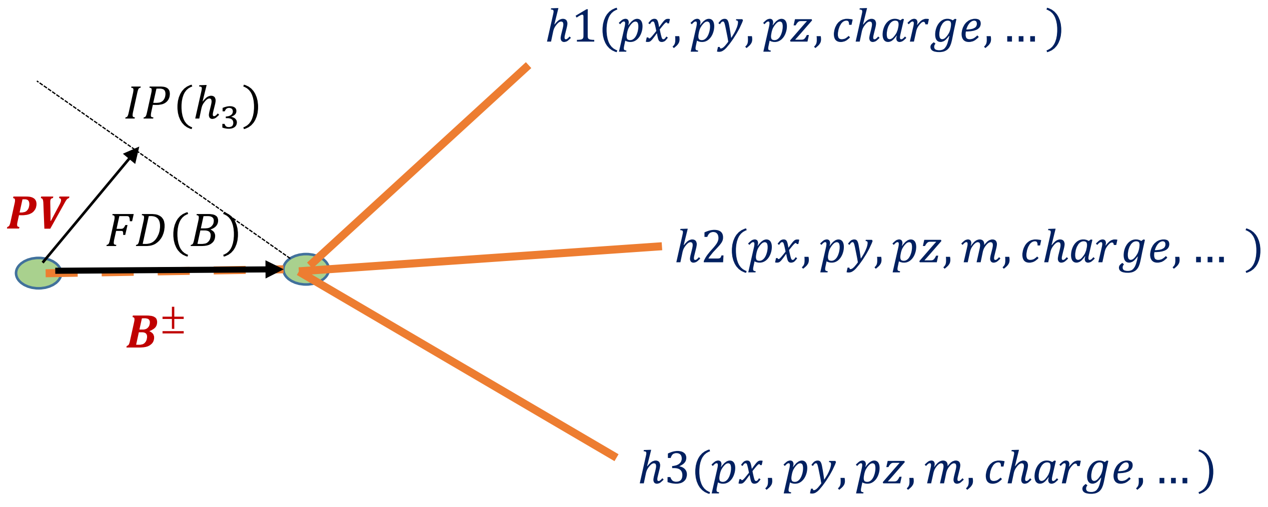
$B^+ \rightarrow K^+K^-K^+$
$B^- \rightarrow K^+K^-K^-$

Γ_{413}	$K^+K^-K^+$	$(3.40 \pm 0.14) \times 10^{-5}$



Project – observation of direct CPV

$B^+ \to K^+K^-K^+$
$B^- \to K^+K^-K^-$



Description (CERN Open Data): [hands-on]

Description [AOM]

Project – Dalitz plots in three body B decays

under construction