

Matter – antimatter asymmetry

Particle Physics
project for FPACS PhD students

Agnieszka Obłąkowska-Mucha, Tomasz Szumlak

AGH UST Kraków

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.**

$$p \neq \bar{p}$$

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 эссе С. Окубо
при большой температуре
для Вселенной смена знака
по ее кривой функции

НАРУШЕНИЕ СР-ИНВАРИАНТНОСТИ, С-АСИММЕТРИЯ
И БАРИОННАЯ АСИММЕТРИЯ ВСЕЛЕННОЙ

А.Д.Сакхаров

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

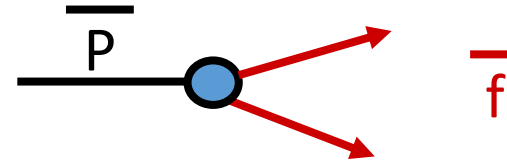
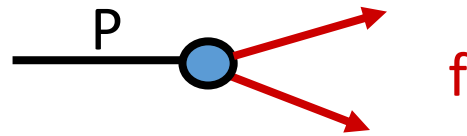


Andrei Sakharov:

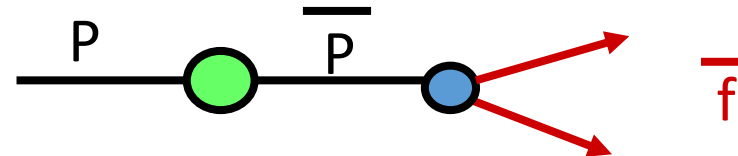
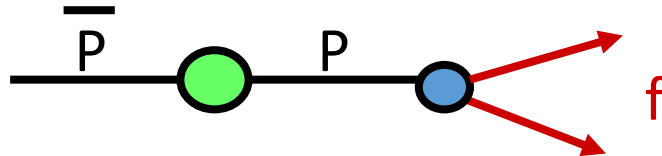
- „father” of Soviet hydrogen bomb
- Dissident
- Nobel Peace Prize Winner

Types of CP Violation

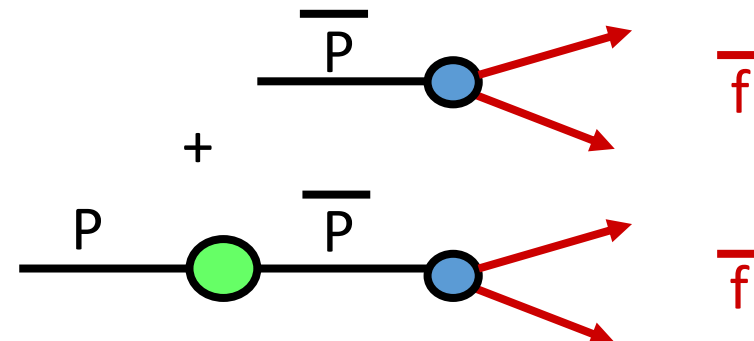
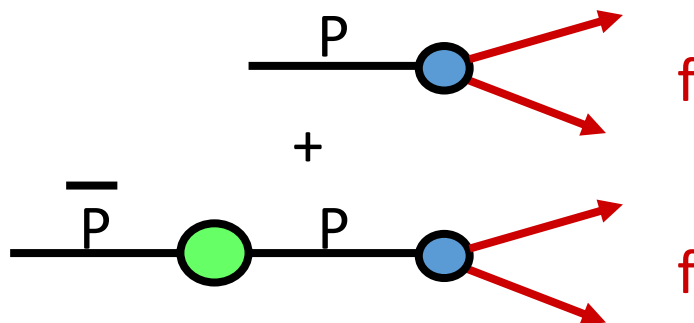
I. CP violation in decay (direct CP Violation)



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 $\Gamma(P \rightarrow f)$ with $\Gamma(\bar{P} \rightarrow \bar{f})$
2. This is a method for direct \mathcal{CPV} in decay amplitudes, when two amplitudes with different phases interfere.
3. If we define the asymmetry between \mathcal{CP} conjugated decays, for charged and neutral mesons:

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

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

3. Amplitude A_f :
 - is defined as a matrix element that describes the transition between state P and f , such that $P \rightarrow f$ depends on:
 $A_f = \langle f | H | P \rangle$ and $\bar{P} \rightarrow \bar{f}$ on: $\bar{A}_f = \langle \bar{f} | H | \bar{P} \rangle$
 - 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.

4. Final state f can be \mathcal{CP} eigenstate or not \mathcal{CP} eigenstate. In the former additional amplitudes are written: $\overline{A}_{\bar{f}}$ and $A_{\bar{f}}$
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 \mathcal{CP} violation** (in decay) and decay rates will be different :

$$\Gamma(P \rightarrow f) \neq \Gamma(\bar{P} \rightarrow \bar{f})$$

- most general form of asymmetry:

$$A = \frac{|\overline{A}_f|^2 - |A_f|^2}{|\overline{A}_f|^2 + |A_f|^2} = \frac{2|A_1| |A_2| \sin(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2)}{|A_1|^2 + |A_2|^2 + |A_1| |A_2| \cos(\delta_1 - \delta_2) \cos(\phi_1 - \phi_2)}$$

amplitude interference!

CP Violation in decay

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

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

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

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

$$\Gamma(P \rightarrow f) \neq \Gamma(\bar{P} \rightarrow \bar{f})$$

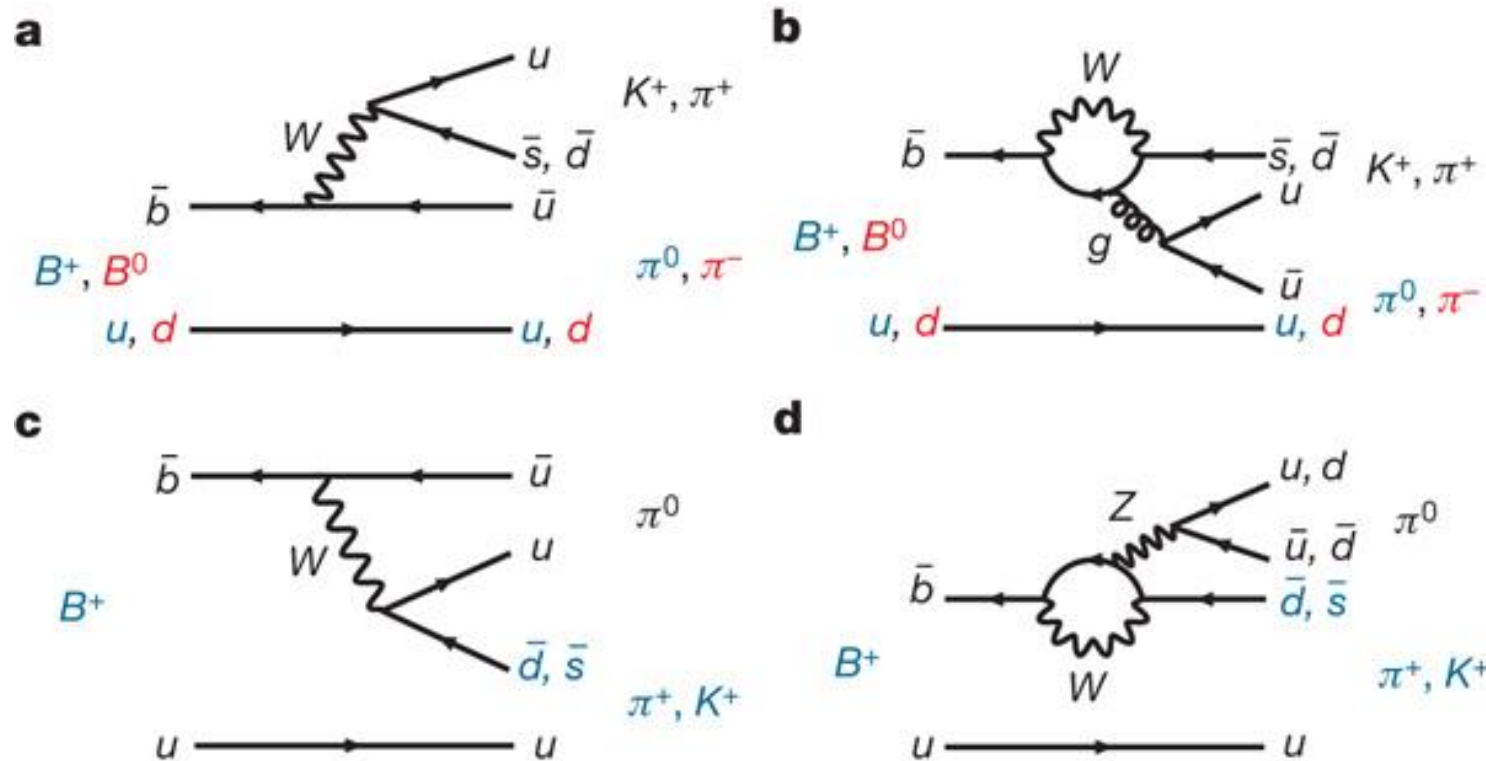
- or (if there are more amplitudes leading to the state f) we can express this by:

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

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

if \mathcal{CP} is conserved:

$$\left| \frac{A_f}{\bar{A}_{\bar{f}}} \right| = 1$$



Think about experimental challenges!

- combinatorics,
- tagging,
- probability....

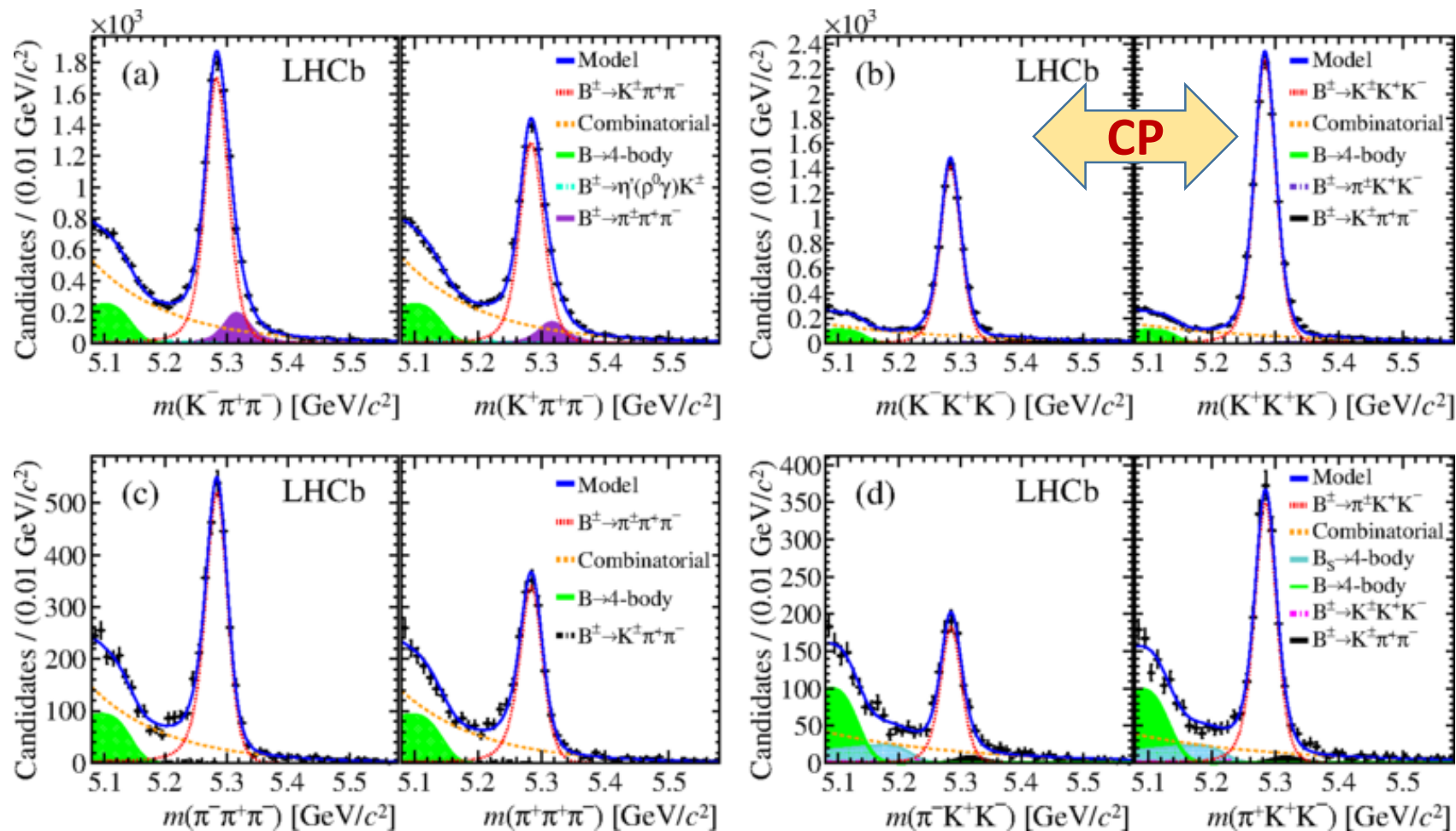
It is very common in flavour physics that simple ideas (CPV in differences in decay rates) are the most difficult for experiment.

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.

Fraction (Γ_i / Γ)

BOTTOM MESONS

$(B = \pm 1)$

$B^+ = u \bar{b}$, $B^0 = d \bar{b}$, $\bar{B}^0 = \bar{d} b$, $B^- = \bar{u} b$,
similarly for B^+ 's

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

▼ Inclusive modes

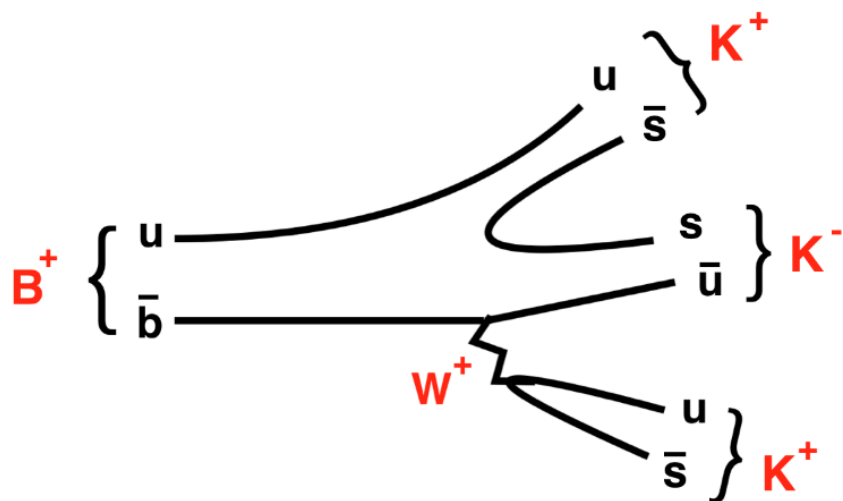
Γ_{37}	$D^0 X$	$(8.6 \pm 0.7)\%$
Γ_{38}	$\bar{D}^0 X$	$(79 \pm 4)\%$
Γ_{39}	$D^+ X$	$(2.5 \pm 0.5)\%$
Γ_{40}	$D^- X$	$(9.9 \pm 1.2)\%$
Γ_{41}	$D_s^+ X$	$(7.9^{+1.4}_{-1.3})\%$
Γ_{42}	$D_s^- X$	$(1.10^{+0.40}_{-0.32})\%$
Γ_{43}	$\Lambda_c^+ X$	$(2.1^{+0.9}_{-0.6})\%$
Γ_{44}	$\bar{\Lambda}_c X$	$(2.8^{+1.1}_{-0.9})\%$
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

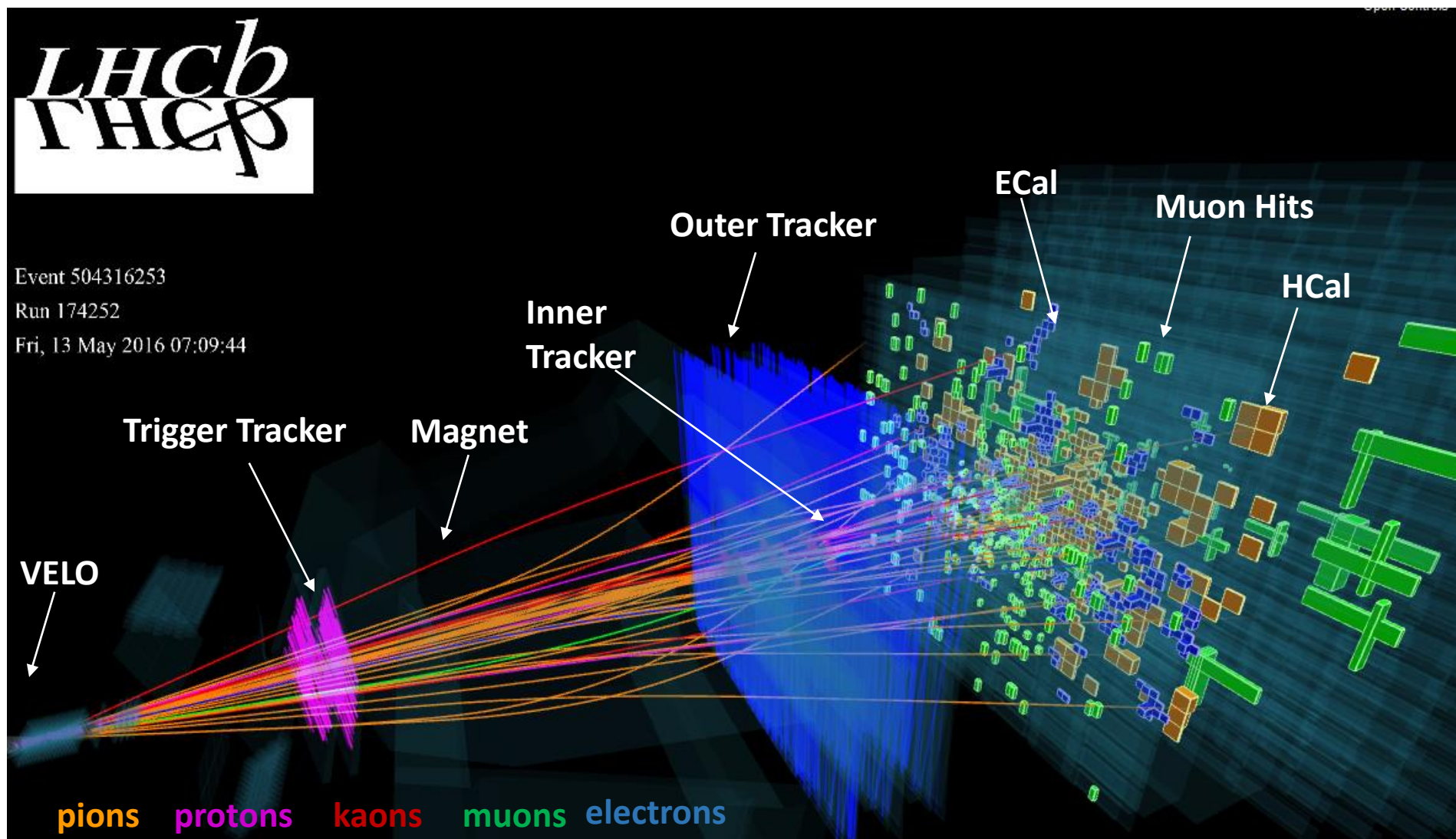
$$B^+ \rightarrow K^+ K^- K^+$$

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

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



The LHCb Spectrometer



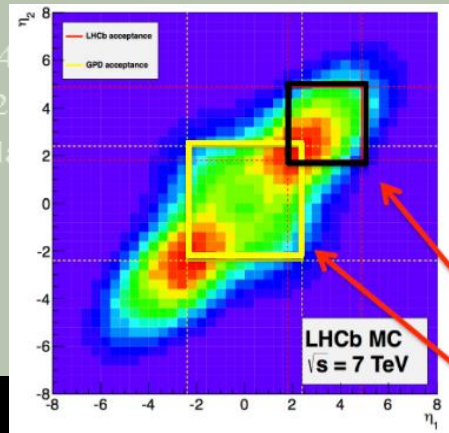
The LHCb Spectrometer

The detector dedicated for studying flavour physics at LHC.
Especially **CP violation** and **rare decays** of beauty and charm mesons.

Complementary kinematical
coverage to CMS and ATLAS

Performance:

- ~ 9 fb⁻¹ (Run II) accumulated data
- excellent vertex resolution and decay time resolution ~50 fs,
- precise tracking: $\delta p/p \sim 0.4 - 1.0\%$,
- particle identification in wide momentum range 2-100 GeV/c.



LHCb
 $2 < \eta < 5$

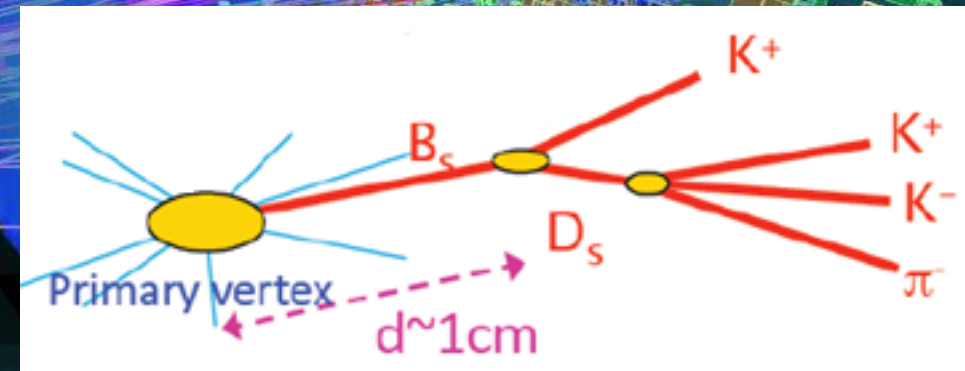
ATLAS, CMS:
 $|\eta| < 2.5$

Inner Tracker

VELO

The crucial requirements for a **Vertex Detector**:

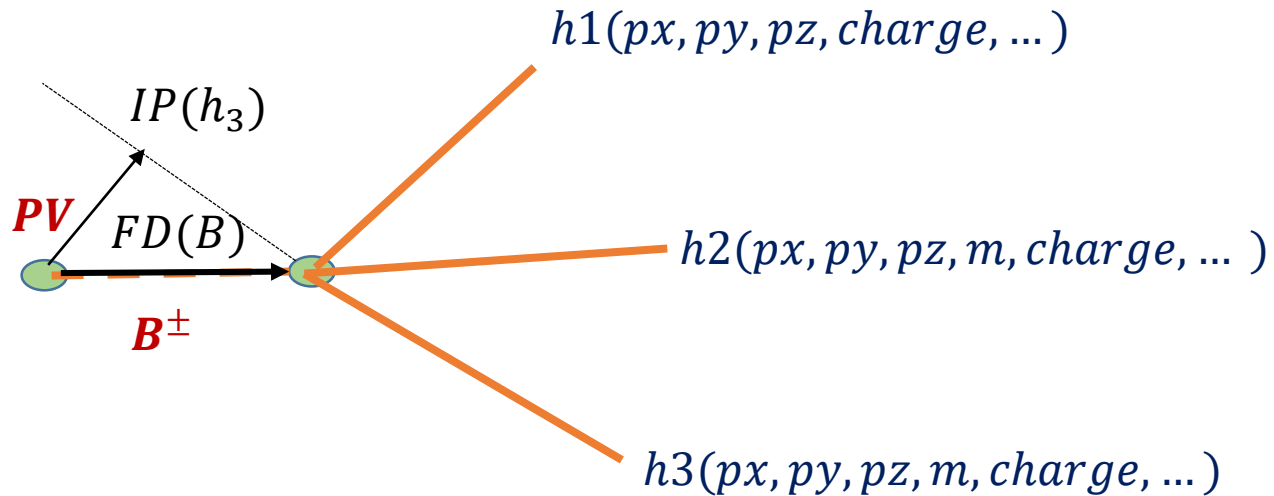
- very good **vertex** separation power, IP resolution,
- fast **tracking** for the High Level Trigger,
- withstand severe **radiation** environment,



Project – observation of direct CPV

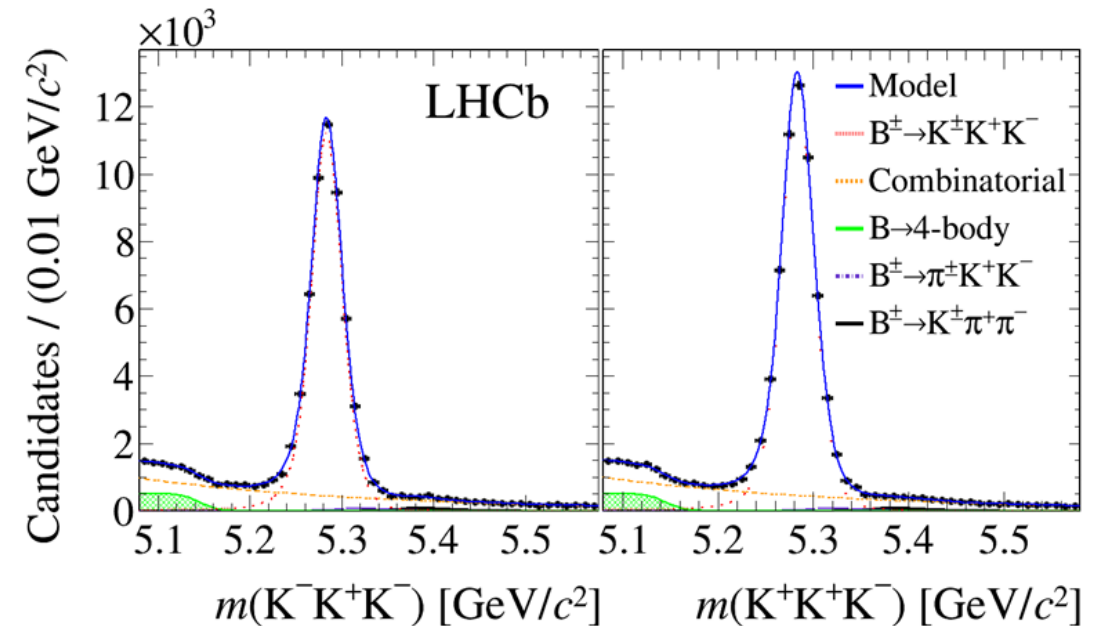
$$B^+ \rightarrow K^+ K^- K^+$$

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



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

Description [AOM](#)



Project – Dalitz plots in three body B decays

under construction