

IoP Masterclass

The Physics of Flavour at the Large Hadron Collider

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The Standard Model

Fermions
("matter")

Bosons
("forces")

$$\left\{ \begin{array}{l} \text{Quarks} \\ uuu \quad ccc \quad ttt \\ ddd \quad sss \quad bbb \\ \\ \text{Leptons} \\ e \quad \mu \quad \tau \\ \nu_e \quad \nu_\mu \quad \nu_\tau \end{array} \right\} \times \left\{ \begin{array}{l} \text{MATTER} \\ \text{ANTIMATTER} \end{array} \right\}$$

$gggggggg$

γ

W^+

W^-

Z

H

Some Questions

- What is antimatter?
- Why are there three “colours” of quarks?
- Why are there so many bosons?

These questions have well-understood answers

Some More Questions

- Why are there so many fermions?
- Why are there three “generations” of both quarks and leptons?
- Why are matter and antimatter different?

(“flavour”)

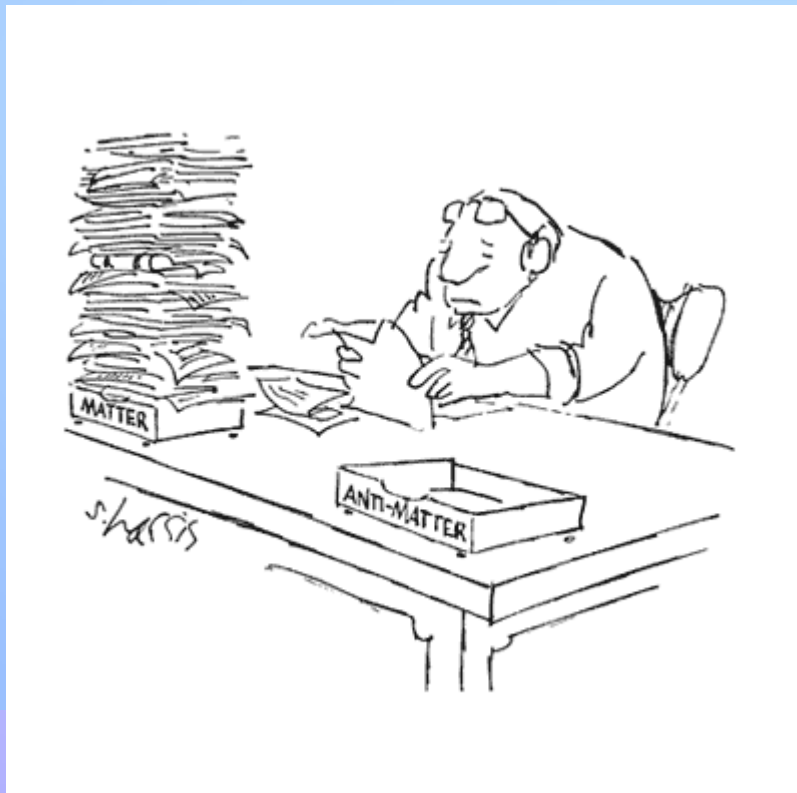
(“CP violation”)

We do not know the answers to these questions!

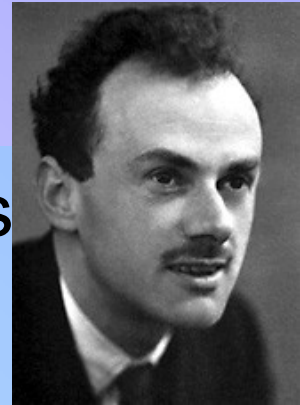
Matter vs. antimatter

- In the Big Bang, matter and antimatter should have been produced in equal quantities
- In the Universe today, we observe only matter

⇒ need *CP violation*



Asymmetry of the Universe



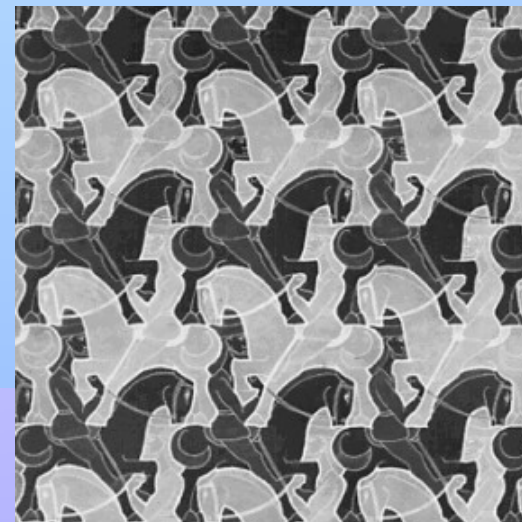
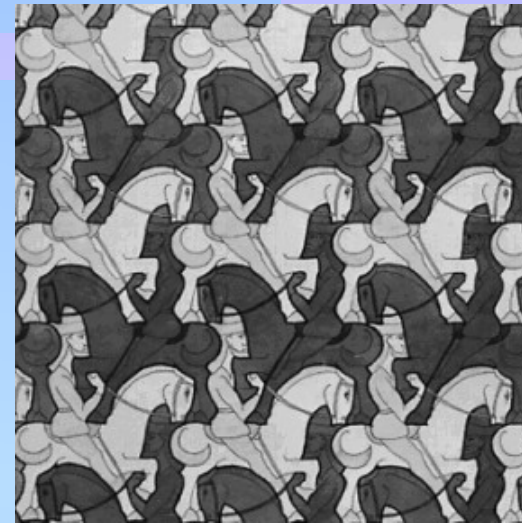
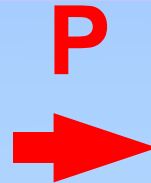
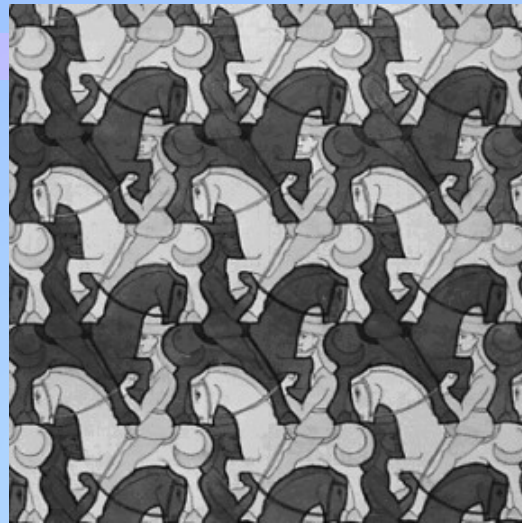
- Paul Dirac, one of the greatest British physicists of all time, won the 1933 Nobel Prize for his prediction of the existence of antimatter
- In his Nobel lecture, Dirac concludes:
 - “... we must regard it rather as an accident that [the solar system] contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind.”
- **It turns out there are not any antimatter stars**
- Dirac did not know about CP violation!

What is CP Violation?

- Symmetries are powerful tools to understand nature
- Two important discrete symmetries are
 - **C : charge conjugation**
(exchange particle and antiparticle)
 - **P : parity**
(mirror transform all spatial coordinates)

Need violation of combined CP symmetry to distinguish absolutely between matter & antimatter

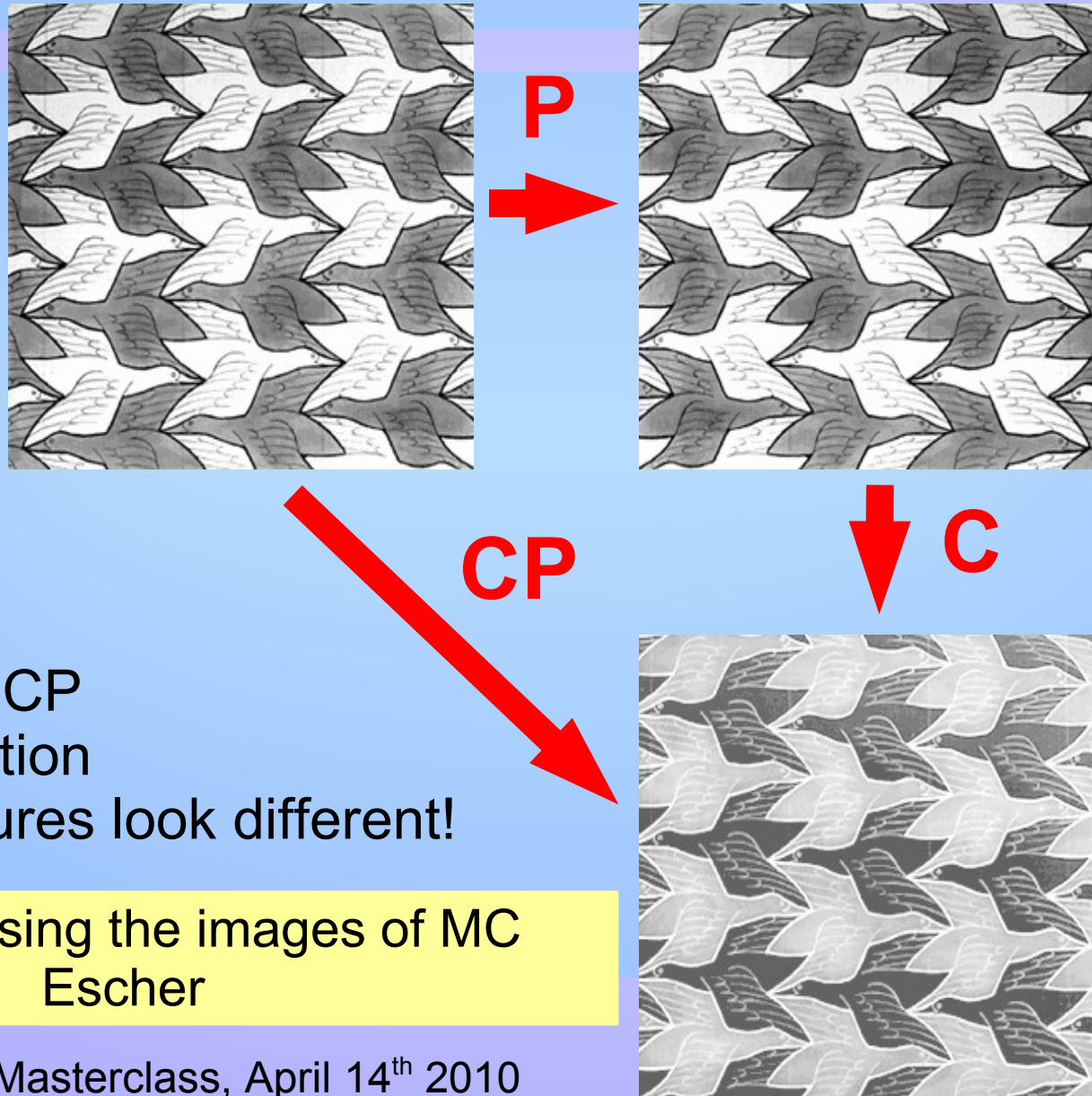
CP Symmetry



Combined CP
transformation
⇒ pictures look the same

Illustrated using the images of MC
Escher

CP Violation



Combined CP
transformation
⇒ pictures look different!

Illustrated using the images of MC
Escher

The CKM Matrix

- Quark mixing described by Cabibbo-Kobayashi-Maskawa matrix

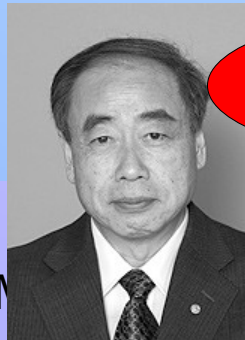
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

down-type quarks as seen by the weak interaction

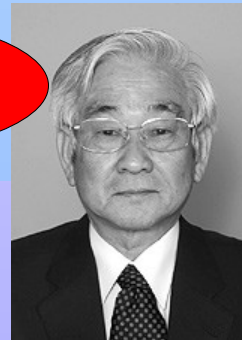
physical down-type quarks (with well-defined masses)

- Matrix elements are complex numbers
 - interactions of quarks and antiquarks can be different
 ⇒ CP violation!

Makoto Kobayashi



Nobel Prize in Physics 2008



Toshihide Maskawa

B Physics at the LHC

- CP violation appears to be central to understanding the questions discussed above
 - *eg. as shown by Kobayashi & Maskawa (1973), need at least three generations for CP violation to occur*
- Kobayashi-Maskawa mechanism predicts large CP violation effects in particles containing b quarks
 - *need dedicated experiments to test KM predictions*
- Exploit copious production of b quarks at the CERN Large Hadron Collider
 - *LHCb experiment*

The LHC at CERN

- The world's largest machine
- Located at CERN laboratory near Geneva
- 26 659 m circumference
- Emptier (10^{-13} atm) and colder ($1.9 \text{ K} = -271.3^\circ \text{ C}$) than outer space
- 1232 superconducting dipole magnets (8.33 T)
- Total cost \sim £5 billion

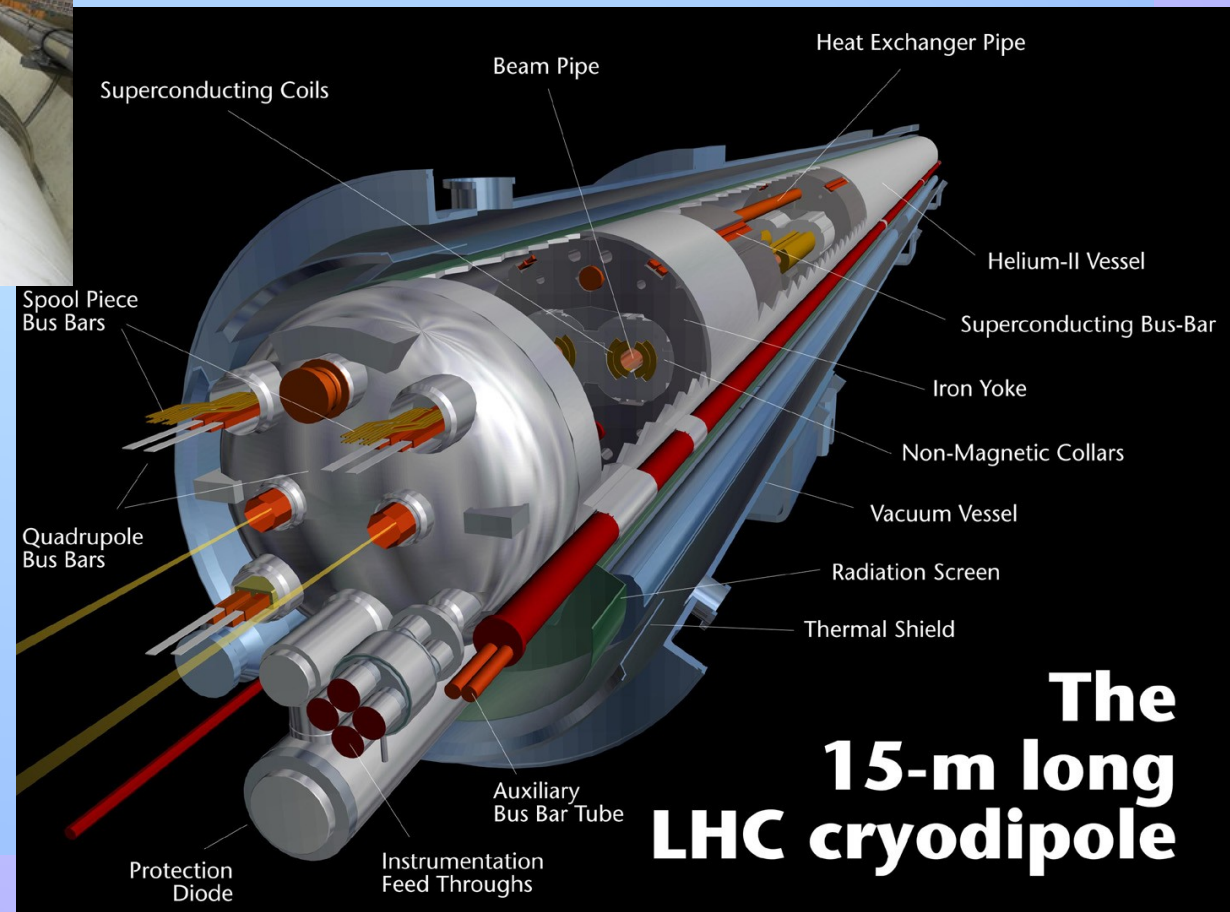
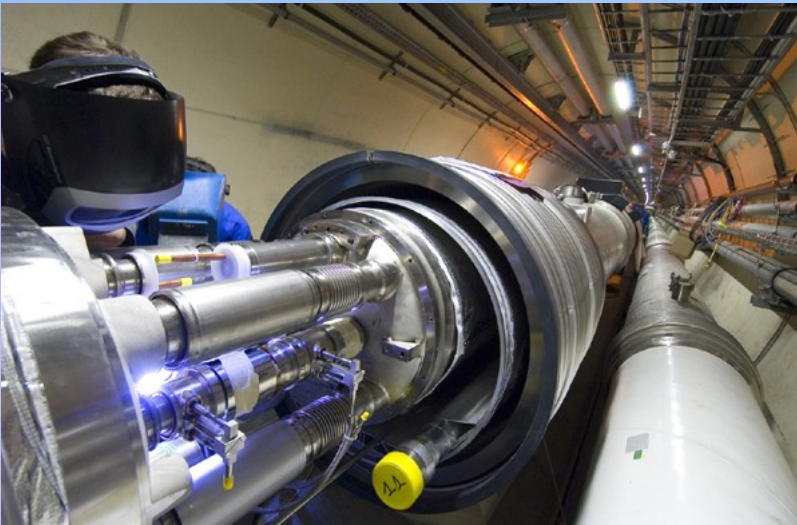


Main CERN site

LHCb experiment

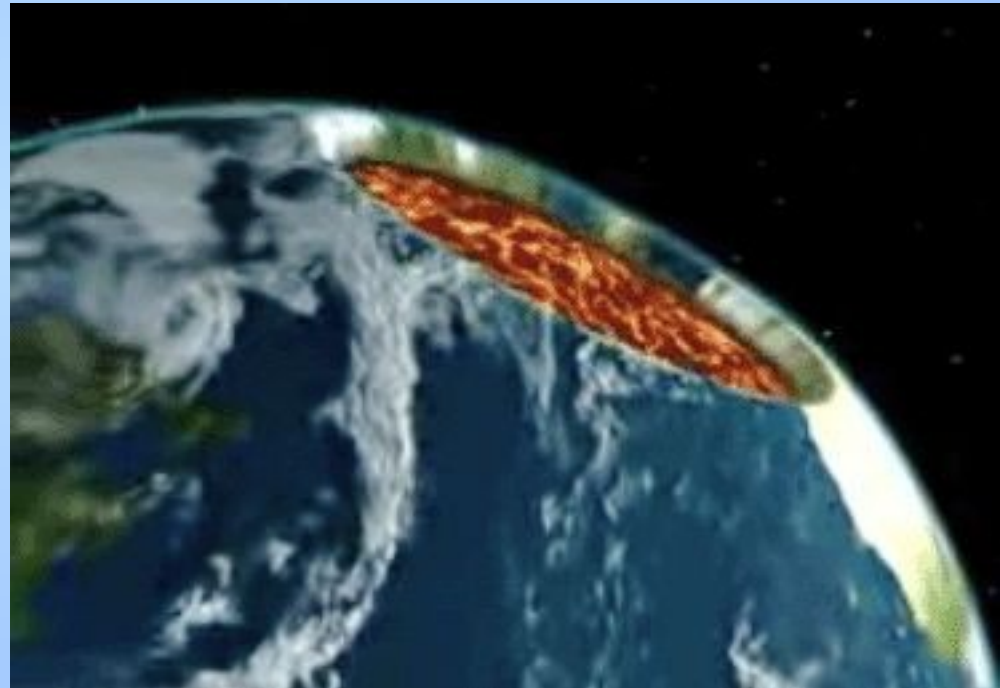
Geneva airport

LHC dipole magnets



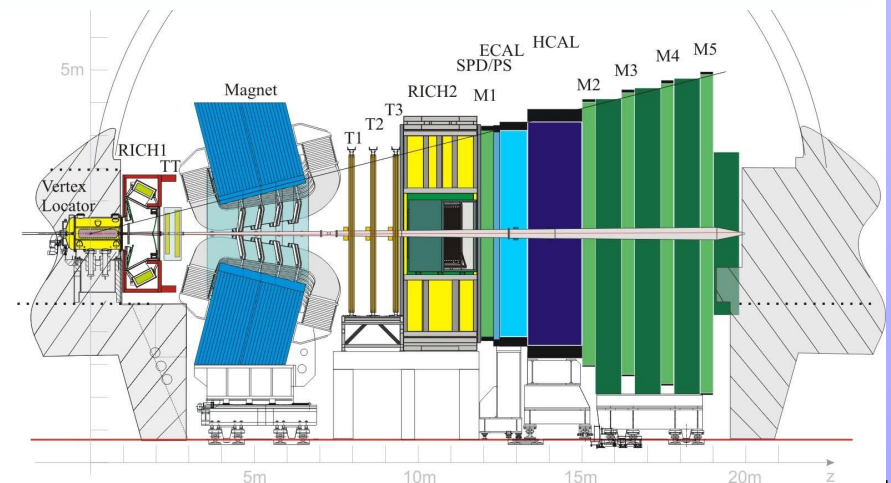
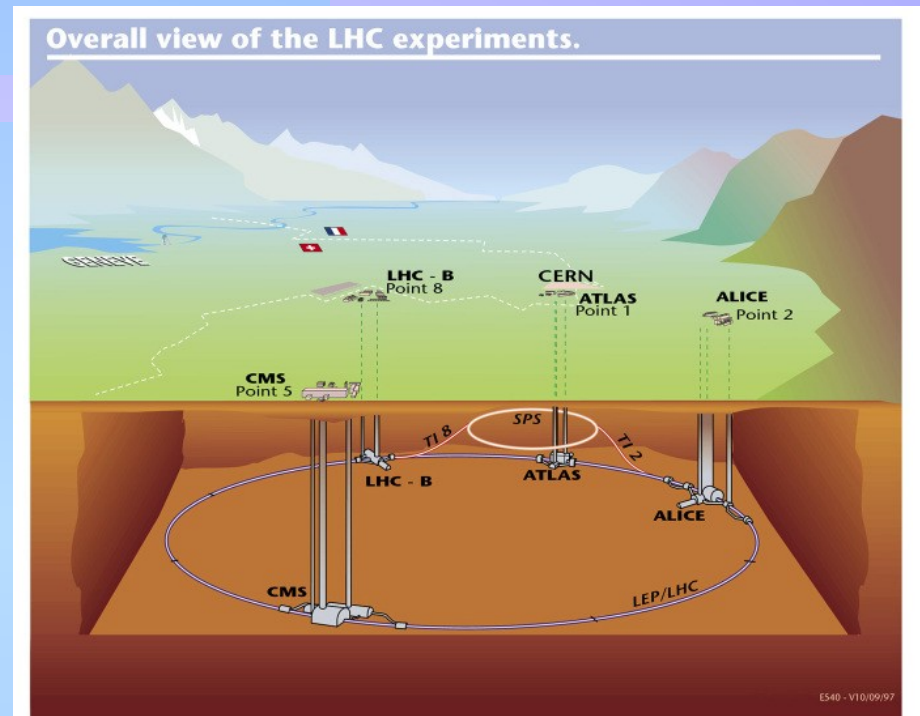
Will the LHC
destroy the earth?

No!



The LHCb Experiment

- Searching for new sources of CP violation
 - compare **matter** and **antimatter**
 - look for **disagreement** with Standard Model predictions
 - **search for unexpected effects**
- Requires an ultra-high precision detector
 - **operated by a collaboration of 700 physicists**



The LHCb Vertex Locator

- Need to precisely measure B hadrons decay positions
 - put **silicon detectors** as close as possible to the beam
 - 42 modules
 - inner radius : 7 mm
 - **inside LHC vacuum system**



Can the LHC be used to make antimatter bombs?



No!



Summary

- Studies of B physics provide excellent opportunities to address one of the biggest questions about our Universe
 - **What causes the excess of matter over antimatter?**
- By learning more about B physics and CP violation we hope to find clues about the theoretical structure of the Standard Model (and any theories beyond it)
 - **Why are there three generations of quarks and leptons?**
- The Warwick group is actively involved in experiments at the forefront of this exciting area of research
 - **We hope the LHCb experiment will provide some answers!**