The Beauty of LHCb

Original VELO modules

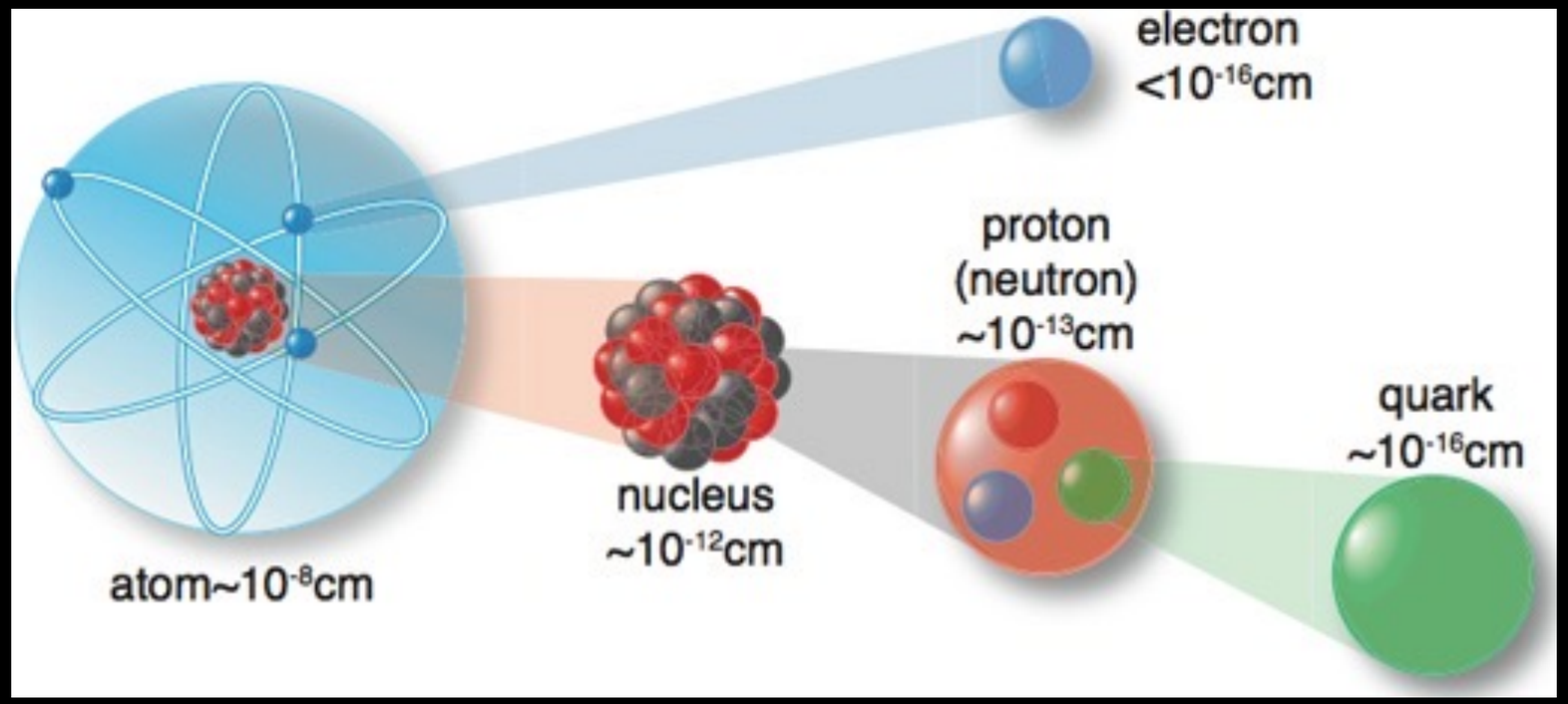
UNIVERSITY OF LIVERPOOL

Dr Paras Naik

Liverpool Particle Physics Masterclass 2025

Matter

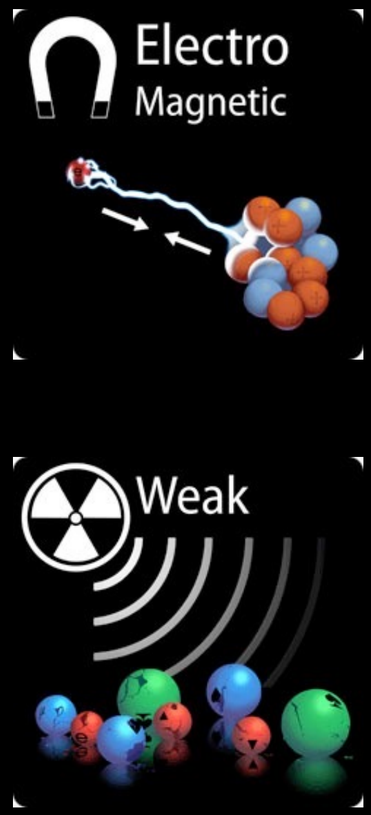
- Matter occupies space and has rest mass
- Common example: The atom



- **Common types of matter**
  - quarks [*up* and *down* quarks that make up nuclei]
  - leptons
    - charged [*electrons*]
    - neutral [neutrinos, which interact very weakly]

Forces

- Interactions between particles of matter take place through the exchange of force carriers (gauge bosons)
- Known Fundamental Forces (and force carrier)
  - Electromagnetic (photon)
  - Strong Nuclear (gluon)
  - Weak Nuclear (W, Z)
  - Gravity (?)



- Some of these are massless (photon, gluon), but the W and Z are very massive compared to most quarks and leptons.

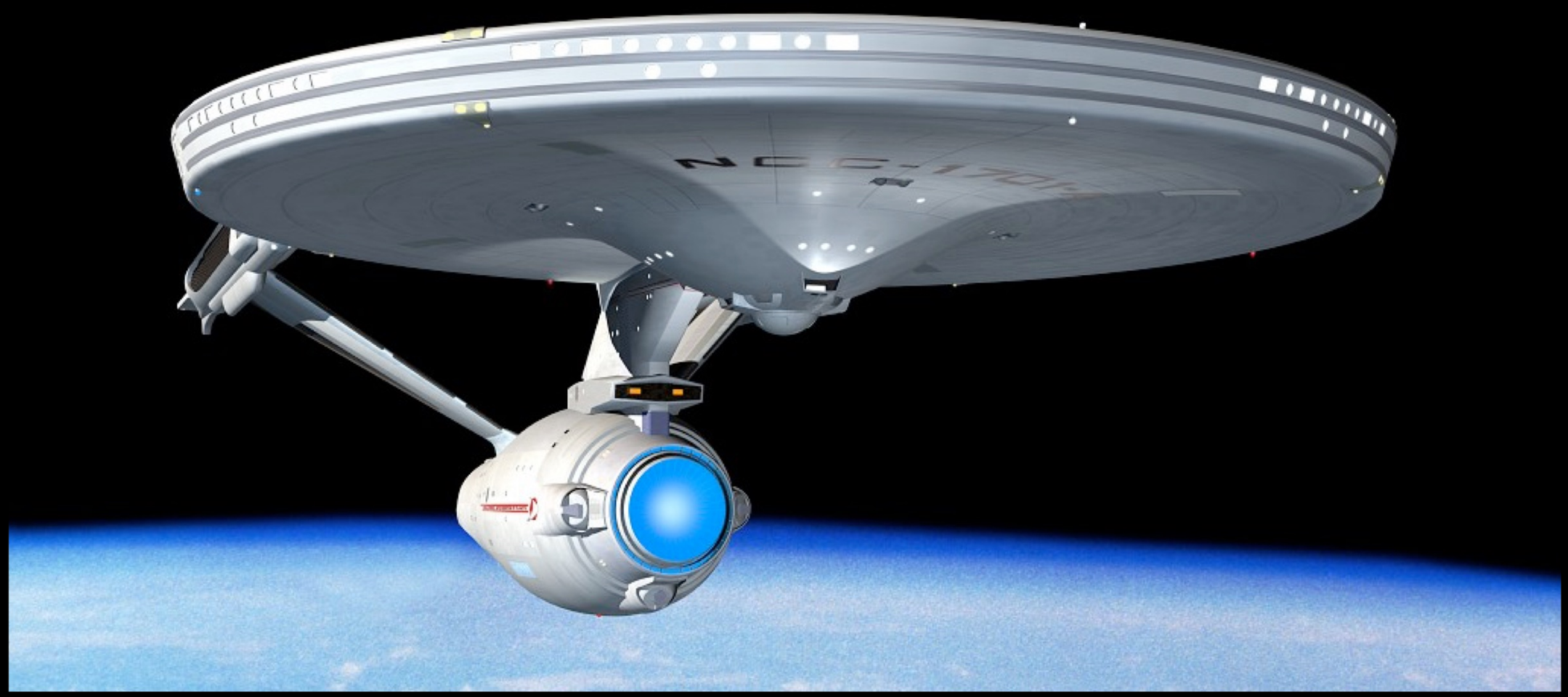
Dirac's Discovery

- **Paul Dirac (1902 - 1984)**
  - Born and educated in the UK
- **"It is more important to have beauty in one's equations than to have them fit experiment"**

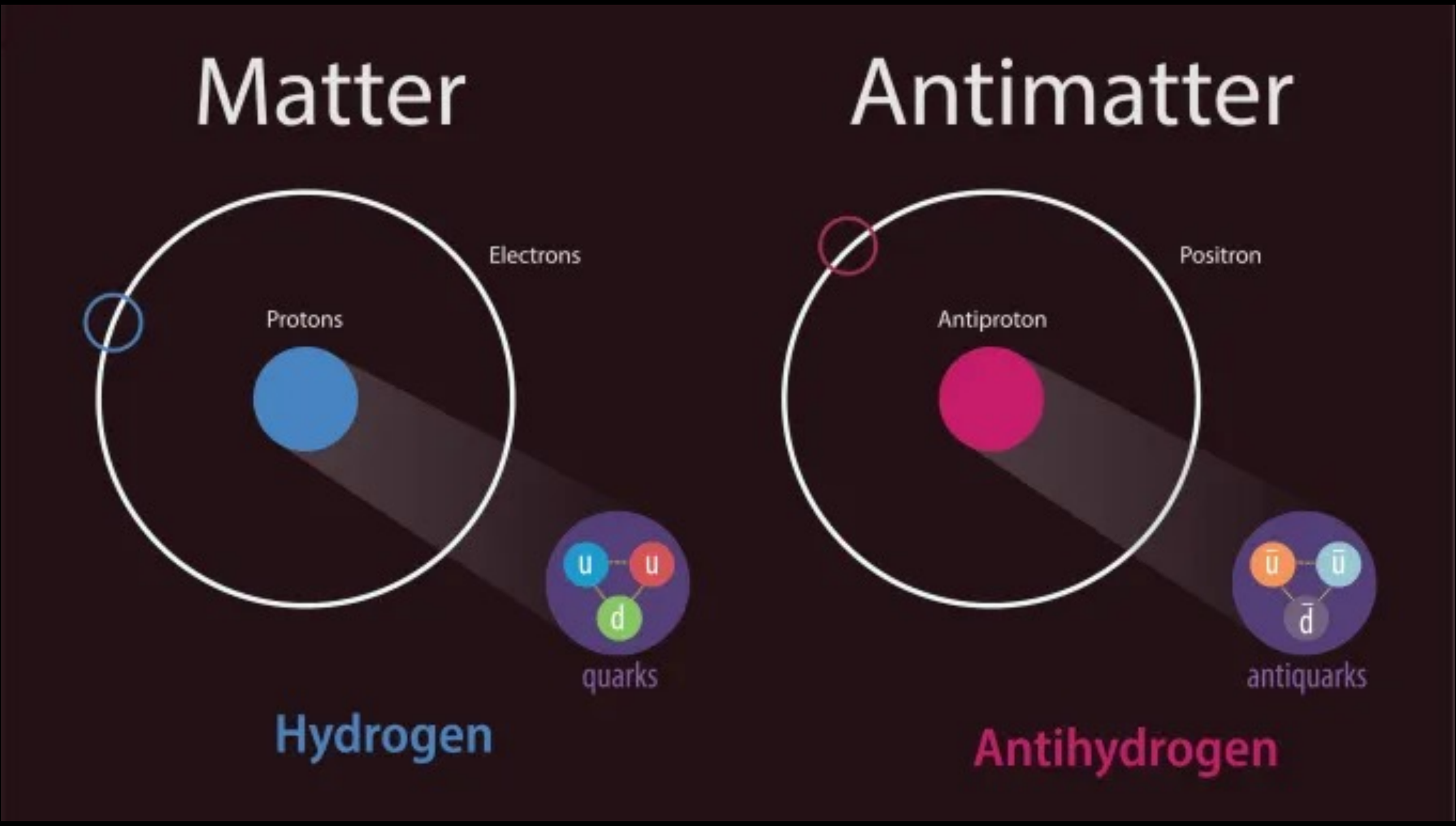
$$\left(i\gamma^{\mu}\partial_{\mu} - m\right)\psi = 0$$

- **What does it mean?**
  - Specifies the motion of matter particles
  - Predicts that particles have spin
  - Predicts the existence of antimatter

Antimatter?



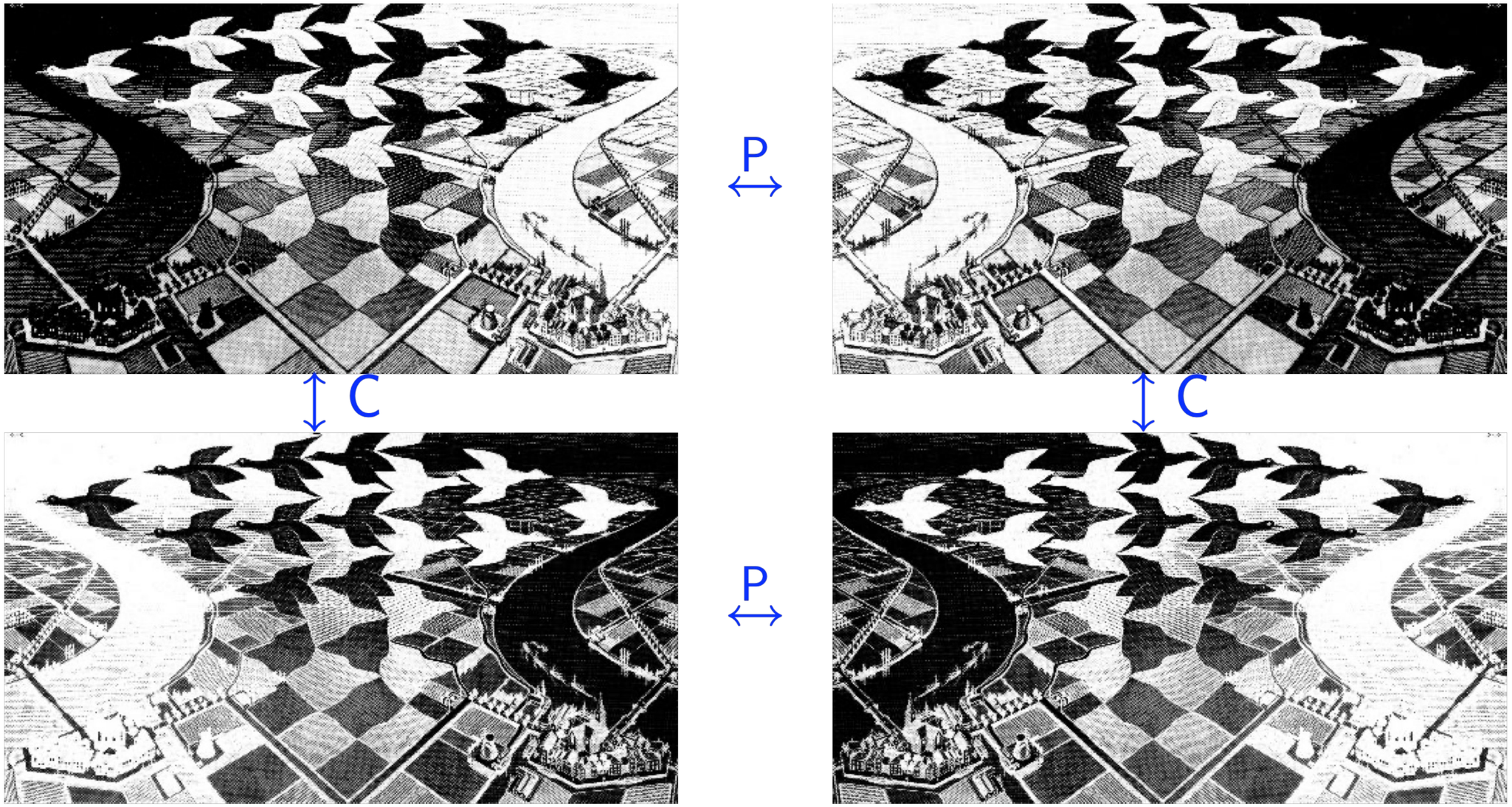
Antimatter?


Matter
Electrons
Protons
u
u
d
quarks
Hydrogen
Antimatter
Positron
Antiproton
ū
ū
d̄
antiquarks
Antihydrogen

Twins

- Matter and antimatter behave differently (“CP Violation”)
- Is this why our Universe is mostly matter?

CP Violation



P = parity (reflection)

C = matter ⇔ antimatter (black ⇔ white)

Picture seems symmetric under CP, at first sight…

The Nobel Prize in Physics 2008

Rewarded two discoveries concerning symmetry violation

"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

Photo: SCANPIX

Yoichiro Nambu

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

Photo: Kyodo/Reuters

Makoto Kobayashi

Photo: Kyoto University

Toshihide Maskawa

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The discovery of CP violation led to the prediction of new quarks

Photo: SCANPIX

Yoichiro Nambu

Photo: Kyodo/Reuters

Makoto Kobayashi

Photo: Kyoto University

Toshihide Maskawa

beauty

discovered 1977

top

discovered 1994

Our Universe

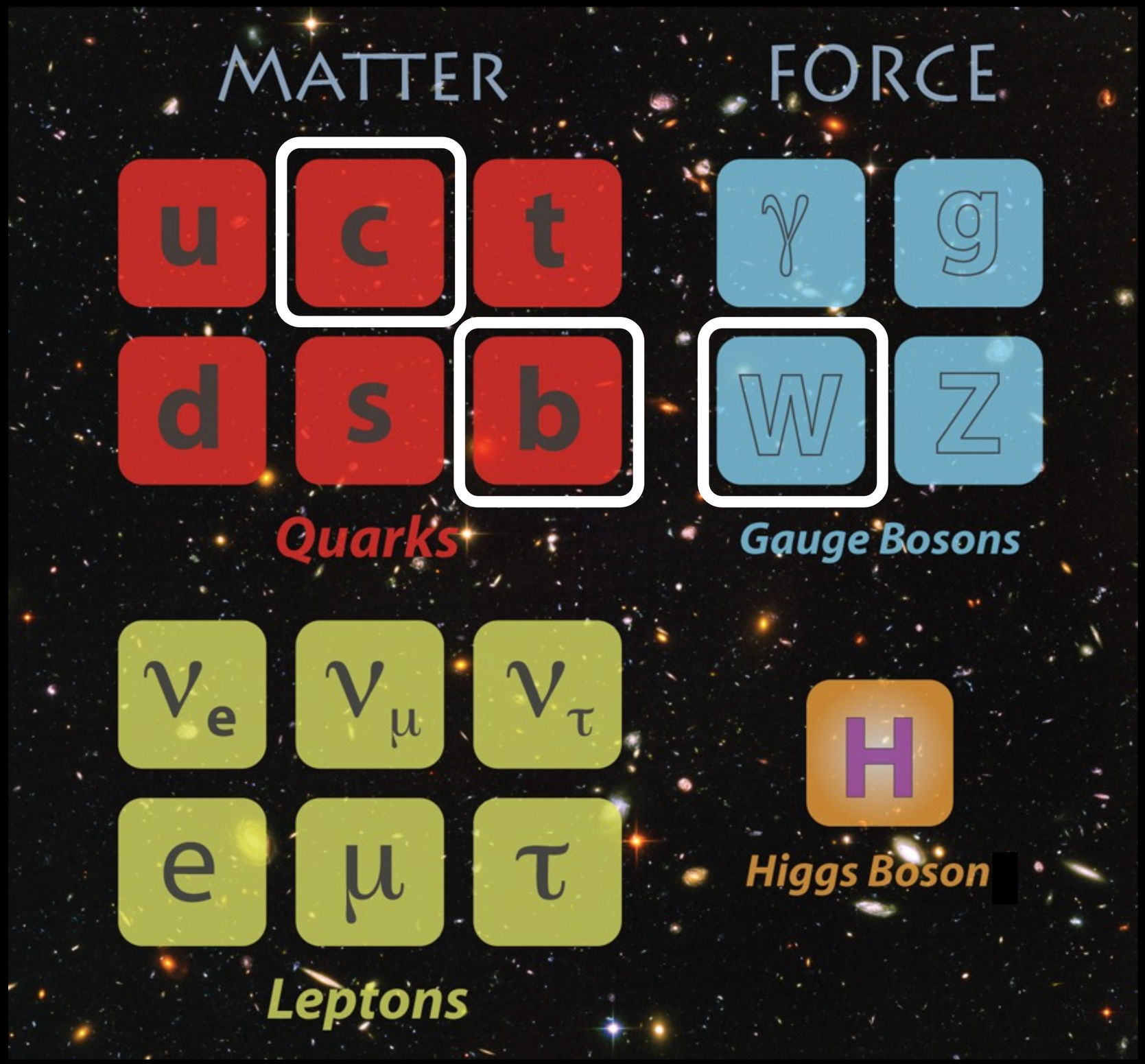
Universe without CP violation

Fortunately for us, the Universe is not symmetrical.

Universe with the amount of CP violation we know about

Understanding symmetry, or the lack of it, is an ongoing task.

The Standard Model



Finding New Physics

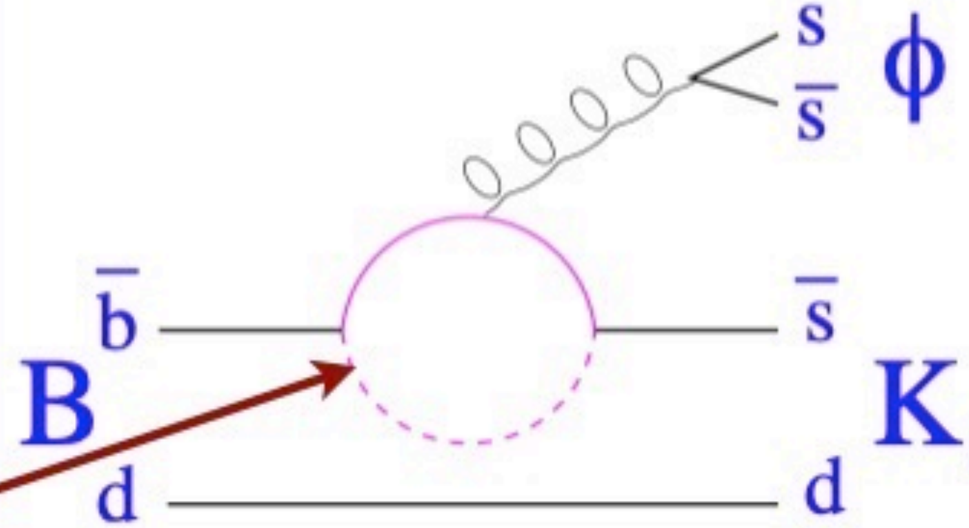
Direct Observations

Particles with $mc^2 > E$
cannot be produced directly

$E = mc^2$

Indirect Effects

… but they can have an effect
as virtual particles, especially in loops

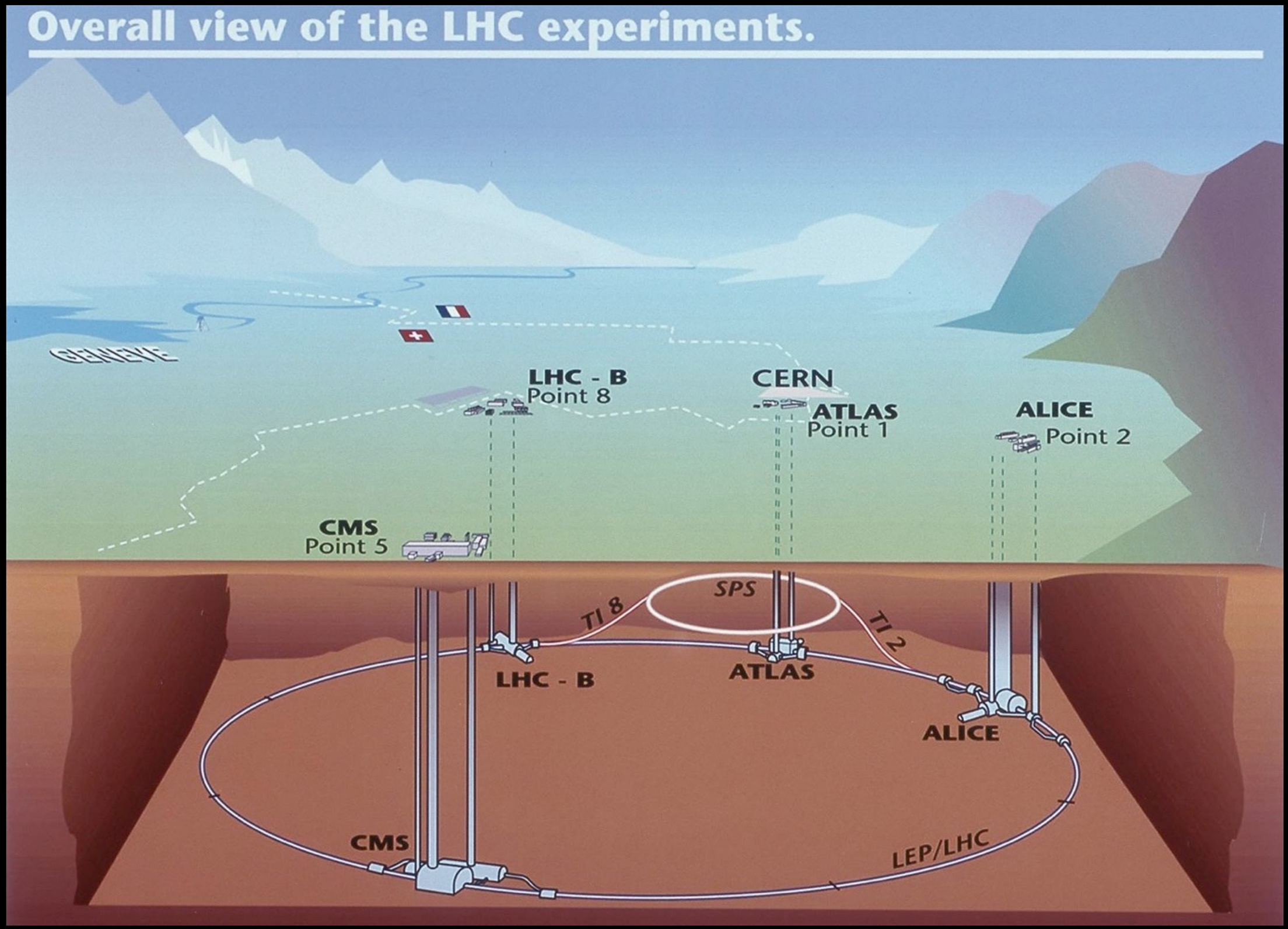


This kind of approach is sensitive to particles
far heavier than those directly produced in a collider.

Flavour physics lets you *see beyond the energy frontier*...
LHCb is designed for this!

Large Hadron Collider (LHC) at CERN

CERN


Overall view of the LHC experiments.
GENEVE
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC

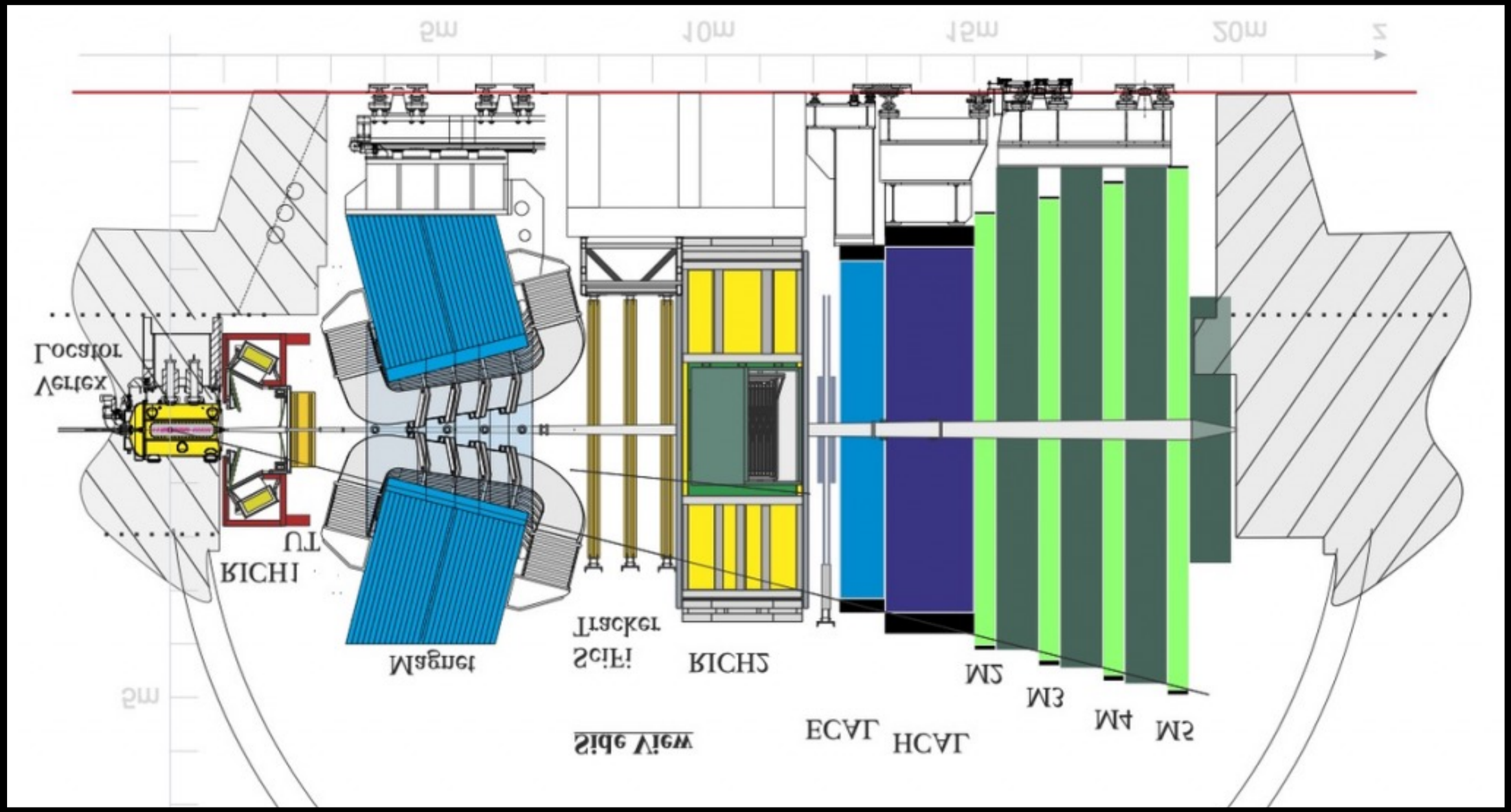
LHCb Collaboration

1725 members from 98 institutes in 24 countries

LHCb Collaboration

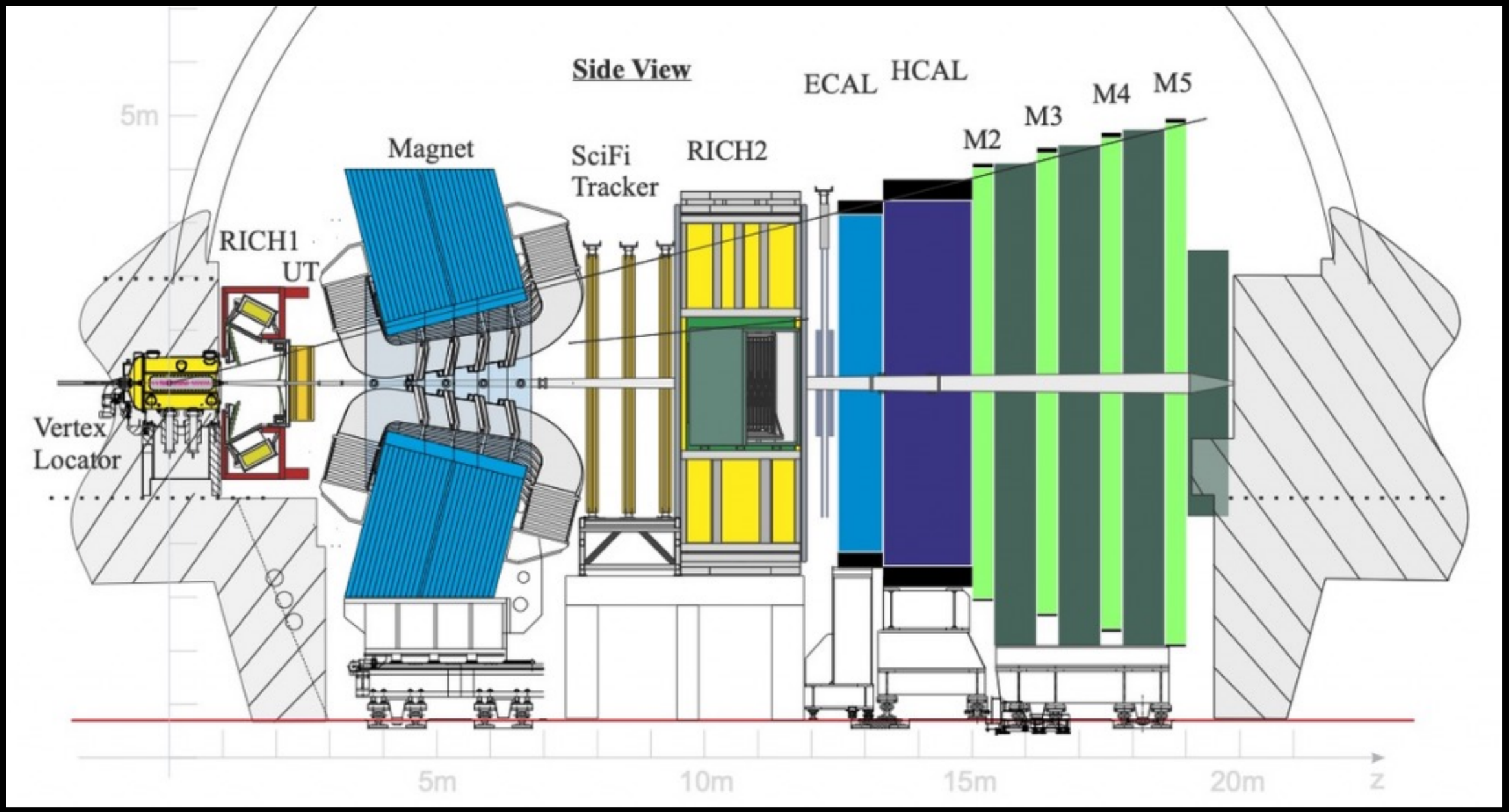
Me

1725 members from 98 institutes in 24 countries



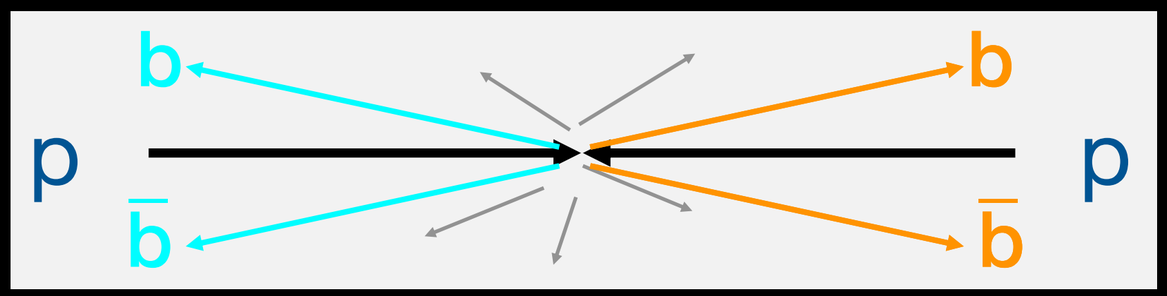
LHCb Detector

LHCb Detector



Capturing quarks

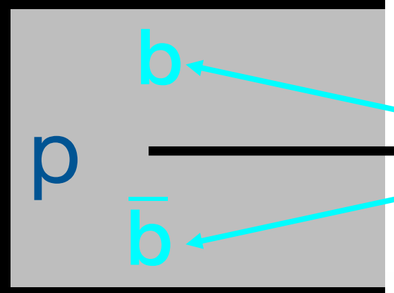
Beauty (and Charm) quarks are produced in forward directions

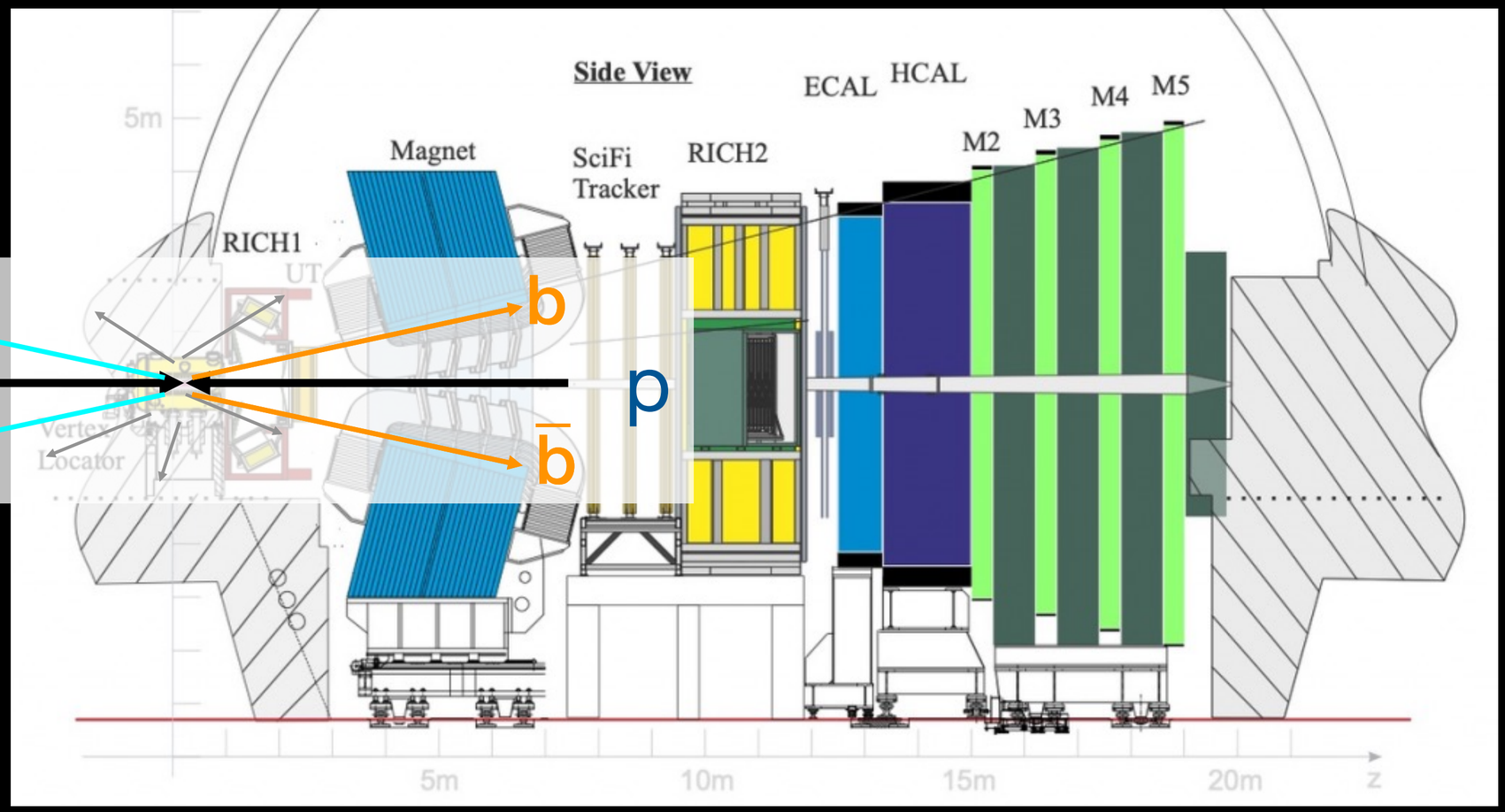


LHCb!

Beauty (and Charm) quarks are produced in forward directions

We built our detector to focus on finding these events

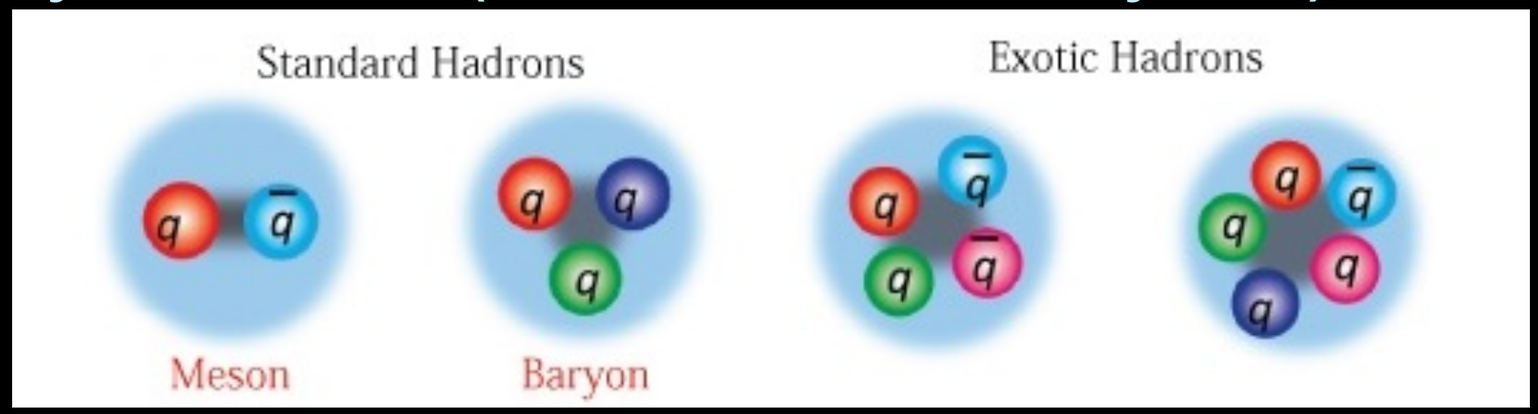




LHCb!

- **Optimised** for quark flavour physics, especially *the precision study of beauty quark and charm quark decays.*
- **100,000 b anti-b pairs per second** at the LHCb interaction point. (and 20 times as much charm!)

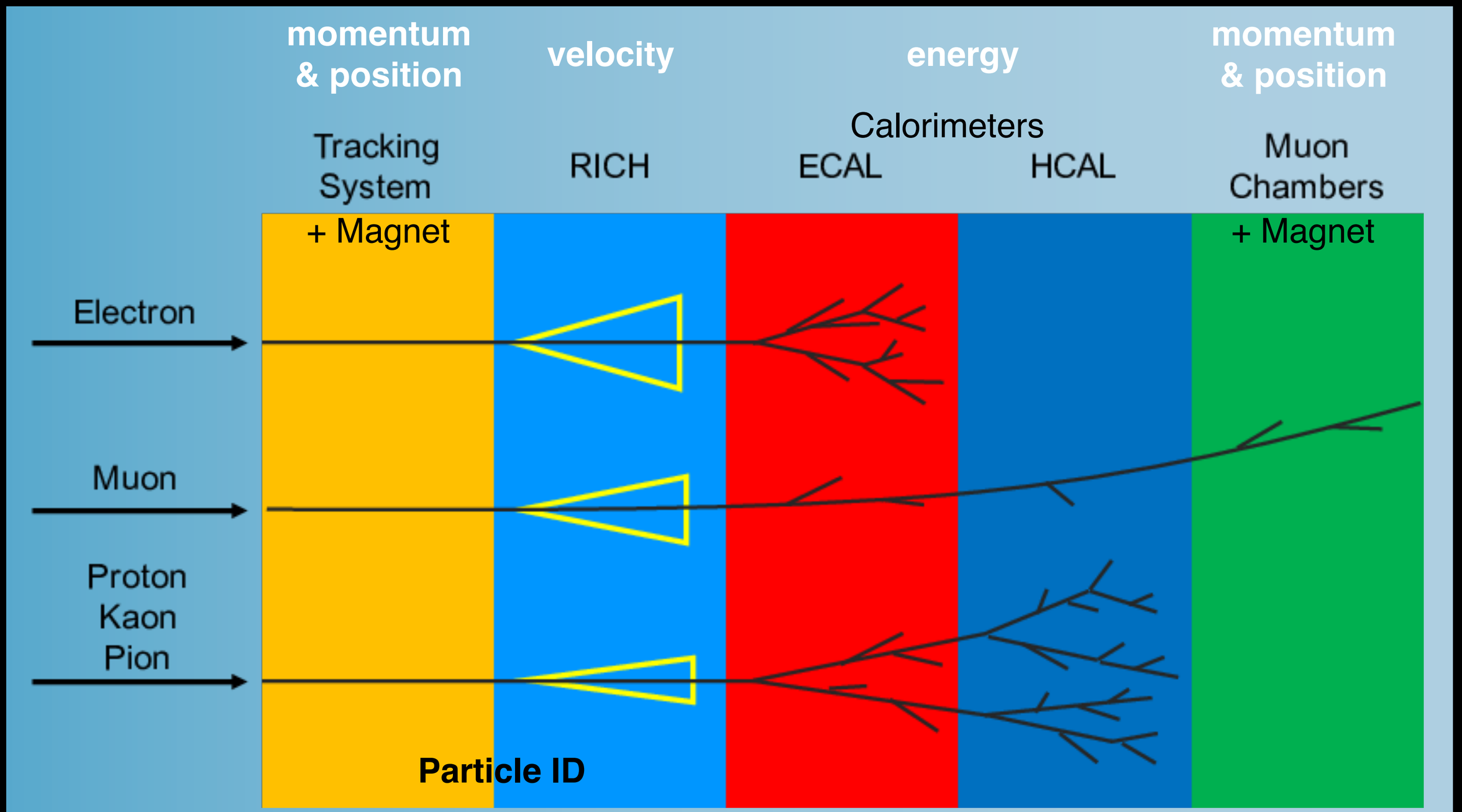
- We study hadrons (mesons and baryons)



- Vast quantities of all b-hadron (B^0, B_s, ...) and c-hadron (D^0,D_s, ...) species

Putting it all together

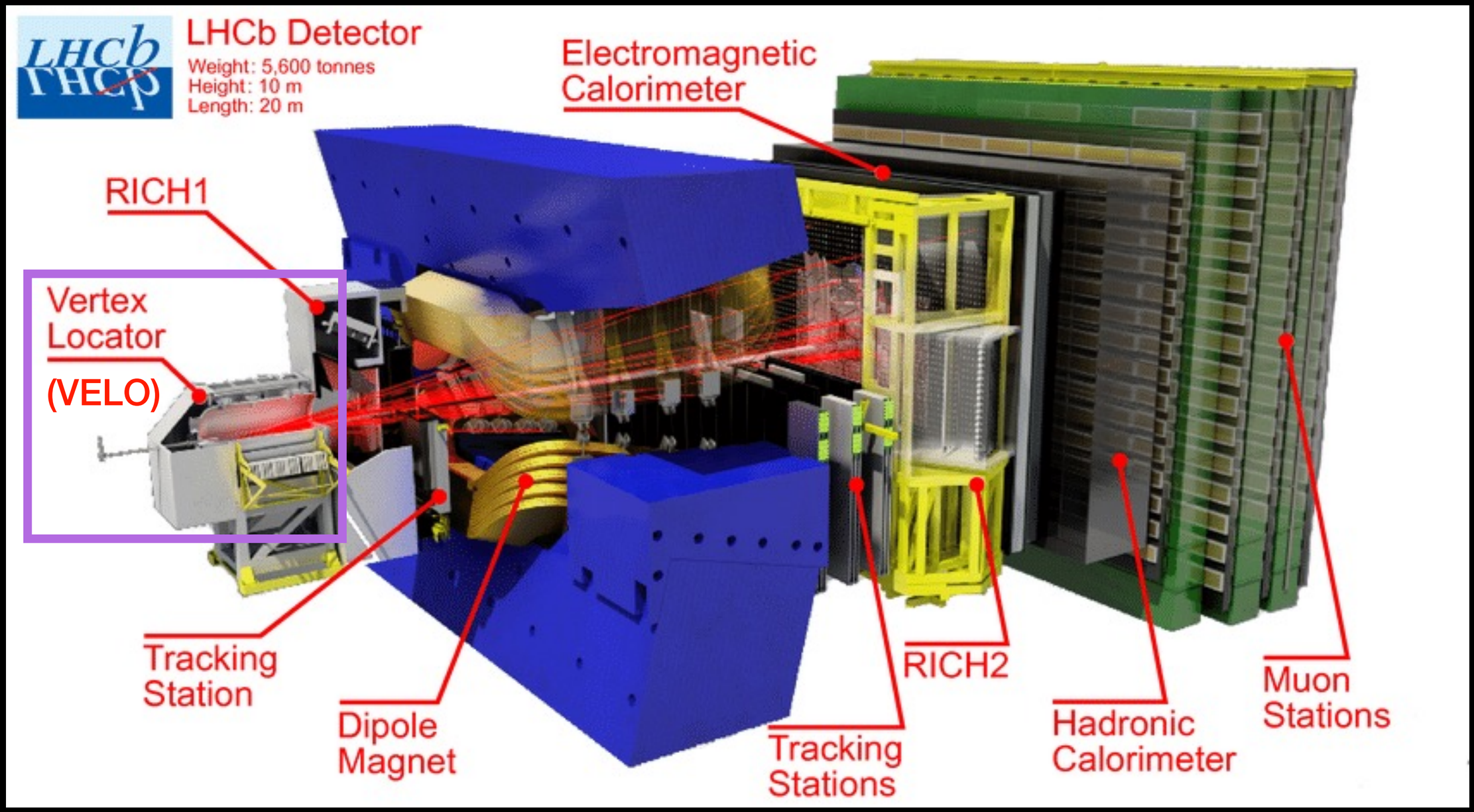
Heavy quark hadrons do not live very long, decaying to other, relatively stable, particles.



Vertex Locator (VELO)

We need extremely precise detectors to observe the particles.

Particularly at the collision point!

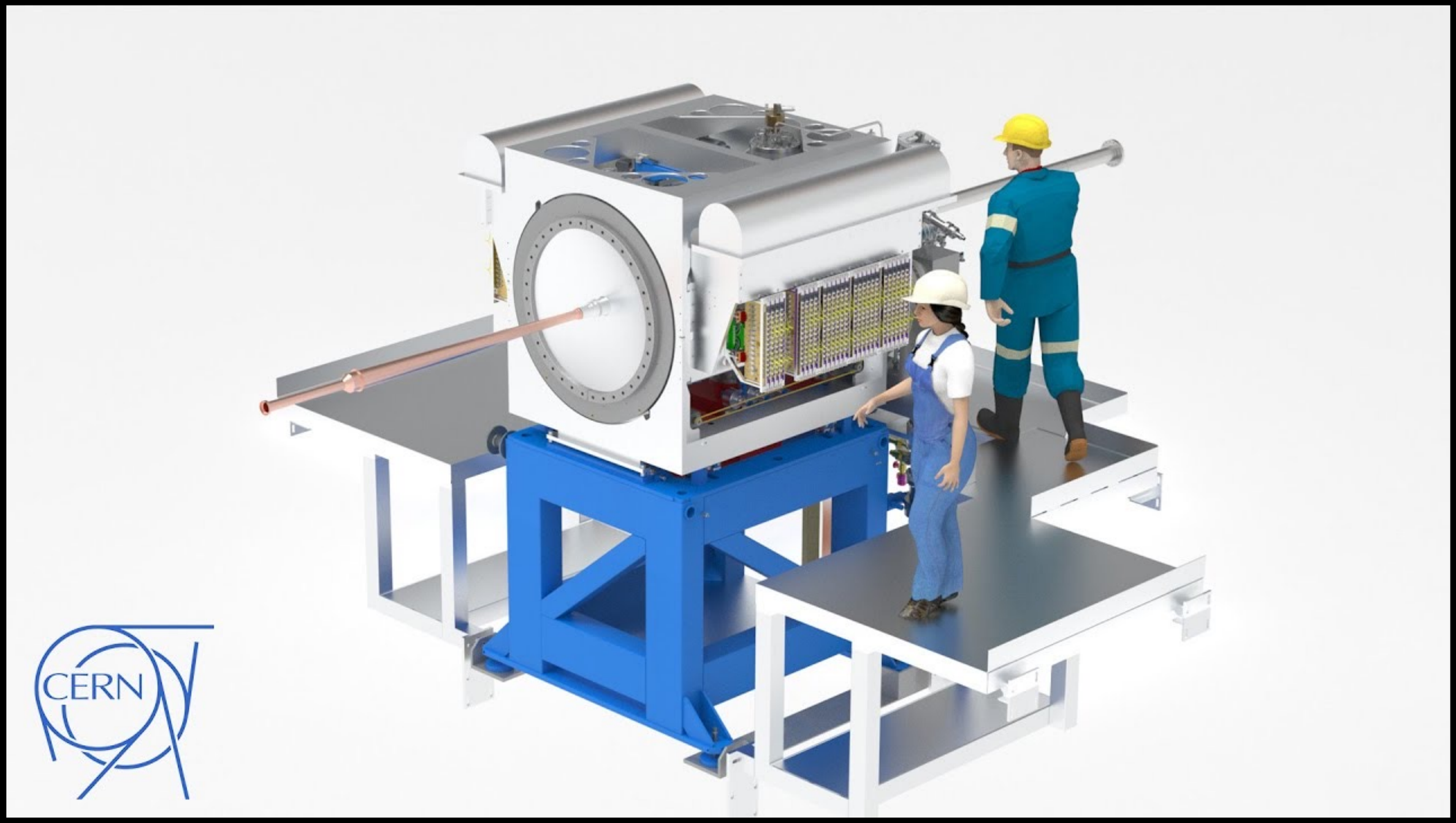


Built in Liverpool!

The 41-million-pixel Vertex Locator (VELO) was assembled right here at the University of Liverpool!

New VELO modules (McCoy Wynne)

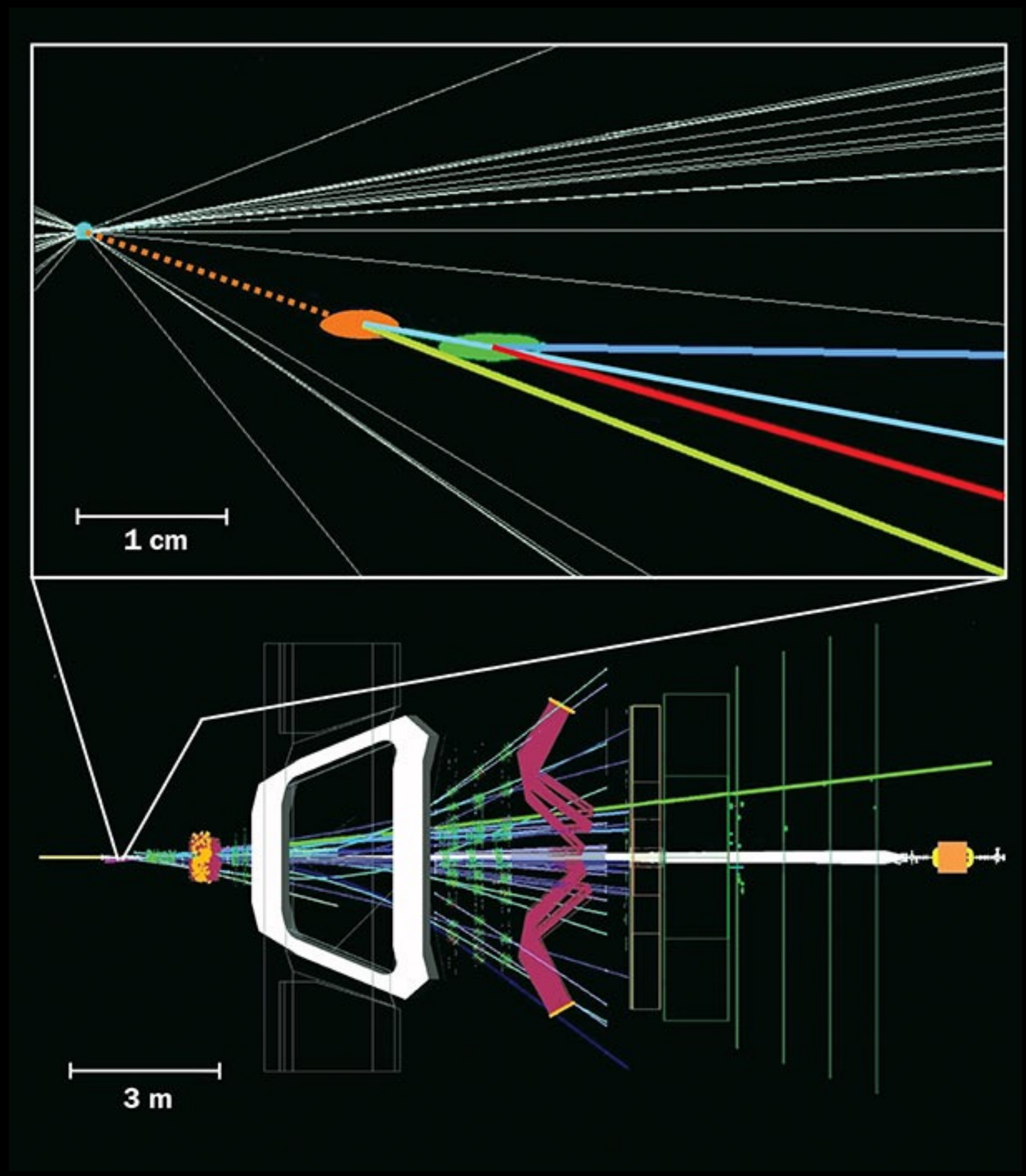
Inside the VELO



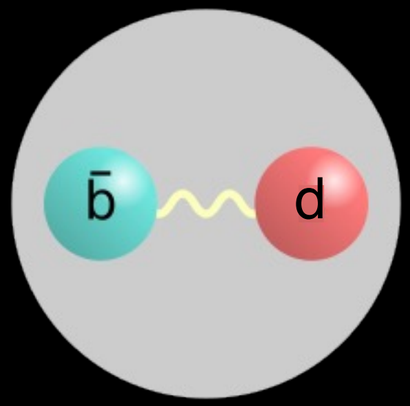
First 2 minutes of YouTube Video from Marco Kraan (Nikhef)

Inside the VELO!

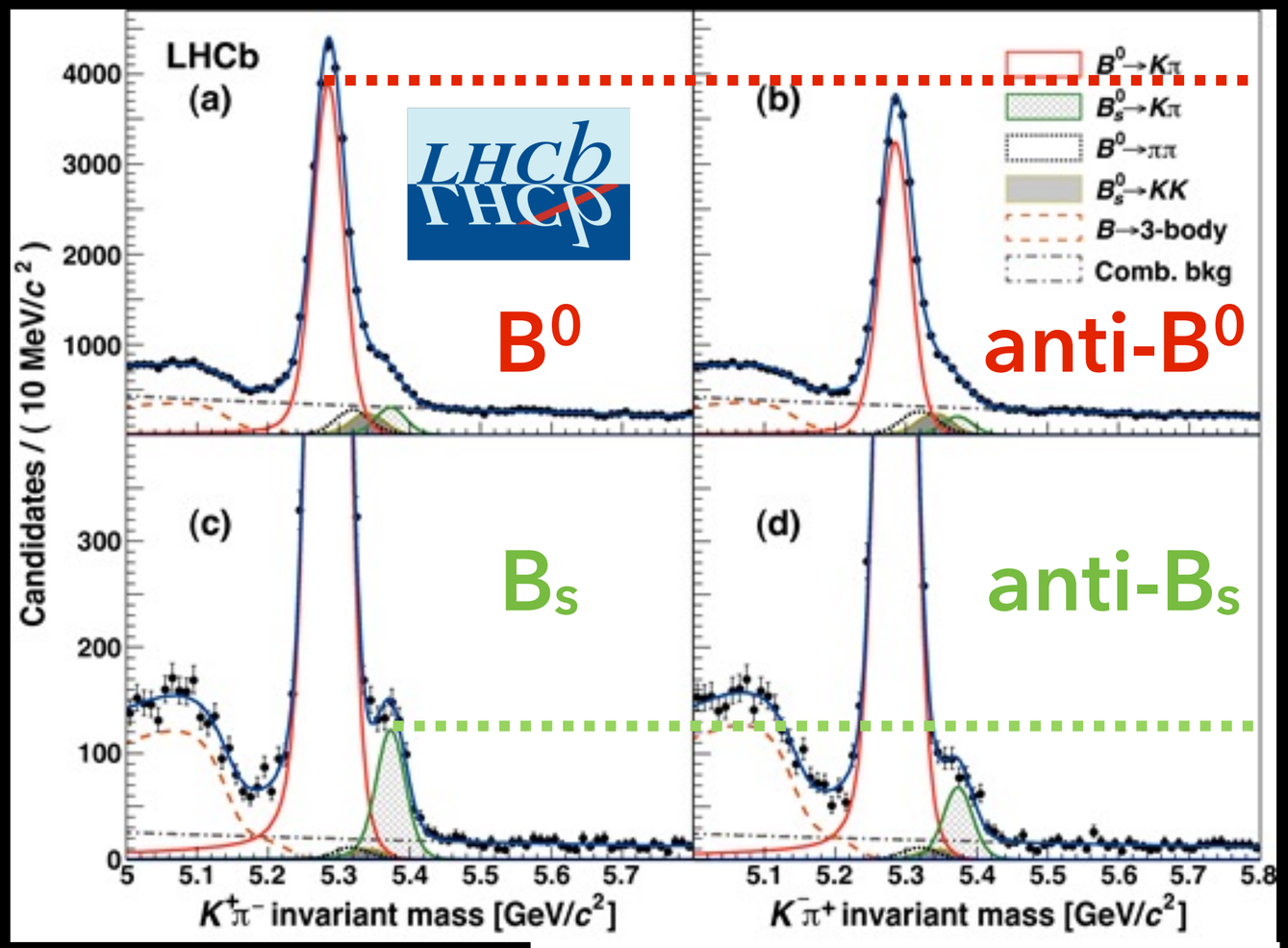
- One proton-proton collision
- A neutral particle containing a b-quark travels along the dotted path
- It then decays (in a millionth of a millionth of a second!) via the weak force into another particle containing a c-quark and one other particle
- The c-quark containing particle travels further and decays into three charged particles



This Matters

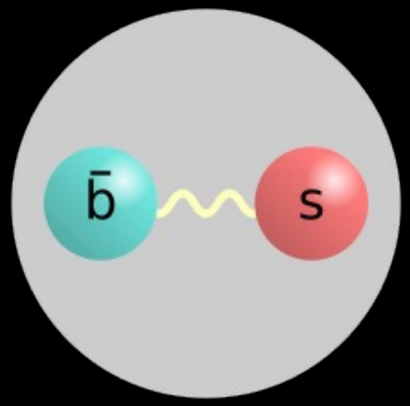


Improved measurement of CP violation in "B^0" mesons



Phys. Rev. Lett. 110 (2013) 221601

First Observation of direct CP violation in "B_s" mesons

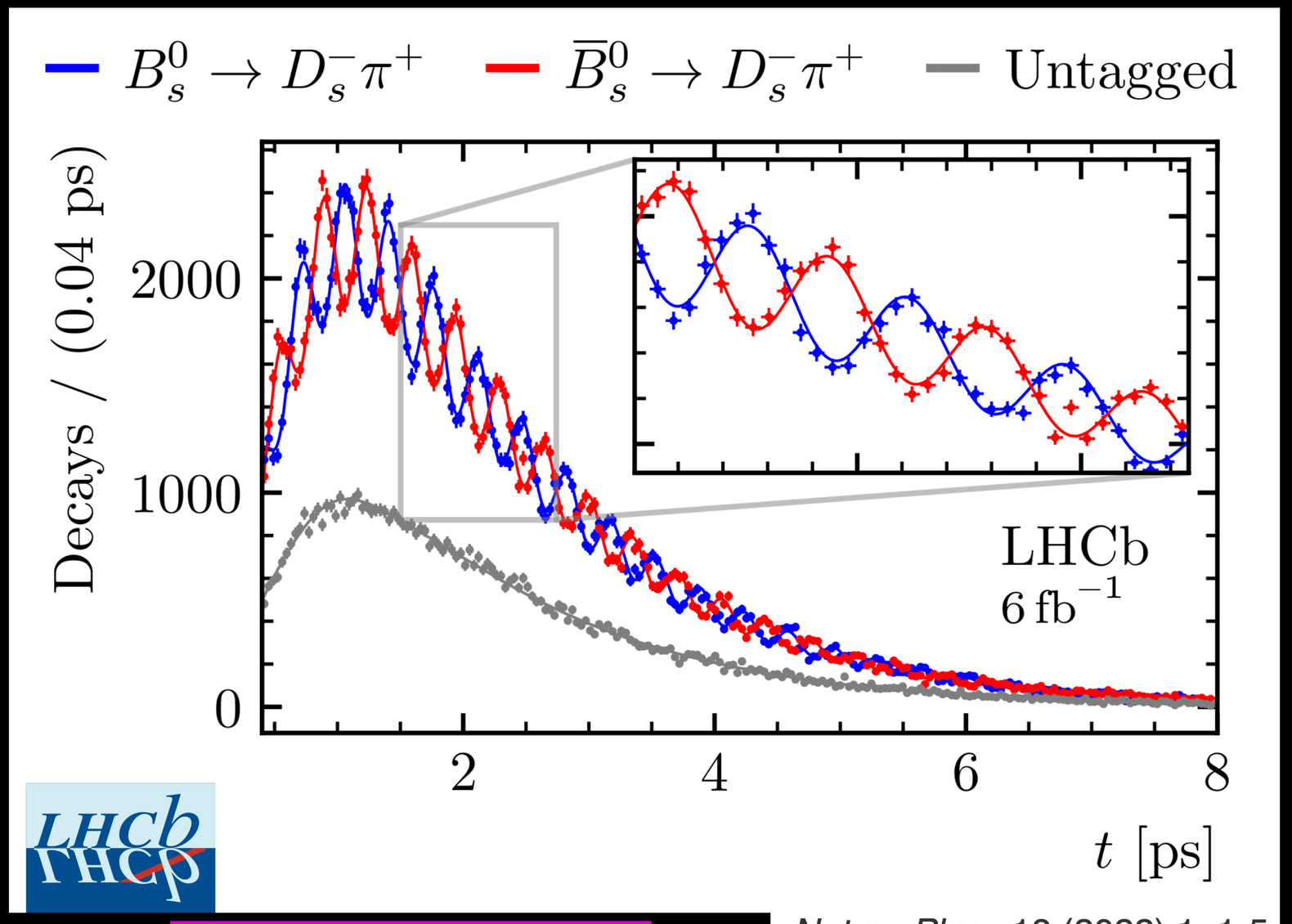


Oscillations!

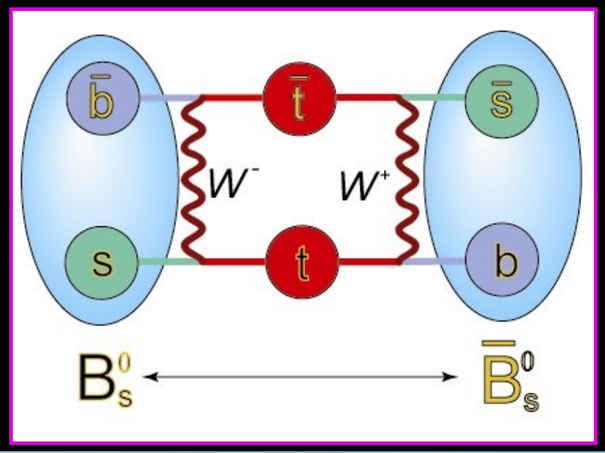
Decay time distribution of a neutral beauty-strange meson for many thousands of decays

Matter and anti-matter can oscillate into each other trillions of times per second!

LHCb precisely measures how fast this oscillation occurs

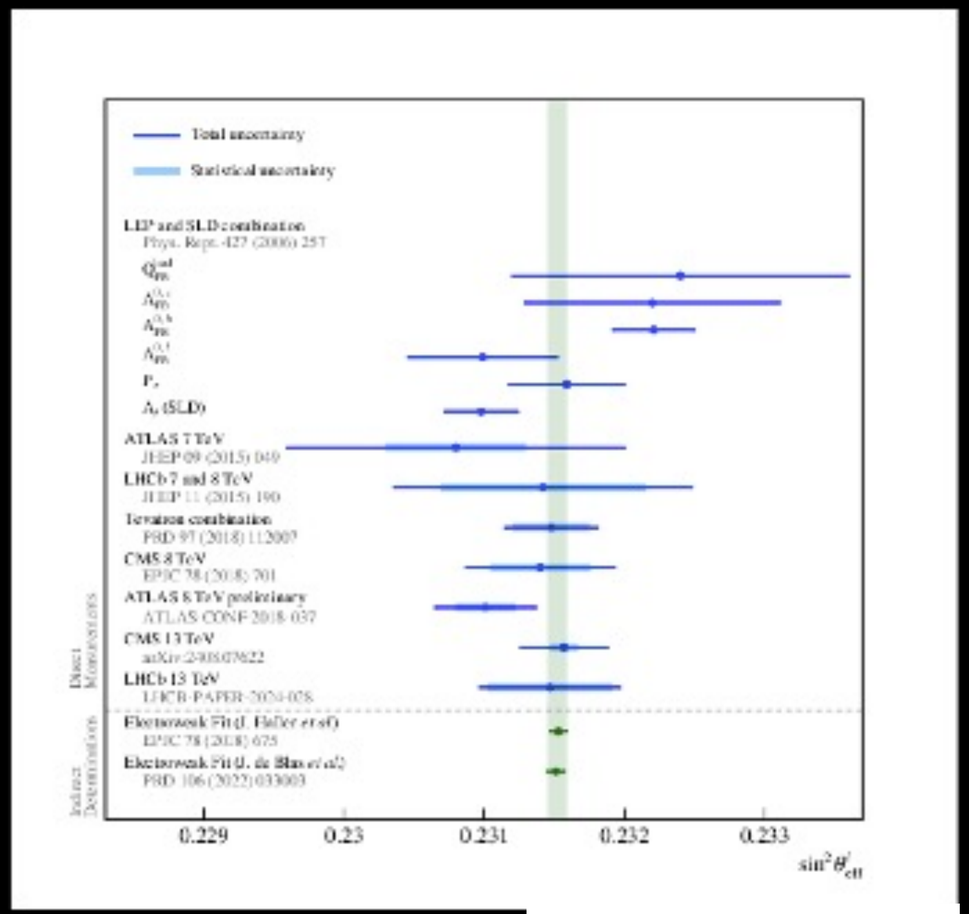


Nature Phys. 18 (2022) 1, 1-5



A new Liverpool measurement!

New Measurement of $sin^2\theta^W_{eff}$



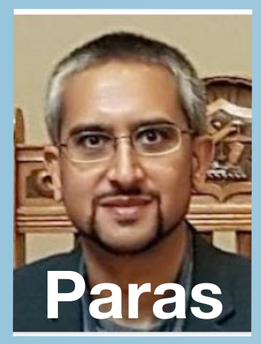
JHEP 12 (2024) 026

- LHCb have published a new measurement of the effective leptonic weak mixing angle ($sin^2\theta^W_{eff}$)
- The measurement has strong Liverpool involvement

Measuring this precisely is essential for testing the Standard Model and searching for new physics.

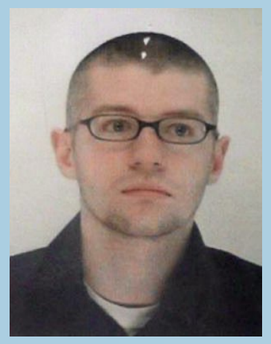
The Friendly Faces of LHCb Liverpool






(at CERN)


Involved Today

● Students!

We are an active group, leading the field...

We've built/invented detectors, techniques, and tools used to collect/analyse LHCb data.

Perhaps you can join us in 2030?

Want to know more?

- **Videoconference with LHCb @ CERN this afternoon!**

- **Search the web for “Liverpool Particle Physics” or seek: https://www.liverpool.ac.uk/physics/research/particle-physics/ and click on links and the video for more information!**

- **Meet LHCb: https://lhcb-outreach.web.cern.ch/**

- **http://scaleofuniverse.com/**

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The End