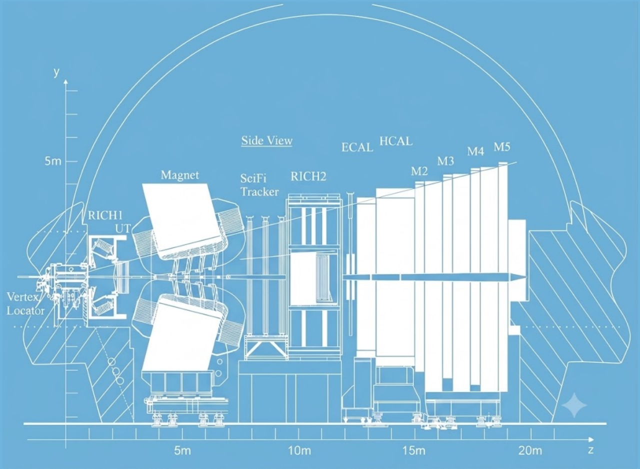
Searching for New Physics with the LHCb Experiment at CERN



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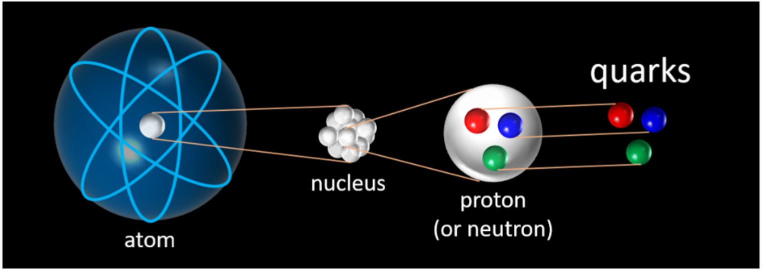
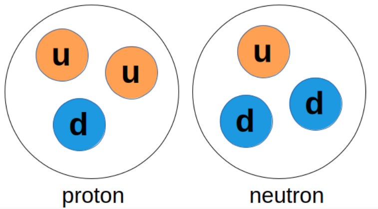
Protons and neutrons are not fundamental!

Protons and neutrons are made up of **quarks**.

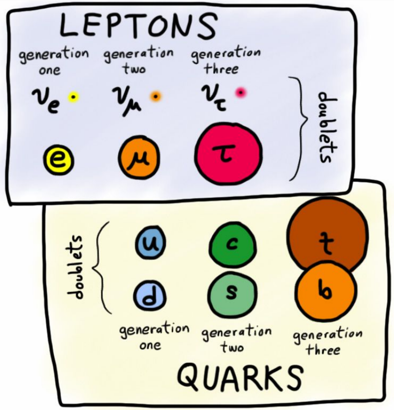




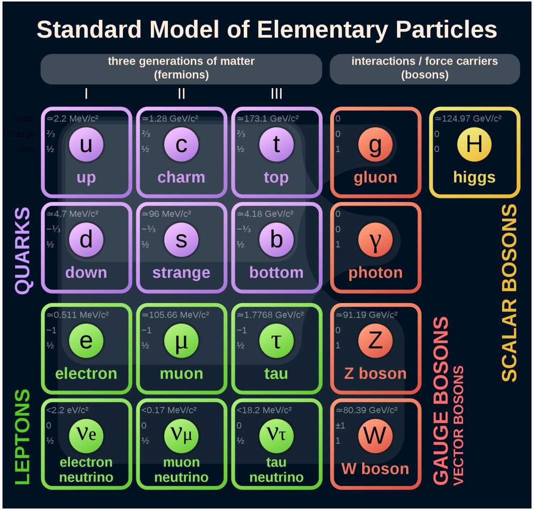
How can we categorise particles?

Quarks and leptons each come in **three generations** (families)

- The quark sector shows a clear **symmetry**: each generation contains one *up-type* and one *down-type* quark
  - Gen 1: (u, d)
  - Gen 2: (c, s)
  - Gen 3: (t, b)
- The lepton sector **mirrors** this pattern: one charged lepton + one neutrino per generation
  - Gen 1: (e, ν_e)
  - Gen 2: (μ, ν_μ)
  - Gen 3: (τ, ν_τ)
- **But:** quarks mix between generations whereas the charged leptons appear **not to**!



The Standard Model



The Standard Model is incredibly successful!

But we know it is **incomplete**...

One key question: how do quarks actually **change** from one type to another?

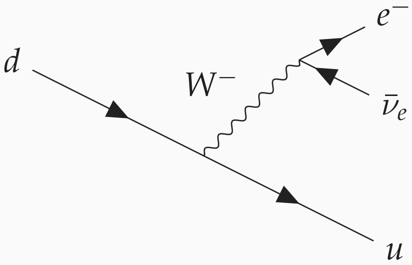
- Via the **weak interaction**, a quark can transform into a quark from a *different* generation by emitting a W^+ or W^- boson
- Classic example: **beta decay**

$$n \to p + e^- + \bar{\nu}_e$$

At the quark level:

$$d \to u + W^- \to u + e^- + \bar{\nu}_e$$

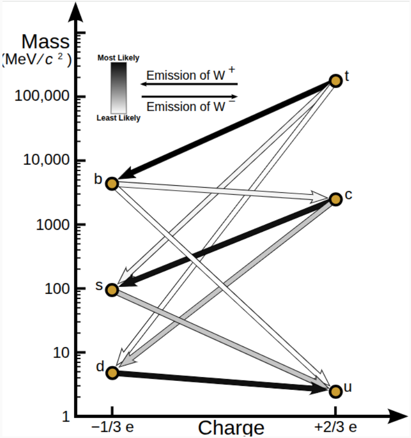
Beta Minus Decay: $d \to u + W^-$



- **Same** generation $\to$ very **likely**
- **One** generation jump $\to$ **rare**
- **Two** generation jumps $\to$ **very rare**

How likely is each transition?

- The diagram shows **all possible** quark transitions via the weak force
- **Arrow shade** $\propto$ transition probability:
  - $t \to b$ **very likely** — same generation
  - $t \to s$ **rare** — one jump
  - $t \to d$ **very rare** — two jumps
- **LHCb** precisely measures these rare transitions
- The **rarer** the process, the more **sensitive** it is to new undiscovered particles!

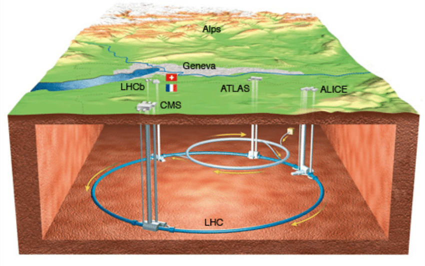


What is Flavour Physics?

- **Flavour physics** is the study of how one type of quark changes into another
- By studying these processes — especially the **rarest** ones — we can test the Standard Model very precisely
- Any deviation from the predicted rates could be a sign of **new physics!**
- So, how do we look for new physics?

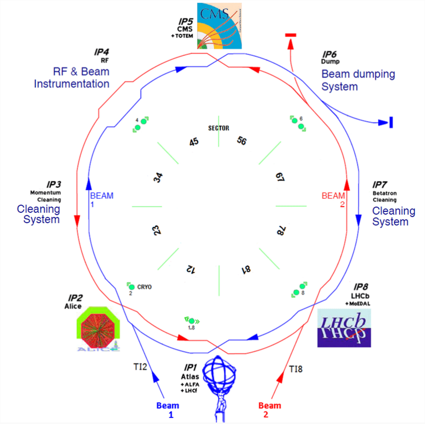
The Large Hadron Collider

- The **Large Hadron Collider** (LHC) is the world's largest and most powerful particle accelerator
- Located at **CERN** near Geneva, Switzerland — **100m underground**
- A **27km ring** in which protons are accelerated to **nearly the speed of light**
- Two beams travel in **opposite directions** and are smashed together at four **collision points**
- Each collision produces thousands of new particles



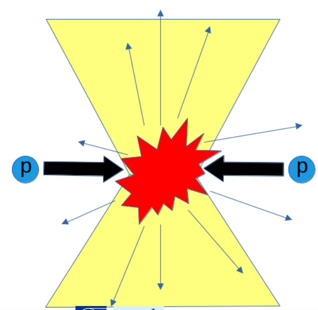
Four experiments at the LHC

- There are **four main detectors** positioned at the collision points around the ring
- **ATLAS & CMS** — general purpose detectors
  - Surround the collision point on **all sides**
  - Look for **new heavy particles** produced directly in collisions
  - Discovered the **Higgs boson** in 2012!
- **ALICE** — studies quark-gluon plasma from heavy ion collisions
- **LHCb** — designed specifically to study **beauty quarks**
  - Very different design to CMS/ATLAS



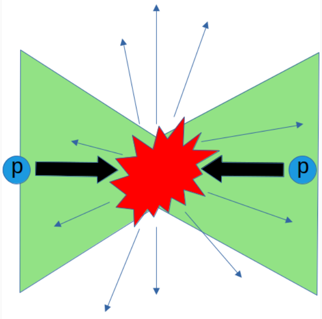
CMS & ATLAS — Multipurpose

- **Barrel shaped** — surrounds the collision point on **all sides**
- Catches particles flying out in **every direction**



LHCb — Forward Spectrometer

- Only looks in **one direction**: forward along the beam
- Beauty quarks are produced **close to the beam axis** so this is all we need!



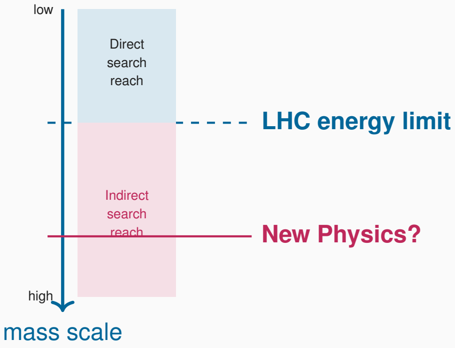
Two strategies to find New Physics

Direct searches (CMS/ATLAS)

- Smash protons with enough **energy** to directly *create* new particles
- **Limited by energy** — if a particle is too heavy, we simply cannot make it

Indirect searches (LHCb)

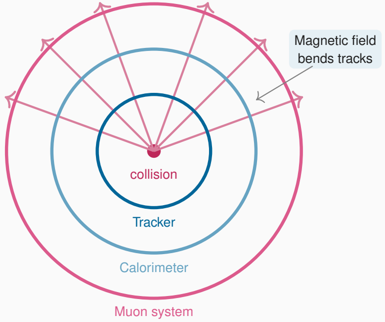
- New heavy particles can still **influence** rare decays via quantum effects — even if we can't create them directly
- **Not limited by energy** — sensitive to particles far beyond LHC reach!



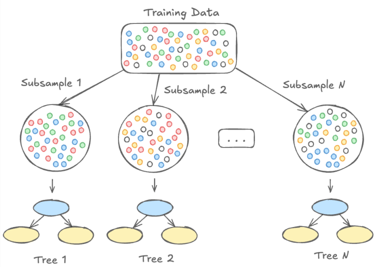
Any deviation from the predicted rates
$\Rightarrow$ **New Physics!**

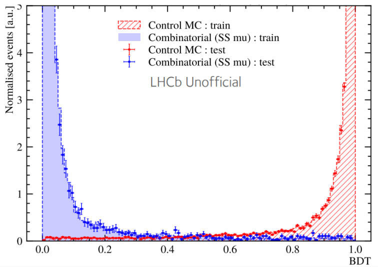
How does a particle detector work?

- When particles collide, hundreds of new particles **fly outwards** in all directions
- A detector is built in **layers** — each layer measures something different:
  - **Tracking** — where did the particle go?
  - **Calorimeters** — how much energy did it deposit?
  - **Particle Identification** — what *type* of particle is it?
- Charged particles bend in a **magnetic field** — the amount of bending tells us the particle's **momentum**
- By combining all layers we can **reconstruct** what happened in the collision



- Use a range of machine learning techniques for pattern recognition
  - Reconstruction (e.g. particle identification)
  - Selection (e.g. separating signal from background)

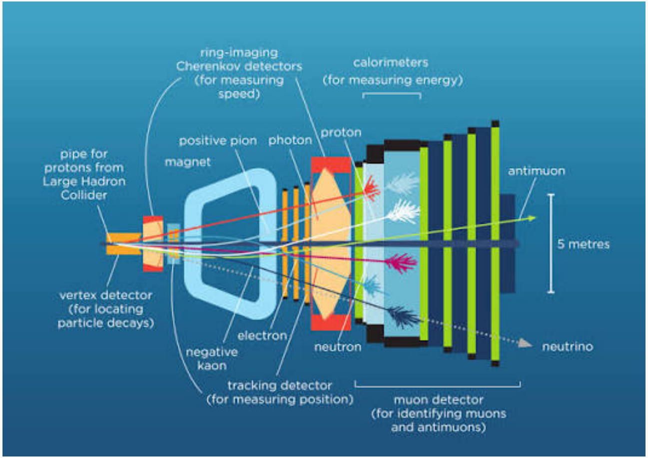




The LHCb Experiment

LHCb is designed to study processes involving beauty and charm quarks.

THE LHCB DETECTOR

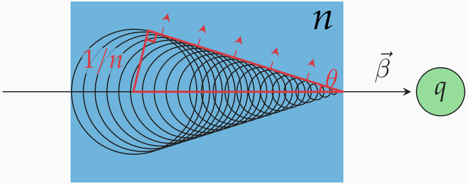


Particle Identification: Cherenkov Radiation

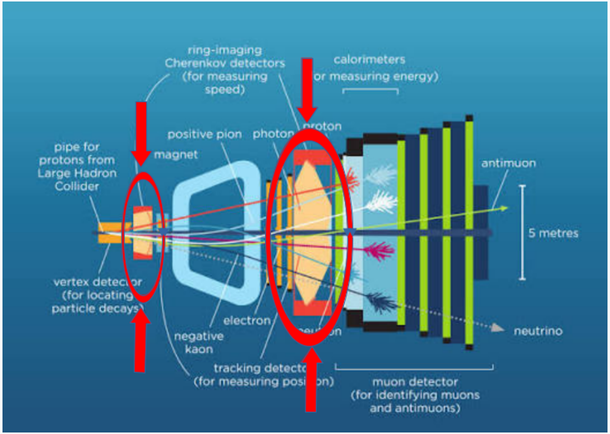
- In a **medium**, light slows to $v = c/n$ where $n > 1$ is the **refractive index**
- A fast charged particle can therefore travel **than light does** in that medium — emitting a cone of light called **Cherenkov radiation**
- The **opening angle** depends on velocity:

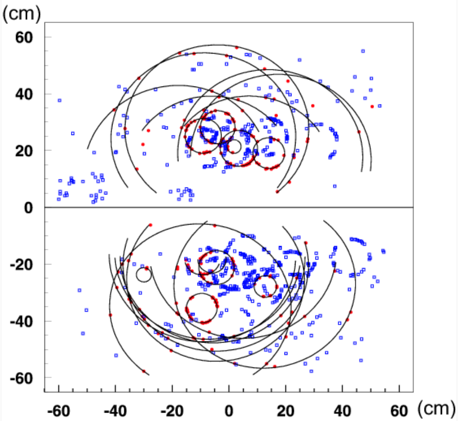
$$\cos\theta = \frac{1}{n\beta}, \quad \beta = v/c$$

- Measure $\theta \Rightarrow$ know $\beta \Rightarrow$ combined with **momentum** from tracking $\Rightarrow$ get **mass** $\Rightarrow$ **particle identified!**



The Ring Imaging Cherenkov Detectors





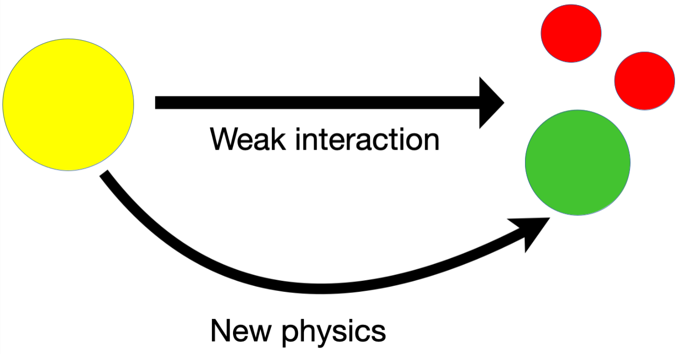
So — what are we actually looking for?

We have the machine (LHC), the detector (LHCb), and the tools (RICH, tracking, Machine Learning) —

now let's use them to hunt for new physics

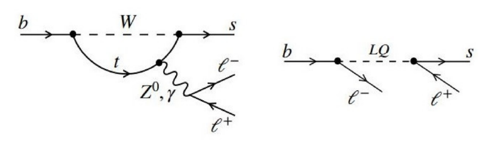
- We know the Standard Model is **incomplete**
- We can't always create new particles **directly**
- But new particles can **hide in rare decays** — subtly changing the rates we measure
- LHCb is perfectly designed to spot exactly this

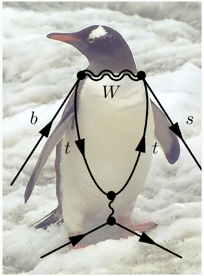
How often does the yellow particle turn into the green and red particles?



ARE WE SEEING NEW PARTICLES?

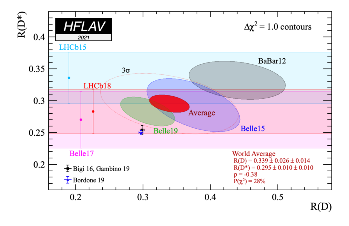
- Even if new particles are **too heavy** to create directly, they can still affect rare decays
- Due to quantum mechanics, particles can briefly **pop in and out** of existence in loops — *virtual particles*
- A new undiscovered particle could be **hiding in these loops** — subtly changing the decay rate
- This is exactly what **LHCb** is looking for!



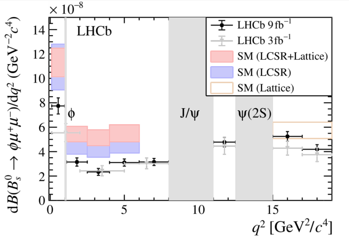


IMPERIAL

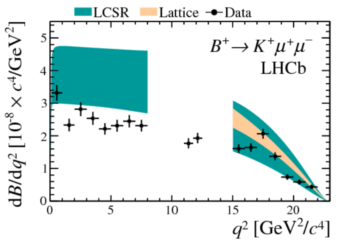
Several LHCb measurements show **tensions** with the Standard Model prediction!



$R(D)$ vs $R(D^*)$



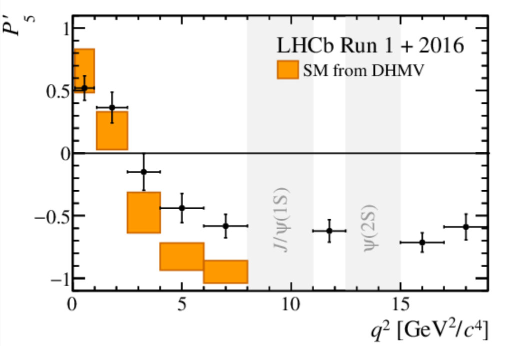
P_5' angular observable



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

Hints of something new?

- Several measurements **disagree** with the prediction!
- This could be a statistical fluke — or it could be a sign of **something new**
- More data is needed to know for sure — but it is **very exciting!**

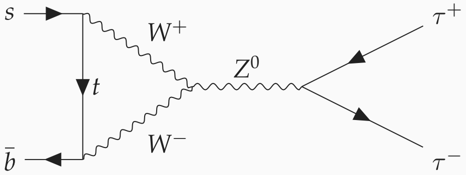


My Research: Searching for $B_s^0 \to \tau^+\tau^-$

- The B_s^0 meson contains a **beauty (b) quark** and a **strange (s) quark**
- We search for it decaying into a **tau lepton pair** $(\tau^+\tau^-)$
- **Incredibly rare** — the Standard Model predicts:

$$\mathcal{B}(B_s^0 \to \tau^+\tau^-) \approx 7.73 \times 10^{-7}$$

- **Challenge:** τ leptons decay before we can see them — we reconstruct them from their decay products



Any deviation from prediction $\Rightarrow$ **New Physics!**

Summary

- LHCb is an experiment based at the LHC at CERN designed to measure decays involving b quarks
- There are specialised sub-detectors (e.g. Vertex Locator, Ring Imaging Cherenkov Detectors) to **measure** and **identify** decayed particles
- Results involving $b \to s\ell\ell$ transitions indicate potential contributions from physics Beyond the Standard Model!
- Still need to analyse more data and other $b \to s\ell\ell$ decays to understand these anomalies better
- **Very exciting times ahead!**

Thank you for listening!

Any questions?

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