Study of matter, antimatter and dark matter at the LHCb experiment

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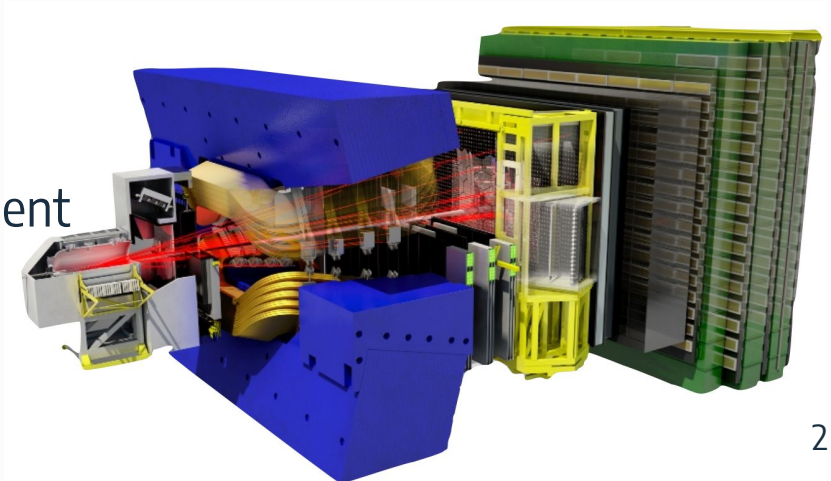
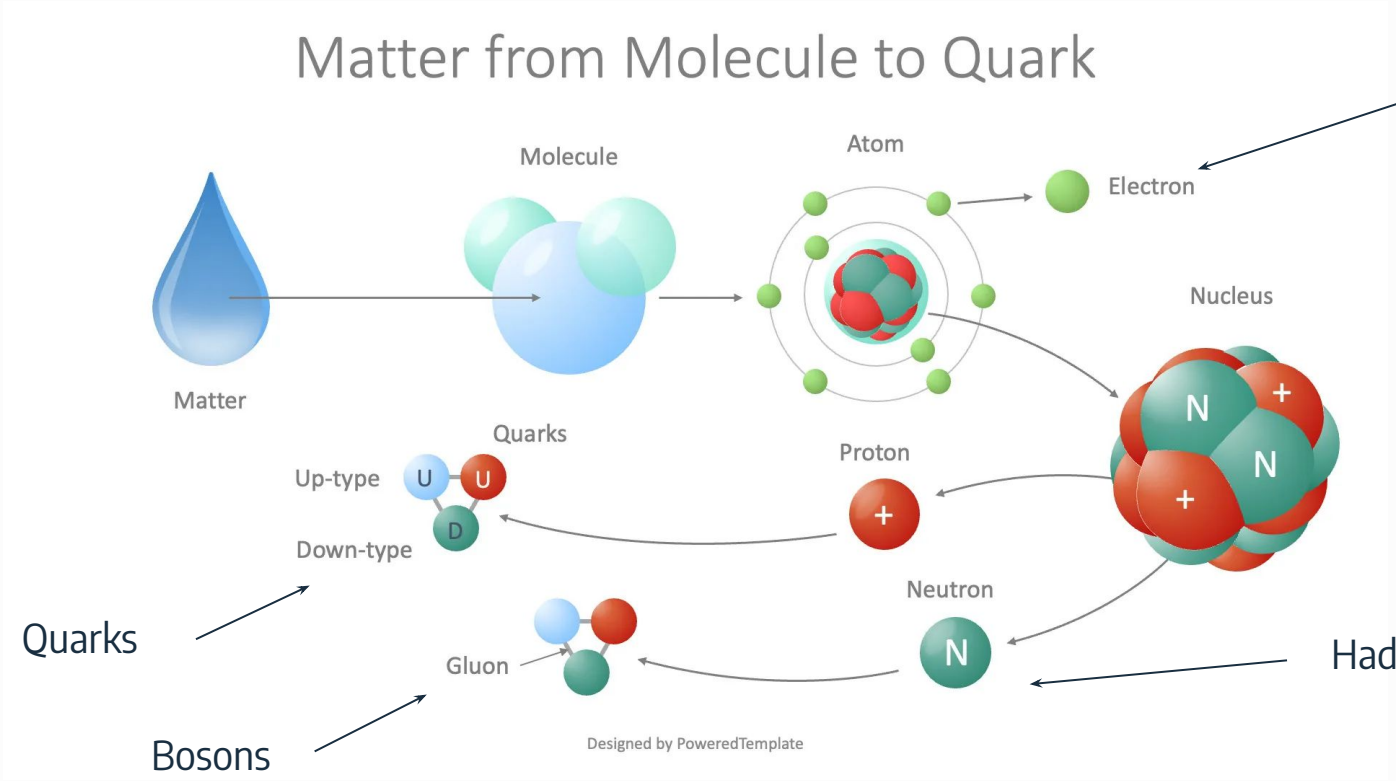
Outline

- The Standard Model of Particle Physics
- The Large Hadron Collider (LHC) at CERN
- The LHCb Detector and Physics Reconstruction
- Matter vs. Antimatter and CP Violation
- Search for Dark Matter at the LHCb Experiment
- Conclusion and Summary



The Standard Model of Particle Physics

Standard Model of Particle Physics



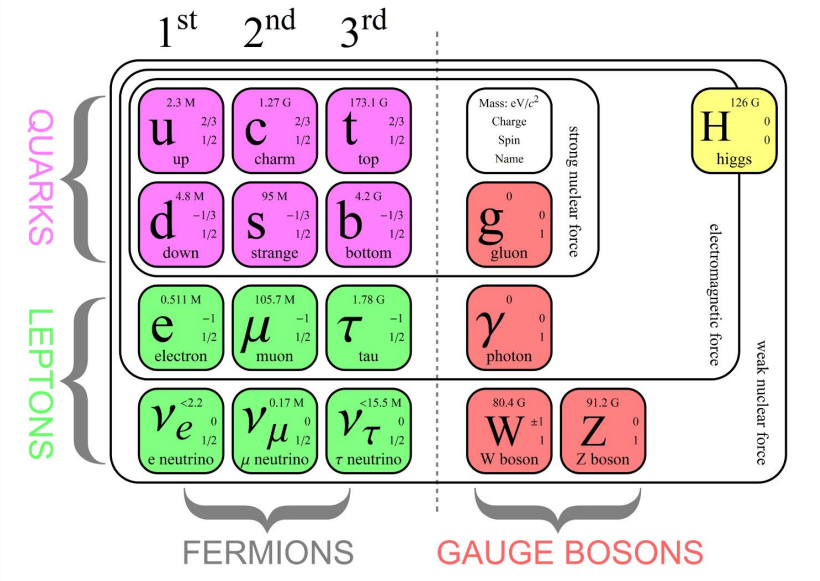
Lepton

Quarks

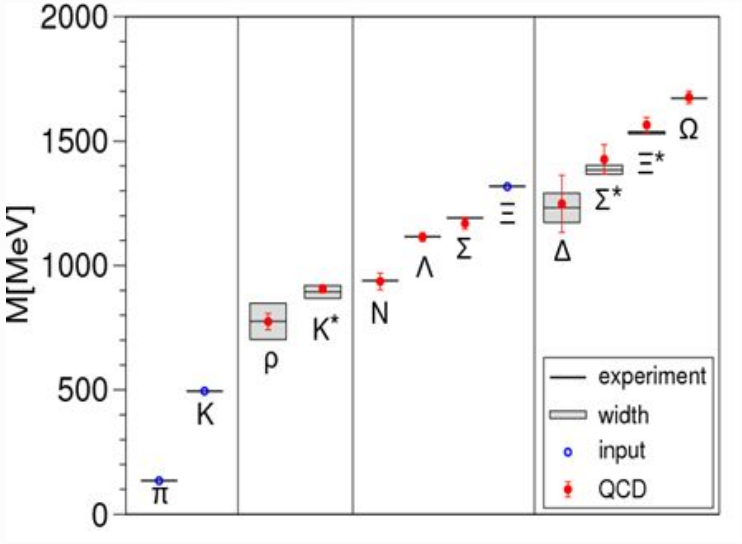
Hadrons

Bosons

Standard Model of Particle Physics



Provides framework for understanding the behaviour of the fundamental particles and their interactions through strong, weak and EM forces

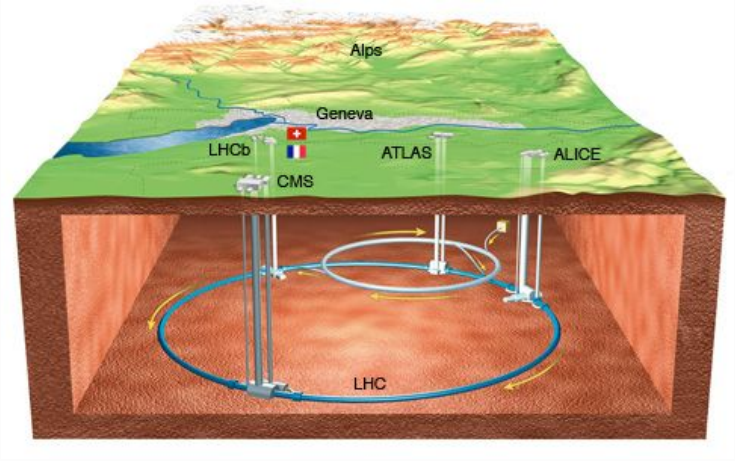


Amazing predictive capability in particle transitions, solid and until now undefeated

The Large Hadron Collider (LHC) at CERN

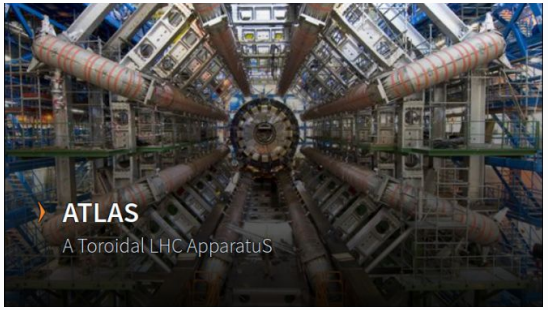
The Large Hadron Collider at CERN

- The **Large Hadron Collider (LHC)** is the world's largest particle collider.
- It was designed and built by the **European Organization for Nuclear Research (CERN)** between 1998 and 2008.
- The accelerator is located in a **26.7 km** long tunnel, **3.8 m wide**, at a depth ranging from **50 to 175 m** beneath the France-Switzerland border near Geneva
- In the LHC, two beams of **protons** (or **ions**) travel in opposite directions and collide at a center-of-mass energy of **13.6 TeV.**
- These collisions produce a wide variety of particles, which are studied by different experiments.



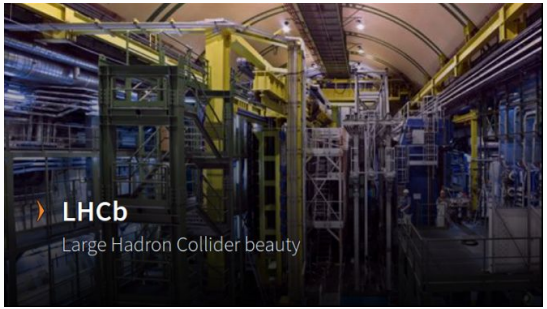
The Large Hadron Collider at CERN

- The **four** main LHC experiments are:



General purpose detectors designed to study collisions producing high transverse momentum particles.

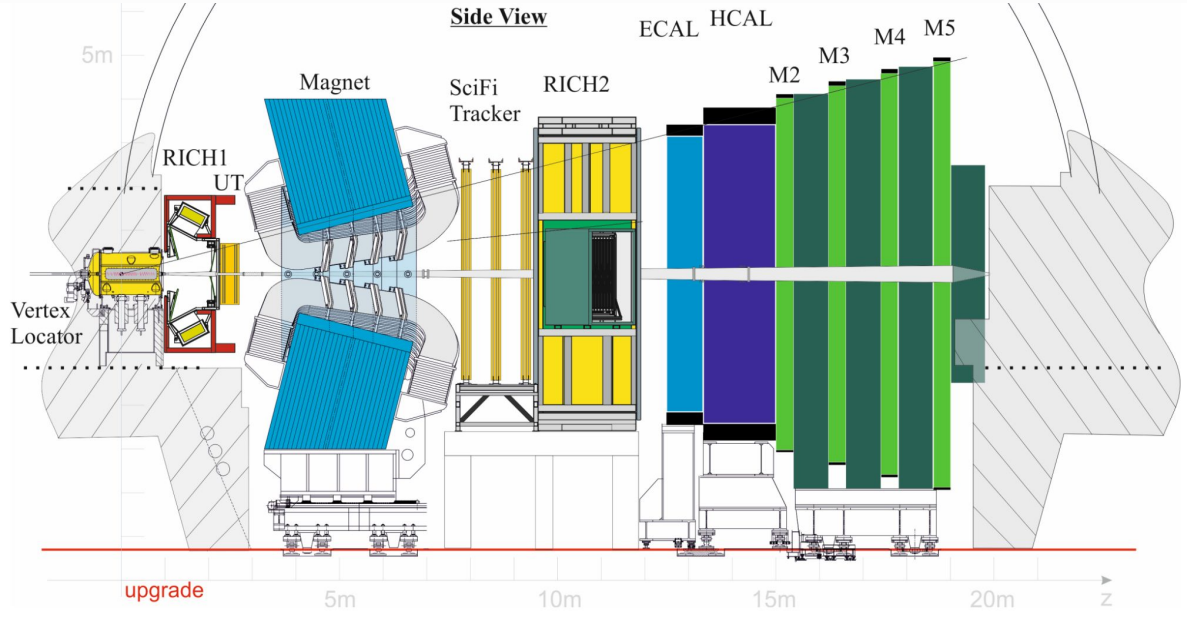
Detector designed to study quark-gluon plasma with heavy ion collisions.



Detector designed to study quark-gluon plasma with heavy ion collisions.

LHCb detector and physics reconstruction

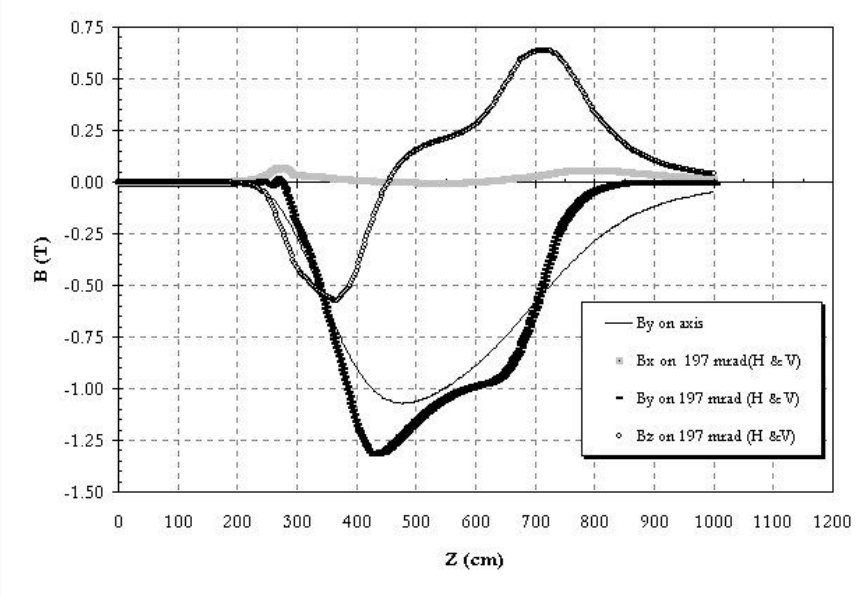
LHCb detector and physics reconstruction

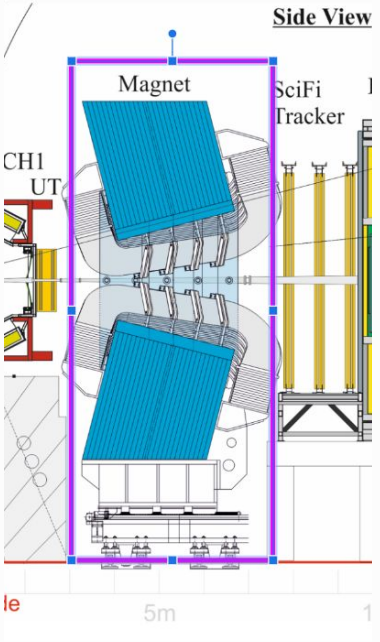


- **LHCb** is a single-arm spectrometer with a forward angular acceptance, covering the range **10-300 mrad** in the horizontal plane.
- The primary goal of the **LHCb experiment** is to record the decays of beauty **(b) and charm (c) hadrons**.
- Due to their high mass, these hadrons and their decay products remain close to the beamline.
- **LHCb** can precisely determine the **identity, trajectory, momentum**, and **energy** of each particle.

The dipole magnet

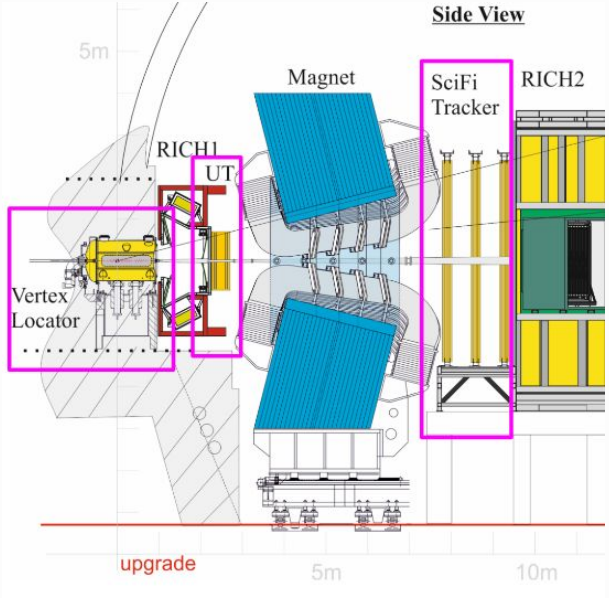
- The **magnet's** two coils are each **7.5 m long, 4.6 m wide,** and **2.5 m high**.
- The dipole magnet is designed to provide a total integrated field of **4 Tm**.
- This magnetic field is used for **momentum measurement** of charged particles: the curvature of their trajectory in the magnetic field reveals information about their momentum.



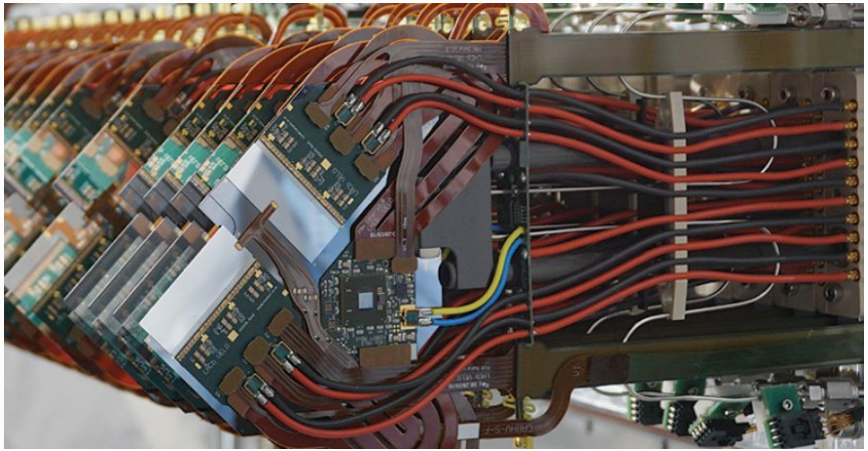


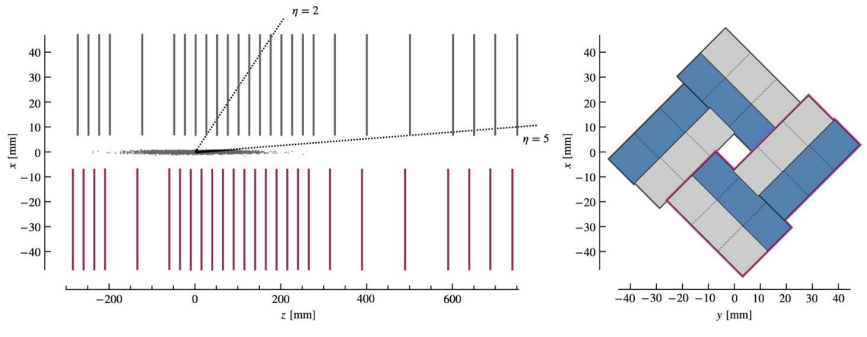
The trackers

- Trackers are detectors used to determine the trajectory of charged particles.
- In the **LHCb experiment**, there are three main trackers:
  - **VErtex LOcator (VELO)**:
    - Pixelated hybrid silicon detectors
    - Located close to the collision point
  - **Upstream Tracker (UT)**:
    - Silicon microstrip sensors
    - Located just before the dipole magnet
  - **Scintillating Fibre tracker (SciFi)**:
    - Scintillating fibres combined with Silicon Photomultiplier (SiPM)
    - Located just after the dipole magnet



The VELO tracker

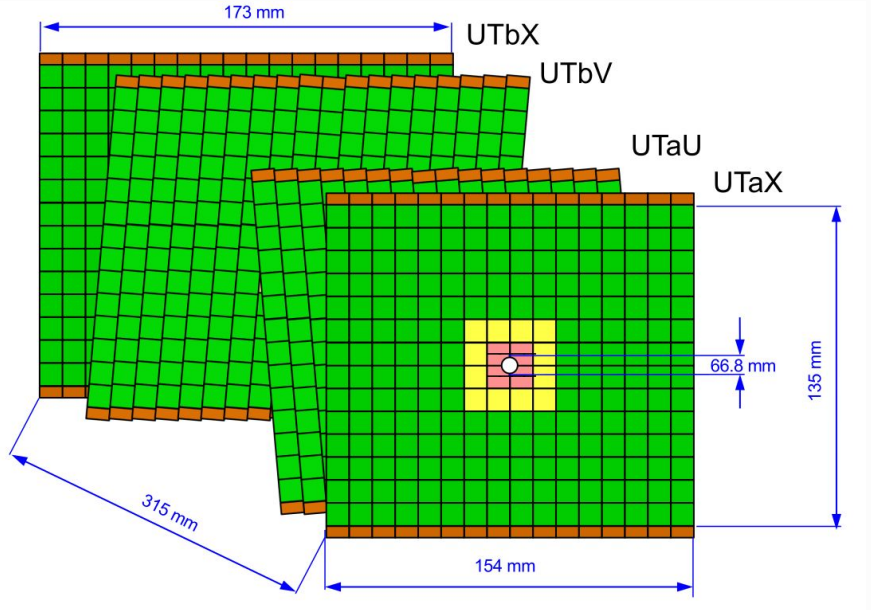




- The **VELO** contains **52 silicon detector elements**, positioned just **5 mm** from the point where protons collide.
- These detector elements allow VELO to reconstruct all charged particle tracks generated by the proton-proton collisions, identifying their points of origin, known as **primary vertices**.
- When a neutral particle decays into multiple charged particles inside VELO, it can also determine the origin of the decay, known as **secondary vertices**.
- By knowing the positions of the **primary** and **secondary vertices**, more complex information can be computed, such as the **flight distance** and **directional angle**.

The UT detector

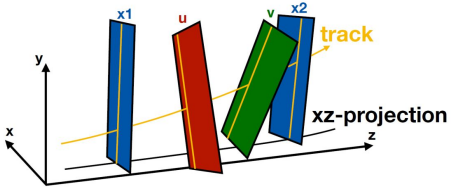
- The **UT detector** consists of four planes of silicon detectors organized into two stations: **UTa** and **UTb**.
  - Two planes are **x-measuring layers** with vertical strips.
  - The other two are **stereo layers**, with strips inclined at **± 5º**, providing additional **Y information**.
- The stereo layers improve momentum resolution by adding **y-coordinate** information to particle trajectories.
- The UT detector enhances momentum estimation for charged particle tracks and helps suppress **fake-track rates**.
- It also detects **Long-Lived Particles (LLPs)** that decay after the VELO.



The SciFi Tracker

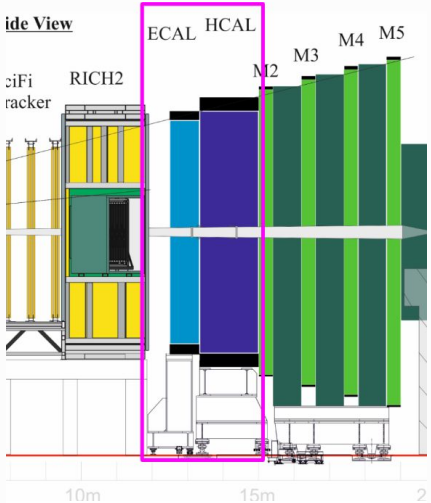
- The SciFi Tracker consists of **12 detection** planes arranged in **3 stations** (T1, T2, T3).
- Each station contains 4 layers in an **X-U-V-X** configuration:
  - **X layers** have vertically oriented fibres for x-position measurement.
  - **U** and **V layers** are rotated by **± 5º** to measure **y-position information**.
- The tracker provides a **single-hit** position resolution of better than **100 µm**.

Each station



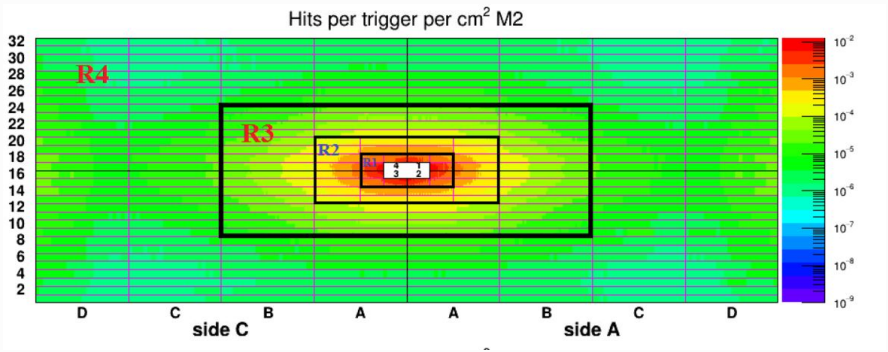
The calorimeter system

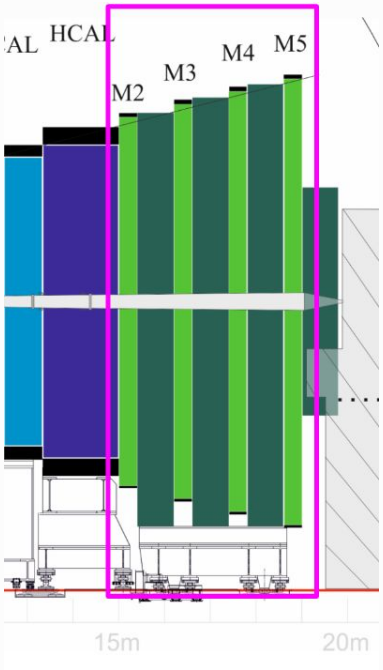
- The **calorimeter system** is designed to stop particles as they pass through, measuring the energy lost as each particle grinds to a halt.
- In the **LHCb experiment**, there are two types of calorimeters:
  - **ECAL (Electromagnetic Calorimeter)**: Measures energy from **electrons** and **photons**.
  - **HCAL (Hadron Calorimeter)**: Measures energy from **hadrons** (e.g., protons, neutrons)
- Both calorimeters have a **sandwich-like structure** with alternating layers of **metal** and **plastic (scintillator)** plates.
  - Particles hitting the metal plates produce showers of secondary particles.
  - These secondary particles excite polystyrene molecules in the scintillator plates, emitting **ultraviolet (UV) light**.
  - The amount of UV light is proportional to the energy of the particles entering the calorimeter.



The Muon system

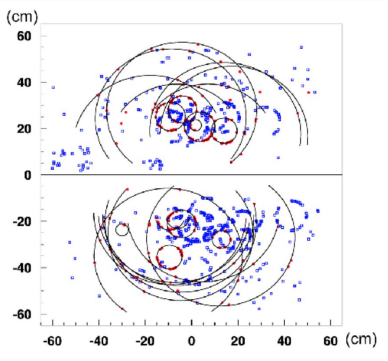
- The **LHCb muon system** consists of **four stations** (M2 to M5), with each station containing **276 multiwire proportional chambers (MWPCs)**, covering a total area of **386 m²**.
- Located at the far end of the detector, downstream of the calorimeters, this region is only accessible to **muons**.
- The muon chambers provide additional measurements for **muon tracks**, which are used for **muon identification** and improve the **momentum resolution** of muon tracks.

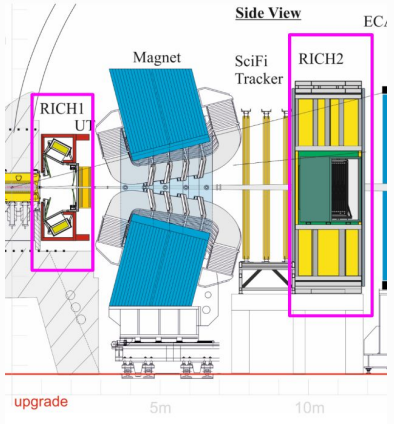


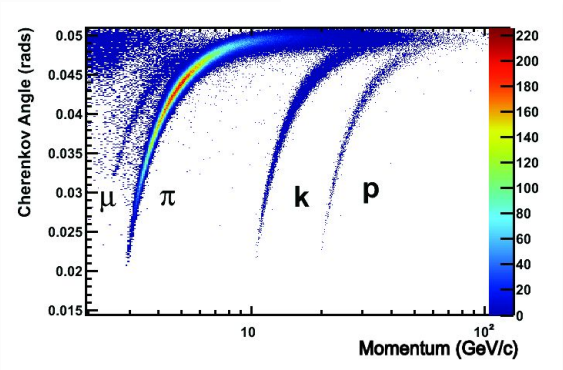


The RICH detector

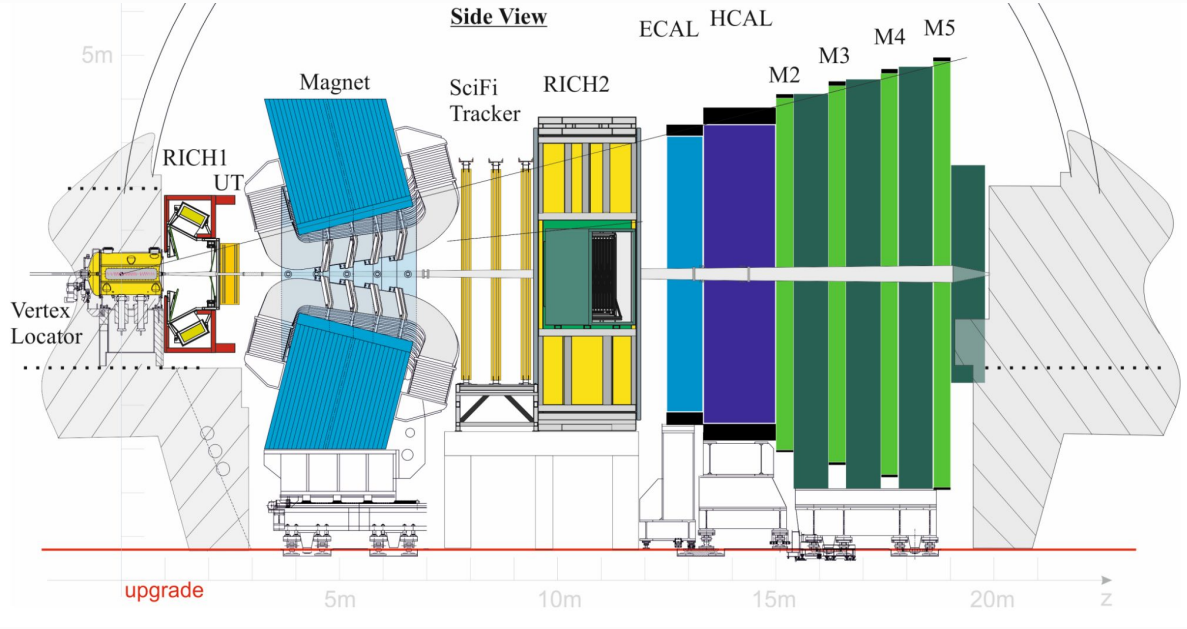
- **Two Ring Imaging Cherenkov (RICH) detectors** are used for **particle identification (PID)**.
- **RICH** detectors measure **Cherenkov radiation** emitted when a charged particle travels through a medium (like a dense gas) faster than light does in that medium.
- The particle emits a **cone of light**, which is reflected onto an array of sensors using mirrors.
- The shape of the light cone depends on the particle's velocity, and when combined with **momentum estimation**, it provides **PID information**







LHCb detector and physics reconstruction



- **Charged particles** are reconstructed using **trackers**, with energy determined from momentum and a mass hypothesis:

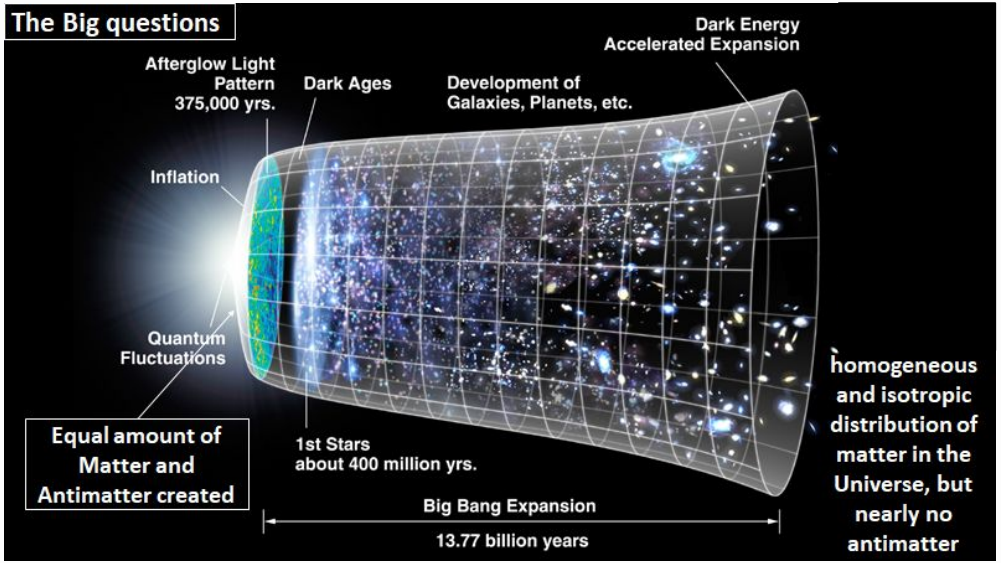
$$M^2 = E^2 - P^2$$

- Neutral particles, such as **photons**, are reconstructed with **calorimeters**.
- The RICH detectors provide additional **PID information**, while the **ECAL** and **Muon stations** can further assist in identifying **leptons** (electrons or muons).

Matter vs Antimatter and CP Violation

Matter vs Antimatter

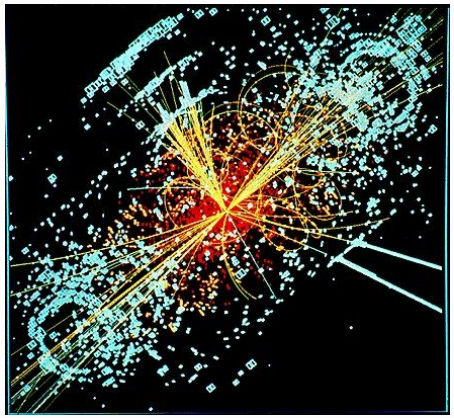
- **Antimatter particles** have the same mass as their matter counterparts, but opposite properties, such as **electric charge**.
- Matter and antimatter particles are always produced in pairs, and when they come into contact, they **annihilate**, leaving behind pure energy.
- The **Big Bang** should have created equal amounts of matter and antimatter.
- However, as the universe cooled and expanded, antimatter almost completely disappeared just one second after the Big Bang, leaving **matter** to form everything we see today.



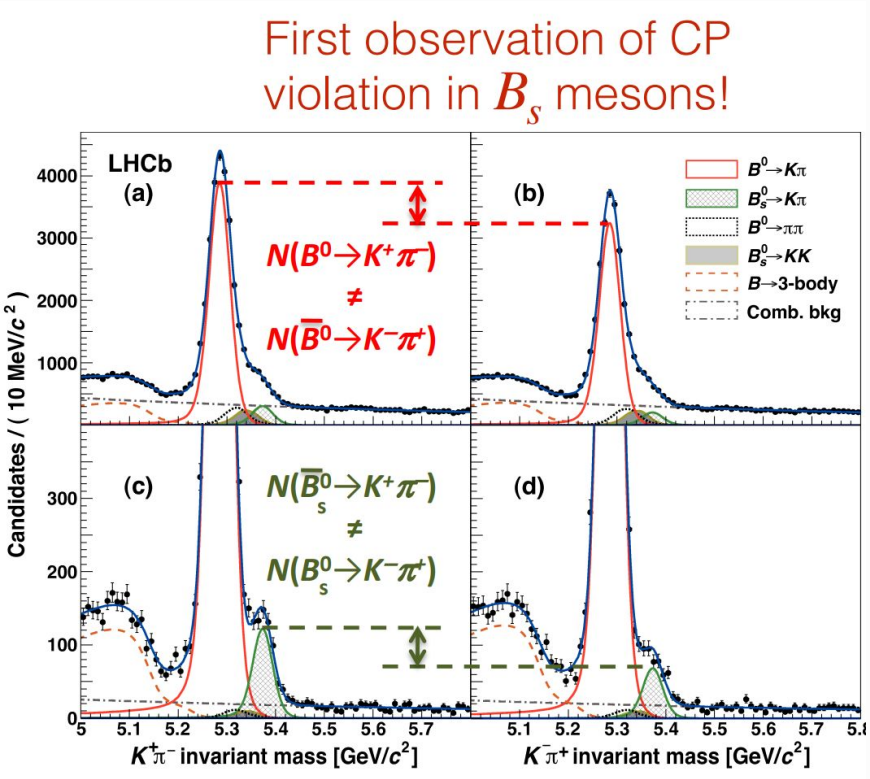
Matter–antimatter imbalance

CP Violation

- **What is CP Symmetry?**
  - CP symmetry combines two operations: flipping a particle into its **antiparticle (C)** and reversing its **spatial coordinates (P)**.
- **What is CP Violation?**
  - **CP violation** occurs when the laws of physics are not identical for particles and their antiparticles under these transformations, meaning they behave differently.
- **Why Does CP Violation Matter?**
  - CP violation introduces a small **difference** in how matter and antimatter behave, allowing slightly more matter to survive, which is why we have a universe full of matter today.
- One of the main physics programs of the **LHCb experiment** is the study of **CP violation**.



CP Violation in LHCb



- LHCb successfully observed the first **CP violation** (CPV) in **B_s mesons**, thanks to its excellent **reconstruction** and **particle identification** performance!
- Direct CP violation means that the number of B → f decays is different from the number of $\overline{B} \to \overline{f}$ decays.
- The observable for CPV is defined as:

$$A_{CP} = \frac{\Gamma(\overline{B}^0_{(s)} \to \bar{f}) - \Gamma(B^0_{(s)} \to f)}{\Gamma(\overline{B}^0_{(s)} \to \bar{f}) + \Gamma(B^0_{(s)} \to f)}$$

- What we measure experimentally at LHCb is:

$$A_{CP}(B^0_s \to K^-\pi^+) = 0.27 \pm 0.04\,(\text{stat}) \pm 0.01\,(\text{syst})$$

$$A_{CP}(B^0 \to K^+\pi^-) = -0.080 \pm 0.007\,(\text{stat}) \pm 0.003\,(\text{syst})$$

If $A_{CP} \neq 0$ → CP violation

CKM matrix

- The **Cabibbo–Kobayashi–Maskawa (CKM)** matrix describes the mismatch between the quantum states of quarks during free propagation and in weak interactions.

$$[\text{quark}]_{\text{flavour}} = V_{\text{CKM}}\,[\text{quark}]_{\text{mass}}$$

weakly interacting — strongly produced

- A single complex phase in the CKM matrix can explain CP violation.

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3[1-\rho-i\eta] & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

Wolfenstein parameterization; expansion in $\lambda \sim 0.2$

- This is known as the **Kobayashi-Maskawa mechanism**, which earned the 2008 Nobel Prize in Physics.

We need more CP violation!

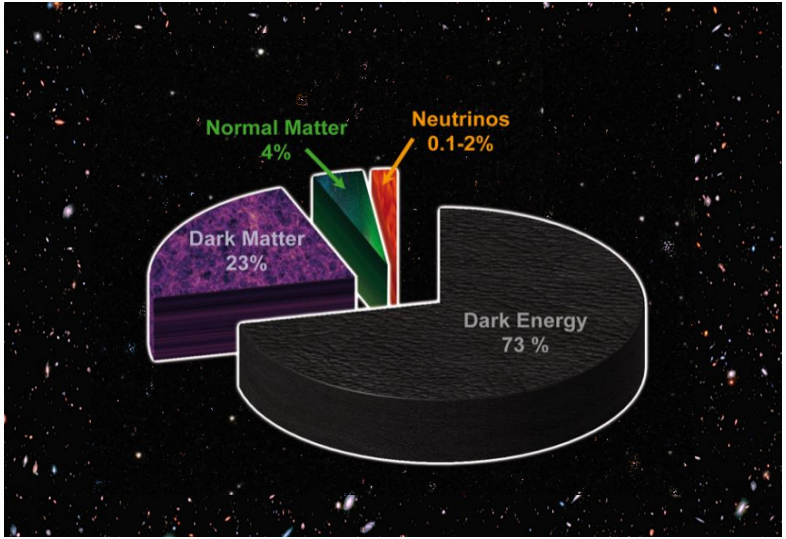
- In principle, the Standard Model (SM) can explain CP violation, but the CP violation predicted by the Kobayashi-Maskawa (KM) mechanism is too small to account for the matter-antimatter asymmetry. This suggests that CP violation beyond the SM must exist!
- **Where might we find it?**
  - **Quark sector**: Deviations from CKM predictions
  - **Lepton sector**: CP violation in neutrino oscillations
  - **Other new physics theories**:
    - Almost all **TeV-scale new physics theories** contains new sources of CP violation.
    - The precision measurement of **flavour observables** are sensitive to potential additions beyond the Standard Model.

The **LHCb experiment** is an ideal candidate to search for new sources of **CP violation**!

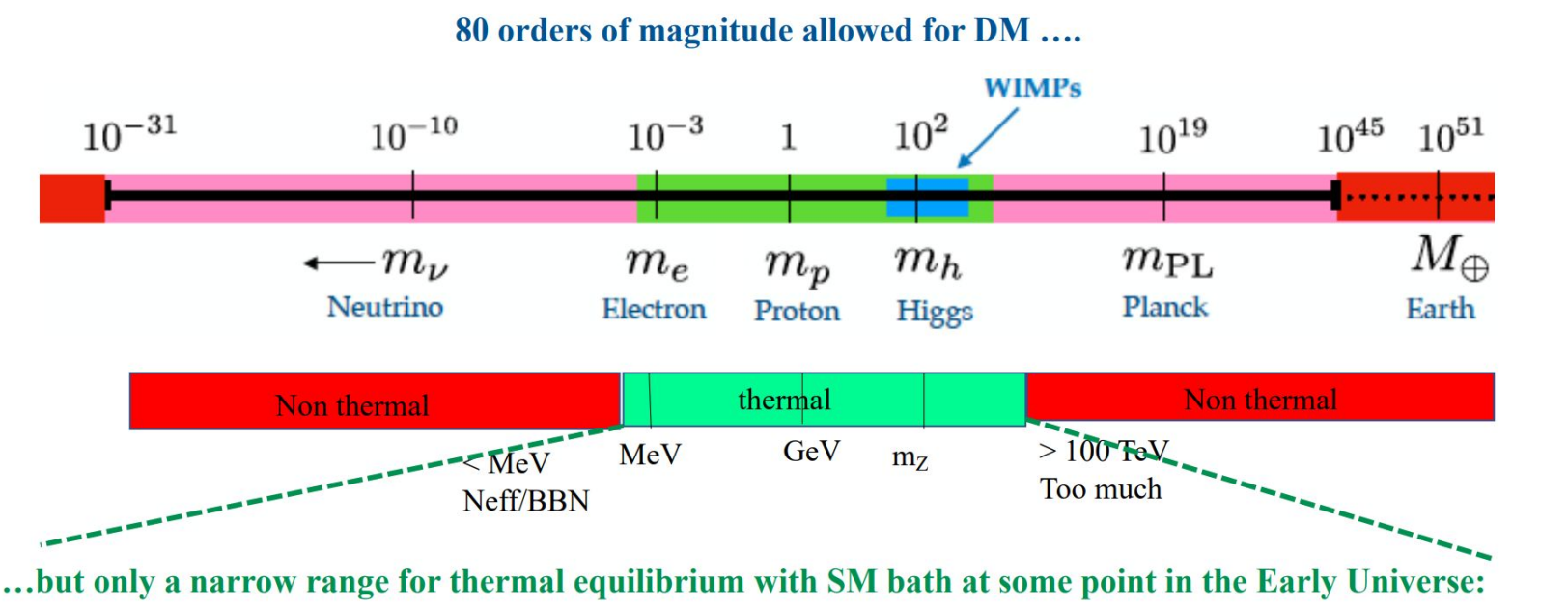
Search for Dark Matter at LHCb experiment

Dark Matter

- The **standard Lambda-CDM model** of cosmology predicts that the universe's mass-energy content is **23% dark matter** and **4% normal matter**.
- The most widely accepted explanation is that dark matter consists of **Weakly Interacting Massive Particles (WIMPs)**:
  - Interact only through the **weak nuclear force** and **gravity**
  - Have a **large mass** compared to standard particles
- It's possible to search for these particles through high-energy proton-proton (p-p) collisions at the **LHCb experiment**.



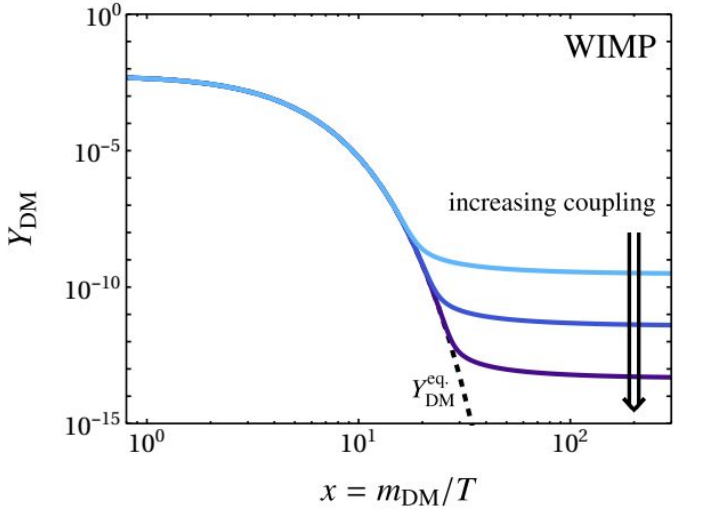
Dark matter masses



Thermal relic abundance

relic abundance from cosmic expansion and particle properties

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle_{\chi\chi\to\mathrm{SM}}\left(n_\chi^2 - n_\chi^{\mathrm{eq}2}\right)$$



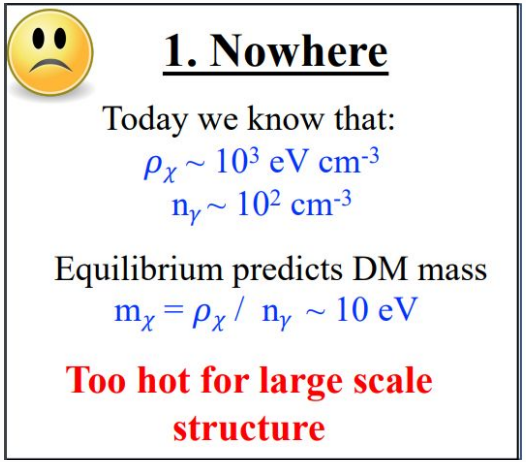
Cosmology observation

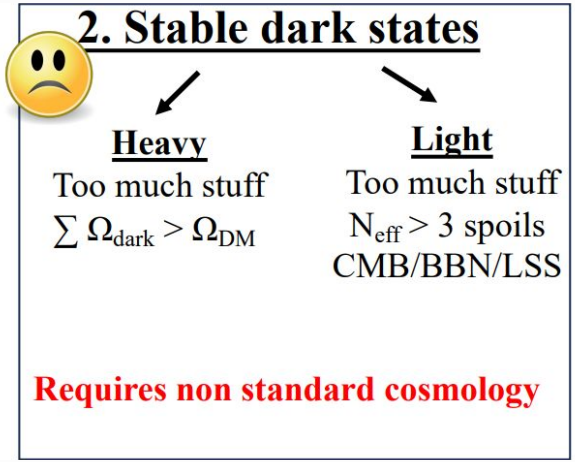
$$\Omega_\chi \propto \frac{1}{\langle\sigma v\rangle_{\mathrm{fo}}}, \qquad \Omega_{\mathrm{DM}}h^2 = 0.12$$

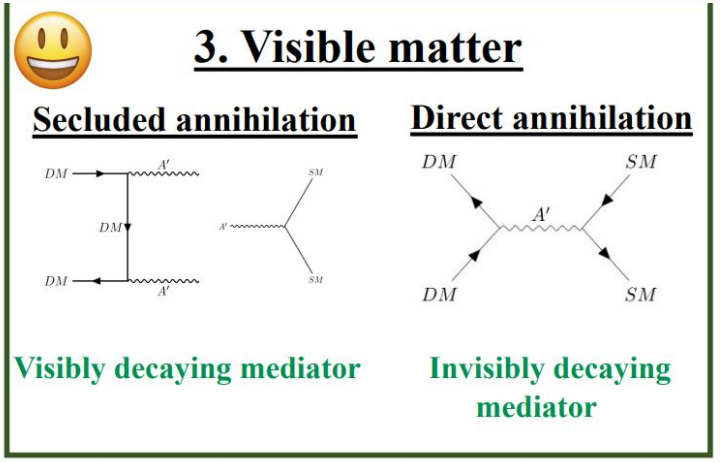
$$\langle\sigma v\rangle_{\mathrm{fo}} \sim 2\times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$$

Thermal relic

If Dark Matter was in equilibrium at some point, where did its density/entropy go?







DM has to interact to SM particles to deplete its initial abundance.

Dark Matter interactions

Mediator: vector or scalar

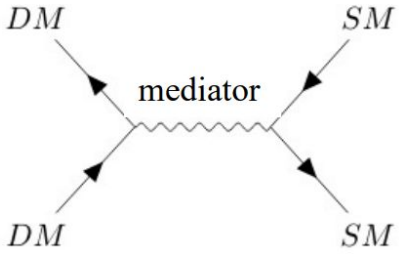
Accelerator-based experiments

Production of DM at accelerators
(via SM (electron/proton/..) particles)

$\langle \sigma v \rangle = f(m_{DM}, m_{med}, g_{DM}, g_{SM})$

DM Direct detection experiments

DM scattering with e/protons



$\sigma = f'(m_{DM}, m_{med}, g_{DM}, g_{SM})$

Astroparticle, cosmology

Direct DM annihilation
(main process to get the thermal relic abundance)

$$\Omega_{DM} h^2 \sim \frac{10^9\ \mathrm{GeV}^{-1}}{M_{pl}} \frac{1}{\langle \sigma v \rangle}$$

Dark Matter interactions

- **Extending the Standard Model (SM)** with the minimal set of **lowest-dimension, gauge-invariant, and renormalizable operators**:
  - This approach **preserves the theoretical structure** of the SM
  - **Any new physics** introduced is a simple extension of our current understanding
  - By adding minimal operators, we can explore physics **beyond the Standard Model** while maintaining consistency with its foundational principles.

Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2)H^\dagger H$
Axion, a	$\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a}G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Sterile Neutrino, N	$y_N LHN$

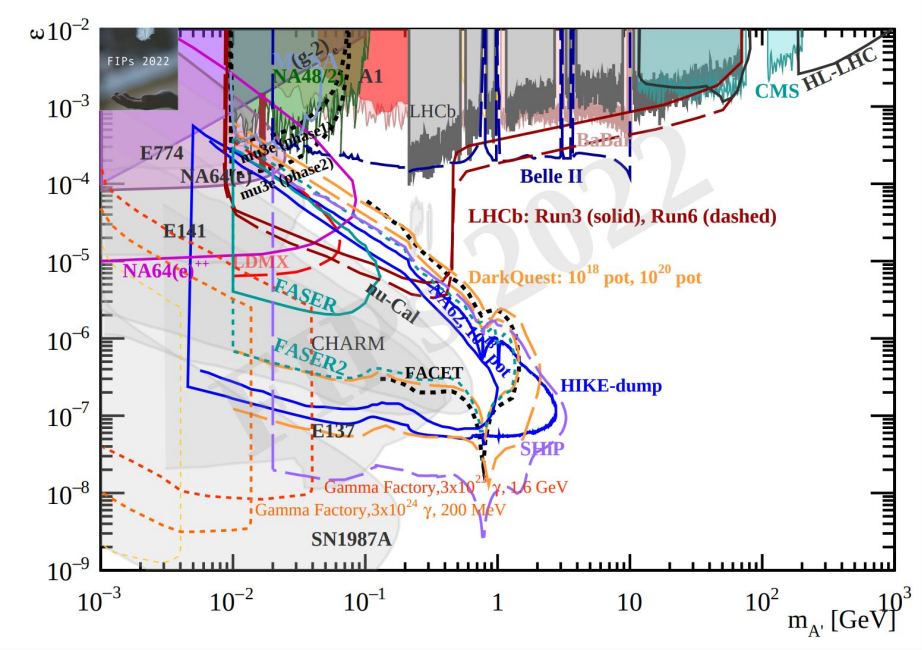
Best portals for thermal light dark matter

In micro-eV range

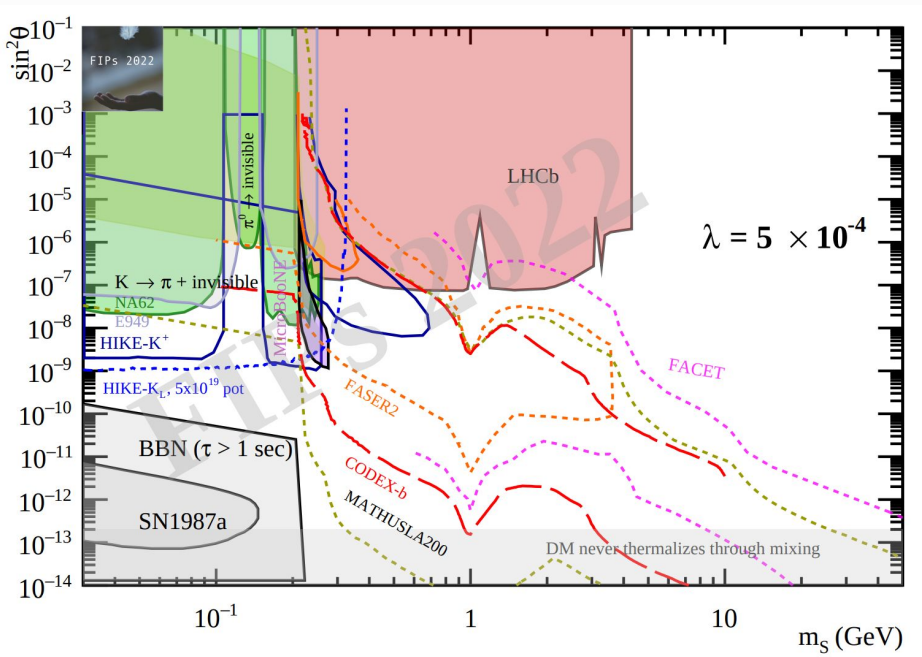
Coupling too small to produce thermal DM

Dark Matter searching

How dead is the WIMP? 90% CL exclusion limits



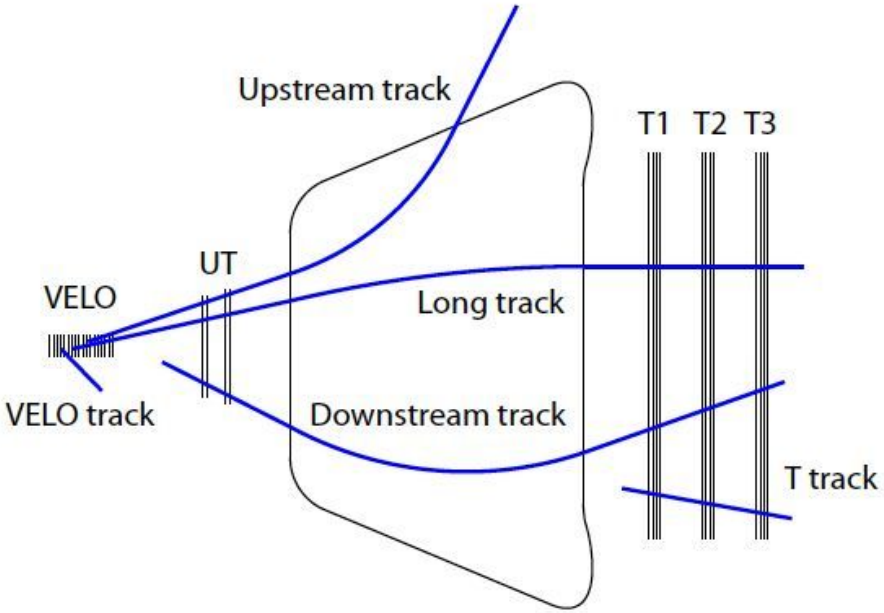
Dark photon into visible final states



Sensitivity to light dark scalar (BC5)

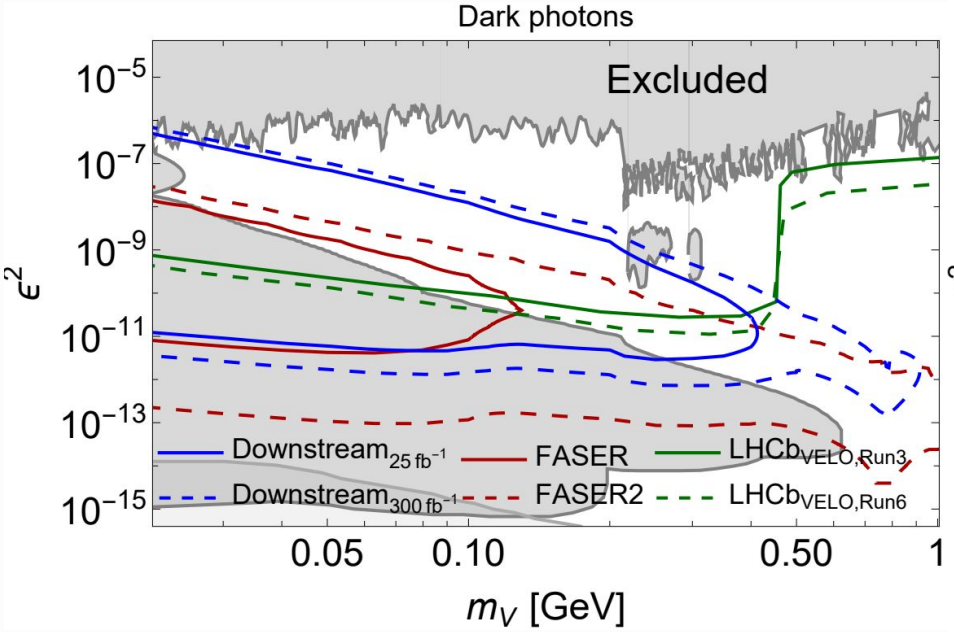
Dark Matter searching

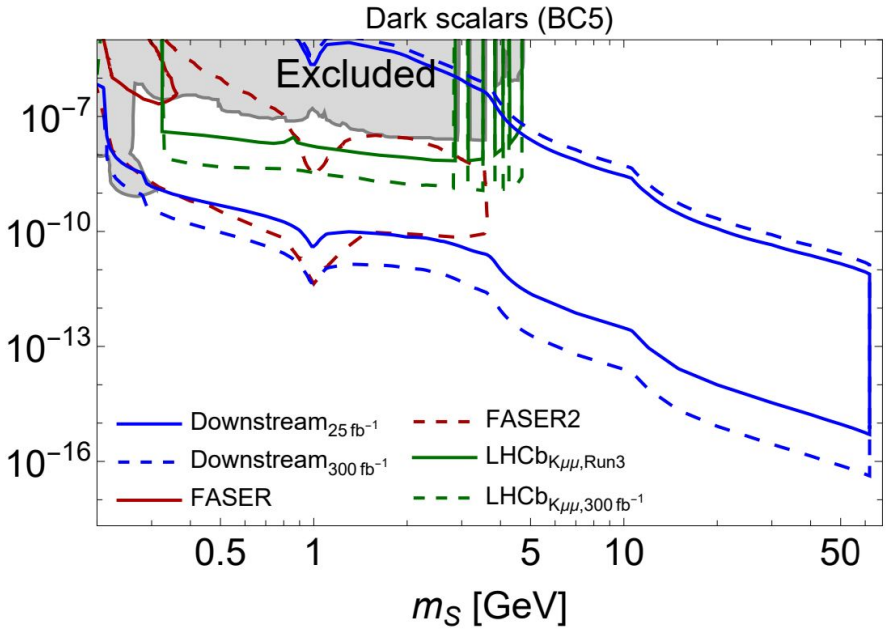
LHCb improvement in Dark Matter searching



- **Reconstructing tracks** using only the **UT** and **SciFi detectors** significantly increases the effective decay volume at the LHCb experiment.
- These tracks are known as **Downstream tracks**.
- The related **reconstruction and trigger algorithms** were recently implemented and deployed for **Run 3 data-taking (2022-2025)**.
- The **LHCb-IFIC group** at the **University of Valencia** is the main author of these algorithms.

Dark Matter searching





Summary

Summary

- The **LHCb experiment** studies **CP violation** to understand the **matter-antimatter asymmetry** in the universe.
- **LHCb detectors** include VELO, UT, and SciFi trackers, RICH for particle identification, calorimeters, and the muon system.
- **Precision measurements** at LHCb are sensitive to new physics, including potential new sources of CP violation.
- The experiment is searching for **dark matter candidates**, like WIMPs, through high-energy proton collisions.
- The **LHCb-IFIC** group has developed new algorithms for reconstructing downstream tracks, enhancing the search for **dark matter** in Run 3.

Thank you for your attention