Video of the lecturer

Part 3: Principles of Particle Detectors

Olaf Steinkamp, Андрей голутвин, Giovanni de Lellis

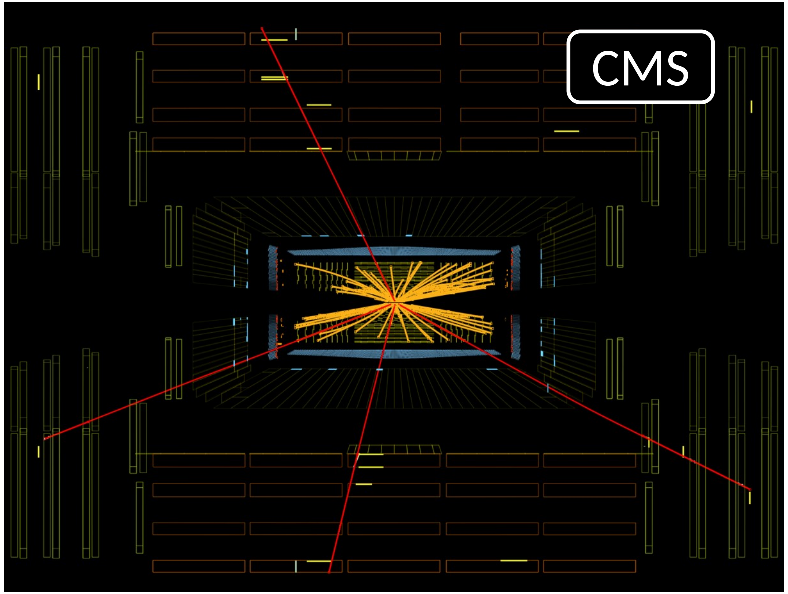
Part 3: Principles of Particle Detectors

Video of the lecturer

In Part 2 you learnt how photons and charged particles interact in material

In this part, you'll learn how we use the interaction of particles with the material of a detector to

- detect particles and reconstruct their basic properties (momentum, energy, type)
- combine the information from individual particles to reconstruct an "event"



[https://cds.cern.ch/record/1406073]

Part 3: Principles of Particle Detectors

Video of the lecturer

Lecture 1: particle physics experiments (OS)

- layout and main components

Lecture 2: particle identification (АГ)

- distinguish different types of particles

Lecture 3: tracking detectors (OS)

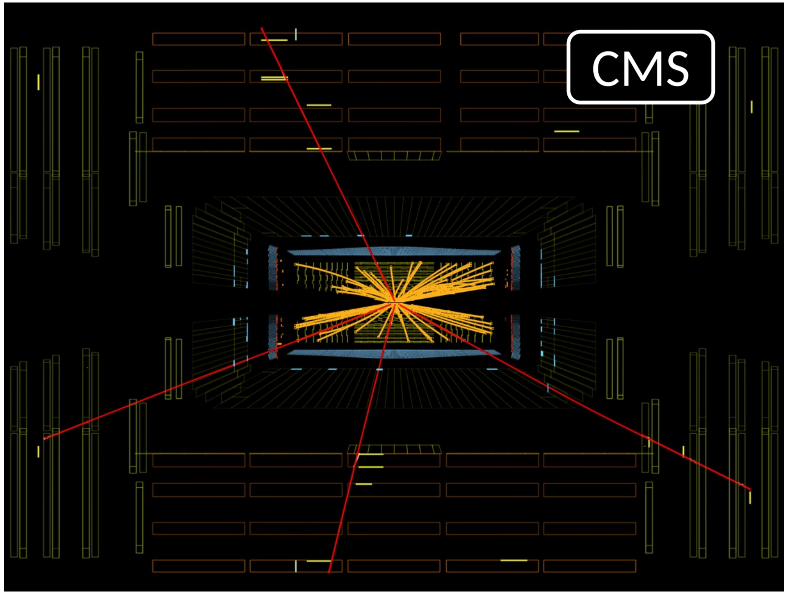
- measure flight direction and momentum

Lecture 4: calorimeters (GdL)

- measure the energy of particles

Lecture 5: emulsion detectors (GdL)

- tracking for special applications



[https://cds.cern.ch/record/1406073]

Particle physics experiments

Video of the lecturer

Produce a beam of particles

- electrons / positrons
- protons / antiprotons
- heavy ions (e.g. lead)

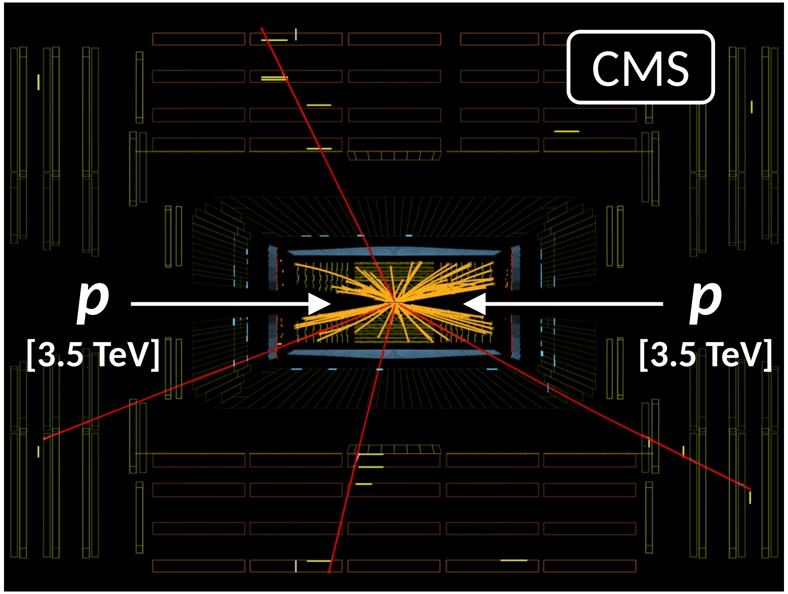
} charged, stable

Accelerate to high energy and collide with

- another beam of particles (“collider”)
- a target at rest (“fixed target”)

Observe the particles that are produced in the collisions and measure their properties

→ **DETECTOR**



[https://cds.cern.ch/record/1406073]

Particle physics experiments

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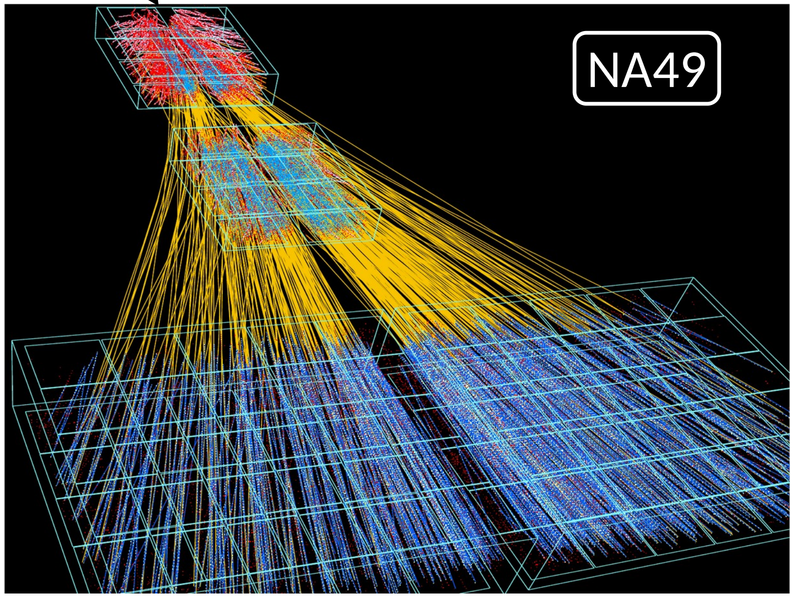
→ **DETECTOR**

Pb
[158 GeV/nucleon]



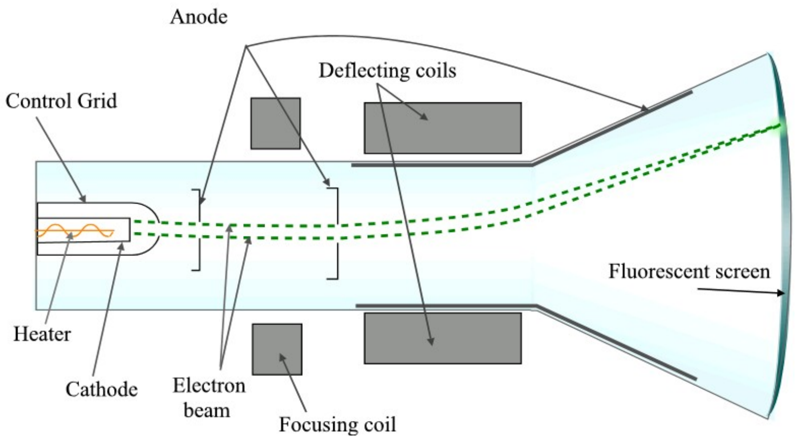
[http://na49info.web.cern.ch/Public/Press/LogBook.html]

Particle Accelerators

Video of the lecturer

Use **electric fields** to accelerate particles,

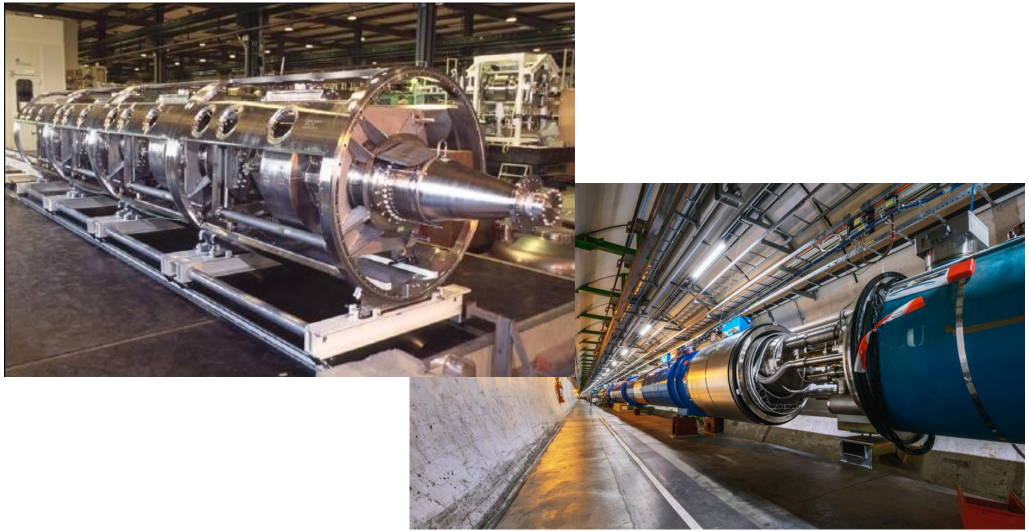
use **magnetic fields** to steer them



Cathode ray tube

→ colour TV: 25 - 35 keV

→ materials research: > 100 keV

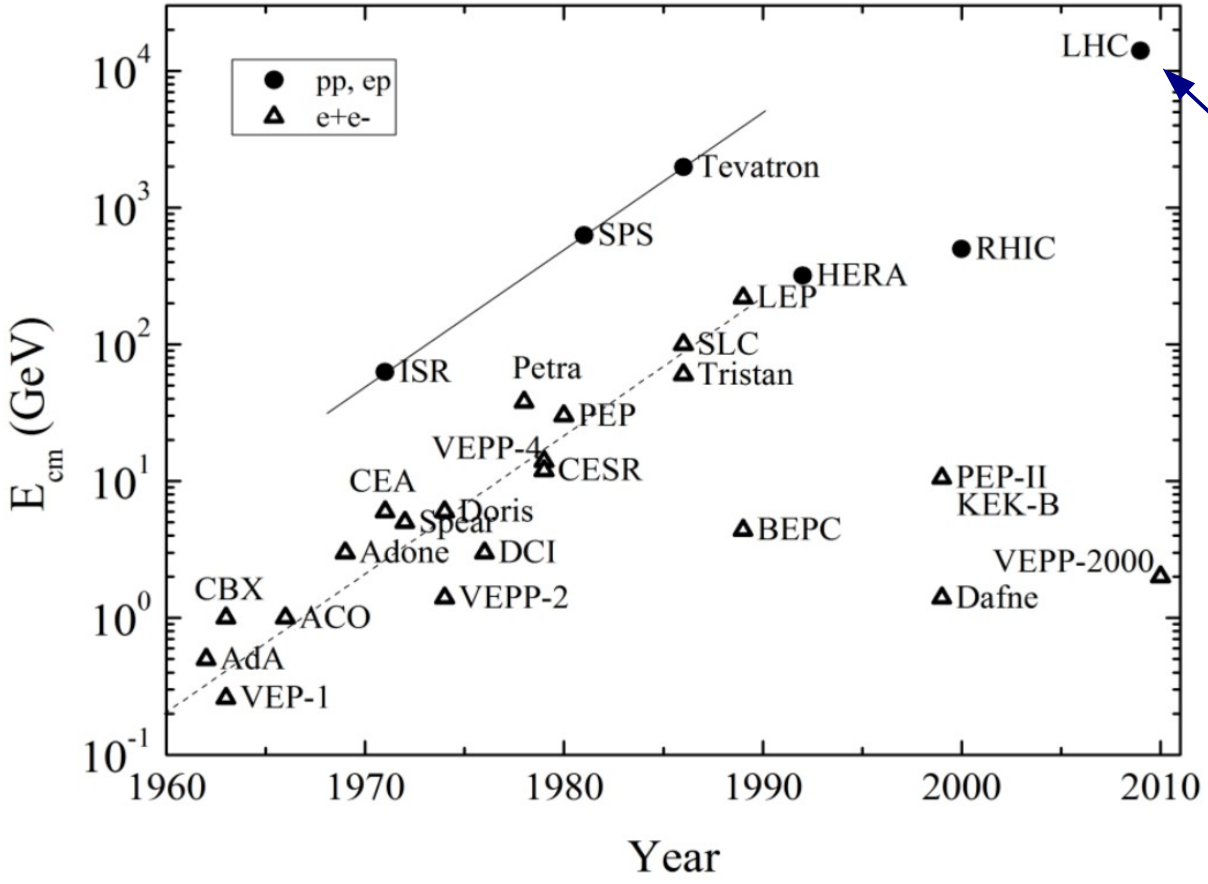


LHC

6.5 TeV = 6’500’000’000 keV

Particle Accelerators

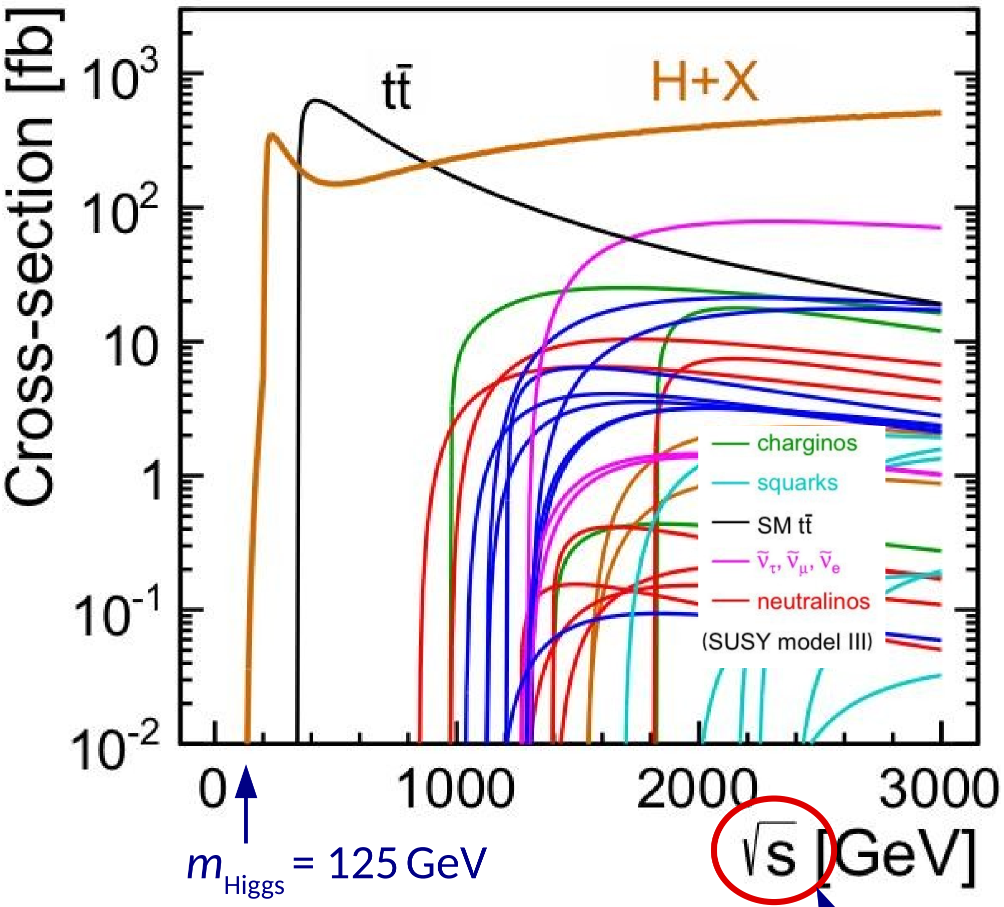
Video of the lecturer



2×6.5 TeV
$= 13$ TeV

Particle Accelerators

Video of the lecturer



m_{Higgs} = 125 GeV

Collide particles at the highest possible energy:

- to probe high masses

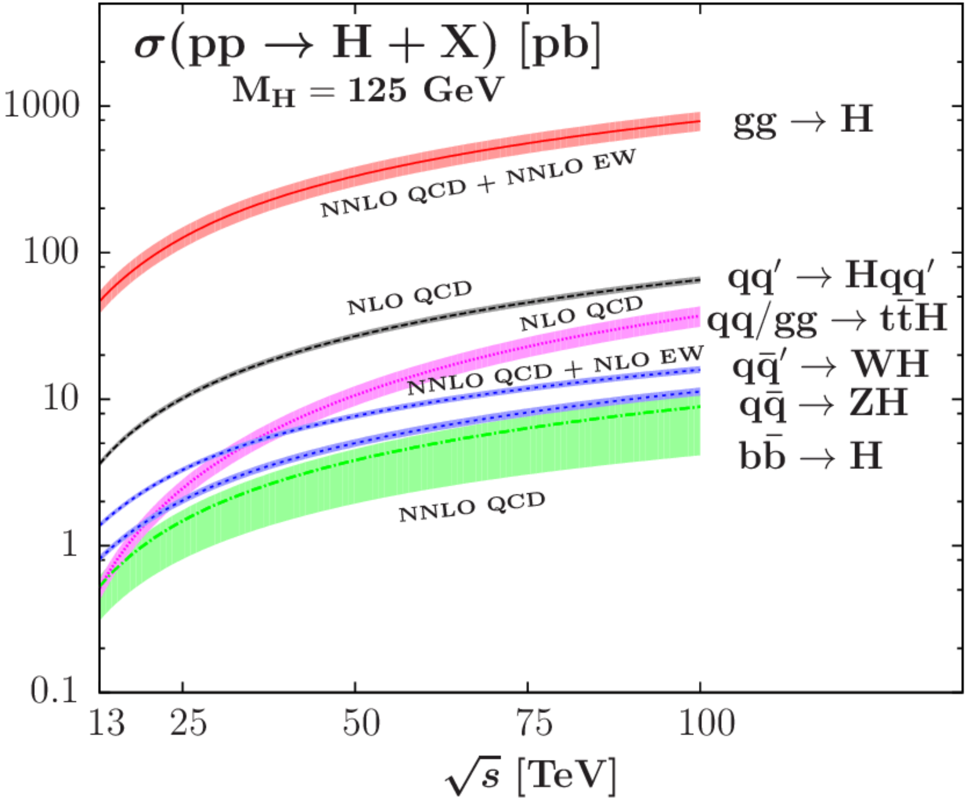
$$E = mc^2$$

Mandelstam variable

$s \equiv (p_1 + p_2)^2 = E^2$

Particle Accelerators

Video of the lecturer



Collide particles at the highest possible energy:

- to probe high masses

$$E = mc^2$$

Particle Accelerators

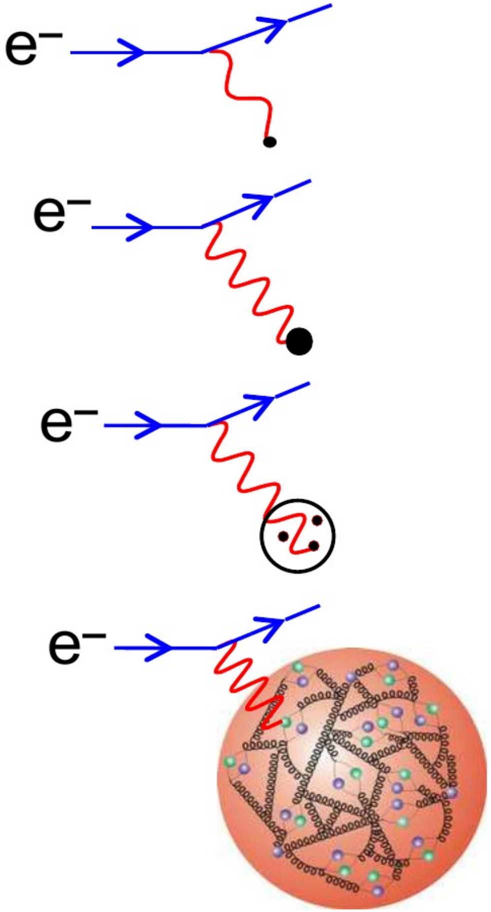
Video of the lecturer

$$\frac{\hbar}{p} \gg r_p$$

$$\frac{\hbar}{p} \approx r_p$$

$$\frac{\hbar}{p} < r_p$$

$$\frac{\hbar}{p} \ll r_p$$



Collide particles at the highest possible energy:

- to probe high masses

$$E = mc^2$$

- to probe small distances

$$\lambda = 2\pi \frac{\hbar}{p}$$

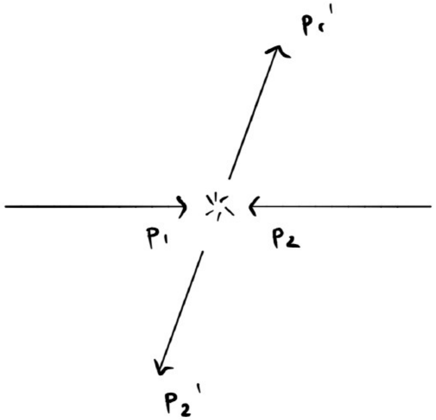
Particle Accelerators

Video of the lecturer

Energy in the center-of-mass system (c.m.s.)

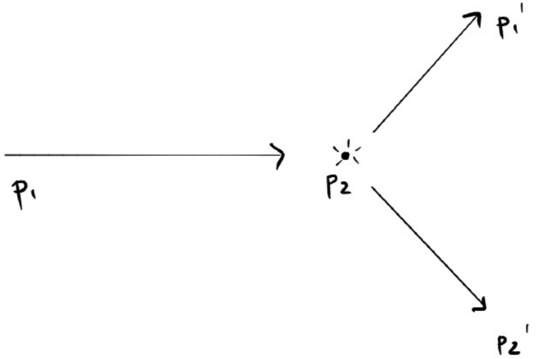
- collider: c.m.s. at rest in lab system$^{(*)}$

$$\rightarrow E_{\text{c.m.s.}} = 2 \times E_{\text{beam}}$$



- fixed target: c.m.s. forward boosted

$$\rightarrow E_{\text{c.m.s.}} \ll E_{\text{beam}}$$



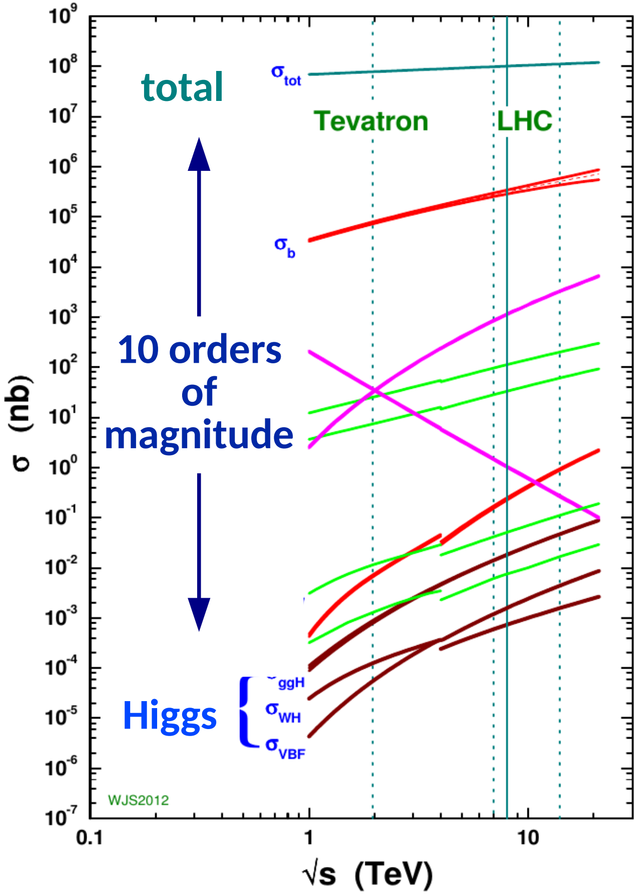
Example LHC @ 6.5 TeV

collider: $E_{\text{c.m.s.}} = 13$ TeV

fixed target: $E_{\text{c.m.s.}} = 114$ GeV

Particle Accelerators

Video of the lecturer



Collide particles at highest possible rate

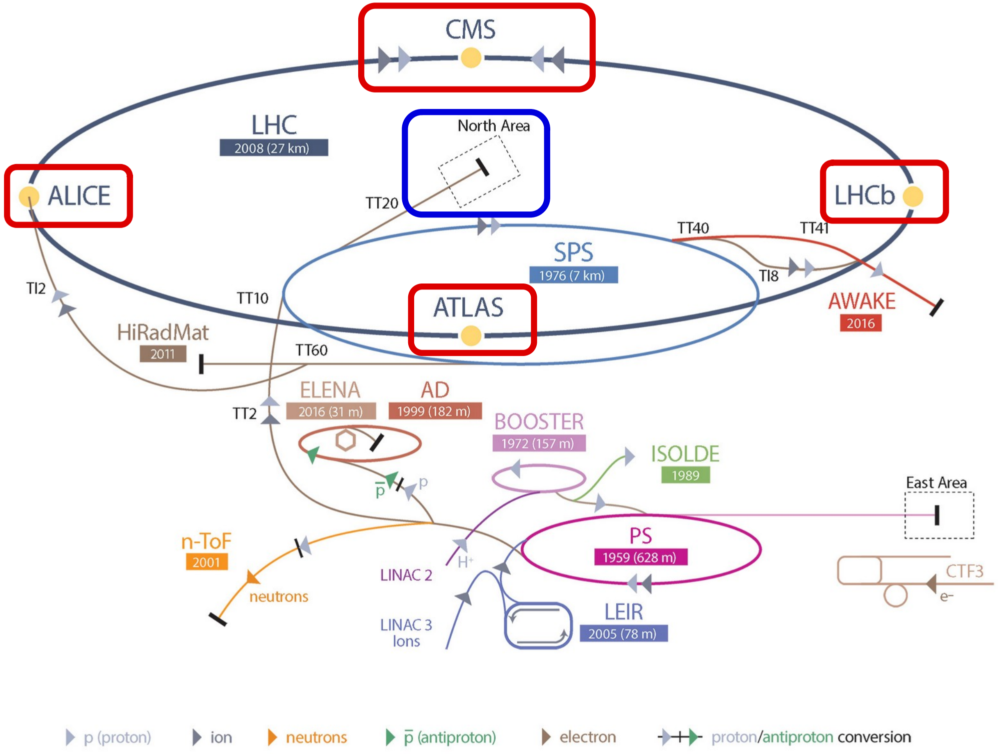
- to probe very rare processes

LHC: 10^9 *pp* collisions / **second**
to produce 3×10^6 Higgs bosons / **year**

- fixed target: higher density → higher rate

CERN

Video of the lecturer



Colliding beam (LHC):

6.5 TeV p ↔ 6.5 TeV p

Fixed target (e.g. North Area):

450 GeV p beam

(e.g. SHiP experiment)

[https://stfc.ukri.org/research/particle-physics-and-particle-astrophysics/large-hadron-collider/cern-accelerator-complex]

Quiz I

Video of the lecturer

At the LHC, what are electric fields used for?

(a) to accelerate the protons
(b) to focus the proton beams
(c) to keep protons on a circular trajectory

What are magnetic fields used for?

(a) to accelerate the protons
(b) to focus the proton beams
(c) to keep protons on a circular trajectory

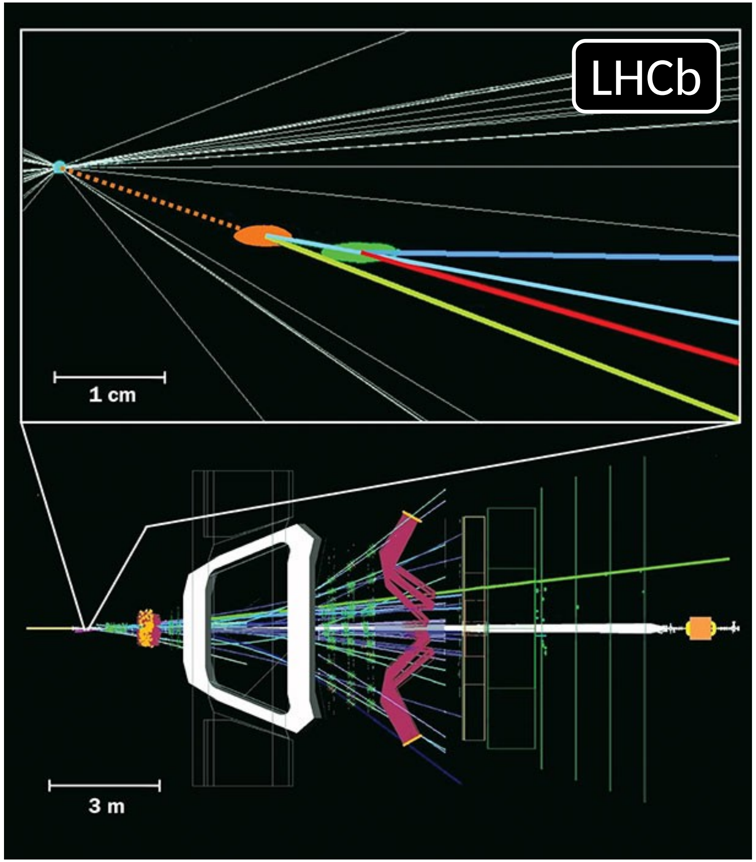
Why do we want to accelerate particles to the highest possible energies?

(a) to produce massive particles
(b) to resolve small distances
(c) to study rare processes

note: questions can have more one correct answer --- or none ;-)

Kinematic reconstruction

Video of the lecturer



Most of the "interesting" particles are very short lived

- e.g. B^0 meson: 1.6×10^{-12} sec

What we see in our detector are the stable or long-lived decay products

- electrons/positrons ($e^{\pm}$)
- protons/antiprotons ($p/\bar{p}$)
- muons ($\mu^{\pm}$), pions ($\pi^{\pm}$), kaons ($K^{\pm}$)

[https://cerncourier.com/a/beauty-quarks-test-lepton-universality]

Kinematic reconstruction

Video of the lecturer

Deduce the production of short-lived particles by kinematic reconstruction from the measured momenta and energies of their decay products

$$E^2 = m^2 + p^2$$

(using "natural units" with $c \equiv 1$)

Energy and momentum conservation in the decay

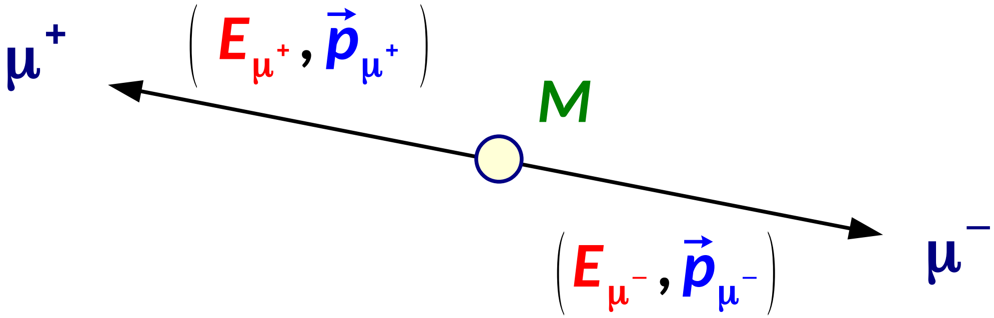
Mass of decaying particle

$$M^2 = \left(\sum E_i \right)^2 - \left| \sum \vec{p}_i \right|^2$$

Energies and momenta of the decay products

Example: particle decays to $\mu^+ \mu^-$

Video of the lecturer



Measure the momenta of the μ^- and the μ^+

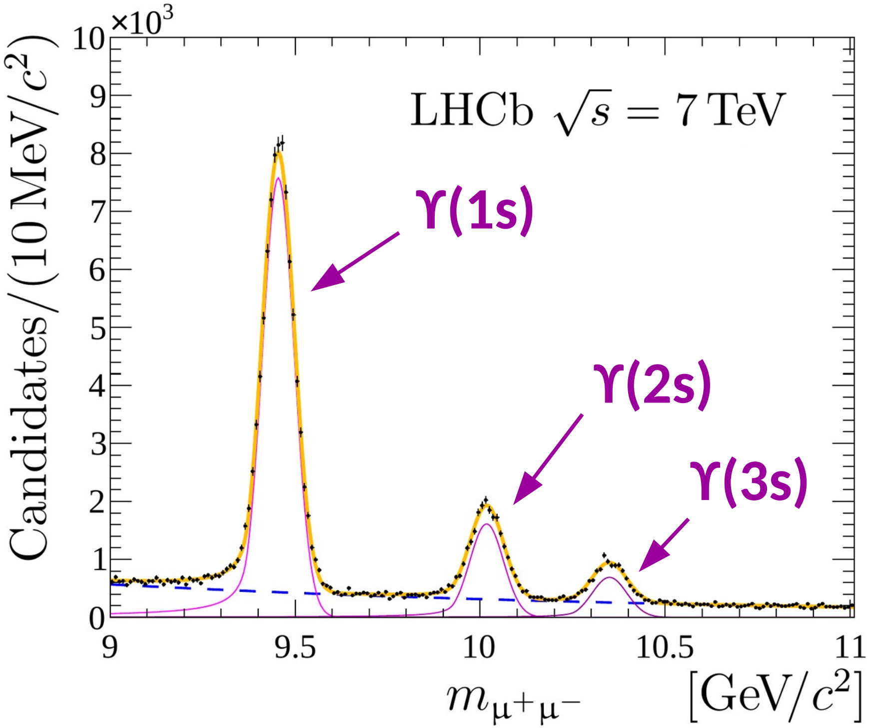
- **calculate their energies ($E^2_{\mu^\pm} = m^2_\mu + p^2_{\mu^\pm}$)**
- **calculate the mass of the decaying particle:**

$$M^2 = \left(E_{\mu^+} + E_{\mu^-}\right)^2 - \left|\vec{p}_{\mu^+} + \vec{p}_{\mu^-}\right|^2$$

Example: particle decays to μ⁺ μ⁻

Video of the lecturer

flat distribution: "background" from random combinations of μ^+ and μ^-



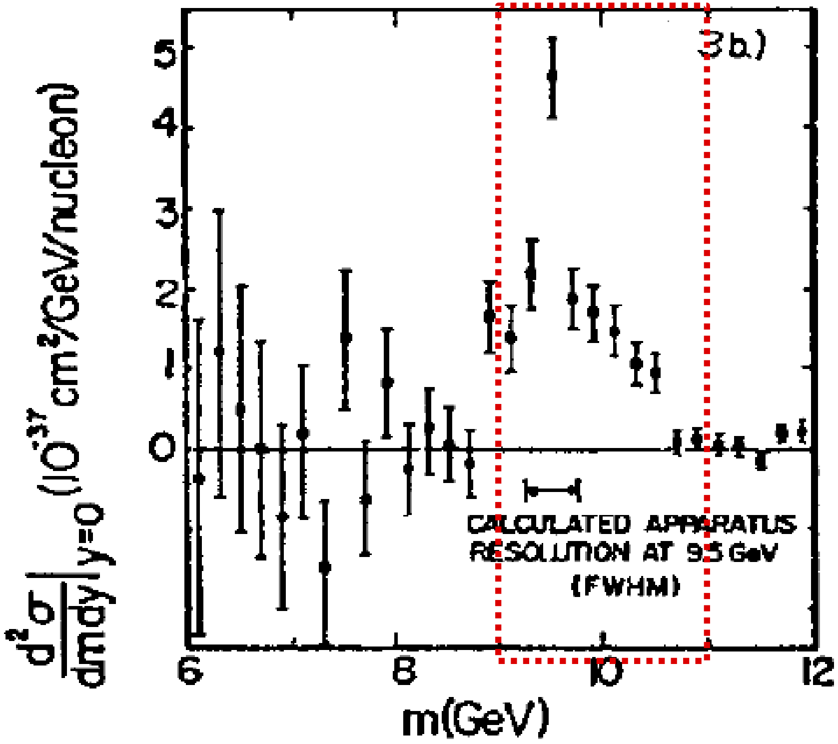
narrow peaks: "signal" from short-lived particles decaying into $\mu^+\mu^-$

[J.High Energy Phys.(2015) 103]

$$m_{\mu^+\mu^-} = \sqrt{\left(E_{\mu^+} + E_{\mu^-}\right)^2 - \left|\vec{p}_{\mu^+} + \vec{p}_{\mu^-}\right|^2}$$

Υ “resonances”

Video of the lecturer



Discovered in 1977

- interpreted as bound states of a b quark and a $\overline{b}$ quark

Important discovery

- first direct evidence for a 3rd family of elementary particles

[https://en.wikipedia.org/wiki/Upsilon_meson]

“Yesterday’s sensation ...”

Video of the lecturer

**Yesterday's sensation
is today's calibration channel**

(Richard P. Feynman)

[https://en.wikipedia.org/wiki/Richard_Feynman]

"… today's calibration channel"

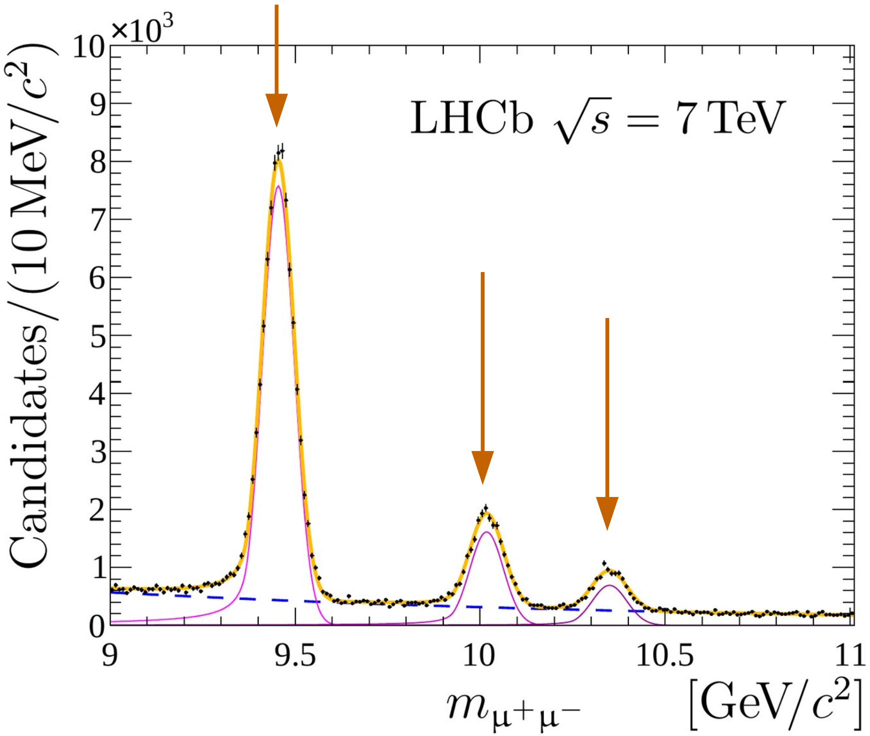
Video of the lecturer

Calibrate momentum measurement: compare the position of the peak with the known masses of the ϒ resonances

$$m_{\mu^+\mu^-} = \sqrt{\left(E_{\mu^+} + E_{\mu^-}\right)^2 - \left|\vec{p}_{\mu^+} + \vec{p}_{\mu^-}\right|^2}$$

with

$$E_{\mu^\pm} = \sqrt{m_\mu^2 + p_{\mu^\pm}^2}$$



[J.High Energy Phys.(2015) 103]

"… today's calibration channel"

Video of the lecturer

Determine momentum resolution from the width of the peak

$$m_{\mu^+\mu^-} = \sqrt{\left(E_{\mu^+} + E_{\mu^-}\right)^2 - \left|\vec{p}_{\mu^+} + \vec{p}_{\mu^-}\right|^2}$$

with

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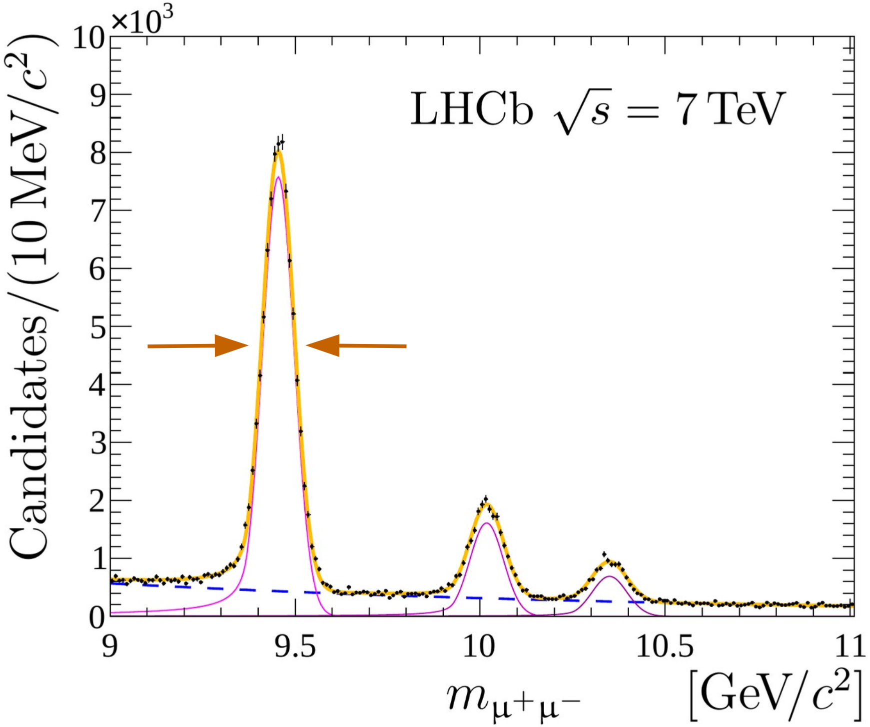

[J.High Energy Phys.(2015) 103]

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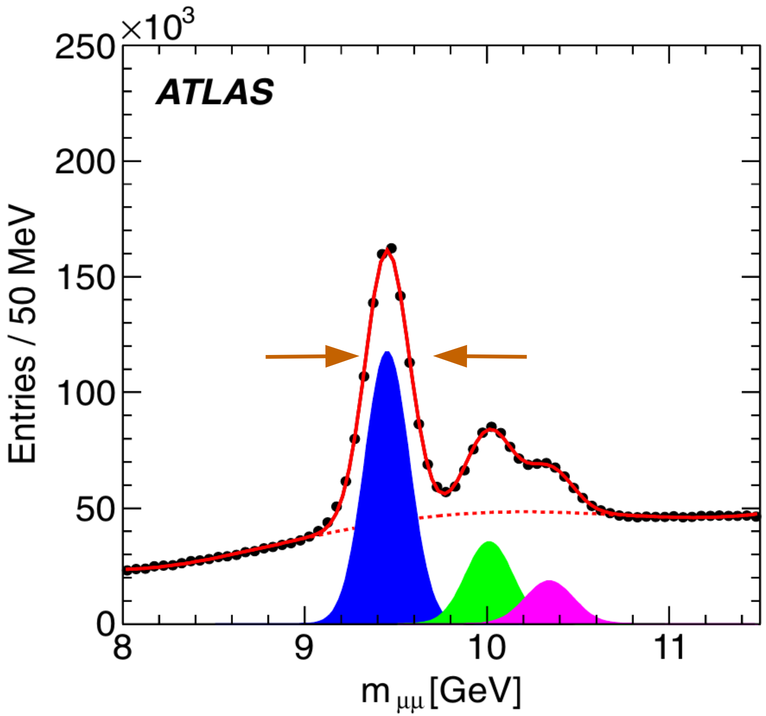
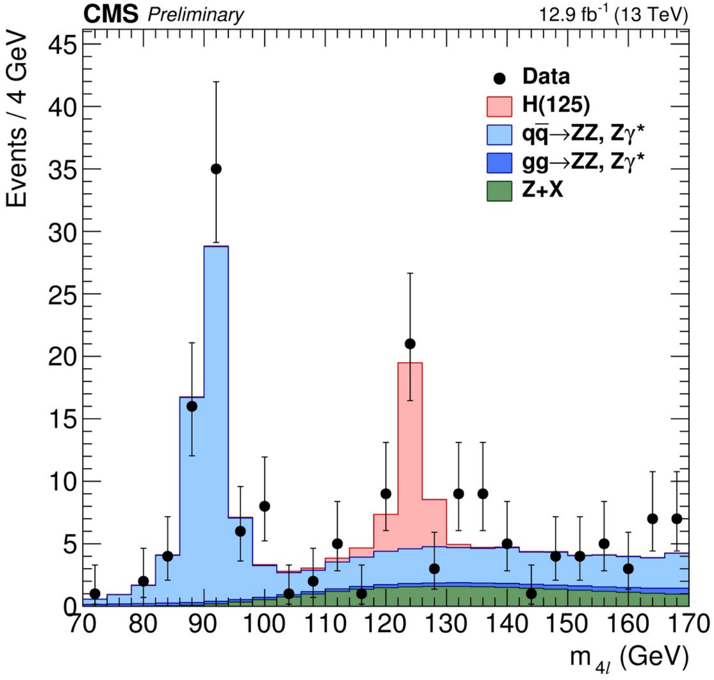


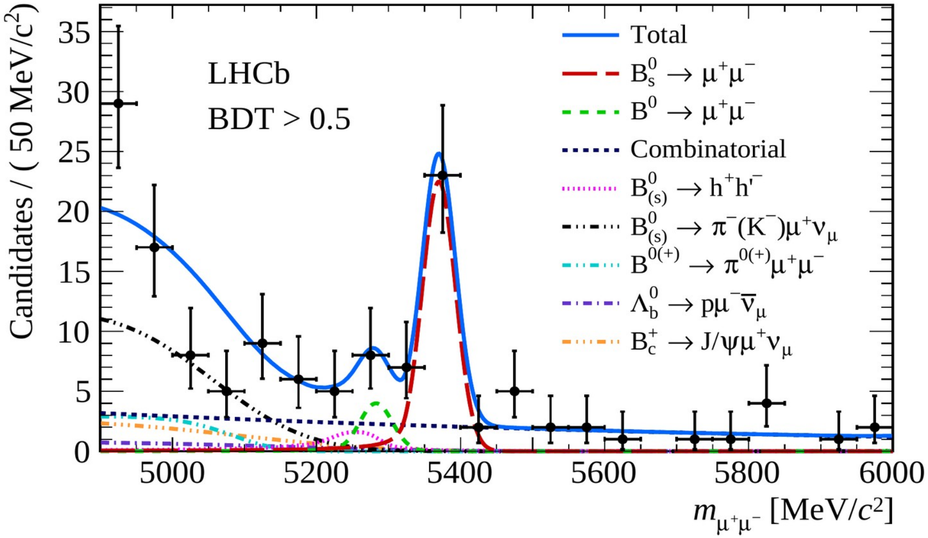
[Phys.Rev.D 87 (2013) 052004]

Today's "sensations"

Video of the lecturer



Higgs → 4 leptons in CMS



$B_s^0 \to \mu^+\mu^-$ in LHCb

Quiz II

Video of the lecturer

To reconstruct the mass of a short-lived particles, which properties of its decay products to we have to determine?

(a) their energy
(b) the magnitude of their momentum
(c) their flight direction
(d) their mass

(a) and (b)
(a) and (d)
(b) and (d)

(a) and (b) and (c)
(a) and (c) and (d)
(b) and (c) and (d)

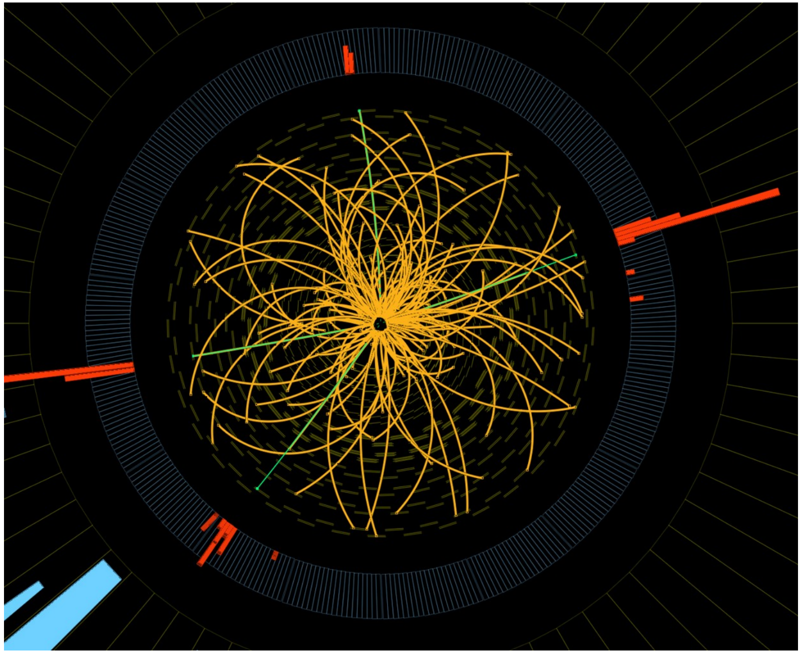
note: questions can have more one correct answer --- or none ;-)

Long-lived particles

Video of the lecturer

To reconstruct short-lived particles, detect the long-lived decay products and measure or determine their

- **momentum** (direction and magnitude)
  - tracking detectors in magnetic field
- **energy**
  - calorimeters
- **particle type** ($e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, $p/\overline{p}$)
  - combination of different detectors



[https://cds.cern.ch/record/1406073]

Momentum (magnitude)

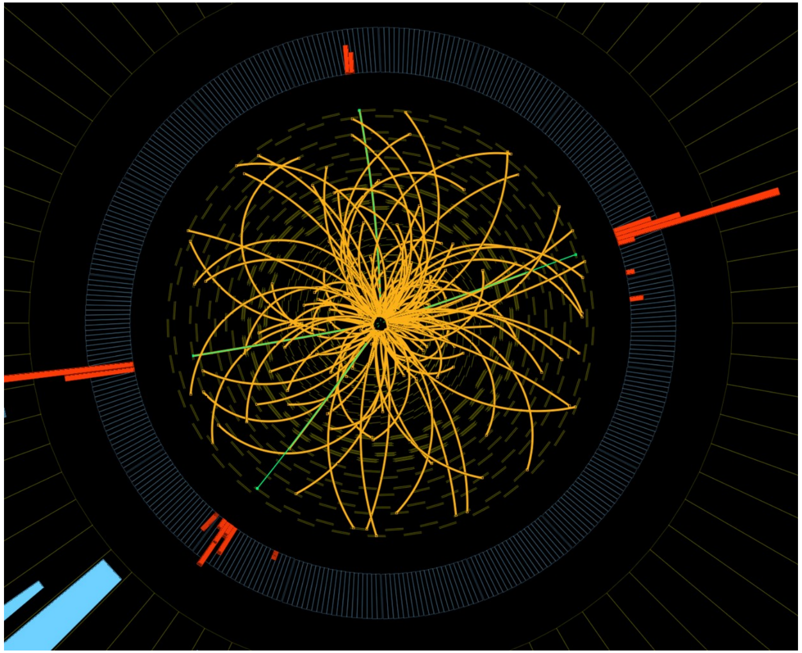
Video of the lecturer

For charged particles only: bending of the trajectory in a magnetic field

$$\left.\begin{aligned} \vec{F}_L &= q \cdot \vec{v} \times \vec{B} \\ \frac{m \cdot v^2}{r} &= q \cdot v \cdot B \end{aligned}\right\} \quad p = q \cdot B \cdot r$$

Layers of position-sensitive detectors to follow the trajectory of the particle

Charge sign of the particle from the direction of curvature



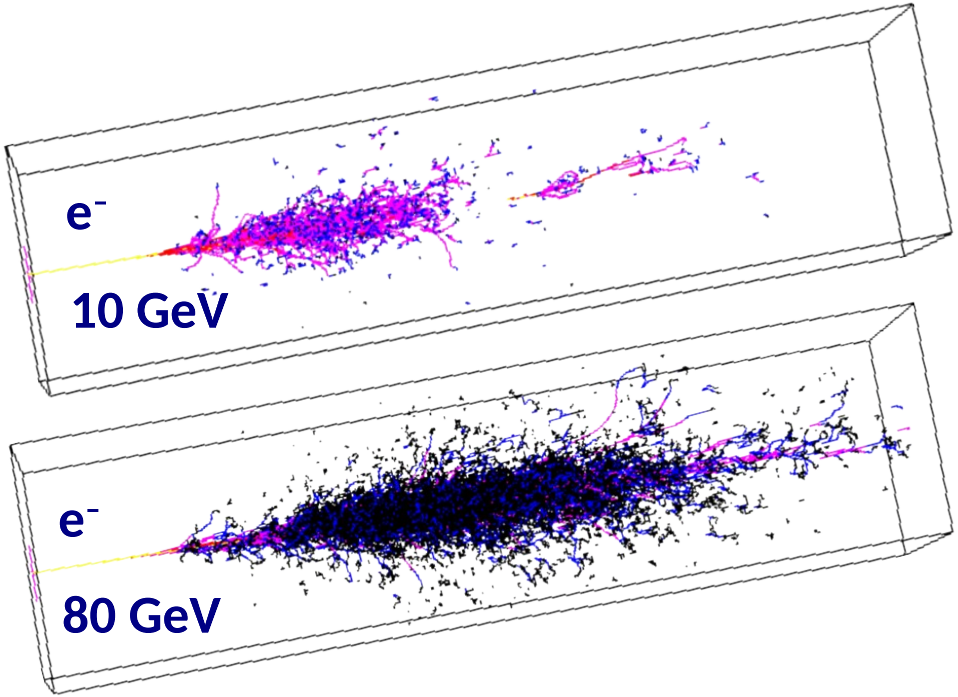
[https://cds.cern.ch/record/1406073]

Energy

Video of the lecturer

Calorimeter (for charged and neutral particles)

- dense detector material: incoming particle initiates shower of secondary particles
- $e^{\pm}$, γ : shower created by electromagnetic interaction (Bremstrahlung, pair production) → electromagnetic calorimeter
- hadrons ($\pi^{\pm}$, $K^{\pm}$, $p/\overline{p}$): shower created by hadronic interactions → hadron calorimeter



[https://www.mpp.mpg.de/~menke/elss/]

Colliding beam experiment

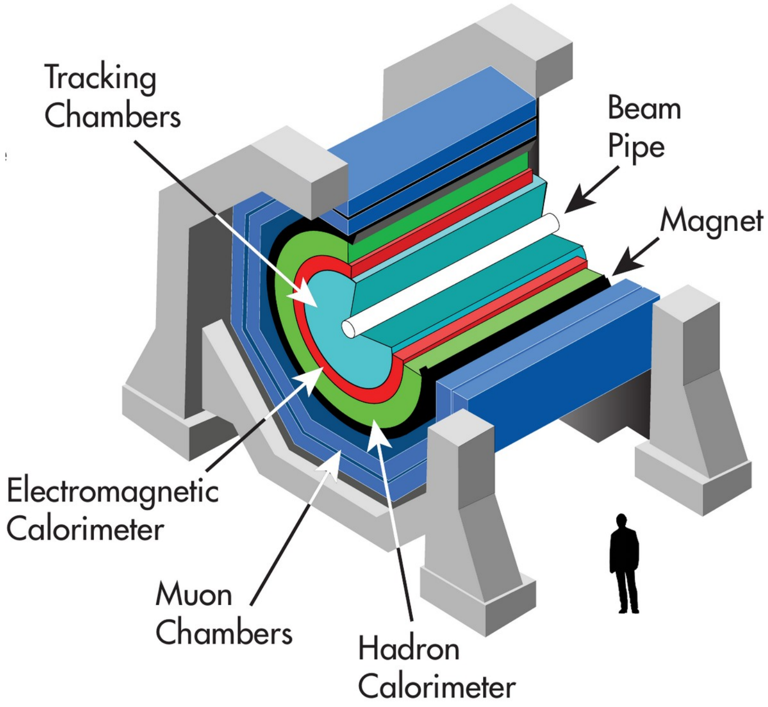
Video of the lecturer

Collide two beams of particles head-on with each other

- particles are produced in all directions
- detector needs to cover full solid angle ("4 π") to detect all produced particles
- usually implemented as barrel + endcaps

Barrel part most important:

- concentric layers of cylindrical detectors ("onion shell")



[https://www.cpepphysics.org/education/]

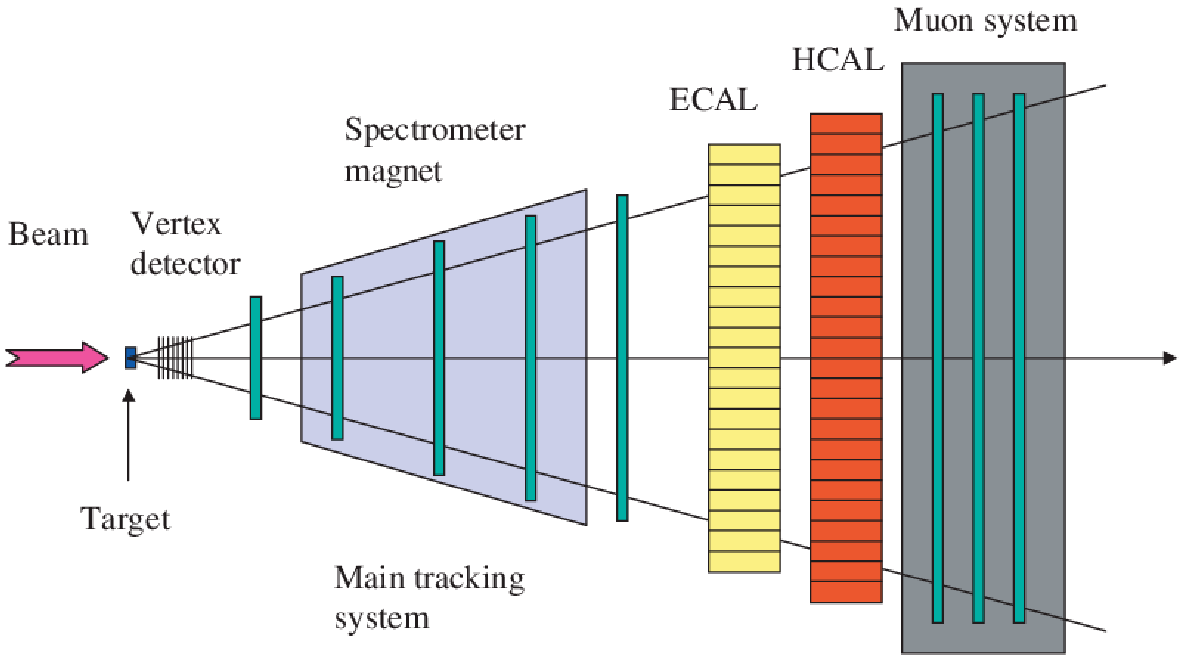
Fixed-target experiment

Video of the lecturer

Shoot a beam of particles into a target at rest

- particles are produced with forward Lorentz boost
- need to equip only a cone in the forward direction to detect all particles

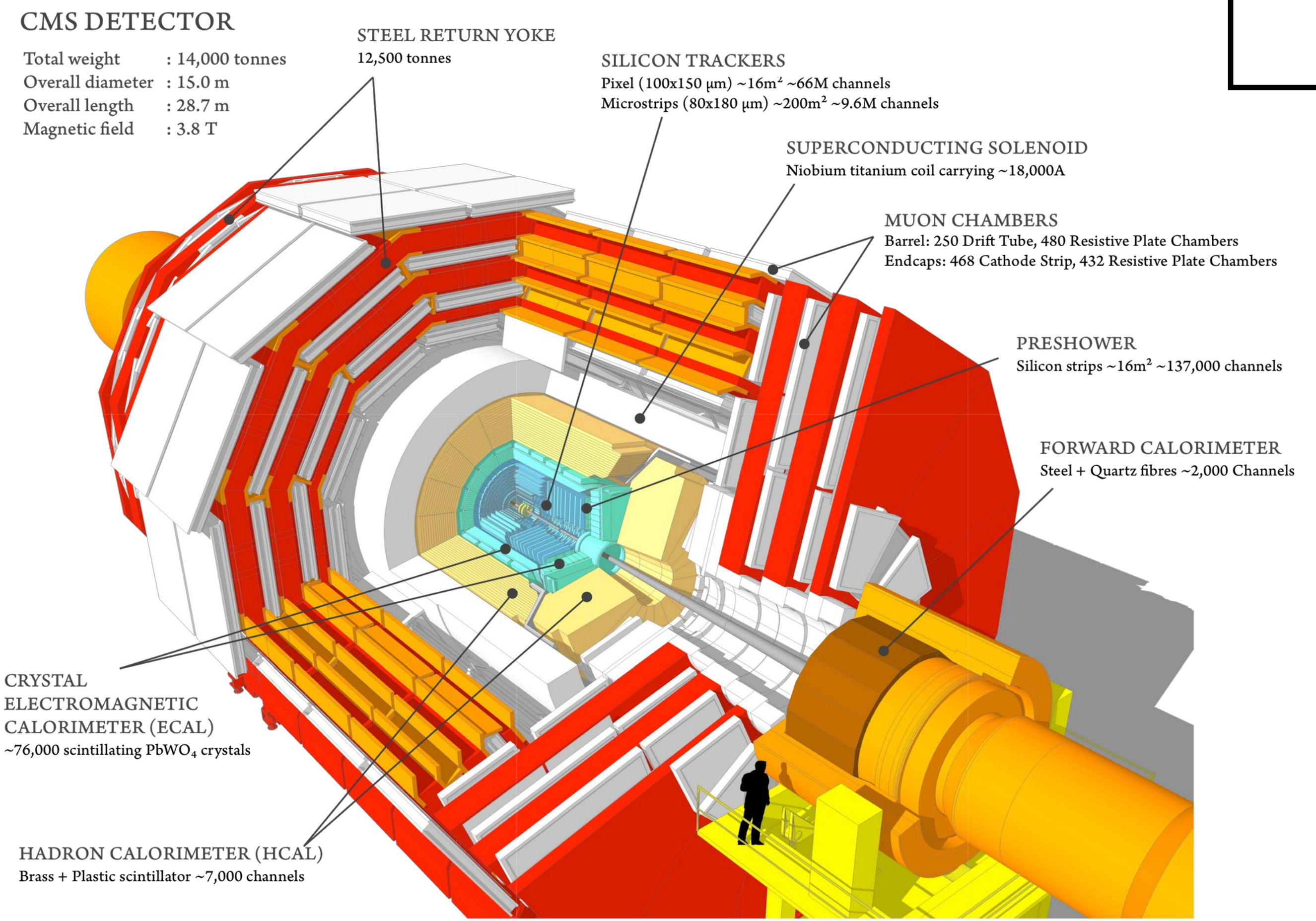
Planar detector layers, orthogonal to beam axis
(“book shelf”)



[arXiv:physics/0402039]

Example: CMS detector at the LHC

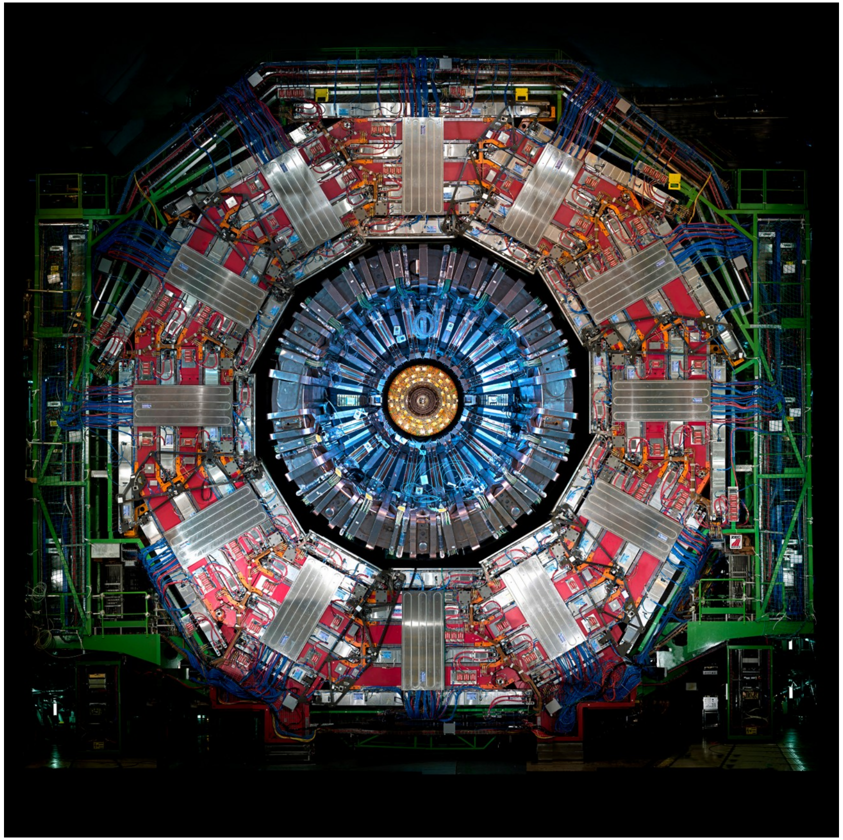
Video of the lecturer



[http://cds.cern.ch/record/1474902]

Example: CMS detector at the LHC

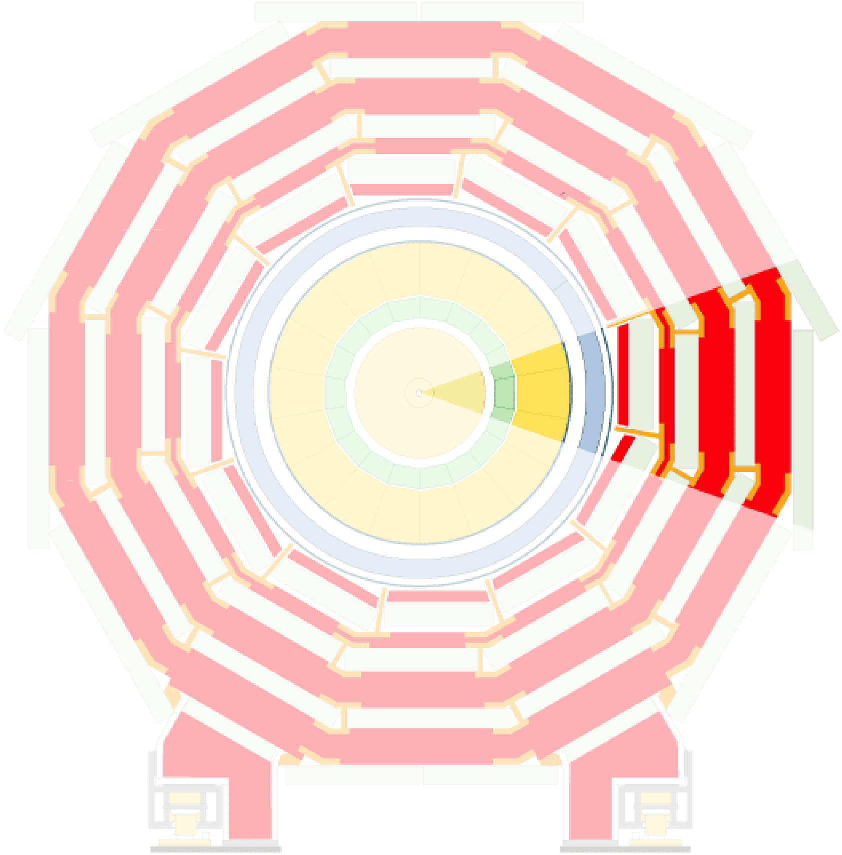
Video of the lecturer



[http://cds.cern.ch/record/2204863]

Example: CMS detector at the LHC

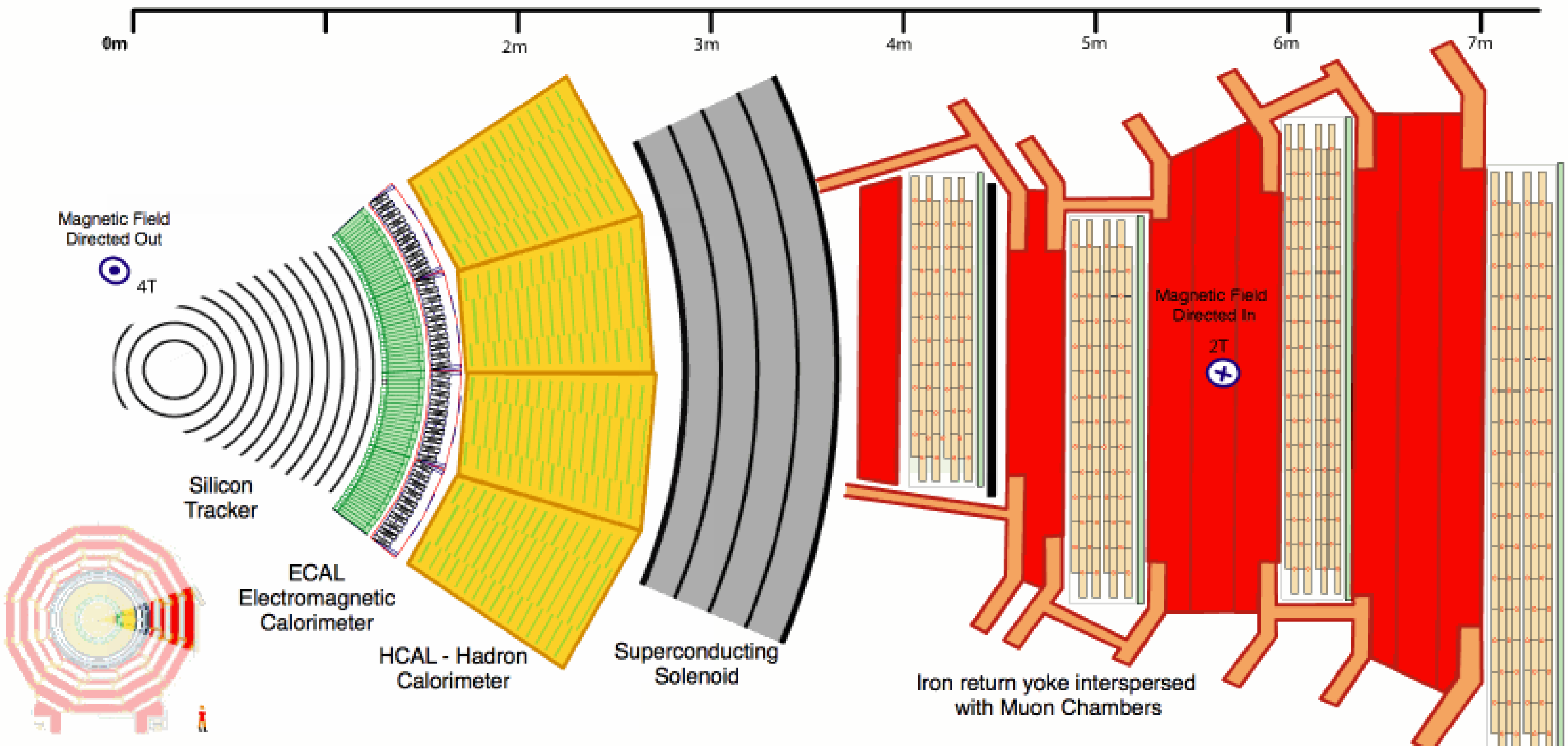
Video of the lecturer



[http://cds.cern.ch/record/2204863]

Example: CMS detector at the LHC

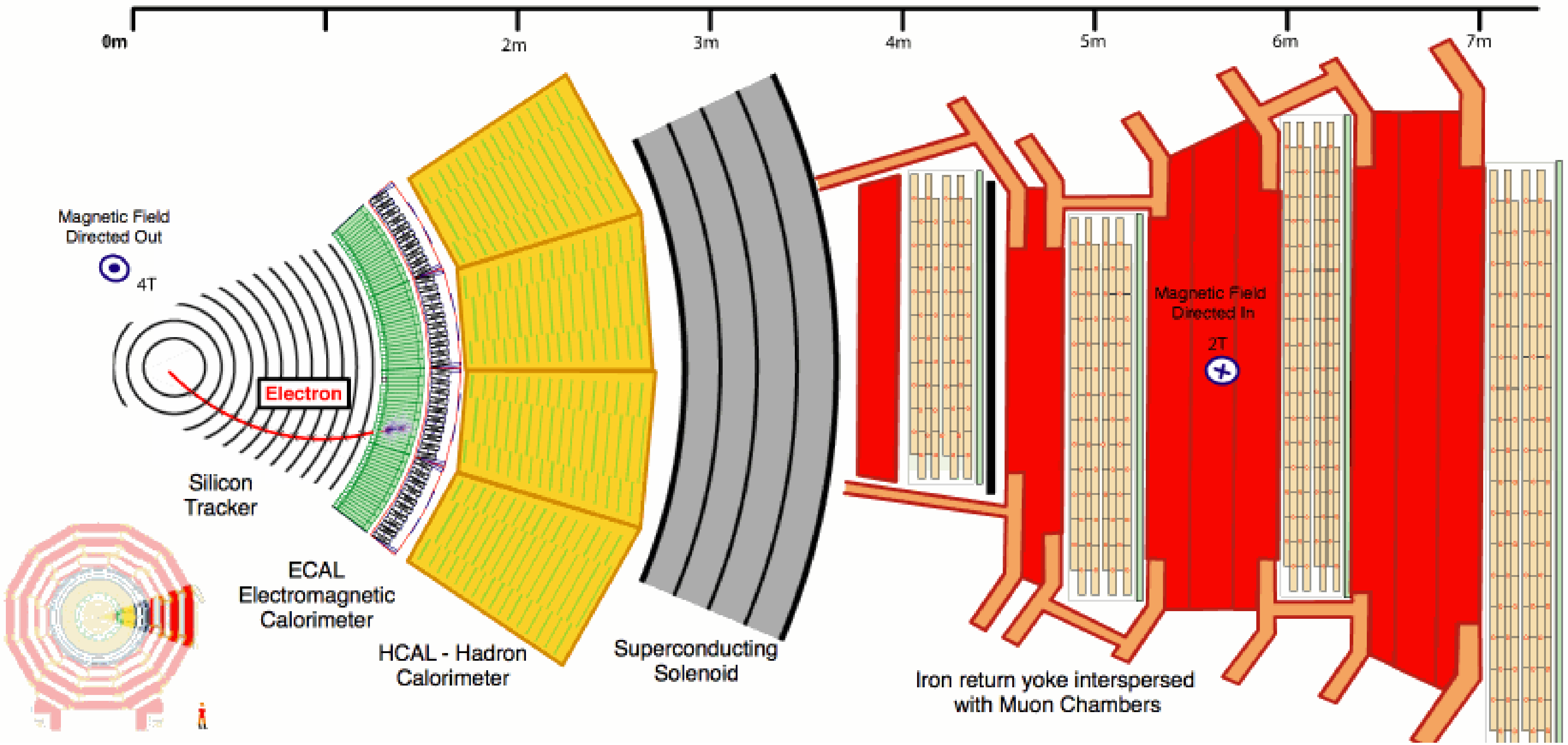
Video of the lecturer



[http://cds.cern.ch/record/2205172]

Electron / positron

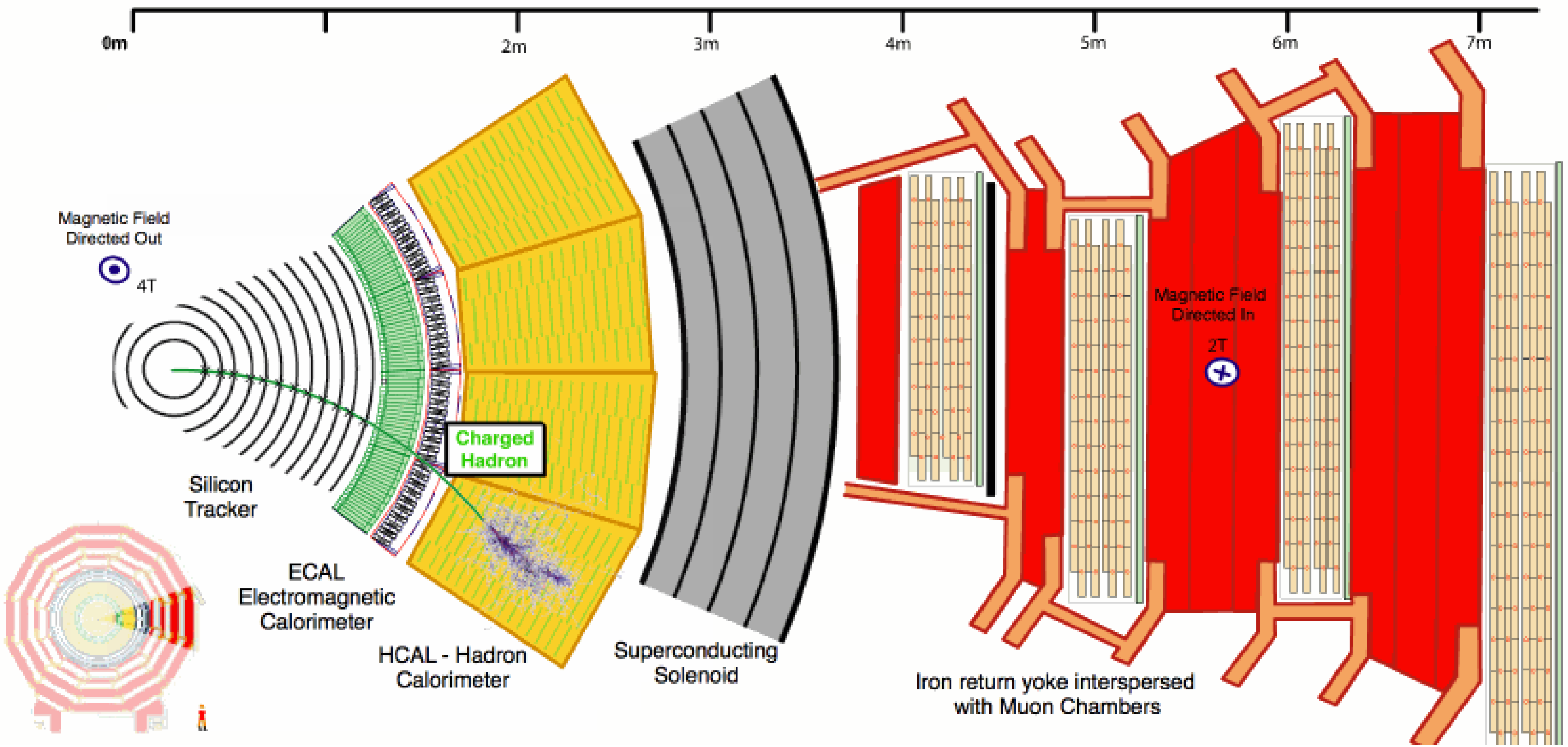
Video of the lecturer



[http://cds.cern.ch/record/2205172]

Charged hadron (proton, kaon, pion)

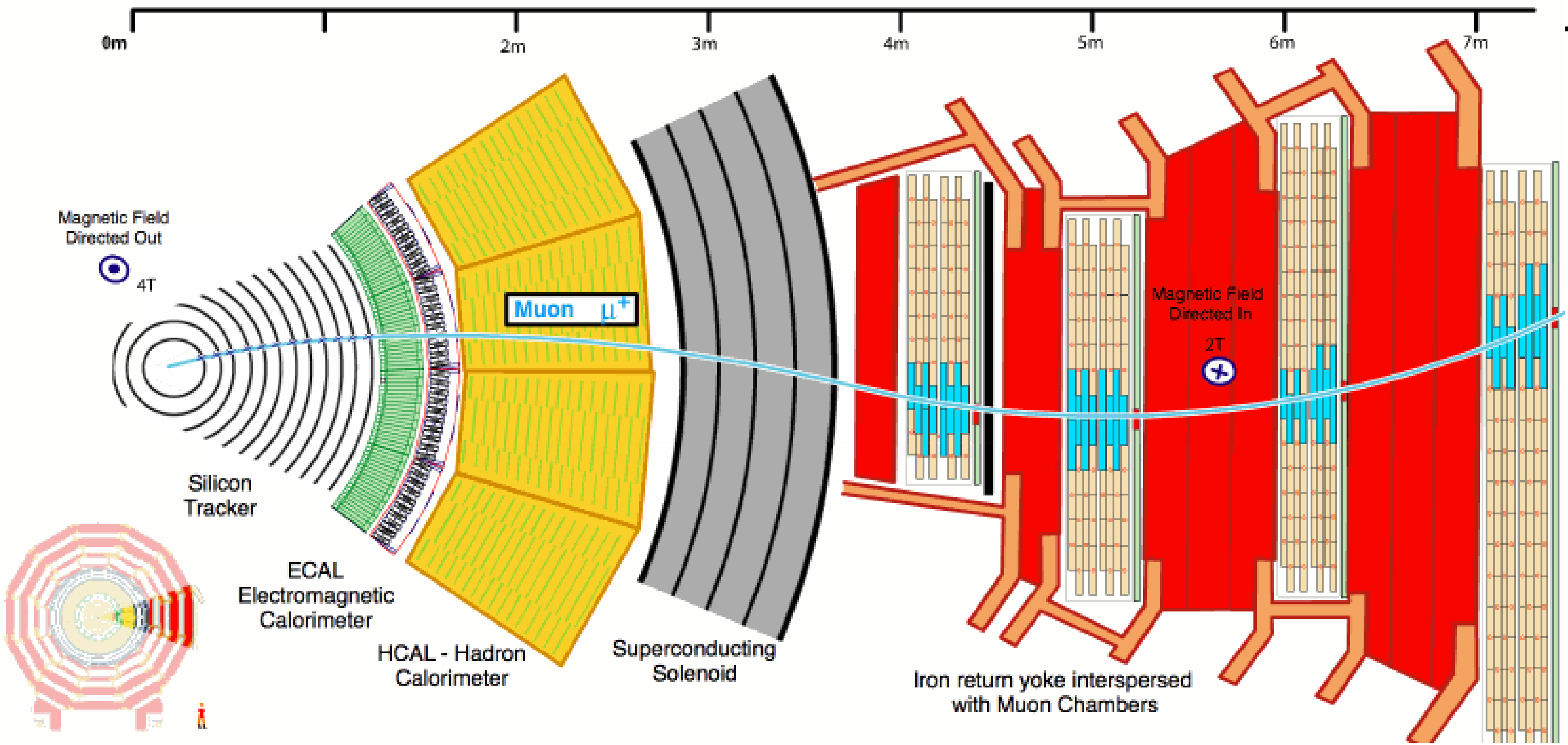
Video of the lecturer



[http://cds.cern.ch/record/2205172]

Muon

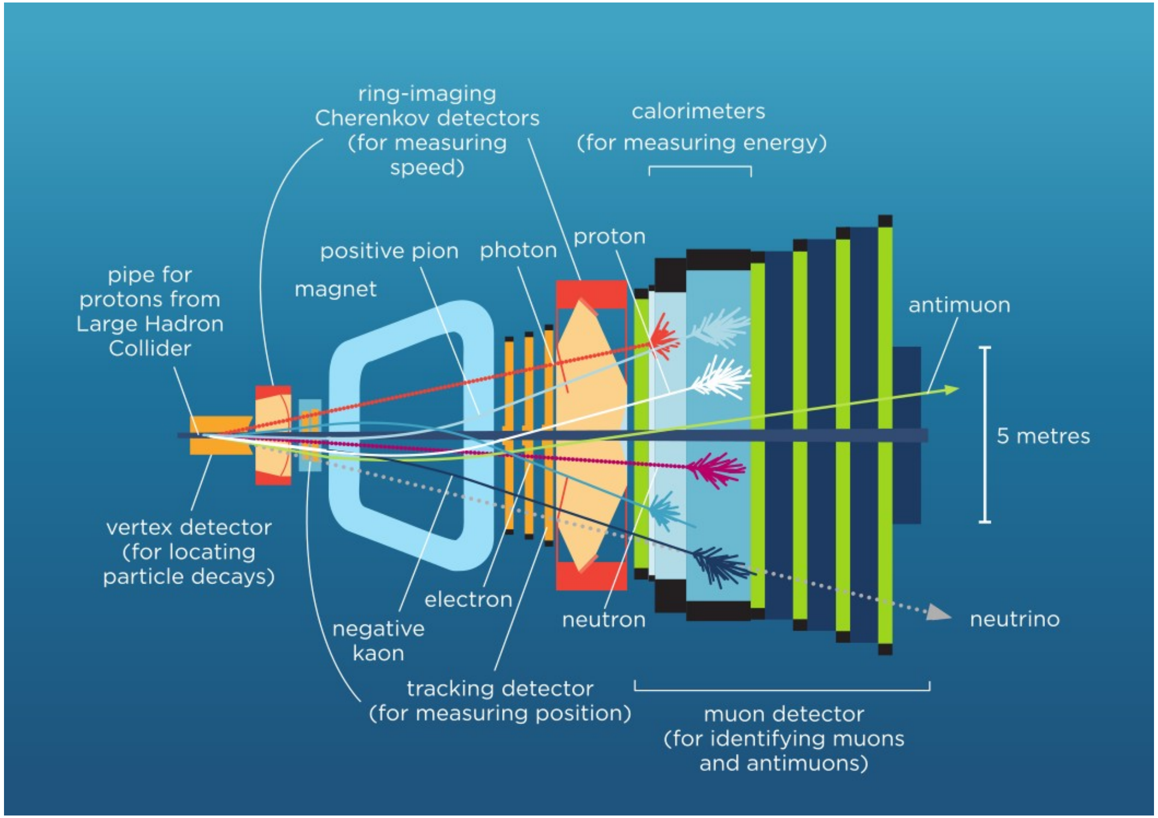
Video of the lecturer



[http://cds.cern.ch/record/2205172]

Example: LHCb detector at the LHC

Video of the lecturer



Similar:

- tracking detectors
- magnet
- calorimeters
- muon detectors

Different:

- Cherenkov detectors
- detector geometry

[http:]

Particle Type

Video of the lecturer

To distinguish between the different types of particles: exploit their different interactions in detector material

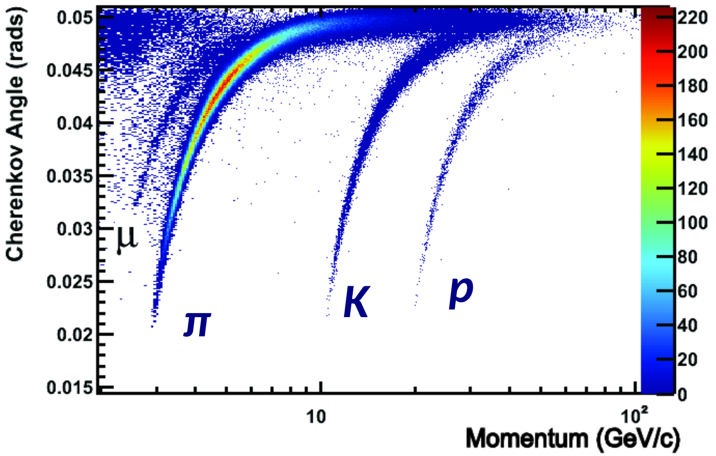
- $e^{\pm}$ shower by electromagnetic interaction → ECAL
- $\pi^{\pm}$, $K^{\pm}$, $p/\overline{p}$ shower by hadronic interaction → HCAL
- $\mu^{\pm}$ do not create showers → muon detectors

To distinguish $p/\overline{p}$, $\pi^{\pm}$, $K^{\pm}$: measure speed (β)
(momentum + speed → mass → particle type)

- Time of flight
- *dE/dx* (Bethe-Bloch)

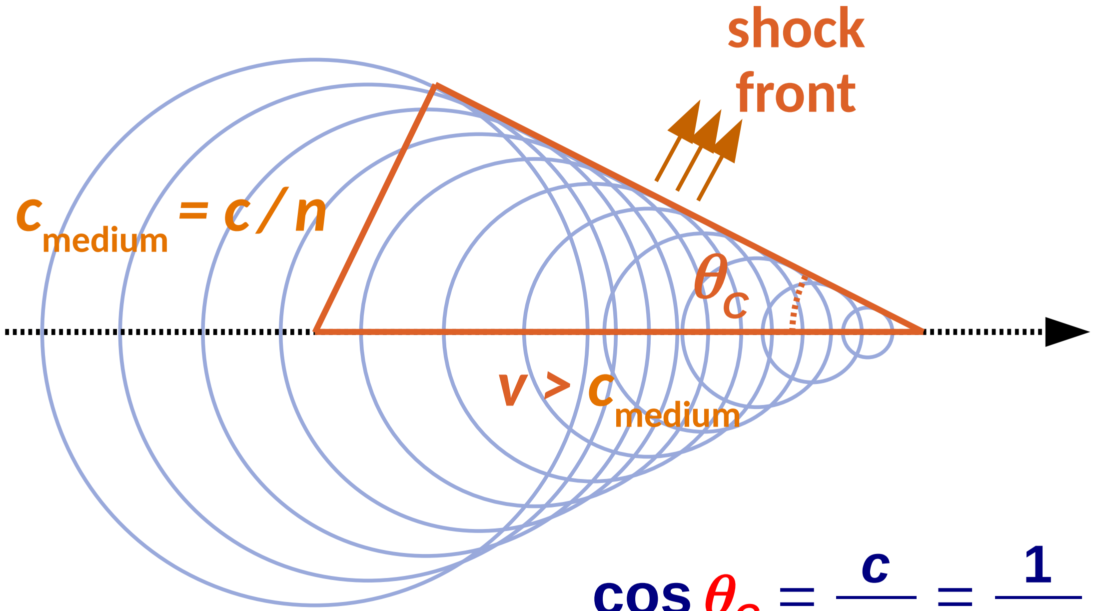
} at low β

- Cherenkov detectors } at high β



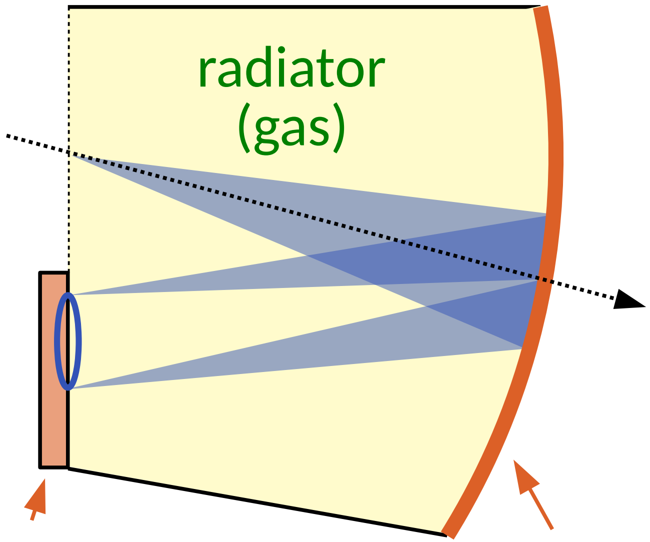
Ring Image CHerenkov Detectors

Video of the lecturer



$$\cos\theta_c = \frac{c}{v\,n} = \frac{1}{\beta\,n}$$

$$\beta = \frac{p}{E} = \frac{p}{\sqrt{p^2 + m^2}}$$



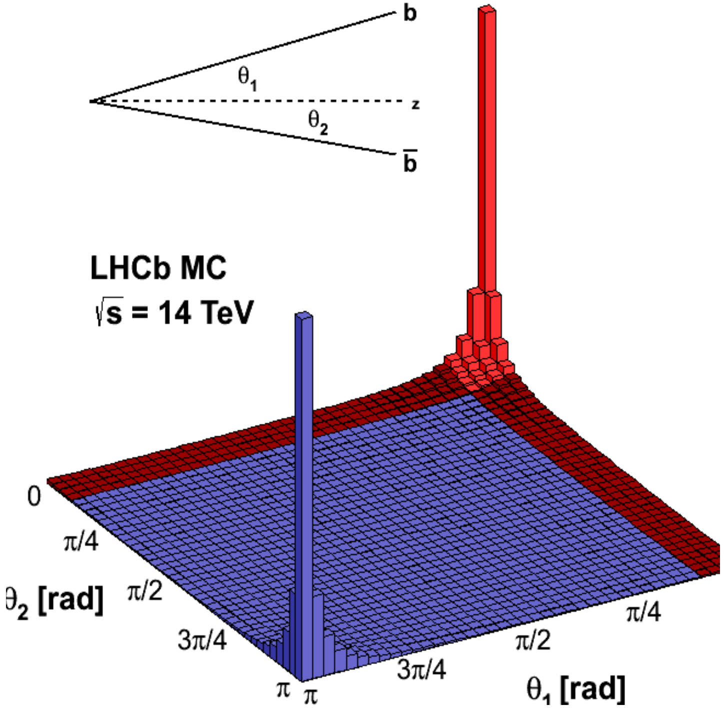
LHCb detector geometry

Video of the lecturer

The main goal of LHCb is to study decays of particles that contain a b or $\bar{b}$ quark

- these particles are produced mostly under small angles with respect to the proton beam axis
- more cost efficient to build a detector that covers only the relevant angles
- (plus some other advantages)

Experiments are optimized for the physics processes they are meant to study !



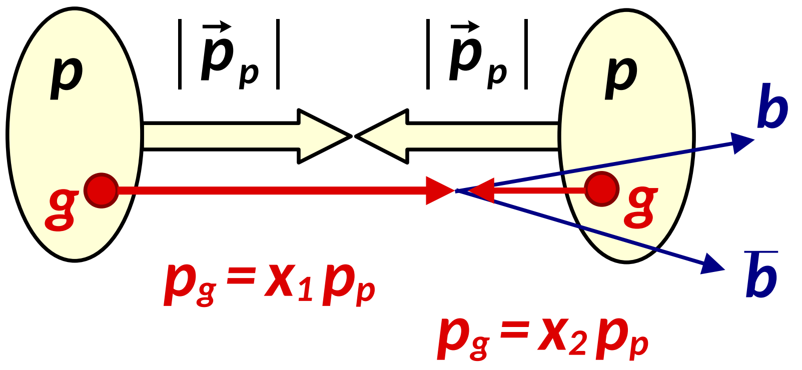
[http://cds.cern.ch/record/1474902]

LHCb detector geometry

Video of the lecturer

Why are particles containing a b or $\bar{b}$ quark produced under small angles to the beam axis ?

- $b\,\bar{b}$ quark pairs are produced through the interaction of two gluons (or two quarks) inside the colliding protons
- each of the interacting gluons carries a fraction of the momentum of its proton
- these fractions are different → asymmetric collision → boost along the beam axis



Quiz III

Video of the lecturer

What are magnetic fields used for in particle-physics detectors?

(a) to measure the momentum of neutral particles
(b) to measure the speed of charged particles
(c) to measure the energy of neutral and charged particles
(d) all of the above
(e) none of the above

note: questions can have more one correct answer --- or none ;-)

Which of these arrangements make sense in a barrel detector (inside → out)?

(a) tracking → ECAL → HCAL → magnet coil → muon stations
(b) tracking → magnet coil → ECAL → HCAL → muon stations
(c) tracking → ECAL → HCAL → muon stations → magnet coil

Slide 41 explains why at the LHC particles containing a b or $\bar{b}$ quark are produced mostly at small angles with respect to the beam axis. Why is this not true for Higgs bosons?

(a) the Higgs boson has a much shorter lifetime than particles containing a b or $\bar{b}$ quark
(b) the Higgs boson has a much higher mass than particles containing a b or $\bar{b}$ quark