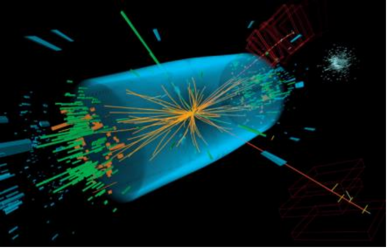


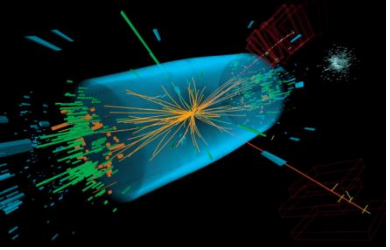
Particle identification

Roger Forty (CERN)

Review of the techniques of particle identification used in high energy physics experiments

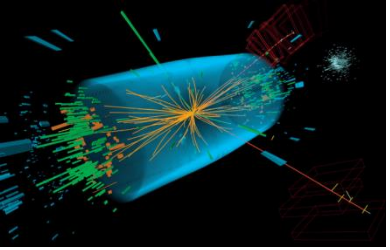
1. Introduction
2. Techniques to identify elementary particles
3. Charged hadron identification
   Time of flight, *dE/dx*, Transition radiation
   Cherenkov detectors

3rd EIROforum School of Instrumentation, CERN, 28 May 2012



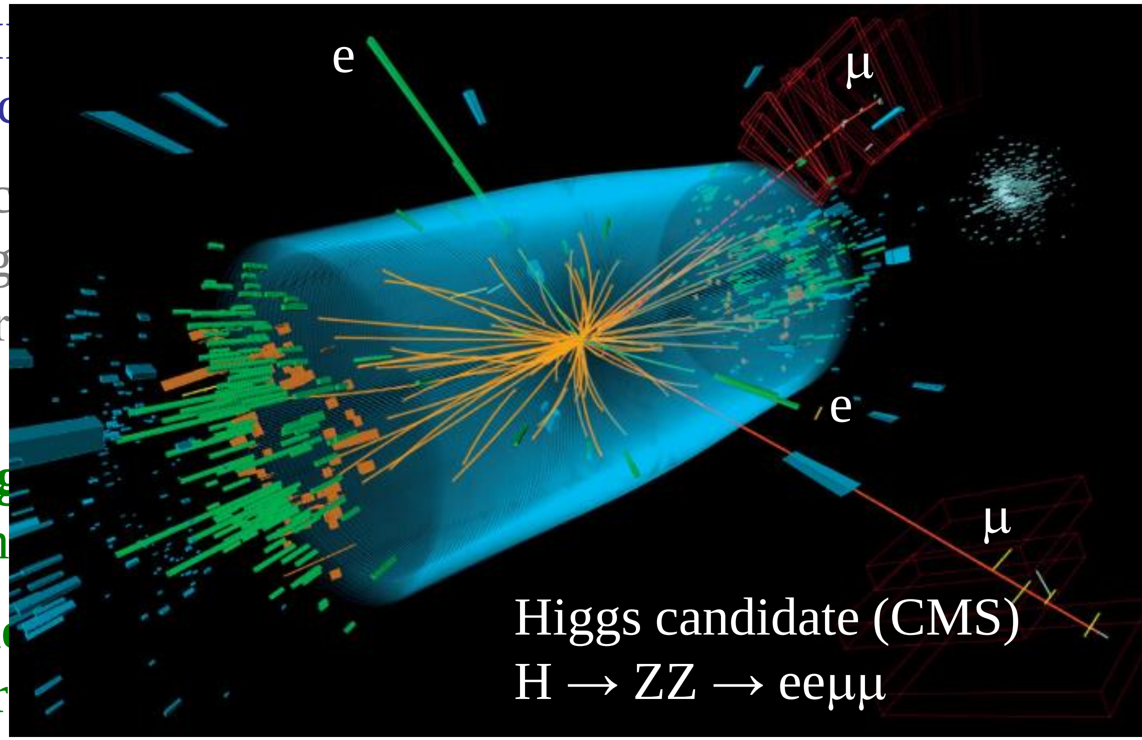
1. Introduction

- Particle ID is a crucial aspect of high energy physics experiments
  The detectors used depend on the physics that is under study
- In a typical experiment beams collide inside the detectors
  (or a single beam collides with a fixed target)
  Wish to reconstruct as fully as possible the resulting “events”
  in which many particles emerge from the interaction point
- **Tracking** detectors determine whether the particles are charged
  With a magnetic field, measure the sign of charge + momentum of particle
- **Calorimeters** detect neutral particles, measure the energy of particles,
  and determine whether they have electromagnetic or hadronic interactions
- What other information is needed?
  Want to identify the *type* of particles produced: **Particle ID**



1. Introduction

- Particle I … nts
  The detec
- In a typic
  (or a sing
  Wish to r
  in which
- **Tracking** … d
  With a m … n of particle
- **Calorim** … articles,
  and deter … nteractions



- What other information is needed?
  Want to identify the *type* of particles produced: **Particle ID**

Elementary particles

- The elementary particles of the Standard Model of particle physics:

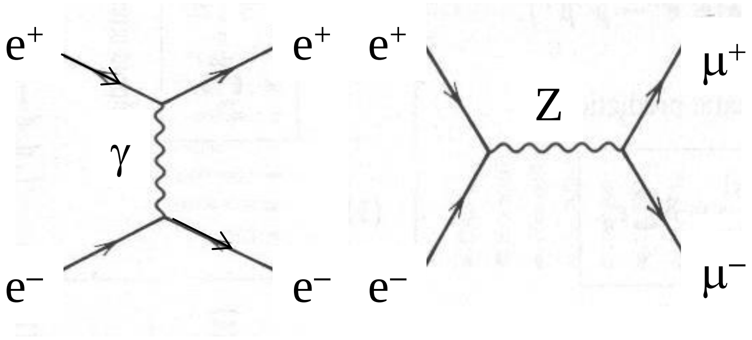
Type	Name			Charge	Spin
Generation	1st	2nd	3rd		
Leptons	**e**	**μ**	**τ**	1	1/2
	$\boldsymbol{\nu_e}$	$\boldsymbol{\nu_\mu}$	$\boldsymbol{\nu_\tau}$	0	1/2
Quarks	**u**	**c**	**t**	2/3	1/2
	d	**s**	**b**	1/3	1/2
Force	Strong	EM	Weak		
Gauge bosons	**g**	**γ**	**Z**		
			W		
Higgs boson	**H**				

Must also be ready to detect particles from *beyond* the Standard Model (e.g. Supersymmetry)

- The Higgs boson was the last missing component of the Standard Model
  Discovered last year at the LHC (couplings still have to be checked)
  How can each of these be identified in an experiment?

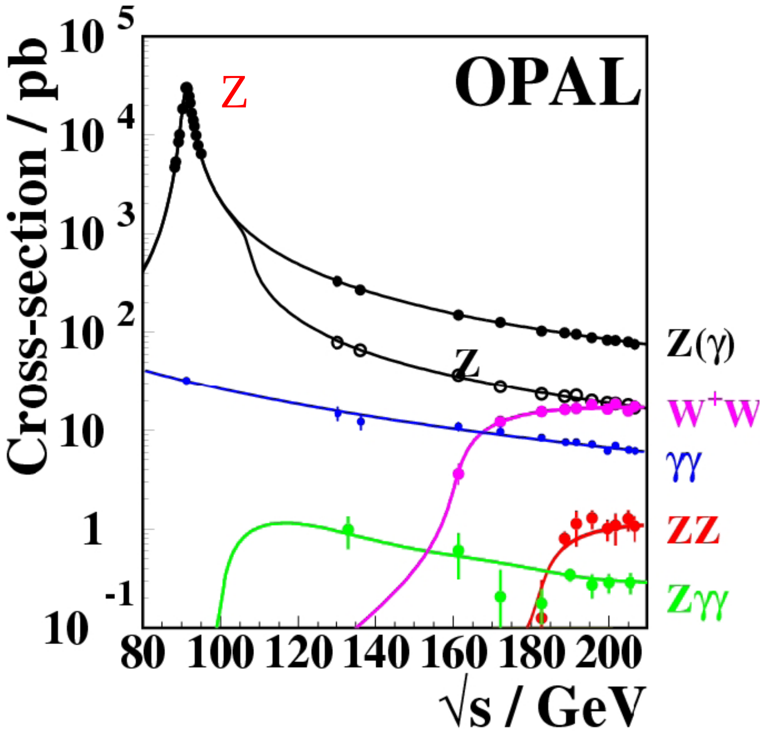
Gauge bosons

- Gauge boson play the role of (virtual) particles exchanged between fermions:



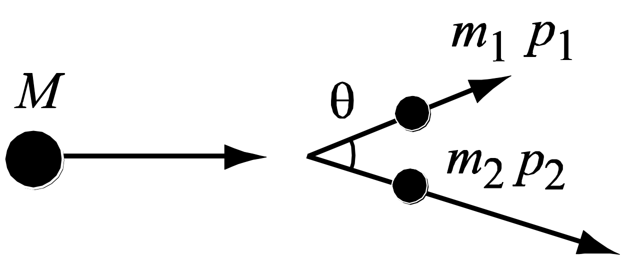
- However, real, massless **photons** can be produced, and be seen in the experiment
- Weak vector bosons (W, Z) are massive, and therefore very short lived
- They can be seen from the variation of production cross-section with energy, or from their decay products

Cross-section for $e^+ e^-$ collisions (LEP)



Invariant mass

- From relativistic kinematics, the relation between energy E, momentum p, and (rest) mass m is: $E^2 = p^2 + m^2$
  (The full expression: $E^2 = p^2c^2 + m^2c^4$ but factors of c are often dropped)
- Consider a particle that decays to give two daughter particles:



- The *invariant mass* of the two particles from the decay:

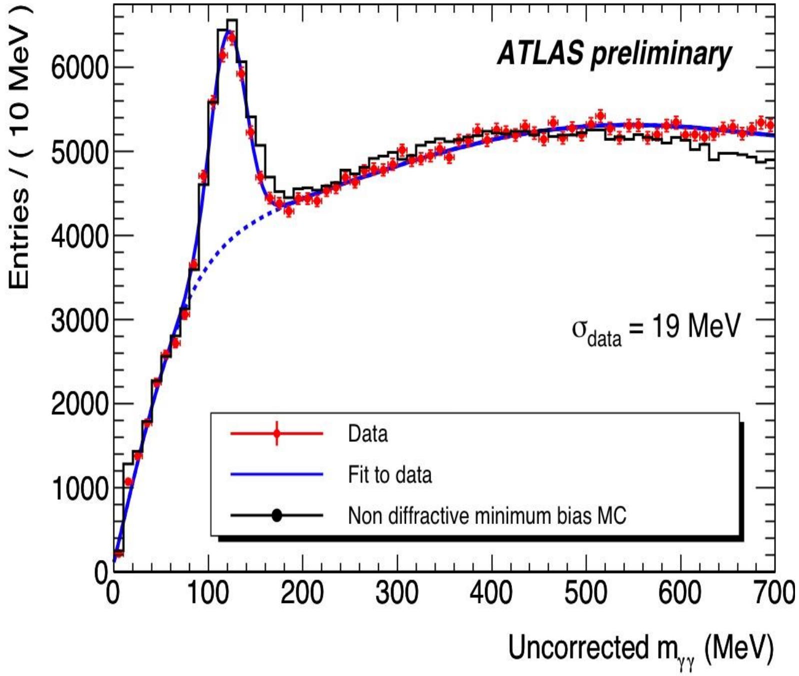
$$M^2 = m_1{}^2 + m_2{}^2 + 2(E_1E_2 - p_1p_2\cos\theta)$$

$\rightarrow$ to reconstruct the parent mass a precise knowledge of the momentum and the angle θ of decay products is needed, from the tracking system, as well as their particle **type**, which determines their masses m_1 and m_2

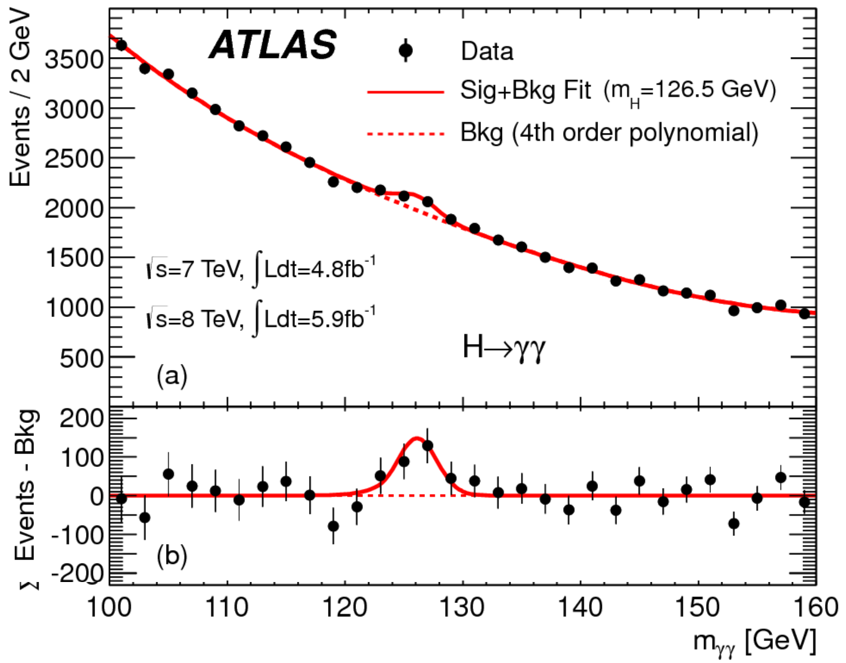
Mass reconstruction

- Typical example of reconstruction of a particle decay: $\pi^0 \to \gamma\gamma$
  one of the first composite particles reconstructed in the LHC experiments
- This technique can also be used to search for more exciting signals:

$m(\pi^0) = 135$ MeV

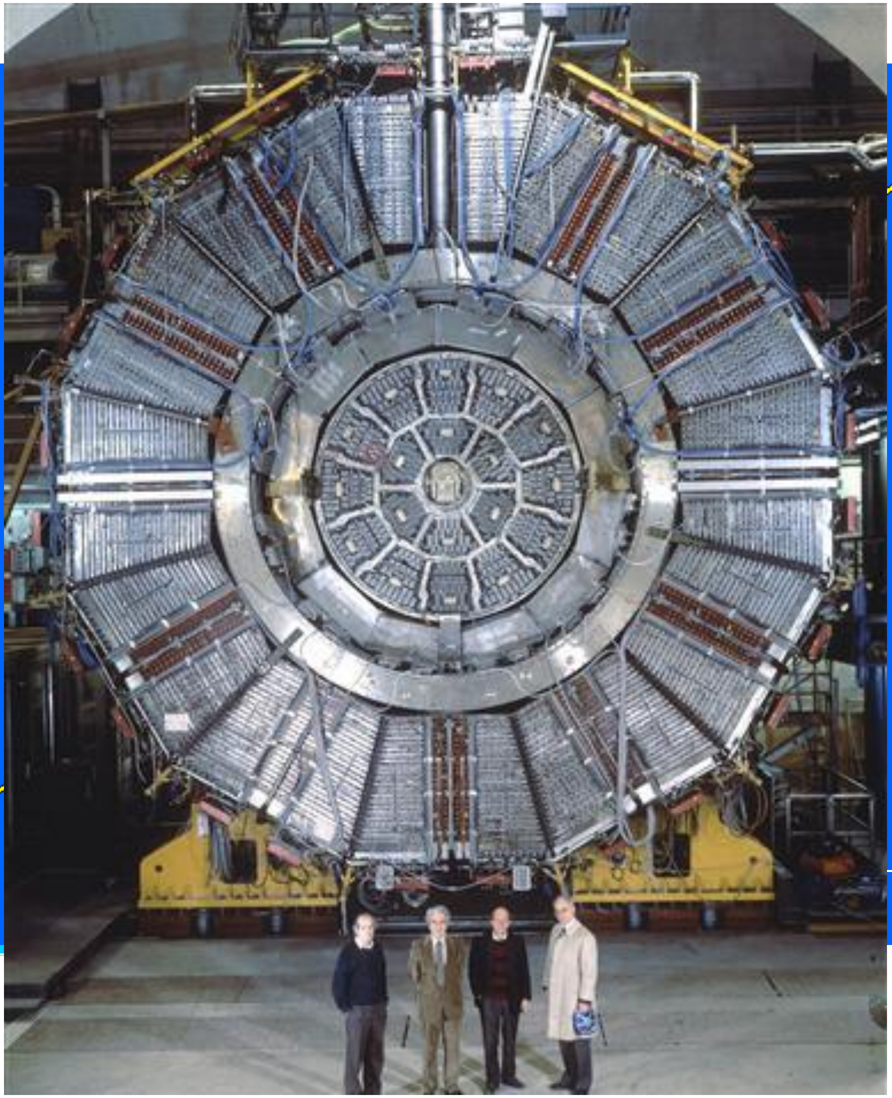


$H \to \gamma\gamma$



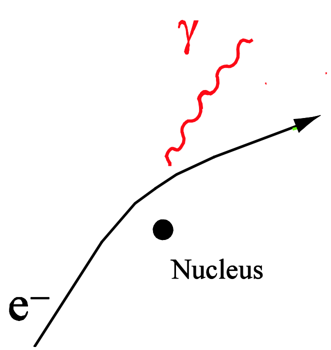
Event display

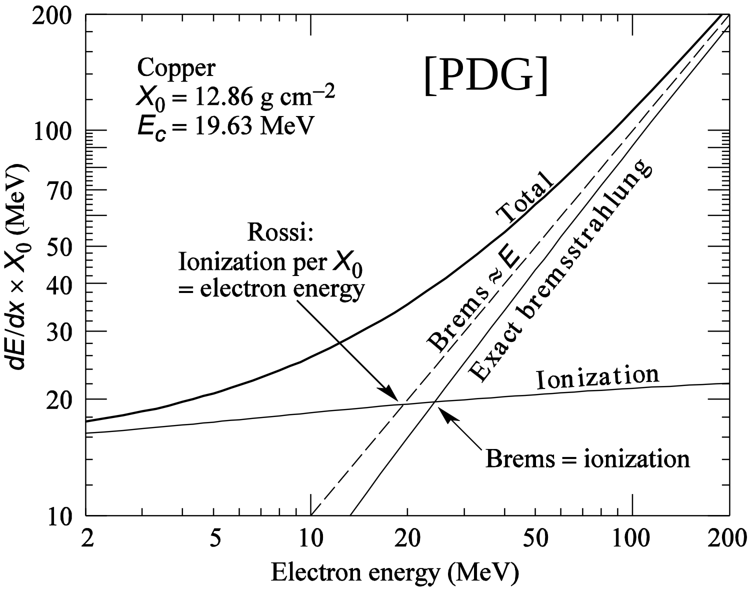
- The different particle signatures can be illustrated using events from of one of the experiments at LEP (the previous accelerator to the LHC at CERN)
- ALEPH took data from 1989–2000, studying e^+e^- collisions from LEP
- Since colliding e^+ and e^- are elementary particles, events are simpler than pp collisions at the LHC



2. Identification techniques

- The various elementary particles give different characteristic signatures in the separate detectors that make up the experiment
- Charged leptons leave tracks due to ionization in the tracking detectors
- Electrons are stable particles and have low mass (m_e = 0.51 MeV)
  They produce Bremsstrahlung radiation when passing through matter

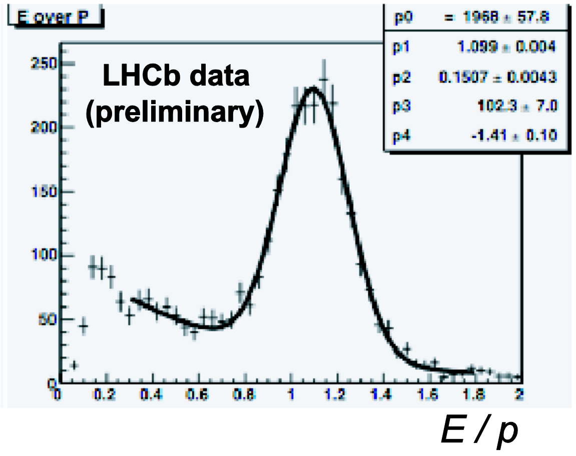




- $\Delta E \propto 1/m^2$
  Dominates for electrons with
  E > 100 MeV

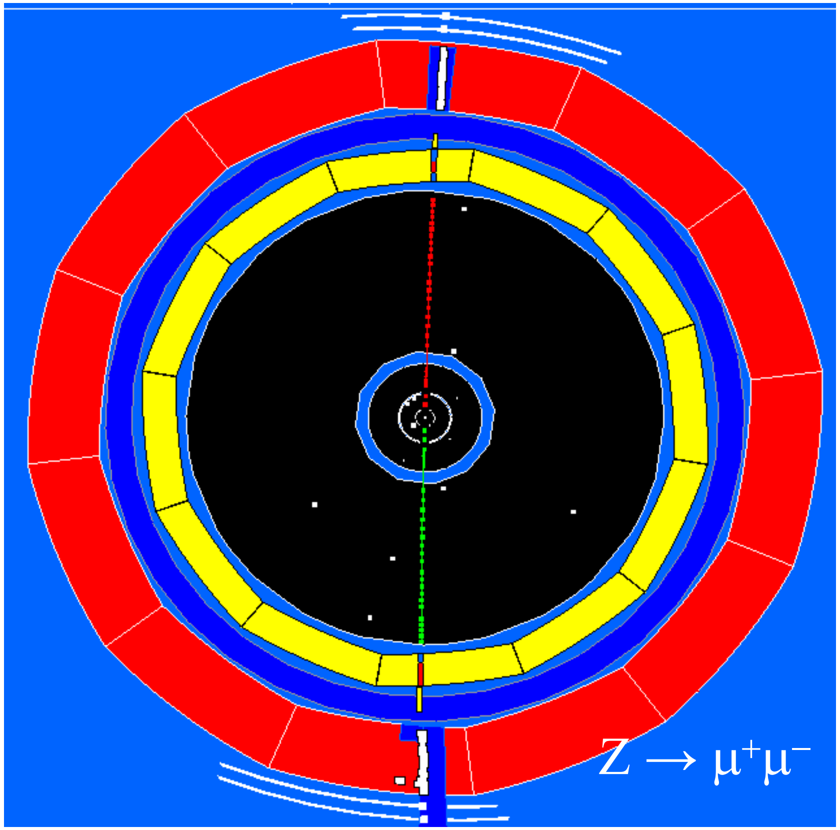
e/γ identification

- When incident on matter at high energy, photons convert to e^+e^- pairs
  The electrons (and positrons) produce more photons by Bremsstrahlung,
  a shower develops of $e^\pm$ and γ, until the energy of incident particle used up
  → Identified by *calorimeters* via their characteristic showers
- Radiation length X_0 = mean distance to reduce energy by $1/e$
  eg $X_0 = 1.76$ cm for Fe, so these *electromagnetic* showers are compact
- Similar showers produced by electrons and photons
  Distinguished by whether a *track* points towards the shower
- For electrons, E (energy from calorimeter) and p (momentum of track) should be equal:
  $E/p = 1$
  (not the case for other charged particles)
- See calorimeter lecture for more details



Muons

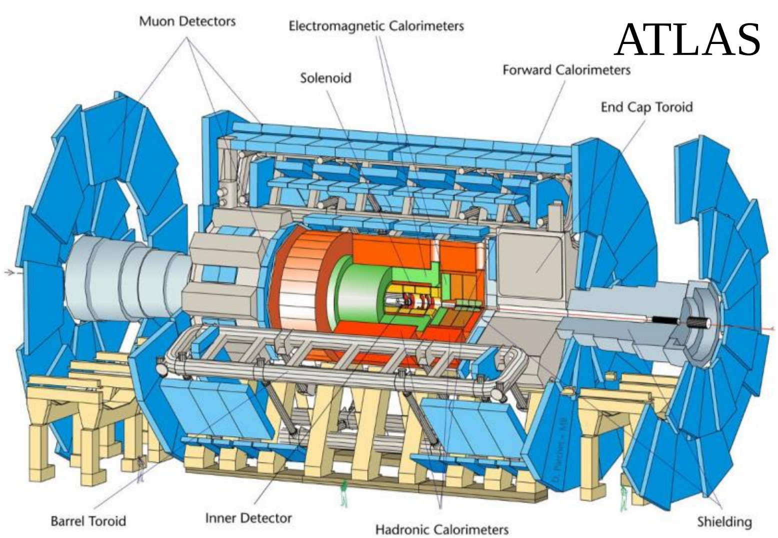
- Muons are like heavier versions of the electron: $m_\mu = 105.7$ MeV
- Decay to electrons $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$ with (proper) lifetime $\tau_\mu = 2.2\ \mu s$
- Distance they travel (on average) before decay: $d = \beta\gamma\, c\tau_\mu$
  where *velocity* $\beta = v/c$
  boost $\gamma = E/m = 1/\sqrt{(1-\beta^2)}$
- So a 10 GeV muon flies ~ 60 km before decay >> detector size
  $\rightarrow$ effectively stable
- Since mass is large, Bremsstrahlung radiation is small, and as a lepton it does not feel the strong interaction

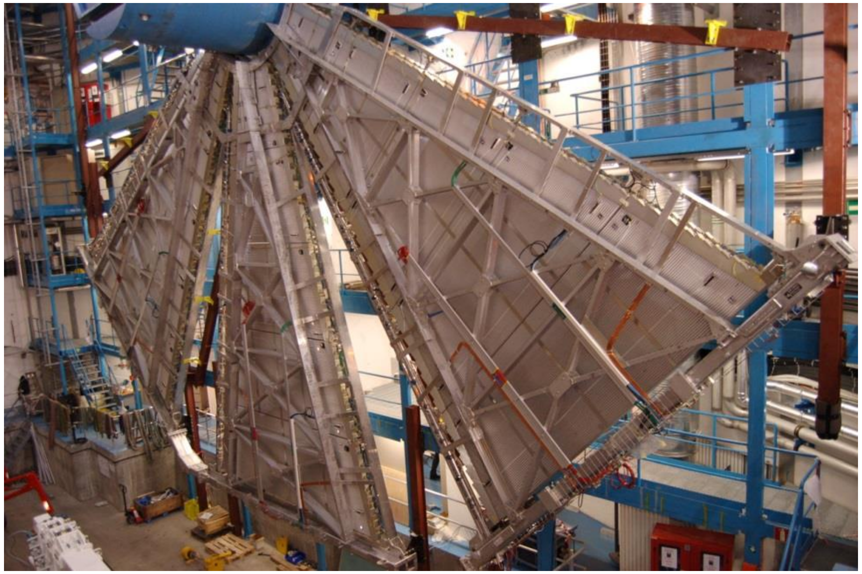


$\rightarrow$ most penetrating charged particle

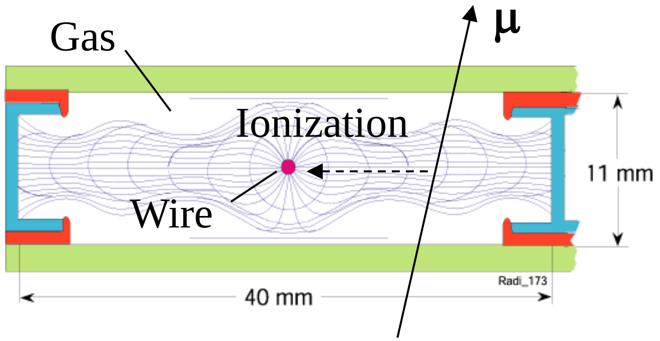
Muon detectors

- Since they are sited on the outside of an experiment, muon detectors tend to dominate their appearance



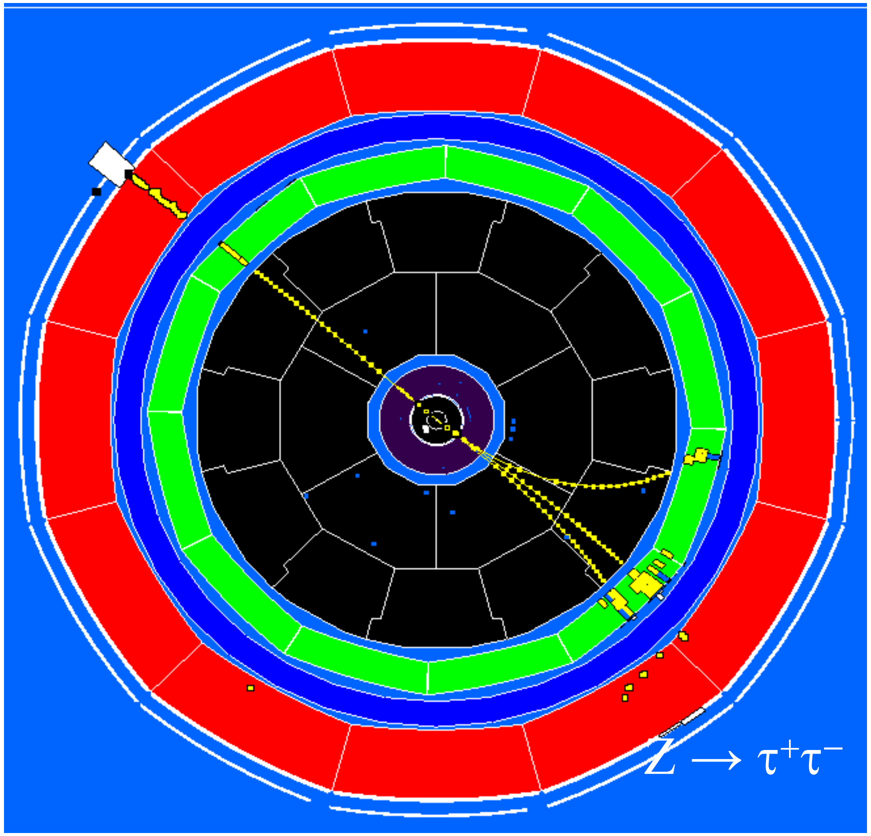


- They must be inexpensive, low granularity but precise enough for *p* measurement e.g. wire chambers with long drift volume



Tau leptons

- Taus are heavier still: m_τ = 1.78 GeV
- Heavy enough that can decay to many final states: $\tau^- \to \mu^-\nu_\mu\nu_\tau$, $\pi^-\nu_\tau$, $\pi^-\pi^0\nu_\tau$, $\pi^-\pi^-\pi^+\nu_\tau$, …
- Lifetime τ_τ = 0.29 ps (ps = 10^{-12} s) so a 10 GeV tau flies ~ 0.5 mm
- Typically too short to be seen directly in the detectors, instead the decay products are seen
- Accurate vertex detectors can detect that they do not come exactly from the interaction point

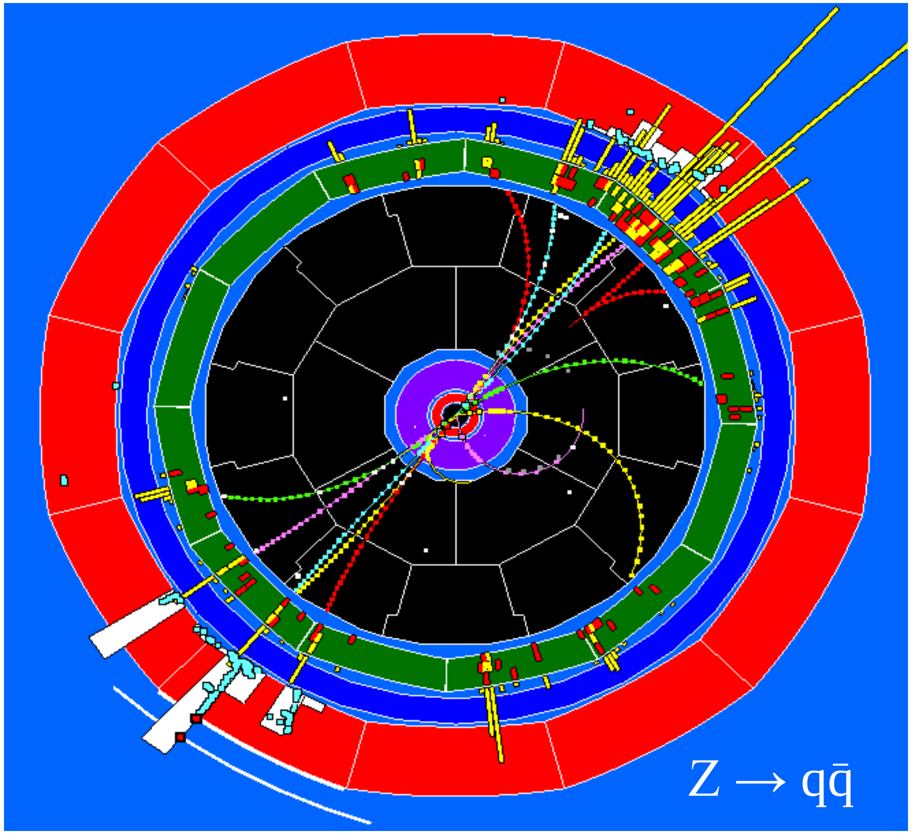


Neutrinos

- Neutral (so no track) and only weak interaction $\rightarrow$ pass though matter easily
  Interaction length λ_{int} = A /($\rho\sigma N_A$), cross section $\sigma \sim 10^{-38}$ cm$^2 \times E$ [GeV]
  $\rightarrow$ a 10 GeV neutrino can pass through > million km of rock
- Neutrinos are usually detected in HEP experiments through *missing energy* (applying E conservation to rest of the event, usually in transverse plane E_T)
- This is also the signature for other weakly interacting particles, from new physics beyond the Standard Model (e.g. the lightest Supersymmetric particle)
- Neutrinos *can* be detected if you produce enough of them, and the detector is sufficiently massive:
- > 1000 tons of instrumented target! Located underground in Italy detecting neutrinos from CERN (730 km away)

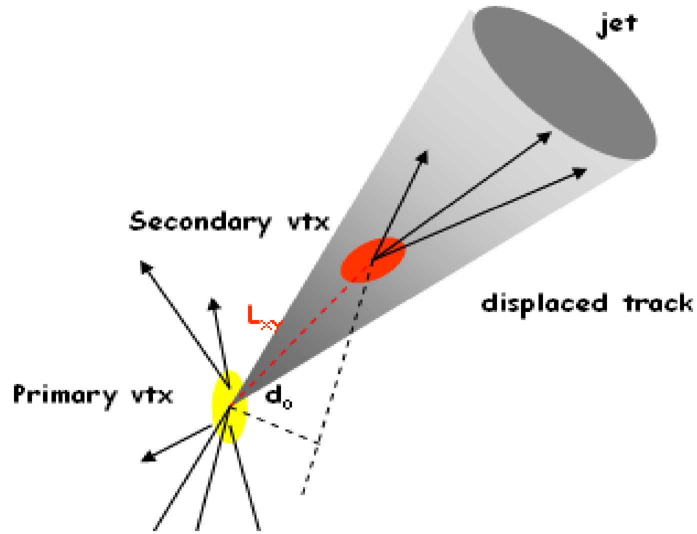
Quarks

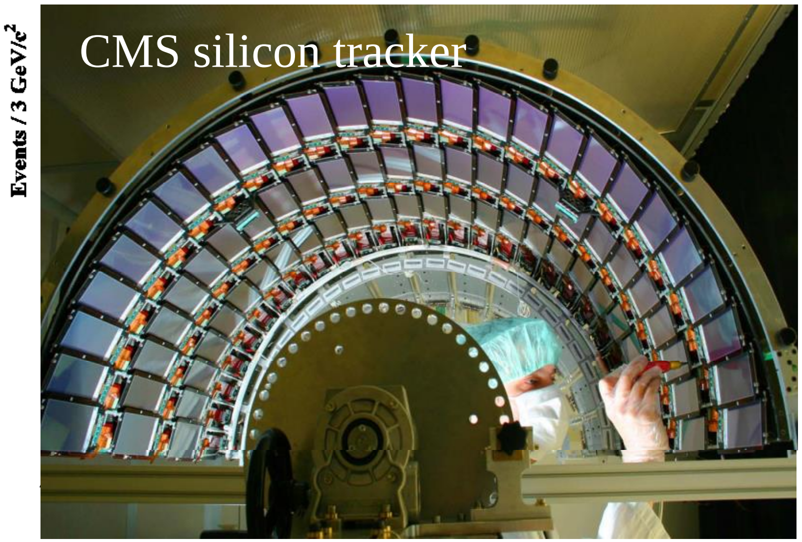
- Quarks feel the strong interaction, mediated by gluons
- Not seen in the detector, due to the confinement property of QCD
- Instead, they *hadronize* into mesons ($q\bar{q}$) or baryons (qqq)
- At high energy >> m_q initial quark (or gluon) produces a "jet" of *hadrons*
- Gluon and quark jets are difficult to distinguish: gluon jets tend to be wider, and have a softer particle spectrum



Jet reconstruction

- Jets are reconstructed by summing up the particles assigned to the jet
- Typically performed using a conical cut around the direction of a "seed" particle, or by iteratively adding up pairs of particles that give the lowest invariant mass
- Different quark flavours can be separated (at least statistically) by looking for displaced tracks from b- and c-hadron decays
- The jet properties can be used to approximate the quark or gluon e.g. here in the Higgs search





Hadrons

- Instead of making do with jet reconstruction, often the physics under study requires the identification of *individual* hadrons
- Most are unstable, and decay into a few long-lived particles:

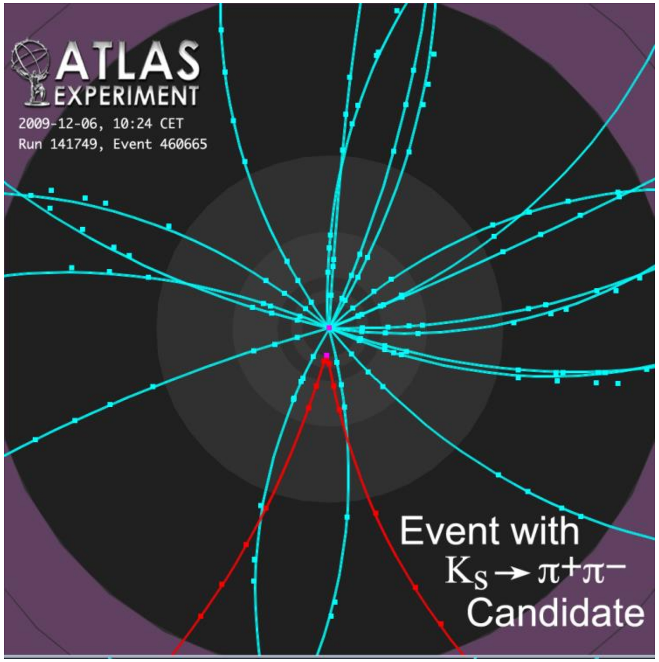
Particle	***m* [MeV]**	**Quarks**	**Main decay**	**Lifetime**	***c*τ [cm]**
$\pi^{\pm}$	140	$u\bar{d}$	$\mu\nu_{\mu}$	2.6×10^{-8} s	780
$K^{\pm}$	494	$u\bar{s}$	$\mu\nu_{\mu}$, $\pi\pi^{0}$	1.2×10^{-8} s	370
K_S^{0}	498	$d\bar{s}$	$\pi\pi$	0.9×10^{-10} s	2.7
K_L^{0}	498	$d\bar{s}$	$\pi\pi\pi$, $\pi l\nu$	5×10^{-8} s	1550
p	938	uud	stable	$> 10^{25}$ years	∞
n	940	udd	$pe\nu_{e}$	890 s	2.7×10^{13}
Λ	1116	uds	$p\pi$	2.6×10^{-10} s	7.9

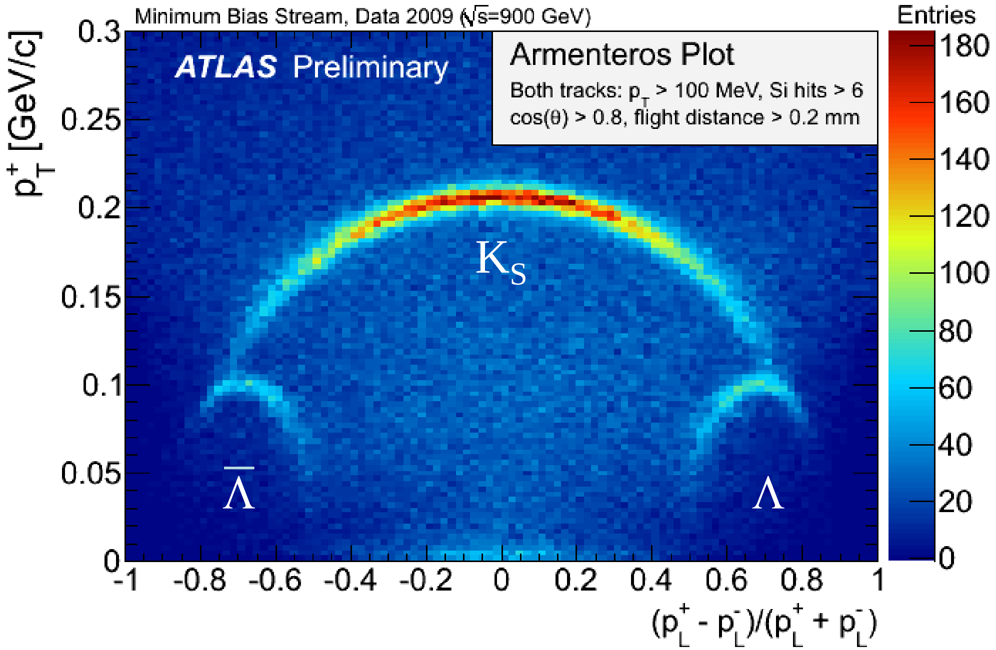
(along with some rarer baryons, deuterons, etc.)

- Decay lengths ($\beta\gamma\, c\tau$) >> size of typical experiment, apart from K_S and Λ

V^0s

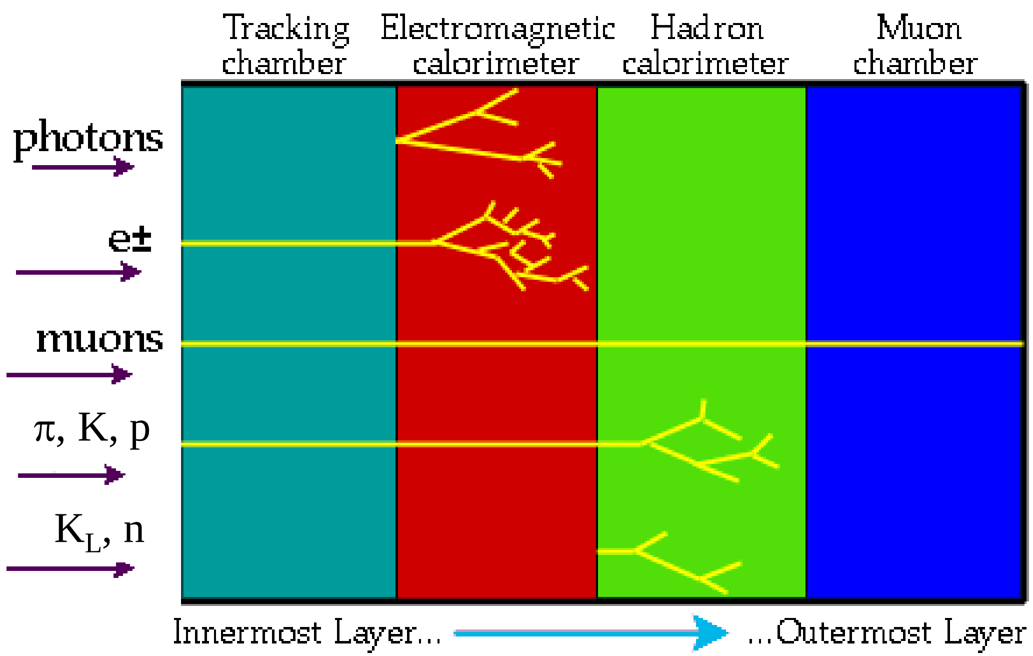
- $K_S{}^0$ and Λ are collectively known as V^0s, due to their characteristic two-prong decay vertex
- V^0s can be reconstructed from the kinematics of their positively and negatively charged decay products, without needing to identify the π or p





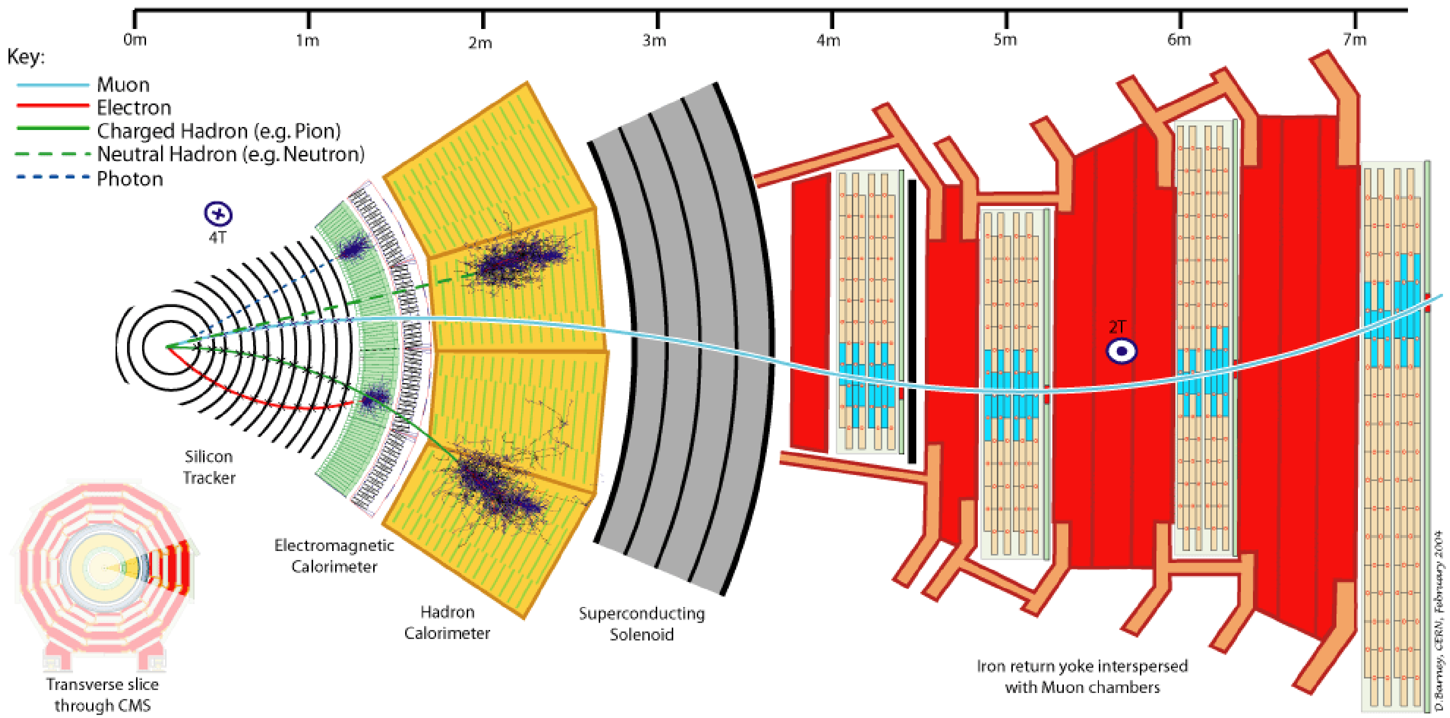
Other neutral hadrons

- neutrons and K_L^0 are detected in the hadronic calorimeter
  They feel the strong force, and when incident at high energy onto matter they produce showers of other hadrons
- Relevant scale is the nuclear interaction length λ_I = 16.8 cm for Fe $\approx 10\times X_0$
  so hadronic showers are longer than EM → HCAL sits behind ECAL



General purpose detectors

- Have now discussed the set of detectors used for particle identification in a typical “general purpose” HEP experiment, such as ATLAS and CMS

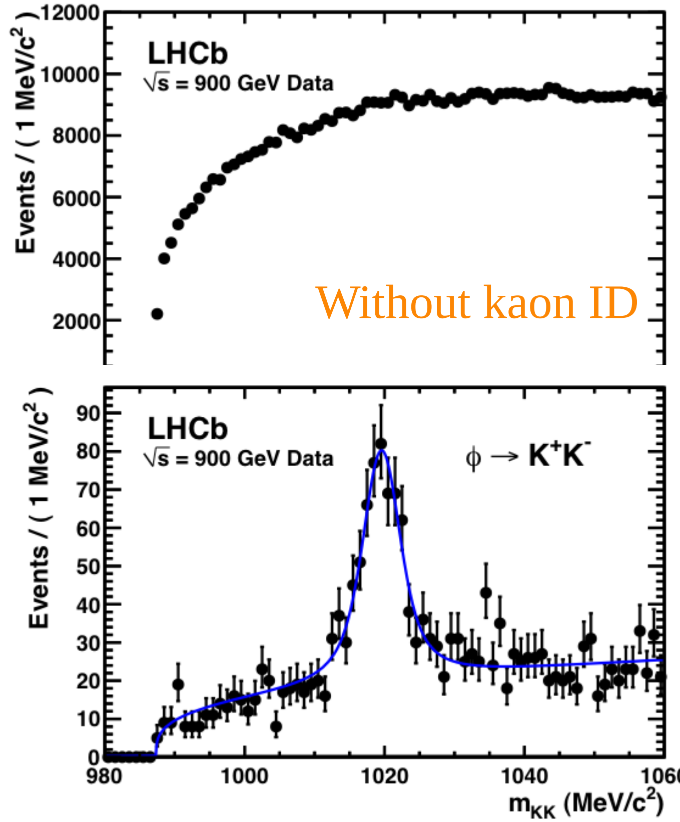


- One task that such detectors do *not* do very well is to identify different charged hadrons (π, K, p)

3. Charged hadron ID

- Charged hadrons (π, K, p) are all effectively stable, and have similar interactions
  $\rightarrow$ track + hadronic shower
- However, identifying them can be crucial, in particular for the study of hadron decays
  e.g. $\phi \rightarrow K^+ K^-$

  Just making all two-track combinations in an event and calculating their invariant mass
  $\rightarrow$ large *combinatoric* background
  (most tracks are pions, from other sources)
- By identifying the two tracks as kaons the signal becomes visible
  Distinguishing kaons from pions is critical



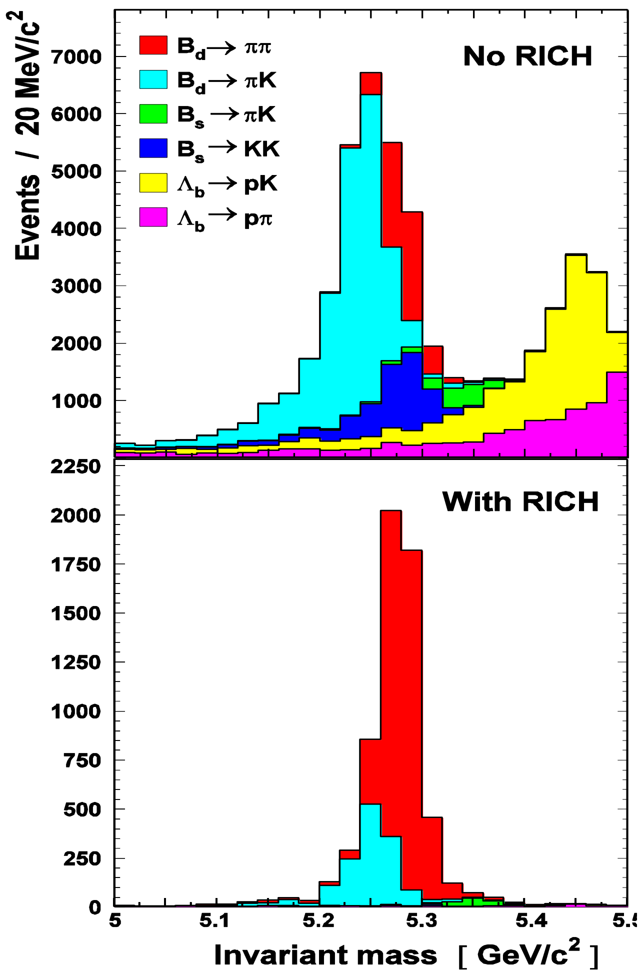
Flavour physics

- Hadron ID is crucial for *flavour physics*: the study of hadrons containing the different quarks, in particular b and c
- This can shed light on the reason the Universe did not disappear soon after the Big Bang, from the annihilation of the matter and antimatter: *CP violation* can give rise to an excess of matter

  e.g: $\mathcal{B}(B^0 \to K^+ \pi^-) > \mathcal{B}(\overline{B}^0 \to K^- \pi^+)$

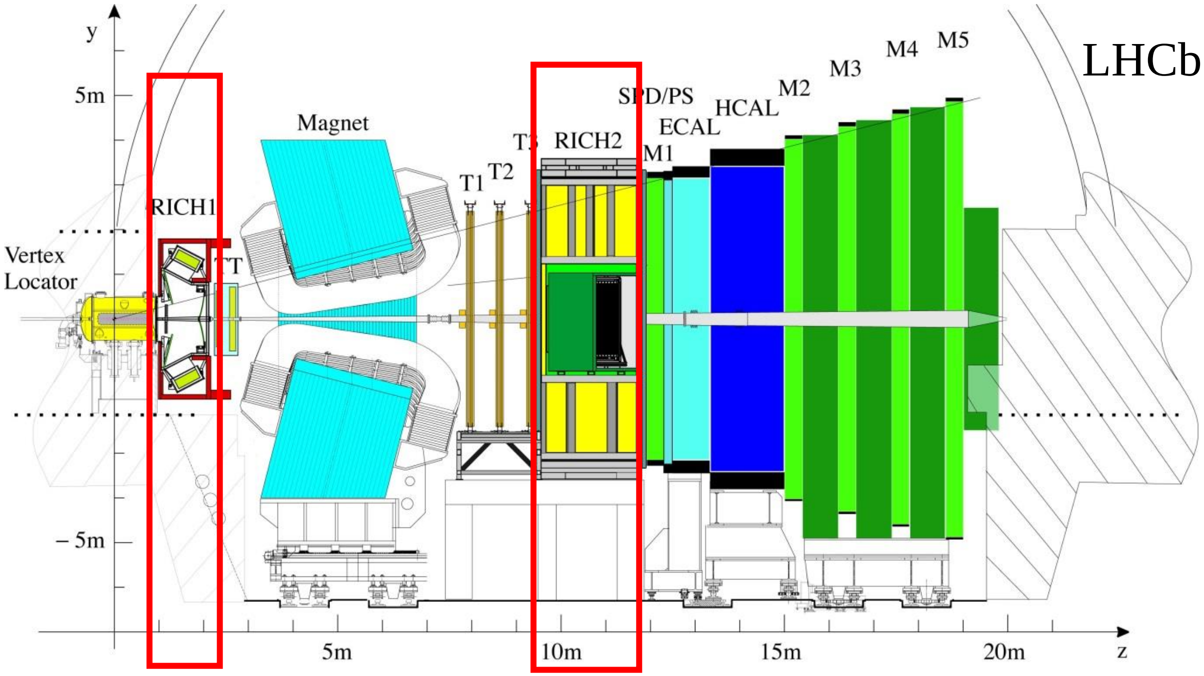
- Making combinations of all two-body B decays many different modes overlap → very difficult to study their properties
- Applying hadron ID, the different components can be separately studied

LHCb simulation



Dedicated detector

- LHCb is a dedicated detector for flavour physics at the LHC
- Since B hadrons are light ~ 5 GeV << E_{cm} (14 TeV) they tend to be produced in the forward direction, so LHCb is a forward spectrometer:



- Otherwise it looks like a slice out of a General Purpose experiment, apart from two extra detectors – for identifying charged hadrons

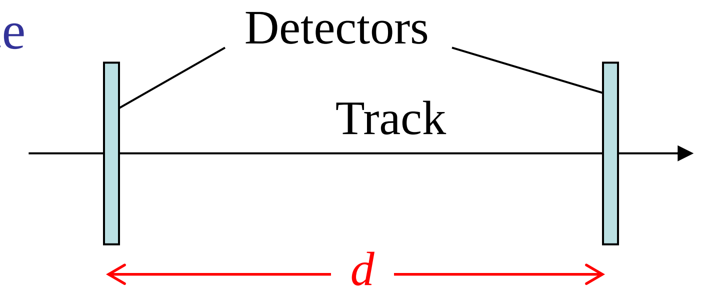
How?

- Since the interactions of charged hadrons are similar, the most direct way to distinguish them is to determine their (rest) *mass*
- Their momentum is measured by the tracking system, so this is equivalent to determining their *velocity*, since $p = \gamma m \mathrm{v}$, so $m = p/\gamma \mathrm{v} = p/\gamma\beta c$
  There are four main processes that depend on the velocity of a particle:

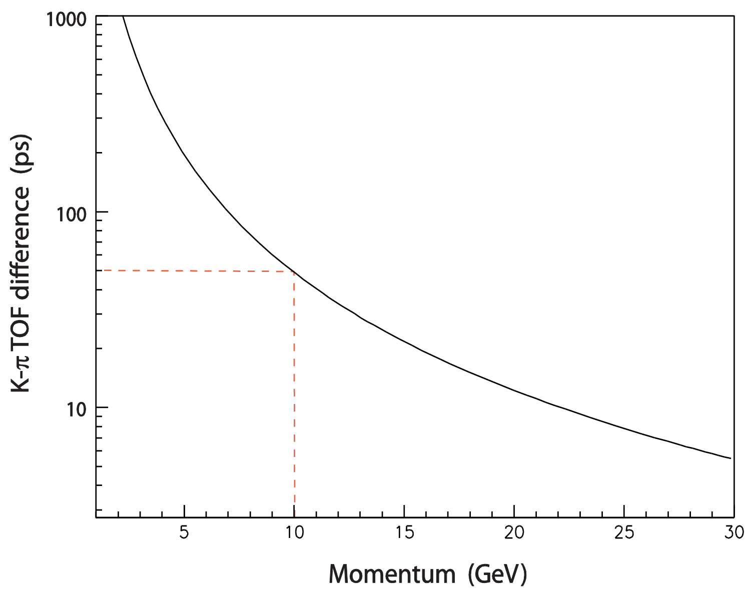
1. Most direct is to measure the **Time of flight** (TOF)
   of the particles over a fixed distance
2. Looking in detail at their interaction with matter:
   the main source of energy loss is via **Ionization** (*dE/dx*)
3. If a particle passes through material with varying refractive index
   it will radiate photons: **Transition radiation**
4. If a particle travels at *greater* than the local speed of light,
   it will radiate photons: **Cherenkov light**

Time of flight

- Simple concept: measure the time difference between two detectors: $\beta = d / c\Delta t$
- At high energy, particle speeds are relativistic, closely approaching to *c*
  For a 10 GeV π, the time to travel 12 m is 40.00 ns, whereas for a kaon it would be 40.05 ns, so the *difference* is only 50 ps
- Modern detectors + readout electronics have resolution σ_t ~ few ns, fast enough for the LHC (bunch crossings 25 ns apart) but need σ_t < 1 ns to do useful TOF
- TOF gives good ID at low momentum
  Very precise timing required for p > 5 GeV
  ALICE has achieved ~70 ps using multigap resistive plate chambers

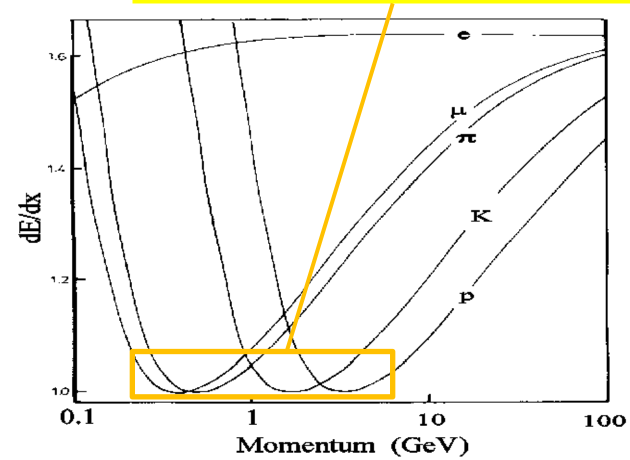


TOF difference for d = 12 m

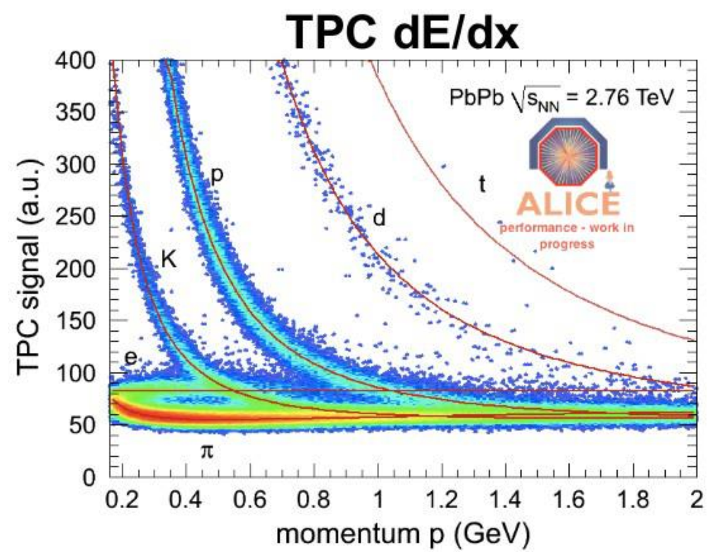


Ionization

Difficult in minimum-ionizing regime, where *dE/dx* is same

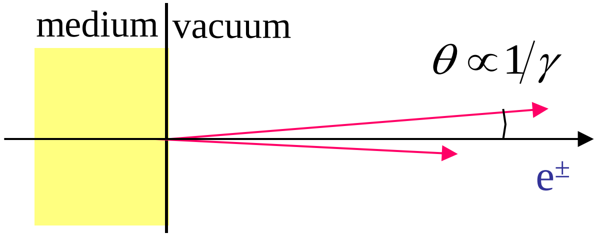


- Charged particles passing through matter knock out electrons from it: *ionization*
- Energy loss described by the Bethe-Bloch formula, which gives the universal velocity dependence: $dE/dx \propto \log(\beta^2\gamma^2) / \beta^2$
- This can be used to identify particles, particularly at low momentum where *dE/dx* varies rapidly
- *Advantage:* uses existing detectors needed for tracking (but requires the accurate measurement of the charge < ~5%)
- *Note:* these techniques all provide signals for charged leptons (e, μ) as well as π, K, p But $m_\mu \approx m_\pi$, so they are not well separated (dedicated muon detectors do a better job)



Transition radiation

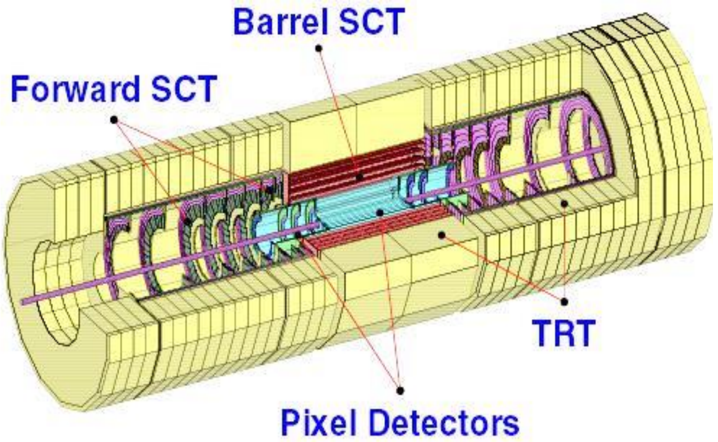
- Local speed of light in a medium with refractive index n is $c_p = c/n$
  If its relative velocity $\mathbf{v}/c_p$ changes, a particle will radiate photons:
  1. Change of |v| (passing through matter) $\rightarrow$ Bremsstrahlung radiation
  2. Change of direction $\mathbf{v}$ (in magnetic field) $\rightarrow$ Synchrotron radiation
  3. Change of refractive index n of medium $\rightarrow$ Transition radiation
- Energy emitted is proportional to the boost γ of the particle: $\Delta E = \alpha\, h\omega_p \gamma /3$
  Plasma frequency $h\omega_p$ depends on the electron density in the material
  ~ 20 eV for a low-Z material such as plastic (e.g. polypropylene)
  For a 10 GeV electron, $\gamma \sim 2 \times 10^4$, so $\Delta E \sim$ keV (X-ray energy)
- Radiation emitted in the very forward direction, in cone of angle $1/\gamma$ around the particle direction
  $\rightarrow$ photons will be seen in same detector as the ionization from the track

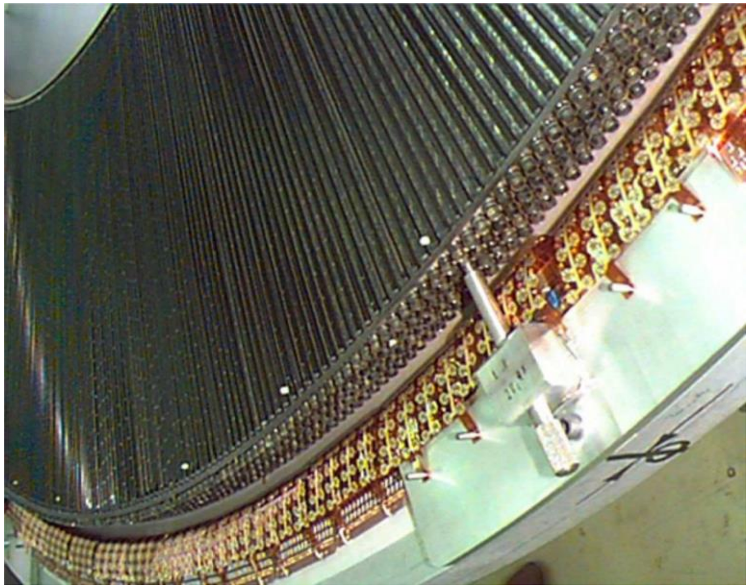


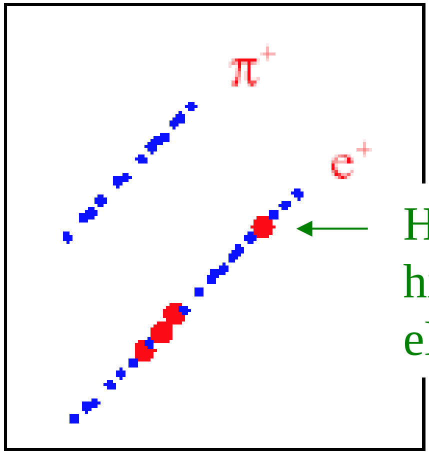
- Particularly useful for electron ID

ATLAS TRT

- Transition Radiation Tracker: also acts as a central tracker using ~ 300 000 straw tubes
- 15 μm-thin polypropylene foils (radiator) interleaved with straws → transition radiation
- Xe as active gas for high X-ray absorption

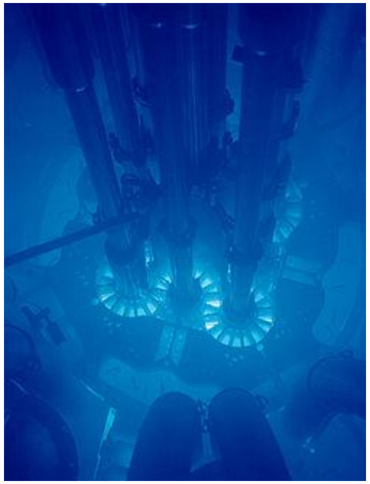






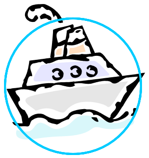
Cherenkov light

- Named after the Russian scientist Pavel Cherenkov who was first to study the effect in depth (Nobel Prize in 1958)
- From Relativity, nothing can go faster than the speed of light *c* (in vacuum) However, due to the refractive index *n* of a material, a particle *can* go faster than the *local* speed of light in the medium $c_p = c/n$
- Analogous to the bow wave of a boat travelling over water or the sonic boom of an aeroplane travelling faster than the speed of sound



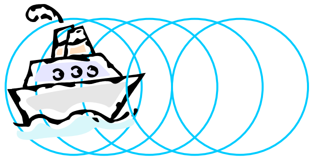
Propagating waves

- A stationary boat bobbing up and down on a lake, producing waves



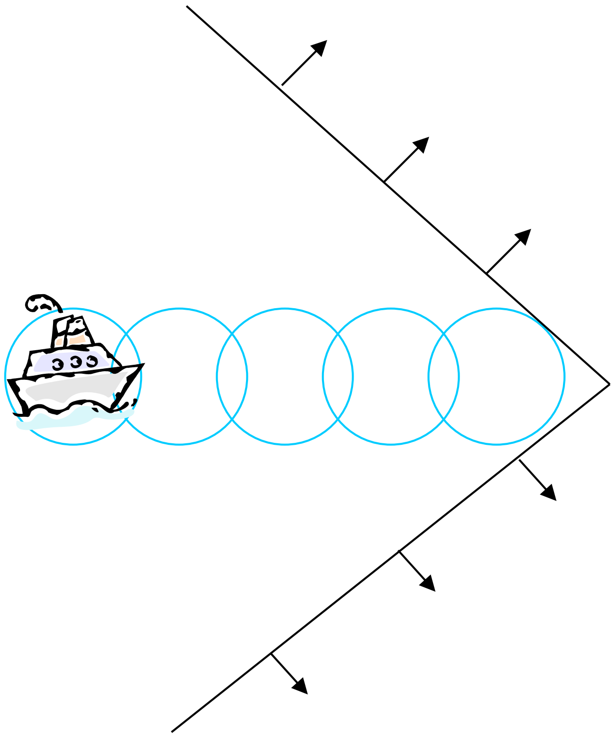
Propagating waves

- Now the boat starts to move, but slower than the waves
- No coherent wavefront is formed



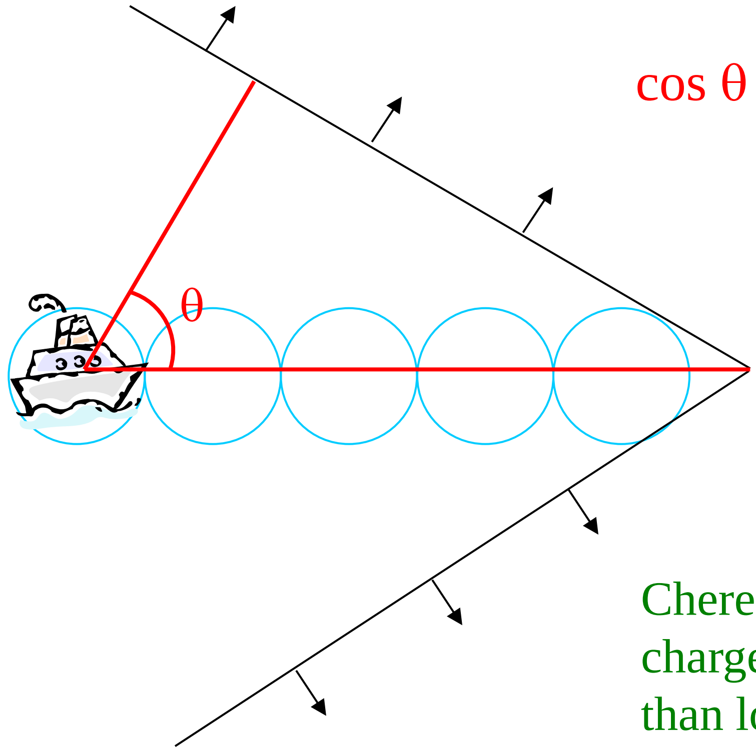
Propagating waves

- Next the boat moves faster than the waves
- A coherent wavefront is formed



Propagating waves

- Finally the boat moves even faster
- The angle of the coherent wavefront changes



$$\cos \theta = \frac{v_{wave}}{v_{boat}}$$

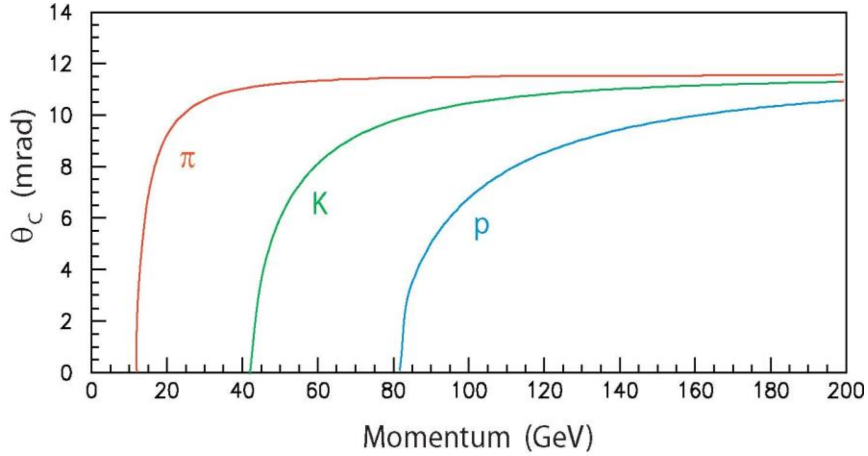
Cherenkov light is produced when charged particle ($v_{boat} = \beta c$) is faster than local speed of light ($v_{wave} = c/n$)

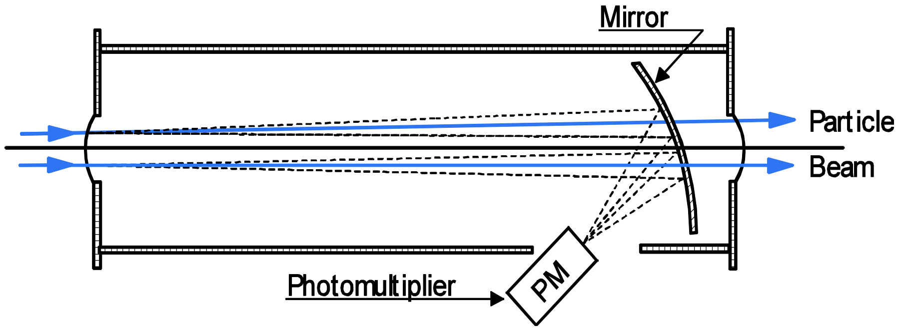
$\rightarrow \cos \theta_C = 1 / \beta n$

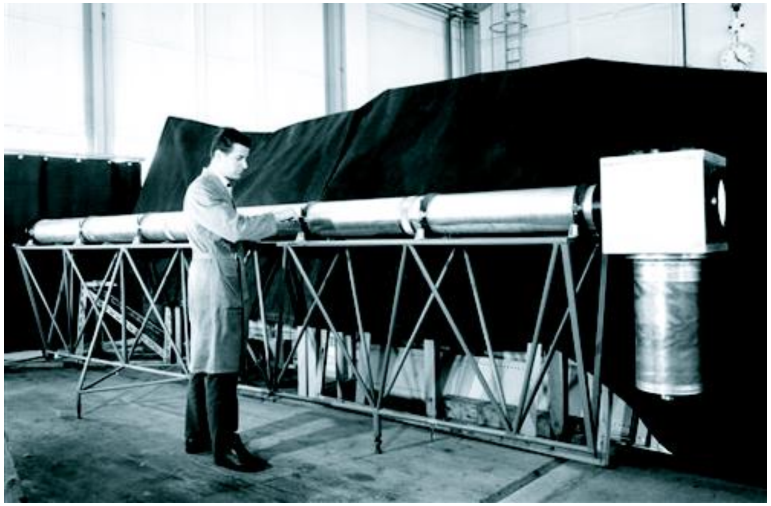
Threshold counters

- There is a threshold for Cherenkov light production at $\beta = 1/n$
  - Tracks with $\beta < 1/n$ give no light
  - Tracks with $\beta > 1/n$ give light
- By choosing a medium with suitable refractive index, can arranged that e.g. π produces light, but K does not

For Ne gas ($n = 1.000067$)

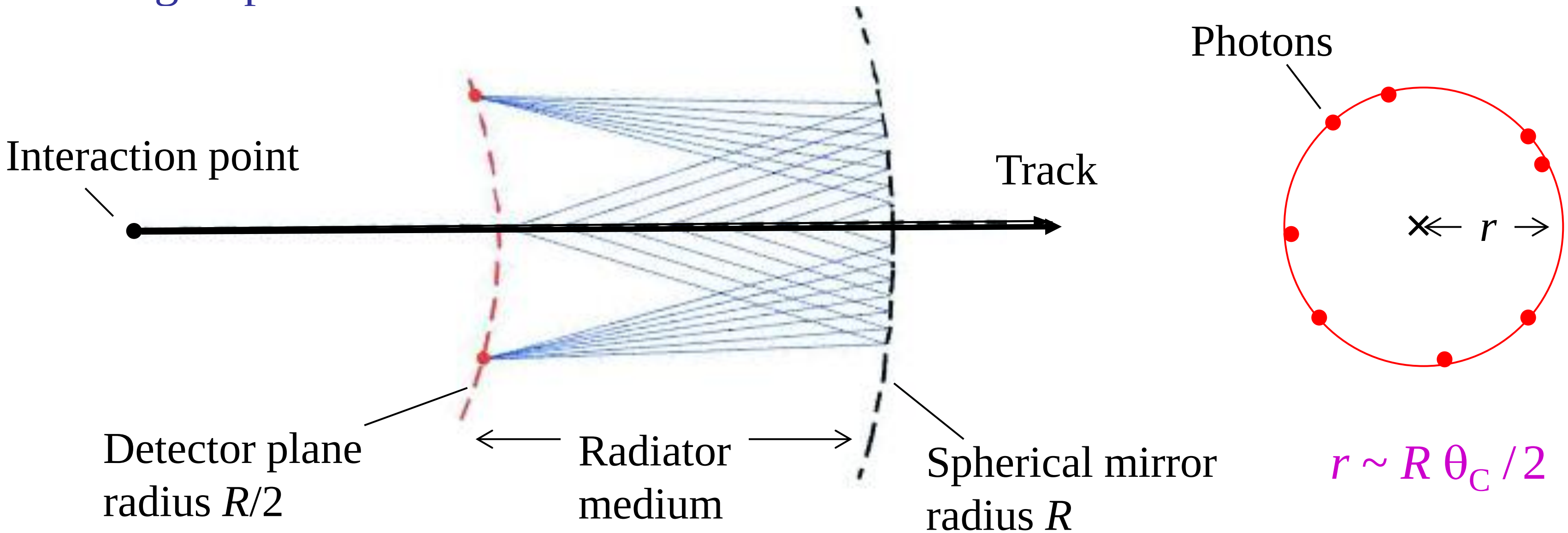






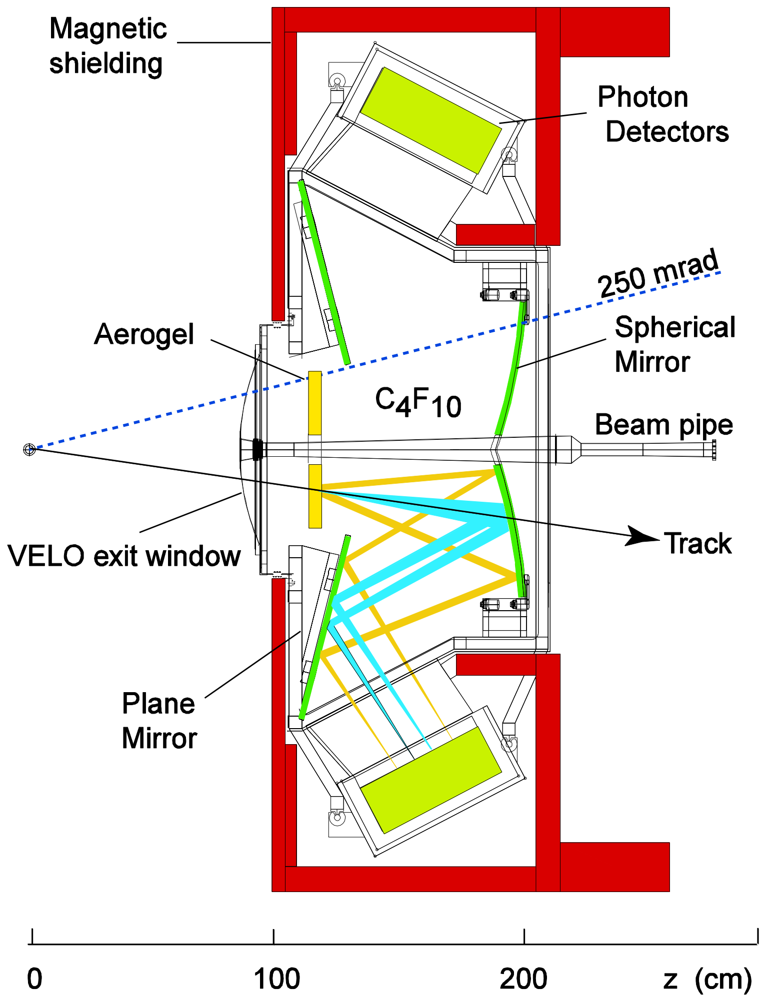
Ring imaging

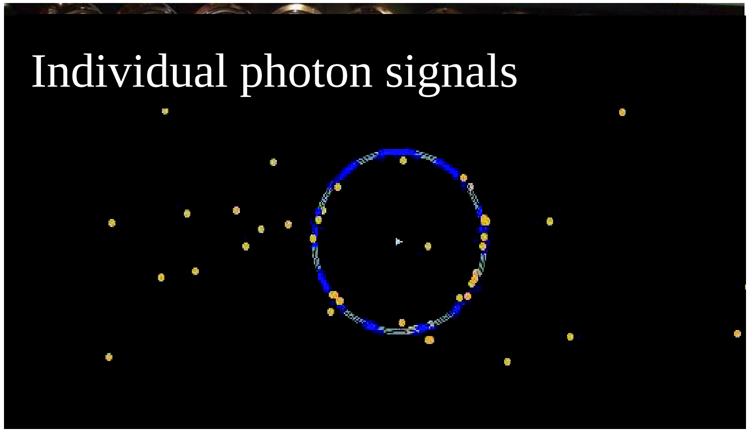
- To extract more information the Cherenkov cone can be imaged into a ring, using a spherical mirror

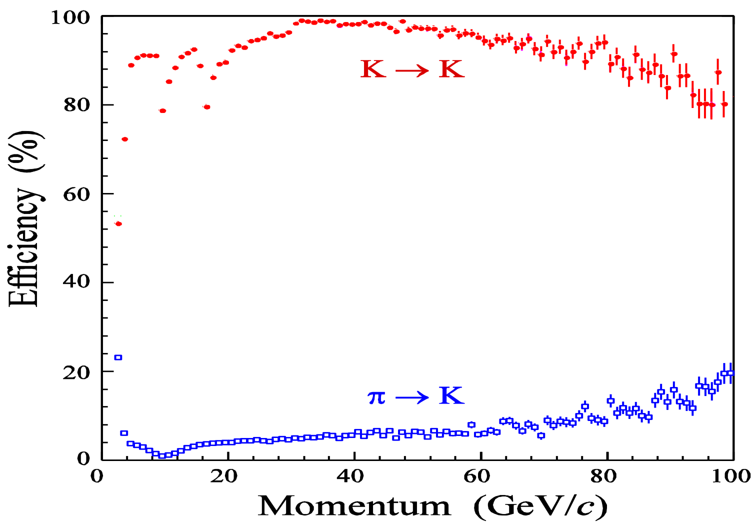


- Measuring the ring radius r allows the Cherenkov angle θ_C to be determined
  This is principle of Ring-imaging Cherenkov (RICH) detectors, widely used to provide charged hadron particle ID over a wide momentum range

LHCb RICH detector

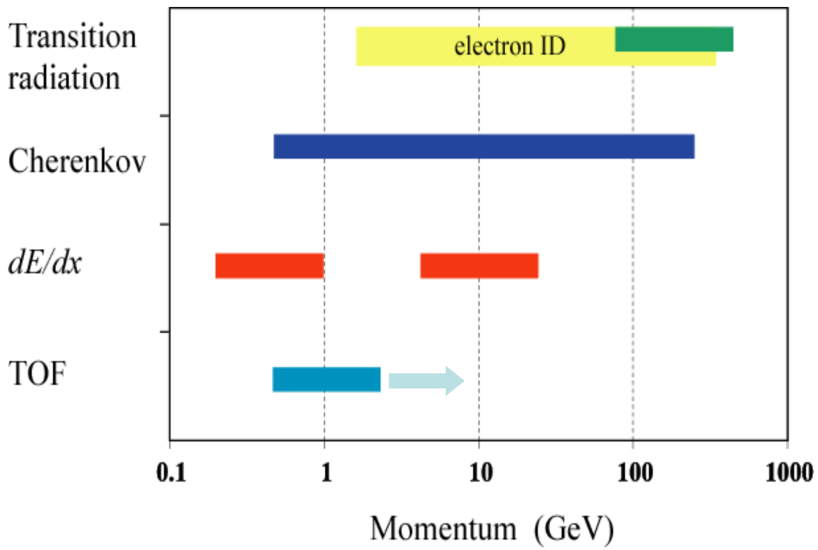






Summary

- Particle ID is a crucial element of high energy physics experiments, along with tracking and calorimetry
- Distinguishing e, γ, μ, and quark jets is achieved by most experiments using tracking + calorimeters + muon detectors
- Identification of charged hadrons (π, K, p) requires specialized detectors
- Important for experiments studying flavour/hadronic physics
- Different techniques used depending on momentum range:

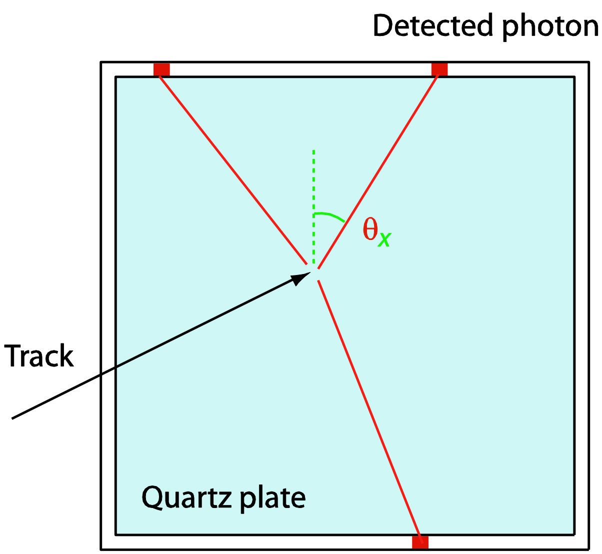


- There is always room for new ideas, for the next generation of experiments Maybe one of *your* ideas?

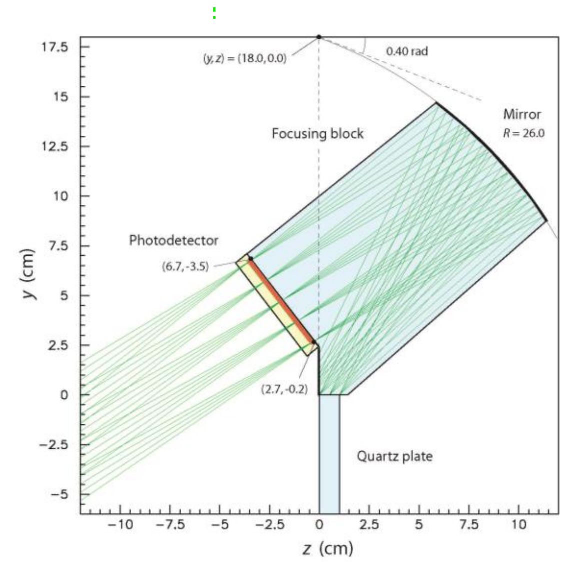
Additional material

- I am currently working on the design of a new concept for Particle ID for the upgrade of LHCb (planned to follow after ~ 5 years of data taking)
- Uses a large plate of quartz to produce Cherenkov light, like a DIRC
  But then identify the particles by measuring the photon arrival times
  Combination of **TO**F and **RICH** techniques → named TORCH
- Detected position around edge gives photon angle (θ_x)
- Angle (θ_z) out of plane determined using focusing
- Uses fast photon detectors (~ 50 ps)

See poster by
Lucia Castillo Garcia



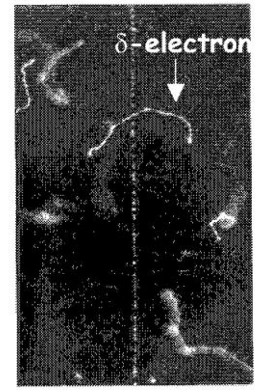
Front view

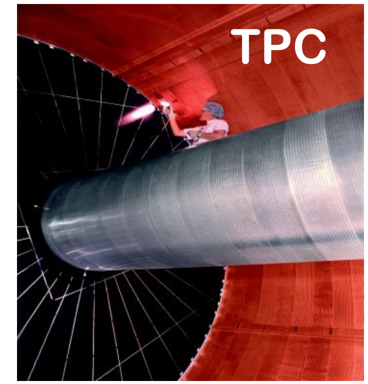


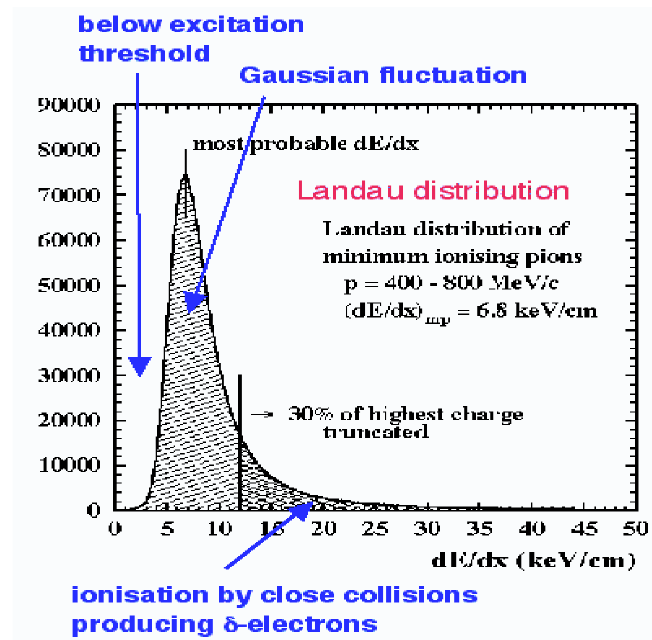
Side view

dE/dx

- Ionization is used in ~ all tracking detectors (see the Tracking lectures)
  Tracking measures the *position* of ionization for particle ID measure the *amount (dE/dx)* = Energy deposited per unit track length
- This is subject to large fluctuations due to ejection of δ-electrons (Landau distribution)
- To avoid bias from the long tail, best to have many independent samples of the ionization, and perform a truncated mean
- Excellent *dE/dx* measurements achieved with TPCs (many samples) and silicon detectors (good energy resolution)







ID performance

- The number of standard deviations separation for a time of flight detector is

$$N_\sigma = \frac{|m_1^2 - m_2^2|\, d}{2\, p^2\, \sigma_t\, c} \qquad \text{(TOF)}$$

- Note the similarity to the expression for RICH detectors:

$$N_\sigma = \frac{|m_1^2 - m_2^2|}{2\, p^2\, \sigma_\theta \sqrt{n^2-1}} \qquad \text{(RICH)}$$

- However, in that case there is an "amplification" factor of $1/\sqrt{n^2-1}$ which allows RICH detectors to reach high momentum coverage (with a suitable n)
- Combination of TOF with *dE/dx* can help remove ambiguities: