Particle Identification

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Review of the techniques of Particle Identification used in High Energy Physics experiments in two lectures

I am a member of LHCb, one of the four major experiments at the LHC, and will mostly take examples from the LHC

ICFA Instrumentation School (Cuba) 1-2 December 2017

Contents

References

- These lectures are an updated version of ones I gave 7 years ago, at a previous ICFA school in Argentina: http://fisica.cab.cnea.gov.ar/particulas/html/icfa/
- Those were in turn based on material from earlier ICFA schools in particular the lectures of E. Nappi and J. Engelfried
  Other interesting lectures can be found here, particularly by O. Ullaland
  http://lhcb-doc.web.cern.ch/lhcbdoc/presentations/lectures/Default.htm
- The Particle Data Group provides useful reviews: http://pdg.lbl.gov/
  Talks at the RICH series of workshops give more details: http://rich2016.ijs.si/
  Information about the LHC experiments: http://user.web.cern.ch/
- There is unavoidably some overlap with the other lectures at this school so those bits can be treated as revision…
- If you have questions (or corrections…) please let me know
  You can contact me after the school by email: Roger.Forty@cern.ch

1. Introduction

- **Particle Identification** (ID) is a crucial aspect of most High Energy Physics experiments: the detectors used depend on the physics under study
- In a typical experiment two beams of particles collide within the detectors (or a single beam collides with a fixed target)
  The resulting *events* should be reconstructed as fully as possible, where usually many particles emerge from the interaction point
- **Tracking** detectors determine whether the particles are charged, and (in conjunction with a magnetic field) measure their momentum and the sign of their charge
- **Calorimeters** measure the energy of particles, determine whether they have electromagnetic or hadronic interactions, and detect neutral particles
- What other information do we need?

  What *type* of particles are produced → "particle identification"

Elementary particles

- The elementary particles of the Standard Model are the following:

Type	**Name**			**Charge**	**Spin**
Generation:	1st	2nd	3rd		
Leptons: *charged*	**e**	**μ**	**τ**	–1	1/2
neutral	**ν_e**	**ν_μ**	**ν_τ**	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**	0	1
			W	±1	1
Higgs boson	**H**			0	0

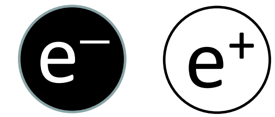
Fermions *"building blocks" of matter* (leptons and quarks)

Bosons "force carriers" (gauge bosons and Higgs boson)

- Plus their respective antiparticles…

Antimatter

- Each elementary particle has a corresponding antiparticle with opposite quantum numbers such as their charge



- Although very rare in the every-day world, antiparticles are abundantly produced in high-energy collisions, in ≈ equal amounts as particles
  Energy is transformed into matter ($E = mc^2$) but particles and antiparticles are produced in pairs e.g. photon conversion: $\gamma \rightarrow e^+ e^-$

- There are three possible discrete transformations:

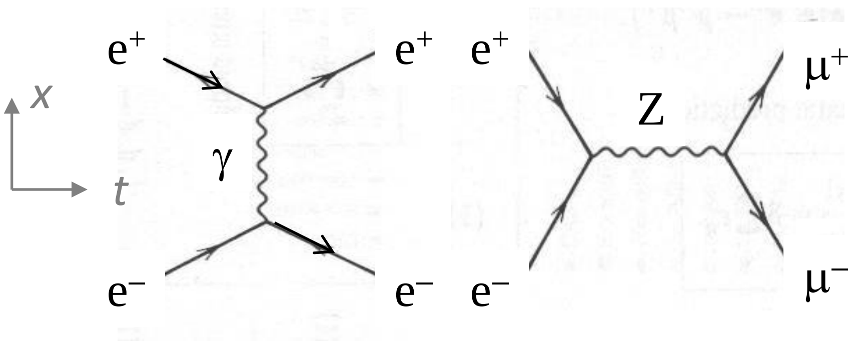
C = charge conjugation	particles ↔ antiparticles
P = parity "reflection"	spatial coordinates $x, y, z \rightarrow -x, -y, -z$
T = time reversal	time $t \rightarrow -t$

- Combined operation of all three = **CPT**
  Invariance under CPT is a fundamental property of ≈ all field theories, it implies that particles have exactly the same mass as their antiparticles

- How are the elementary particles identified? → Discuss each in turn

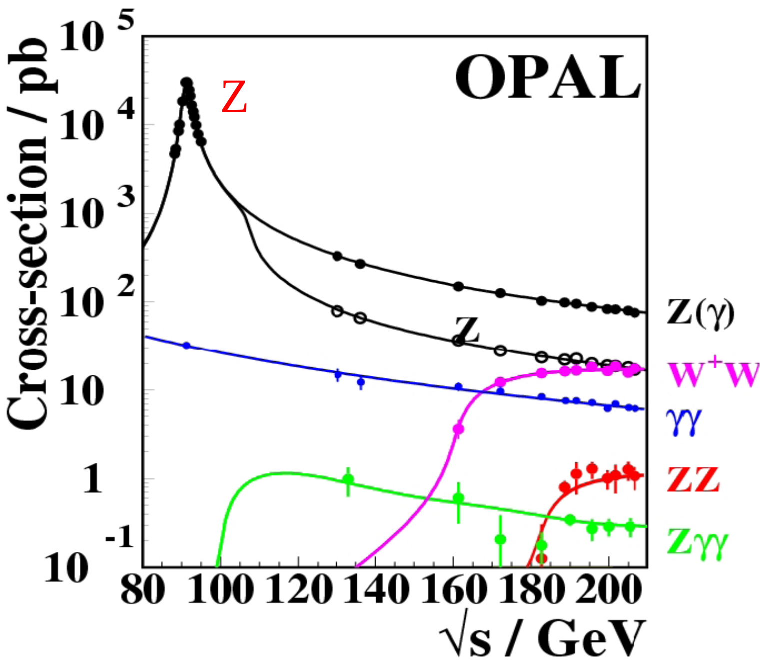
Gauge bosons

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



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

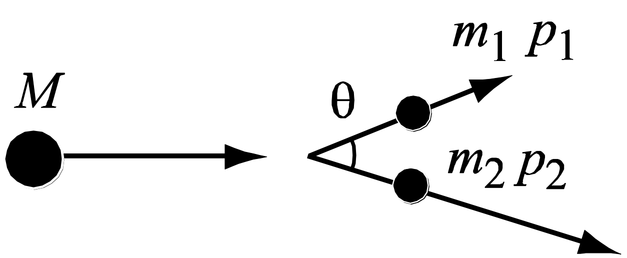
Cross-section for $e^+ e^-$ collisions (at LEP, the previous collider to the LHC at CERN)



Lifetime determined from resonance width using the Uncertainty Principle
$\Delta E \cdot \Delta t \sim \hbar \rightarrow 10^{-25}$ s

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:

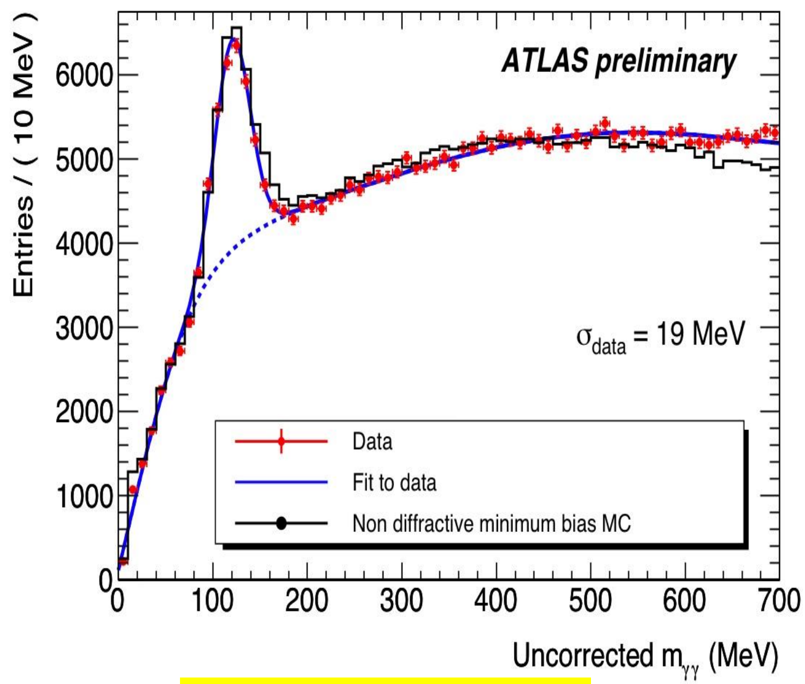
$$M^2 = m_1^2 + m_2^2 + 2(E_1E_2 - p_1p_2\cos\theta)$$

$\rightarrow$ 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

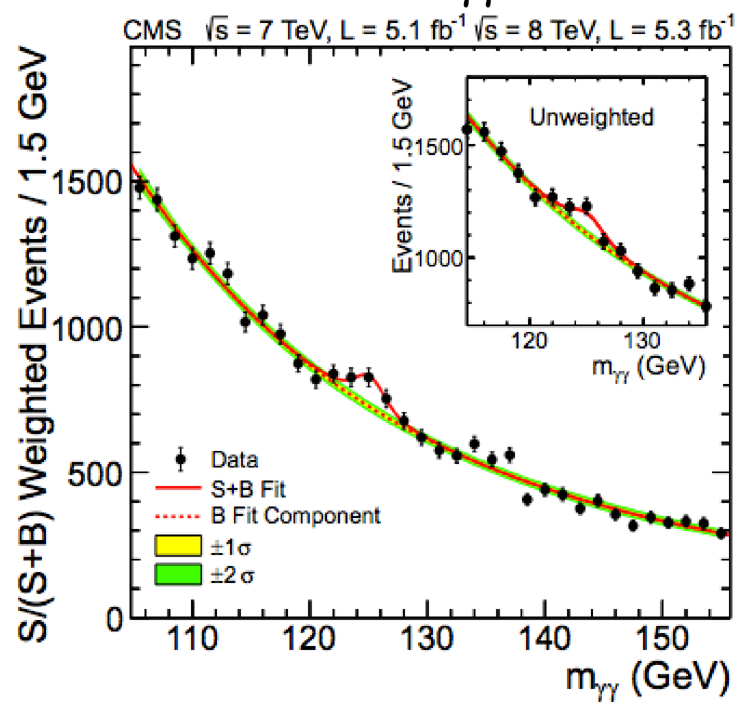
Mass reconstruction

- Typical example of reconstruction of a particle decay: $\pi^0 \to \gamma\gamma$
  one of the first composite particles reconstructed in the LHC experiments
- Technique also used to search for more exciting signals, like the **Higgs boson**
  Last missing piece of the Standard Model, discovered 5 years ago at the LHC

$\pi^0 \to \gamma\gamma$



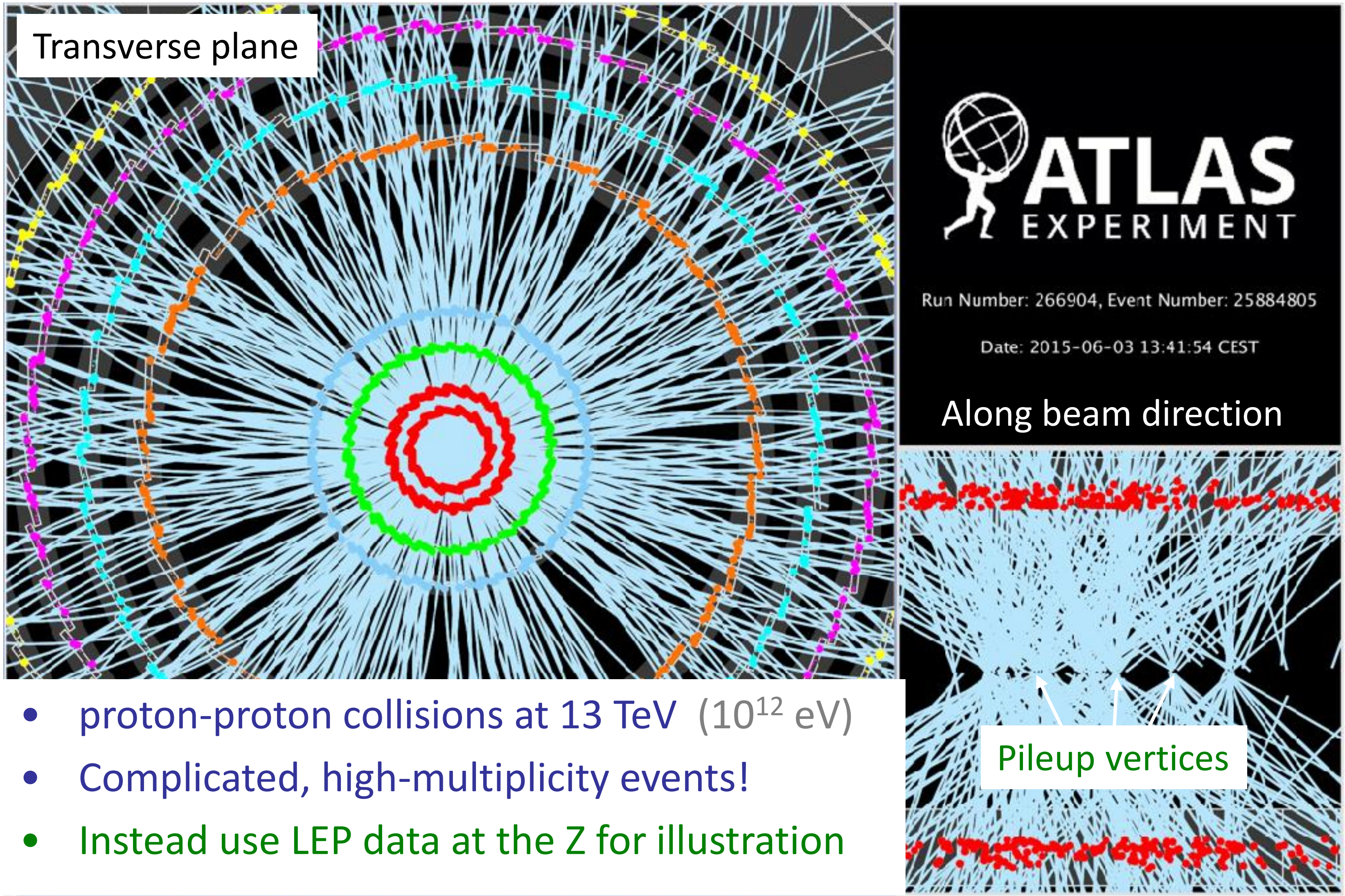
H $\to \gamma\gamma$



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

$m(H)$ = 125 GeV

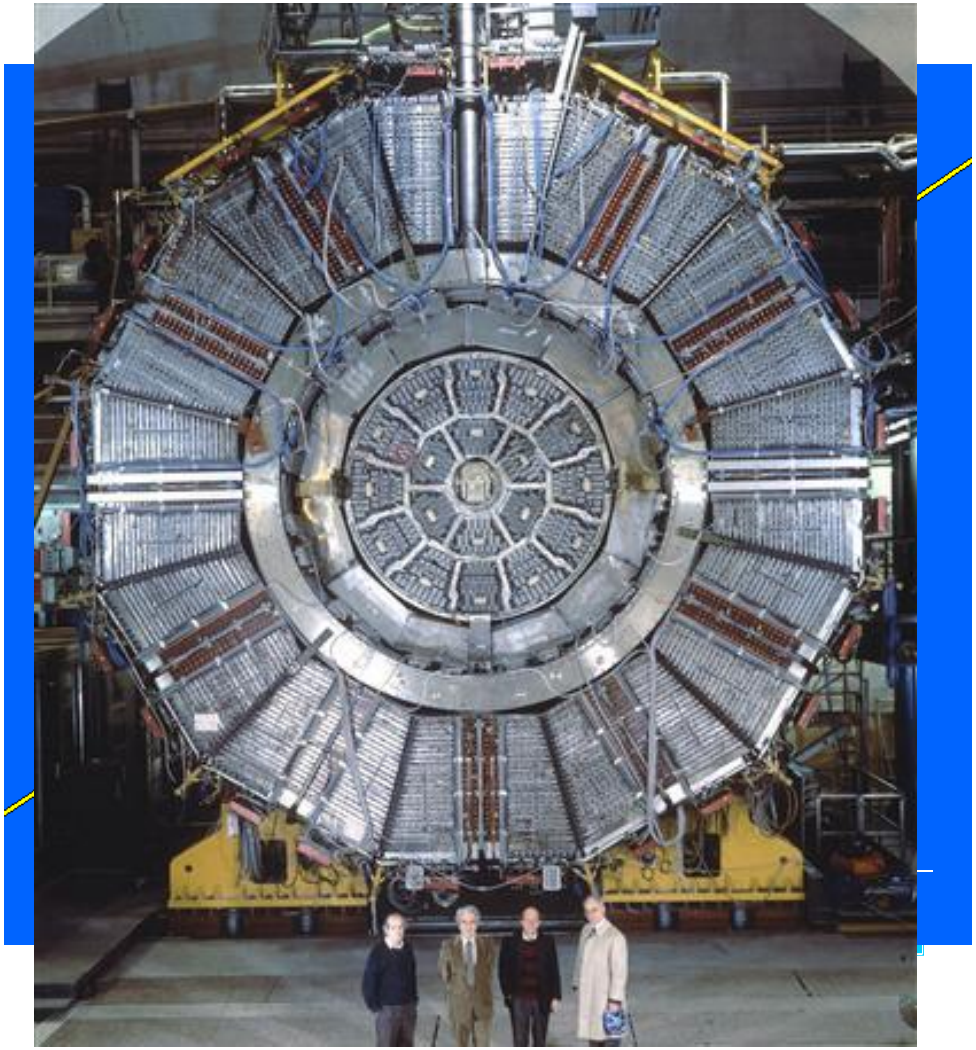
A typical LHC event



- proton-proton collisions at 13 TeV (10^{12} eV)
- Complicated, high-multiplicity events!
- Instead use LEP data at the Z for illustration

Event display

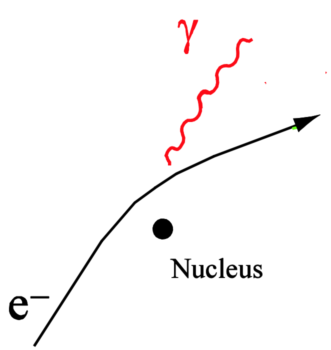
- Use real events to illustrate the different particle signatures: $e^+ e^- \to Z \to f\bar{f}$
- **ALEPH** experiment at LEP took data from 1989-2000: typical layout of a General Purpose detector, with concentric detector layers
- Display is fish-eye view in the plane transverse to the beams, showing hits in the different detectors

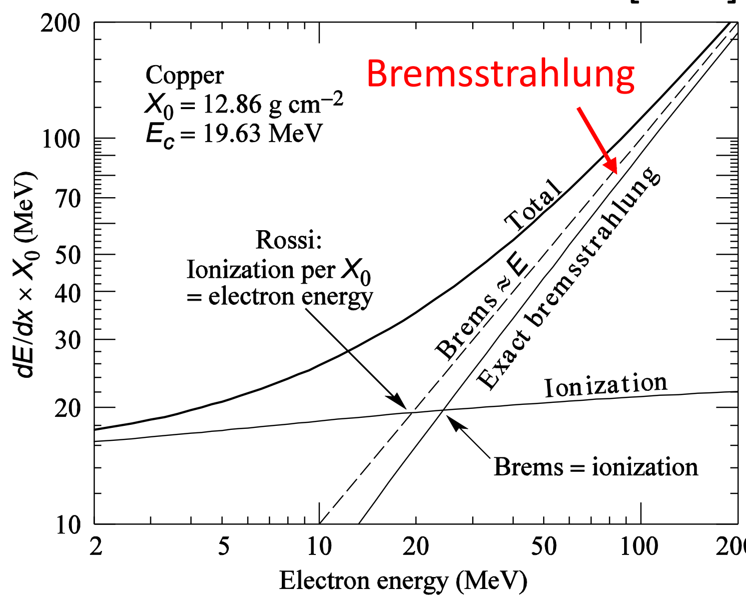


2. Identification techniques

- 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

[PDG]

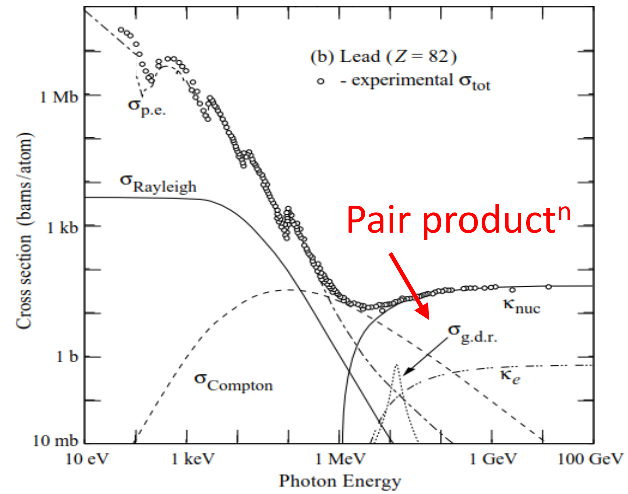




- $\Delta E \propto 1/m^2$
  Dominates for electrons with
  E > 100 MeV

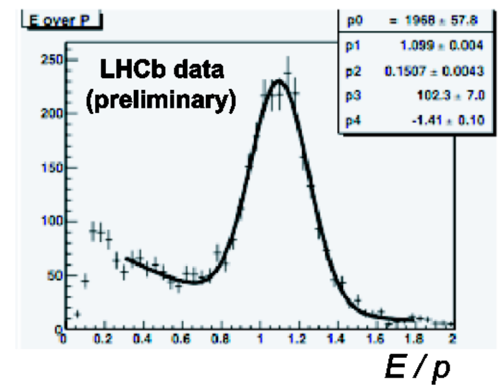
e/γ identification

[PDG]



- When incident on matter at high energy, **photons** convert to e^+e^- pairs
  Since the electrons (and positrons) produce more photons by Bremsstahlung, a shower develops of $e^\pm$ and γ, until the energy of the incident particle has been used up
  (→ see the Calorimeter lectures)

- **Radiation length** X_0 = mean distance to reduce energy by $1/e$, e.g. X_0 = 1.76 cm for Fe, so these *electromagnetic* showers are compact

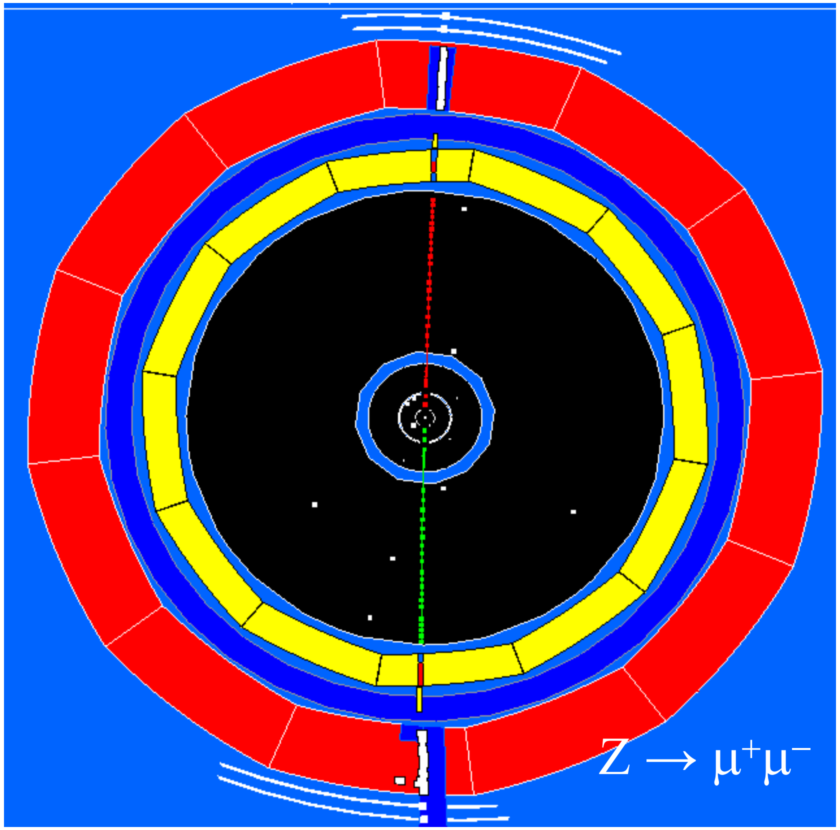


- Showers are similar for electrons and photons
  Distinguished by the existence (or not) of a track associated to the shower

- For the electron, E (energy from EM calorimeter) and p (momentum from tracker) should be equal: $E/p = 1$ (not case for other charged particles)

Muons

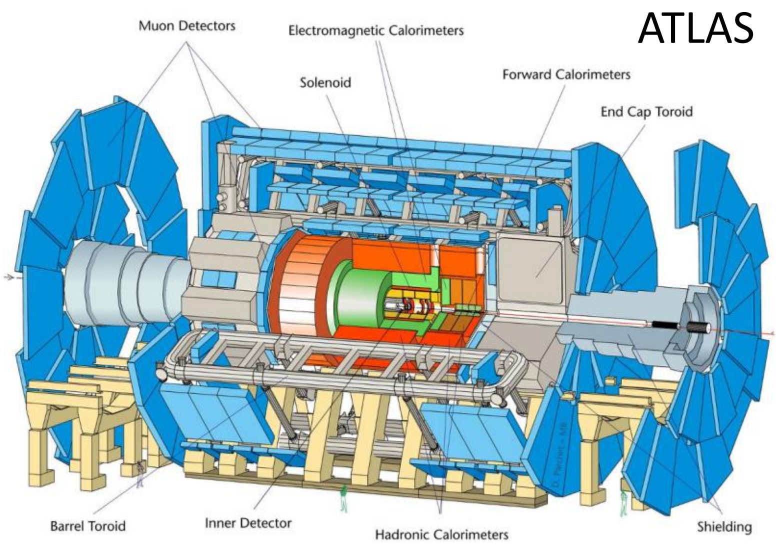
- **Muons** act like heavier versions of the electron, with mass 105.7 MeV
- They decay to electrons $\mu^- \to e^- \bar{\nu}_e \nu_\mu$ with (proper) lifetime τ_μ = 2.2 μs
- Distance they travel (on average) before decay: $d = \beta\gamma c\tau_\mu$
  where *velocity* $\beta = v/c$
  boost $\gamma =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

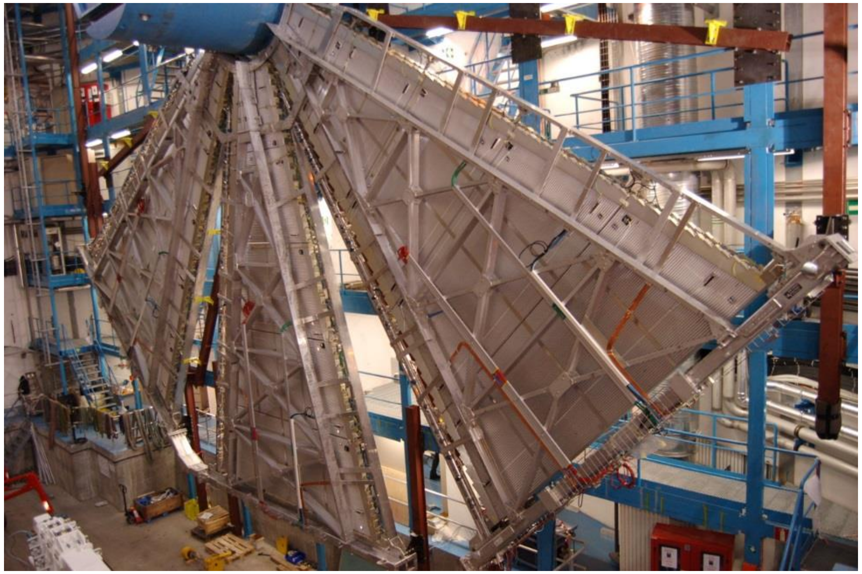


→ most penetrating charged particle

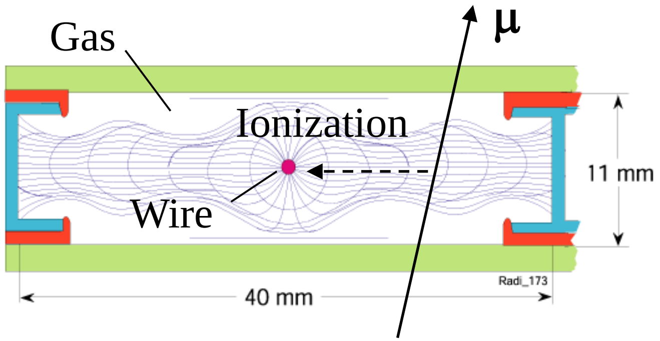
Muon detectors

- Muon detectors are sited on the outside of an experiment, and tend to dominate their appearance



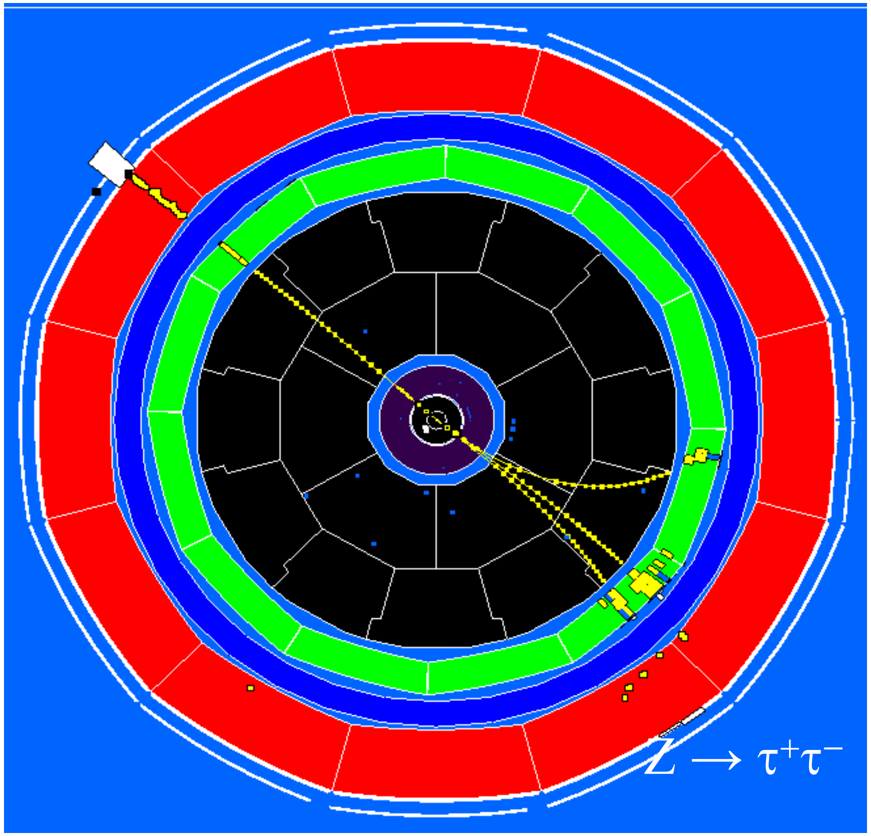


- They must be inexpensive, low granularity but precise enough for *p* measurement e.g. wire chambers with long drift volume (cross-section of a CMS chamber shown)



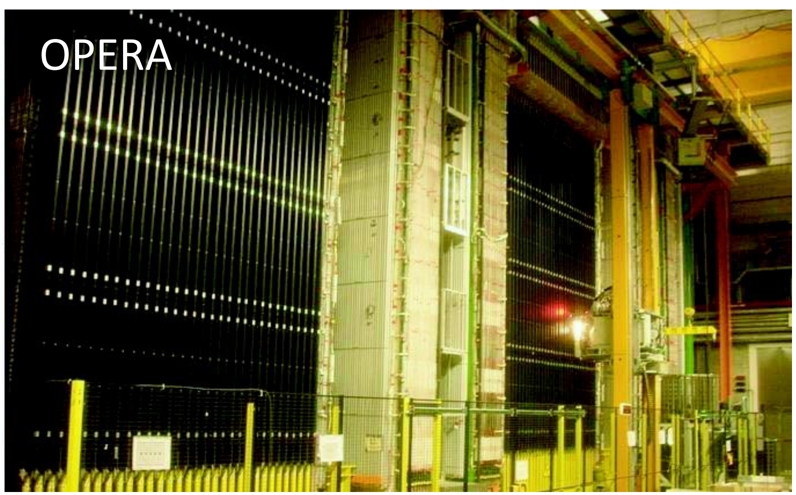
Tau leptons

- **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
- This is 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 (i.e. no track) and only *weak* interaction → pass though matter easily
  Interaction length $\lambda_{int} = A/(\rho\sigma N_A)$, cross-section $\sigma \sim 10^{-38}$ cm$^2 \times E$ [GeV]
  → 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)
  Needs care: this can also come from instrumental effects (or new physics!)
- Nevertheless their interactions can be detected if you produce enough of them, and the detector is sufficiently massive

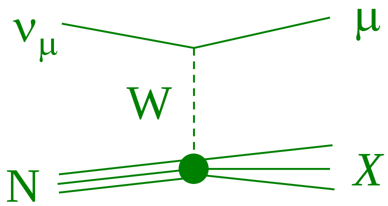


> 1 kton of instrumented target mass!

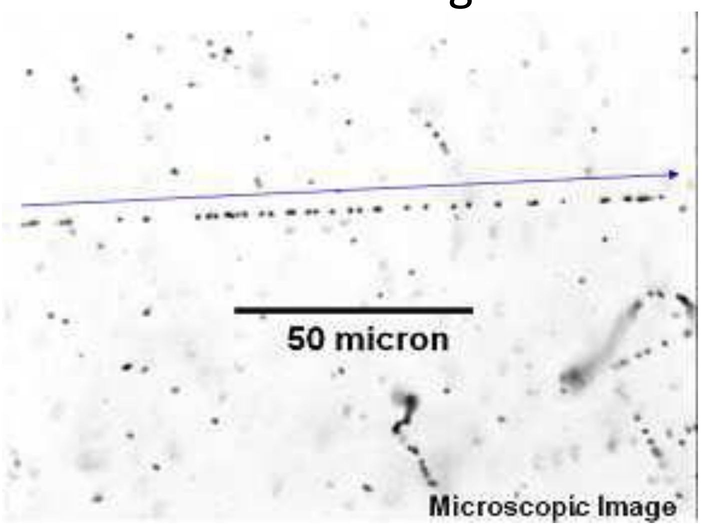
DUNE will be even bigger, aiming for 40 kton of liquid argon

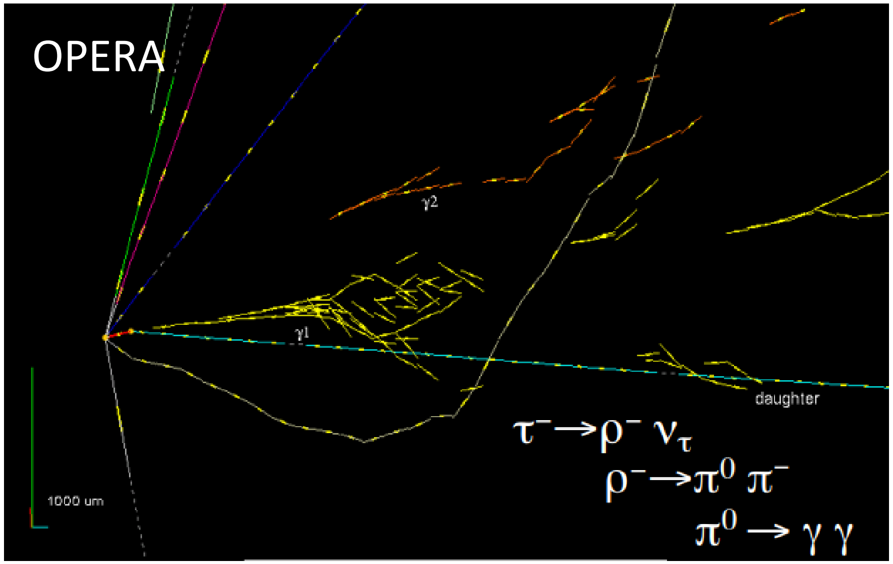
Neutrino flavours

- Can even determine the neutrino flavour (ν_e, ν_μ, ν_τ) via their charged-current interaction: $\nu_\mu N \to \mu^- X$, etc
- **OPERA** searched for ν_τ created by neutrino oscillation from a ν_μ beam (sent 730 km from CERN to Italy)
- Tau decay seen as track kink in a high precision emulsion detector, interleaved with lead sheets to provide the high mass of the target



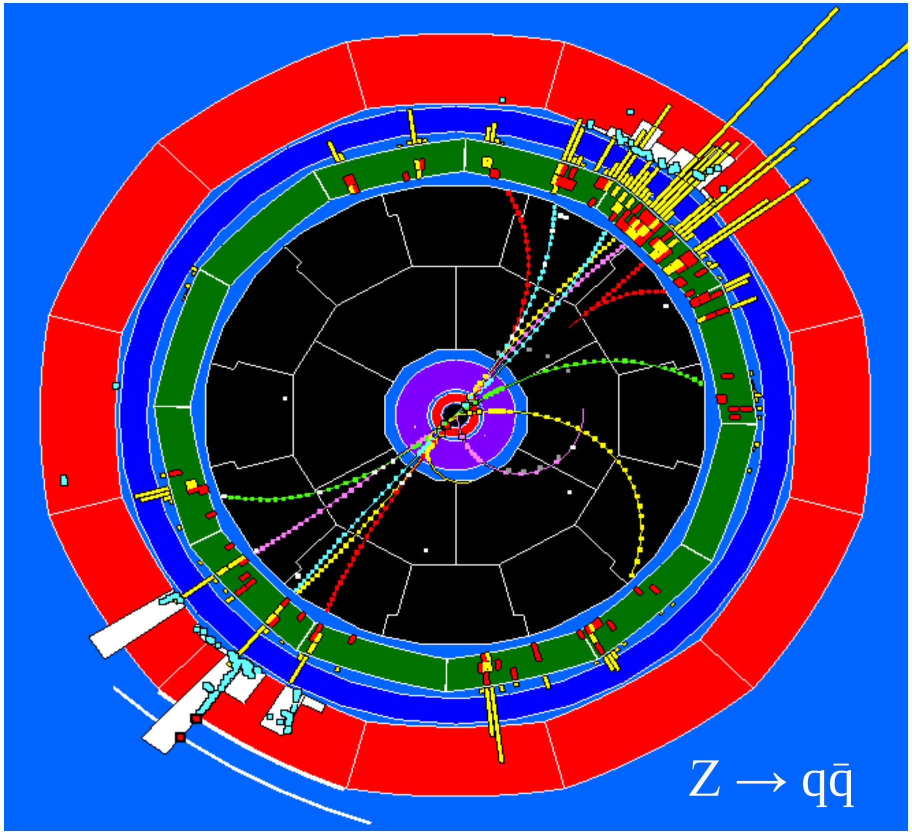
Emulsion image





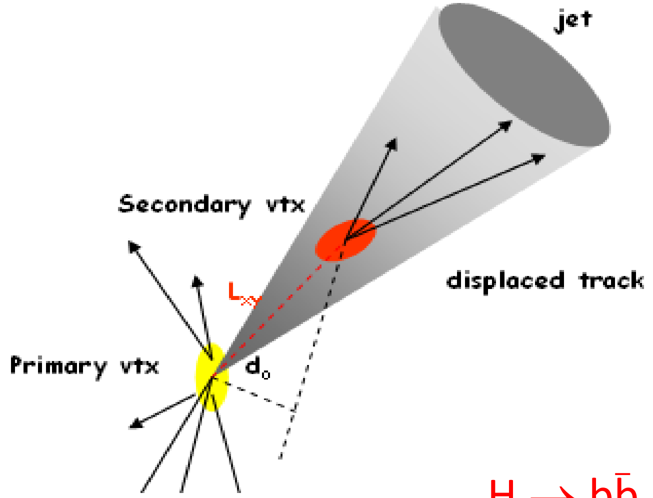
Quarks

- **Quarks** feel the strong interaction, mediated by gluons
- Not seen in the detector, due to 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 such hadrons
- Jets initiated by quarks & gluons and are difficult to distinguish: **gluon** jets tend to be wider, and have a softer particle spectrum

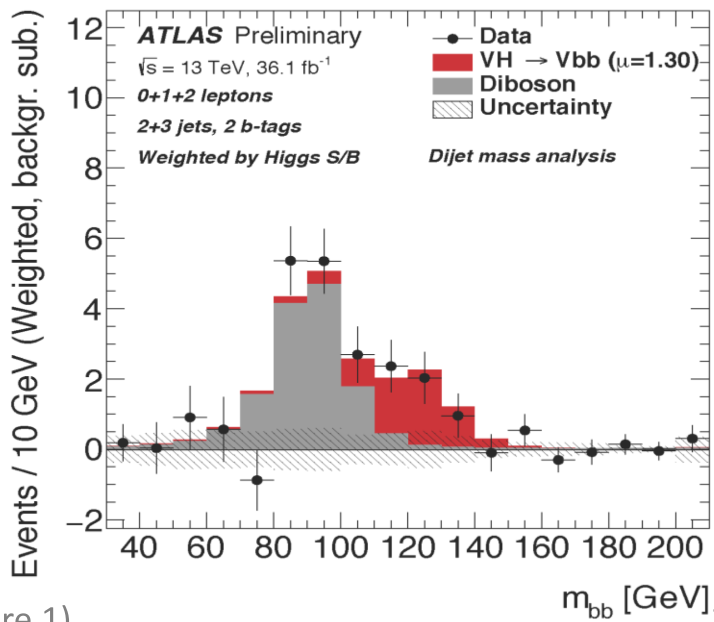


Jet reconstruction

- 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 combining *pairs* of particles that give the lowest invariant mass, and iterating
- 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. when studying Higgs decays:



$H \rightarrow b\bar{b}$



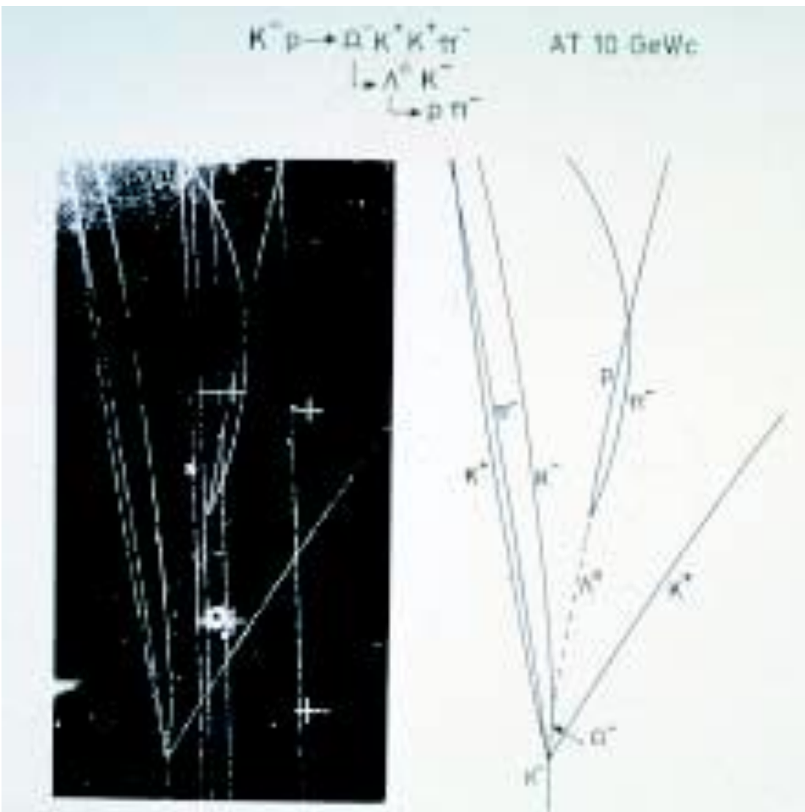
Hadrons

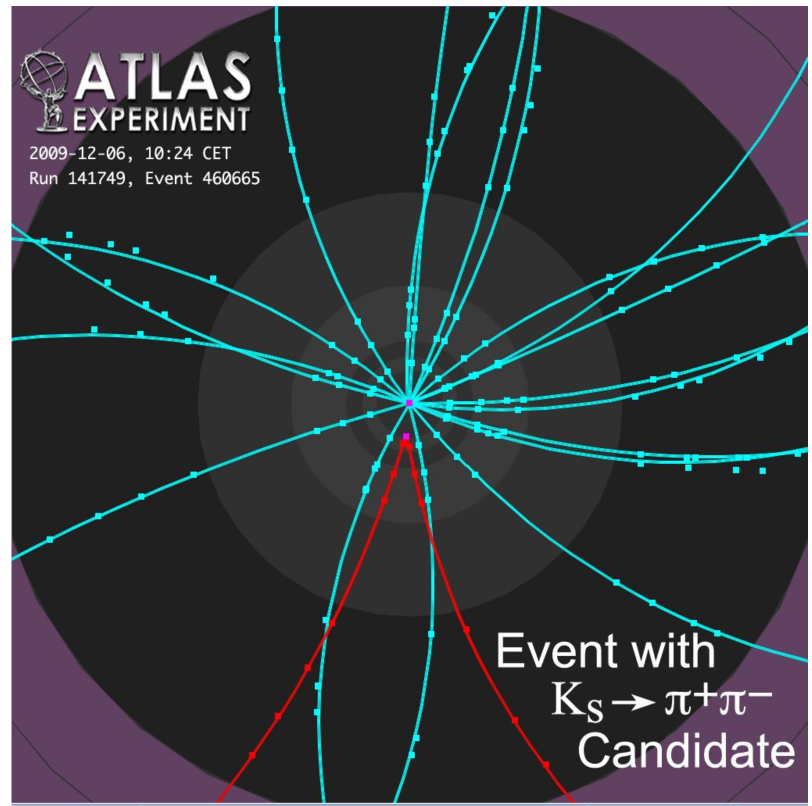
- Instead of making do with jet reconstruction, often the physics under study requires the identification of *individual* hadrons
- There are hundreds of hadrons, all listed in the PDG (~ 1000 pages long)
- However, most are unstable, and decay into a few long-lived particles:

Particle	m [MeV]	Quarks	Main decay	Lifetime	$c\tau$ [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

V^0s

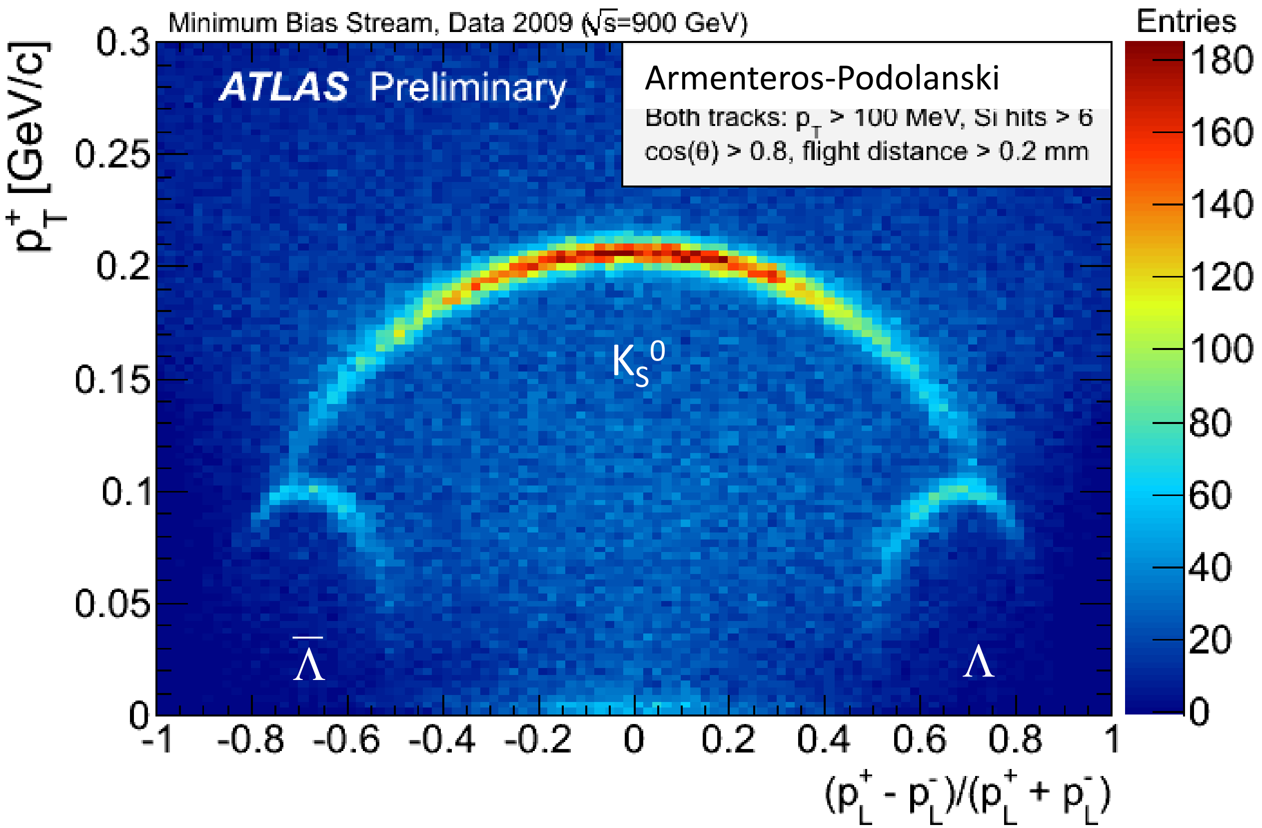
- $K_S{}^0$ and Λ are collectively known as V^0s, due to their characteristic two-prong decay vertex





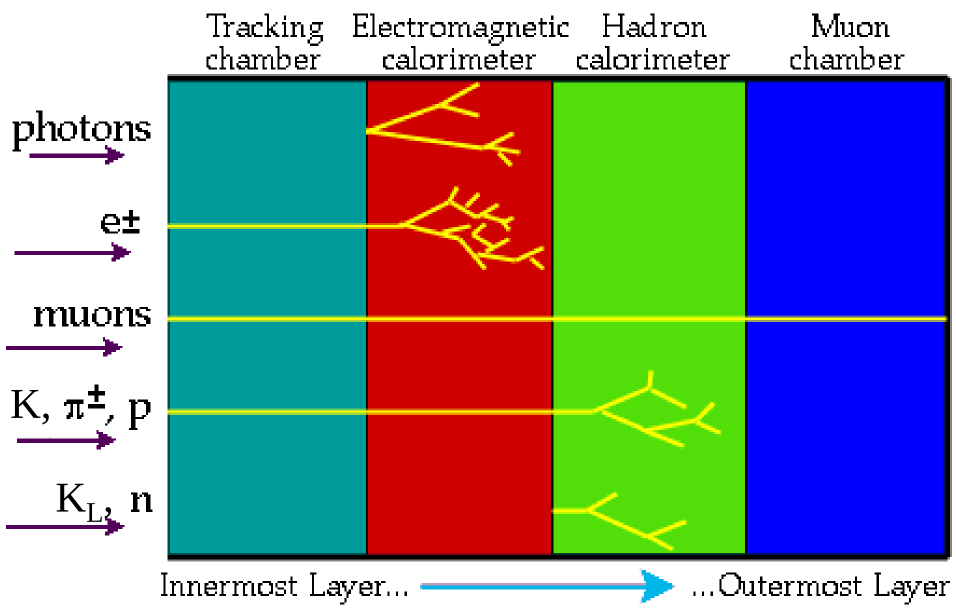
V^0 reconstruction

- 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

- Long-lived neutral hadrons (K_L^0 and n) 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

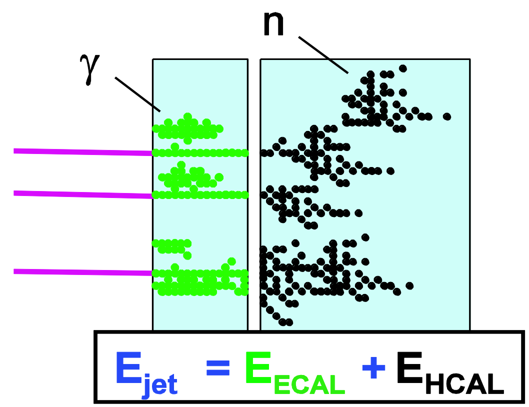


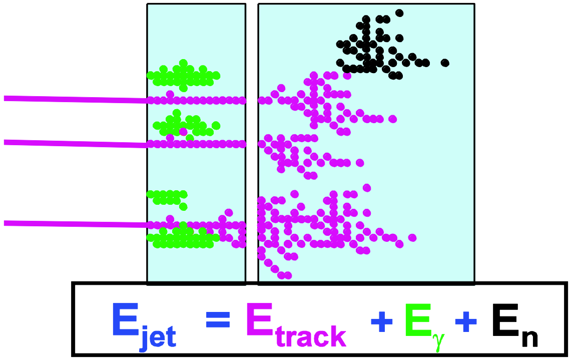
Particle Flow

Meeting point of calorimetry, tracking & particle ID

- In a typical jet
  - 60 % of jet energy is from charged hadrons
  - 30 % from photons (mainly from π^0)
  - 10 % from neutral hadrons (n and K_L^0)
- The traditional approach to jet reconstruction:

  Measure all of jet energy in calorimeters
  → ~ 70 % of energy measured in HCAL
  HCAL limits jet resolution: $\Delta E/E \sim 60\% / \sqrt{E}$





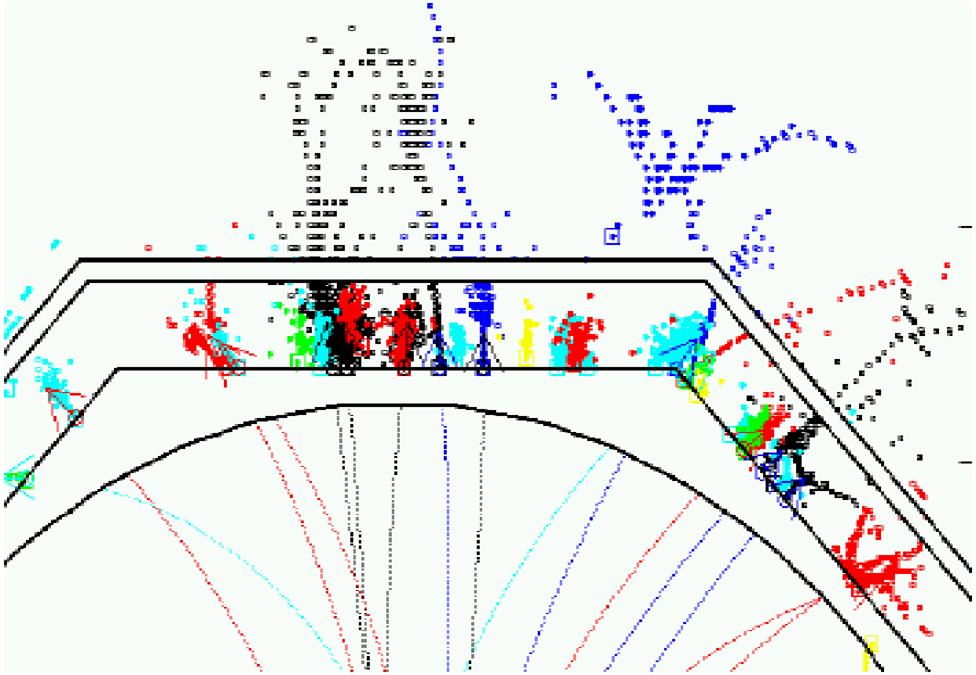
- **Particle Flow** approach:
  - Charged particles well measured in tracker
  - Photons in ECAL
  - Neutral hadrons (only) in HCAL

→ Only 10 % of jet energy taken from HCAL: $\Delta E/E \sim 30\% / \sqrt{E}$ can be achieved

Particle-flow calorimetery

- The main remaining contribution to the jet energy resolution comes from the confusion of contributions, from overlapping showers etc.
- Most important is to have high *granularity* of calorimeters to help the (complicated) pattern recognition
- This is the approach being studied for detectors at a future e^+e^- linear collider (e.g. ILC or CLIC)

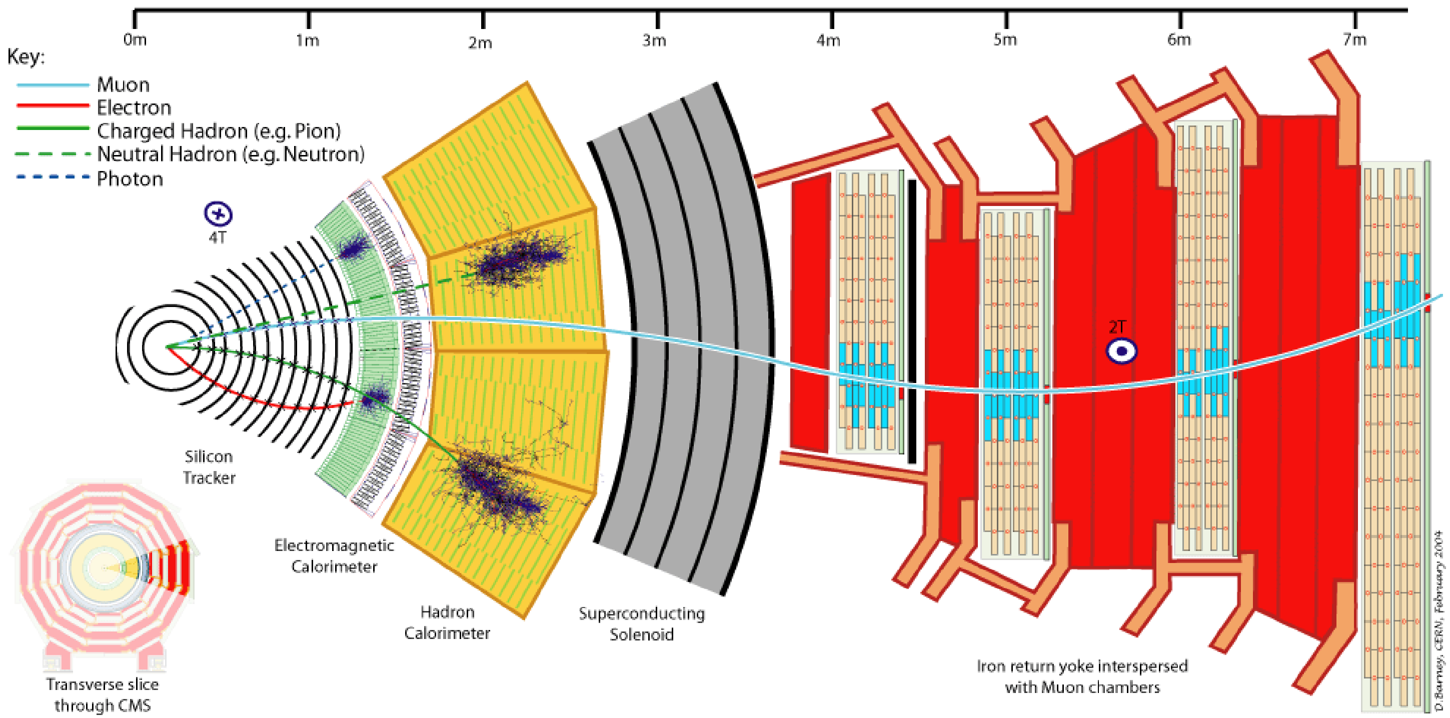
Simulated event in an ILC detector



Similar technology has recently been adopted for the CMS forward calorimeter in the upgrade (HGC, 6M ch!)

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

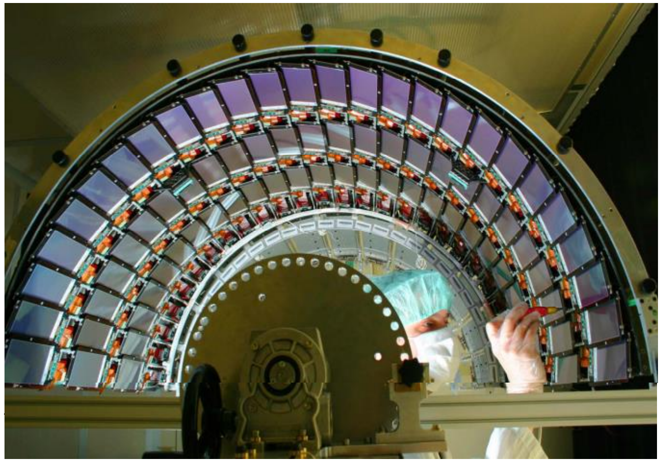


- One task that such General Purpose detectors do *not* do very well is to identify different charged hadrons (π, K, p)

Why not?

- General Purpose experiments like ATLAS and CMS typically focus on **high p_T** (transverse momentum) physics, such as decays of new heavy particles
- At high p_T the quarks and gluons produced in the event all form jets, typically made up of many hadrons

CMS vertex detector

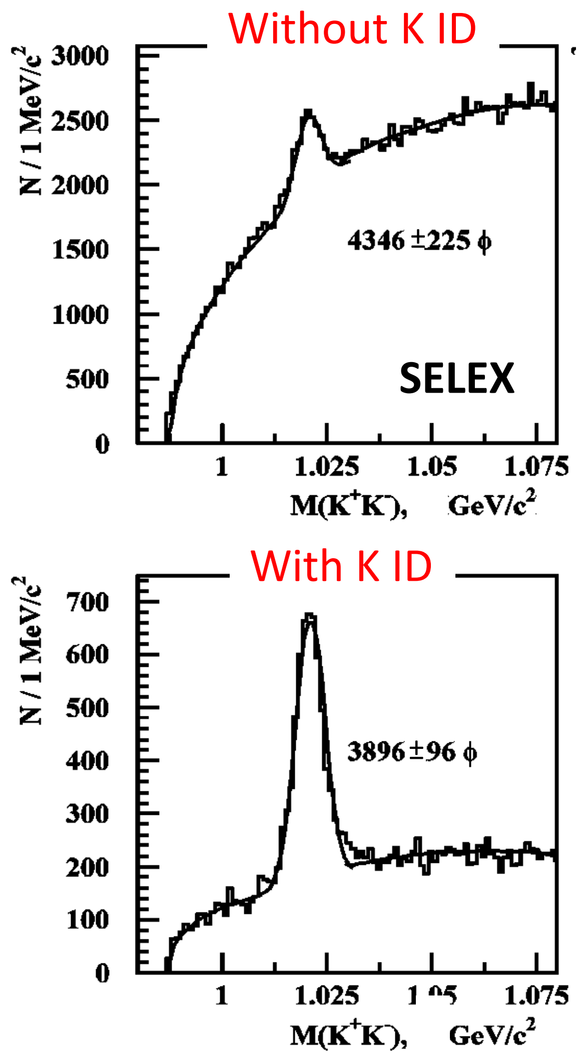


- The light quark and gluon jets are difficult to distinguish, but the jets coming from b quarks can be identified by their offset tracks (due to b-hadron lifetime) → fancy vertex detectors
- A lot of the physics can be done using the jet properties; adding a dedicated detector for charged hadron ID takes space (and cost)
- For lower p_T physics where the identification of hadrons is essential (as in LHCb and ALICE) it is worth the extra expense for such detectors

3. Charged hadron ID

- Charged hadrons (π, K, p) are all effectively stable, and have similar interactions
  → track + hadronic shower
- However, identifying them can be crucial, in particular for the study of hadronic decays
- *For example:* the hadronic decay $\phi \rightarrow K^+ K^-$

  Making all two-track combinations in an event and calculating their invariant mass
  → huge *combinatoric* background
  (most tracks are pions, from other sources)
- By identifying the two tracks as kaons, the signal to background ratio is much improved

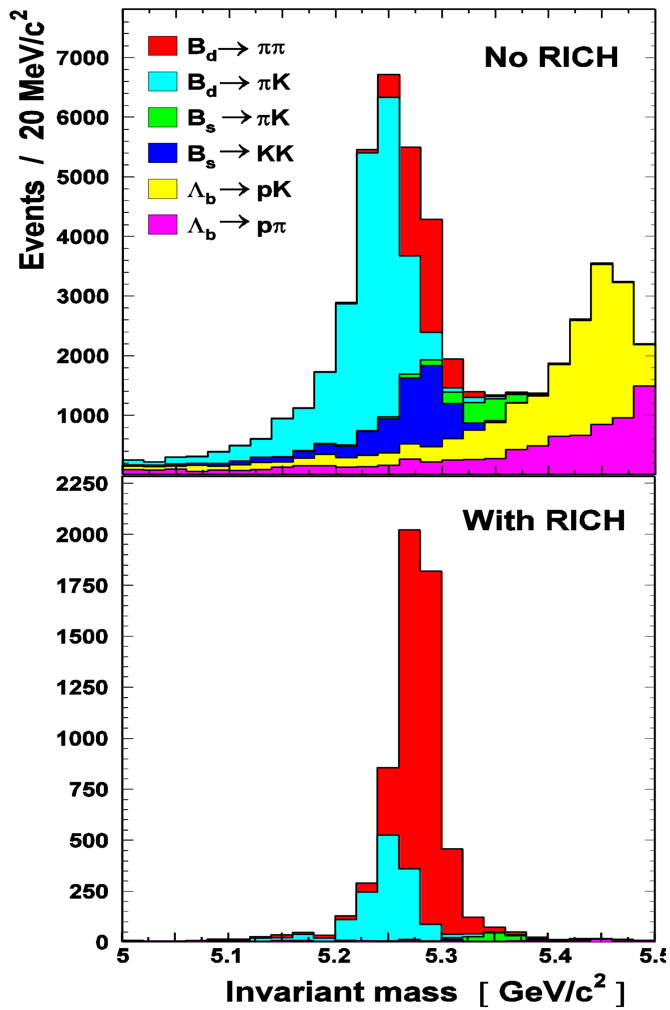


B physics

- Another example where hadron ID is crucial is in **B physics**: the study of hadrons containing the b quark
- B physics can help understand why the Universe did not disappear immediately after the Big Bang, from annihilation of the matter and antimatter: CP violation can give rise to an excess of matter

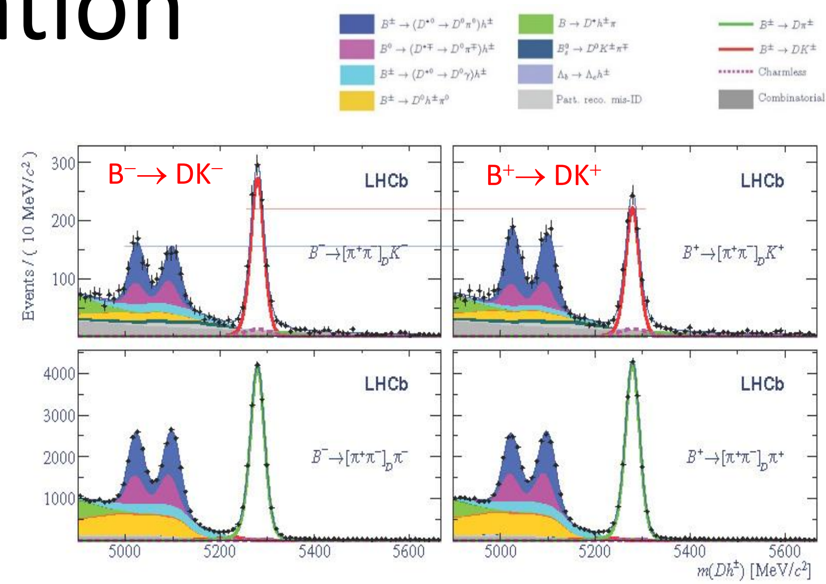
  e.g: $\mathcal{B}(B^0 \rightarrow K^+ \pi^-) > \mathcal{B}(\overline{B}^0 \rightarrow K^- \pi^+)$
- If combinations are made of all two-body B decays many different modes overlap
  → very difficult to study their properties
- Applying hadron ID, the different components can be separately studied

LHCb simulation



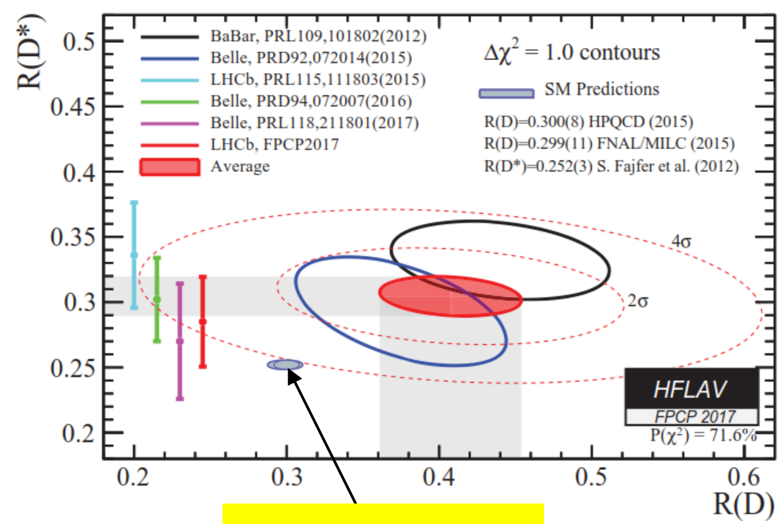
CP violation

- Example of a measurement showing clear CP violation: $B \to DK$



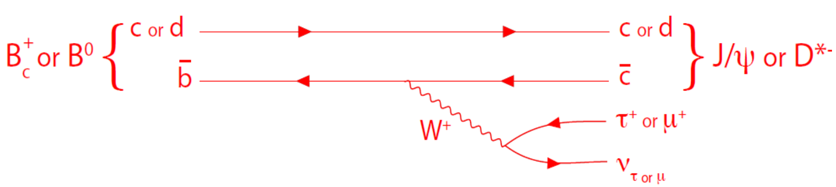
- The largest evidence for discrepancy with the SM seen so far at the LHC are in so-called **flavour anomalies**
  e.g. comparing $B^0 \to D^*\tau\nu$ and $D^*\mu\nu$

$$R(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu)}$$



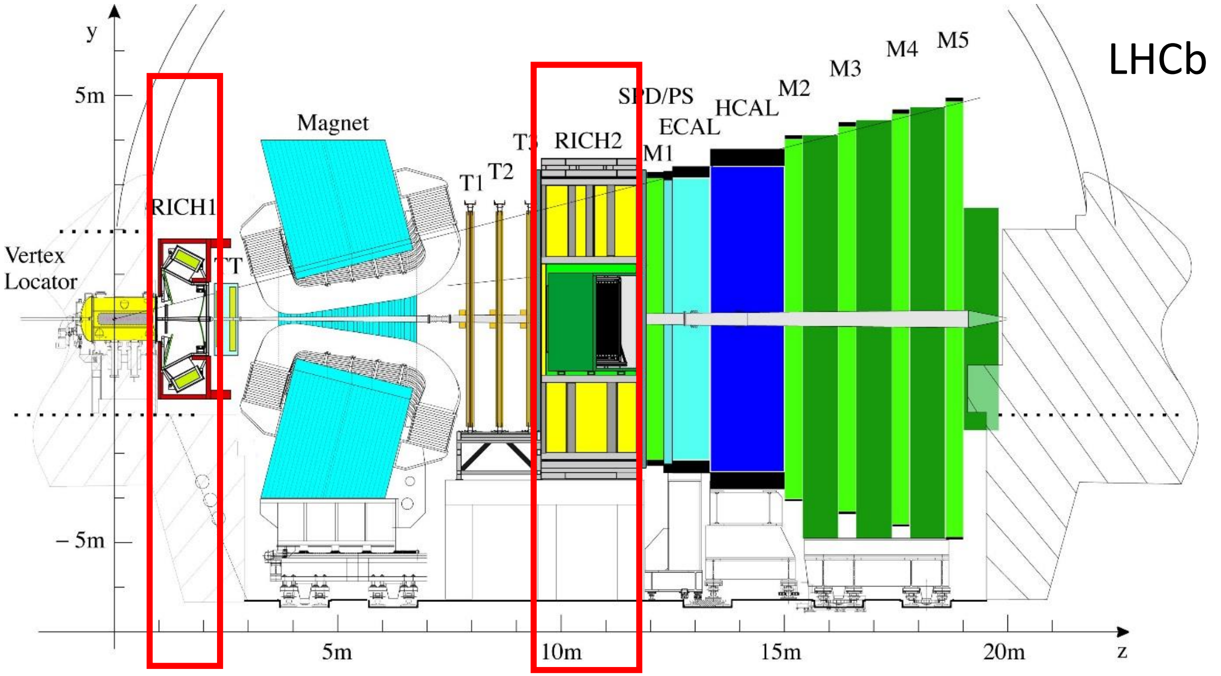
> 4σ from SM!

- Important to pursue this and confirm if the discrepancy is real
  Particle identification is crucial!



LHCb

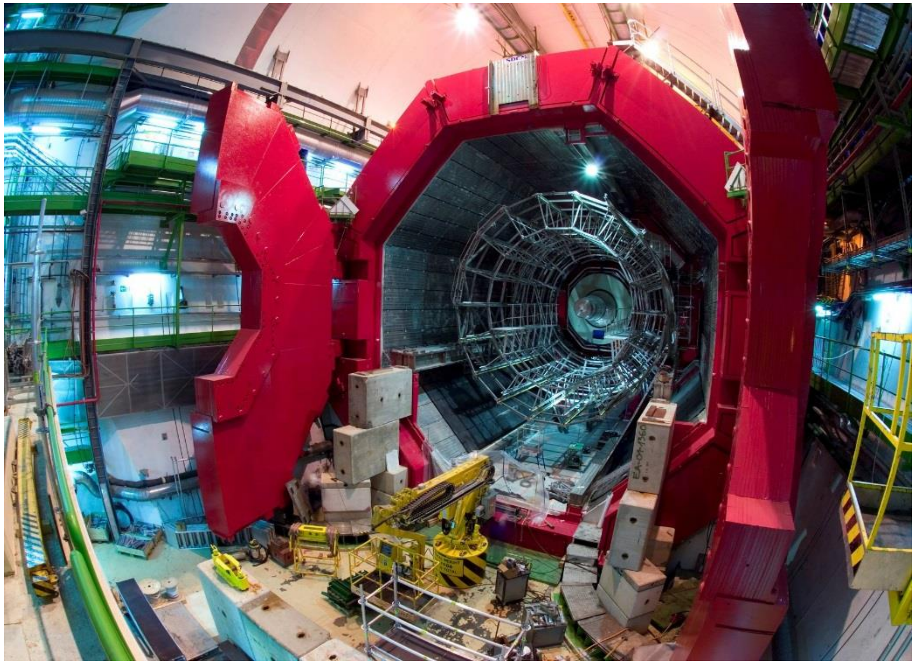
- LHCb is the dedicated experiment for B physics at the LHC
- Since b hadrons are light ~ 5 GeV << E_{cm} (13 TeV) they tend to be produced in the forward direction, so LHCb is a forward spectrometer:



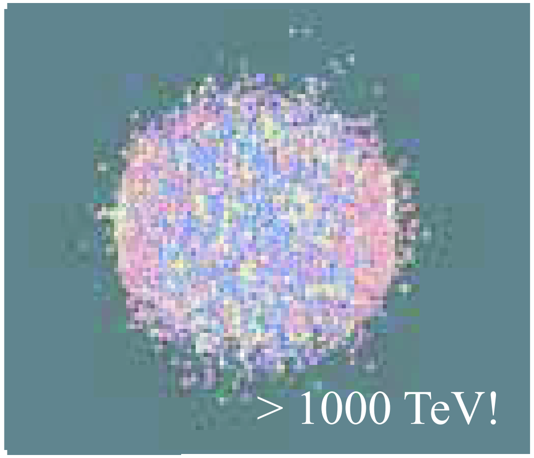
- Otherwise it looks like a slice out of a General Purpose experiment, apart from two extra detectors – for identifying charged hadrons

ALICE

- The fourth major experiment at the LHC: **A L**arge **I**on **C**ollider **E**xperiment Optimized for the study of Heavy Ion collisions, particularly at low p_T
- ALICE reused the magnet of one of the LEP experiments (L3)



Simulation of collision between two Pb nuclei (Lorentz contracted)



- ALICE is notable for using detectors that rely on *all four* of the different particle ID techniques that can identify 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 $p = \gamma m v$, so $m = p/\gamma v = p/\gamma\beta c$
  There are four main processes that depend on the velocity of a particle that will be discussed in turn:

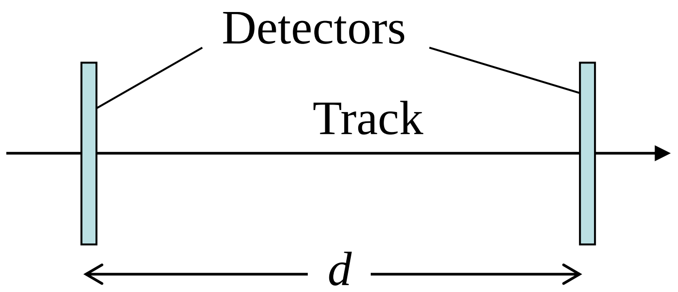
  1. Most direct is to measure the **Time Of Flight** (TOF) of the particles over a fixed distance
  2. Alternatively one can look at the detail of their interaction with matter The main source of energy loss is via **Ionization** (*dE/dx*)
  3. If the velocity of the particle changes compared to the local speed of light it will radiate photons, detected as **Transition Radiation**
  4. If a particle travels at *greater* than the local speed of light, it will radiate **Cherenkov Radiation**

Time Of Flight

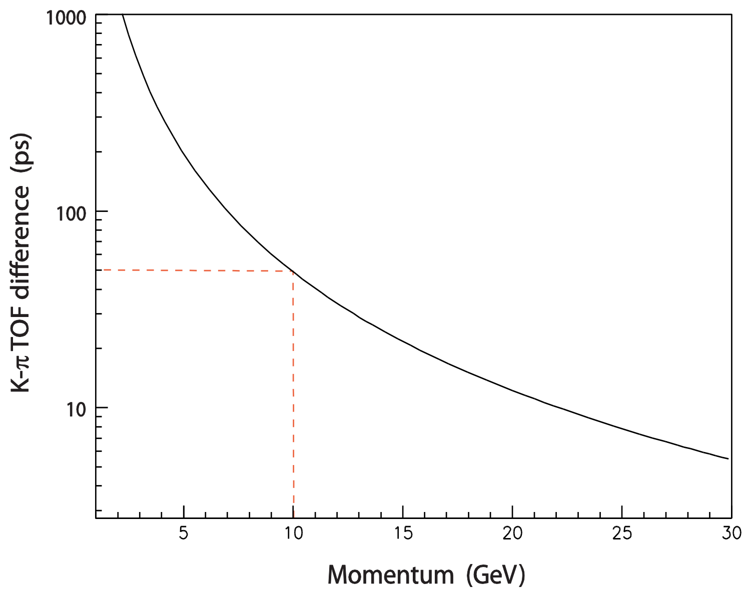
- *Simple concept:* measure time difference Δt between two detector planes

  $\beta = d / c\Delta t$

- At high energy, particle speeds are relativistic, closely approaching to *c*
- For a 10 GeV K, the time to travel 12 m is 40.05 ns, whereas for a π it would be 40.00 ns, so the difference is only 50 ps
- Modern detectors & readout electronics have resolution σ_t ~ 10 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



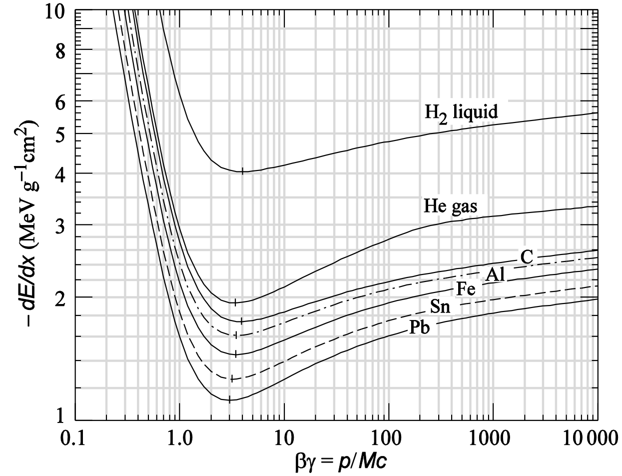
TOF difference for *d* = 12 m

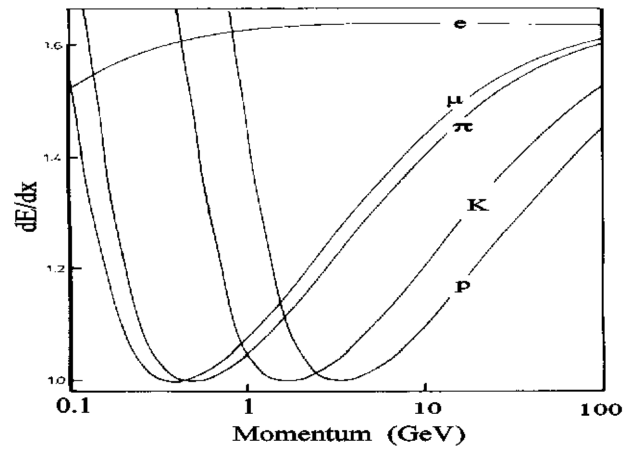


Ionization

- Charged particles passing through matter can knock out electrons from atoms of the medium: **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)
- *Note:* these techniques all provide signals for charged leptons e, μ as well as π, K, p
But $m_\mu \approx m_\pi$, so not well separated — dedicated detectors do a better job

[PDG]

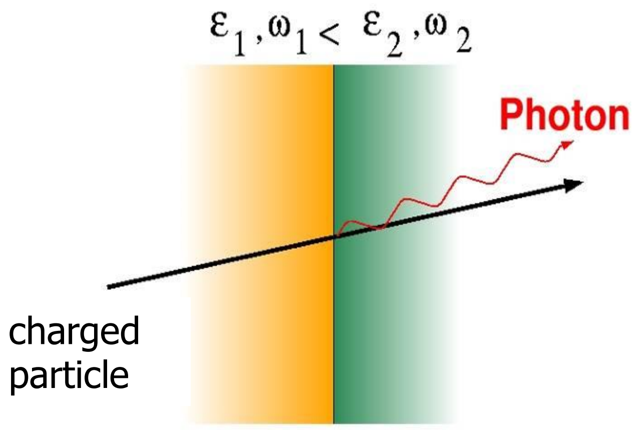




Transition radiation

- Local speed of light in a medium with refractive index n is $c_p = c/n$
- If its relative velocity $\boldsymbol{v}/c_p$ changes, a particle will radiate photons:
  1. Change of direction $\boldsymbol{v}$ (in magnetic field) $\rightarrow$ **Synchrotron** radiation
  2. Change of $|v|$ (passing through matter) $\rightarrow$ **Bremsstrahlung** radiation
  3. Change of refractive index n of medium $\rightarrow$ **Transition** radiation
- Transition radiation is emitted whenever a relativistic charged particle traverses the border between two media with different dielectric constants ($n \sim \sqrt{\varepsilon}$)
- The energy emitted is proportional to the boost γ of the particle

  $\rightarrow$ Particularly useful for electron ID
  Can also be used for hadrons at high energy



Cherenkov light

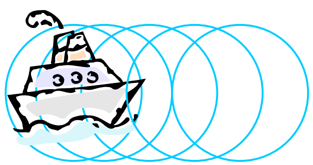
- Named after the Russian scientist P. Cherenkov who was the first to study the effect in depth (he won the Nobel Prize for it in 1958)
- From Relativity, nothing can go faster than the speed of light *c* (in vacuum)
- However, due to the refractive index *n* of a material, a particle *can* go faster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

Propagating waves

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

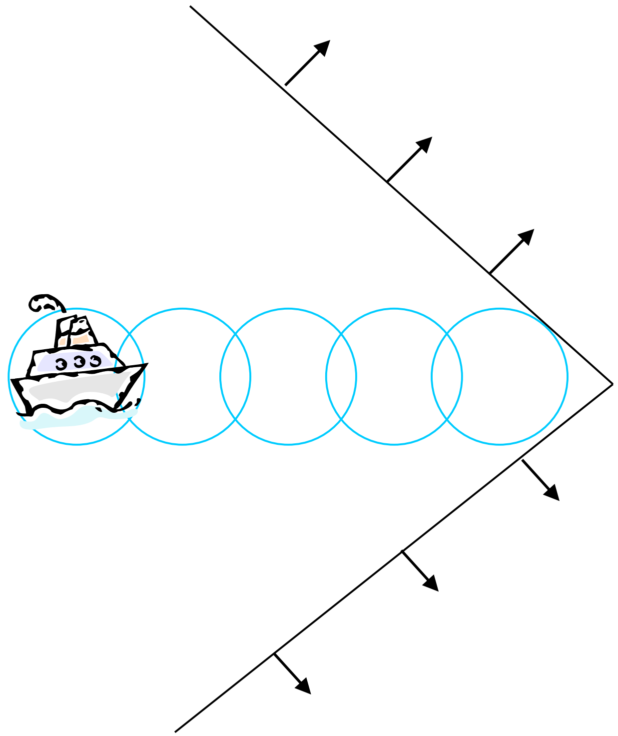
Propagating waves

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



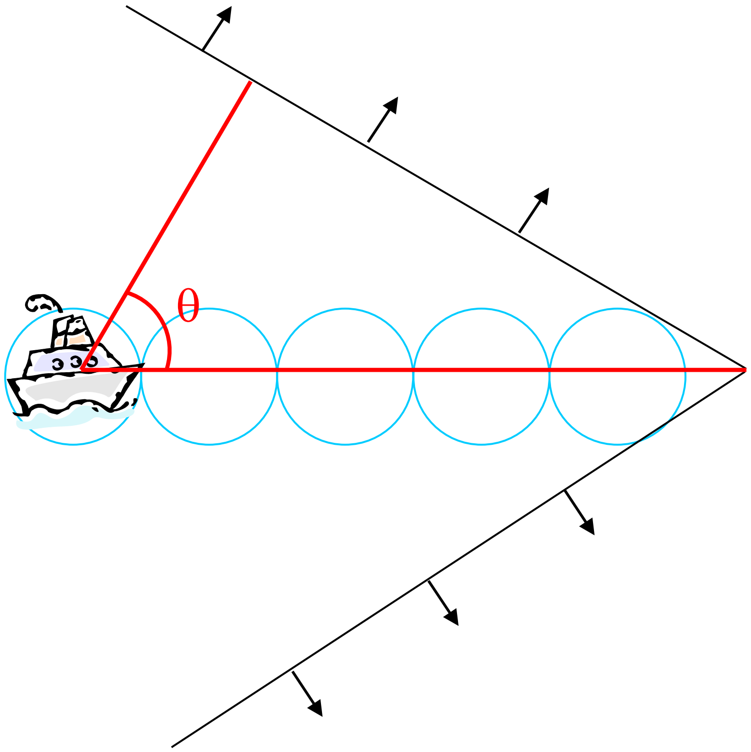
Propagating waves

- 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

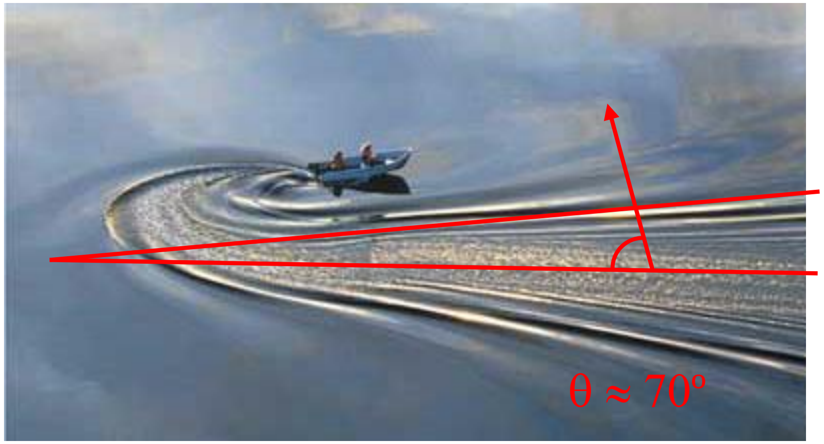


$$\cos\theta = \frac{v_{wave}}{v_{boat}}$$

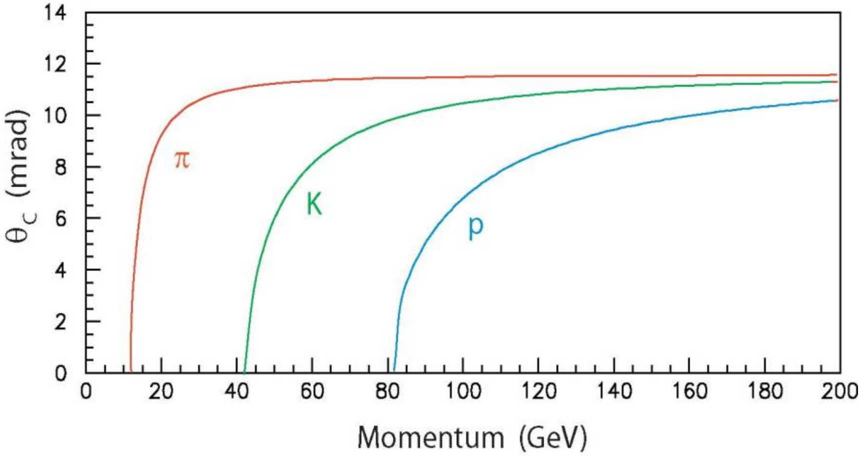
Speed calculation

- Using this construction, we can determine (roughly) the boat speed:
  $\theta \approx 70^o$, v_{wave} = 2 knots on water
  → $v_{boat} = v_{wave}/\cos\theta \approx$ 6 knots
- Cherenkov light is produced when charged particle ($v_{boat} = \beta c$) goes faster than the speed of light ($v_{wave} = c/n$)

  → $\cos\theta_C = 1 / \beta n$
- Produced in three dimensions, so the wavefront forms a *cone* of light around the particle direction
- Measuring the opening angle of cone
  → particle velocity can be determined
  Requires detection of low-energy γ



For Ne gas (n = 1.000067)



Summary

- Particle identification is a crucial aspect of most high energy physics experiments, in addition to tracking and calorimetry
- Short-lived particles are reconstructed from their decay products
- Most long-lived particles seen in an experiment can be identified from the combination of their signatures in the different detectors
- Distinguishing the different long-lived charged hadrons (π, K, p) is more challenging, and usually requires dedicated detectors
- Their identification is based on four main processes: TOF, *dE/dx*, Transition Radiation and the Cherenkov effect
- How these techniques are applied in actual detectors will be described in the second lecture