Particle Identification

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Review of the techniques of Particle Identification used in High Energy Physics experiments, over 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, Bariloche, 19-20 January 2010

Contents

References

- These lectures are based on material from previous ICFA schools,
  in particular the lectures of E. Nappi and J. Engelfried
  (including borrowing some of their figures) – my thanks to them
  http://www.ifm.umich.mx/school/ICFA-2002/

  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 the details: (Google RICH2007)

- Information about the LHC experiments can be found on their web pages:
  http://user.web.cern.ch/ and follow the links

- There is unavoidably some overlap with the other lectures at this school
  particularly "Particle Interactions with Matter" (C. Joram),
  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 at Roger.Forty@cern.ch

1. Introduction

- Particle Identification (PID) is a crucial aspect of most High Energy Physics (HEP) experiments
  The detectors which are used depend on the physics that is under study

- In a typical experiment beams collide within the detectors
  (or a single beam collides with a fixed target)
  We 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, and in conjunction with a magnetic field, measure the sign of the charge and the momentum of the particle

- **Calorimeters** detect neutral particles, measure the energy of particles, and determine whether they have electromagnetic or hadronic interactions

- What other information do we need?

Elementary particles

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

Type	Name			Charge	Spin
Generation	1st	2nd	3rd		
Leptons	e	μ	τ	1	1/2
	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

- Higgs Boson has not yet been discovered (observation expected at the LHC)
  How can each of these be identified in the experiment?
 Also need to be ready to detect particles from *beyond* the SM (eg SUSY)

Gauge bosons

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

Cross section for $e^+ e^-$ collisions (LEP)
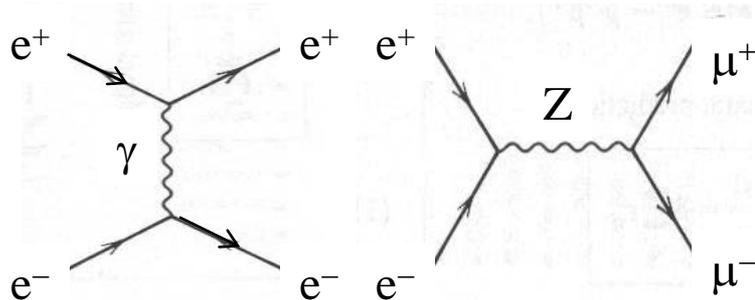
- However, real, massless photons can be produced, and seen in the experiment

- Weak vector bosons (W, Z) are massive, and therefore very short lived

- They can be seen from the variation of cross section with energy, or from their decay products
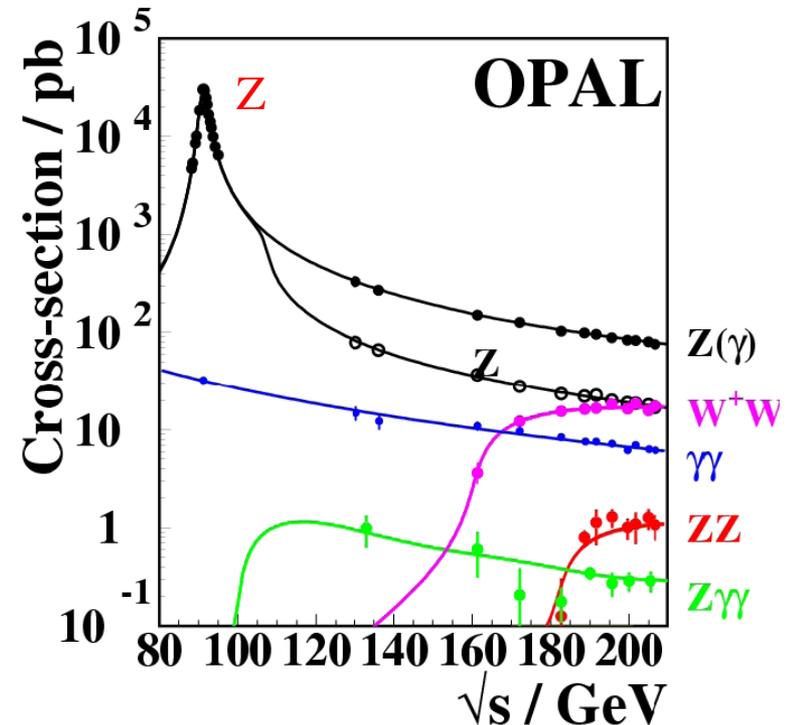
Invariant mass

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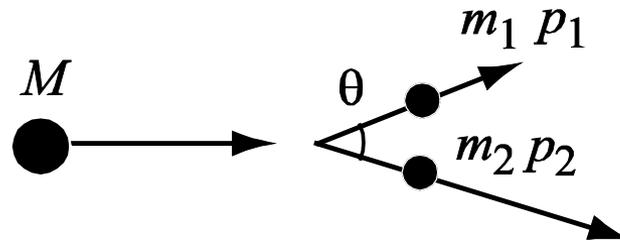
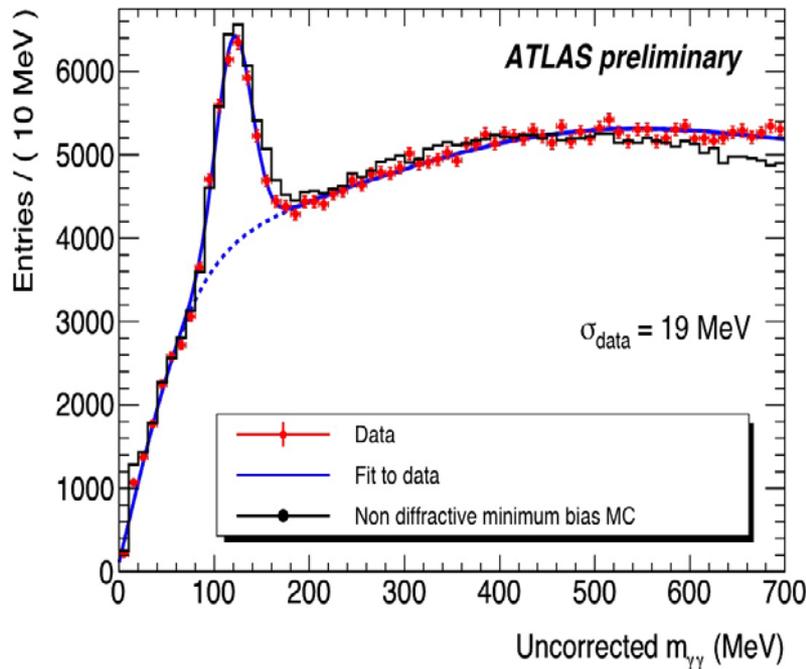- The *invariant mass* of the two particles from the decay:

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

$\rightarrow$ 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
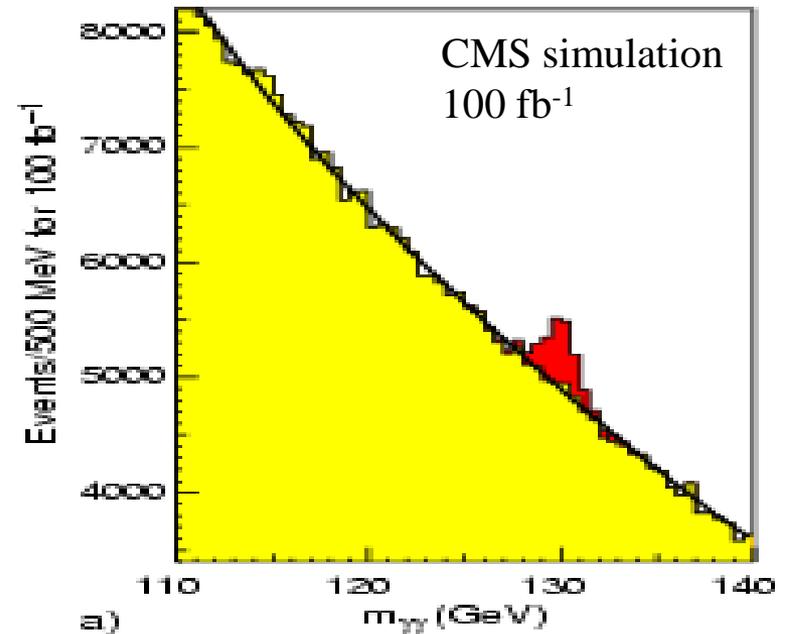
Mass reconstruction

- Typical example of reconstruction of a particle decay: $\pi^0 \rightarrow \gamma\gamma$
  one of the first composite particles reconstructed in the LHC experiments

- This technique an also be used to search for more exciting signals:

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

$H \rightarrow \gamma\gamma$

ATLAS preliminary

$\sigma_{data} = 19$ MeV

Data
Fit to data
Non diffractive minimum bias MC

Entries / (10 MeV)

Uncorrected $m_{\gamma\gamma}$ (MeV)

CMS simulation
100 fb^{-1}

Events/500 MeV for 100 fb^{-1}

$m_{\gamma\gamma}$ (GeV)

a)

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

- Event display is fish-eye view in the plane transverse to the beams, showing the hits in the different detectors
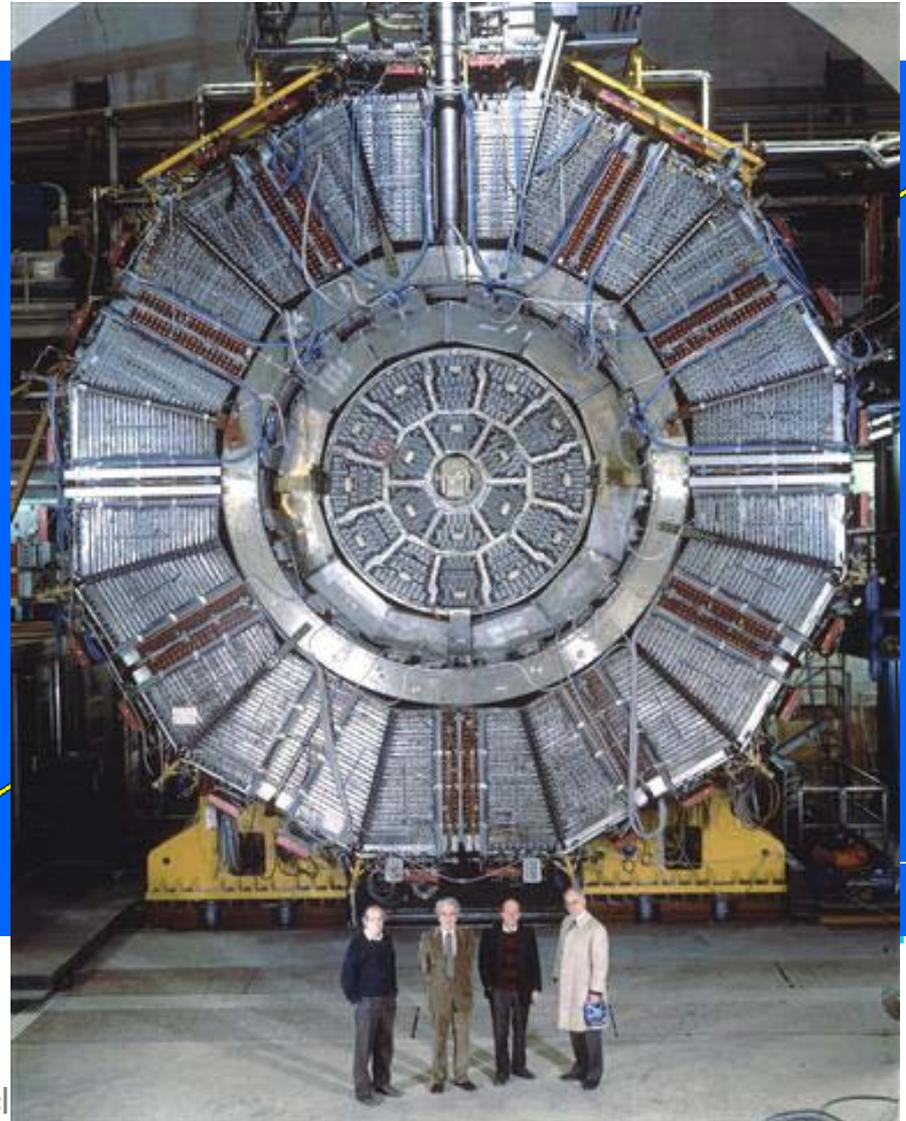
2. Identification techniques

- 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 $(m_e = 0.51 \text{ MeV})$
  They produce Bremsstrahlung radiation when passing through matter
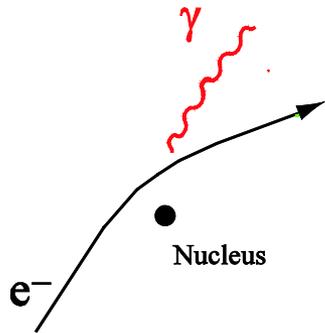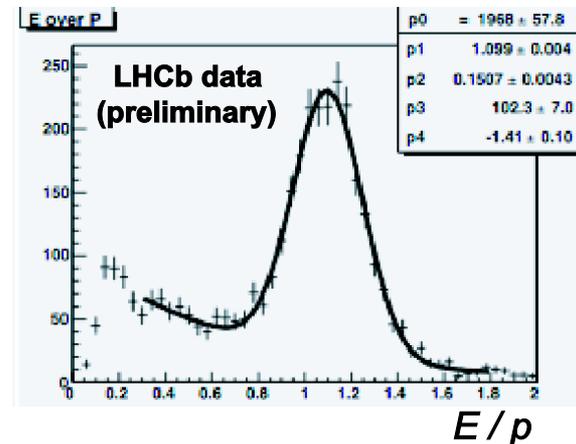

- $\Delta E \propto 1/m^2$
 Dominates for electrons with $E > 100 \text{ MeV}$
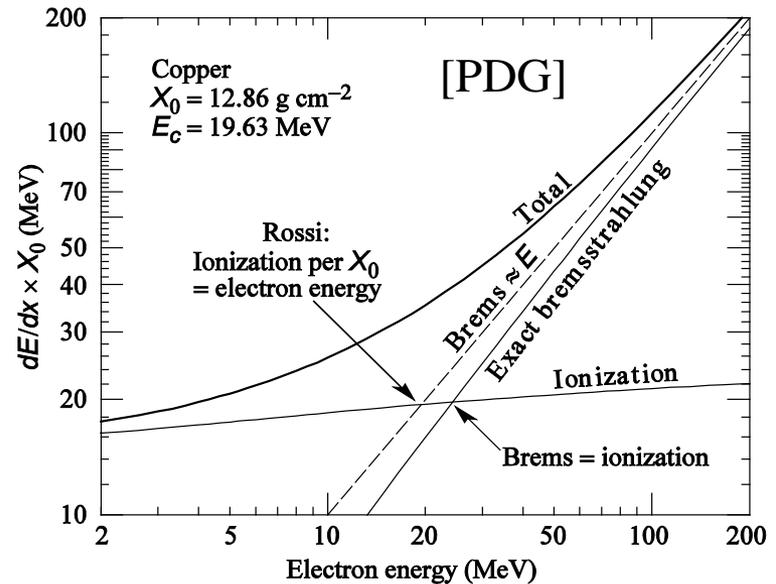
e/γ identification

- 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 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 $1/e$
  eg $X_0 = 1.76$ cm for Fe, so these *electromagnetic* showers are compact

- Such 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 measured in EM calorimeter) and p (momentum from tracker) should be equal: $E/p = 1$

- Not the case for other charged particles

LHCb data
(preliminary)

E over P

p0	= 1968 ± 57.8
p1	1.099 ± 0.004
p2	0.1507 ± 0.0043
p3	102.3 ± 7.0
p4	-1.41 ± 0.10

E/p

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 $\tau_\mu = 2.2$ μs

- Distance they travel (on average) before decay: $d = \beta\gamma c\tau_\mu$
  where $velocity$ $\beta = v/c$
  $\quad\quad\quad boost$ $\gamma = E/m = 1/\sqrt{(1-\beta^2)}$

- So a 10 GeV muon flies ~ 60 km before decay >> detector size
  $\to$ effectively stable

- Since mass is large, Bremsstrahlung radiation is small, and as a lepton it does not feel the strong interaction

$Z \to \mu^+\mu^-$
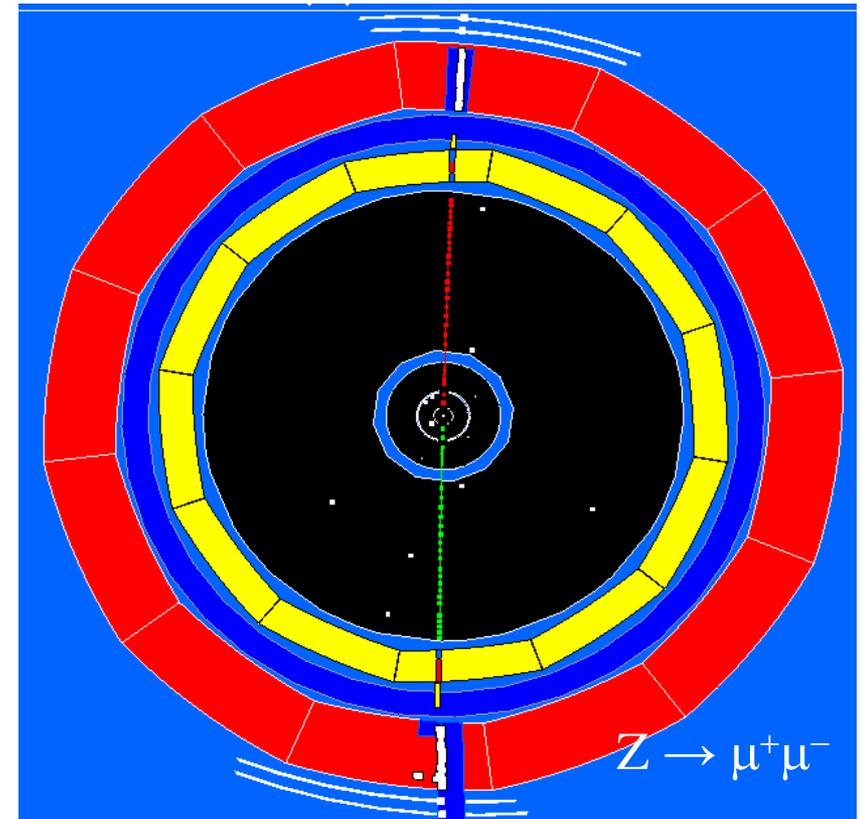
$\to$ most penetrating charged particle

Muon detectors

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


ATLAS
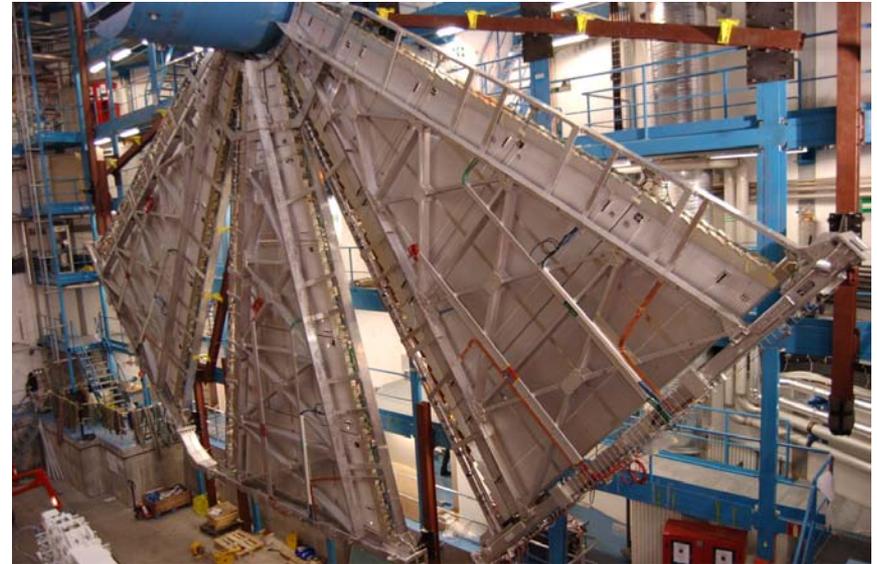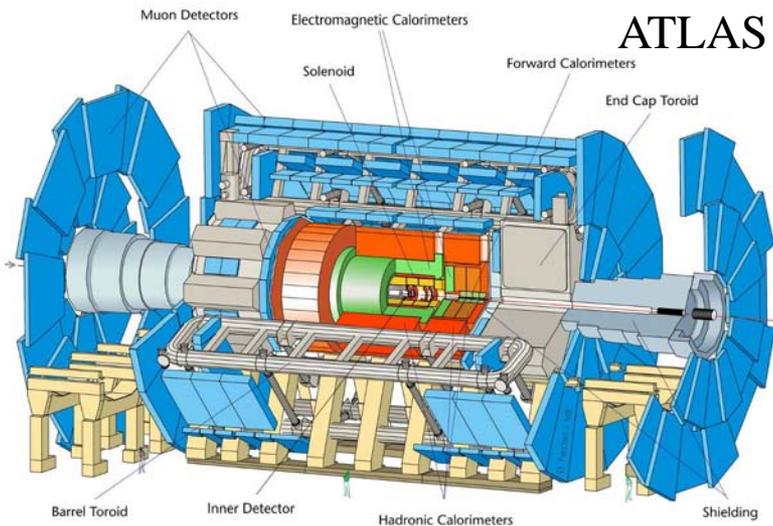
- They must be inexpensive, low granularity but precise enough for p measurement eg wire chambers with long drift volume (cross section of a CMS chamber shown)
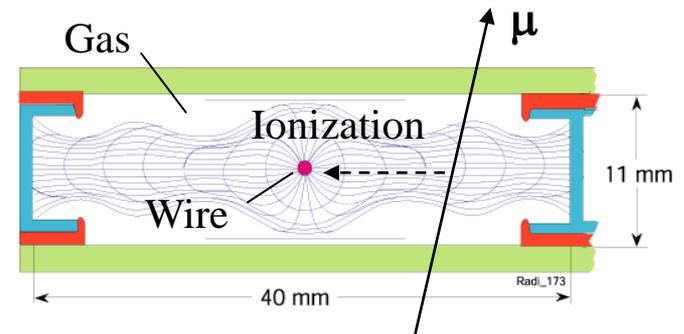
Tau leptons

- Taus are heavier still, $m_\tau = 1.78$ 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 $\tau_\tau = 0.29$ 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

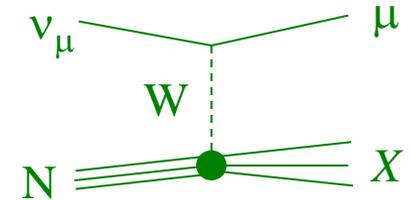- Accurate vertex detectors can detect that they do not come exactly from the interaction point

$Z \to \tau^+ \tau^-$
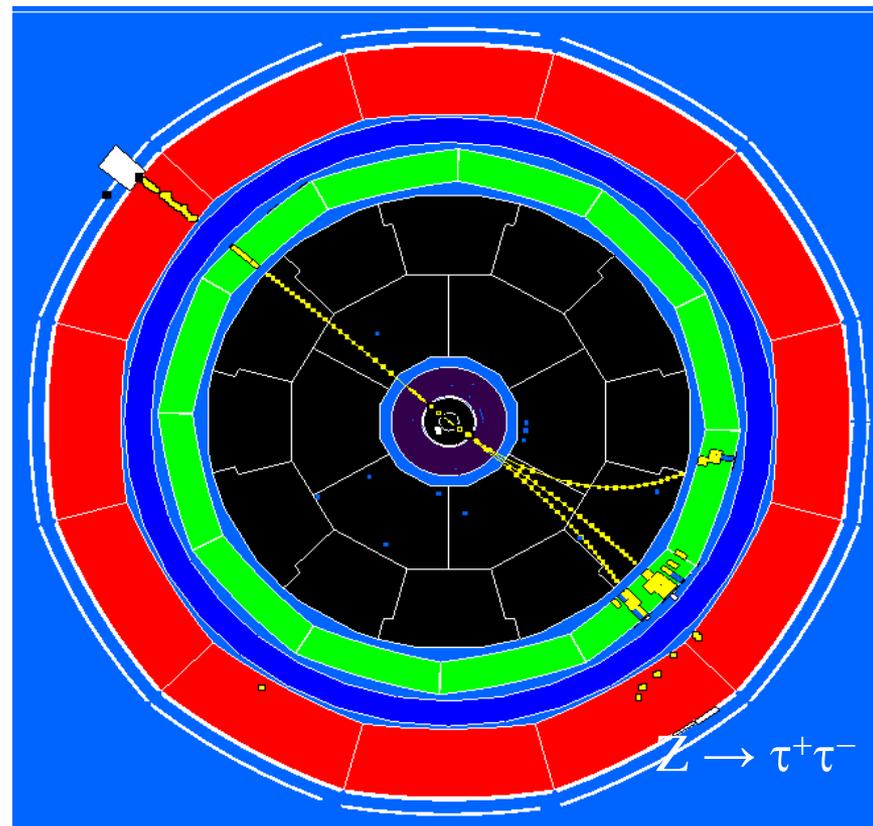
Neutrinos

- Neutral (i.e. 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)

- Nevertheless their interactions can be detected if you produce enough of them, and the detector is sufficiently massive
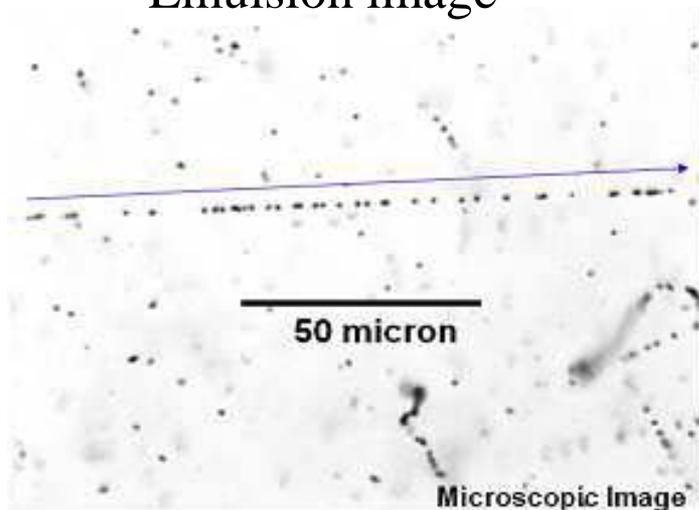

OPERA

> 1 kton of instrumented target mass!

Neutrino flavours

- Can even determine the neutrino flavour (ν_e, ν_μ, ν_τ) from their charged-current interaction: $\nu_\mu \, N \rightarrow \mu^- \, X$, etc

- OPERA searches 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

50 micron

Microscopic Image

OPERA
PRELIMINARY

Kink

e.m. showers

The charmed hadron is "inside" the hadronic jet and back to back with the muon

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 $\gg m_q$ 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

$Z \rightarrow q\bar{q}$
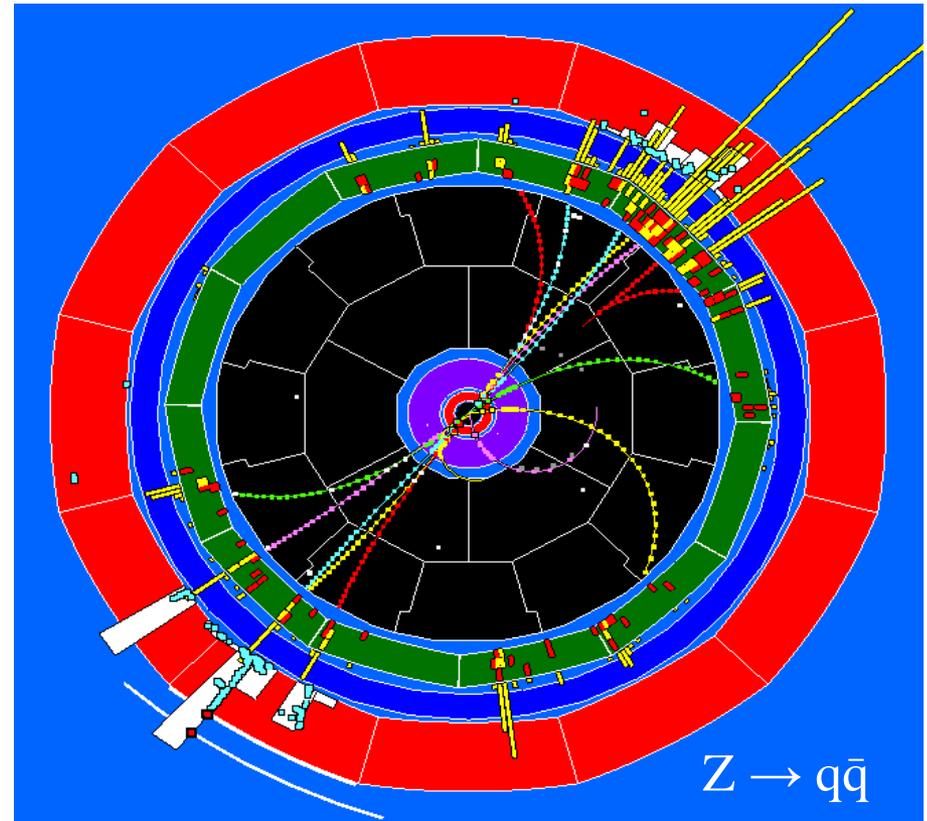
Jet reconstruction

- 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, for example here in the Higgs search
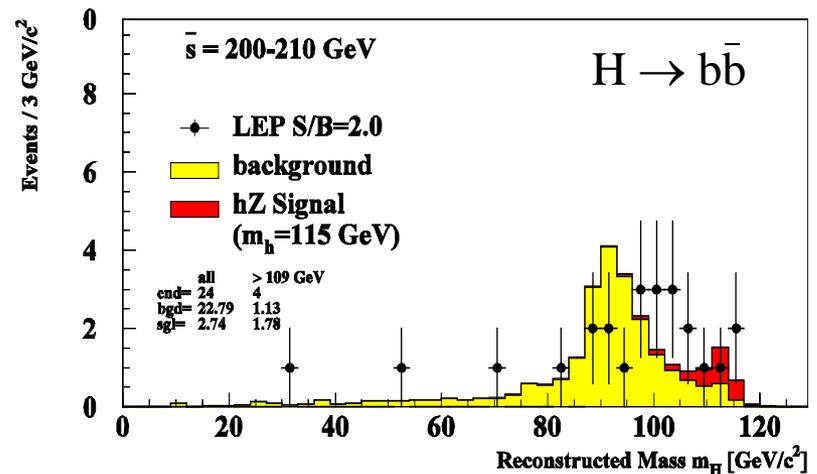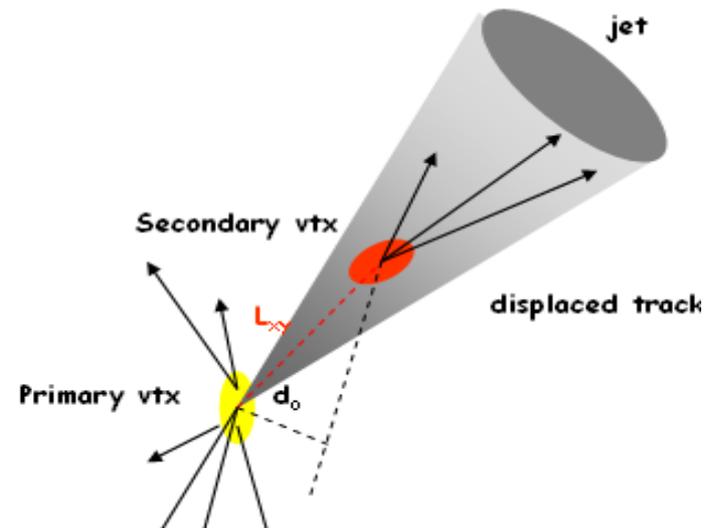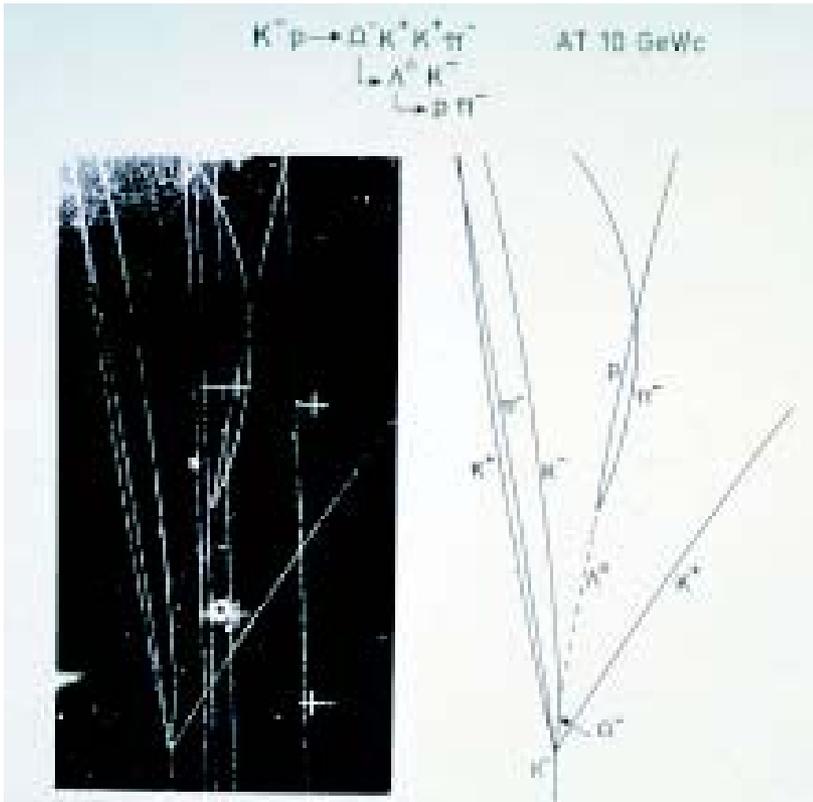
Hadrons

- 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	$c\tau$ [cm]
π	140	$u\bar{d}$	$\mu\nu_\mu$	2.6×10^{-8} s	780
K	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

V⁰s

- K_S^0 and Λ are collectively known as V⁰s, due to their characteristic two-prong decay vertex

V⁰ reconstruction

- V⁰s can be reconstructed from the kinematics of their positively and negatively charged decay products, without needing to identify the π or p
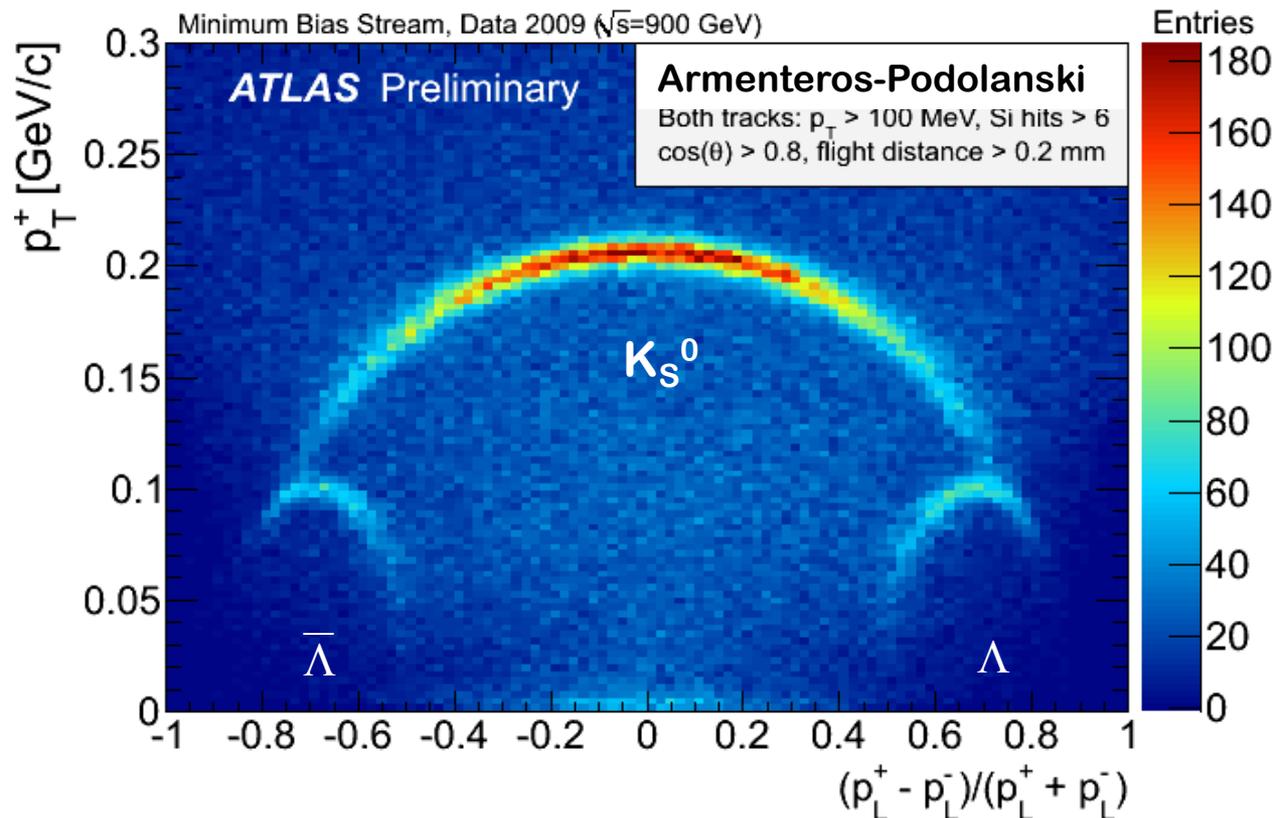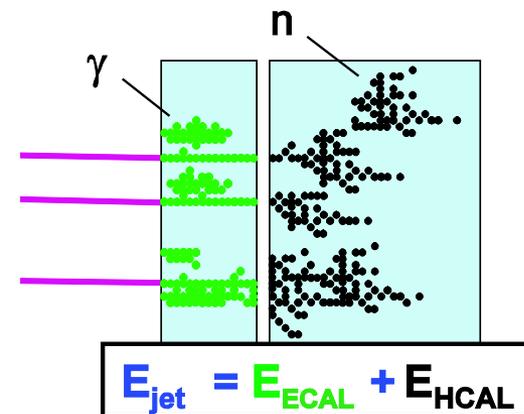
Other neutral hadrons

- K_L^0 and neutrons 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 $\lambda_I = 16.8$ cm for Fe $\approx 10 \times X_0$ so hadronic showers are longer than EM $\rightarrow$ HCAL sits behind ECAL
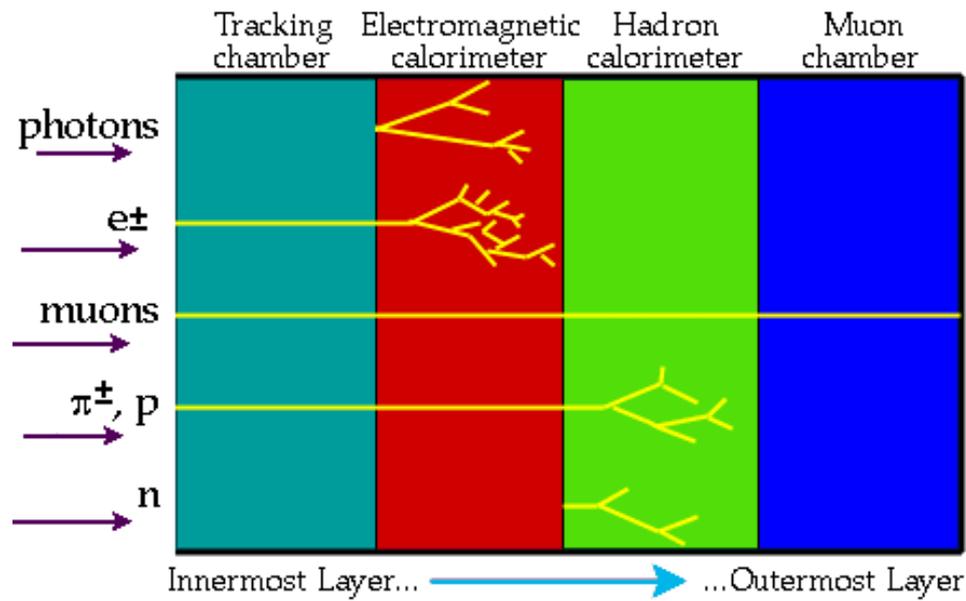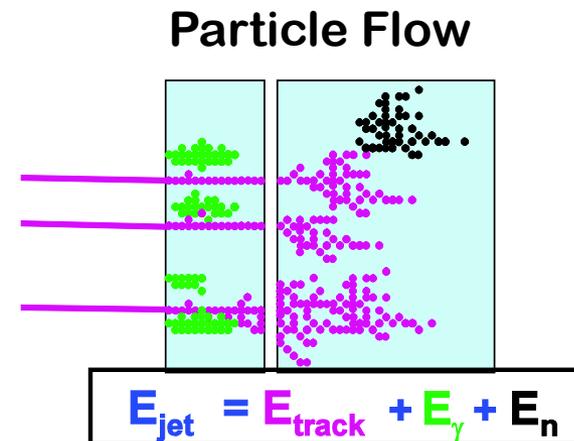
Particle Flow

- 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

  $\rightarrow$ ~ 70 % of energy measured in HCAL

 Poor HCAL resolution limits jet energy 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

  $\rightarrow$ Only 10 % of jet energy taken from HCAL

  $\Delta E/E \sim 30\% /\sqrt{E}$ may be achieved

$$E_{jet} = E_{ECAL} + E_{HCAL}$$

Particle Flow

$$E_{jet} = E_{track} + E_{\gamma} + E_{n}$$

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 the future e^+e^- linear collider (ILC or CLIC)

Simulated event in an ILC detector
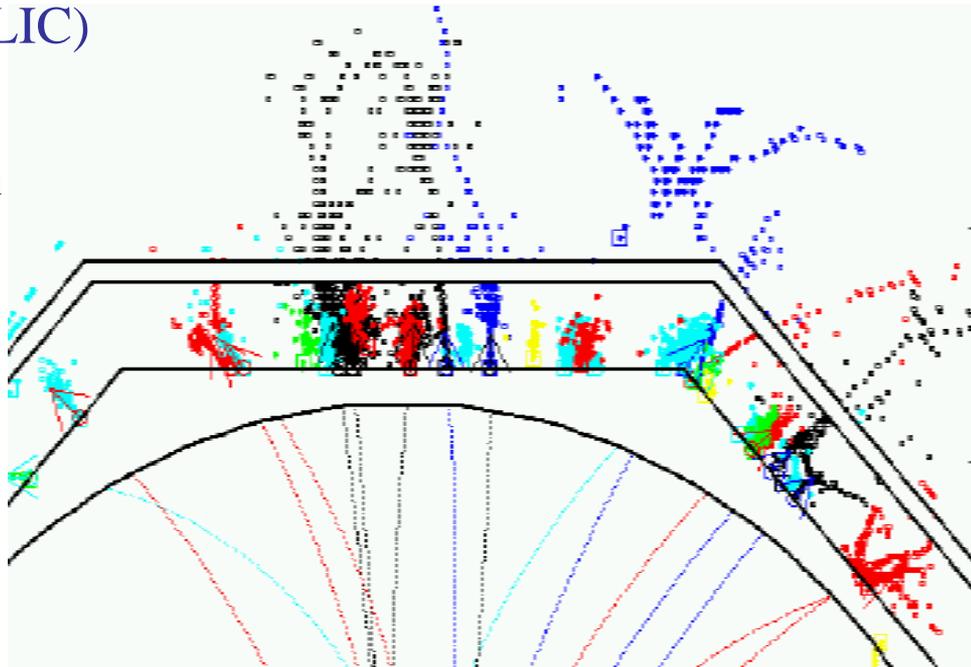
General purpose detectors

- Have now discussed the set of detectors used for particle identification in a typical General Purpose HEP experiment, such as ATLAS and CMS
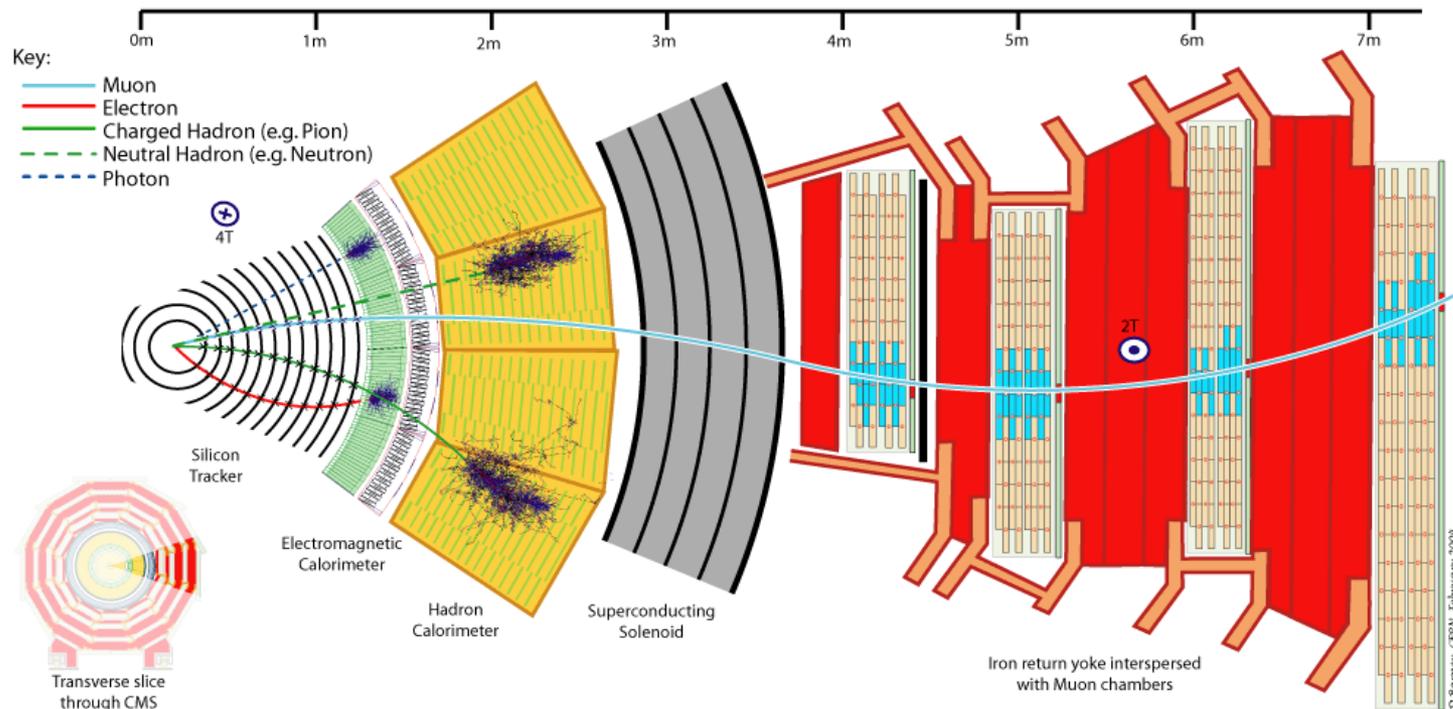
- One task that such General Purpose detectors do *not* do very well is to identify different charged hadrons (π, K, p)

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 hadronic decays

- *Example:* the hadronic decay $\phi \rightarrow K^+ K^-$

  If we just make all two-track combinations in an event and calculate their invariant mass
  $\rightarrow$ large *combinatoric* background
  (most tracks are pions, from other sources)

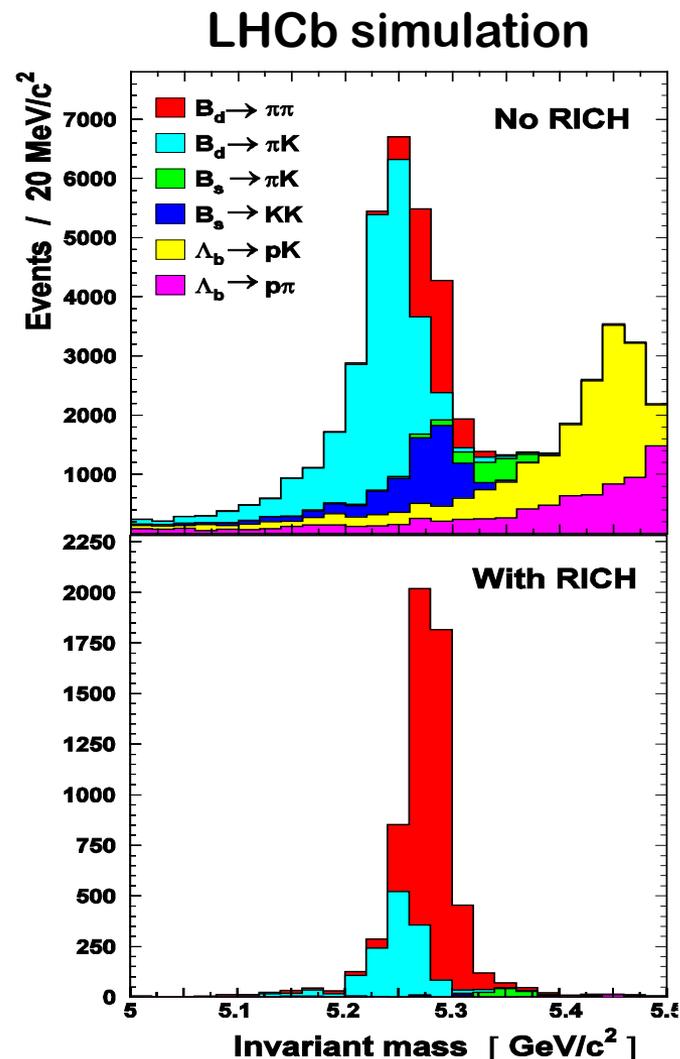- By identifying the two tracks as kaons, signal to background ratio is much improved
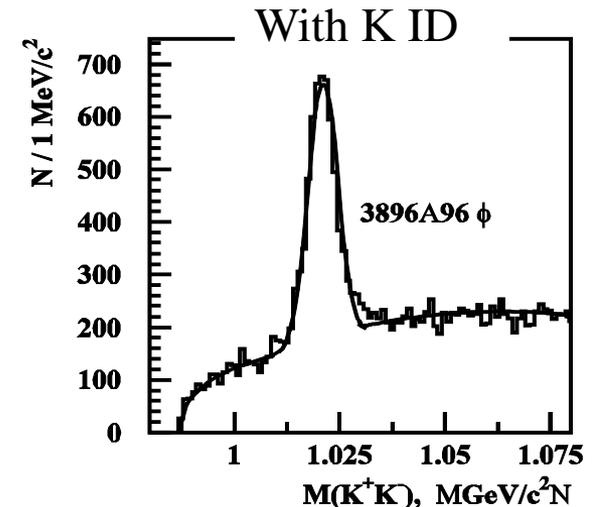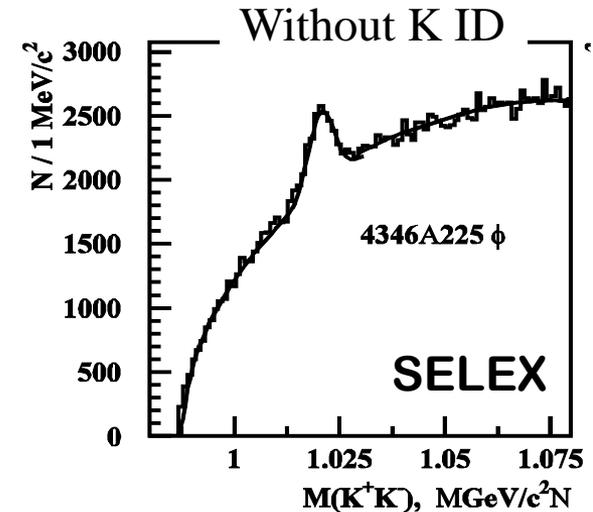
B physics

- Another example where hadron ID is crucial is in *B physics*: the study of hadrons containing the b quark

- B physics can 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

  eg: $B(B^0 \rightarrow K^+ \pi^-) > B(\overline{B}^0 \rightarrow K^- \pi^+)$

- If one makes 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

Legend:
- $B_d \rightarrow \pi\pi$
- $B_d \rightarrow \pi K$
- $B_s \rightarrow \pi K$
- $B_s \rightarrow KK$
- $\Lambda_b \rightarrow pK$
- $\Lambda_b \rightarrow p\pi$

No RICH

With RICH

Invariant mass [GeV/c^2]

Events / 20 MeV/c^2

Dedicated detector

- LHCb is a dedicated detector for B 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:
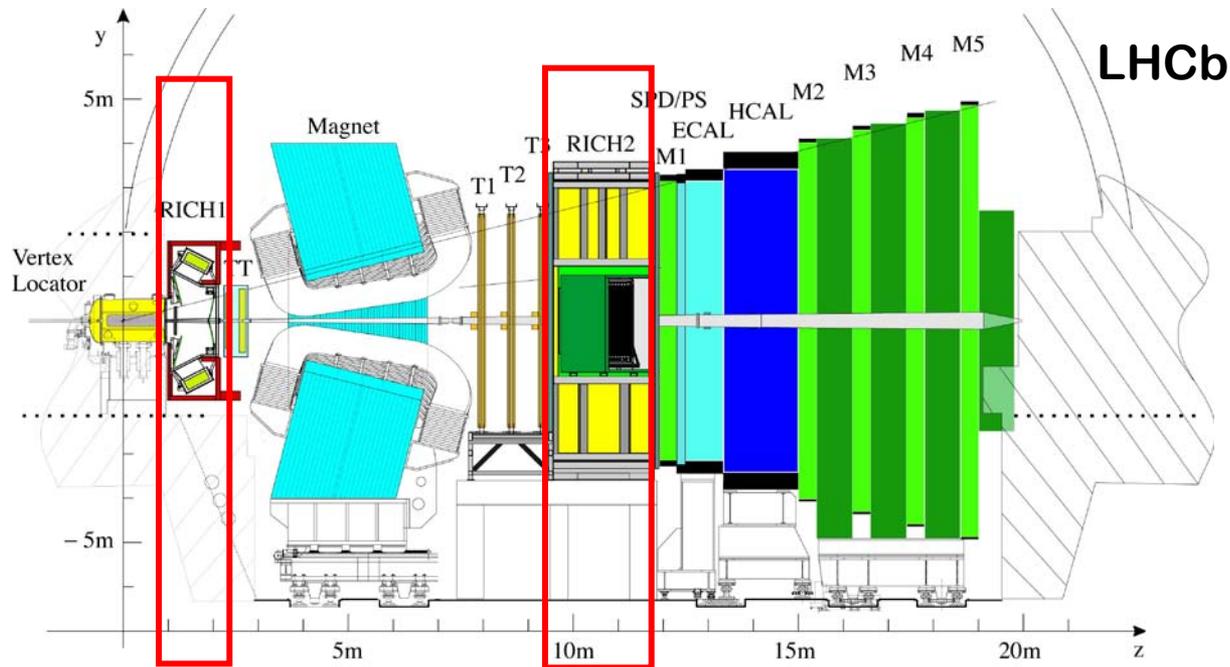

- Otherwise it looks like a slice out of a General Purpose experiment, apart from two extra detectors – for identifying charged hadrons

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, such as Pb-Pb

- ALICE reuses the magnet of one of the LEP experiments (L3)
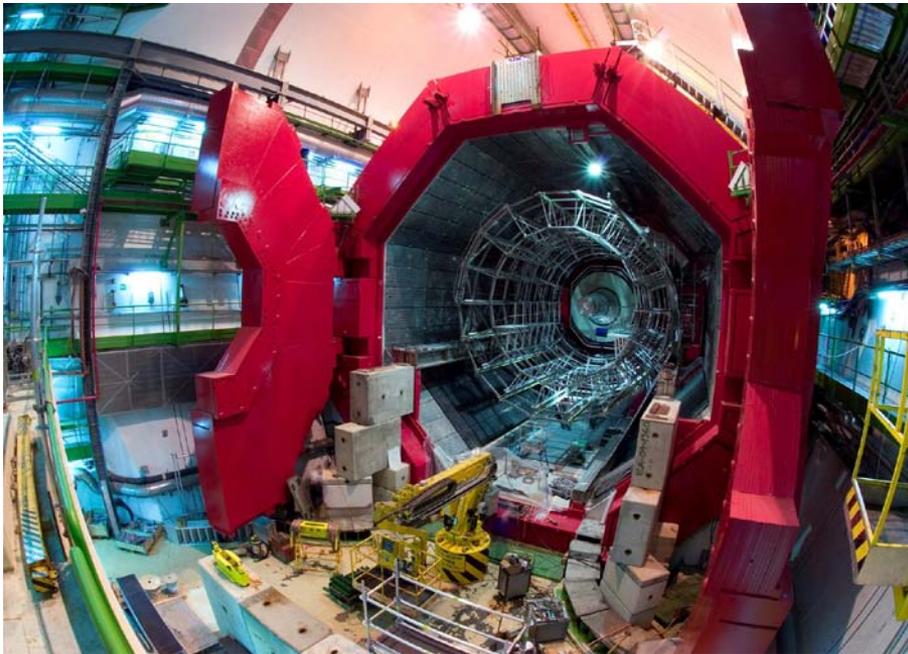
Simulation of collision between two Pb nuclei (Lorentz contracted)


> 1000 TeV!
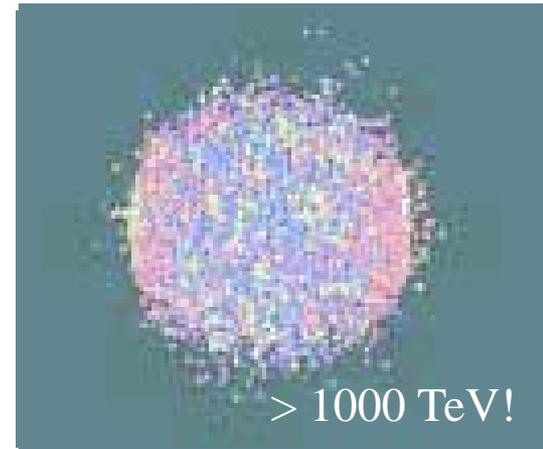
- ALICE is notable for using detectors that rely on *all four* of the different particle ID techniques that can identify charged hadrons

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 the time difference 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 $\sigma_t \sim 10$ ns, fast enough for the LHC (bunch crossings 25 ns apart) but need $\sigma_t < 1$ ns to do useful TOF

- TOF gives good ID at low momentum Very precise timing required for $p > 5$ GeV

Detectors

Track

d

TOF difference for $d = 12$ m

K–π TOF difference (ps)

Momentum (GeV)
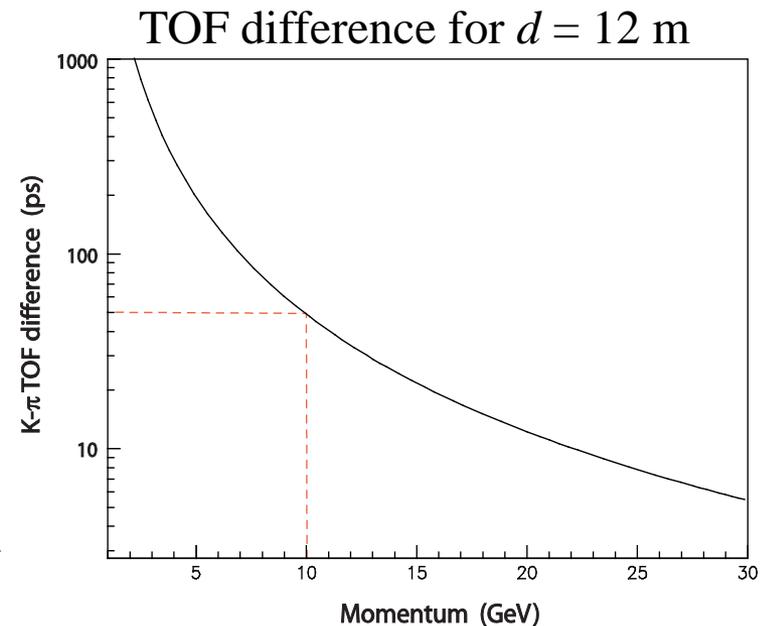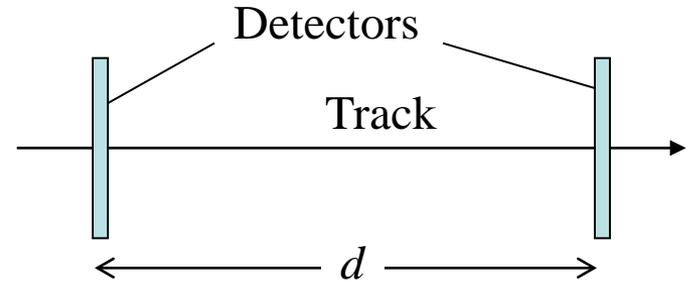
Ionization

- 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 they are not well separated (dedicated detectors do a better job)
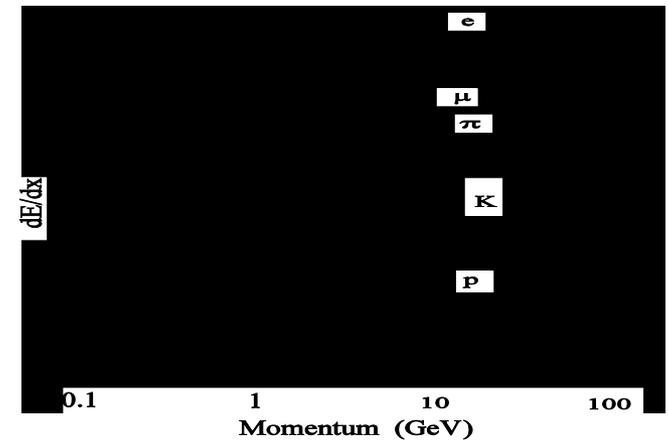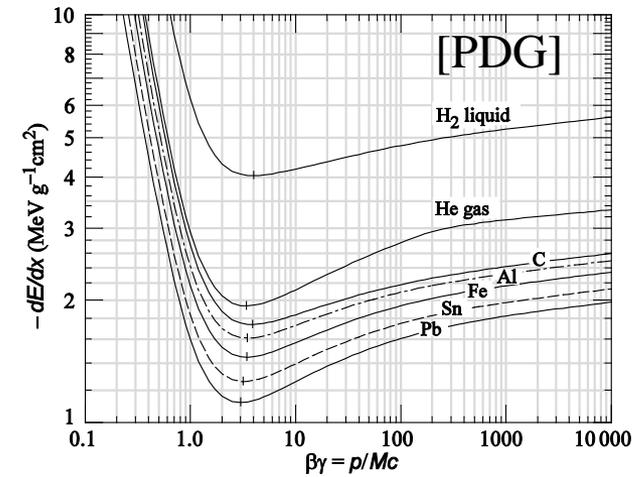
Transition radiation

- Local speed of light in a medium with refractive index n is $c_p = c/n$

- If its relative velocity v/c_p changes, a particle will radiate photons:

    1. Change of direction 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
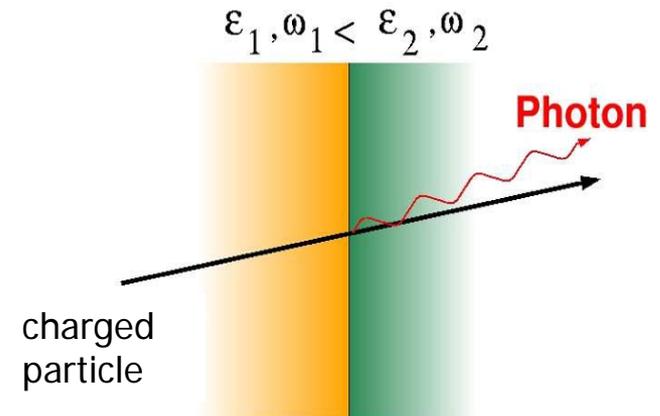
Cherenkov light

- 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 aeroplane travelling faster than the speed of sound
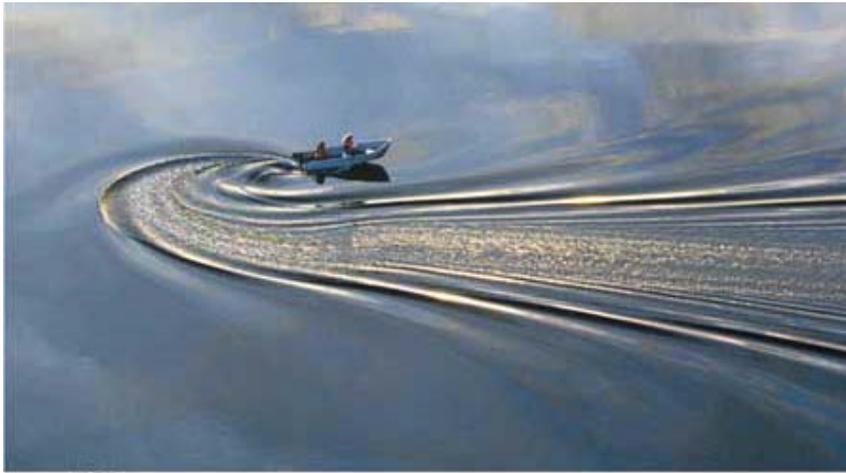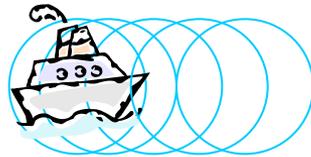
Propagating waves

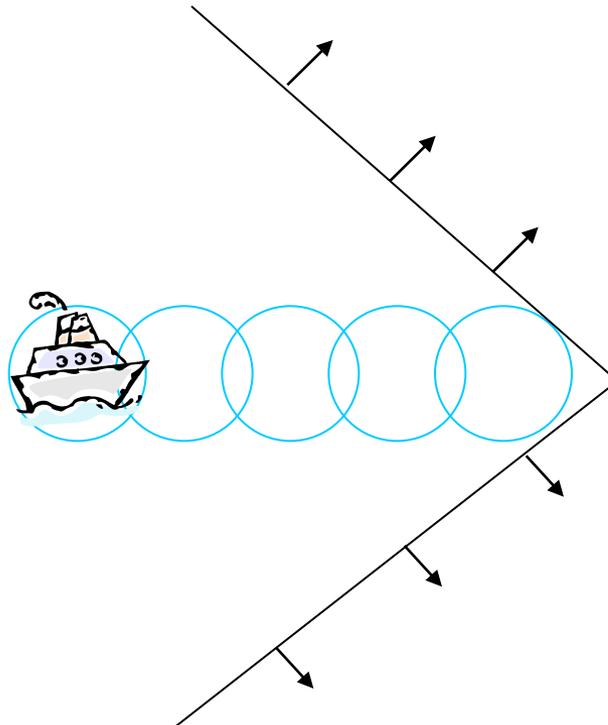- A stationary boat bobbing up and down on a lake, producing waves

Propagating waves

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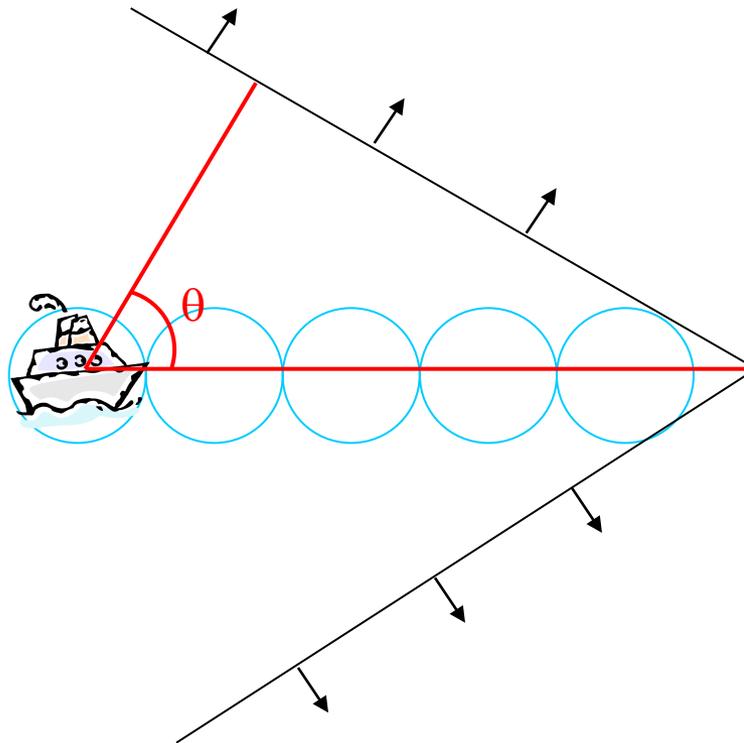
- No coherent wavefront is formed

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

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

Speed calculation

- Using this construction, we can determine (roughly) the boat speed:

  $\theta \approx 70°$, $v_{wave} = 2$ knots on water

  $\rightarrow$ $v_{boat} = v_{wave}/\cos\theta \approx 6$ knots

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

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

- Produced in three dimensions, so the wavefront forms a *cone* of light around the particle direction

- Measuring the opening angle of cone $\rightarrow$ particle velocity can be determined

$\theta \approx 70°$

For Ne gas ($n = 1.000067$)
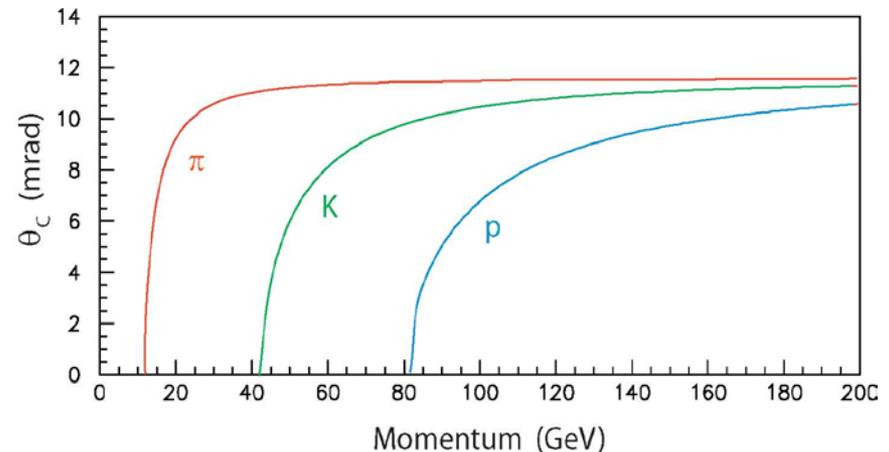
Summary

- 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 the experiment can be identified from their signatures in the various 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

- Application of these techniques in actual detectors will be described in Lecture II