Accelerators

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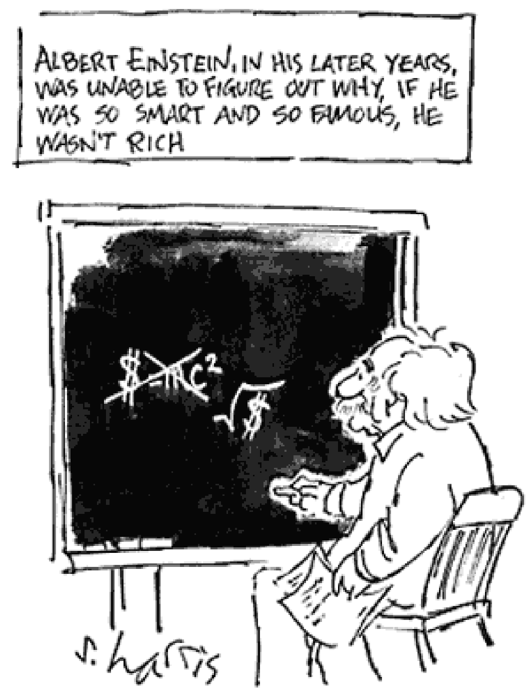
Particle Physics

4th Handout

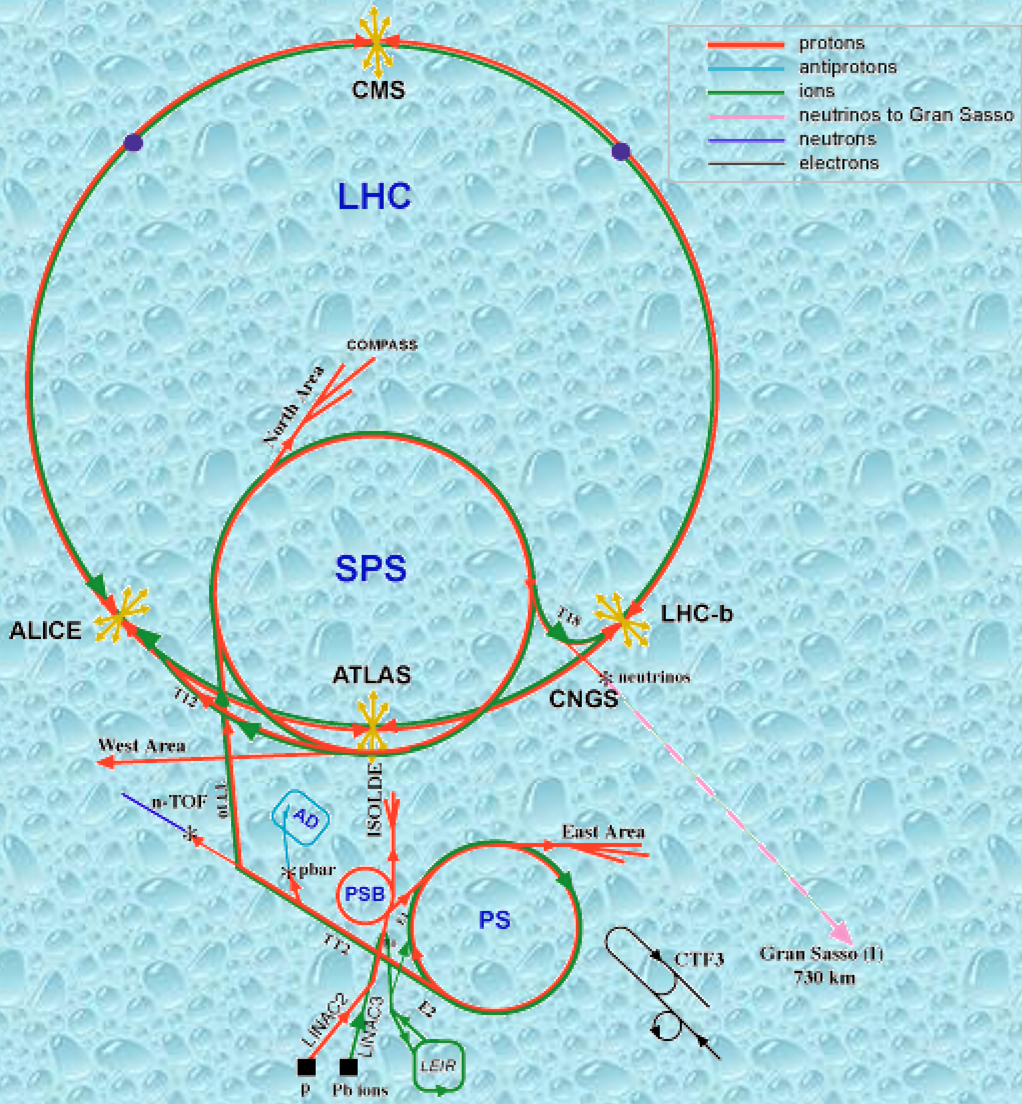
Accelerators & Detectors

- Luminosity and cross-sections
- Fixed target vs collider
- linac vs circular
- Detectors: fixed target, collider
- Detector elements



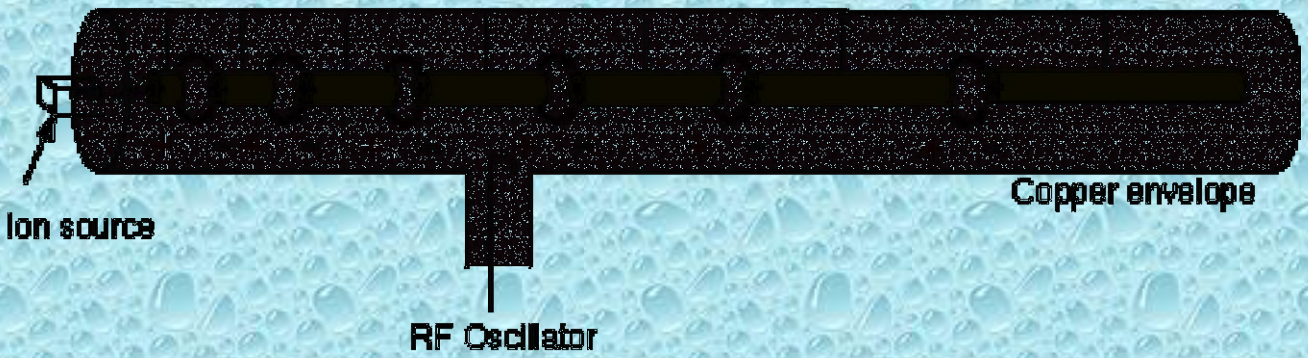
High Energies in Accelerators

- Produce new particles
  - e.g. W, Z,
  - … Higgs ?
- Probe small scale structure
  - p=h/λ, e.g. proton structure



Accelerators

- Electric Fields to accelerate stable charged particles to high energy
- Simplest Machine – d.c. high V source
  - 20MeV beam
- High frequency a.c. voltage
  - Time to give particles successive kicks

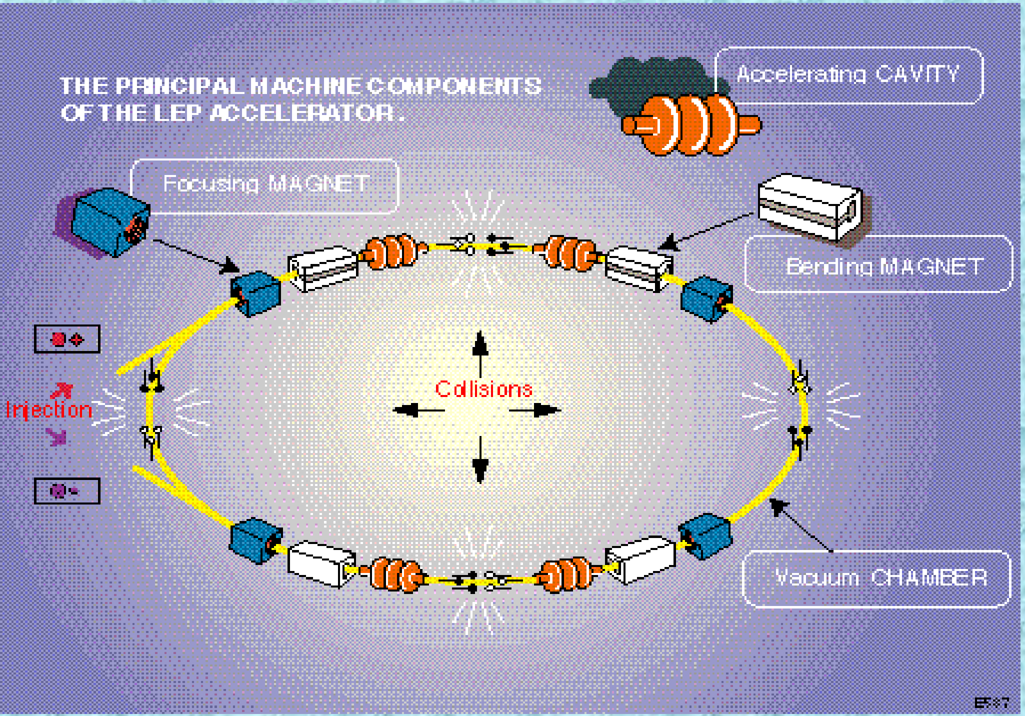


Fermilab linac

\> MeV Energy speed ~c, hence length of tubes same

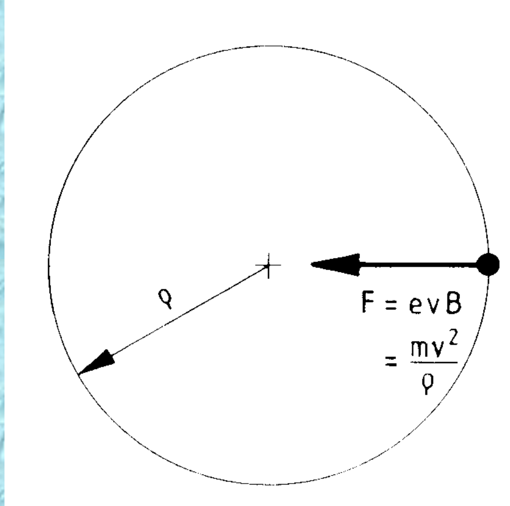
Linear Accelerator - Linac

Synchrotron



B field (bending) and
E-field (accelerating cavity)
Synchronised with particle
velocity

- pp,ep collider – need different magnets
- p anti-p, or e^-e^+
  - **One set of magnets,one vacuum tube**
  - LEP (e+e-), Tevatron(p anti-p)
- Need to produce anti-particles
  - Positron – OK, anti-protons difficult
  - from proton nucleus collisons

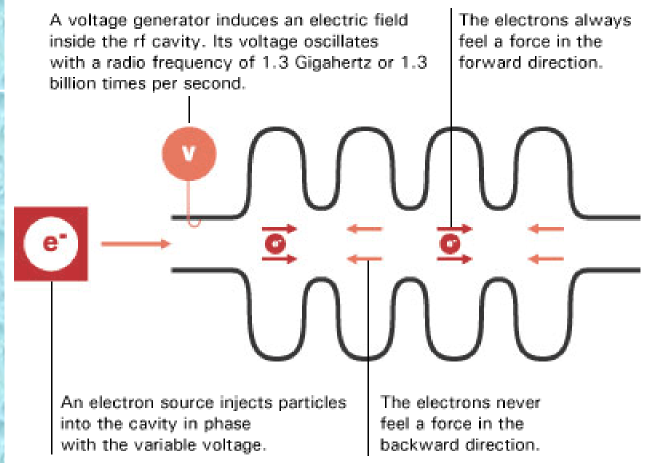


radius

$$p(GeV/c) = 0.3B\rho$$

Accelerating Cavities

- International Linear Collider plan for 35 MV/m
- Length for 500 GeV beams ?



A voltage generator induces an electric field inside the rf cavity. Its voltage oscillates with a radio frequency of 1.3 Gigahertz or 1.3 billion times per second.

The electrons always feel a force in the forward direction.

An electron source injects particles into the cavity in phase with the variable voltage.

The electrons never feel a force in the backward direction.

Niobium, superconducting

Magnets

1200 dipole superconducting (1.9K) magnets, 14.3m long, 8.35 T

Proton energy 7 TeV,
minimum ring circumference ?

Energy considerations:

1)Fixed Target vs Collider

- Energy
  - Achieve higher sqrt(s) at collider
    - Direct new particle searches
- Stable particles
  - Colliding beam expts use p,e^- (muons?)
- Rate
  - Higher luminosity at fixed target

2) Linac vs synchrotron

- Linac Energy
  - length & voltage per cavity
- Synchrotron Energy
  - Radius, max B-field
  - Synchrotron radiation

Higher E = bigger machine

Energy: Fixed Target Experiment

b at rest: $E_b = m_b$

$$s = (E_a + m_b)^2 - p_a{}^2 \approx 2E_a m_b \quad \text{for} \quad E_a >> m_a, m_b$$

$$\sqrt{s} \propto E_a{}^{\frac{1}{2}}$$

Energy: Colliding Beam

Symmetric beams – lab frame =CM frame Particle & anti-particle collision

$$E_a = E_b \qquad \mathbf{p_a} = -\mathbf{p_b}$$

$$s = (E_a + E_b)^2 + 0 = 4E_a{}^2$$

$$\sqrt{s} \propto E_a$$

Synchrotron Radiation

Energy lost as particles bent to travel in circle

$$\Delta E = \frac{q^2 \beta^3 \gamma^4}{3\varepsilon_0 \rho}$$

ρ is radius of curvature of orbit
So for relativistic particles $\beta \approx 1$

$$\Delta E \propto \gamma^4$$

Limits energy for a electron/positron machine
< ~ 100GeV/beam

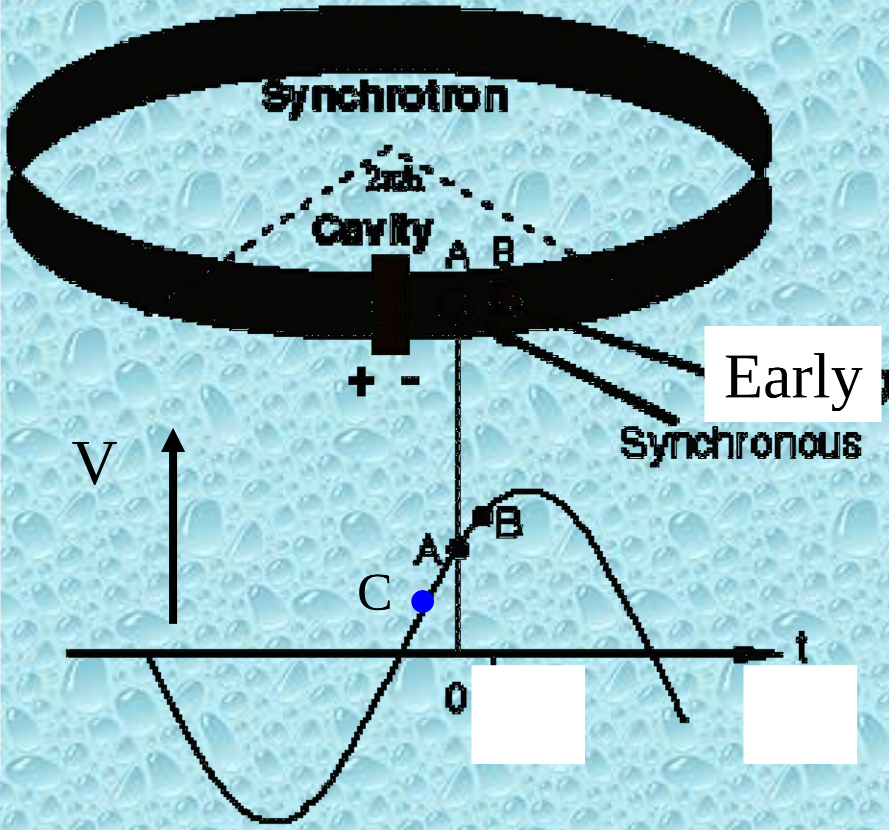
Hence, LHC proton collider

Also a useful source of high energy photons for material studies

Diamond Synchrotron started operation recently in Oxfordshire

Synchrotron: Beam Stability

- Particles accelerated in bunches LHC $N=10^{10}$
- Particle accelerated just enough to keep radius constant – in reality…
- Synchrotron Oscillations
  - Movement of particles wrt bunch
  - out of phase with ideal, stability ensured



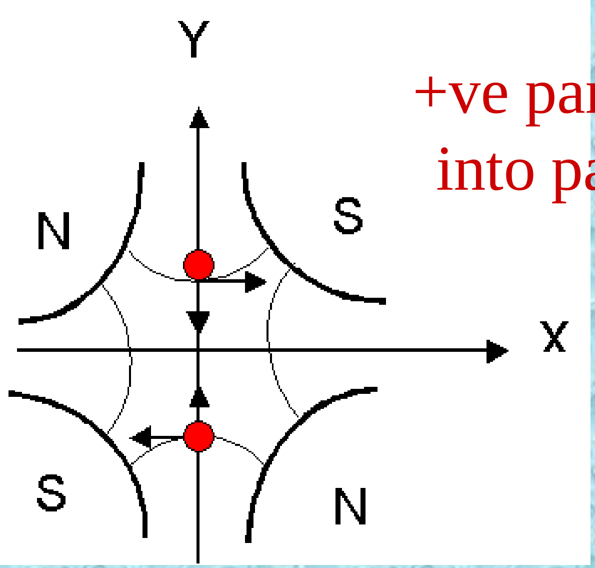
Particle B arriving early receives a larger RF pulse
moves to a larger orbit and arrives later next time

Particle C arriving late received smaller acceleration, smaller orbit, earlier next time

Focussing

- Particles also move in transverse plane
  - Betatron oscillations
  - Origin - natural divergence of the originally injected beam and small asymmetries in magnetic fields.
- Beams focussed using quadropole magnets.

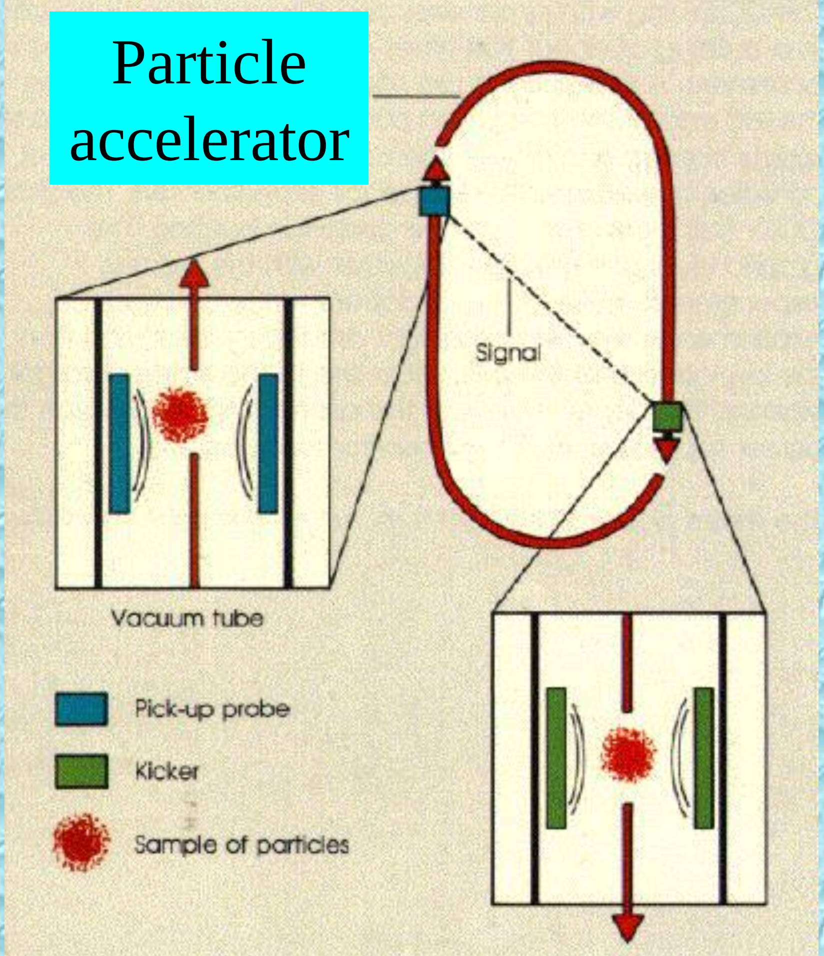
Focussing in vertical/ horizontal planes
Force towards centre of magnet.
Alternate vertical / horizontal
net focussing effect in both planes.



+ve particle into paper

N.B. Dipoles=bending, Quadropoles=focussing

Cooling



- Initially particles have a wide spread of momentum and angle of emission at production
- Need to “cool” to bunch
- One methods – stochastic cooling used at CERN for anti-protons
- Sense average deviation of particles from ideal orbit
- Provide corrective kick
- Note particles travelling at c and so does does electrical signal !

Cross-Sections

We perform an experiment: $p + p \rightarrow p + p + \pi^0$ Smashing beam into a target

How many pions do we expect to see ?

$\propto$Duration of expt(t)
$\propto$Volume of target seen by beam (V)
$\propto$Density of p in target (ρ)
$\propto$Beam incident /sec/Unit area (I)
$\propto$Solid angle of detector ($\Delta\Omega$)
$\propto$Efficiency of experiment (trigger/analysis) (ε)
$\propto$ (I t) (Vρ) $\Delta\Omega$ ε
ΔN $\propto$(1/Area)(N_o) $\Delta\Omega$ ε

The constant of proportionality – the bit with the real physics in ! – is the differential cross-section

$$\frac{d\sigma}{d\Omega}$$

Integration over 4π gives total cross-section

$$\Omega = \int_0^{2\pi} d\phi \int_0^{\pi} \sin\theta d\theta$$

Can divide total xsec into different reactions e.g.

$$\sigma_T = \sigma_{EL} + \sigma_{INEL}$$

xsec measured in barn, pb etc…

Luminosity

For colliding beams no V (target volume) term.
Require two narrow beams with complete overlap at collision point
Typical beam sizes 10-100μm in xy and cm in z

Interaction rate is

$$N = (n_1 n_2 f / a)\sigma \quad \text{in s}^{-1}$$

n_1, n_2 are number of particles in a bunch
f is the frequency of collisions
e.g. rotation in circular collider, this can be high, LHC 40 MHz!
a is the bunch area of overlap at collision point (100% overlap)

$(n_1 n_2 f / a)$ is known as the luminosity
LHC plans up to 10^{34} cm^{-2} s^{-1}

Linac – one shot machine
Synchrotron – particles circulate for many hours

Fixed target luminosity can be higher
e.g. 10^{12} p on 1m long liquid-H target gives~10^{37}cm^{-2} s^{-1}

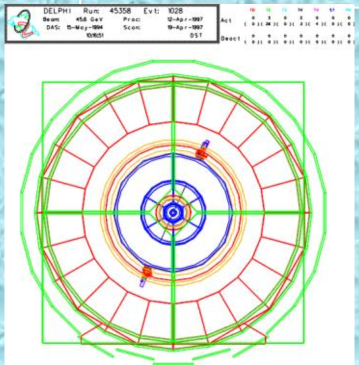
Number of events = lumi **x** xsec **x** time

Typically good machine running time is ~1/3 yr (1x10^7s)

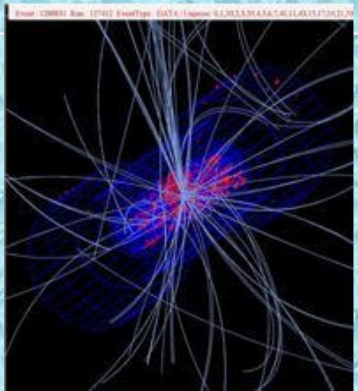
Electrons vs Protons ?

- Useful centre-of-mass energy electron vs proton
- Proton is composite, ~10% root(s) useful energy
- 100 GeV LEP, 1TeV Tevatron had similar reach

- Electron-positron much cleaner environment
  - No extra particles
  - Can detect missing energy e.g. neutrinos, new neutral particles
- Proton
  - Higher energies, less synchrotron radiation
  - Electron-positron – “high precision machine”
  - Proton-proton – “discovery machine”

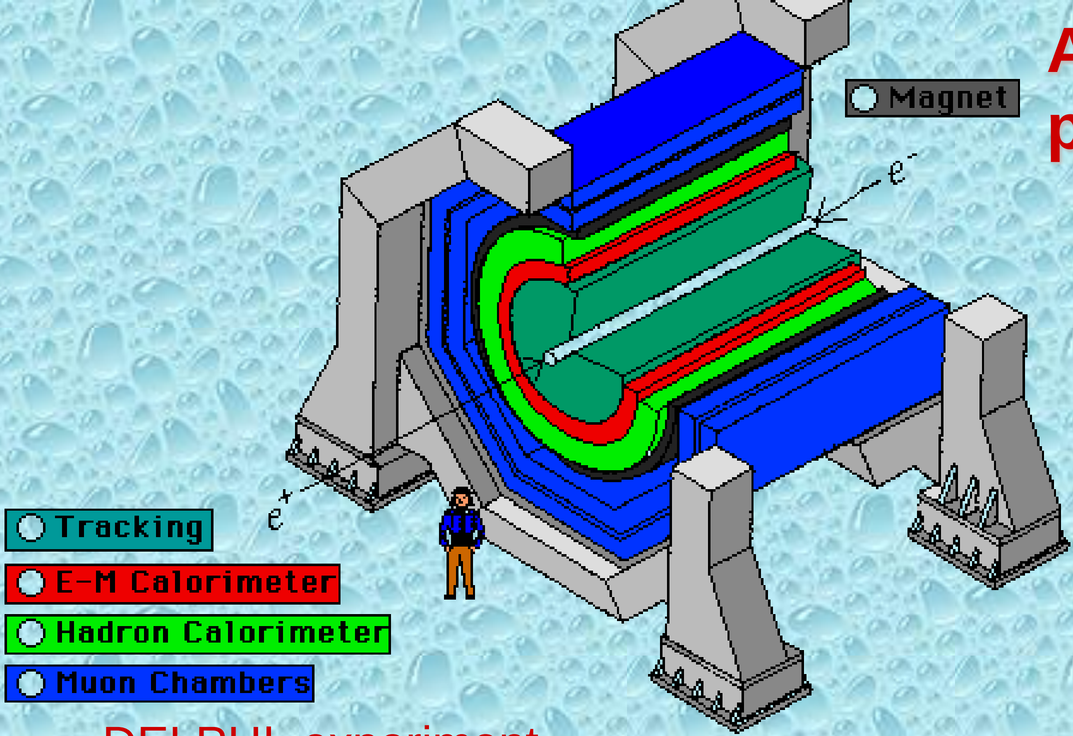


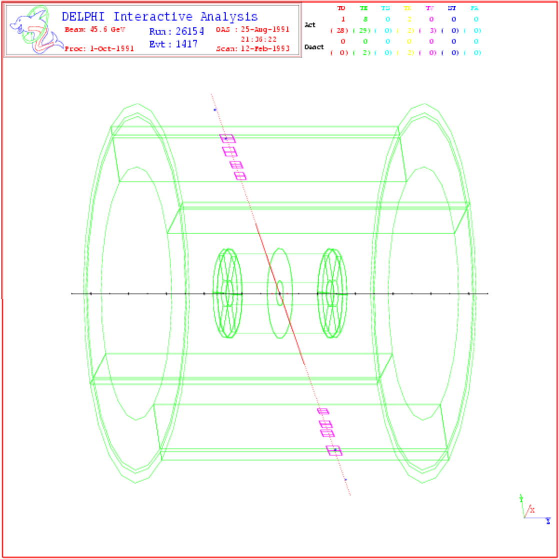
LEP Event



Tevatron Event

A typical modern particle physics experiment





DELPHI Interactive Analysis

Beam: 45.6 GeV

Proc: 1-Oct-1991

Run: 26154

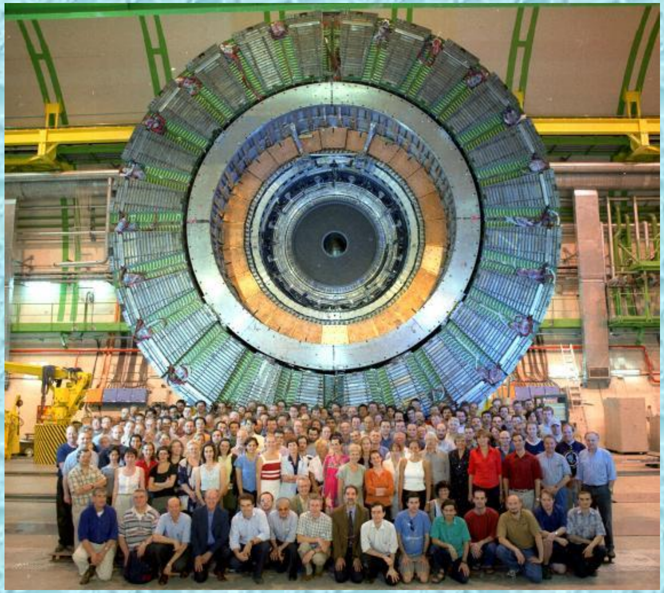
Evt: 1417

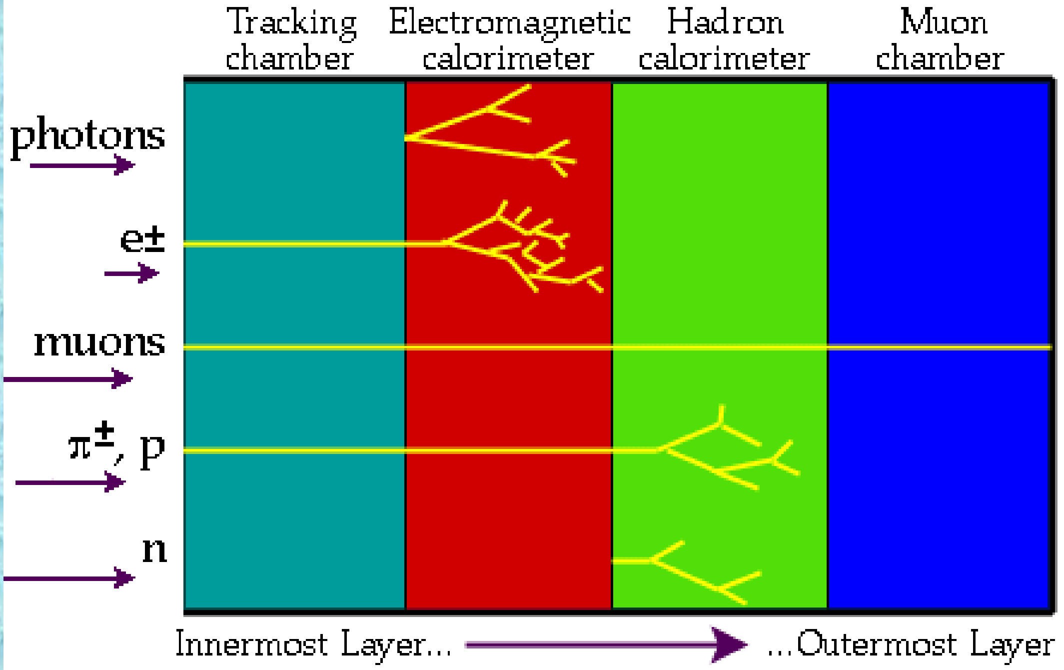
DAS: 25-Aug-1991 21:36:22

Scan: 12-Feb-1993

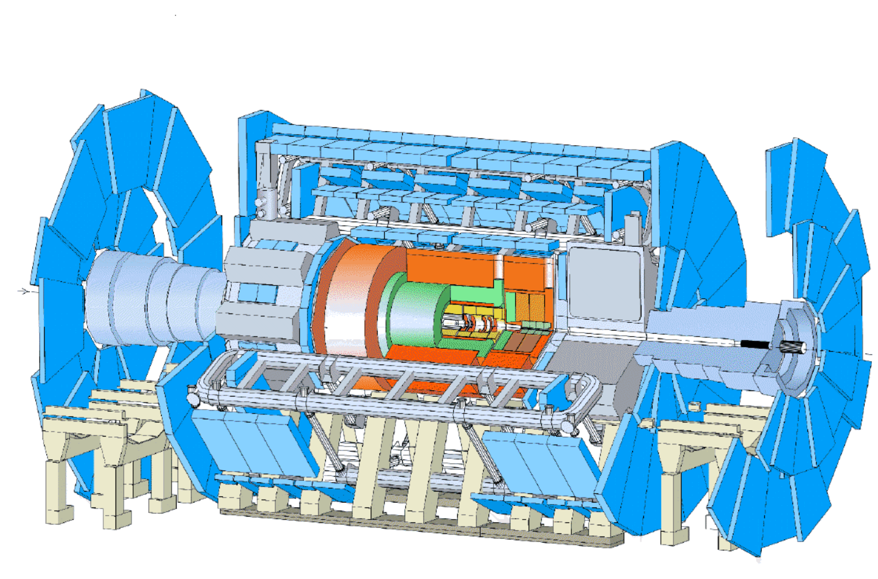
	TD	TE	TS	TK	TV	ST	PA
Act	1	8	0	2	0	0	0
	(28)	(29)	(0)	(2)	(3)	(0)	(0)
Deact	0	0	0	0	0	0	0
	(0)	(2)	(0)	(2)	(0)	(0)	(0)

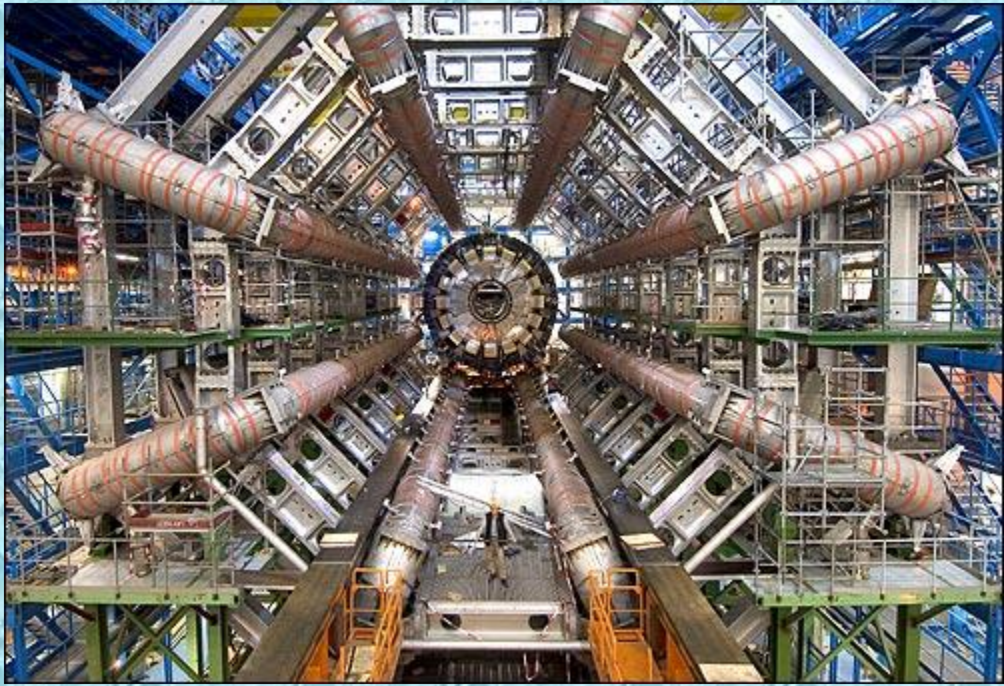
DELPHI experiment
@ LEP collider





Example Particle Detector- ATLAS





Detector Components:
Tracking systems, ECAL/HCAL, muon system
+ magnet – several Tesla - momentum measurement

Time Resolution:
LHC 40Mz=25ns

Tracking: Spatial Resolution 5-200μm

ECAL: Energy Resolution $\Delta E / E \approx 0.05 / \sqrt{E}$

HCAL: $\Delta E / E \approx 0.5 / \sqrt{E}$

Elements of Detector System

- Sensitive Detector Elements: e.g.
  - Tracking - silicon sensors, gaseous ionisation detectors
  - Calorimeters – lead, scintillators
- Electronic readout:e.g.
  - Custom designed integrated circuits, custom pcbs,
  - Cables, power supplies.
- Support Services: e.g.
  - Mechanical supports
  - Cooling
- Trigger System
  - LHC 40 MHz, write to disk 2kHZ
  - Which events to take ?
  - Parallel processing, pipelines
  - Trigger levels
  - Add more detector components at higher levels

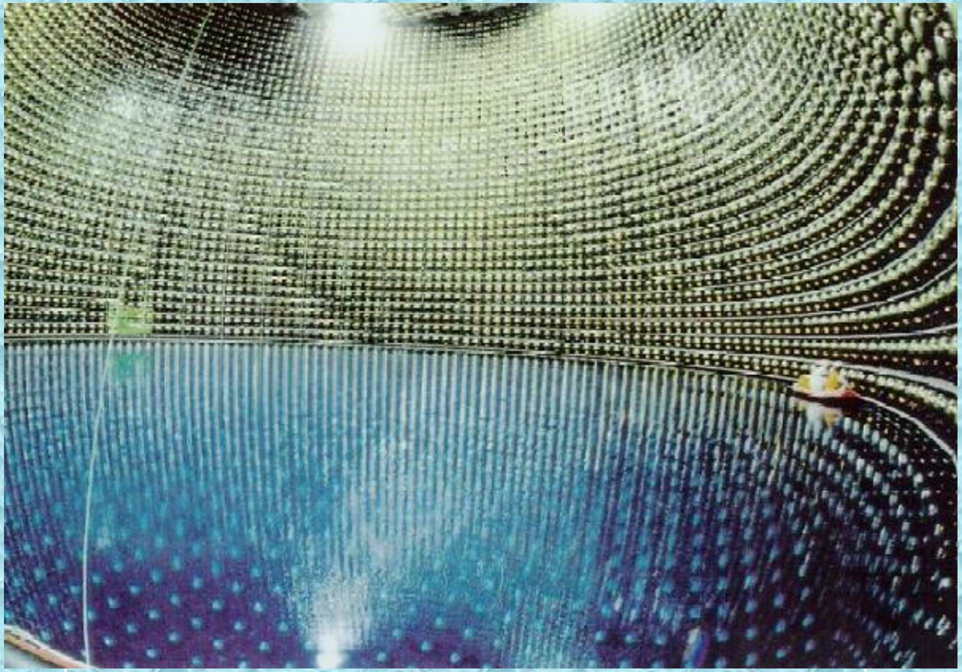
Computing in HEP
Each event 100kB-1MB
1000MB/s, 1PB/year
Cannot analyse on
single cluster
Worldwide computing
Grid

Example Neutrino Detector

But not all detectors look like previous examples

Example – neutrino detector

- Very large volume
- Low data rate

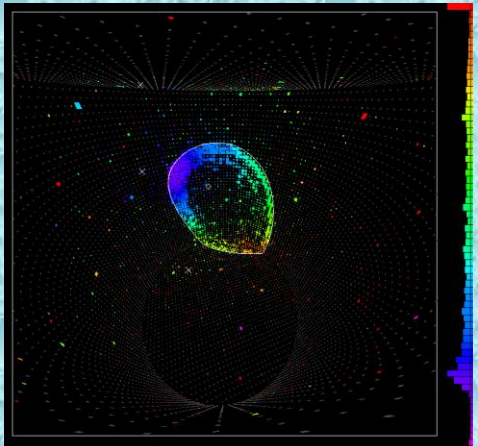


Super-Kamiokande
half-fill with water

50,00 tonnes of water
11000 photomultiplier tubes
Neutrinos interact

$$\nu + e^- \rightarrow \nu + e^-$$

Chereknov light cone given off
and detected by photomultipliers



Accelerator Summary

Considerations for an accelerator.
- Reaction to be produced
- Energy required
- Luminosity required
- Events expected

Particles are accelerated by electric field cavities.
Achievable Electric fields few MV/m
Higher energy = longer machine

Fixed target expt. – not energy efficient but sometimes unavoidable (e.g. neutrino expts)

Particles are bent into circles by magnetic fields.
Synchrotron radiation – photons radiated as particle travels in circle
E lost increases with γ^4, so heavy particles or bigger ring
Or straight line…

Synchrotron oscillations controlled by rf acceleration
Quadropole magnets used to focus beams in transverse plane

Linac – repetition rate slower as beams are not circulating
Synchrotron – beams can circulate for several hours