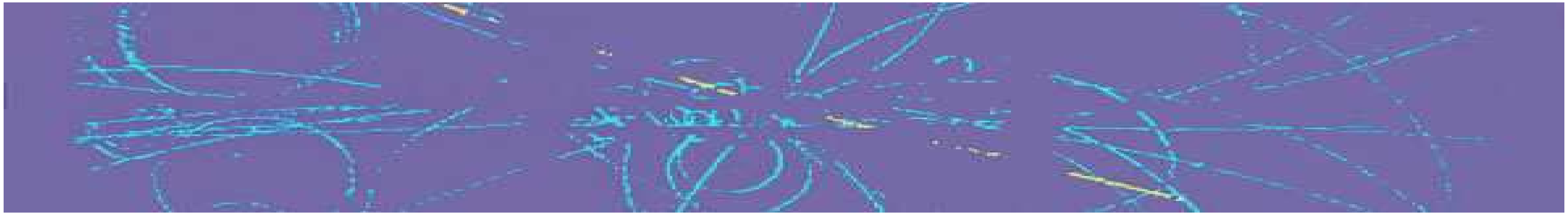
The Particle World



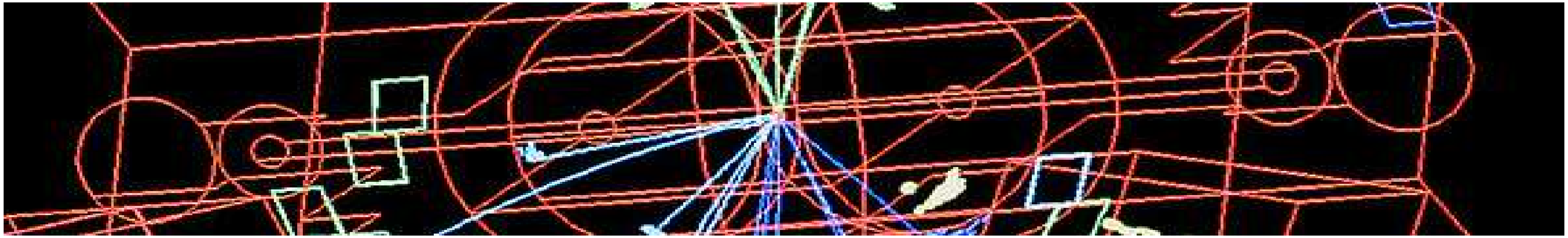
- What is our Universe made of?
- Where does it come from?
- Why does it behave the way it does?

Particle physics tries to answer these questions.

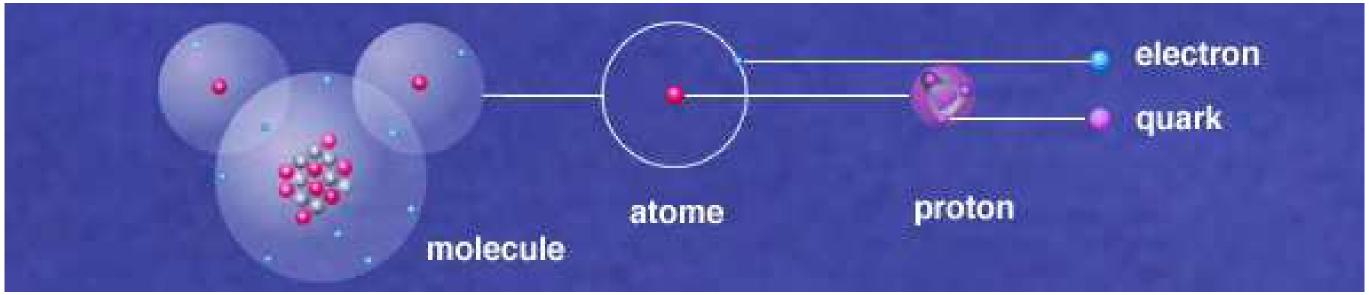
This talk:

- particles as we understand them now (the Standard Model)
- prepare you for the exercise

Later: future of particle physics.



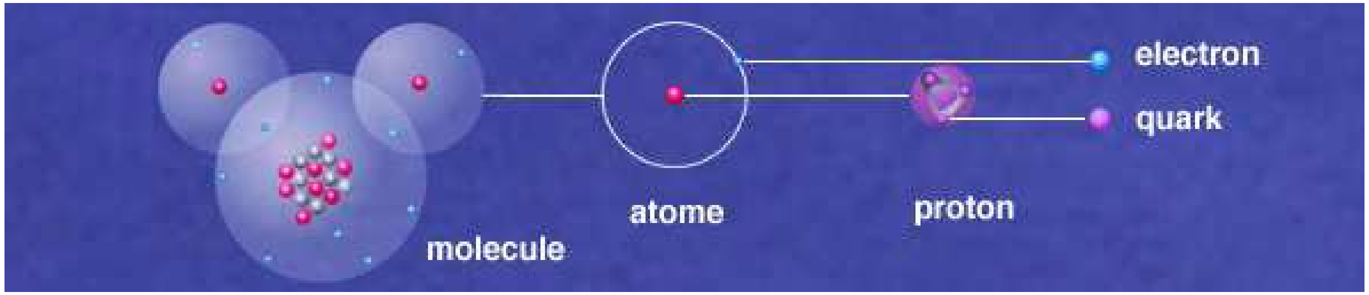
Beginning of the 20th century: atoms have a nucleus and a surrounding cloud of electrons.



The electrons are responsible for almost all behaviour of matter:

- emission of light
- electricity and magnetism
- electronics
- chemistry
- mechanical properties

. . . technology.



Nucleus at the centre of the atom: tiny yet contains almost all the mass of the atom. Yet, it's composite, made up of protons and neutrons (or nucleons).

Open up a nucleon . . . it contains quarks.

Normal matter can be understood with just two types of quark.

- u or up quark, charge $+2/3$
- d or down quark, charge $-1/3$

Subsequently, particle physicists have discovered four more types of quark, two more pairs of heavier copies of the up and down:

- c or charm quark, charge $+2/3$
- s or strange quark, charge $-1/3$
- t or top quark, charge $+2/3$
- b or bottom quark, charge $-1/3$

Existed only in the early stages of the universe and nowadays created in high energy physics experiments.

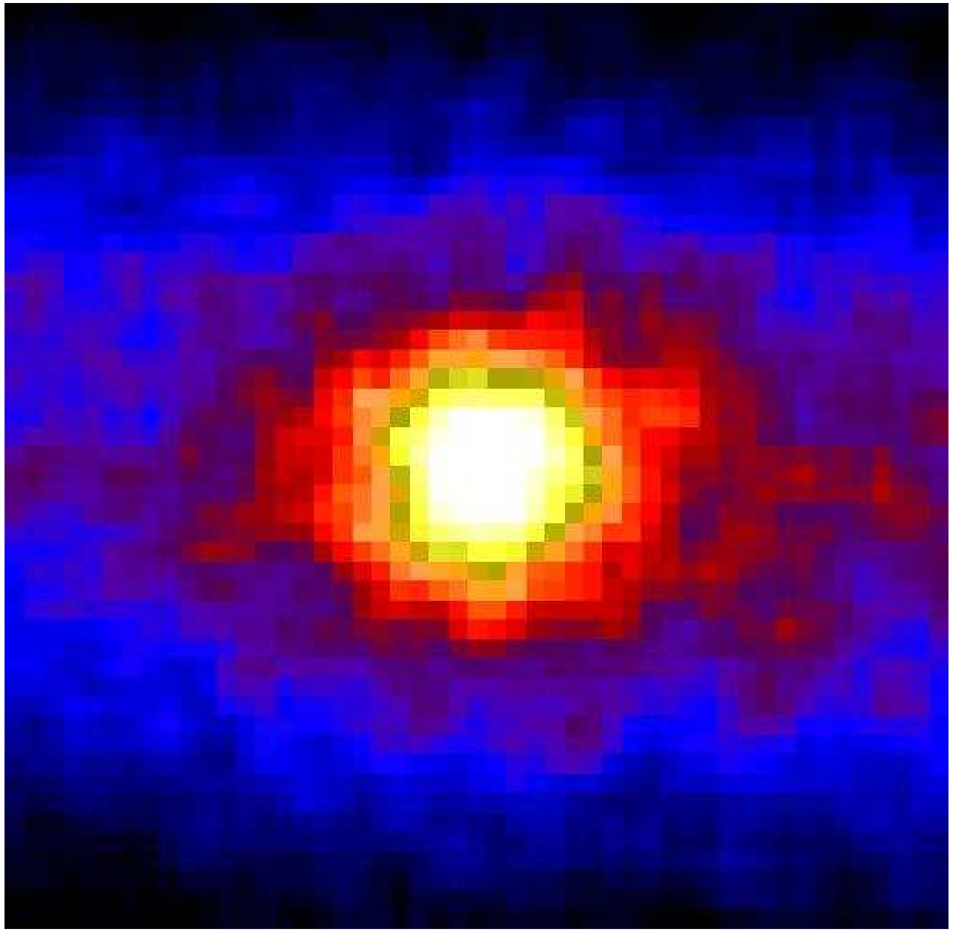
But this is not all. . .

The electron has a friend the electron-neutrino, ν_e. Needed to ensure energy and momentum are conserved in β-decay:

$$n \longrightarrow p + e^- + \overline{\nu}_e$$

Neutrino: no electric charge, (almost) no mass, hardly interacts at all.

Sun is a huge neutrino factory: have learned a lot from studying solar neutrinos as well as using neutrinos produced in reactors and particle physics experiments.



There are heavier ‘copies’ of the electron and its neutrino:

μ or muon	ν_μ or muon neutrino
τ or tau	ν_τ or tau neutrino

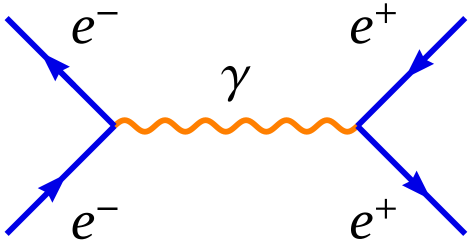
Together these are the leptons

Not really sure why we have extra copies of quarks and leptons, but in total they make up three generations.

But this is still not all... Forces are mediated by force carriers.

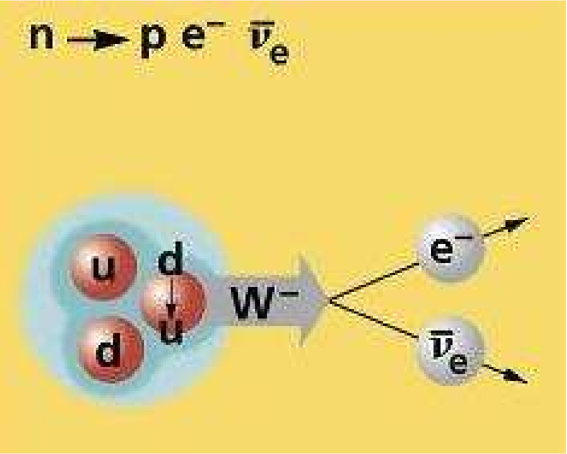
Electromagnetic force

Electrons have electric charge and are affected by electromagnetism. Particle physics views the electromagnetic force as the exchange of photons.



Weak Force

Weak decays, eg β-decay, $n \to p + e^- + \overline{\nu}_e$ is understood as decay of a d quark, mediated by a W particle.



Also have a friend of the charged $W^\pm$, the neutral Z. The W and Z are massive, around 80 and $90\,\mathrm{GeV}$ respectively.

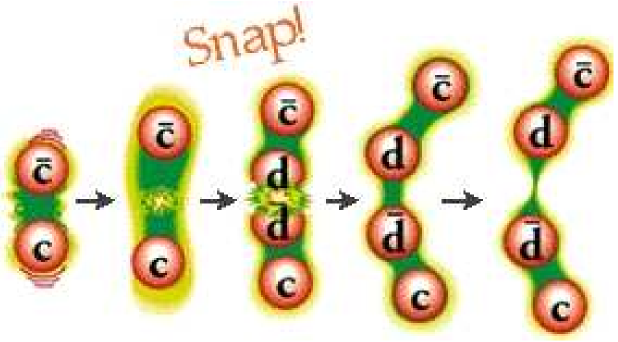
Strong Force

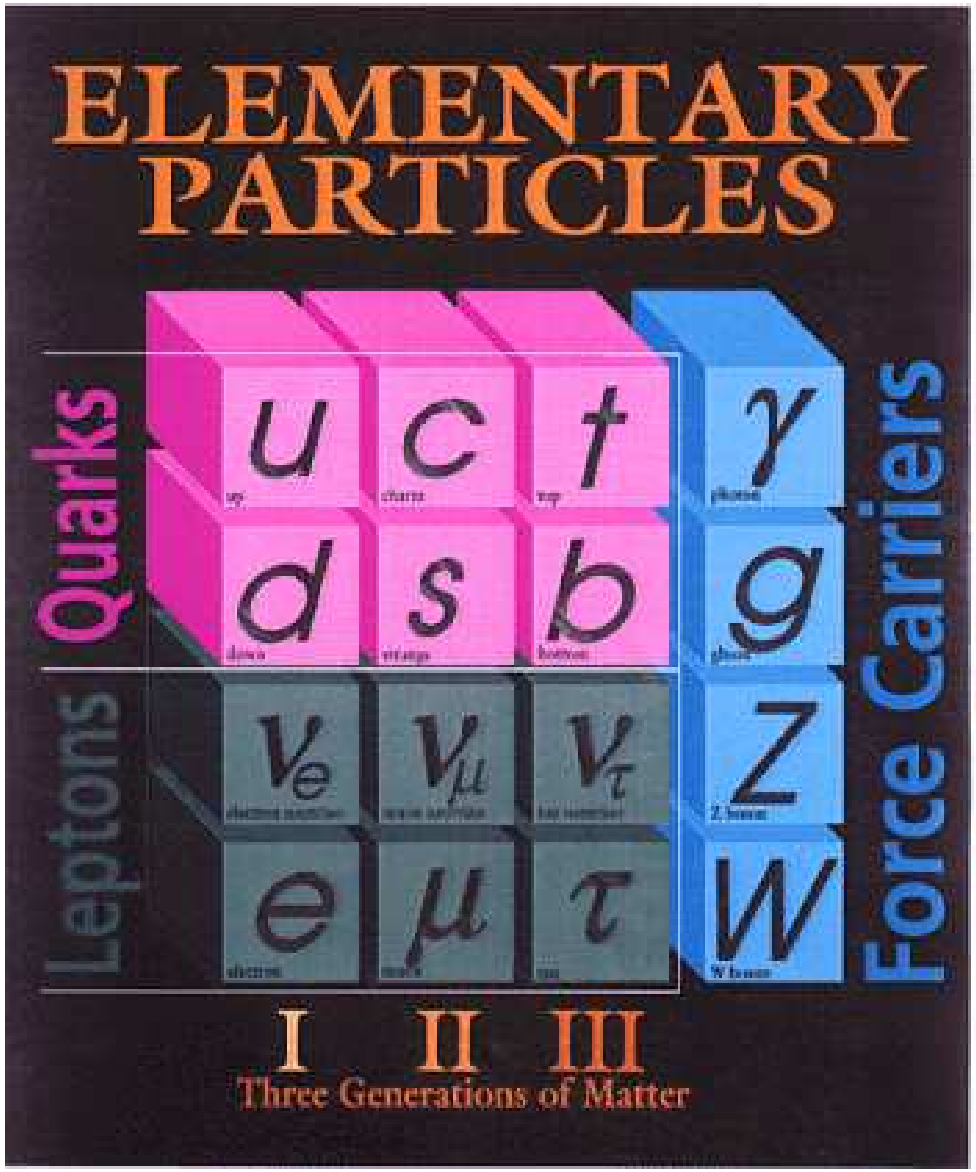
Binds nucleons in the atomic nucleus.

Binds quarks into nucleons and other hadrons

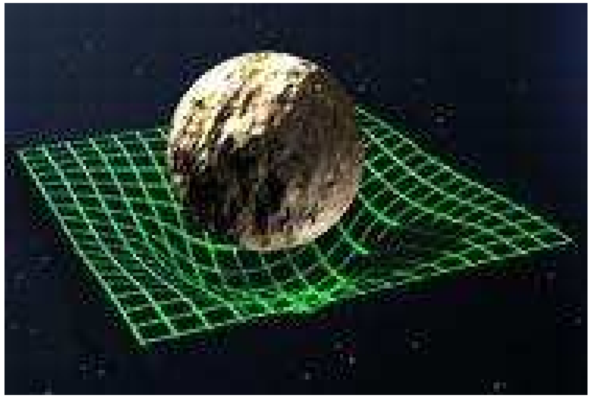
Quarks come in three colours. Exchange of coloured gluons between quarks is the mechanism of the strong force.

The strong force confines quarks inside hadrons. We never find isolated quarks experimentally. If you try to pull two quarks apart, so much energy is needed that it's favourable to create a new quark-antiquark pair instead: you end up with two hadrons rather than separated quarks.




ELEMENTARY PARTICLES
Quarks
Leptons
Force Carriers
u
up
c
charm
t
top
γ
photon
d
down
s
strange
b
bottom
g
gluon
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
Z
Z boson
e
electron
μ
muon
τ
tau
W
W boson
I
II
III
Three Generations of Matter

Gravity



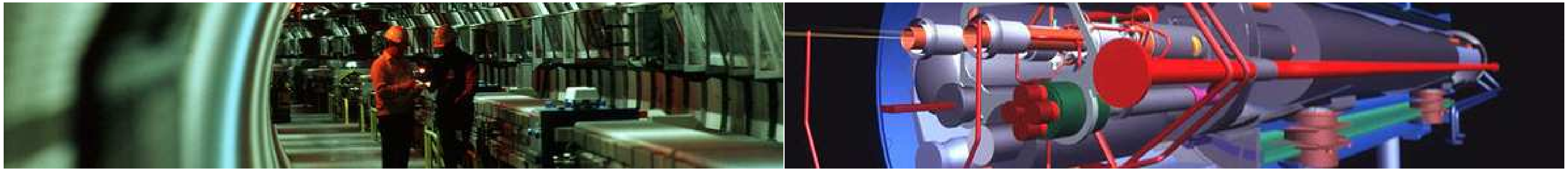
Don’t need to worry about gravity here.

Higgs Boson

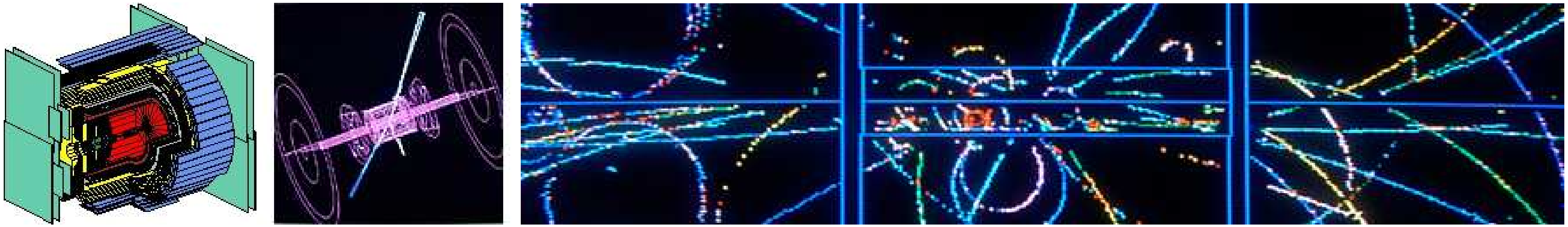
There’s one more particle, the Higgs boson, whose existence is tied up with the mechanism used to give mass to the other particles.

‘Nearly’ discovered at LEP: first job of the LHC is to look for the Higgs (but that’s in a few years’ time).

Studying Particles



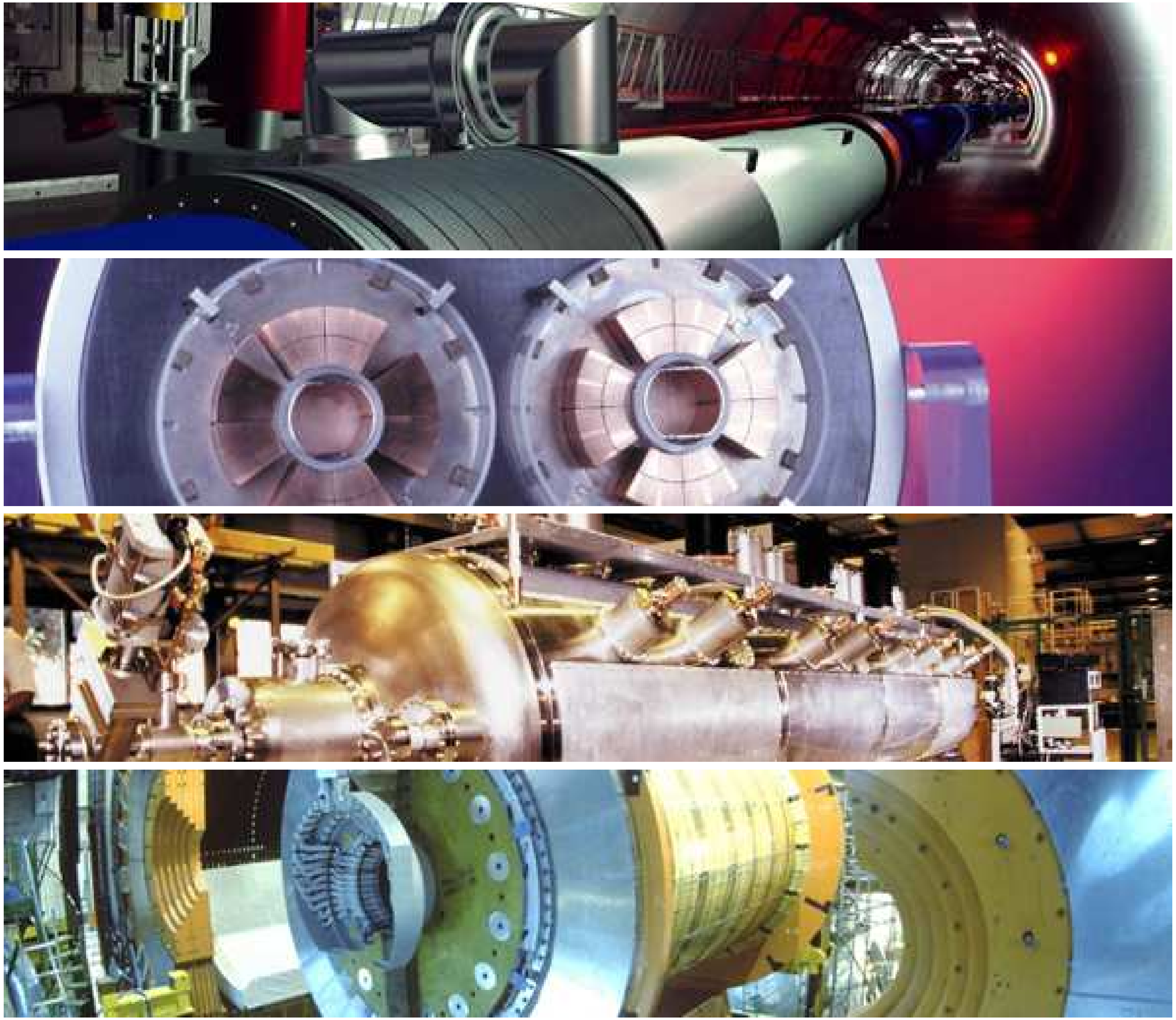
- Produce beams and smash them together: accelerators
- Look at what comes out: detectors



LEP: the Large Electron Positron Collider

$27\,\mathrm{km}$ long tunnel,
$100\,\mathrm{m}$ underground,
straddling
French-Swiss border,
just outside Geneva.

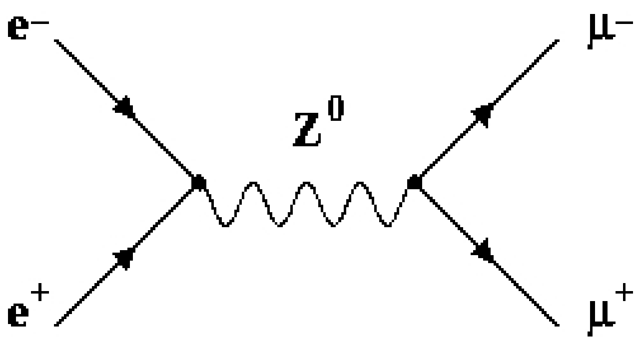
LEP



Bend particles around with magnets. Kick them with electric fields on each orbit to raise energy. Collide the beams at intersection points inside detectors.

Studying Collisions at LEP

Collide beams of electrons and positrons head-on at high energy. Here, an electron (e^-) and a positron (e^+) collide to produce a Z^0. Because the initial e^- and e^+ have momenta which are opposite in direction and equal in magnitude the Z^0 has no net momentum and is stationary. After a very short time (about 10^{-25} s) the Z^0 decays to produce a muon (μ^-) and an antimuon (μ^+) which fly apart 'back to back'.



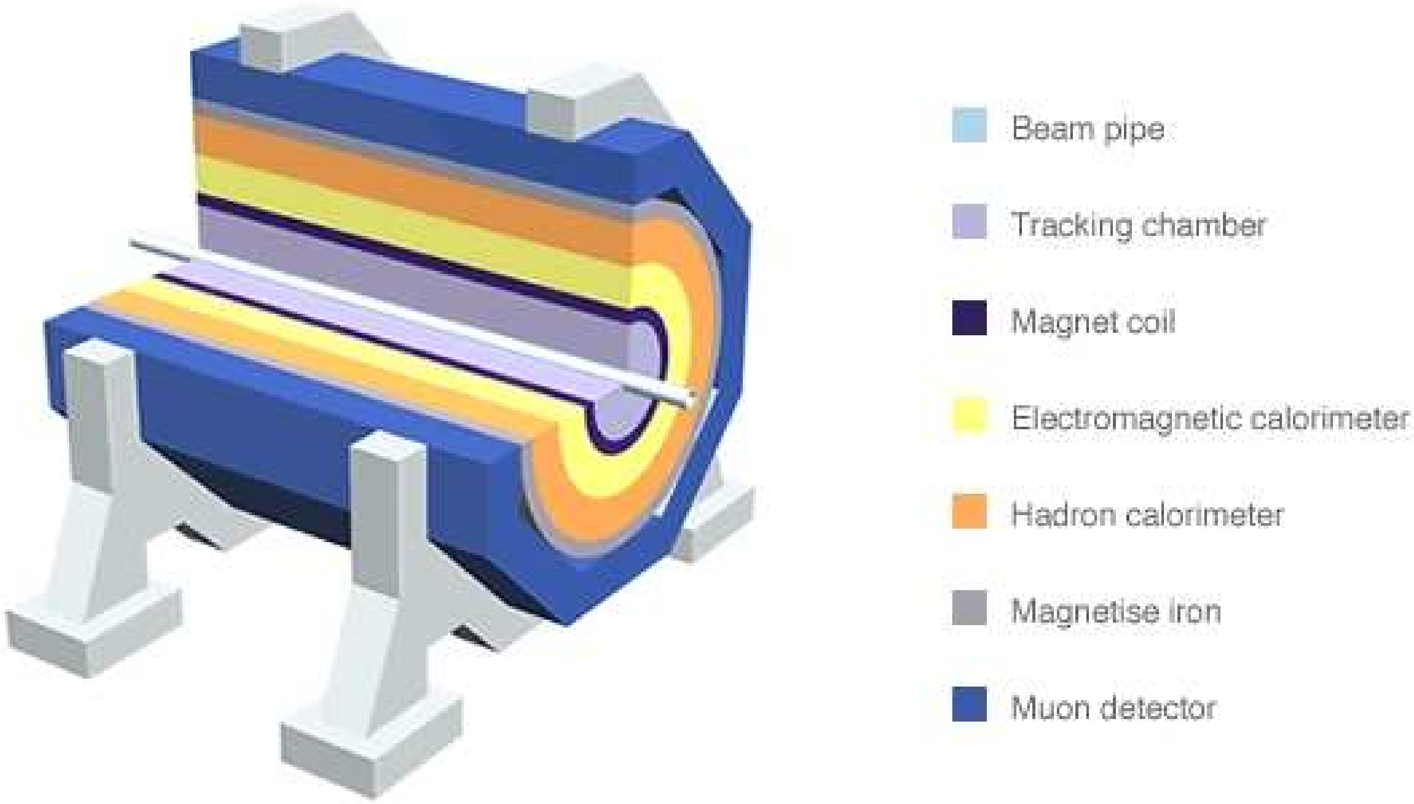
We surround the place where the Z^0 is produced with detectors, which enable us to see the particles produced when it decays.

Later, you'll look at collisions where produce pairs of W's.

The OPAL Detector

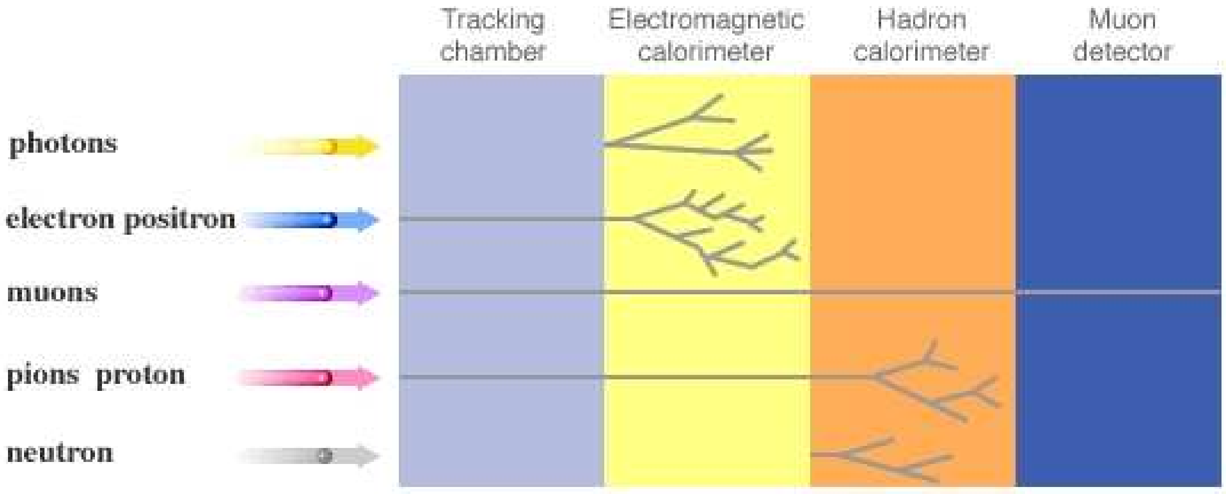
Study events recorded by OPAL, one of the four detectors at LEP.

OPAL was approximately cylindrical. Particles produced on-axis axis at the centre and travelled out through several layers of detectors. Different types of particle leave different signals in the various detectors: this lets us distinguish them.



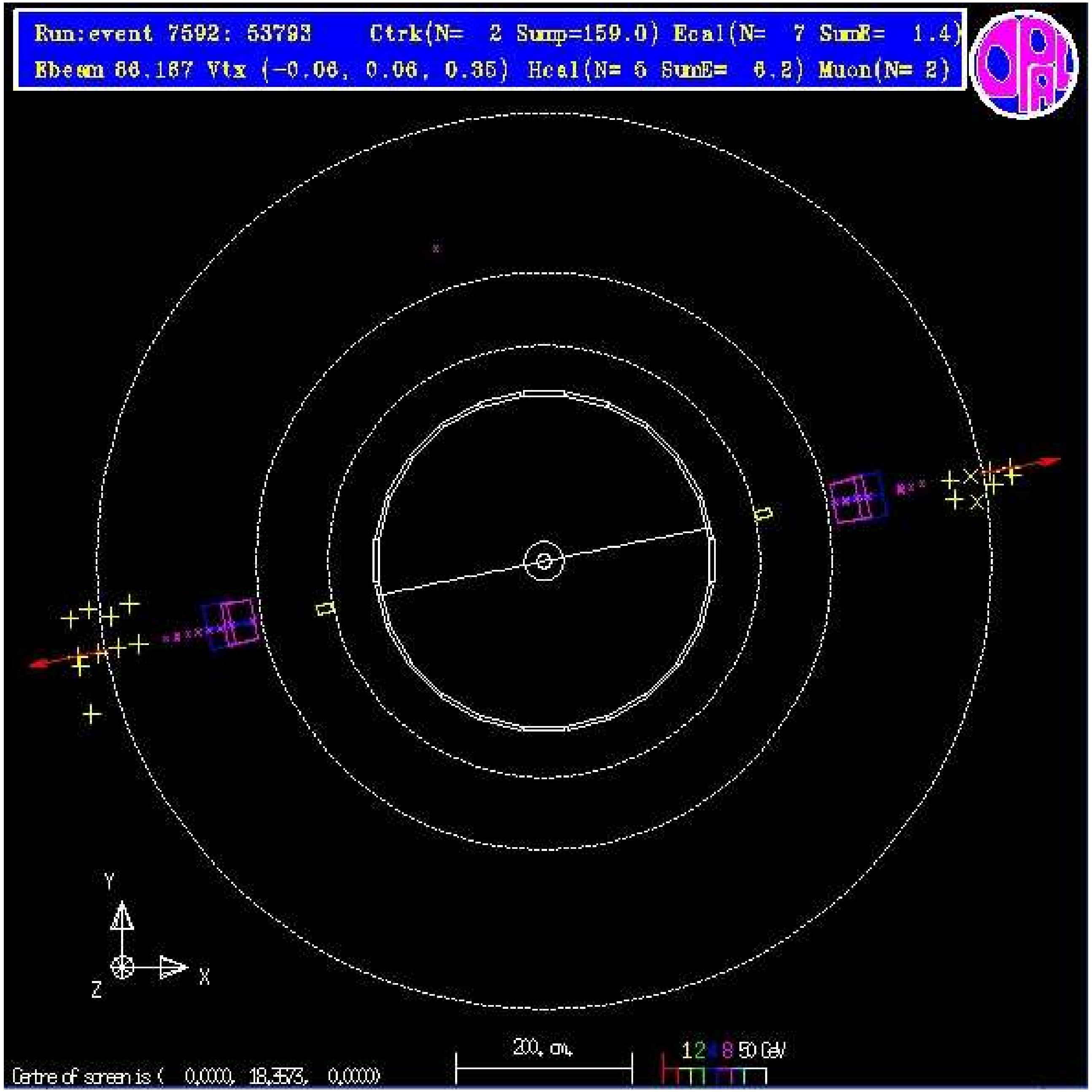
Detector Ingredients

- Tracking chamber: records the tracks of charged particles
- Electromagnetic calorimeter or ecal: measures energy of light particles (electrons, photons) as they interact with electrically charged particles inside matter
- Hadron calorimeter: measures energy of hadrons as they interact with atomic nuclei
- Muon detectors: muons get right through the calorimeters; outer muon detectors observe charged particles (rather like the tracking detectors)



Detecting Muons

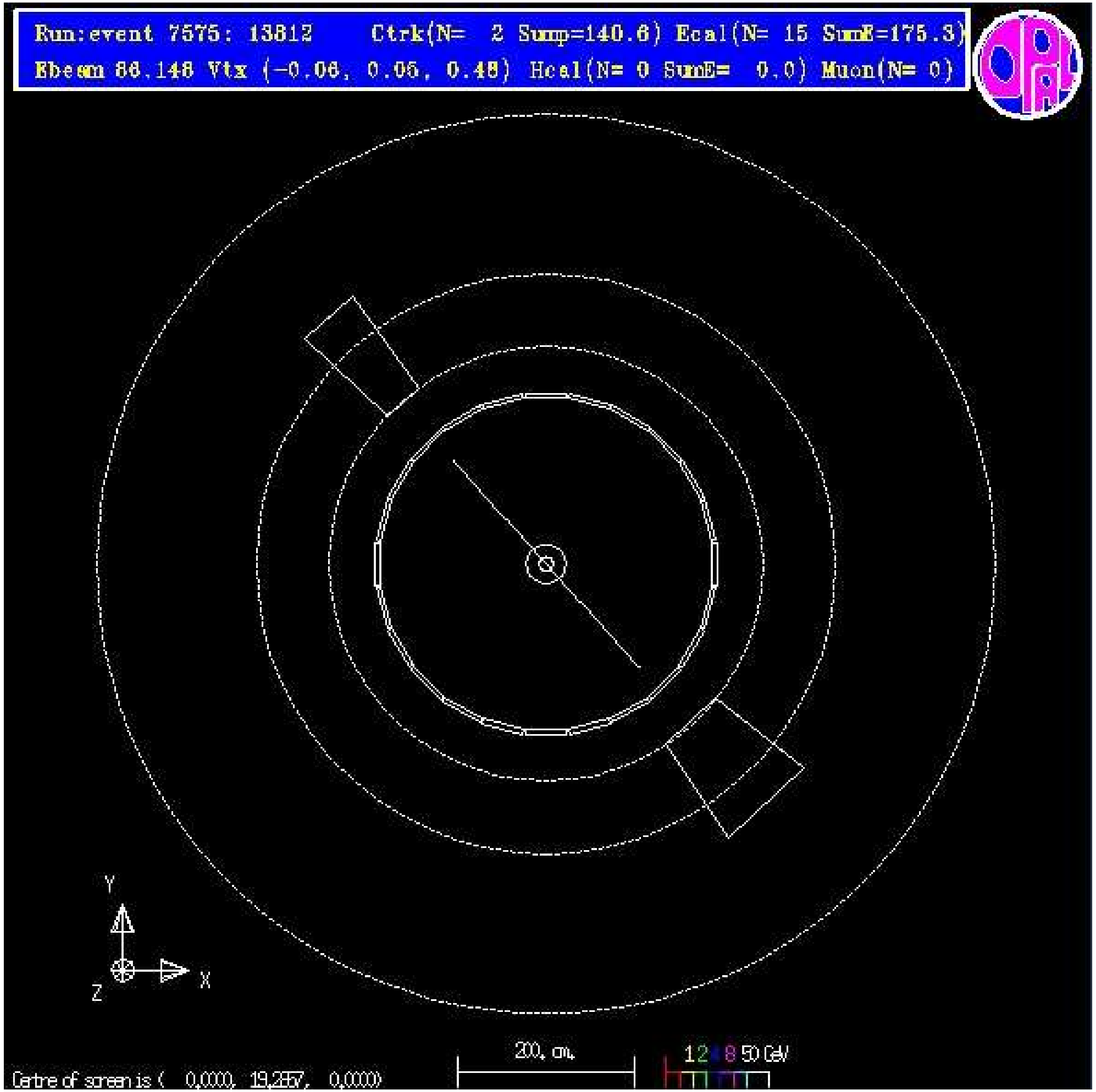
Only type of particle that has a high probability of passing through all the calorimeters and leaving signals in the muon chambers.



Detecting Electrons

Electrons lose all their energy in the ecal.

- Momentum of charged track should be similar to energy observed in ecal ⇒ track and cluster usually same colour.
- No signal in hadronic calorimeter or muon chambers.



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Run:event 7575: 13812     Ctrk(N=  2 Sump=140.6) Ecal(N= 15 SumE=175.3)
Ebeam 86.148 Vtx (-0.06, 0.05, 0.48) Hcal(N= 0 SumE=  0.0) Muon(N= 0)
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Centre of screen is (   0.0000,  19.2857,   0.0000)
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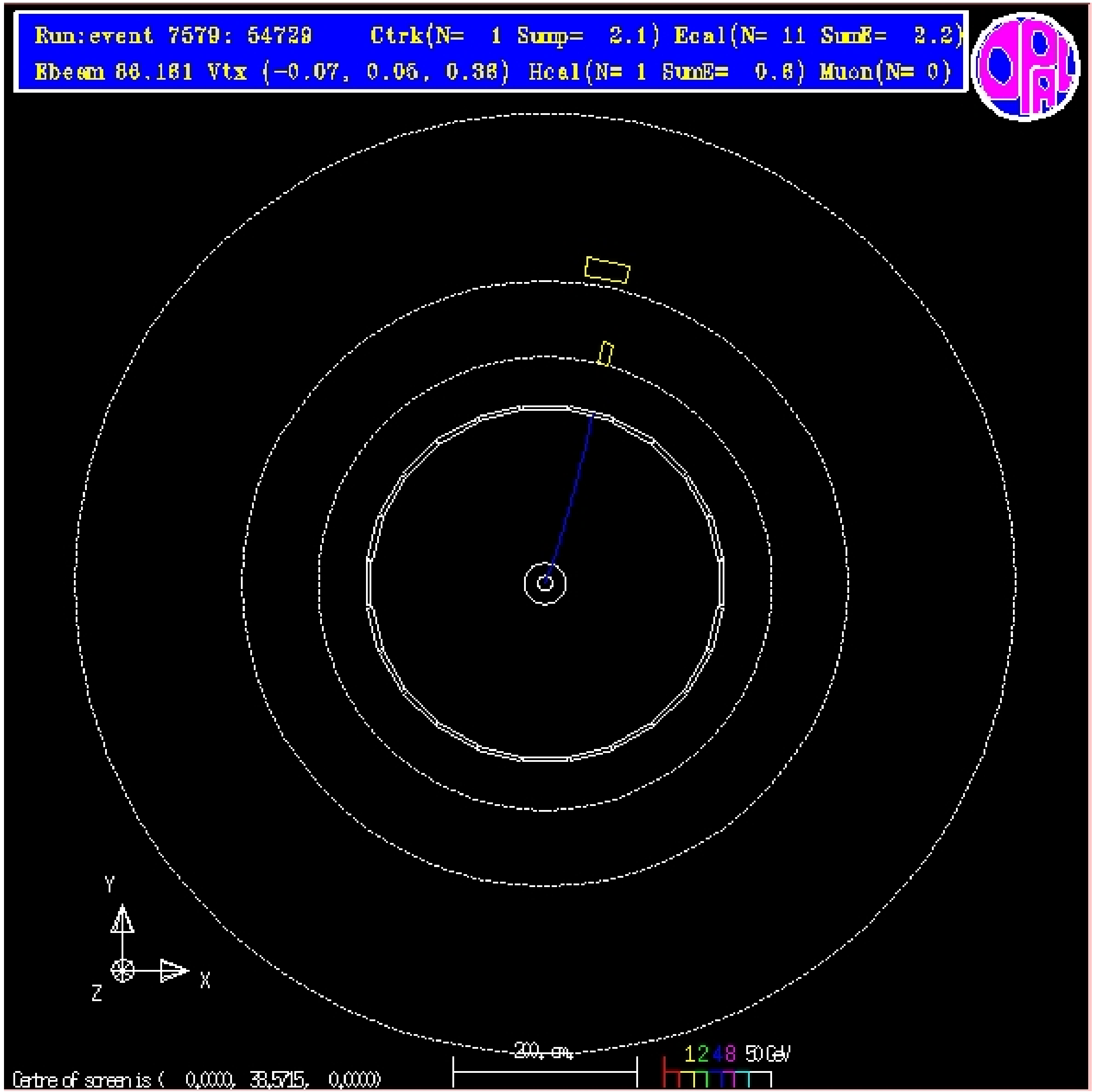
Detecting Hadrons

Hadrons made of quarks, antiquarks and gluons.

- Track momentum usually larger than energy dumped in ecal.
- No signals in muon chambers.
- Energy often visible in hadronic calorimeter.

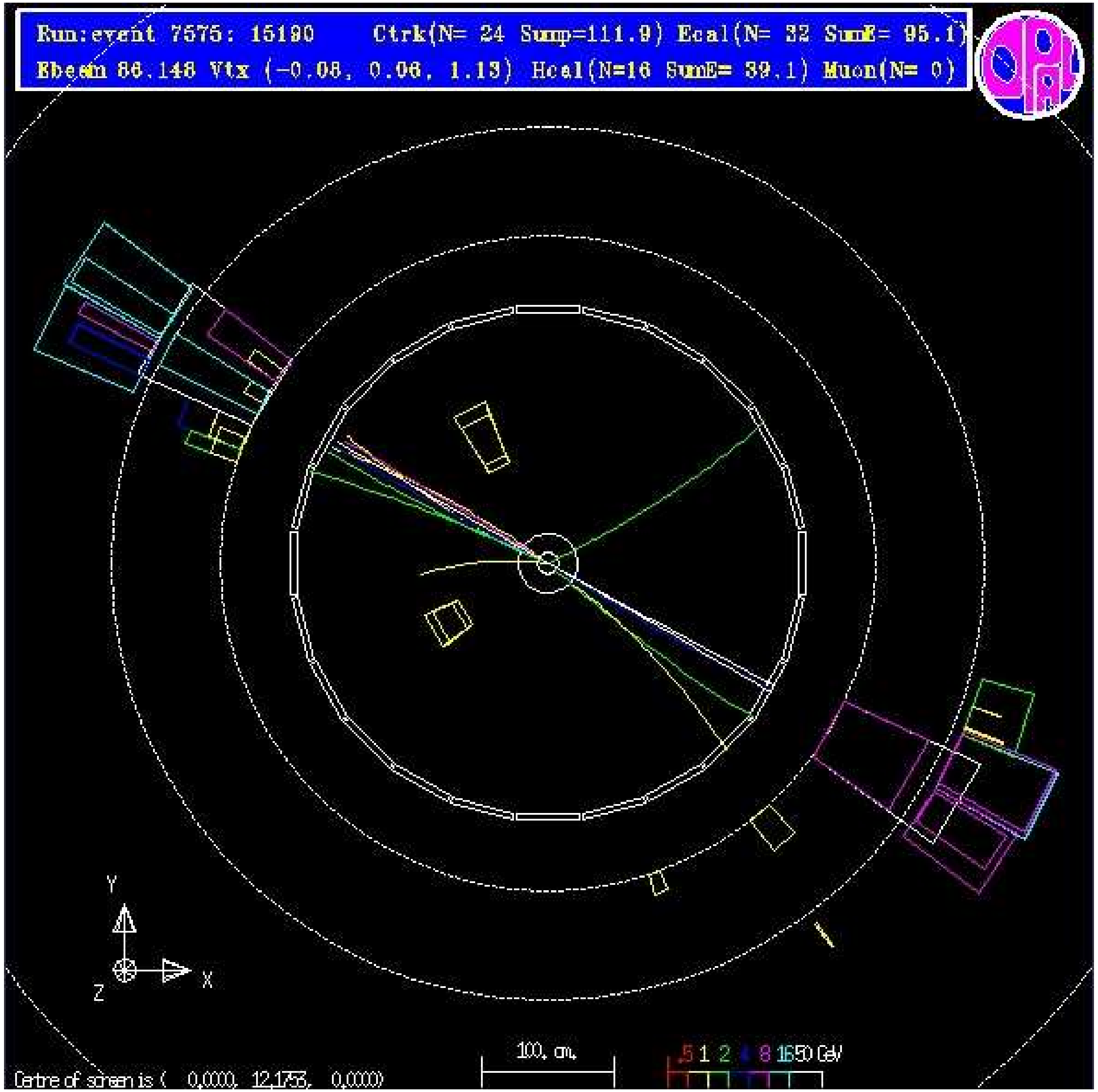
Signals less clear-cut than for electrons or muons. If unsure, ask: Is this particle an electron? Is this particle an muon? If 'no' to both, safe to assume it's a hadron!



Detecting Quarks

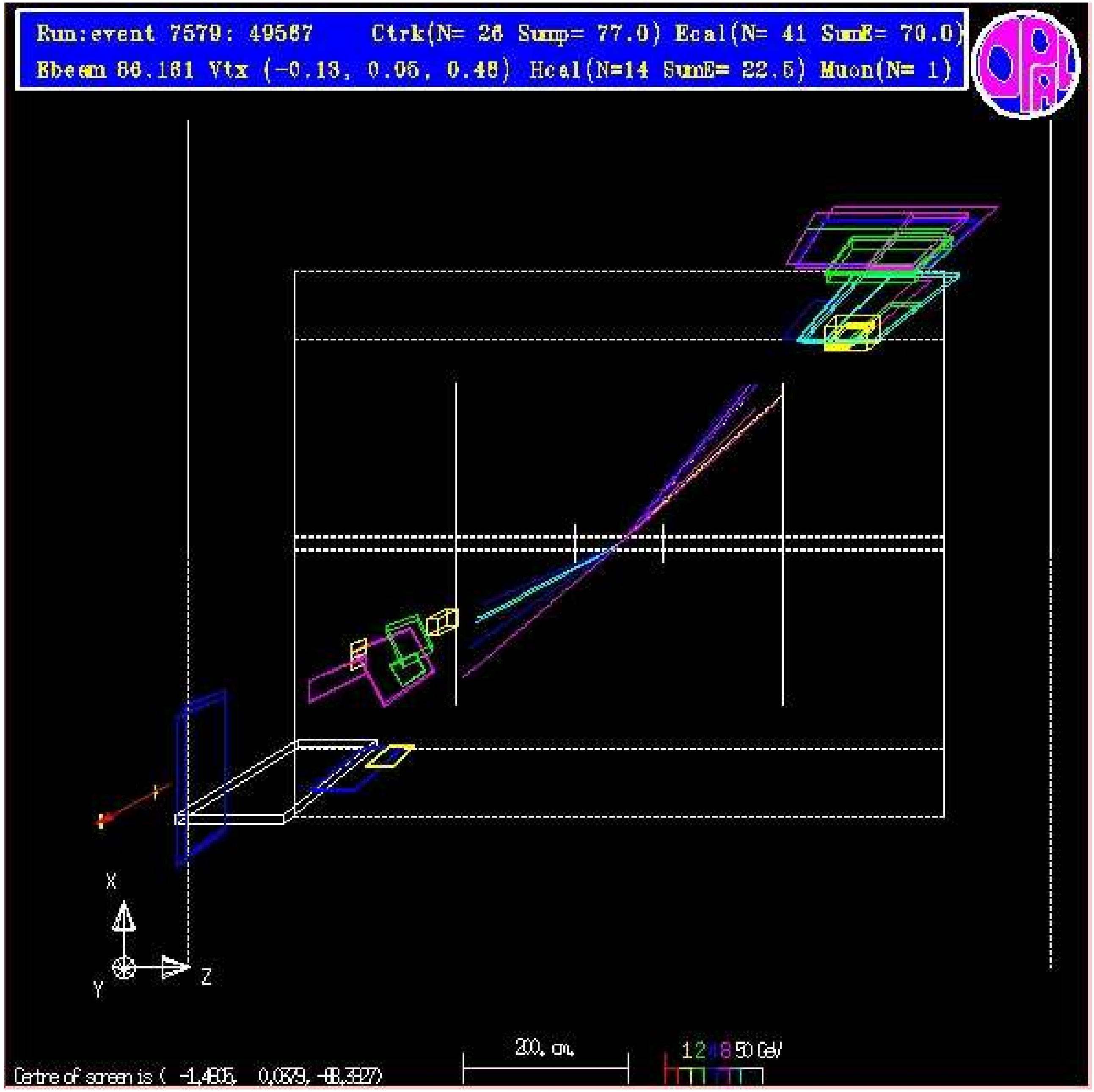
Quarks not seen directly:

- See a shower or jet of particles, flying off in direction of original quark.
- Most particles in the jet are hadrons: see a number of charged particle tracks and energy deposited in the electromagnetic and hadronic calorimeters.



Detecting Quarks (2)

Sometimes a jet may contain an electron or muon (as in this example) as well as hadrons.



Terrible τ's

Don't see τ's directly: they decay after travelling a fraction of a millimetre.

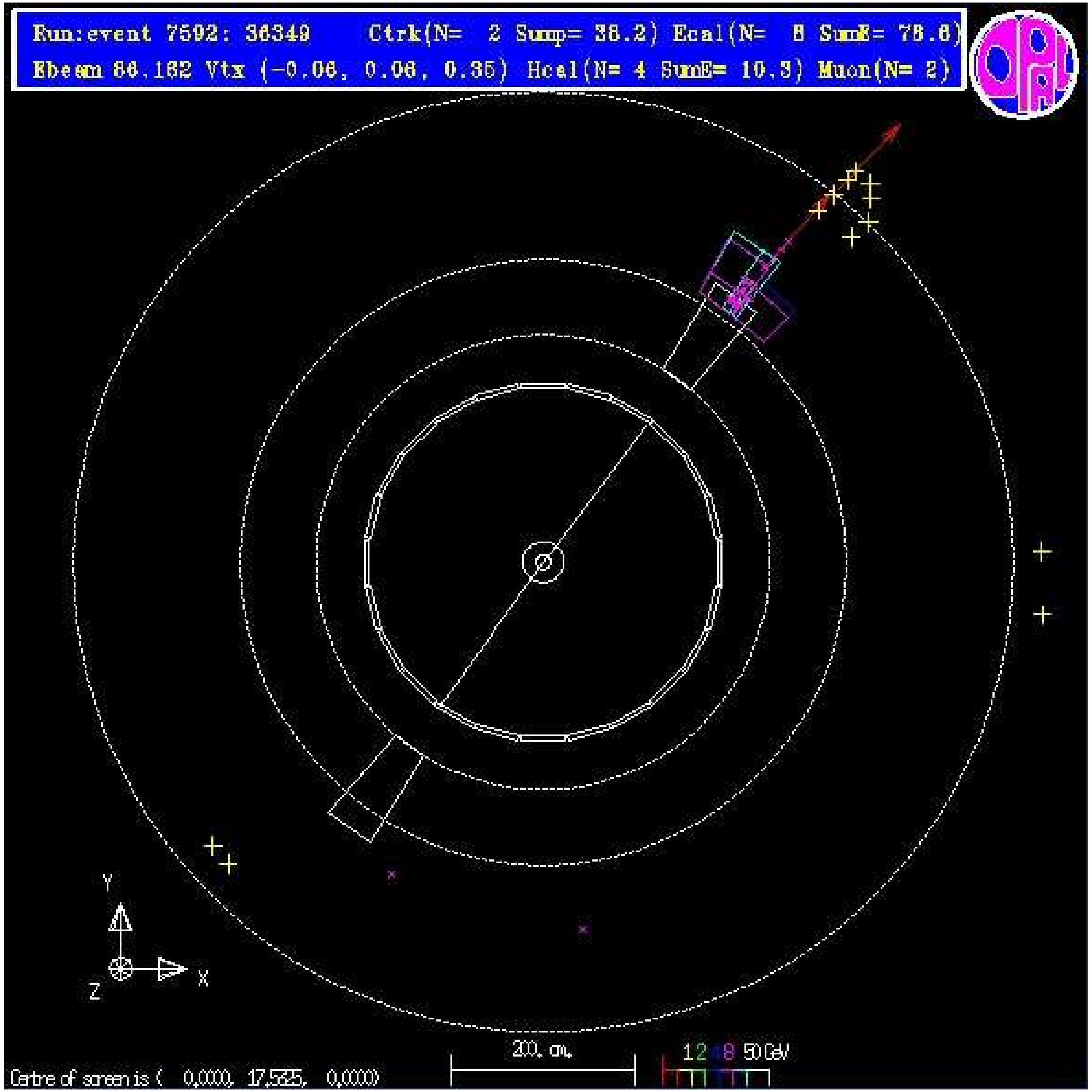
17%	$\tau \longrightarrow \nu_\tau + e^- + \overline{\nu}_e$
17%	$\tau \longrightarrow \nu_\tau + \mu^- + \overline{\nu}_\mu$
66%	$\tau \longrightarrow \nu_\tau + \text{hadrons}$

- Neutrinos escape without being detected (infer their presence using energy-momentum of observed particles).
- The 66% of hadronic decays comprises

16%	with one charged hadron
50%	with three charged hadrons

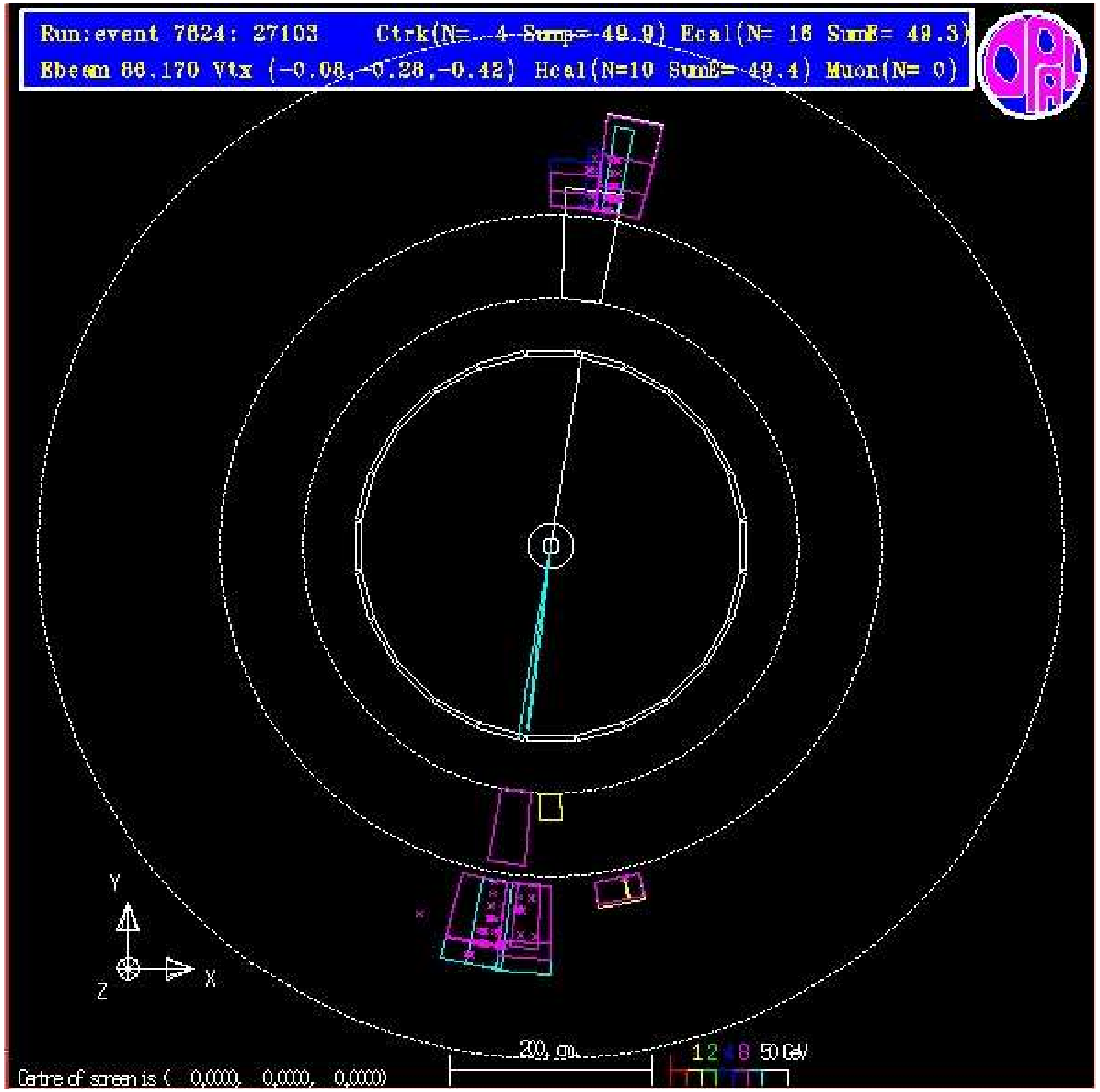
Both τ's decay leptonically.

$$e^+e^- \;\rightarrow\; Z^0 \rightarrow \tau^+\tau^-$$
$$\rightarrow\; e + \mu + \text{neutrinos}$$



τ's decay to hadrons.

$$
\begin{aligned}
e^+e^- &\rightarrow Z^0\\
&\rightarrow \tau^+\tau^-\\
&\rightarrow \text{3 chgd hadrons}\\
&\quad + \text{1 chgd hadron}\\
&\quad + \text{neutrinos}
\end{aligned}
$$



```
Run:event 7824: 27103     Ctrk(N=  4 Sump= 49.9) Ecal(N= 16 SumE= 49.3)
Ebeam 86.170 Vtx (-0.08,-0.28,-0.42) Hcal(N=10 SumE= 49.4) Muon(N= 0)
```

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Centre of screen is (  0.0000,  0.0000,  0.0000)
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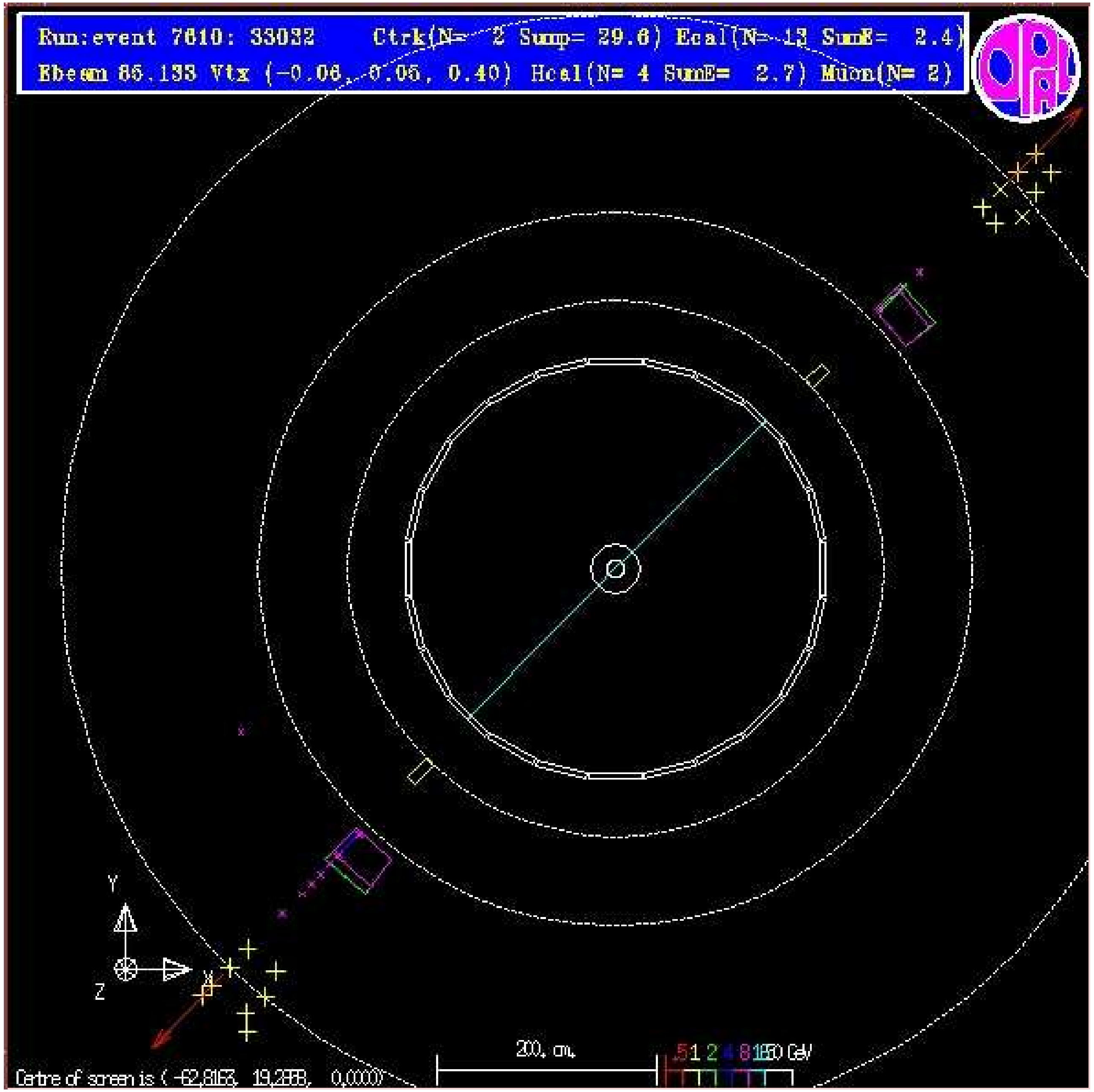
τ's decay to muon pair. . .

$$\begin{aligned} e^+e^- &\rightarrow Z^0 \\ &\rightarrow \tau^+\tau^- \\ &\rightarrow \mu^+ + \mu^- \\ &\qquad + \text{neutrinos} \end{aligned}$$

Looks like $Z^0 \rightarrow \mu^+\mu^-$,

but check energy.



W Decays

W decays to a pair of particles, either quarks or leptons.

- Must conserve charge. W has charge either $+1$ or -1, so must the total of the decay products.
- Decay products must have less mass than the W they started from, or energy would not be conserved. This *excludes* the top quark.

The following decays are possible:

$W^- \rightarrow$	$W^+ \rightarrow$
down and anti-up quarks	anti-down and up quarks
strange and anti-charm quarks	anti-strange and charm quarks
electron and anti-neutrino	positron and neutrino
muon and anti-neutrino	anti-muon and neutrino
tau lepton and anti-neutrino	anti-tau lepton and neutrino

W^+W^- Decays and Counting Colours

Consider

$$e^+e^- \to W^+W^-$$

with the $W^\pm$ subsequently decaying.

Each W can decay to any of the three leptons and to two types of quark-antiquark pair. *But*, quarks come in n colours, so if all decay modes are equally likely, expect for each W:

- three leptonic modes
- $2n$ quark (hadronic) modes

For a large number of W^+W^- *pair* decays, expect the following relative numbers of different decay modes:

Leptonic	Mixed	Four jets
ℓ	m	f
9	$12n$	$4n^2$

Count event types to fix number of colours:

$$n = \frac{3}{4}\frac{m}{\ell}$$

$$n = \frac{3}{2}\sqrt{\frac{f}{\ell}}$$

$$n = 3\frac{f}{m}$$