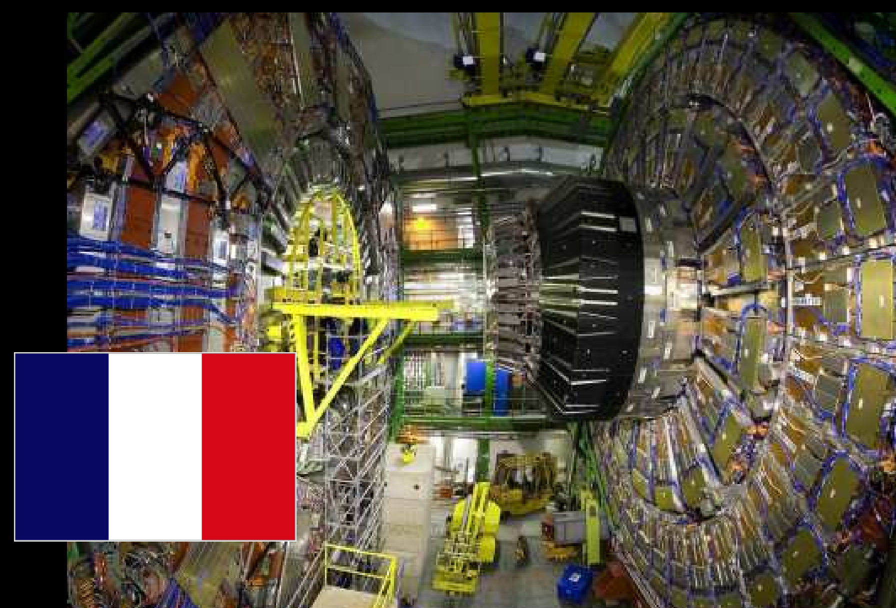
the Large Hadron Collider (LHC)

Kristian Harder

RAL Particle Physics Masterclasses, March 2009

a typical LHC person



we are an international bunch!

red areas = countries involved: ATLAS: ≈35 countries
ALICE: ≈30 countries
CMS: ≈40 countries
LHCb: ≈15 countries

These are only countries officially involved with institutions.
Many individual colleagues from additional countries working with us!

table-top experiment

J.J. Thomson with apparatus used to identify electron as elementary particles (Cambridge, 1897)

table-top experiment

LHC is bigger

J.J. Thomson with apparatus used to identify electrons as elementary particles (Cambridge, 1897)

University-/Lab-scale experiment

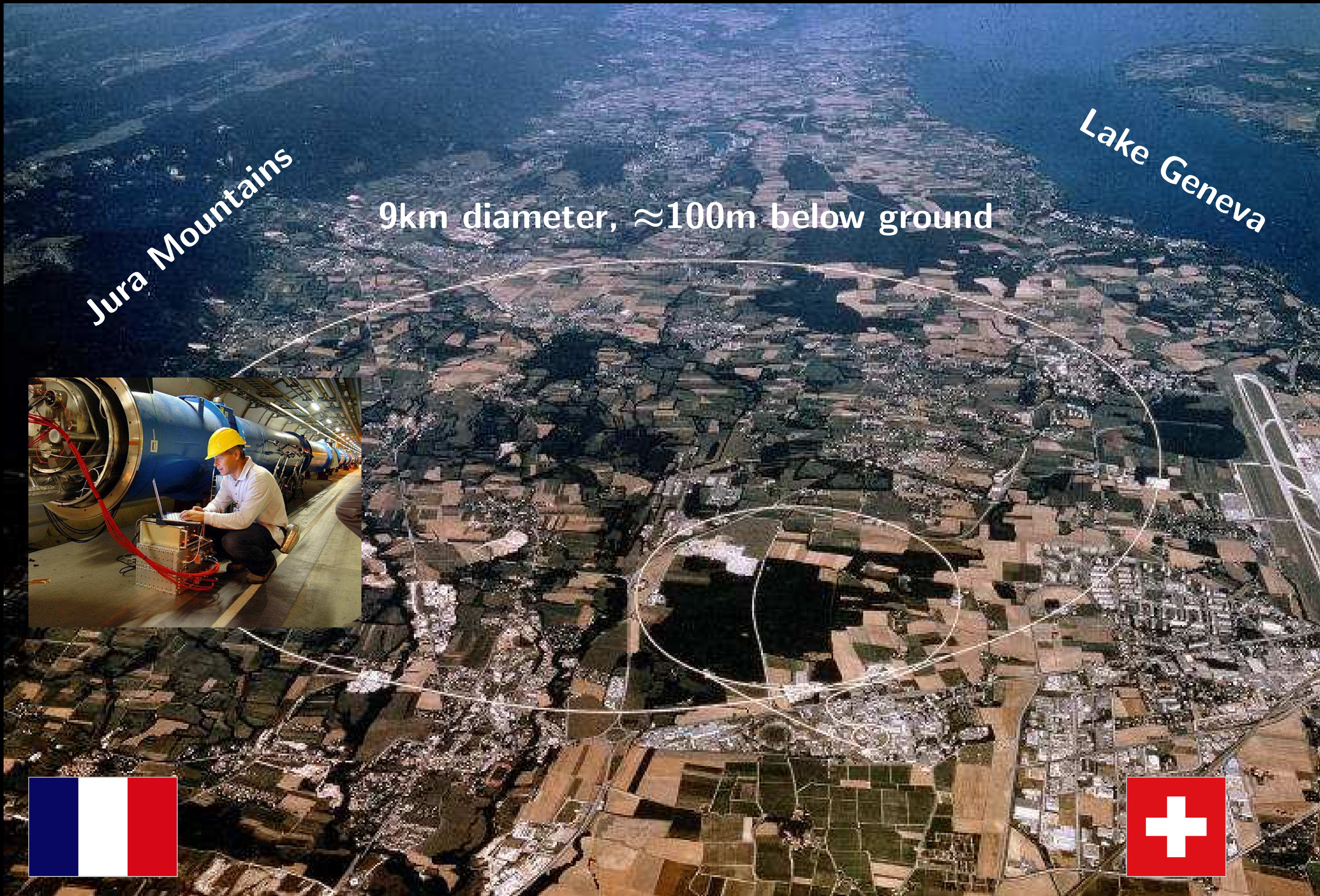
Bevatron 6.5 GeV proton accelerator, Berkeley, USA.
discovery of the antiproton (1955) and antineutron (1956)

University-/Lab-scale experiment

LHC is bigger

Bevatron 6.5 GeV proton accelerator, Berkeley, USA:
discovery of the antiproton (1955) and antineutron (1956)

the largest experiment ever built!



why did we build LHC?

Youtube & Co make many suggestions:

creating black holes
to swallow Earth?

opening a stargate
for the return of Satan?

creating antimatter bombs
to destroy Vatican?

the LHC rap, live!

just trying to be cool?

why did we *really* build LHC?

None of the accusations on the previous page are true.
The real reason is entirely scientific.
Some people call it ...

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status of particle physics

we have a beautiful theory of particle physics (the Standard Model):

- many phenomena can be predicted with unprecedented precision
- it has withheld all attempts to find flaws in it for decades

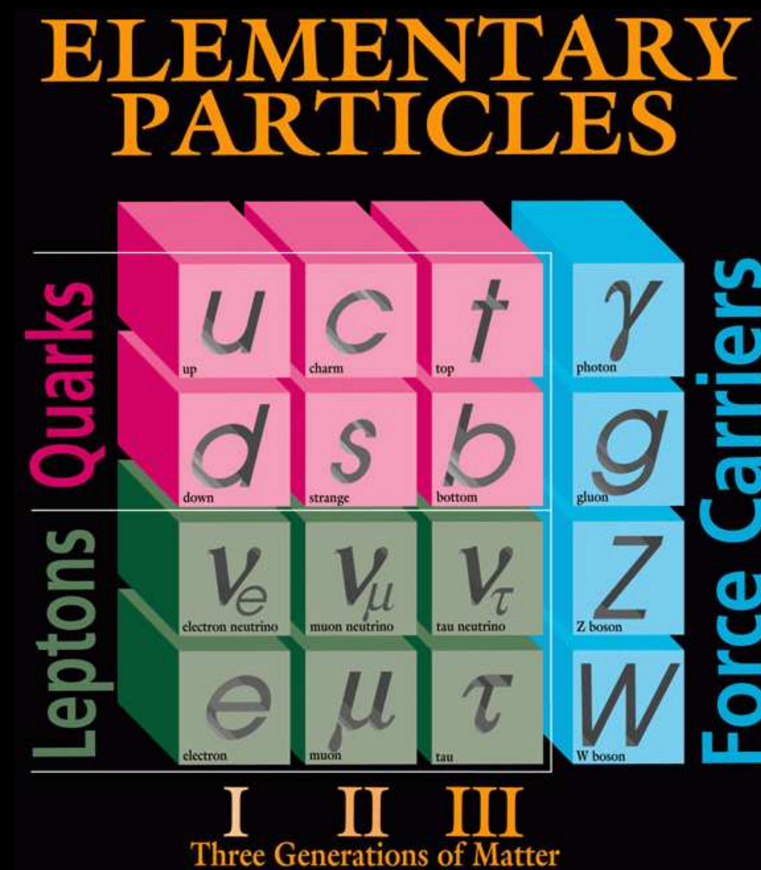
the theory has just two problems:

a) it is incomplete

- how to explain gravity?
- how to explain dark matter+energy?
- how to explain mass?

b) it is "wrong"

- mathematical inconsistencies
  at higher energies (i.e. the Standard Model is a low energy approximation)
- some things just don't feel right
  - so many free parameters
  - so many different mass scales



why?

how to make progress

for some problems there are very promising approaches:

- how to explain dark matter+energy?
- how to explain mass?

- mathematical inconsistencies at higher energies (i.e. the Standard Model is a low energy approximation)

...some of the other open questions might then be (partially) answered as well

how to make progress

for some problems there are very promising approaches:

build higher energy collider
to find new particles
that were inaccessible
to previous machines

- how to explain dark matter+energy?
- how to explain mass?

build higher energy collider
that will produce
Higgs particles if they exist

- mathematical inconsistencies at higher energies (i.e. the Standard Model is a low energy approximation)

build higher energy collider
to see what happens
in that energy region

...some of the other open questions might then be (partially) answered as well

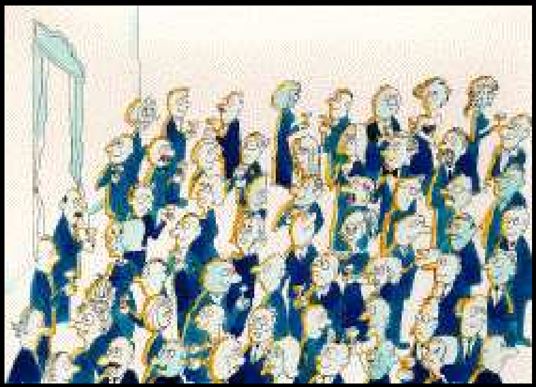
example: the Higgs particle

in our theory, forces are mediated by particles (photon, gluon, W, Z).
the mathematics only works if the force particles are massless,
but some are not!

➡ potentially explained by the Higgs mechanism proposed in the 1960s by theoretician Peter Higgs and others:

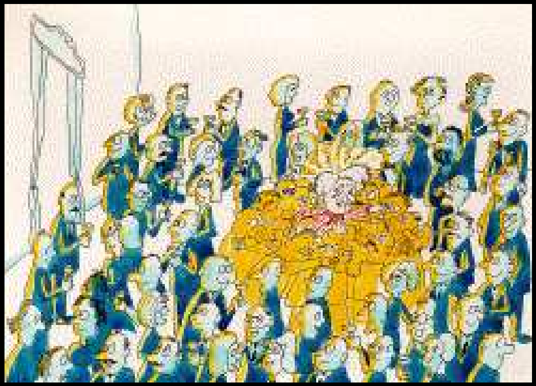
maybe massive particles only *appear* massive
due to some background interaction?

Higgs mechanism: simple analogy



Imagine a room full of physicists discussing quietly. This is like space filled with the Higgs field.

When a famous physicist enters the room, people will cluster around him to talk to him.



This creates resistance to his movement — he acquires mass, like a particle moving through the Higgs field!

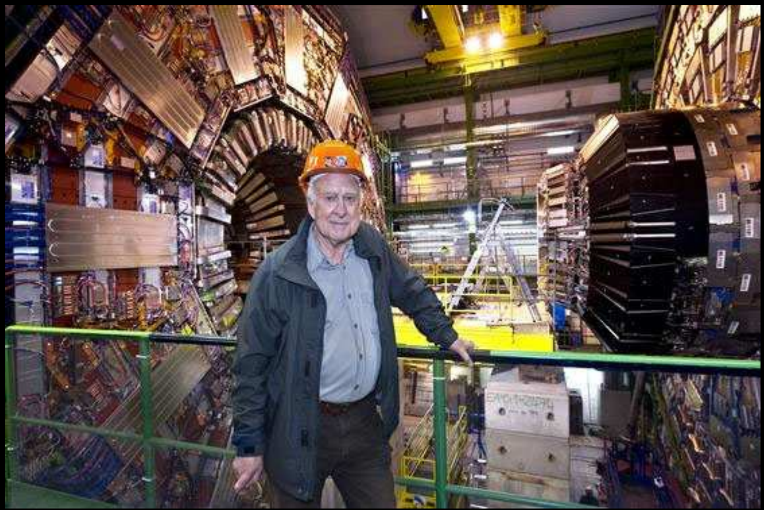
the Higgs field is a background field permeating space, the Higgs boson is a field quantum!

finding the Higgs

if the Higgs mechanism is real, we should see an extra massive particle (the Higgs boson).

we've been looking for it for 40 years! why haven't we found it?
massive particles can only produced with high energy particle colliders ($E=mc^2$),
and the energy of previous colliders was obviously not enough!

we don't quite know the mass of the Higgs particle, but
the LHC energy is high enough to give us a definite answer!



Prof. Peter Higgs (Edinburgh University) in front of the experiment that might prove him right after over 40 years!

LHC wishlist overview

we hope to

- find the Higgs or exclude it once and for all!
- understand how forces behave at higher energy
- find new particles at higher energy
- specifically, look for Supersymmetry
(double the number of particles, many theory problems solved)
- check whether quarks+leptons might be composite
- watch out for tiny extra spatial dimensions

many interesting options!

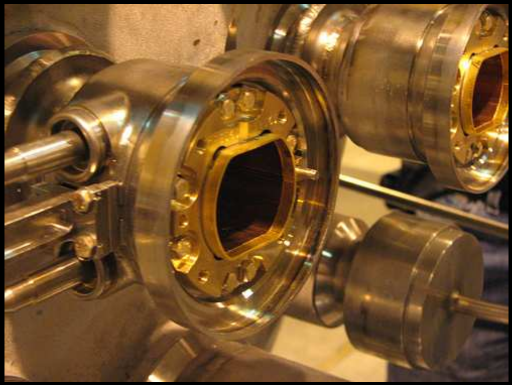
so, let's go and explore the unknown!

- how does the LHC work?
- what do the detectors do?
- how do we process data?
- how do we learn new things from them?

recipe for building LHC

objective: smash protons into each other with enormous energy

1. get a bottle of protons (use hydrogen and ionise it!)
   use them sparingly: one LHC fill has
   2 beams $\times$ $\approx$3000 bunches $\times$ 10^{11} protons,
   i.e. about 1 nanogram, which should circulate $\approx$ one day



2. keep your protons in vacuum pipes at all times so your protons don't get disturbed too much
   LHC: 1/10,000,000,000,000th of atmospheric pressure!
   (better vacuum than space around the Intl. Space Station)

recipe for building LHC (II)

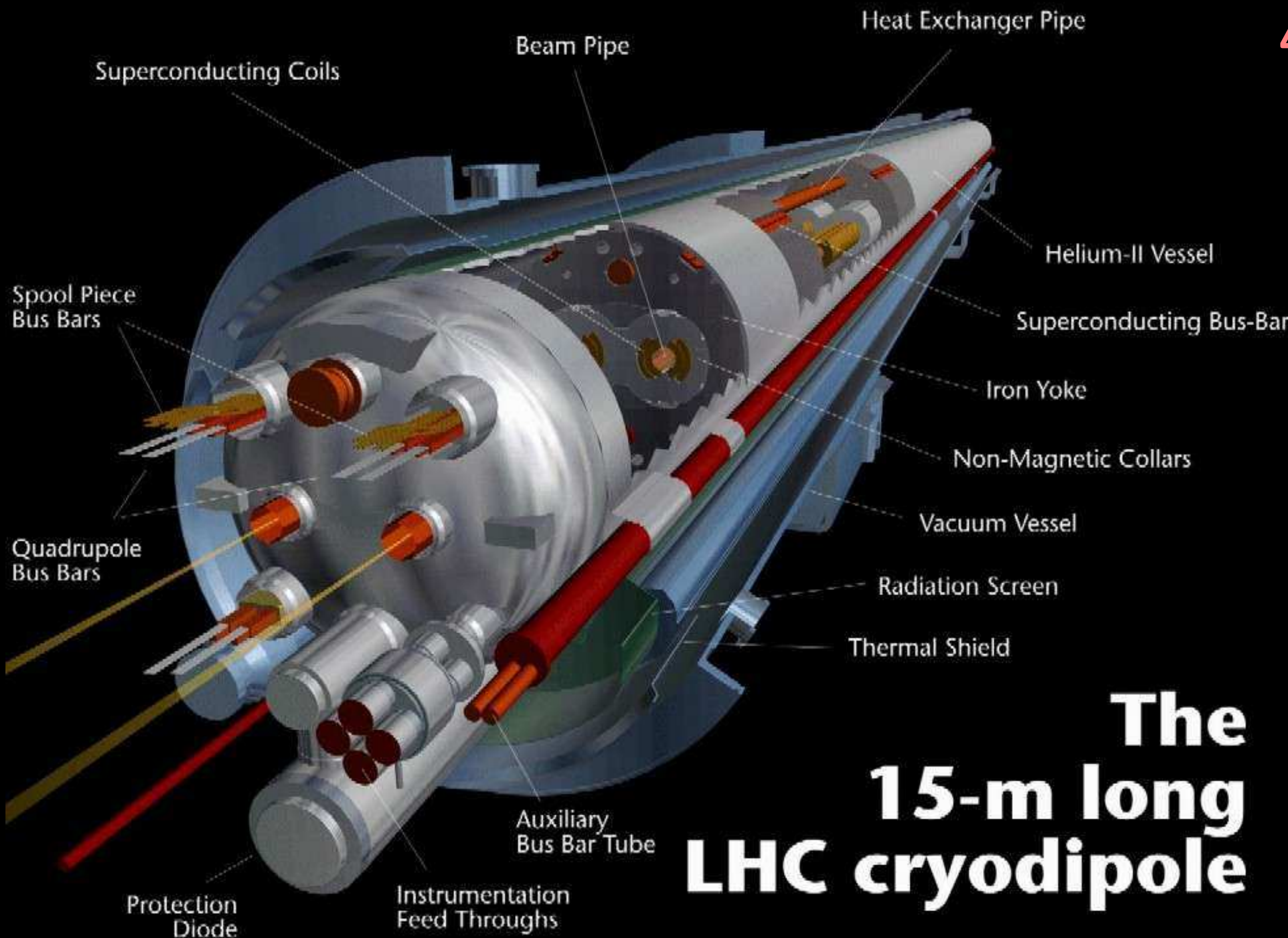
3. accelerate your proton beams with electric fields
   LHC: protons will achieve ≈ speed of light,
   total kinetic energy of proton beam:
   Eurostar train at ≈100 mph!

cannot get that much energy from one pass through the accelerating cavities!
will have to bend beam around with magnetic fields
and accelerate it repeatedly

ever tried to force a 100 mph Eurostar onto a circle using only magnets?

- need stroooong magnets
- need a laaaarge circle (9 km diameter!)

recipe for building LHC (III)



4. use strong magnets to steer the proton beams

   strong magnets require huge currents —
   only manageable with **superconducting magnets!**

   LHC is the largest fridge on the planet!
   6000 tons kept at -271°C

corresponding to ≈150,000 household fridges
at a temperature colder than the coldest regions of outer space!

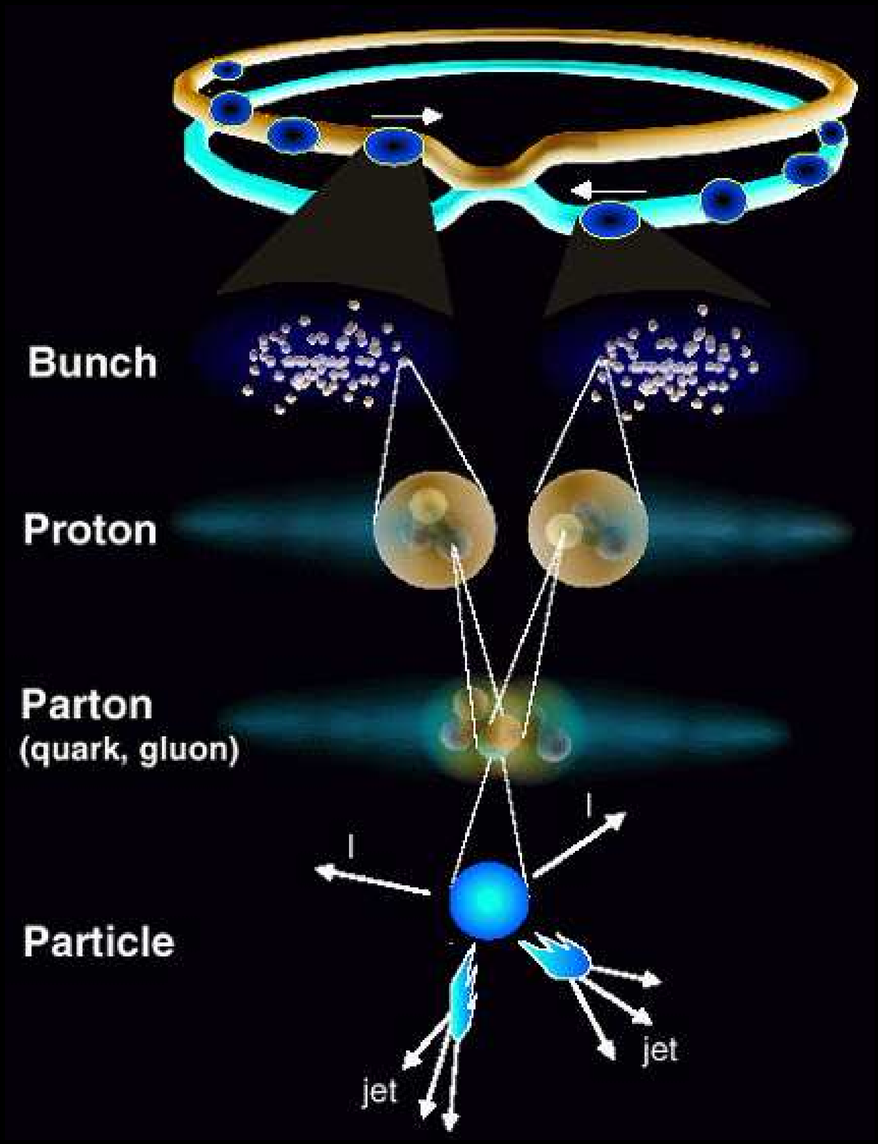
collisions!

two beams circulating in opposite directions, each with $\approx$3000 bunches of 10^{11} protons

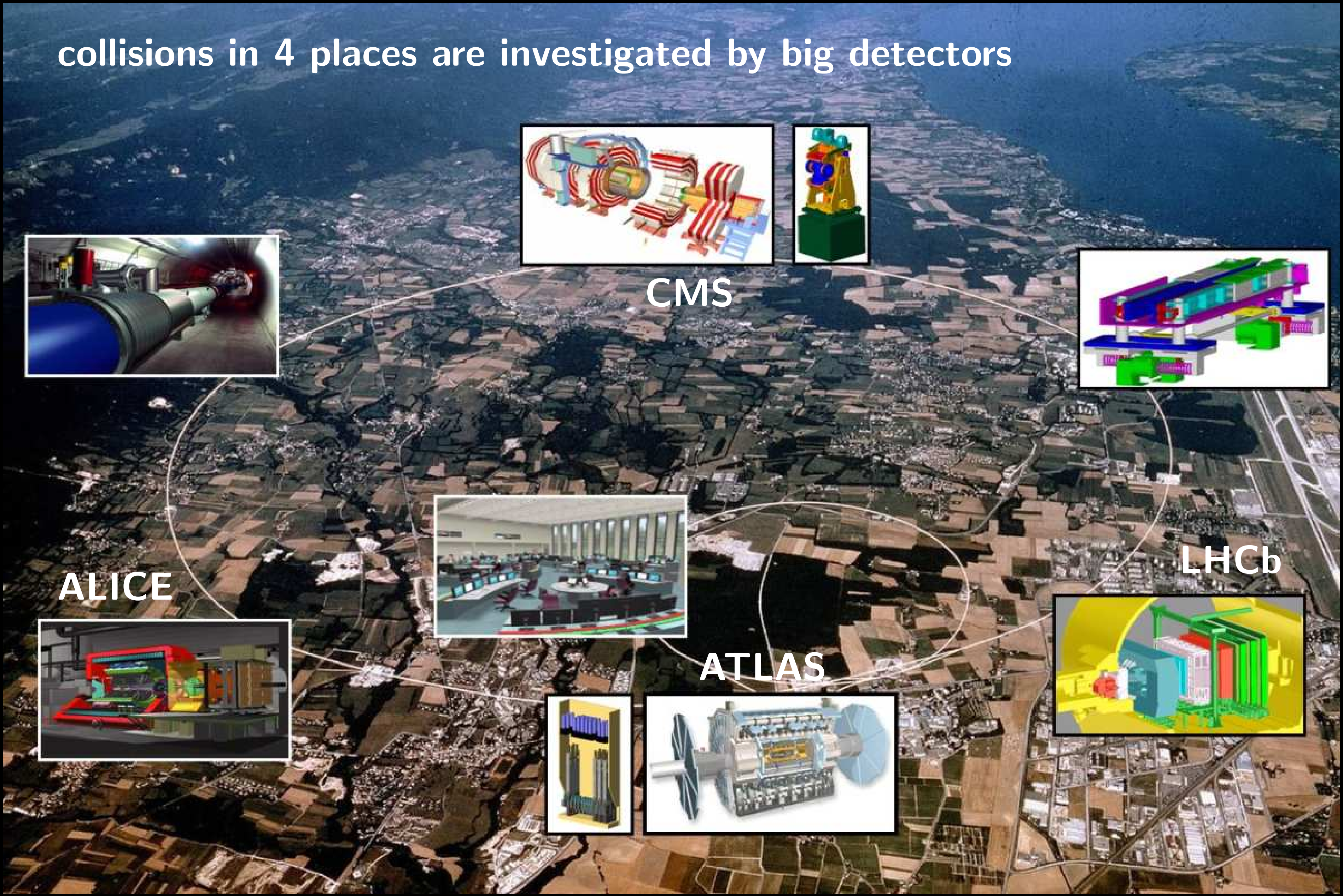
usually in separate pipes, but crossing each other in 4 places

$\approx$20 collisions every 25 ns!

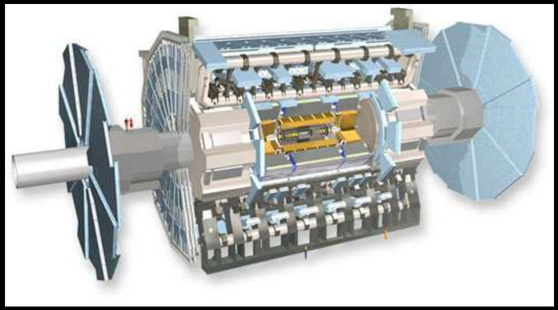
need gazillion collisions because the interesting things might only happen once per billion or trillion collisions!



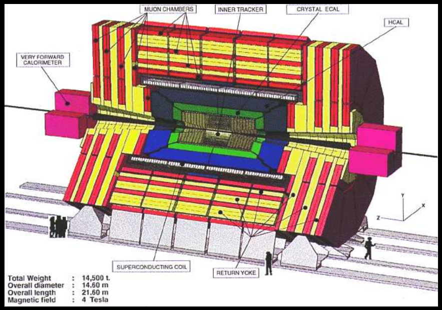
detectors


collisions in 4 places are investigated by big detectors
CMS
ALICE
LHCb
ATLAS

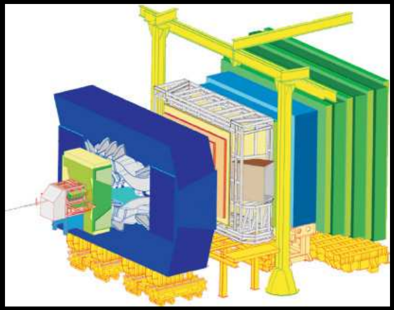
the four large LHC detectors



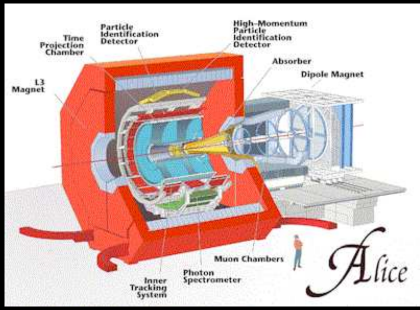
ATLAS (general purpose)
7000 tons, 25m diameter, 46m length
2500 scientists & engineers



CMS (general purpose)
14500 tons, 15m diameter, 22m length
3000 scientists & engineers



LHCb (b physics)
5600 tons, 13m width, 21m length
700 scientists & engineers



ALICE (heavy ion physics)
10000 tons, 16m diameter, 26m length
1000 scientists & engineers

RAL involvement

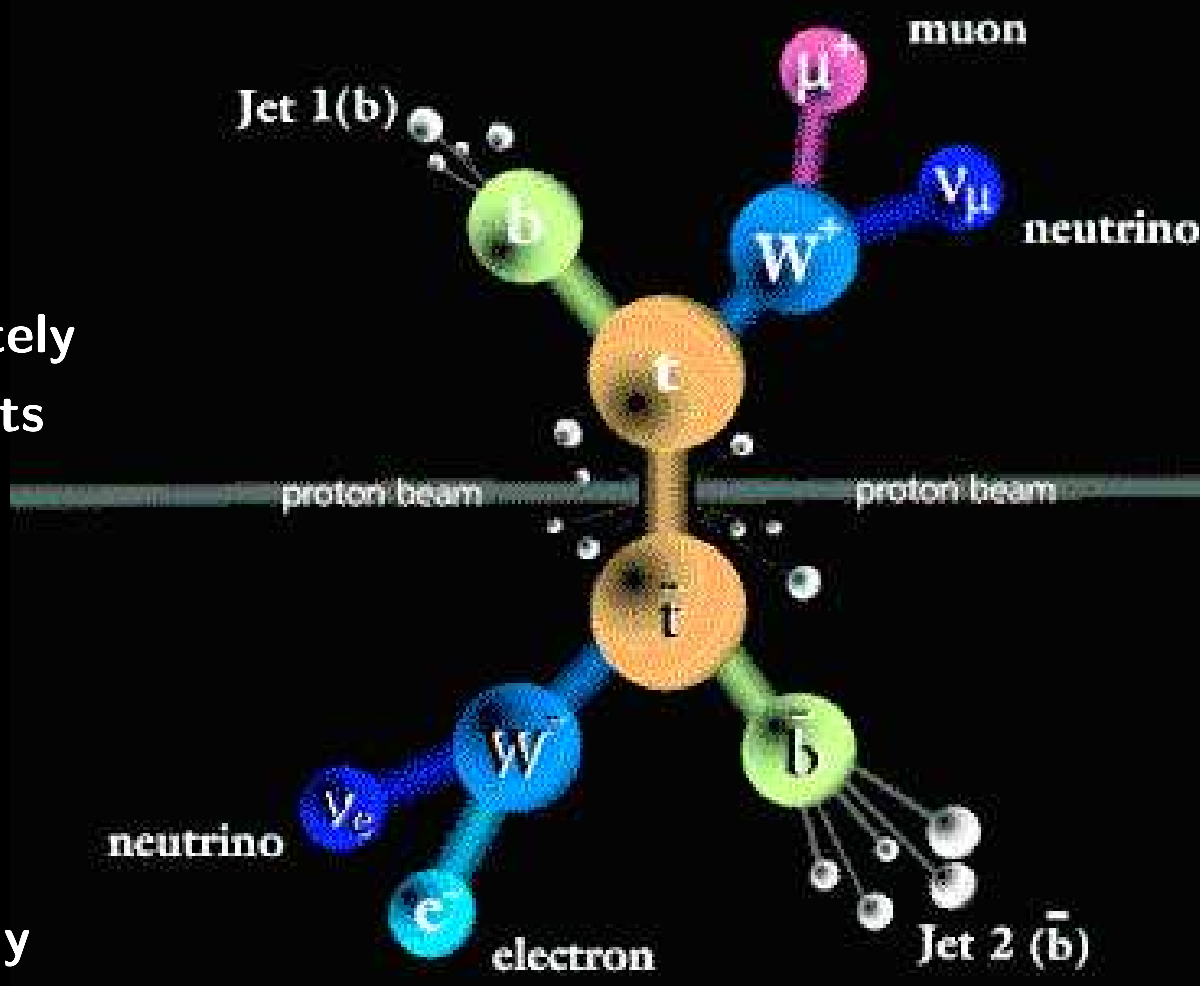
general role of detectors

quarks+gluons

- protons smash into each other at specific locations in LHC
- interesting massive particles are created
- interesting massive particles typically decay almost immediately
- not so interesting decay products fly in all directions

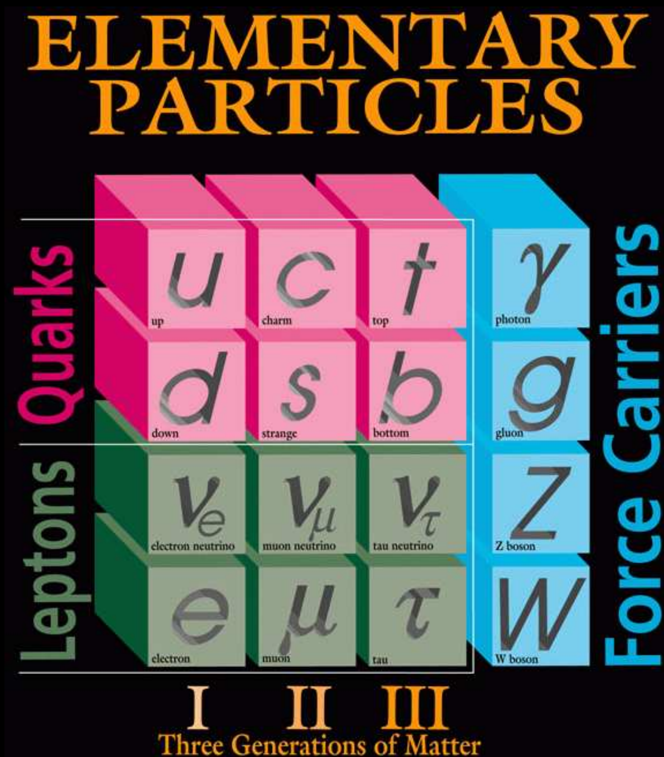
⬇

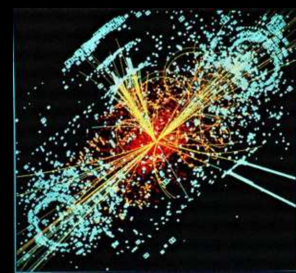
- intercept and analyse those with *detectors*,
- reconstruct the interesting part of the event mathematically using computers & brains



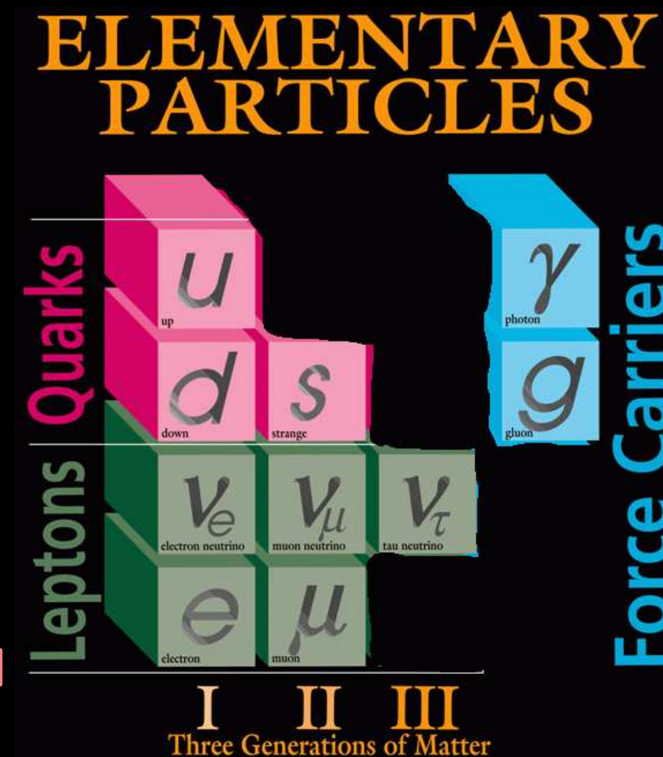
what detectors detect

most interesting particles decay very quickly:





a few mm → → → further out from where the collision happened



and it gets worse:

- neutrinos are undetectable
- quarks and gluons never appear isolated, always give rise to whole bundle of protons, pi mesons, neutrons etc (a *jet*)

charged particle detection

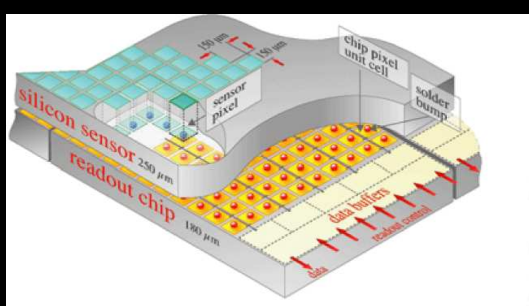
charged particles ionise **material they pass through**

if we put a small amount of material in their way
and **detect ionisation charge** in there
and **localise** where the ionisation happened

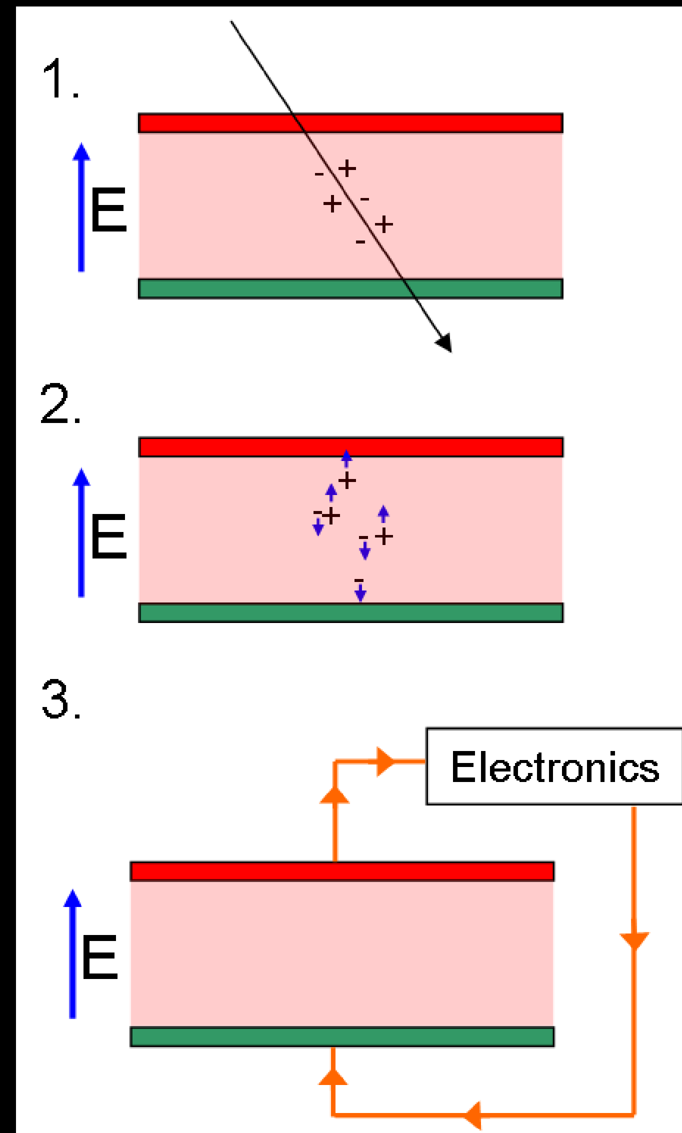
then we can follow the path of charged particles
almost without disturbing them!

we typically use layers of silicon detectors:

- quite thin (few hundred micrometer)
- high resolution (few micrometer)
- radiation hard (survive LHC collisions for years)
- mass production technology → cost benefits



see hardware display
during today's
computer exercise



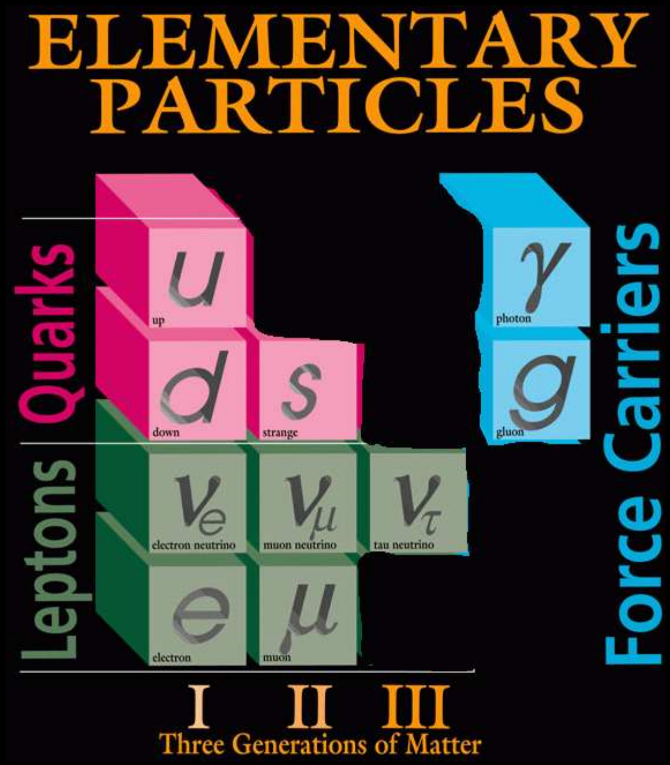
charged particle detection (II)

another trick to derive information about charged particles:

immerse the tracking detector in a magnetic field
$\longrightarrow$ path of particle gets bent
$\longrightarrow$ can calculate particle momentum from curvature!

BUT: high energy collider $\longrightarrow$ high energy particles $\longrightarrow$ small curvature!
need large tracking detector (few meter flight distance)
and high spatial resolution (few micrometer)
to get a useful measurement!

detecting more particles



tracking detectors cover charged particles:

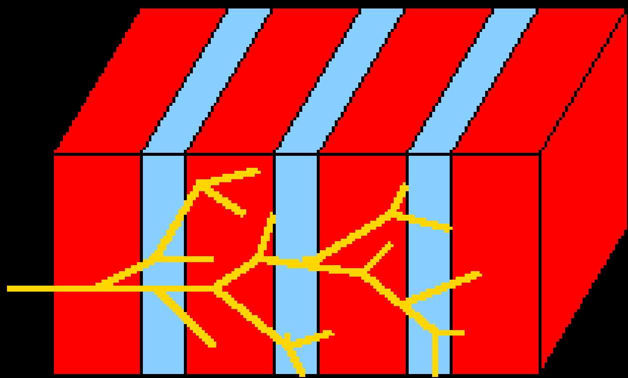
- electrons
- muons
- protons
- charged pions
- ...

but what about the neutrals?

- photons
- neutrons
- neutral pions
- ...

use a complementary detector type: calorimeters!

calorimeters



put massive amount of material in particle path
(obviously after they passed the tracking detectors!)

- particle loses energy due to material interaction
- creating showers of secondary particles

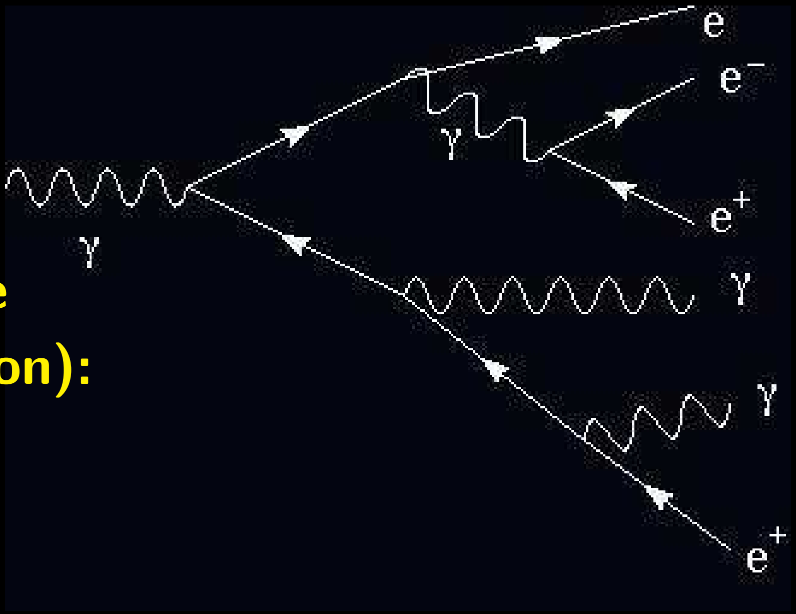
- use absorbers to stop the particle
  → all kinetic energy transformed into shower energy
- use detectors to measure the shower energy
  (ionisation, light, number of charged secondary particles, ...)

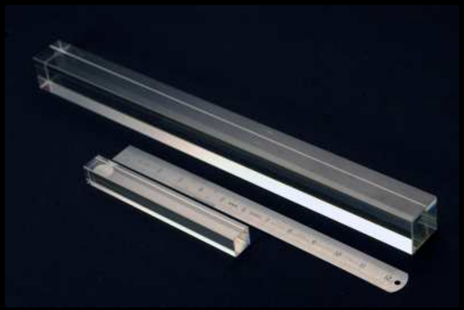
- derive energy of the particle from observed shower energy!
  (and get flight direction from location of the shower)

calorimeter types

two main classes of calorimeters:

- **electromagnetic calorimeter:**
  absorption via electromagnetic cascade
  of lightweight particles (electron, photon):





see hardware display
during computer exercise today!

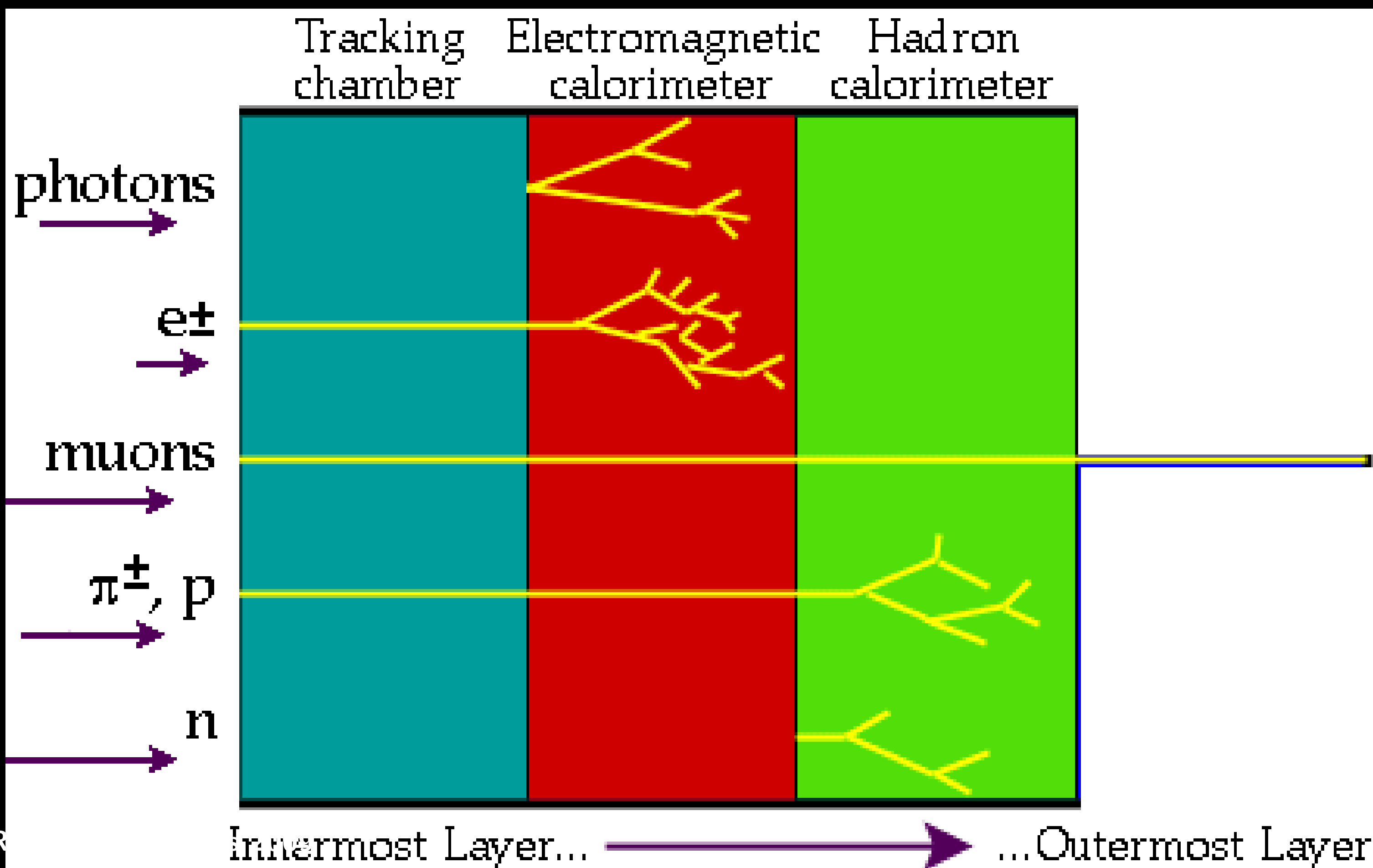
- **hadronic calorimeter:** nuclear interaction with absorber

BUT: high energy particles → need very thick material (few meter)
of high density (iron, lead, even uranium)

particle identification

observing particle energy and momentum is not enough!
we need to know particle type!

solution:
use tracker, electromagnetic calorimeter and hadronic calorimeter together



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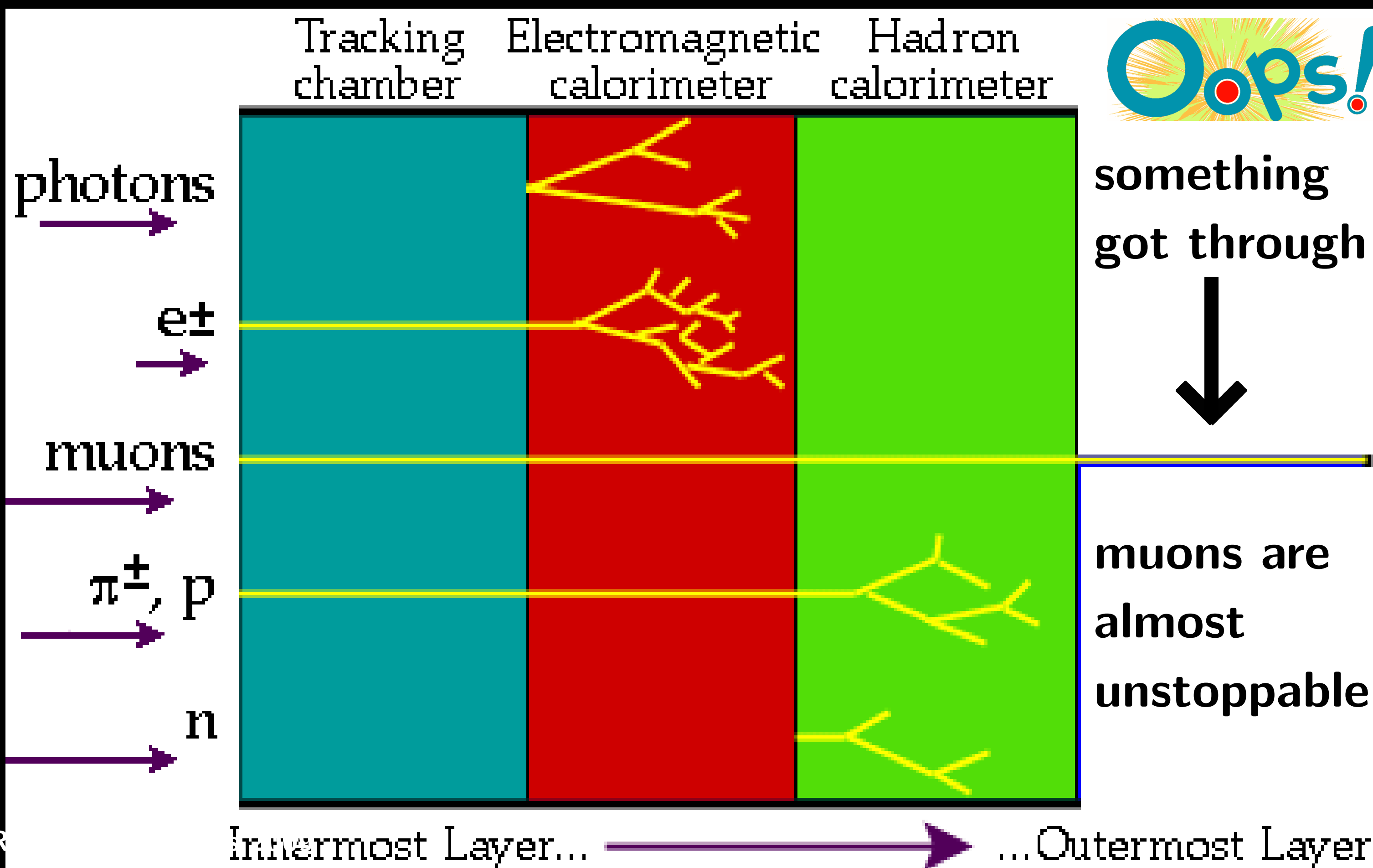


muon detectors

muons are a special case:

- too heavy to develop electromagnetic showers
- no nuclear interactions $\longrightarrow$ no hadronic shower
- could be identified from feeble signals in calorimeters (not very reliable)

➡ use yet another detector type behind tracker & calorimeters:

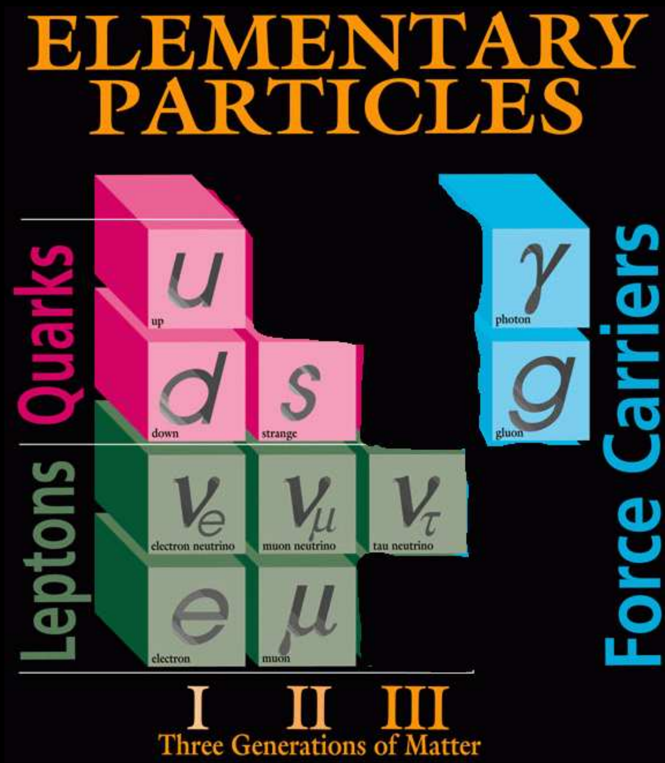
muon detectors

often like a coarse tracker to identify muon direction without help of main tracking detector
it can even have its own magnets to measure muon momentum independent of tracker!

now muons are easy to identify:
whatever gets through the calorimeters and is visible is probably a muon

leftovers

We've seen tools to detect and identify almost all particles we can catch:



important exeption:

neutrinos!

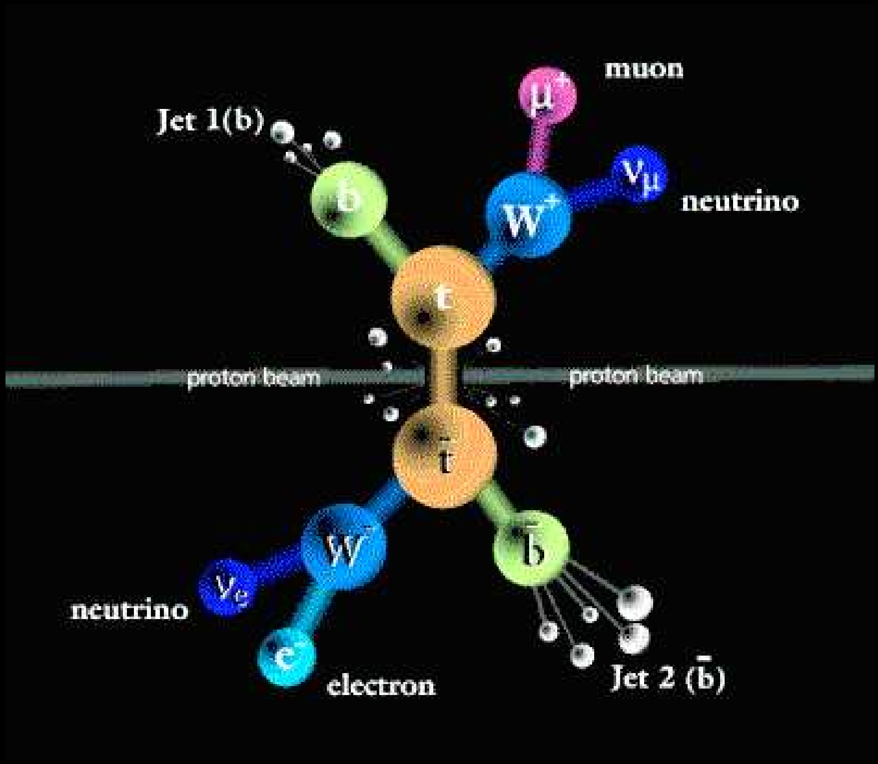
neutrinos cannot be detected.

also: there might be unknown particles that do not interact with normal matter!

is there any way we can tag their presence anyway?

missing momentum

we cannot see neutrinos, but we can measure the momentum they carry away!



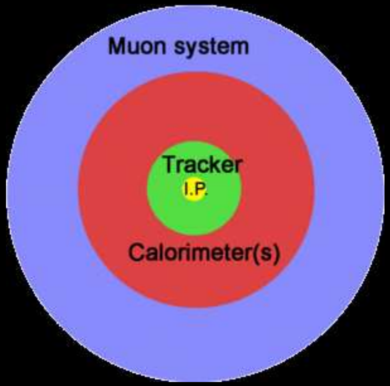
momentum conservation:

before collision:
zero momentum perpendicular to beams

after collision:
must also be zero net momentum perpendicular to beams!

add up momenta of all visible particles — is there an imbalance?
this might be momentum carried away by a neutrino!

missing momentum identification requires our detectors to be "wrapped around" the interaction region! ("hermetic detector")



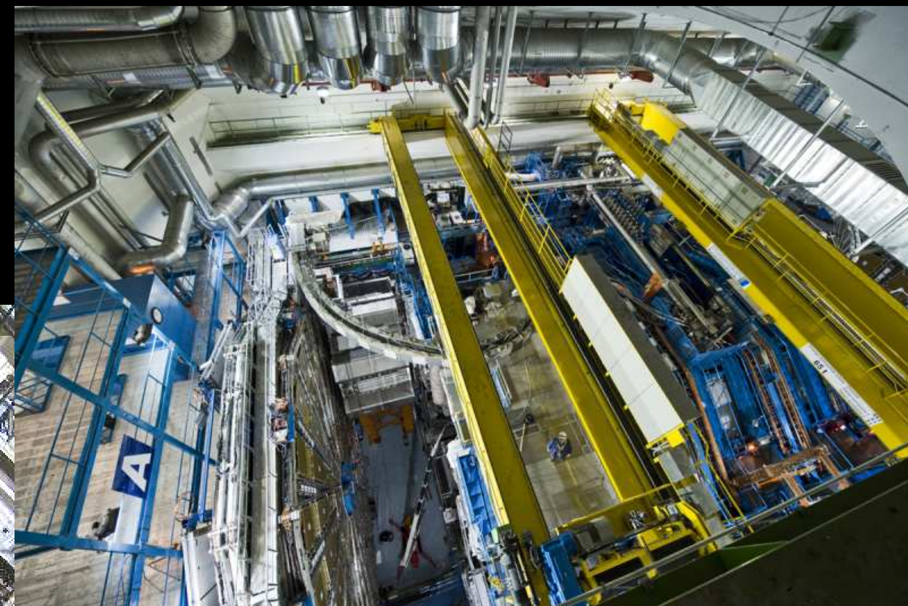
and now: the real thing!

one of the LHC experiments: ATLAS — aerial view of experimental area

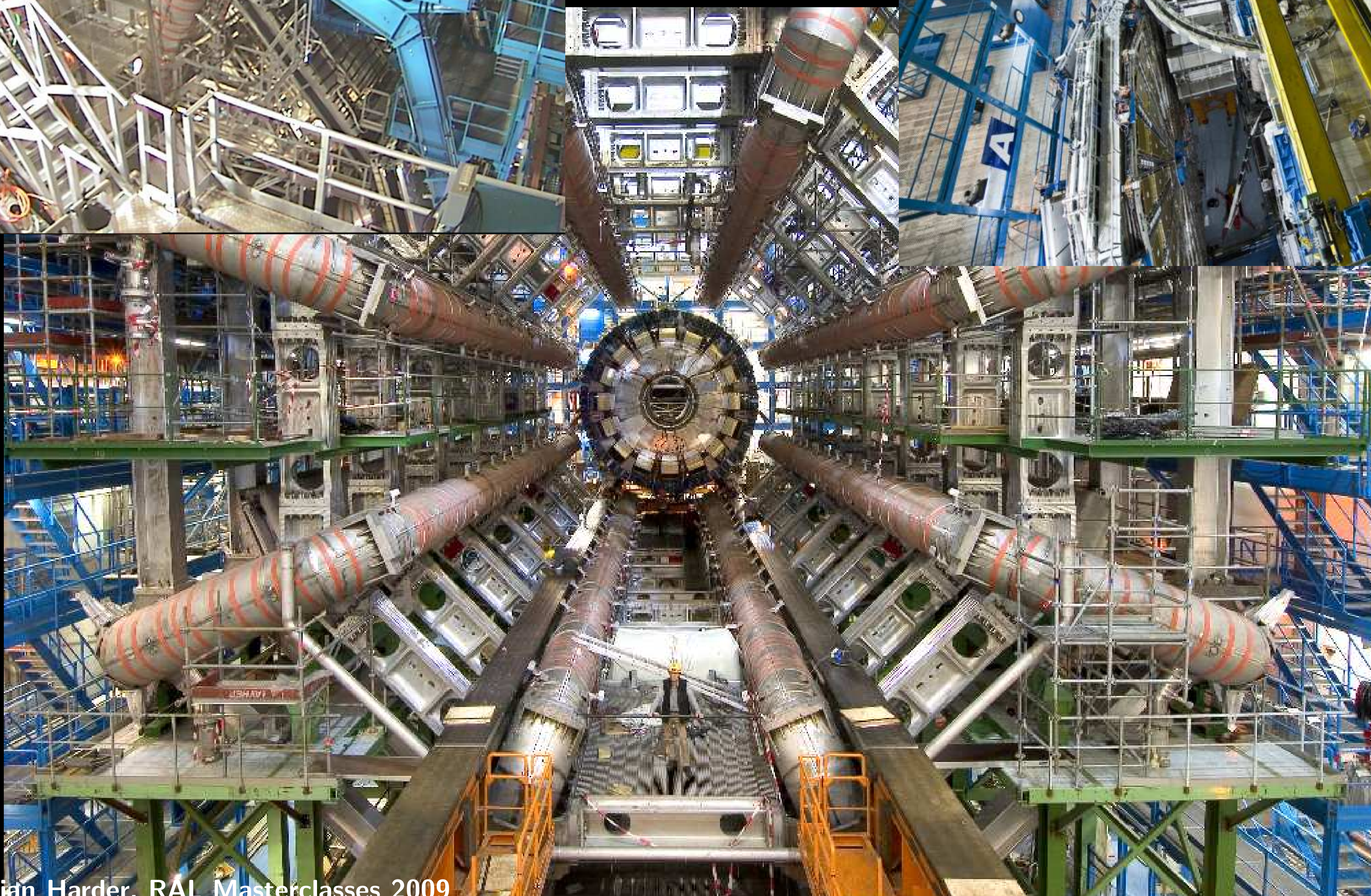
trying to take photos of ATLAS

last week

2008



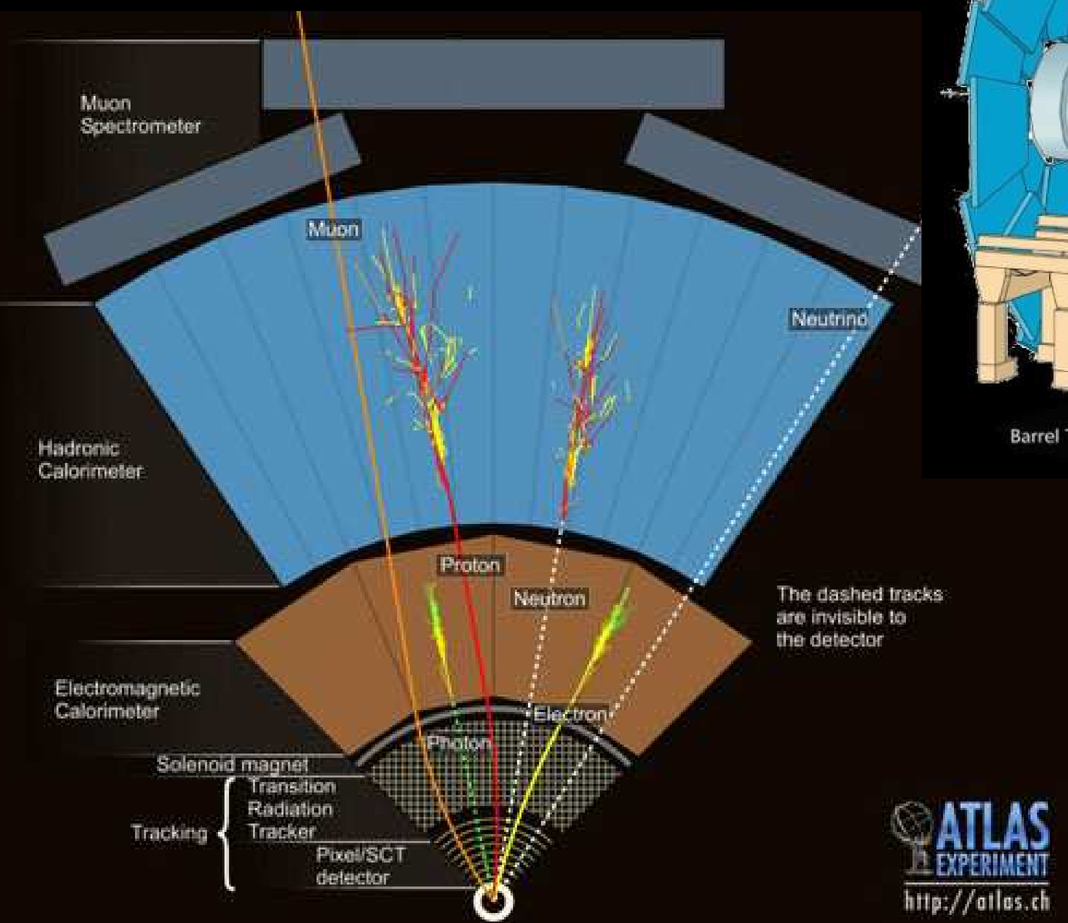
2003

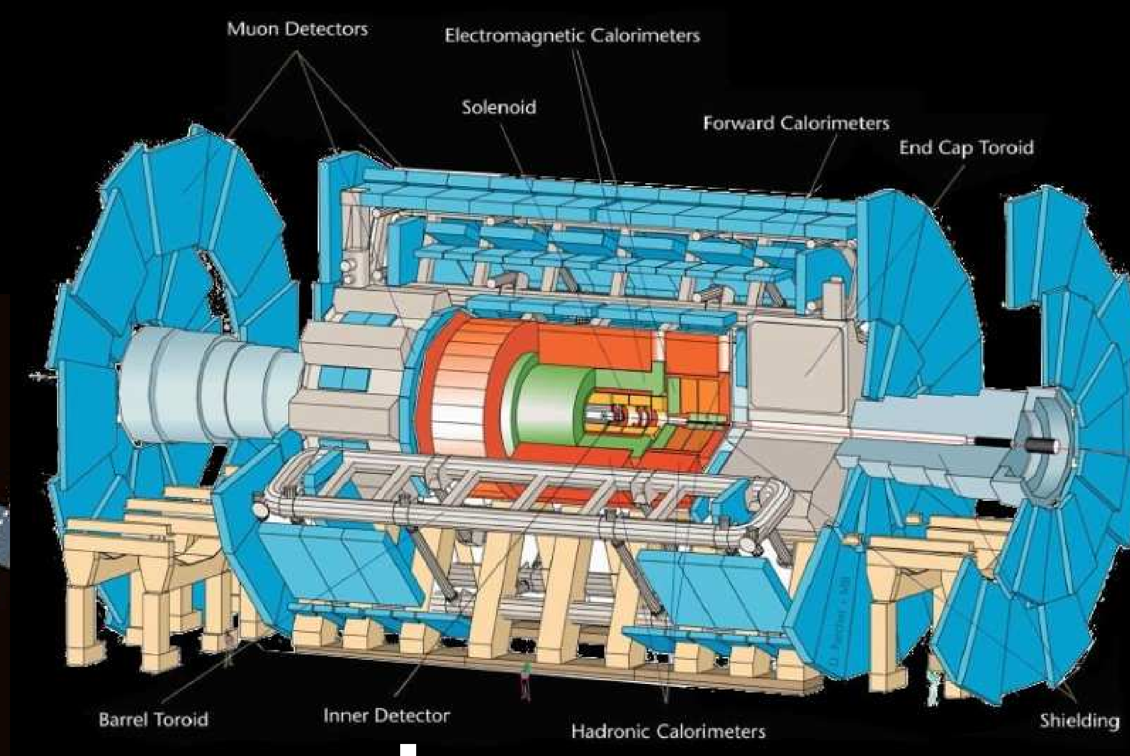


not much space left down there!

the ATLAS detector

25m diameter, 46m length,
$\approx$ 70 m^2 of silicon detectors
7000 tons





silicon tracker built at RAL!

running the detector

most subsystems need 24/7 monitoring by experts!

➡ ATLAS control room staffed around the clock

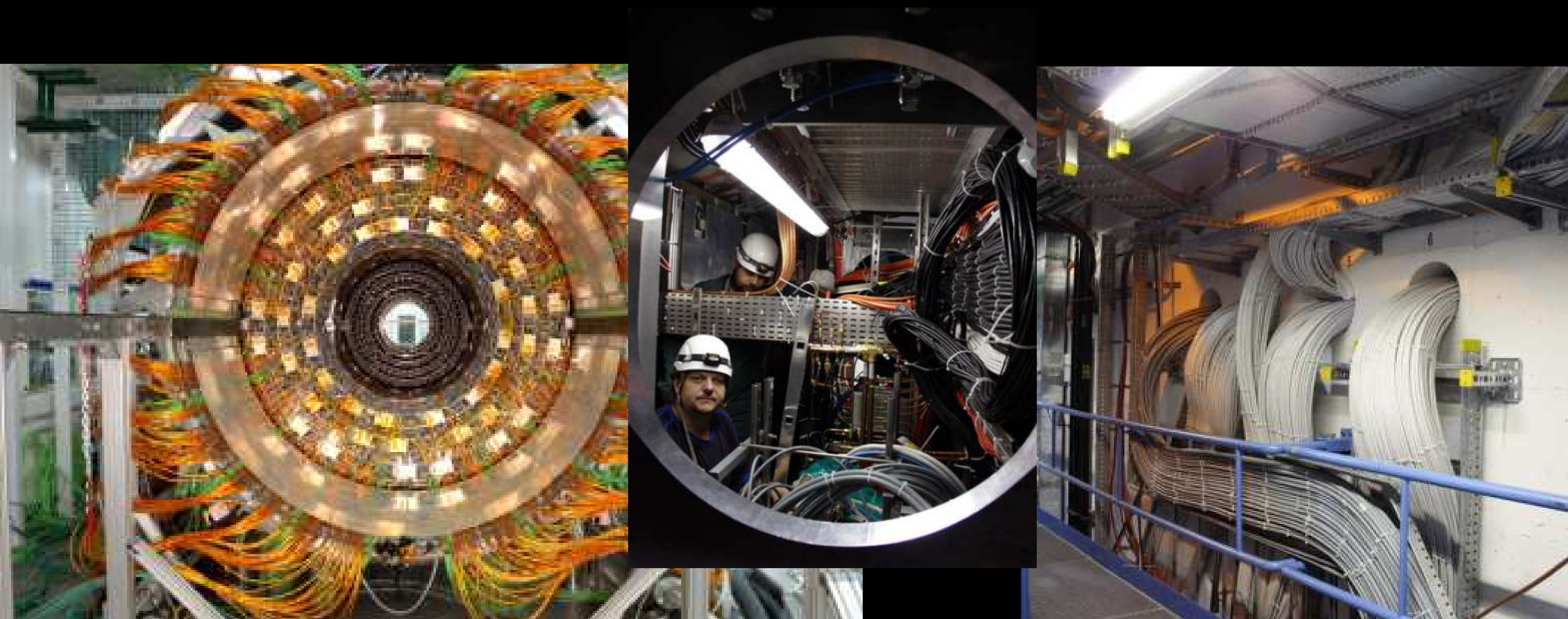
ATLAS control room is close to detector, but it could be elsewhere! CMS has a control room near Chicago (Fermilab) — turns night shifts into day shifts!

reading data from ATLAS

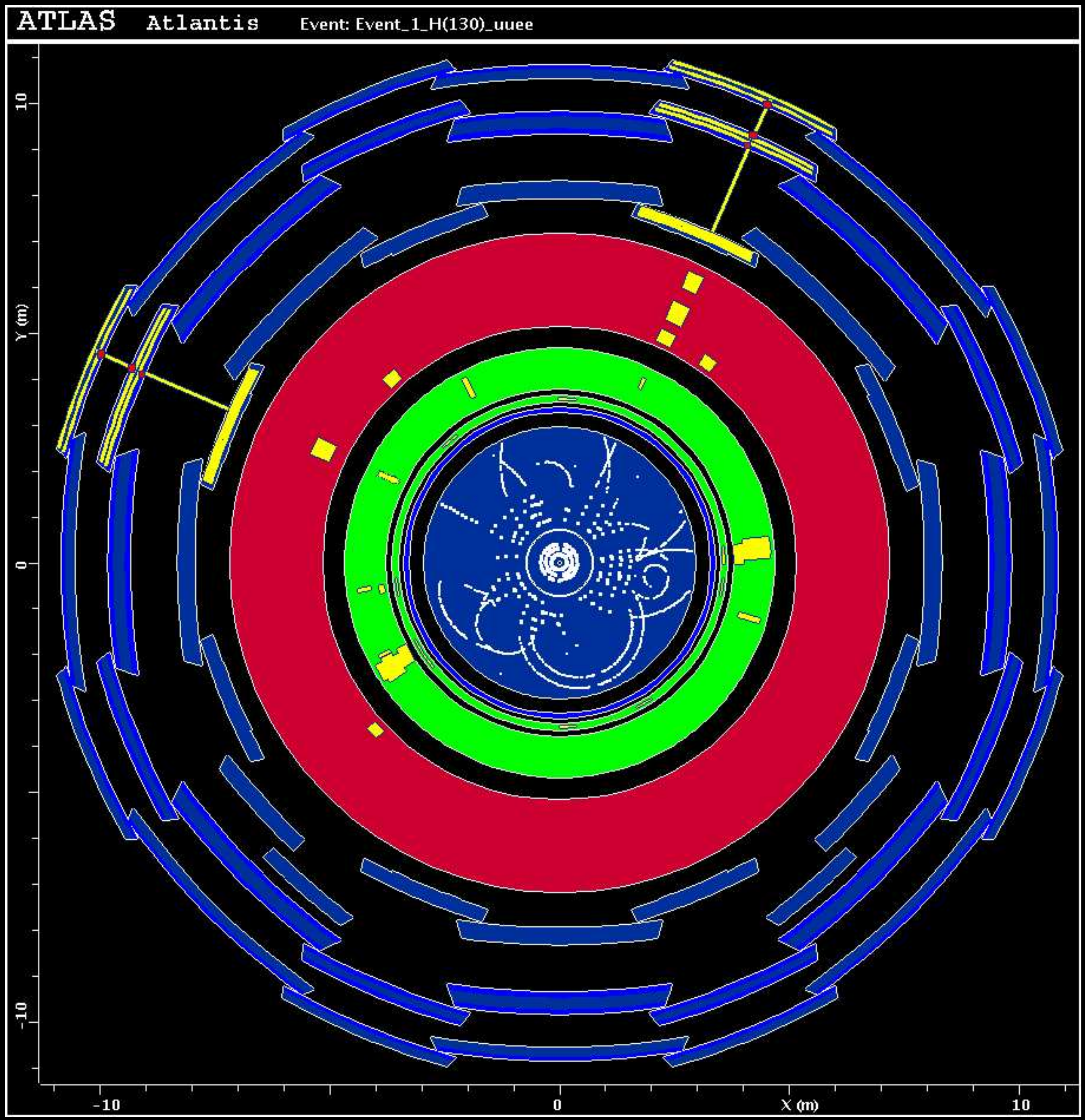
- 100 million individual readout channels (pixels, cells, modules, ...)
- signals need to be digitised for computer processing

  lots of specialised electronics

  3000 km of cables



example events (simulation)

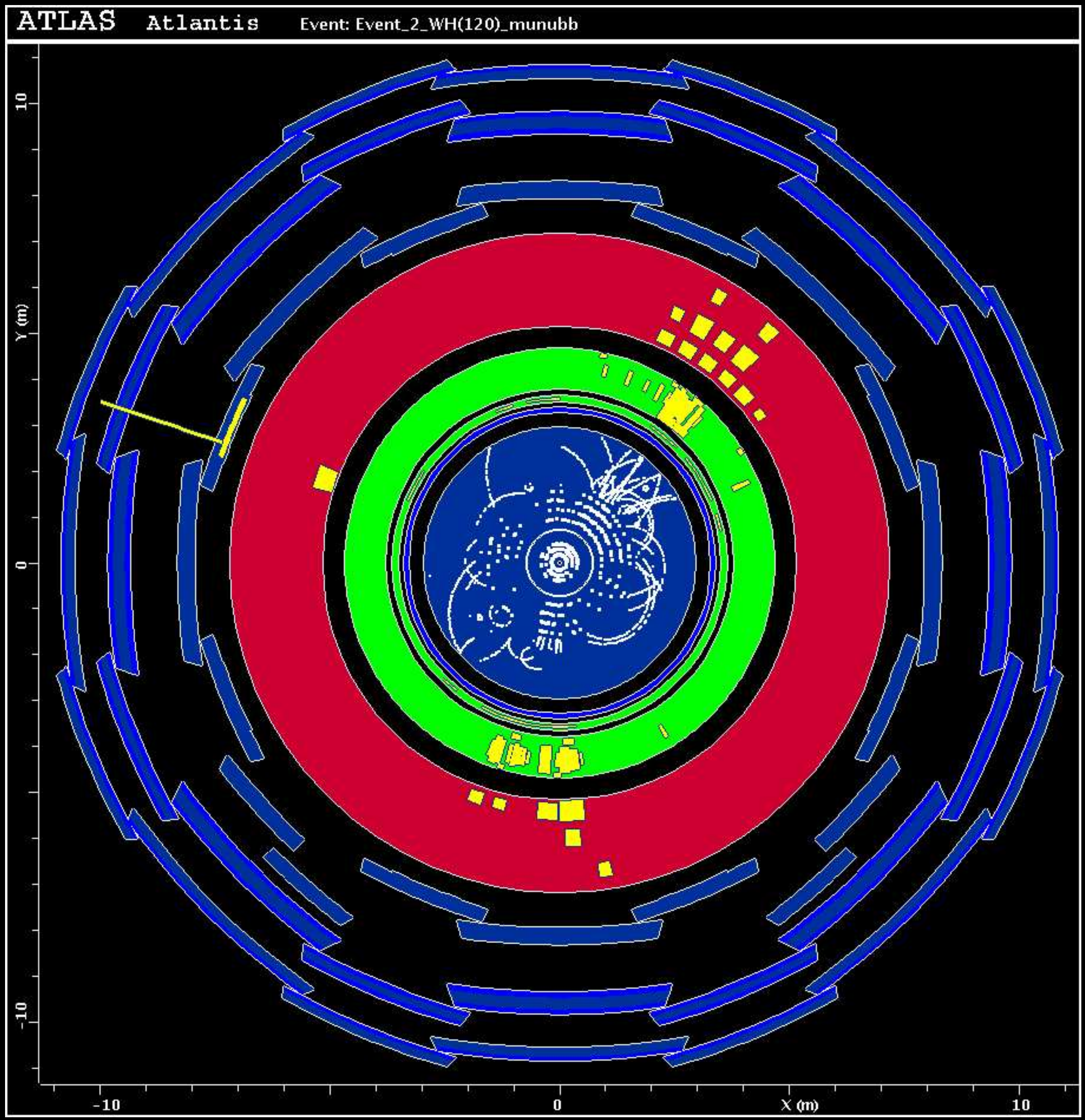


simulated example collision ("event") in ATLAS:

Higgs particle decaying to ZZ decaying to $e^+e^-\mu^+\mu^-$

- two strong electron signals
- two straight muon tracks

example events (simulation)



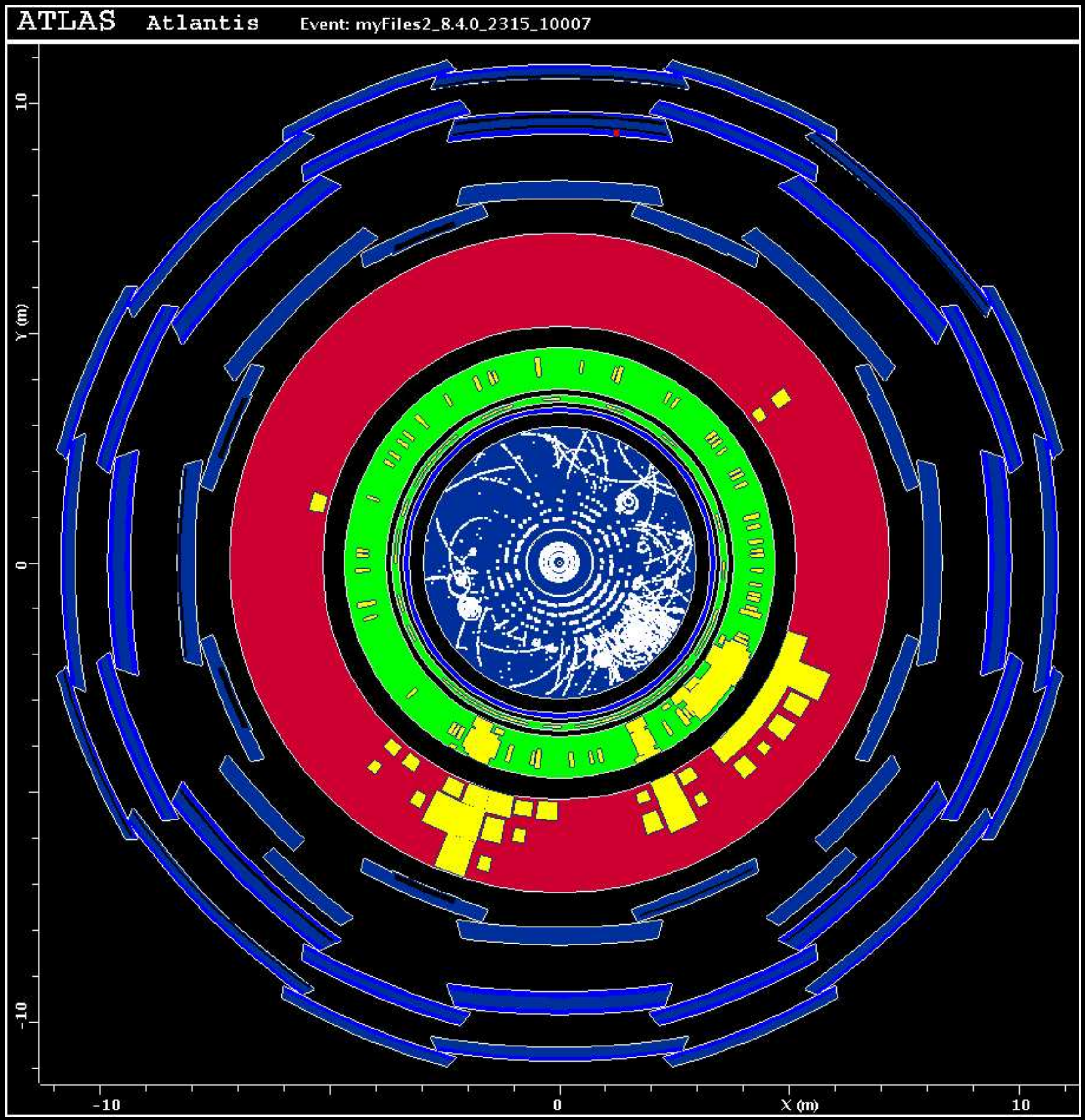
another simulated event:

a W decaying to $\mu\nu_\mu$
and
a Higgs decaying to two jets

- one muon (w/o track!)
- two jets

Neutrino disappears, but in this case no obvious momentum imbalance (need to look at numbers)

example events (simulation)



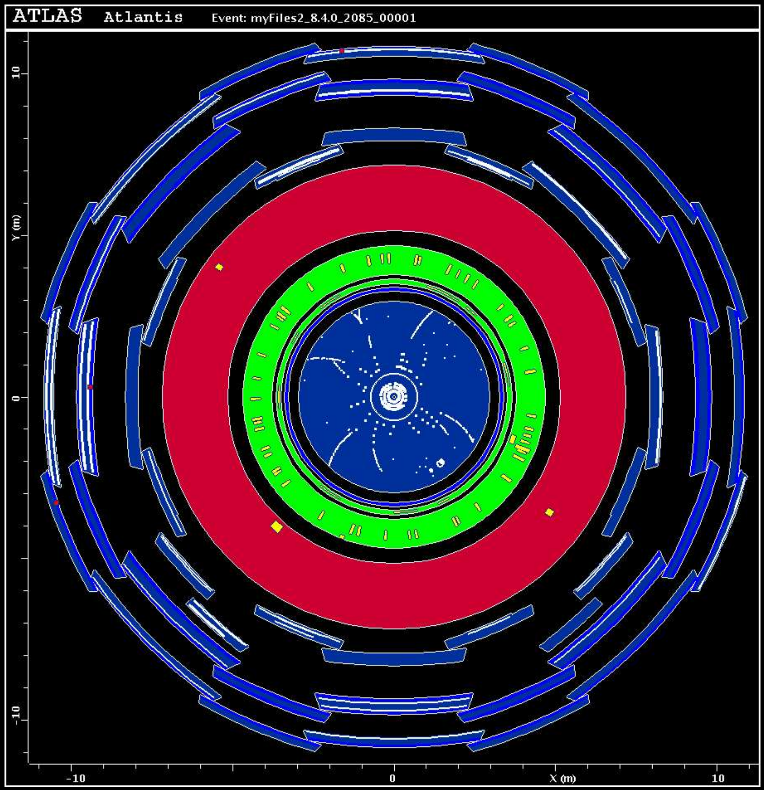
yet another simulated event:

- two jets
- clearly missing momentum

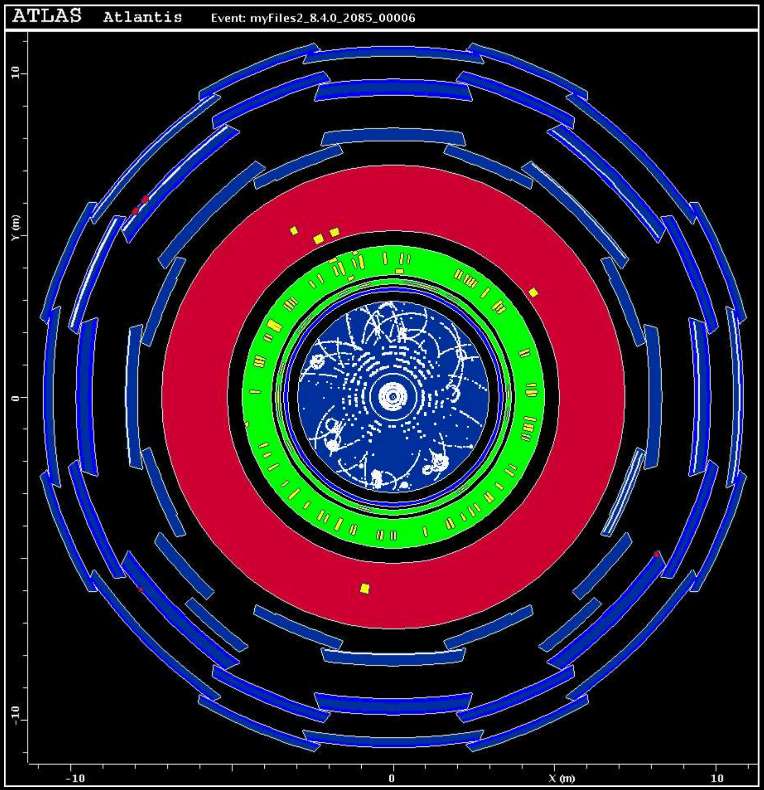
exotic particle escaping the detector unnoticed!

event selection

These example events were very special ones.
The vast majority of events looks like these:

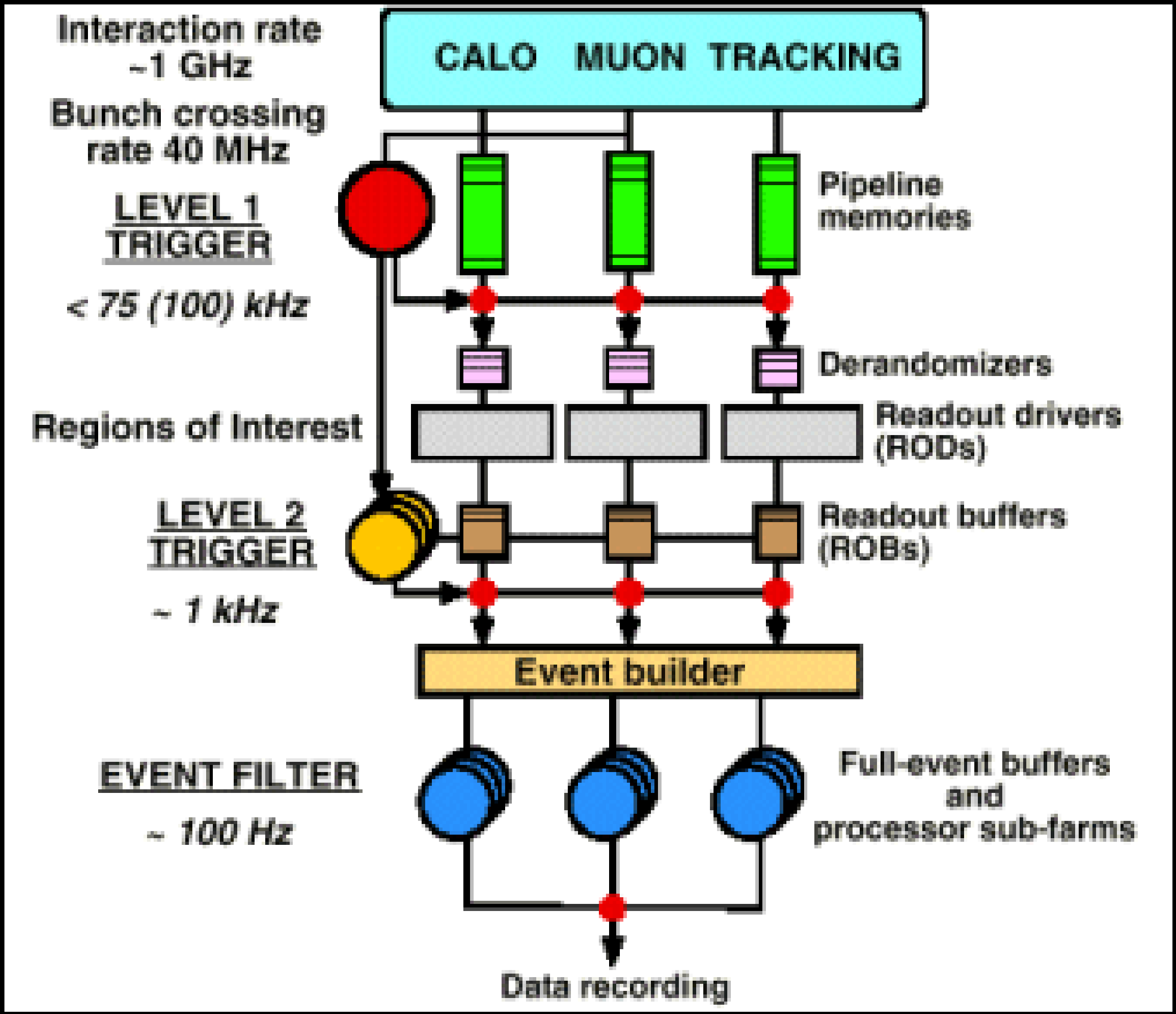


quarks just brushing past each other



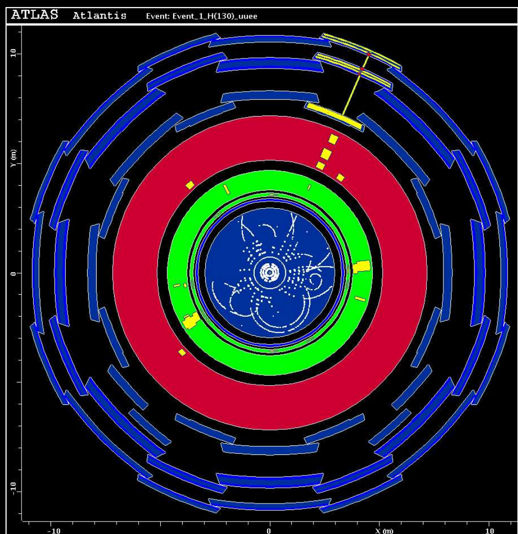
Who volunteers to browse through 40 million events per second?

ATLAS trigger and data acquisition



- fast special electronics identifies interesting signals
- selection in several stages of increasing complexity and precision
- higher levels done by PC farms
- ≈ 100 events per second stored permanently (filling ≈1 CD per second), distributed all over planet for computerized reconstruction and analysis

how data analysis works



reminder:

only the "boring" particles show up in the detector,
e.g. the muons and electrons,
but not the Higgs that decayed into them!

How do we reconstruct what happened before?

simple example: $Z \rightarrow \mu^+\mu^-$ (same concept works for e.g. Higgs)

- find events with two muons
- *assume* these muons come from a Z decay
- calculate mass of supposed Z from muon momenta
- do we get consistent results for the mass?
  - YES: we found the Z!
  - NO: these muons do not come from Zs

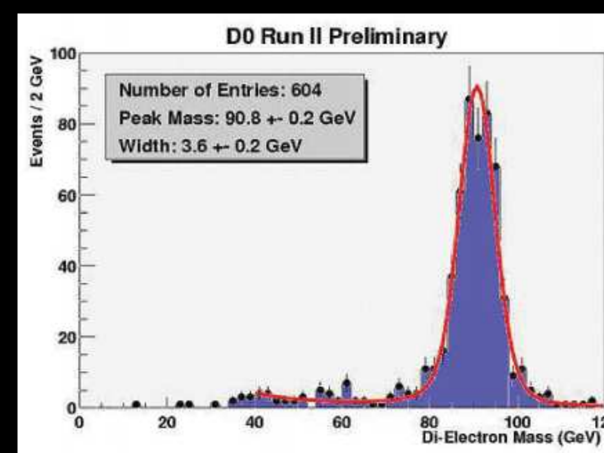


Figure 5. Dielectron mass spectrum showing the Z peak.

let’s get started!

we are ready to go!

- the LHC detectors are ready and running
- we did lots of training on simulated data
- all we need now is the LHC to start running!
  - LHC did start up last September, but suffered a major setback
  - repairs are ongoing

  new attempt to get going this year!
- it will definitely take months (years?) until we accumulate enough data to see something and understand it

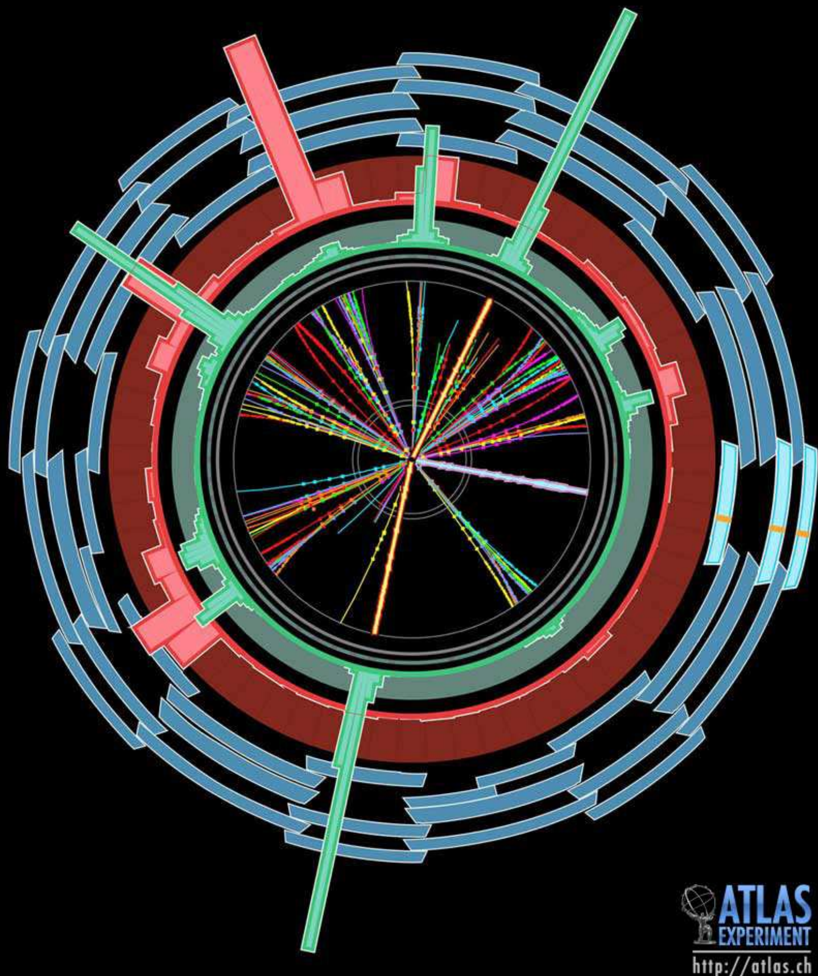
the dawn of a new age?

- particle physicists have spent decades finding mostly the expected
  we have an excellent description of the universe, but with holes and flaws
- the LHC data will have dramatic impact on particle physicists
  new confusion
  new theories
  lack of sleep
- machine will run for 10–20 years, with various upgrades in between.
  plenty of time for you to study physics and join us!

stop talking now, Kristian!

(backup slides start here)

black holes at the LHC



if gravity becomes unusually strong at small distances (e.g. related to extra dimensions) then LHC energy *might* be enough to create tiny black holes in collisions!

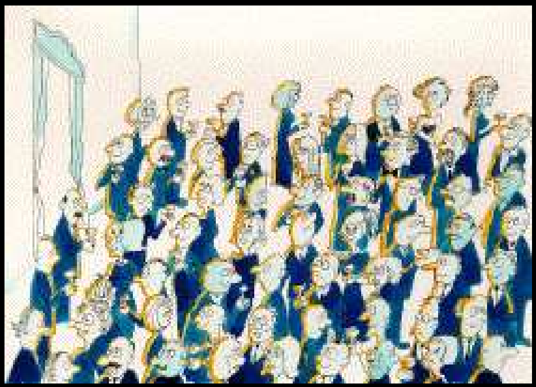
small black holes decay very quickly (Hawking radiation)

how does black hole decay look like?
many high energy particles,
thermal distribution of flavours,
...

we *know* these black holes (if they exist) won't eat Earth!

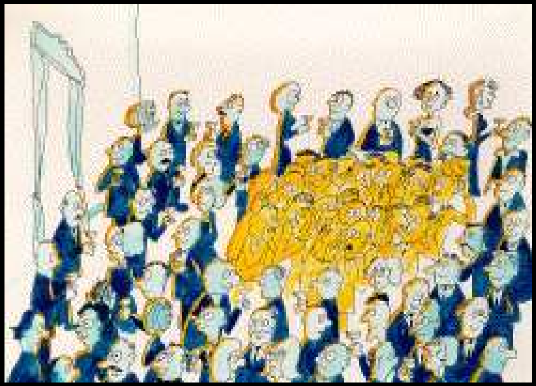
high energy cosmic rays didn't cause that, so we won't!

Higgs mechanism: the Higgs particle



Let's go back to that room of scientists doing smalltalk.

Now someone spreads a rumour of an important discovery!



This creates the same kind of clustering, but this time among the physicists themselves. In the real world, these clusters would correspond to Higgs particles!

a planetary scale experiment

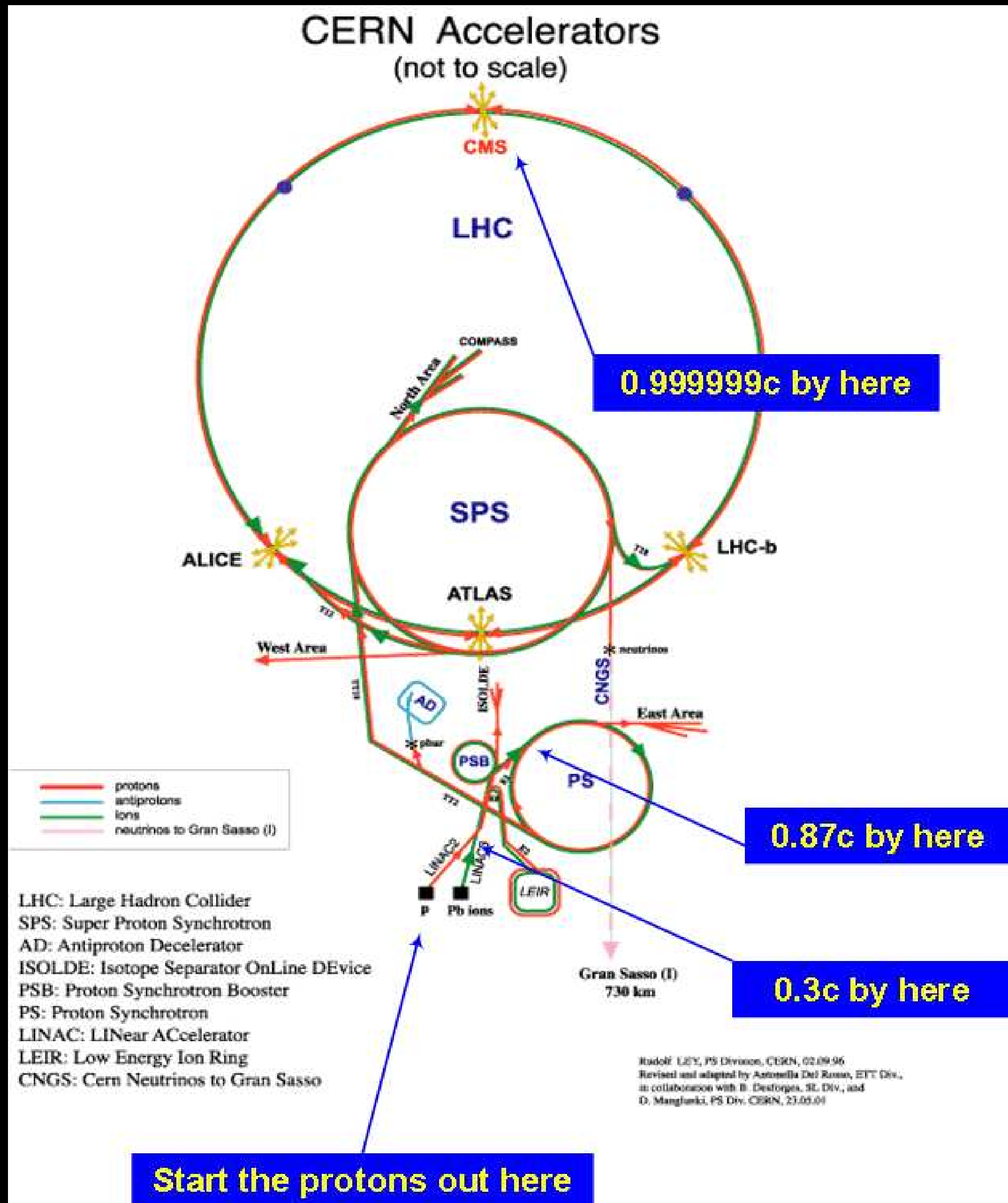
o collider (not to scale)

x experiment control rooms

data processing centres

The collider itself is not quite as big, but still...

CERN accelerators



cost of building the LHC

annual UK contribution to LHC construction (for 10 years):	$\approx$ 35 million
annual budget of the UK Medical Research Council (2008):	$\approx$ 700 million
annual budget of UK health care:	$\approx$ 100,000 million

➡ the UK is spending *3000 times* as much on health than on the LHC.
I would say this is an appropriate way of setting priorities!

total cost of building the LHC (shared by >100 nations):	$\approx$ GBP 3 billion
'06 US congress estimate of weekly Iraq war expenditures:	$\approx$ USD 2 billion
	$\approx$ GBP 1.5 billion

➡ building the entire LHC only cost as much as *two weeks* of the Iraq war!

Let's talk about priorities here!

particle physics cost/benefits

UK contribution to particle physics: about a pint of beer per person per year

What do you get in return?

- skilled people earning lots of money
  (once they leave government funded science)
  $\longrightarrow$ paying lots of taxes
- skilled people creating jobs
  $\longrightarrow$ producing even more taxes and happy workers
- local companies making money building high tech equipment for us
  (magnets, silicon, electronics, cryogenics, vacuum technology, ...)

most of the LHC money does not even stay in particle physics labs — it is being paid to commercial suppliers of custom made components!

➡ building the LHC is a very targeted stimulus for high tech industry

specific particle physics benefits

Particle physics advances technology on all fronts. A few specific examples:

- medical applications (MRI, for example)
- a long time ago: cathode ray tubes (TV sets!)
- a while back: pushing computer technology (e.g. cheap PC farms)
- a while back: *the world wide web* (economic impact? yes!)
- soon: GRID computing? other forms of massive data processing?
- long-term: *who knows?!?*

Understanding how the Universe works is always a good thing:

- quantum physics $\longrightarrow$ lasers $\longrightarrow$ medicine, machining, DVD players
- theory of relativity $\longrightarrow$ GPS
- synchroton radiation $\longrightarrow$ lots of applications (see other lectures today)

...and infinitely many more benefits!

acknowledgments

- title picture from Scottish Universities Summer School 2009 poster
- many pictures + ideas from previous lecturer Monika Wieler's slides
- lots of photos from CERN, ATLAS, CMS, LHCb and ALICE web pages
- J.J. Thomson photo from aip.org
- Higgs analogy from Prof. David Miller (UCL)

disclaimer: the example Higgs event shown in this presentation did not come out of the simulation like this; I modified it to emphasize its main properties.
For any question or comments, feel free to contact me. Several of my e-mail addresses can be found on Google.