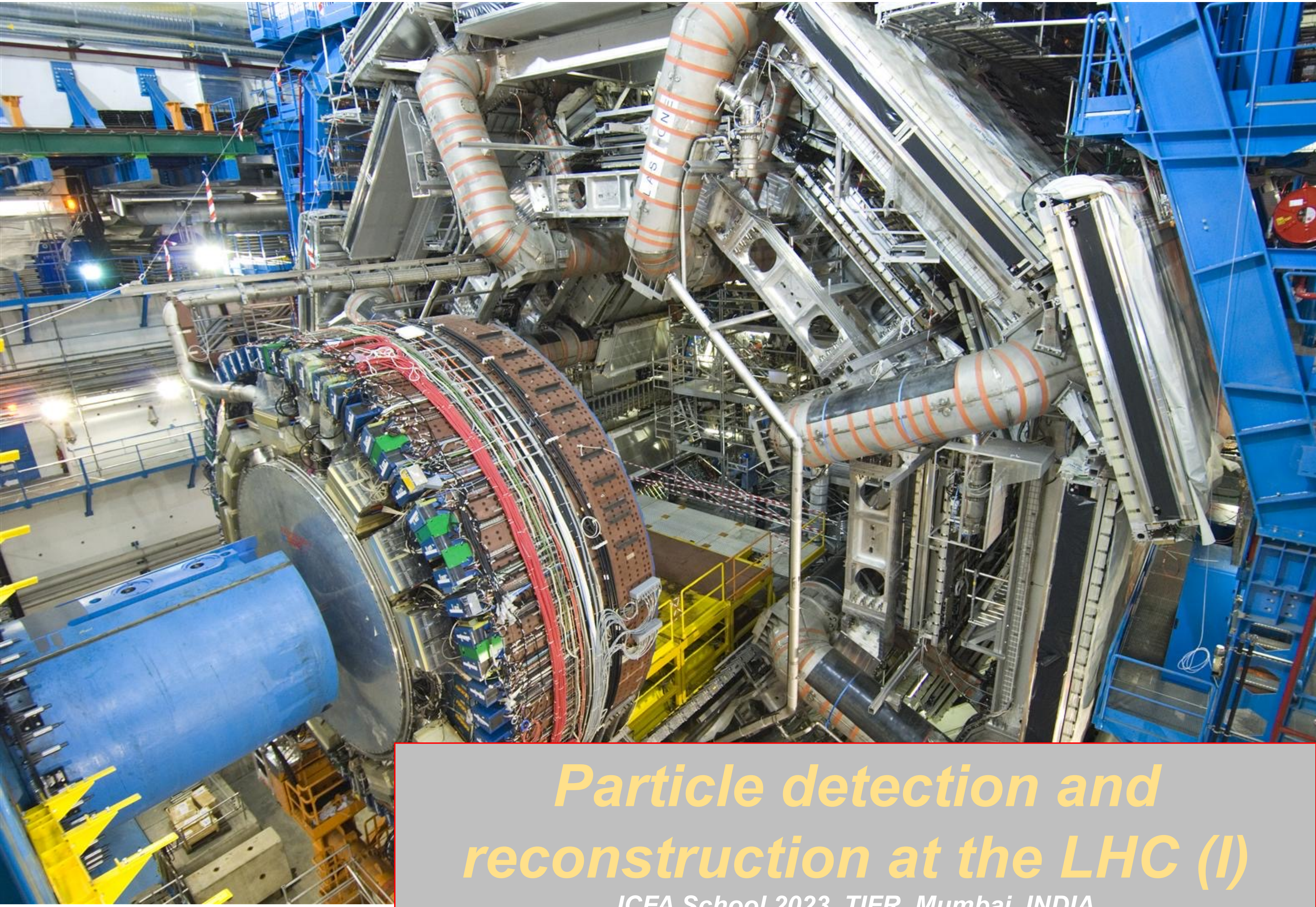


Particle detection and reconstruction at the LHC (I)

ICFA School 2023, TIFR, Mumbai, INDIA

13th to 24th of February 2023 (D. Froidevaux, CERN)

Particle detection and reconstruction at the Large Hadron Collider

Lecture 1 and 2

- Introduction to ATLAS/CMS experiments at the LHC
- Experimental environment and main design choices

Lectures 2 and 3

- Detector techniques: tracking

Lecture 3 and 4

- Detector techniques: calorimetry
- Detector techniques: trigger overview

Lecture 5

- A glimpse from ATLAS performance and physics results

History of Particle Physics

1895: X-rays	**W.C. Röntgen**
1896: Radioactivity	**H. Becquerel**
1899: Electron	**J.J. Thomson**
1911: Atomic Nucleus	**E. Rutherford**
1919: Atomic Transmutation	**E. Rutherford**
1920: Isotopes	**E.W. Aston**
1920-1930: Quantum Mechanics	**Heisenberg, Schrödinger, Dirac**
1932: Neutron	**J. Chadwick**
1932: Positron	**C.D. Anderson**
1937: Mesons	**C.D. Anderson**
1947: Muon, Pion	**C. Powell**
1947: Kaon	**Rochester**
1950: QED	**Feynman, Schwinger, Tomonaga**
1955: Antiproton	**E. Segre**
1956: Neutrino	**C. Cowan, F. Reines**

Etc. etc. etc.

History of Instrumentation

1906: Geiger Counter	**H. Geiger, E. Rutherford**
1910: Cloud Chamber	**C.T.R. Wilson**
1912: Tip Counter	**H. Geiger**
1928: Geiger-Müller Counter	**W. Müller**
1929: Coincidence Method	**W. Bothe**
1930: Emulsion	**M. Blau**
1940-1950: Scintillator, Photomultiplier	
1952: Bubble Chamber	**D. Glaser**
1962: Spark Chamber	
1968: Multi-Wire Proportional Chamber	**G. Charpak**

Etc. etc. etc.

Ideas and tools: both are important!

"New directions in science are launched by new tools much more often than by new concepts.

The effect of a concept-driven revolution is to explain old things in new ways.

The effect of a tool-driven revolution is to discover new things that have to be explained"

Freeman Dyson

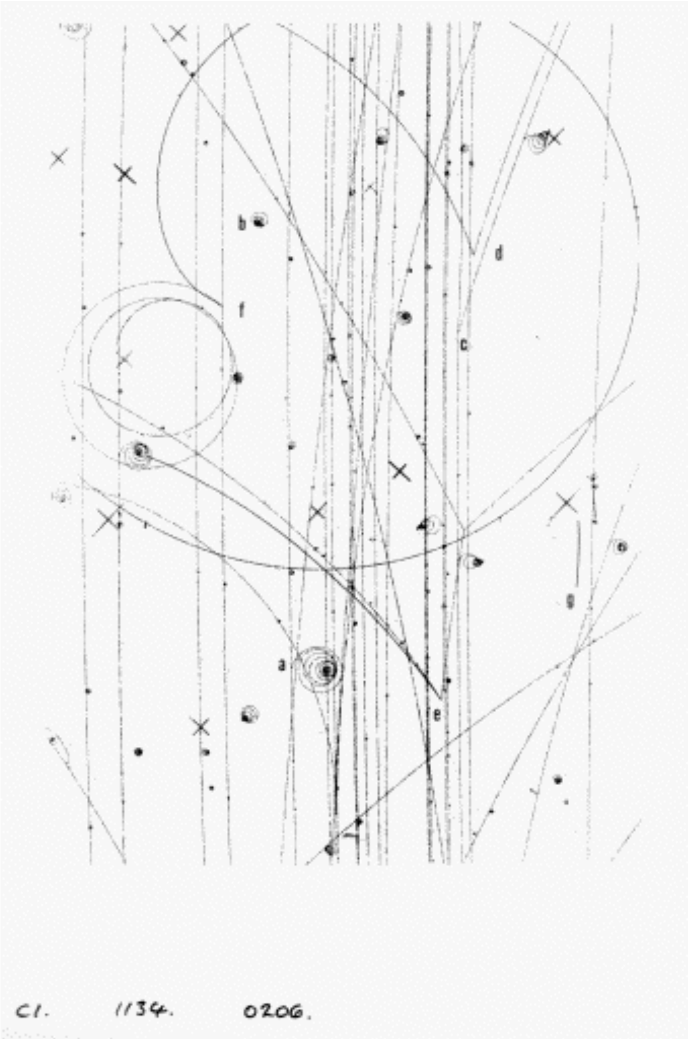
→ New tools and technologies developed over more than 20 years will hopefully lead to exciting discoveries at the LHC!!

Physics Nobel Prizes for Instrumentation

1927: C.T.R. Wilson, Cloud Chamber
1939: E. O. Lawrence, Cyclotron & Discoveries
1948: P.M.S. Blacket, Cloud Chamber & Discoveries
1950: C. Powell, Photographic Method & Discoveries
1954: Walter Bothe, Coincidence method & Discoveries
1960: Donald Glaser, Bubble Chamber
1968: L. Alvarez, Hydrogen Bubble Chamber & Discoveries
1992: Georges Charpak, Multi-Wire Proportional Chamber

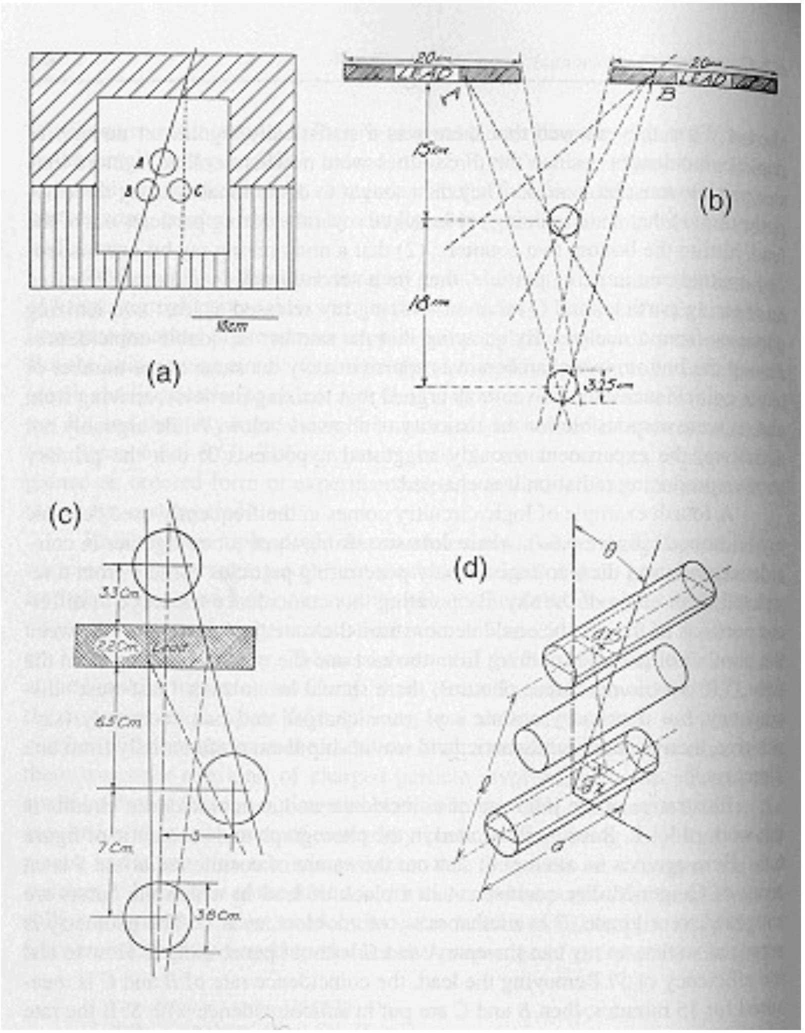
History of Instrumentation

Image Detectors



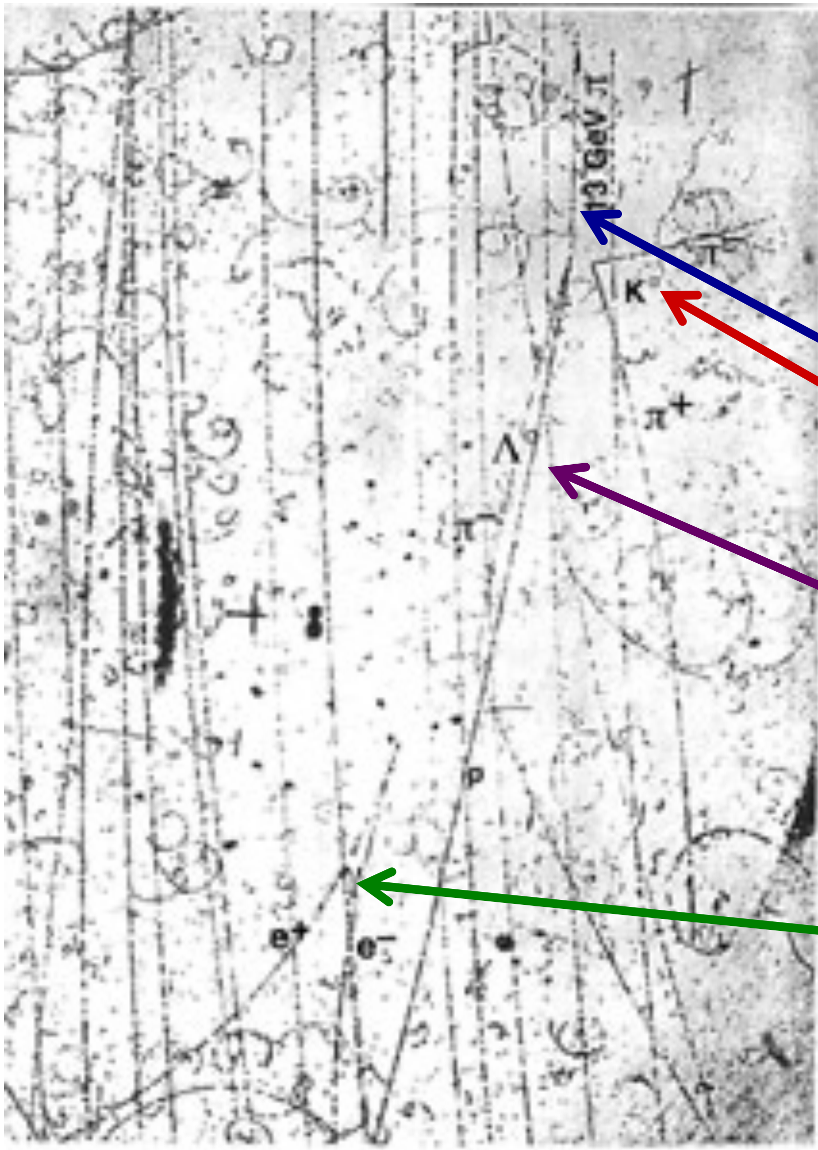
Bubble chamber photograph

'Logic (electronics) Detectors '



Early coincidence counting experiment

Bubble Chamber



In a bubble chamber, with a density about 1000 times larger than a cloud chamber, the liquid acts both as the target and the detecting medium.

Picture:

A propane chamber with a magnet discovered the Σ° in 1956.

A 1300 MeV negative pion hits a proton to produce a neutral kaon (decaying to $\pi^+\pi^-$)and a Σ° , decaying into a Λ° and a photon.

The Λ^0 decays into a proton and a pion

The photon converts into an electron-positron pair.

•Historical perspective: the 80's in UA1/UA2 at the SppS

•From the beginning, with the observation of two-jet dominance

•and of 4 W → eν and 8 Z → e⁺e⁻ decays

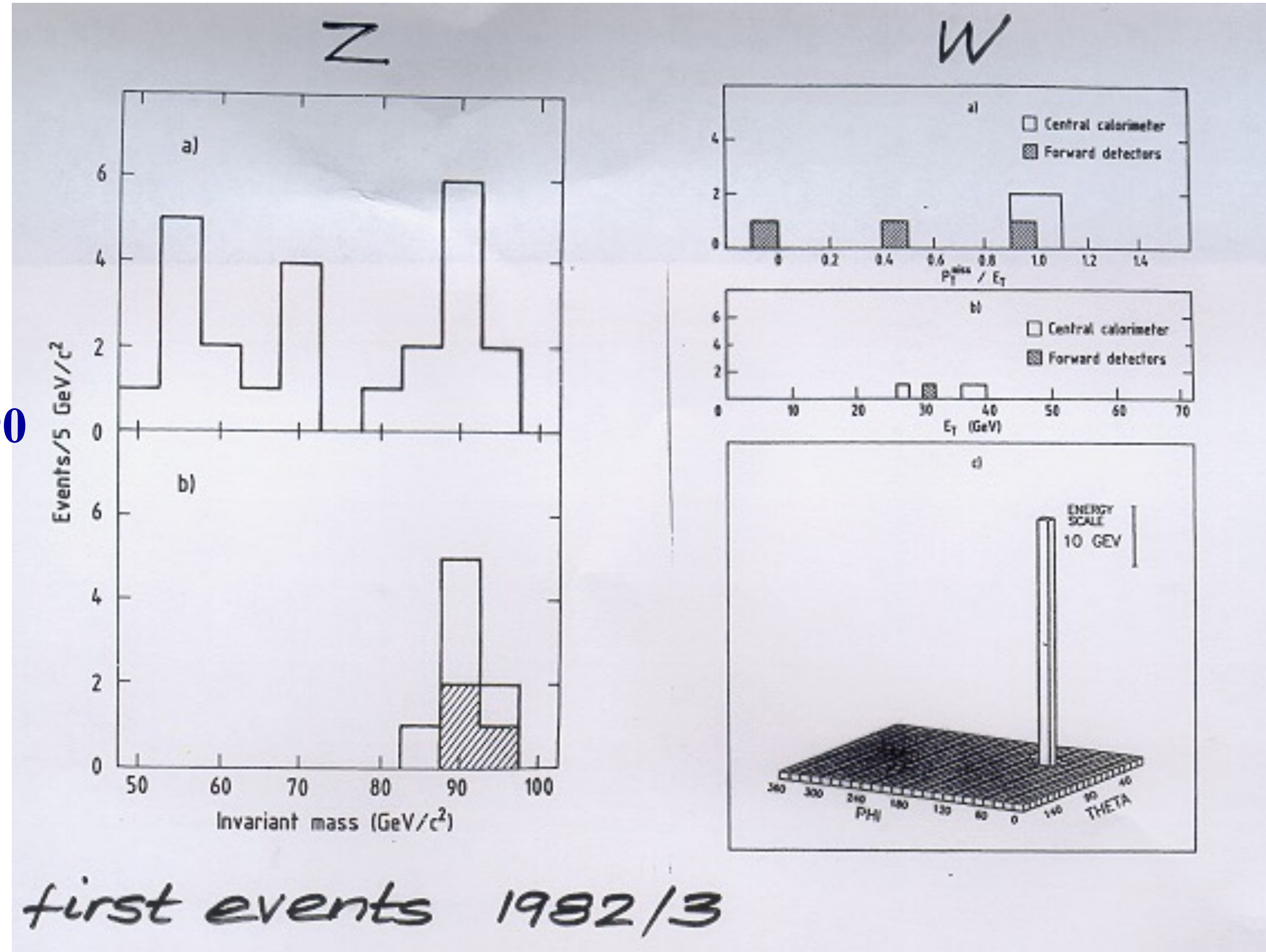
• $\sqrt{s}$ = 546 GeV, L ~ 10^{29} $cm^{-2}s^{-1}$

- **UA2 was perceived**
- **as large at the time:**

10-12 institutes
from 50 to 100 authors
cost ~ 10 MCHF
duration 1980 to 1990

- **Physics analysis was**
- **organised in two groups:**

- **Electrons → electroweak**
- **Jets → QCD**



Bubble Chambers: Rise and Fall

The excellent position (5μm) resolution and the fact that target and detecting volume are the same (H chambers) made the bubble chamber almost unbeatable for the reconstruction of complex decay modes.

The killing drawback of bubbles chambers is their low rate capability (a few tens of events / second).
At the LHC, 10^9 collisions occur every second.

In addition, the fact that bubble chambers cannot be triggered selectively means that every interaction must be photographed.

Analysing the millions of images by 'operators' has been a quite labour-intensive and tedious task in the past.

This explains why electronic detectors took over in the seventies.

Detector Physics and Simulation

Precise knowledge of the processes leading to signals in particle detectors is necessary.

The reason is that modern detectors are nowadays working close to the limits of theoretically achievable measurement accuracy and, in certain cases, of operation and survival – even in large systems.

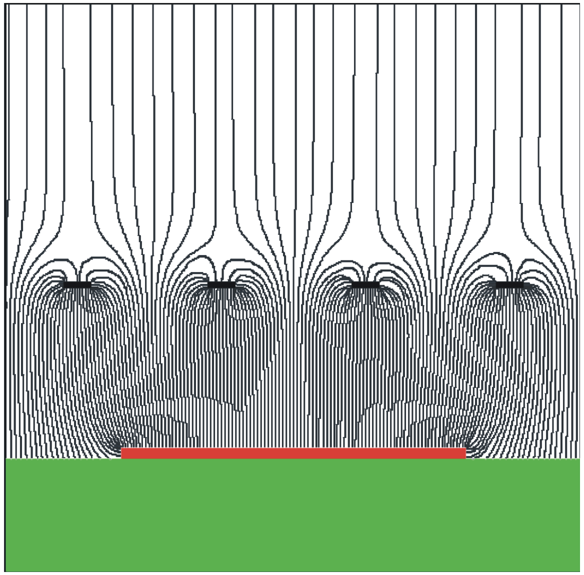
Thanks to the huge available computing power, detectors can be simulated to within 5-10% of reality, based on a very precise description of:

a) **the fundamental physics processes at the microscopic level (atomic and nuclear cross-sections)**
b) **the signal processing (electronics and readout),**
c) **the detector geometry (tens of millions of volumes)**

For the first time, this procedure has been followed for the LHC detectors: the first physics results show that it has paid off!

Particle Detector Simulation

Electric Fields in a Micromegas Detector

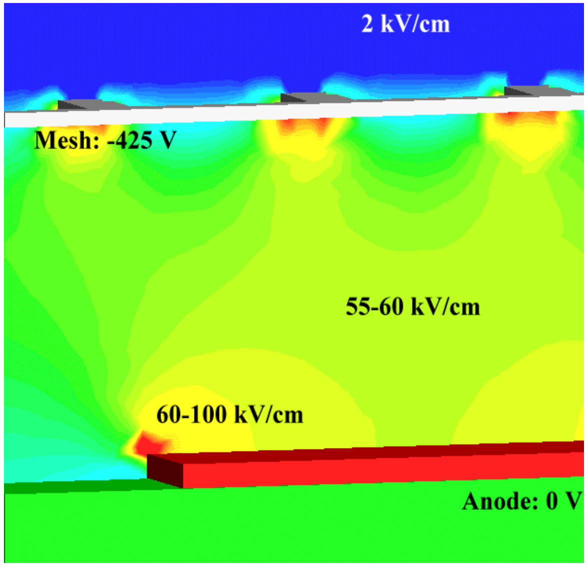


Very accurate simulations of particle detectors are possible due to availability of Finite Element simulation programs and computing power.

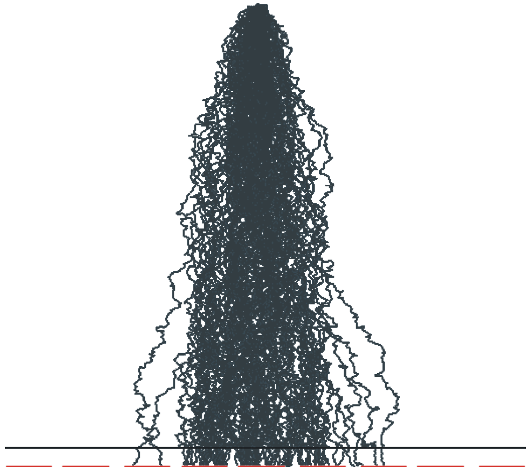
Follow every single electron by applying first-principle laws of physics.

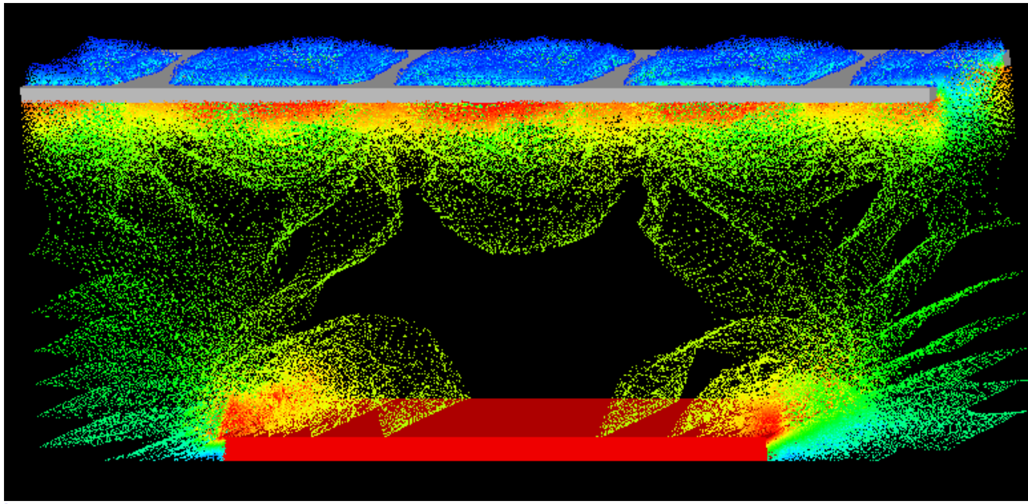
For gaseous detectors: GARFIELD by R. Veenhof

Electric Fields in a Micromegas Detector



Electron avalanche multiplication





Particle Detector Simulation

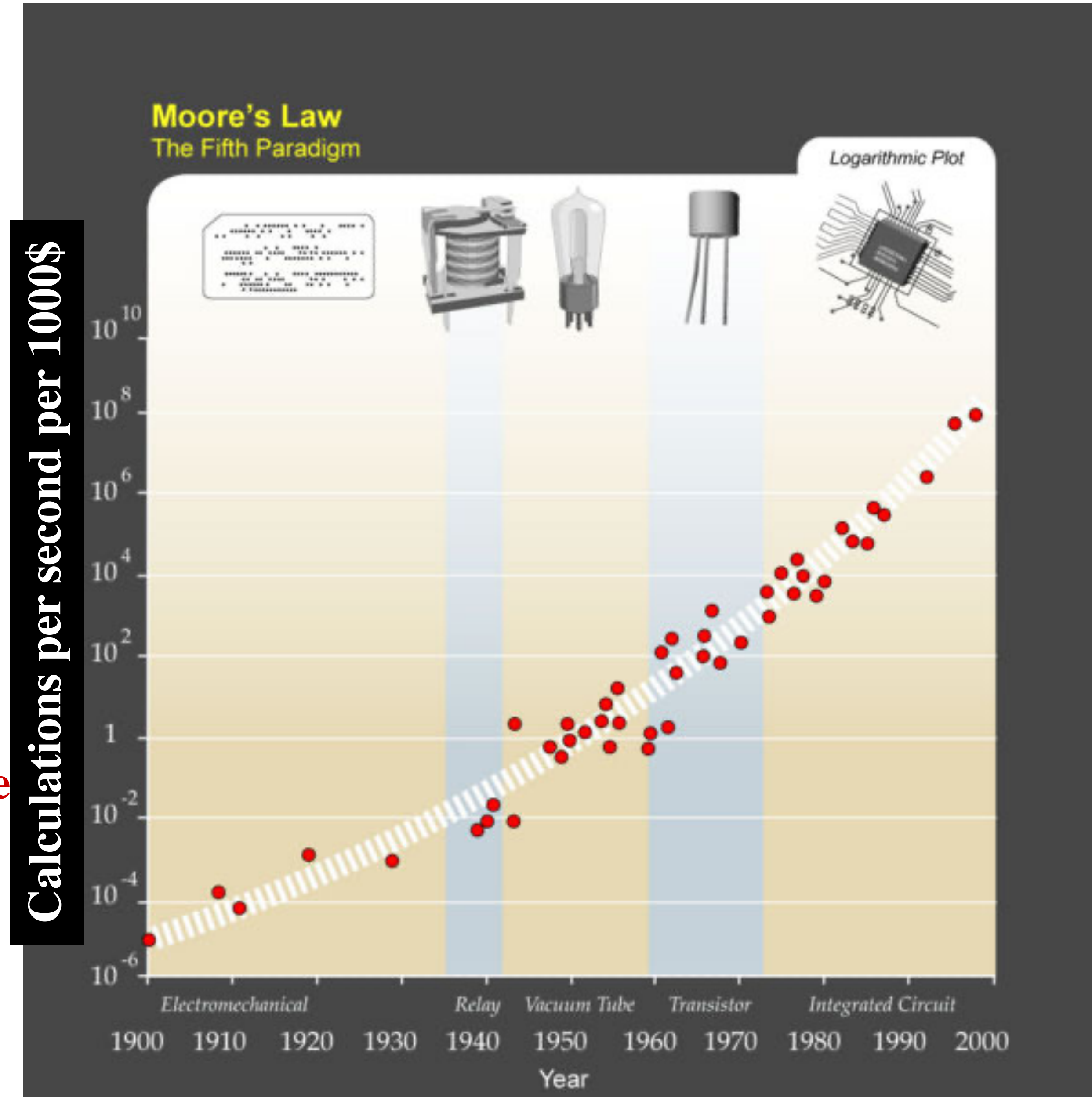
I) C. Moore's Law:

Computing power doubles every 18 months.

II) Modern World's Law:

The use of the human brain for solving a problem is inversely proportional to the available computing power.

Design and construction of LHC detectors has taken advantage of Moore's law (it would most likely not have been possible without it) but has also been the result of the combined power of human brains and modern computers.



Knowing the basics of particle detectors is essential!!

Experimental particle physics: 1976 to 2010

✦ Today we are able to ask questions we were not able to formulate 25-30 years ago when I was a student:

- ✓ What is dark matter? How is it distributed in universe?
- ✓ What is the nature of dark energy?
- ✓ Is our understanding of general relativity correct at all scales?
- ✓ Will quantum mechanics fail at very short distances, in conscious systems, elsewhere?
- ✓ Origin of CP violation, of baryons, what about the proton lifetime?
- ✓ Role of string theory? Duality?

✦ Some of these questions might well lead me towards astrophysics or astro-particle physics today if I would become a young student again!

✦ The more we progress, the longer will be the gap between the reformulation of fundamental questions in our understanding of the universe and its complexity? This gap is already ~ equal to the useful professional lifetime of a human being? This poses real problems.

Theories and models

Unification of terrestrial and celestial gravitation

- Newton 1680

Unification electricity and magnetism

- Faraday & Ampère 1830

Unification of optics and electromagnetism

- Maxwell 1890

Unification of space and time

- Einstein 1905

Unification of gravitation and electromagne

- Kaluza 1919 (5 dimensions, 4 for space and one for time, curvature of additional dimension generates electromagnetic force)

Unification of weak and electromagnetic interactions

- Glashow,Weinberg,Salam 1967

Endless loop of experimental physicist: measure, simulate, talk to theorists …

Observations (measurements: build detectors)

- An apple falls from a tree
- There are four forces + matter particles

Models (simulations)

- $P=GmM/R^2$
- Standard Model

Predictions (theories, ideas)

- Position of planets in the sky
- Higgs boson, supersymmetric particles

Huge success of Standard Model in particle physics:

Predictions in agreement with measurements to 0.1%

Magnetic moment of electron:

agreement to 11 significant digits between theory and experiment!

Discovery of W, Z, top quark, ν_τ, Higgs boson After prediction by theory!

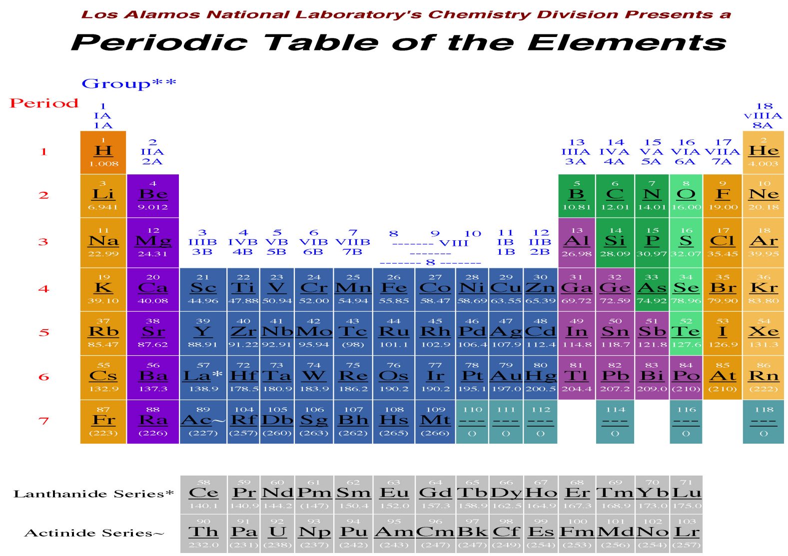
Still incompatible today from a theoretical viewpoint

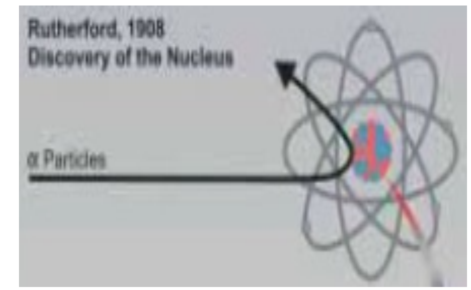
Main success of general relativity:

Predictions in agreement with measurements to 0.1%

Since the dawn of time, humankind has been wondering about the elementary constituents of matter

Philosophy	Classical Physics	Semi-Classical Physics



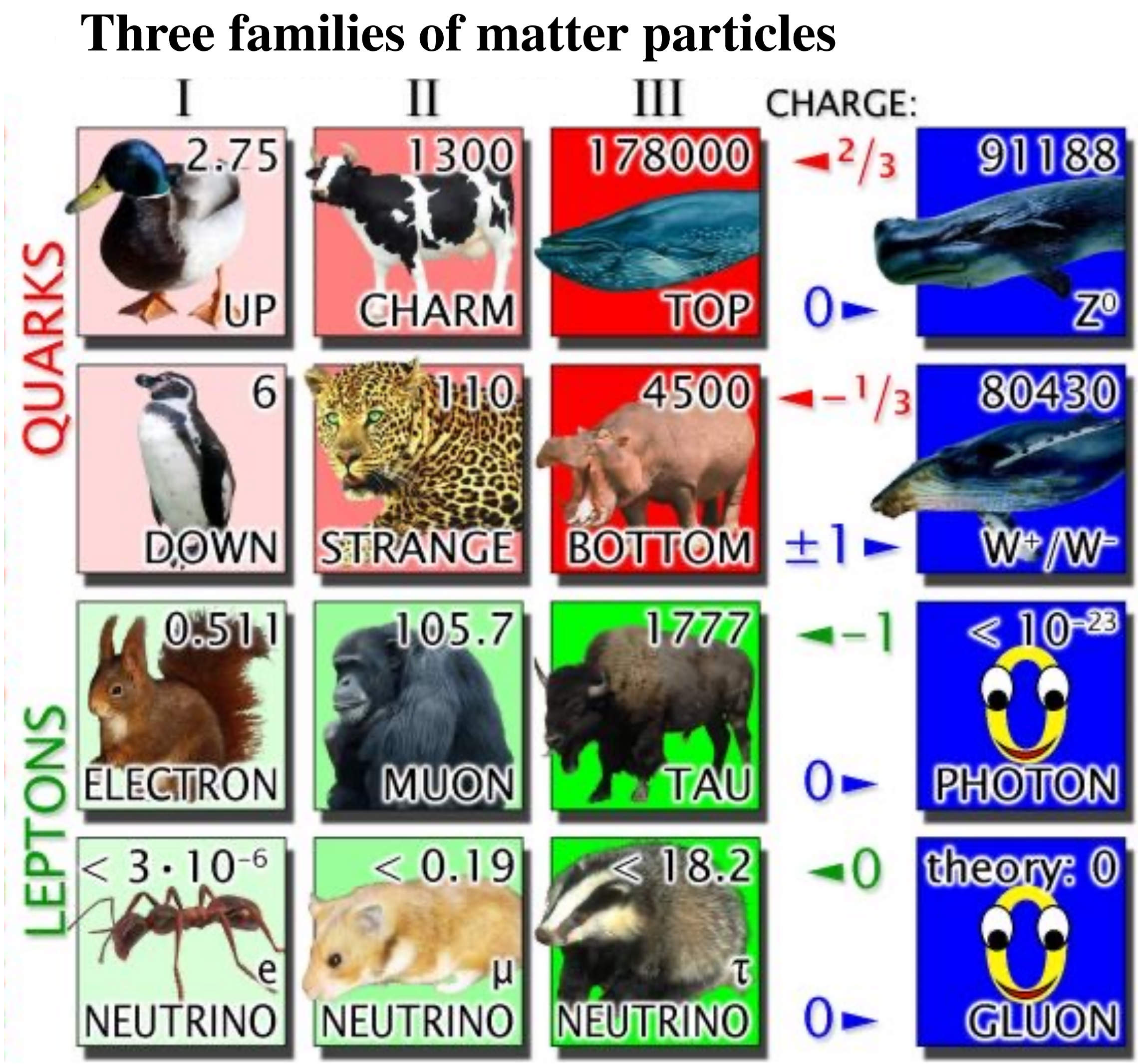


EMPEDOCLES (492-432 B.C.)
4 basic elements

MENDELEEV (19th century)
Periodic Table:
>100 basic elements

BOHR, RUTHERFORD (beg 20th century)
2 basic elements: electron and nucleus

The zoo of elementary particles in the Standard Model

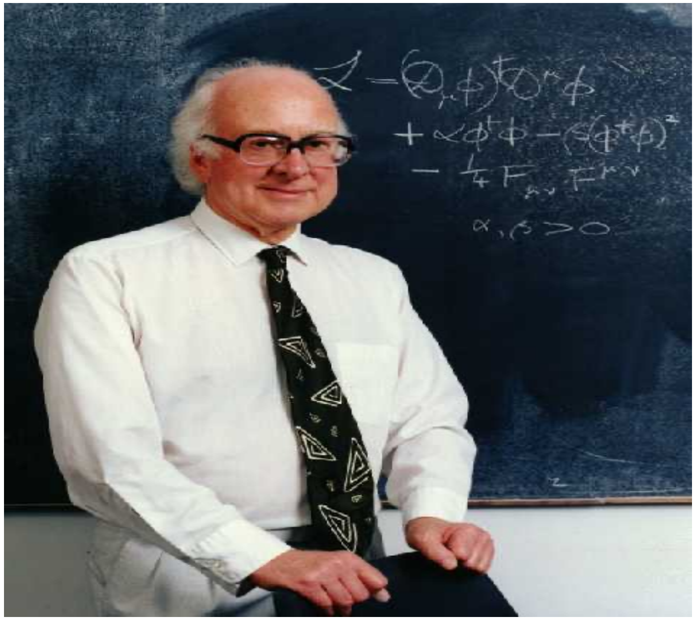


Masses are in MeV or millions of electron-volts.
The weights of the animals are proportional to the weights of the corresponding particles.

What about the Higgs boson?

Higgs boson has been with us for many decades as:

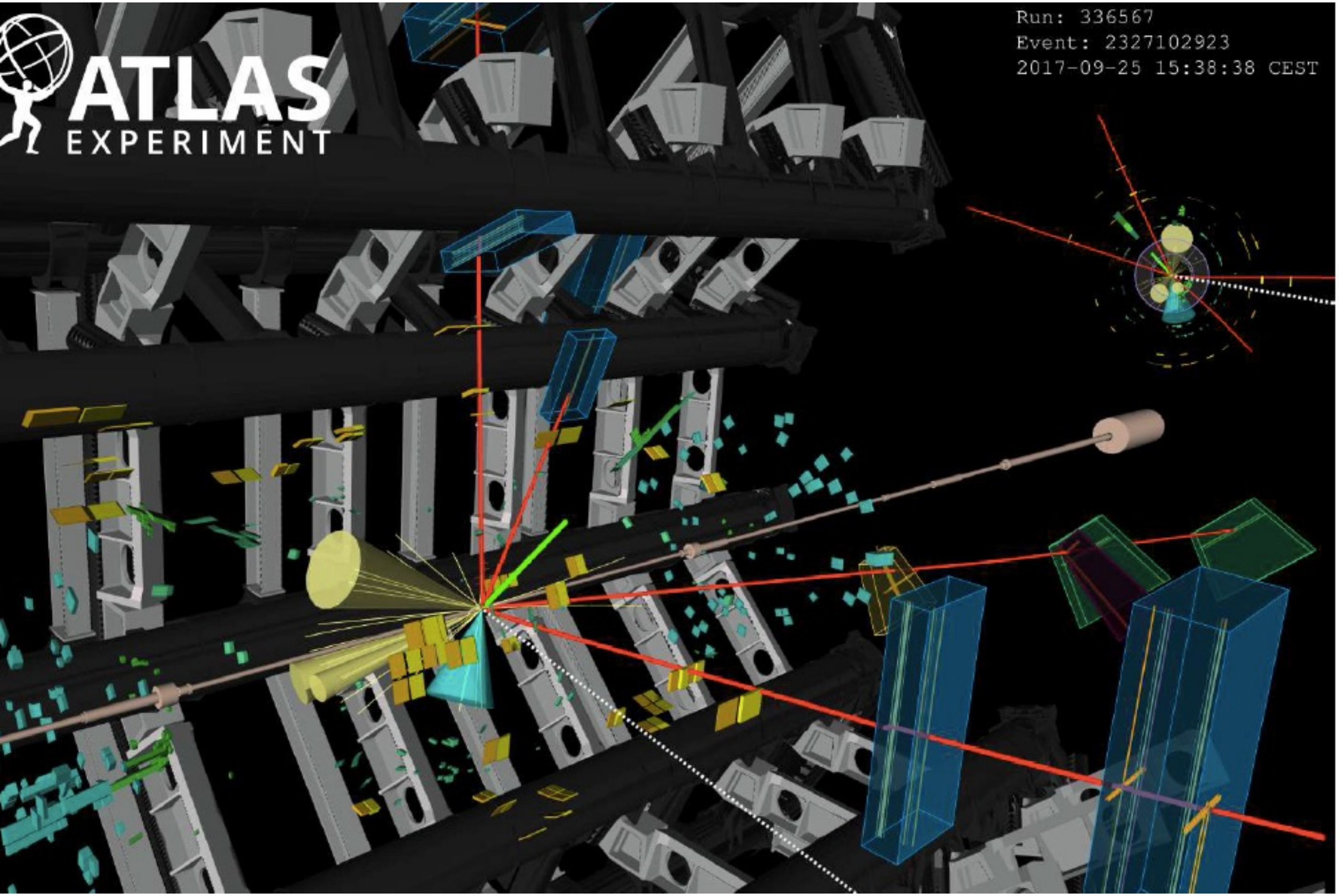
1. a theoretical concept,
2. a scalar field linked to the vacuum,
3. the dark corner of the Standard Model,
4. an incarnation of the Communist Party, since it controls the masses (L. Alvarez-Gaumé in lectures for CERN summer school in Alushta),
5. a painful part of the first chapter of our Ph. D. thesis



P.W. Higgs, Phys. Lett. 12 (1964) 132

Only unambiguous example of observed Higgs

Please show me a Higgs boson!

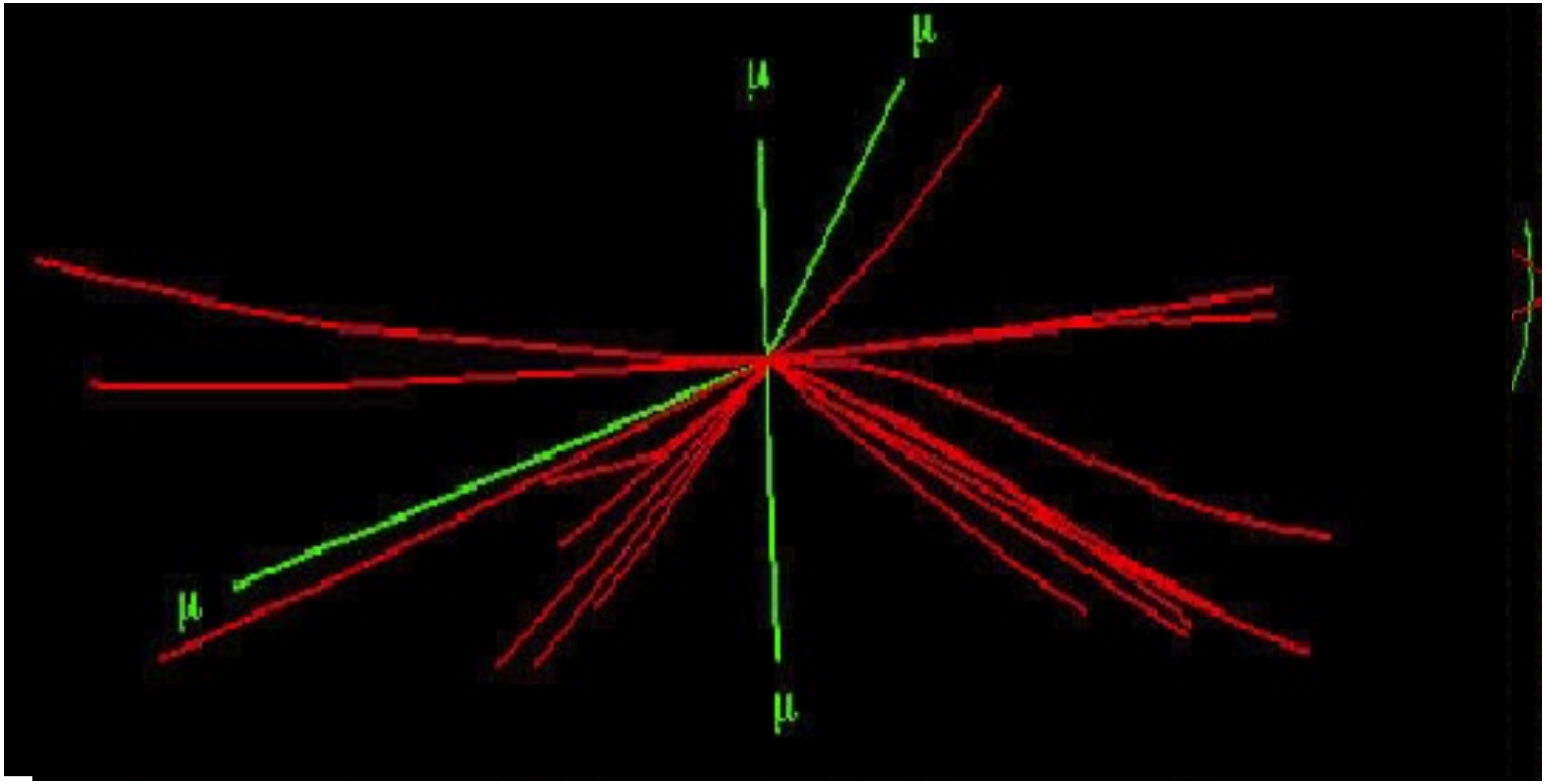


4 muon event with mass 124.4 GeV, one Z mass of 89,3 GeV and the lower mass of 33 GeV, one electron, four jets, lowest pT has tight b-tagging.

$$s/b \sim 30$$

Physics at the LHC: the challenge

How to extract this… … from this …

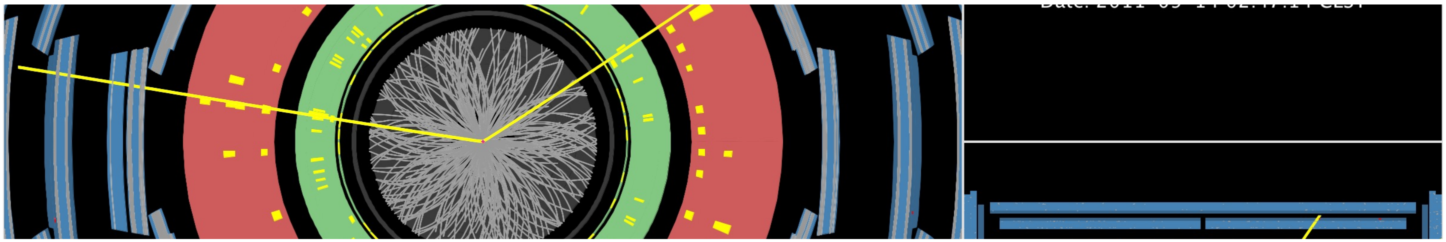


Higgs ⟶ 4μ +30 min. bias events

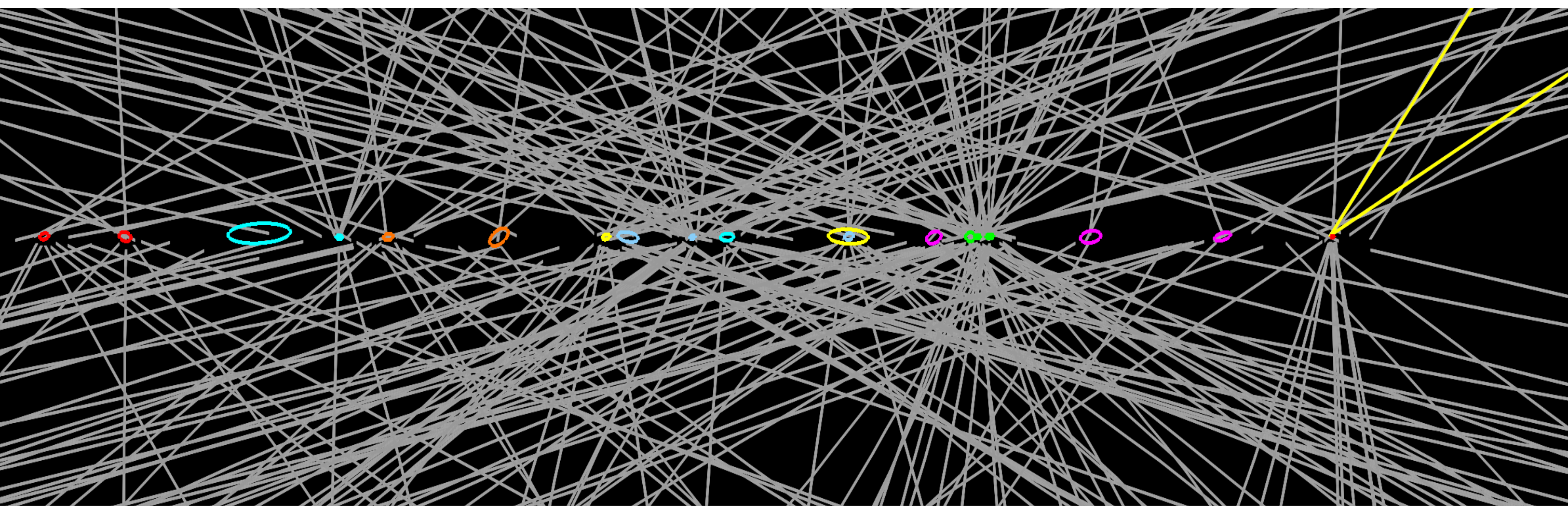
Without knowing really where to look for!

ATLAS status report: a snapshot after reaching $L = 3.3\ 10^{33}\ cm^{-2}s^{-1}$ (18 months and 3.2 fb^{-1} after first collisions at 7 TeV).

Now have <pile-up> ~ 14 per bunch crossing.
a challenge for tracking and for low-p_T jets!



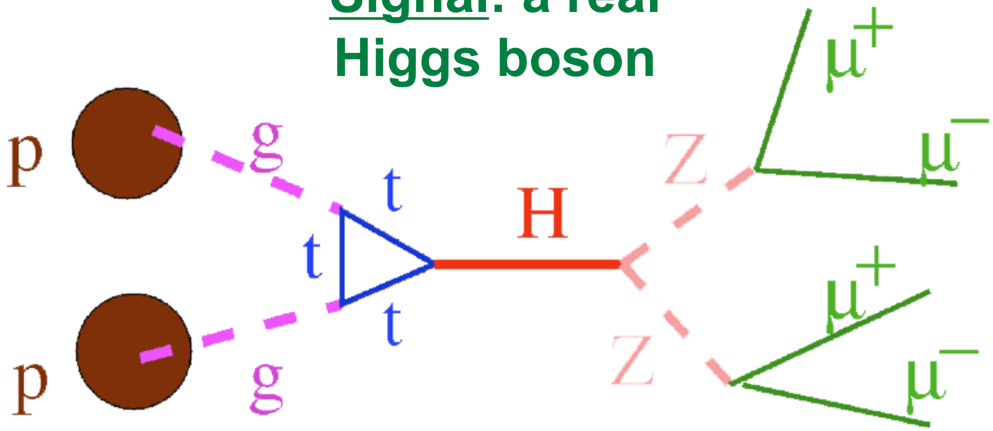
Example of Z → μμ decay with 20 reconstructed vertices
Total scale along z is ~ ± 15 cm, p_T threshold for track reco is 0.4 GeV
(ellipses have size of 20σ for visibility)



No pictures of Higgs boson itself: only of its decay products

Sometimes (rarely) the Higgs boson decays to four muons:

Signal: a real Higgs boson

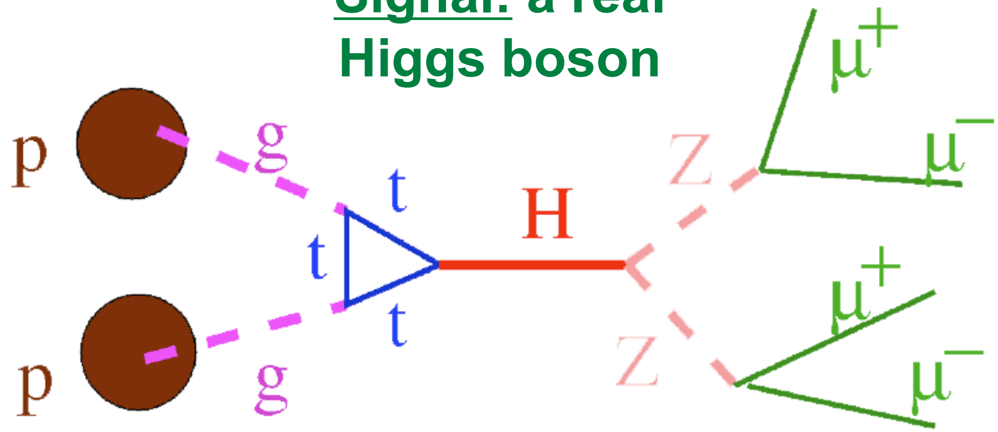


So let's look for four muons with high energy because the Higgs boson mass is larger than 114 GeV (inheritance from LEP machine and experiments)

No pictures of Higgs boson itself

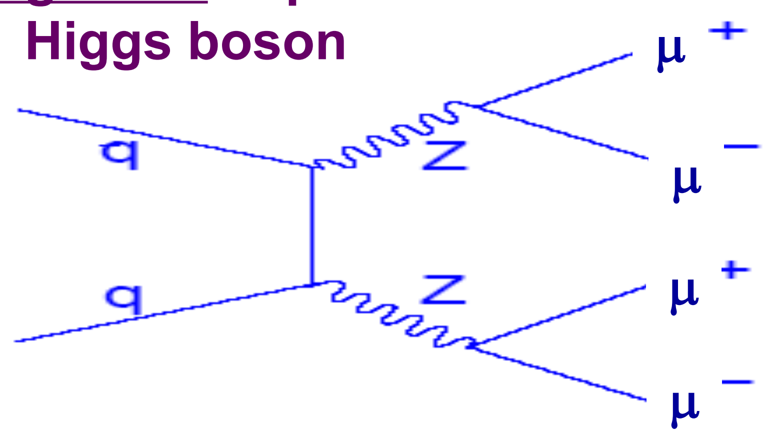
Sometimes the Higgs boson decays into four muons:

Signal: a real Higgs boson



But four muons may also be produced without any Higgs boson (process predicted by the Standard Model and therefore constituting an irreducible background)

Background: a pseudo Higgs boson

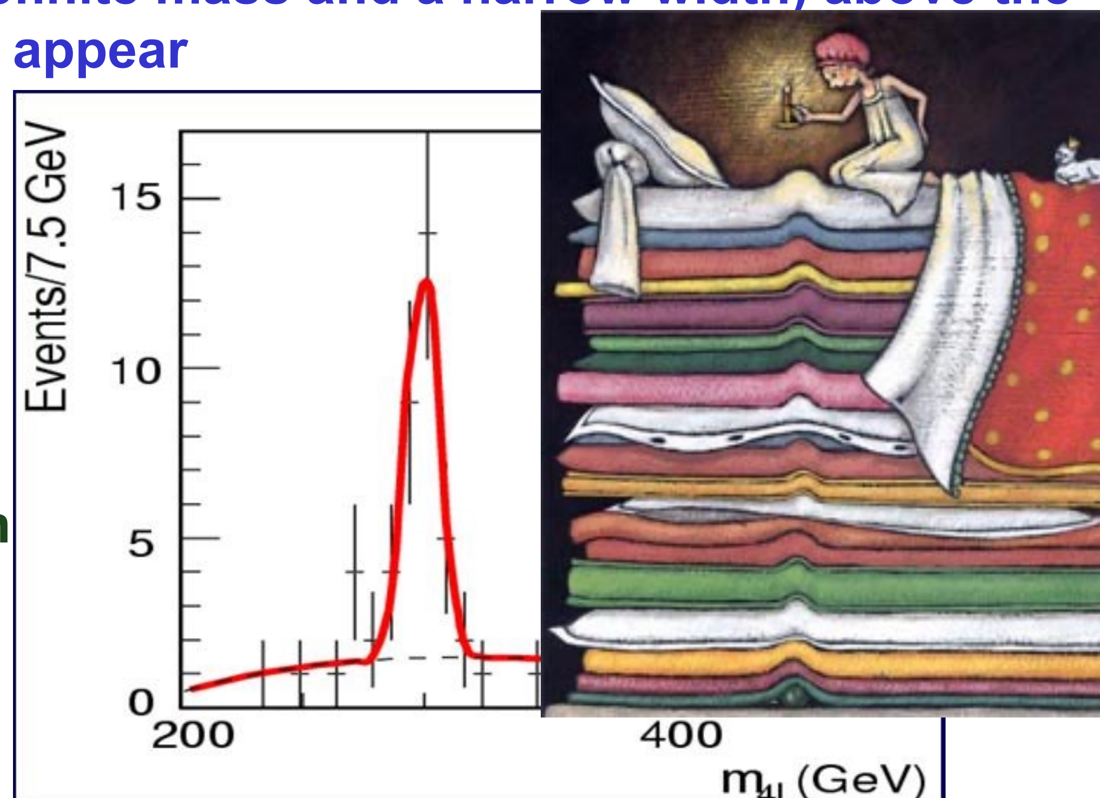


No pictures of Higgs boson itself:
but how can we find it? how can we eliminate background?

- We have to use the precise measurements obtained with each of the four muons to find back their parents (Z bosons) through the simple laws of energy and momentum conservation (in a relativistic world)
- We therefore calculate the mass of the "particle" which might have given birth to the four muons. The Higgs boson should manifest itself as a narrow peak (it has a definite mass and a narrow width) above the background which will itself appear at all possible masses

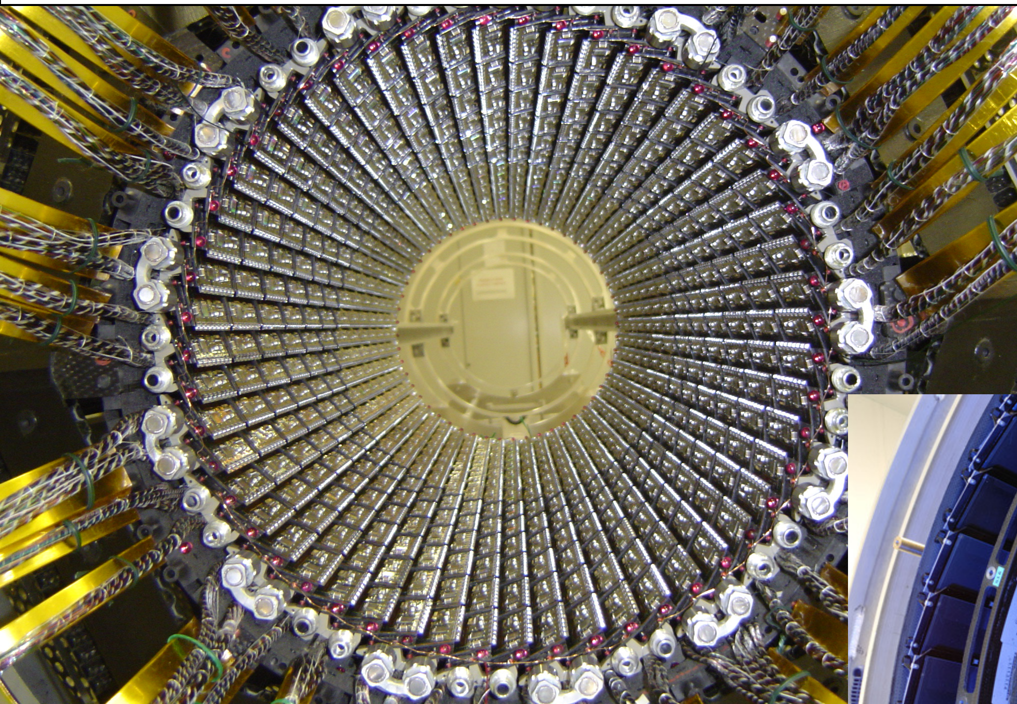
- Example: m_H = 300 GeV

  We will have to wait for end 2011/2012 to know more about the Higgs boson … because, even if it is there, it is produced very rarely and hides very well!



We must remain humble!
Remember that tracking at the LHC is a risky business!

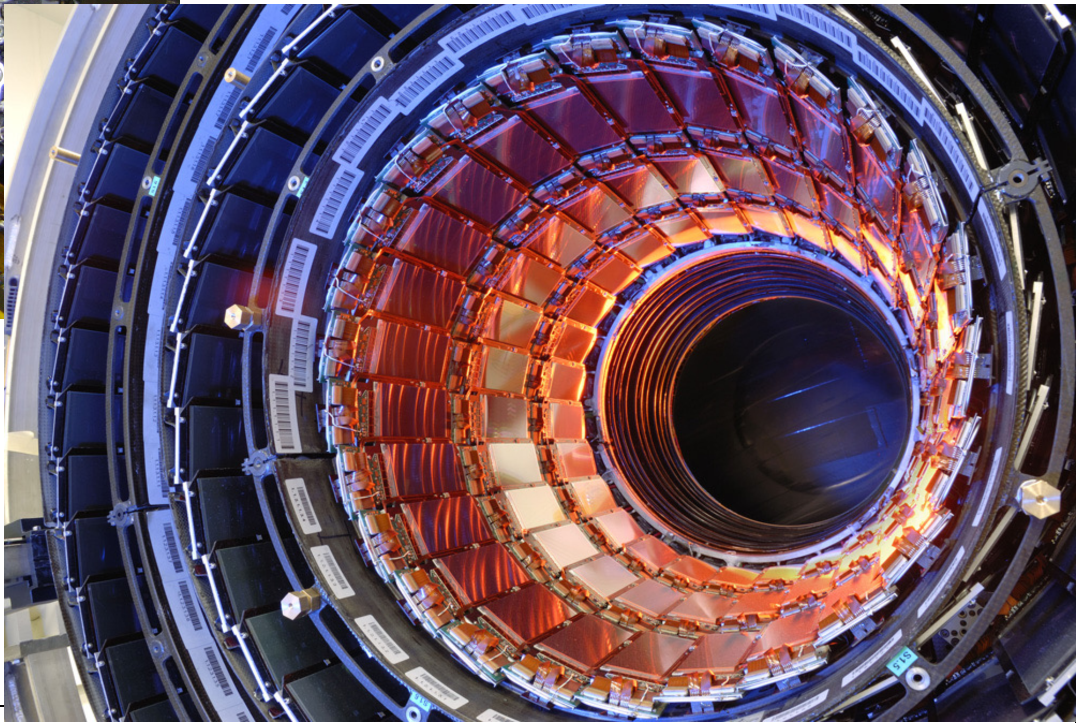
ATLAS pixels, September 2006



- All modules and services integrated and tested
- 80 million channels !
- 10%-scale system test with cosmics done at CERN
- Inst. in ATLAS: June 2007

CMS silicon strips

- 200 m^2 Si, 9.6 million channels
- 99.8% fully operational
- Signal/noise ~ 25/1
- 20% cosmics test under way
- Inst. in CMS: August 2007



CMS Tracker Inner Barrel, November 2006

D. Froidevaux, CERN

What next?

Should one fear that experimental particle physics is an endangered species with its gigantic scale and long time-scales?

- **The front-wave part of this field is becoming too big for easy continuity between the generations. I have been working on LHC for 25 years already. Most of the analysis will be done by young students and postdocs who have no idea what the 7000 tonnes of ATLAS is made of. More importantly, fewer and fewer people remember for example that initially most of the community did not believe tracking detectors would work at all at the LHC.**
- **The stakes are very high: one cannot afford unsuccessful experiments (shots in the dark) of large size, one cannot anymore approve the next machine before the current one has yielded some results and hopefully a path to follow**
- **Theory has not been challenged nor nourished by new experimental evidence for too long**

What next?

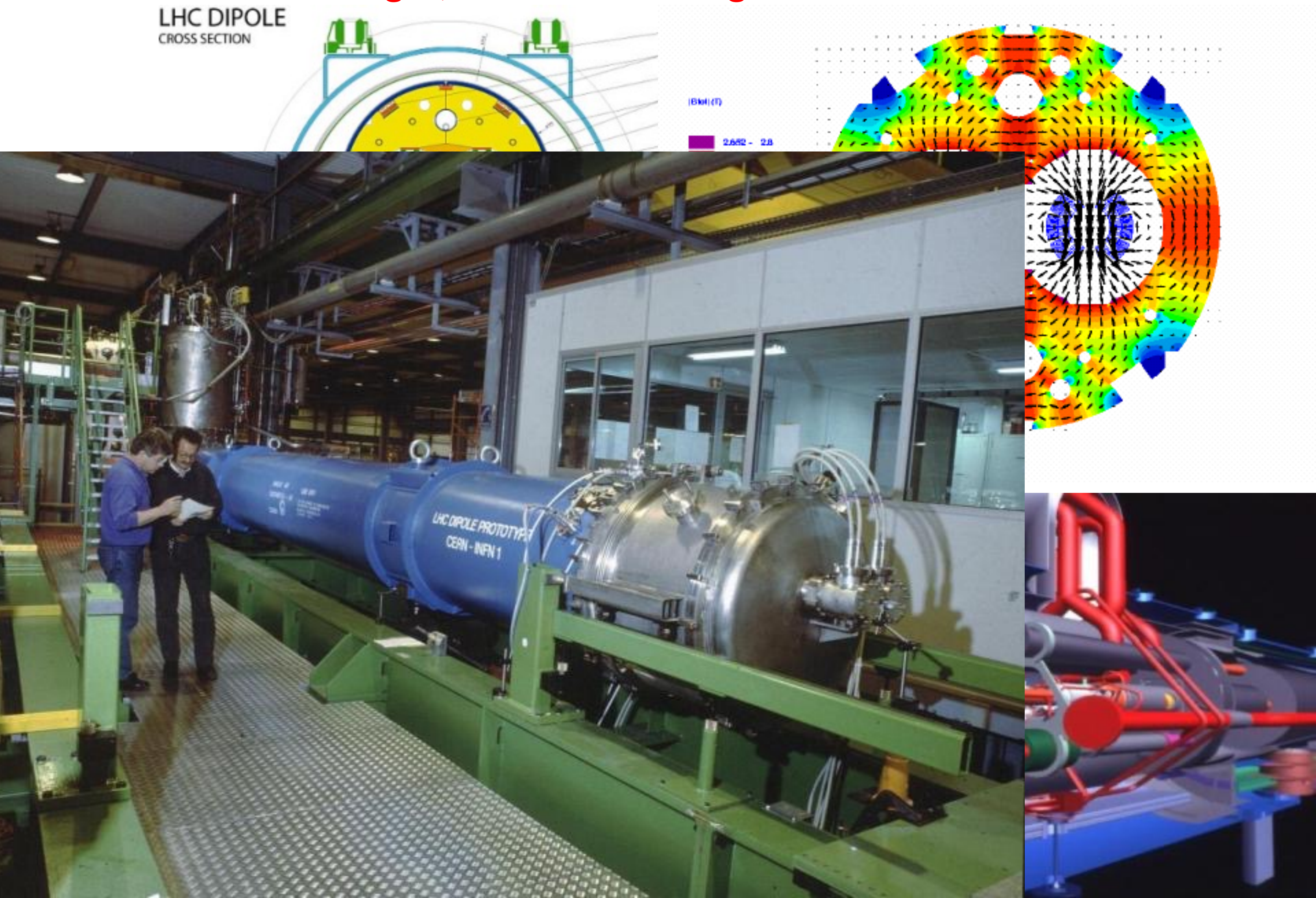
This is why the challenge of the LHC and its experiments is so exhilarating! A major fraction of the future of our discipline hangs on the physics which will be harvested at this new energy frontier.
How ordinary or extraordinary will this harvest be? Only nature knows.

The large instruments built for the LHC by huge international collaborations are now operational. They are the result of extraordinary technological challenges: their solution has been possible only thanks to the progress realised worldwide in extremely diverse areas. But the first and foremost motivation in all of this is our desire to understand better our universe.

Many thanks to
F. Bordry, S. Cittolin, P. Farthouat, C. Rembser and P. Sphicas
for their help!


LEP/LHC 1989/2009
PS 1959
SPS 1976

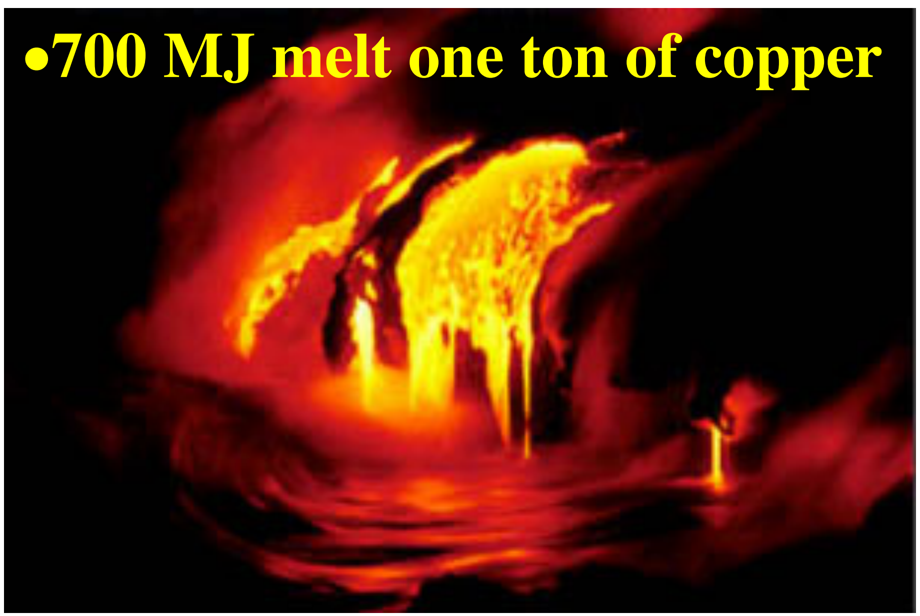
One look to the past: the first long prototype dipole magnet for the LHC. With its 10m length, it reached a magnetic field of 8.73T in 1994.



The giant challenge of the LHC

Collision energy	7 TeV (1 eV = 1,6 × 10^{-19} Joule)
Number of bunches	2808
Protons per bunch	$1.15 \cdot 10^{11}$
Total number of protons	$6.5 \cdot 10^{14}$ (1 ng of H^+)

Energy stored in the two beams:	724 MJoule
Energy to heat and melt one ton of copper:	700 MJoule

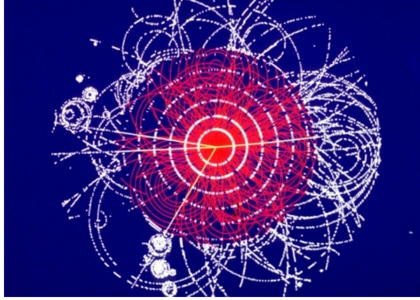


700 MJ dissipated in 88 μs ≅ 8 TW

Total world electrical capacity ≅ 3.8 TW

90 kg of TNT per beam

Is the LHC an efficient machine?

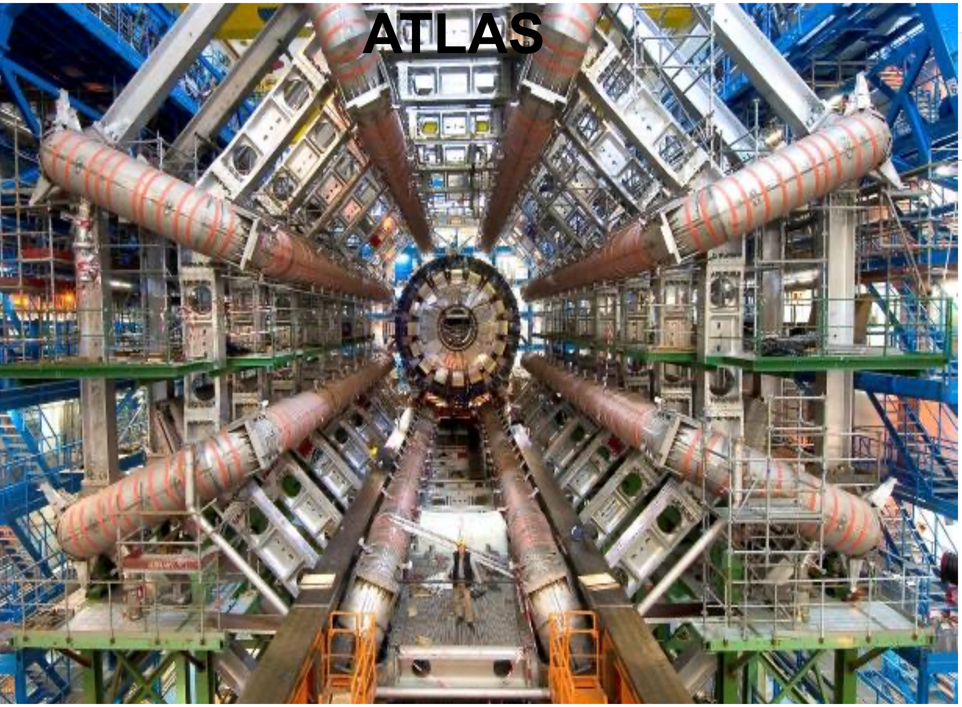
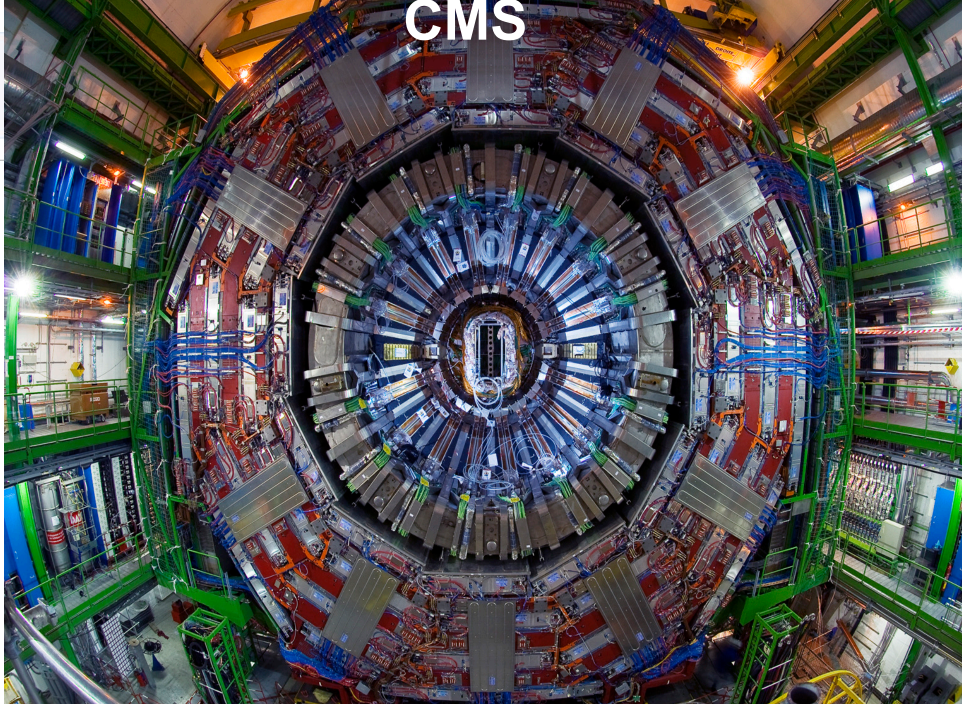
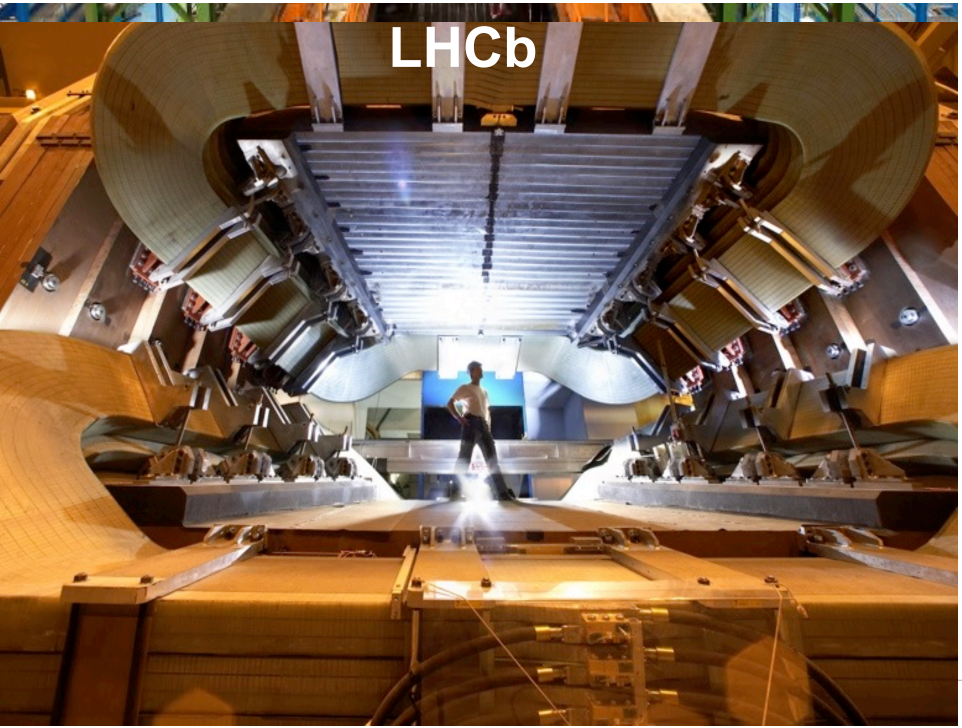
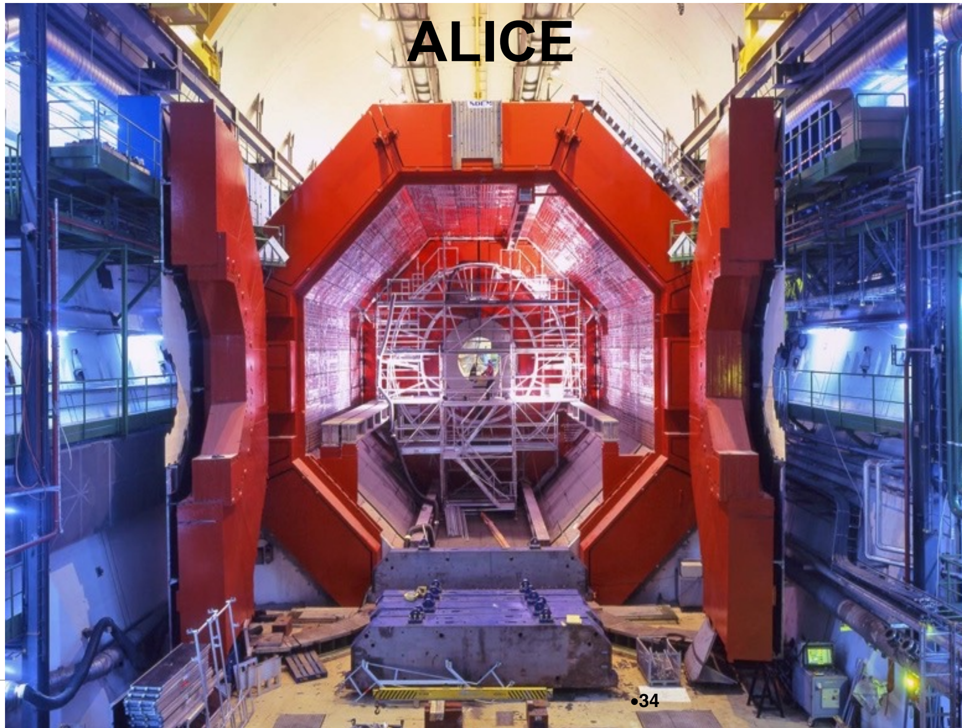


$$\frac{\text{Energy of 100 Higgs bosons}}{\text{Total energy provided by EDF}} \cong 10^{-20}$$

140 MW during 2000 hours: 100 000 GJ

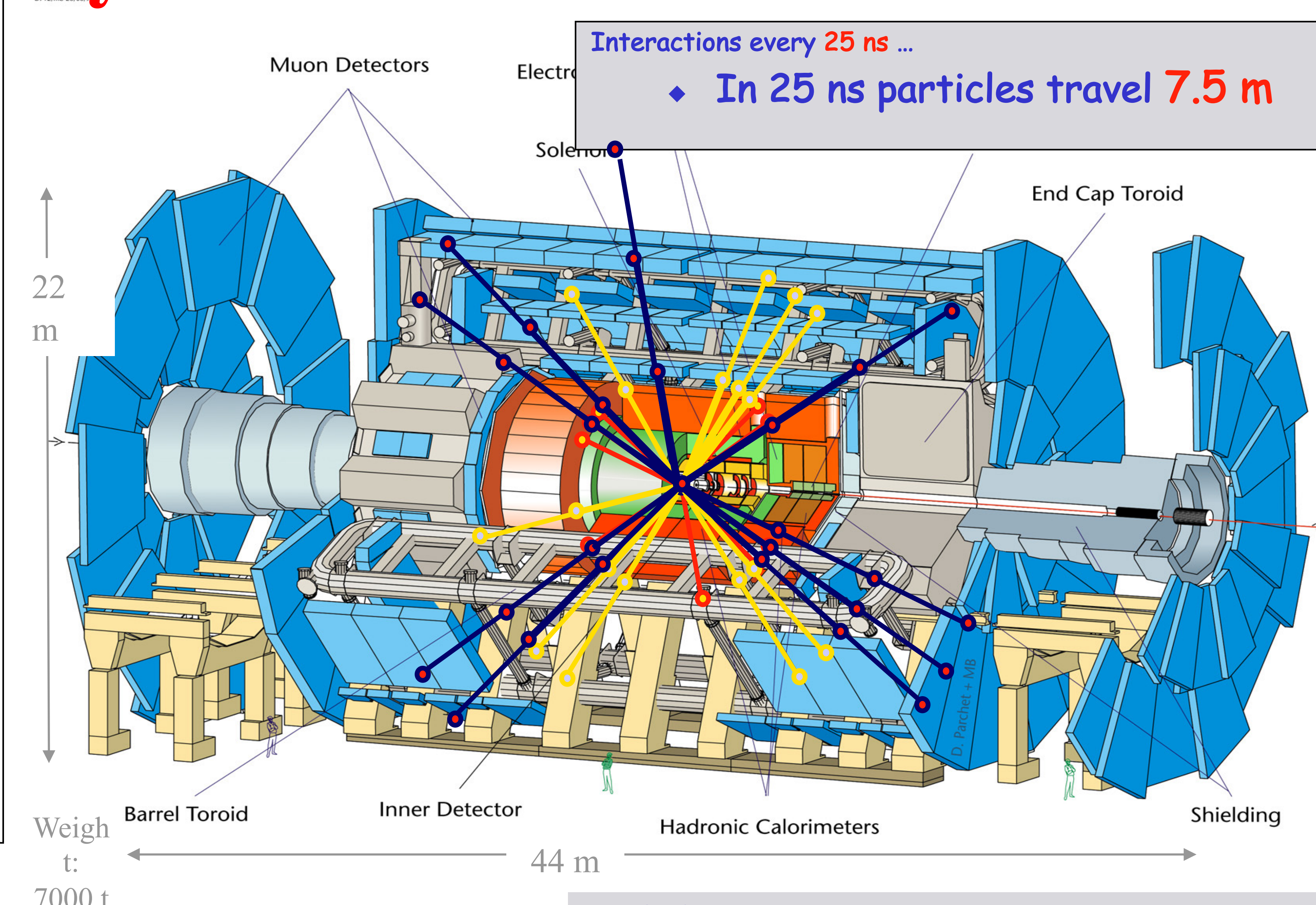
A laughingly small efficiency?

No, an incredible tool produced by humanity to improve our understanding of the fundamental properties of nature


ATLAS

CMS

LHCb

ALICE

Physics at the LHC: the environment

Time-of-flight



Interactions every 25 ns …

- In 25 ns particles travel 7.5 m

Cable length ~100 meters …

- In 25 ns signals travel 5 m

D. Froidevaux, CERN

How huge are ATLAS and CMS?

- Size of detectors
  - Volume: 20 000 m^3 for ATLAS
  - Weight: 12 500 tons for CMS
  - 66 to 80 million pixel readout channels near vertex
  - 200 m^2 of active Silicon for CMS tracker
  - 175 000 readout channels for ATLAS LAr EM calorimeter
  - 1 million channels and 10 000 m^2 area of muon chambers
  - Very selective trigger/DAQ system
  - Large-scale offline software and worldwide computing (GRID)
- Time-scale will have been about 25 years from first conceptual studies (Lausanne 1984) to solid physics results confirming that LHC will have taken over the high-energy frontier from Tevatron (2010)
- Size of collaboration
- Number of meetings and Powerpoint slides to browse through

How huge are ATLAS and CMS?

- Many tens of thousands of electronics circuits,
- Thousands of FPGA circuits for the readout,
- Thousands of commercial CPU's for filtering data in real time and putting together all the bits of the event

Analysis of data garnered by detector is a task of unprecedented scope and complexity!

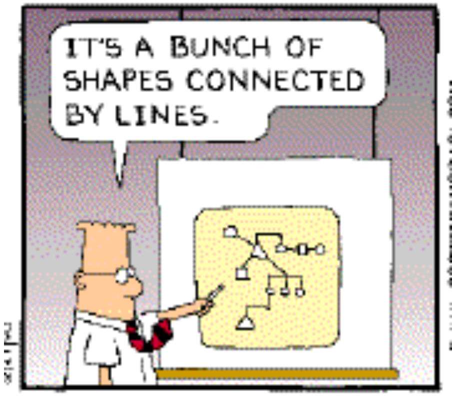
Proton bunch-crossing rate: 40 MHz ➡ 200-400 Hz to mass storage (tape!)

Size of event ~ 1 MByte (10^6 Bytes), data-taking ~ 10^7 seconds per year

Need to store ~ few PBytes of data per year (Peta = 10^{15})

- Equivalent to ~ one billion dictionaries per year
- Equivalent to ~ one DVD every few seconds

Software also very complex to develop and maintain



Only possible solution to analyse these vast amounts of data:

The computing grid: distributed analysis, do not bring the data to your computers, but send your programs where the data happens to be!

ATLAS Collaboration

(As of ~ 2009)

~ 35 Countries
~ 162 Institutions
~ 2500 Scientific Authors
(~ 1600 with a Ph.D.)

+ 

since July 2nd 2010!

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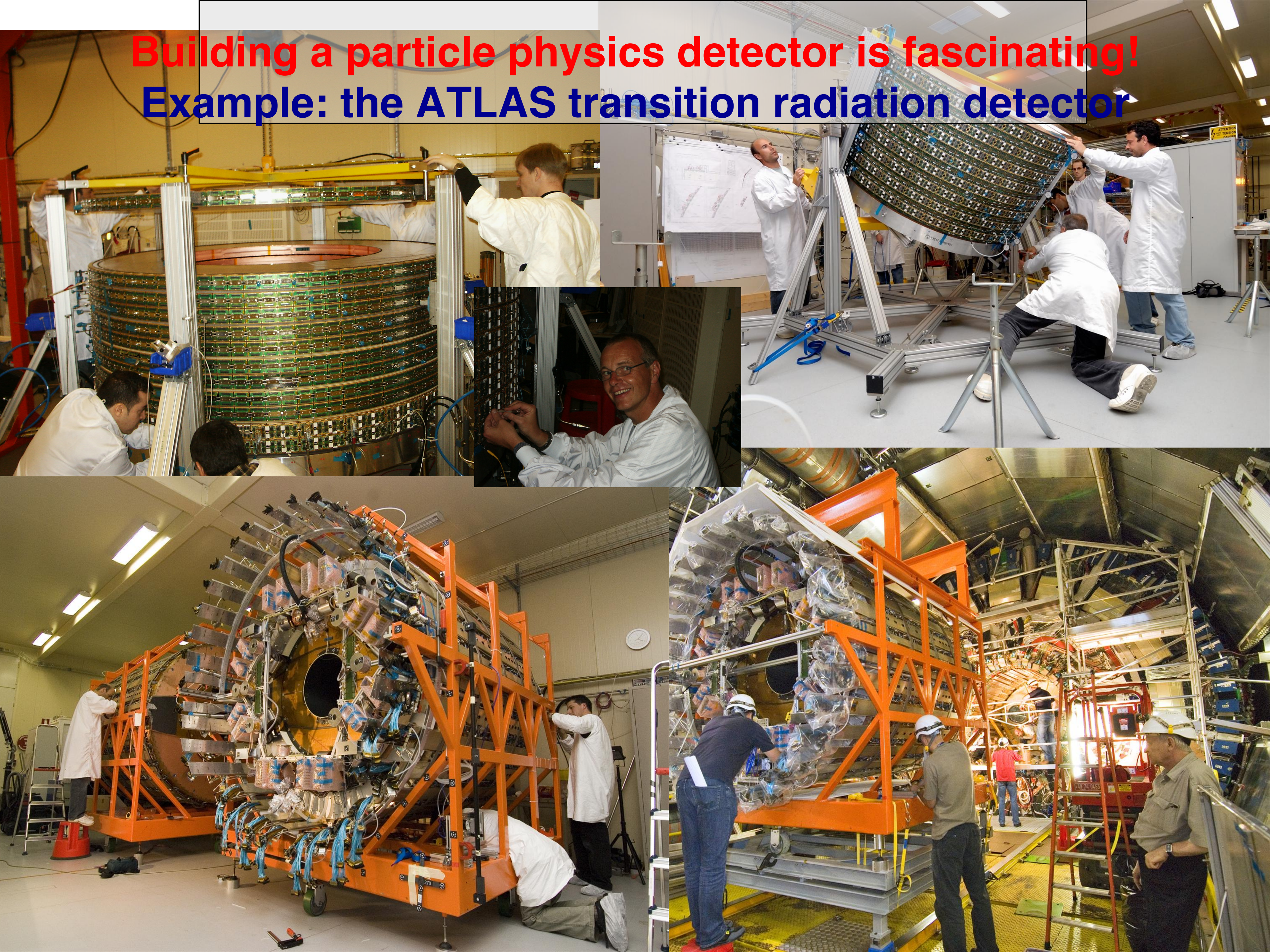
Building a particle physics detector is fascinating!

Example: the ATLAS transition radiation detector



The operation of a particle physics experiment is fascinating!

Example: arrival of the first proton beams in ATLAS in September 2008

What does the operation of an experiment at the LHC mean?

Analogy:

3D digital camera with 100 Megapixels built only once. It is its own prototype. It must survive in an environment close to that of the heart of a nuclear reactor (no commercial components allowed!)

- 40 million pictures per second (taken day and night, 24h/24h, 7 days a week). Each picture is taken in energy density conditions corresponding to those prevailing in the first moments of the life of our universe
- Amount of information: 10,000 encyclopedias per second
- First selection of pictures: 100,000 times per second
- The size of each picture is about 1 MByte
- Each picture is analysed by a worldwide network of about 50,000 processors
- Every second, the camera records on magnetic tape the 200-300 most interesting, which corresponds to 10 million GByte/year (or about three million DVDs/year)
- Each and every day, thousands of physicists look carefully time and time again at some of these pictures.

What do physicists do with their pictures?

Analogy with sport:

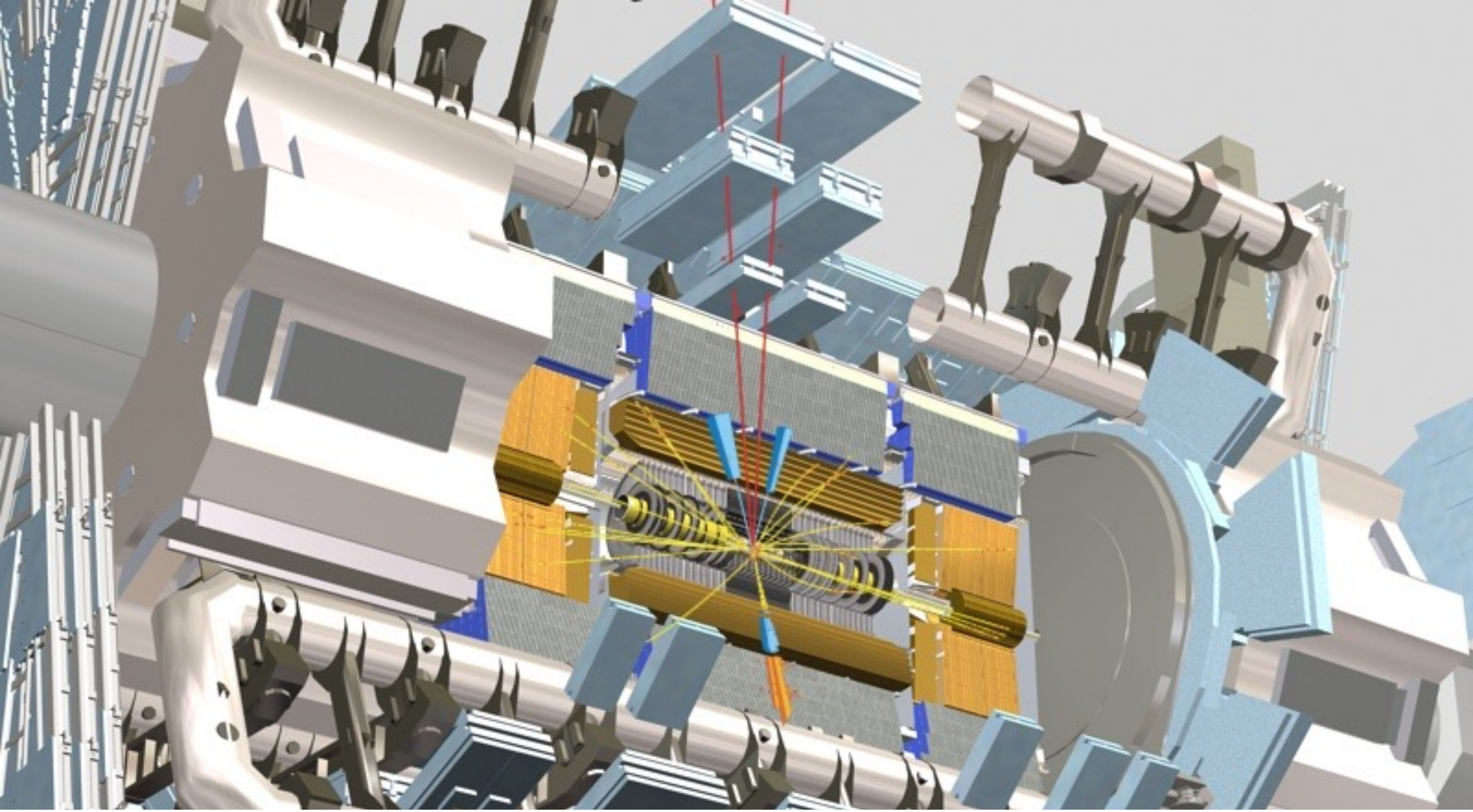
one can understand the rules of football by observing pictures

A good camera provides details by zooming in

By collecting many pictures,

one can find rare events and analyse them

In physics, one does not know who is the referee, nature plays this role and does not obey rules pre-established by us!



Data analysis and the search for the Higgs boson are indeed fascinating activities: our university education has prepared us for this more than for the 25 years of preparation!

Example (simulation): a Higgs boson decaying to two electrons and two muons in the ATLAS detector

Interlude: difference between simulation and reality

Simulation tools are vital components for the design, optimisation and construction of large instruments such as the LHC and its experiments:

- **simulations allow us to make precise predictions of the behaviour of our detectors**
- **simulations allow us to extrapolate from what we know today and to project ourselves towards unknown realms:**
    - **towards higher energies (from Chicago to CERN)**
    - **towards new physics searches (from the Standard Model to supersymmetry which may hold the keys to the dark matter problem)**

Now at last we have pictures of these new realms!

But not yet of new physics…
Patience and doubt are the names of the game.

What next?

Why this fear that experimental particle physics is an endangered species?

- The front-wave part of this field is becoming too big for easy continuity between the generations. I have been working on LHC for 25 years already. Most of the analysis will be done by young students and postdocs who have no idea what the 7000 tonnes of ATLAS is made of. More importantly, fewer and fewer people remember for example that initially most of the community did not believe tracking detectors would work at all at the LHC.
- The stakes are very high: one cannot afford unsuccessful experiments (shots in the dark) of large size, one cannot anymore approve the next machine before the current one has yielded some results and hopefully a path to follow
- Theory has not been challenged nor nourished by new experimental evidence for too long

This is why the challenge of the LHC and its experiments is so exhilarating! A major fraction of the future of our discipline hangs on the physics which will be harvested at this new energy frontier.

How ordinary or extraordinary will this harvest be? Only nature knows.

There is much more to experimental particle physics than its dinosaurs!

Generic features required of ATLAS and CMS

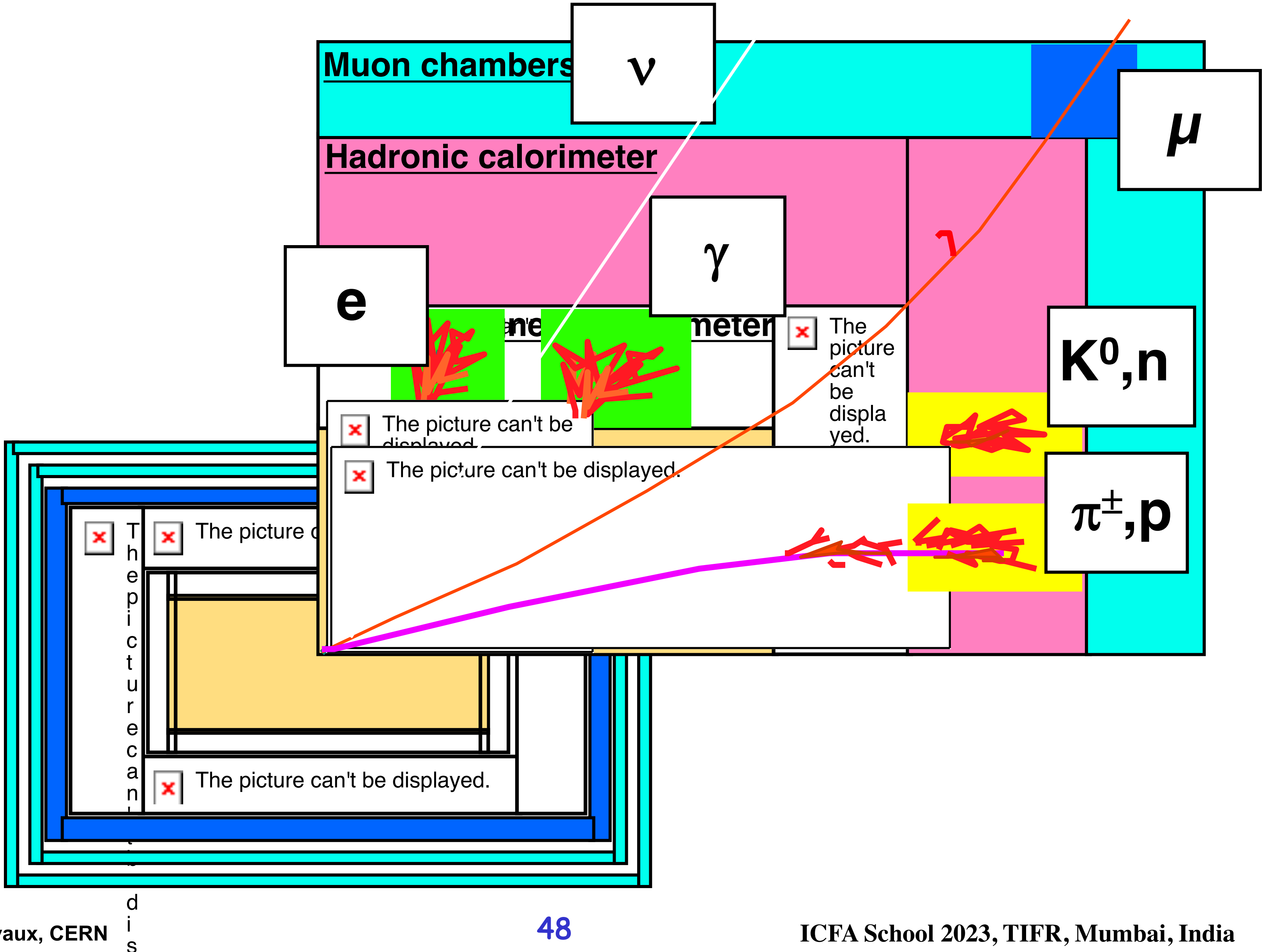
- Detectors must survive for 10 years or so of operation
  - Radiation damage to materials and electronics components
  - Problem pervades whole experimental area (neutrons): NEW!
- Detectors must provide precise timing and be as fast as feasible
  - 25 ns is the time interval to consider: NEW!
- Detectors must have excellent spatial granularity
  - Need to minimise pile-up effects: NEW!
- Detectors must identify extremely rare events, mostly in real time
  - Lepton identification above huge QCD backgrounds (e.g. e/jet ratio at the LHC is ~ 10^{-5}, i.e. ~ 100 worse than at Tevatron)
  - Signal X-sections as low as 10^{-14} of total X-section: NEW!
  - Online rejection to be achieved is ~ 10^{7}: NEW!
  - Store huge data volumes to disk/tape (~ 10^{9} events of 1 Mbyte size per year: NEW!

Generic features required of ATLAS and CMS

- Detectors must measure and identify according to certain specs
  - Tracking and vertexing: ttH with $H \to bb$
  - Electromagnetic calorimetry: $H \to \gamma\gamma$ and $H \to ZZ \to eeee$
  - Muon spectrometer: $H \to ZZ \to \mu\mu\mu\mu$
  - Missing transverse energy: supersymmetry, $H \to \tau\tau$
- Detectors must please
  - Collaboration: physics optimisation, technology choices
  - Funding agencies: affordable cost (originally set to 475 MCHF per experiment by CERN Council and management)
  - Young physicists who will provide the main thrust to the scientific output of the collaborations: how to minimise formal aspects? How to recognise individual contributions?

Review article on ATLAS and CMS as built (DF and P. Sphicas) at http://arjournals.annualreviews.org/eprint/HMcWjWGjGZHCFNgVvabI/full/10.1146/annurev.nucl.54.070103.181209 (in ARNPS)

Higgs at the LHC: the challenge



Physics at the LHC: the challenge

Small x-sections

need highest luminosity

$\Rightarrow$ $L = 10^{34-35}\ cm^{-2}s^{-1}$

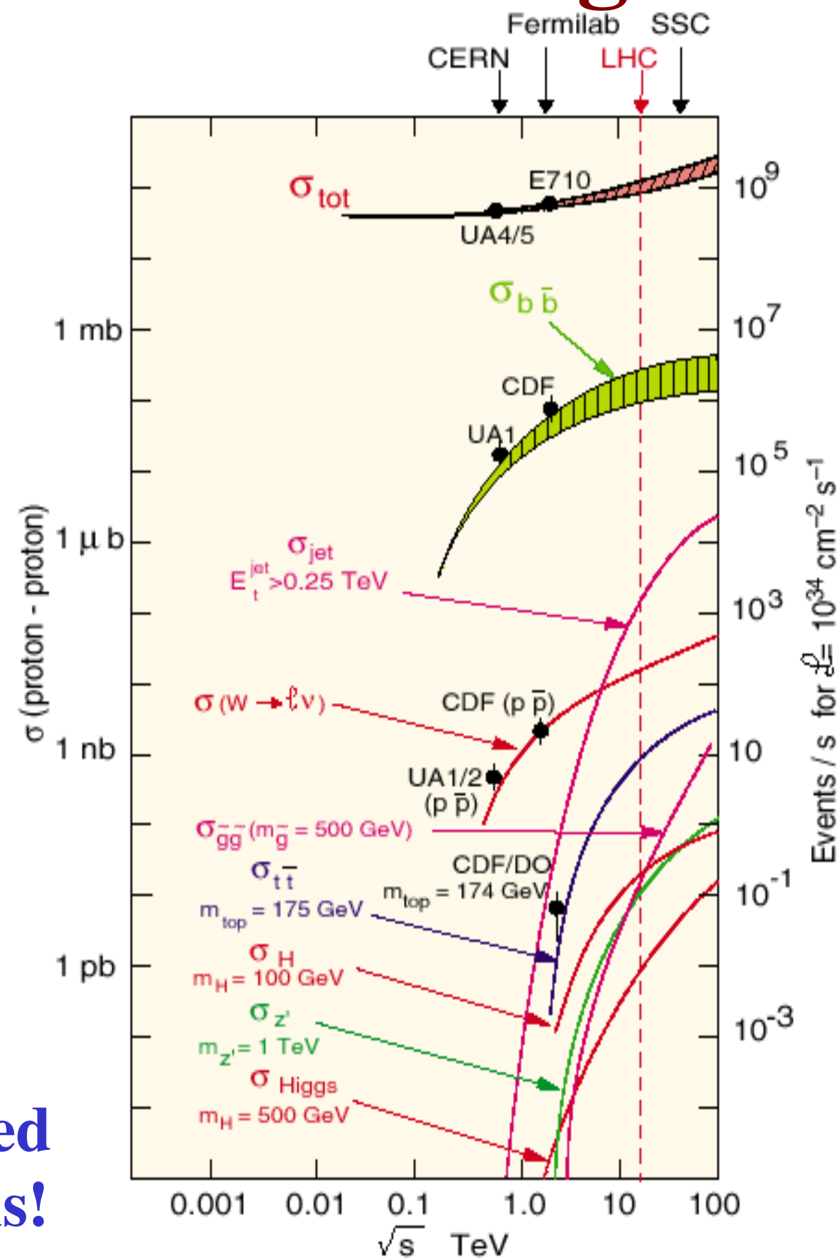
Orders of magnitude of event rates for various physics channels:

- Inelastic : 10^{10} Hz
- W -> lν : 10^{3} Hz
- tt production : 10^{2} Hz
- Higgs (m=100 GeV) : 1 Hz
- Higgs (m=600 GeV) : 10^{-1} Hz

(and include branching ratios: ~ 10^{-2})

Selection power for Higgs discovery ≈ 10^{14-15}

i.e. 100 000 times better than achieved at Tevatron so far for high-p_T leptons!



Physics at the LHC: the challenge

LHC is a "factory" for top, W/Z, Higgs, SUSY, black holes ...

Expected event rates for representative (known and new) physics processes at "low" luminosity ($L=10^{33}$ cm^{-2} s^{-1}) in ATLAS/CMS

Process	Events/s	Events for 10 fb^{-1} (one year)	Total statistics collected elsewhere by 2008 (?)
$W \to e\nu$	30	10^8	10^4 LEP / 10^7 Tevatron
$Z \to ee$	3	10^7	10^6 LEP
Top	2	10^7	10^4 Tevatron
Beauty	10^6	$10^{12} - 10^{13}$	10^9 Belle/BaBar
H (m=130 GeV)	0.04	10^5	
Gluino (m= 1 TeV)	0.002	10^4	
Black holes m > 3 TeV	0.0002	10^3	

Physics at the LHC: the environment

What do we mean by particle reconstruction and identification at LHC?

Elementary constituents interact as such in "hard processes", namely:

Quarks and leptons as matter particles, and

Leptons	e (0.0005)	μ (0.105)	τ (1.777)
	ν_e	ν_μ	ν_τ
Quarks	u (< 0.005)	c (~ 1.25)	t (~ 175)
	d (< 0.005)	s (~ 0.1)	b (~ 4.2)

Gluons and EW bosons as gauge particles

Gluon(0) Colour octet	Photon (0)	W^+,W^- (80.42)	Z (91.188)

All masses in GeV

Electrons, neutrinos and photons are the only rigorously stable particles in the zoo

At collider energies, muons can be considered as stable too

Some of the other particles are considered as long-lived (τ, c, b) meaning that their decay vertex may be measured by vertexing detector (requires excellent accuracy)

All other particles can only be seen through their stable decay products

Physics at the LHC: the environment

Which type of particles does one actually see in the final state?

LHC physics processes are dominated by strong interactions (QCD) :

- **hard processes:** quarks and gluons materialise as hadronic jets, which consist mostly of charged and neutral hadrons (pions, kaons, and to a lesser extent protons and neutrons, which at these energies can be all considered as stable). Jets will be discussed in lecture 4.
- **soft processes:** non-perturbative QCD processes with soft gluons materialising as almost uniform soup of charged and neutral pions, kaons, etc.

- Heavy quarks with "long" lifetime are produced abundantly also
- High-p_T (above ~ 10 GeV) leptons are produced mostly in c,b decays.
- High-p_T isolated leptons may be found in fraction of J/ψ and Y decays
- For p_T > 25 GeV, dominant source of high-p_T leptons: W/Z/tt decays

Main challenge at Tevatron and LHC: find e,γ,μ,τ,b amidst q/g soup

Physics at the LHC: the environment

What drives the luminosity at the LHC?

$L(\alpha=0) = 1.07\ 10^{-4}\ \ 1/\Delta t\ \ N^2\ E\ /\ \ \beta_e\ \ \varepsilon$, where:

- α is the crossing angle between the beams
- Δt is the time between bunch crossings, $\Delta t = 25$ ns
- N is the number of protons per bunch, $N = 10^{11}$
- E is the energy per beam, E = 7 TeV
- β_e is the β-function at the interaction point, $\beta_e = 0.5$ m
- ε is the normalised emittance, $\varepsilon = 15\pi\ 10^{-6}$ m.rad

Physics at the LHC: the environment

Extract number of inelastic collisions per bunch crossing

$$\langle n \rangle = \sigma_{inel} \times L \times \Delta t \; / \; \varepsilon_{bunch}$$

LHC: $\langle n \rangle = 70 \text{ mb} \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \times 25 \text{ ns} \; / \; 0.8 = 23$

Big change compared to recent and current machines:

LEP:	$\Delta t = 22\ \mu s$	and	$\langle n \rangle \ll 1$
SppS:	$\Delta t = 3.3\ \mu s$	and	$\langle n \rangle \approx 3$
HERA:	$\Delta t = 96$ ns	and	$\langle n \rangle \ll 1$
Tevatron:	$\Delta t = 0.4\ \mu s$	and	$\langle n \rangle \approx 2$

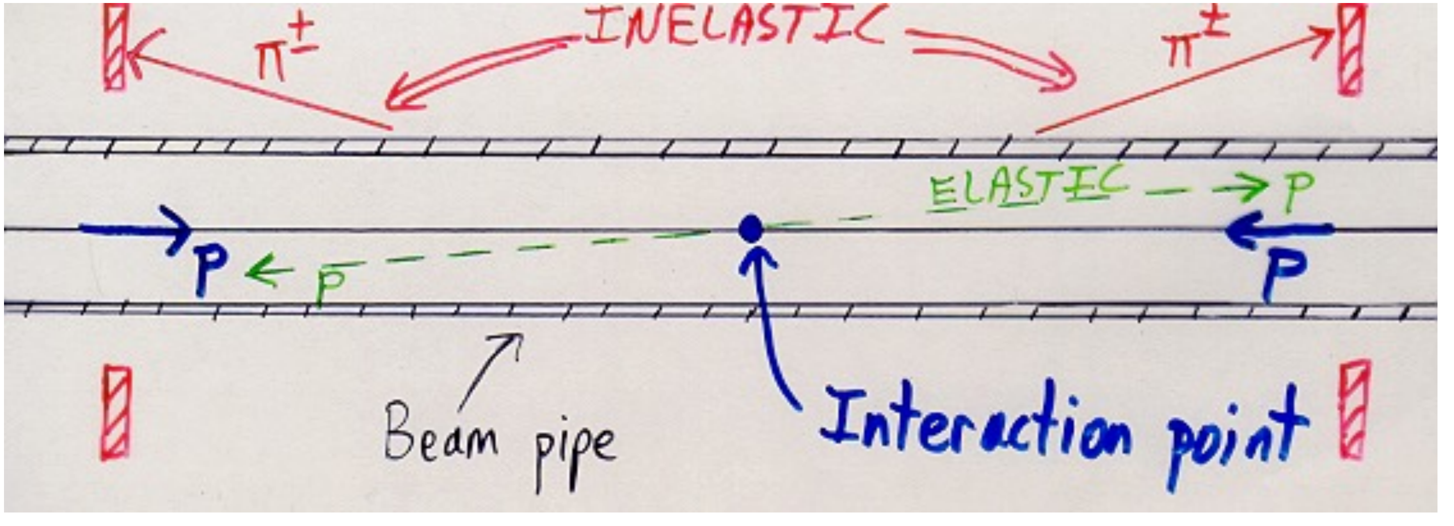
Physics at the LHC: the environment

Experimental environment ≡ Machine performance x Physics

Event rates in detectors:

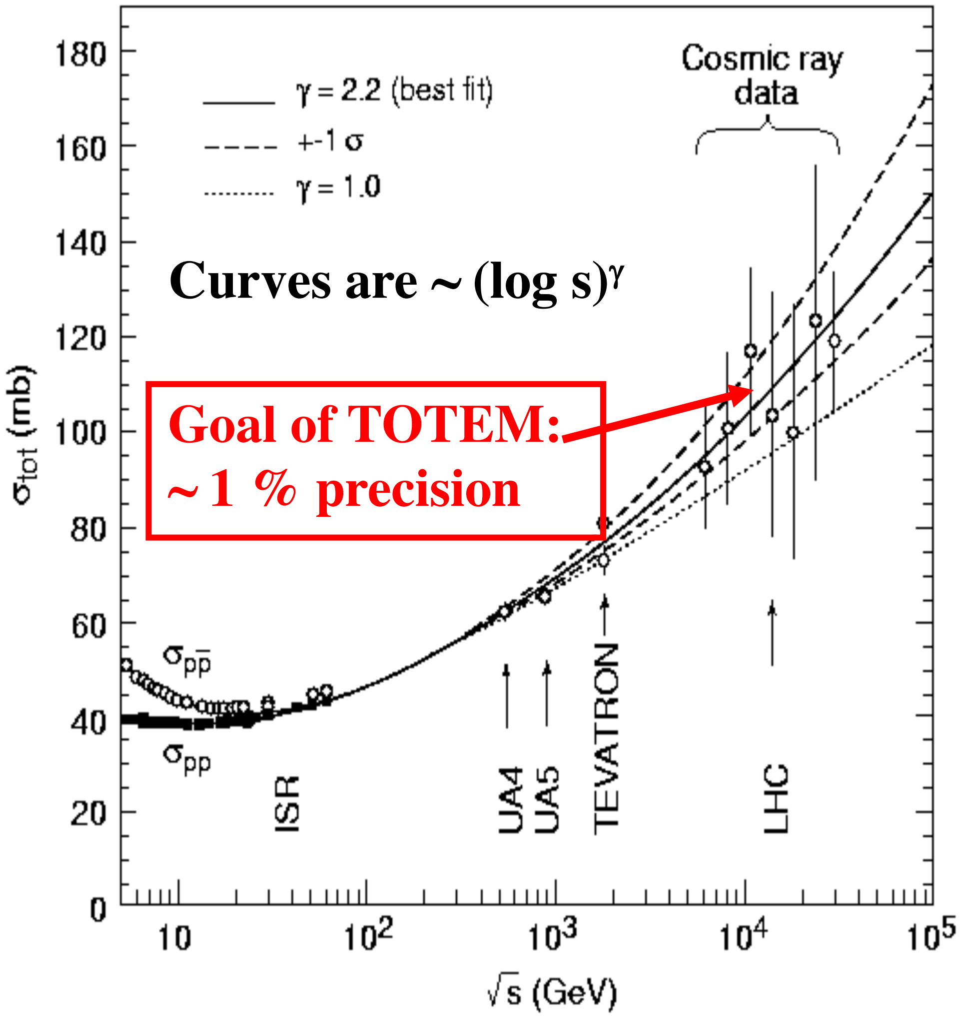
- number of charged tracks expected in inner tracking detectors
- energy expected to be deposited in calorimeters
- radiation doses expected (ionising and neutrons)
- event pile-up issues (pile-up in time and in space)

Need to know the cross-section for uninteresting pp inelastic events:
simple trigger on these ≡ "minimum bias" trigger

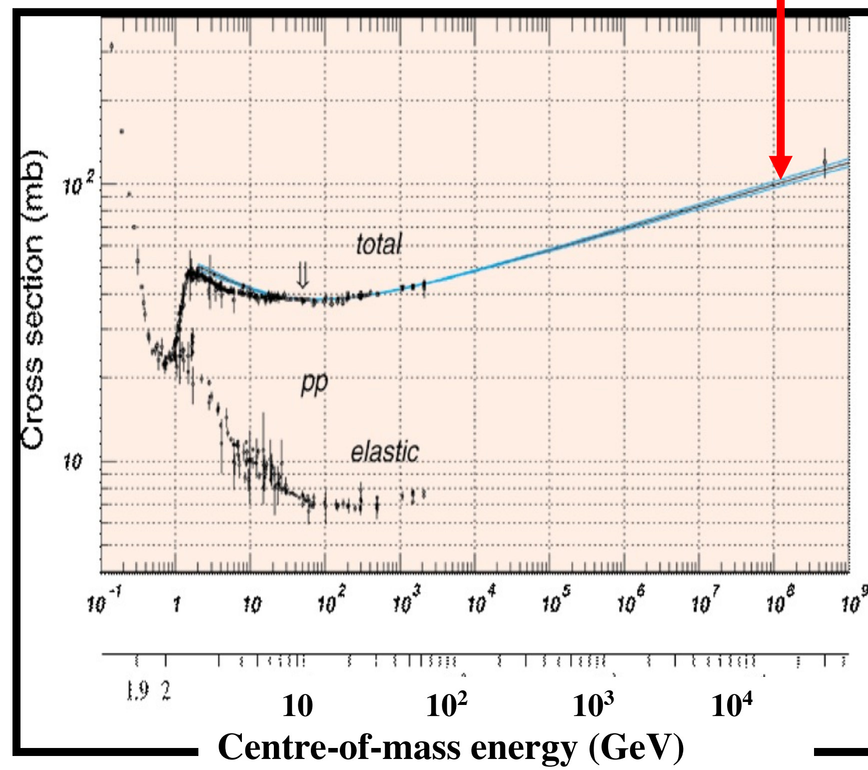


Physics at the LHC: the environment

Measurement of σ_{tot} (pp) and $\sigma_{inel} = \sigma_{tot} - \sigma_{el} - \sigma_{diff}$

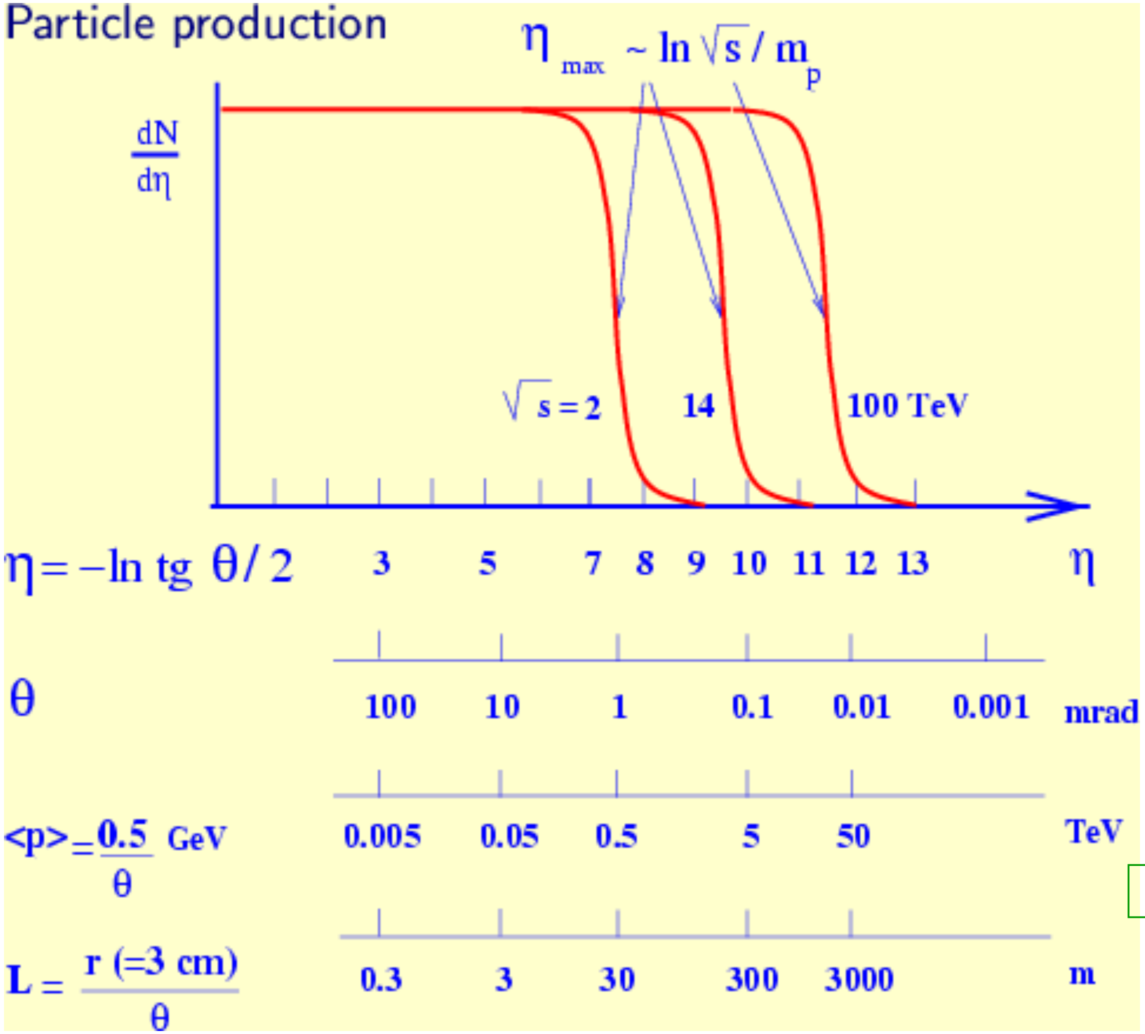


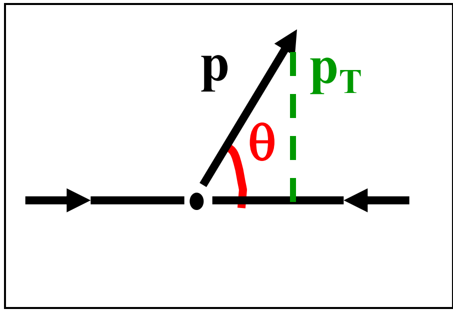
$\sigma_{tot}(pp) \approx 100$ mb



At the LHC, $\sigma_{inel} \approx 70$ mb

Physics at the LHC: the environment

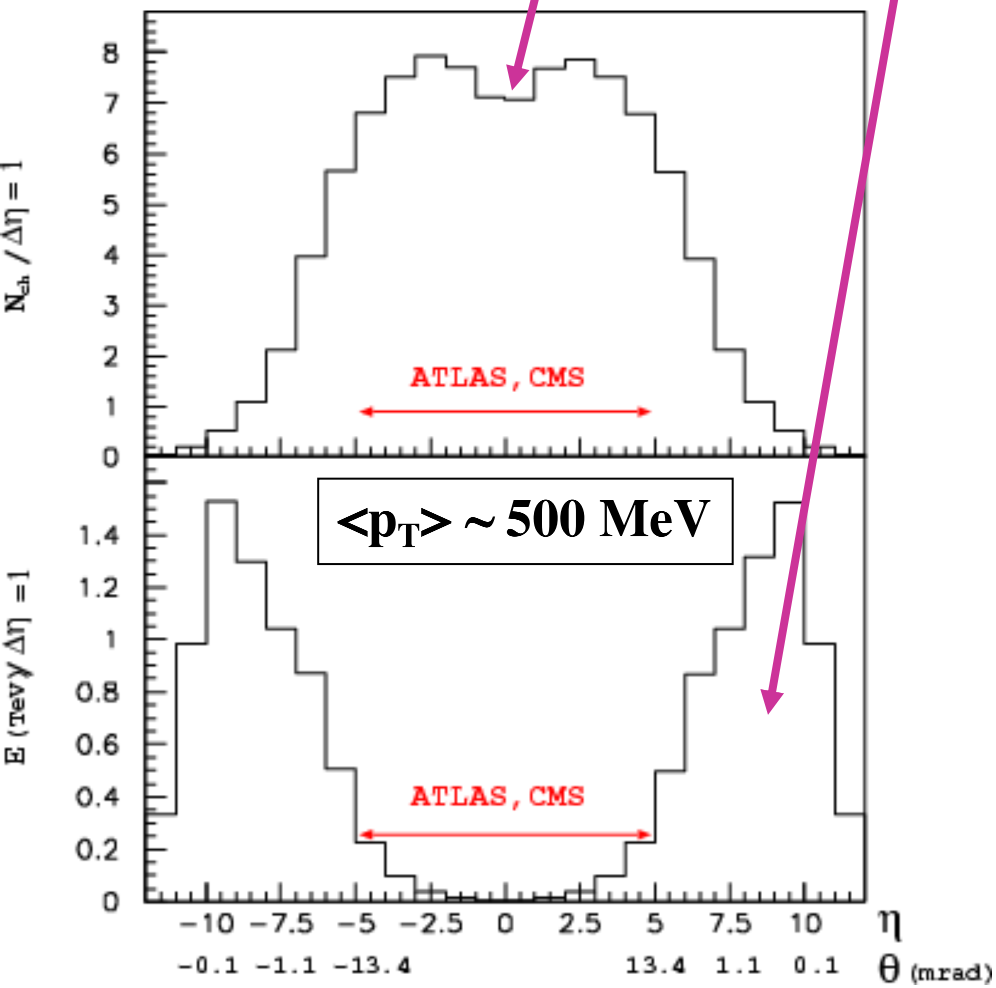




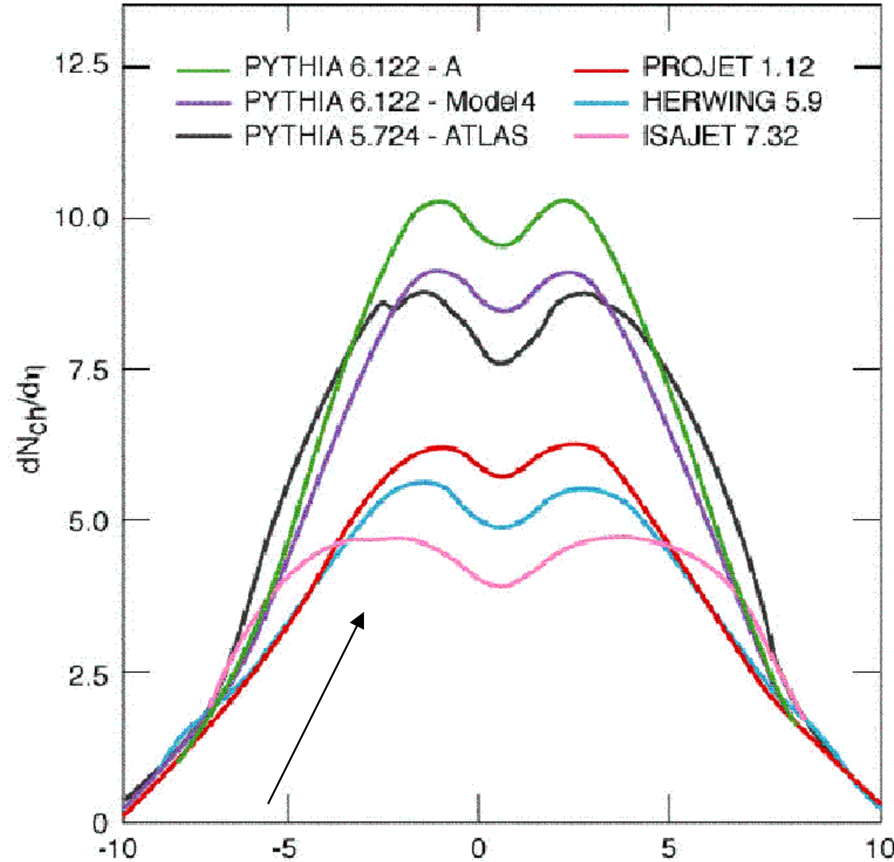
- $d\sigma/dp_T dy$ is Lorentz-invariant
- $\eta = y$ for $m \approx 0$
- Physics is ~ constant versus η at fixed p_T

Physics at the LHC: the environment

Charged particle multiplicity and energy in pp inelastic events at √s = 14 TeV

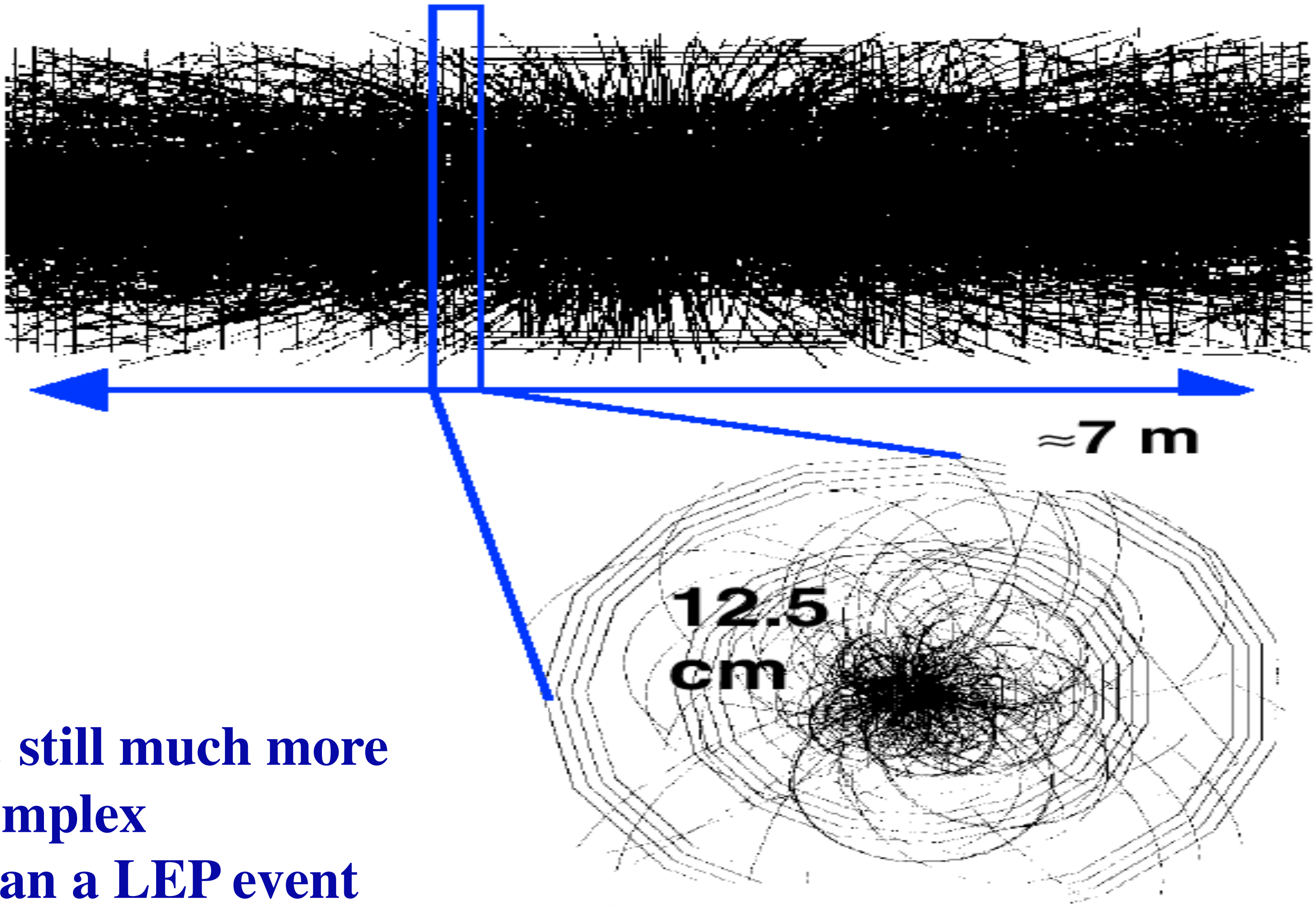


Charged particle multiplicities from different models



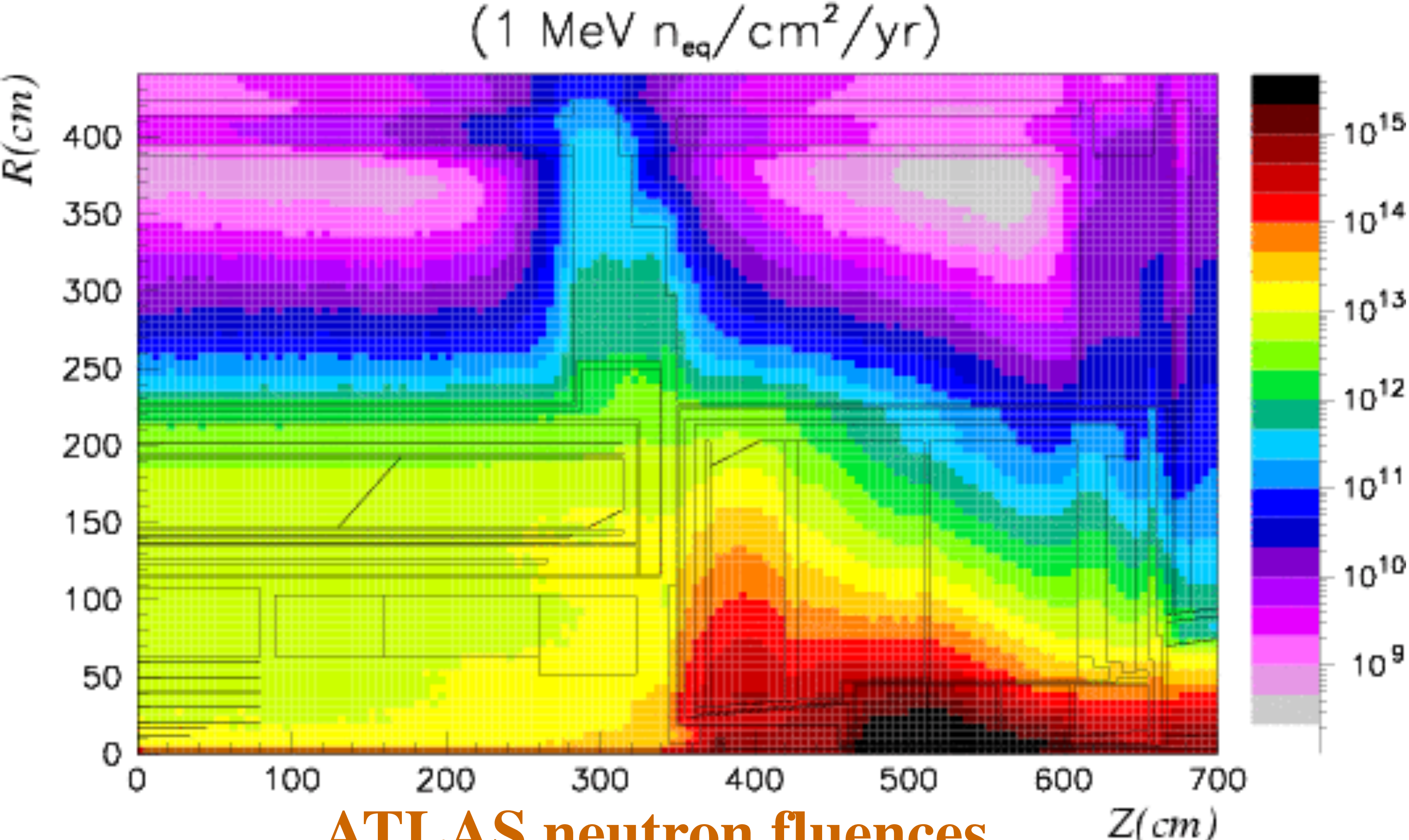
Present models extrapolated from Tevatron give sizeable differences at the LHC

Physics at the LHC: the environment



… still much more complex than a LEP event

Physics at the LHC: the environment



ATLAS neutron fluences

Physics at the LHC: the environment

1. Damage caused by ionising radiation

- caused by the energy deposited by particles in the detector material: ≈ 2 MeV g^{-1} cm^{-2} for a min. ion. particle
- also caused by photons created in electromagnetic showers
- the damage is proportional to the deposited energy or dose measured in Gy (Gray):
  - 1 Gy = 1 Joule / kg = 100 rads
  - 1 Gy = 3 10^9 particles per cm^2 of material with unit density

At LHC design luminosity, the ionising dose is:

$$\approx 2\ 10^6\ \mathrm{Gy} / r_T^2 / \mathrm{year},$$

where r_T (cm) is the transverse distance to the beam

Physics at the LHC: the environment

2. Damage caused by neutrons

- the neutrons are created in hadronic showers in the calorimeters and even more so in the forward shielding of the detectors and in the beam collimators themselves
- these neutrons (with energies in the 0.1 to 20 MeV range) bounce back and forth (like gas molecules) on the various nuclei and fill up the whole detector

- expected neutron fluence is about 3 10^{13} per cm^2 per year in the innermost part of the detectors (inner tracking systems)
- these fluences are moderated by the presence of Hydrogen:
  - ♦ σ(n,H) ~ 2 barns with elastic collisions
  - ♦ mean free path of neutrons is ~ 5 cm in this energy range
  - ♦ at each collision, neutron loses 50% of its energy (this number would be e.g. only 2% for iron)

Physics at the LHC: the environment

- the neutrons wreak havoc in semiconductors, independently of the deposited energy, because they modify directly the cristalline structure
  $\rightarrow$ need radiation-hard electronics (military applications only in the early R&D days)
  - off-the-shelf electronics usually dies out for doses above 100 Gy and fluences above 10^{13} neutrons/cm^2
  - rad-hard electronics (especially deep-submicron) can survive up to 10^5-10^6 Gy and 10^{15} neutrons/cm^2

- most organic materials survive easily to 10^5-10^6 Gy (beware!)

$\Downarrow$

Material validation and quality control during production are needed at the same level as for spatial applications!!

Physics at the LHC: the environment

Pile-up effects at high luminosity

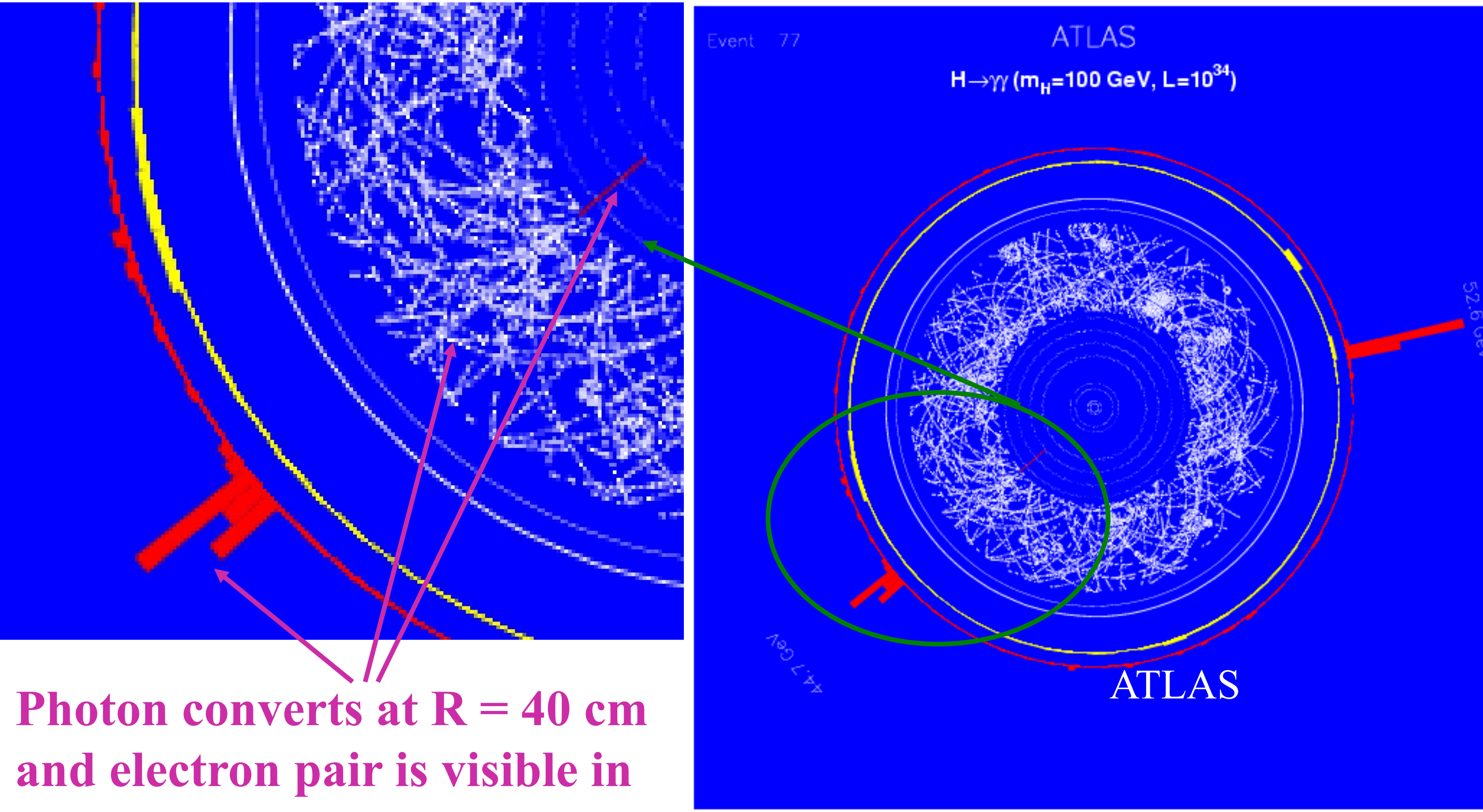
Pile-up is the name given to the impact of the 23 uninteresting (usually) interactions occurring in the same bunch crossing as the hard-scattering process which generally triggers the apparatus

Minimising the impact of pile-up on the detector performance has been one of the driving requirements on the initial detector design:

- a precise (and if possible fast) detector response minimises pile-up in time
  - → very challenging for the electronics in particular
  - → typical response times achieved are 20-50 ns (!)
- a highly granular detector minimises pile-up in space
  - → large number of channels (100 million pixels, 200,000 cells in electromagnetic calorimeter)

Physics at the LHC: the environment

Pile-up effects at high luminosity



Photon converts at R = 40 cm and electron pair is visible in ATLAS TRT and EM calo