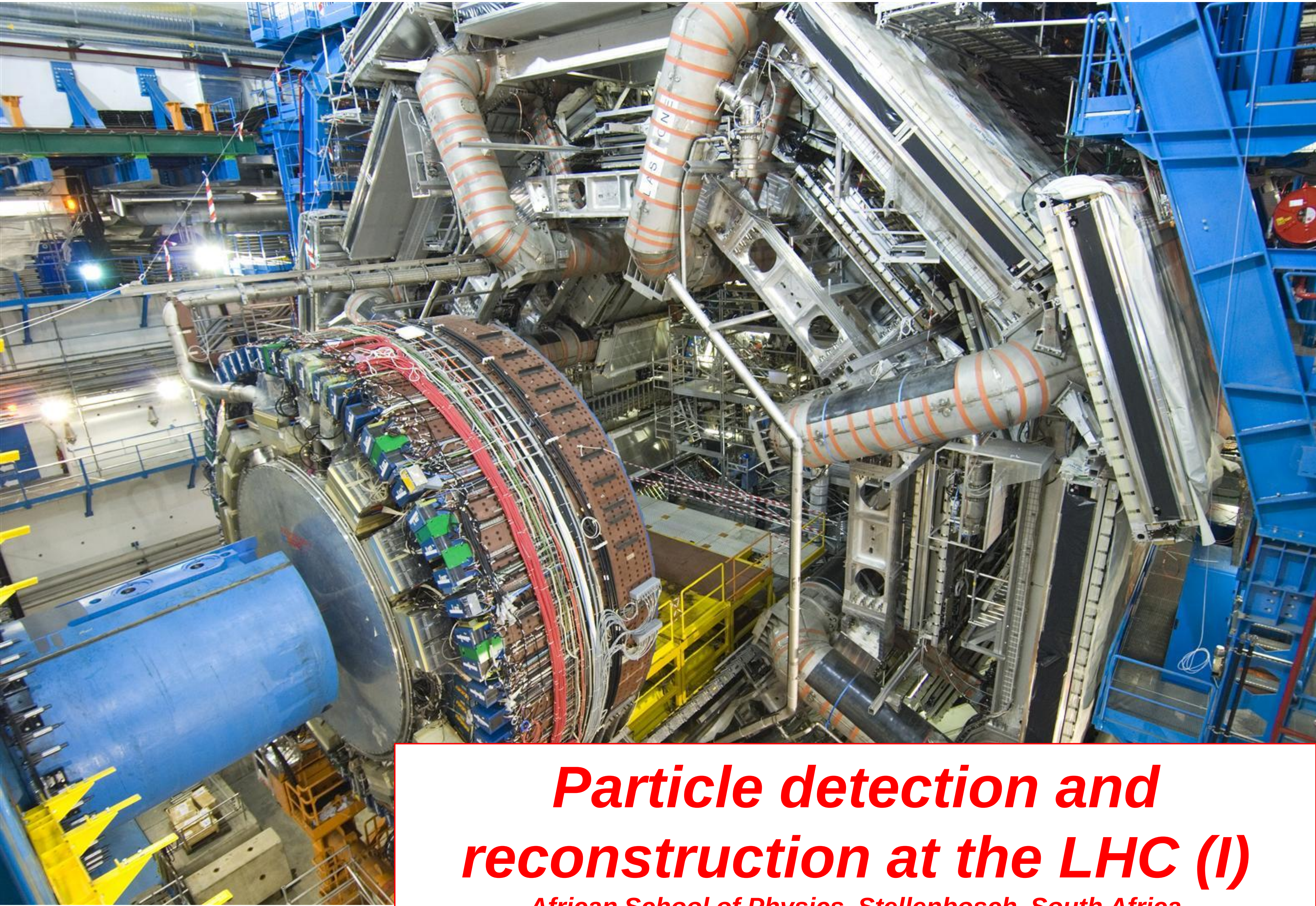


# Particle detection and reconstruction at the LHC (I)

*African School of Physics, Stellenbosch, South Africa*
*August 2010 (D. Froidevaux, CERN)*

# Particle detection and reconstruction at the LHC (and Tevatron)

## Lecture 1

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

## Lecture 2

- Detector techniques: tracking

## Lecture 3

- Detector techniques: calorimetry
- Detector techniques: trigger overview

# 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.

# On Tools and Instrumentation

"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**

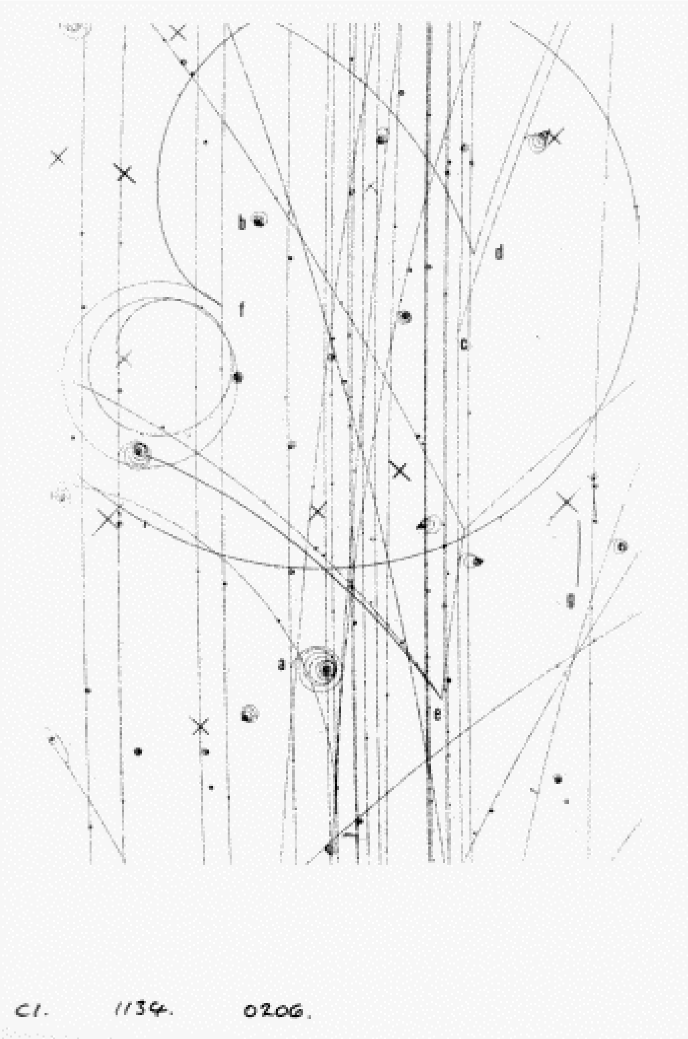
→ New tools and technologies will hopefully lead to exciting discoveries at the LHC

# Physics Nobel Prices 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

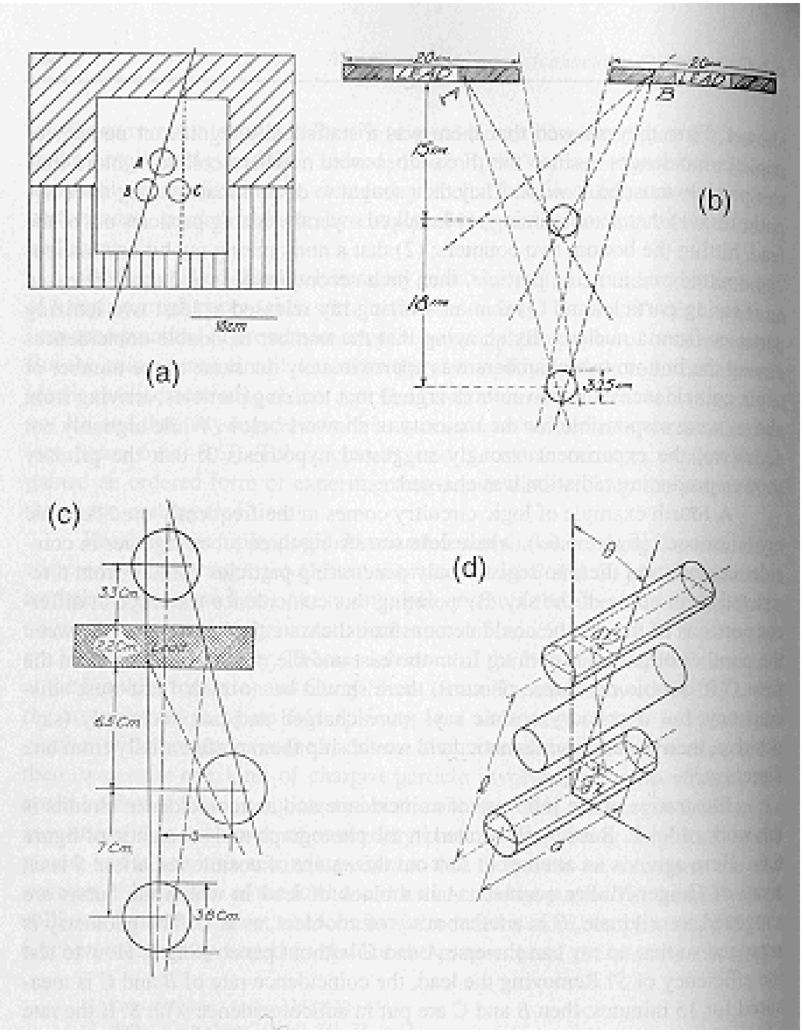
# History of Instrumentation

## Image Detectors



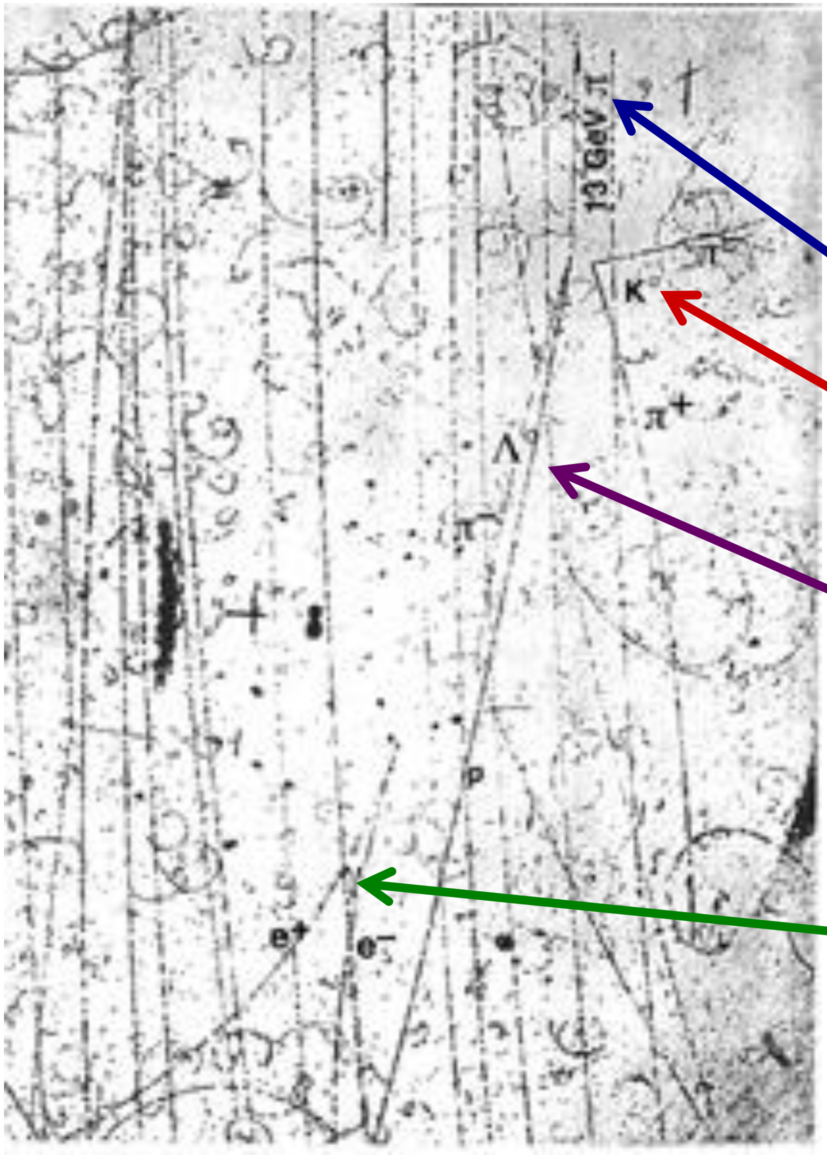
**Bubble chamber photograph**

## ‘Logic (electronics) Detectors ’



**Early coincidence counting experiment**

# Bubble Chamber



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

Picture:

A propane chamber with a magnet discovered the $\Sigma^\circ$ in 1956.

A 1300 MeV negative pion hits a proton to produce a neutral kaon (decaying to $\pi^+\pi^-$ )and a $\Sigma^\circ$, decaying into a $\Lambda^\circ$ and a photon. The $\Lambda^0$ decays into a proton and a pion The photon converts into an electron-positron pair.

# 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 laborious task in the past.**

**This explains why electronic detectors took over in the 70ies.**

# 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.

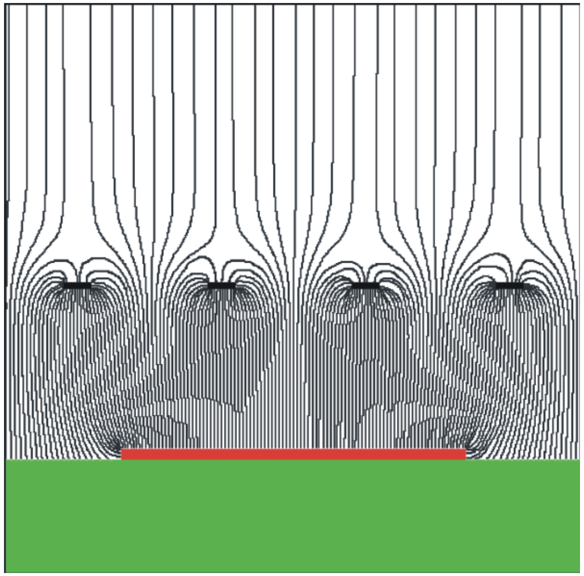
Thanks to the huge available computing power, detectors can be simulated to within 5-10% of reality, based on a very precise description of:

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

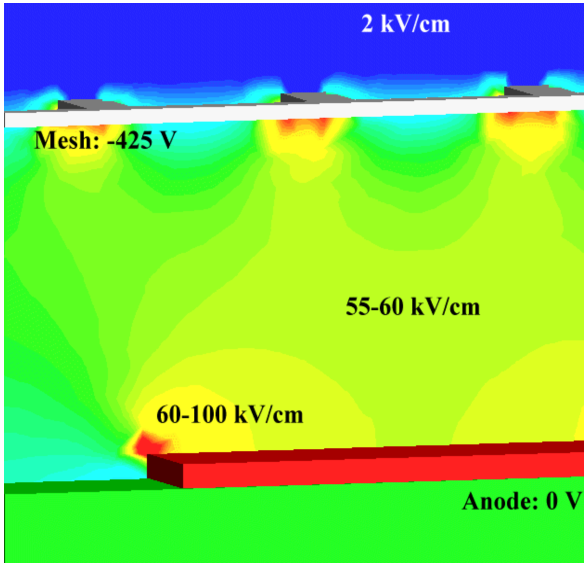


Very accurate simulations of particle detectors are possible due to availability of Finite Element simulation programs and computing power.

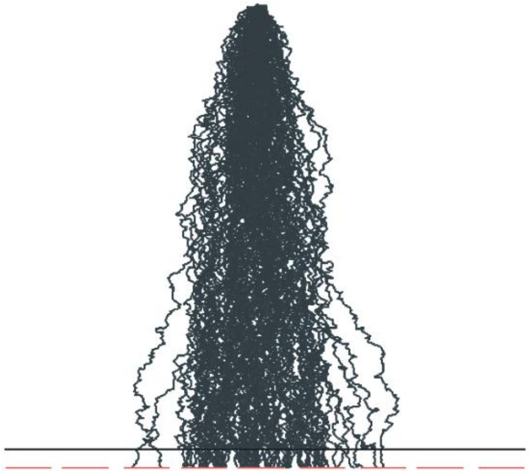
Follow every single electron by applying first principle laws of physics.

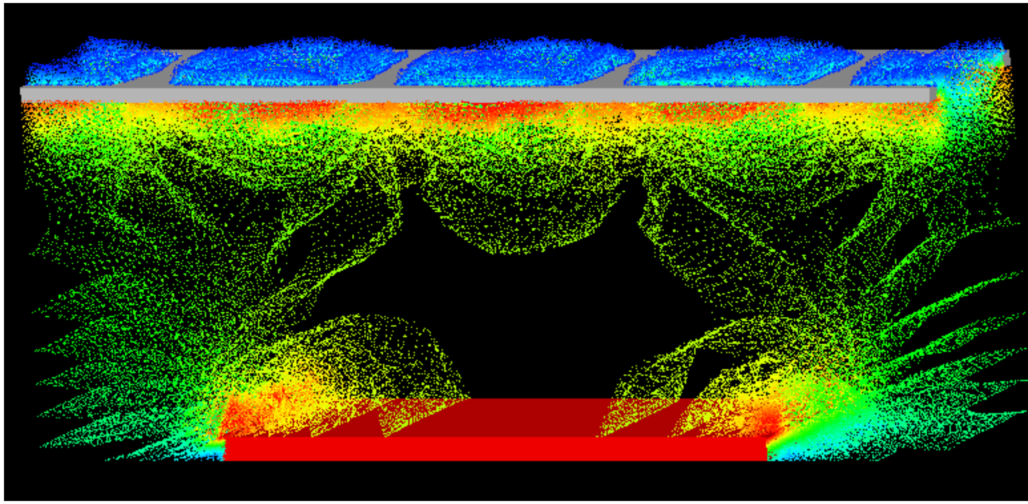
For gaseous detectors:
GARFIELD by R. Veenhof

Electric Fields in a Micromegas Detector



Electron avalanche multiplication





# Particle Detector Simulation

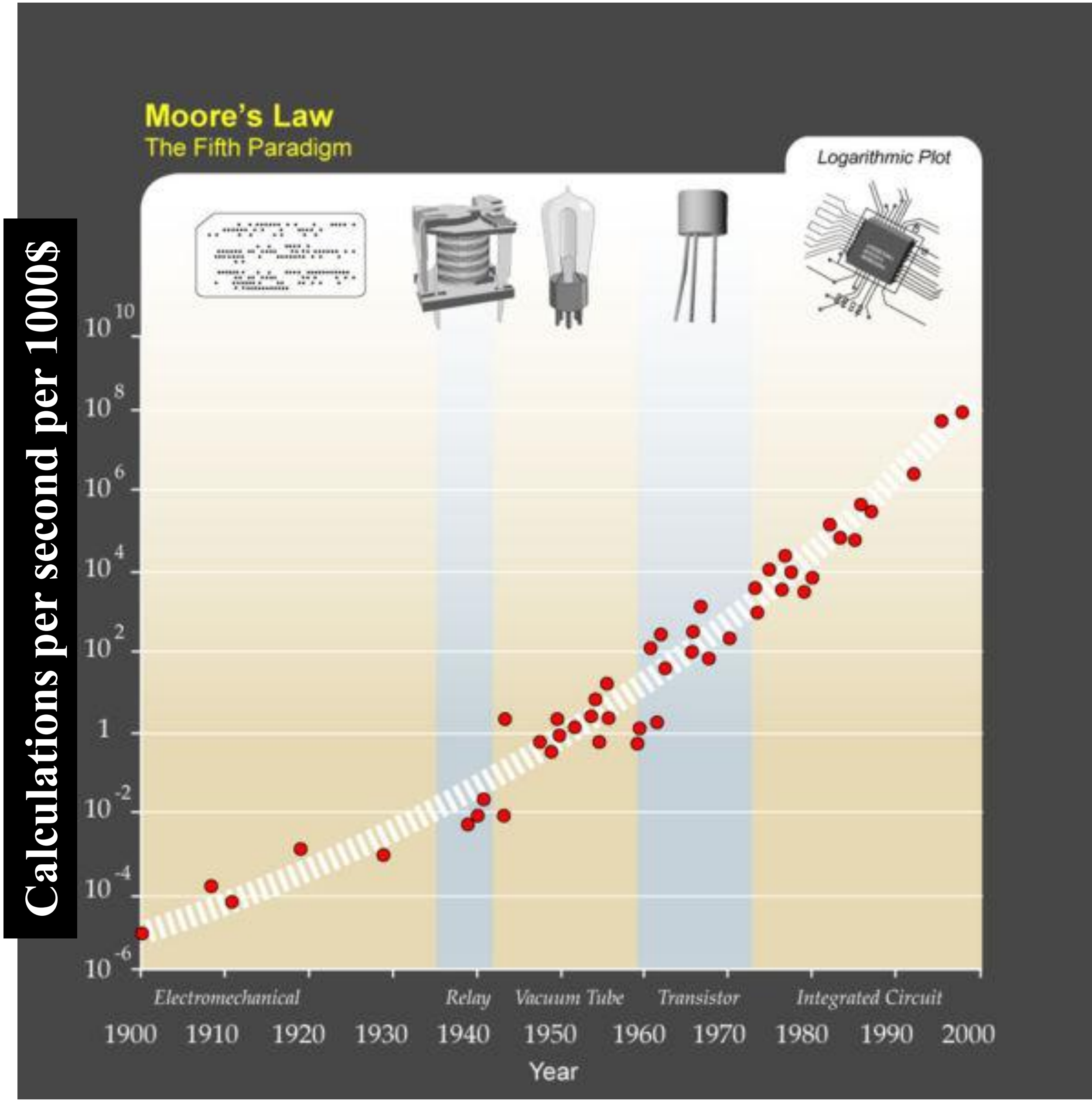
## I) C. Moore's Law:

**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 (I believe it would 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.

# 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.

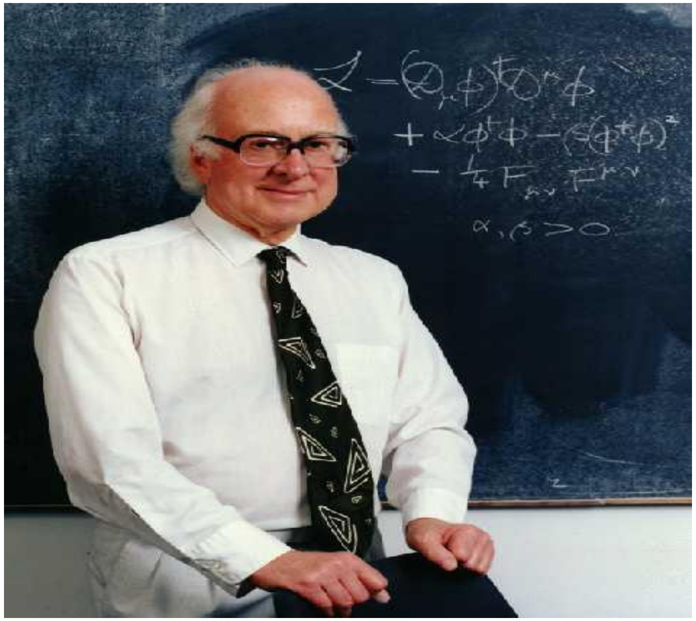
How ordinary or extraordinary will this harvest be? Only nature knows.

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

# Historical introduction

**Higgs boson has been with us for several 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

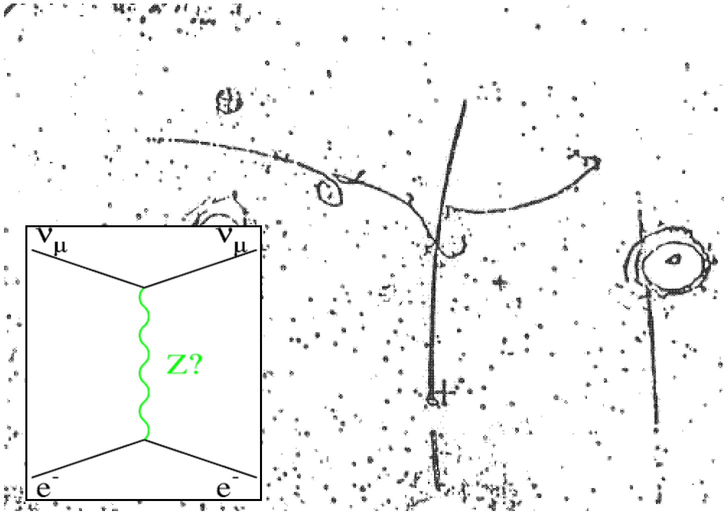
Only unambiguous example of observed Higgs
(apologies to ALEPH collab.)

# Historical introduction

**1964:** First formulation of Higgs mechanism (P.W.Higgs)

**1967:** Electroweak unification, with W, Z and H (Glashow, Weinberg, Salam)

**1973:** Discovery of neutral currents in $\nu_\mu e$ scattering (Gargamelle, CERN)



**1974:** Complete formulation of the standard model with $SU(2)_W \times U(1)_Y$ (Iliopoulos)

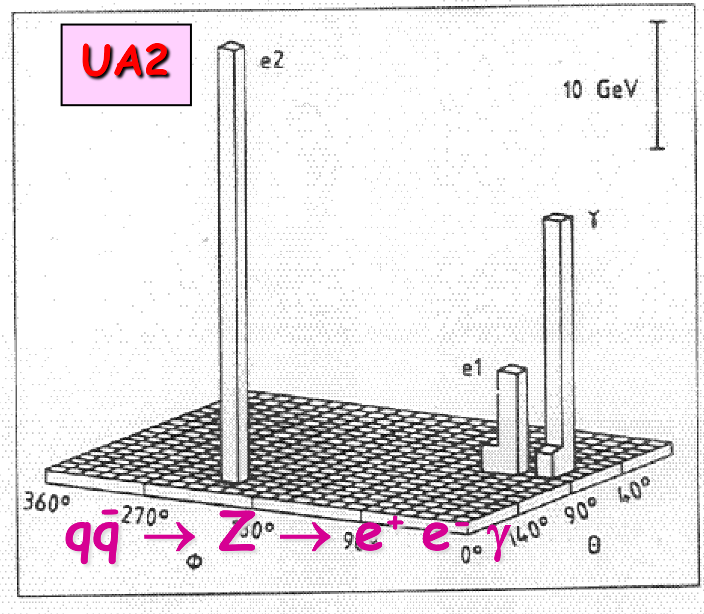
**1981:** The CERN SpS becomes a proton-antiproton collider

LEP and SLC are approved before W/Z boson discovery

**1983:** LEP and SLC construction starts

W and Z discovery (UA1, UA2)

One of the first Z-bosons detected in the world



$q\bar{q} \to Z \to e^+ e^- \gamma$

# Historical introduction

**1984:** Glimmerings of LHC and SSC

**1987:** First comparative studies of physics potential of hadron colliders (LHC/SSC) and $e^+e^-$ linear colliders (CLIC)

**1989:** First collisions in LEP and SLC

Precision tests of the SM and search for the Higgs boson begin in earnest

R&D for LHC detectors begins

**1993:** Demise of the SSC

**1994:** LHC machine is approved (start in 2005)

**1995:** Discovery of the top quark at Fermilab by CDF (and D0)

Precision tests of the SM and search for the Higgs boson continue at LEP2

Approval of ATLAS and CMS

**2000:** End of LEP running

**2001:** LHC schedule delayed by two more years

During the last 13 years, three parallel activities have been ongoing, all with impressive results:

1) Physics at LEP with a wonderful machine
2) Construction of the LHC machine
3) Construction of the LHC detectors after an initial very long R&D period

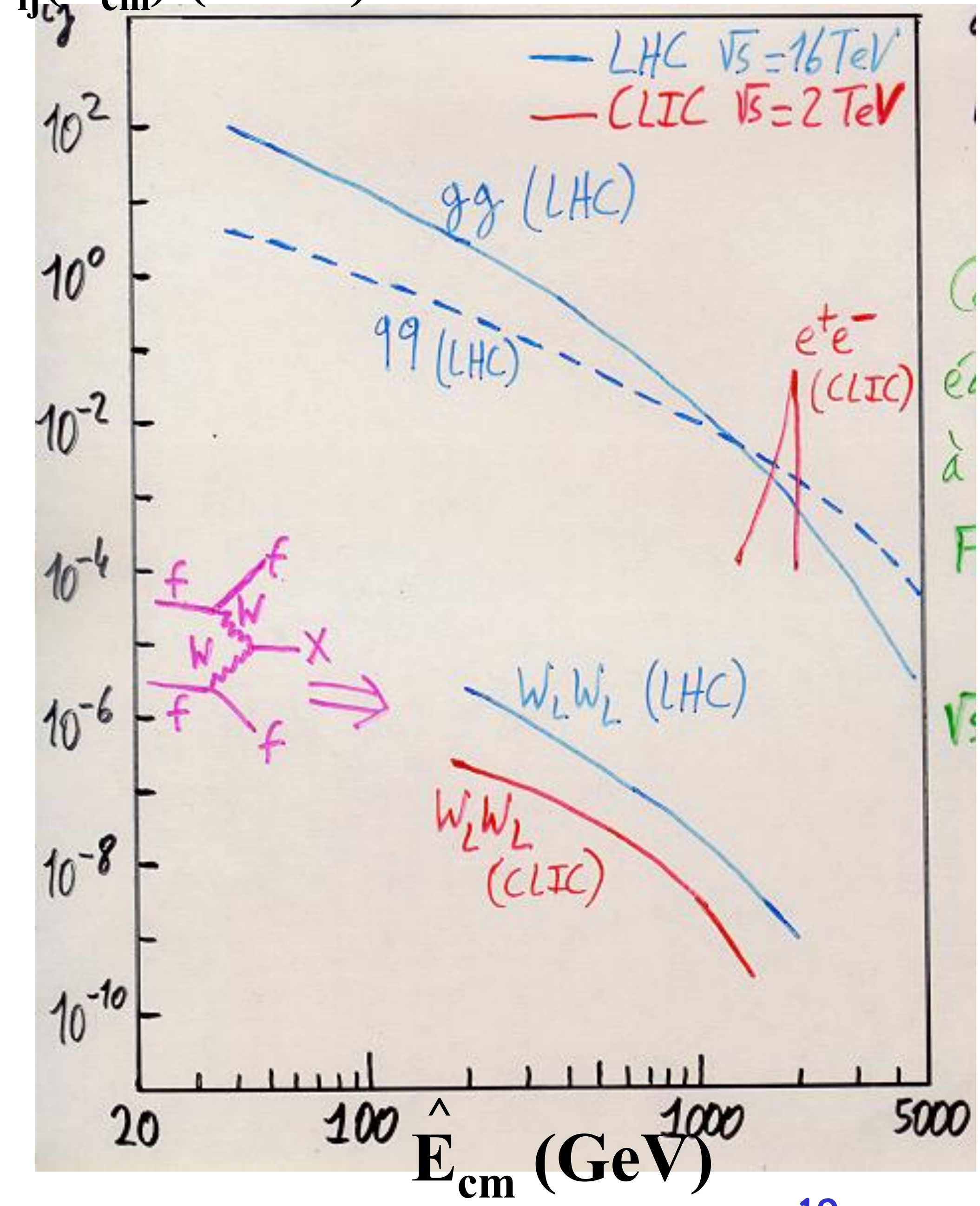
# Historical introduction

**What has been the evolution of our HEP culture over these past 30 years?**

1. **In the 70-80's, the dogma was that $e^+e^-$ physics was the only way to do clean and precise measurements and even discoveries (hadron physics were dirty).**

2. **With the advent of high-energy colliders, the 80-90's have demonstrated that:**
   - **Most discoveries have occurred in hadronic machines**
   - **Unprecedented precision has been reached in electroweak measurements at LEP with state-of-the-art detectors**
     ➚ **remember the first time ALEPH announced that luminosity could be measured to 0.1%!**
   - **Hadronic colliders can rival with the $e^+e^-$ machines in certain areas of precision measurements**
     ➚ **remember the almost simultaneous publication of the Z-mass measurements from CDF and SLC with comparable precision (200 MeV!)**
     ➚ **even with Run I (100 $pb^{-1}$), CDF has been able to compete with LEP in the field of B-physics**

# Historical introduction



Parton luminosities $F_{ij}(\hat{E}_{cm})$

where $\hat{E}_{cm}$ is the centre-of-mass energy of two "partons" i and j,

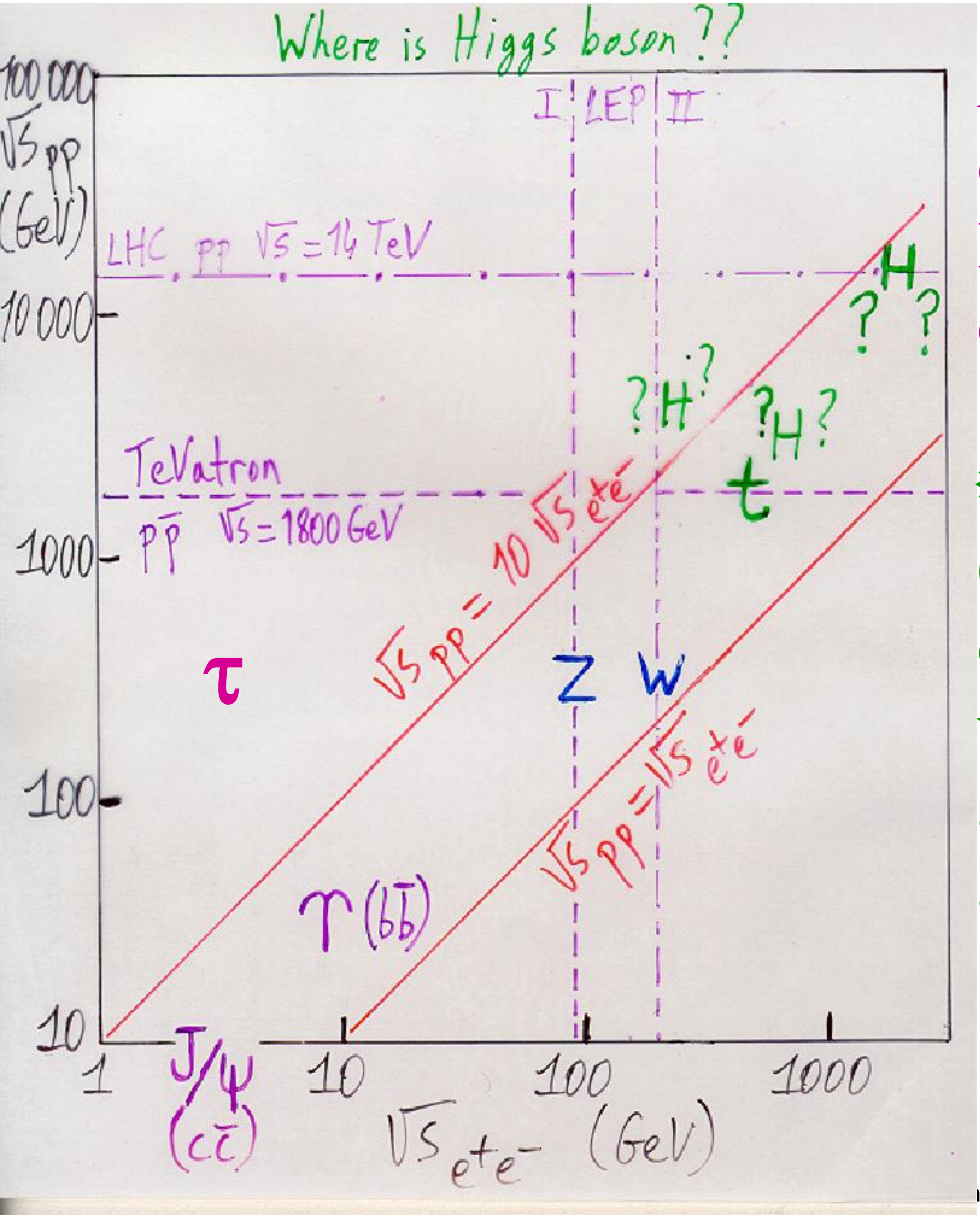
are useful to compare intrinsic potential of different machines

**Important to note that:**

1. as centre-of-mass energy grows, processes without beam-energy constraint such as vector-boson fusion become also important at $e^+e^-$ machines;
2. Proton-proton collisions are equivalent to $e^+e^-$ collisions for

$$\sqrt{s}_{pp} \approx 5\,\sqrt{s}_{e+e-}$$

# Historical introduction



All particles in plot were discovered first at hadron machines with one notable exception:

- the τ-lepton was (and could have been) observed only in vector-boson decays at the CERN proton-antiproton collider.

# 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 (see lectures by A. Yagil)
  - 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 (early 2009?)
- Size of collaboration
- Number of meetings and Powerpoint slides to browse through

# *ATLAS Collaboration*

(As of ~ 2009)

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

+

since July 2nd 2010!

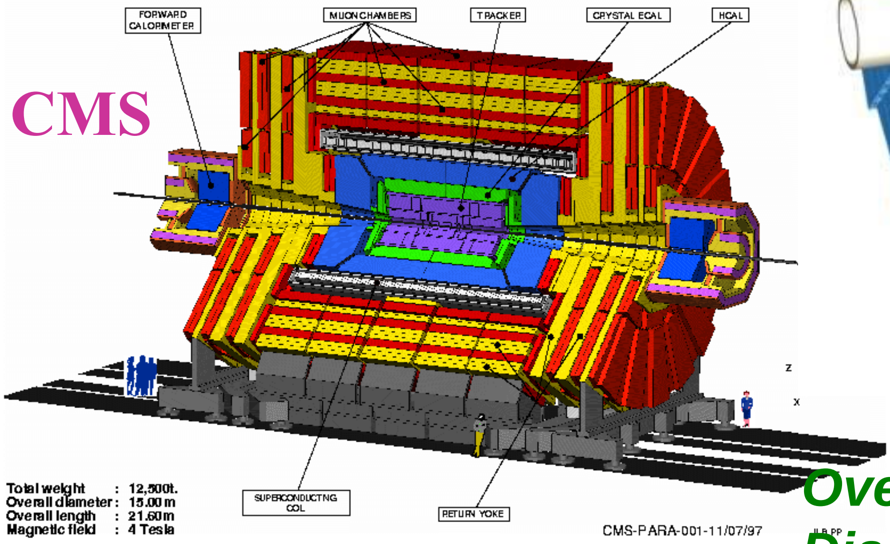
- Argentina
- Armenia
- Australia
- Austria
- Azerbaijan
- Belarus
- Brazil
- Canada
- China
- Czech Republic
- Denmark
- France
- Georgia
- Germany
- Greece
- Israel
- Italy
- Japan
- Morocco
- Netherlands
- Norway
- Poland
- Portugal
- Romania
- Russia
- Serbia
- Slovakia
- Slovenia
- Spain
- Sweden
- Switzerland
- Taiwan
- Turkey
- UK
- USA
- CERN
- JINR

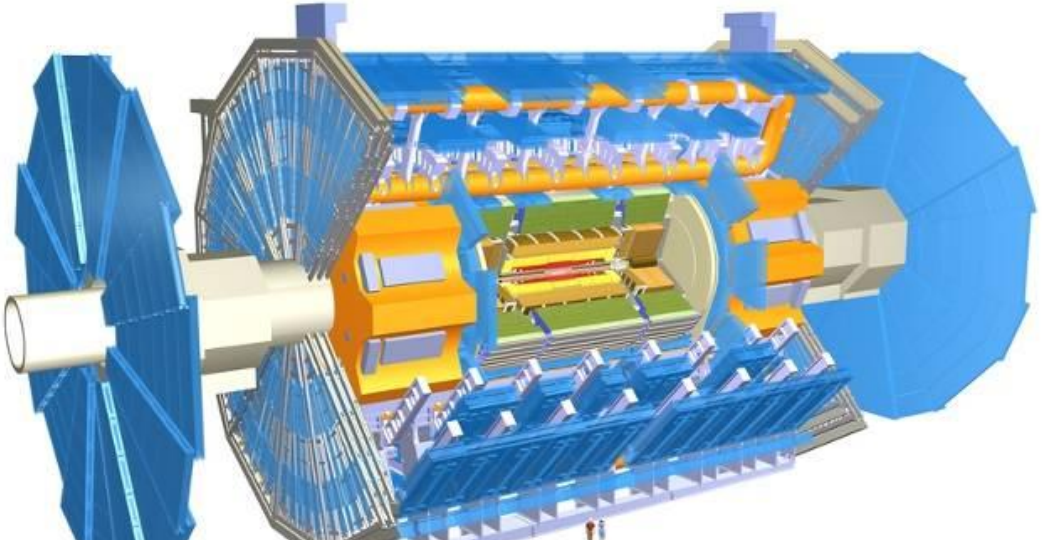
**Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizona, UT Arlington, Athens, NTU Athens, Baku, IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, Bern, Birmingham, Bologna, Bonn, Boston, Brandeis, Bratislava/SAS Kosice, Brookhaven NL, Buenos Aires, Bucharest, Cambridge, Carleton, Casablanca/Rabat, CERN, Chinese Cluster, Chicago, Clermont-Ferrand, Columbia, NBI Copenhagen, Cosenza, AGH UST Cracow, IFJ PAN Cracow, DESY, Dortmund, TU Dresden, JINR Dubna, Duke, Frascati, Freiburg, Geneva, Genoa, Giessen, Glasgow, LPSC Grenoble, Technion Haifa, Hampton, Harvard, Heidelberg, Hiroshima, Hiroshima IT, Humboldt U Berlin, Indiana, Innsbruck, Iowa SU, Irvine UC, Istanbul Bogazici, KEK, Kobe, Kyoto, Kyoto UE, Lancaster, UN La Plata, Lecce, Lisbon LIP, Liverpool, Ljubljana, QMW London, RHBNC London, UC London, Lund, UA Madrid, Mainz, Manchester, Mannheim, CPPM Marseille, Massachusetts, MIT, Melbourne, Michigan, Michigan SU, Milano, Minsk NAS, Minsk NCPHEP, Montreal, McGill Montreal, FIAN Moscow, ITEP Moscow, MEPhI Moscow, MSU Moscow, Munich LMU, MPI Munich, Nagasaki IAS, Naples, Naruto UE, New Mexico, New York U, Nijmegen, BINP Novosibirsk, Ohio SU, Okayama, Oklahoma, Oklahoma SU, Oregon, LAL Orsay, Osaka, Oslo, Oxford, Paris VI and VII, Pavia, Pennsylvania, Pisa, Pittsburgh, CAS Prague, CU Prague, TU Prague, IHEP Protvino, Ritsumeikan, UFRJ Rio de Janeiro, Rochester, Rome I, Rome II, Rome III, Rutherford Appleton Laboratory, DAPNIA Saclay, Santa Cruz UC, Sheffield, Shinshu, Siegen, Simon Fraser Burnaby, Southern Methodist Dallas, NPI Petersburg, SLAC, Stockholm, KTH Stockholm, Stony Brook, Sydney, AS Taipei, Tbilisi, Tel Aviv, Thessaloniki, Tokyo ICEPP, Tokyo MU, Toronto, TRIUMF, Tsukuba, Tufts, Udine, Uppsala, Urbana UI, Valencia, UBC Vancouver, Victoria, Washington, Weizmann Rehovot, Wisconsin, Wuppertal, Yale, Yerevan**

# How huge are ATLAS and CMS?

ATLAS superimposed to the 5 floors of building 40

CMS

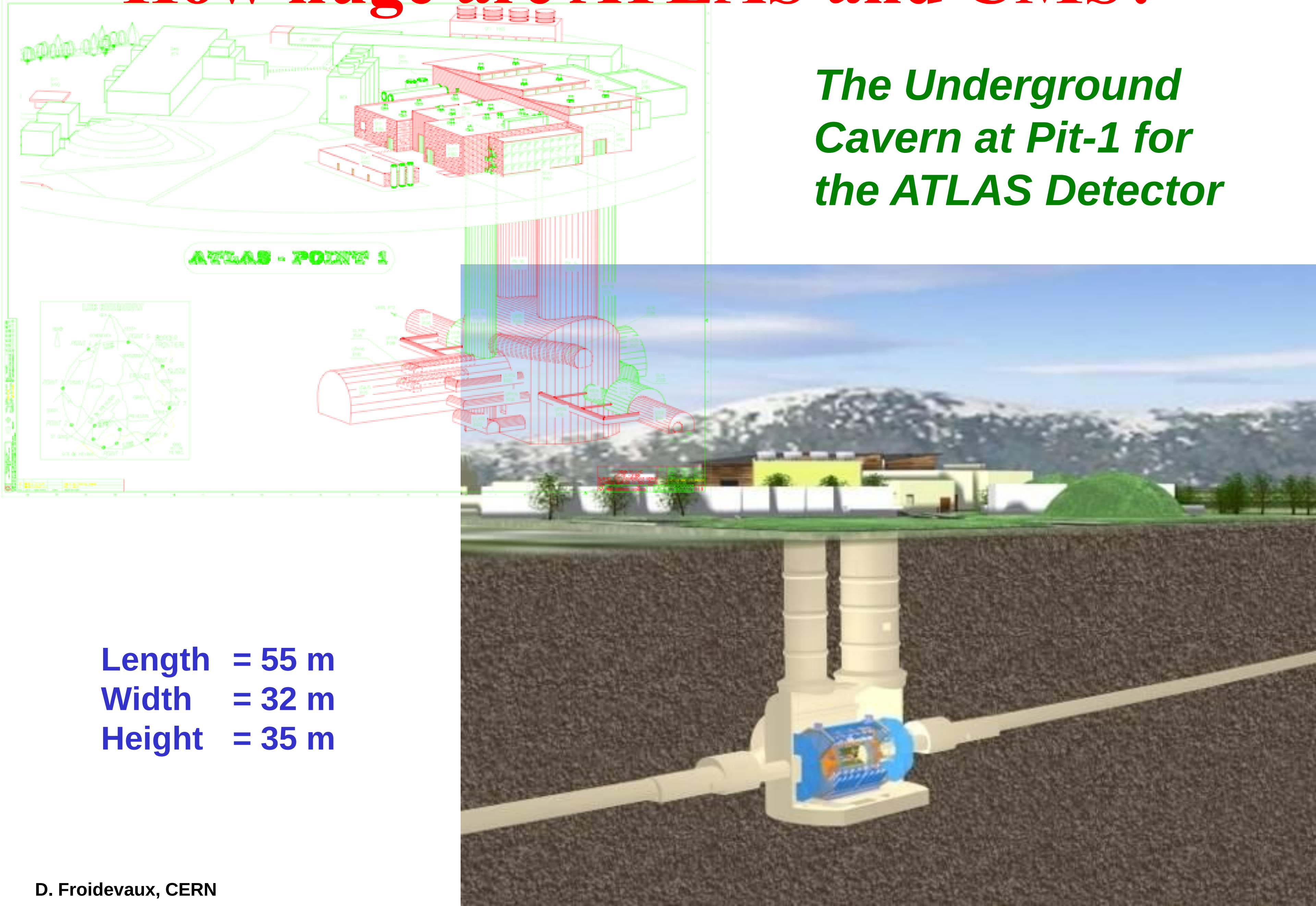




ATLAS

| | *ATLAS* | *CMS* |
|---|---|---|
| *Overall weight (tons)* | *7000* | *12500* |
| *Diameter* | *22 m* | *15 m* |
| *Length* | *46 m* | *22 m* |
| *Solenoid field* | *2 T* | *4 T* |

# How huge are ATLAS and CMS?



***The Underground Cavern at Pit-1 for the ATLAS Detector***

**Length = 55 m**
**Width = 32 m**
**Height = 35 m**

**D. Froidevaux, CERN**

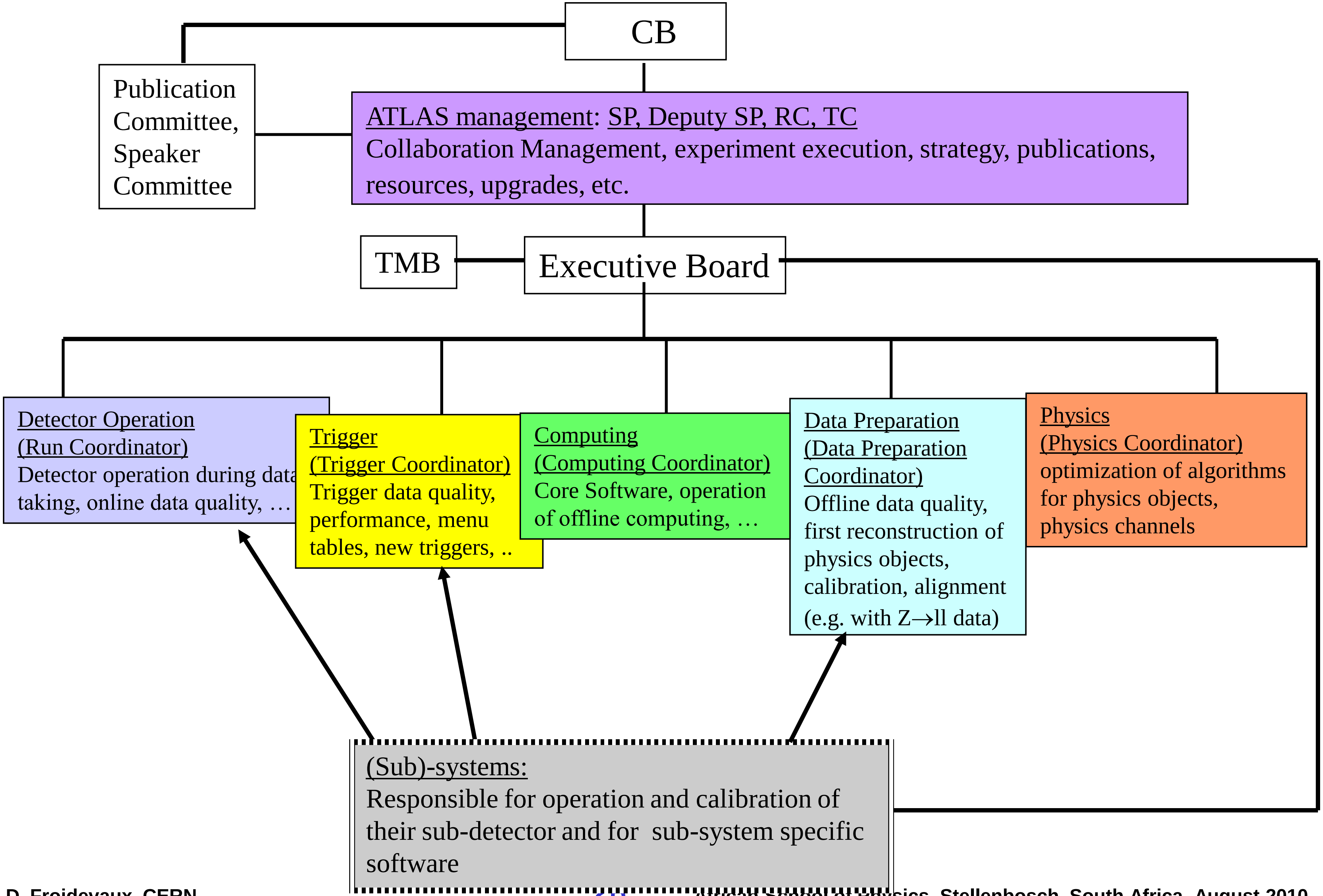
# How huge are ATLAS and CMS?

## An Aerial View of Point-1

(Across the street from the CERN main entrance)

# Operation Model (Organization for LHC Exploitation)

(Details can be found at http://uimon.cern.ch/twiki//bin/view/Main/OperationModel )



CB

Publication Committee, Speaker Committee

ATLAS management: SP, Deputy SP, RC, TC
Collaboration Management, experiment execution, strategy, publications, resources, upgrades, etc.

TMB

Executive Board

Detector Operation
(Run Coordinator)
Detector operation during data taking, online data quality, …

Trigger
(Trigger Coordinator)
Trigger data quality, performance, menu tables, new triggers, ..

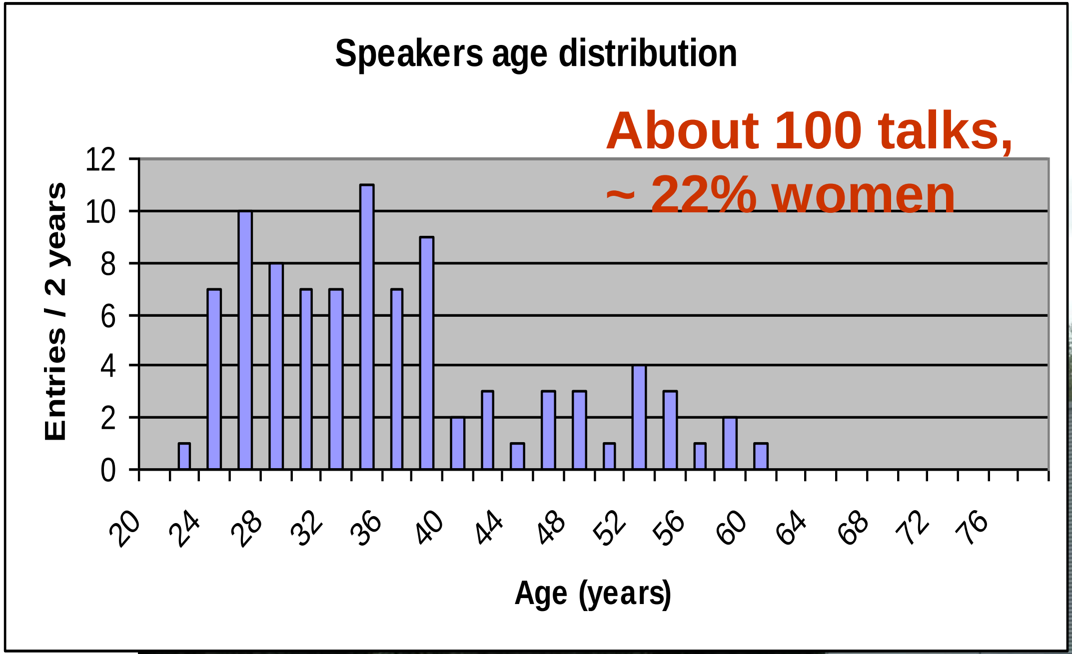
Computing
(Computing Coordinator)
Core Software, operation of offline computing, …

Data Preparation
(Data Preparation Coordinator)
Offline data quality, first reconstruction of physics objects, calibration, alignment (e.g. with Z→ll data)

Physics
(Physics Coordinator)
optimization of algorithms for physics objects, physics channels

(Sub)-systems:
Responsible for operation and calibration of their sub-detector and for sub-system specific software

# ATLAS physics workshop in Rome (June 2005)



**About 100 talks,**
**~ 22% women**

**~ 450 participants**

# Generic features required of ATLAS and CMS

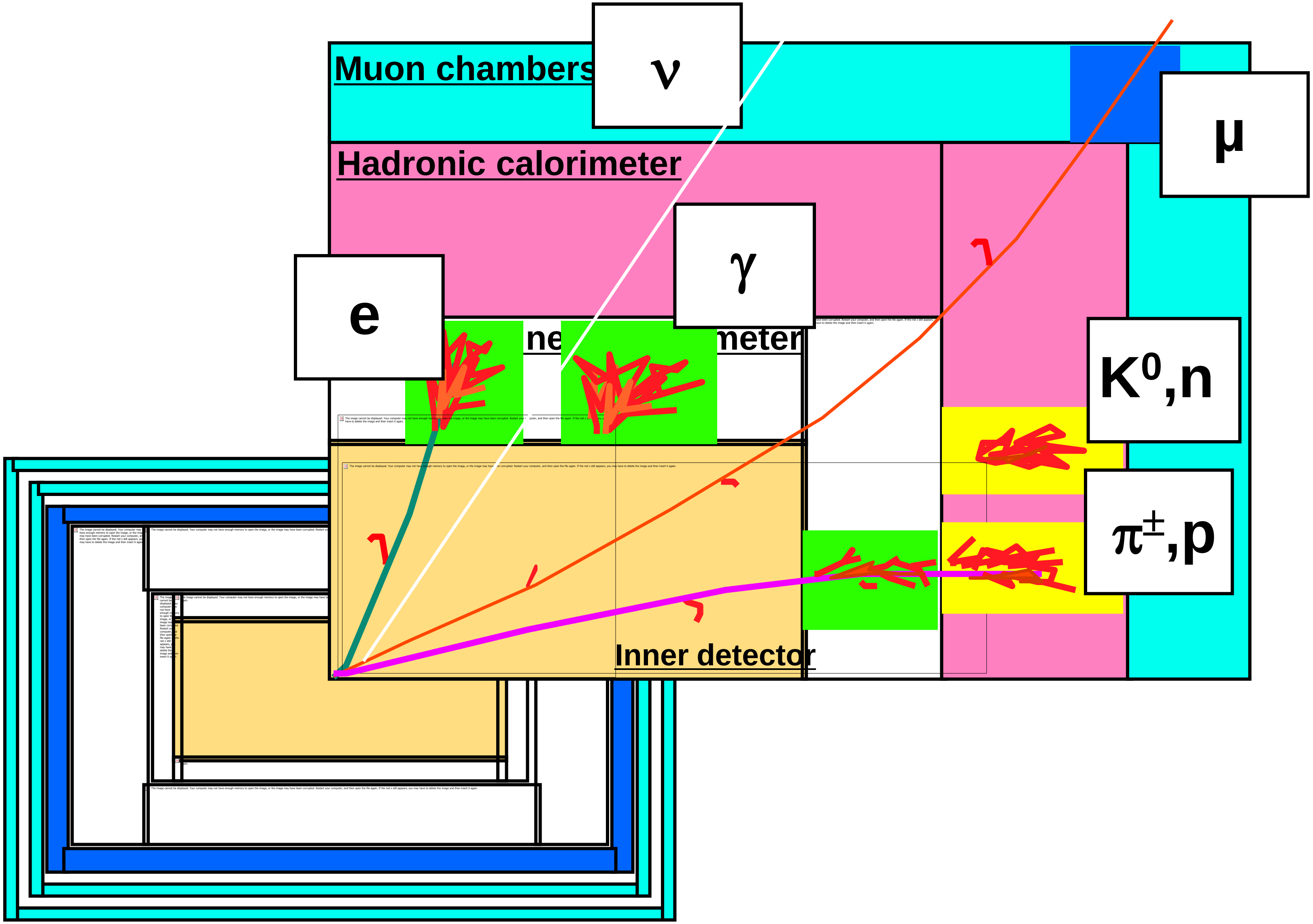
- Detectors must survive for 10 years or so of operation
  - Radiation damage to materials and electronics components
  - Problem pervades whole experimental area (neutrons): NEW!
- Detectors must provide precise timing and be as fast as feasible
  - 25 ns is the time interval to consider: NEW!
- Detectors 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 → bb
  - Electromagnetic calorimetry: H → γγ and H → ZZ → eeee
  - Muon spectrometer: H → ZZ → μμμμ
  - Missing transverse energy: supersymmetry, H → ττ
- **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)

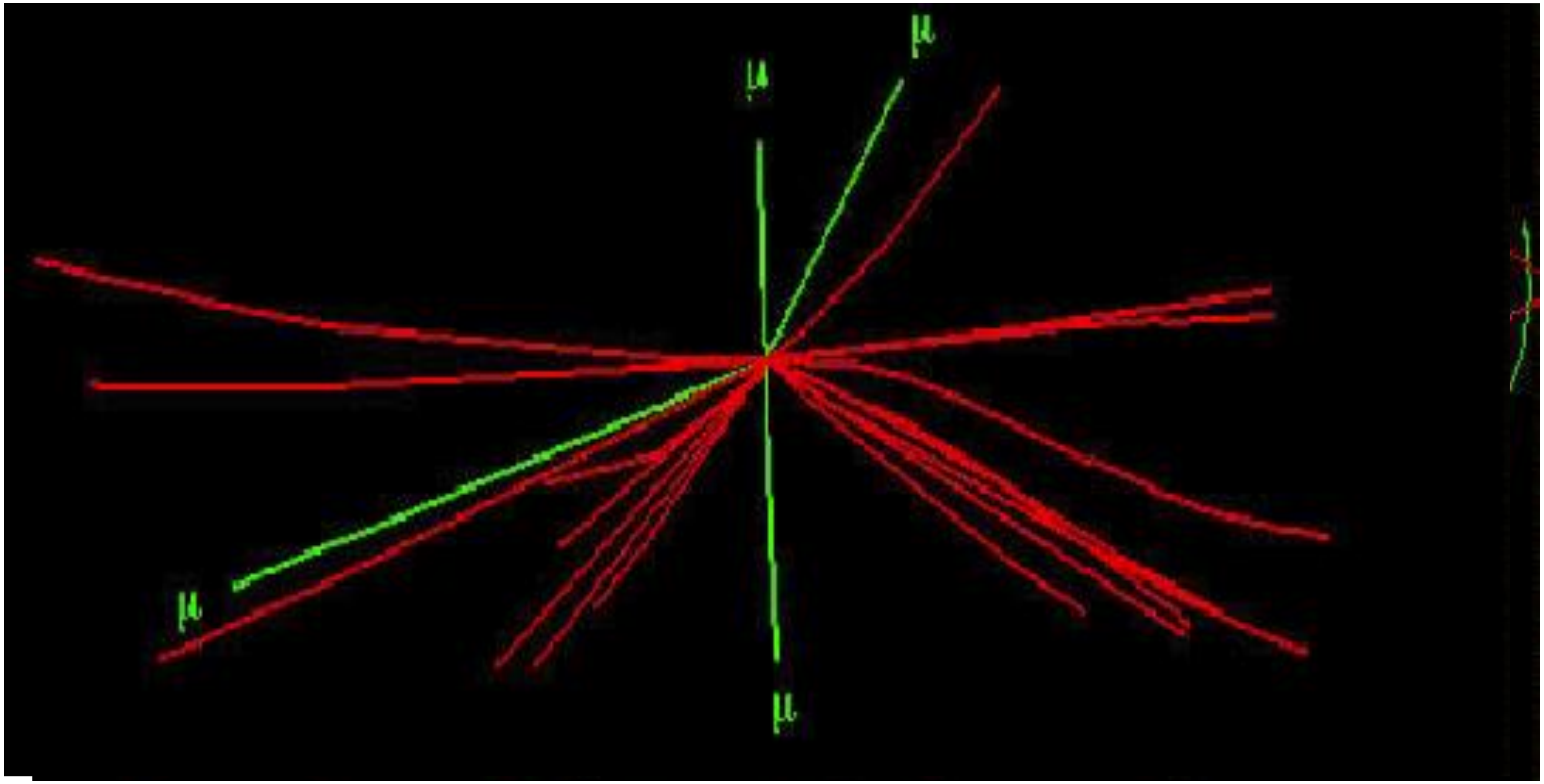
# Higgs at the LHC: the challenge



# Physics at the LHC: the challenge

How to extract this…

… from this …



Higgs ⟶ 4μ

+30 min. bias events

**Without knowing really where to look for!**

# Physics at the LHC: the challenge

Small x-sections

need highest luminosity

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

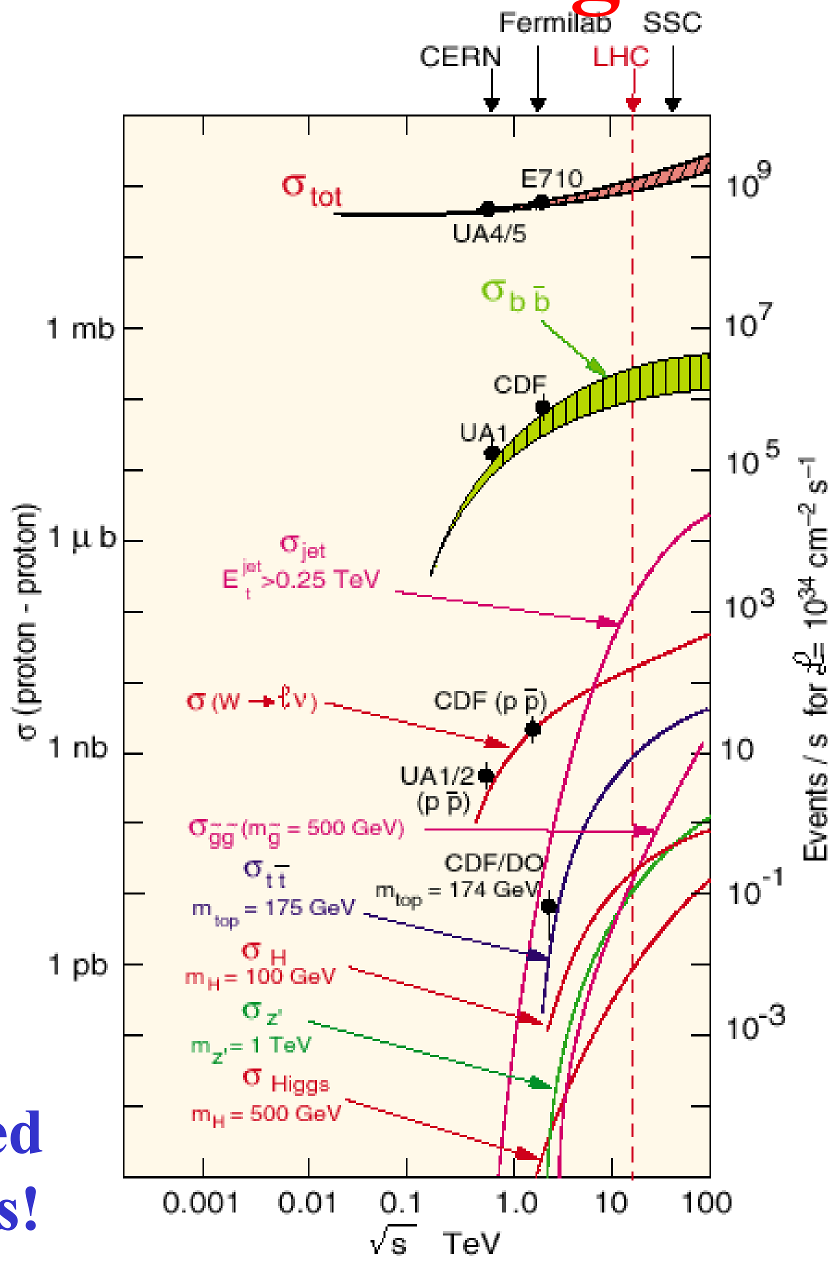
Orders of magnitude of event rates for various physics channels:

- 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) |
| | $\nu_e$ | $\nu_\mu$ | $\nu_\tau$ |
| 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)<br>Colour octet | Photon<br>(0) | $W^+$,$W^-$<br>(80.42) | Z<br>(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 $\Upsilon$ 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:

- $\alpha$ is the crossing angle between the beams
- $\Delta t$ 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
- $\beta_e$ is the $\beta$-function at the interaction point, $\beta_e = 0.5$ m
- $\varepsilon$ 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

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

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

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: | $\Delta t = 96\ \mathrm{ns}$ | and | $\langle n \rangle \ll 1$ |
| Tevatron: | $\Delta t = 0.4\ \mu s$ | and | $\langle n \rangle \approx 2$ |

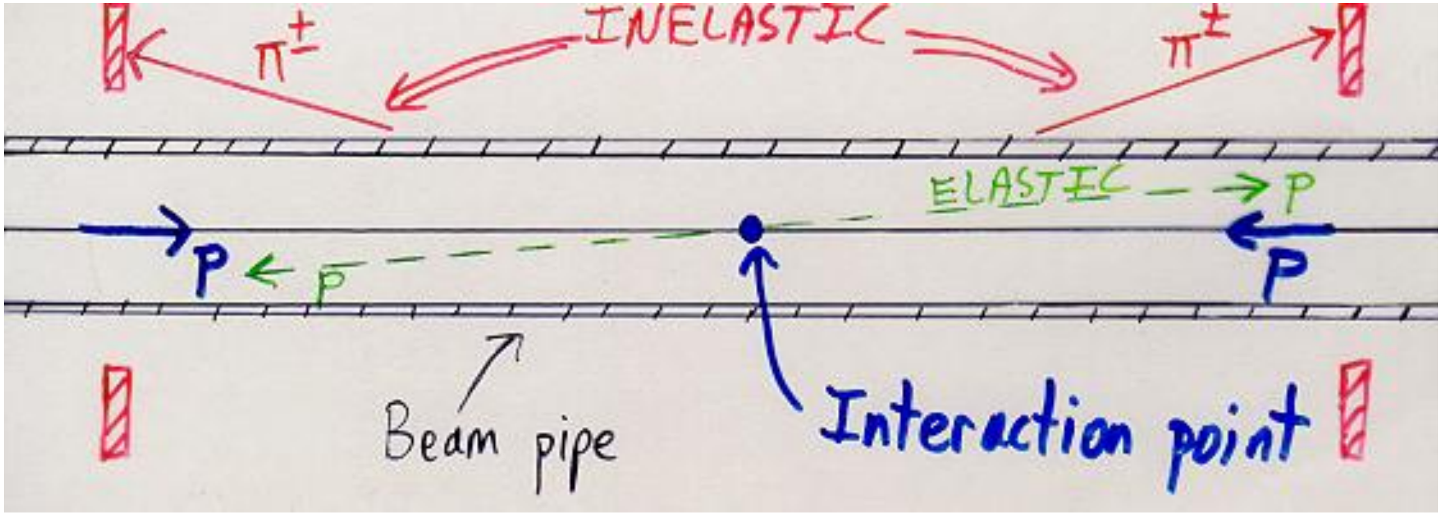
# Physics at the LHC: the environment

## Experimental environment ≡ Machine performance x Physics

### Event rates in detectors:

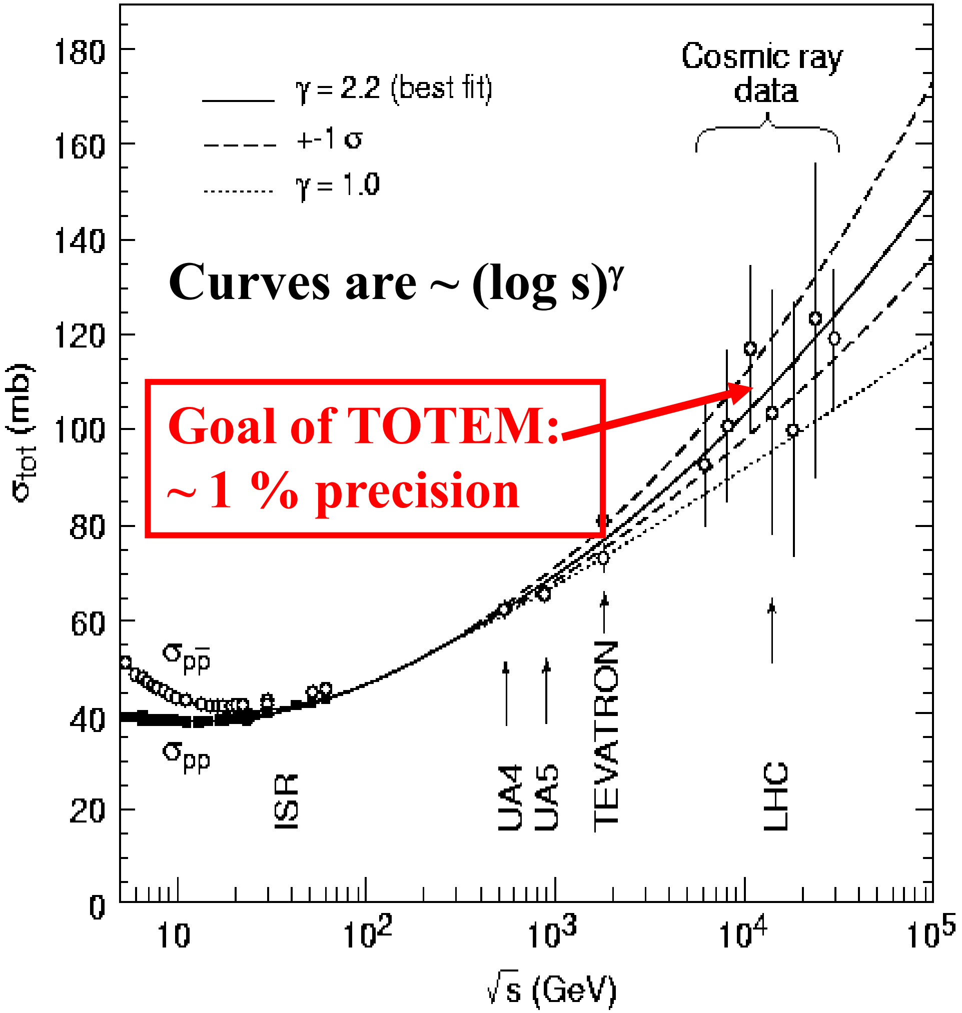
- number of charged tracks expected in inner tracking detectors
- energy expected to be deposited in calorimeters
- radiation doses expected (ionising and neutrons)
- event pile-up issues (pile-up in time and in space)

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



# Physics at the LHC: the environment

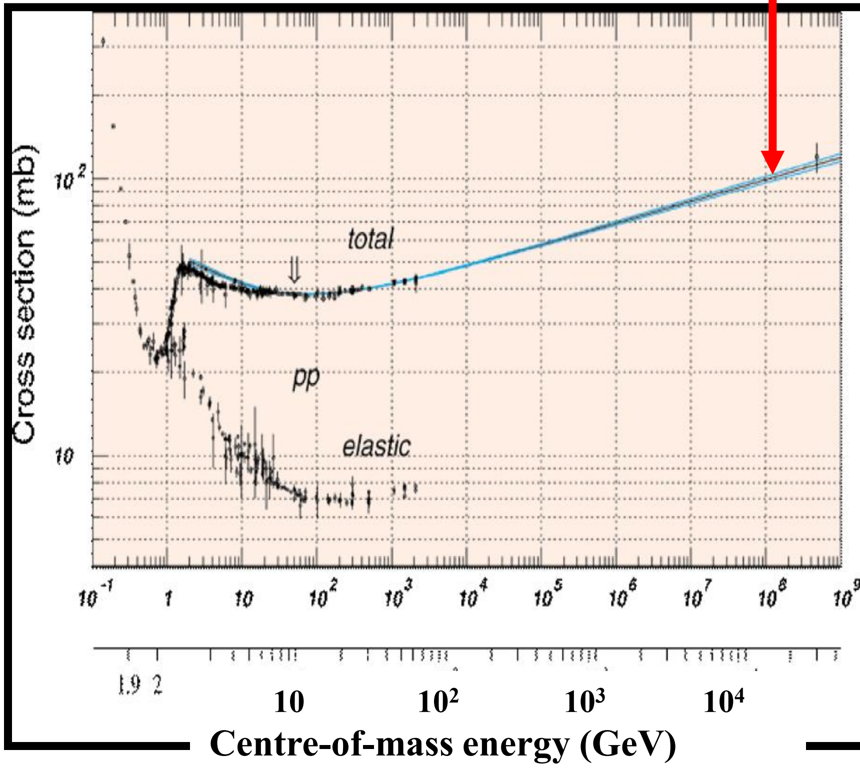
## Measurement of $\sigma_{tot}$ (pp) and $\sigma_{inel} = \sigma_{tot} - \sigma_{el} - \sigma_{diff}$



Curves are ~ $(\log s)^\gamma$

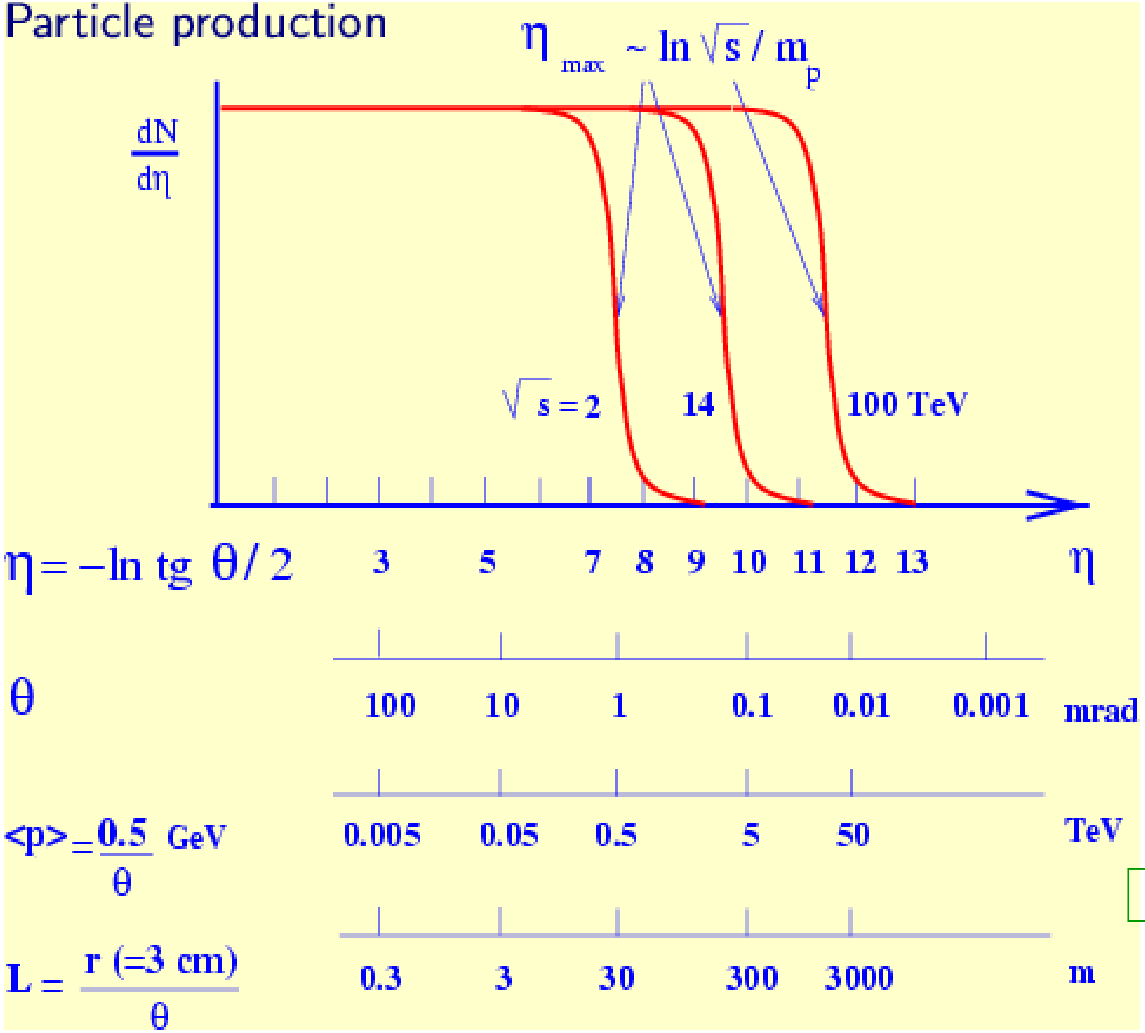
**Goal of TOTEM:**
**~ 1 % precision**

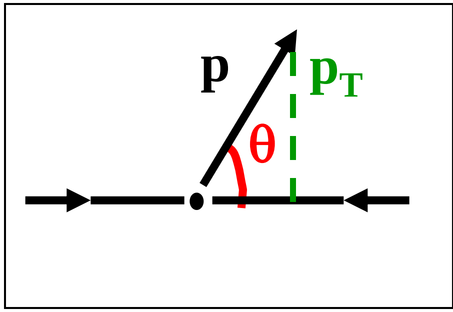
$\sigma_{tot}$(pp)≈100 mb



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

# Physics at the LHC: the environment

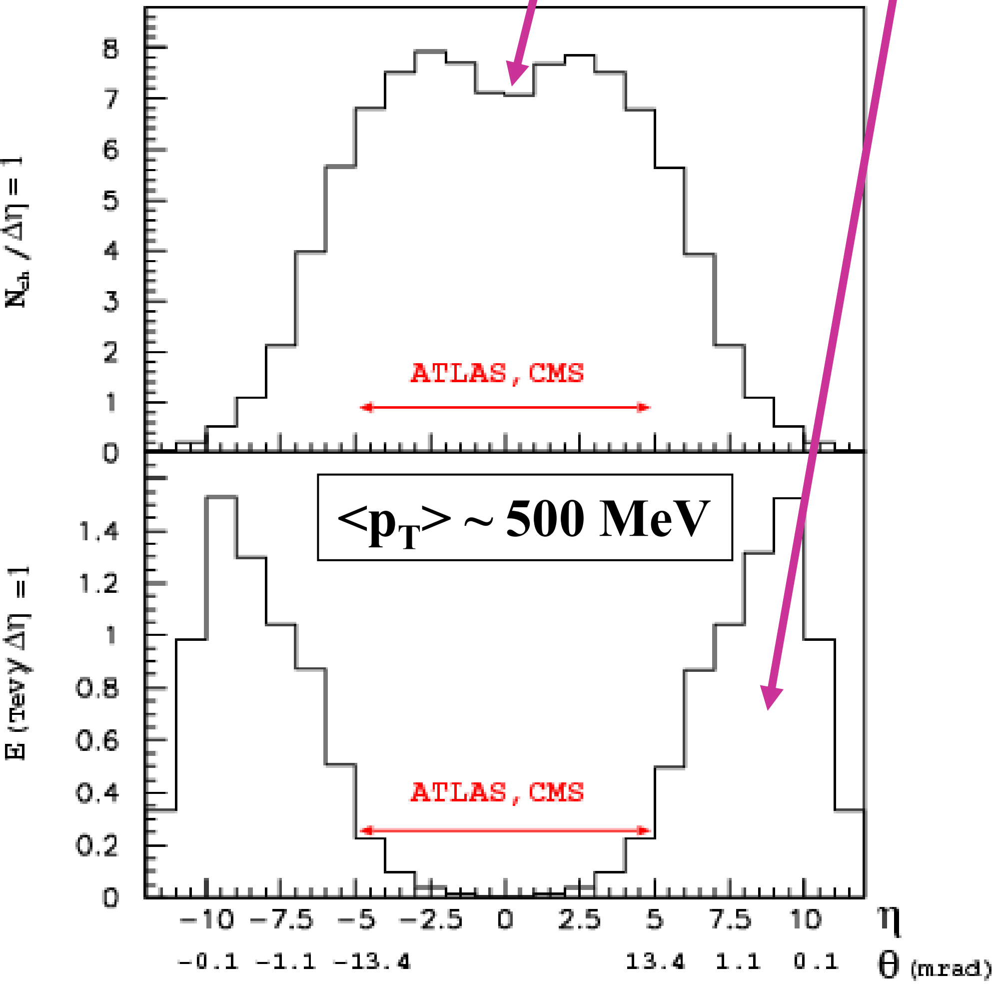




- **$d\sigma/dp_T dy$ is Lorentz-invariant**
- **$\eta = y$ for $m \approx 0$**
- **Physics is ~ constant versus $\eta$ at fixed $p_T$**

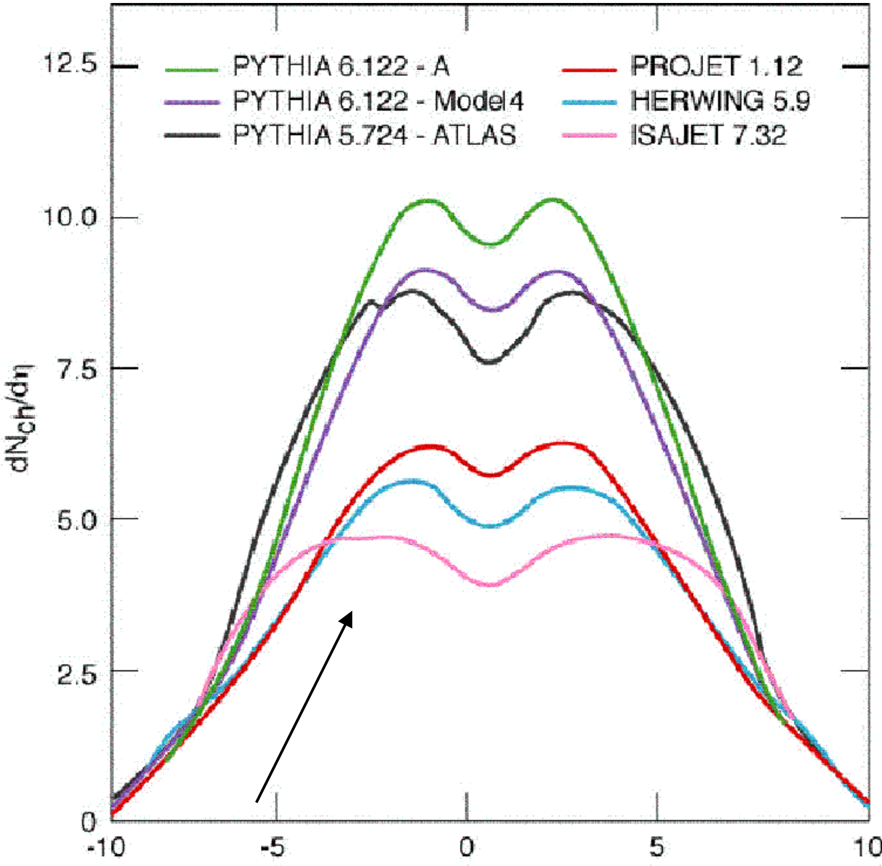
# Physics at the LHC: the environment

**Charged particle multiplicity and energy in pp inelastic events at $\sqrt{s}$ = 14 TeV**



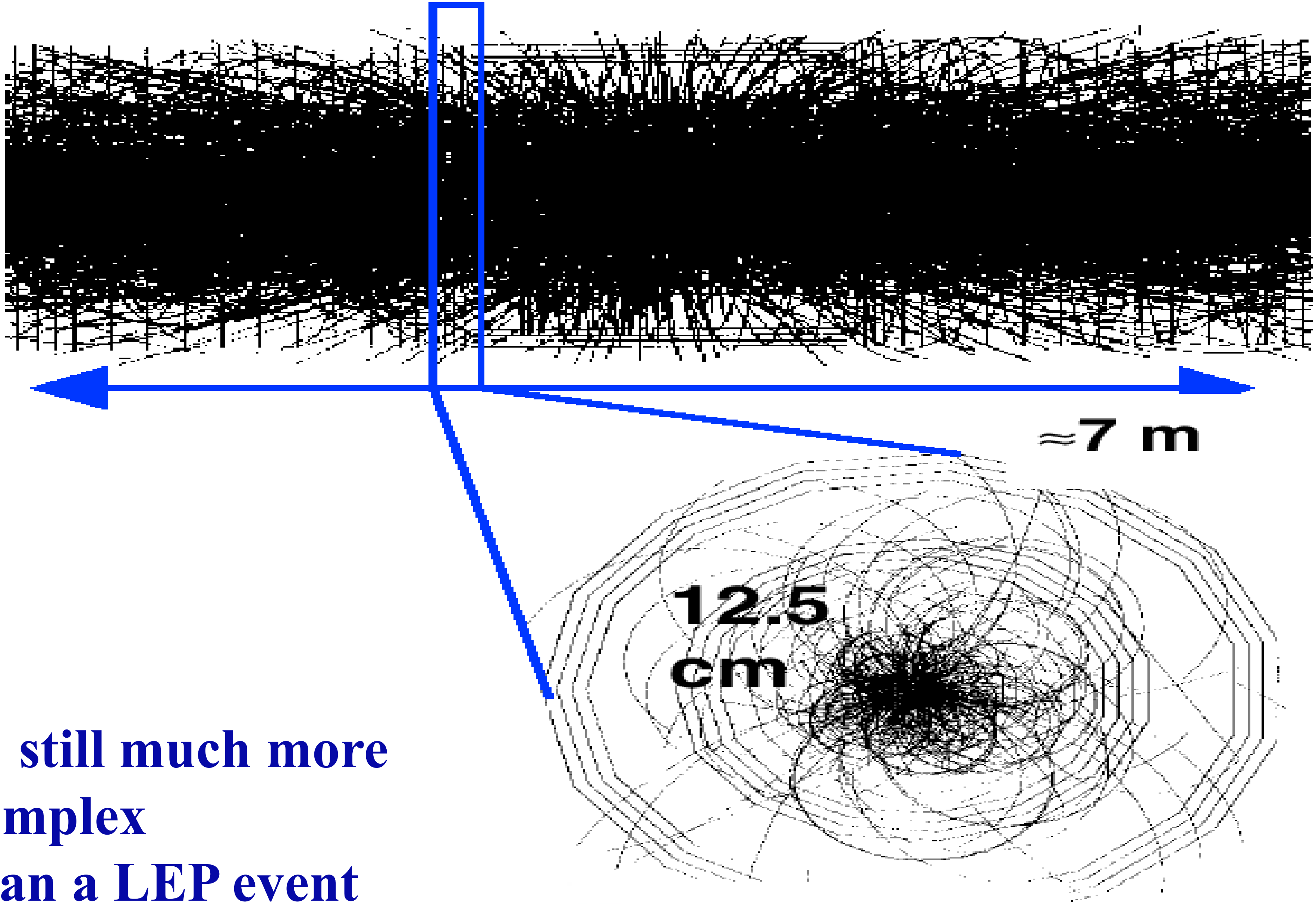
**$<p_T> \sim$ 500 MeV**

**Charged particle multiplicities from different models**



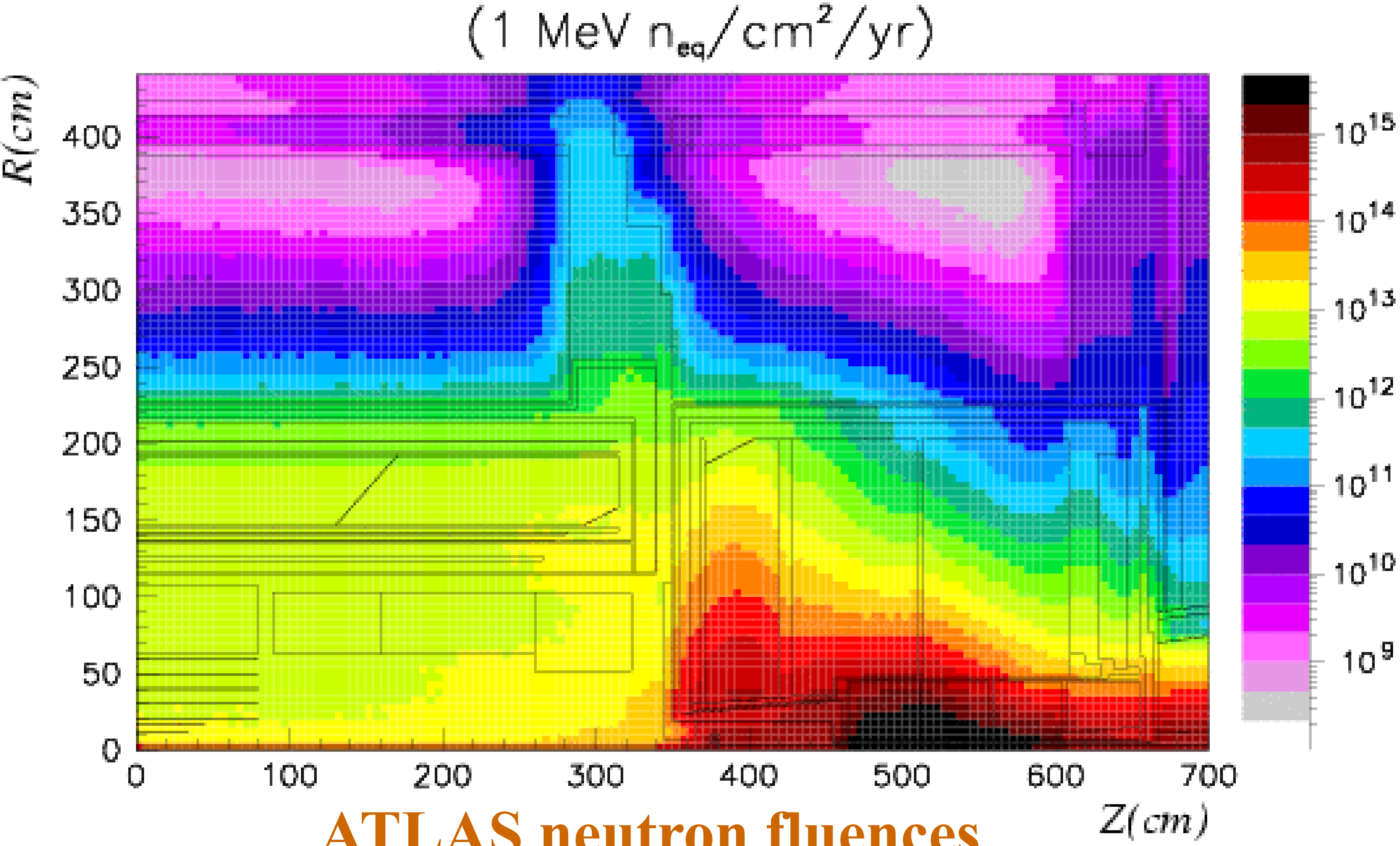
**Present models extrapolated from Tevatron give sizeable differences at the LHC**

# 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: $\approx$ 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:
  - ♦ $\sigma(n,H) \sim 2$ 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**
  **→ 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!)**

**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

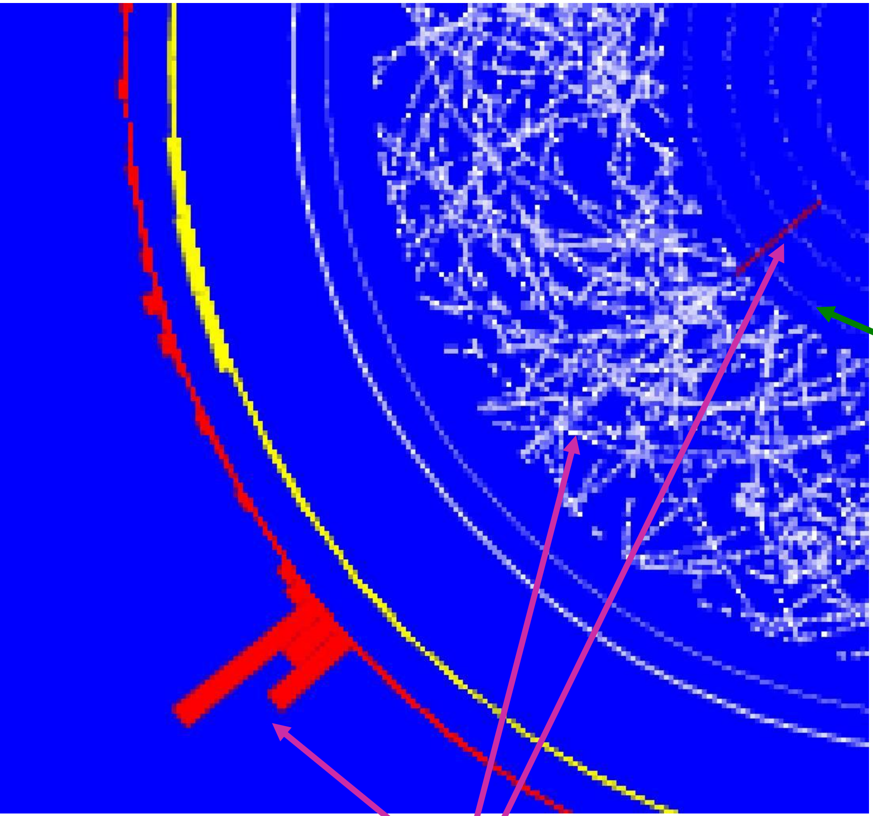
Pile-up is the name given to the impact of the 23 uninteresting (usually) interactions occurring in the same bunch crossing as the hard-scattering process which generally triggers the apparatus

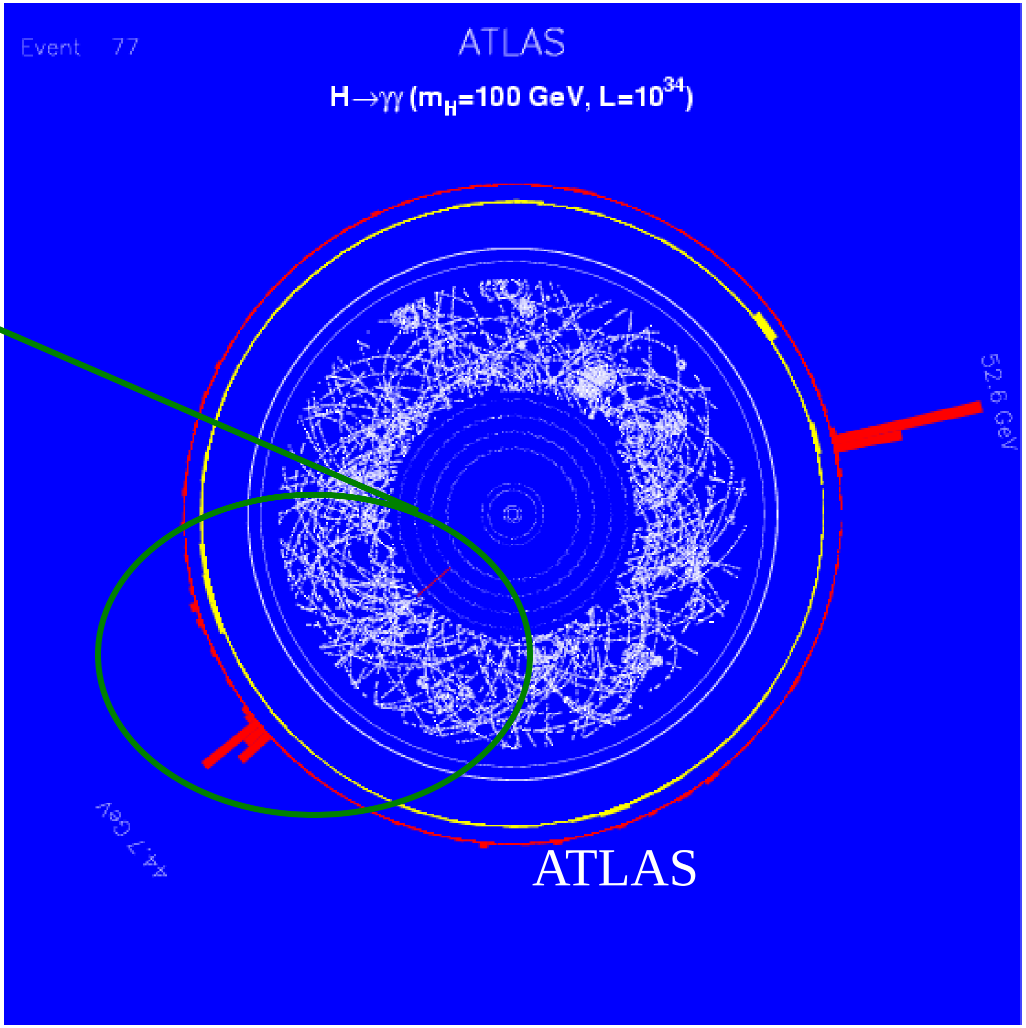
Minimising the impact of pile-up on the detector performance has been one of the driving requirements on the initial detector design:

- 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