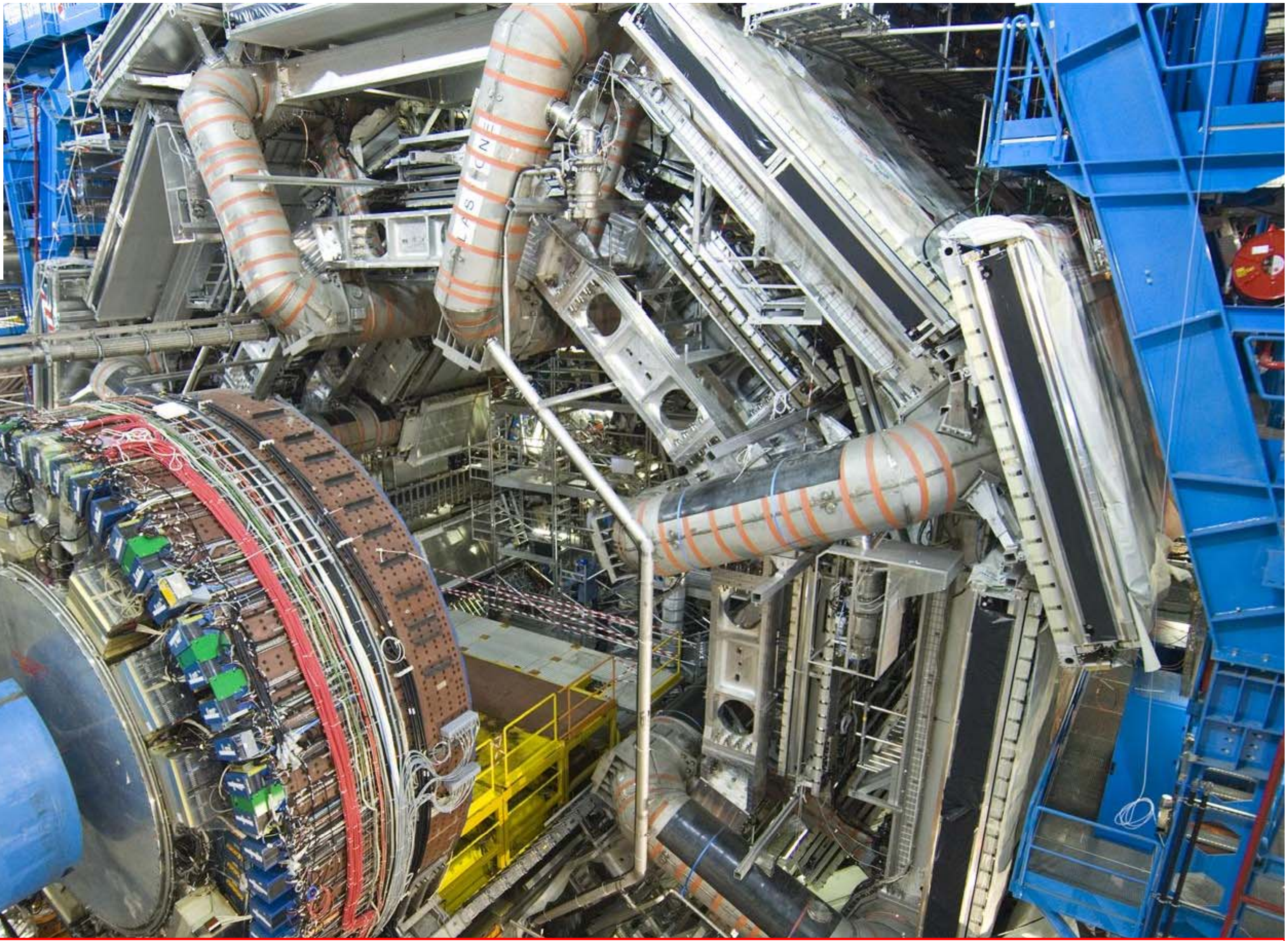


Experimental particle physics on the eve of operation of ATLAS /CMS at the LHC

Experimental particle physics: 1976 to 2010

✦ I believe we are often at least partially shaped by circumstance in our major choices when growing from childhood to adulthood

✦ From 1971 to 1976, I moved from mathematics, to theoretical physics, to finally experimental particle physics

✦ The French often say “un expérimentateur = un théoricien raté”

✦ I also was attracted to astrophysics but at the time it looked a lot like zoology, i.e. extending the catalogue of observations without an underlying predictive theory of the evolution of the universe

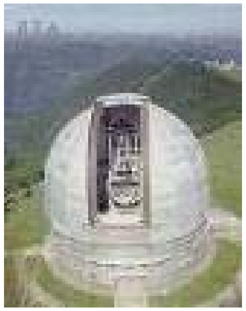
✦ Initially I believed fundamental research meant regular major advances in our understanding

✦ With experience (and listening to the Nobel lecture by D. Gross in 2004), I slowly realised that the years 1975 to 2000 had brought our understanding of fundamental physics one small but also giant step forward

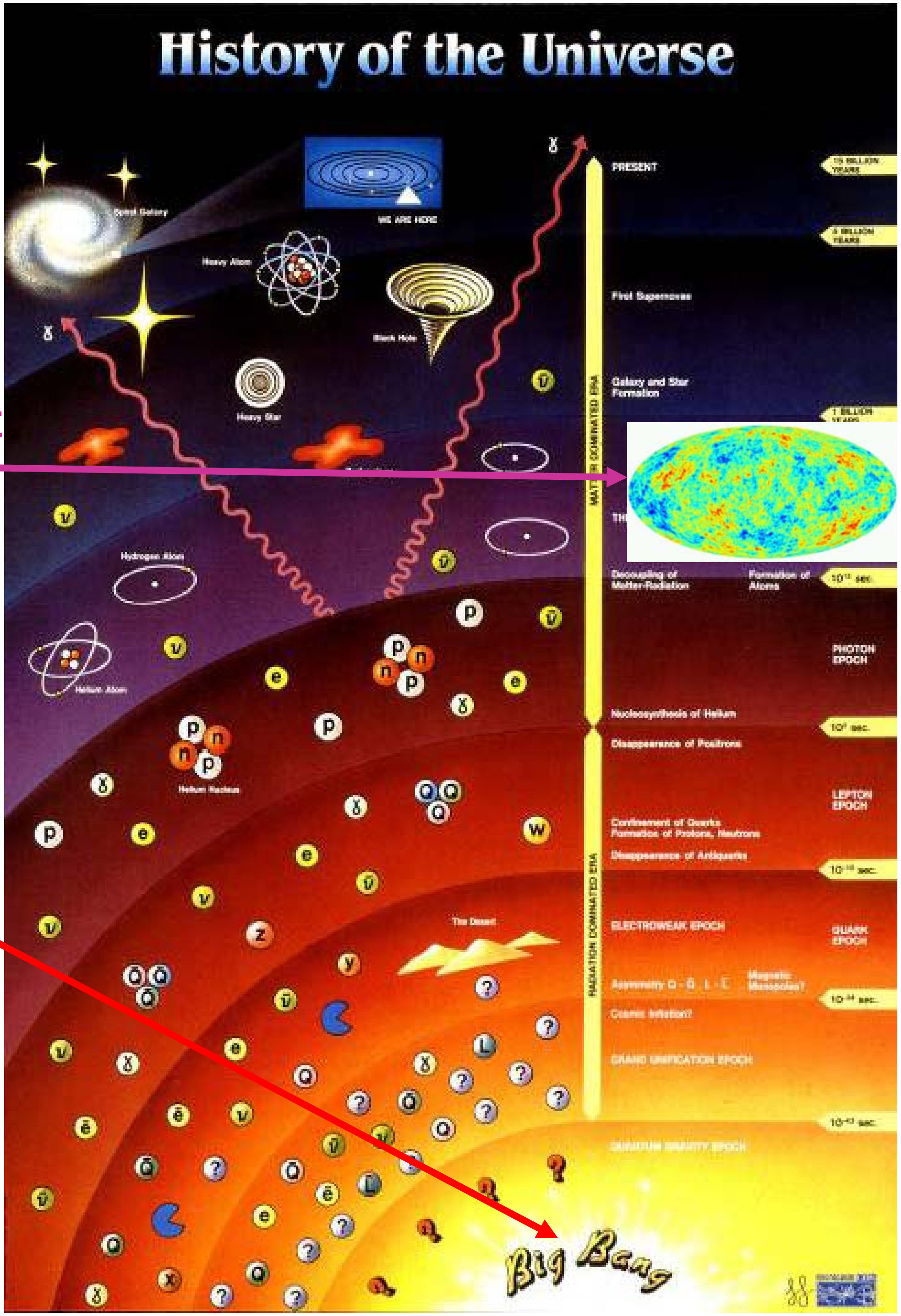
Big Bang ~14 billion years ago

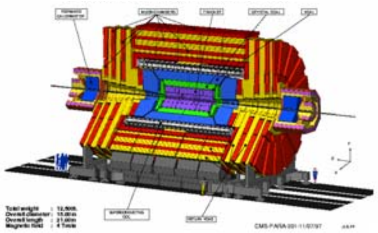
How can we understand our universe?

- **Astrophysics:**
  - explosion of results over past 15 years!

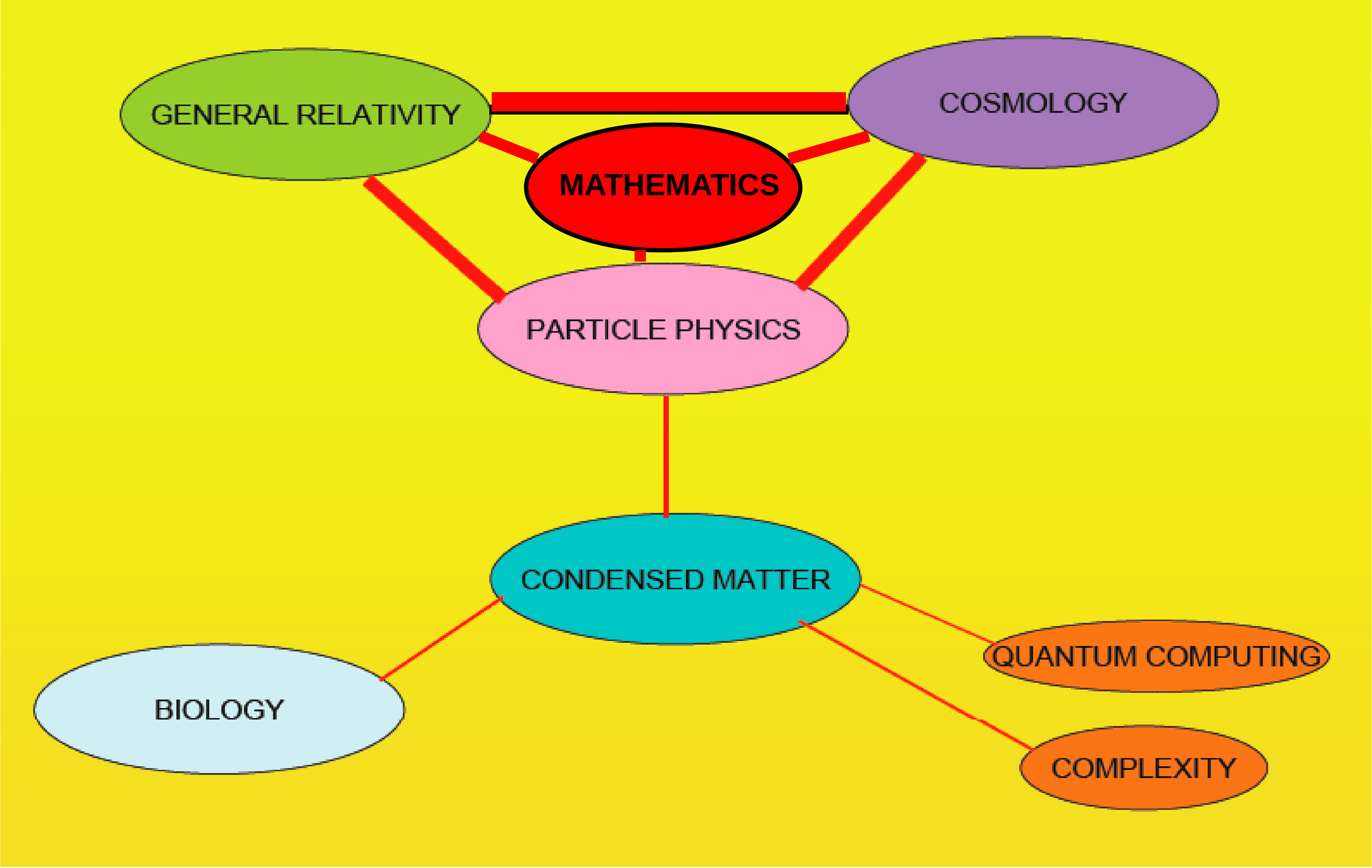


- **Particle physics:**
  - neutrino oscillations over last 10 years…
  - explosion of new results over next 10 years?



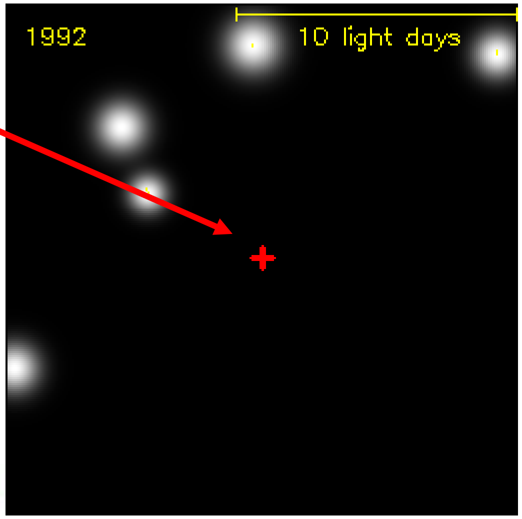


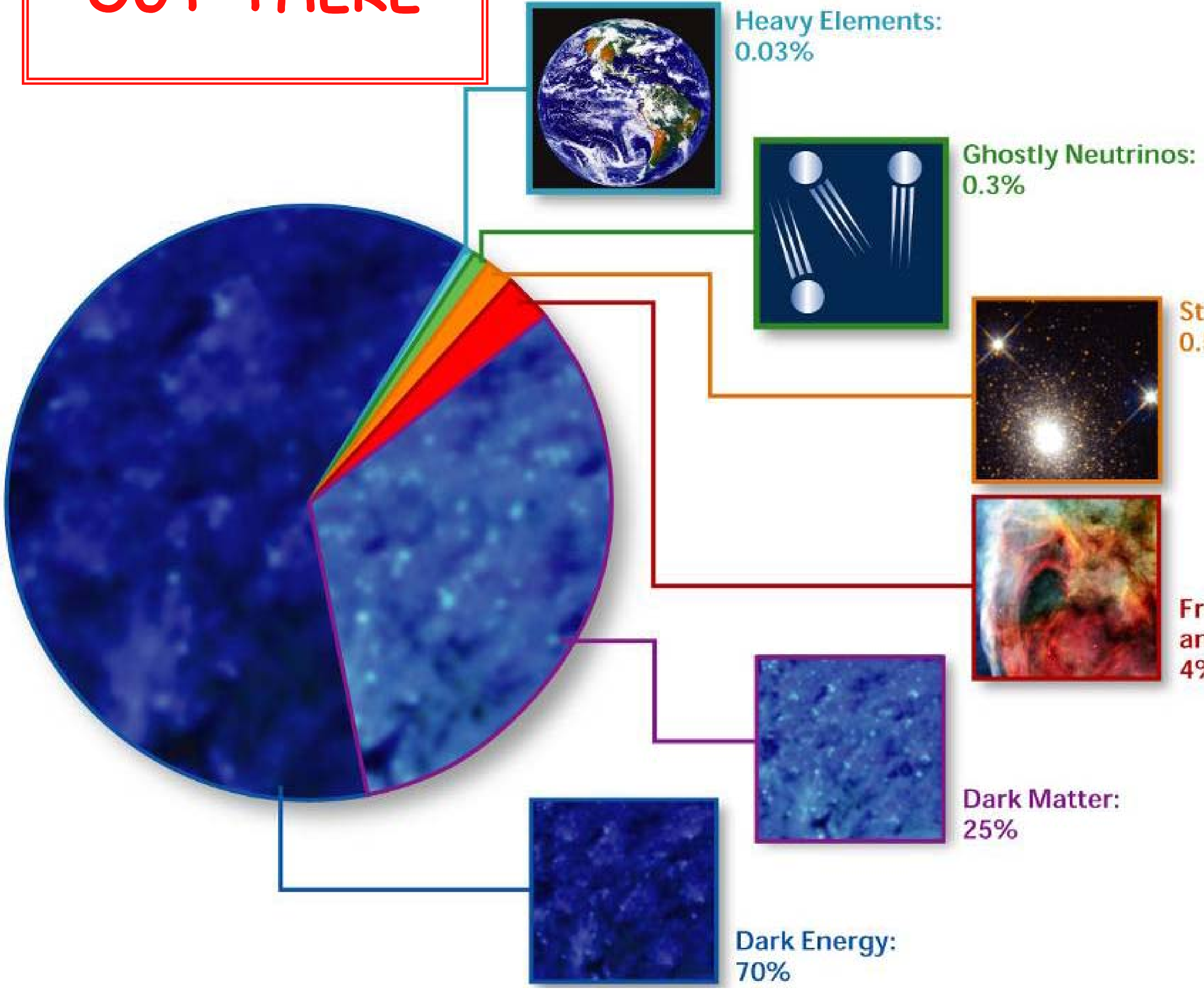
Quest for knowledge is a complex and sometimes unexpectedly tortuous path



> 90%
UNKOWN
STUFF
OUT THERE

Black hole





Experimental particle physics: 1976 to 2010

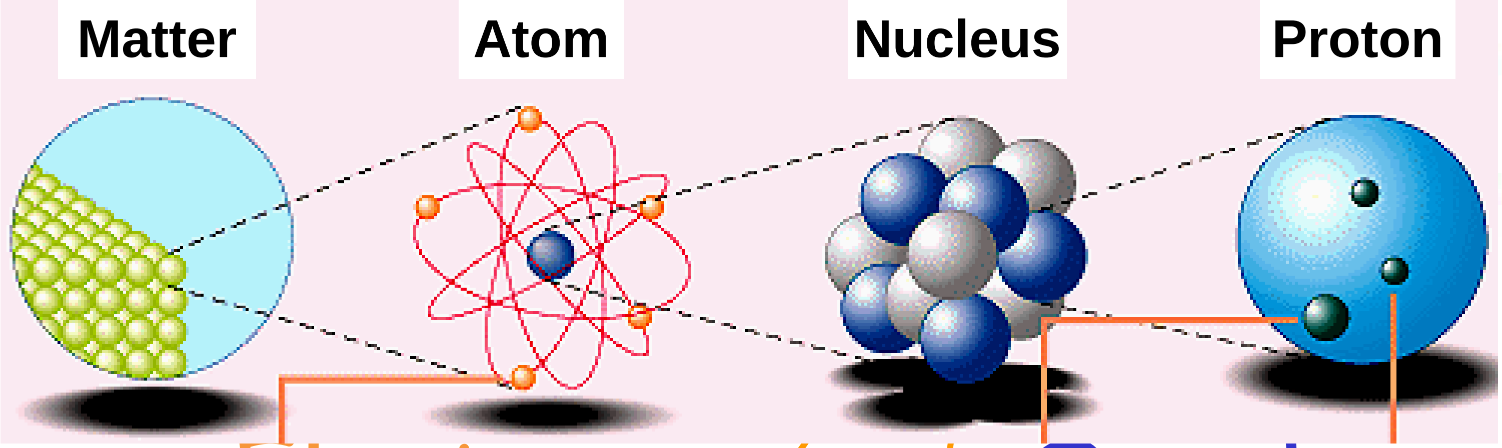
✦ Today we are able to ask questions we were not able to formulate 25-30 years ago when I was a student:

- ✓ 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

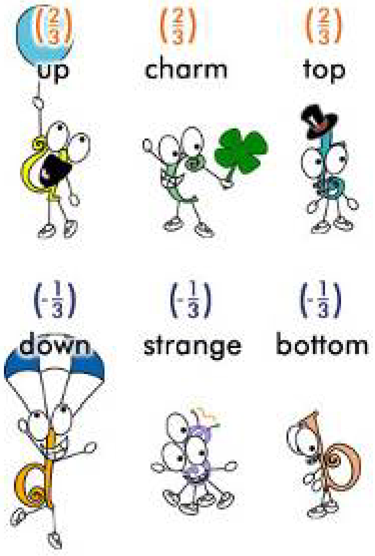
Components of known matter

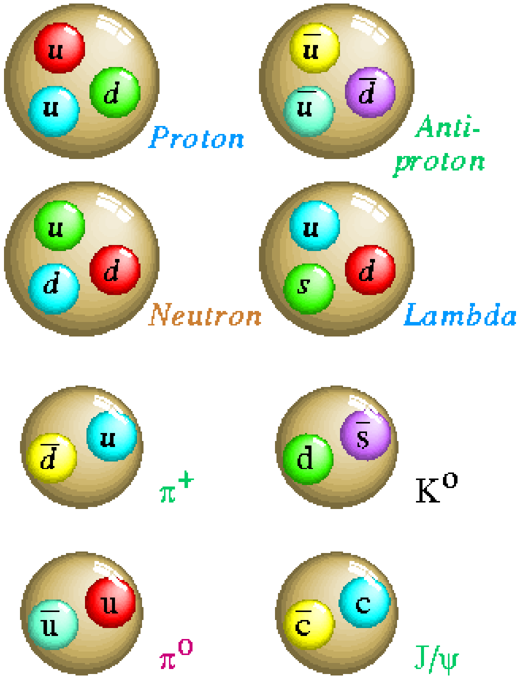


Electrons

Quarks

Protons, neutrons





Theories and models

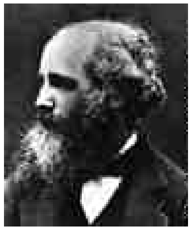
Unification of terrestrial and celestial gravitation

- **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**

Experimental particle physics from 1976 to

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

Observations (measurements: build detectors)

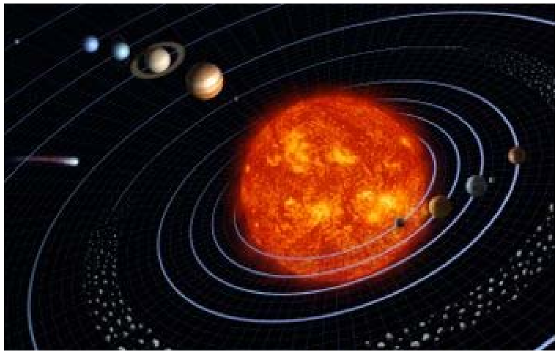
- An apple falls from a tree
- There are four forces + matter particles

Models (simulations)

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

Predictions

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



Main 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 After prediction by theory!

Still incompatible today from a theoretical viewpoint

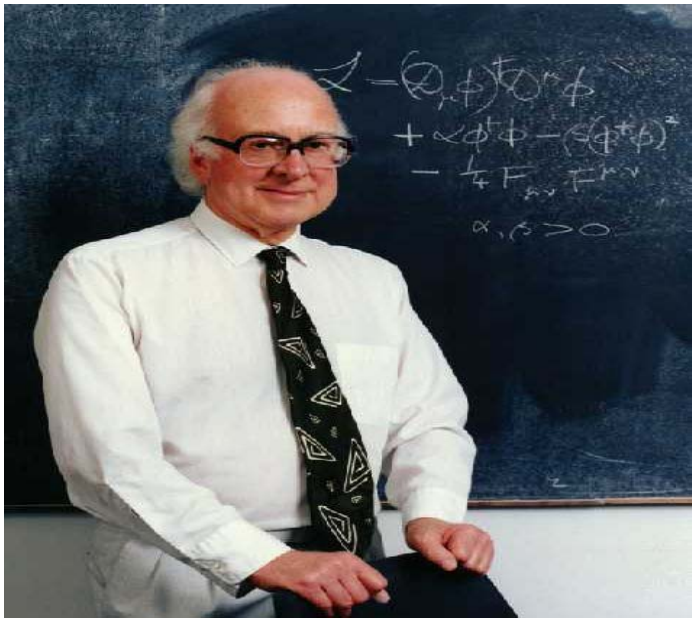
Main success of general relativity:

Predictions in agreement with measurements to 0.1%

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

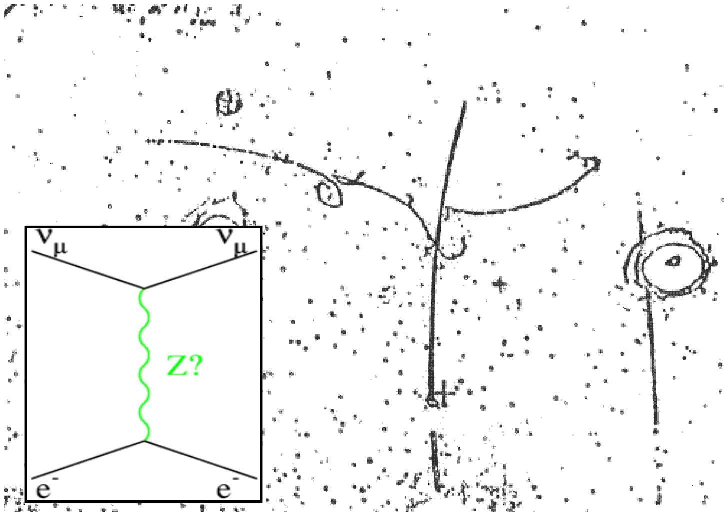
Only unambiguous example of observed Higgs (apologies to ALEPH collab.)

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)

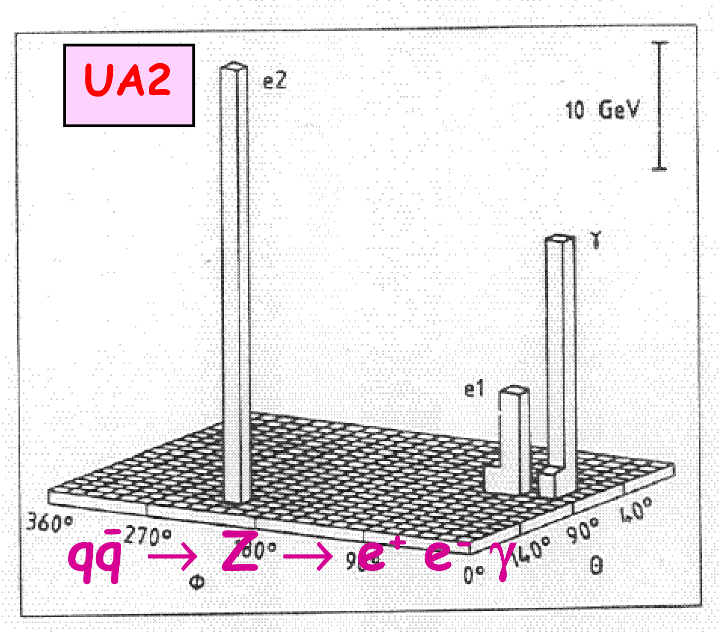
1981: The CERN SpS becomes a proton-antiproton collider

LEP and SLC are approved before W/Z boson discovery

1983: LEP and SLC construction starts

W and Z discovery (UA1, UA2)

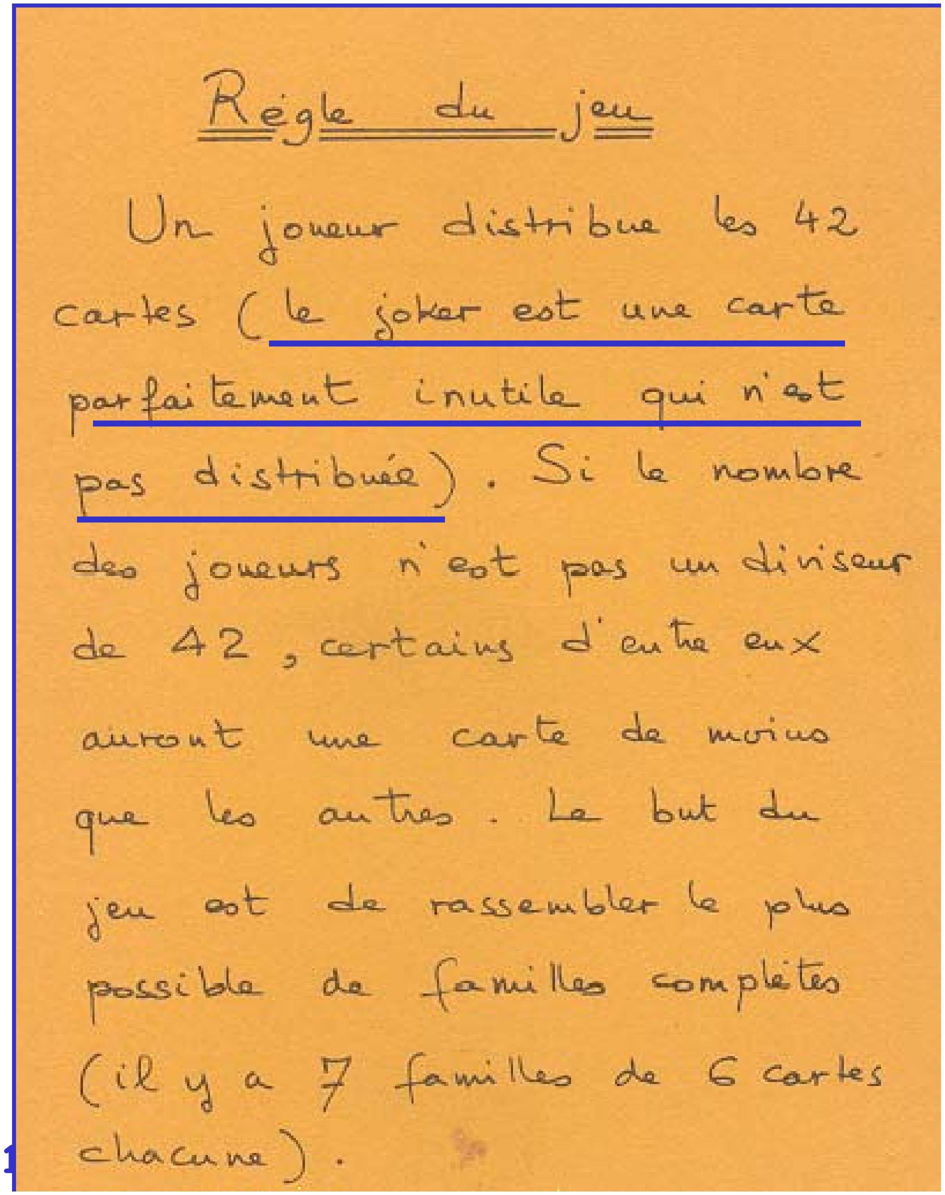
One of the first Z-bosons detected in the world



$q\bar{q} \rightarrow Z^0 \rightarrow e^+ e^- \gamma$

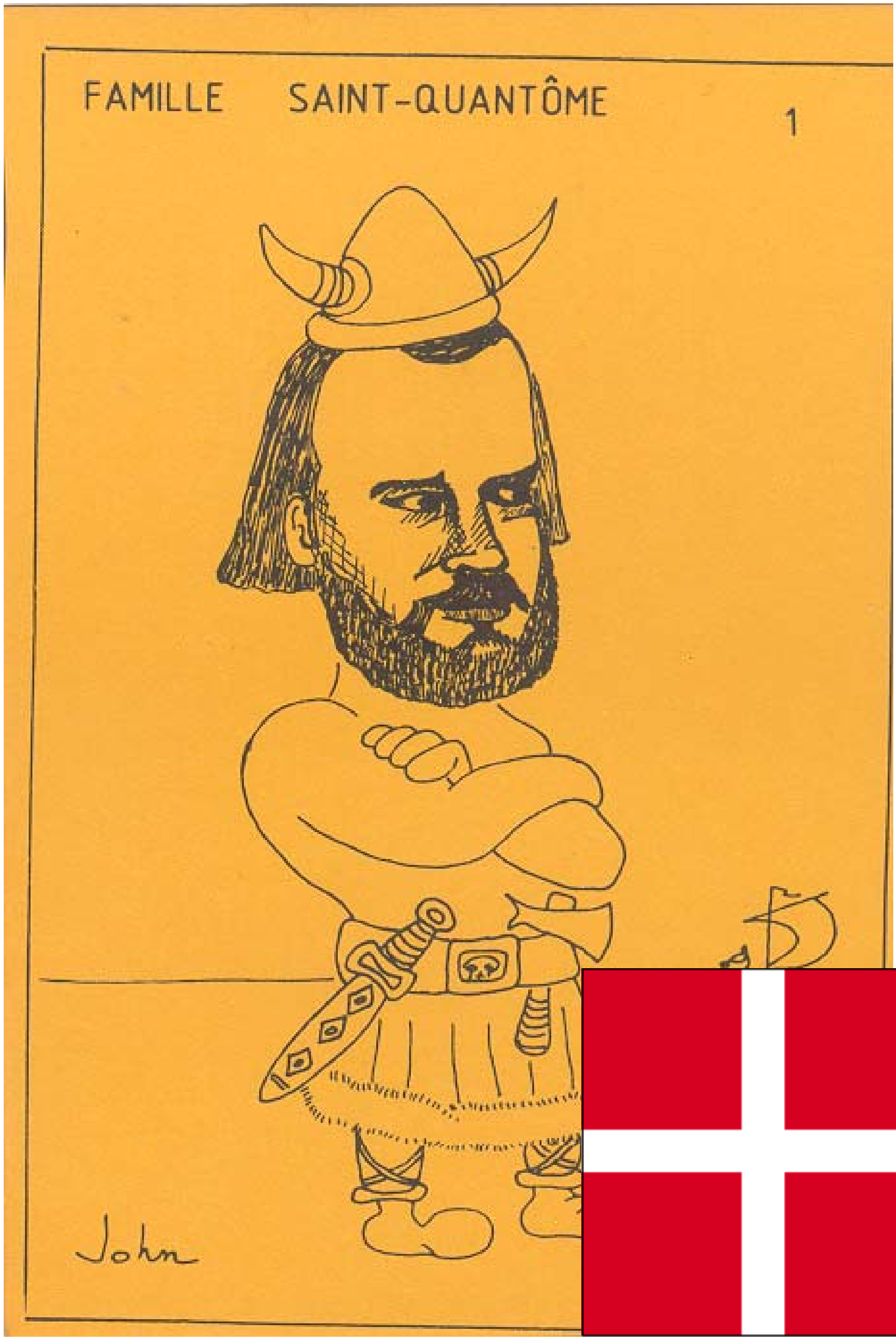
2 authors could make it into a deck of playing car

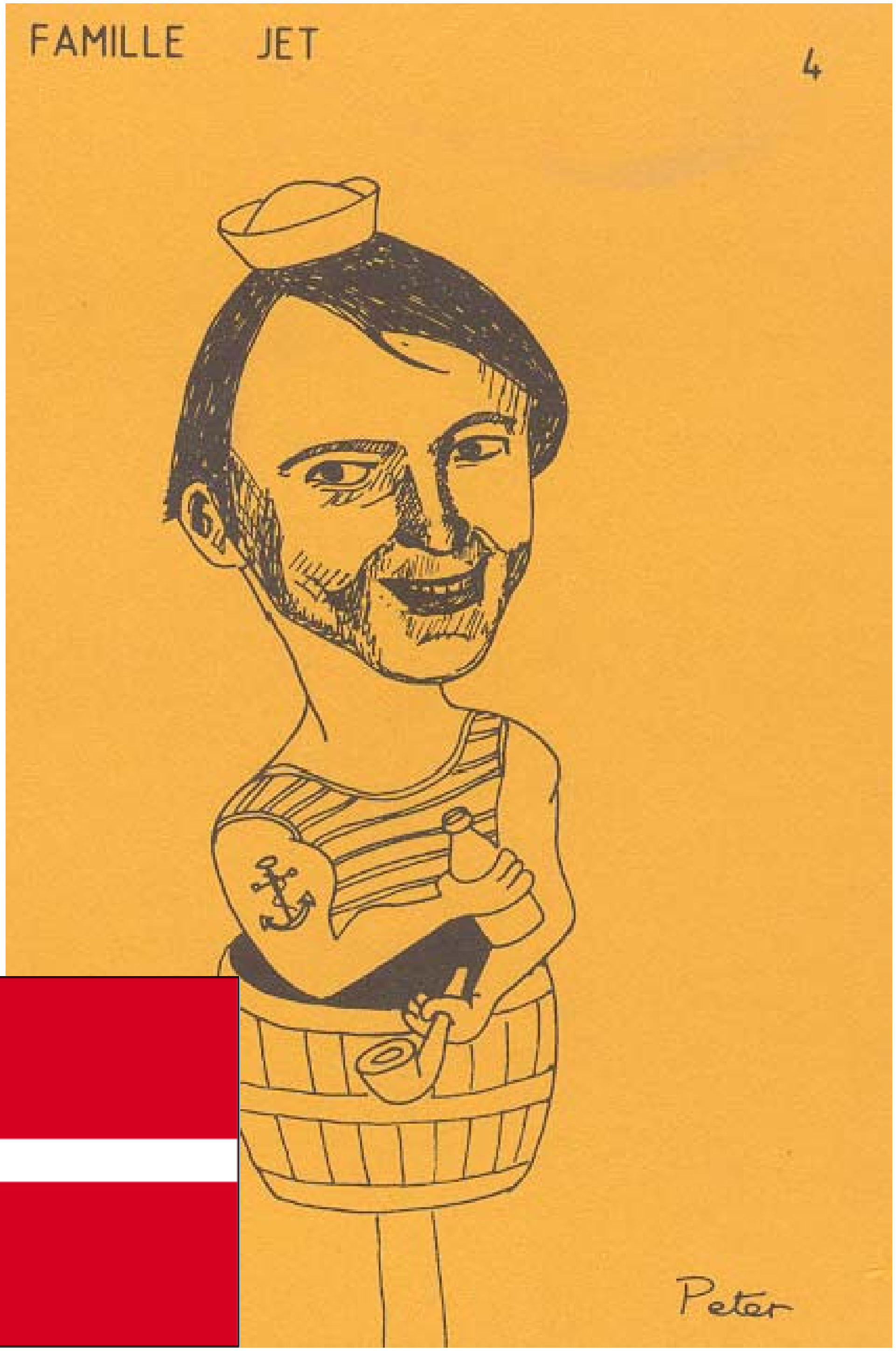
Pictures courtesy of Pierre Darriulat

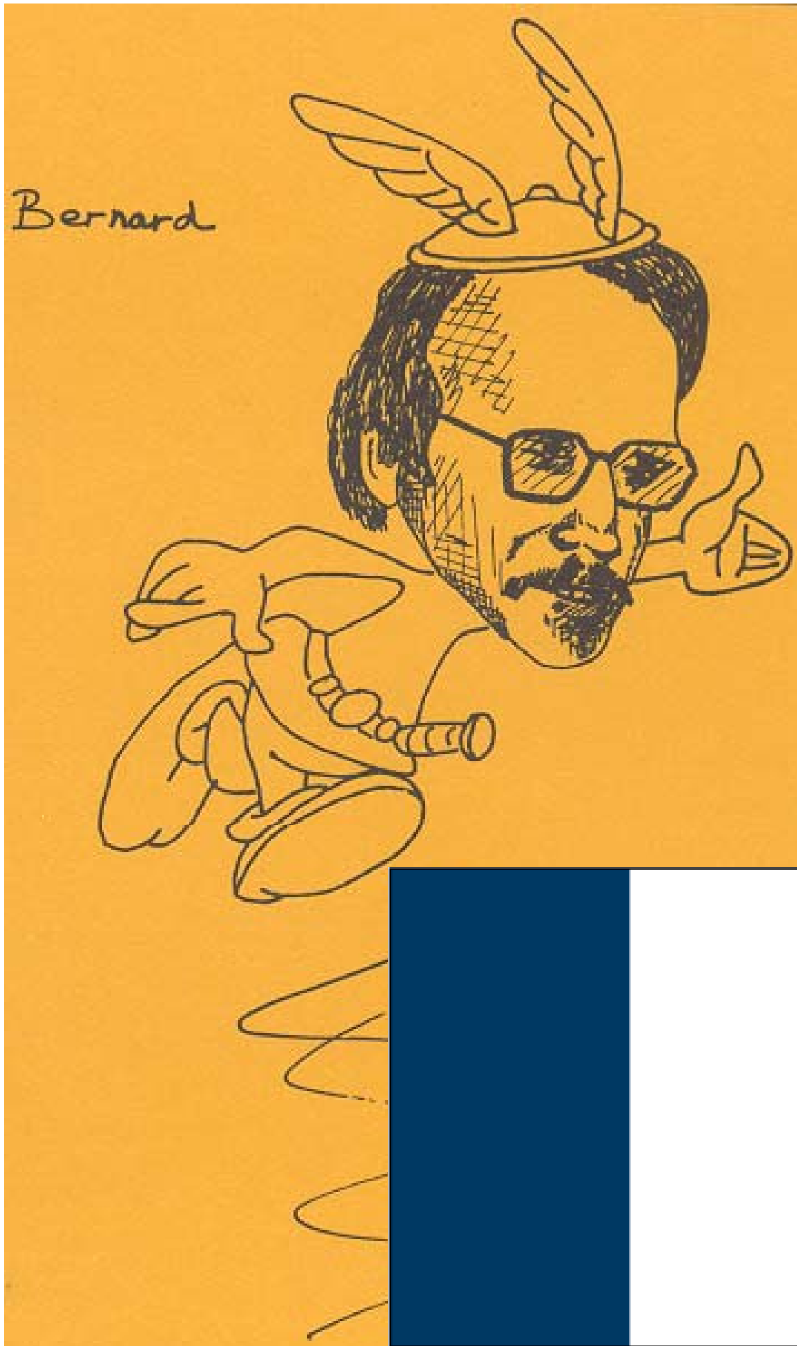


Règle du jeu

Un joueur distribue les 42 cartes (le joker est une carte parfaitement inutile qui n'est pas distribuée). Si le nombre des joueurs n'est pas un diviseur de 42, certains d'entre eux auront une carte de moins que les autres. Le but du jeu est de rassembler le plus possible de familles complètes (il y a 7 familles de 6 cartes chacune).

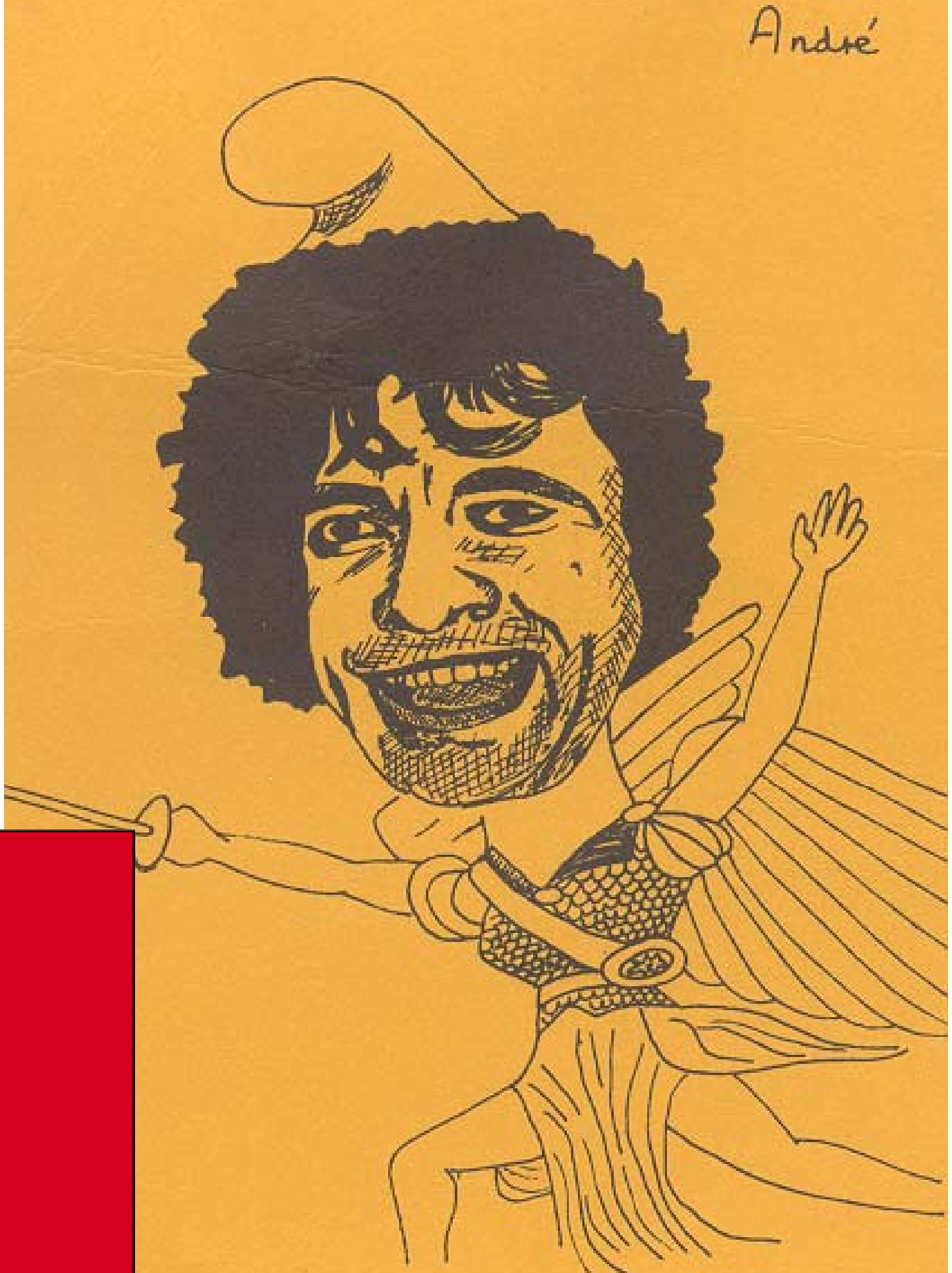

FAMILLE SAINT-QUANTÔME
1
John


FAMILLE JET
4
Peter



6

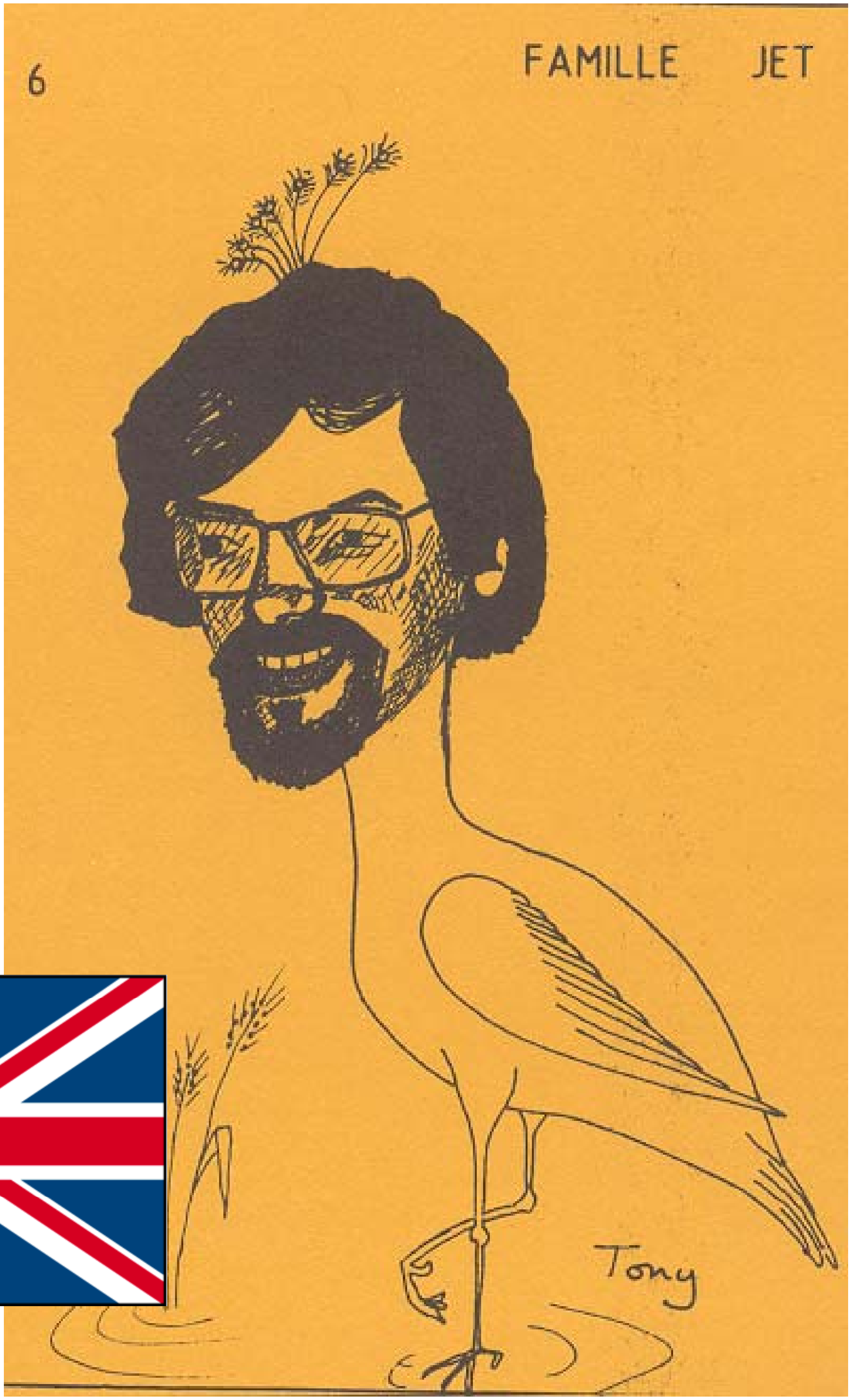
FAMILLE NUTSNBOLTS

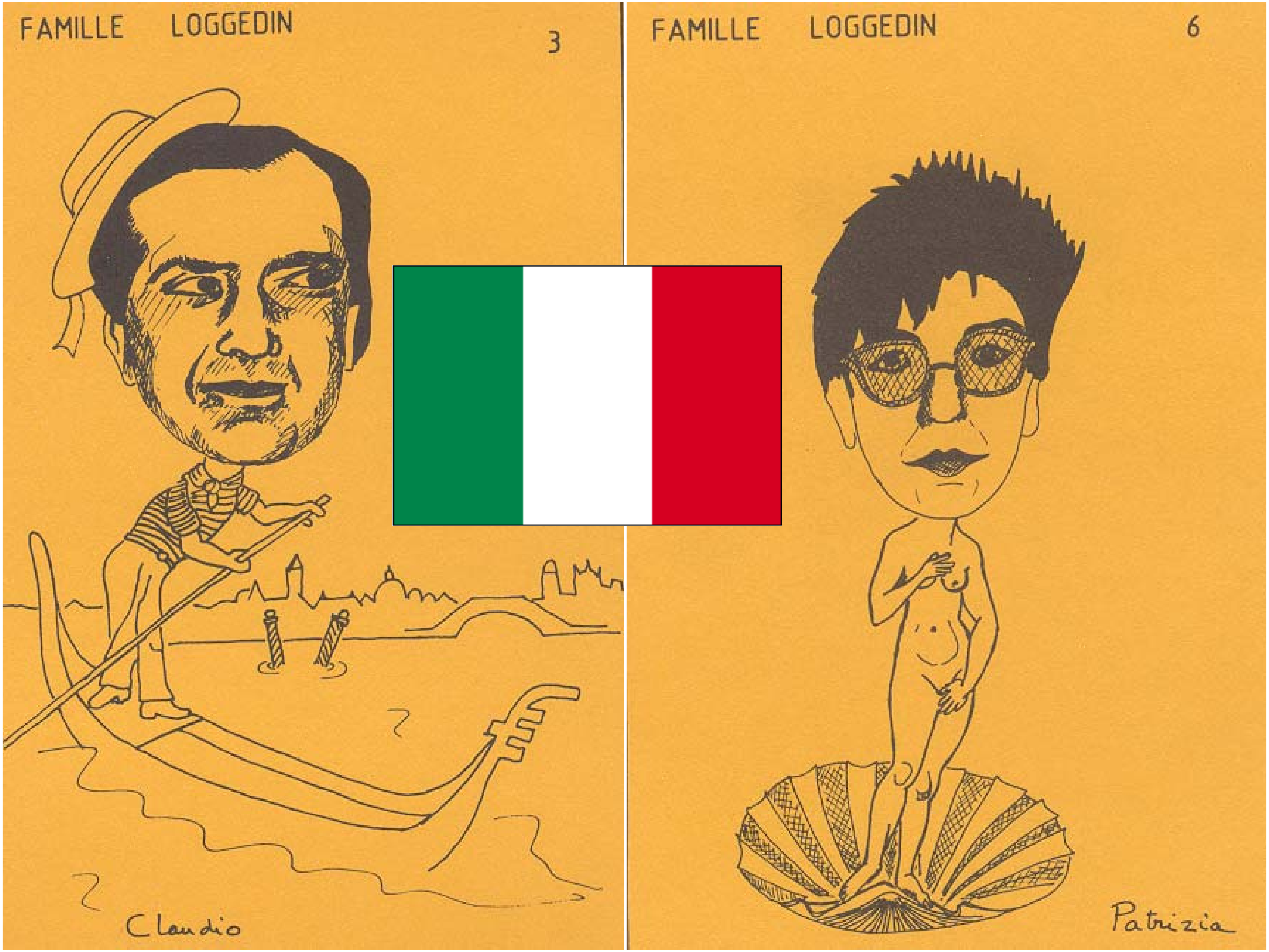


FAMILLE JET

5


FAMILLE TOURNEBANDE
3
Andy


6
FAMILLE JET
Tony


FAMILLE LOGGEDIN
3
Claudio
FAMILLE LOGGEDIN
6
Patrizia


Jürg
4
FAMILLE BOSON


FAMILLE SAINT-QUANTÔME
3
Kurt

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

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!

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 (D.F. and P. Sphicas) at

Sociological aspects become important!

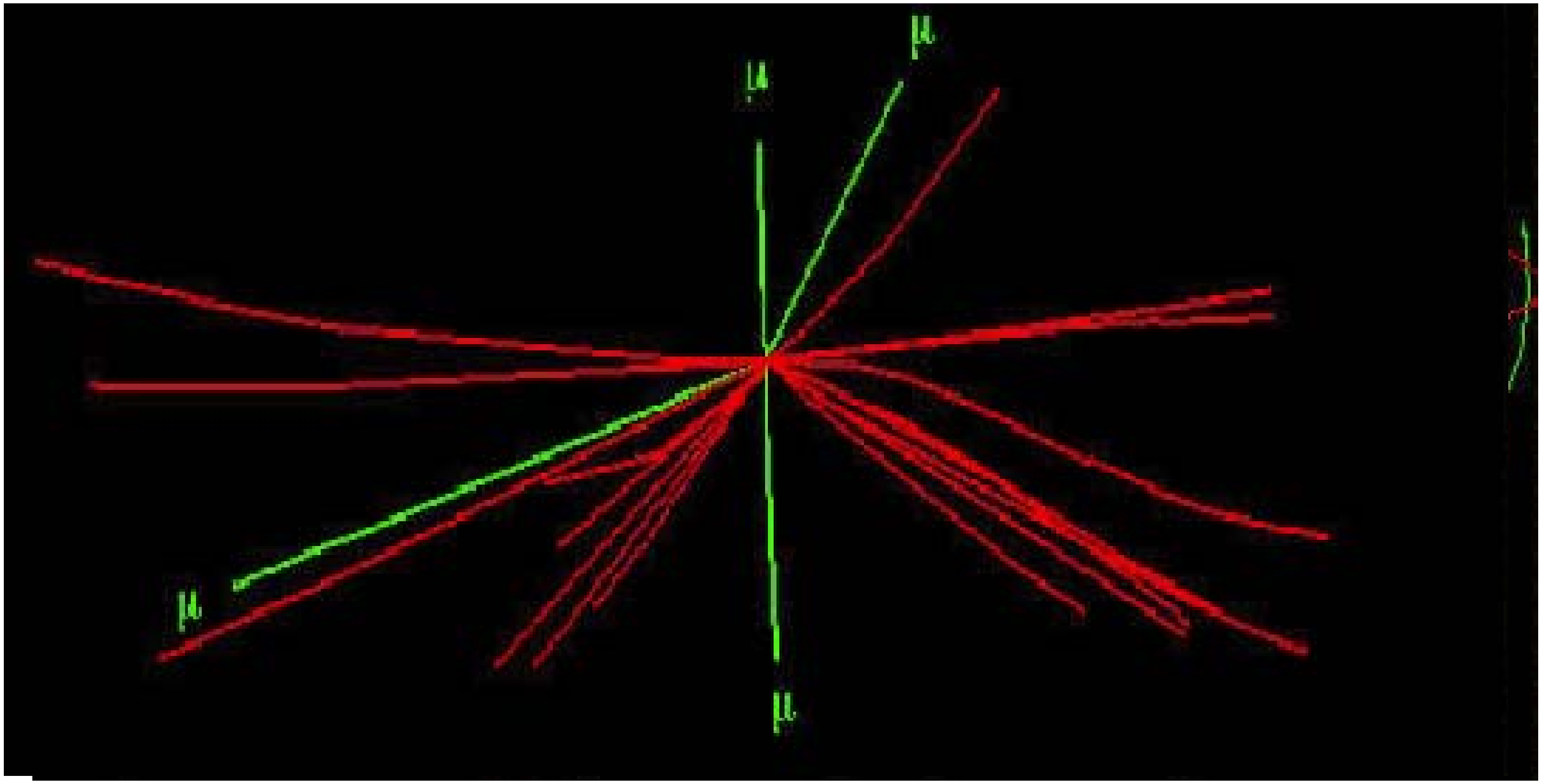
- The bigger the experiment, the more formal it has to be
  - This is the only way to keep people focused towards the same target
  - Strength of international collaboration is huge if formally channelled
  - Must preserve scientific integrity when facing the competition (inside and outside collaboration
- Recognition of individual contributions has to find new path
  - Publications will be always with full author list (as in today's large collaborations
  - Large collaborations can reward their best individuals through internal mobility
  - Conference talks and proceedings become almost the only way to appear as an individual outside collaboration

  - But is this sufficient? Time will tell.

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

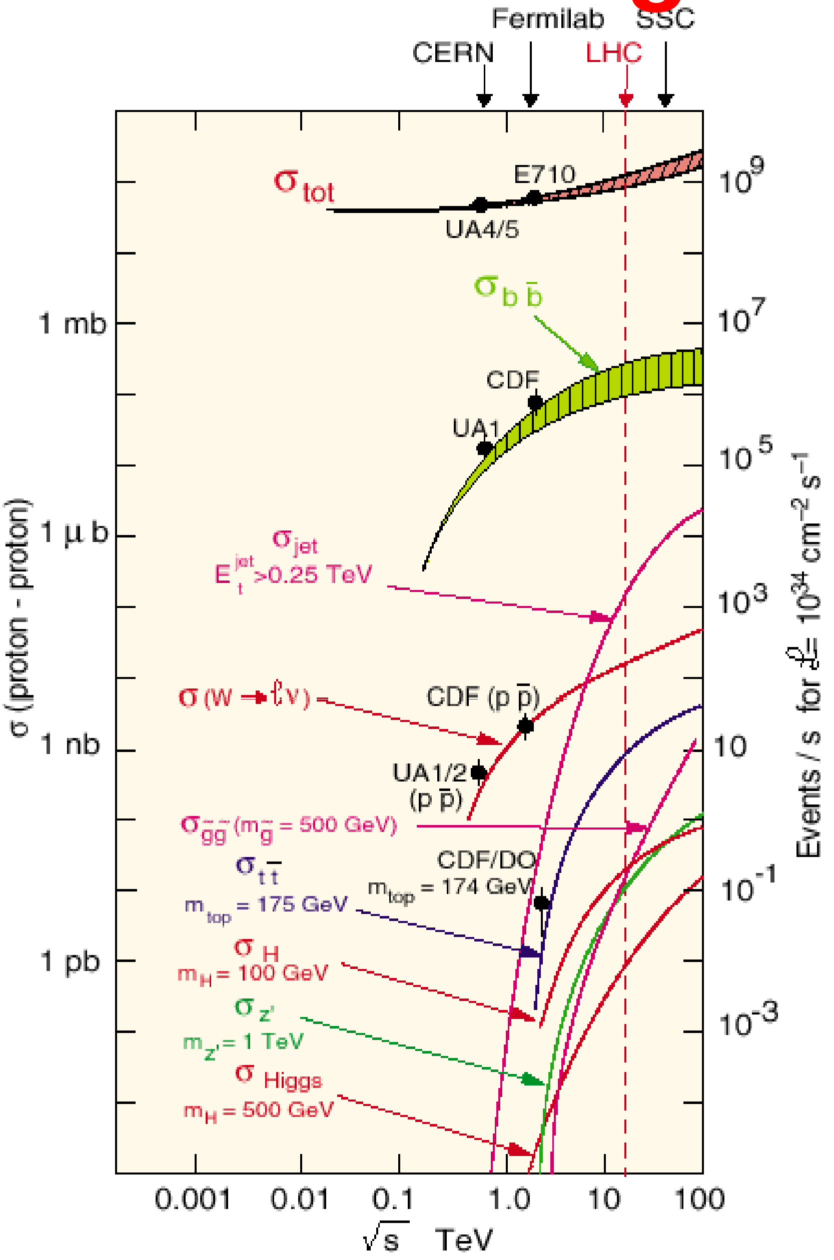
for various physics channels:

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

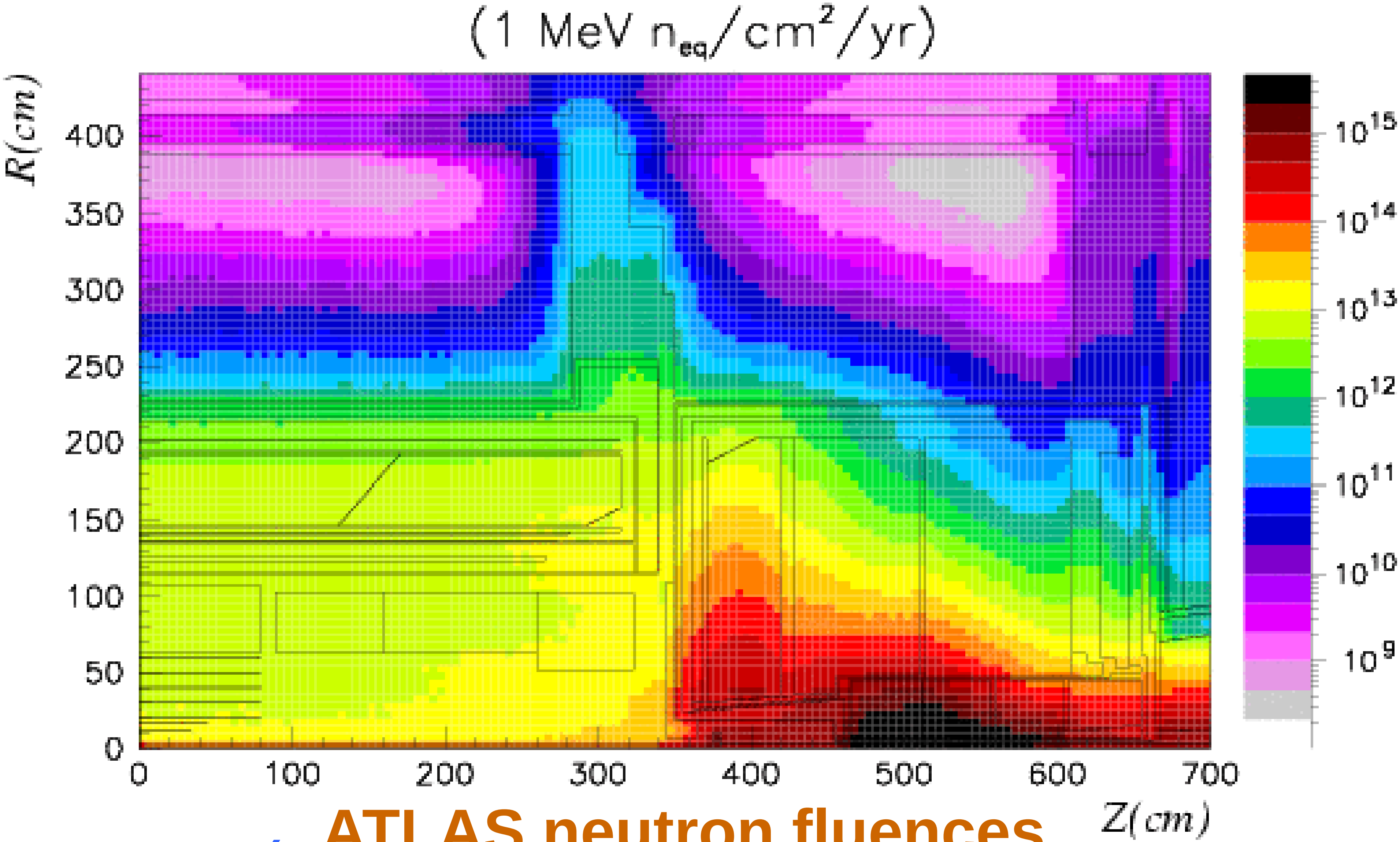
All masses in GeV

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)

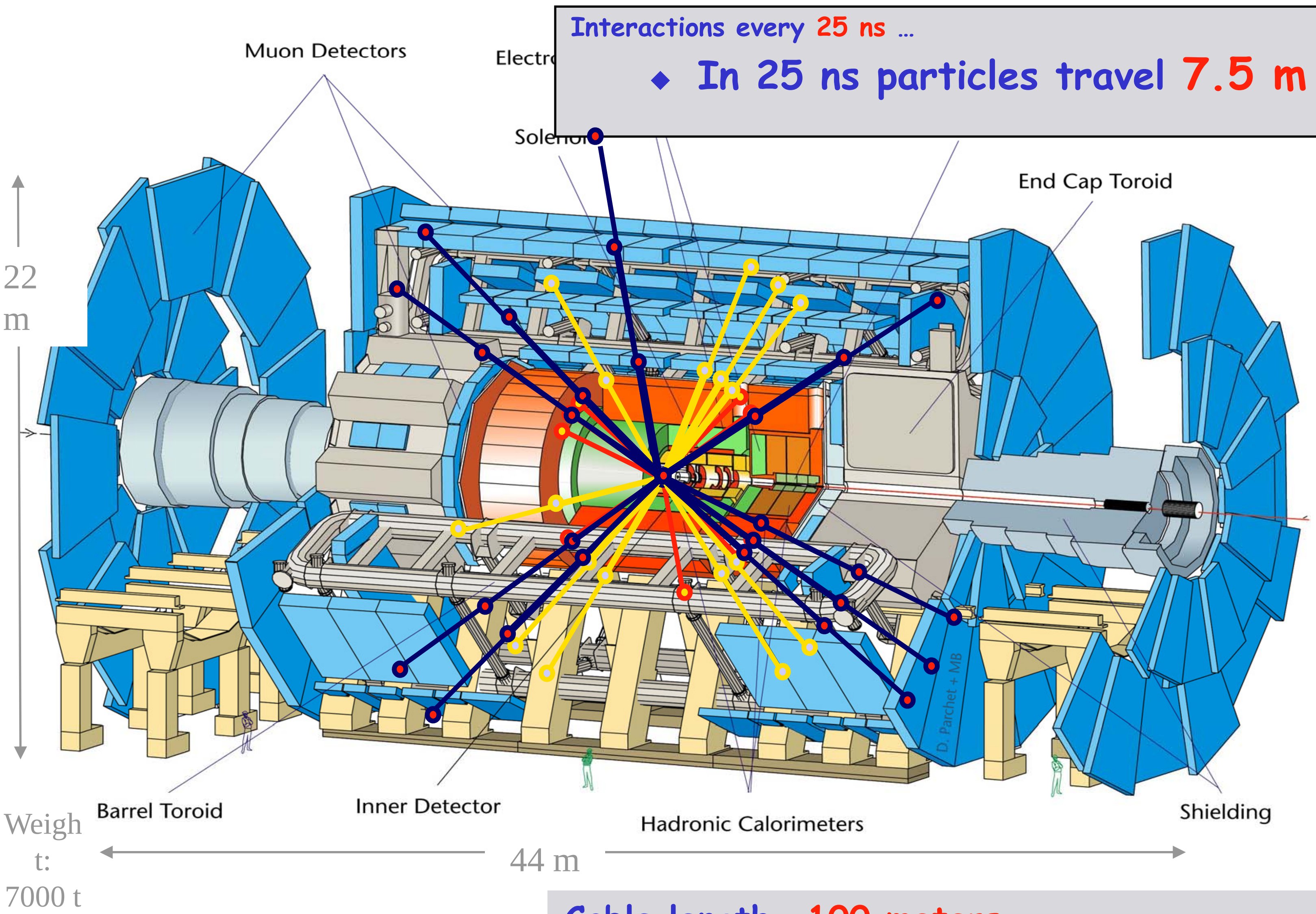
Physics at the LHC: the environment



ATLAS neutron fluences

Physics at the LHC: the environment

Time-of-flight



Interactions every 25 ns …

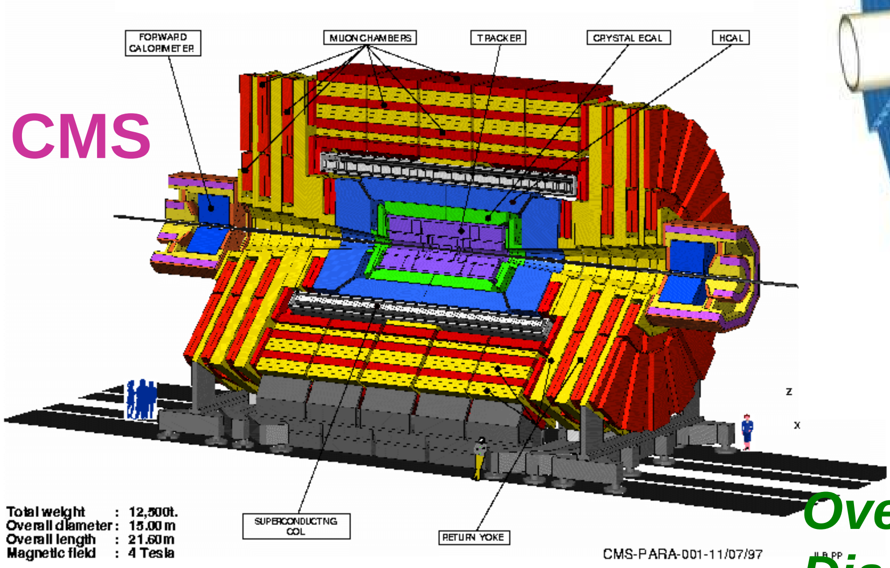
- In 25 ns particles travel 7.5 m

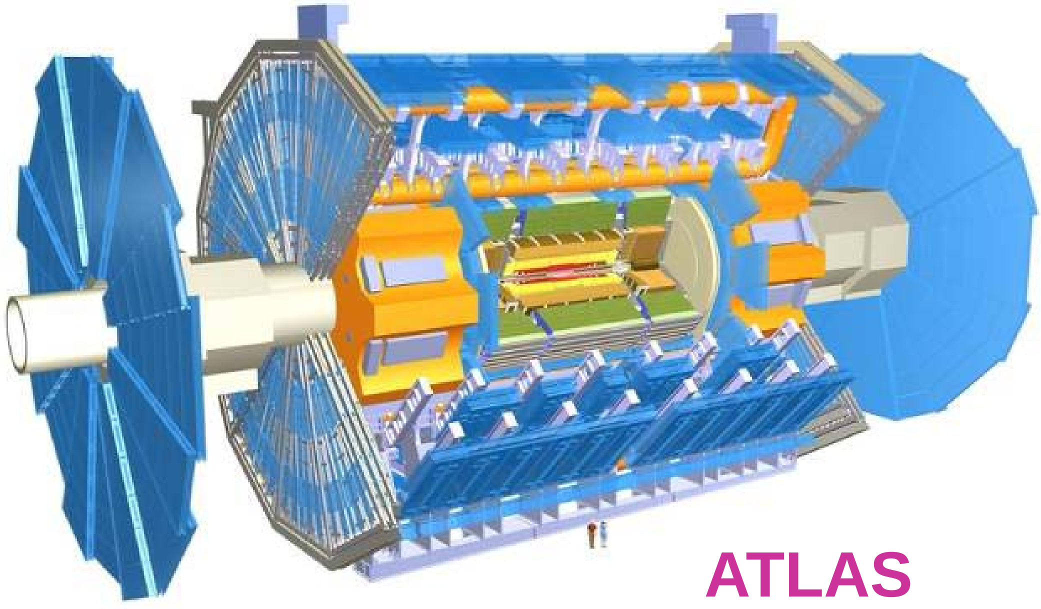
Cable length ~100 meters …

- In 25 ns signals travel 5 m

How huge are ATLAS and CMS?

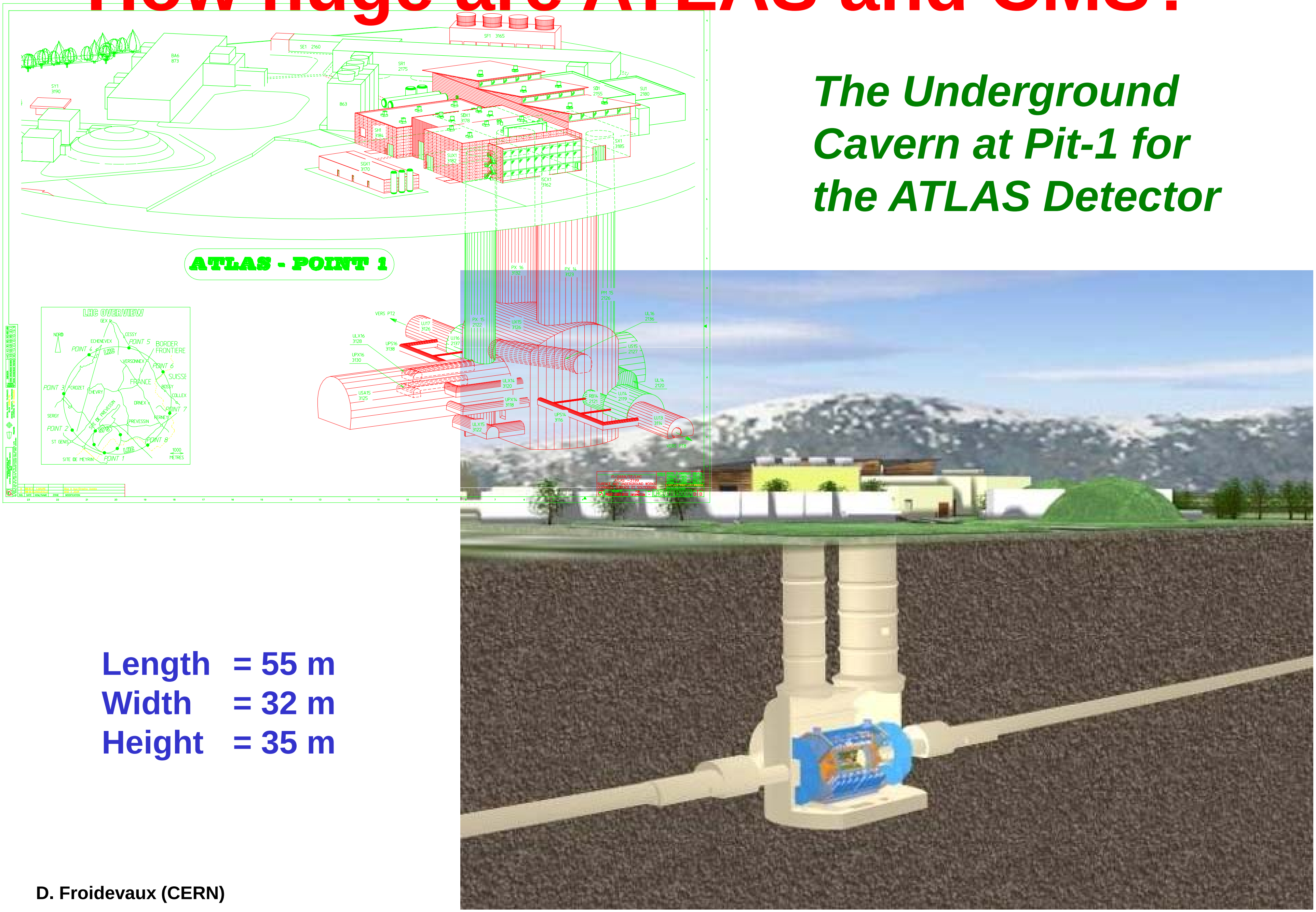
ATLAS superimposed to the 5 floors of building 40





	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?

- 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 (early 2009?)
- 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!

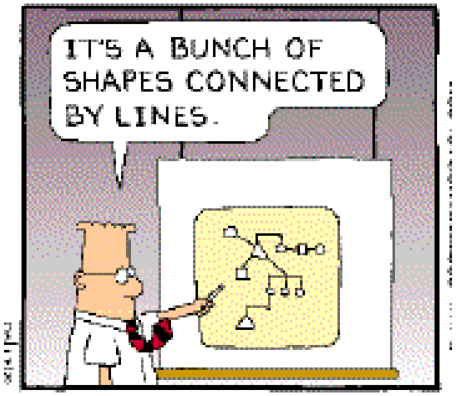
Proton bunch-crossing rate: 40 MHz → 200-400 Hz to mass storage (tape!)

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 July 2006)

35 Countries
162 Institutions
1650 Scientific Authors
(1300 with a PhD)

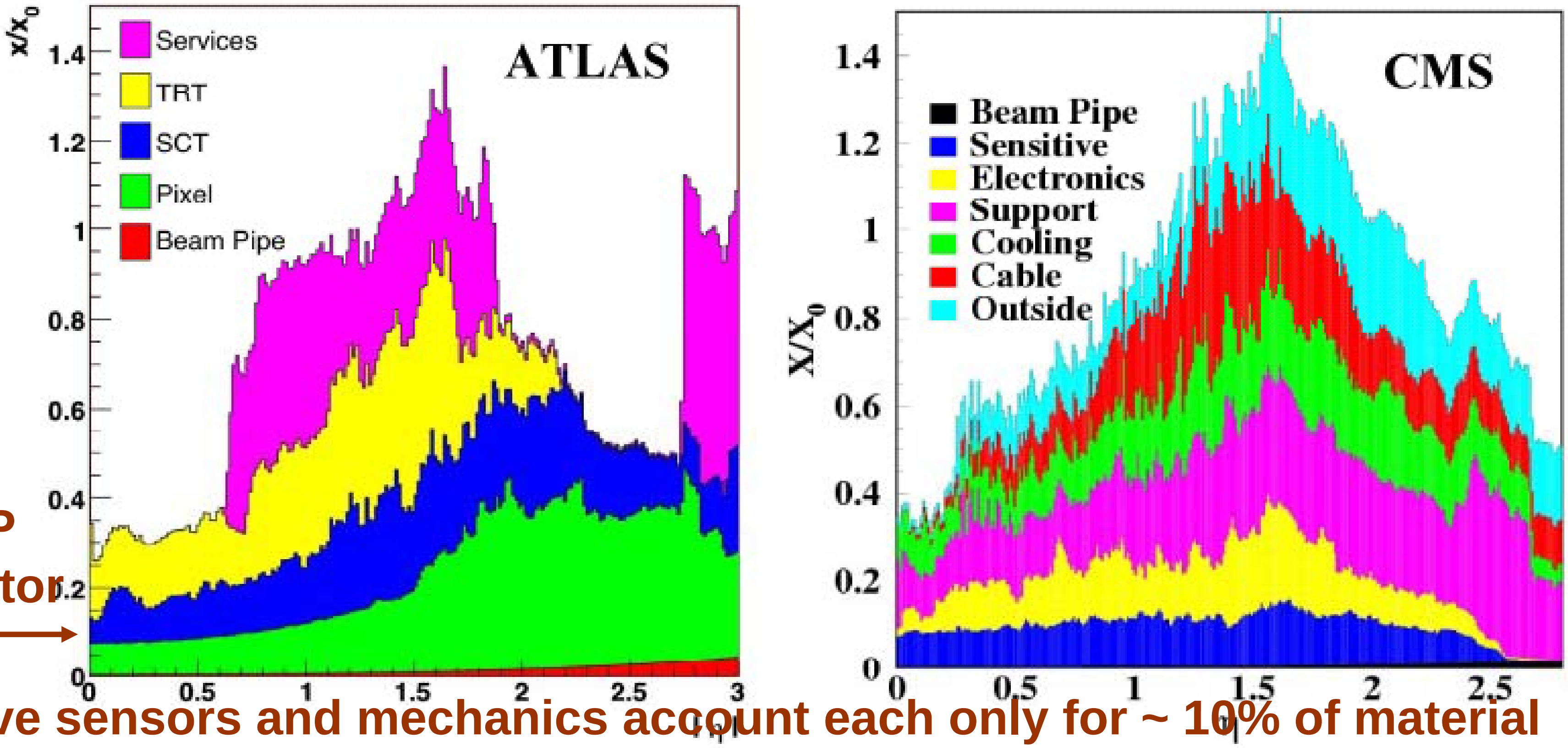
Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizona, UT Arlington, Athens, NTU Athens, Baku,
IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, Bern, Birmingham, Bologna, Bonn, Boston, Brandeis,
Bratislava/SAS Kosice, Brookhaven NL, Buenos Aires, Bucharest, Cambridge, Carleton, 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

ATLAS/CMS: from design to reality

Amount of material in ATLAS and CMS inner trackers

Weight: 4.5 tons

Weight: 3.7 tons

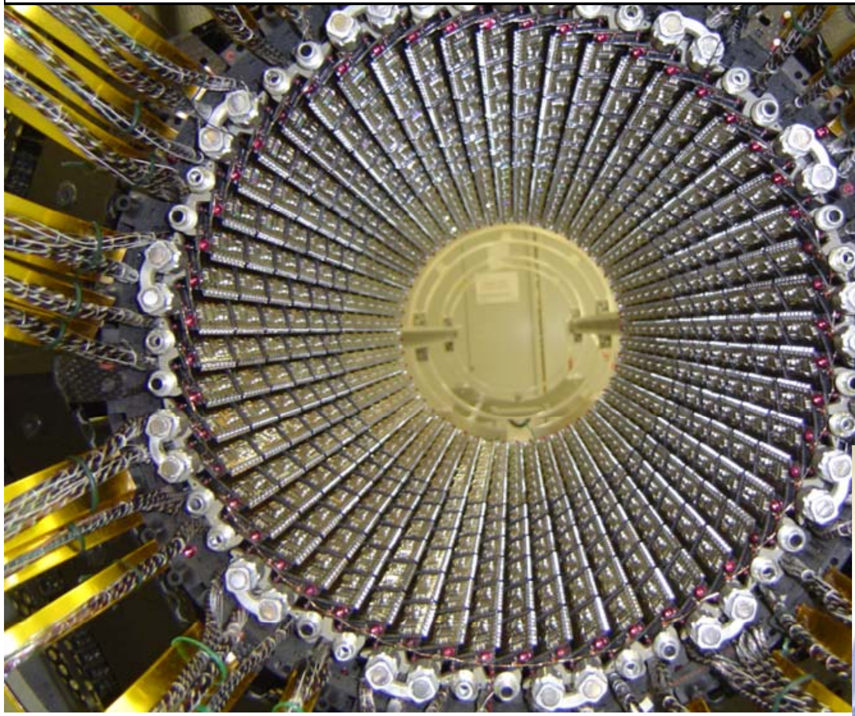


LEP detectors →

- Active sensors and mechanics account each only for ~ 10% of material budget
- Need to bring 70 kW power into tracker and to remove similar amount of heat
- Very distributed set of heat sources and power-hungry electronics inside volume: this has led to complex layout of services, most of which were not at all understood at the time of the TDRs

Remember that tracking at the LHC is a risky business!

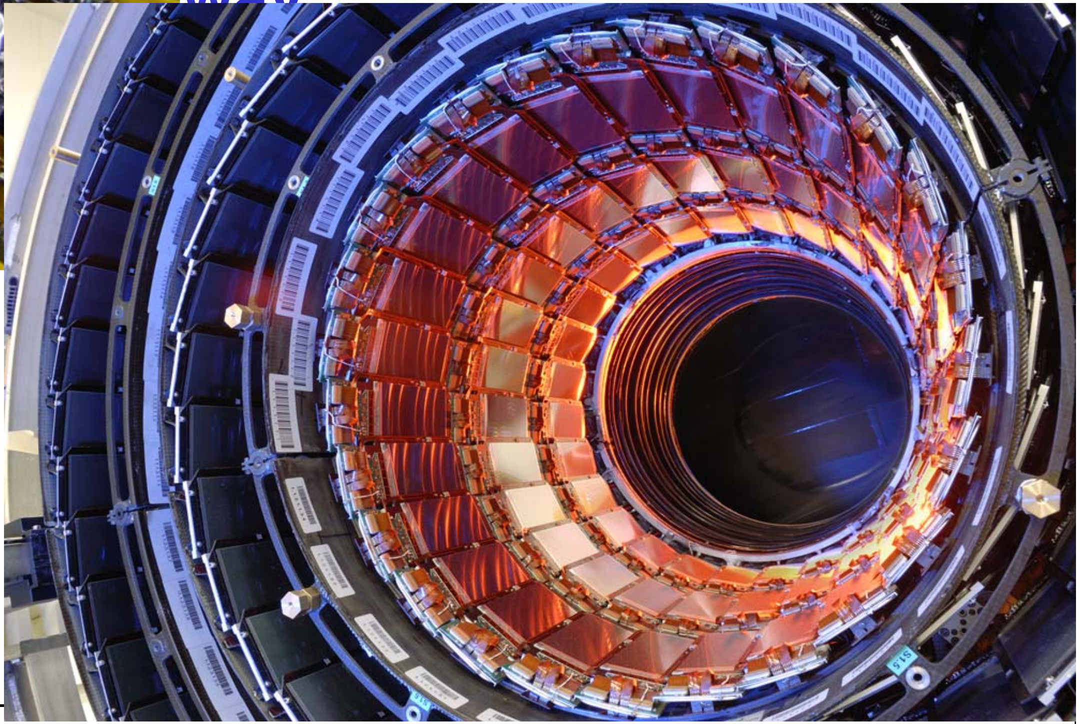
ATLAS pixels, September 2006



- All modules and services integrated and tested
- 80 million channels !
- 10%-scale system test with cosmics done at CERN

CMS silicon strips

- 200 m^2 Si, 9.6 million channels
- 99.8% fully operational
- Signal/noise ~ 25/1
- 20% cosmics test under way



CMS Tracker Inner Barrel, November 2006

How operational will LHC detectors be in summer 2009?

Current status of ATLAS: installation and global commissioning finished

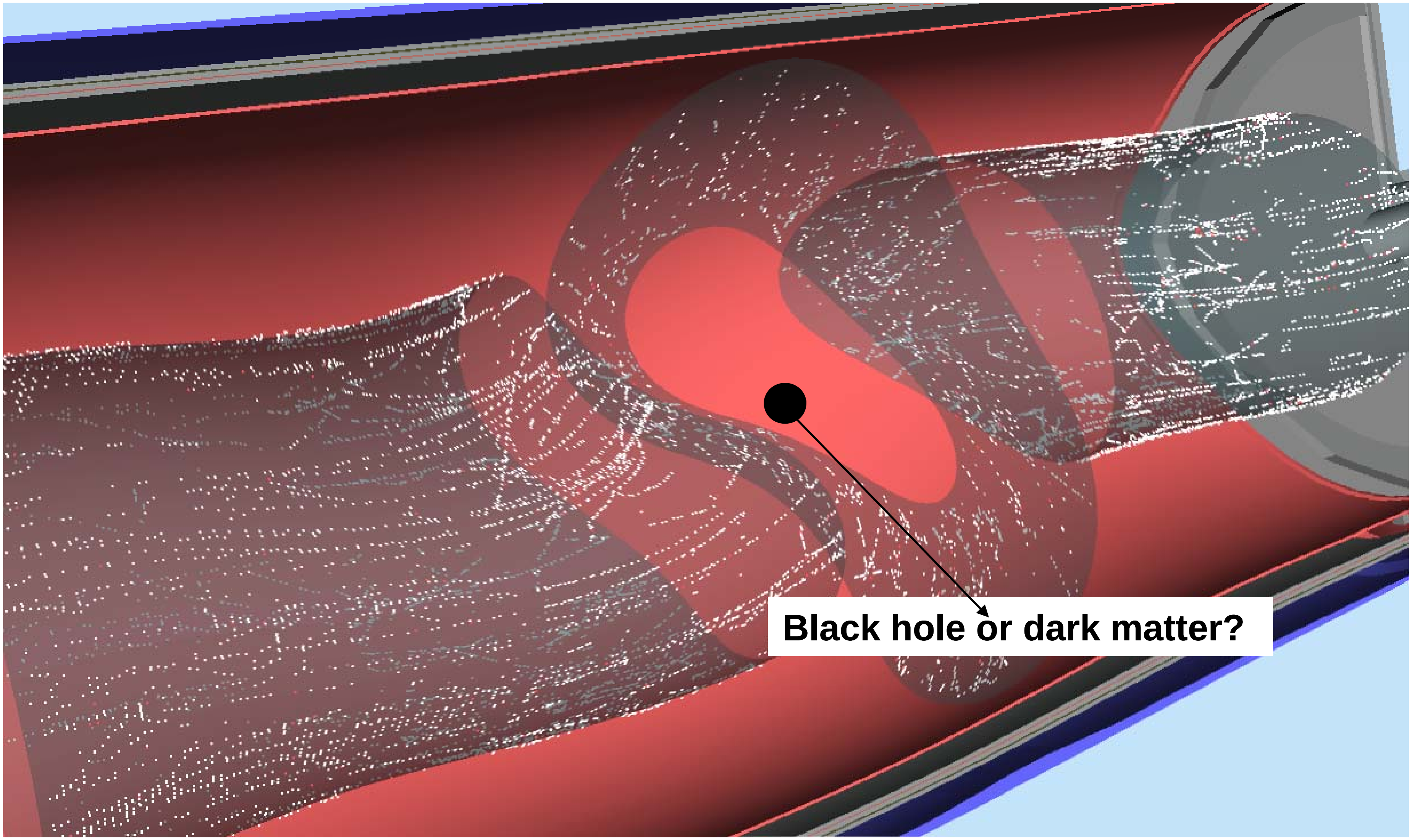
All measurements below given in situ after installation, cabling and sign-off (but not always for 100% of all channels)

ATLAS sub-detector	Nb of channels	Non-working channels(%)
Pixels	$80x10^6$	0.4
Silicon strip detector (SCT)	$6x10^6$	0.3
Transition Radiation Tracker (TRT)	$3.5x10^5$	1.5
Electromagnetic calorimeter	$1.7x10^5$	0.04
Fe/scintillator (Tilecal) calorimeter	9800	0.8
Hadronic end-cap LAr calorimeter	5600	0.09
Forward LAr calorimeter	3500	0.2
Barrel Muon Spectrometer	$7x10^5$	0.5
End-cap Muon Spectrometer (TGC)	$3.2x10^5$	0.02

Current status of CMS:

pixels and end-cap crystals installed last summer, a real feat: just in time!

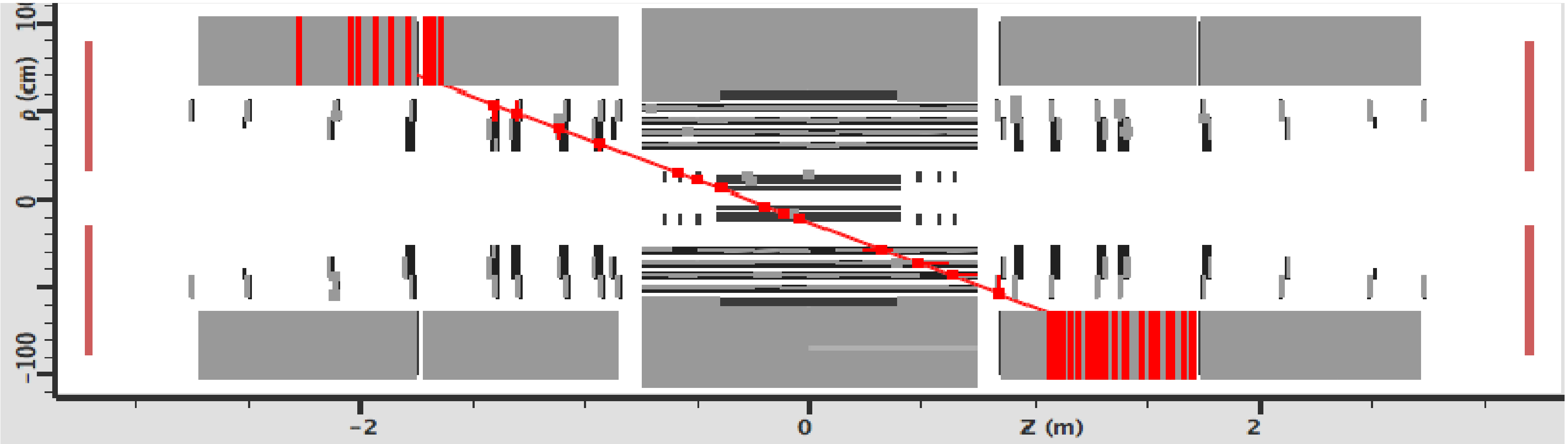
Artist view of beam halo event in ATLAS TRT

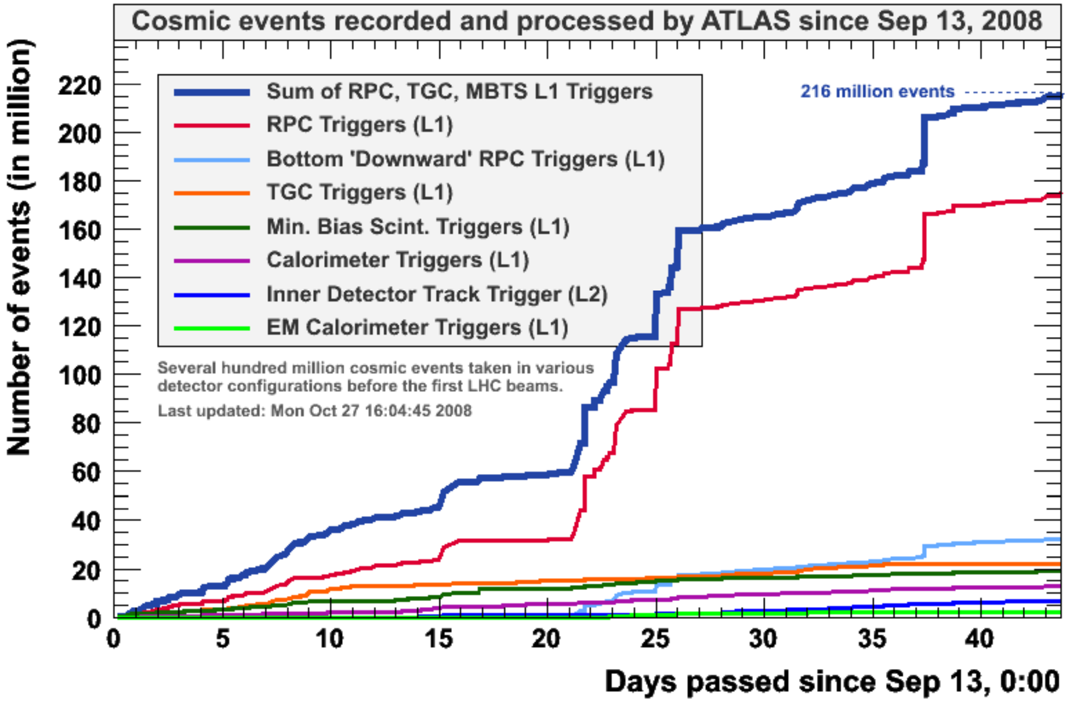


Black hole or dark matter?

Note that beam conditions were not yet considered safe enough to operate ATLAS silicon-strip or pixel detectors at nominal settings

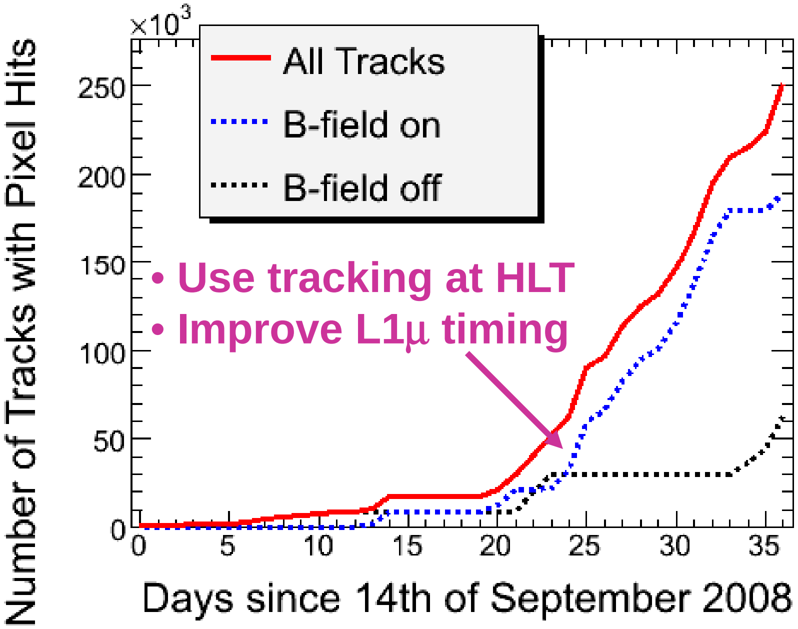
Global cosmics: accumulate data for calibration and alignment and get better prepared for 2009 collisions





Several hundred million cosmic events taken in various detector configurations before the first LHC beams.

Last updated: Mon Oct 27 16:04:45 2008

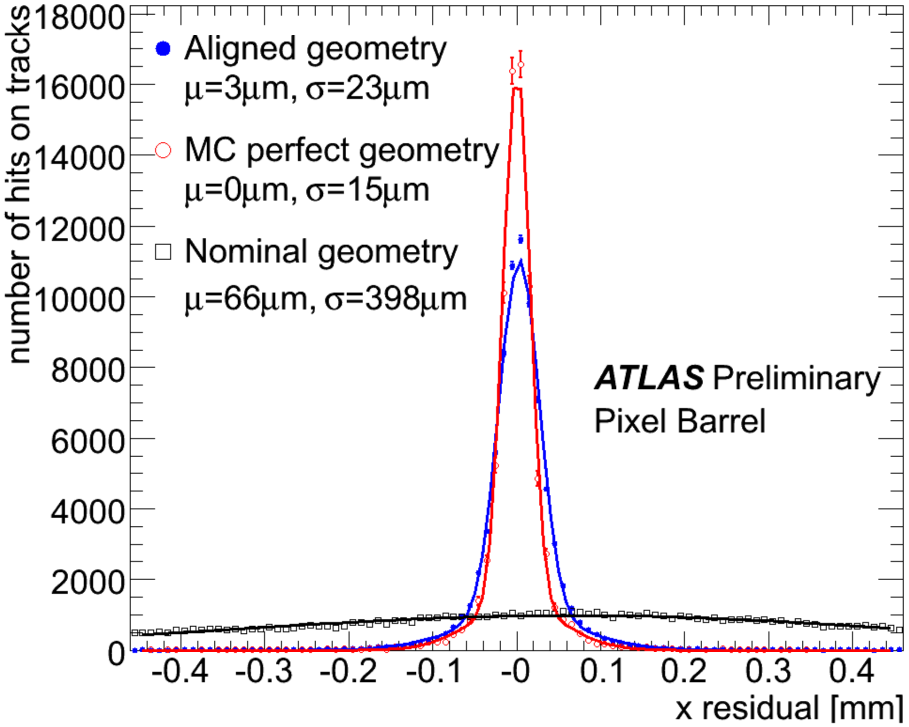


- Use tracking at HLT
- Improve L1μ timing

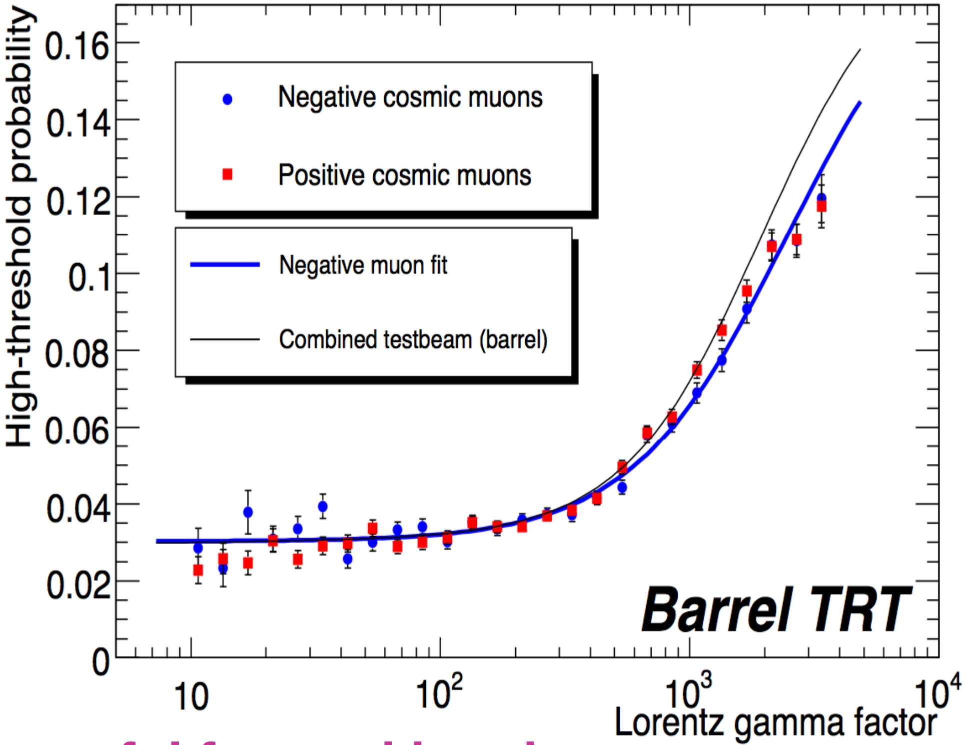
03/04/2009

Global cosmics: accumulate data for calibration and alignment and get better prepared for 2009 collisions

Cosmic-ray data with solenoid on: look at 200k tracks going through pixels



Cosmic-ray data with solenoid on: look at 2M tracks going through barrel TRT



Cosmic-ray data particularly useful for tracking detectors:

- See talks by M.-J. Costa and T. Rodrigo on ATLAS/CMS commissioning
- Calibration of gaseous detectors (e.g. high threshold for TRT)
- Alignment of inner detector and muon spectrometer systems (e.g. pixels)

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 will 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.

Fortunately, there is much more to experimental particle physics than its dinosaurs!