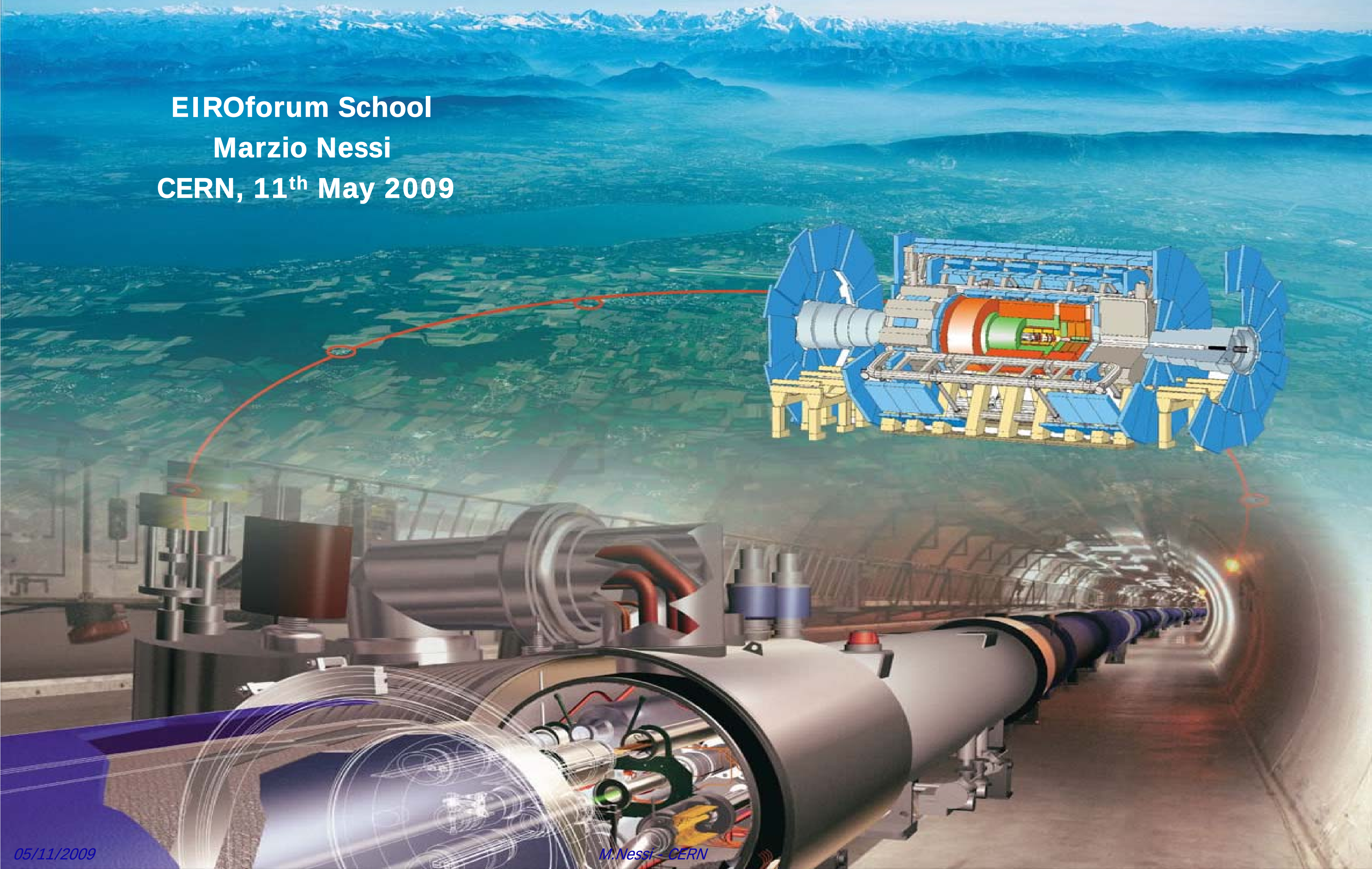
Detector Systems and HEP Applications

EIROforum School
Marzio Nessi
CERN, 11th May 2009



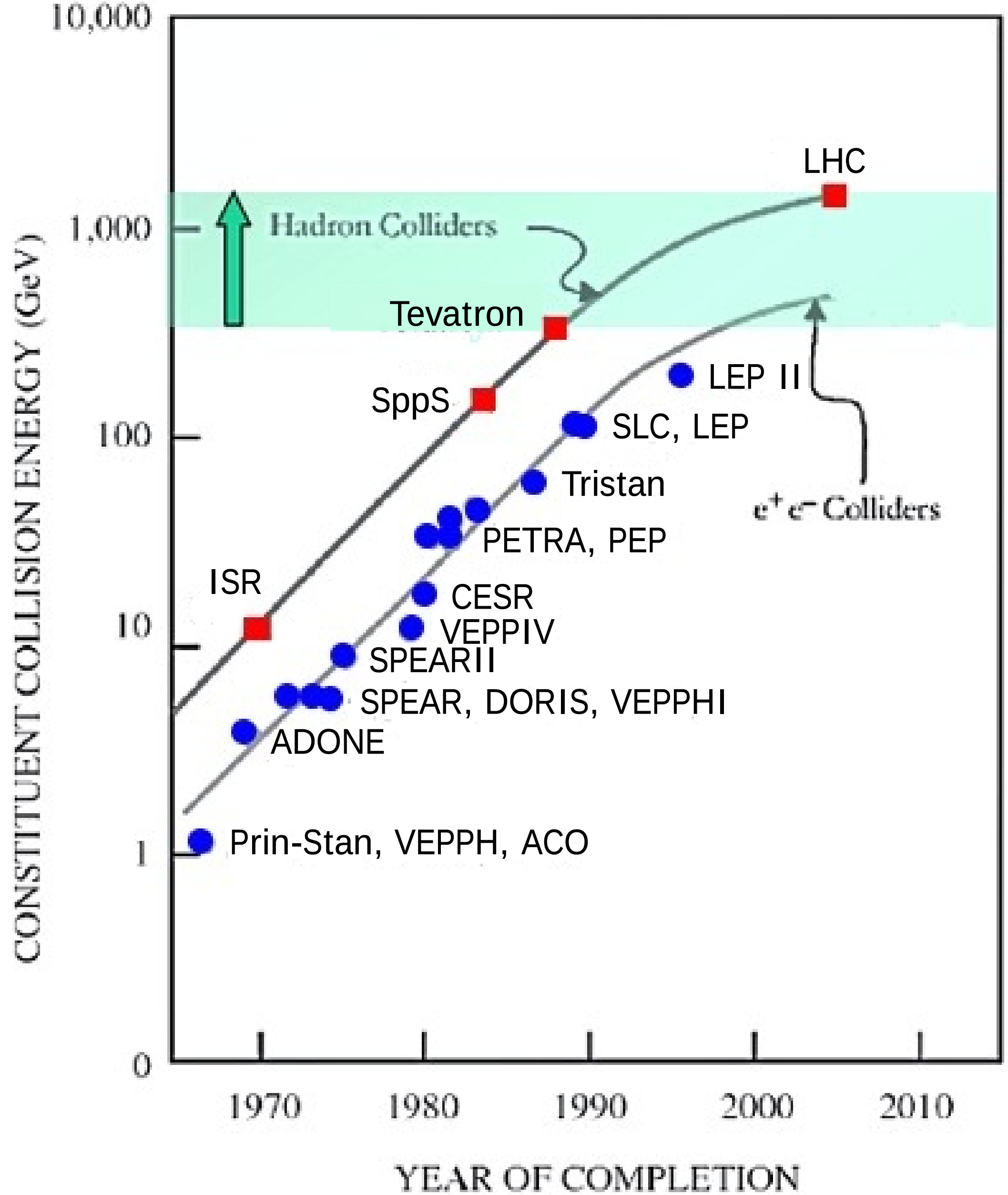
Introduction

- ✓ Today HEP main priority is to investigate the new energy domain opened by the LHC (Large Hadron Collider) : 7 +7 TeV CM energy

- ✓ To arrive there the overall HEP community has invested, as never before, in a single facility (here at CERN) since almost 15 years :

accelerator +

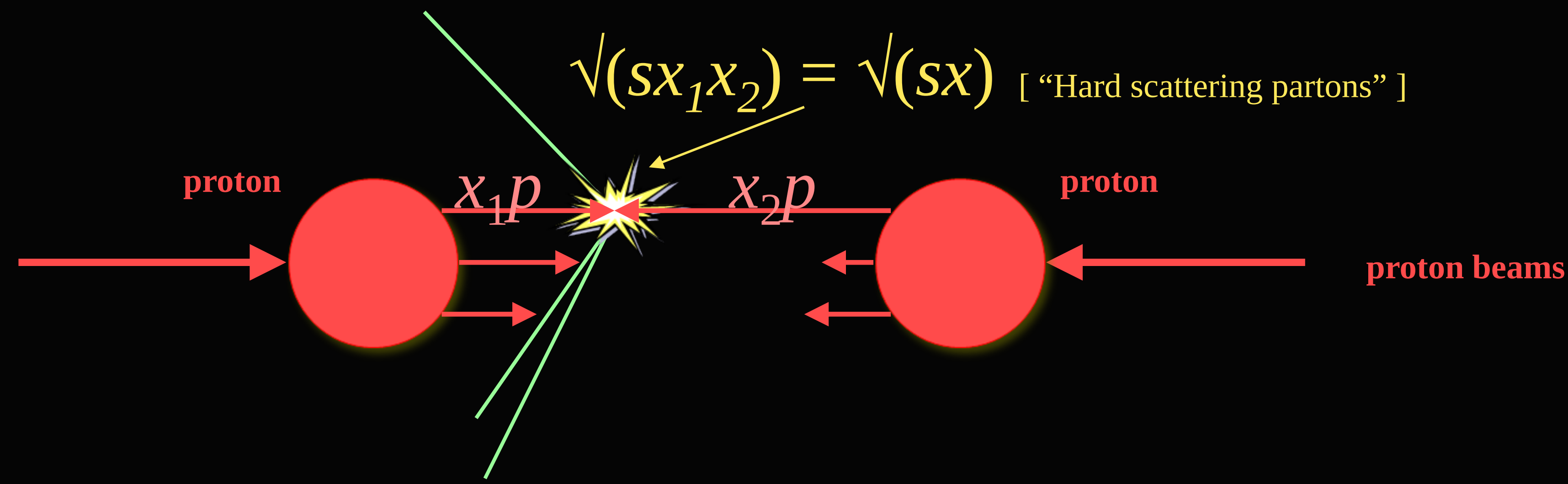
detectors



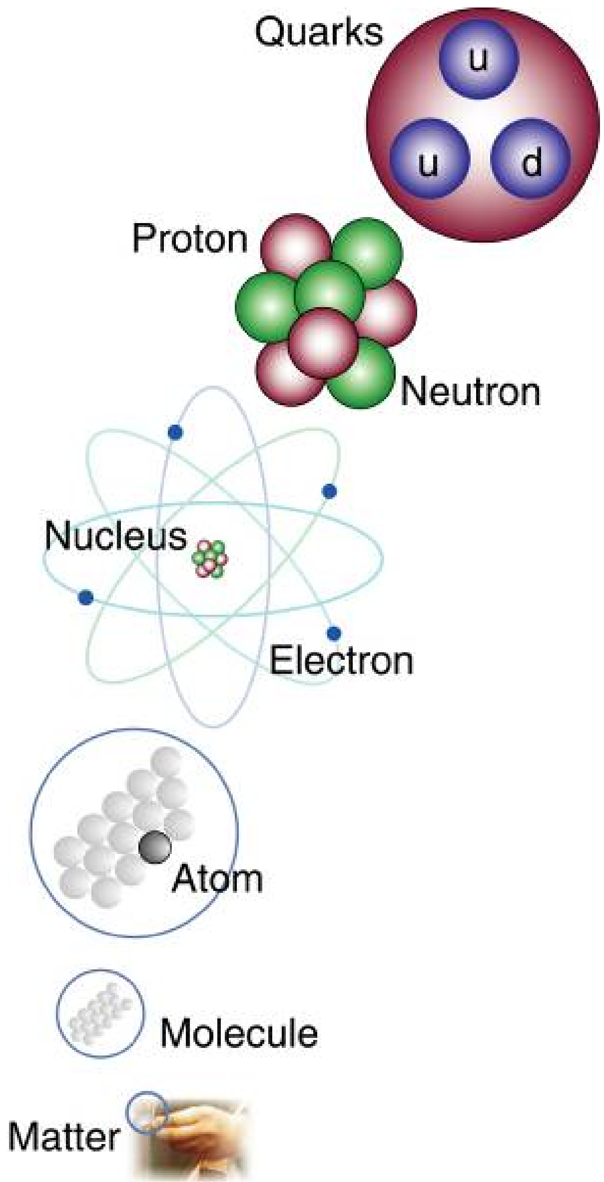
Our Mission

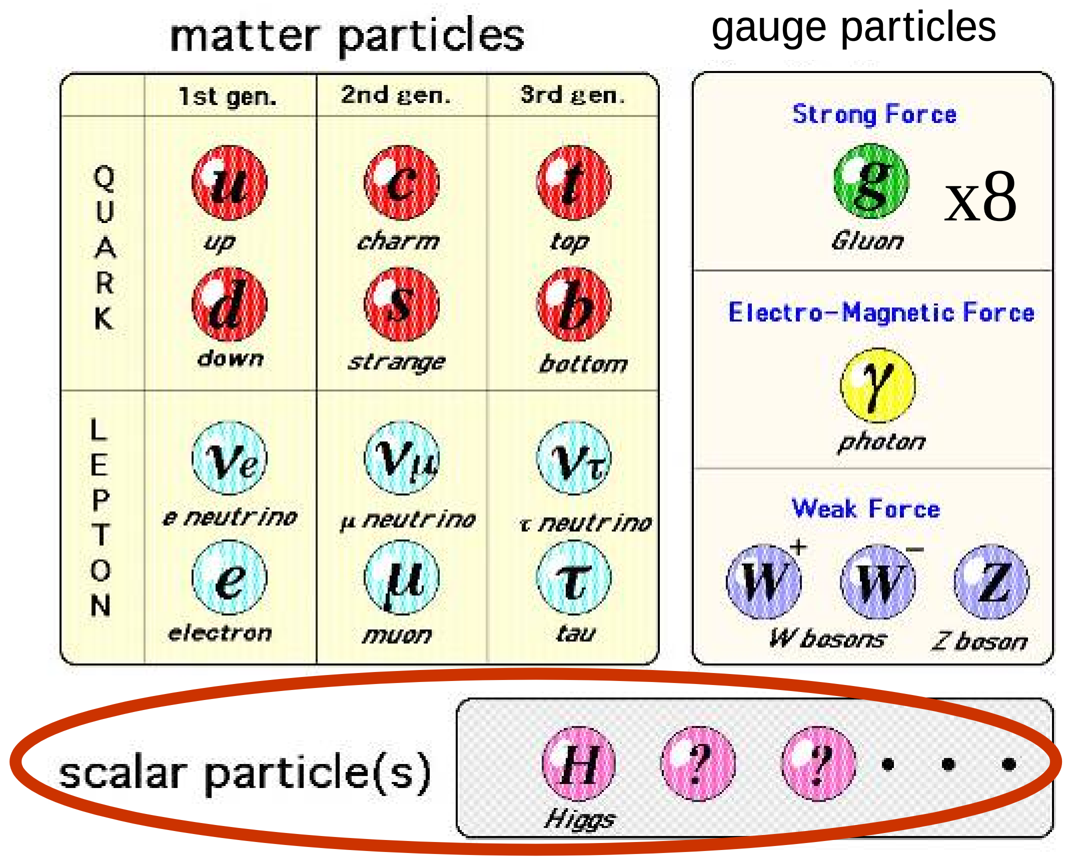
LHC will deliver proton-proton collisions at 14 (7 + 7) TeV.
This will allow us to explore a new energy domain were the matter constituents (partons) will collide with an unprecedented centre-of-mass energy up to 14 TeV

.... with expected peak collision rates ~ 30 MHz for a beam
Luminosity= 10^{34} cm^{-2} s^{-1}



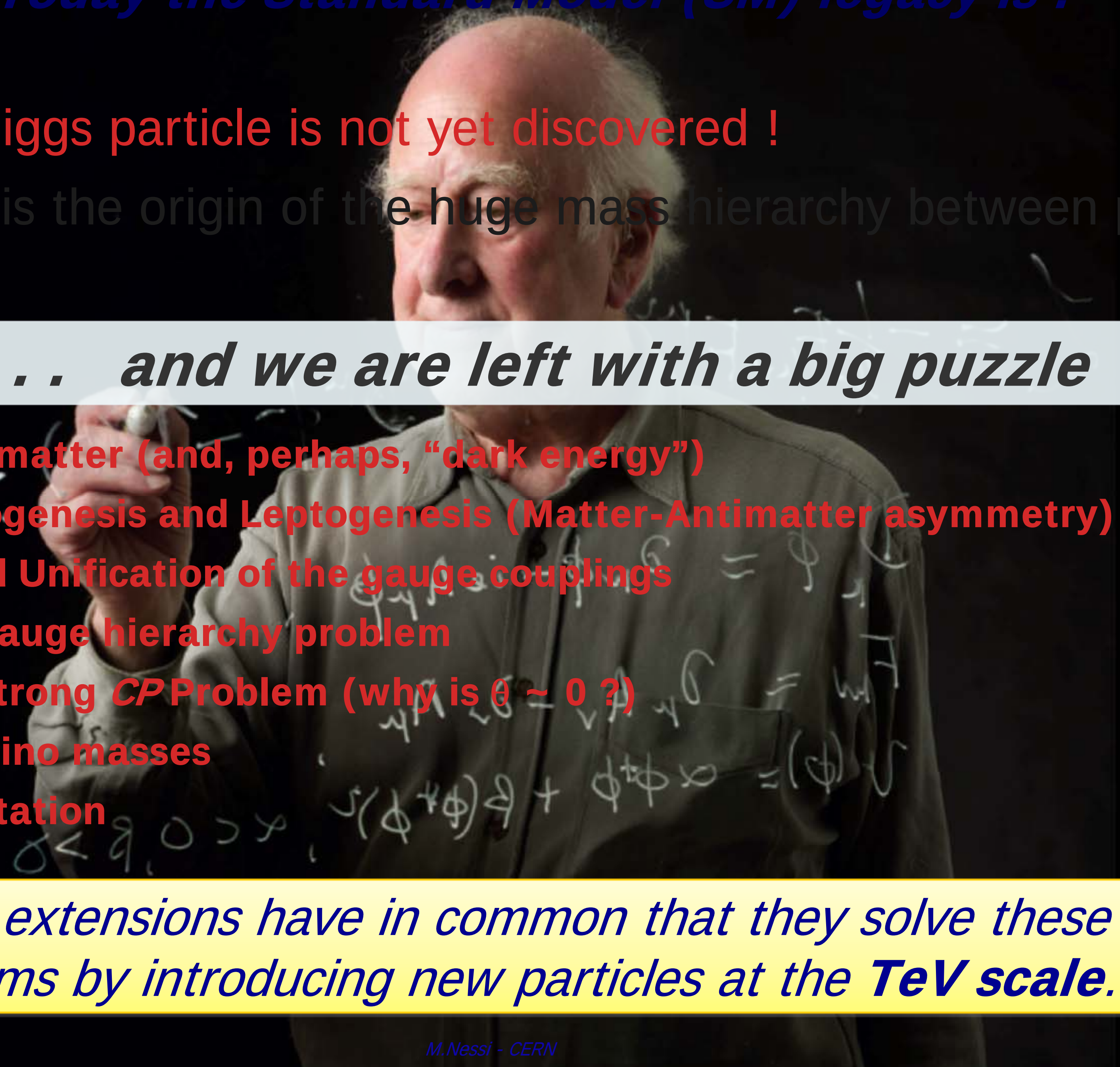
Over several decades, the study of elementary particles and fields and of their interactions has consolidated the present Standard Model





Elements of the Standard Model

Today the Standard Model (SM) legacy is :



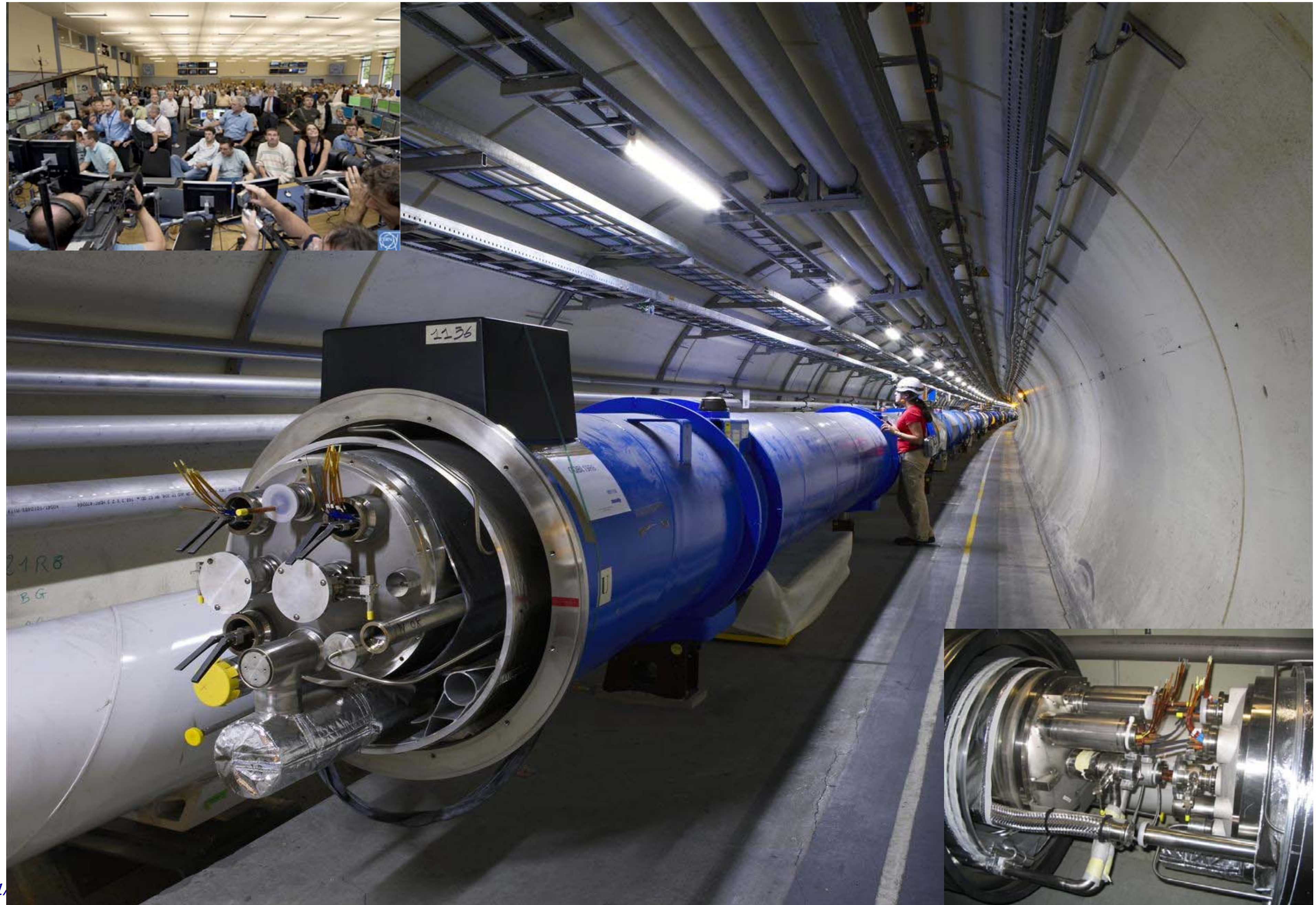
- The Higgs particle is not yet discovered !
- What is the origin of the huge mass hierarchy between particles ?

. . . and we are left with a big puzzle

- ✓ **Dark matter (and, perhaps, "dark energy")**
- ✓ **Baryogenesis and Leptogenesis (Matter-Antimatter asymmetry)**
- ✓ **Grand Unification of the gauge couplings**
- ✓ **The gauge hierarchy problem**
- ✓ **The strong *CP* Problem (why is $\theta \sim 0$?)**
- ✓ **Neutrino masses**
- ✓ **Gravitation**

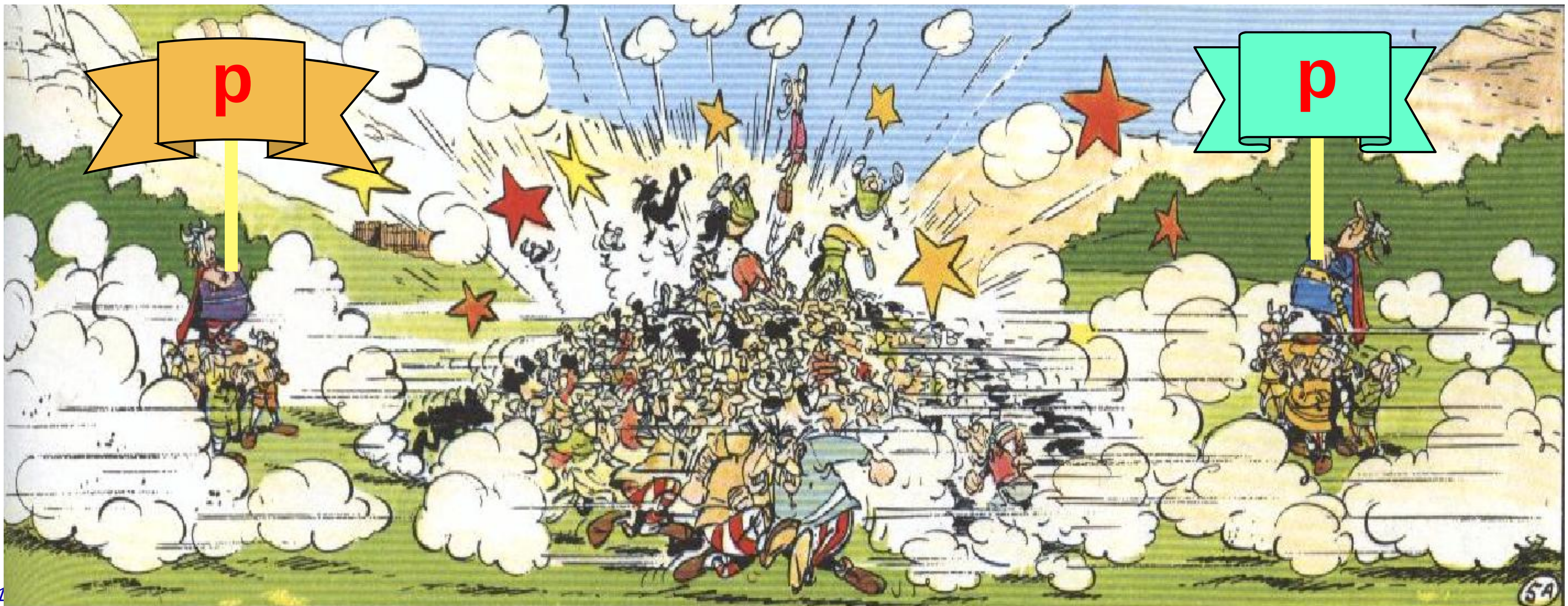
*All SM extensions have in common that they solve these problems by introducing new particles at the **TeV scale**.*

Mandatory : multi TeV accelerator (27 km) = LHC



What we need is a new generation of particle detectors

- Complex detectors around the interaction point:
  - *capable of facing a new environment (high energy, large backgrounds, fast timing, huge amount of data)*
  - *capable of exploring the variety of signals and energy deposition pattern*
  - *capable of facing new physics and be ready for surprises*



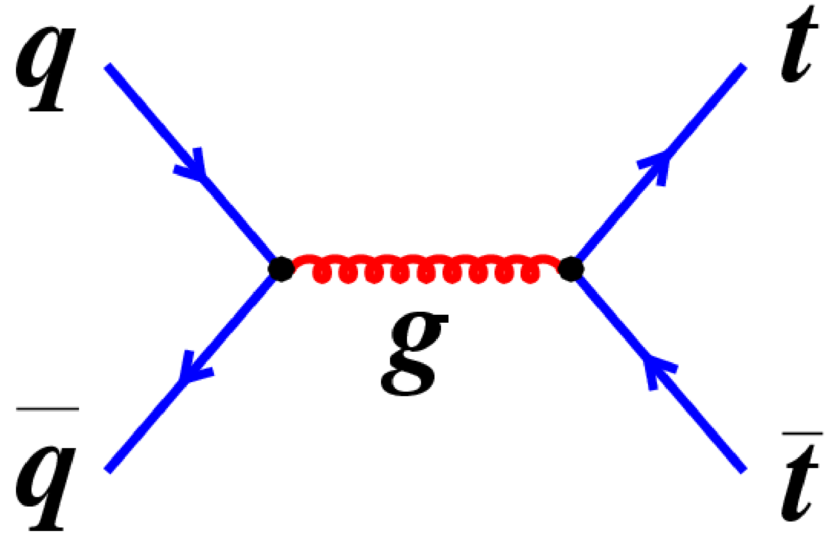
What are we really looking for ?

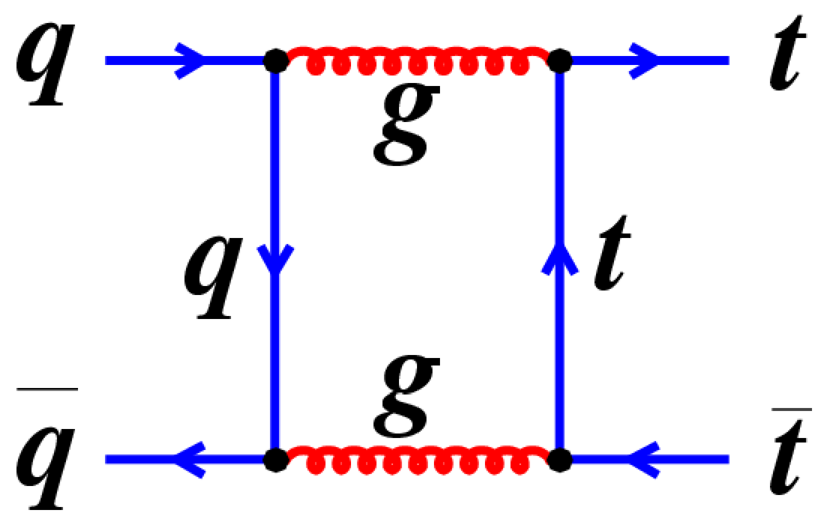
- ✓ Special and rare events, where new physics, new particles are involved

- ✓ Very central collisions between partons where the large energy density is source of new phenomena, large transverse momenta

- ✓ Parton level scattering is very fast ($\sim 10^{-24}$ sec) ... most of the actors involved are unstable and decay promptly into known forms of matter and energy

- ✓ We will learn about this new dynamics, by measuring the kinematics parameters of the visible decay chain through the interaction with the detector matter. We will need to measure momenta and energies of all stable decay products





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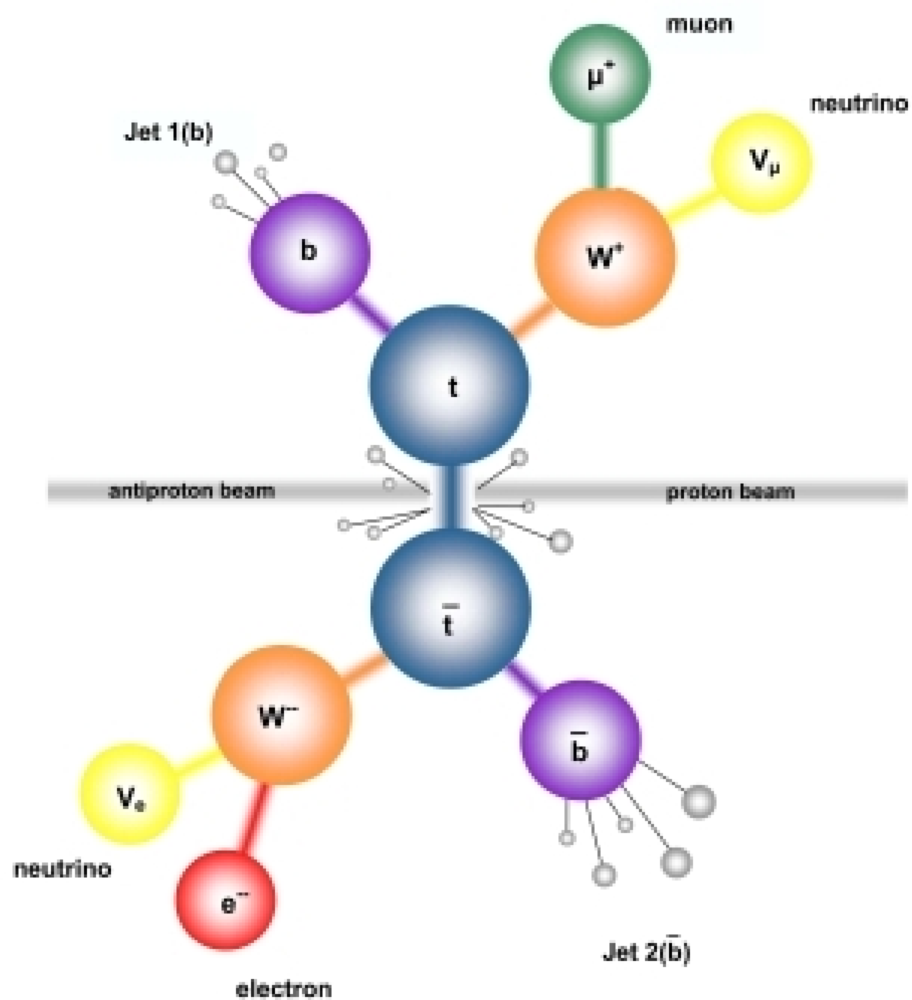

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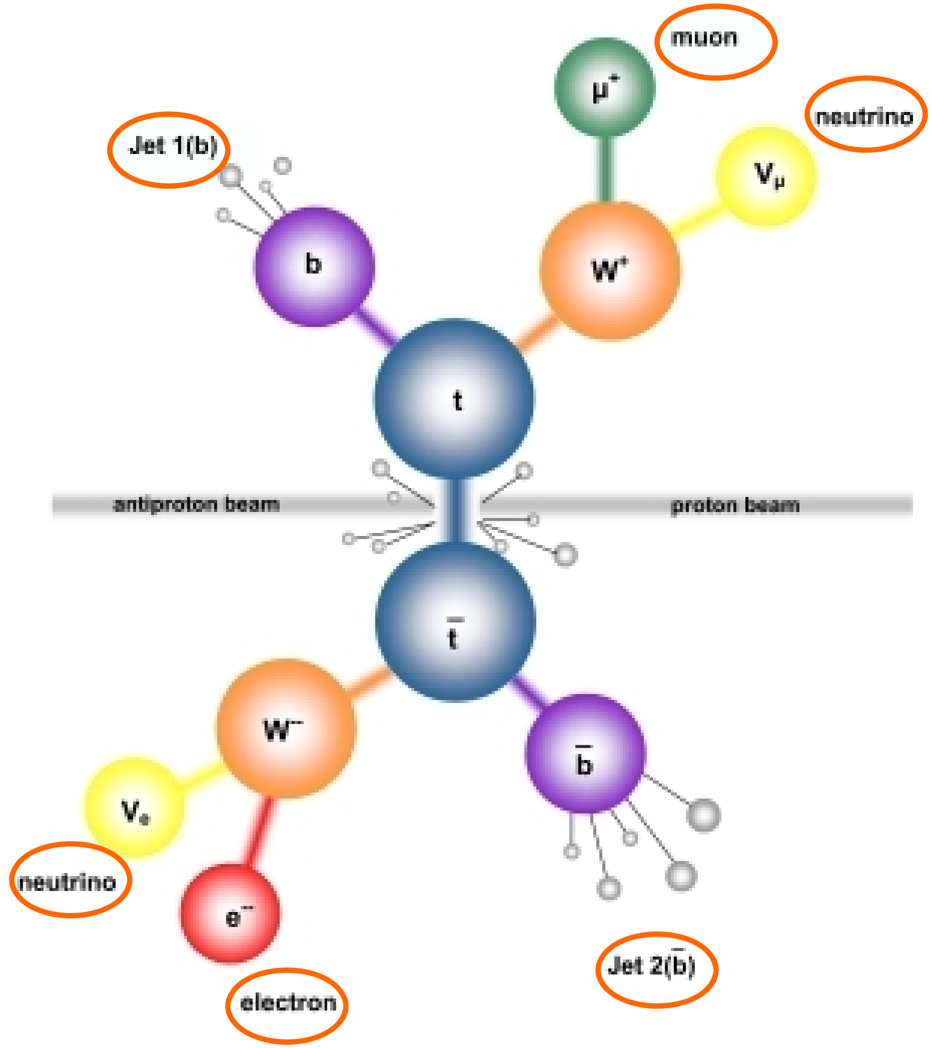


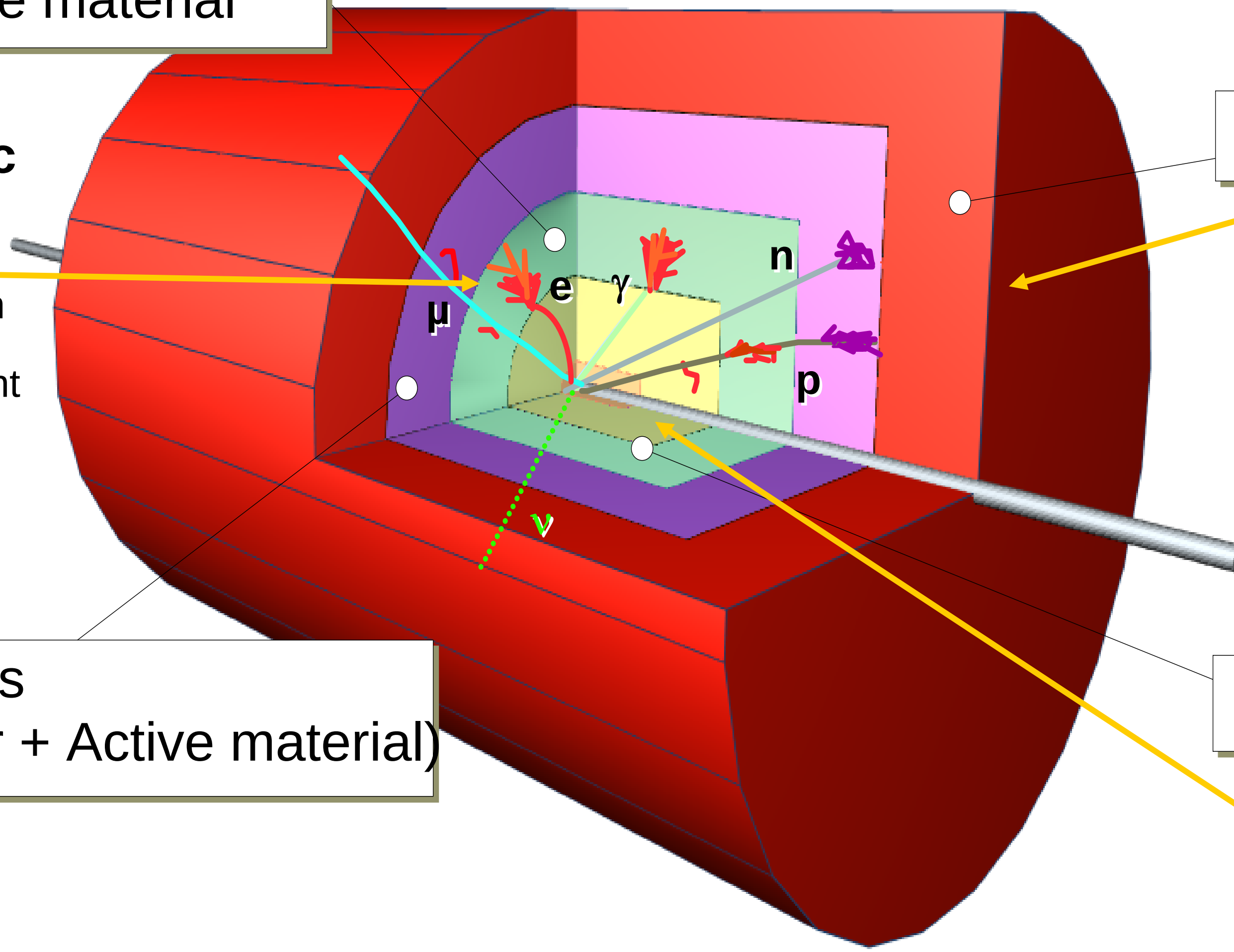
$$E^2 = m^2 + p^2$$

Complex Detector System around IP

Materials with high number of protons + Active material

Hermetic calorimetry
- Missing Et measurements

Electromagnetic and Hadron calorimeters
- Particle identification (e,γ Jets, Missing $\not{E}_T$)
- Energy measurement



Heavy materials

Muon detector
- μ identification

Heavy materials (Iron or Copper + Active material)

Light materials

Central detector
- Tracking, μ MIP
- Em. shower position
- Topology
- Vertex

Detector Ingredients

- ✓ Large Magnetic Fields, capable of bending trajectories of ~100 GeV charged particles by mm (sagitta) ~ 1-4 Tesla Fields .... best not in the calorimeters region

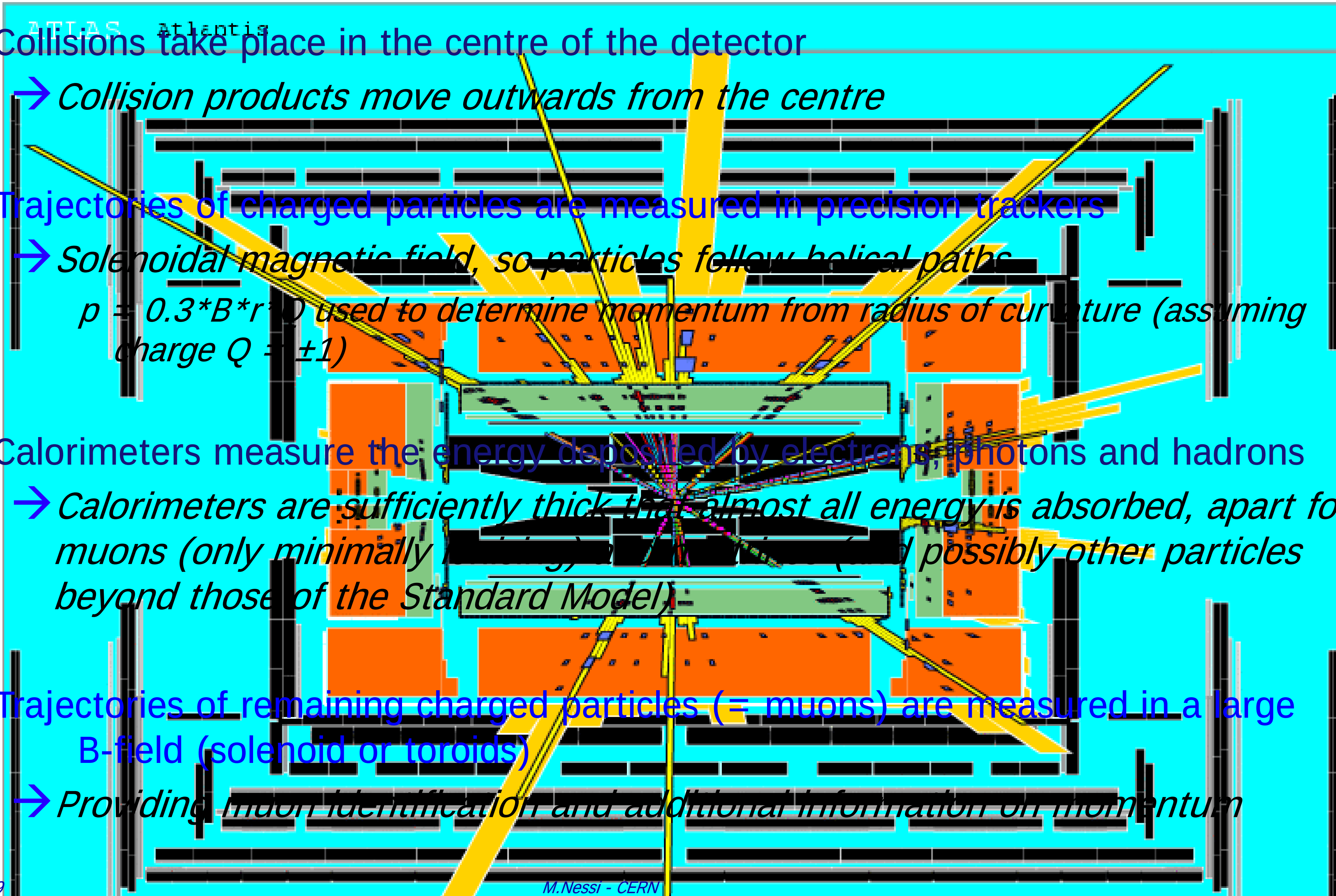
- ✓ Trackers and Calorimeters capable of 1% momentum/energy resolution, high space granularity for particle identification and position resolution and low occupancy

- ✓ Many detection techniques (see previous speakers) based on precision, fast response, particle ID capability, radiation resistance, ...

- ✓ Careful choice of material distribution : very low near to the beam pipe (inner detector), enough material to contain EM and HAD showers in the calorimeters, radiation background (n, γ) moderation/absorption in the muon spectrometer

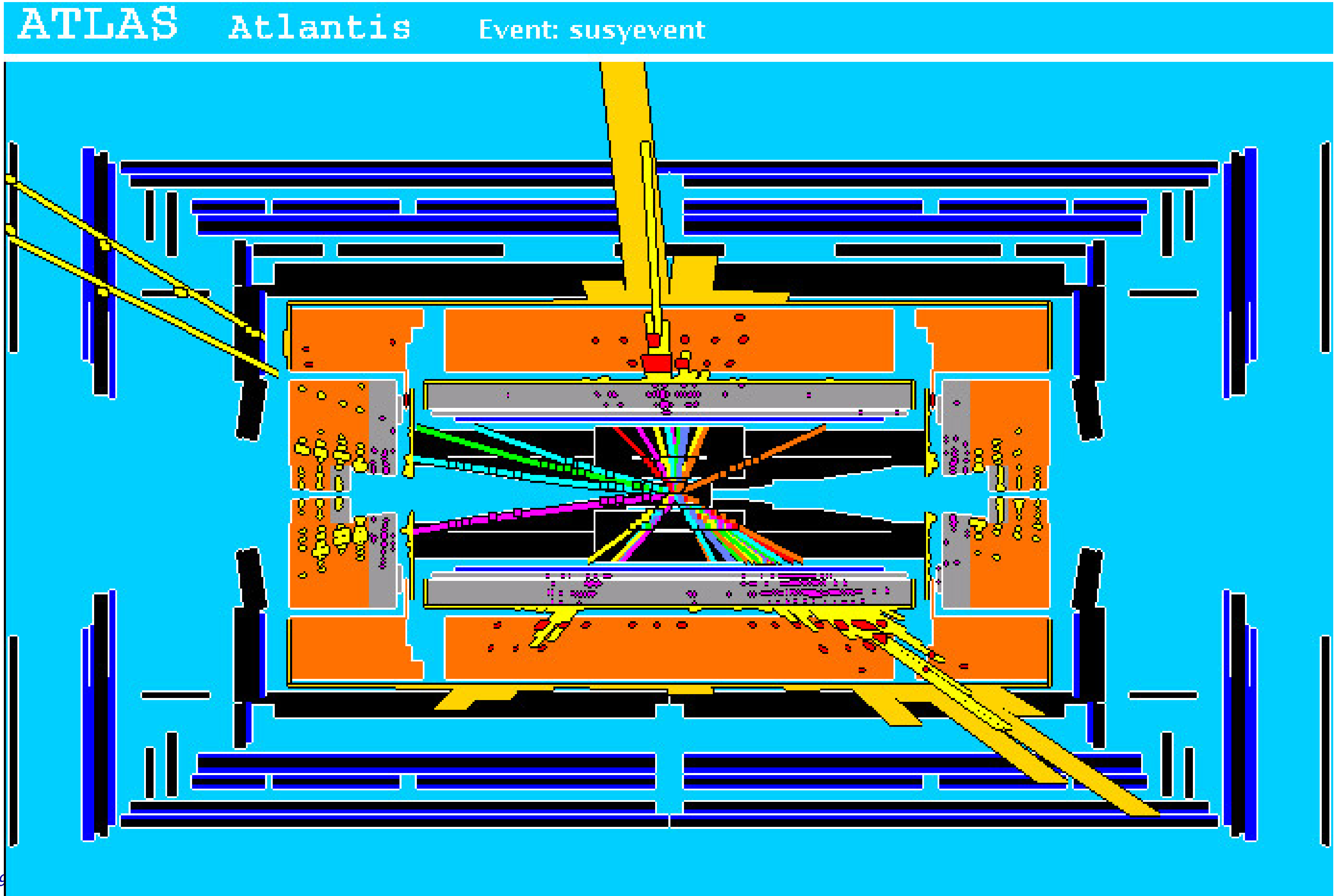
- ✓ Hermetic coverage down to the beam pipe (5-6 cm), in order to measure all the transverse energy flow to allow transverse missing energy identification

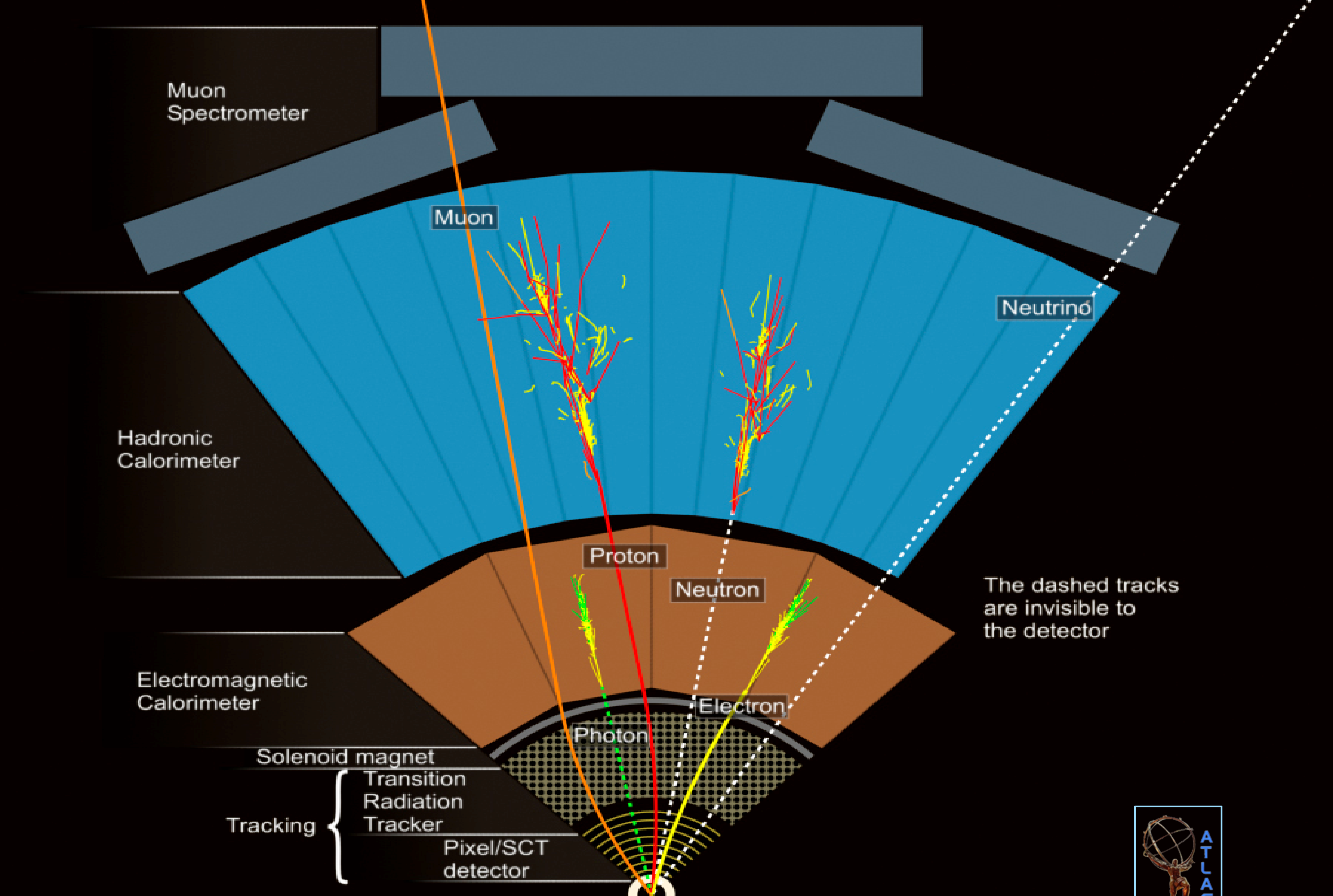
Detector concept



- Collisions take place in the centre of the detector
  - → *Collision products move outwards from the centre*
- Trajectories of charged particles are measured in precision trackers
  - → *Solenoidal magnetic field, so particles follow helical paths*
    - *$p = 0.3*B*r*Q$ used to determine momentum from radius of curvature (assuming charge $Q = \pm 1$)*
- Calorimeters measure the energy deposited by electrons, photons and hadrons
  - → *Calorimeters are sufficiently thick that almost all energy is absorbed, apart for muons (only minimally ionising) and neutrinos (and possibly other particles beyond those of the Standard Model)*
- Trajectories of remaining charged particles (= muons) are measured in a large B-field (solenoid or toroids)
  - → *Providing muon identification and additional information on momentum*

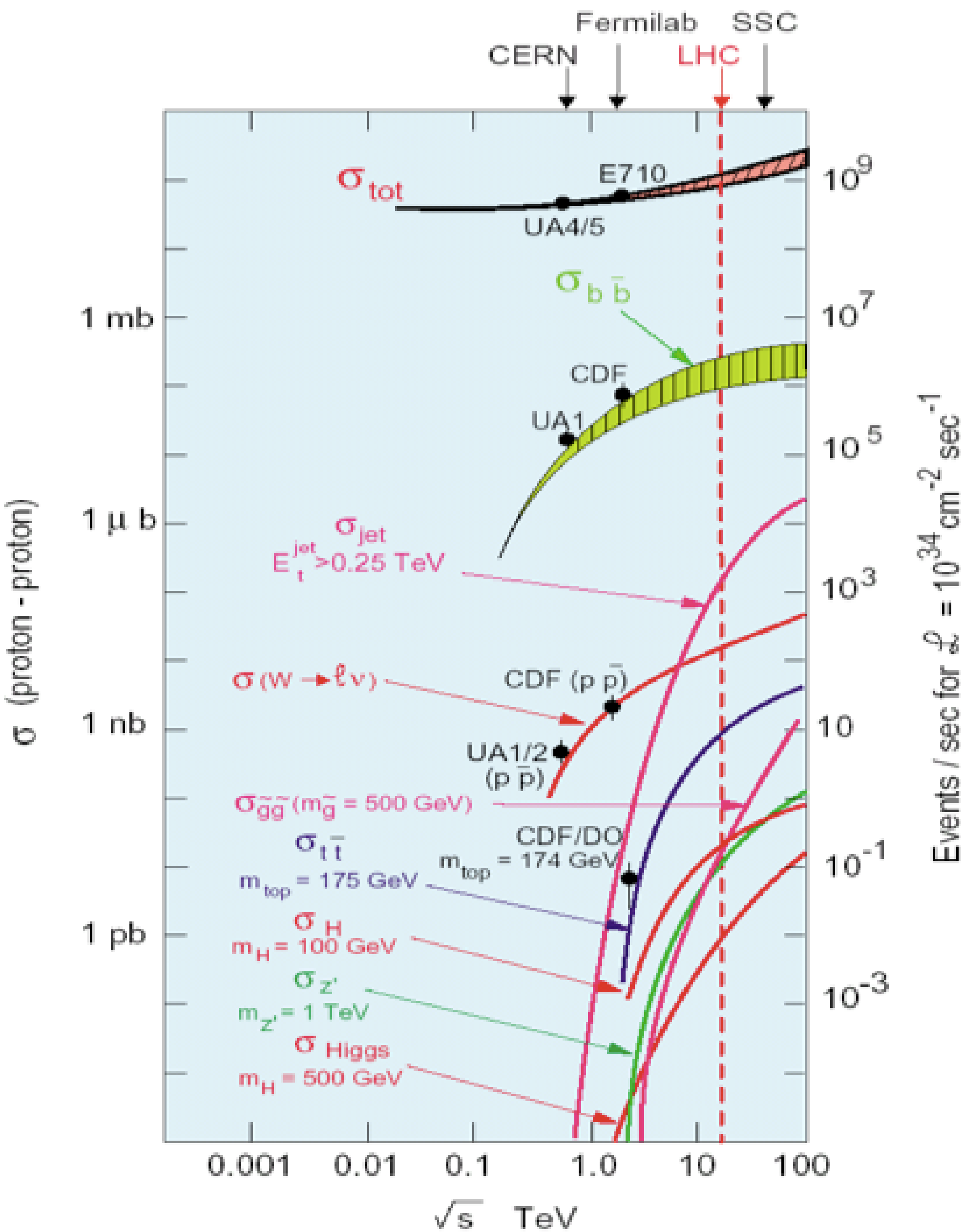
Detector concept




Muon Spectrometer
Muon
Hadronic Calorimeter
Neutrino
Proton
Neutron
The dashed tracks are invisible to the detector
Electromagnetic Calorimeter
Electron
Photon
Solenoid magnet
Transition Radiation Tracker
Tracking
Pixel/SCT detector
ATLAS

Why it is so difficult ?

Cross Sections and Production Rates at 14 TeV (LHC)



New physics events very rare

Rates for $L = 10^{34}$ cm^{-2} s^{-1}: (LHC)

- ✓ Inelastic proton-proton reactions: 10^9 / s
- ✓ bb pairs 5×10^6 / s
- ✓ tt pairs 8 / s
- ✓ W $\to$ e ν 150 / s
- ✓ Z $\to$ e e 15 / s
- ✓ Higgs (150 GeV) 0.2 / s
- ✓ Gluino, Squarks (1 TeV) 0.03/ s

Protons on protons

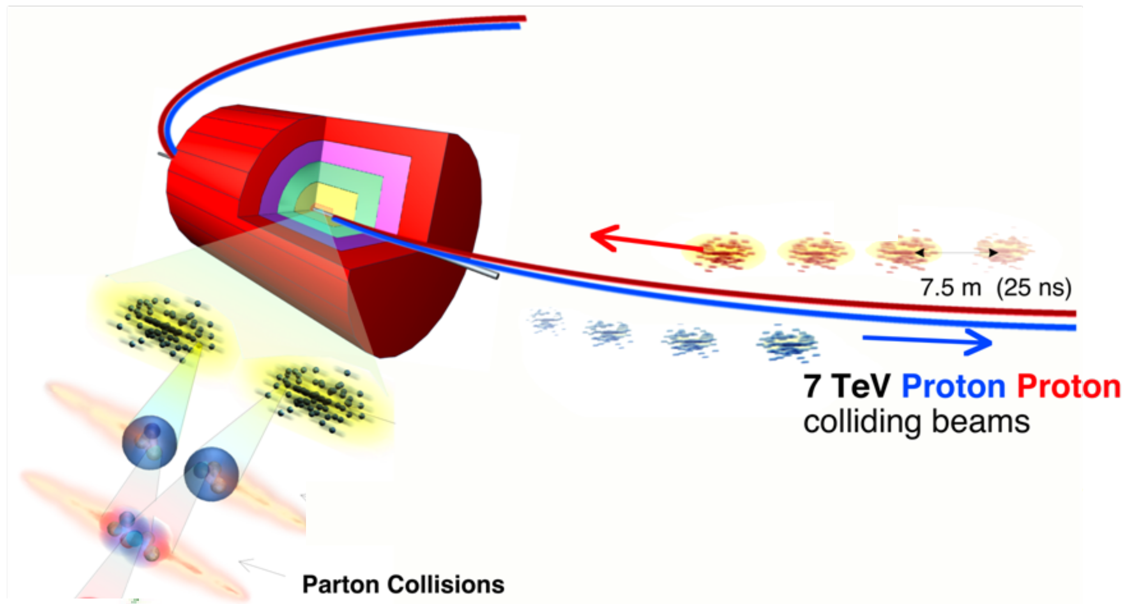
2808 x 2808 bunches

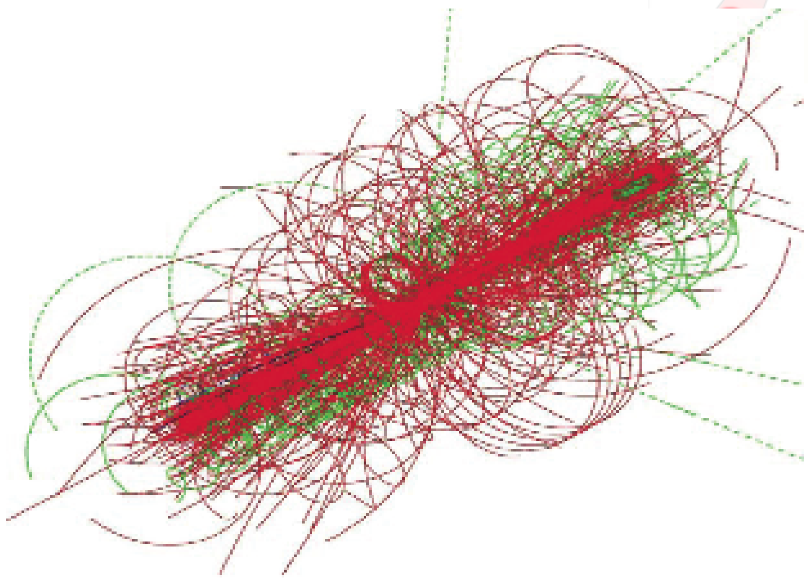
spaced: 7.5 m (25 ns)

10^{11} protons/bunch

bunch collisions 40 million/s

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





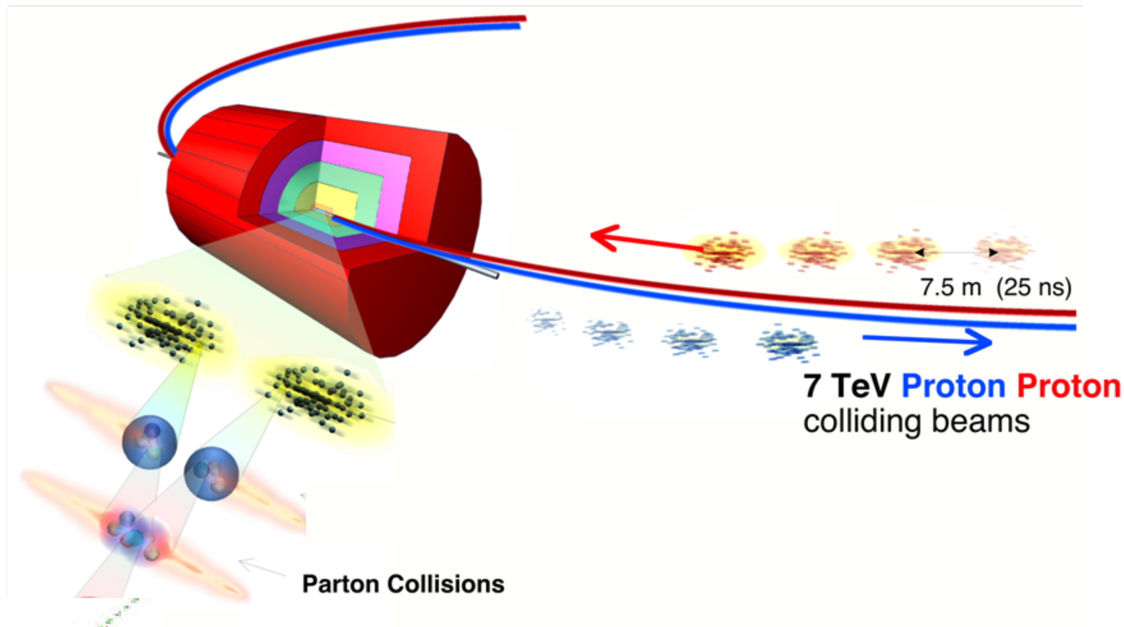
σ (pp) » 0.1 b -> ~ 10^9 pp Collisions / s

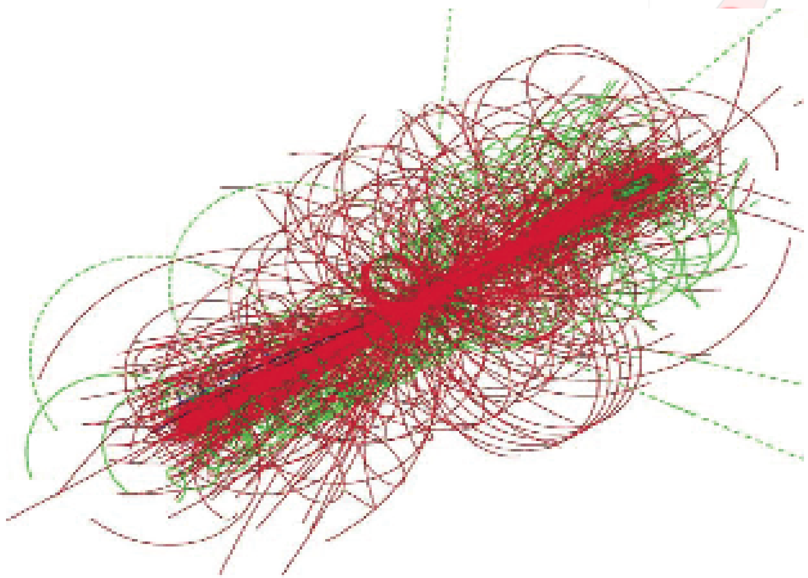
~20 pp interactions per bunch crossing overlapping in time and space

> 1000 particle signals in the detector at 40MHz rate

Protons on protons
2808 x 2808 bunches
spaced: 7.5 m (25 ns)

10^{11} protons/bunch
bunch collisions 40 million/s
Luminosity L = 10^{34} cm^{-2} s^{-1}





σ (pp) » 0.1 b -> ~ 4 10^{10} tracks / s

σ (new physics) < pb ~ 0.01 Hz

If you add the BR (Branching Ratio) typically ~ few%

-> you look for 1 interesting collision in ~10^{13}

Very difficult detector environment

- Bunch crossings every 25 ns .... Fast detector response (ns) .... Bunch crossing identification event by event in order not to mix uncorrelated energy depositions (finite speed of light) ..... Readout at 40 MHz .... 1 Pbytes/sec of data produced

- At each bunch crossing ~ 20 independent events overlap ~ 1000 individual particles to be identified every 25 ns .... Interesting events have large transverse energy .... High density of particles imply high granularity in the detection system ... Large quantity of data .... Large quantity of readout services (100 M channels/active components)

- Large n fluxes, large γ fluxes capable of compromising the mechanical properties of materials and of short-circuiting the electronics components and the semiconductors at large.

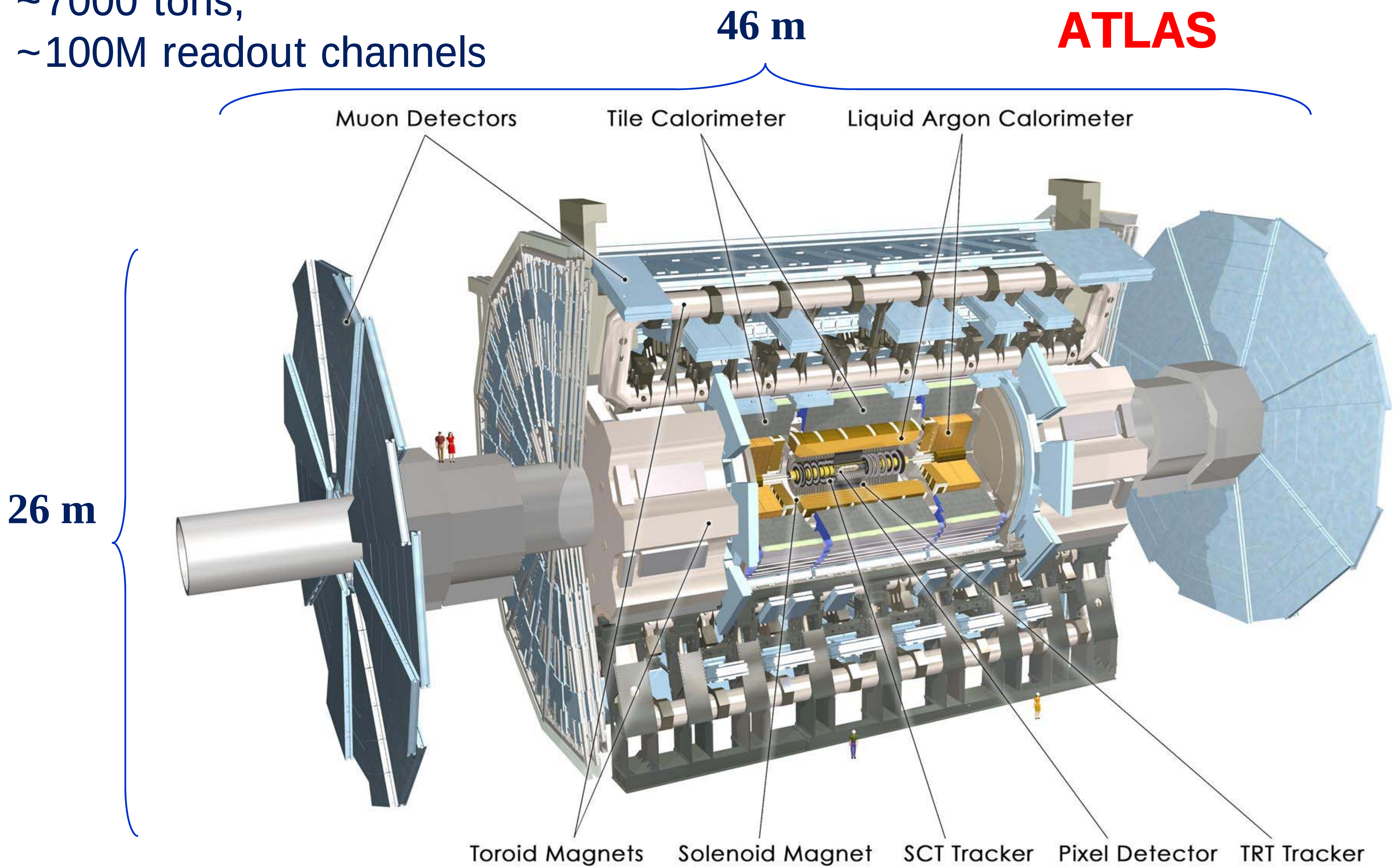
- Large Magnetic Fields in large volumes, which imply usage of superconductivity (cryogenics) and attention to magnetic components (electronics components, mechanical stress, ...)

- Induced radioactivity in high Z materials (activation) which will add complexity to the maintenance process

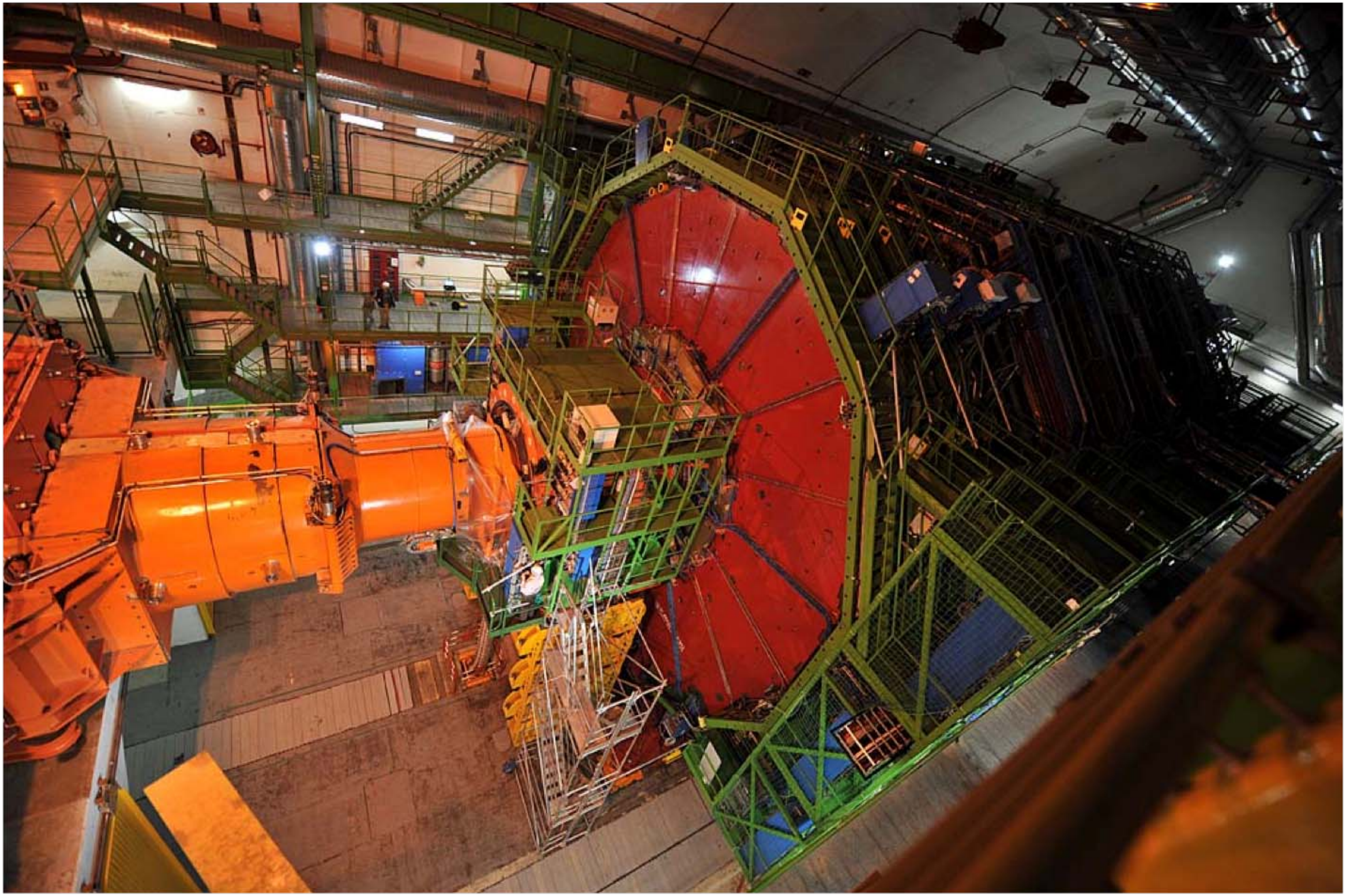
Two General Purpose Detectors

~7000 tons,
~100M readout channels

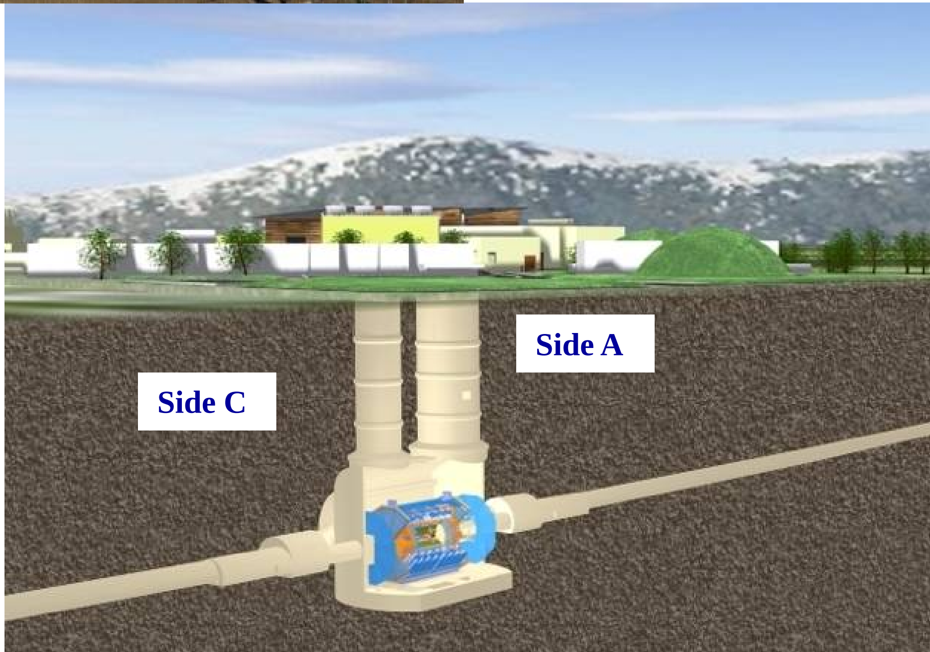
ATLAS



CMS closed and ready for beam



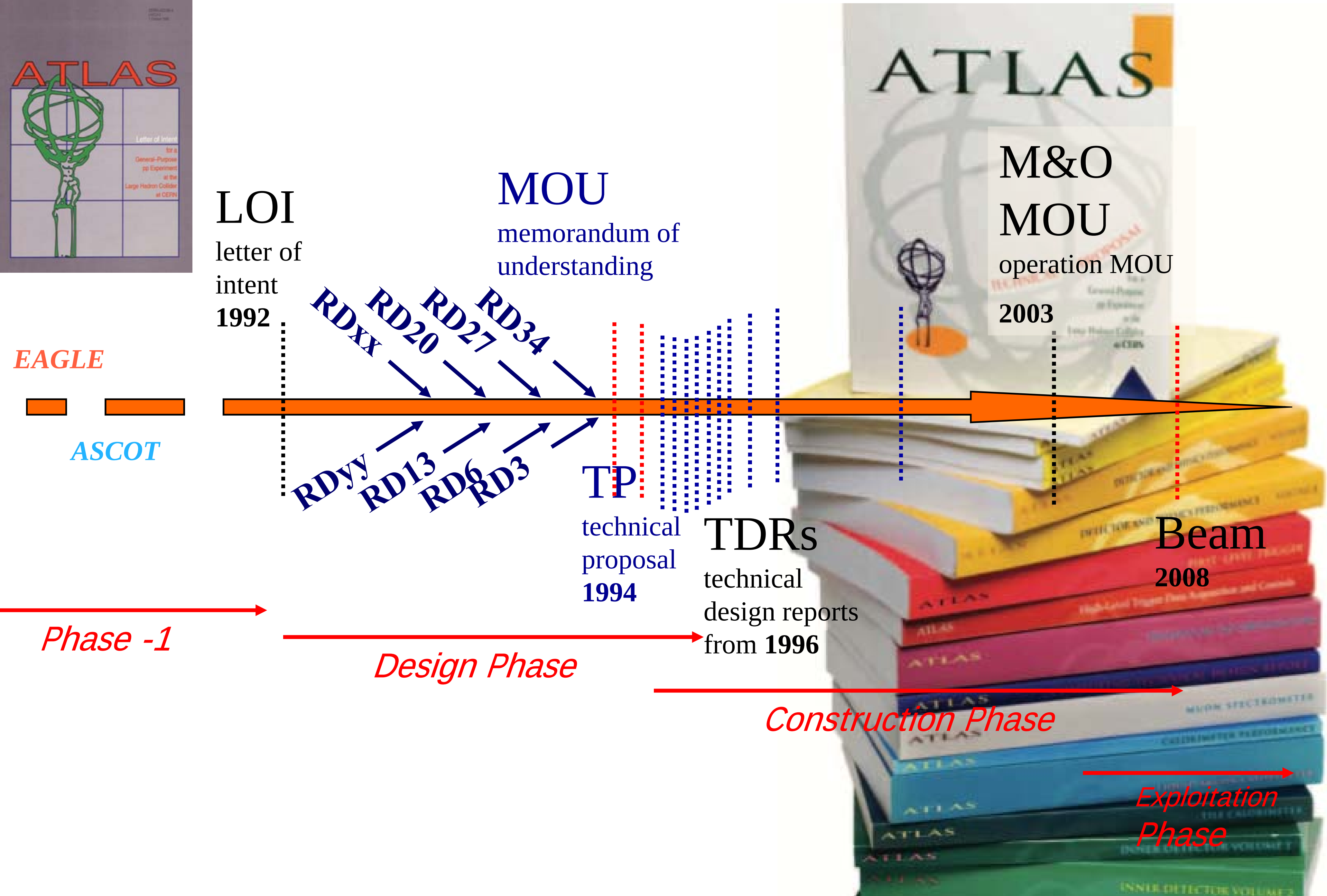
The Underground Cavern at Point-1 for the ATLAS Detector



How did we proceed in creating such a detector infrastructure ?

- various project phases (design, construction, assembly, commissioning) over 2 decades

- a solid Collaboration effort worldwide


ATLAS
Letter of Intent
for a
General-Purpose
pp Experiment
at the
Large Hadron Collider
at CERN
LOI
letter of
intent
1992
EAGLE
ASCOT
RDxx
RD20
RD27
RD34
RDyy
RD13
RD6
RD3
MOU
memorandum of
understanding
TP
technical
proposal
1994
TDRs
technical
design reports
from 1996
ATLAS
M&O
MOU
operation MOU
2003
Beam
2008
Phase -1
Design Phase
Construction Phase
Exploitation
Phase

ATLAS Collaboration

37 Countries
169 Institutions
2800 Scientific Authors
(1850 " " with a PhD)

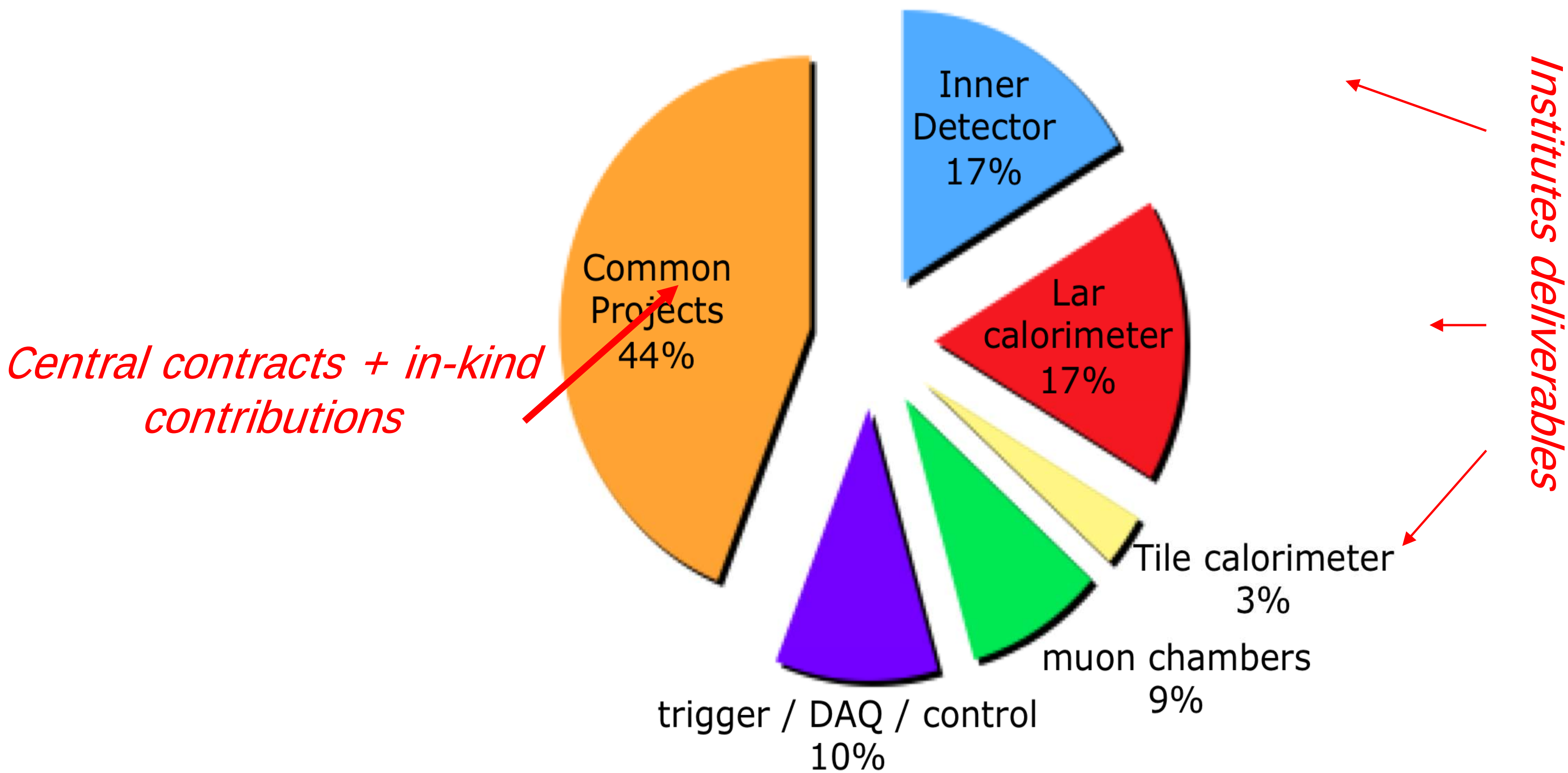
05/11/2009

A GLOBAL PROJECT

Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizona, UT Arlington, Athens, NTU Athens, Baku, IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, HU Berlin, Bern, Birmingham, UAN Bogota, Bologna, Bonn, Boston, Brandeis, Bratislava/SAS Kosice, Brookhaven NL, Buenos Aires, Bucharest, Cambridge, Carleton, CERN, Chinese Cluster, Chicago, Chile, Clermont-Ferrand, Columbia, NBI Copenhagen, Cosenza, AGH UST Cracow, IFJ PAN Cracow, UT Dallas, DESY, Dortmund, TU Dresden, JINR Dubna, Duke, Frascati, Freiburg, Geneva, Genoa, Giessen, Glasgow, Göttingen, LPSC Grenoble, Technion Haifa, Hampton, Harvard, Heidelberg, Hiroshima, Hiroshima IT, 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, CPPM Marseille, Massachusetts, MIT, Melbourne, Michigan, Michigan SU, Milano, Minsk NAS, Minsk NCPHEP, Montreal, McGill Montreal, RUPHE Morocco, FIAN Moscow, ITEP Moscow, MEPhI Moscow, MSU Moscow, Munich LMU, MPI Munich, Nagasaki IAS, Nagoya, Naples, New Mexico, New York, Nijmegen, BINP Novosibirsk, Ohio SU, Okayama, Oklahoma, Oklahoma SU, Olomouc, Oregon, LAL Orsay, Osaka, Oslo, Oxford, Paris VI and VII, Pavia, Pennsylvania, Pisa, Pittsburgh, CAS Prague, CU Prague, TU Prague, IHEP Protvino, Regina, Ritsumeikan, UFRJ Rio de Janeiro, Rome I, Rome II, Rome III, Rutherford Appleton Laboratory, DAPNIA Saclay, Santa Cruz UC, Sheffield, Shinshu, Siegen, Simon Fraser Burnaby, SLAC, Southern Methodist Dallas, NPI Petersburg, Stockholm, KTH Stockholm, Stony Brook, Sydney, AS Taipei, Tbilisi, Tel Aviv, Thessaloniki, Tokyo ICEPP, Tokyo MU, Toronto, TRIUMF, Tsukuba, Tufts, Udine/ICTP, Uppsala, Urbana UI, Valencia, UBC Vancouver, Victoria, Washington, Weizmann Rehovot, FH Wiener Neustadt, Wisconsin, Wuppertal, Würzburg, Yale, Yerevan

among them ~ 800 PhD Students ~ 200 PhD theses/year

Project definition and sharing (ATLAS case)



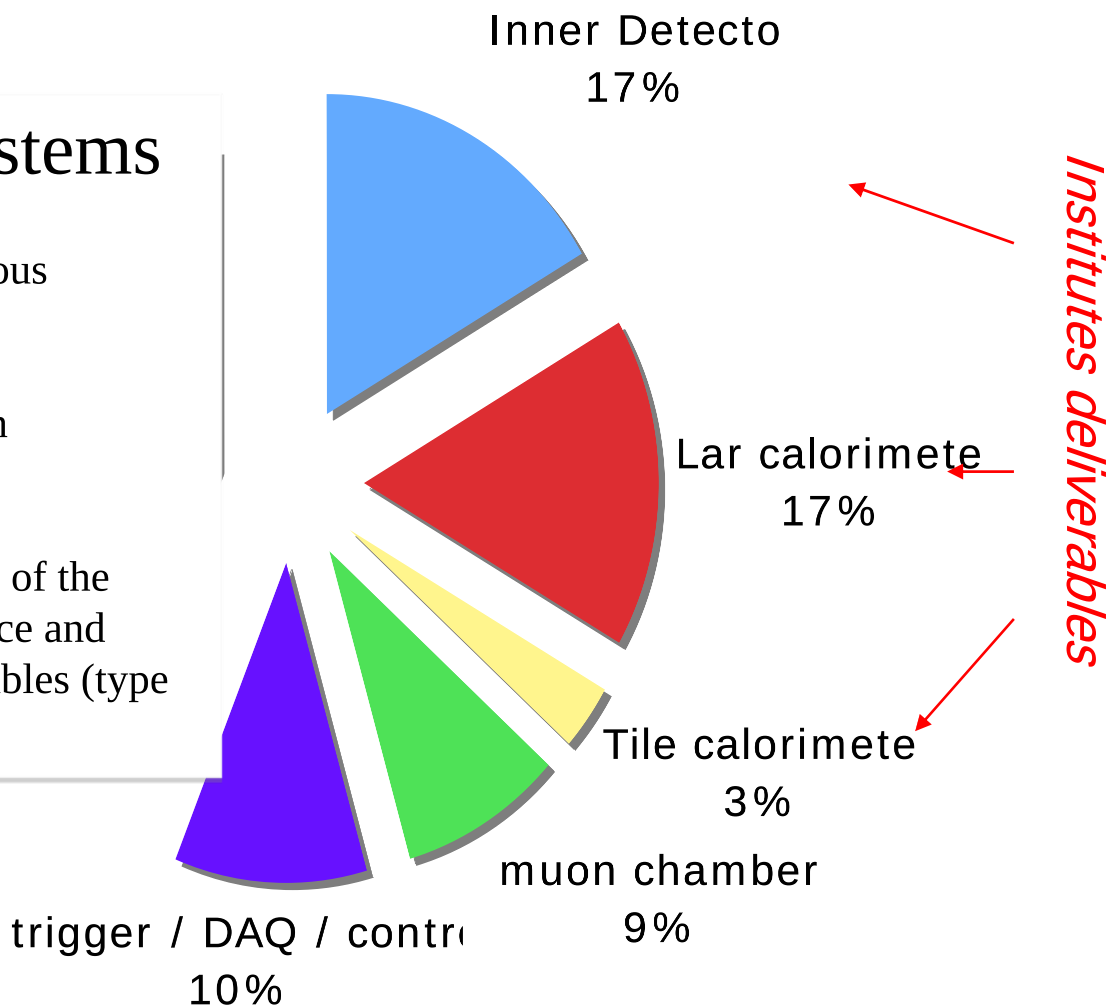
Project definition : Active Detectors

organized in detector systems

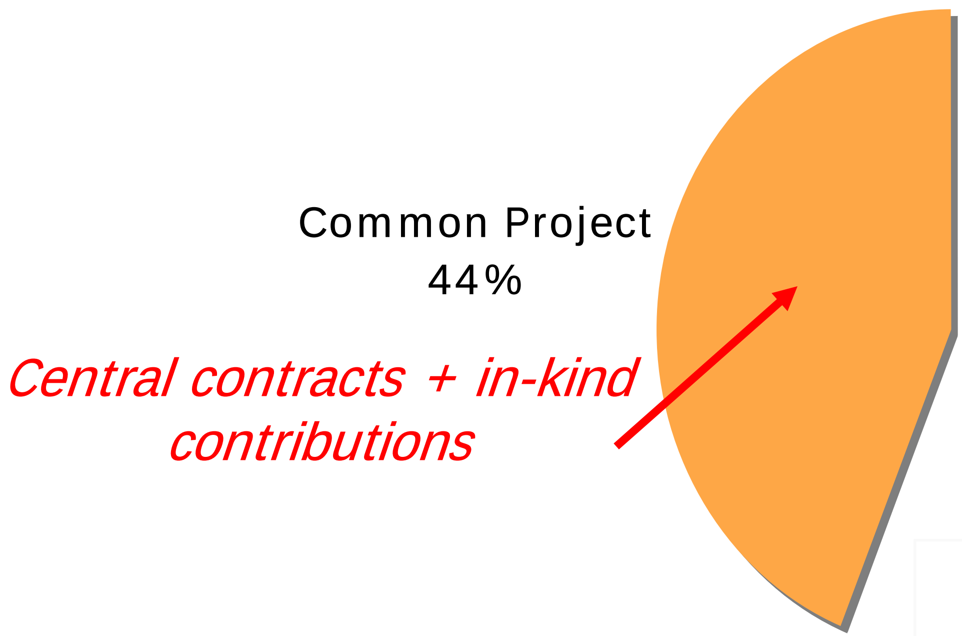
Each system is like a Collaboration of various institutes within the main Collaboration

Each system has his own organization, with management and institutes boards

Each system is responsible to deliver a part of the detector to central ATLAS + its maintenance and operation. Each system defines his deliverables (type B costs). ATLAS monitors the process.



Project definition : Common Activities



Common Projects

All what can not be handled by individual institutes or clusters. Parts of common utility: infrastructures, services, installation at CERN, magnets, cryogenics, labs, mechanical structures, radiation shielding, control rooms, overall M&O …

Centrally organized by ATLAS (type A costs)

Every funding agency shares the cost of it (cash or in-kind) through common funds

The ATLAS project

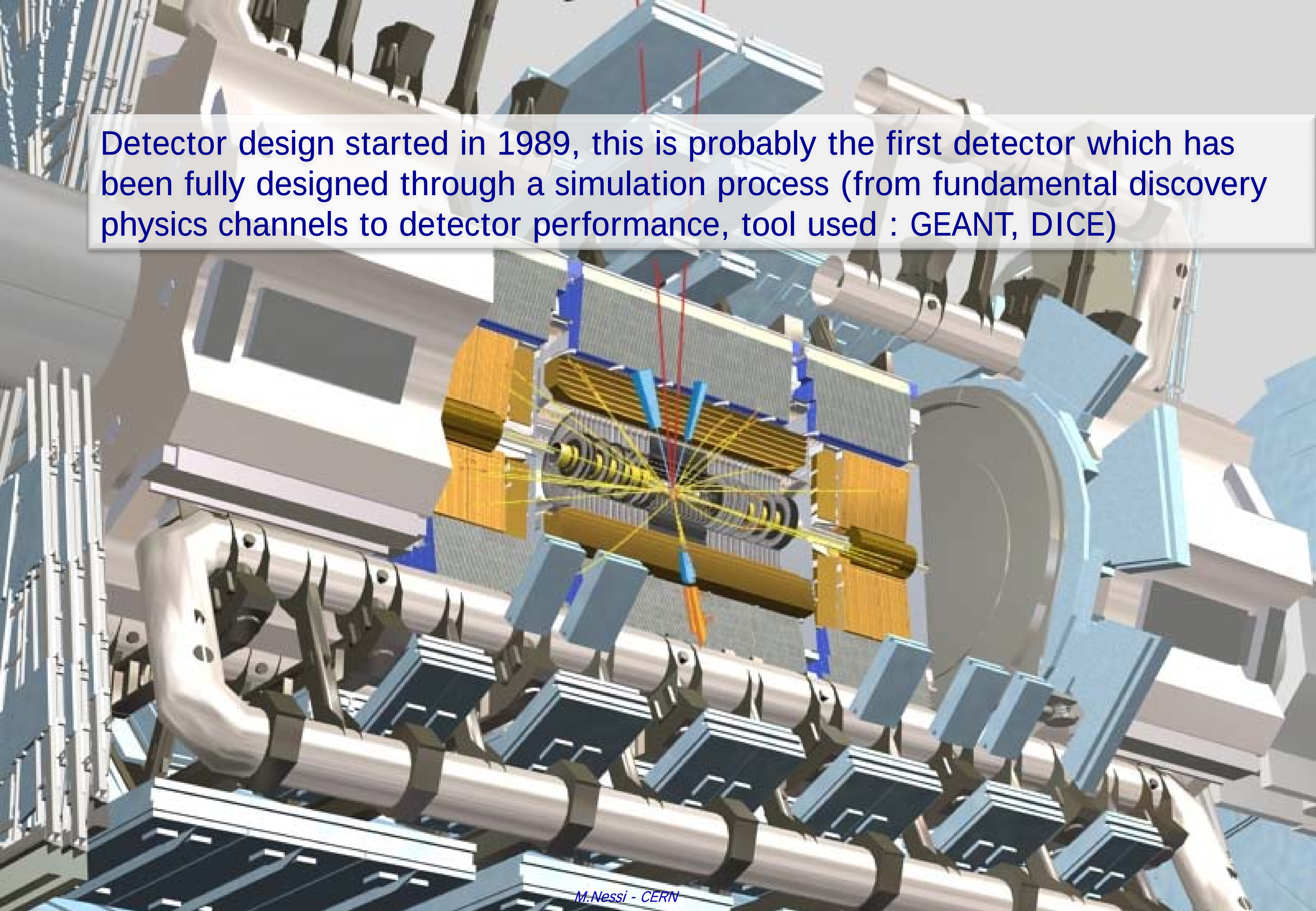
- ATLAS organization and management mode very peculiar, adapted to the historical moment, to the progress on technology and requirements coming from the participating institutions

- Collaboration concept dominates all aspects and daily life. CERN acts as host laboratory

- Project life time spans over 3-4 decades, moving through different phases. Each phase has its mode of operation.

- ATLAS is a GLOBAL project, which makes ample use of local resources for its construction and operation. It re-distributes physics (basic research) to the local universities and participating labs. Fundamental tool of education (~800 thesis/PhD Students at any time)

Detector design started in 1989, this is probably the first detector which has been fully designed through a simulation process (from fundamental discovery physics channels to detector performance, tool used : GEANT, DICE)



How did we proceed in designing the detector ?

- detector performance was benchmarked on few physics discovery channels

Higgs → $\gamma\,\gamma$

Supersymmetry discovery

Why it is difficult ?

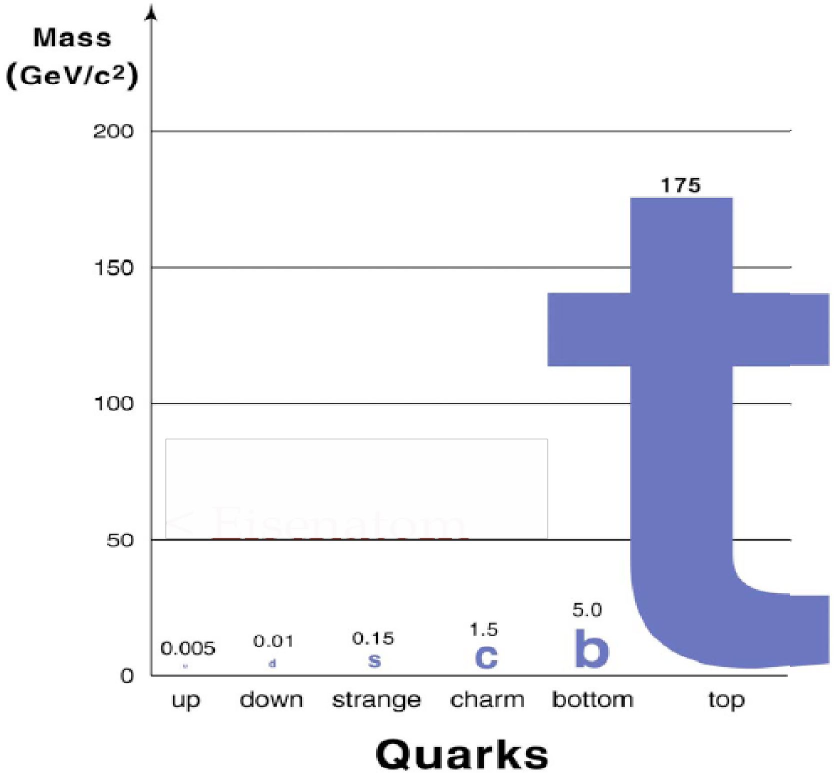
- ✓ Searching for new signals will be relatively easy

- ✓ The problem is to discriminate physics backgrounds, which will produce similar or identical signals, but are not due to Higgs decays or supersymmetric particles

    - *Reducible and irreducible backgrounds*
    - *Backgrounds coming from the random combination or superposition of pile-up events (20/bunch crossing)*

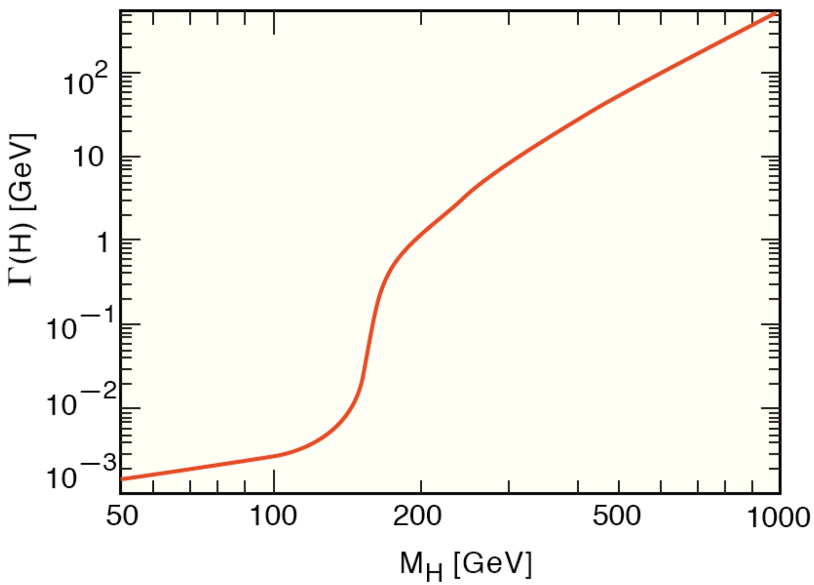
- ✓ The detector must be designed from the beginning so as to minimize such a background (precision, particle identification, correct trigger selection, ….)

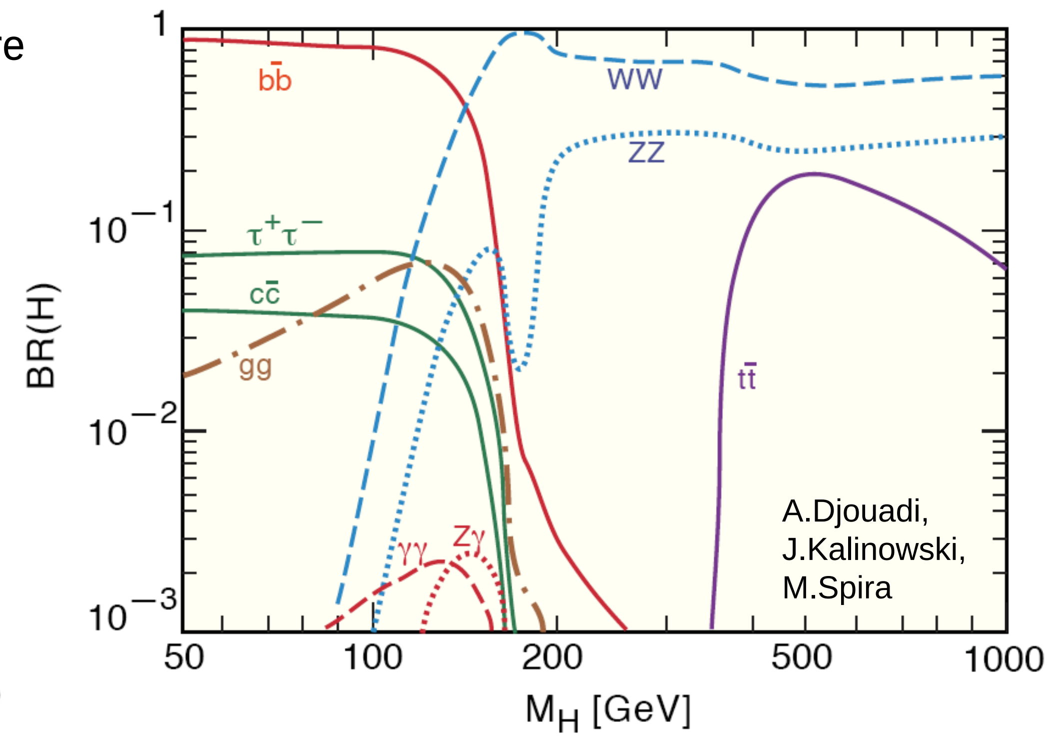
Searching for the Higgs Boson



Searching for the Higgs Boson

For fixed m_H, branching rations (BR) and widths (Γ) for all possible Higgs decays are determined





For small m_H :

b-quark $\rightarrow$ jets, difficult (huge background)

H $\rightarrow \gamma\gamma$ (M_H < 140 GeV) , small cross section, but „clean“ signature

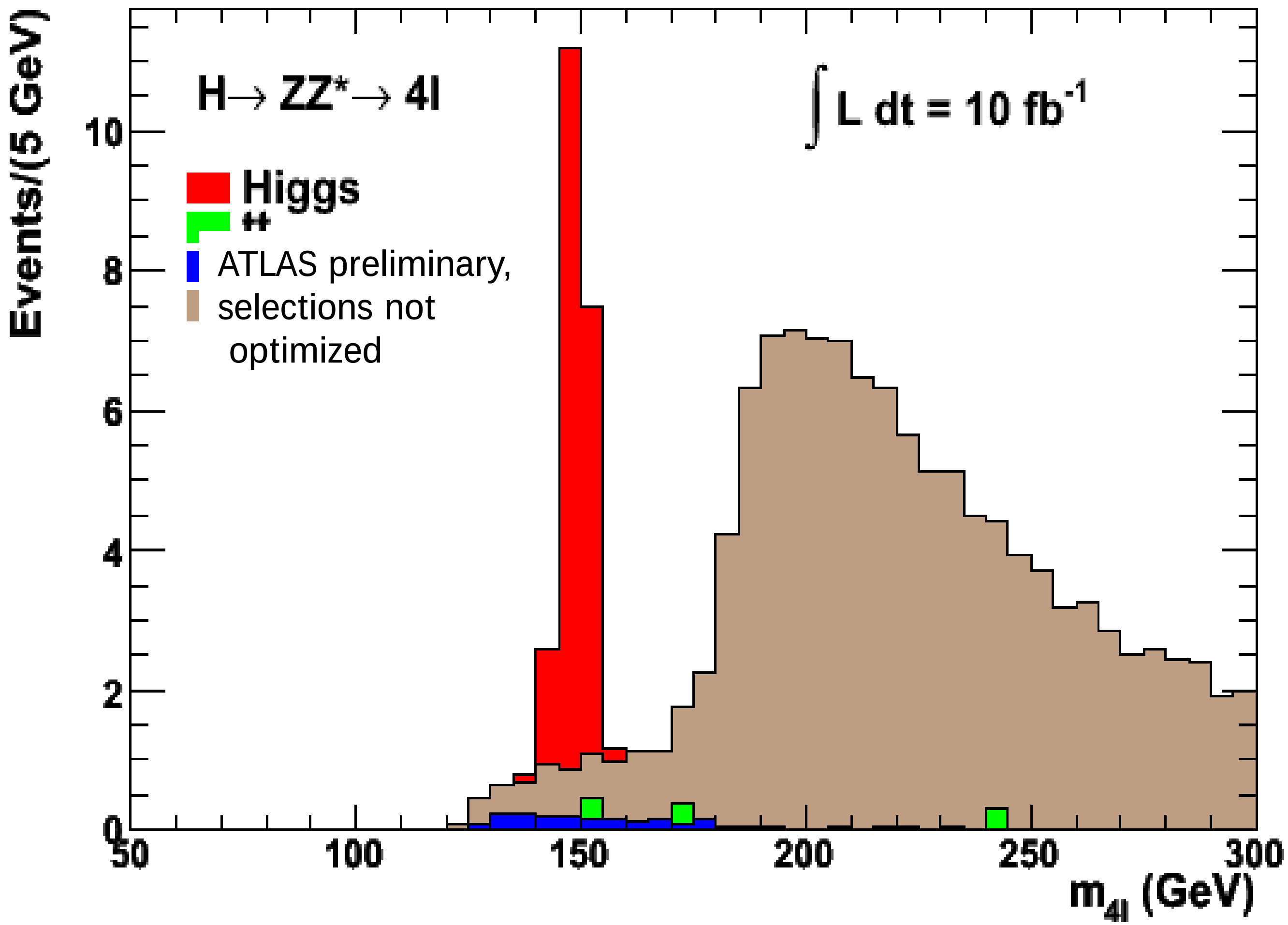
Small width: Detector energy resolution and particle ID are crucial

For large m_H :

H $\rightarrow$ ZZ $\rightarrow 4\ell$, H $\rightarrow$ WW $\rightarrow$ jets or $\ell\,\nu\,\ell\,\nu$

M_H > 130 ... is easier

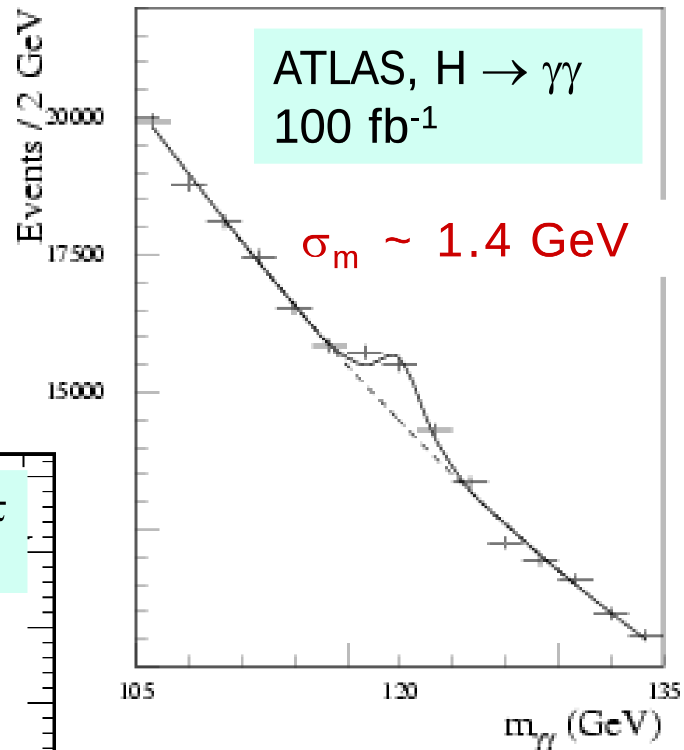
m_H > 130 GeV : $H \rightarrow ZZ^{(*)} \rightarrow 4l$ (gold-plated), $H \rightarrow WW^{(*)} \rightarrow l\nu\ l\nu$



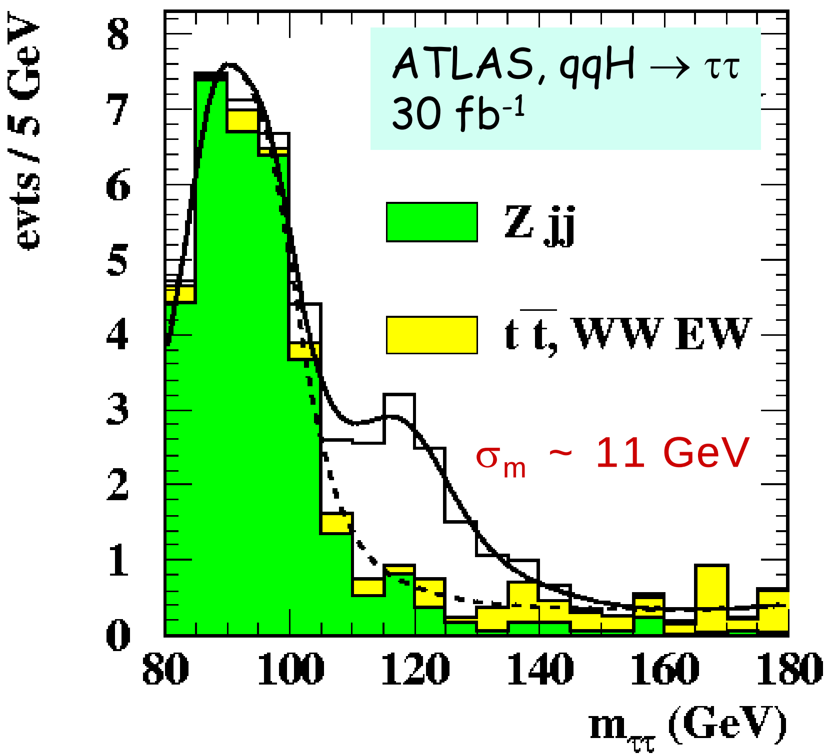
May be observed with 3-4 fb^{-1}

A light Higgs is the most probable one!

$m_H \sim 120$ GeV



It will need a perfectly understood detector in terms of photon identification, calorimetry, tracking, ...



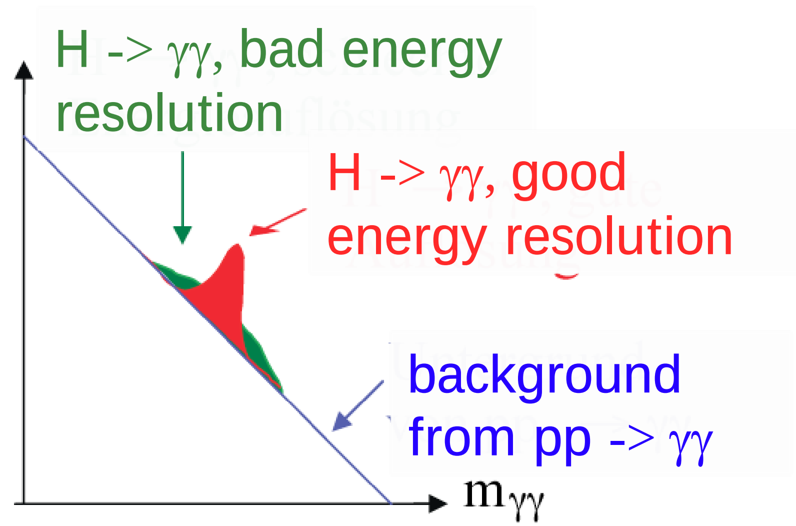
BG dominated by irreducible components

About Higgs to $\gamma\gamma$

$$m_{\gamma\gamma} = \sqrt{2E_{\gamma_1}E_{\gamma_2}(1-\cos\theta_{\gamma\gamma})}$$

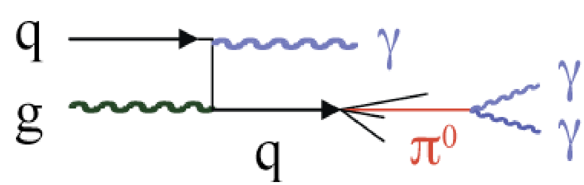
where

$$\frac{\Delta m_{\gamma\gamma}}{m_{\gamma\gamma}} = \frac{1}{2}\left[\frac{\Delta E_{\gamma_1}}{E_{\gamma_1}} \oplus \frac{\Delta E_{\gamma_2}}{E_{\gamma_2}} \oplus \frac{\Delta\theta_{\gamma\gamma}}{\tan(\theta_{\gamma\gamma}/2)}\right]$$



"reducible" background: pp $\rightarrow$ γ jet and pp $\rightarrow$ jet jet

"irreducible" background: pp $\rightarrow$ $\gamma\gamma$

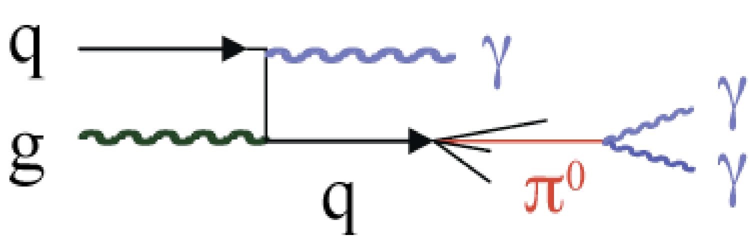


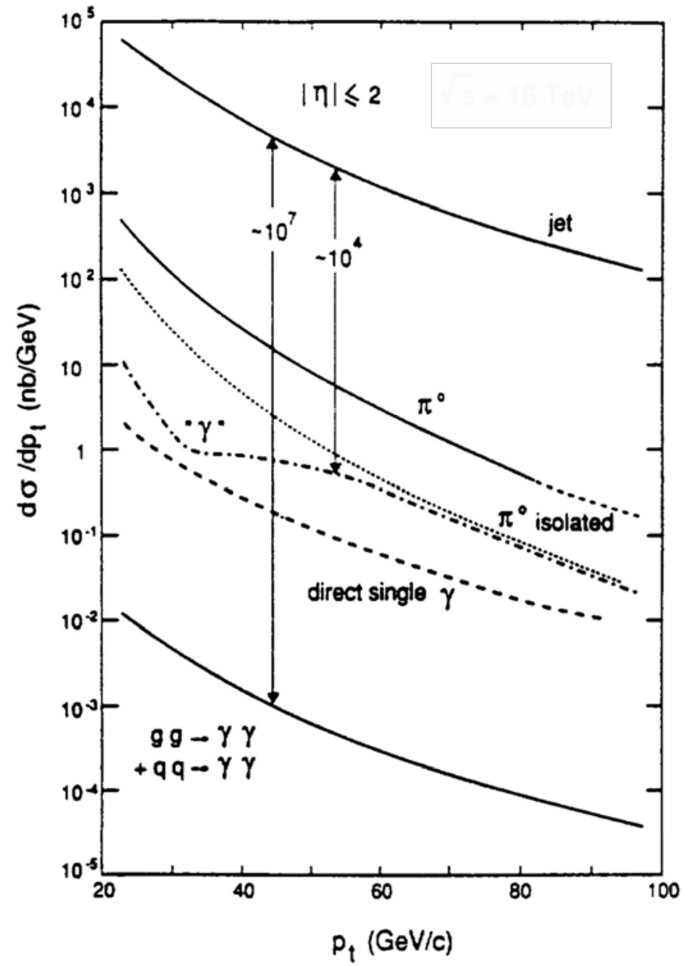
Need to be sure to identify electrons and photons

- ✓ Most channels require to identify electrons and photons in their final states

- ✓ At LHC the di-jets background dominates all high-p_T channels

- ✓ Jet fragmentation into leading π_0s (probability 10^{-4}) represents the main source of identification errors





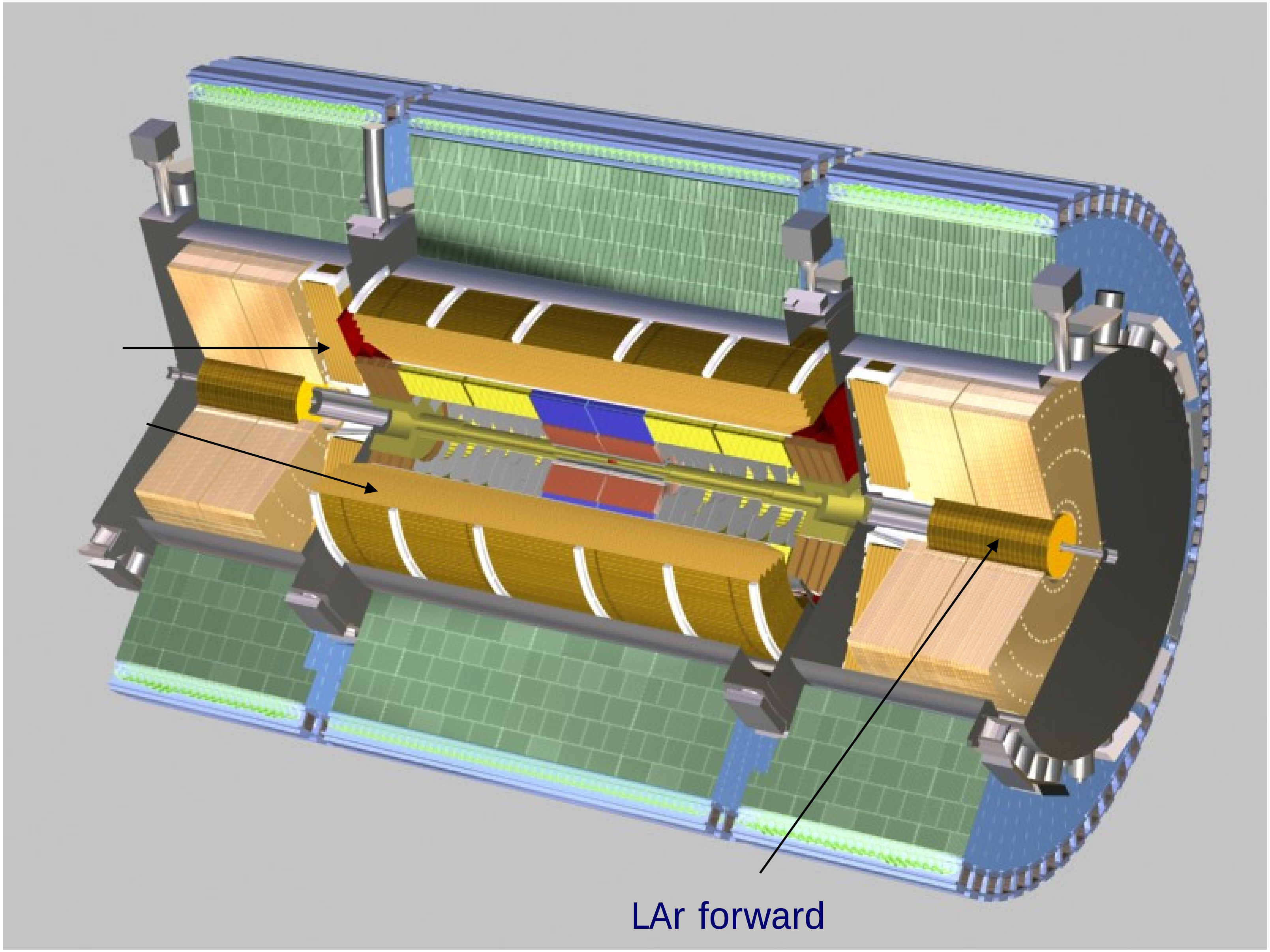
which requires in first place an excellent EM Calorimeter

- ✓ With good energy resolution : longitudinal energy containment, small amount of dead material, easy cells inter-calibration
  - to ensure good energy calibration
- ✓ With good angular resolution : high granularity and longitudinal segmentation

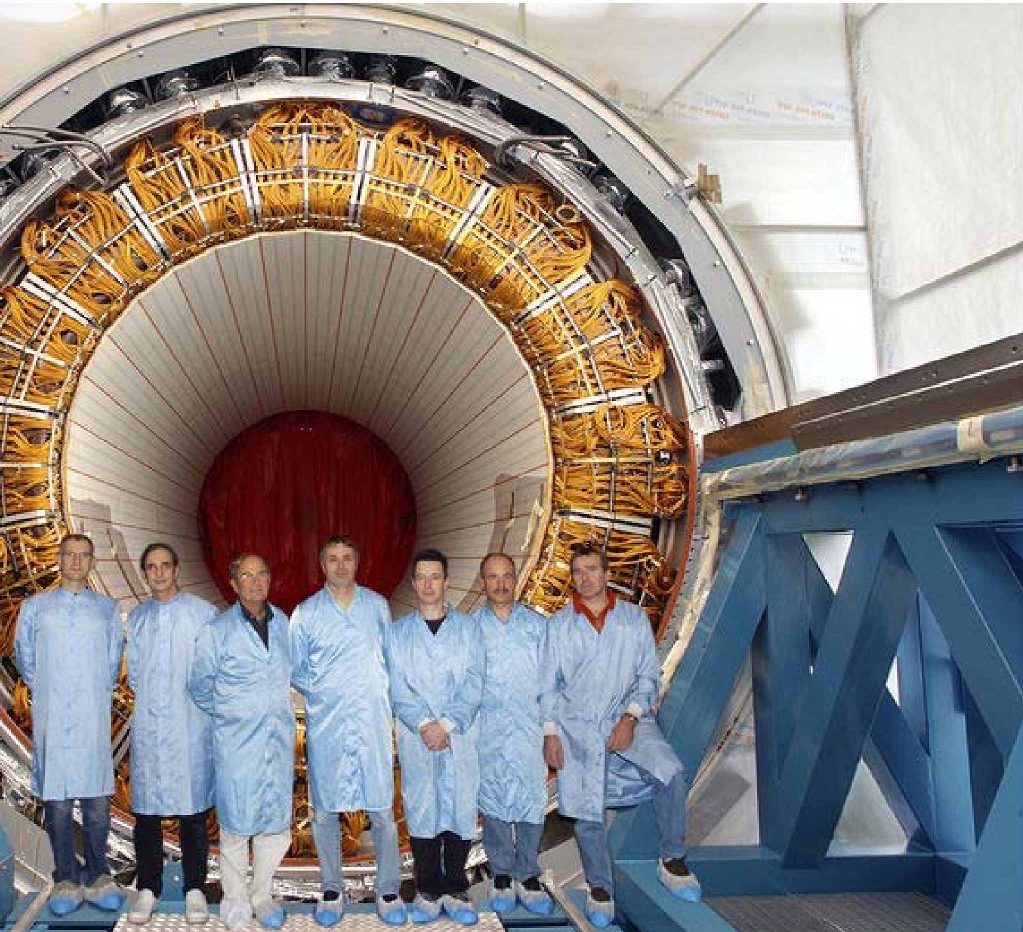
To keep a favorable Signal to Background ratio, we need a Higgs mass resolution at the level of a few %, therefore we will need each of the 3 components to contribute at the 1-2 % level

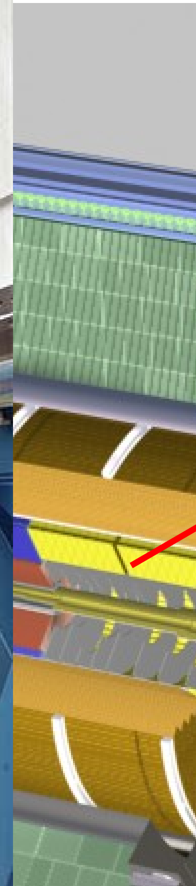
This mean for photons and electrons in an energy range of 20-70 GeV to be measured with an uncertainty in the calorimeters at the level of 1.0-2.0 GeV

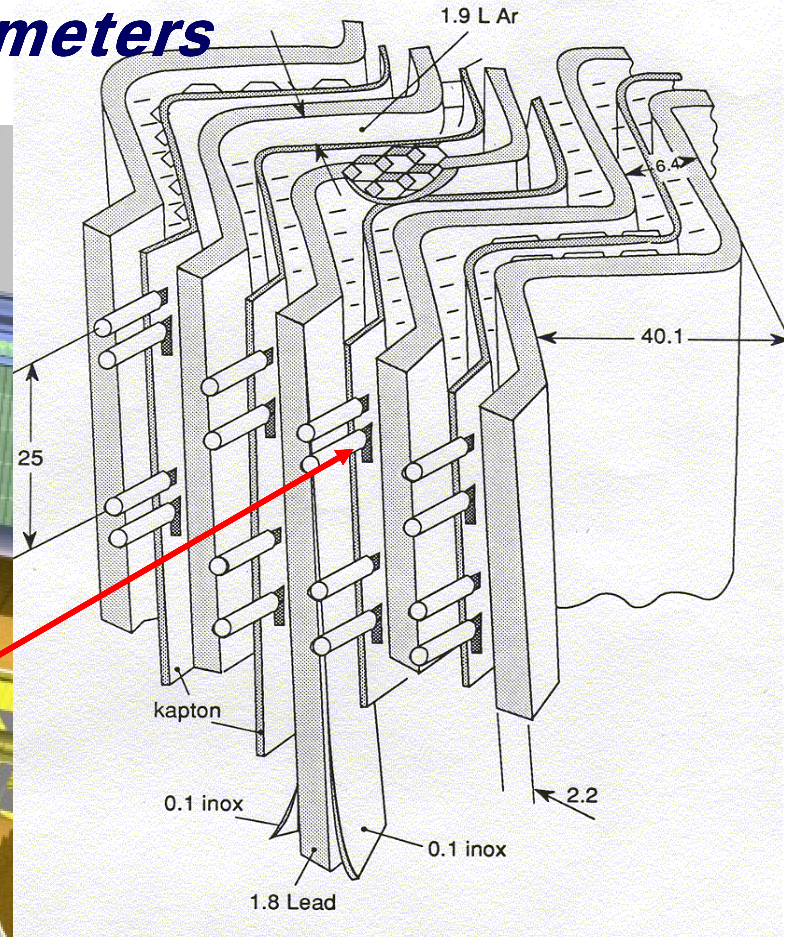
Liquid Argon Calorimeters



Liquid Argon Calorimeters

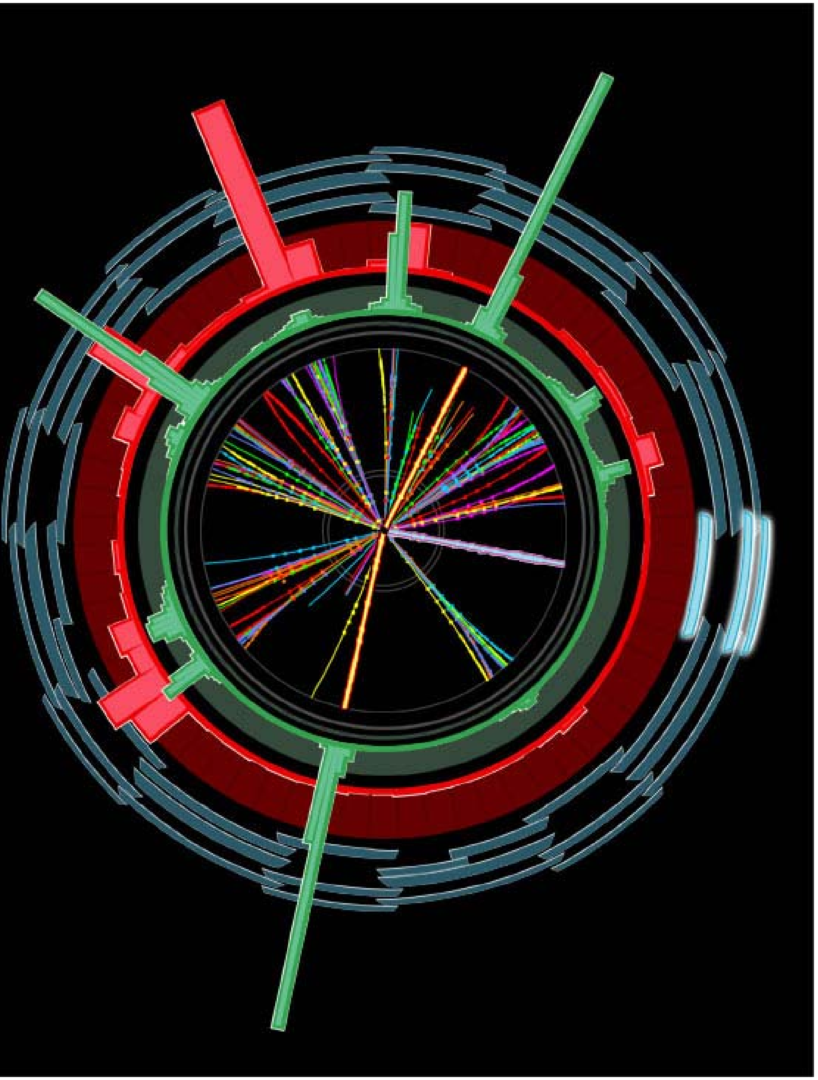


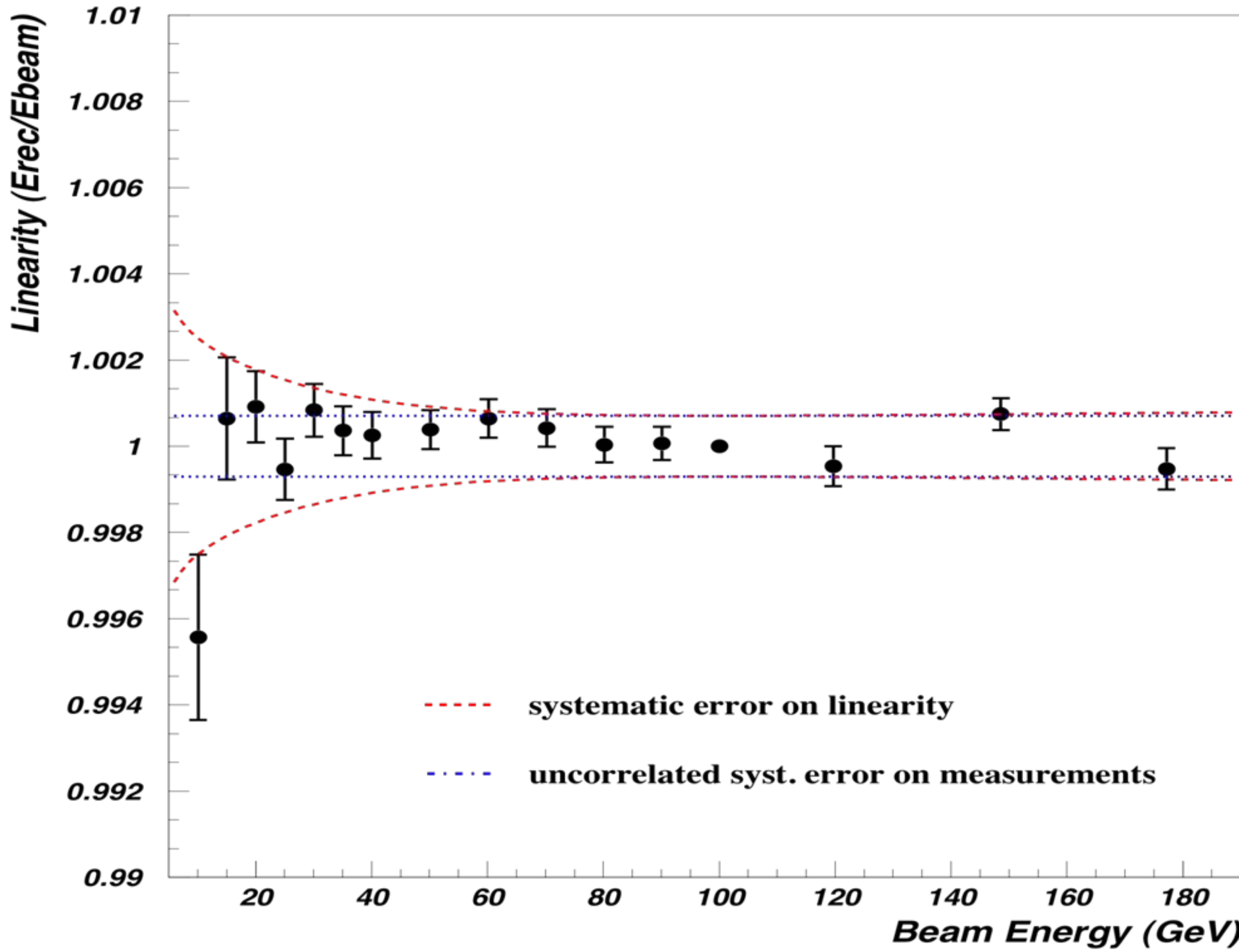




- a very stable and radiation-hard detector
- easy to calibrate
- a lot of freedom in spacial resolution

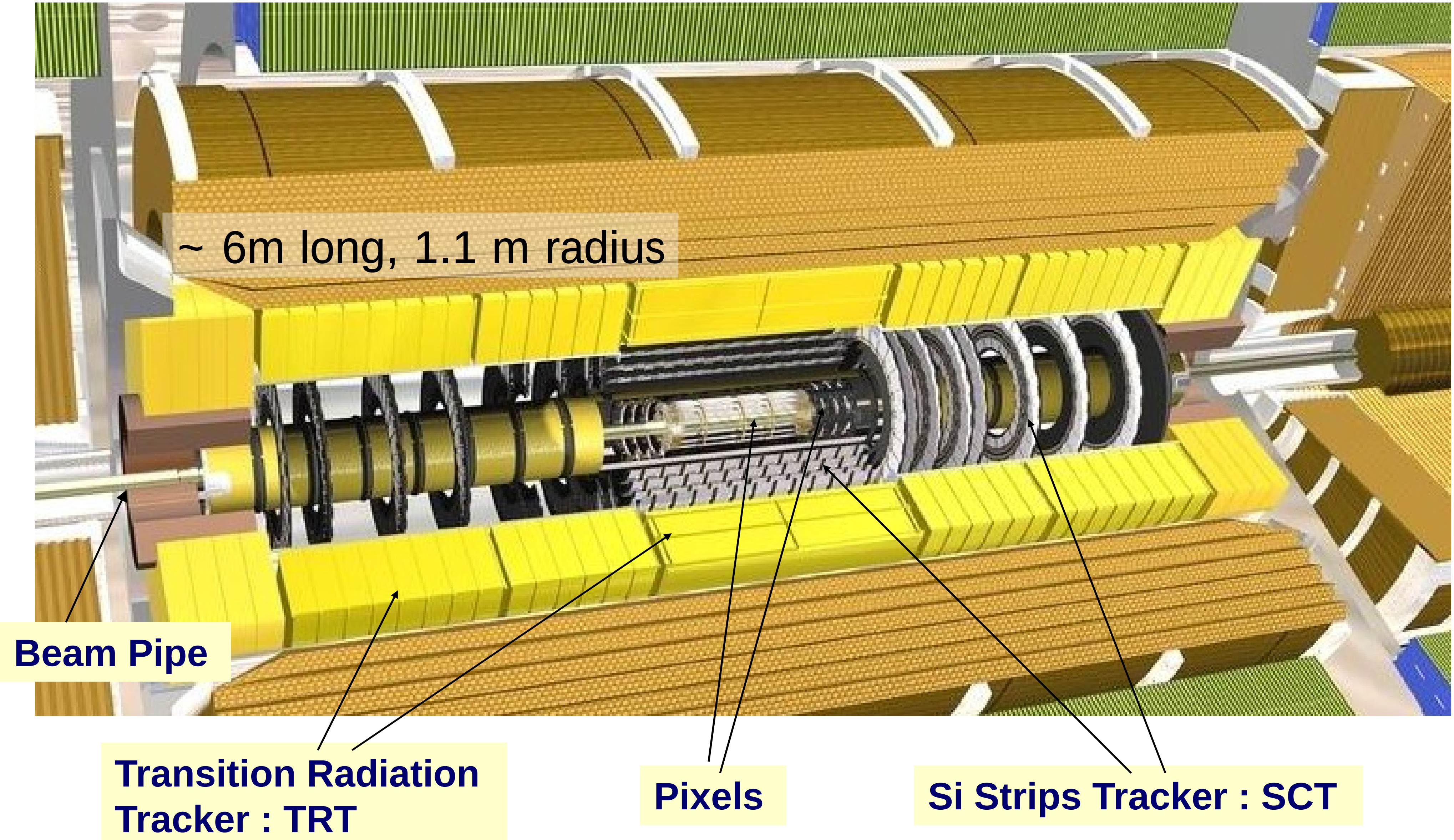
- .... difficult to construct ... because of cryogenics





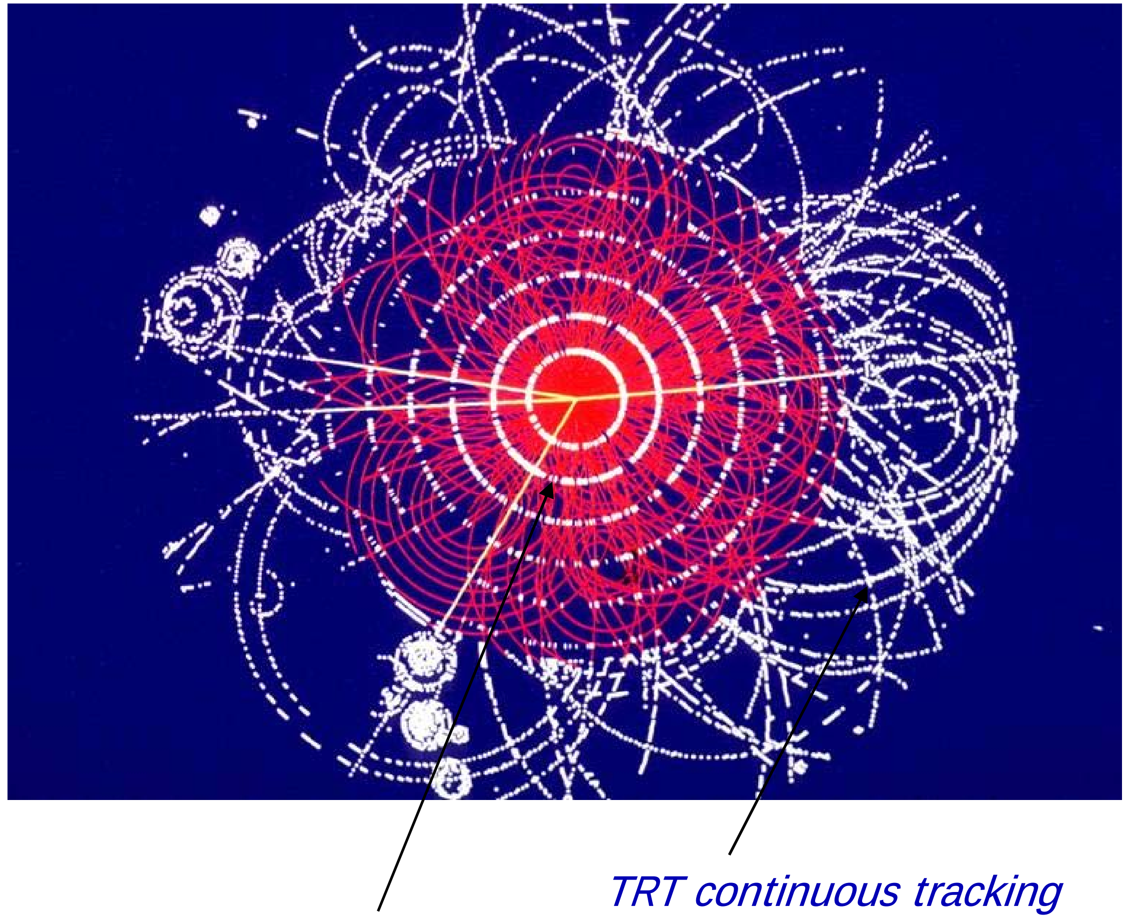
Detector linear within ±0.25% (± 0.1%) for E >10 (40) GeV

The Tracking Detectors

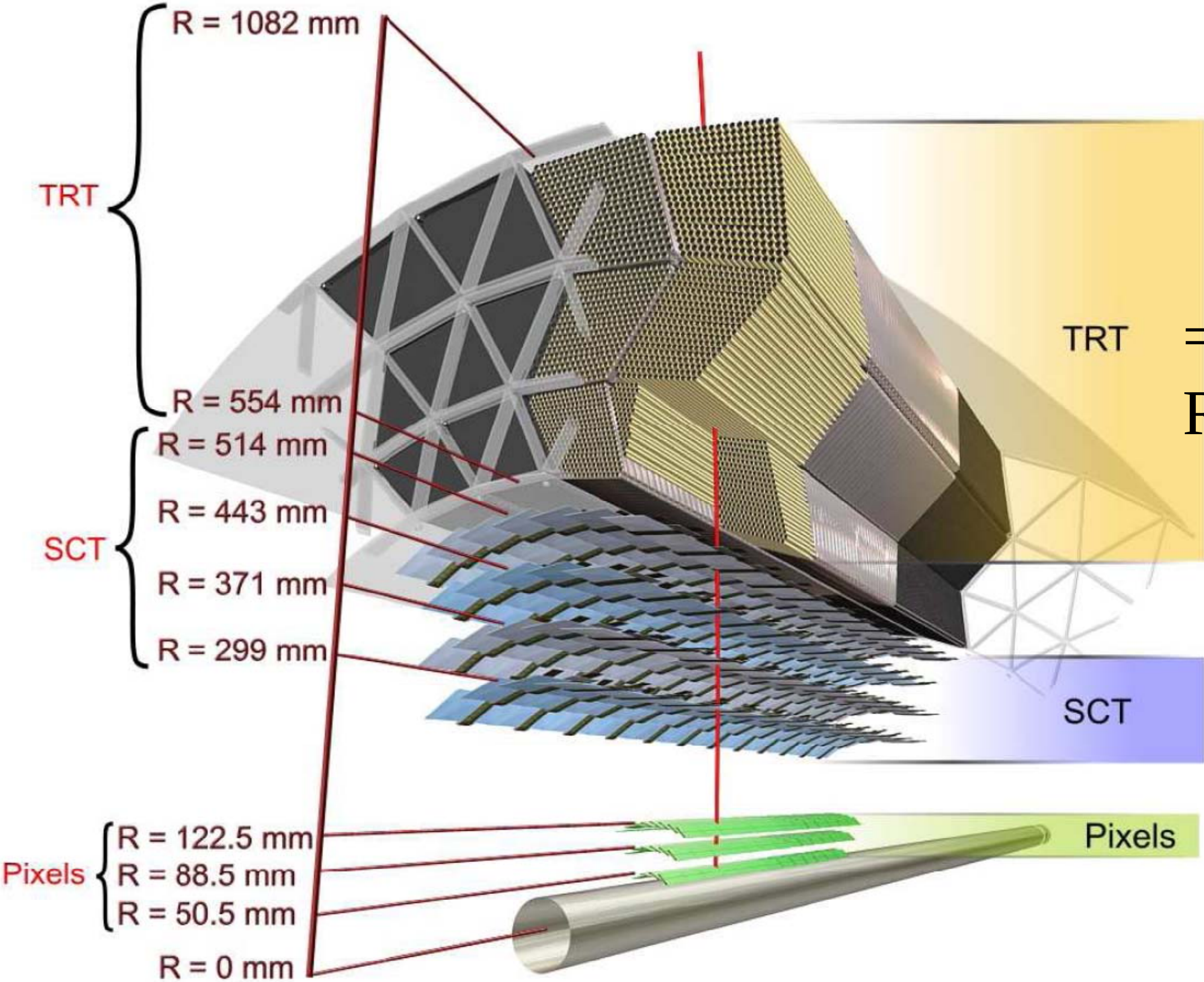


The Tracking Detectors

- Patter recognition:
  Challenging: high track density
  - ✓7 precision points/track (3 pixel+4 SCT)
  - ✓Each r-ϕ and z (40 mrad stereo in SCT)
  - ✓Up to 36 TRT straw hits
  - ✓Continuous tracking... optimised for tracking performance, not TR e-
  - ✓π rejection up to 100 for 80% e-efficiency
- Needs to operate up to an integrated dose between 10 and 60 Mrad
- ID located inside a barrel cryostat including solenoid
  - ✓2T field, non-uniform at high z
    -> Reduces to 1T at z=2.7m
  - ✓Hermetic coverage up to $|\eta|=2.5$

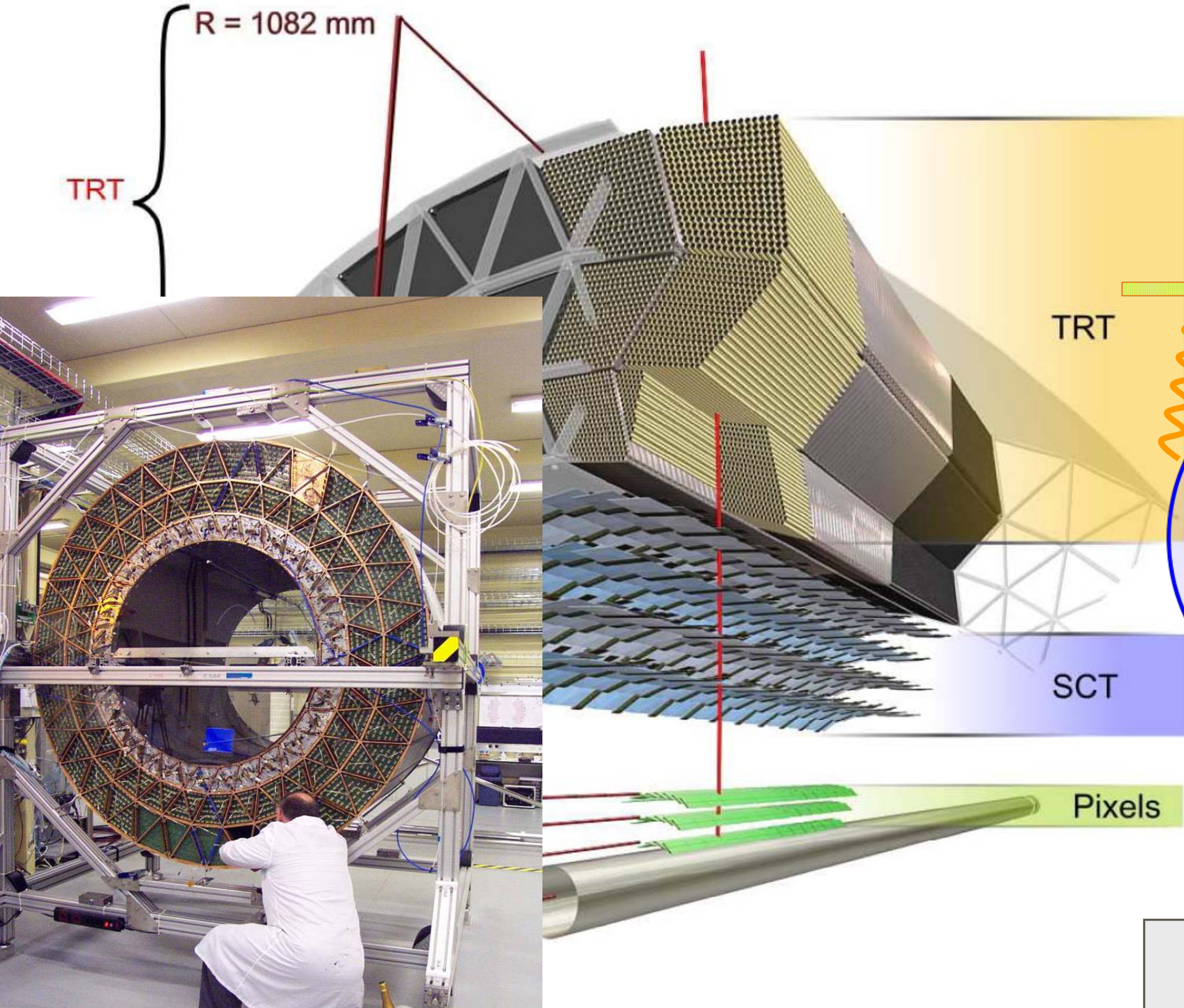


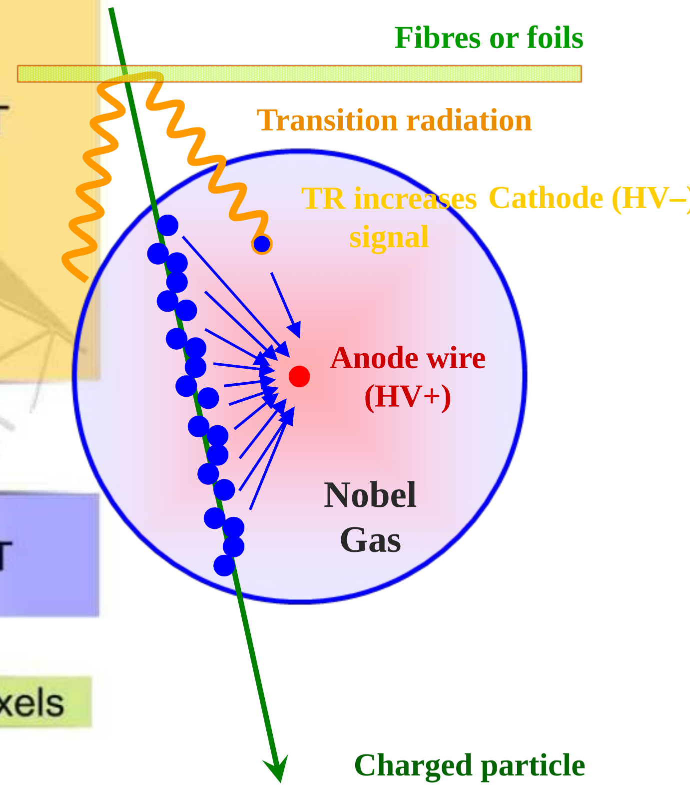
Inner Detector Barrel



= Transition RadiationTracker

Inner Detector Barrel





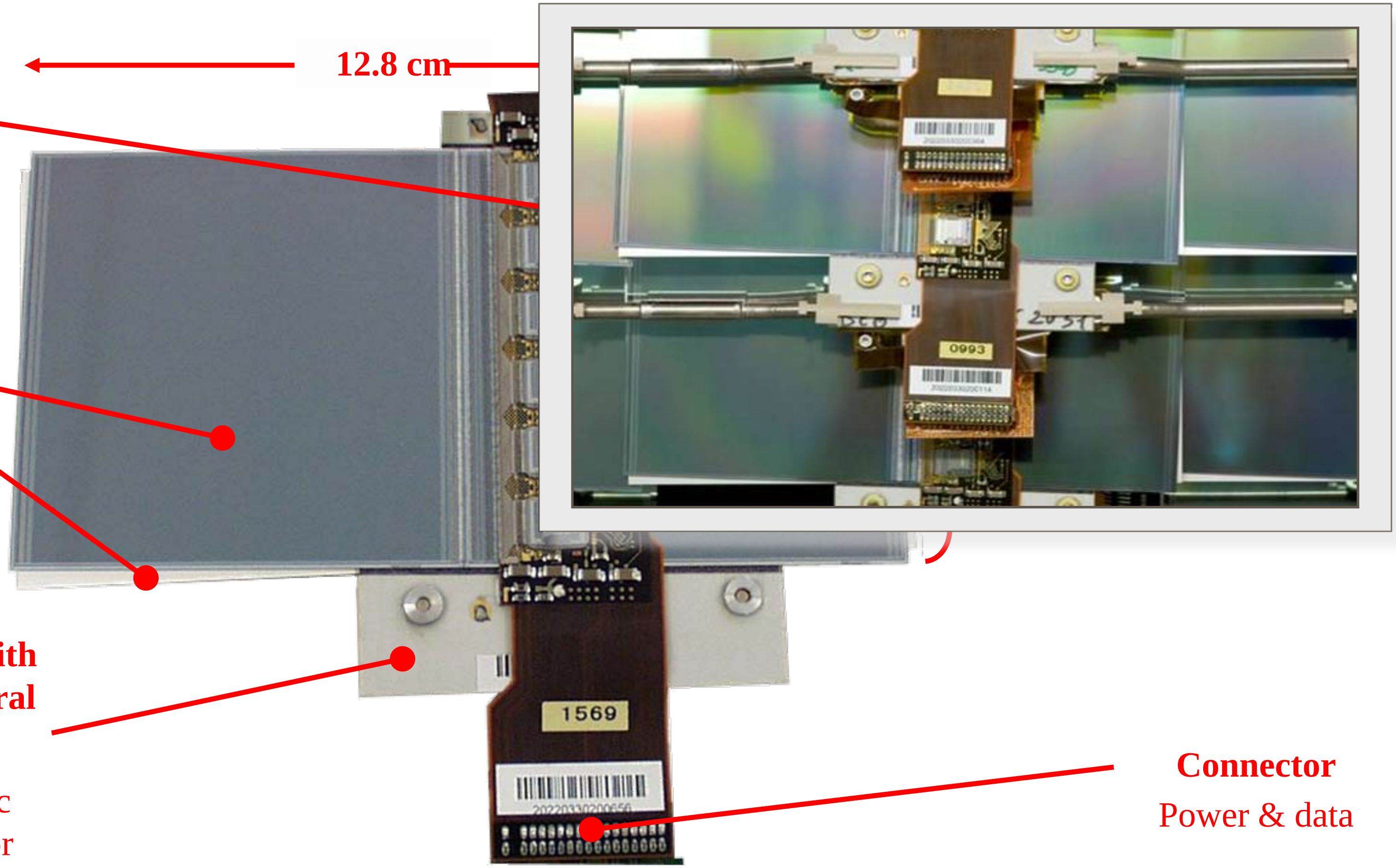
Electrons radiate more → higher signal; info by counting high threshold hits

Barrel SCT module

Hybrid assembly
with readout chips

12.8 cm

4 Silicon sensors
280 μm thick
2.3° stereo angle
Overlap in ϕ & z to adjacent modules

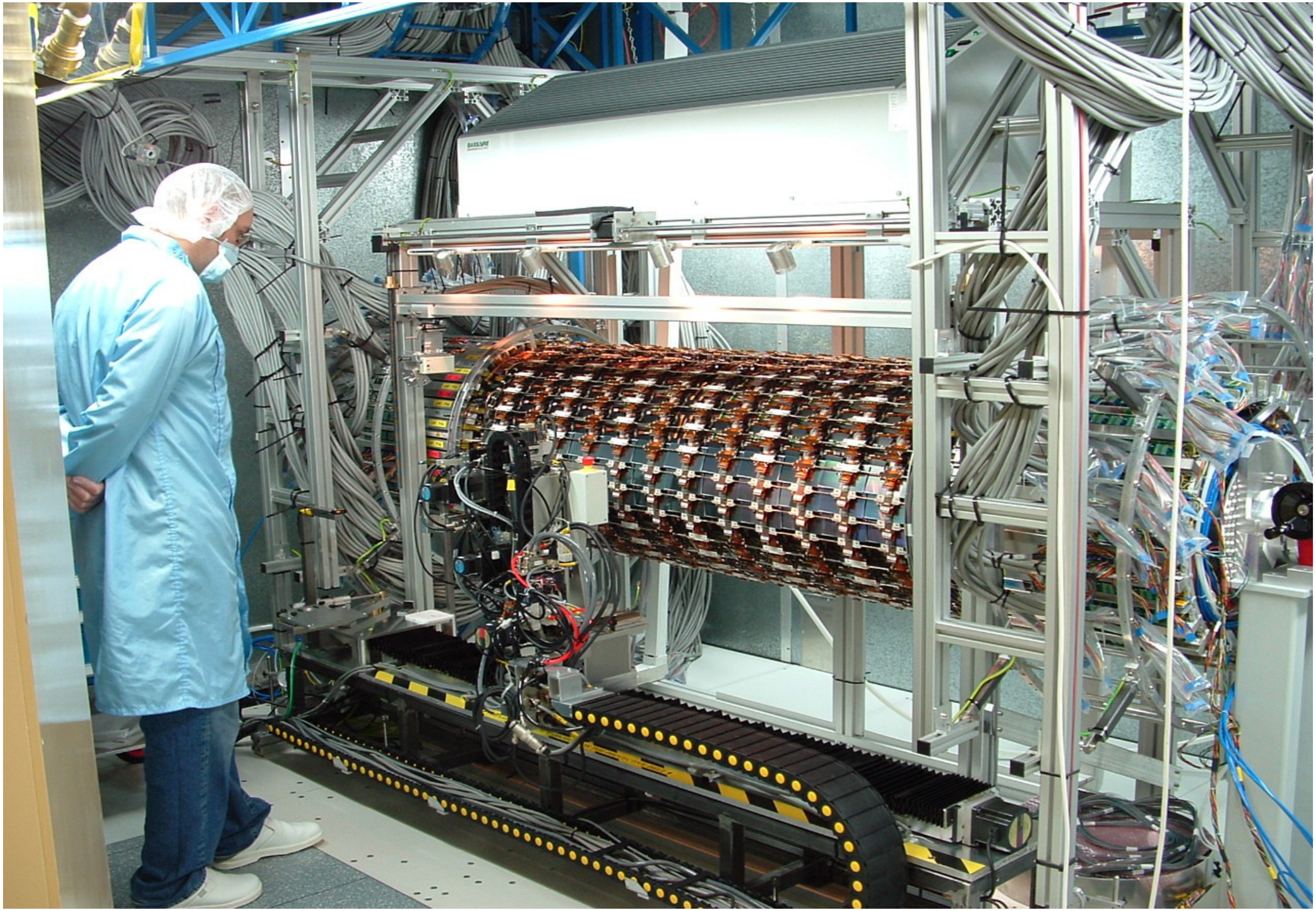


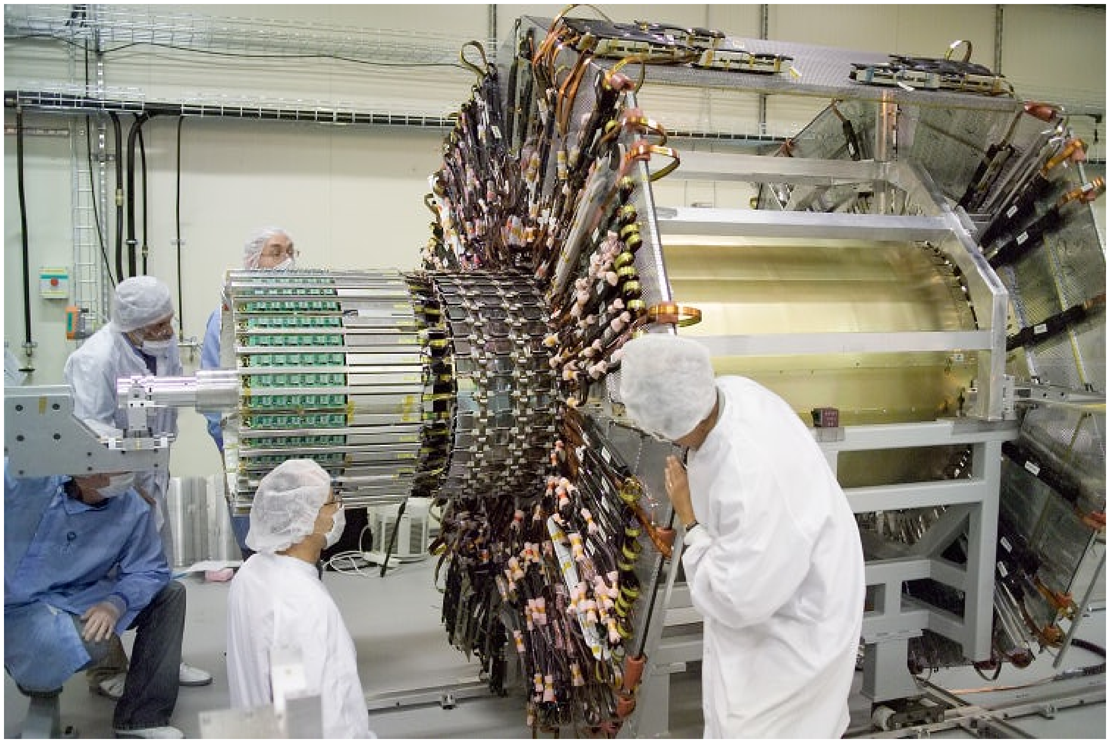
Be module baseboard with mounting points & central TPG

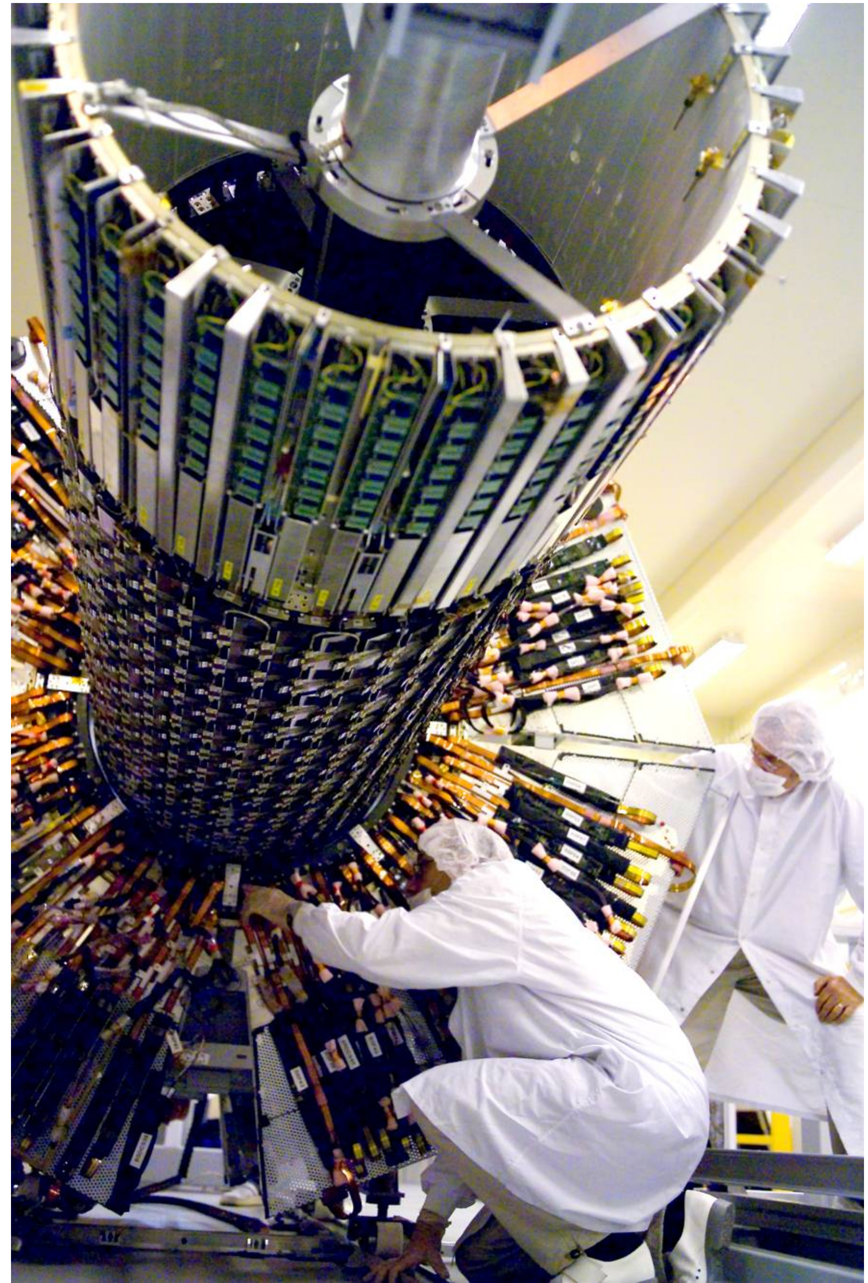
TPG (thermal pyrolythic graphite) plate for sensor cooling

Connector
Power & data

Fully equipped double sided electrical module with baseboard and readout hybrids



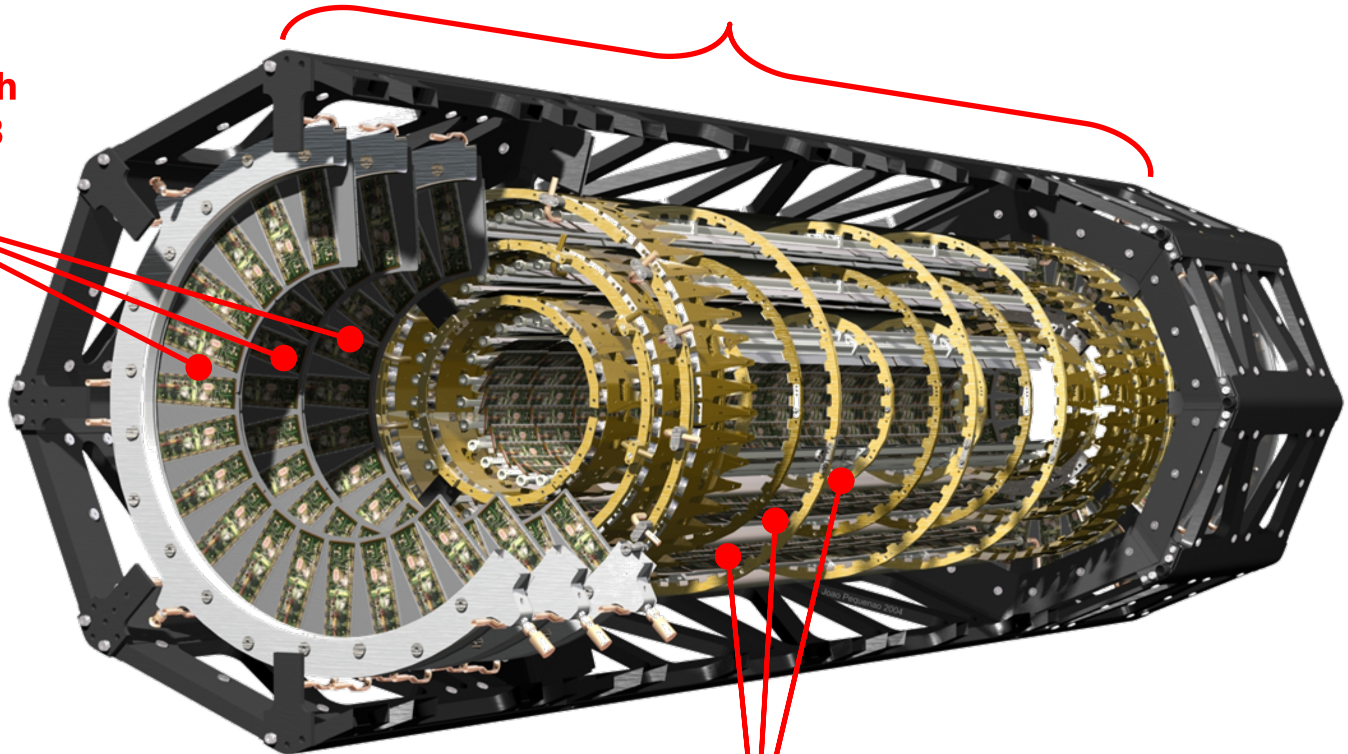




The Pixel detector

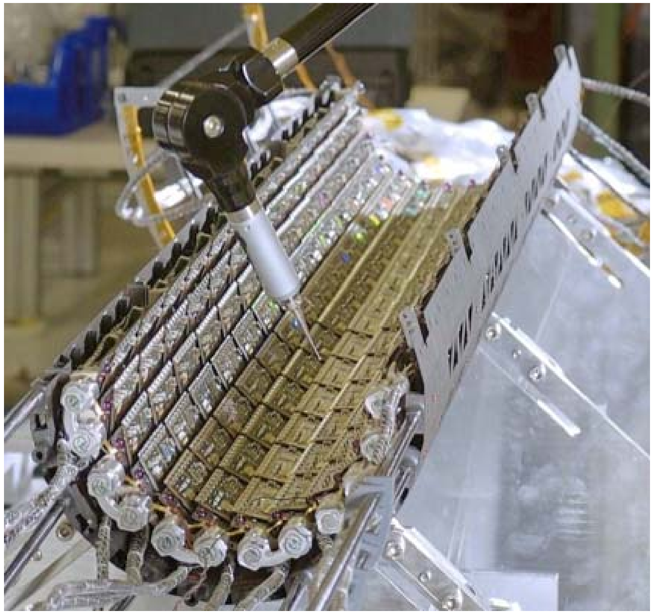
Length: 1.3 m, weight: ~4.4 kg, ∅: 34.4 cm

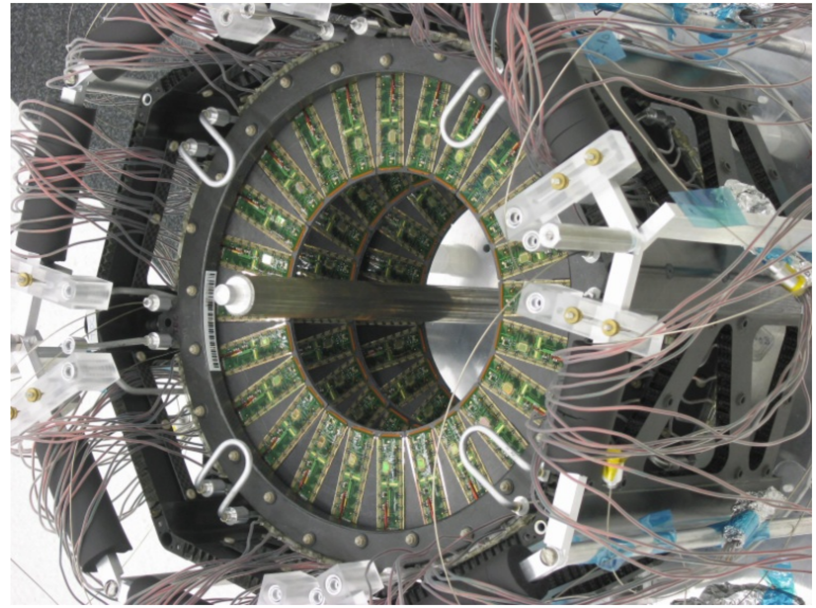
2×3 Endcap disks, each with 8 sectors and 48 modules

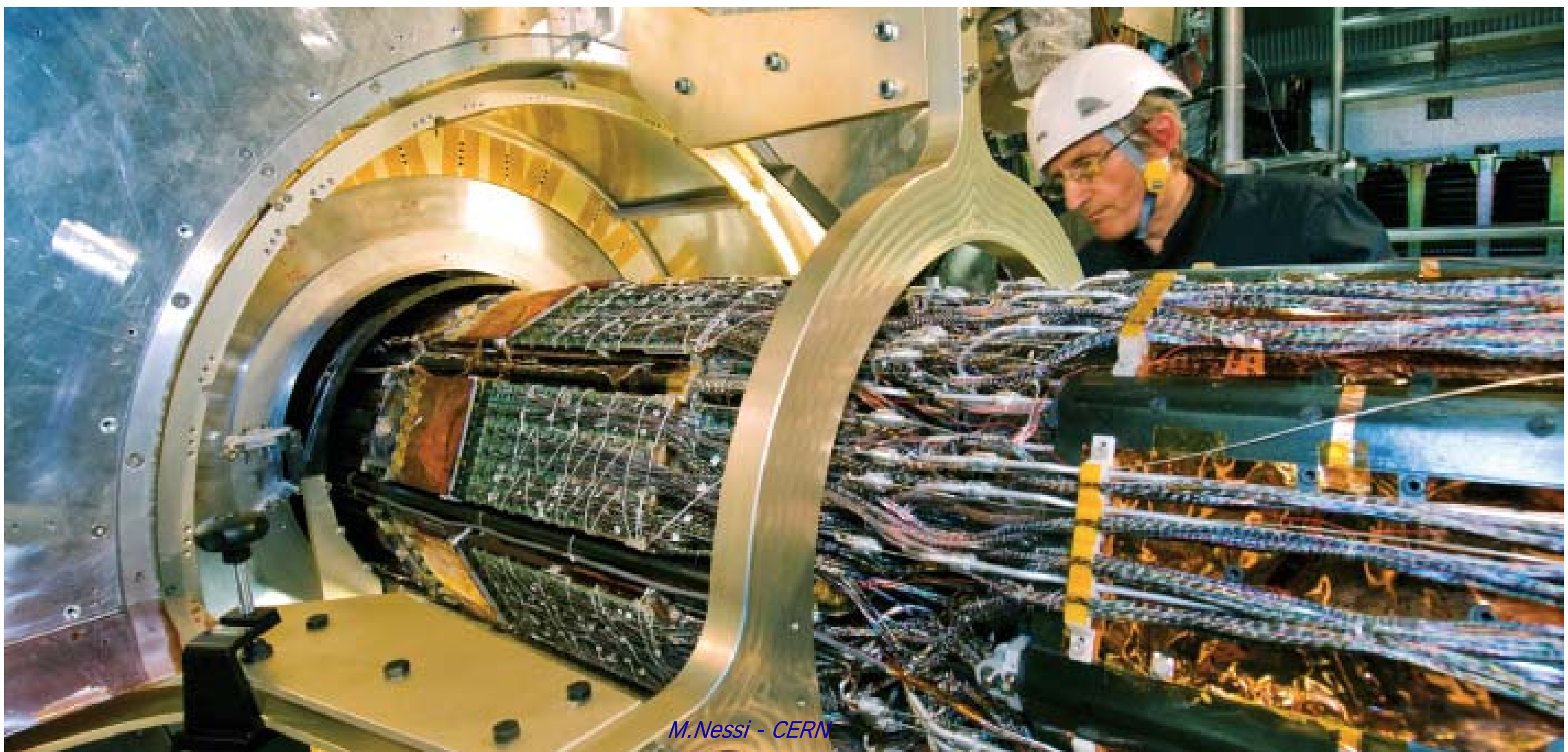


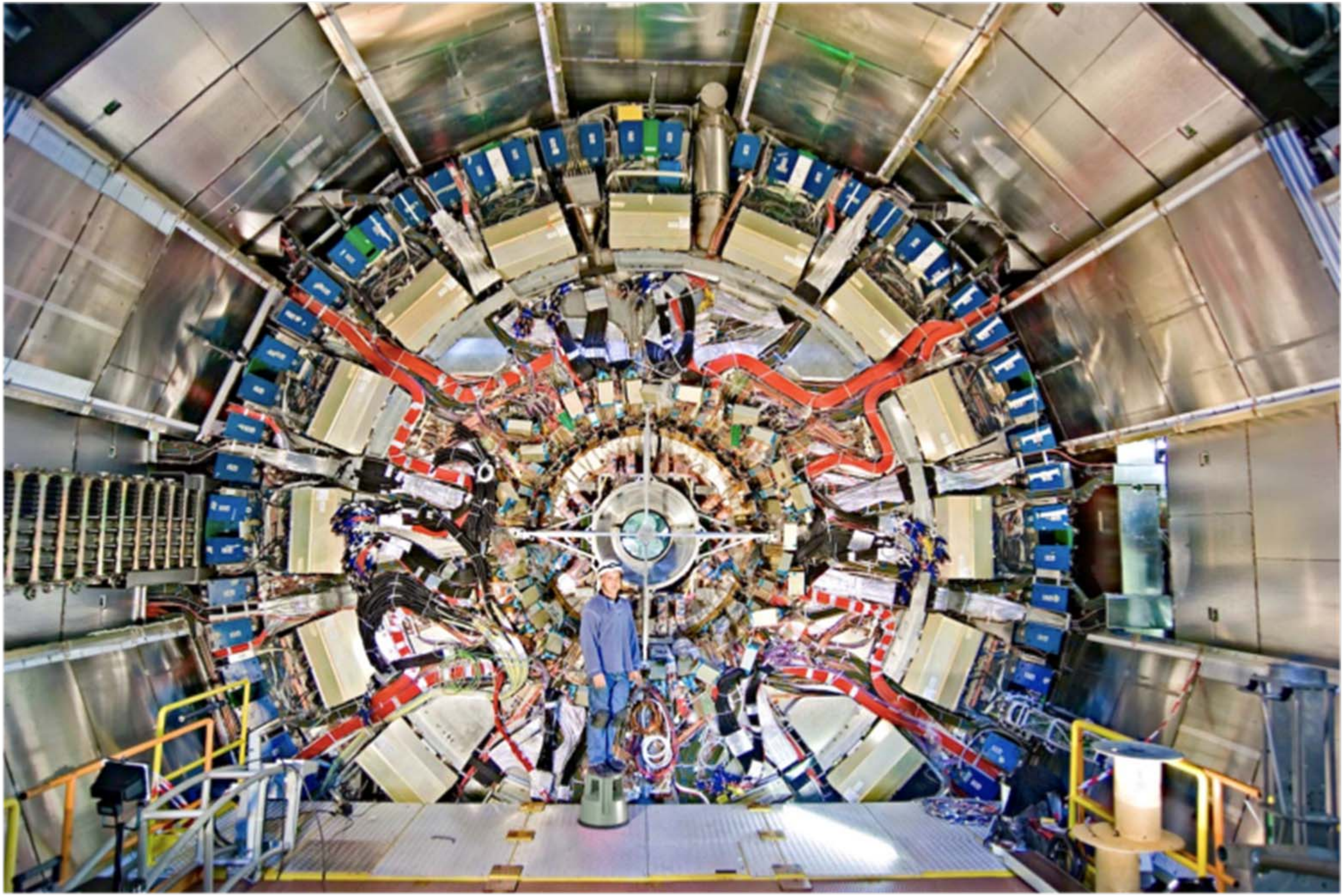
3 Barrel layers (*r* = 5, 9, 12 cm),
Σ = 1456 barrel modules

Typical resolution (barrel):
10 μm [$r\phi$], 115 μm [z]

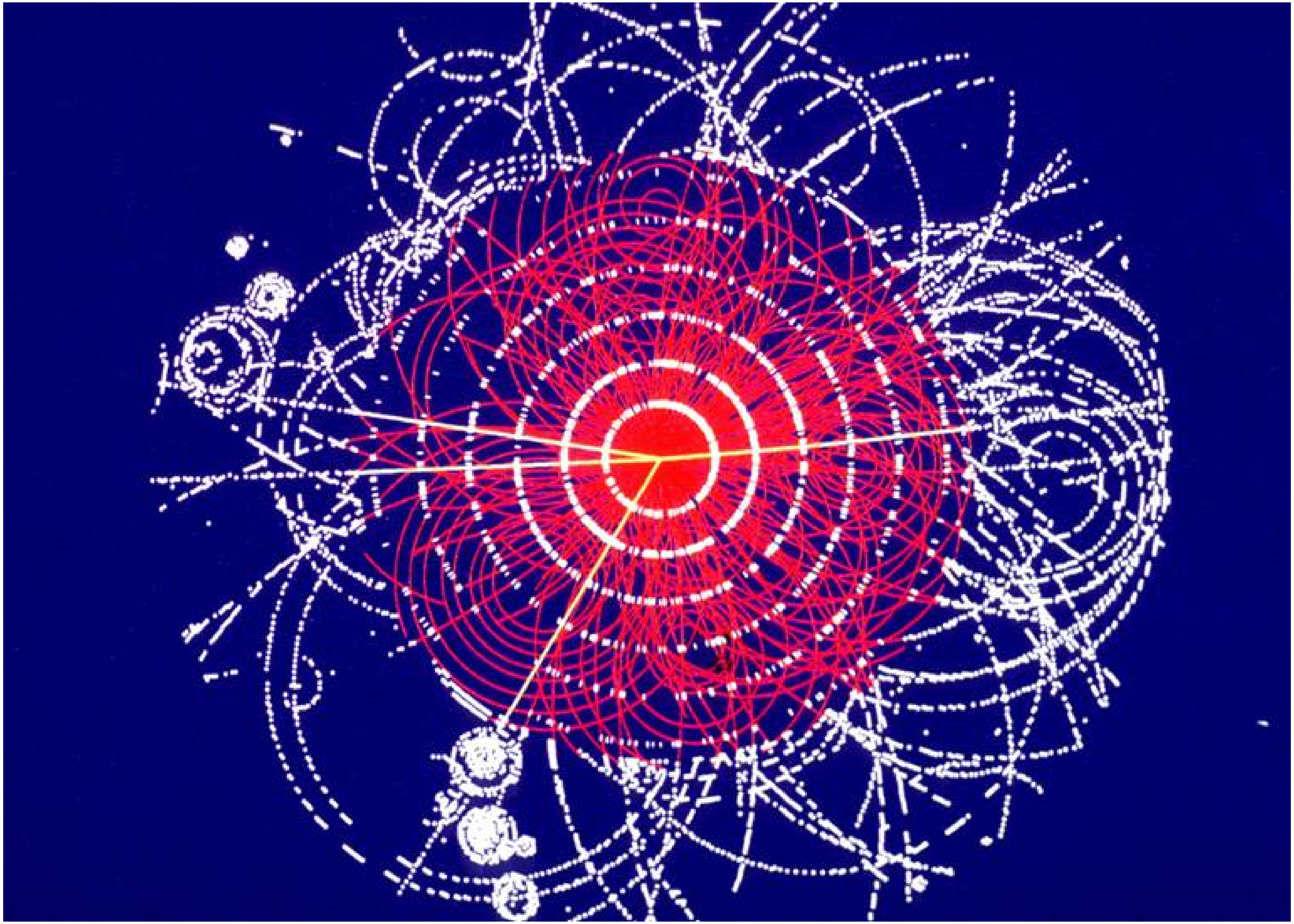


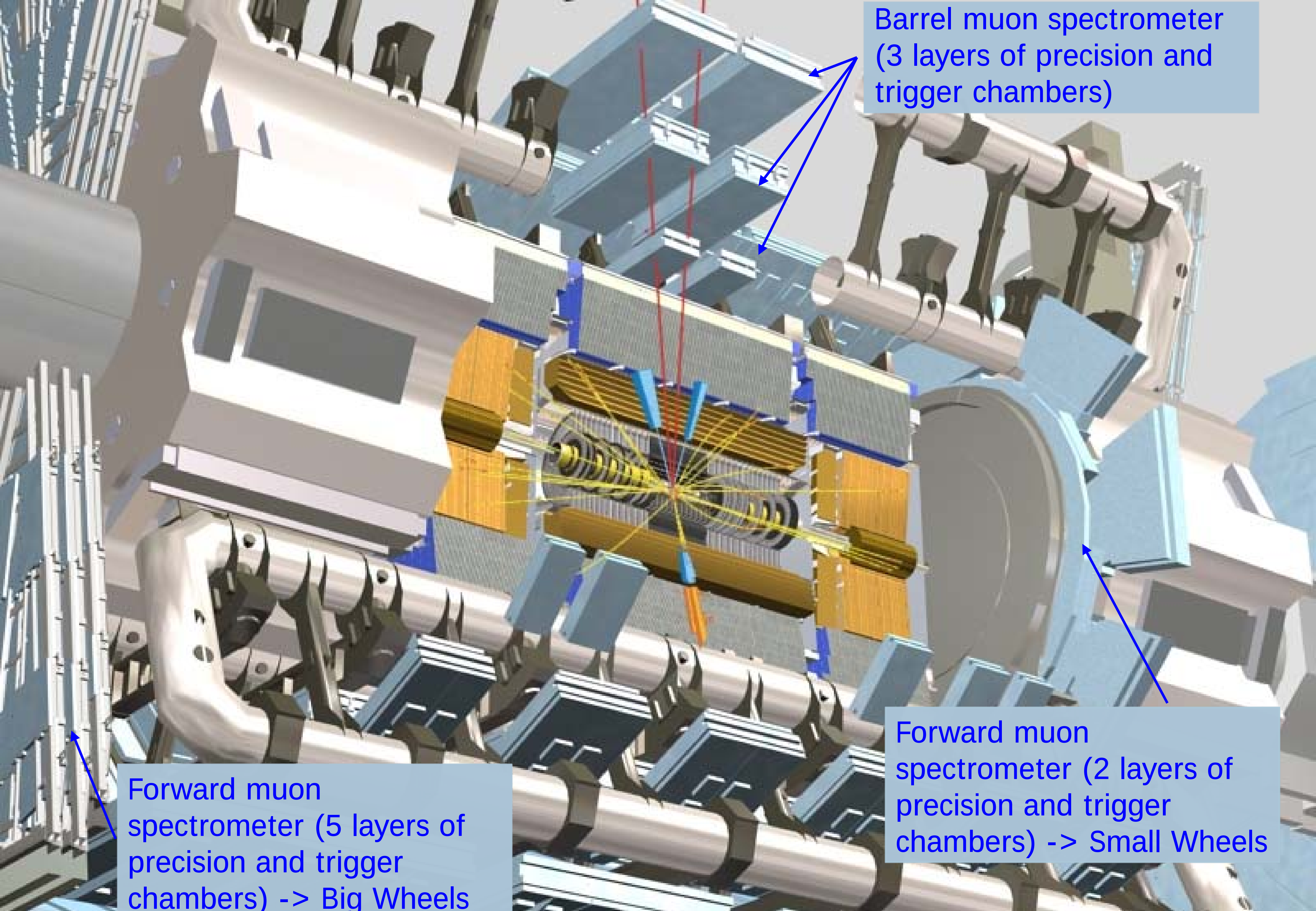


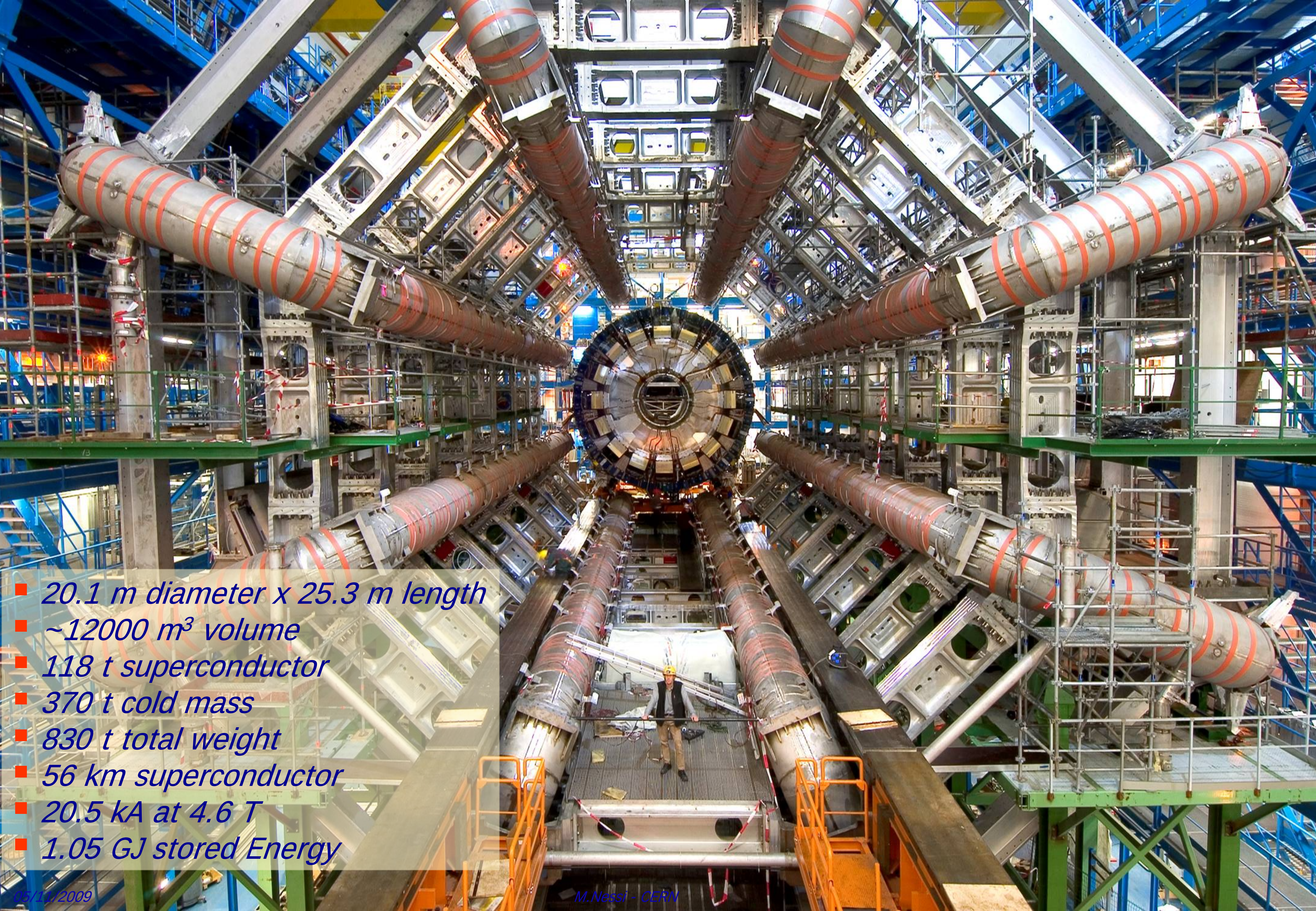




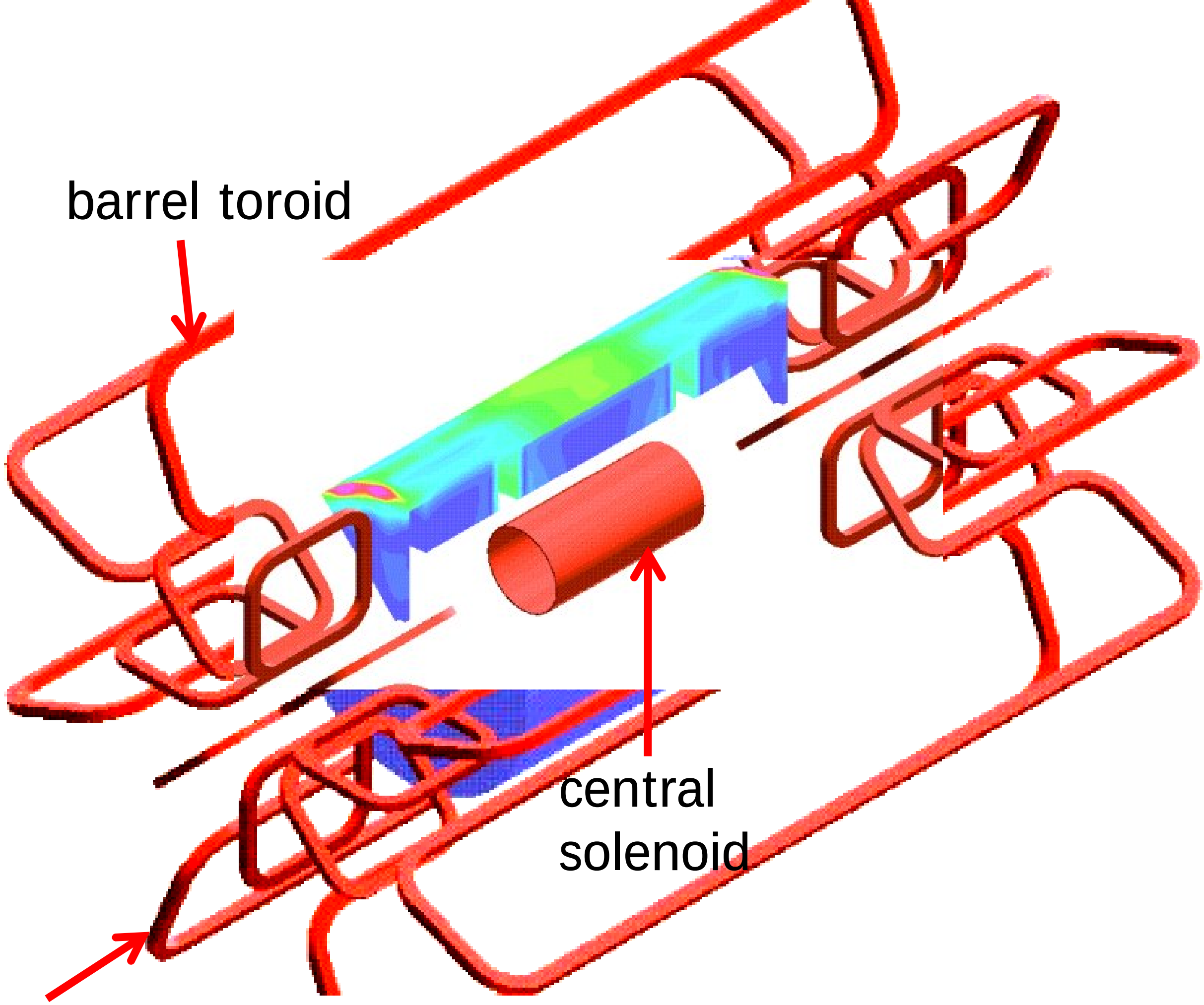
Inner Detector Barrel




Barrel muon spectrometer (3 layers of precision and trigger chambers)
Forward muon spectrometer (2 layers of precision and trigger chambers) -> Small Wheels
Forward muon spectrometer (5 layers of precision and trigger chambers) -> Big Wheels



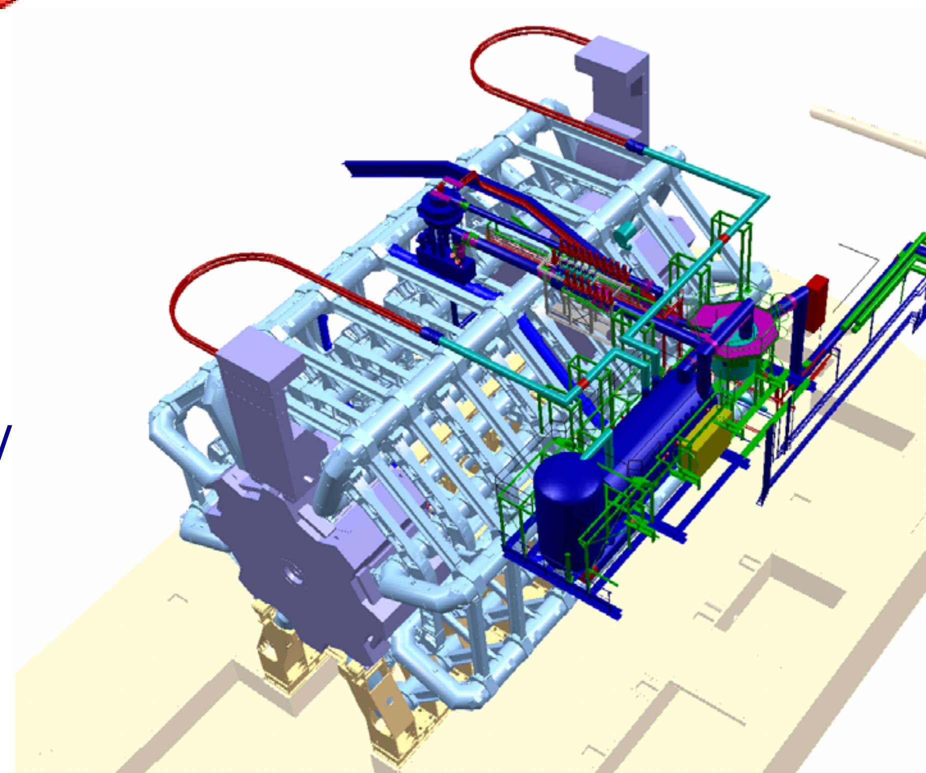
- *20.1 m diameter x 25.3 m length*
- *~12000 m^3 volume*
- *118 t superconductor*
- *370 t cold mass*
- *830 t total weight*
- *56 km superconductor*
- *20.5 kA at 4.6 T*
- *1.05 GJ stored Energy*



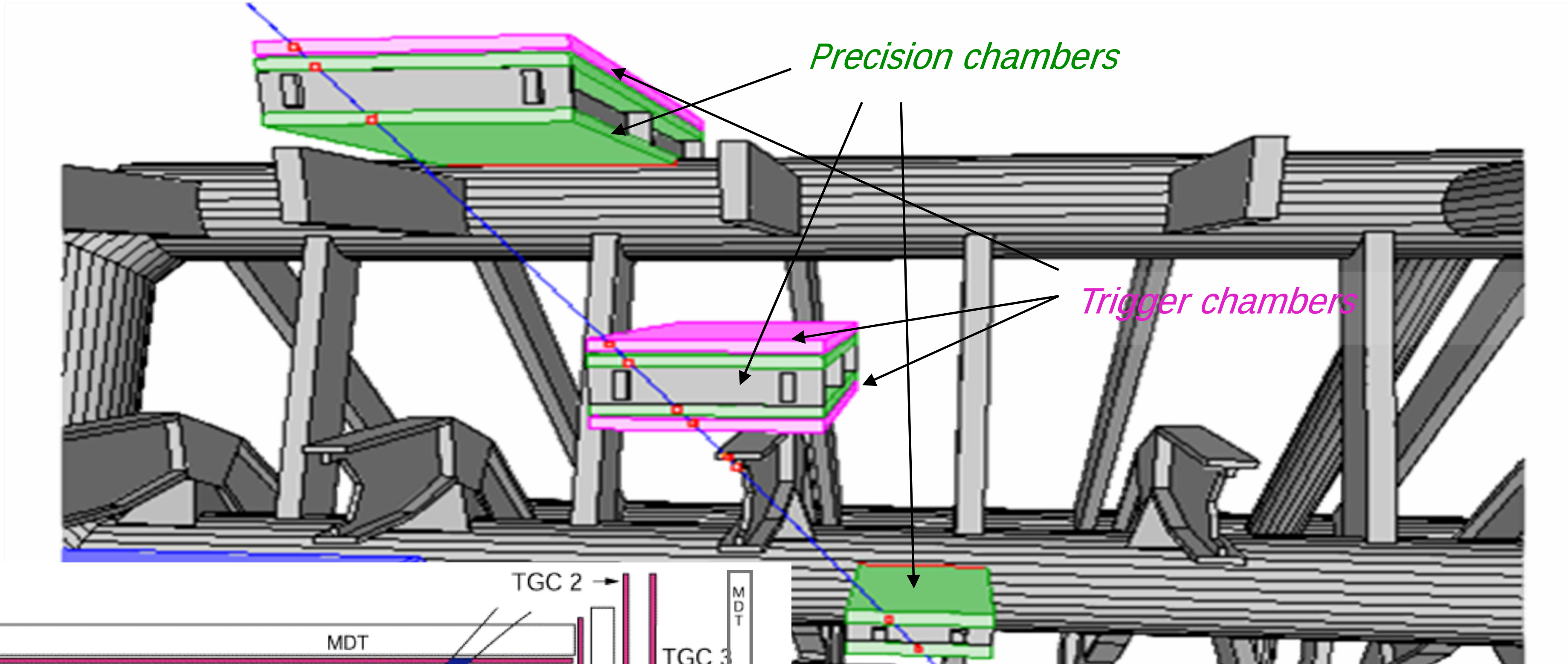
ATLAS has a complex magnet system (4 independent magnets)

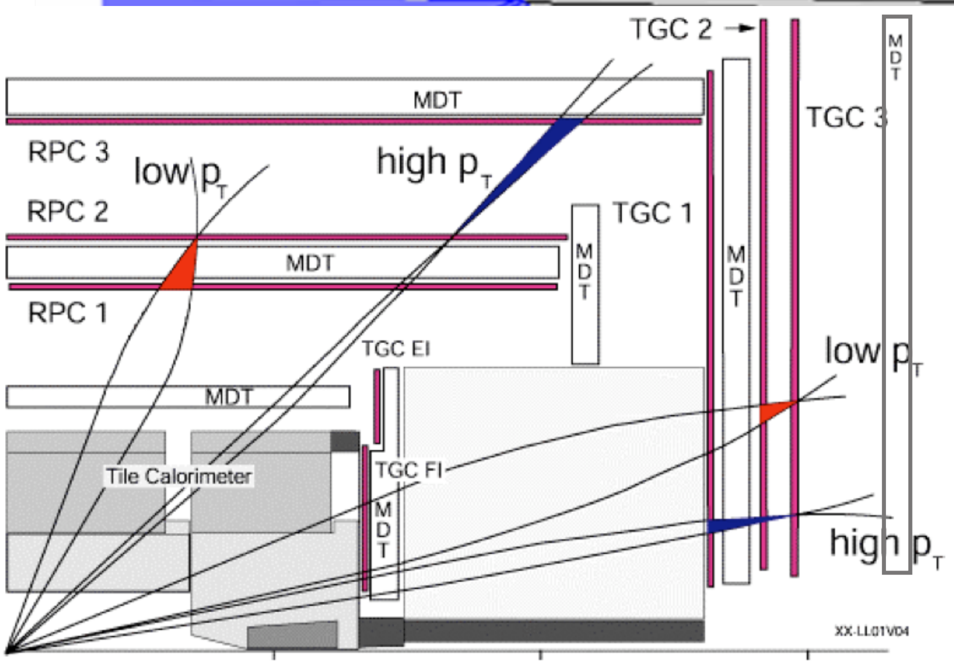
- 2 T central solenoid, around the inner detector with return flux via the hadron tile calorimeter

1 barrel and 2 end-cap toroids, each one built out of 8 individual superconducting coils

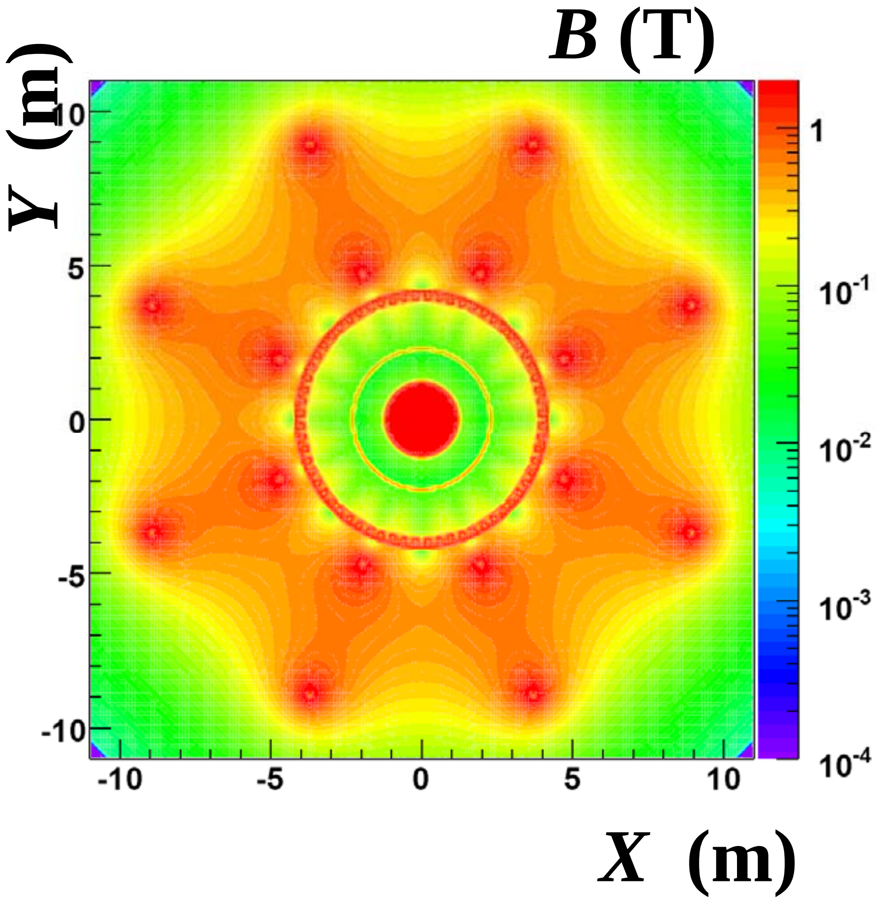


Muon Spectrometer

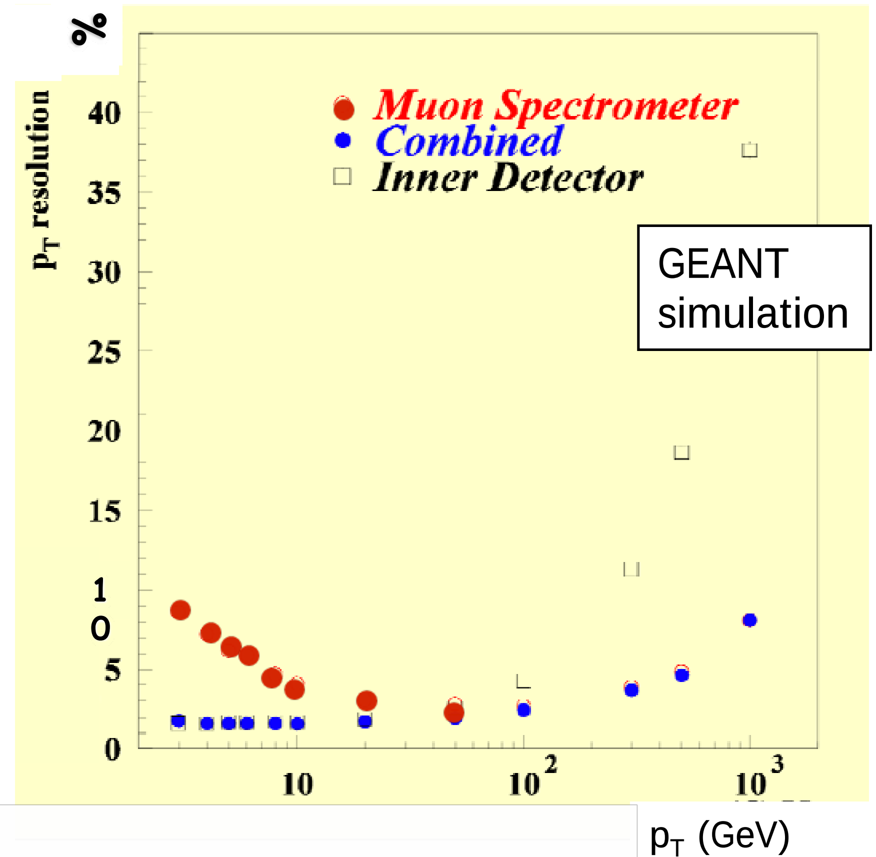




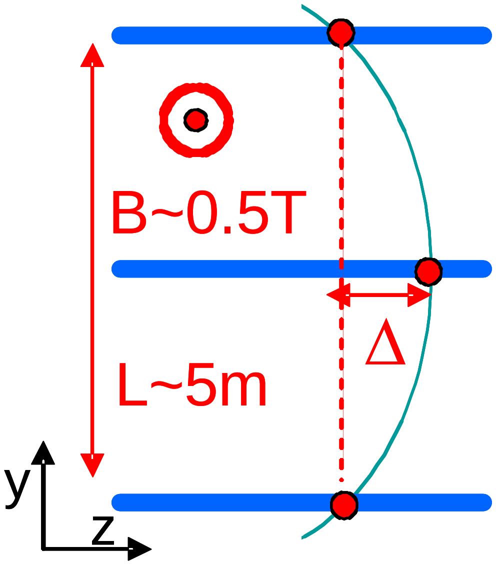
Muon Spectrometer (with stand-alone capability)



Muon momentum resolution



Muon Spectrometer Strategy

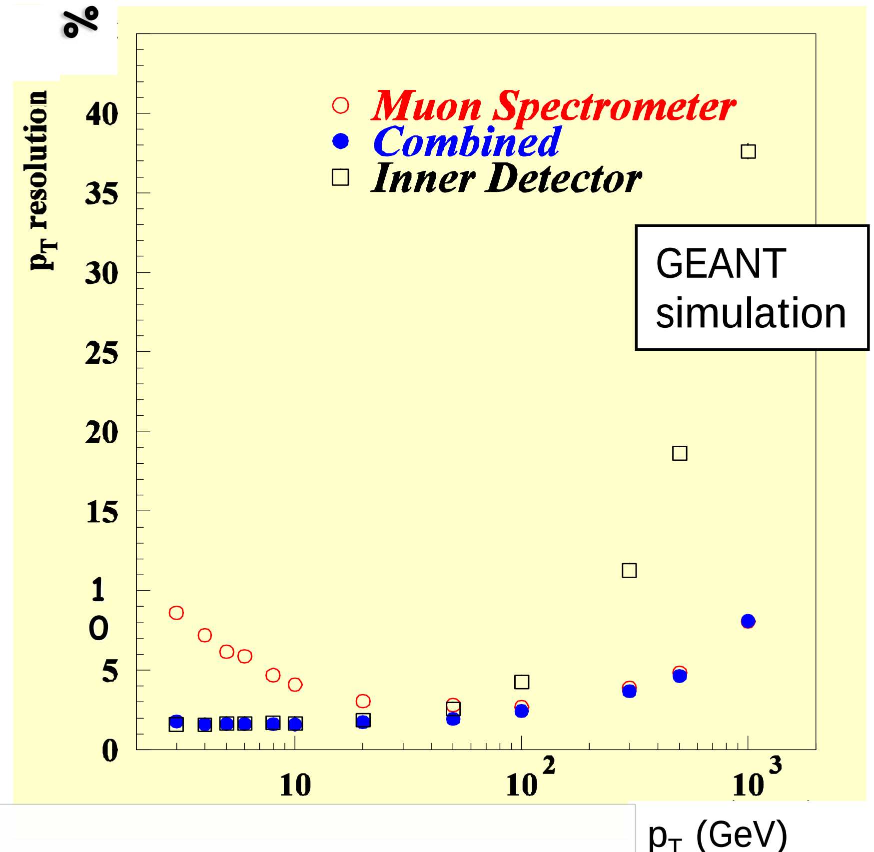


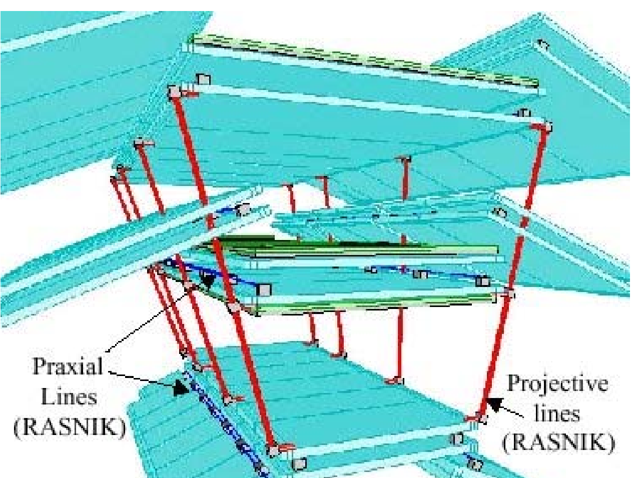
$\sigma/p < 10\%$ for $E\mu \sim$ TeV needed to observe a possible new resonance $X \rightarrow \mu\mu$ as a “narrow” peak

$E_{\mu} \sim 1$ TeV $\Rightarrow \Delta \sim 500\ \mu m$

$\sigma/p \sim 10\% \Rightarrow \delta\Delta \sim 50\ \mu m$

Muon momentum resolution



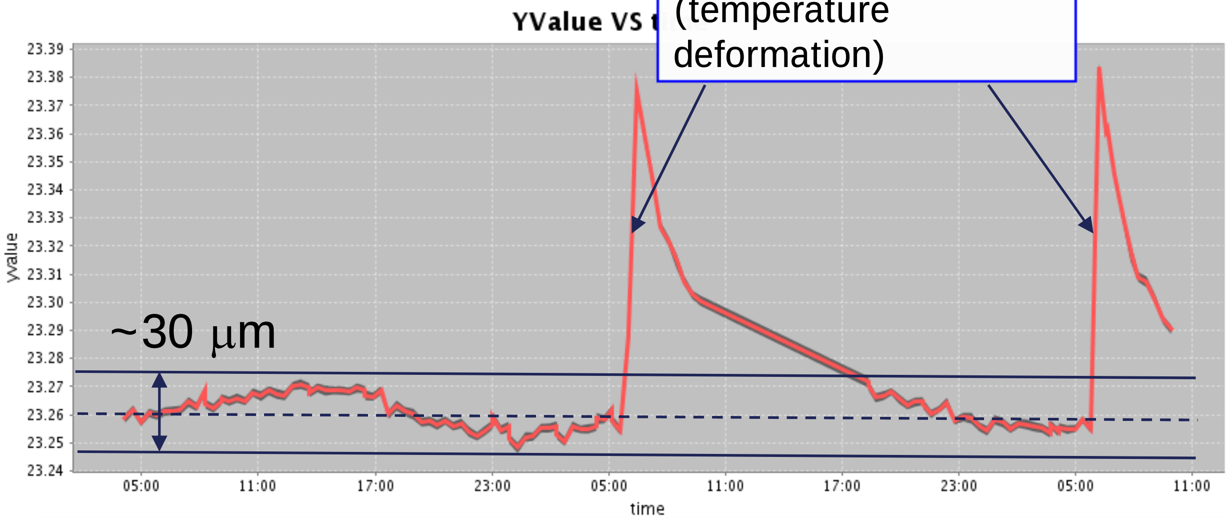


alignment accuracy to $\sim 30\ \mu m$

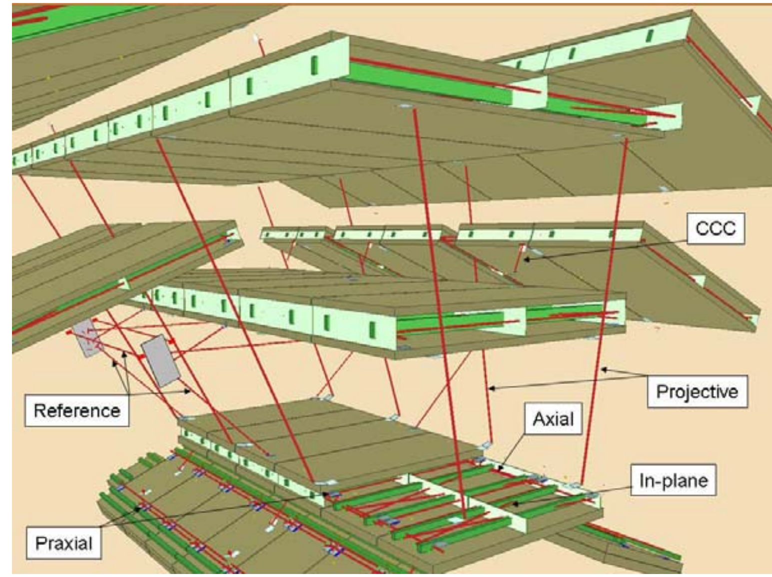
Can we achieve such a precision ?

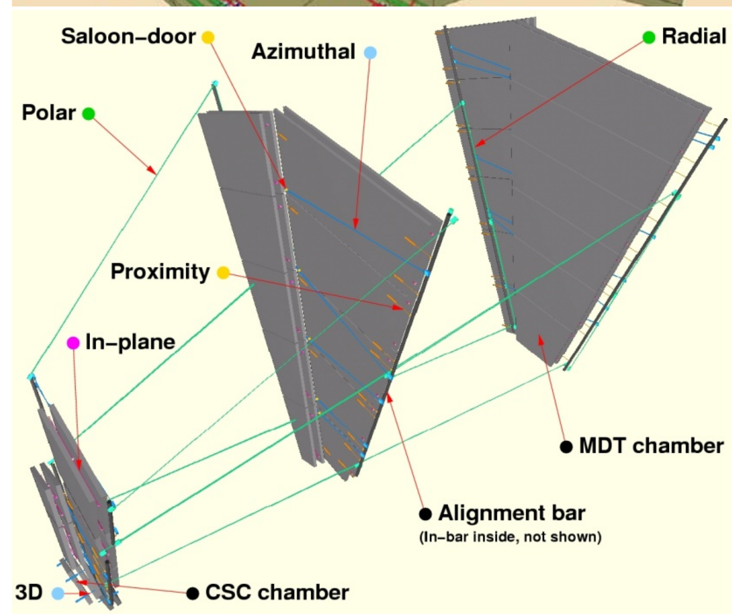
Showing that we know the geometrical position of all chambers in time, using a sophisticated alignment system

Safety Barrel Toroid Magnet heaters periodically turned on (temperature deformation)



Example of one projective line stability

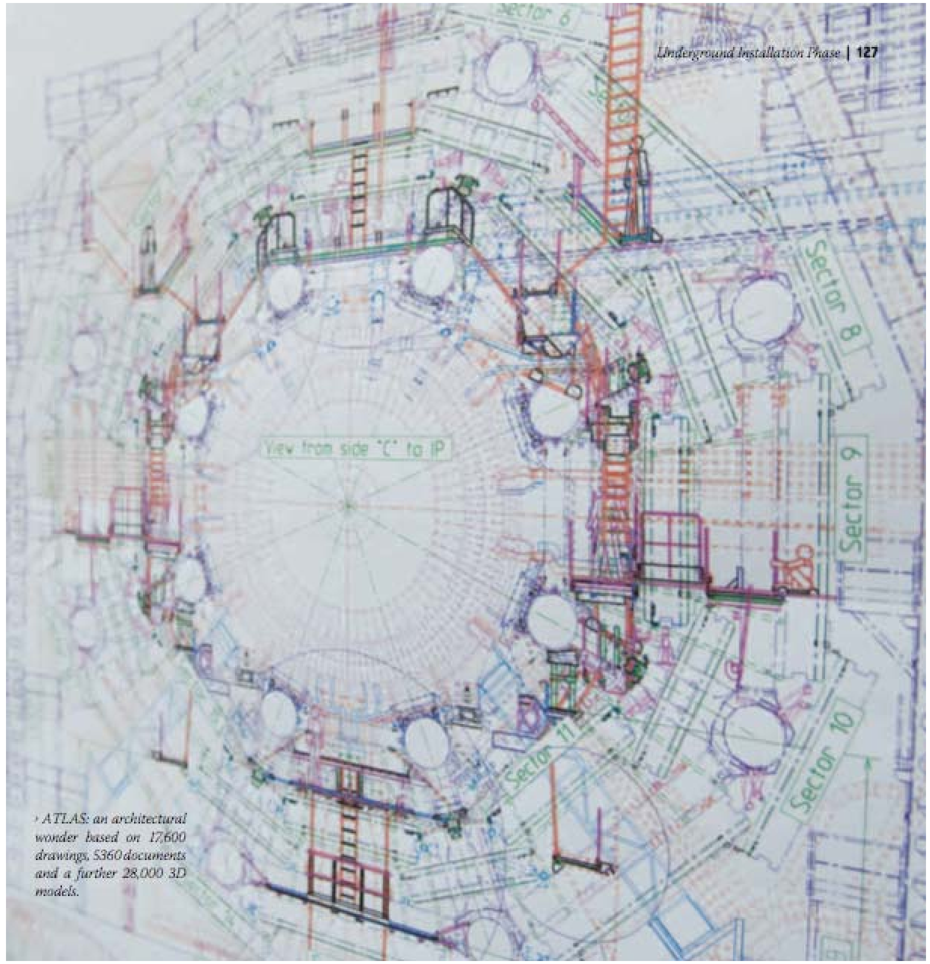




Demonstrated an alignment precision of ±20 μm with the test beam setup already

Underground installation

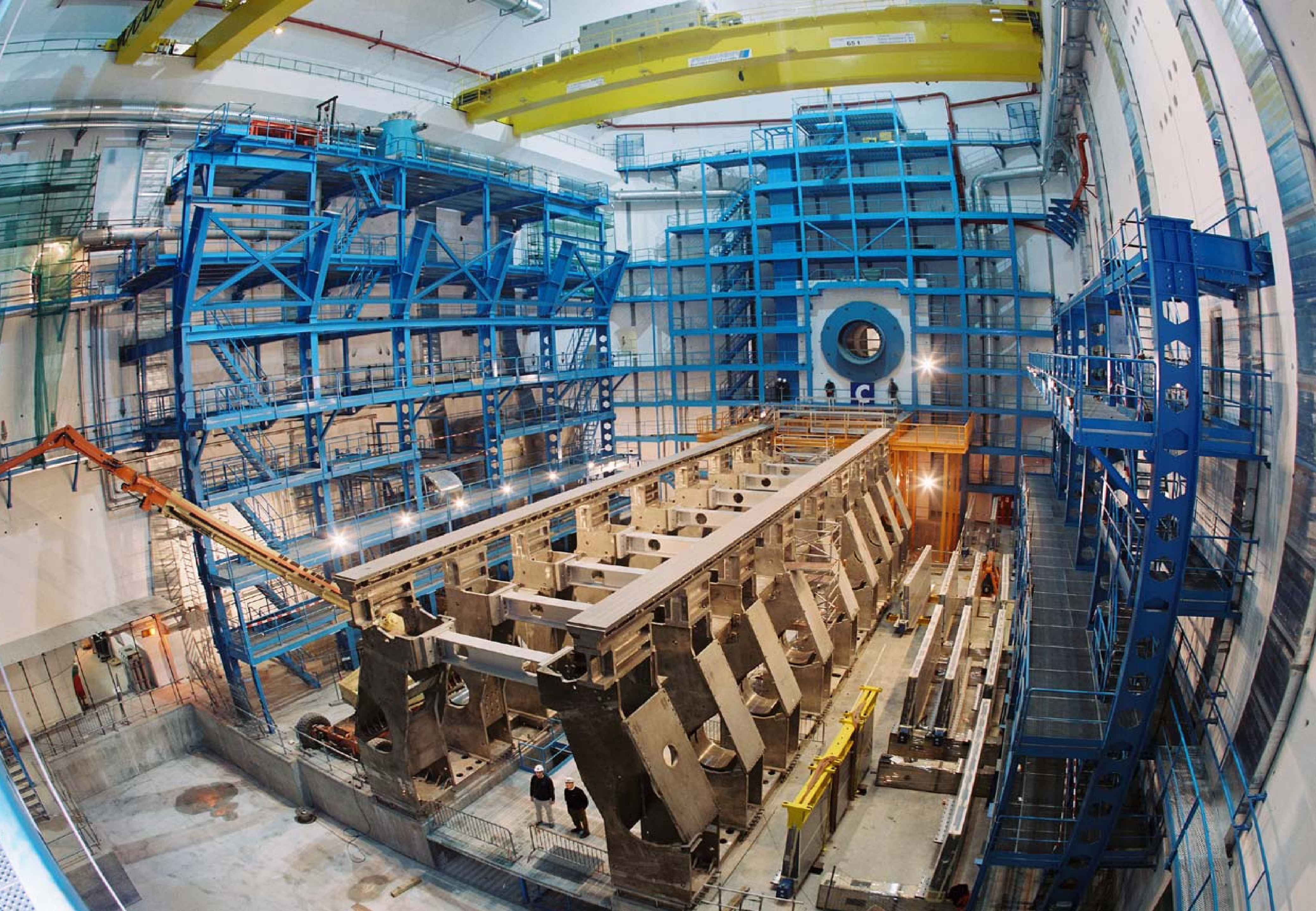
A gigantic 3D puzzle of 20'000 m^3
..... 5 years of great fun !



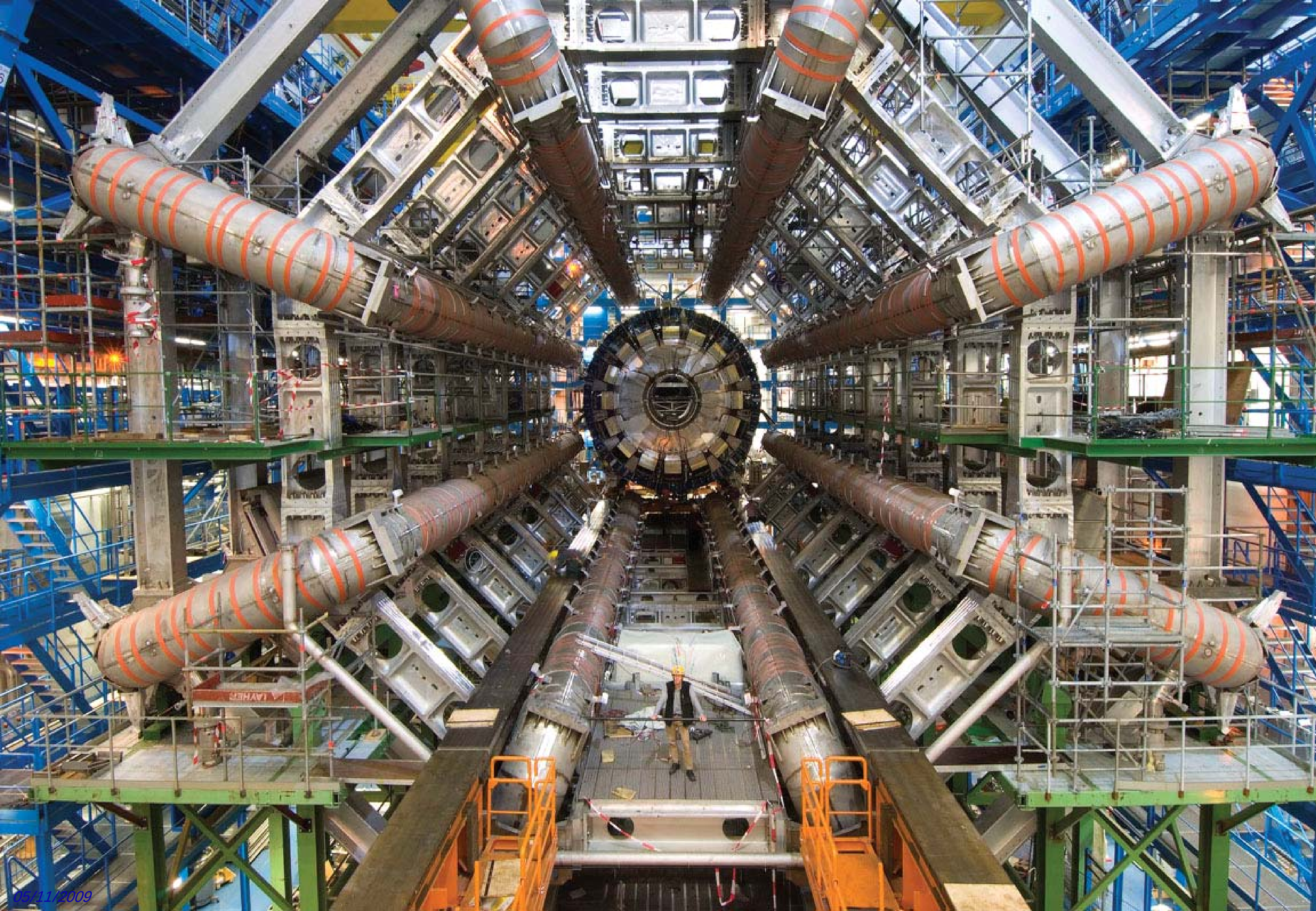

1998
05/11/2009

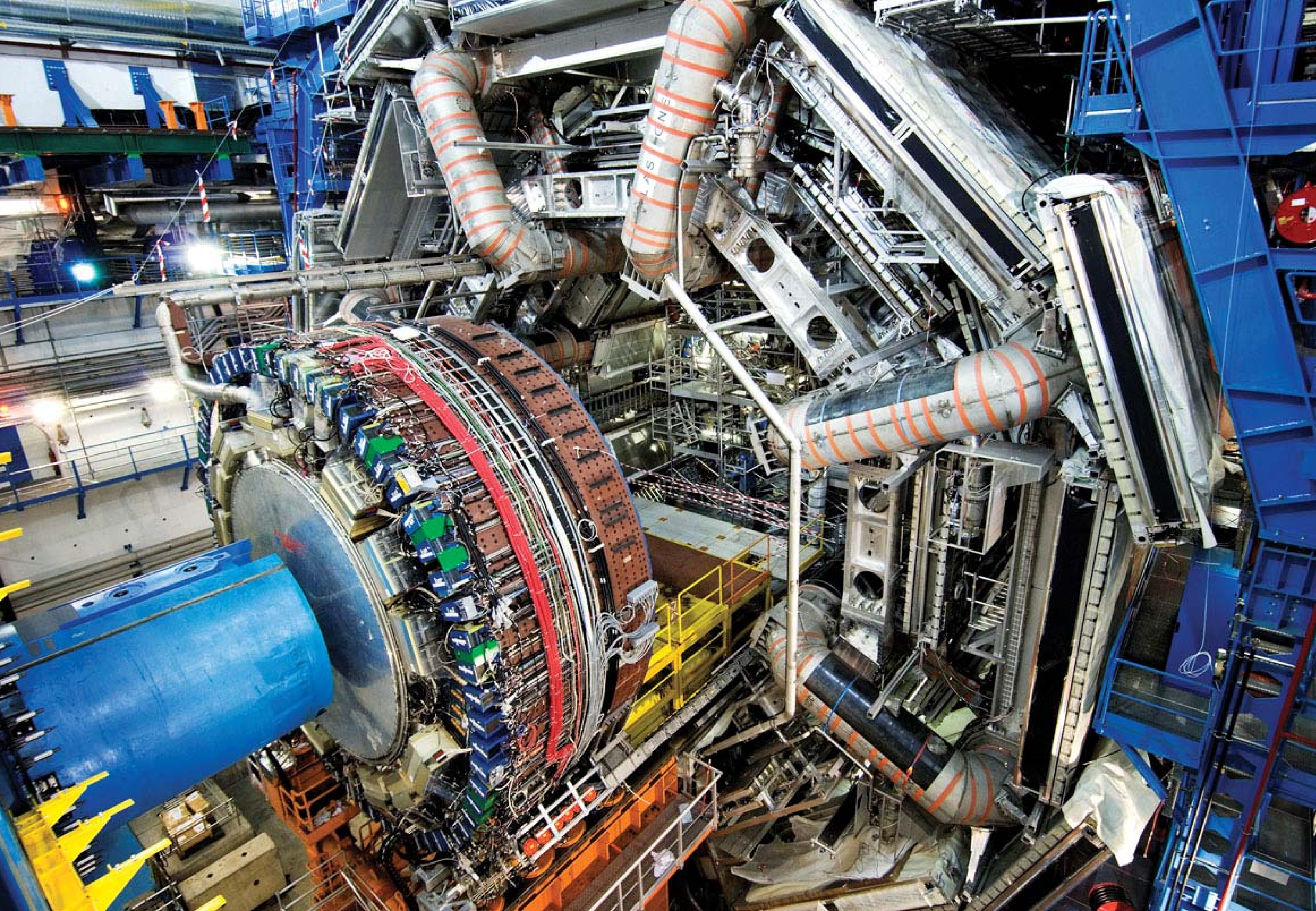

05/11/2009

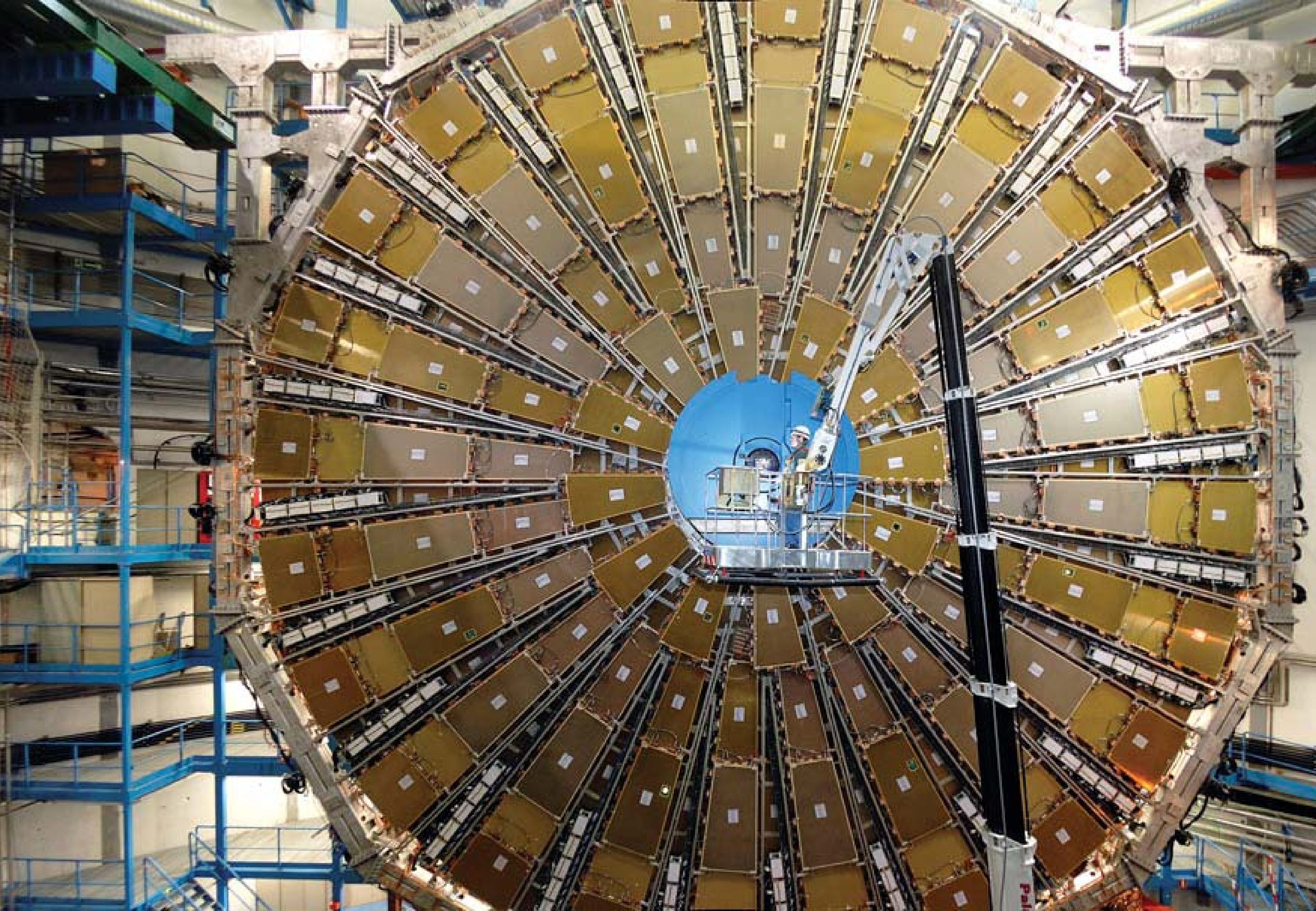
June 2003

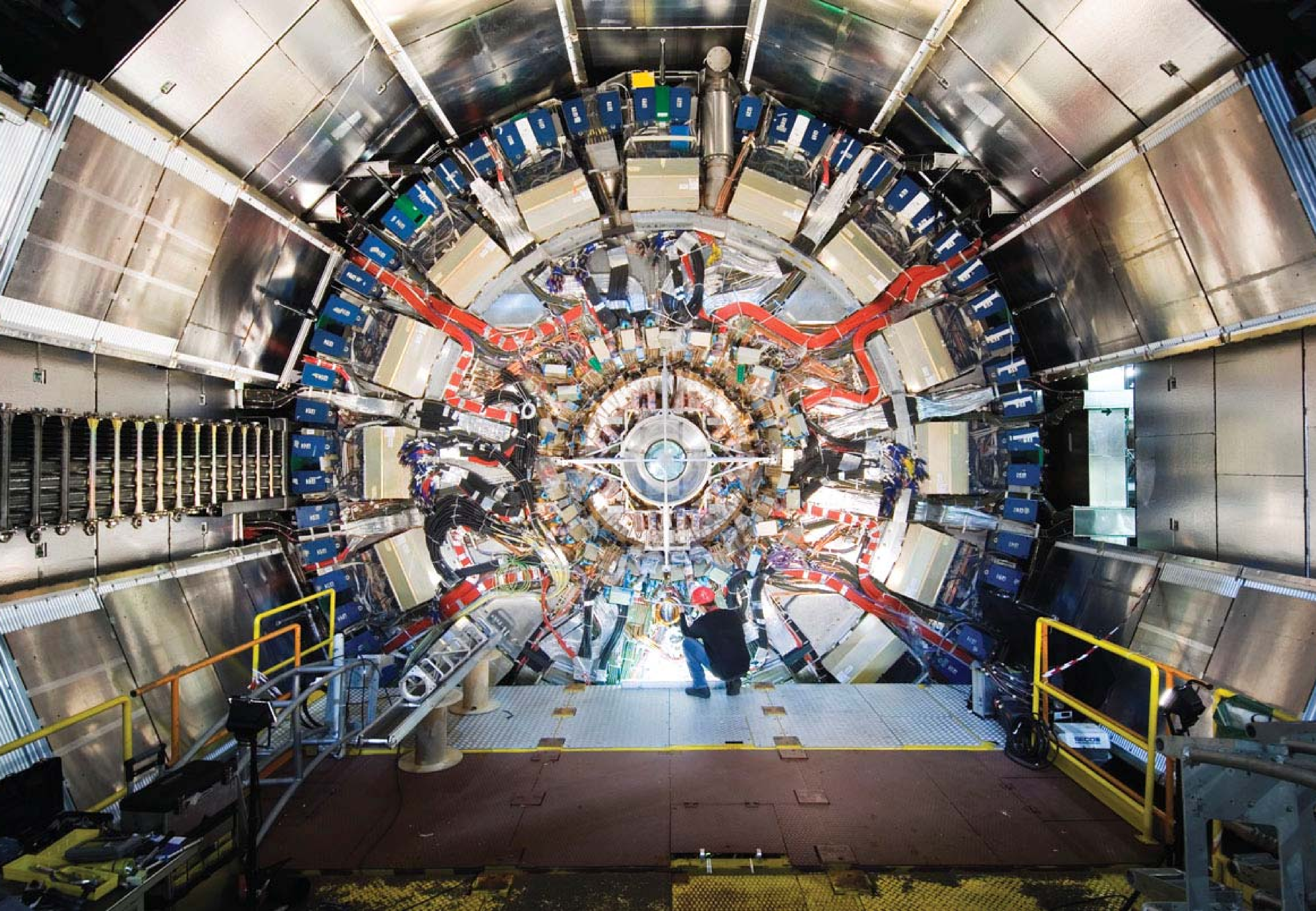

65 t

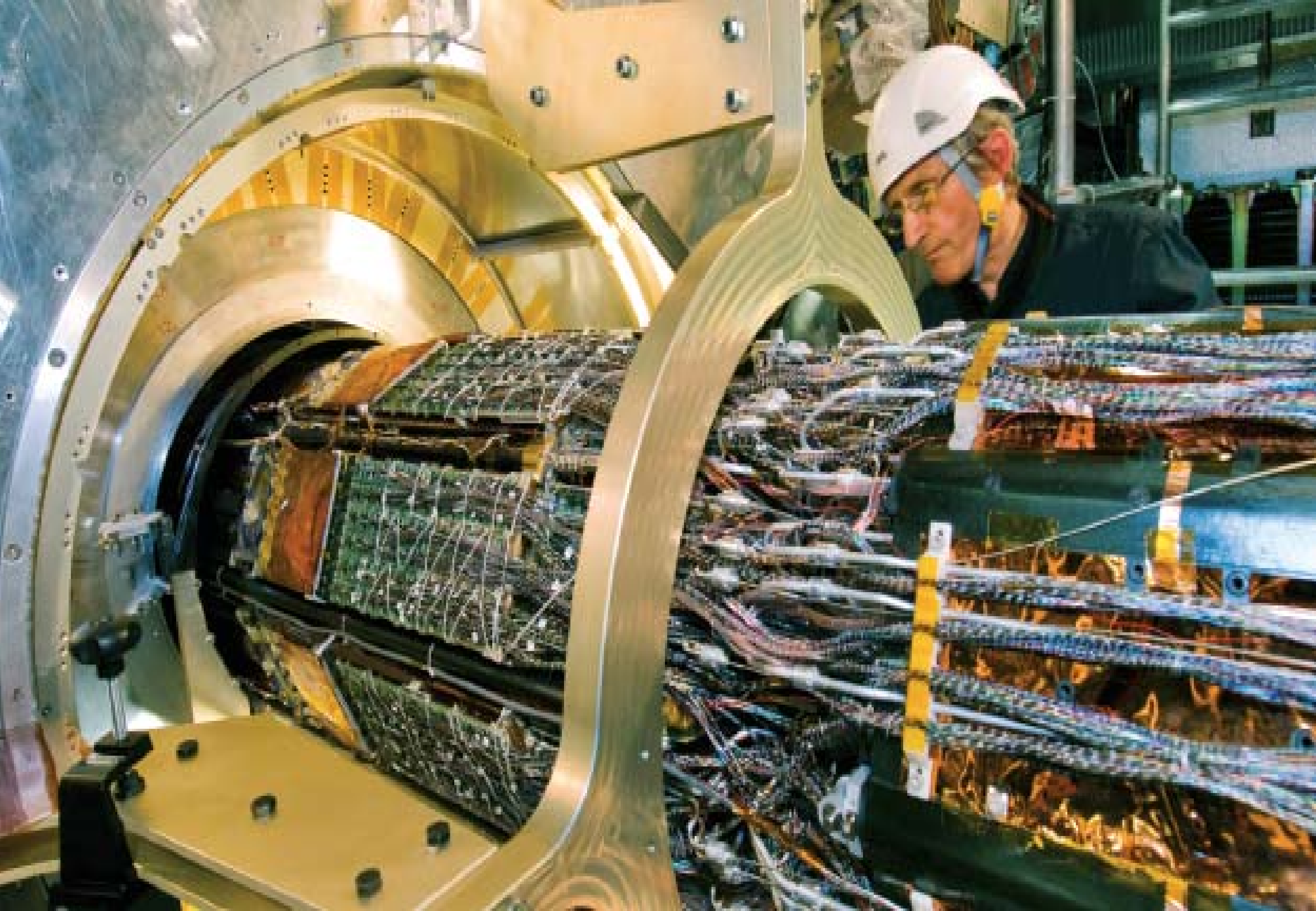

A

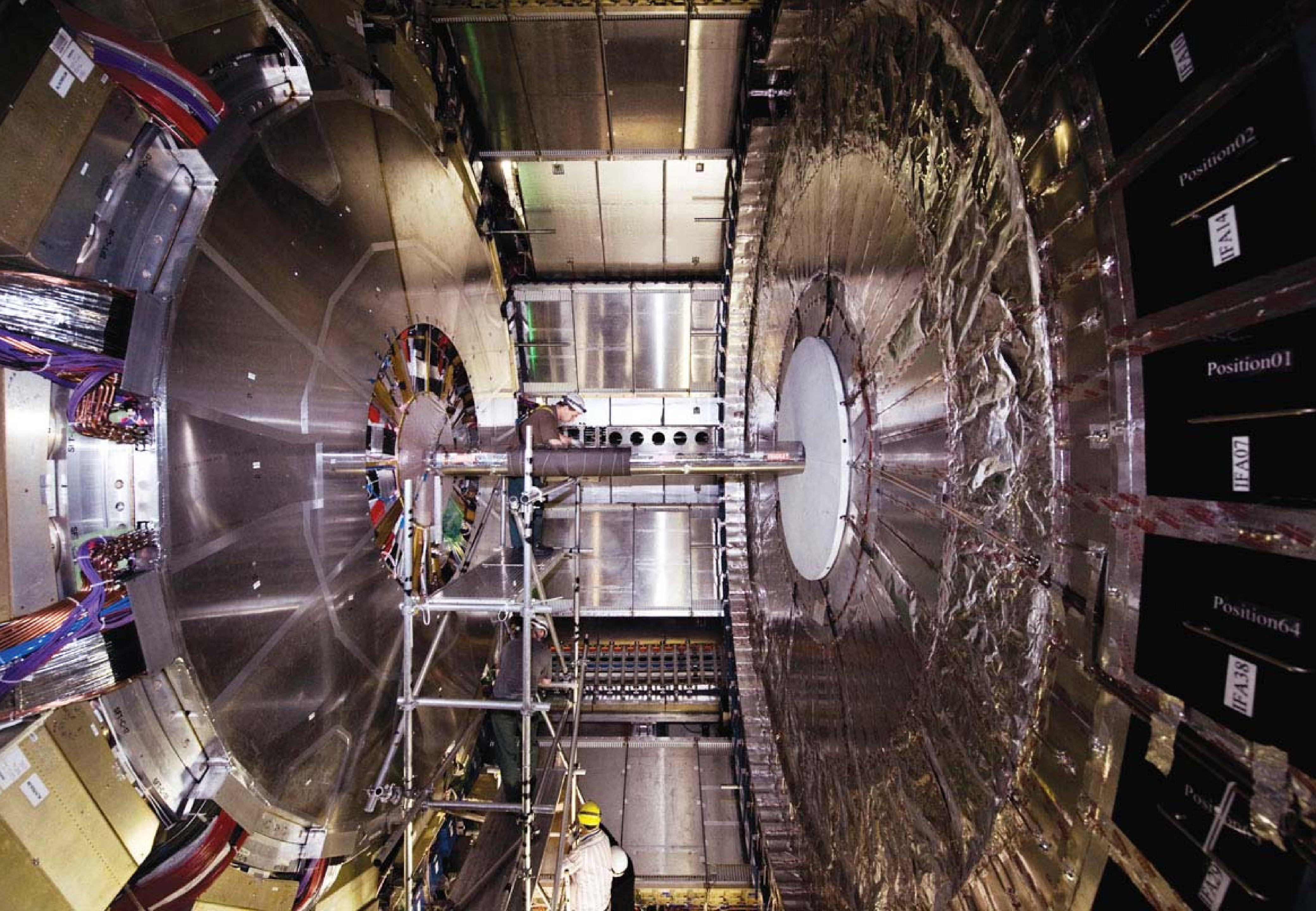




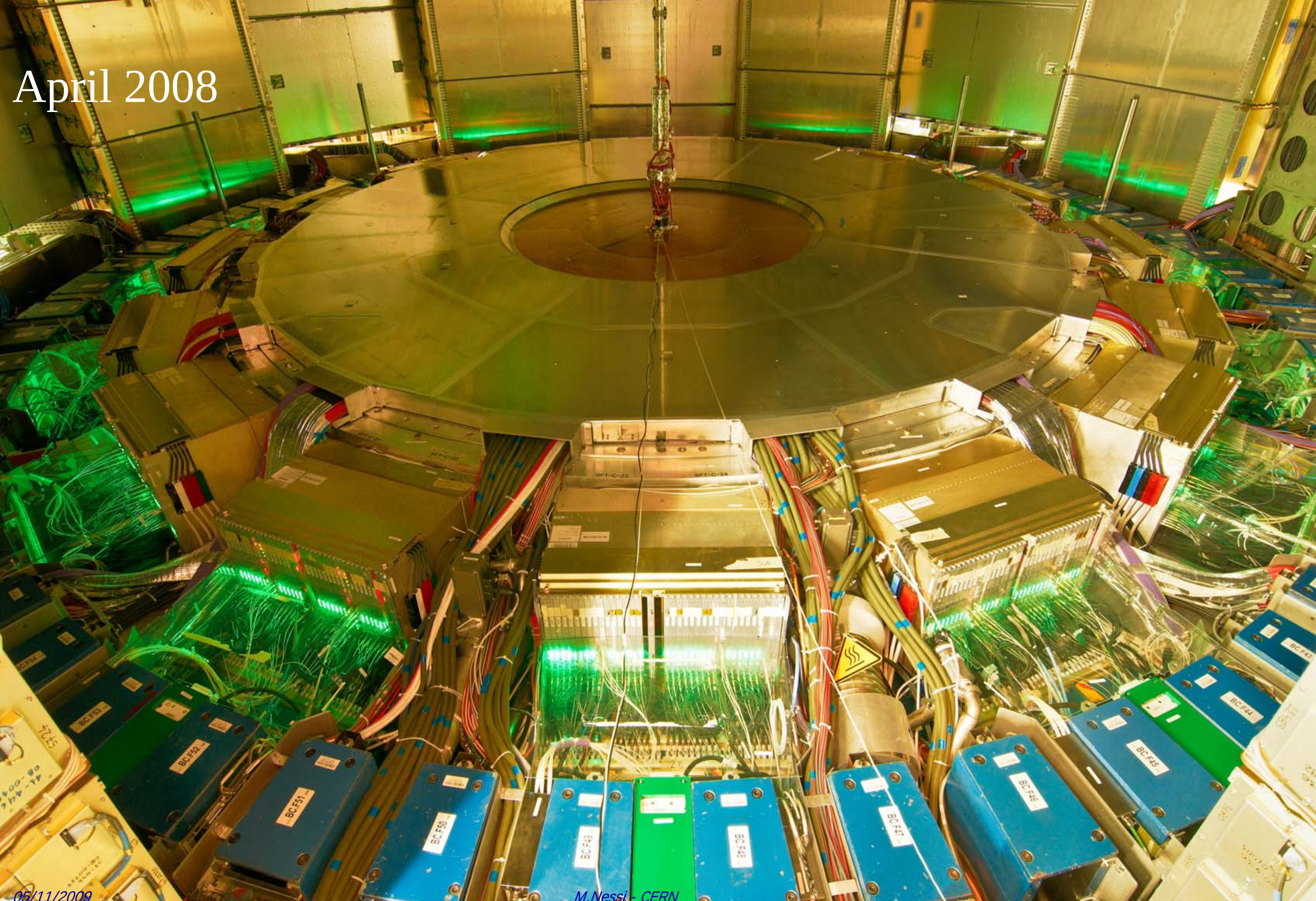




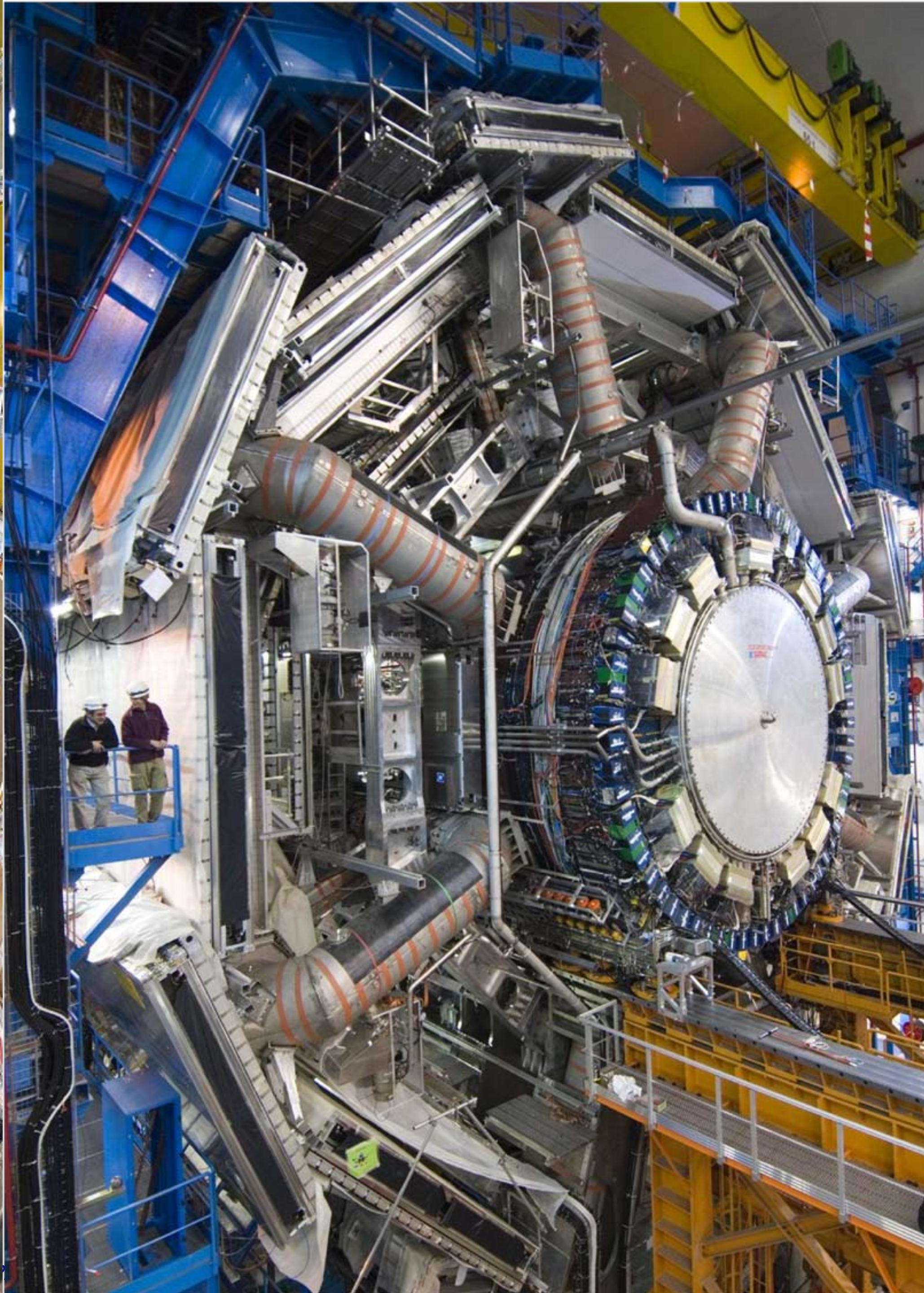



Position02
IFA14
Position01
IFA07
Position64
IFA38

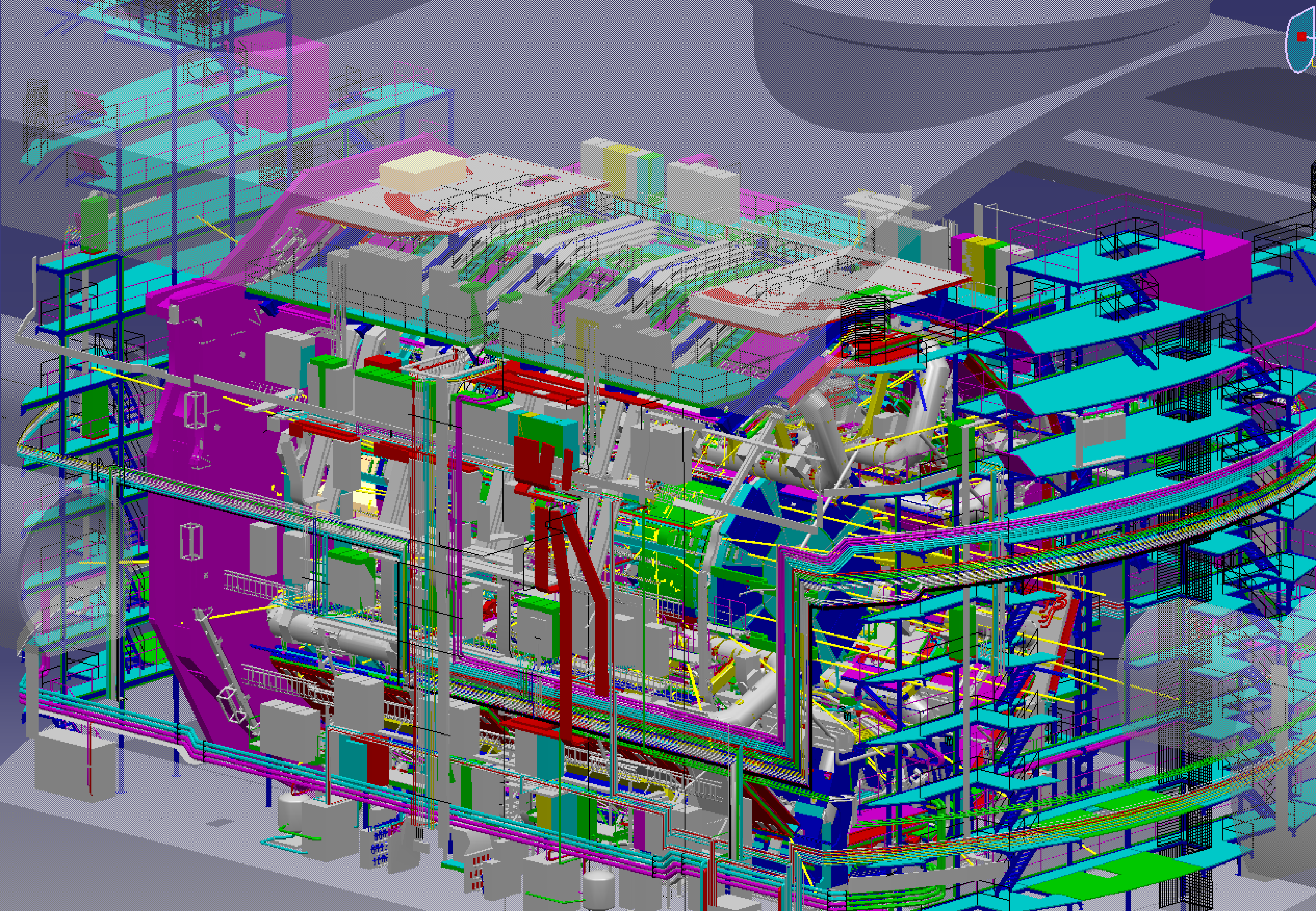
April 2008



BC.F53
BC.F52
BC.F51
BC.F50
BC.F49
BC.F48
BC.F47
BC.F46
BC.F45
BC.F44


July 2008

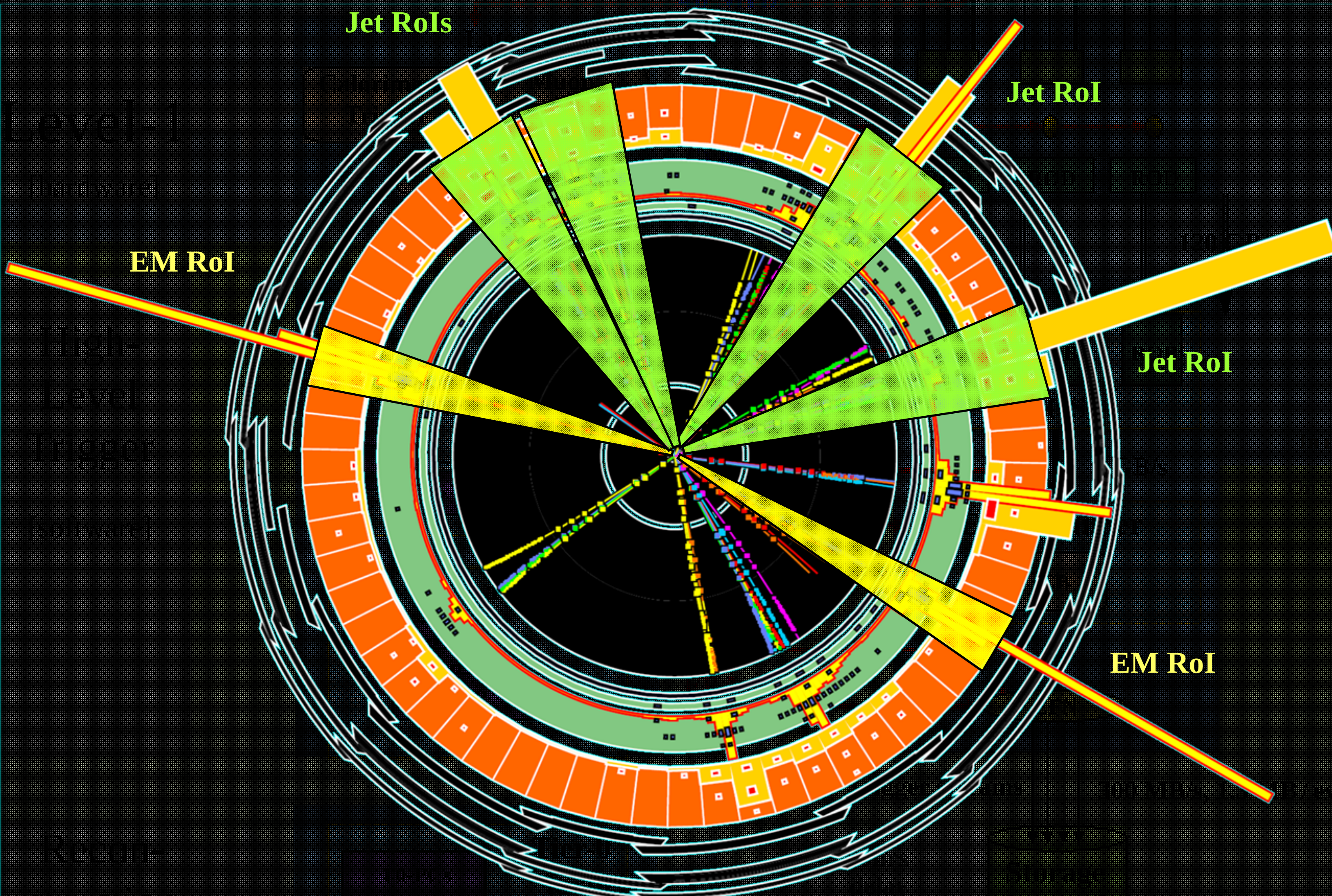


Data acquisition, storage, distribution and processing is as complex as the detector itself

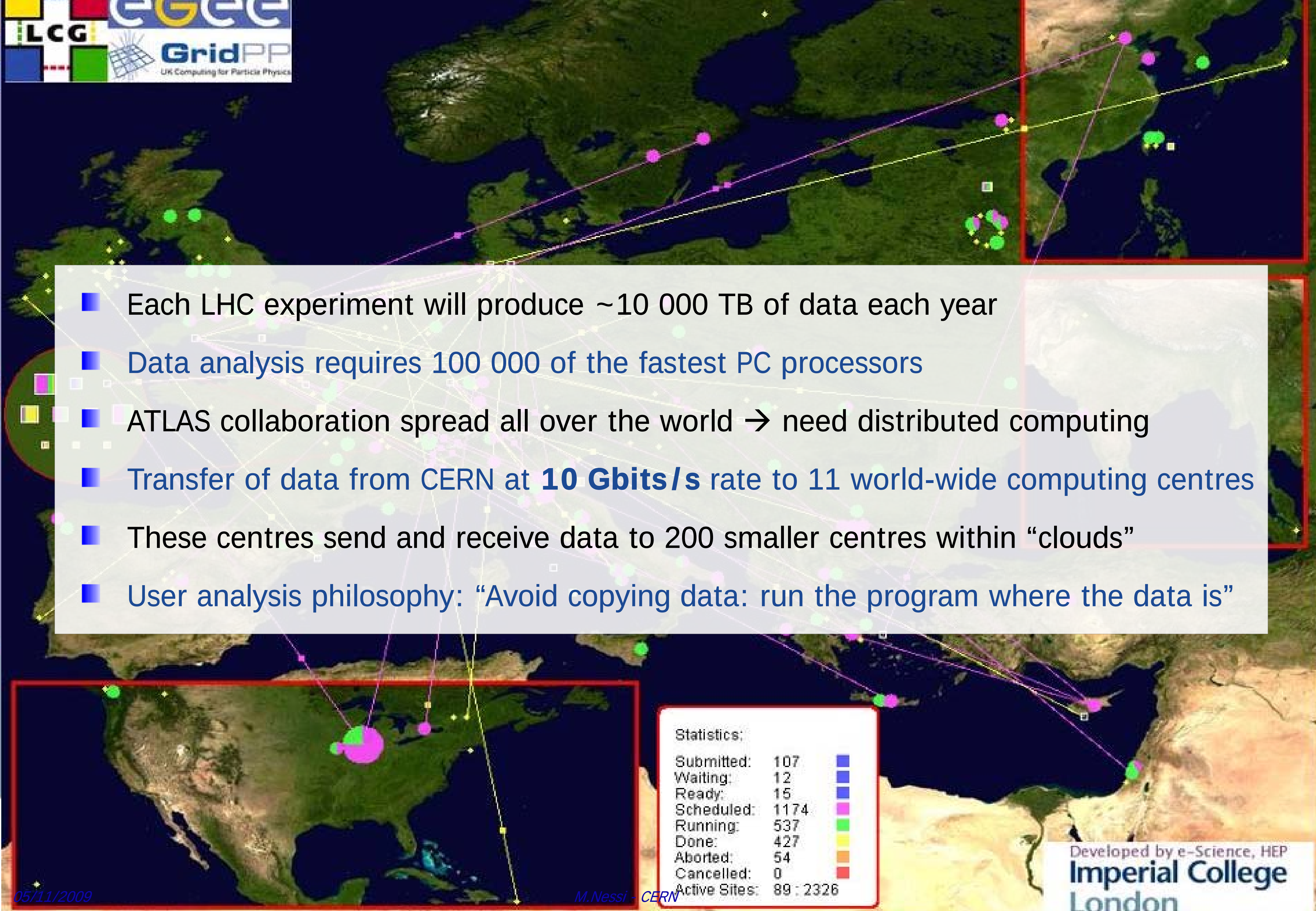
- Large data production (~PB/sec) versus storage capability (~GB/sec)
  forces huge online selection
- 3 levels of triggers (first level fully electronics based)

- Data distribution for offline processing using GRID system

Regions of Interest (RoI)



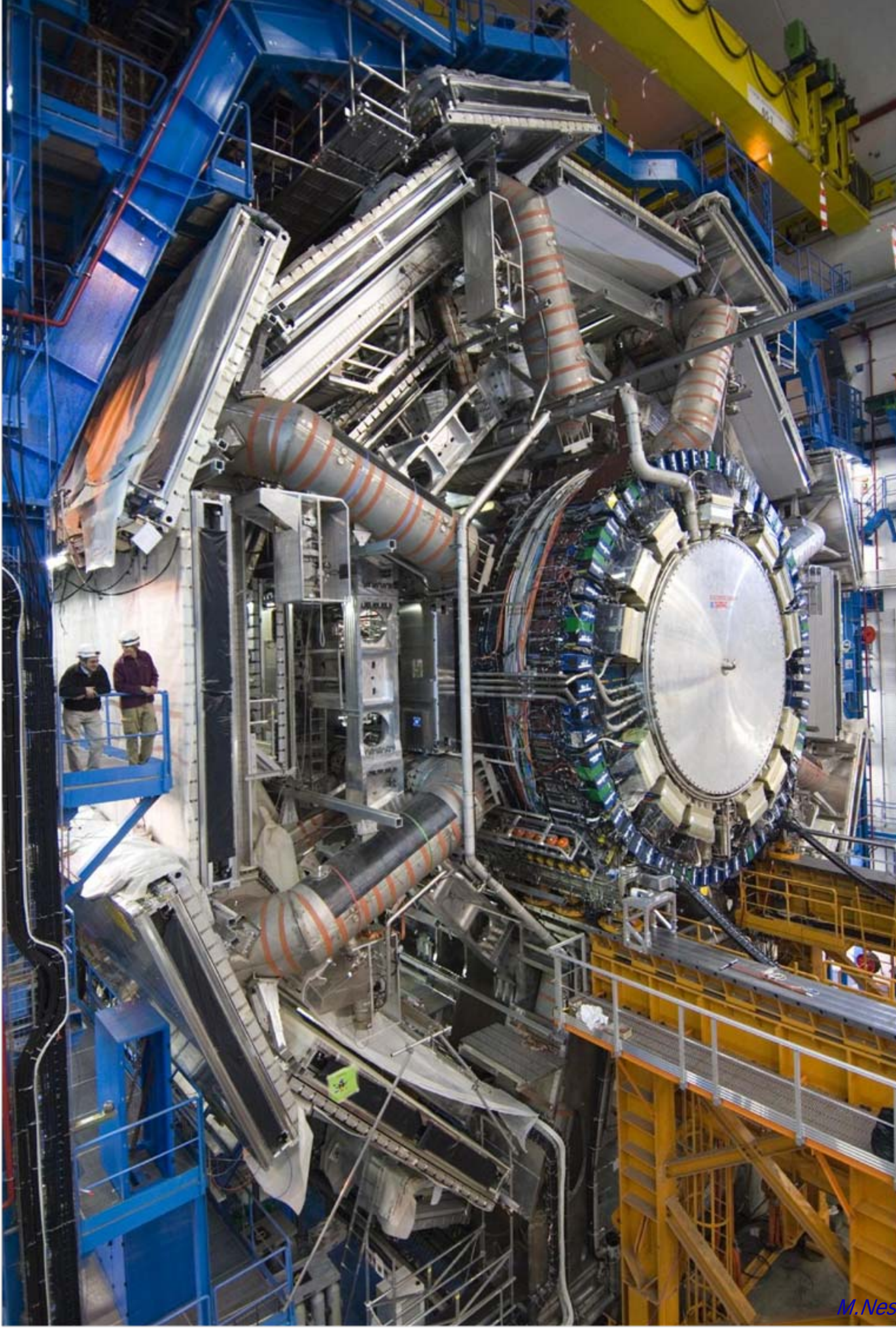
- Each LHC experiment will produce ~10 000 TB of data each year
- Data analysis requires 100 000 of the fastest PC processors
- ATLAS collaboration spread all over the world → need distributed computing
- Transfer of data from CERN at **10 Gbits/s** rate to 11 world-wide computing centres
- These centres send and receive data to 200 smaller centres within “clouds”
- User analysis philosophy: “Avoid copying data: run the program where the data is”



Last generation of HEP detectors incredibly complex and state of the art pieces of technology

- Large use of semiconductors radiation hard technology for trackers
- Calorimeters precise as never before
- Cryogenics detectors and magnet systems
- Detector systems have increased in size and complexity at least a factor 10
- The data flow and data processing is unprecedented

- Projects span over a lifetime of 3-4 decades, involving thousands of scientists



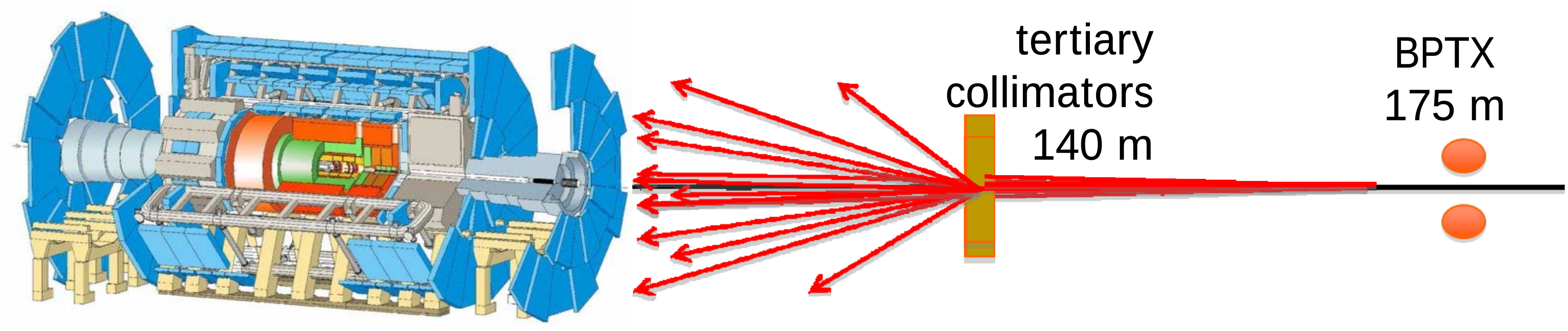
..... but does it really work ?

Over the years we have exposed some % of it to particle beams (SPS, reactors,..)

During assembly we collected millions of cosmics events

10-11 September 2008 first LHC beams

10 September: first beam

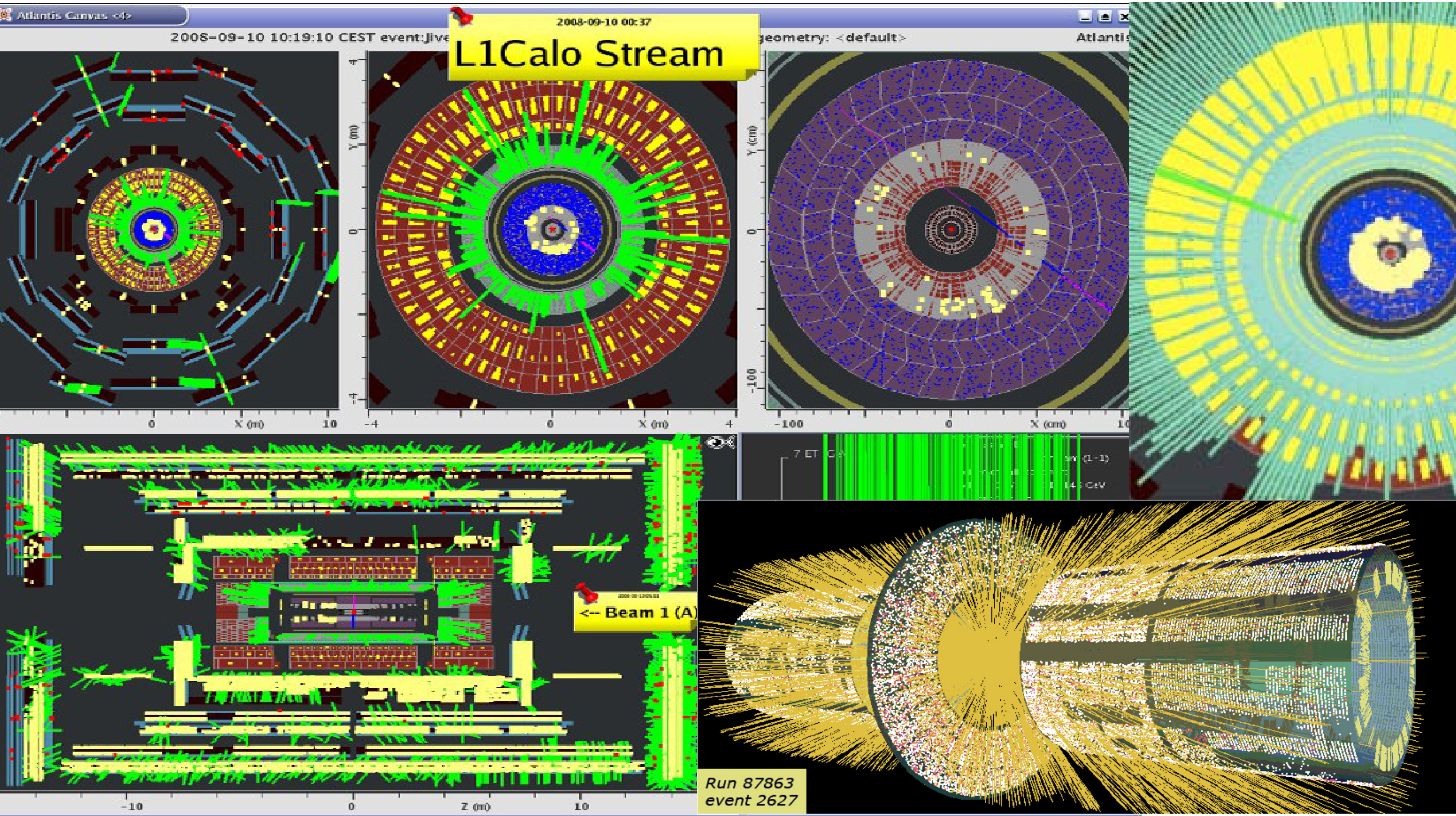


We had no chance to have some beam in advance to test our readout synchronization, all was extrapolated from cosmics runs

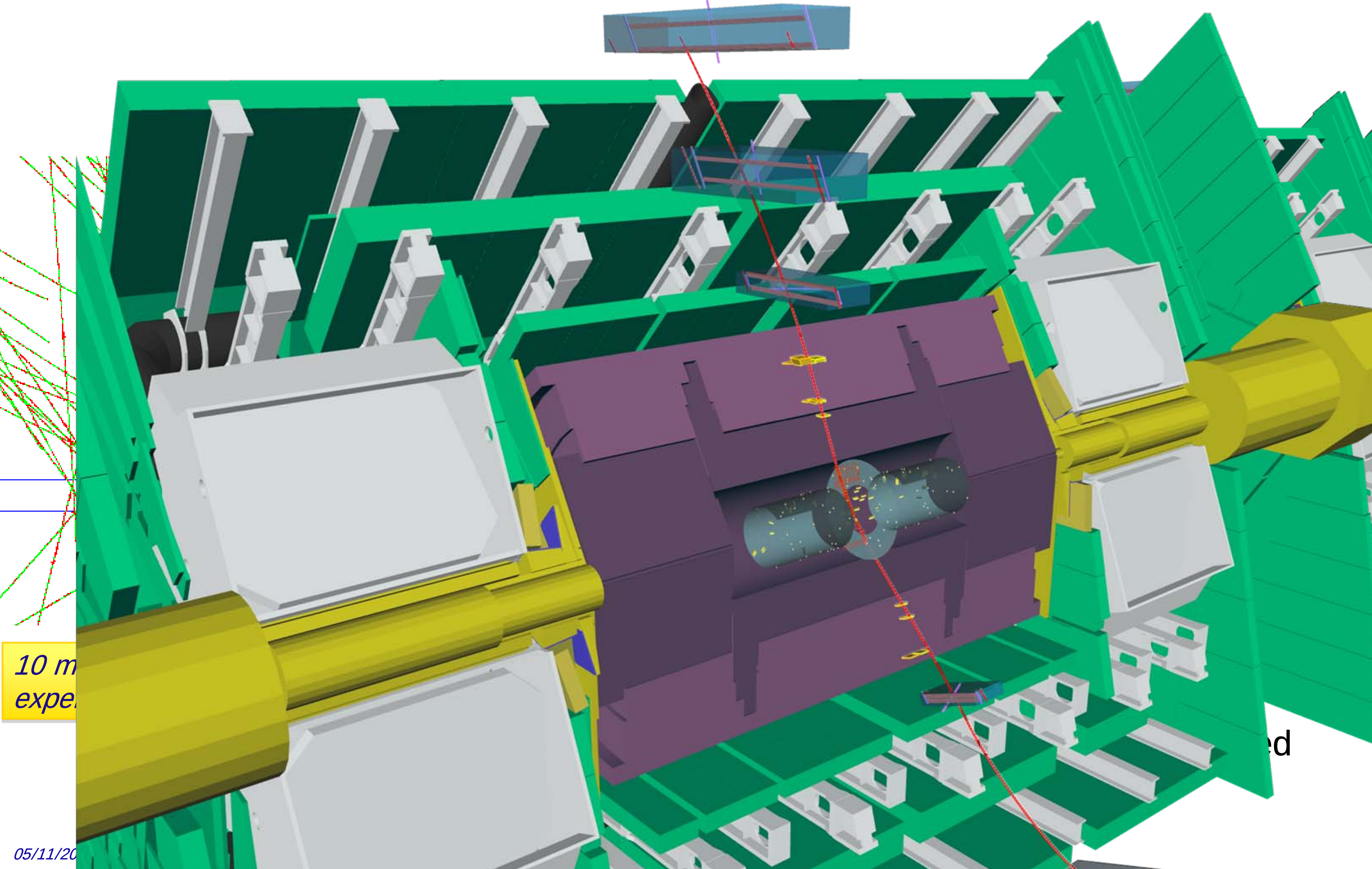
Active detectors near to the beam pipe (inner tracker, forward calorimeters,....) were set at reduced HV .... Pixel detector off

..... and it worked ... first shots, first detector pictures ... a lot of energy released in the detector

..... once beam RF captured, we started looking for beam halo


Atlantis Canvas <4>
2008-09-10 10:19:10 CEST
2008-09-10 00:37
L1Calo Stream
geometry: <default>
X (m)
Y (m)
X (cm)
Y (cm)
Z (m)
<-- Beam 1 (A)
Run 87863
event 2627

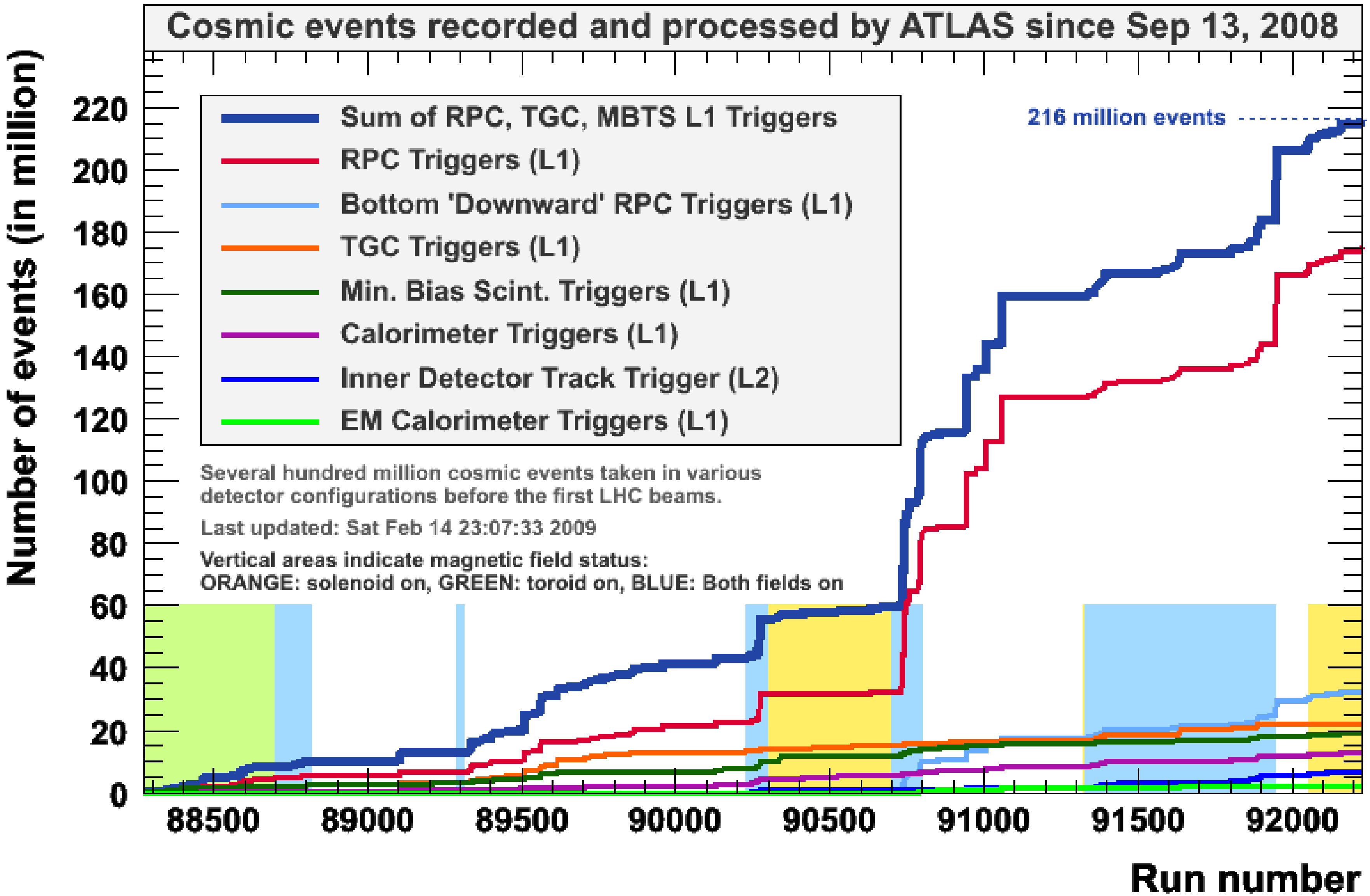
Thanks to cosmic rays … a nice help



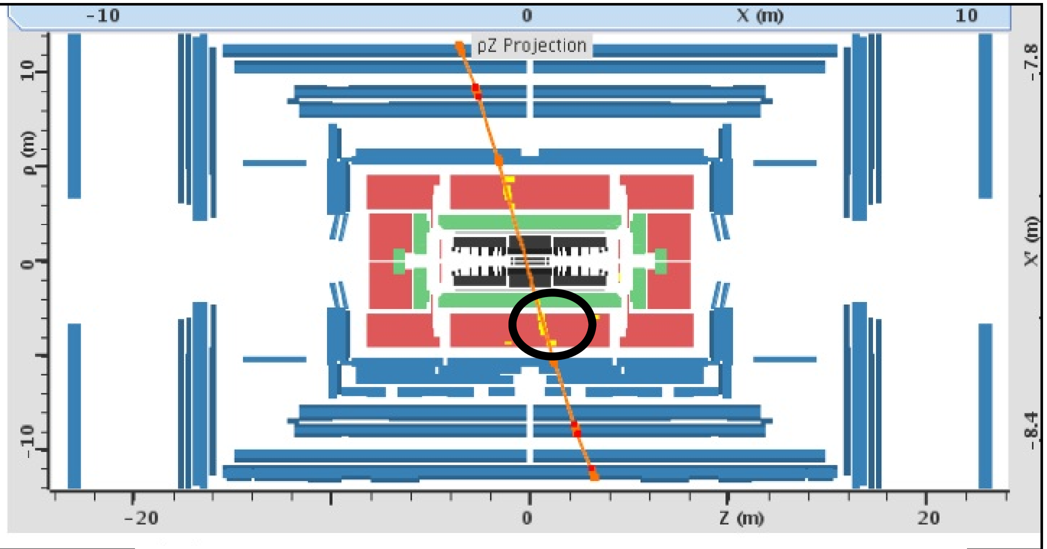
10 m
expe

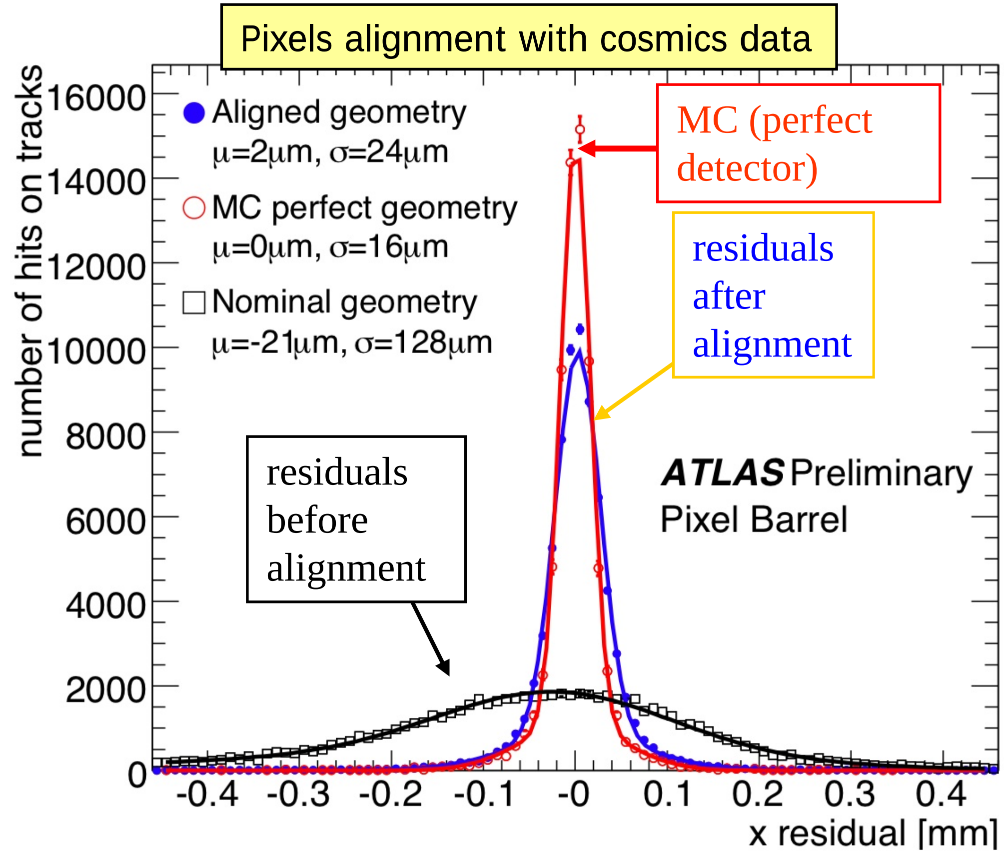
ed

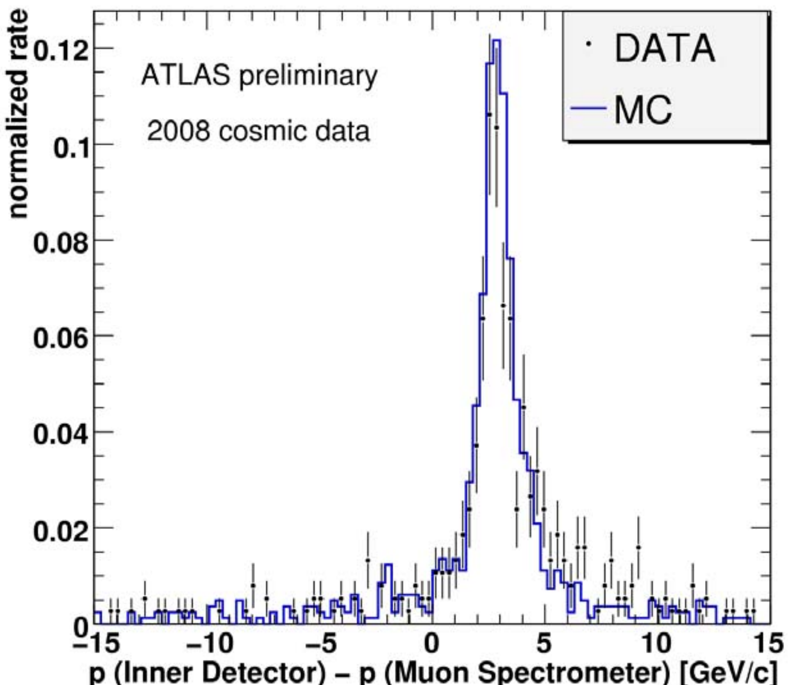
Cosmics run with full detector operational



Cosmics runs results







Difference between the muon momentum measured in the ID and in the MS for tracks in the bottom part of the detector (~ 3 GeV energy loss in the calorimeter)

We have never been so ready for big discoveries !!!!