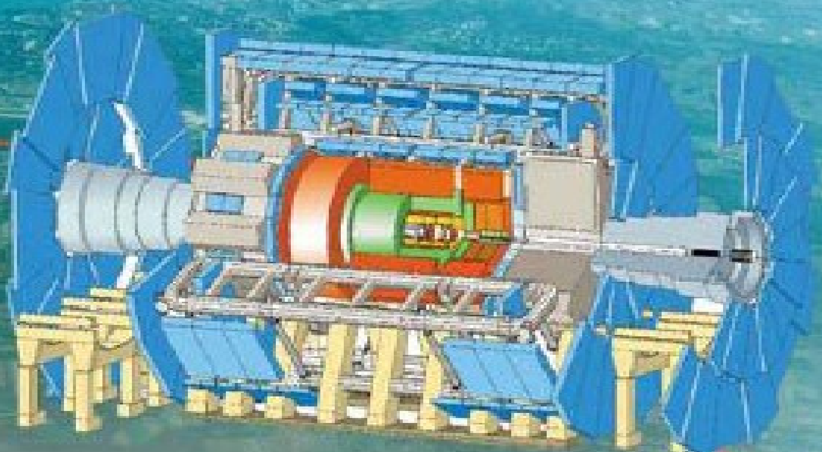
Large Hadron Collider (LHC) experiments

Lectures of the physics
doctoral school of Grenoble

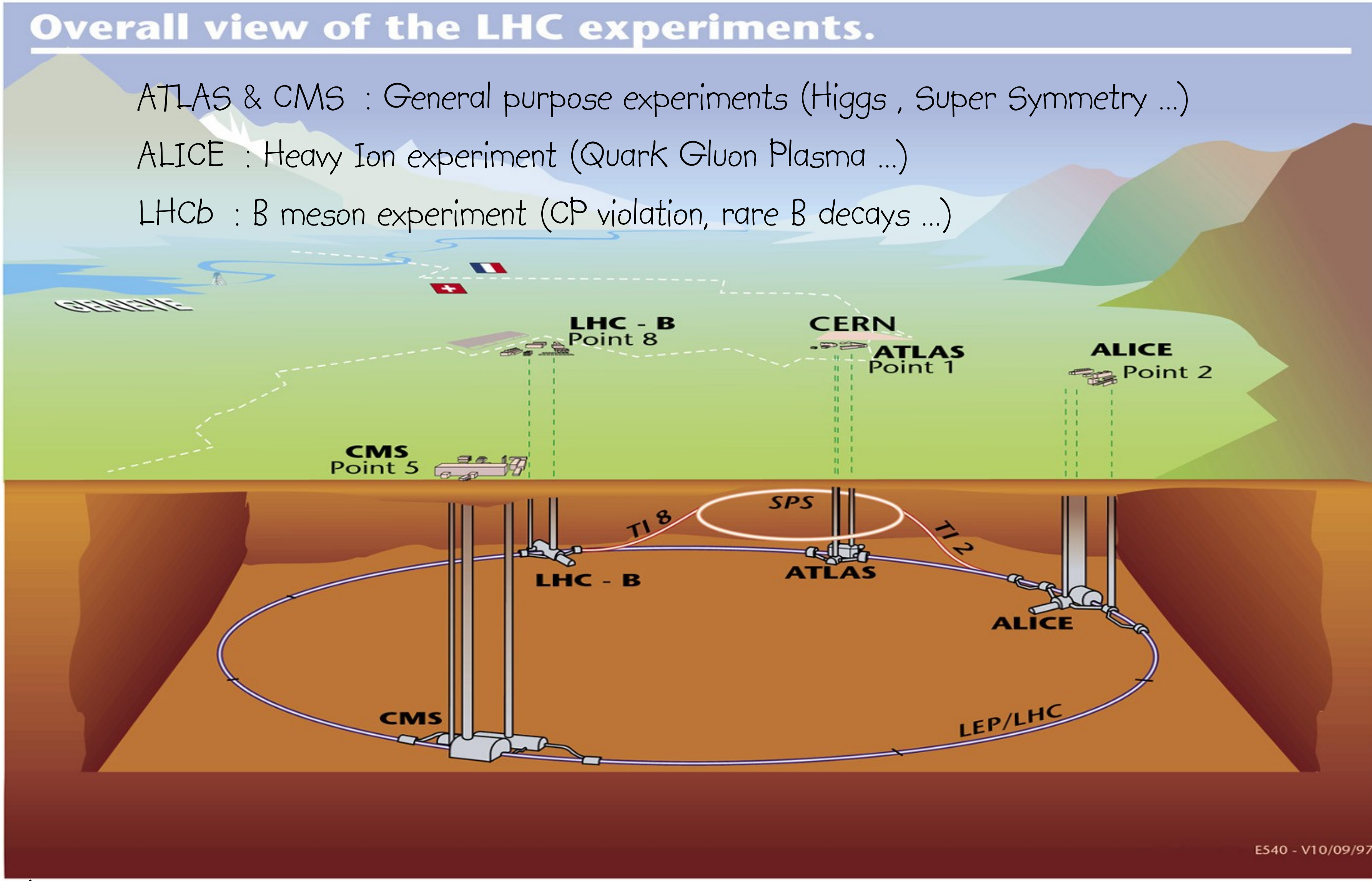
Johann Collot http://lpsc.in2p3.fr/collot
collot@in2p3.fr

LPSC Grenoble

Université Joseph Fourier
CNRS/IN2P3
Grenoble INP



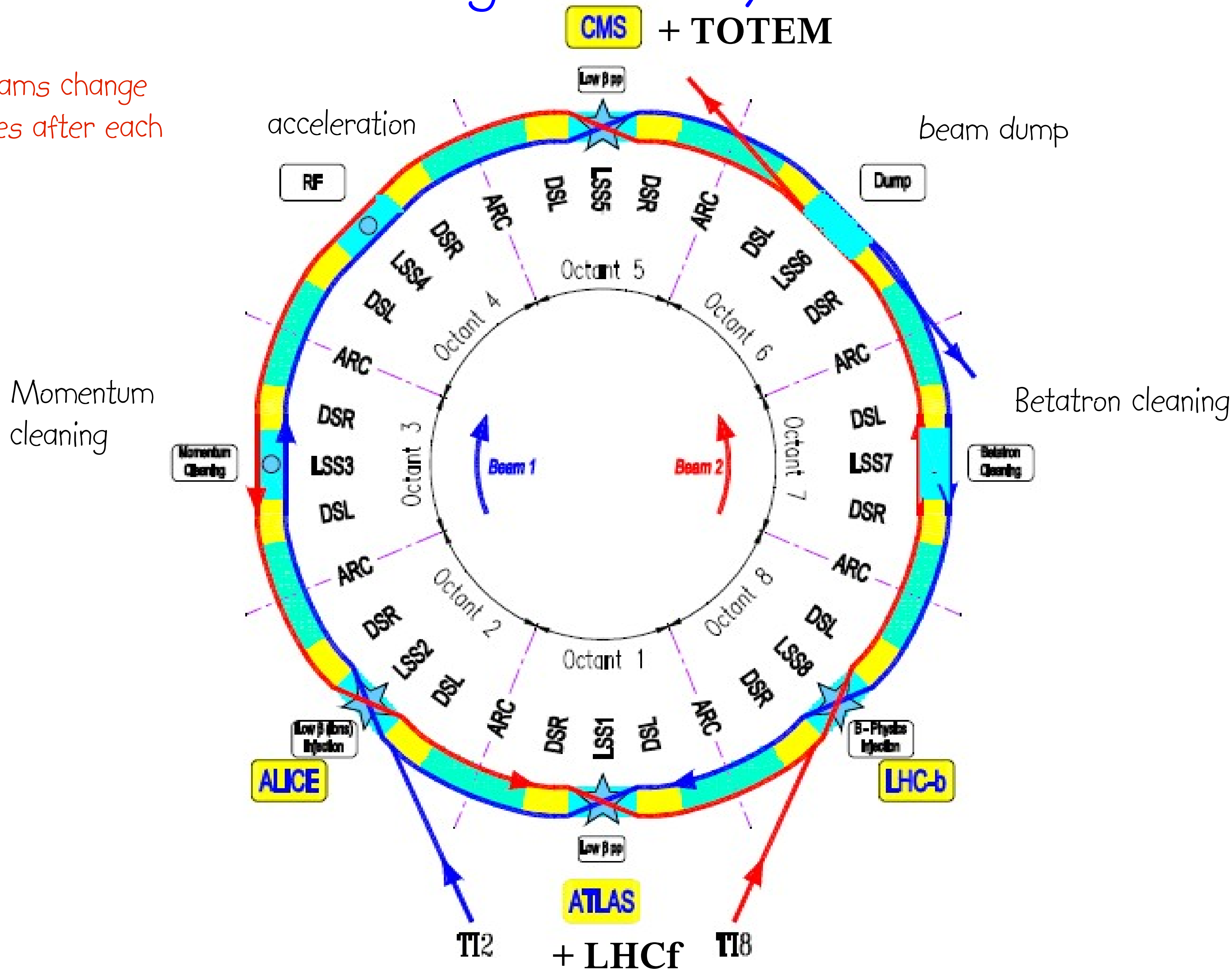
General underground view of experiments



Plus 3 smaller experiments : -TOTEM integrated into CMS : total pp cross section
-LHCf located at +/- 140 m from ATLAS : VHE showers
-MeODAL located next to LHCb : Magnetic monopole

LHC general layout

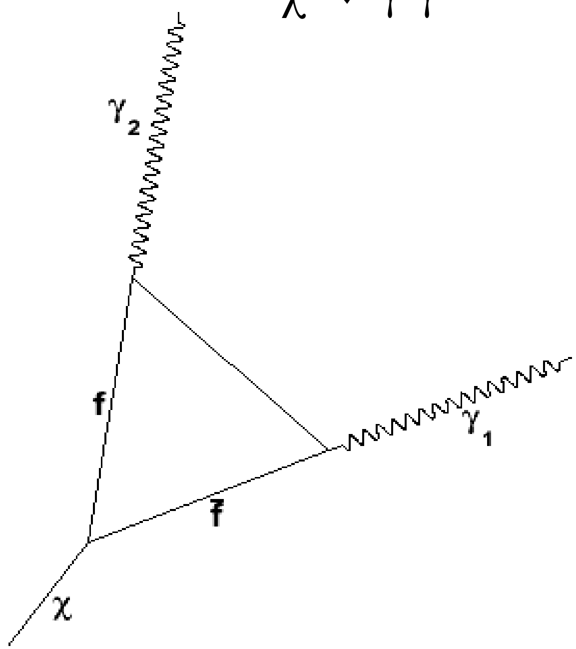
proton beams change beam pipes after each crossing !



Observation of heavy and highly-unstable ($\tau<10^{-21}$s) particles

Higgs :

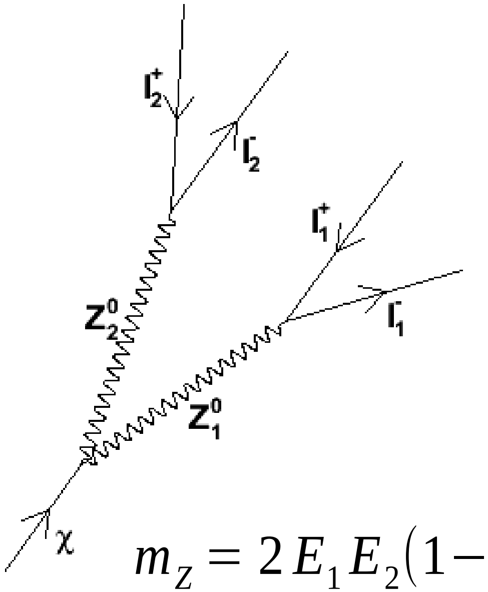
$\chi \rightarrow \gamma\,\gamma$



See exercise on two body decay of a massive particle.

$$m_X^2 = 2\,E_1\,E_2(1-\cos\theta)$$

if : $m_\chi > 2m_Z$, $\chi \rightarrow ZZ$



$$m_Z = 2\,E_1\,E_2(1-\cos\theta)$$

$$m_X = (P_{Z_1} + P_{Z_2})^2$$

$$P_{Z_1} = P_{l_1^+} + P_{l_1^-}$$

We need to measure the energies and the trajectories of produced particles.

Observation of heavy and highly-unstable ($\tau < 10^{-21}$s) particles.

If such a particle decays into n products, sufficiently stable to be observed in a detector :

$$X \to 1+2+\ldots n$$

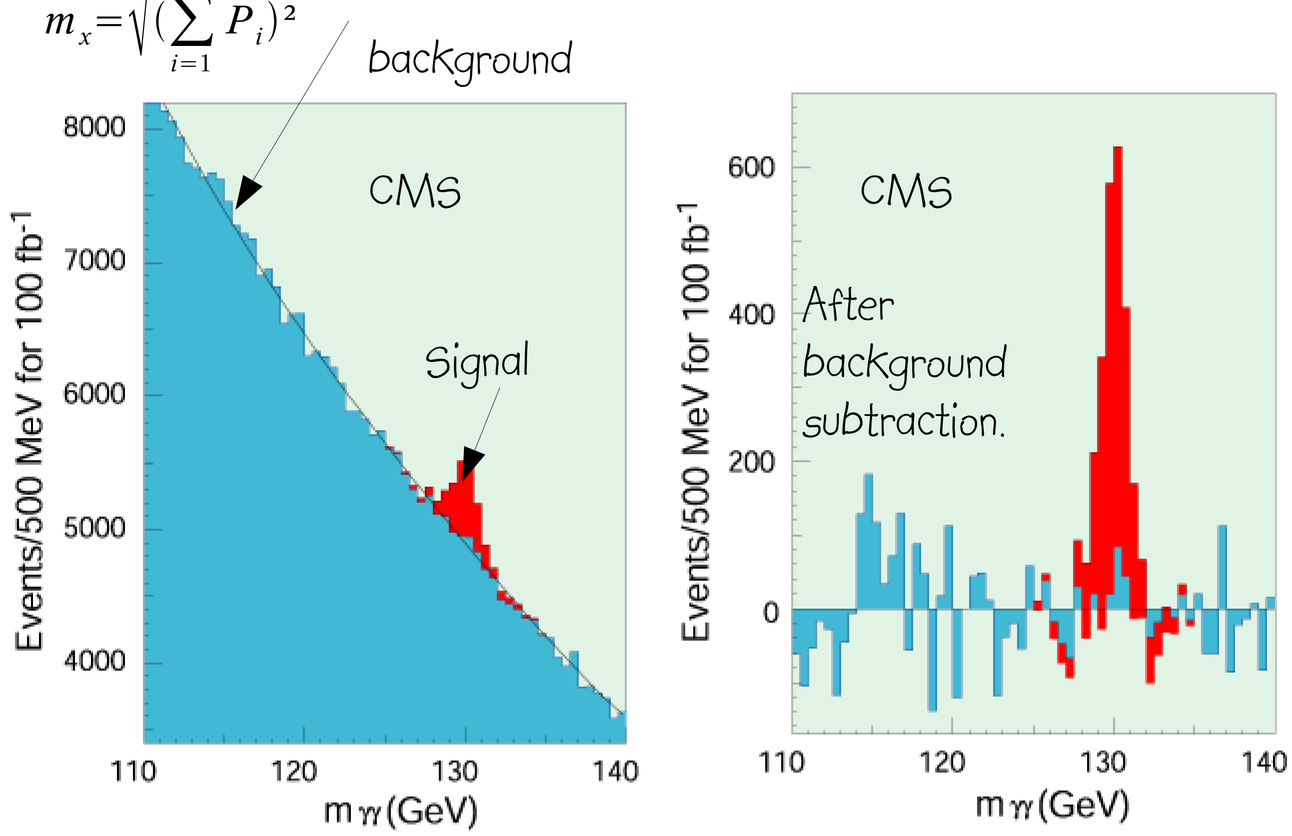
and in case all the final product momenta are measured : $P_i = \begin{vmatrix} E_i \\ \vec{p}_i \end{vmatrix}$

the X mass is : $m_x = \sqrt{\left(\sum_{i=1}^{n} P_i\right)^2}$

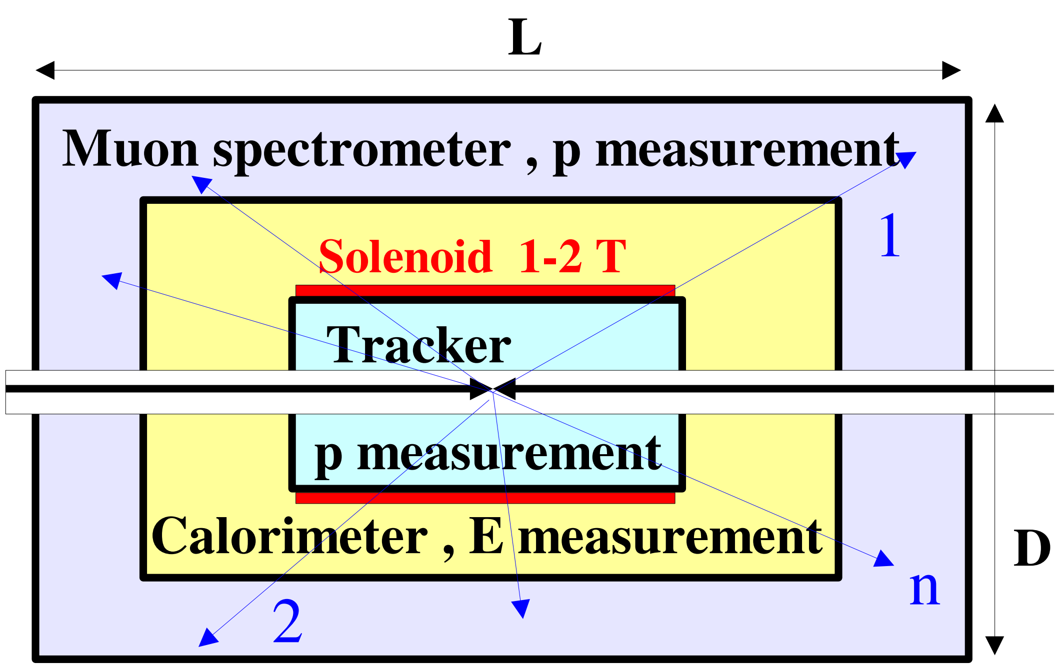
Example :

$$X \to \gamma\gamma$$

for $m_X = 130\,\mathrm{GeV}$



Typical structure of a detector installed on a high-energy collider



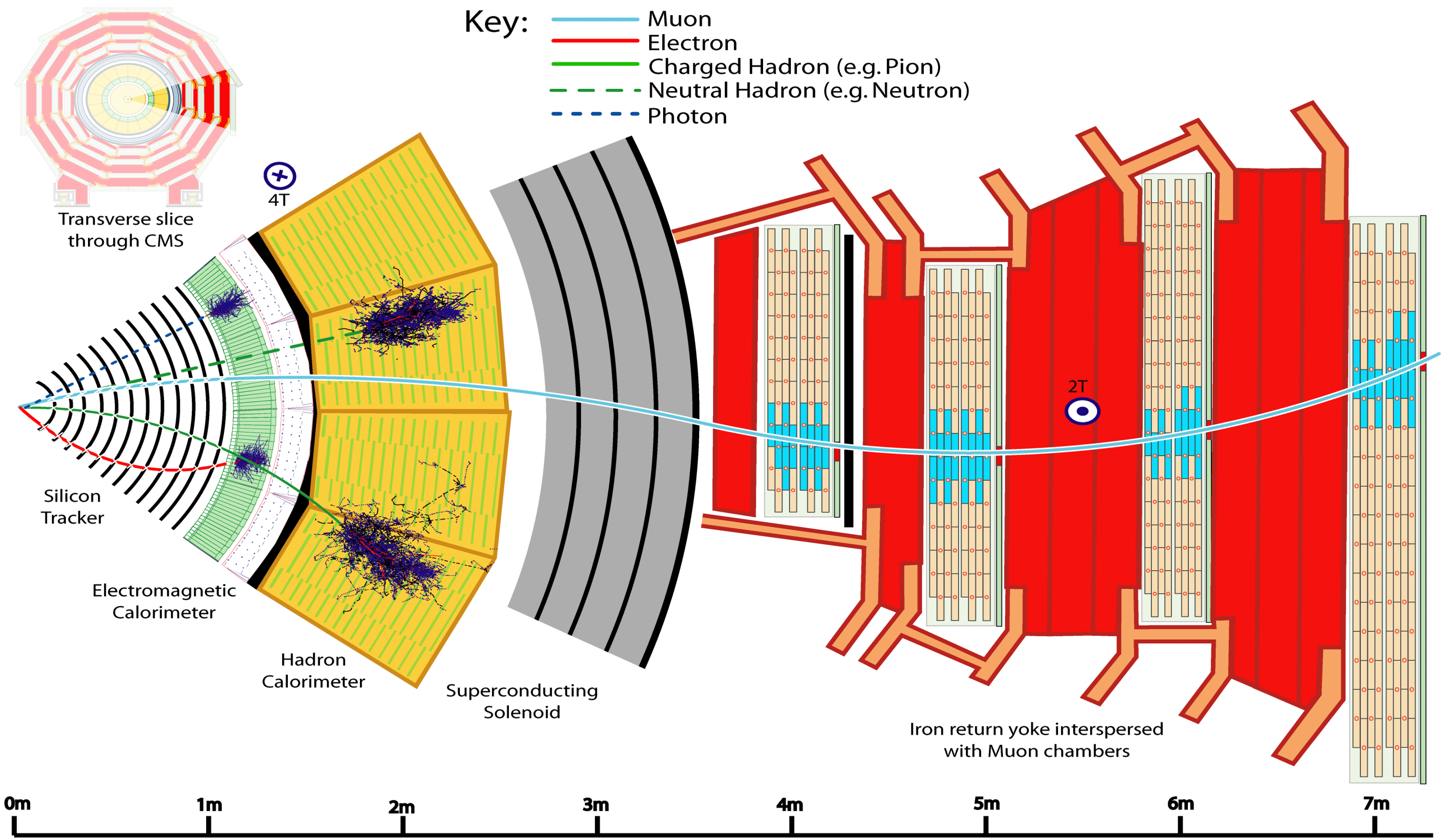
$X \rightarrow 1+2+\ldots n$

D × 2 , L × 2 for E × 10

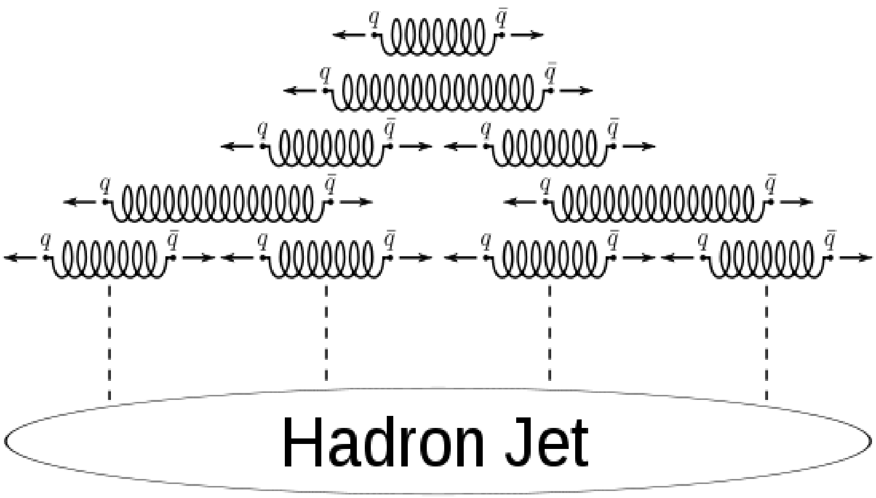
ATLAS : L ~ 46 m
D ~ 25 m
weight ~ 7000 t

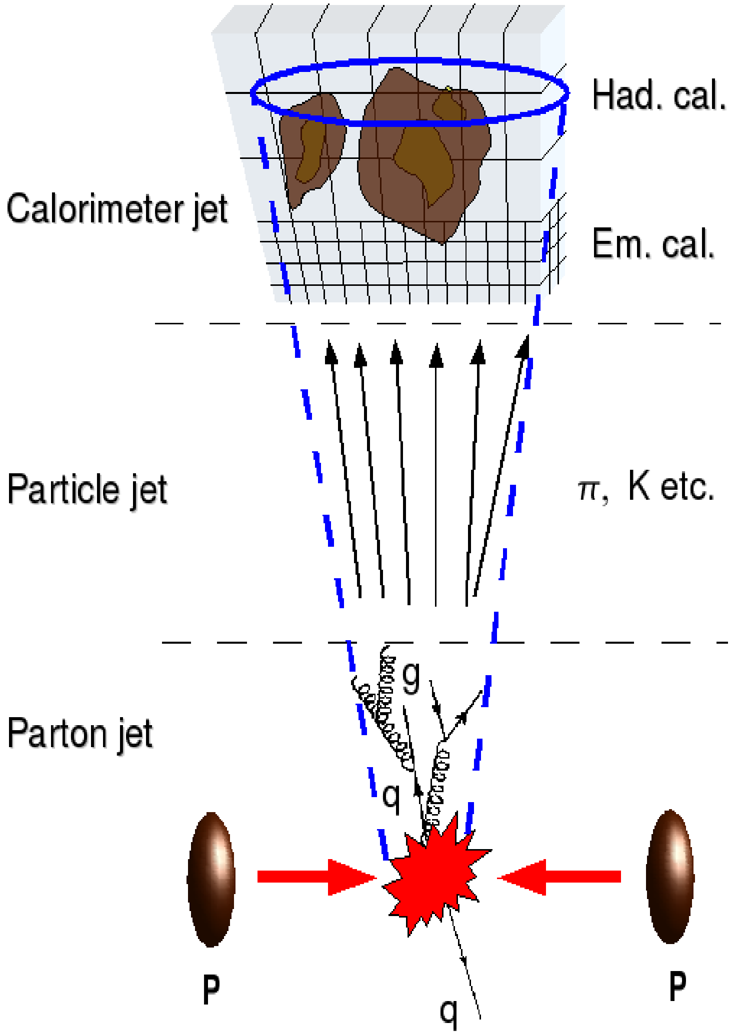
Elementary particle identification

We need to measure the 4-momenta of electrons, muons, photons, taus, quarks, gluons and hadrons.



Hadronic jets

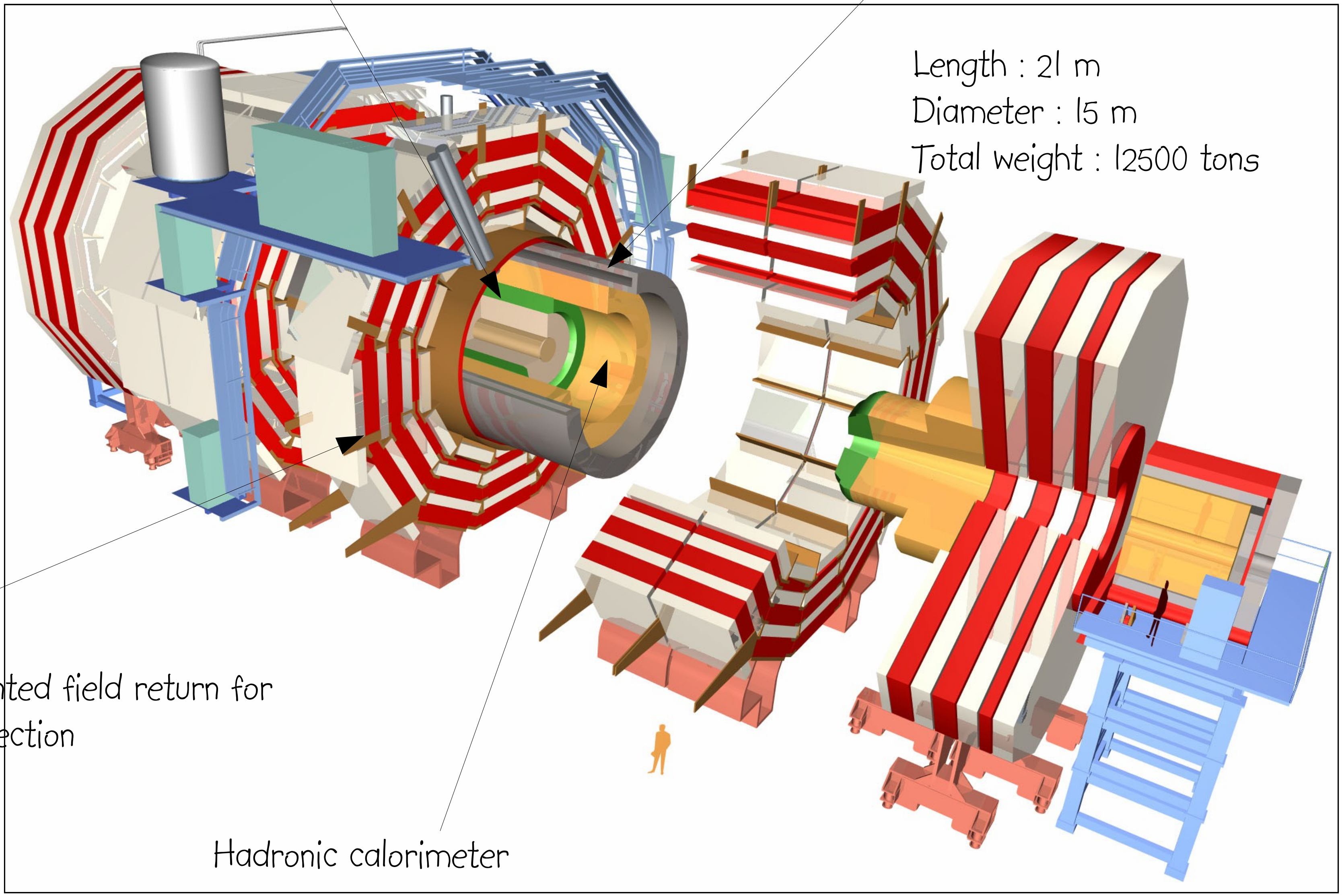




CMS

$PbWO_4$ Electromagnetic calorimeter

4T solenoid

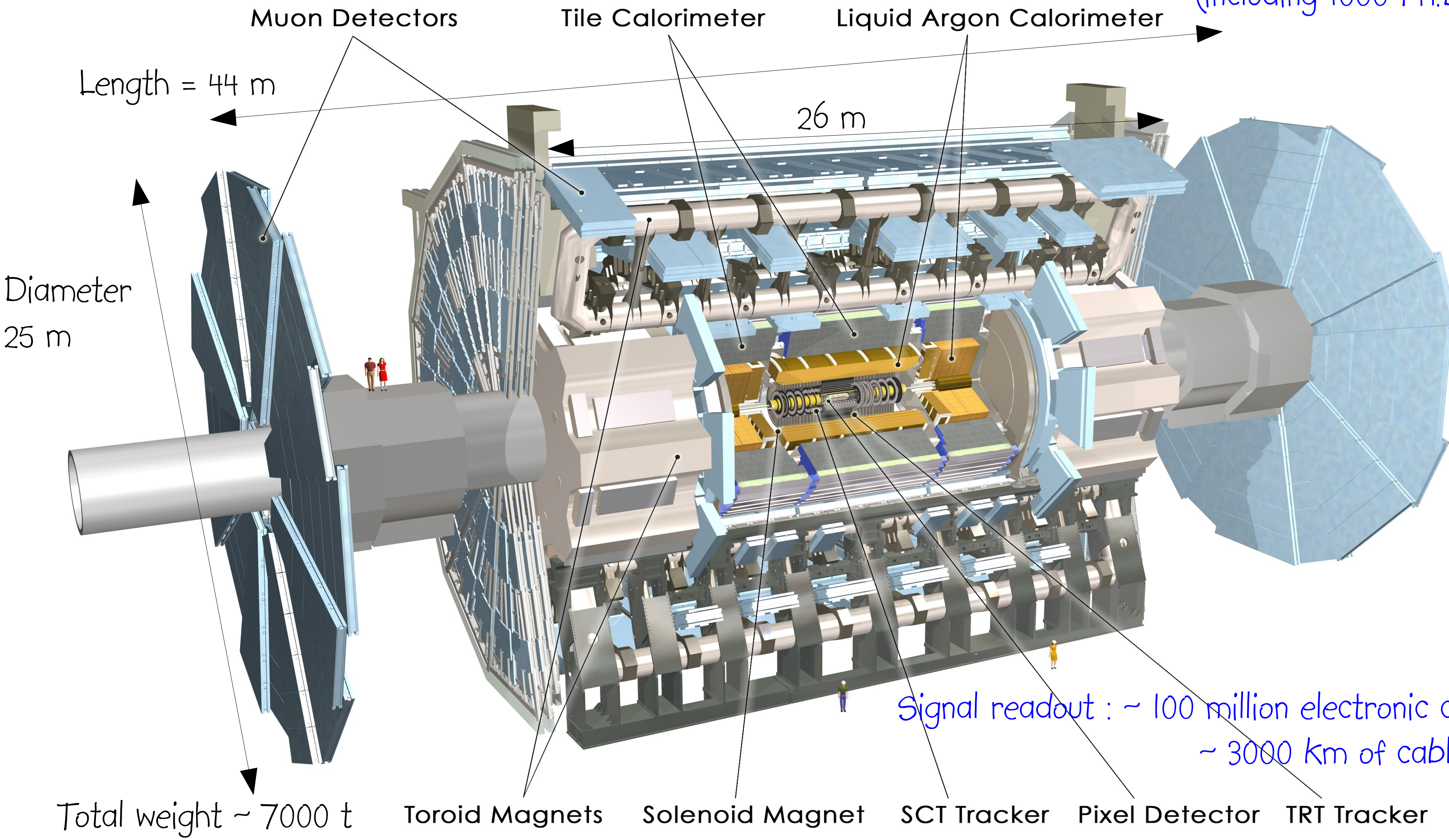


Instrumented field return for muon detection

Hadronic calorimeter

ATLAS

38 countries
174 laboratories
3000 scientific authors
(including 1000 Ph.D.'s)

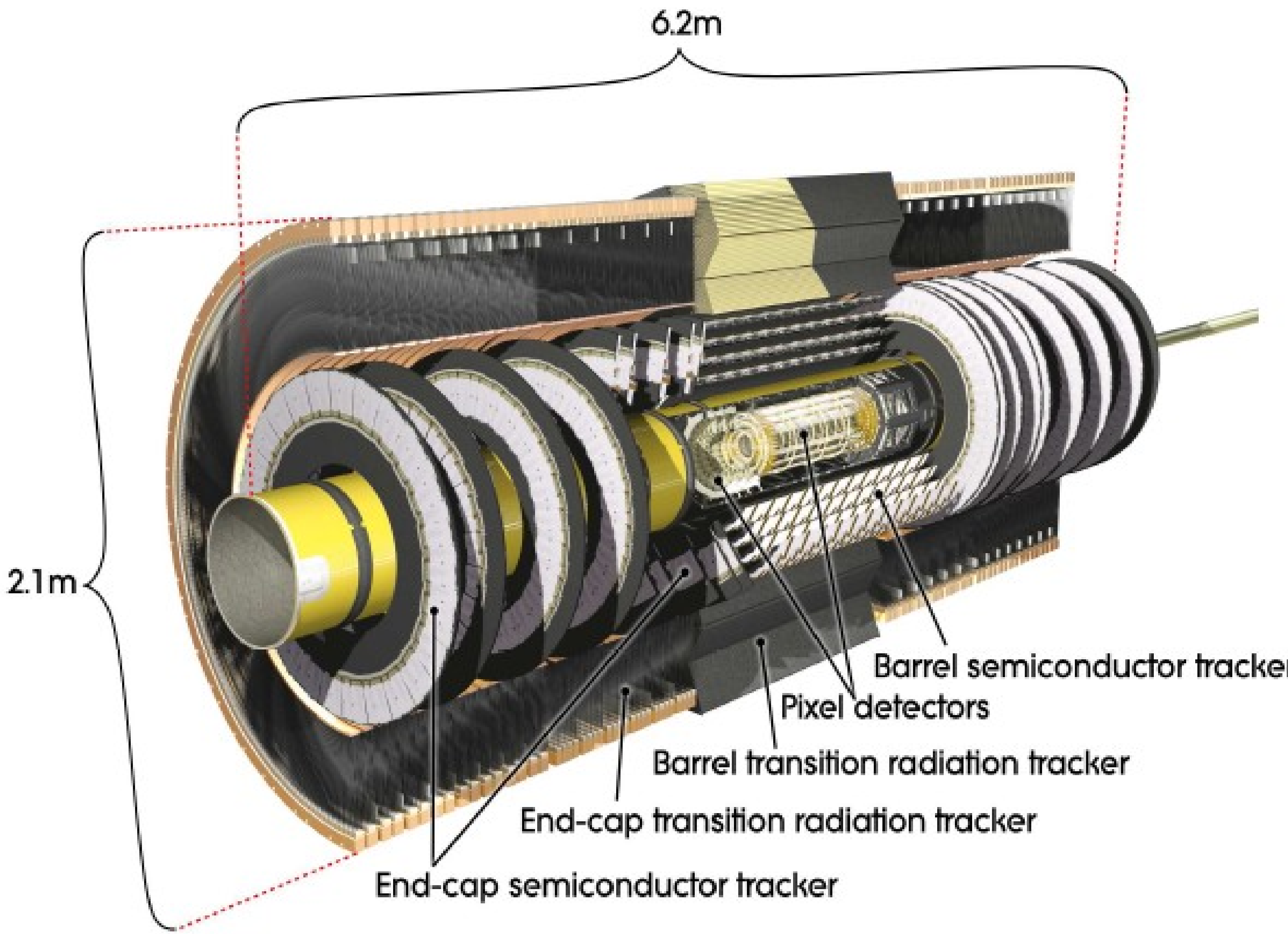


Signal readout : ~ 100 million electronic channels
~ 3000 Km of cables

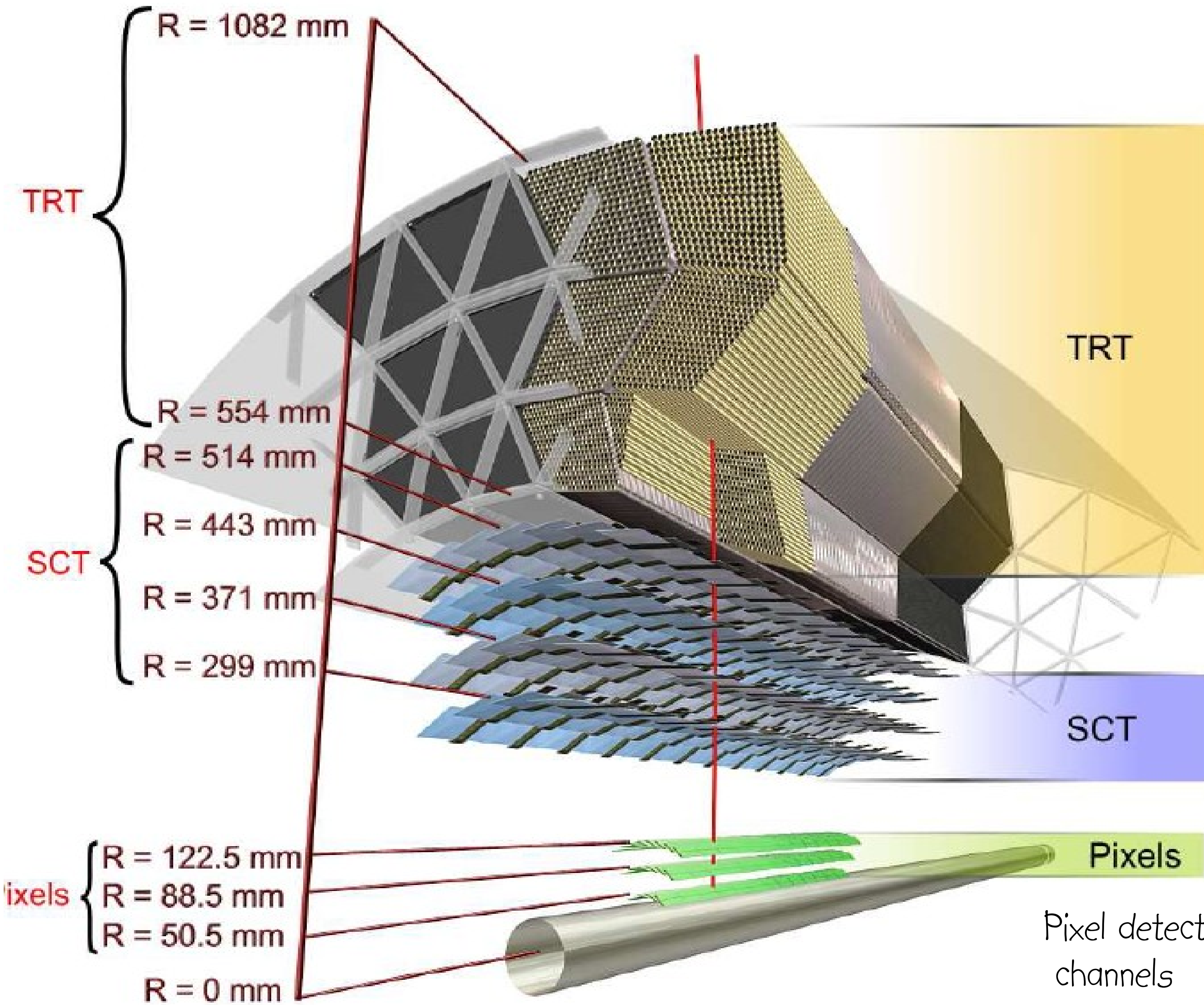
Cost ~ 550 M CHF (~10 K CHF/year/author over 20 years , yearly cost of a university student in France)

ATLAS Tracker

86.4 million channels



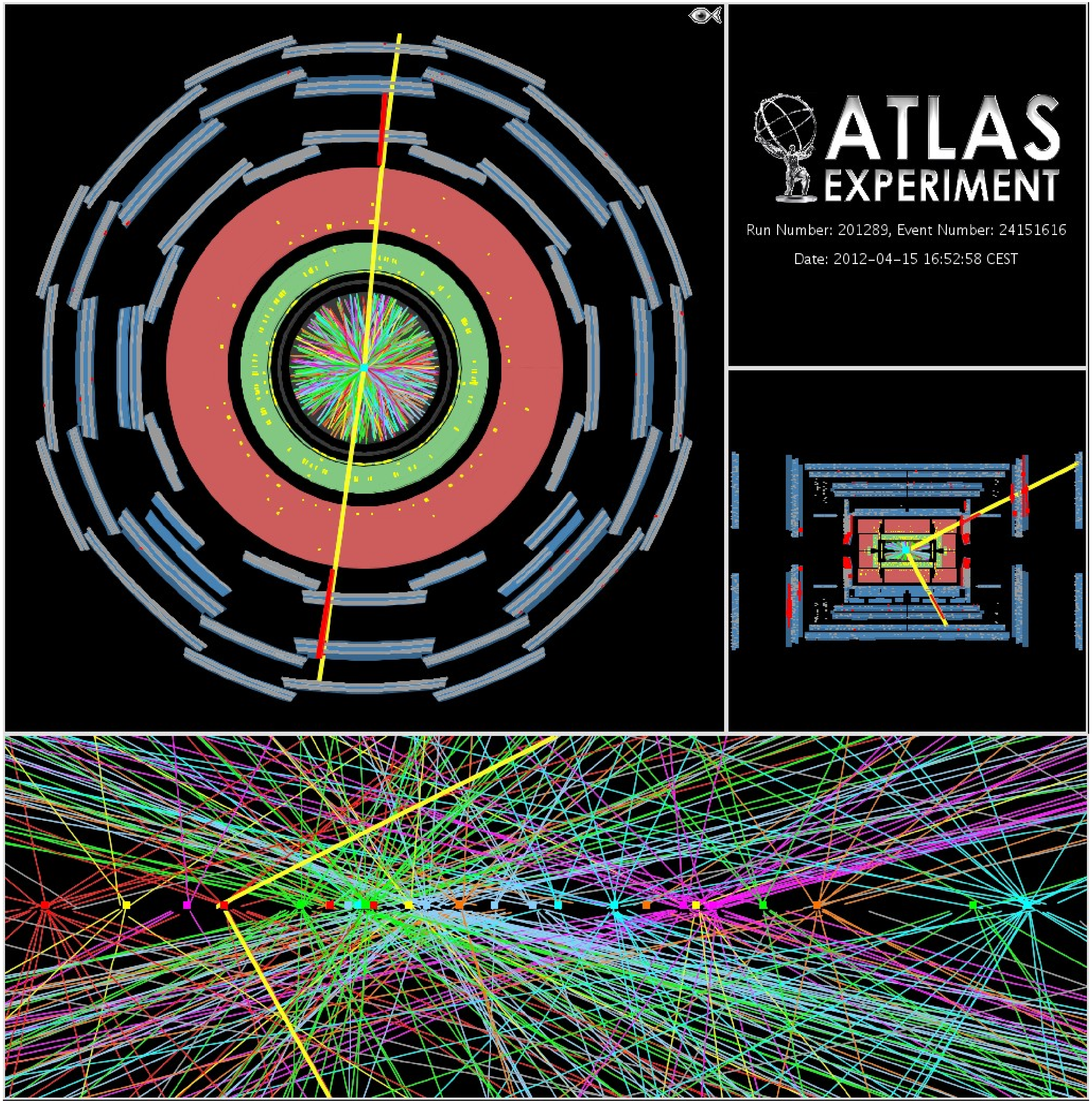
ATLAS tracker



Transition Radiation Tracker : 400 000 channels

SemiConductor Tracker 6 million channels

Pixel detector ; 80 million channels

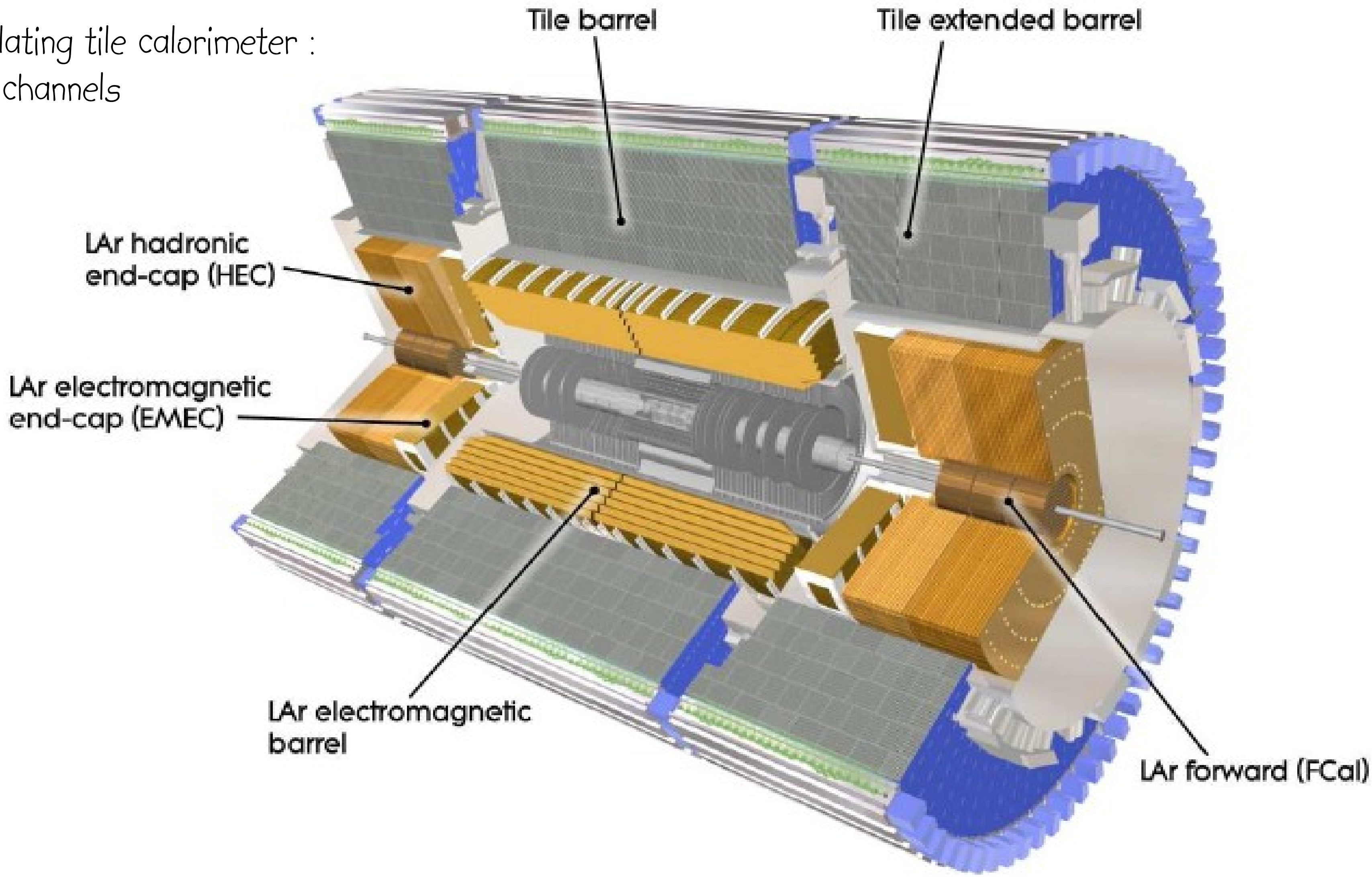


Z into two muons plus 25 pile-up events

ATLAS calorimeter

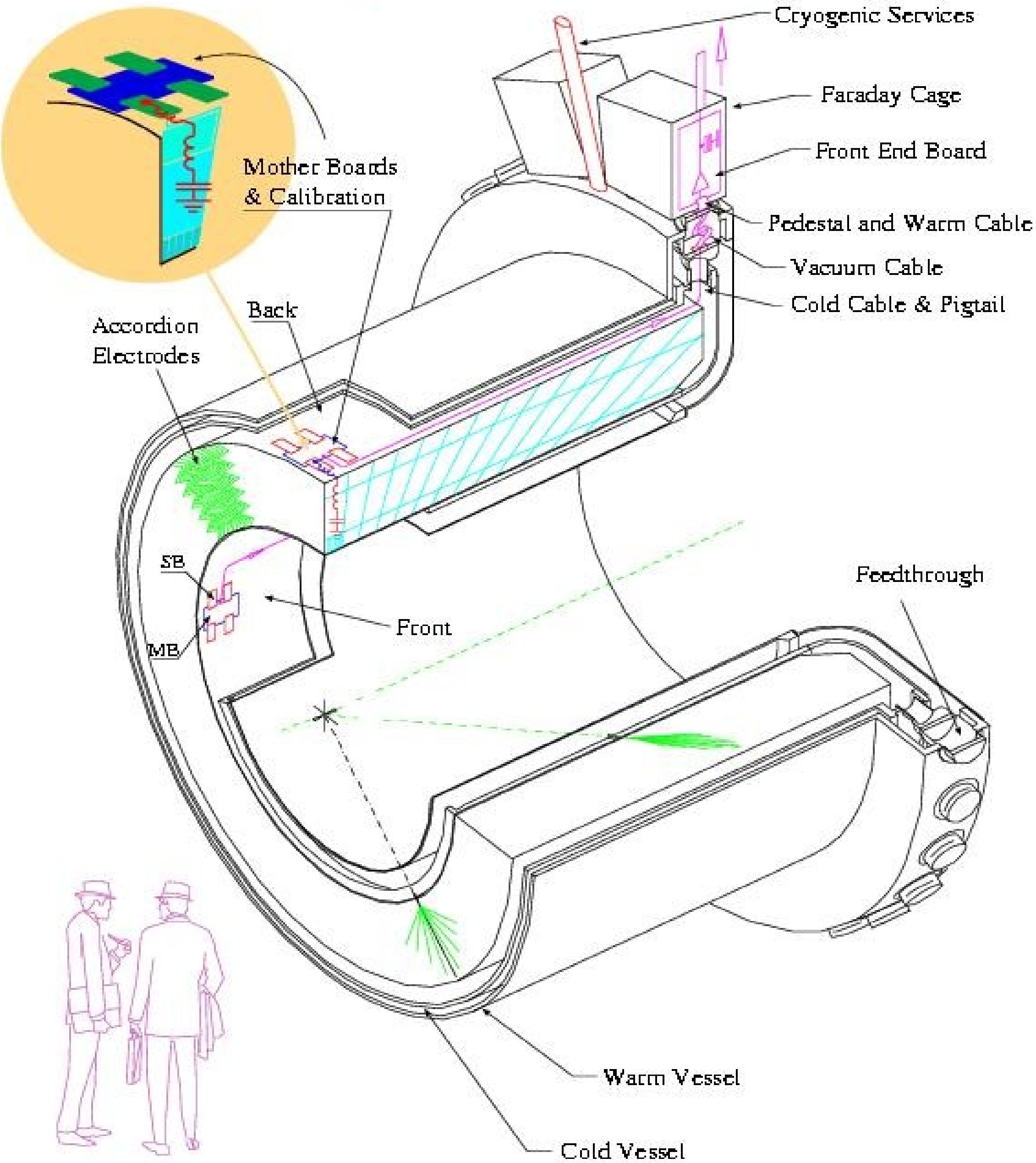
Liquid argon calorimeter : 182468 channels

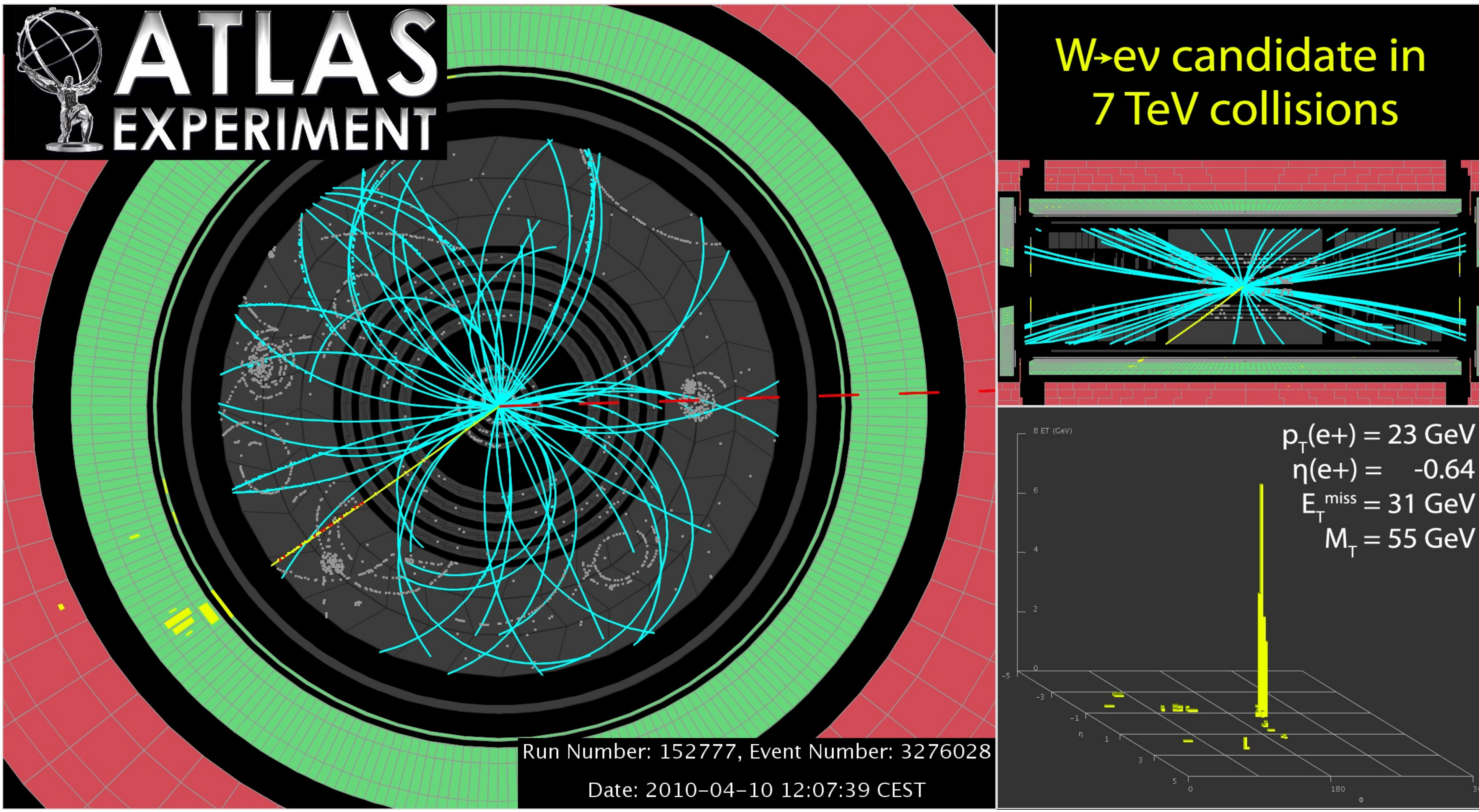
Scintillating tile calorimeter :
9852 channels



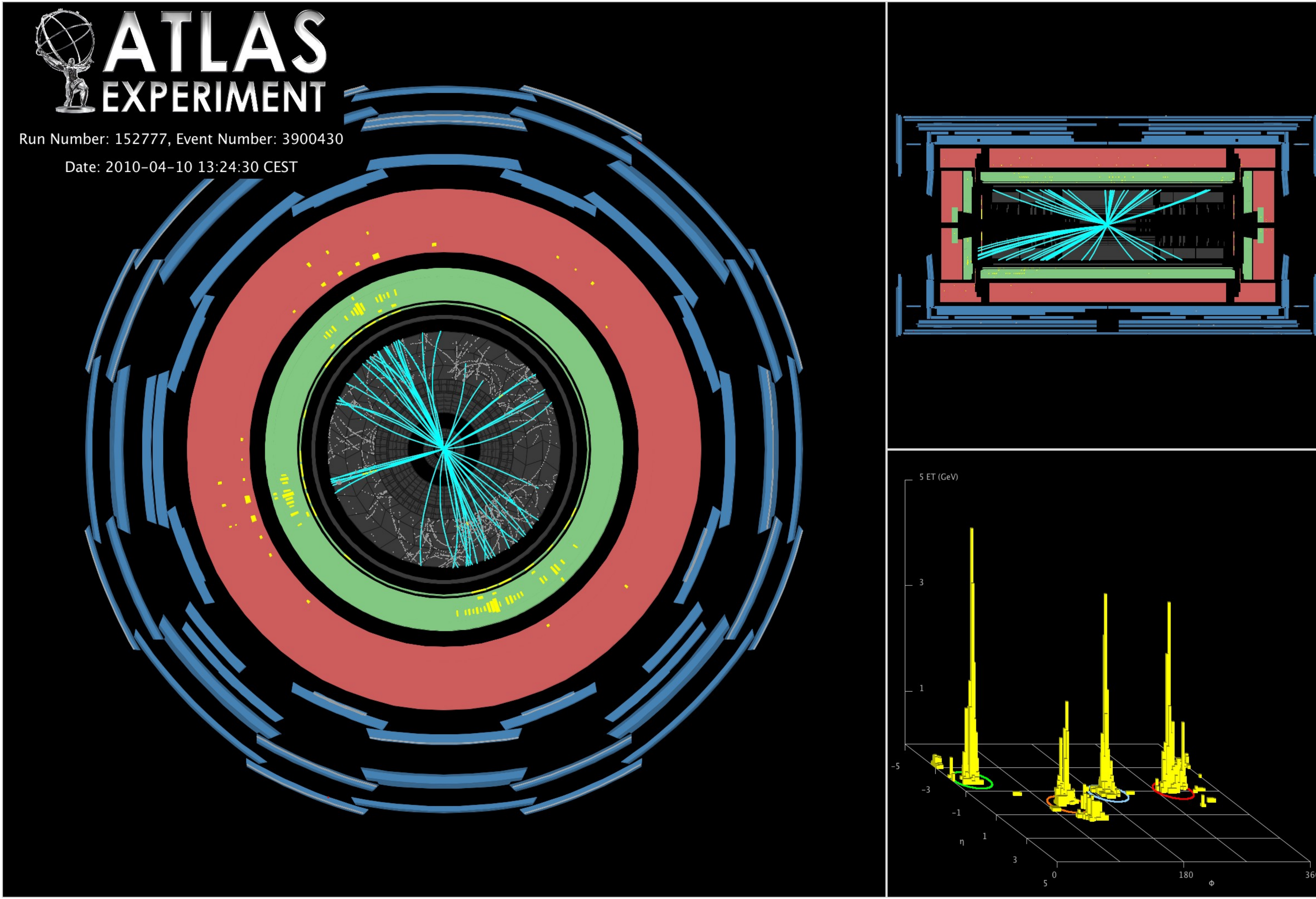
ATLAS LAr Electromagnetic Calorimeter

Signal Channels ~ 10^5 (barrel)

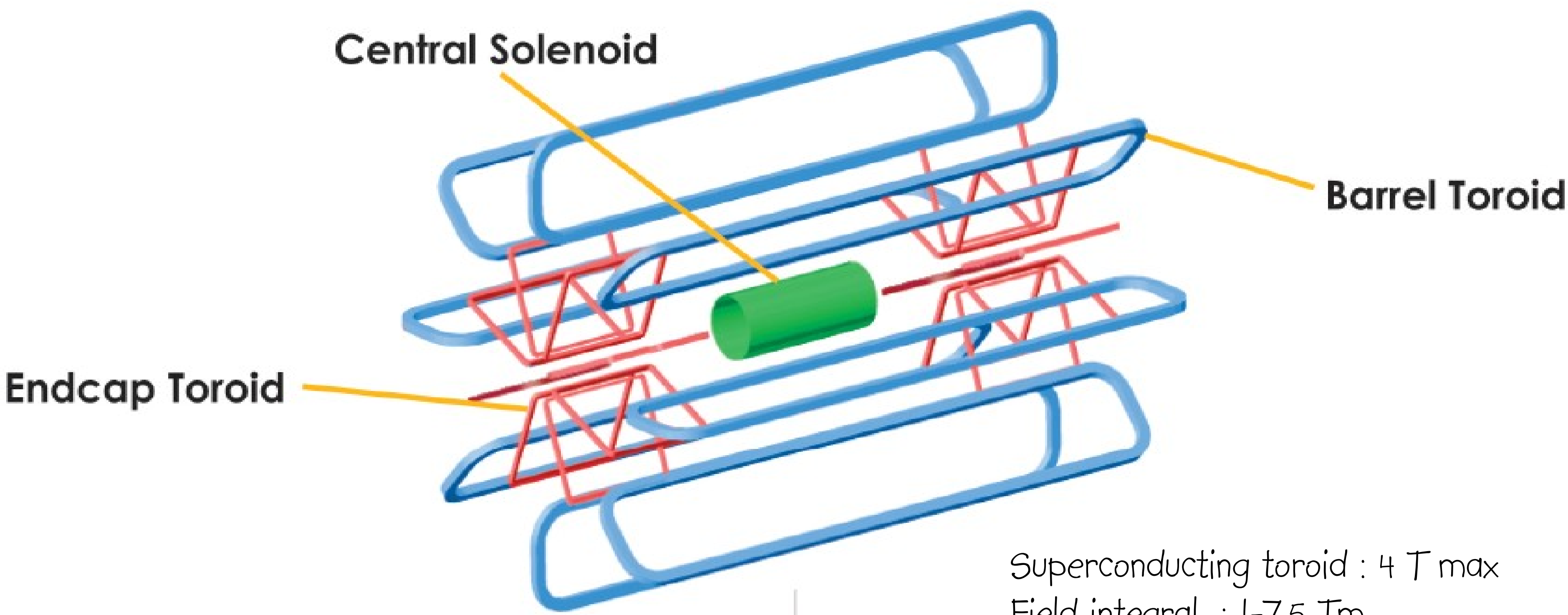



ATLAS EXPERIMENT
W→eν candidate in 7 TeV collisions
$p_T(e+) = 23$ GeV
$\eta(e+) = -0.64$
$E_T^{miss} = 31$ GeV
$M_T = 55$ GeV
Run Number: 152777, Event Number: 3276028
Date: 2010-04-10 12:07:39 CEST

Event with 4 reconstructed hadronic jets



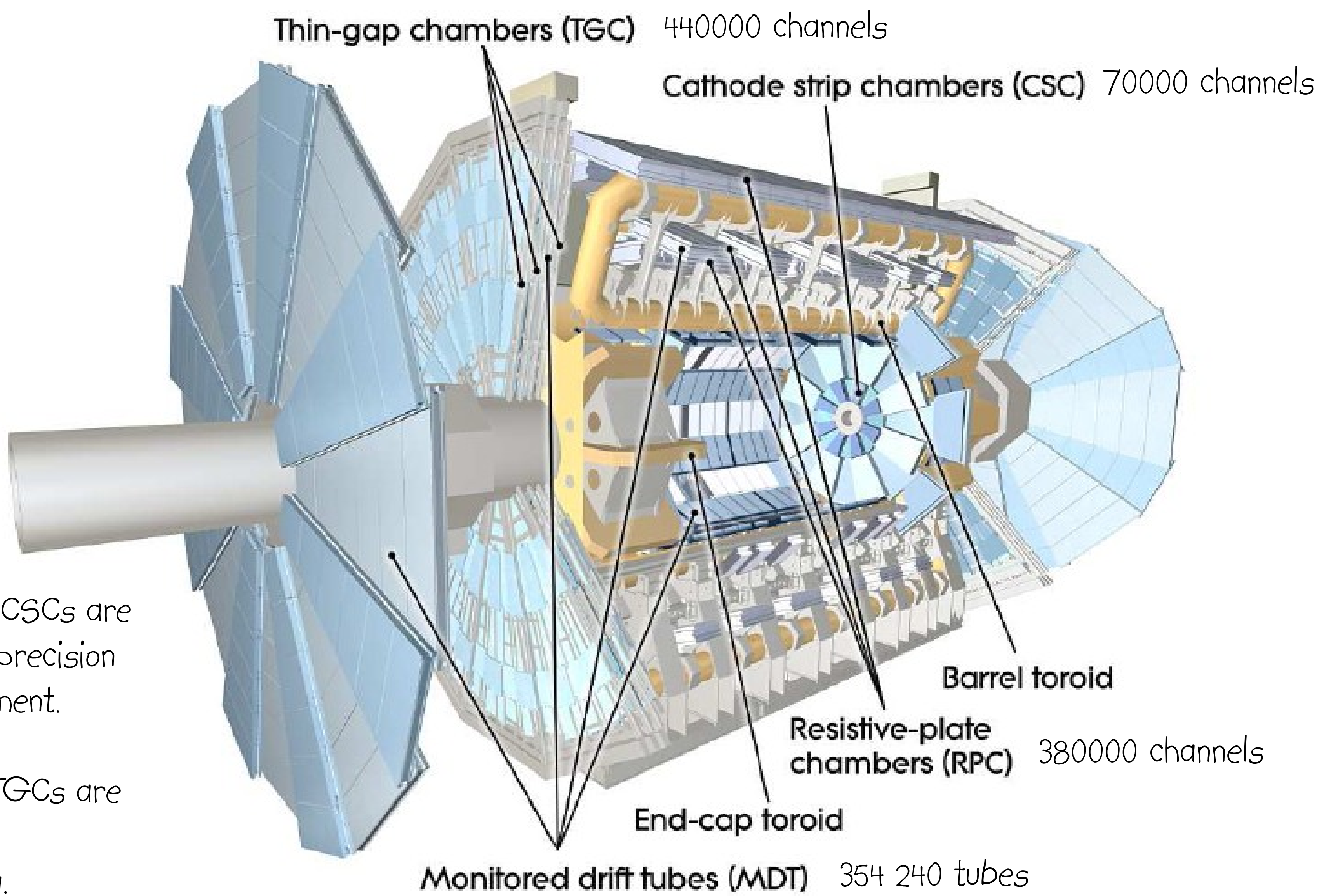
ATLAS Magnet System



2 T superconducting solenoid
Current = 7730 A

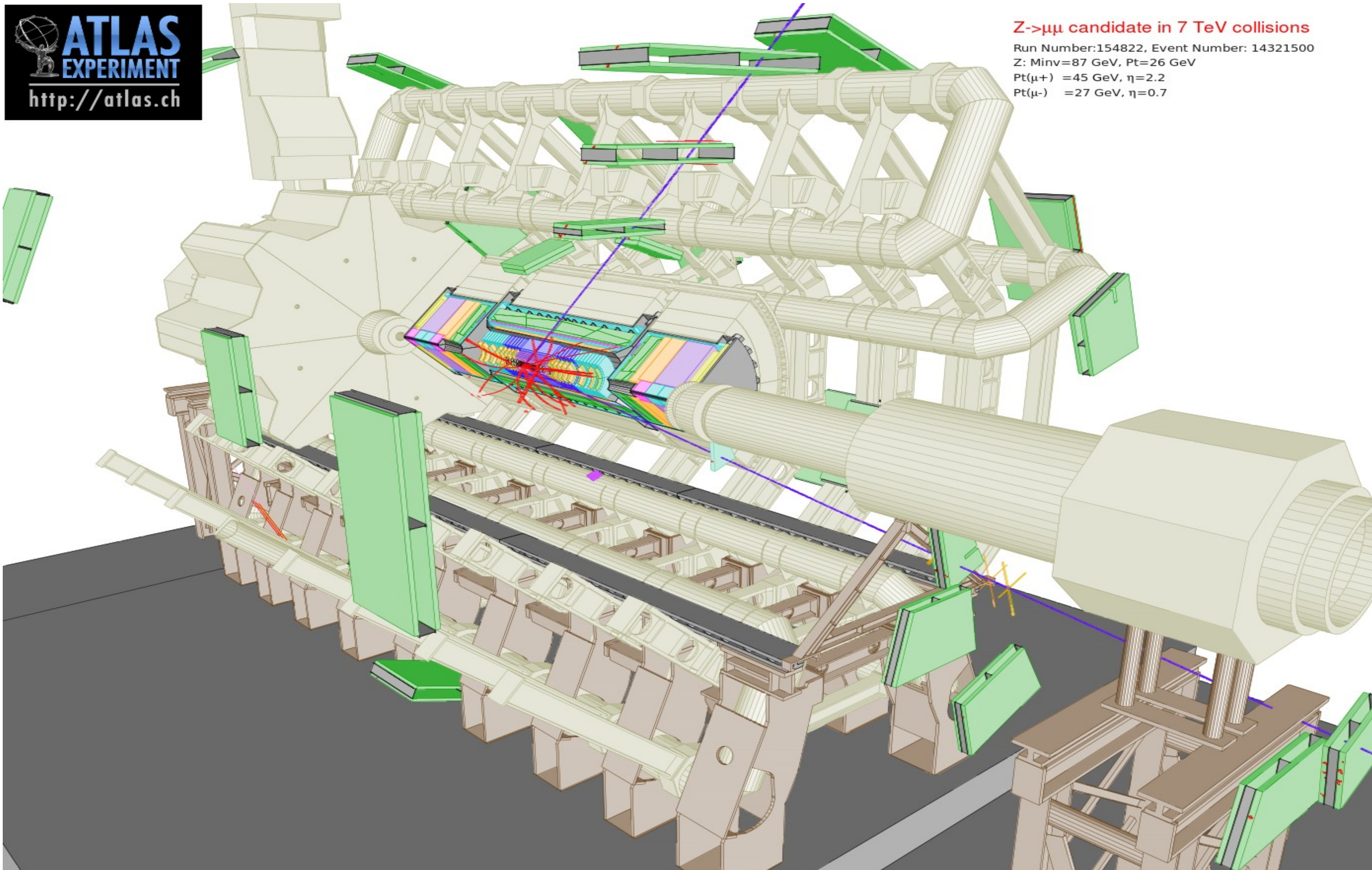
Superconducting toroid : 4 T max
Field integral : 1-7.5 Tm
current : 20500 A
Coil length : 26 m

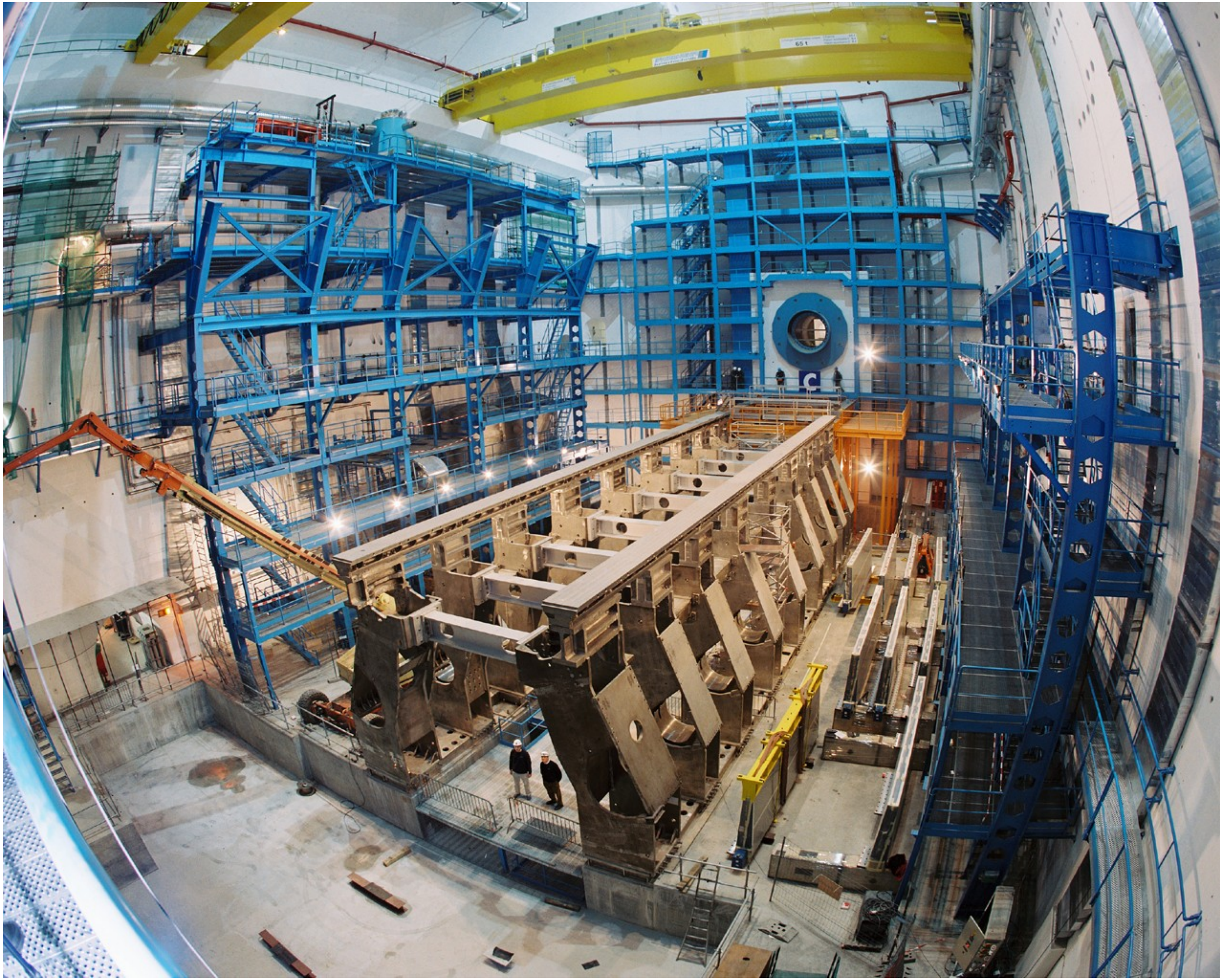
ATLAS muon spectrometer

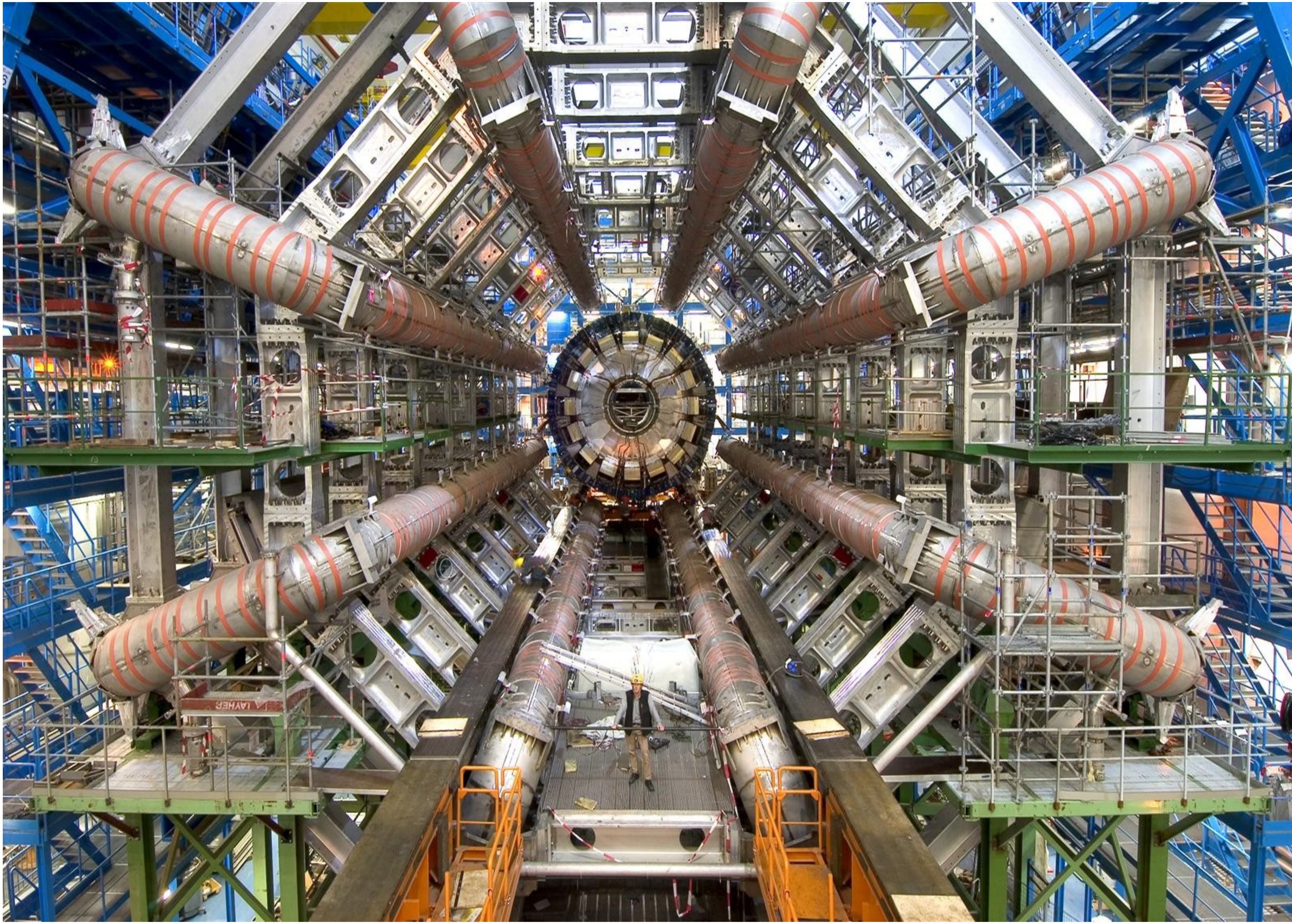


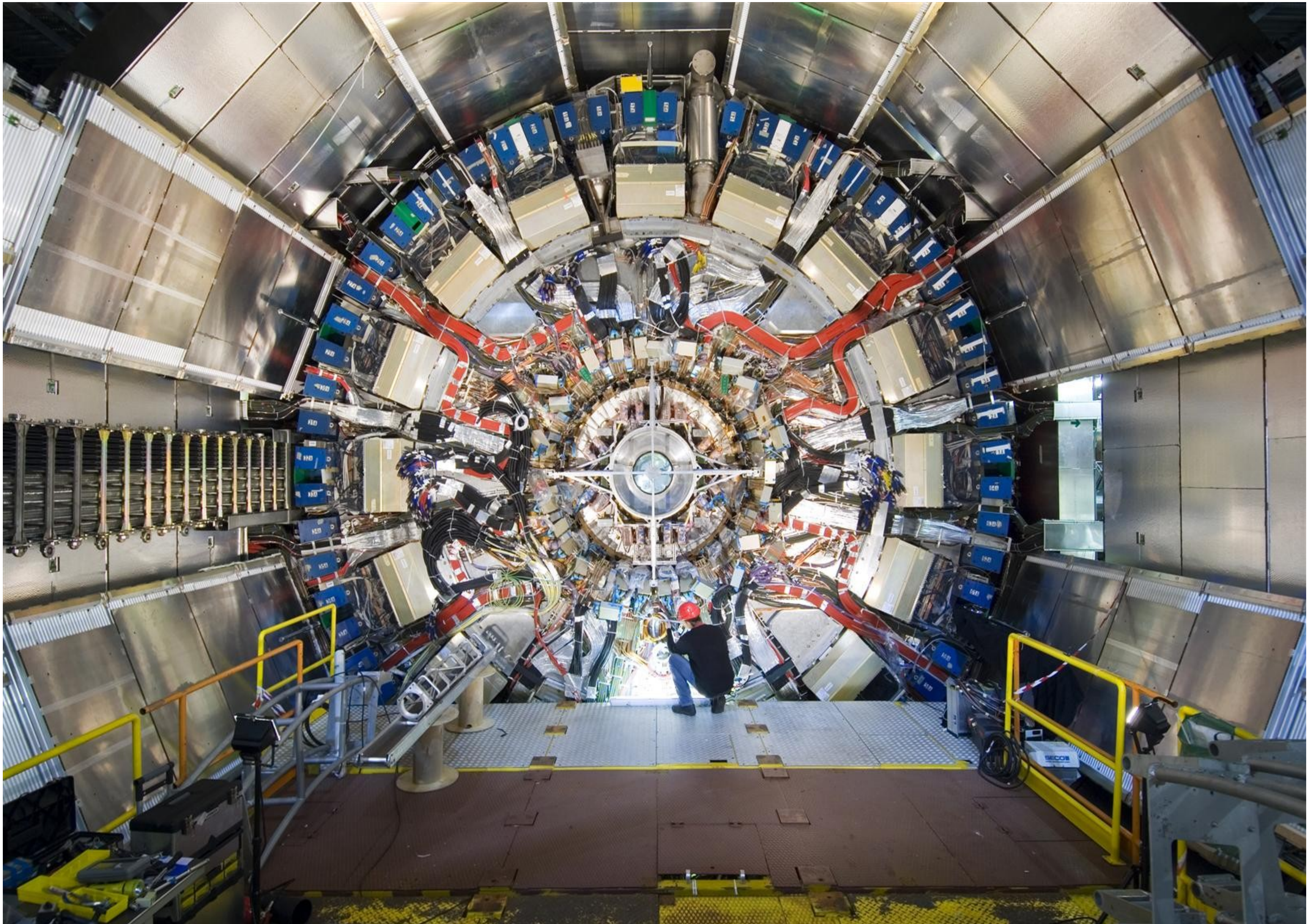
MDTs & CSCs are used for precision measurement.

RPCs & TGCs are used for triggering.

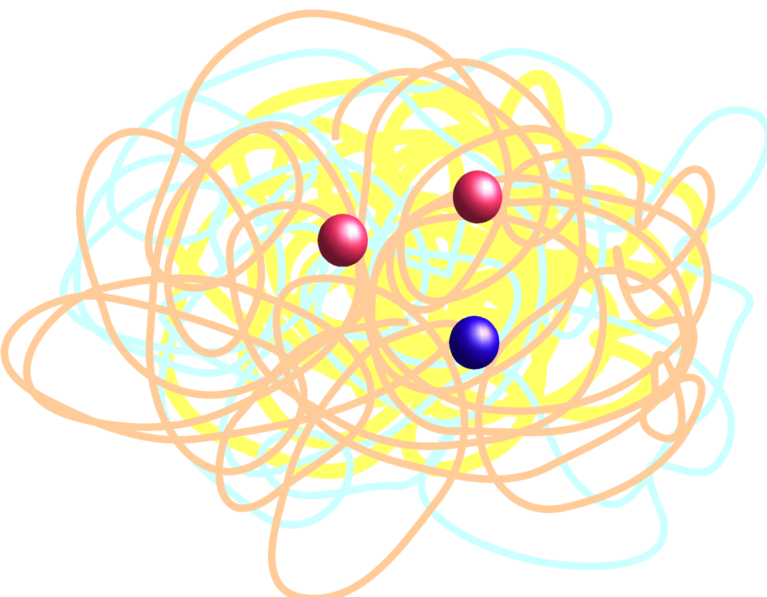

ATLAS EXPERIMENT
http://atlas.ch
Z->μμ candidate in 7 TeV collisions
Run Number:154822, Event Number: 14321500
Z: Minv=87 GeV, Pt=26 GeV
Pt(μ+) =45 GeV, η=2.2
Pt(μ-) =27 GeV, η=0.7







Proton structure



At LHC energies, a proton cannot be considered as being only made of two u quarks and one d quark.

A quark (of very small mass) enclosed in a box featuring a radius less than 1 fm has an energy uncertainty greater than 200 MeV. (Exercise : Use the uncertainty principle to show this)

At LHC, the proton can be seen as a very small box (r<1 fm) filled with a gas of quasi-free quarks and gluons (partons) that share the total proton momentum.

Neglecting the Fermi motion of partons (~ 200 MeV compared to 7 TeV), each of these subconstituents carries a fraction x_i (Feynman variable), between 0 and 1 , of the longitudinal proton momentum , with:

$$\sum_i x_i = 1$$

Proton structure : Partonic Distribution Functions (PDF)

At an energy scale Q, the probability of finding a given parton (u, d, s, c, b, t, g) carrying a fraction xi of the total proton momentum is given by the function: $f_i(x_i, Q^2)$

Gluon

For Q = 0.01 , 0.1 and 1 TeV

Valence u quark (one of the three static proton constituents)

Sea u quark ($u\bar{u}$ pairs)

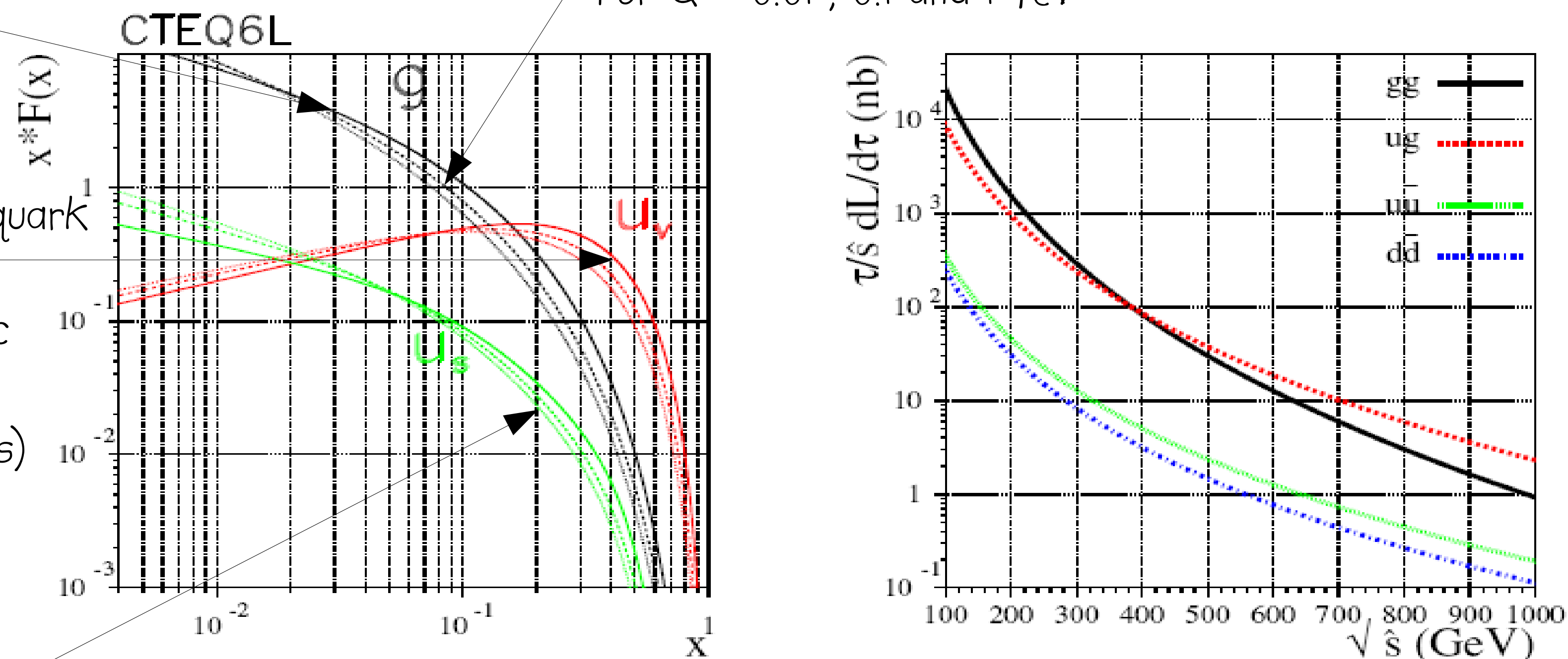


FIG. 1.8 – *Gauche : densités de probabilité du gluon et des quarks u de valence et de la mer dans le proton, en fonction de x. Droite : luminosité partonique en fonction de l'énergie dans le centre de masse des partons incidents, pour différents types de collision.*

Production cross section of a particle of mass M

Integral over the momentum fractions x_i and x_j

$$\sigma(pp \rightarrow M + X) = \sum_{i,j} \iint_o^1 dx_i\, dx_j \;\; f_i(x_i, M^2)\, f_j(x_j, M^2) \;\; \sigma(i\, j \rightarrow M)$$

Sum over all possible parton pairs

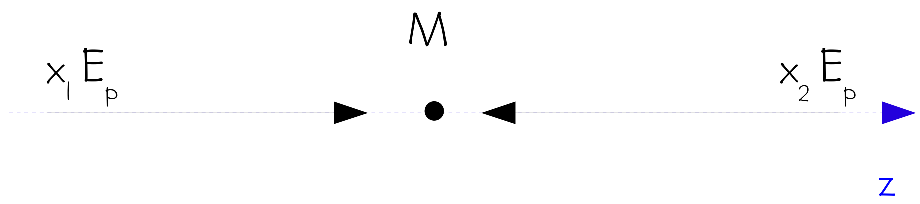
Parton Density
Functions of i and j

Two parton cross section :
i j -> M

As a consequence, hadron colliders have a more complex phenomenology than the $e^+ e^-$ colliders

Parton Kinematics :

$$P_1 \begin{vmatrix} x_1 E_p \\ 0 \\ 0 \\ x_1 E_p \end{vmatrix} \qquad P_2 \begin{vmatrix} x_2 E_p \\ 0 \\ 0 \\ -x_2 E_p \end{vmatrix}$$



Massless partons

Total center-of-mass energy : $\sqrt{s} = 2 E_p$

Total parton energy in the parton center-of-mass frame : $\hat{s} = (P_1 + P_2)^2 = x_1 x_2 \, s$

If the particle resonance is narrow : $\hat{s} = M^2 = x_1 x_2 s$

With the hypothesis $x_1 > x_2$:

M moves along (o,z) in the positive direction

$$P_M \begin{vmatrix} \sqrt{M^2 + p_M^2} = M \cosh \zeta_M \\ 0 \\ 0 \\ p_M = M \sinh \zeta_M \end{vmatrix}$$

$\zeta_M = \tanh^{-1} \beta_M$ M rapidity

Parton Kinematics

$$P_1+P_2=P_M \;\Rightarrow\; P_1-P_M=P_2 \;\Rightarrow\; (P_1-P_M)^2=0$$

leading to : $x_1=\frac{M}{\sqrt{s}}e^{\zeta_M}$ and : $x_2=\frac{M}{\sqrt{s}}e^{-\zeta_M}$

Or rewritten :

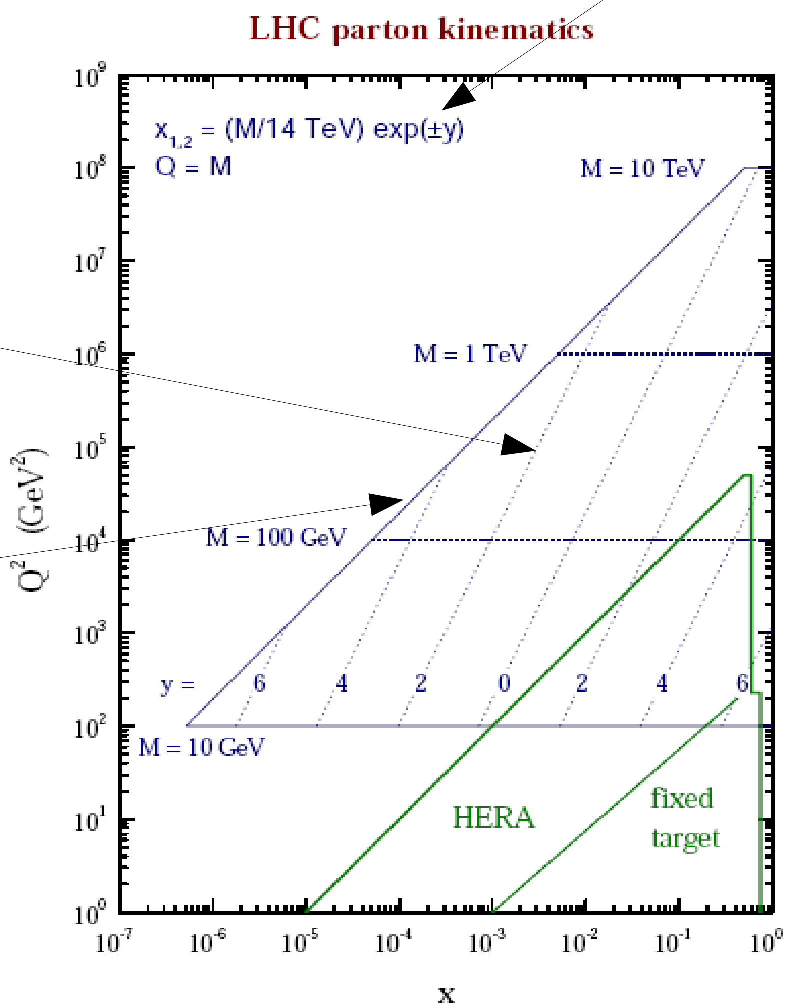
$$\ln(M^2)=2\ln(x_1)+\ln(s)-2\zeta_M$$

if : $x_1=1$ then : $x_2=\frac{M^2}{s}$

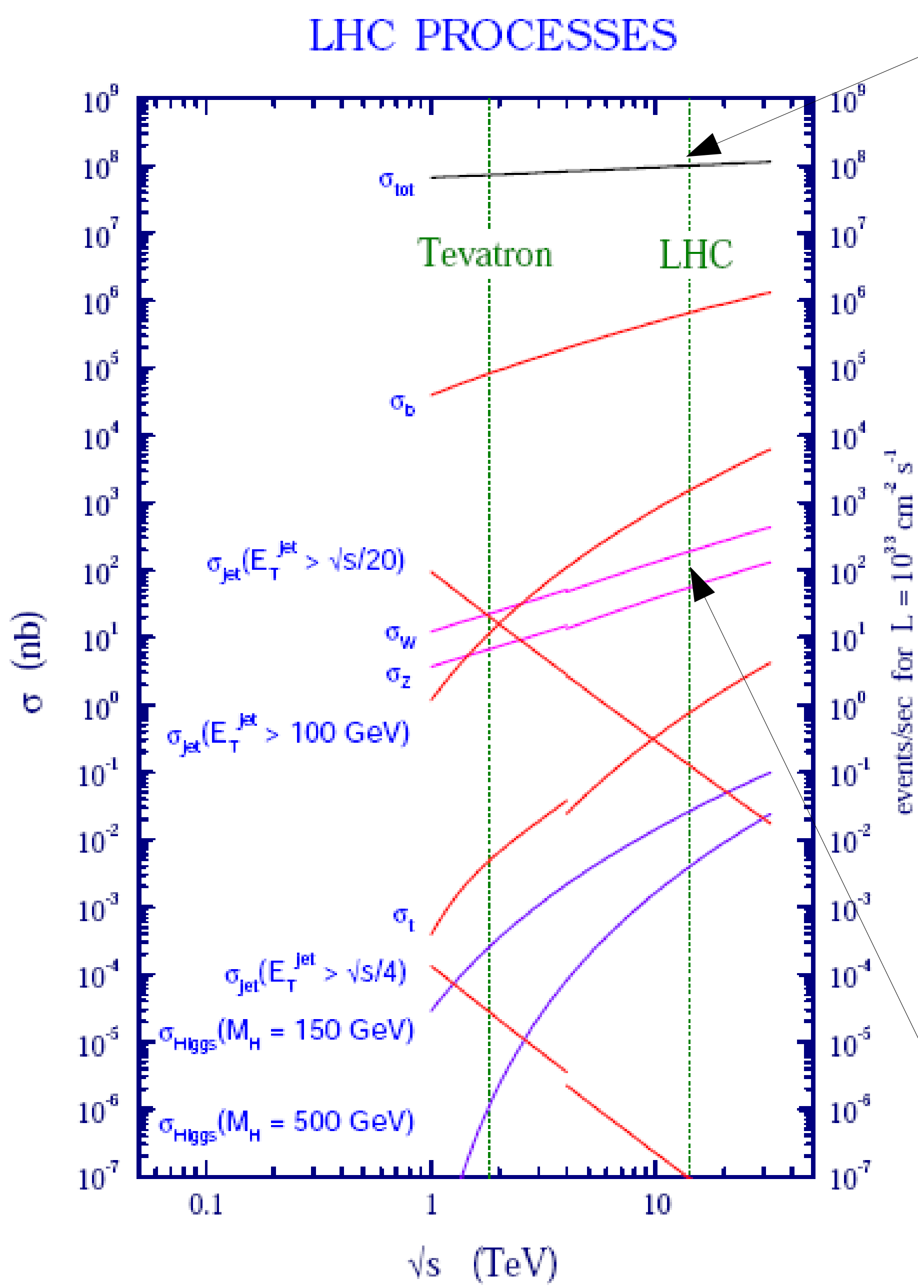
$$\ln(M^2) = \ln(x_2)+ \ln(s)$$

In this picture : $y=\zeta_M$

and : Q = M



Reaction rates



1 GHz at nominal luminosity : 10^{34} cm^{-2}s^{-1} = 10 (nb)$^{-1}$ s^{-1}

On average, 25 minimum bias events are produced per proton-proton crossing.

But these events are essentially soft hadronic collisions (minimum bias events) that will result in the production of a large amount of hadronic particles generating a soft noise for low energy detection.

Per event, a minimum bias event may contain up to 90 charged-particle tracks to be measured in the inner tracker.

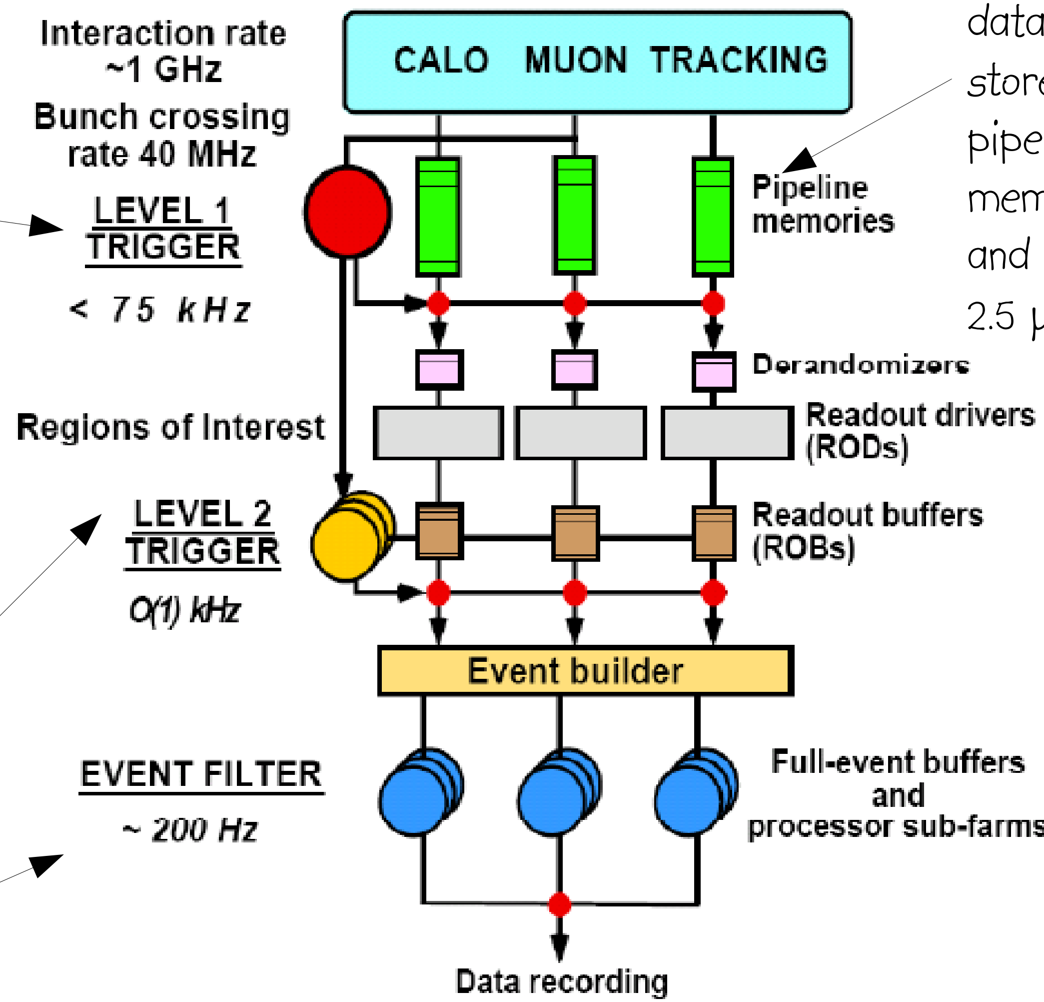
The signals of interest correspond to reaction rates much lower.
Given the detector coverage & efficiency, 200 Hz will be sufficient to record all the signals of primary interest.

Event acquisition Trigger

The first trigger level recognizes an event of interest in less than 2.5 μs - The event rate is reduced to 75 KHz.

Level 2 performs a first event analysis by focusing on regions of interest : detector places where electrons, photons, jets and muons were detected. It reduces the event rate to about 3.5 KHz with a computing time per event of about 40 ms (parallel computing)

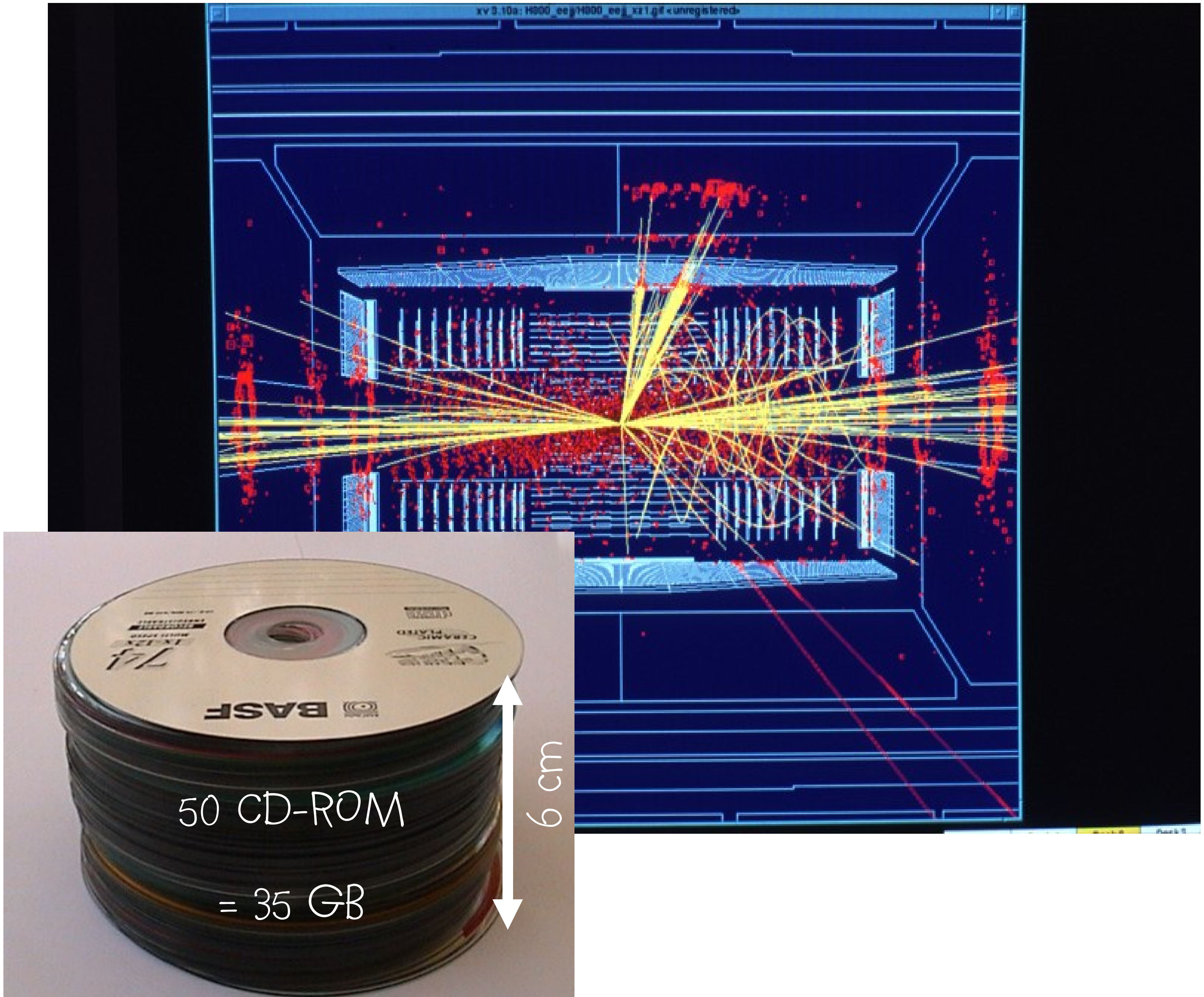
The final level of trigger performs a complete analysis of the full event and records it if it is declared of interest.

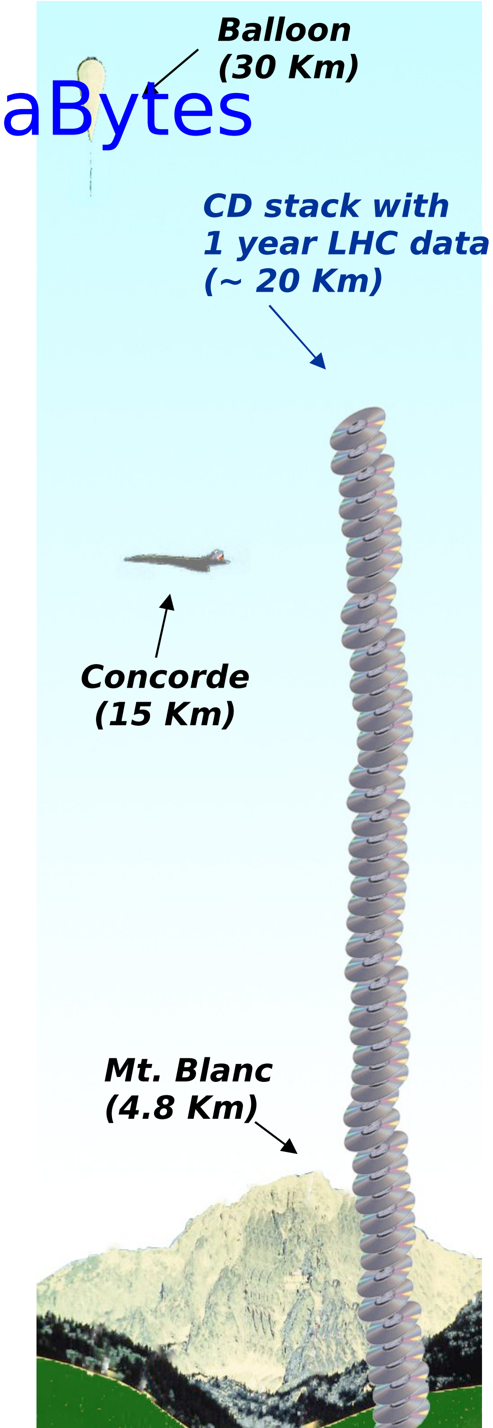


Every 25 ns, all detector data is stored in pipeline memories and kept for 2.5 μs

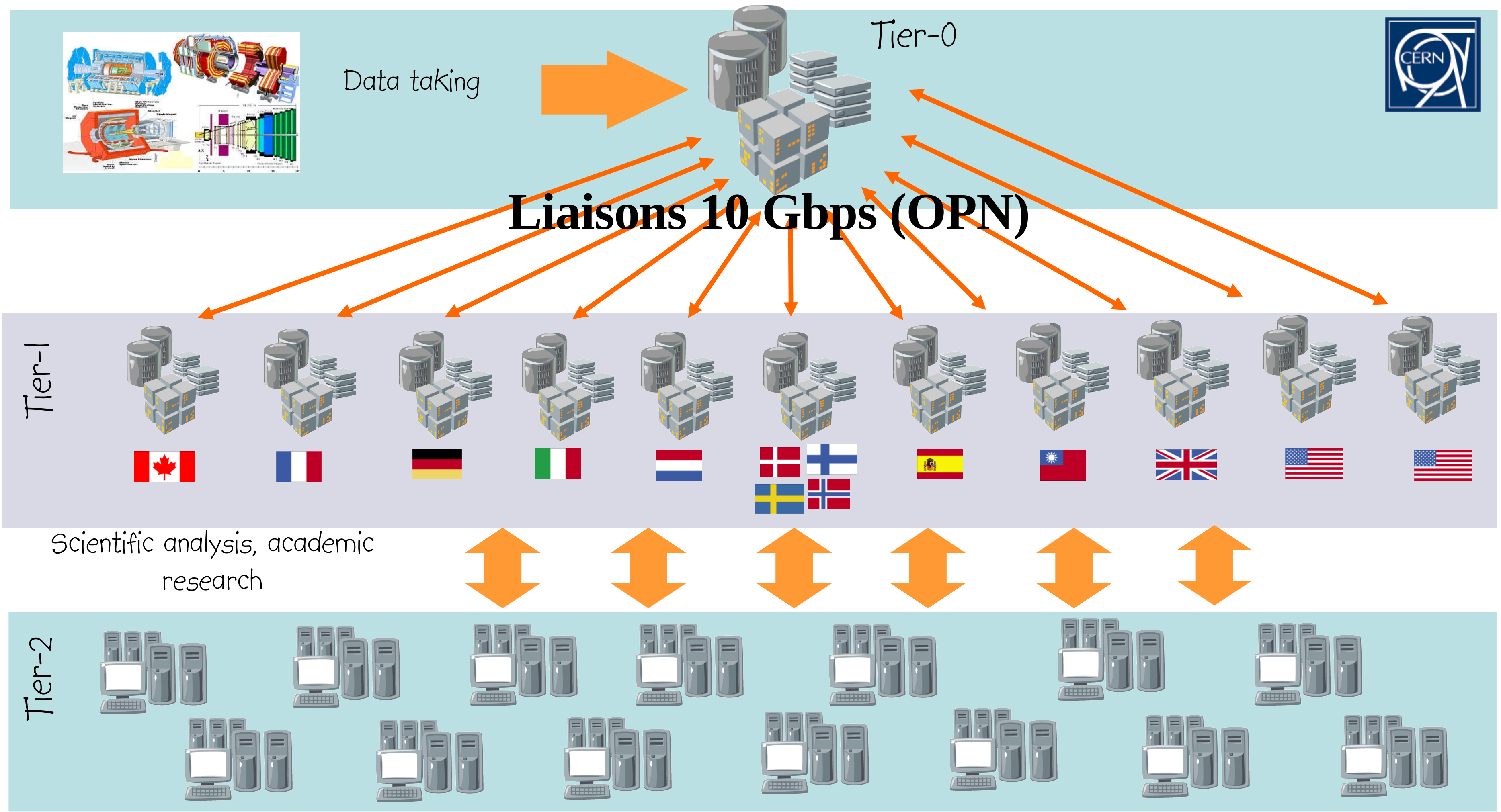
1,5 MB/event
3 PB/year

Data storage per year: ~ 15 PetaBytes





Architecture du calcul des expériences LHC



World LCG real time monitoring

p://gridportal-ws01.hep.ph.ic.ac.uk/old_applet/running_frame.ht