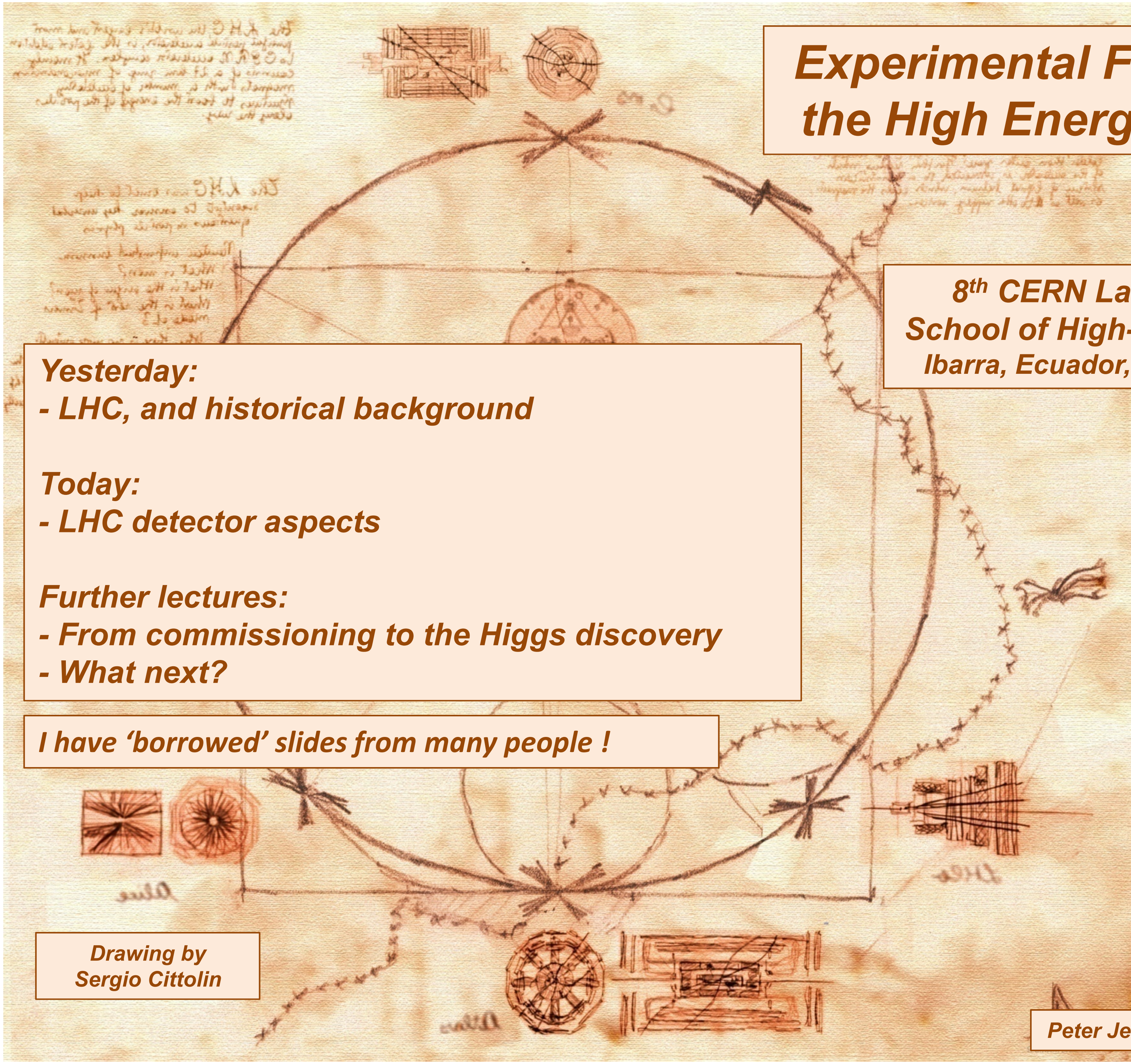
Experimental Facilities at the High Energy Frontier

8th CERN Latin-American School of High-Energy Physics
Ibarra, Ecuador, 4-17 March 2015



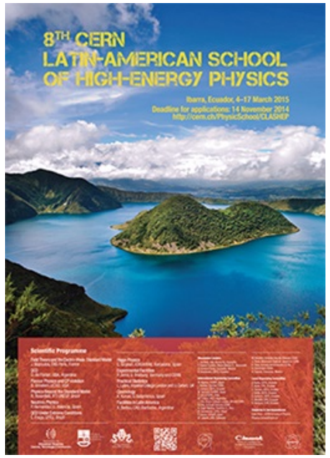
Yesterday:
- LHC, and historical background

Today:
- LHC detector aspects

Further lectures:
- From commissioning to the Higgs discovery
- What next?

I have 'borrowed' slides from many people !

Drawing by Sergio Cittolin



Peter Jenni, Freiburg and CERN

Arguing after the mid-1980s of being ambitious and design a general purpose detector …

A very simplified summary:

detector signature	accessible physics process
$\mu^\pm$	$H \to ZZ \to 4\mu^\pm$ $Z' \to \mu^+\mu^-$ (σ_m ?)
$\mu^\pm$, jets, p_T	add: $H \to ZZ \to \mu^+\mu^-\nu\bar{\nu}$ $W' \to \mu^\pm\nu$ compositeness $\tilde{q}, \tilde{g}$ (direct decays) jet spectroscopy
e, $\mu^\pm$, jets, p_T (non-)magnetic central part (reduced tracking)	add: 4× rate $H \to ZZ \to 4\ell^\pm$ 2× rate $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ 2× rate Z', W' $\tilde{q}, \tilde{g}$ (also cascade decays) mass resolution eμ heavy Q, L $H \to \gamma\gamma$
$e^\pm$, $\mu^\pm$, $\tau^\pm$, jets, p_T full momentum and tracking	add: more redundancy and cross-checks on above, H^+, SUSY-H, heavy flavour tags

Lepton detection at LHC is crucial. Small rates are expected for many potential signals

⇒ detection of e and μ

Muons are relatively easy to identify but hard to measure well

(precise μ measurements may mean hundreds of MCHF)

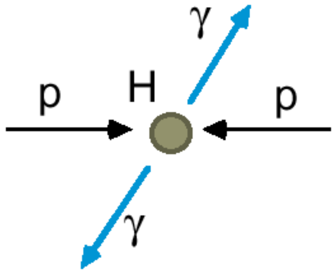
Electrons are relatively easy to measure but hard to identify at 10^{34}

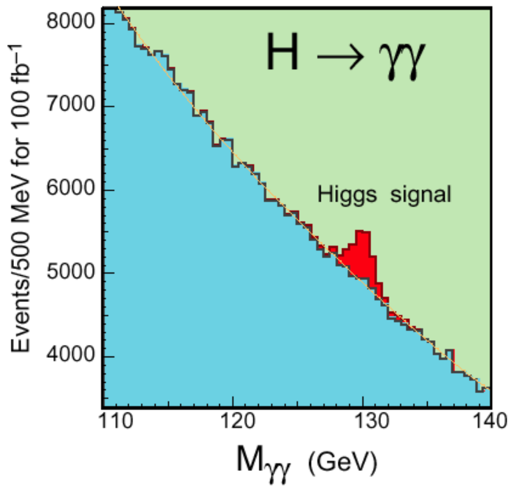
(radiation-hard inner detector)

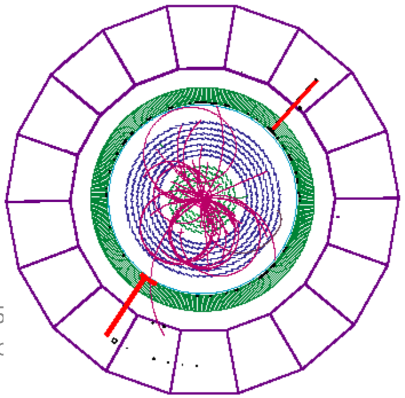
Lepton isolation criteria are also important to reject back-grounds from heavy flavour decays

Higgs signals (in CMS)

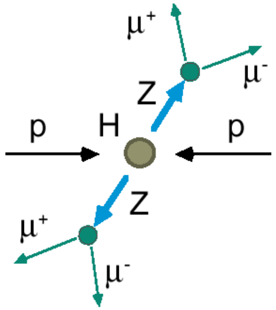
Low M_H < 140 GeV/c²

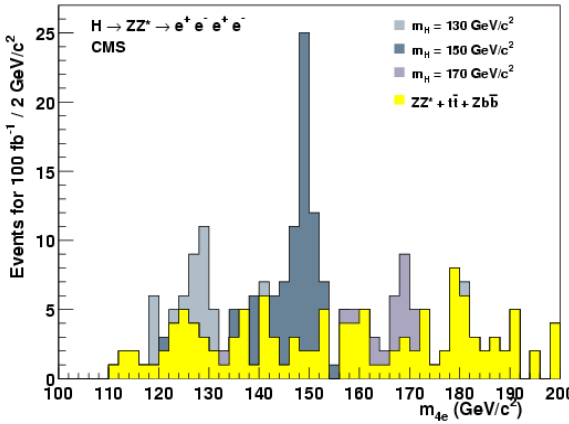


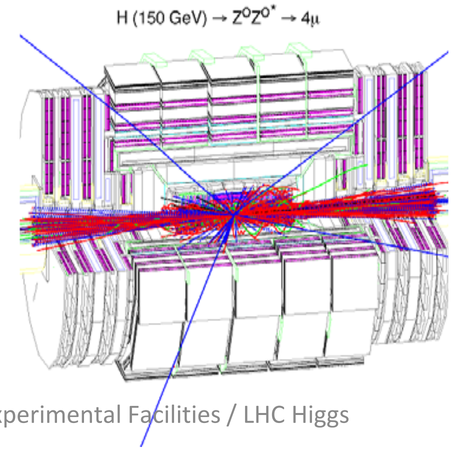




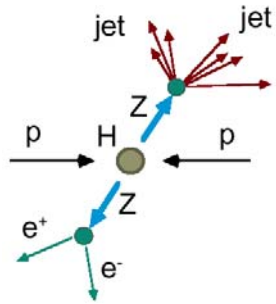
Medium 130<M_H<500 GeV/c²

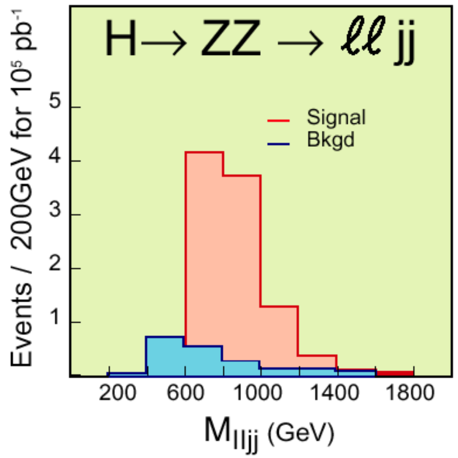


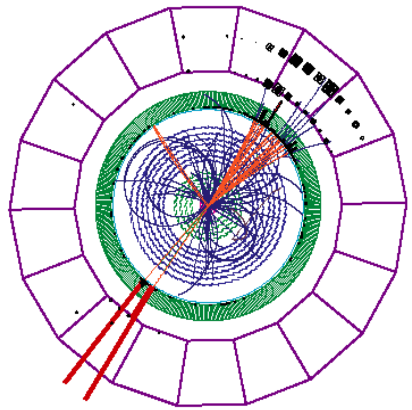




High M_H > ~500 GeV/c²

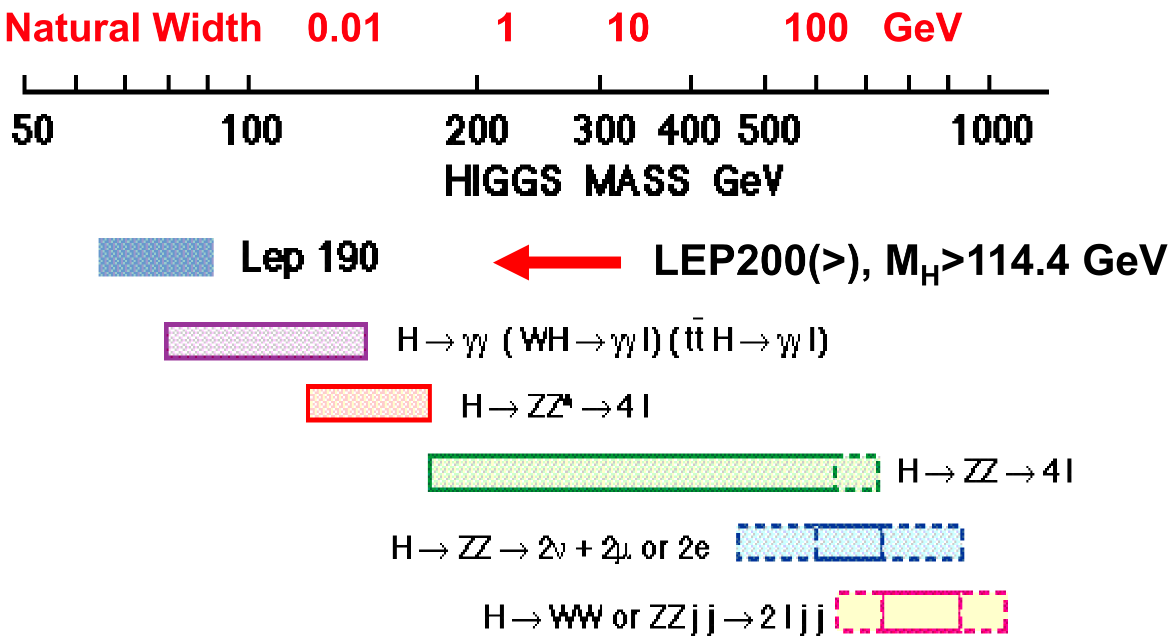


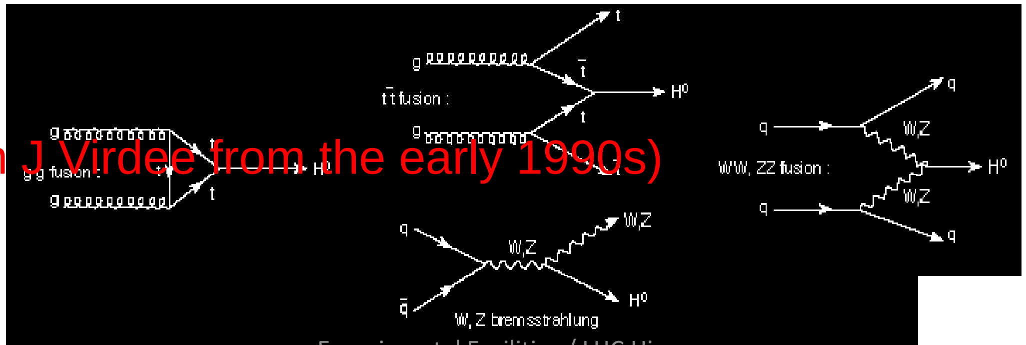




Design Benchmark - Higgs Production

At the LHC the SM Higgs provides a good benchmark to test the performance of a detector





(A slide from J Virdee from the early 1990s)

Physics Landscape:

General event properties

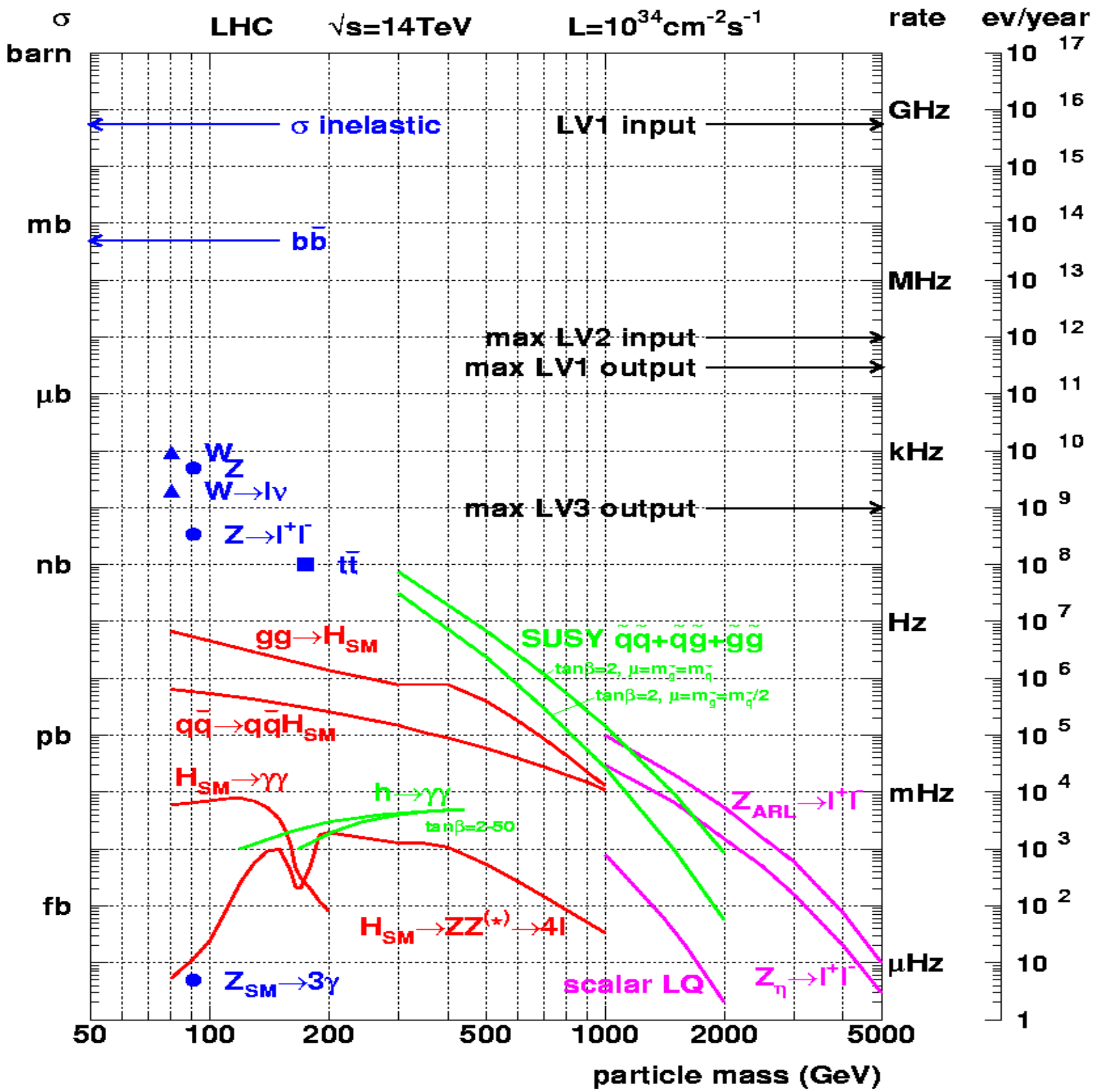
Heavy flavour physics

Standard Model physics
including QCD jets

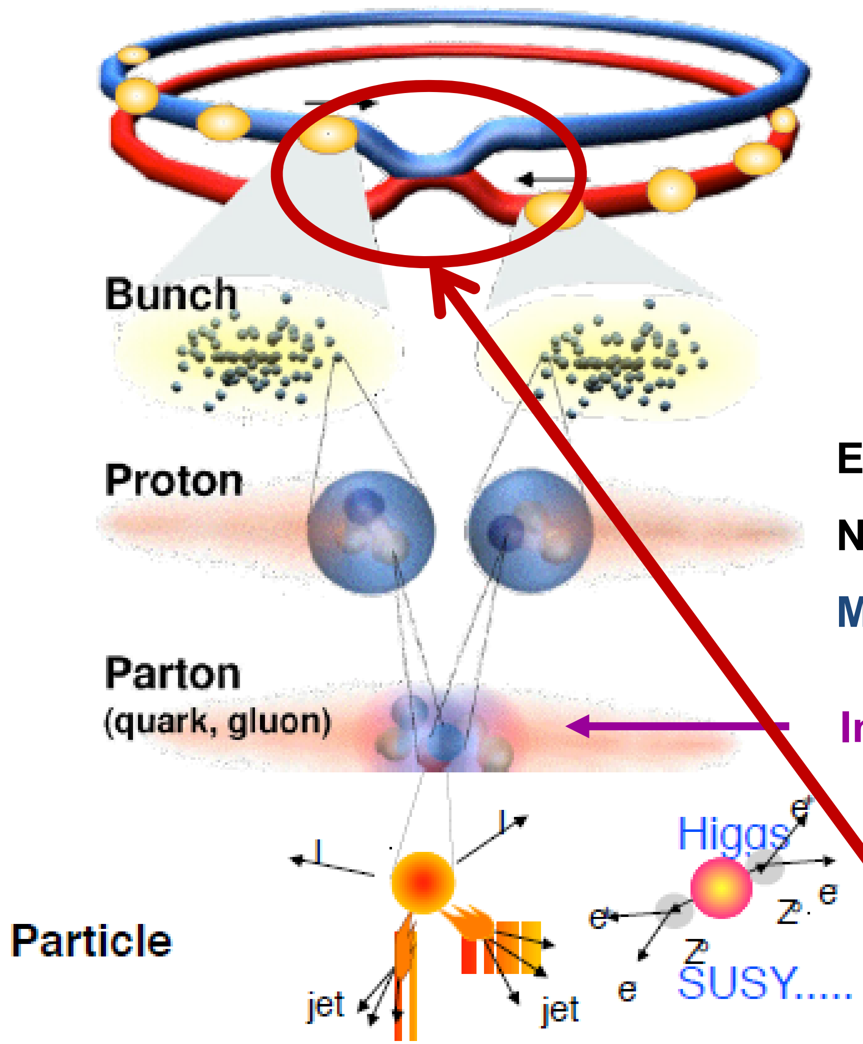
Higgs searches

Searches for SUSY

Searches for ‘exotic’
new physics



Collisions at the LHC



Proton - Proton	2808 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	$10^{34} cm^{-2} s^{-1}$
Crossing rate	40 MHz

Event rate:

$N = L \times \sigma(pp) \approx$ 10^9 interactions/s

Mostly soft (low p_T) events

Interesting hard (high-p_T) events are rare

New physics rate ≈ .00001 Hz

Event selection:
1 in 10,000,000,000,000

→ Interesting events are very, very rare
→ One needs highly sophisticated instruments to find them

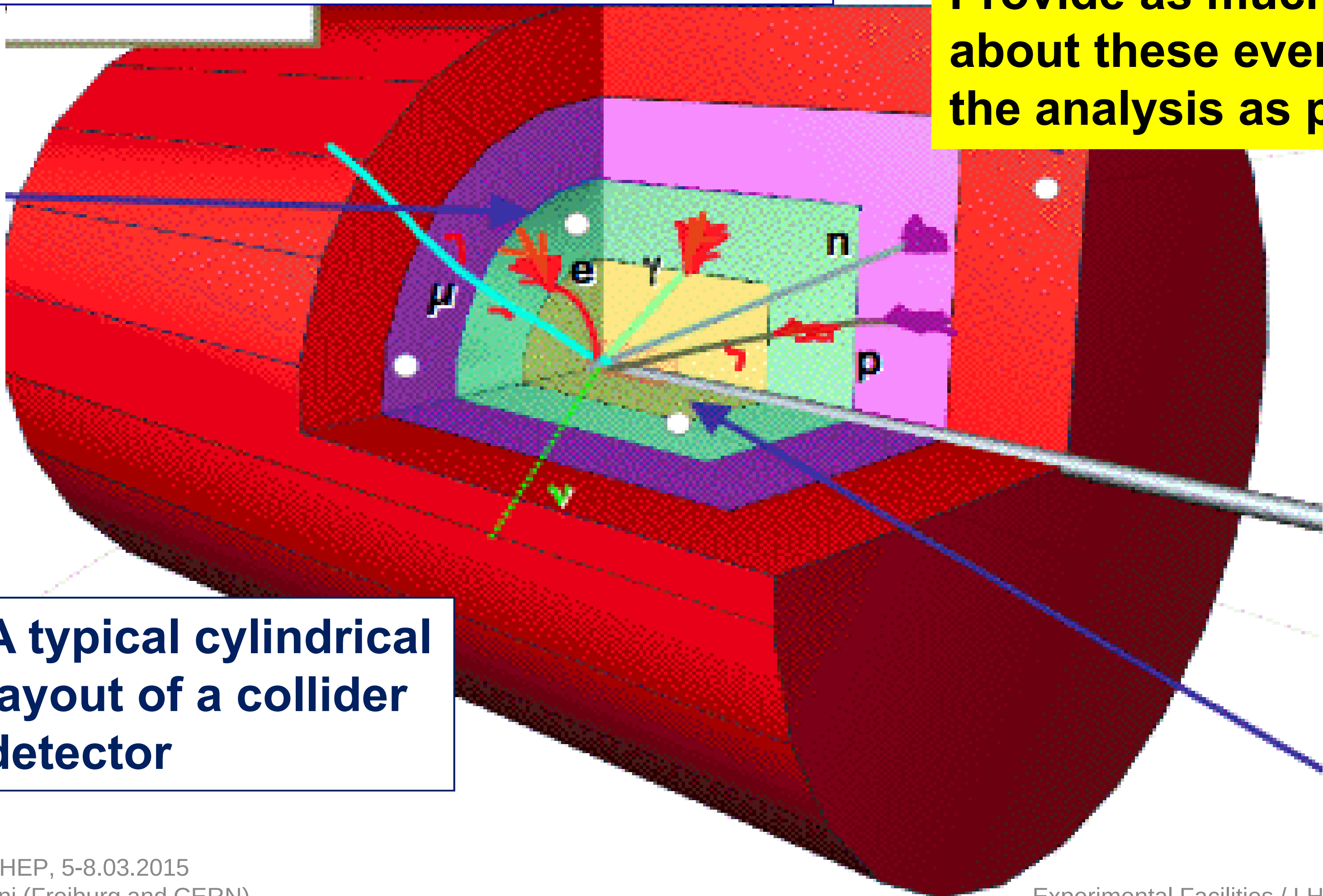
Detectors for particle physics

Cover the whole angular range around the collision point to detect as much of the particles produced in the collision as possible.

Dual role of detectors:

Select potentially interesting collision events

Provide as much information about these events for the analysis as possible



A typical cylindrical layout of a collider detector

A typical experiment at the ISR (R702, August 1977)

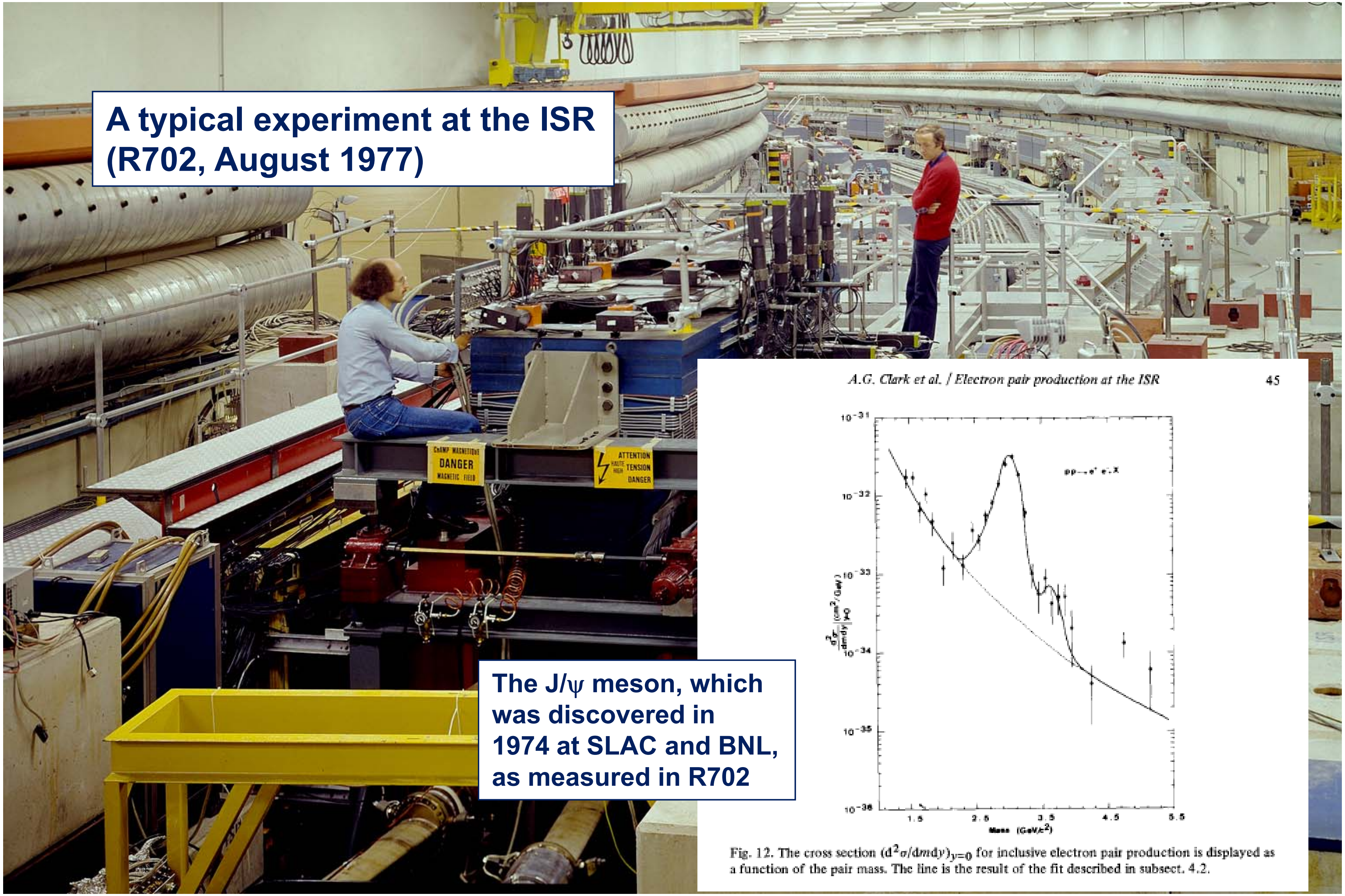
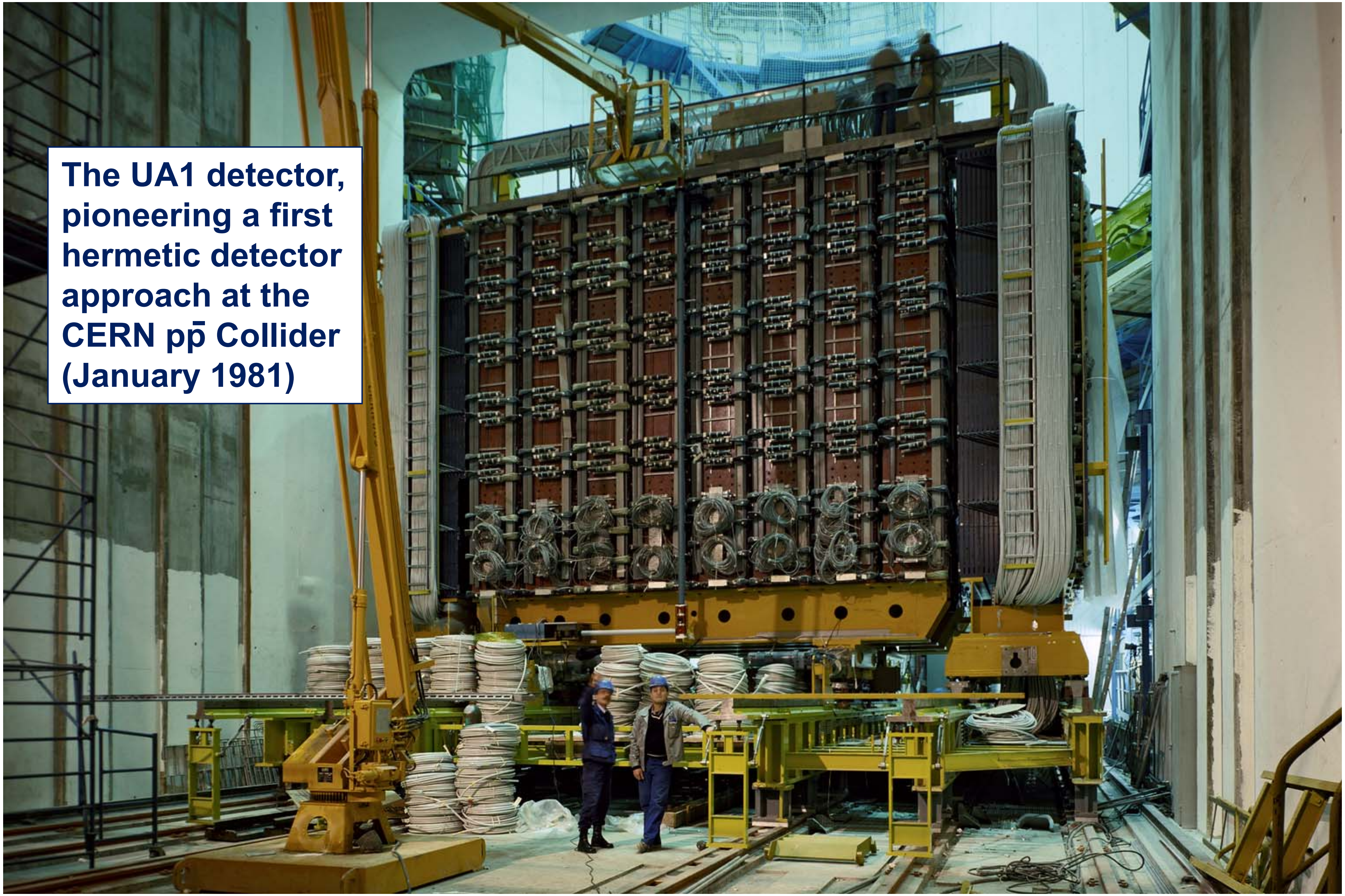
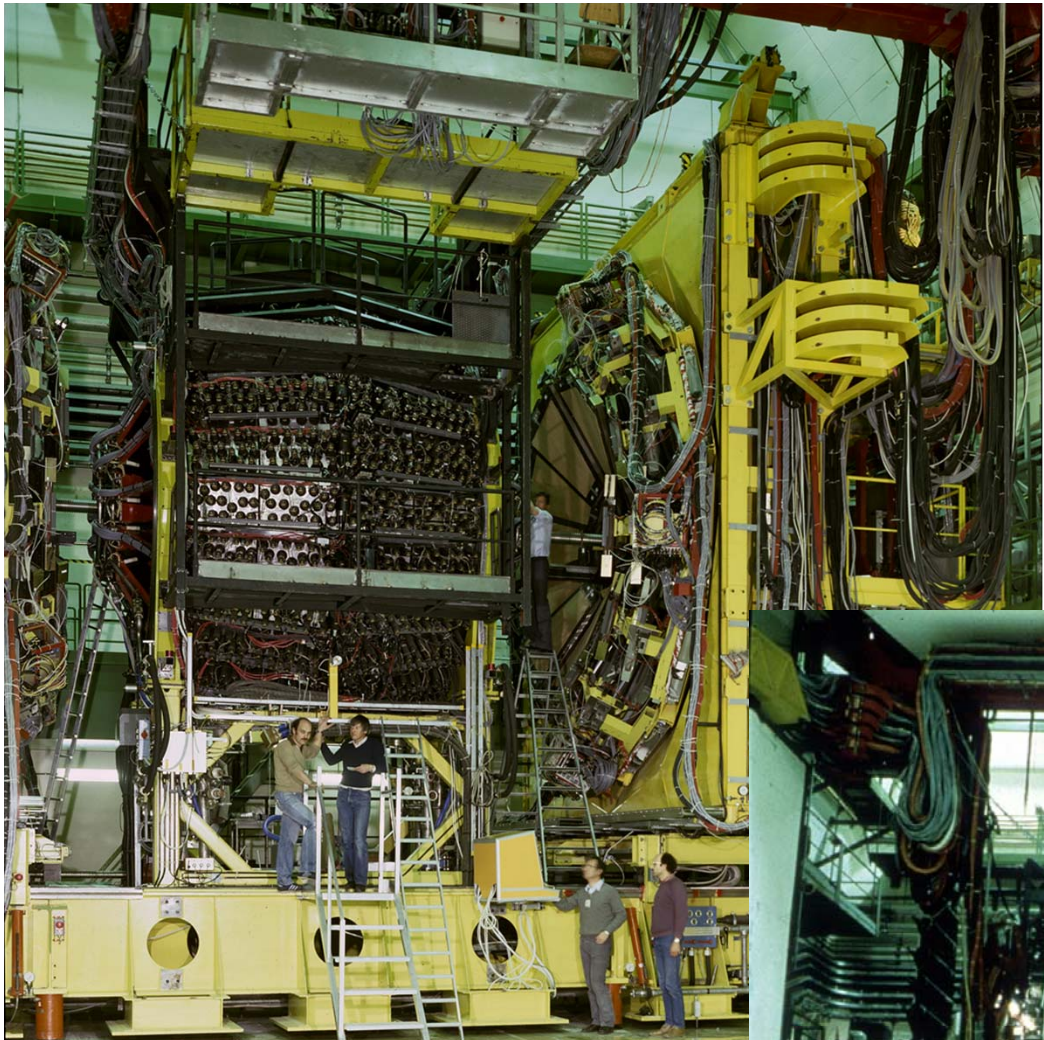


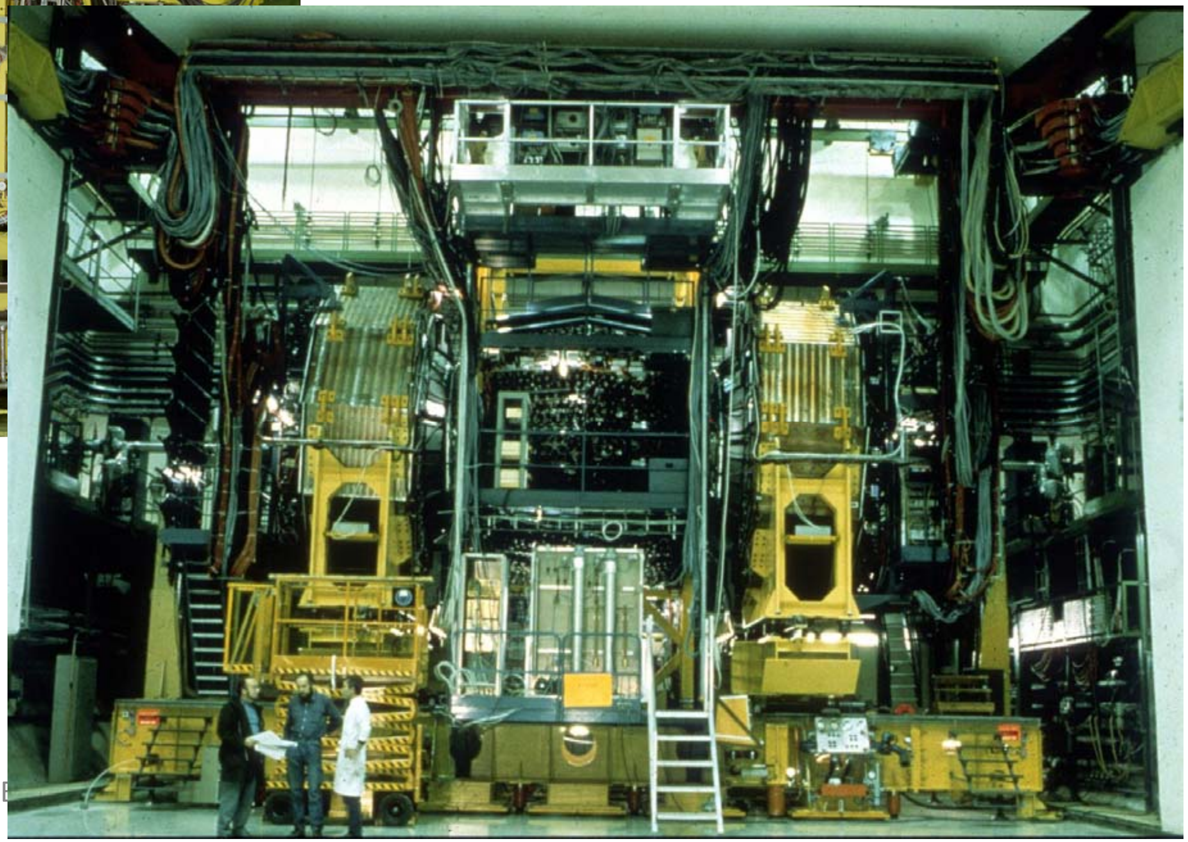
Fig. 12. The cross section $(d^2\sigma/dmdy)_{y=0}$ for inclusive electron pair production is displayed as a function of the pair mass. The line is the result of the fit described in subsect. 4.2.

The J/ψ meson, which was discovered in 1974 at SLAC and BNL, as measured in R702

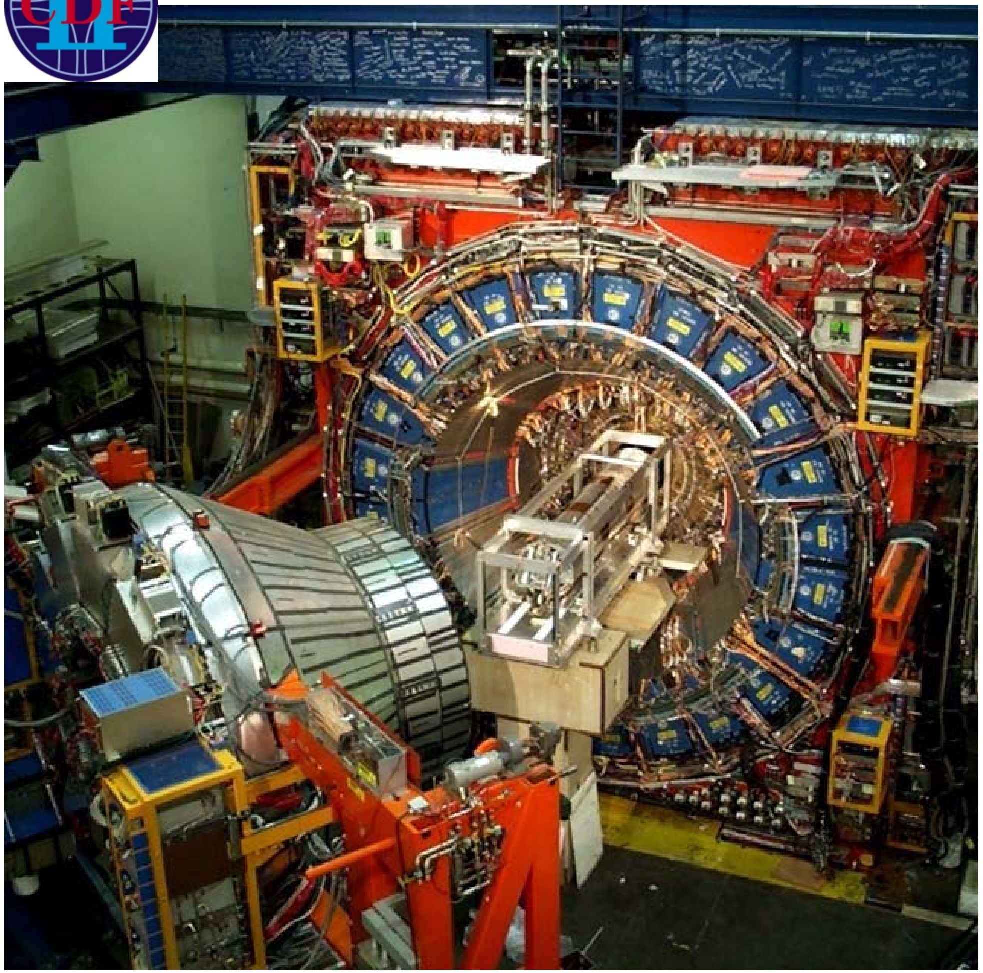

The UA1 detector, pioneering a first hermetic detector approach at the CERN $p\bar{p}$ Collider (January 1981)



UA2' (1987-90)
with new hermetic end-cap calorimeters for SUSY …



UA2 (1981-85)



The CDF and D0 Collaborations pioneered many of the modern analysis methods that are now used and further developed at LHC

Experimental LHC Challenges

Bunches, each containing 100 billion protons, cross 40 million times a second in the centre of each experiment

1 billion proton-proton interactions per second in ATLAS and CMS (few orders of magnitudes less in ALICE and LHCb)

Large Particle Fluxes

~ thousands of particles stream into the detector every 25 ns

⇨ **large number of channels (~ 100 M channels in ATLAS and CMS)**

$\Rightarrow$ **~ 1 MB/25ns i.e. 40 TB generated per second !**

High Radiation Levels

⇨ **radiation hard (tolerant) detectors and electronics**

Therefore:

LHC detectors must have fast response

Otherwise will integrate over many bunch crossings → large "pile-up"

→ integrate over 1-2 bunch crossings → pile-up of 25-50 min-bias

→ very challenging readout electronics

LHC detectors must be highly granular

Minimize probability that pile-up particles be in the same detector element as interesting object (e.g. γ from $H \rightarrow \gamma\gamma$ decays)

→ large number of electronic channels

→ high cost

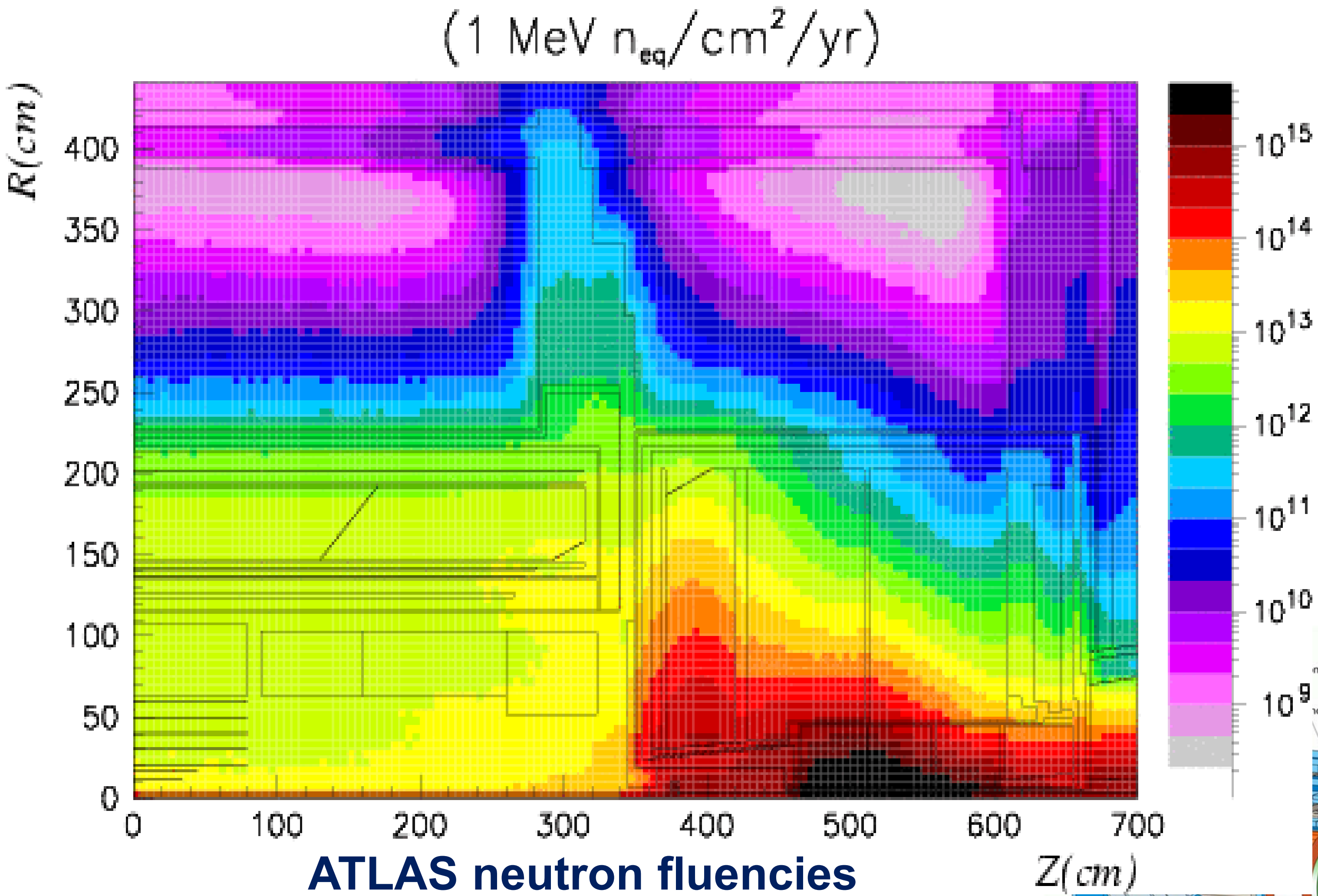
LHC detectors (and electronics) must be radiation resistant:

high flux of particles from pp collisions → high radiation environment e.g. in forward calorimeters:

- up to 10^{17} n/cm^2 in 10 years of LHC operation

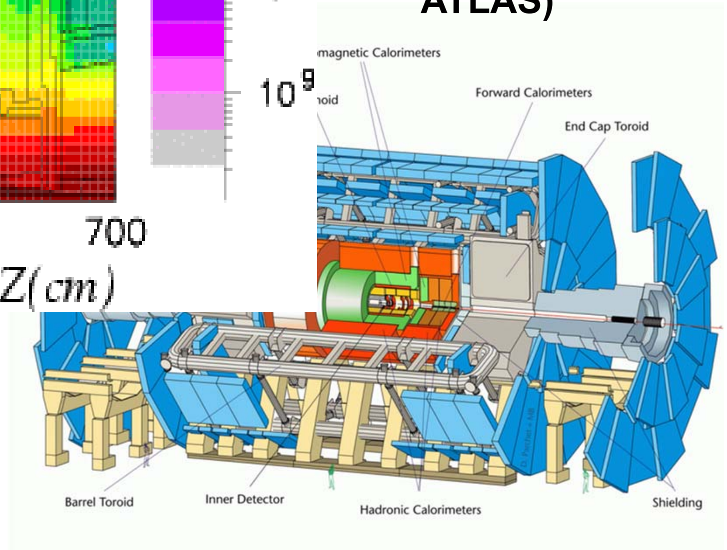
- up to 10^7 Gy (1 Gy = unit of absorbed energy = 1 Joule/Kg)

Example of expected n radiation exposure



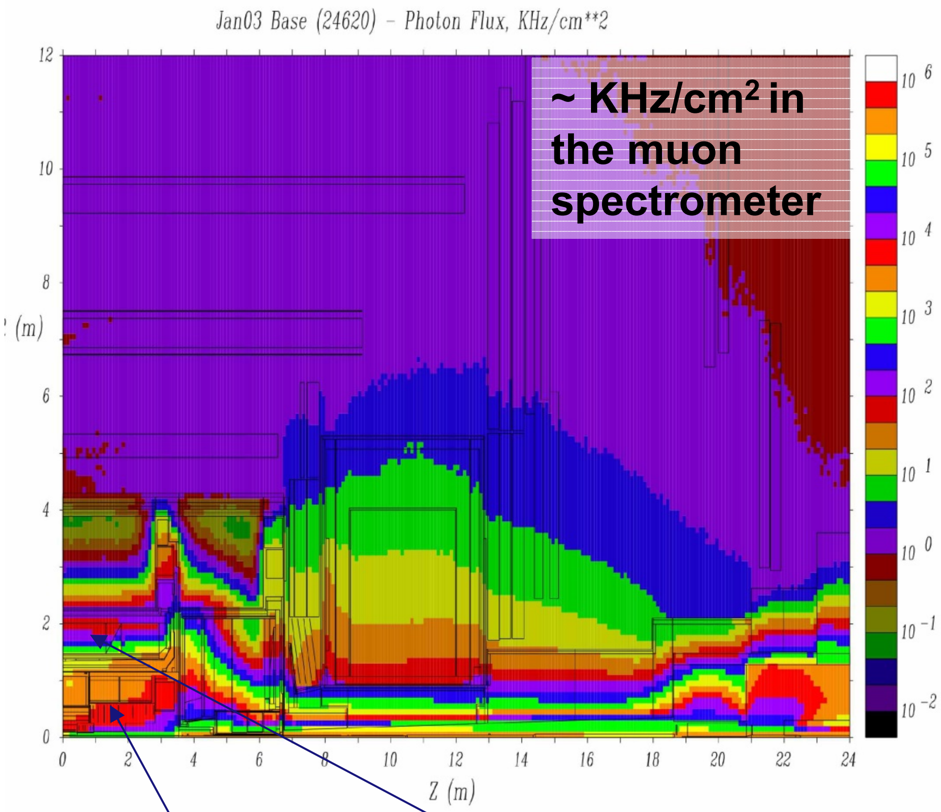
ATLAS neutron fluencies

(Shown in one quarter of the inner part of ATLAS)



High background radiation

Photon flux in kHz/cm²



~1 MHz/cm² in the ID

~50 kHz/cm² in the EM Barrel Calorimeter

Radiation mostly coming from the interaction point and proportional to the luminosity …. Mostly dominated by shower production in the beam pipe material

Radiation effects:

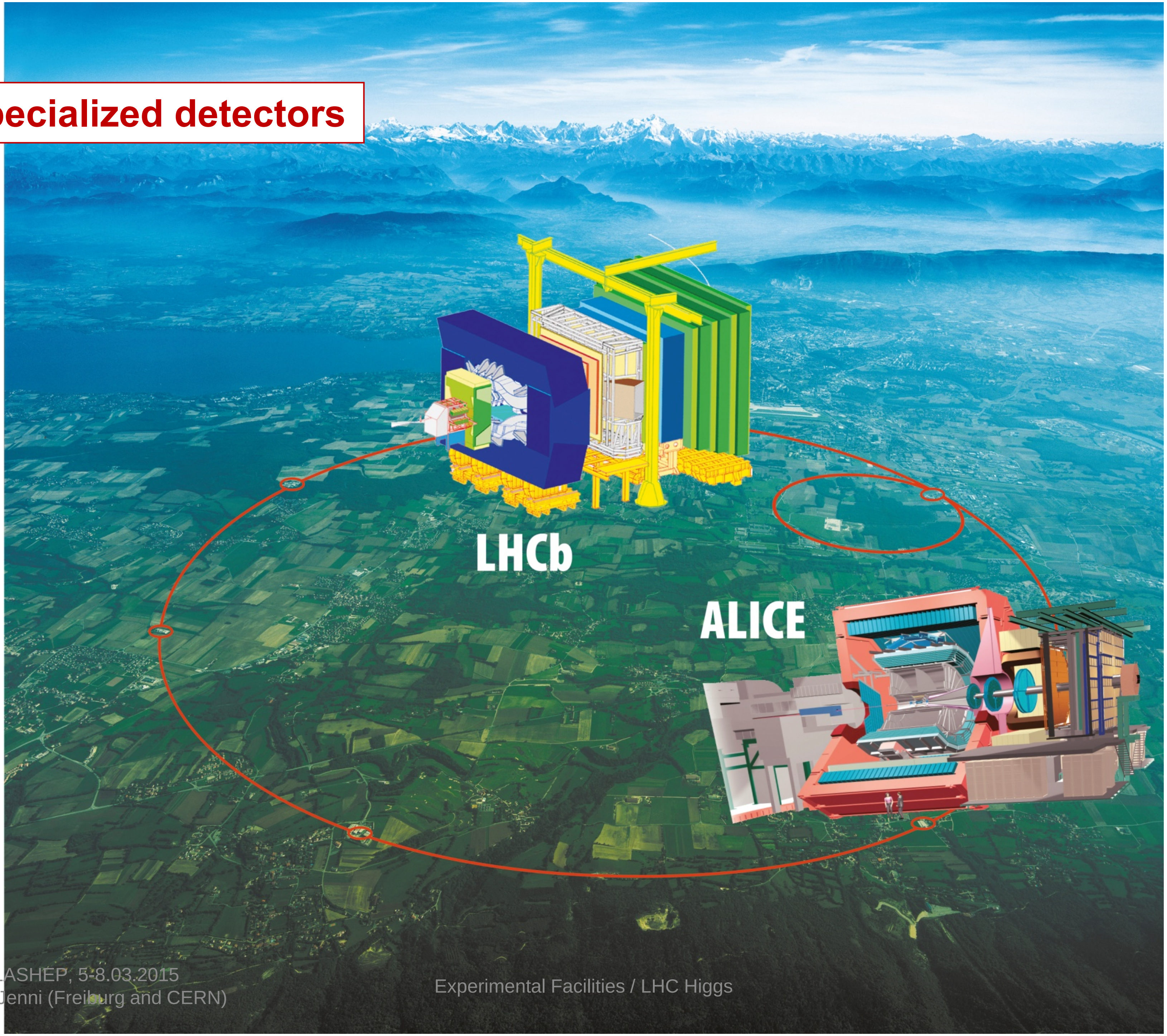
- ✓ ***life time of the electronics components on the detector***
- ✓ ***Increases noise occupancy in the various active cells***
- ✓ ***Changes the mechanical properties of certain materials***
- ✓ ***Initiate an aggressive chemical behavior of various material, gases …***

The SM is not a complete theory: LHC physics challenges

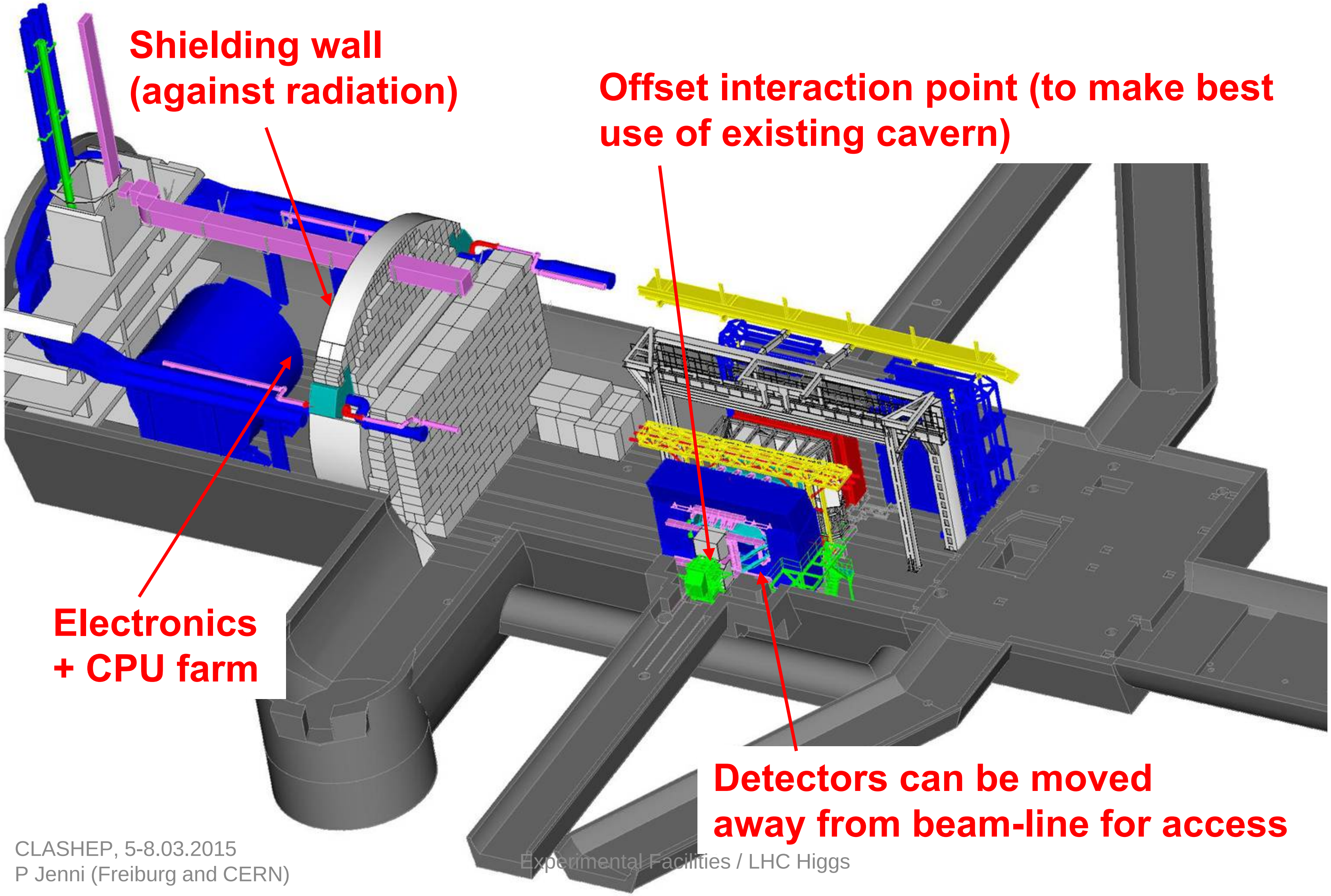
Some of the outstanding questions in fundamental physics were/are

(~✔)	**What is the origin of the elementary particle masses ?**	**ATLAS, CMS**
	What is the nature of the Universe dark matter ?	**ATLAS, CMS**
	Why is only matter observed in the Universe as primary constituents and not anti-matter ?	**LHCb**
	What are the features of the primordial plasma present ~10 μs after the Big Bang ?	**ALICE**
	What happened in the first moments of the Universe ~10^{-11} s after the Big Bang ?	**ATLAS, CMS**
	Are there other forces in addition to the known four ? **Are there additional (microscopic) space dimensions ?** **….**	**ATLAS, CMS**

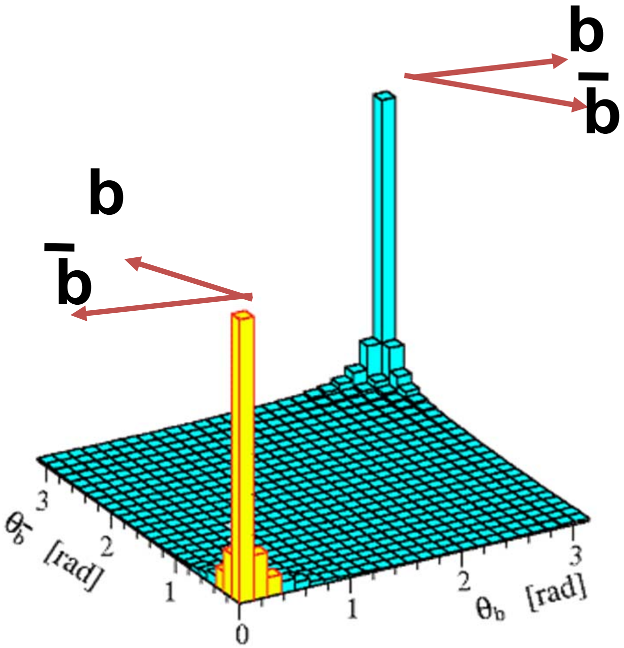
Specialized detectors



LHCb in its cavern (~100 m deep)



The LHCb Experiment



- **Advantages of beauty physics at hadron colliders:**
  - ***High value of bb cross section at LHC:***

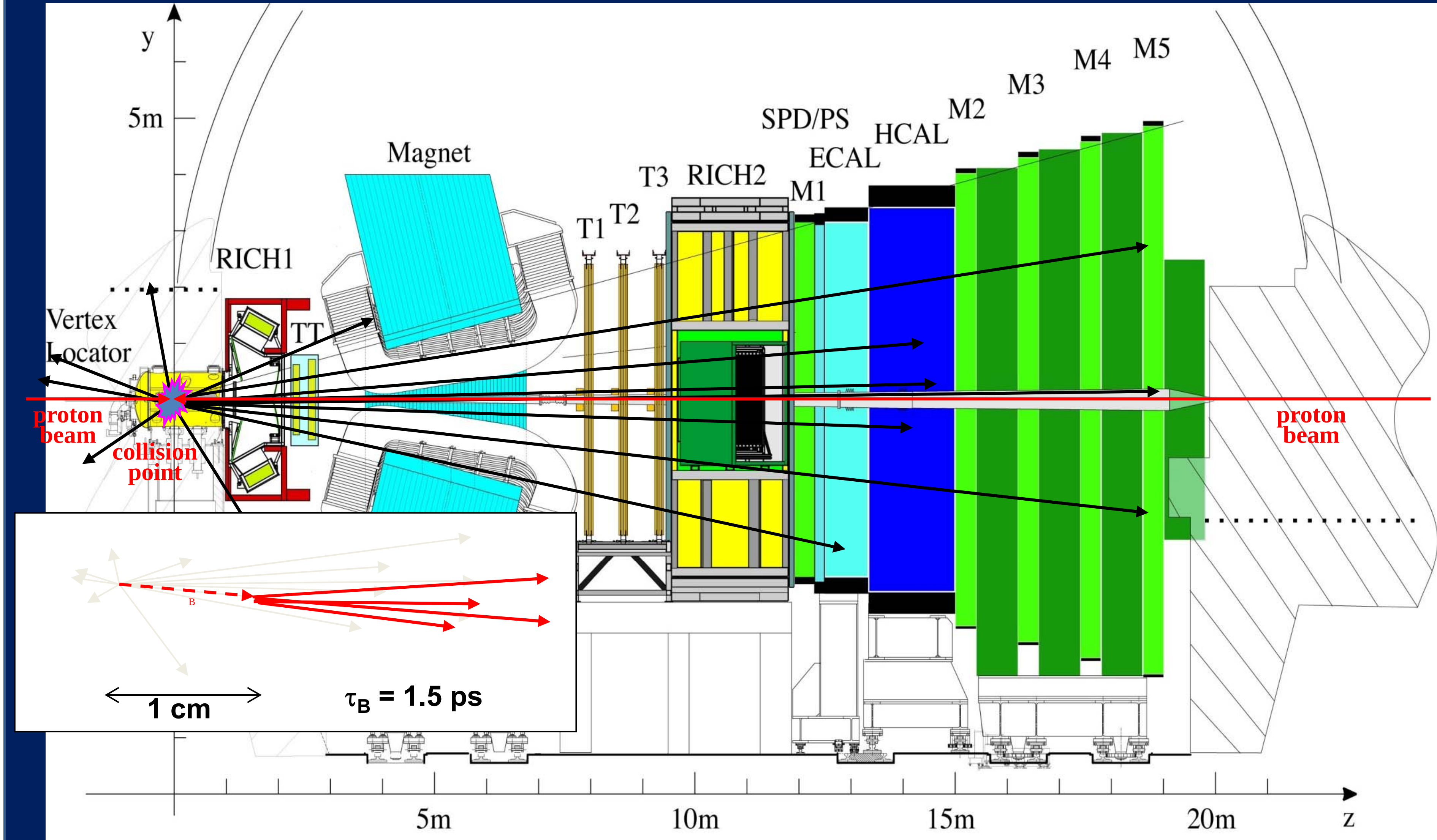
    σ_{bb} ~ 300 - 500 μb at 10 - 14 TeV

    (e+e- cross section at Y(4s) is 1 nb)
  - ***Access to all quasi-stable b-flavoured hadrons***

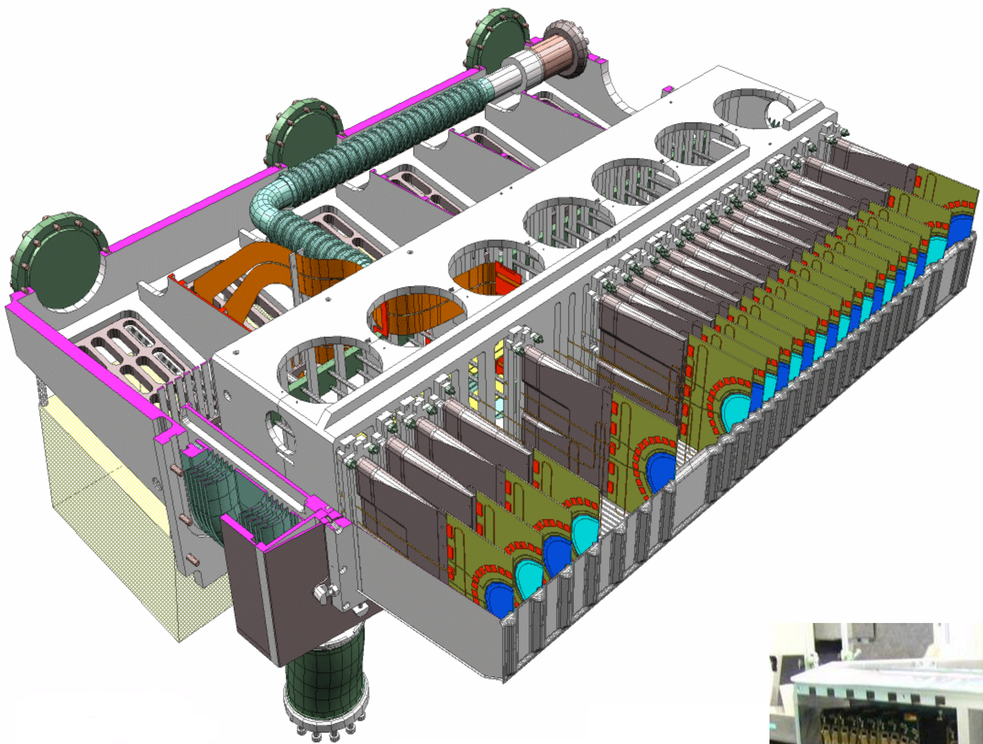
- **The challenge**
  - ***Multiplicity of tracks (~30 tracks per rapidity unit)***
  - ***Rate of background events: σ_{inel}~ 80 mb***

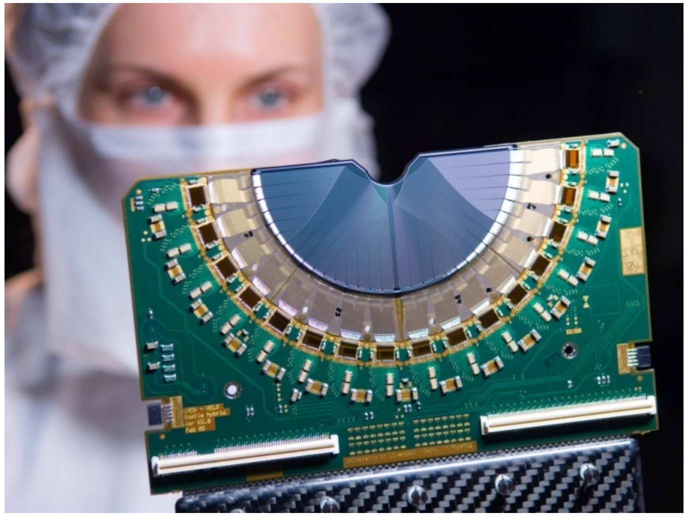
- **LHCb running conditions:**
  - ***Luminosity limited to ~2 × 10^{32} cm^{-2} s^{-1} by not focusing the beam as much as for ATLAS and CMS***
    - ***Maximize the probability of single interaction per bunch crossing LHCb design ~ 0.7 pp interaction/bunch, operated with double***
    - ***LHCb reached nominal luminosity soon after start-up***
  - ***2fb^{-1} per nominal year (10^7s), ~ 10^{12} bb pairs produced per year***

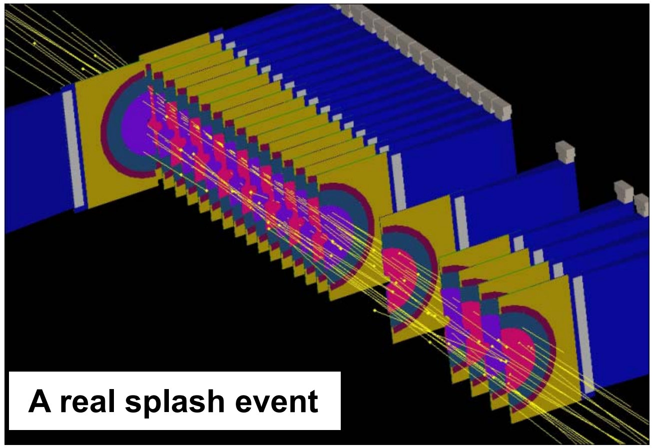
The LHCb experiment

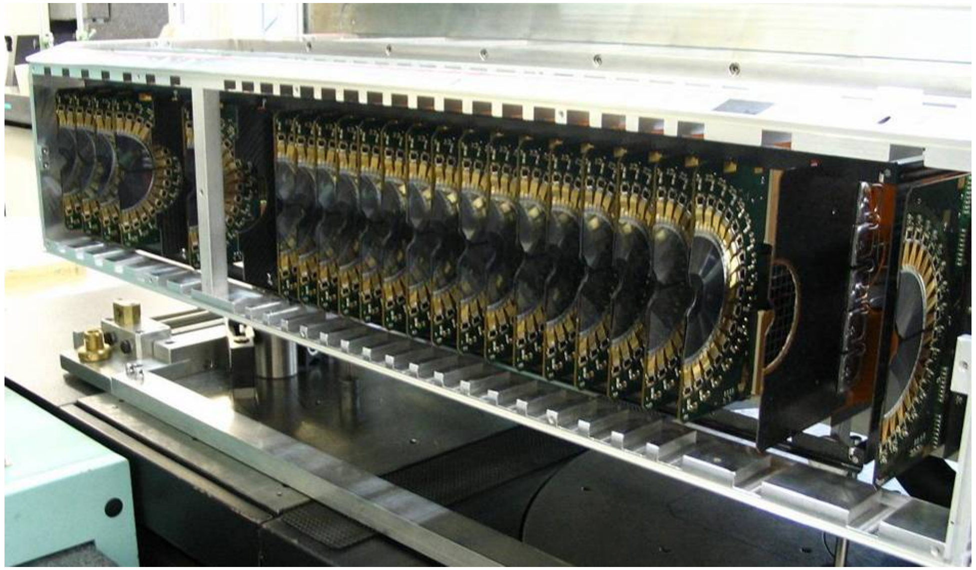


LHCb Vertex Locator (VELO)

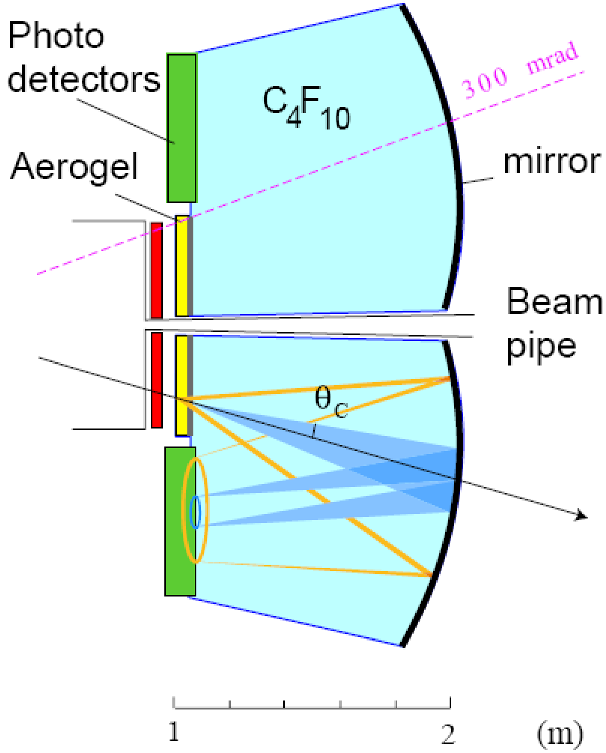


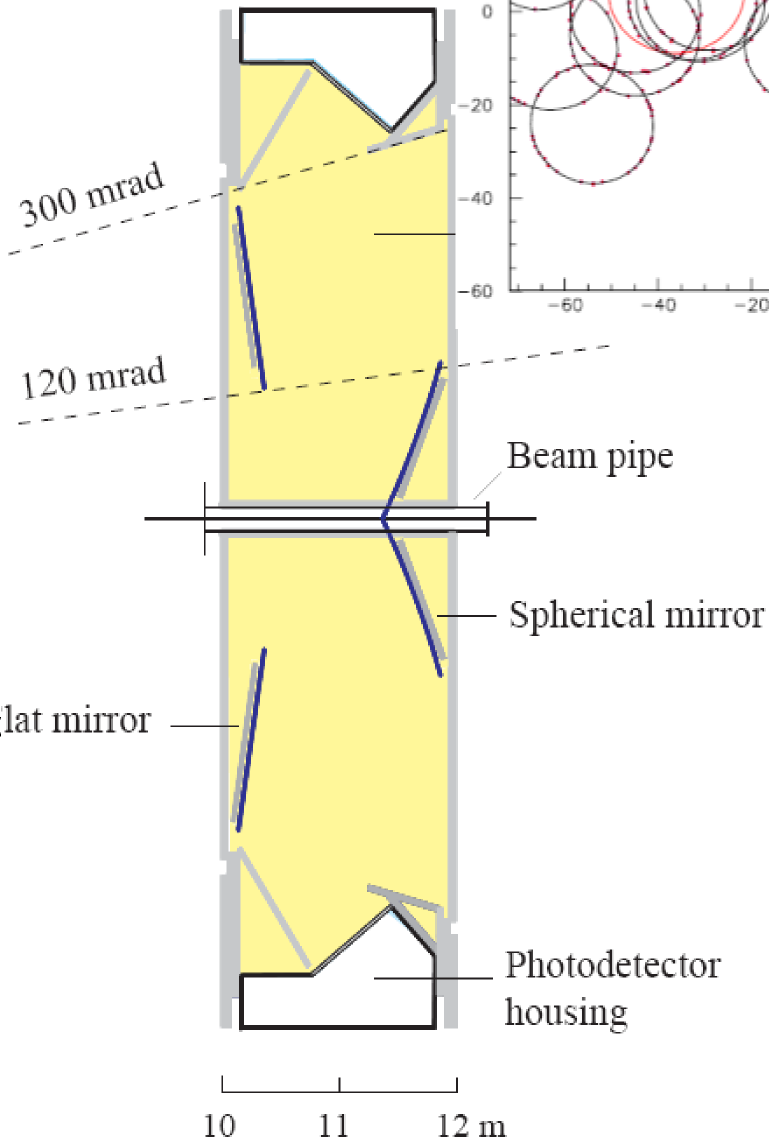


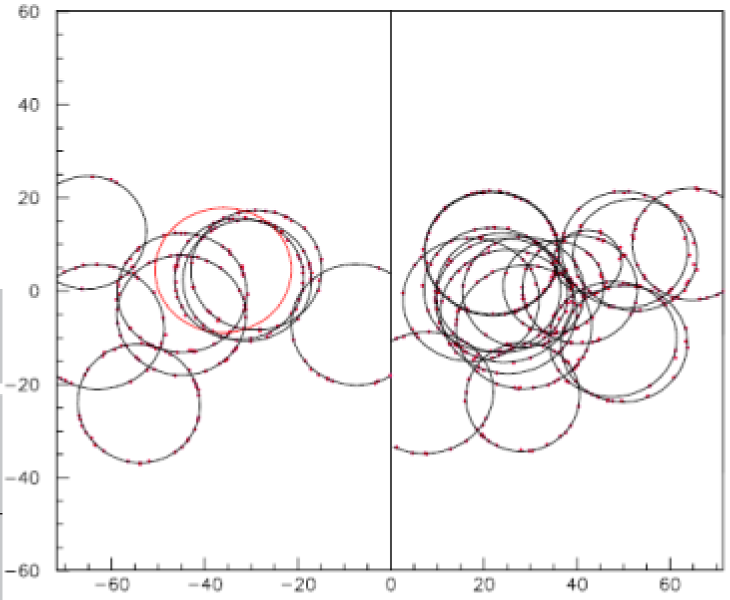


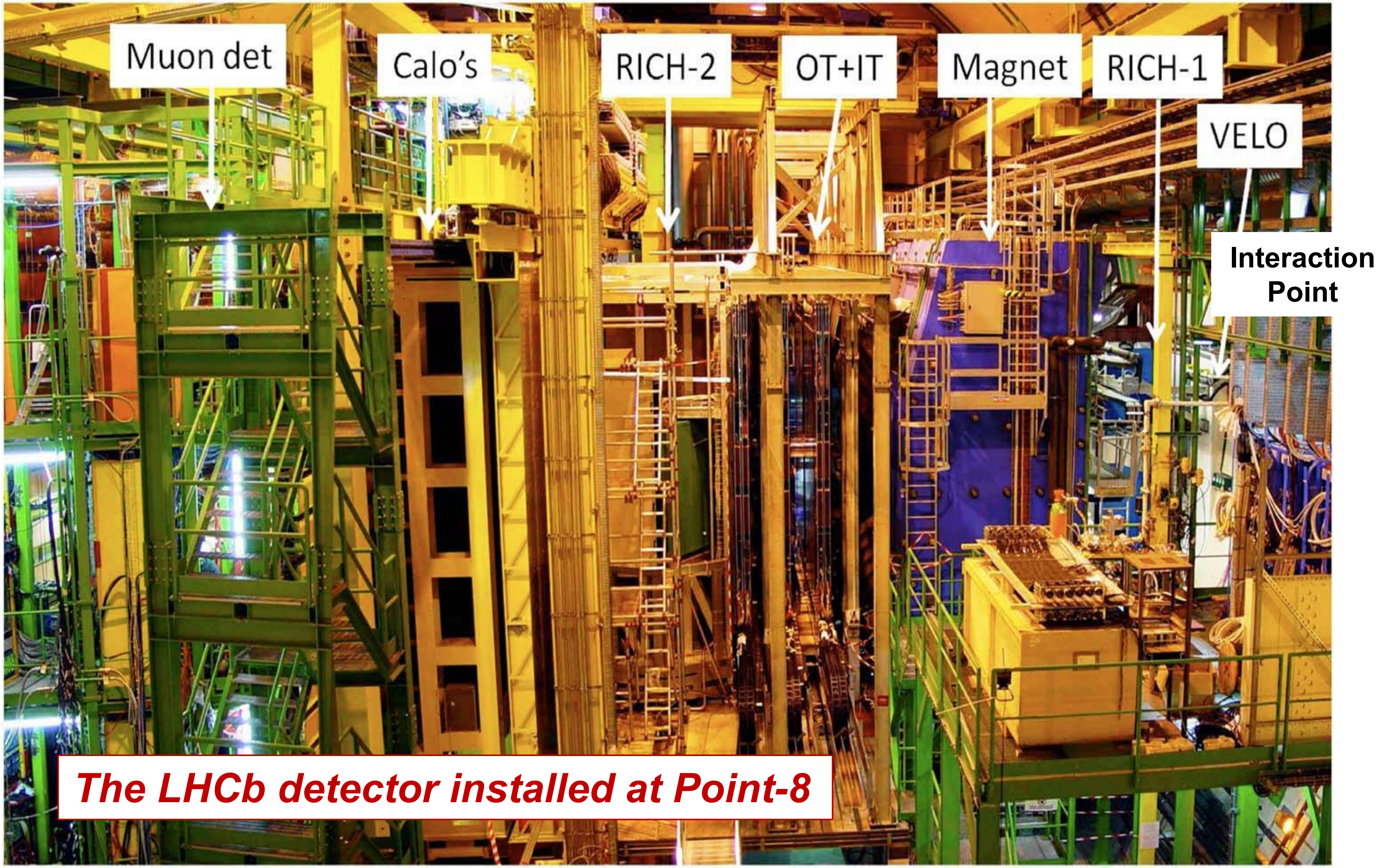


LHCb Ring Imaging Cherenkov Counters (RICH) for particle identification

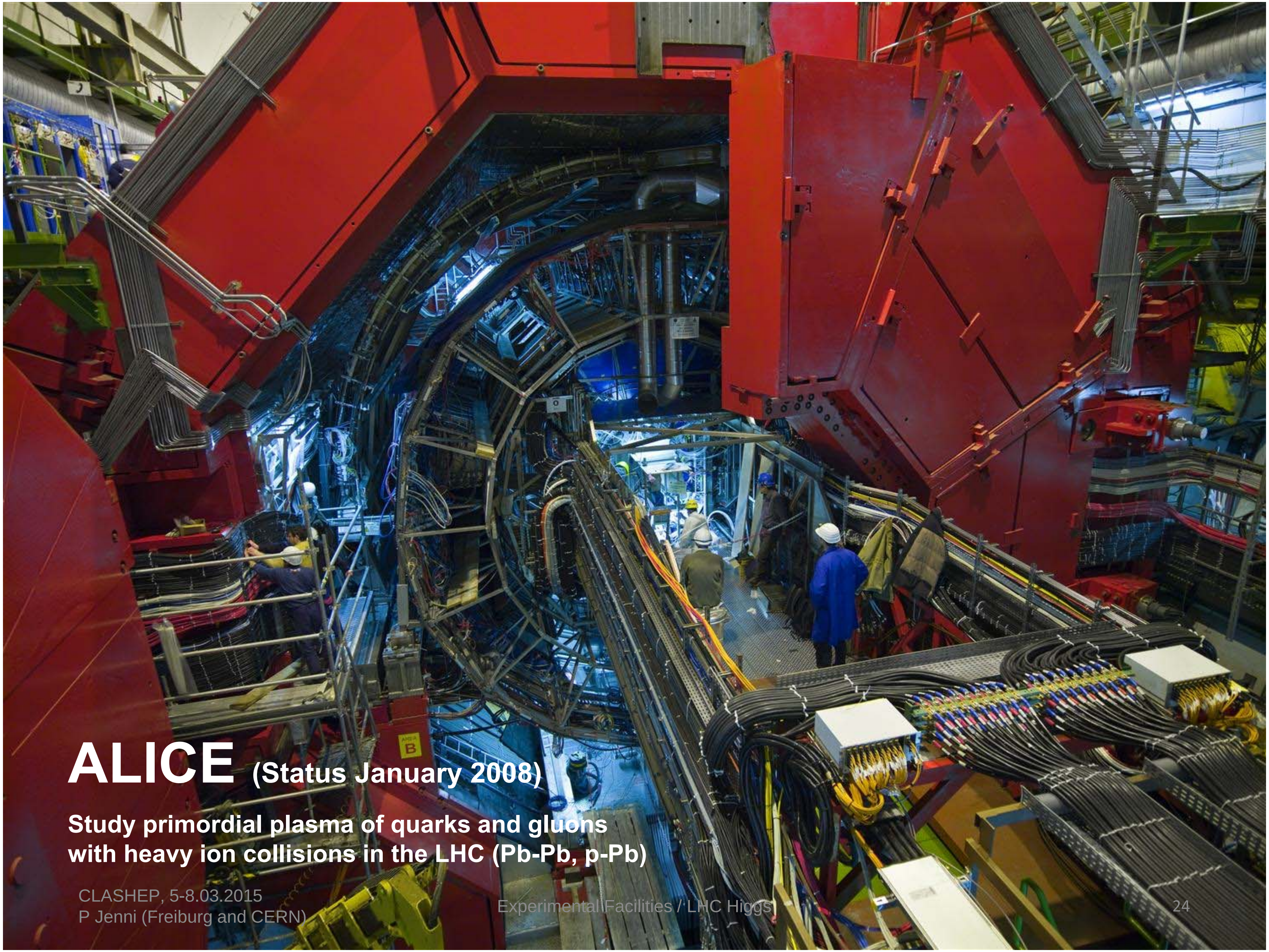








The LHCb detector installed at Point-8

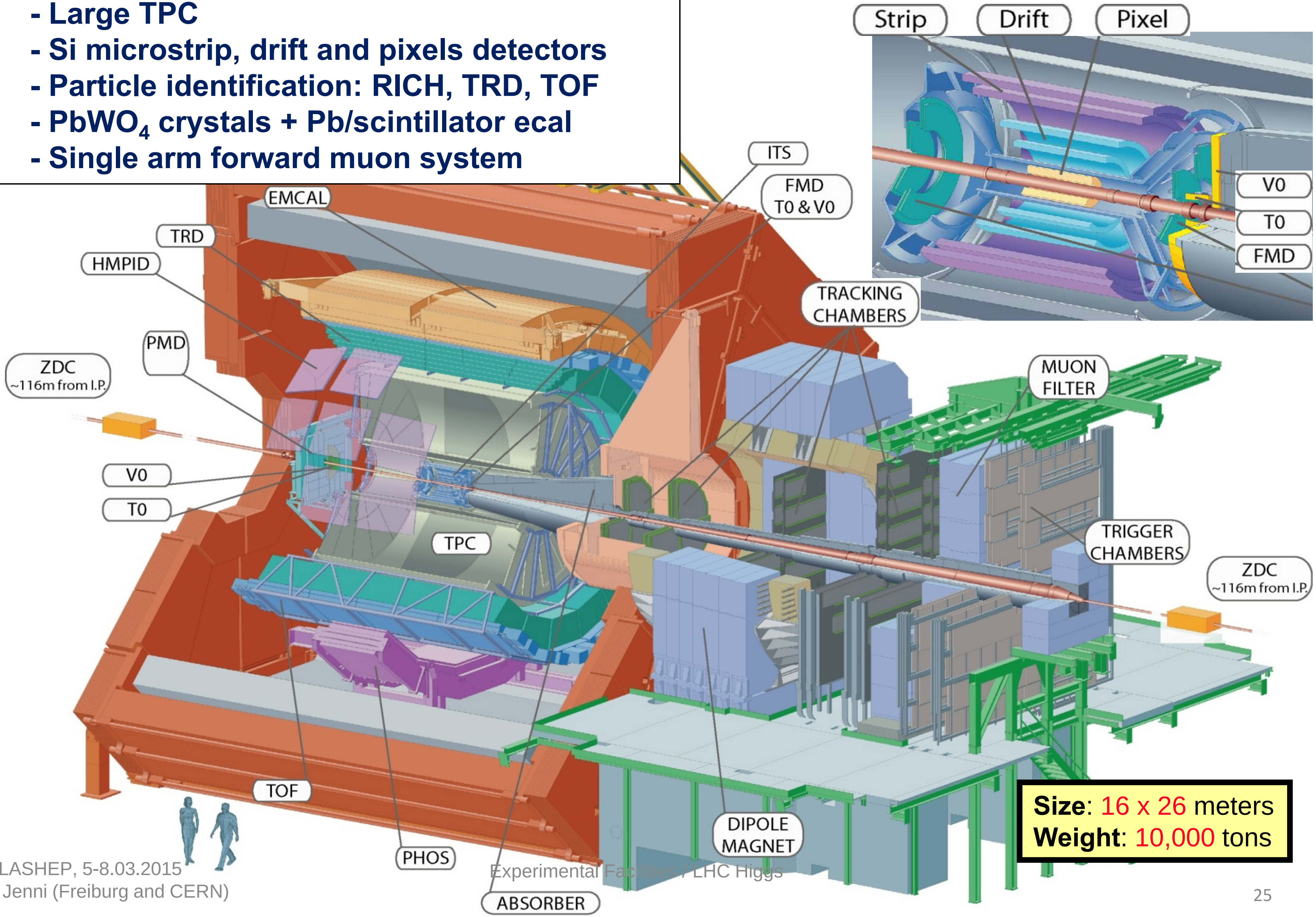


ALICE (Status January 2008)

Study primordial plasma of quarks and gluons
with heavy ion collisions in the LHC (Pb-Pb, p-Pb)

ALICE: study of quark-gluon plasma

- L3 solenoid
- Large TPC
- Si microstrip, drift and pixels detectors
- Particle identification: RICH, TRD, TOF
- $PbWO_4$ crystals + Pb/scintillator ecal
- Single arm forward muon system



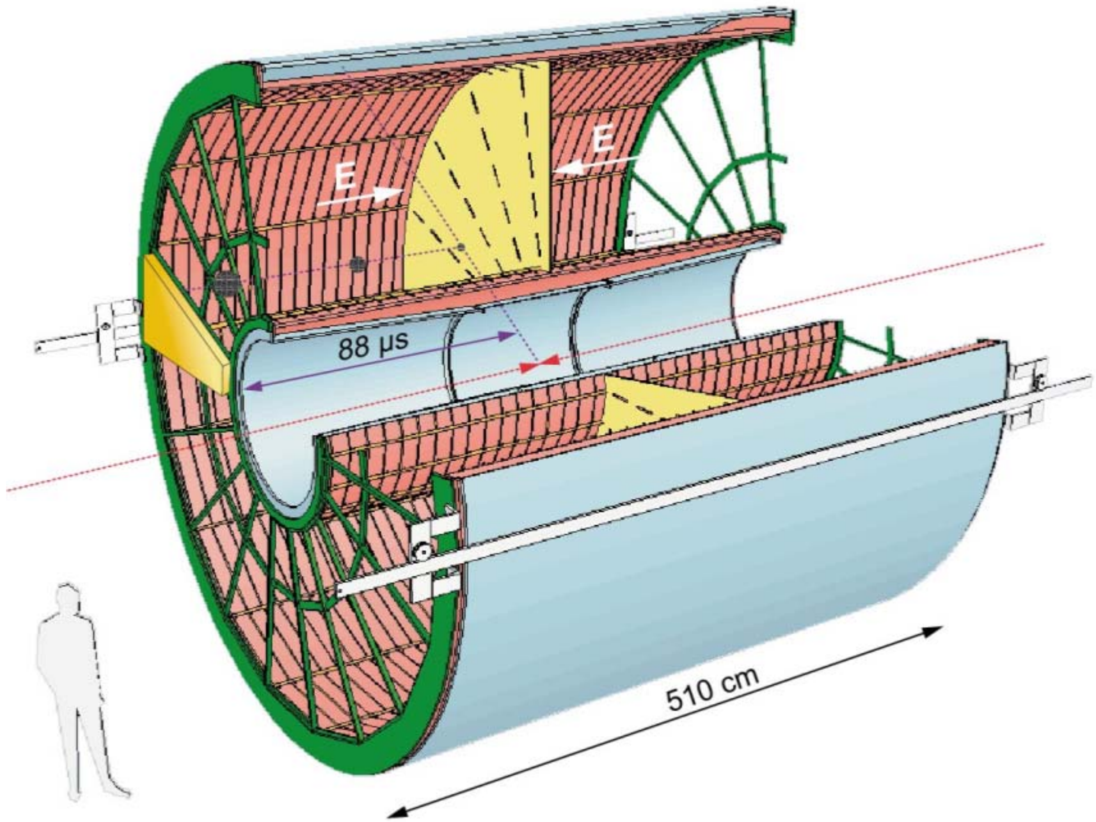
Size: 16 x 26 meters
Weight: 10,000 tons

ALICE Time Projection Chamber (TPC)

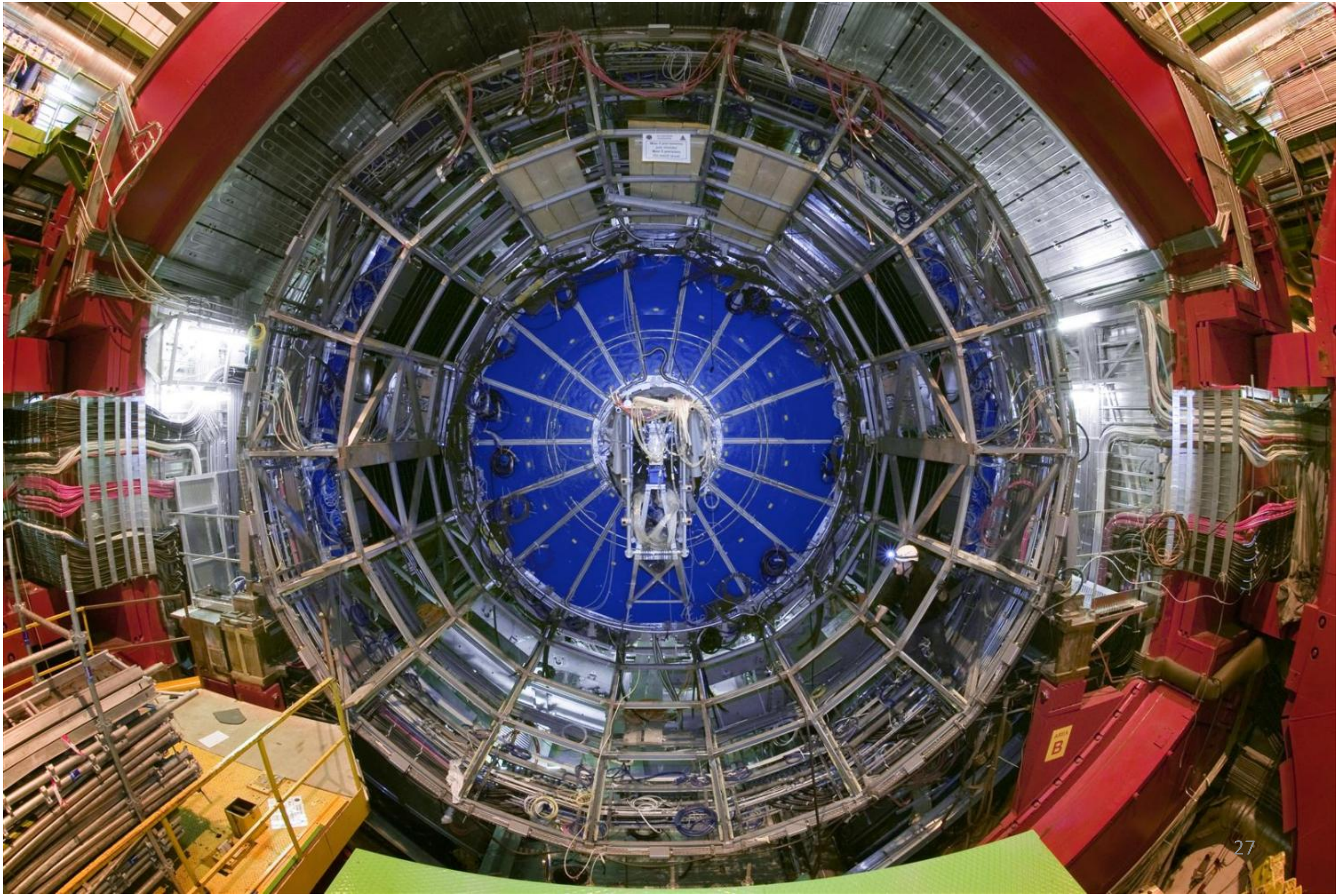
- **Largest TPC:**
  - **Length 5m**
  - **Diameter 5m**
  - **Volume 88m^3**
  - **Detector area 32m^2**
  - **Channels ~570 000**

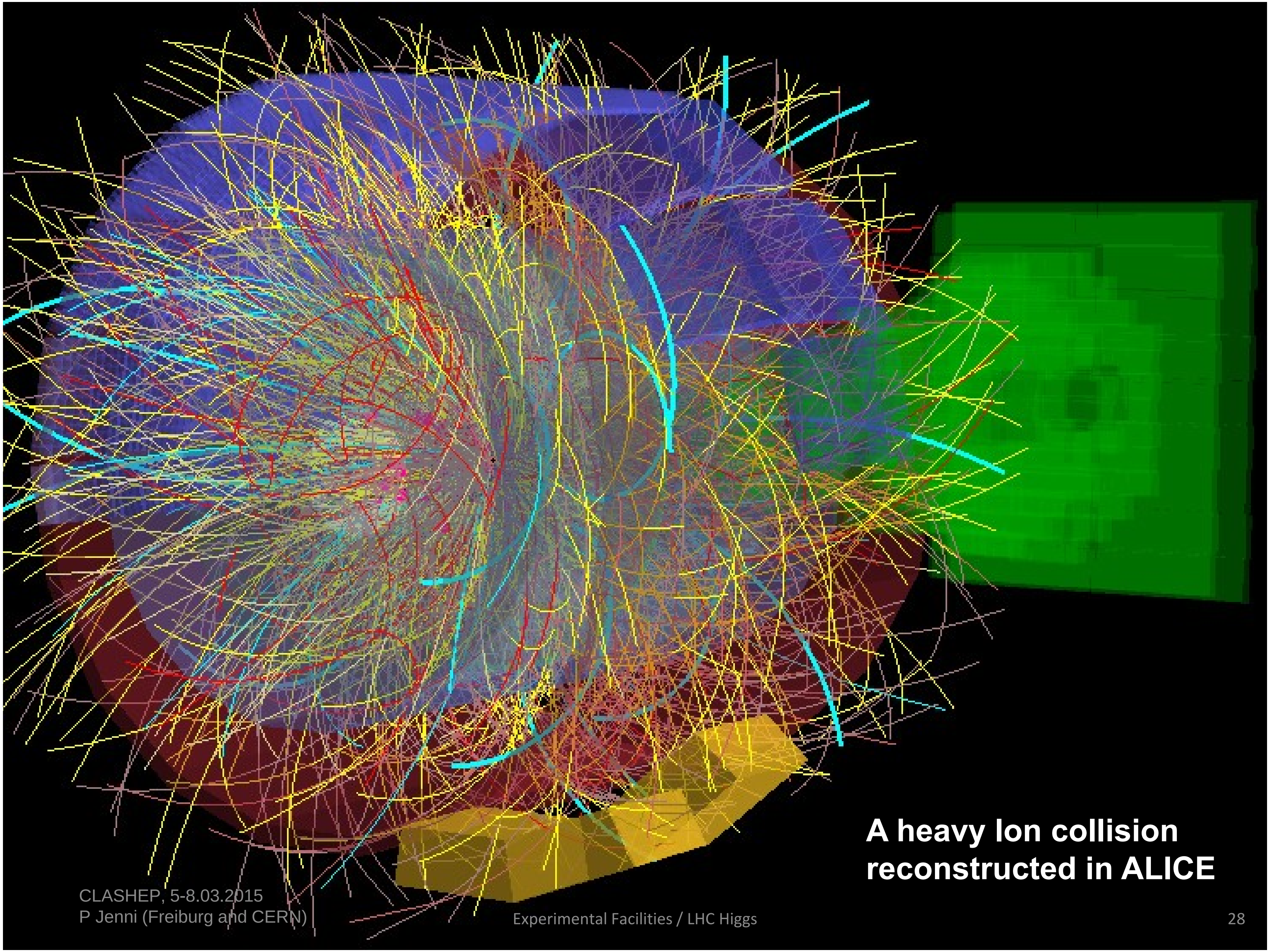
- **High Voltage:**
  - **Cathode -100kV**

- **Material X_0**
  - **Cylinder from composite materials from airplane industry (X_0= ~3%)**

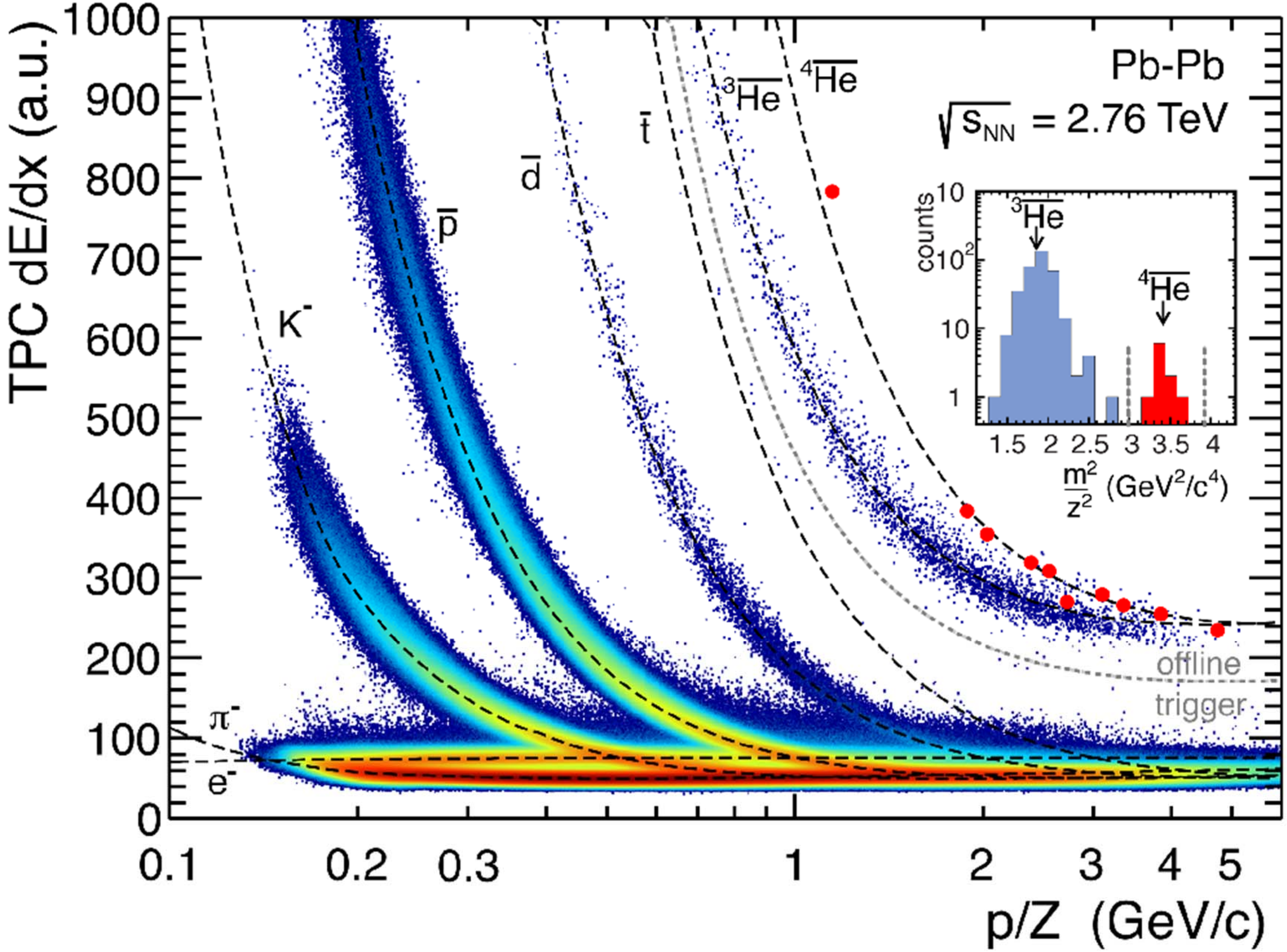


TPC installed in the ALICE Experiment

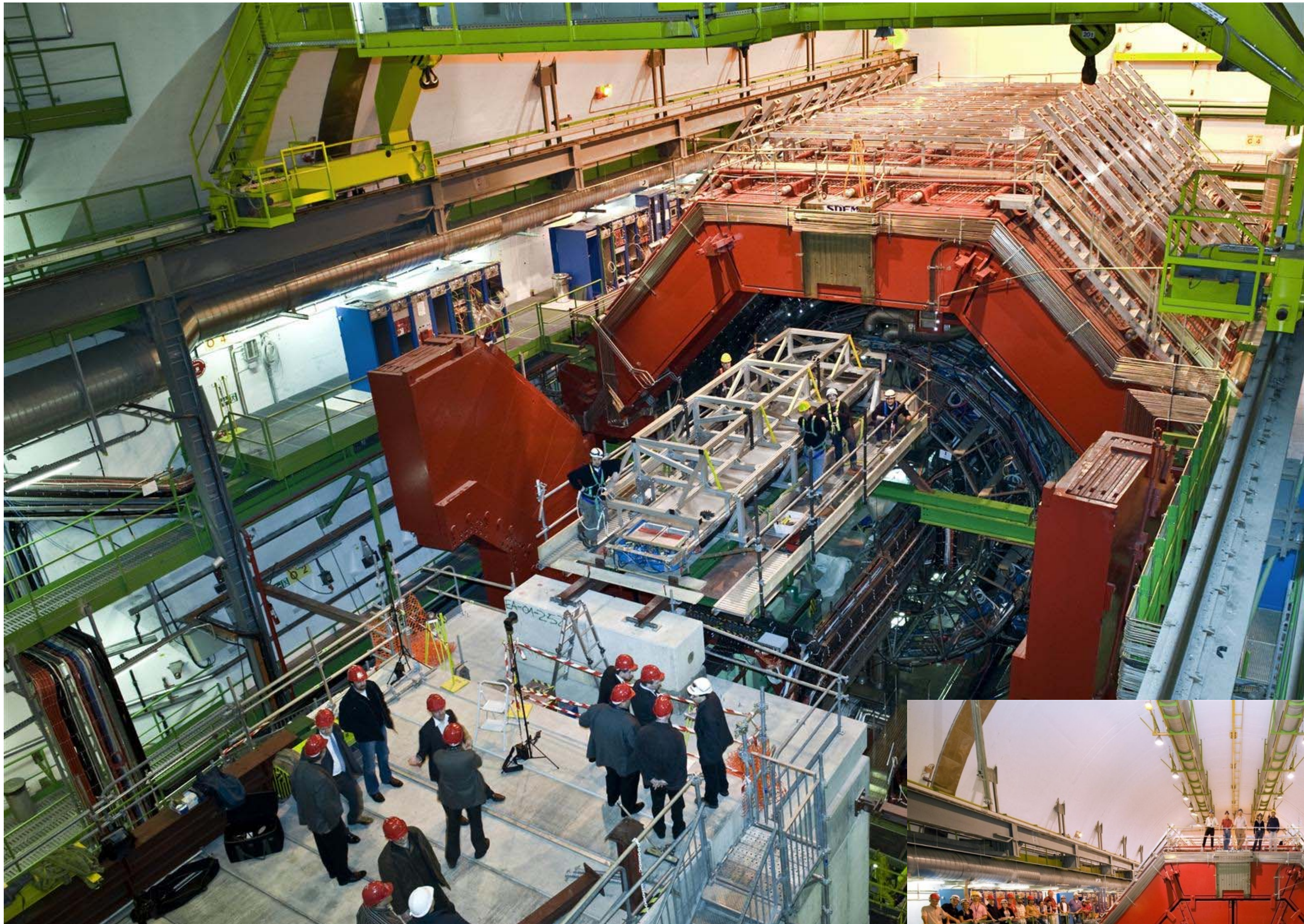




A heavy Ion collision reconstructed in ALICE



Simultaneous measurement of dE/dx and momentum provides particle identification in ALICE

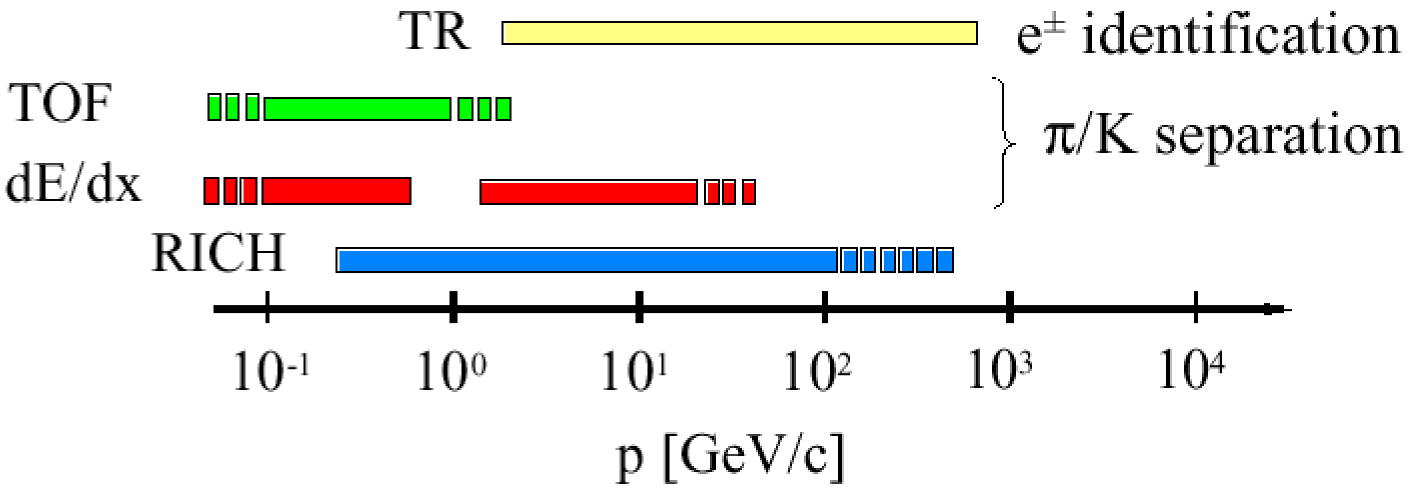


Installation of a ALICE TOF module May 2008

Formal end of ALICE installation July 2008

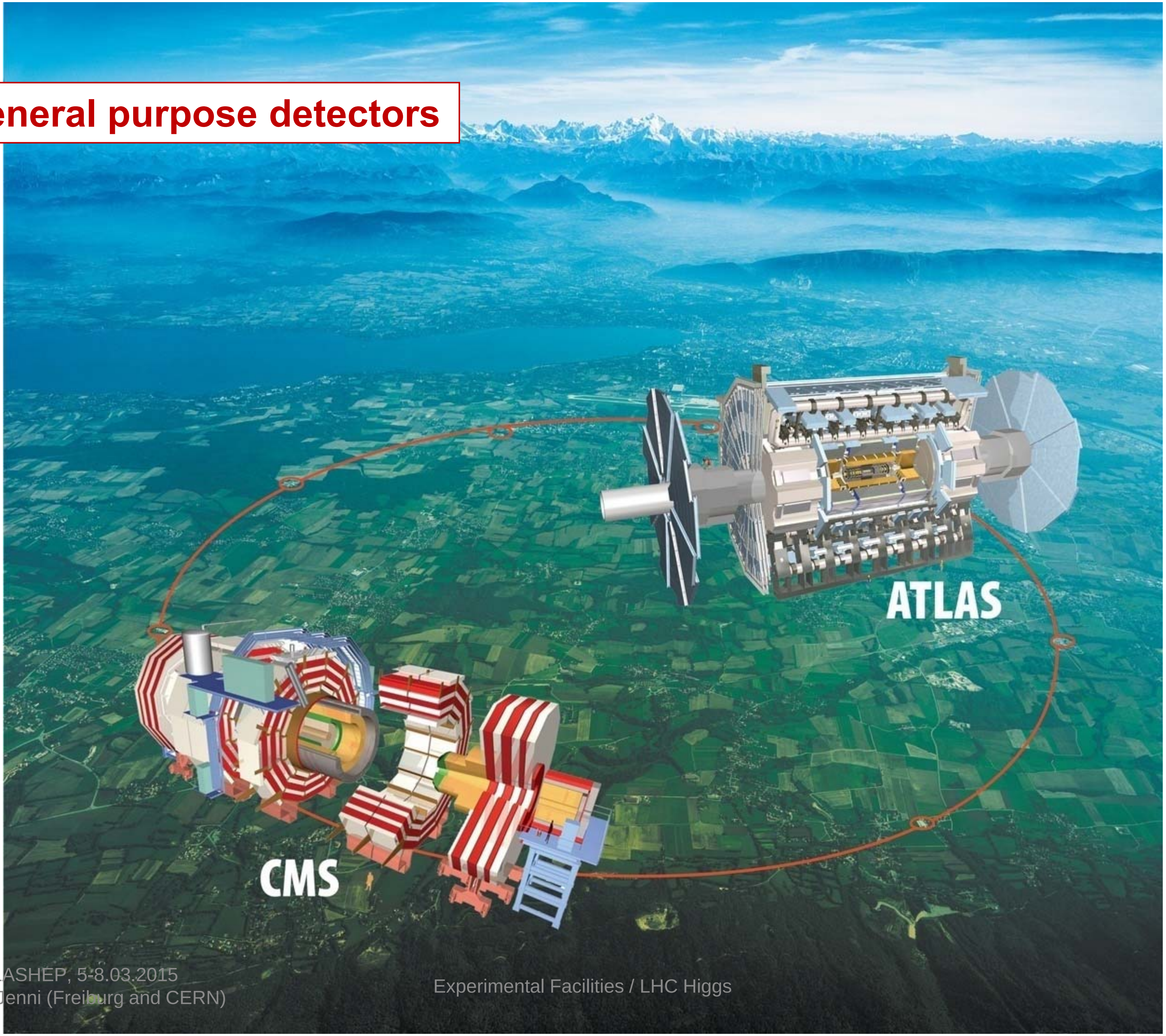
Particle Identification

A very coarse plot ….



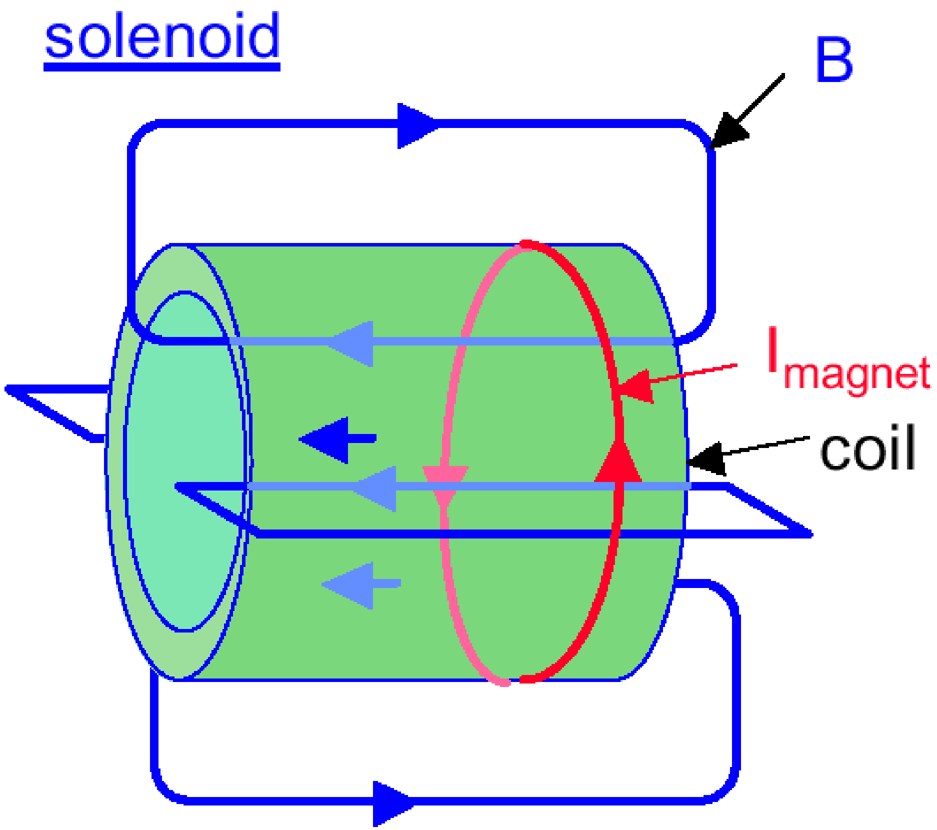
In addition we should keep in mind that EM/HAD energy deposition provide particle ID, matching of p (momentum) and EM energy the same (electron ID), isolation cuts help to find leptons, vertexing help us to tag b,c or τ, missing transverse energy indicate a neutrino, etc so a number of methods are finally used in experiments.

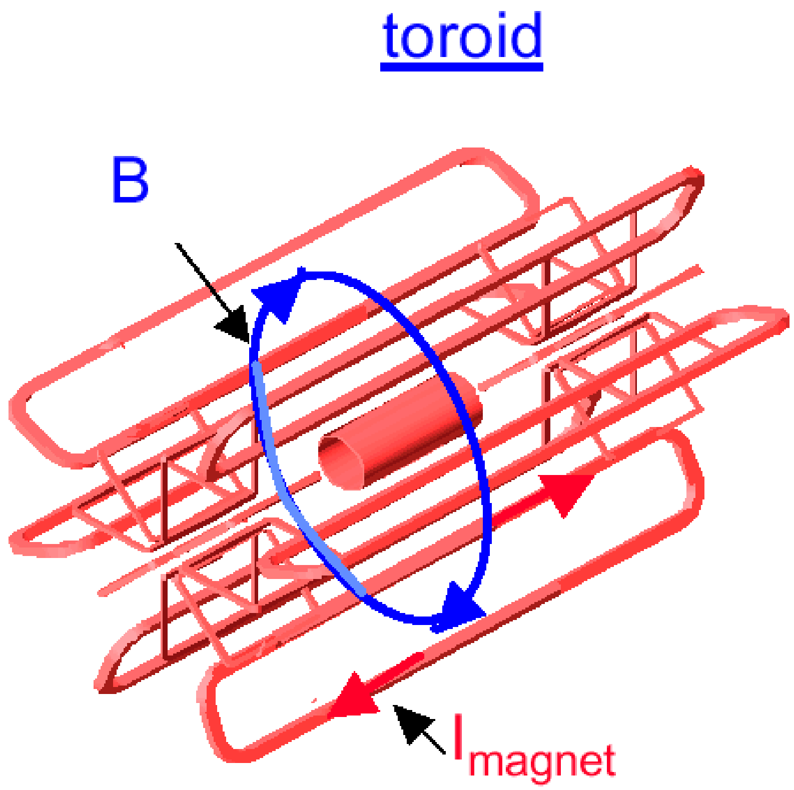
General purpose detectors



Magnetic fields

Magnetic field configurations:



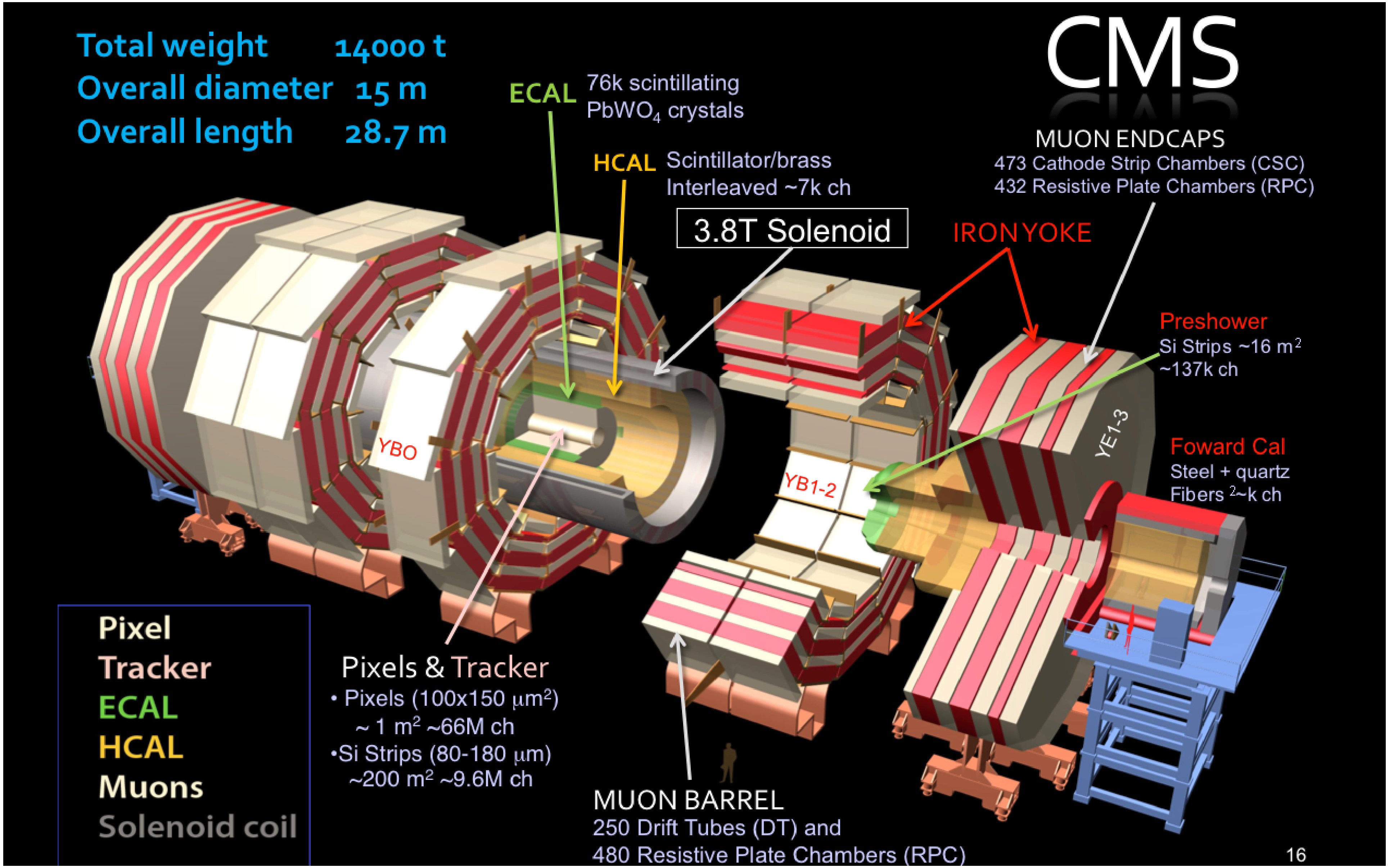


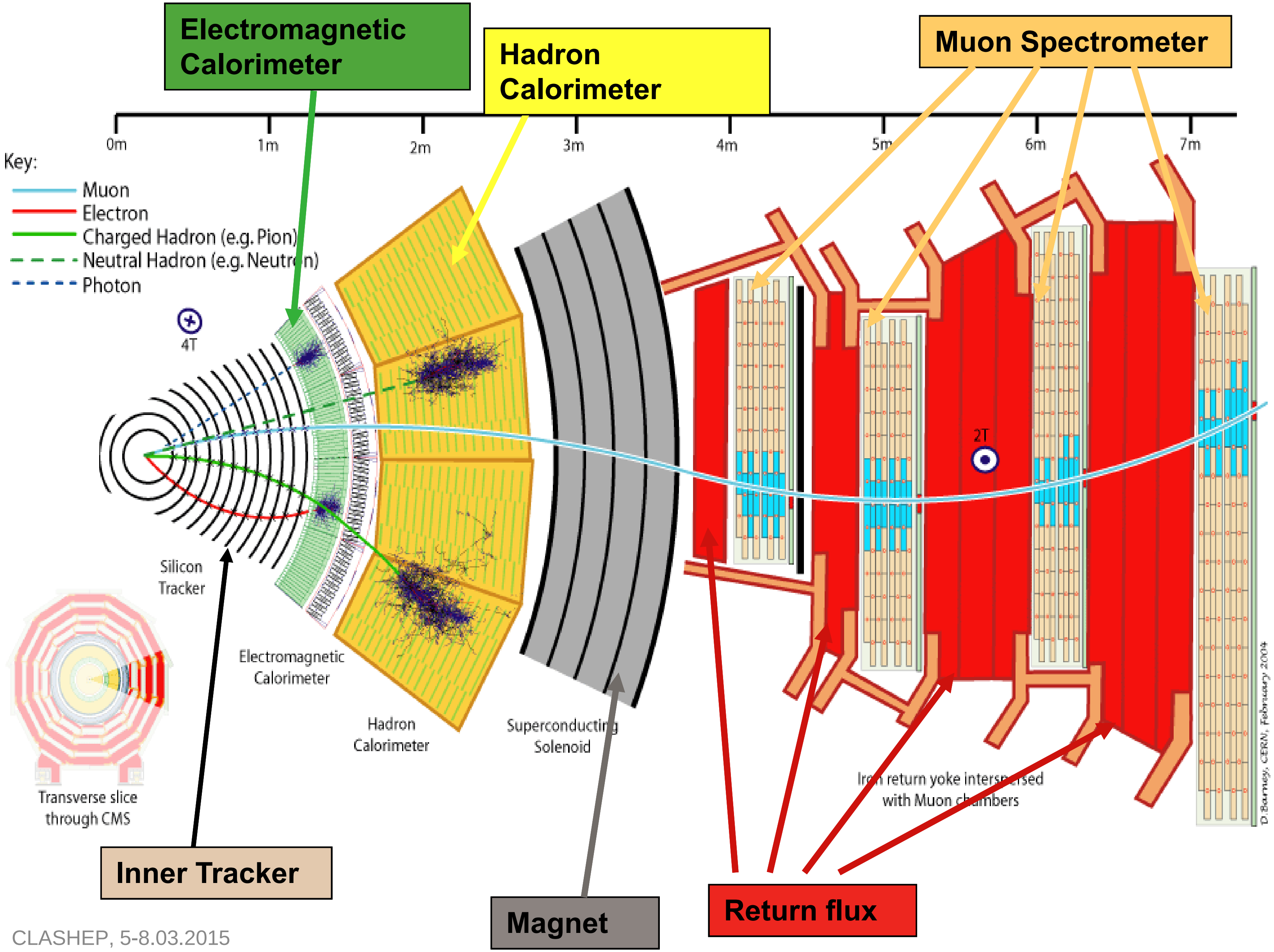
From C.Joram

TABLE 3 Main parameters of the CMS and ATLAS magnet systems

	CMS	ATLAS		
Parameter	**Solenoid**	**Solenoid**	**Barrel toroid**	**End-cap toroids**
Inner diameter	5.9 m	2.4 m	9.4 m	1.7 m
Outer diameter	6.5 m	2.6 m	20.1 m	10.7 m
Axial length	12.9 m	5.3 m	25.3 m	5.0 m
Number of coils	1	1	8	8
Number of turns per coil	2168	1173	120	116
Conductor size (mm^2)	64×22	30×4.25	57×12	41×12
Bending power	$4\ T \cdot m$	$2\ T \cdot m$	$3\ T \cdot m$	$6\ T \cdot m$
Current	19.5 kA	7.7 kA	20.5 kA	20.0 kA
Stored energy	2700 MJ	38 MJ	1080 MJ	206 MJ

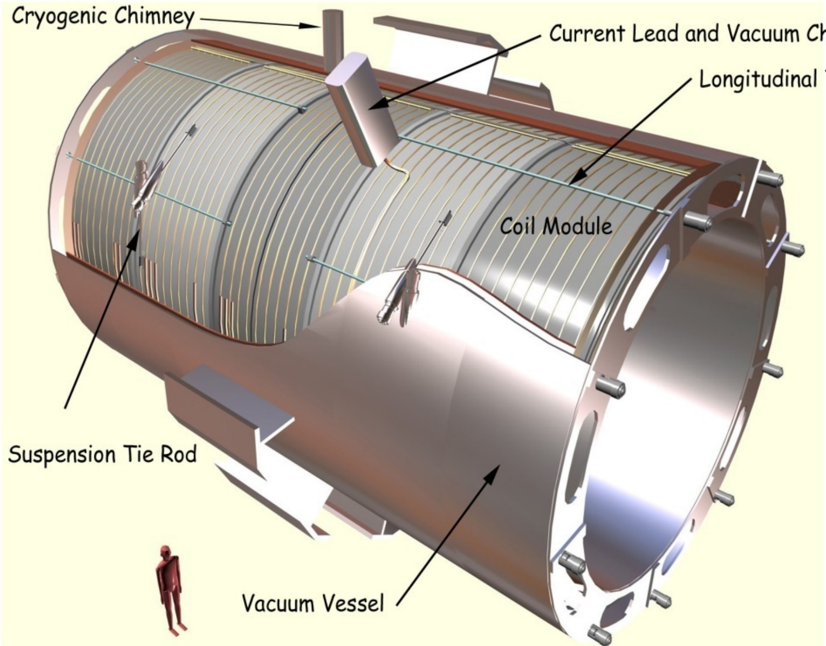
Exploded View of CMS




Electromagnetic Calorimeter
Hadron Calorimeter
Muon Spectrometer
0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004
Inner Tracker
Magnet
Return flux

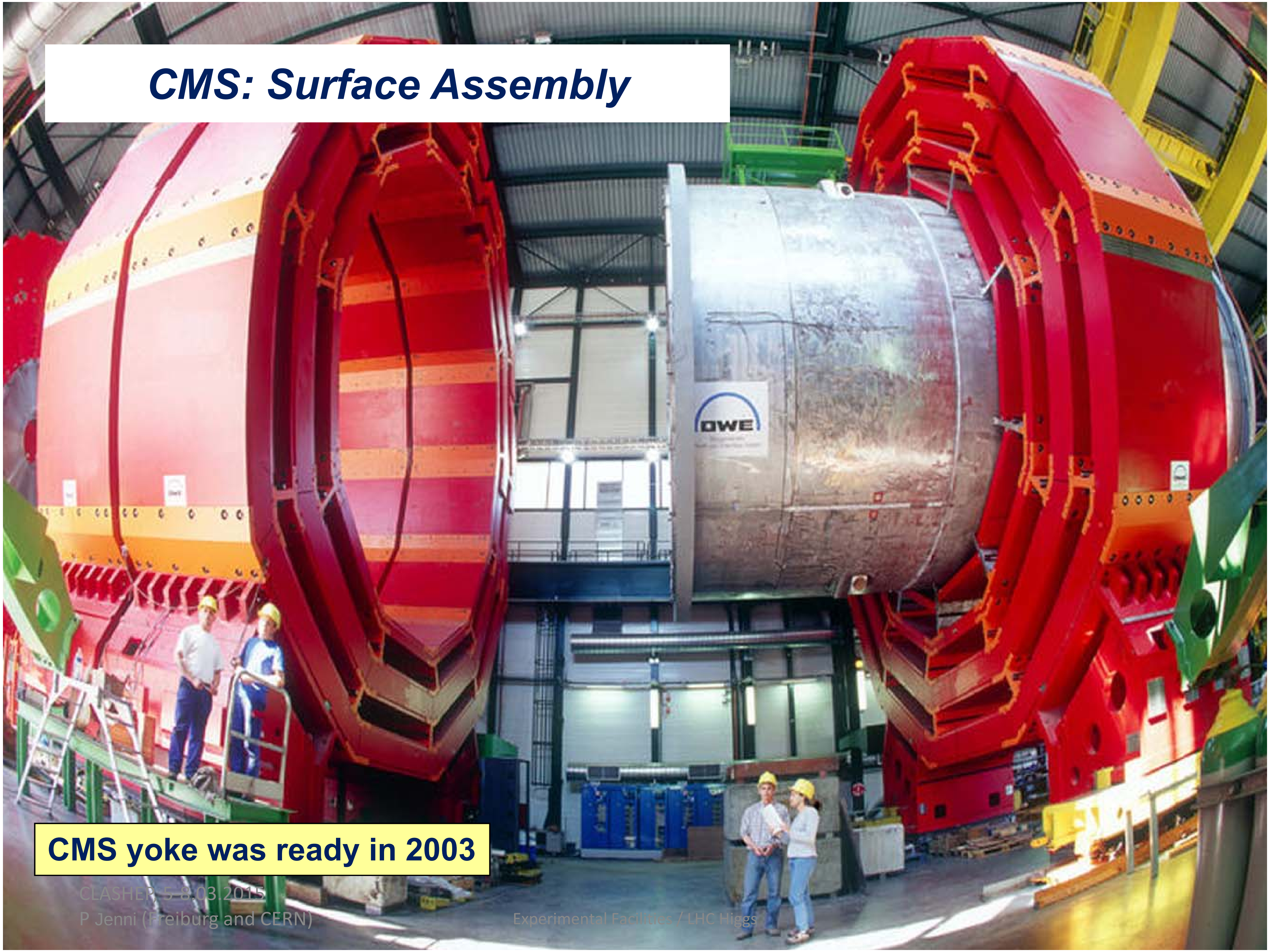
CMS Solenoid

The CMS Superconducting Solenoid



	CMS	ALEPH	factor
Inner Bore	6.3 m	4.96 m	1.25
Length	12.5 m	6.35 m	2
Central field	4 T	1.5 T	2.6
Nominal current	19 kA	5 kA	3.8
Stored Energy	2.65 GJ	137 MJ	20
Cold mass	220 t	25 t	9

CMS: Surface Assembly

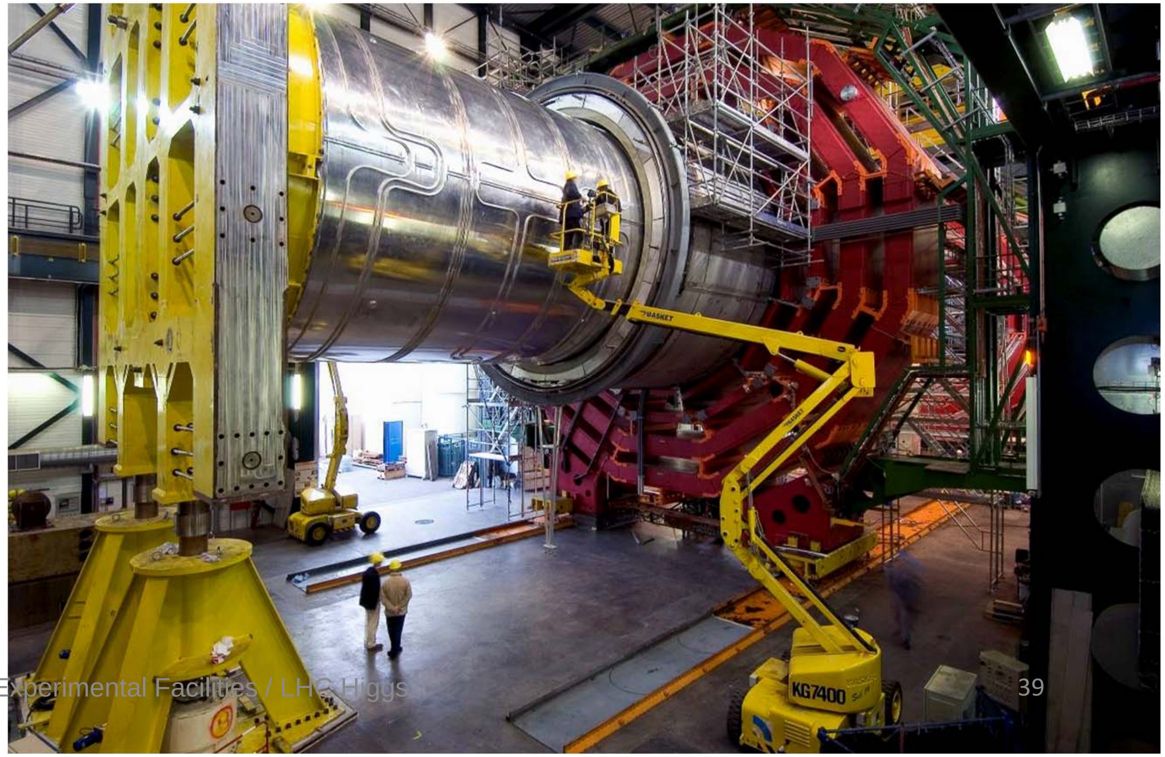


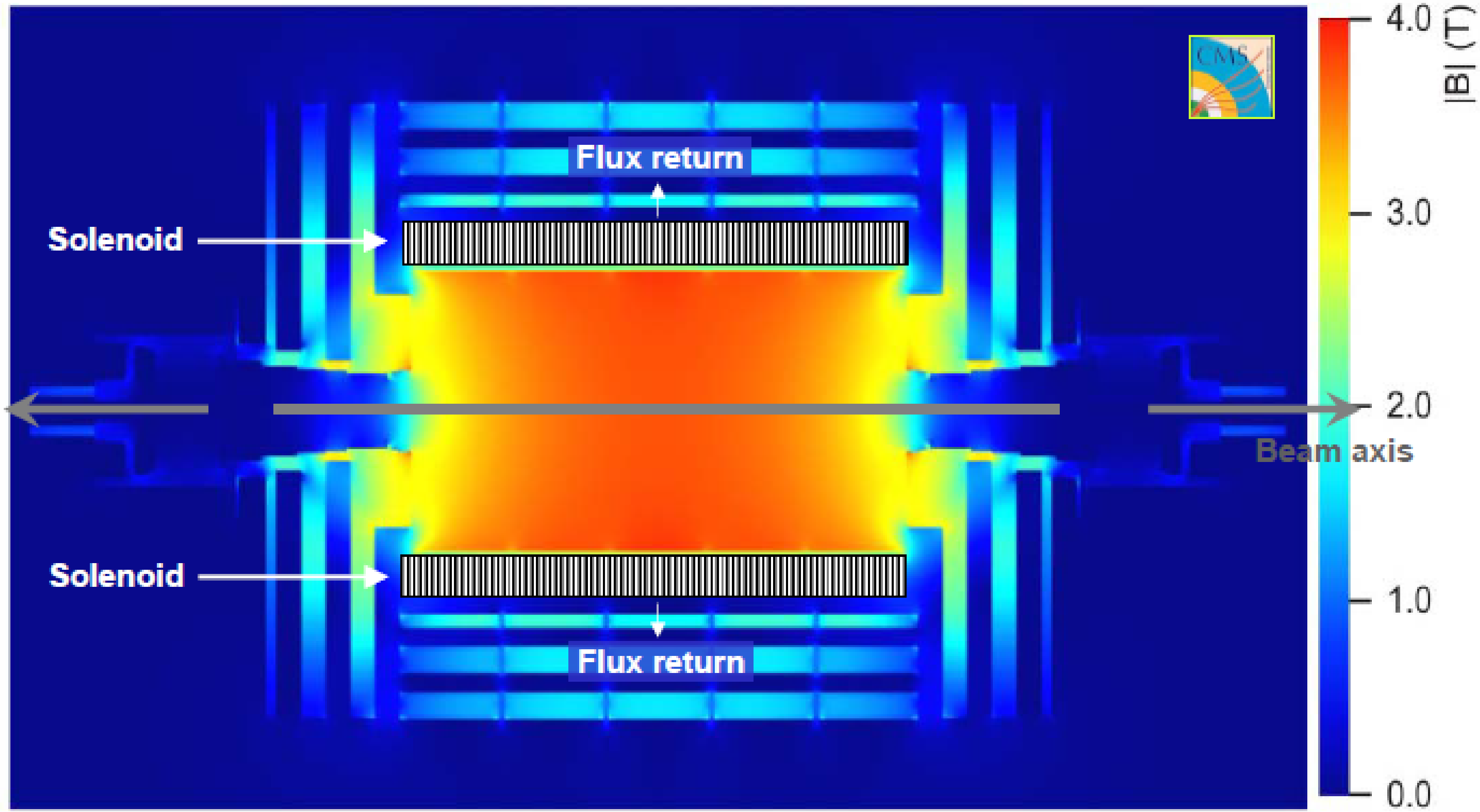
CMS yoke was ready in 2003

An Example of an Engineering Challenge: CMS Solenoid

CMS solenoid:	
Magnetic length	12.5 m
Diameter	6 m
Magnetic field	4 T
Nominal current	20 kA
Stored energy	2.7 GJ

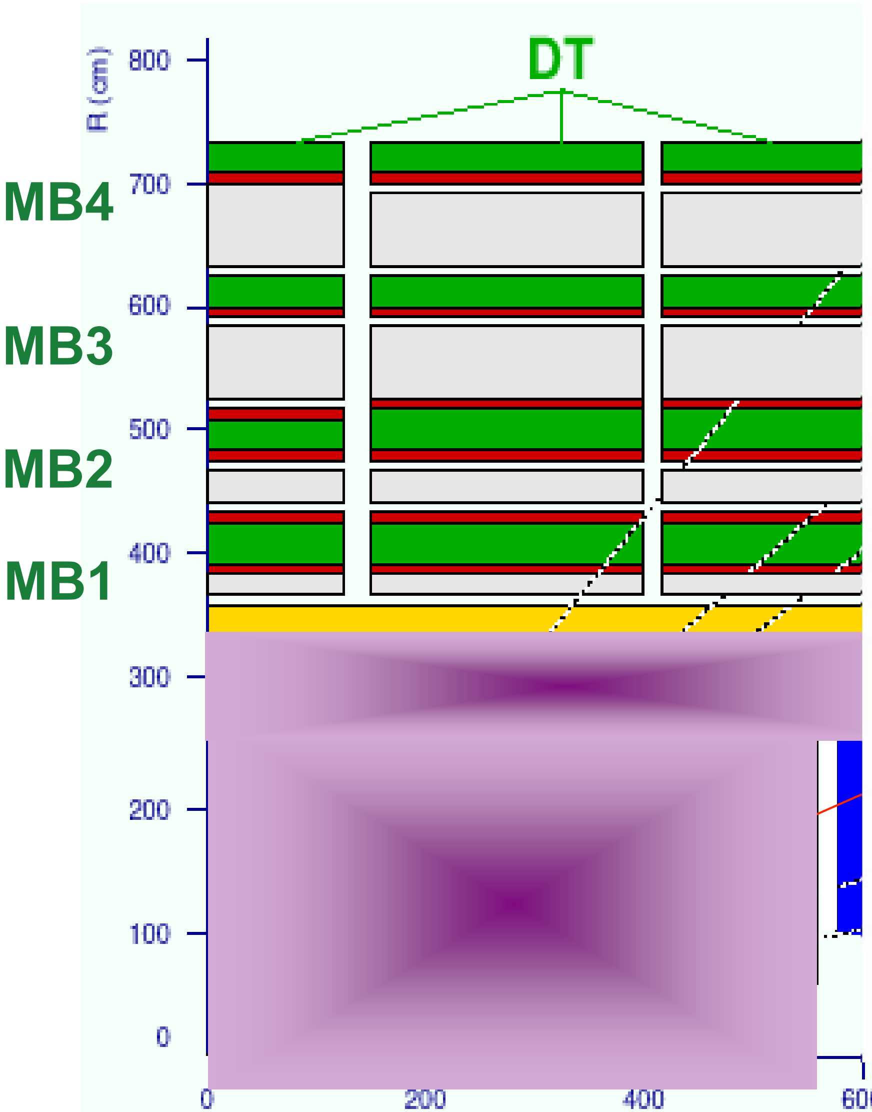
Tested at full current in Summer 2006

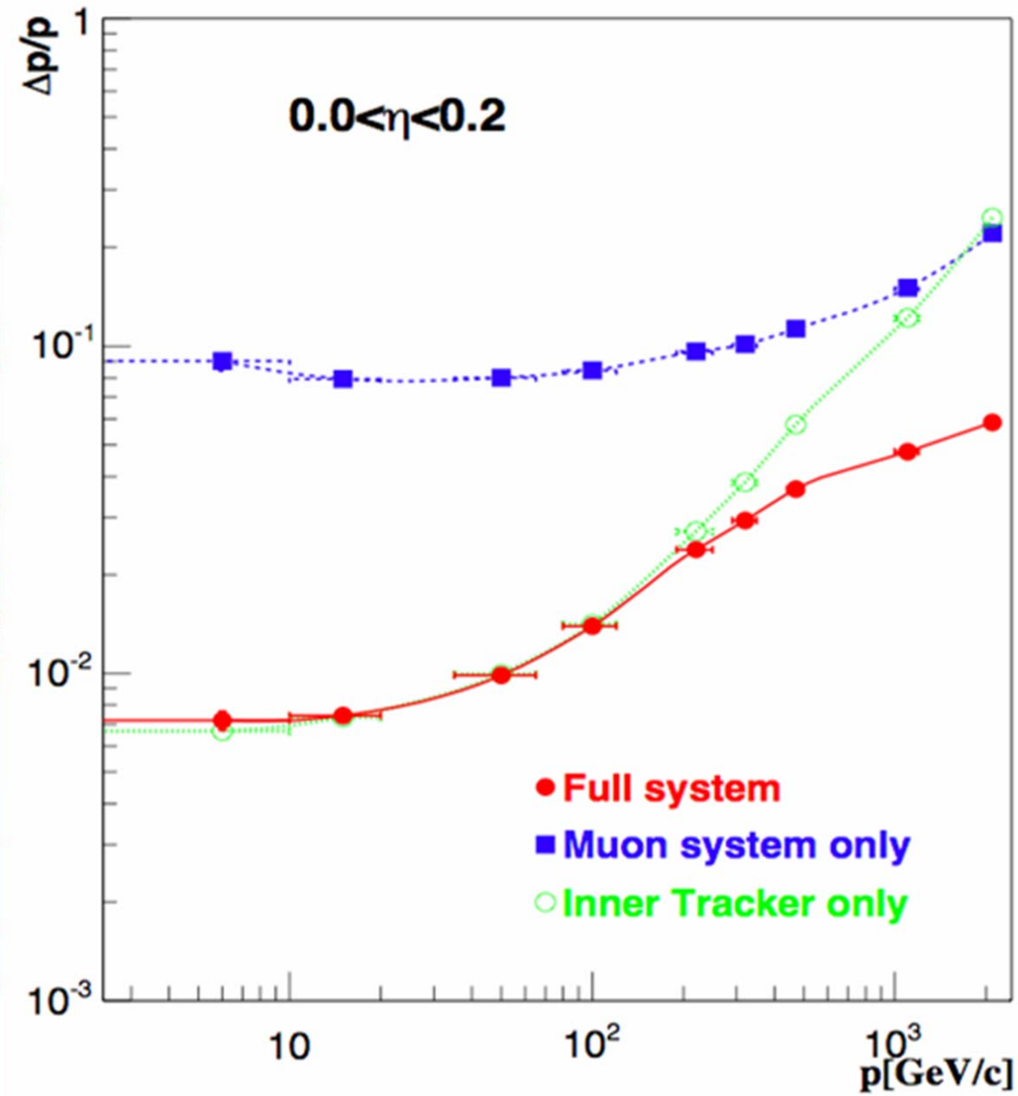




Magnetic field in CMS

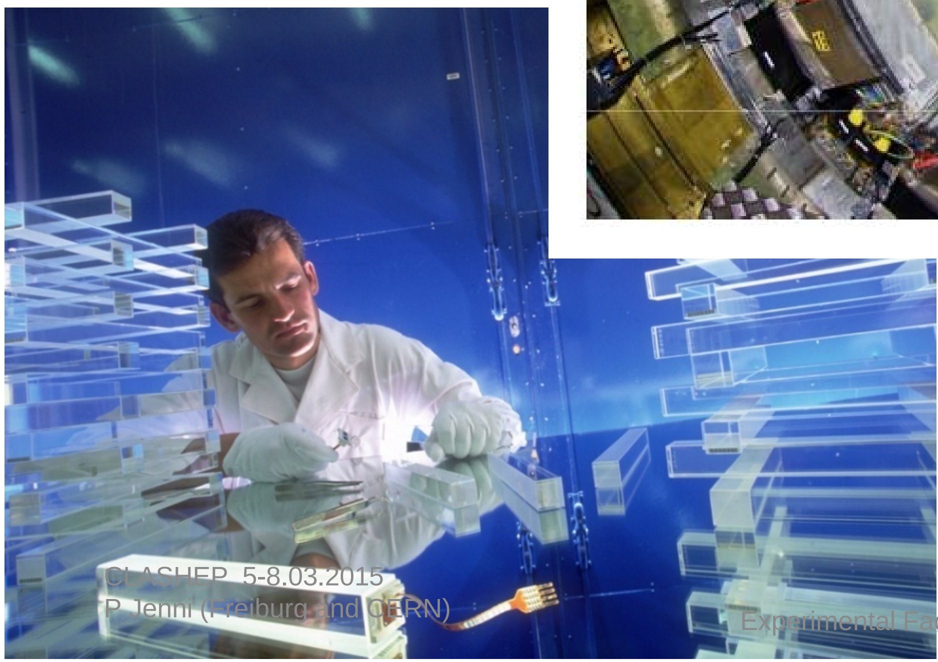
CMS Muon Detectors

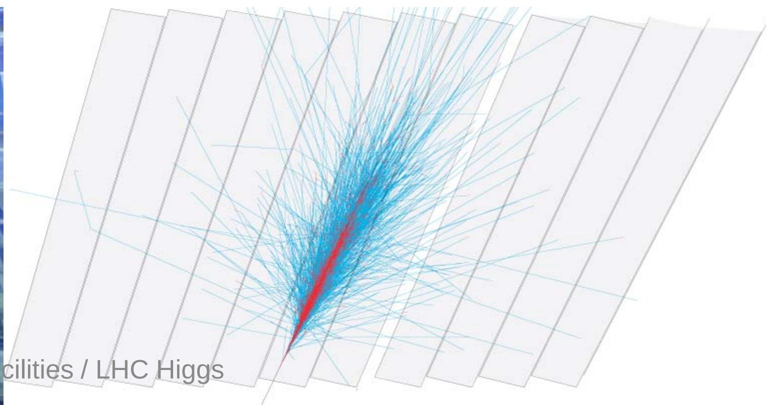




CMS Electron and Photon calorimeter:
76 000 $PbW0_4$ crystals

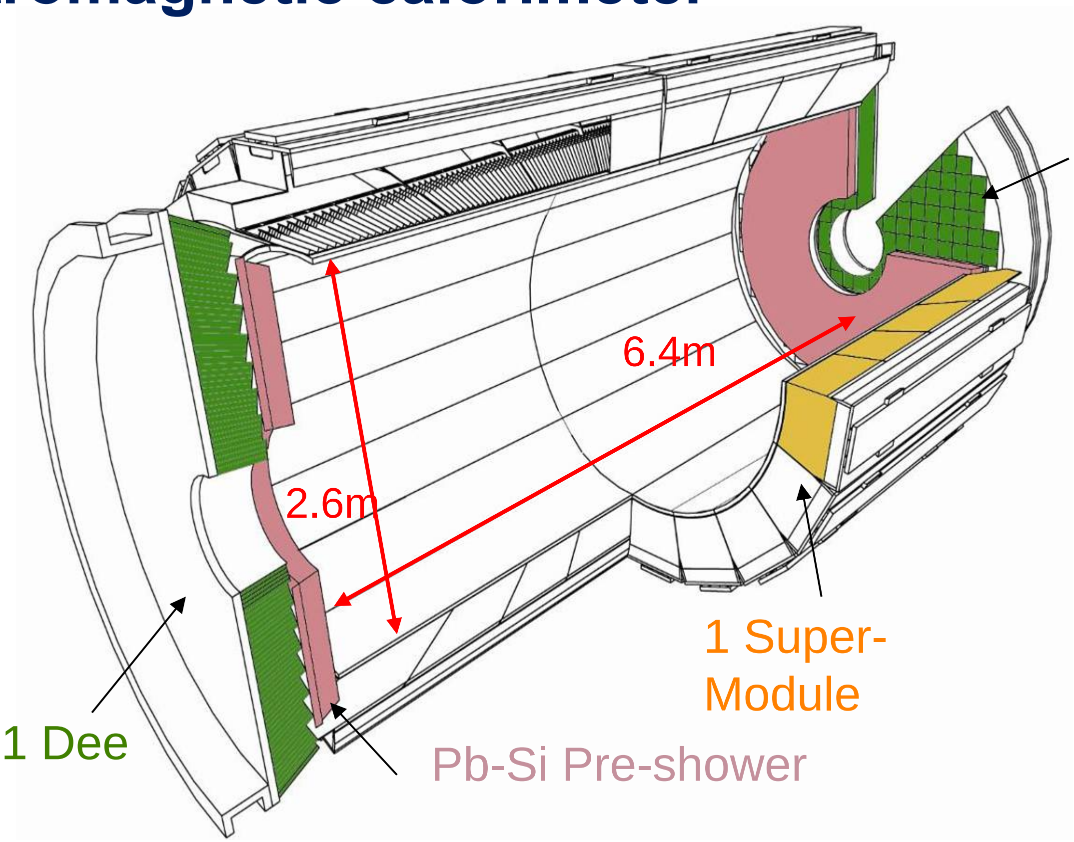
End-cap was on the critical path for many years, but it was completed just in time before final closure, a major achievement by CMS



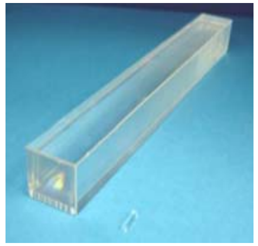


CMS electromagnetic calorimeter

Homogenous Lead Tungstate ($PbWO_4$) Crystal Calorimeter + Pb-Si Preshower



Crystals are projective and positioned pointing slightly off the IP to avoid cracks.



Barrel (EB):

- 61200 crystals
- 36 Supermodules (SM), each 1700 crystals
- $|\eta| < 1.48$

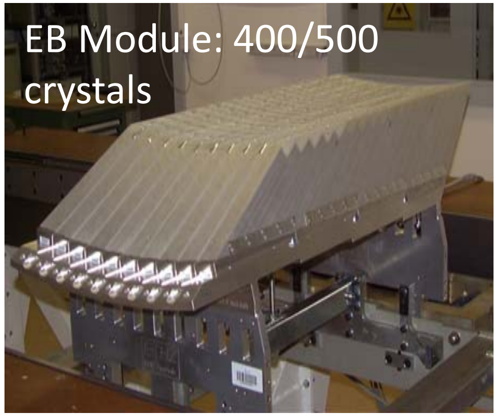
Endcap (EE):

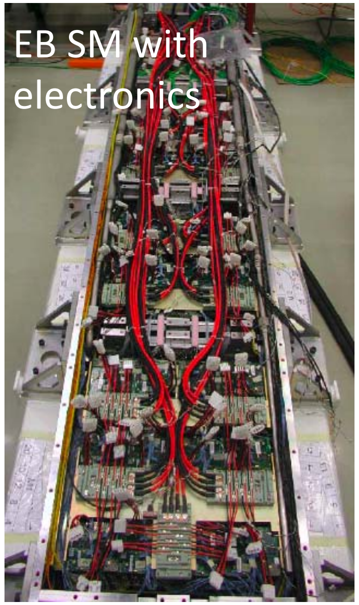
- 14648 crystals
- 4 Dees, SuperCrystals of 5x5 xtals
- $1.48 < |\eta| < 3.0$

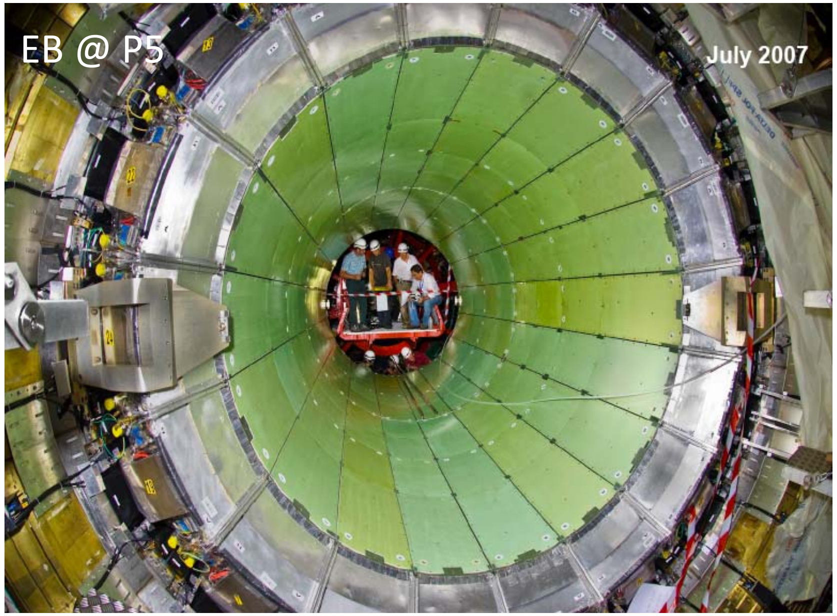
Preshower (ES):

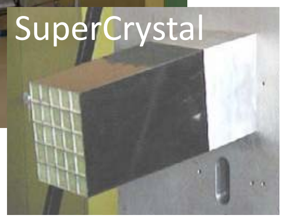
- Pb-Si
- 4 Dees
- 4300 Si strips
- $1.65 < |\eta| < 2.6$

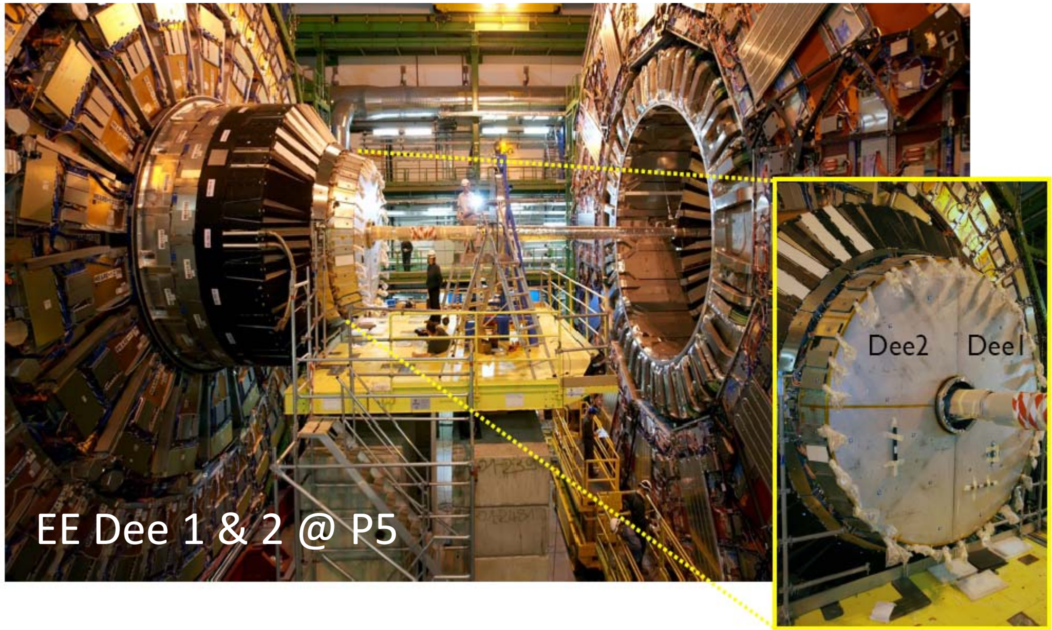
CMS ECAL construction



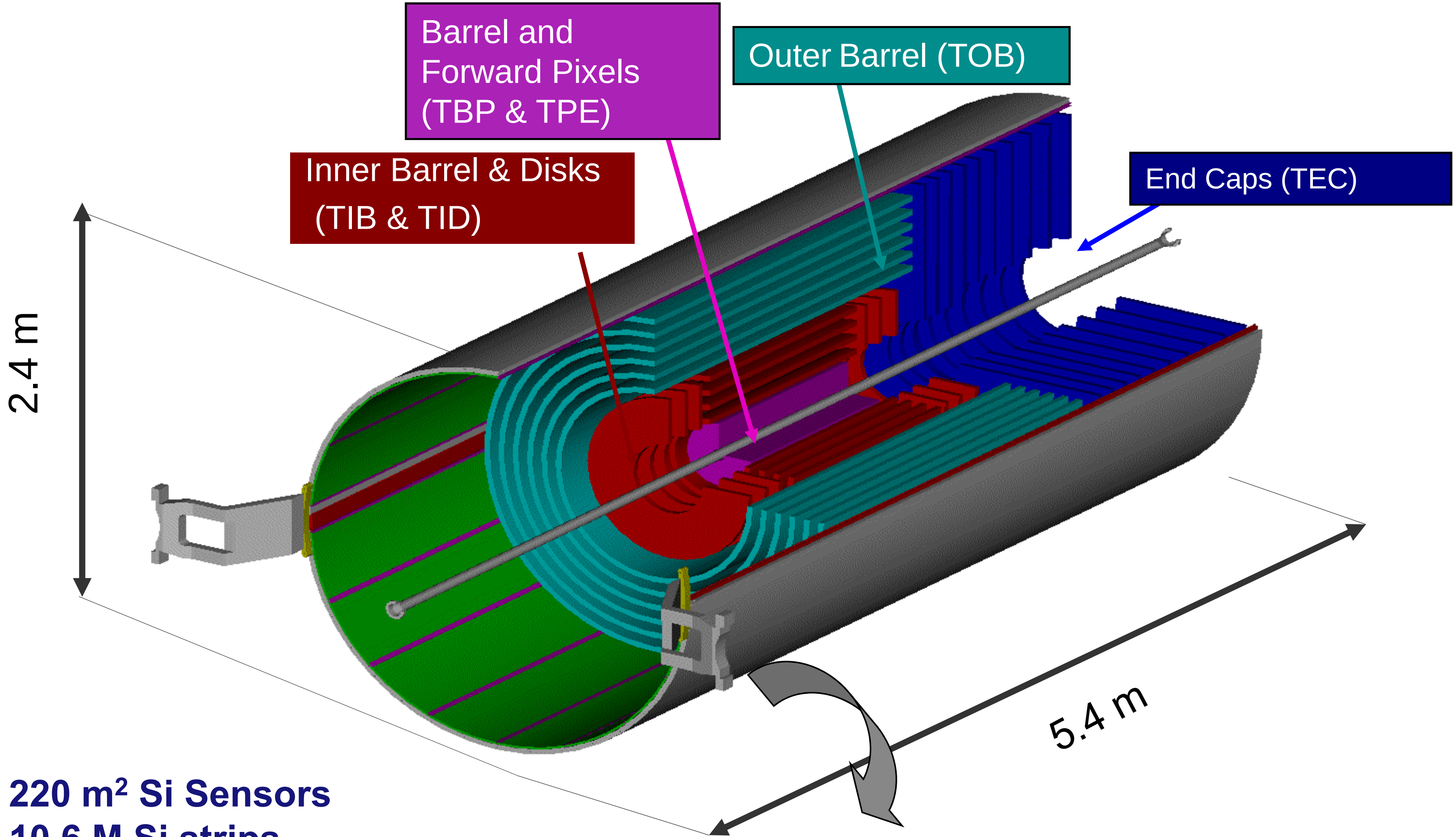








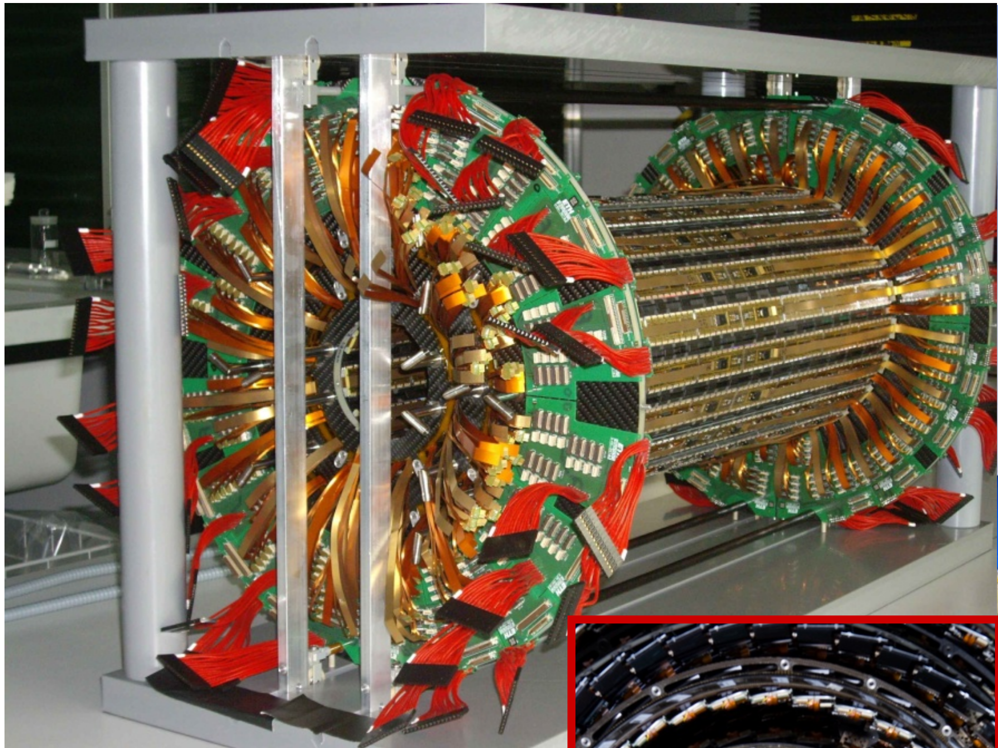
The CMS Inner Tracker (all Silicon detectors)

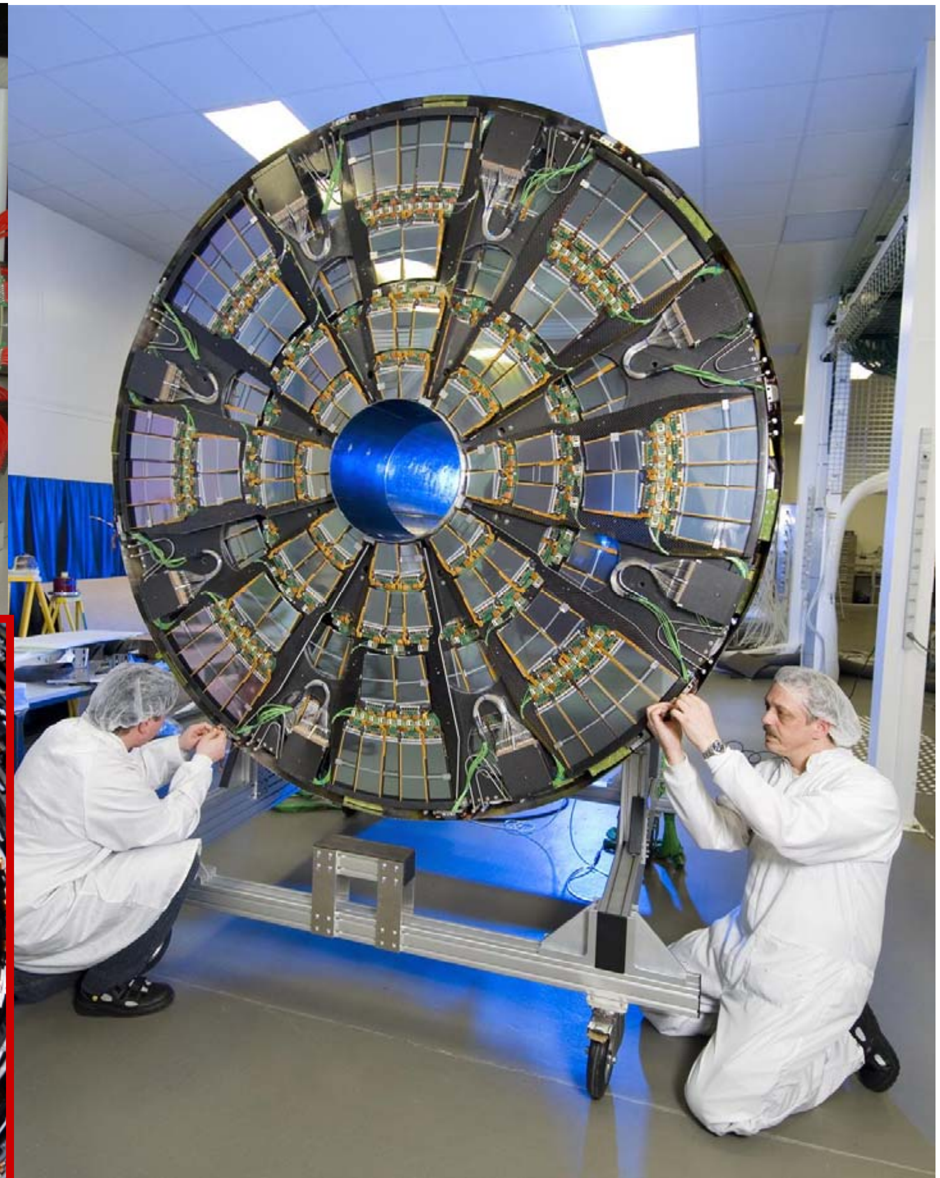


220 m^2 Si Sensors
10.6 M Si strips
65.9 M Pixels ~ 1.1 m^2

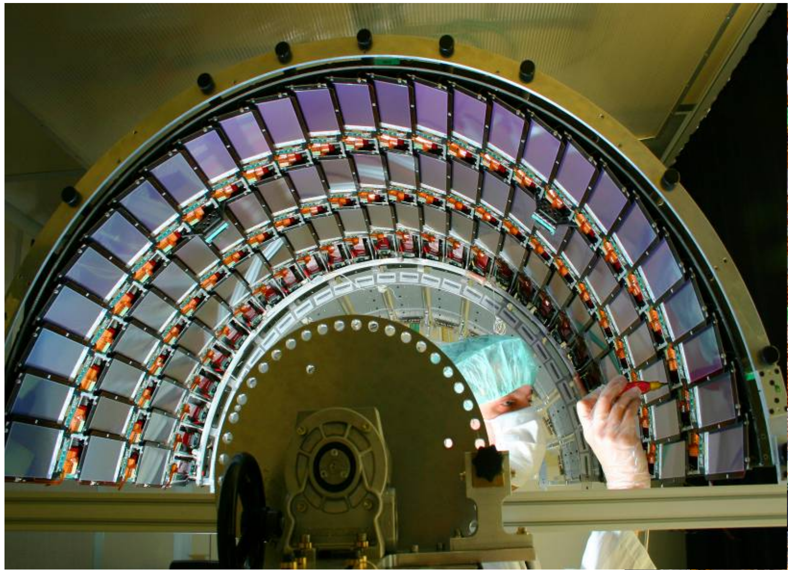
Volume 24.4 m^3
Operating temperature – 20 ^{0}C

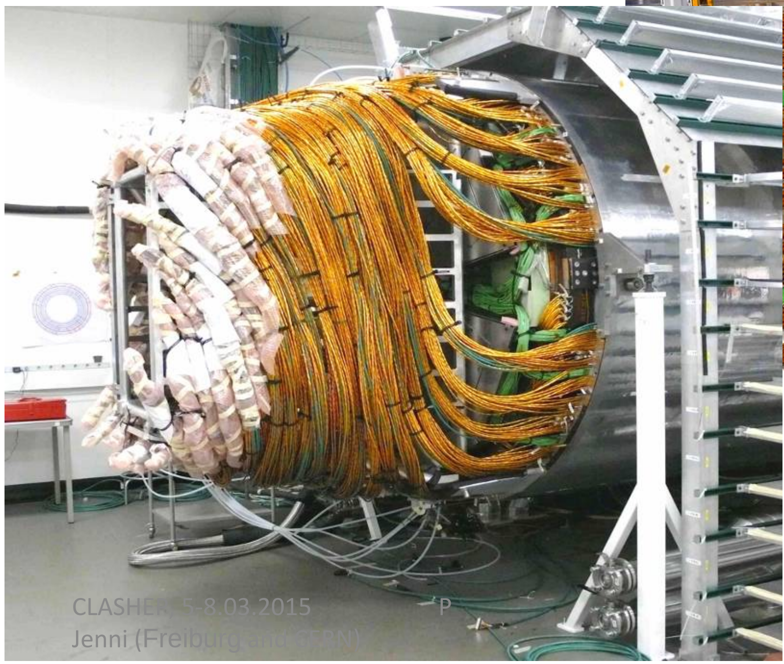
CMS Inner Tracking

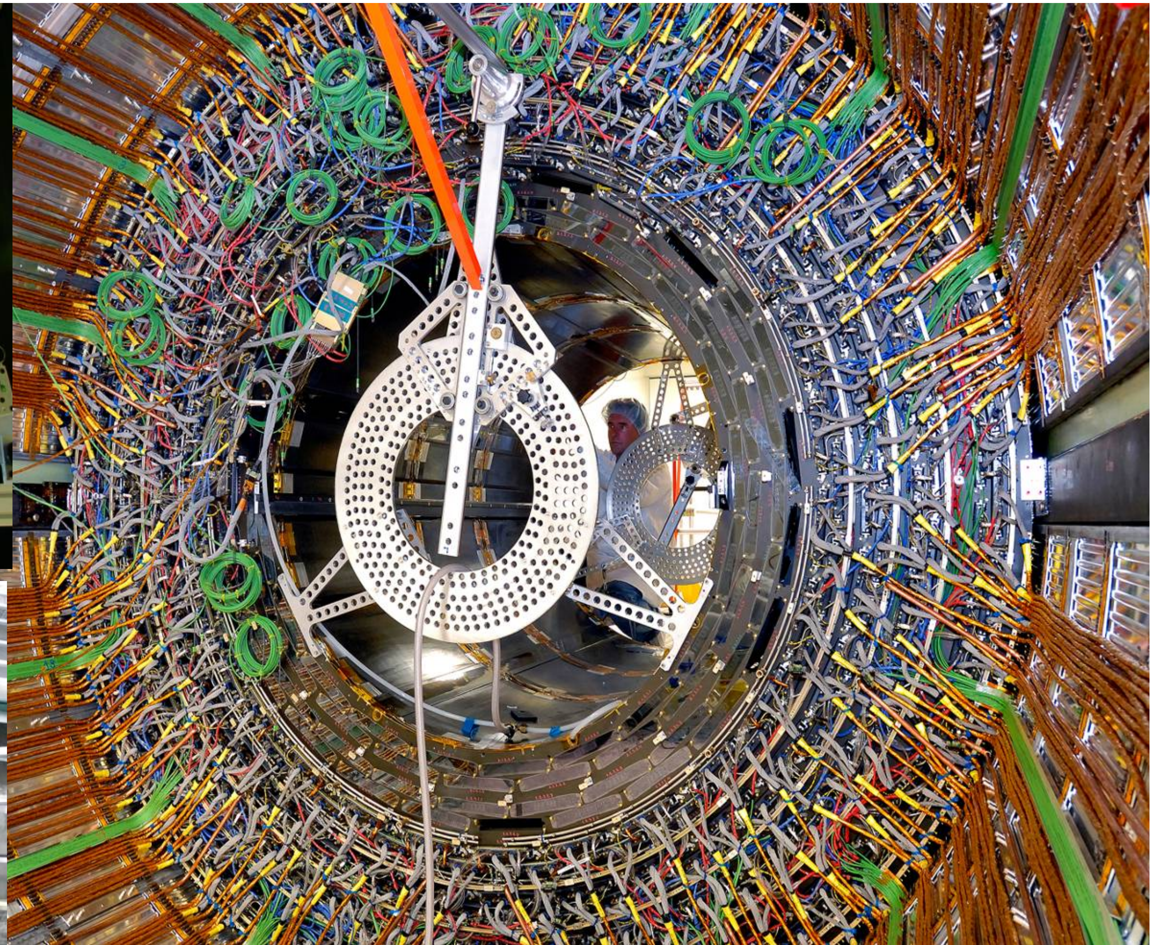




CMS Silicon Tracker

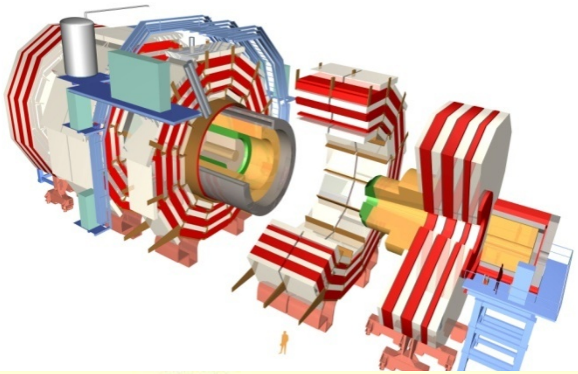


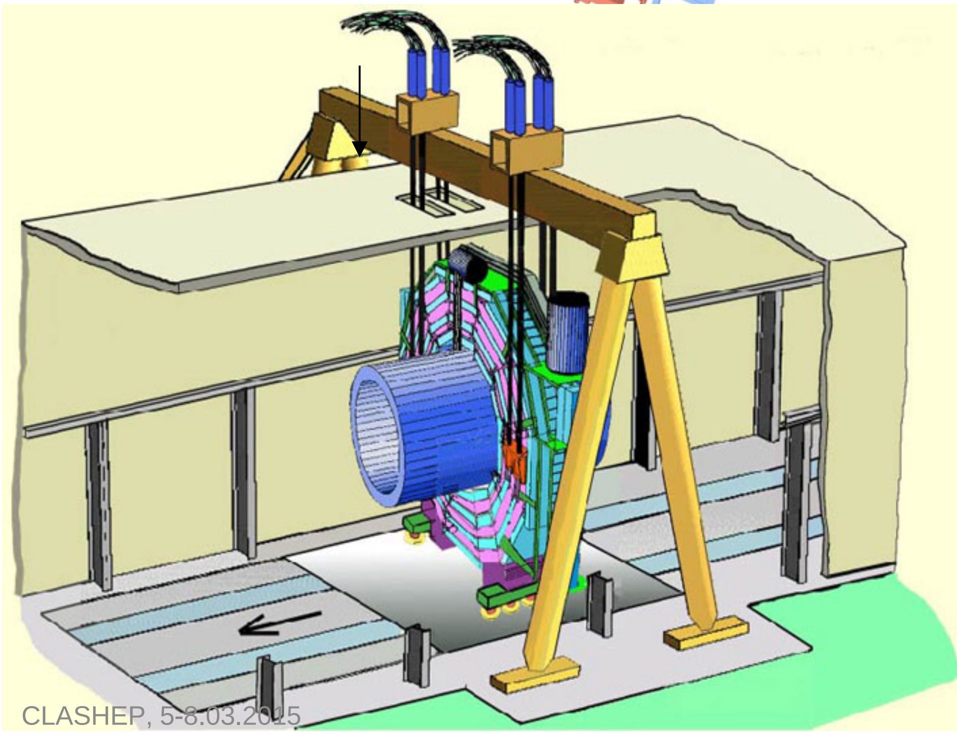


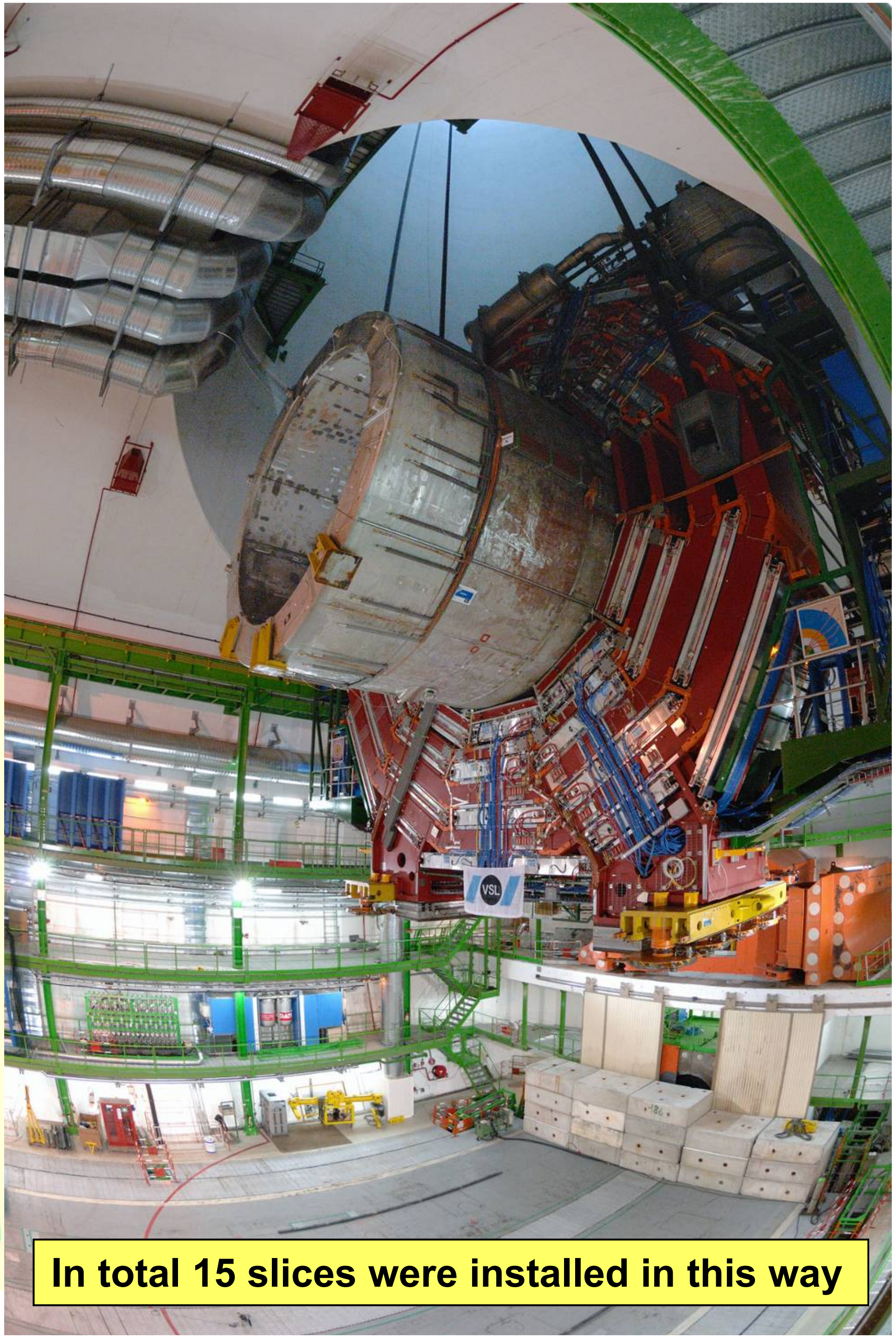


The Silicon tracker ($200m^2$) has 10 M channels
- Commissioned at operating temperature (-15°C)
- ~ 5 M cosmic rays recorded on the surface

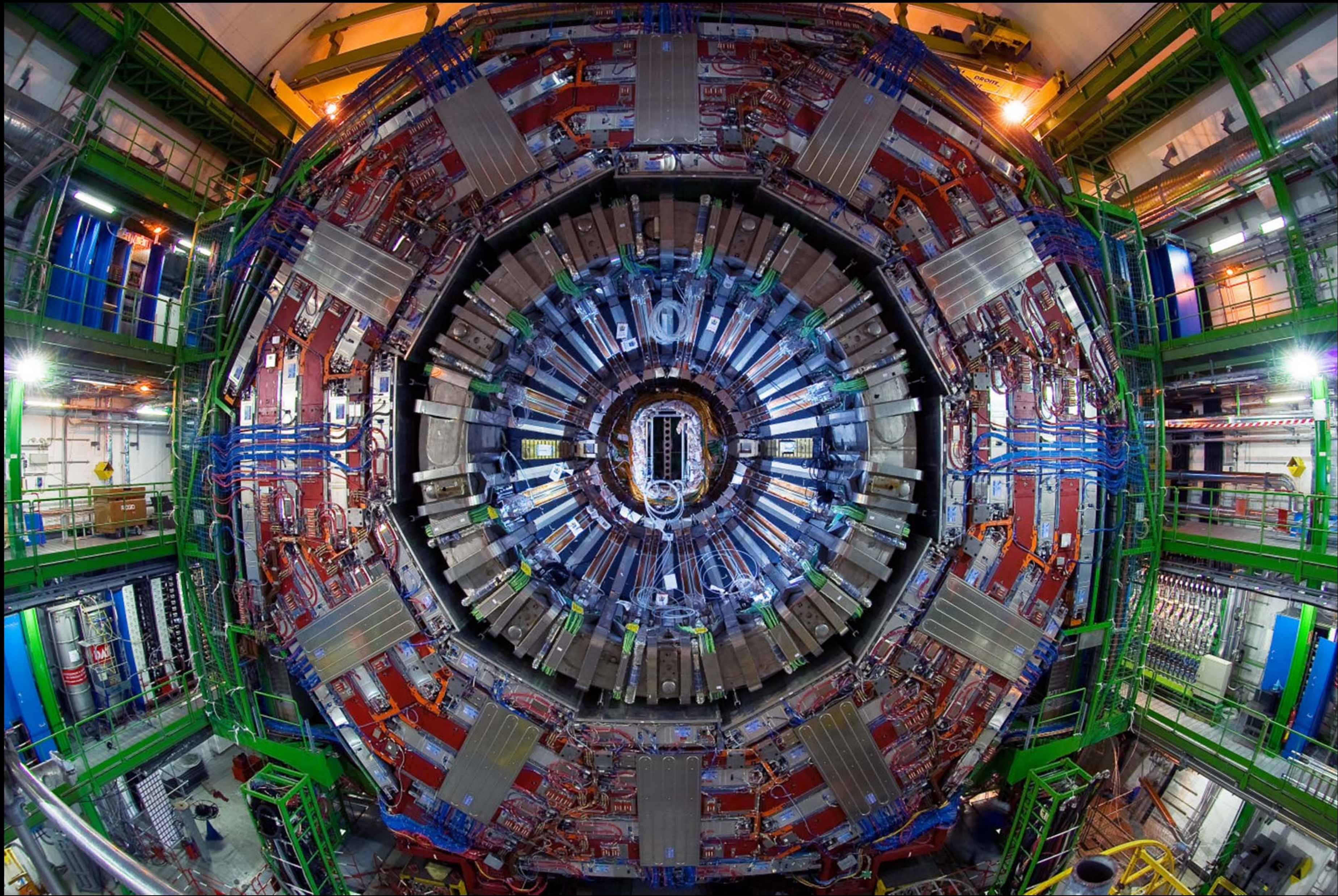
The central, heaviest slice (2000 tons) including the solenoid magnet lowered in the underground cavern in Feb. 2007



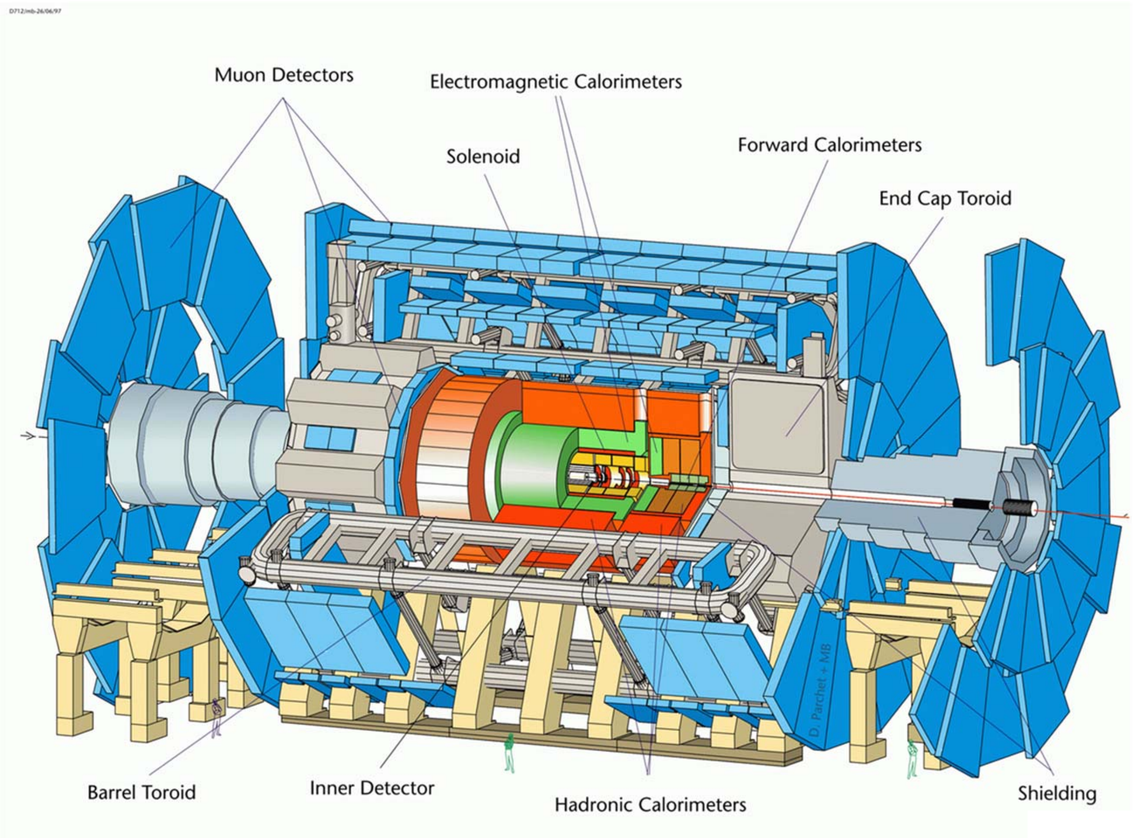




In total 15 slices were installed in this way



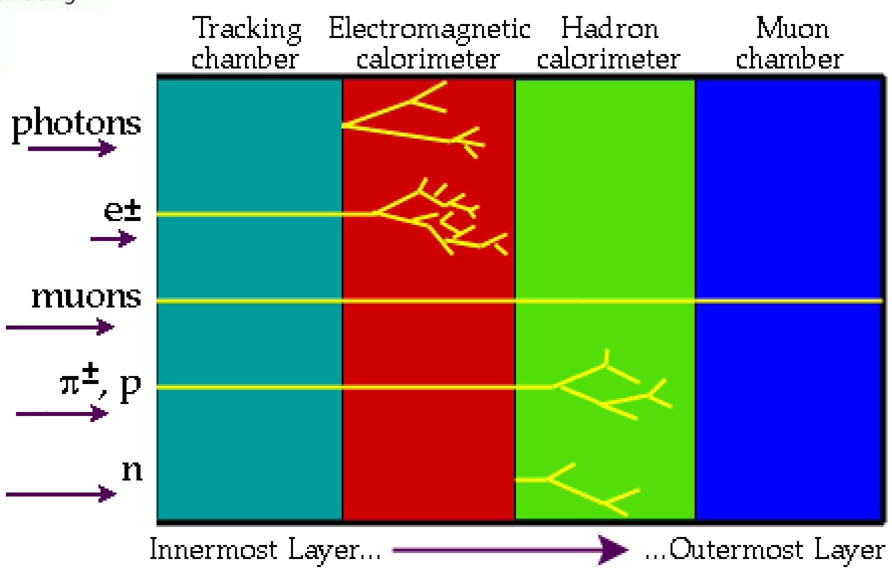
CMS before closure 2008

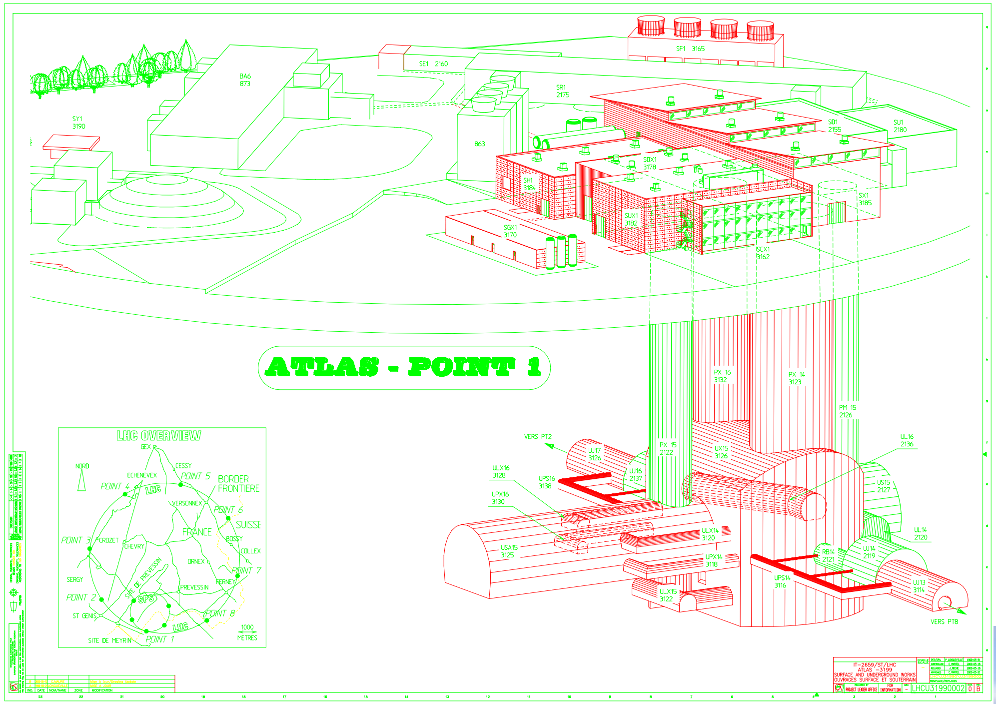


ATLAS

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~ 10^8 electronic channels
~ 3000 km of cables

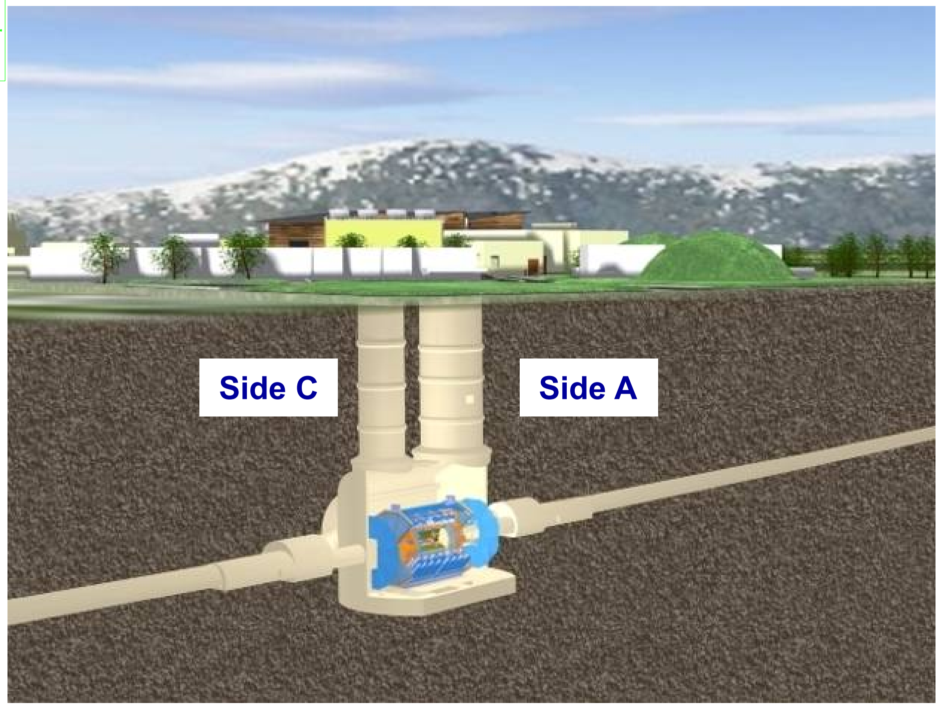
- **Tracking (|η|<2.5, B=2T) :**
  - -- Si pixels and strips
  - -- Transition Radiation Detector (e/π separation)
- **Calorimetry (|η|<5) :**
  - -- EM : Pb-LAr
  - -- HAD: Fe/scintillator (central), Cu/W-LAr (fwd)
- **Muon Spectrometer (|η|<2.7) :**
  - -- air-core toroids with muon chambers





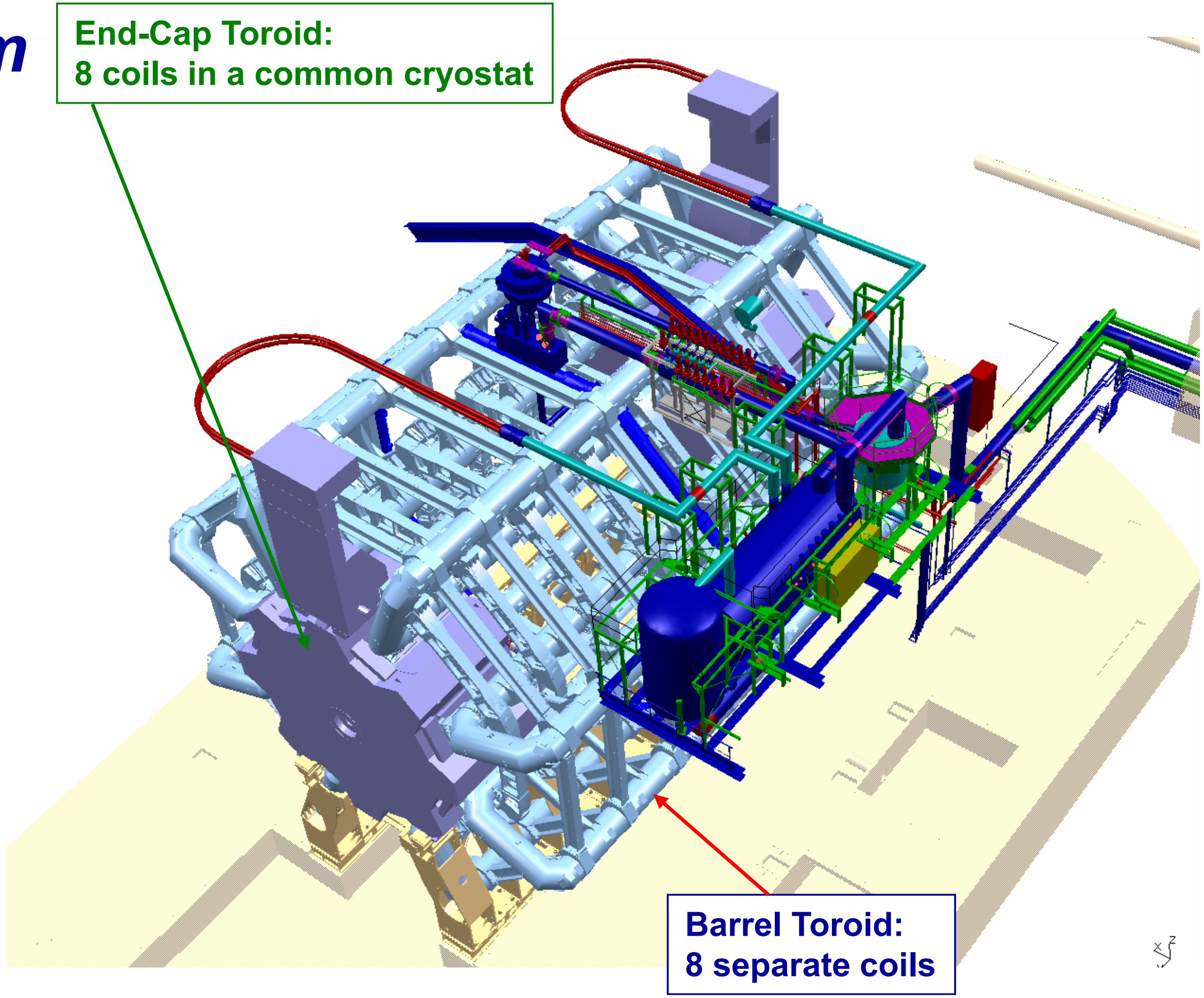
The Underground Cavern at Point-1 for the ATLAS Detector

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



LHC Point 1 - UX 15 Cavern - Concrete walls 6th lift - 20-02-2003 - CERN ST-CE

ATLAS Toroid Magnet System



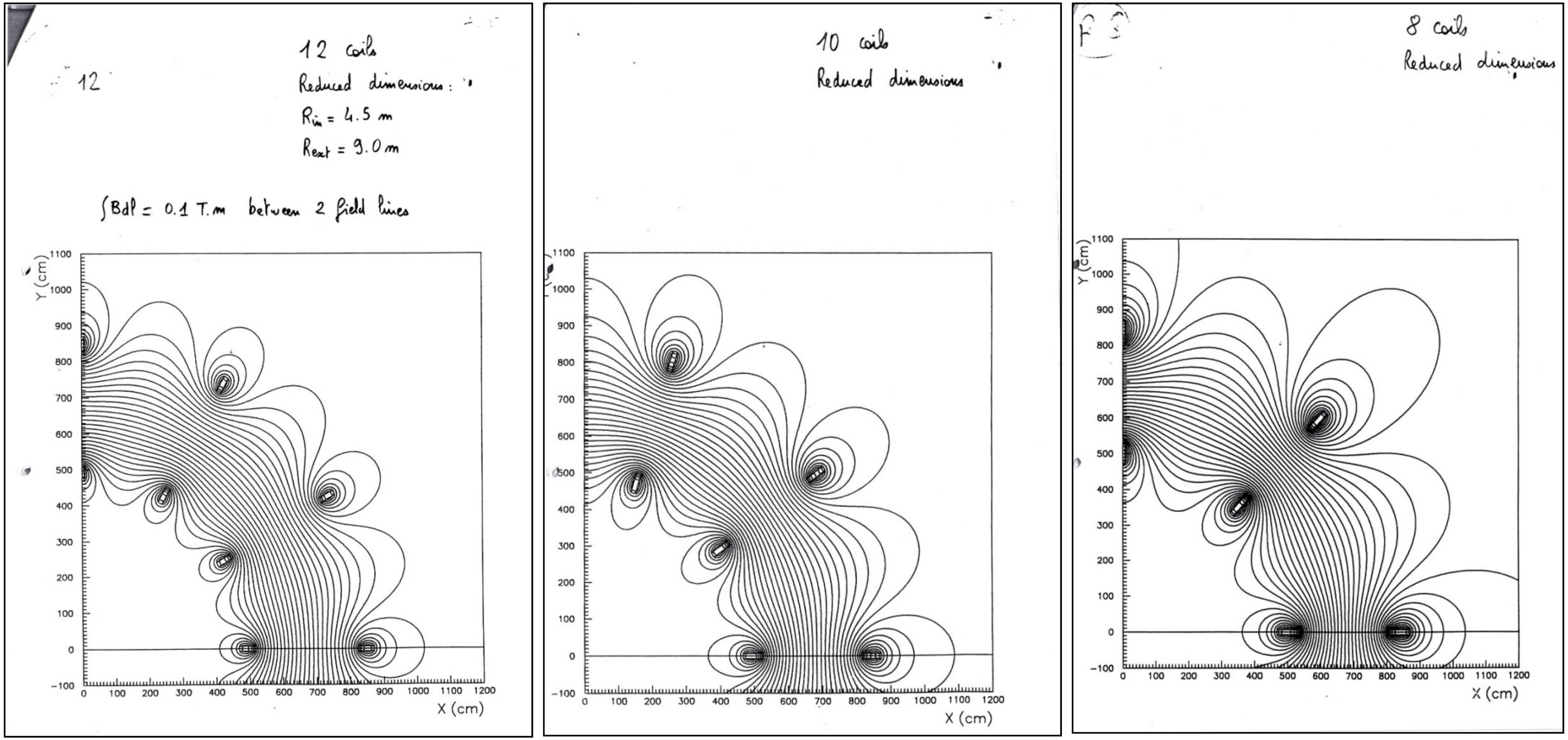
Barrel Toroid parameters

25.3 m length
20.1 m outer diameter
8 coils
1.08 GJ stored energy
370 tons cold mass
830 tons weight
4 T on superconductor
56 km Al/NbTi/Cu conductor
20.5 kA nominal current
4.7 K working point

End-Cap Toroid parameters

5.0 m axial length
10.7 m outer diameter
2x8 coils
2x0.25 GJ stored energy
2x160 tons cold mass
2x240 tons weight
4 T on superconductor
2x13 km Al/NbTi/Cu conductor
20.5 kA nominal current
4.7 K working point

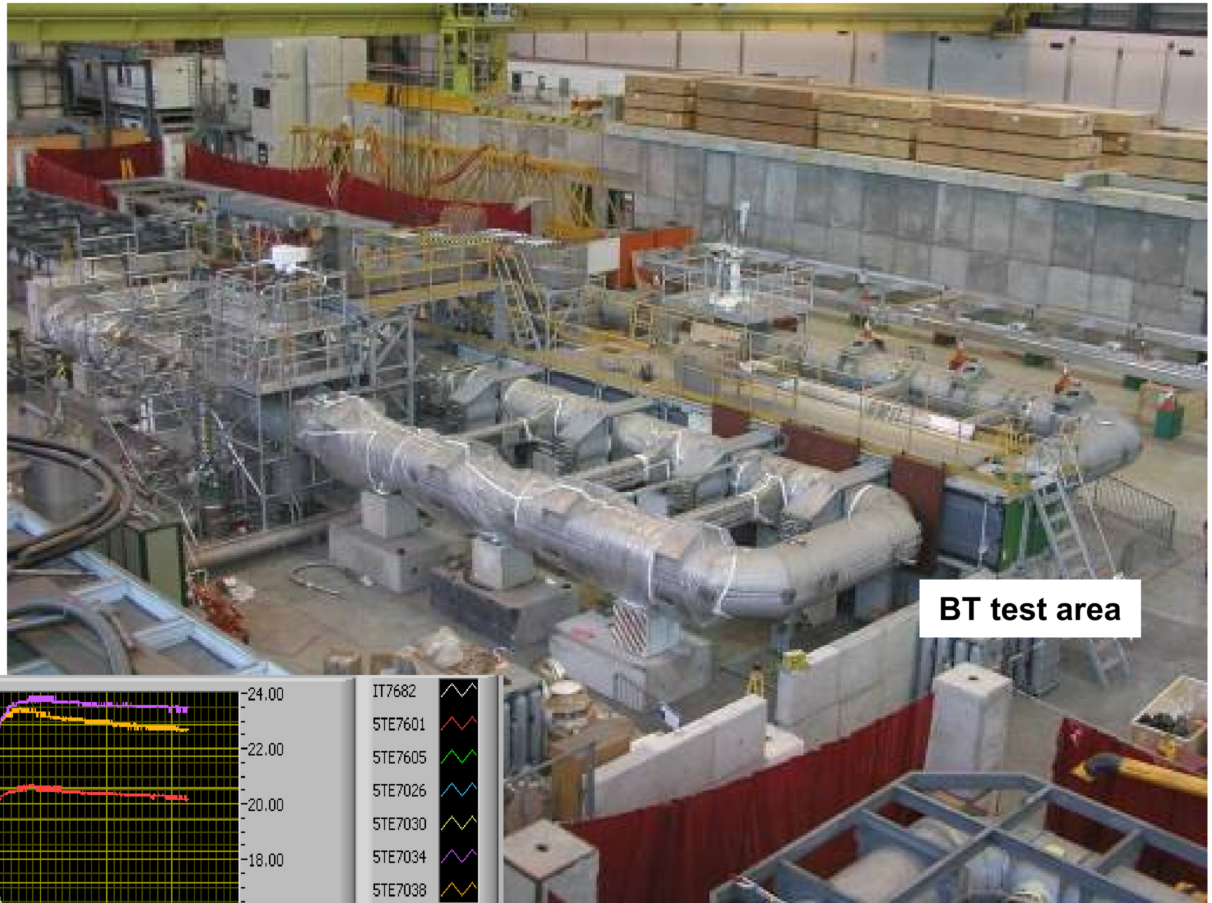
One of many ingredients to make the experiment affordable …

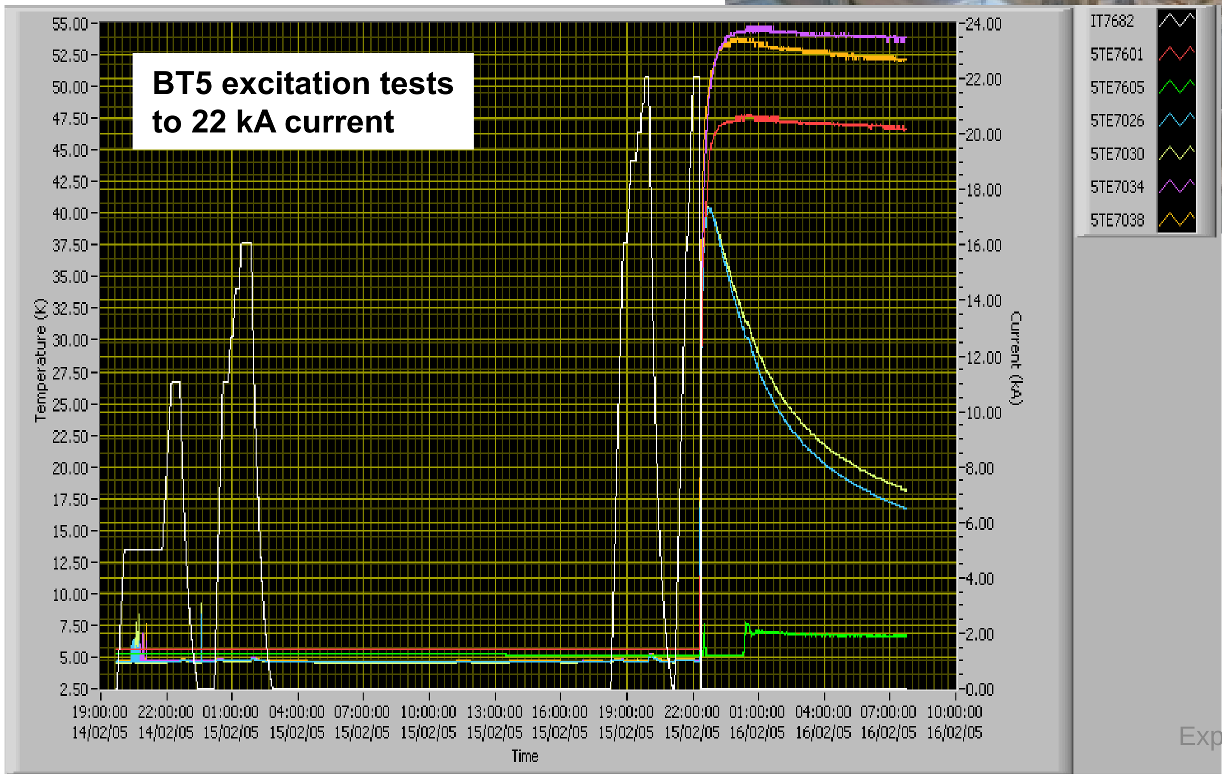


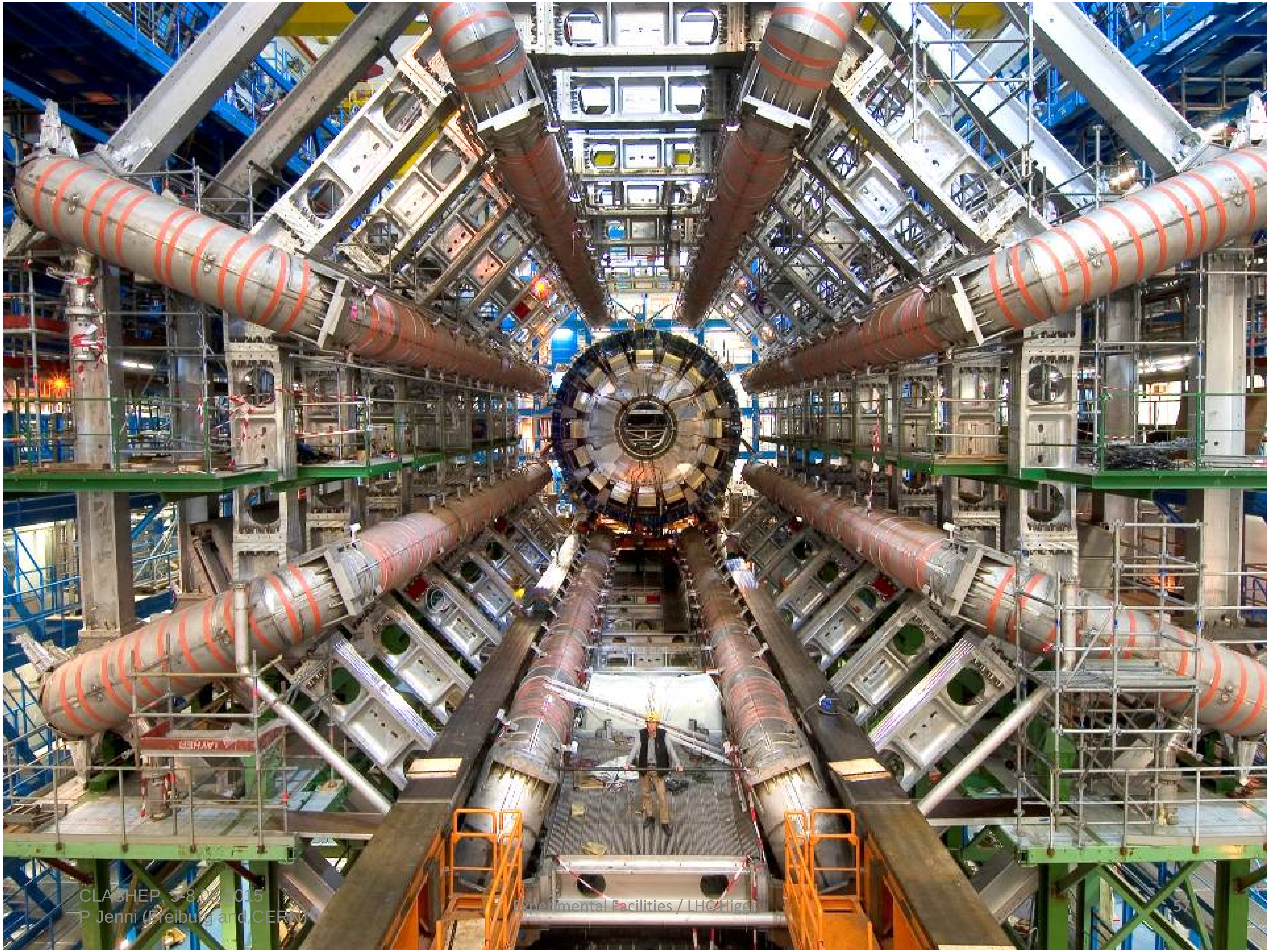
… initial ideas of a toroid with 12 coils were 'descoped' to a 8 coil design (which turned out to be an excellent choice also to have more 'air' in the air-core spectrometer)

ATLAS Barrel Toroid construction

Series integration and tests of the 8 coils at the surface were finished in June 2005







ATLAS End-cap Toroid installation, as an example

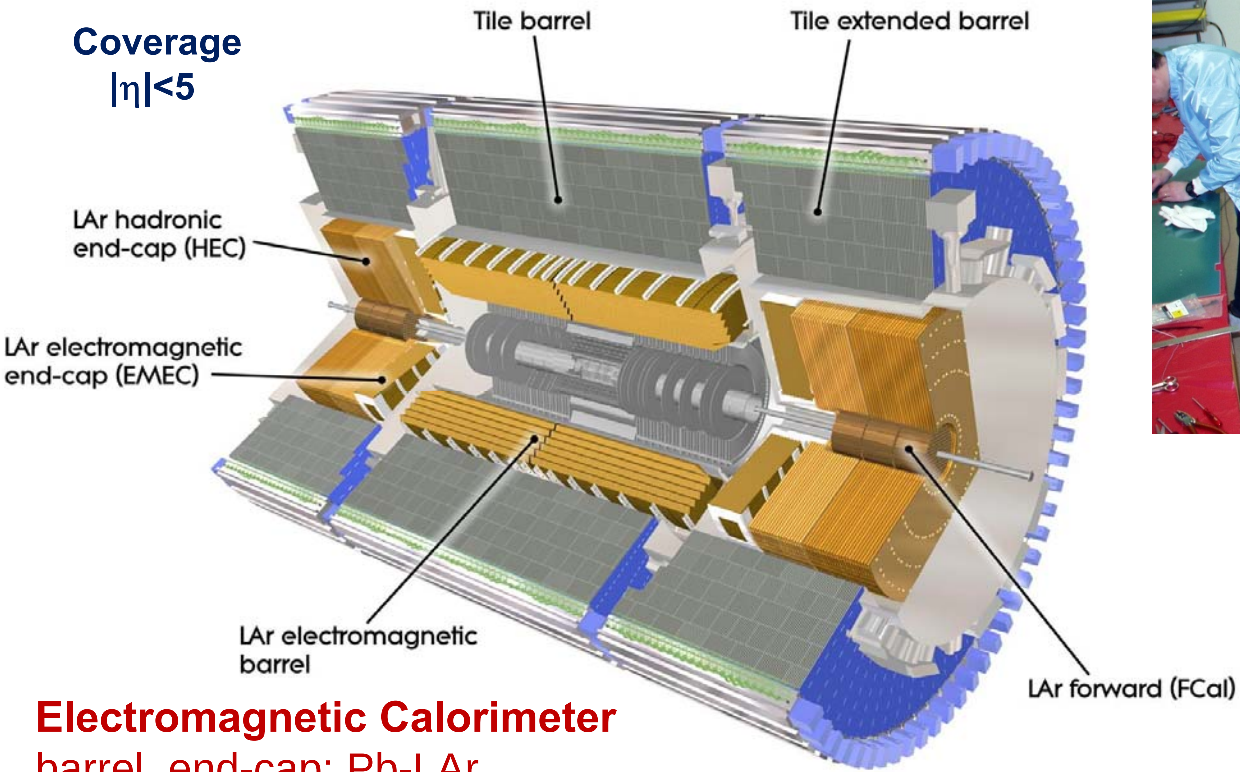
The transports and installations were major operations, involving also specialized firms

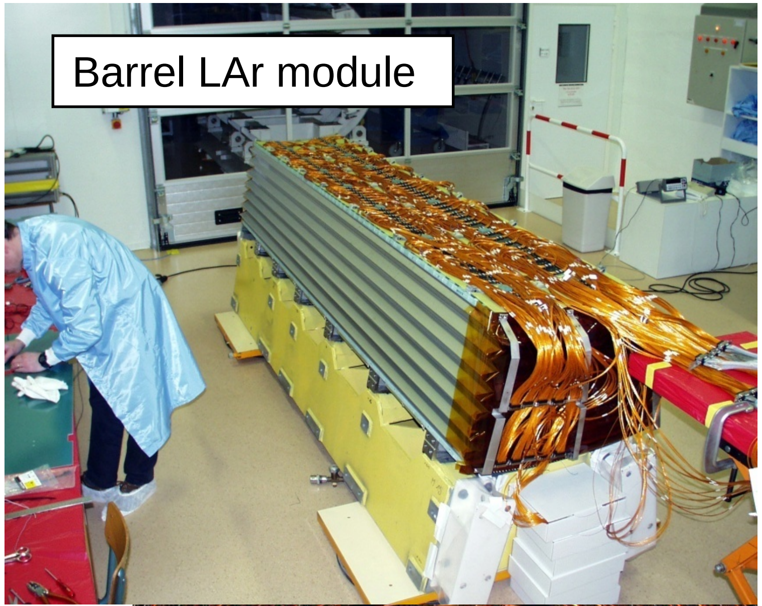
The ECTs are 250 tons, 15 m high, 5 m wide

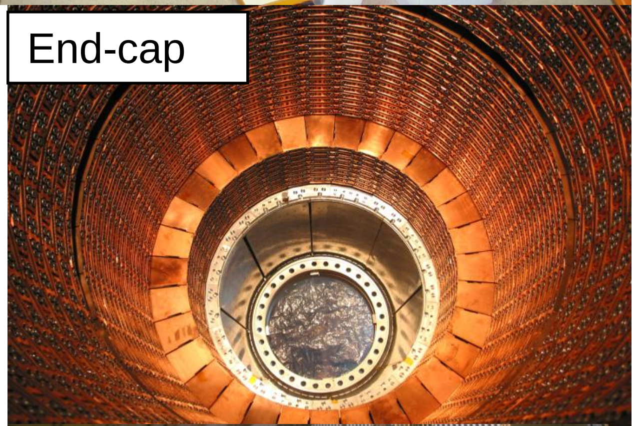
ECT-A was lowered on 13th June 2007, and ECT-C on 12th July 2007

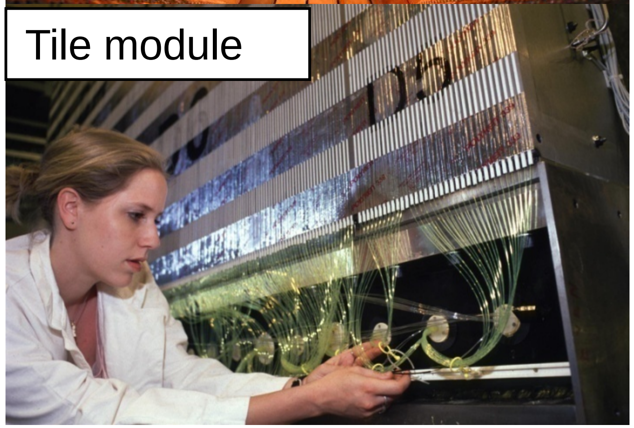
ATLAS Calorimetry

Coverage
|η|<5









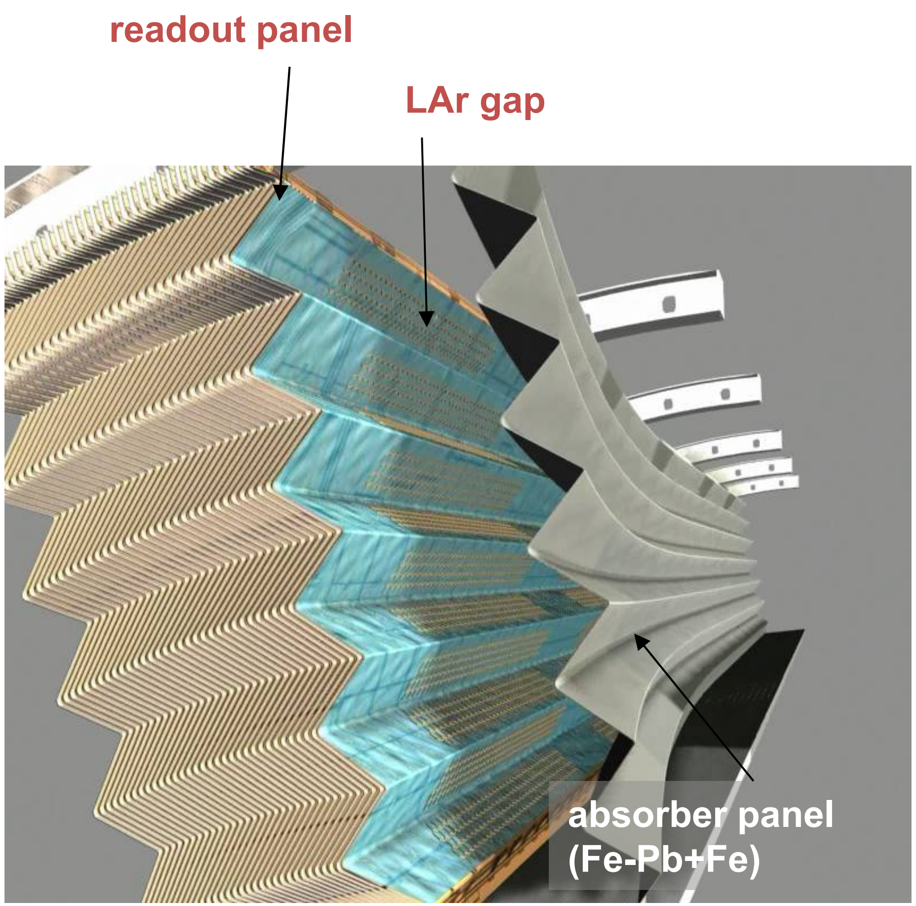
Electromagnetic Calorimeter
barrel, end-cap: Pb-LAr
~10%/√E energy resolution e/γ
180'000 channels: longitudinal segmentation

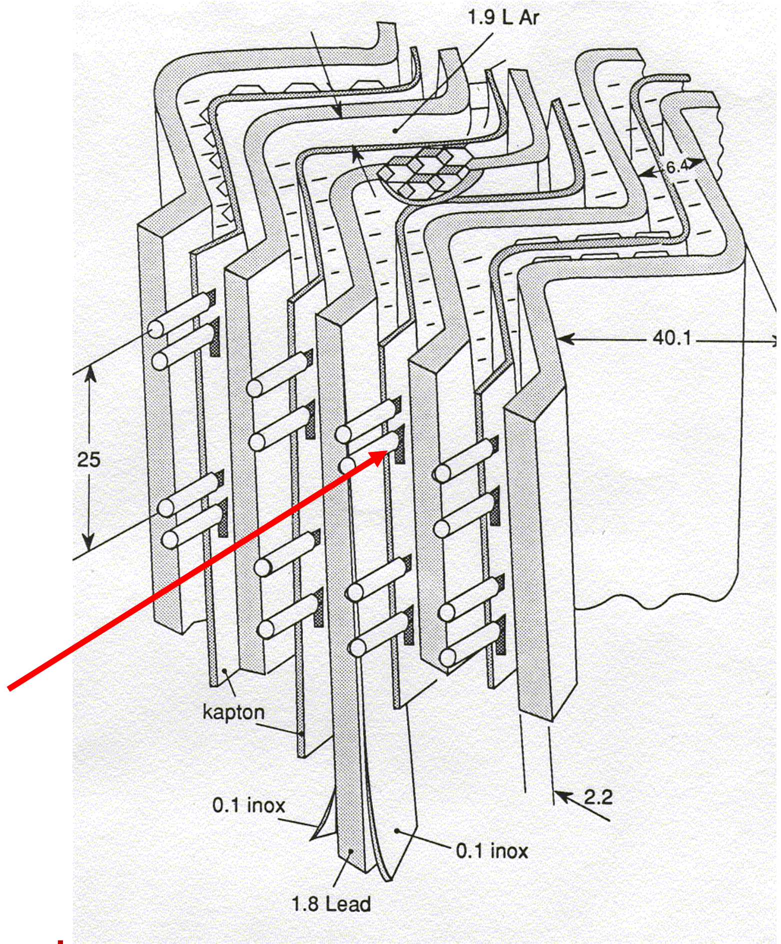
Hadron Calorimeter
barrel Iron-Tile, EC/Fwd Cu/W-LAr (~20'000 channels)
$\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$ pion (10 λ)

Trigger for e/γ , jets, missing E_T, etc

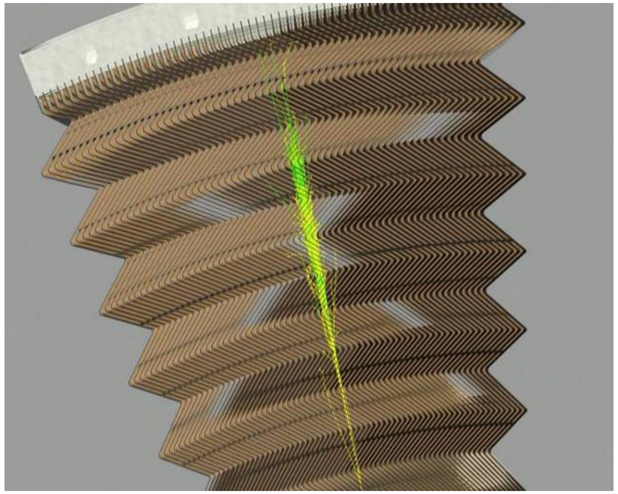
ATLAS Electromagnetic Calorimeters

LAr sampling calorimeter with ‘accordion’ geometry, was ‘invented’ and developed for LHC in the early 1990s





Why ?
- **readout speed**
- **radiation hard**
- **electronically inter-calibrated**
- **allows longitudinal segmentation**
- **hermetic in phi**
- **good energy and angular resolution**

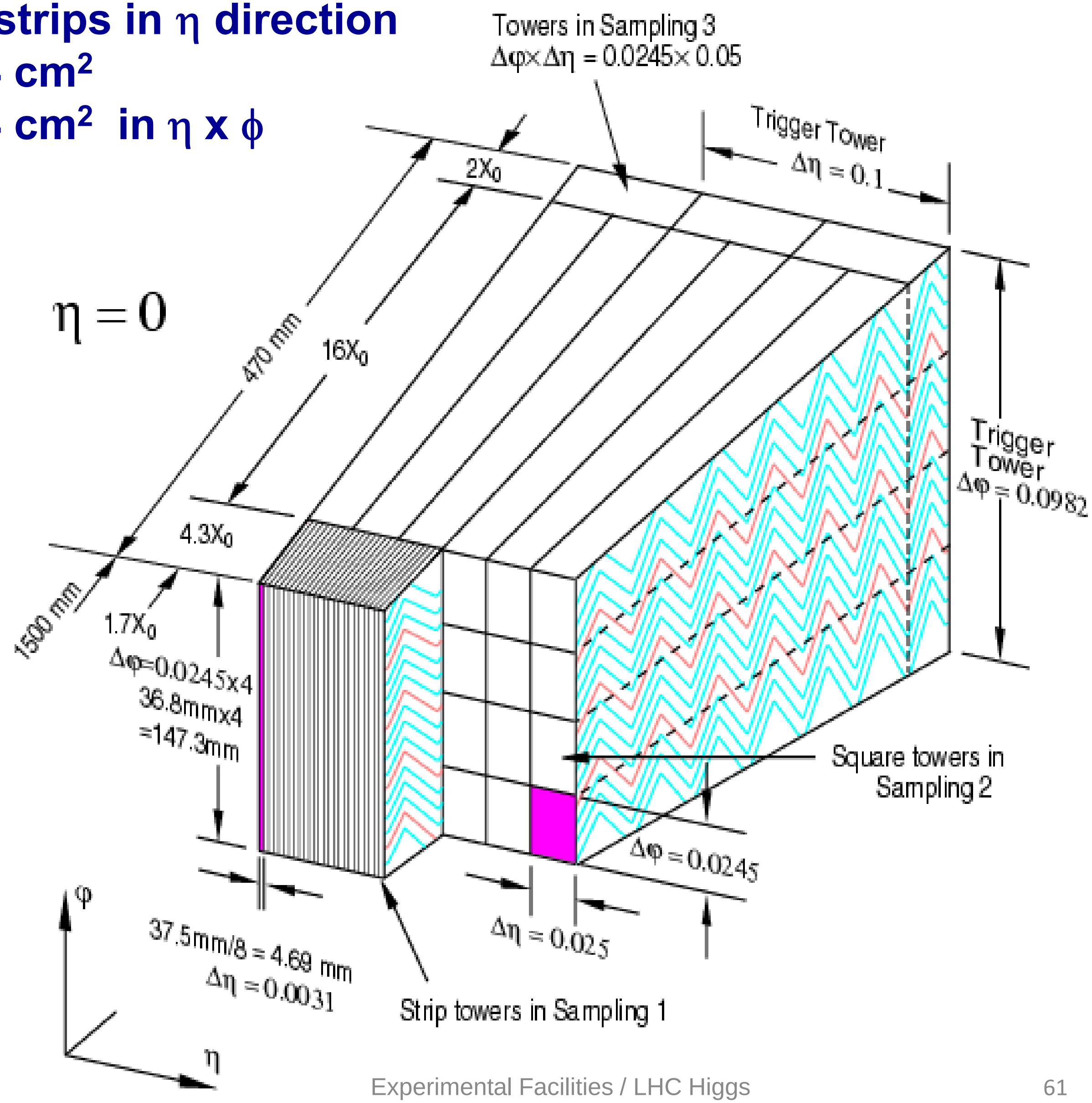


Fine segmentation and granularity :
(longitudinally 3 compartments)

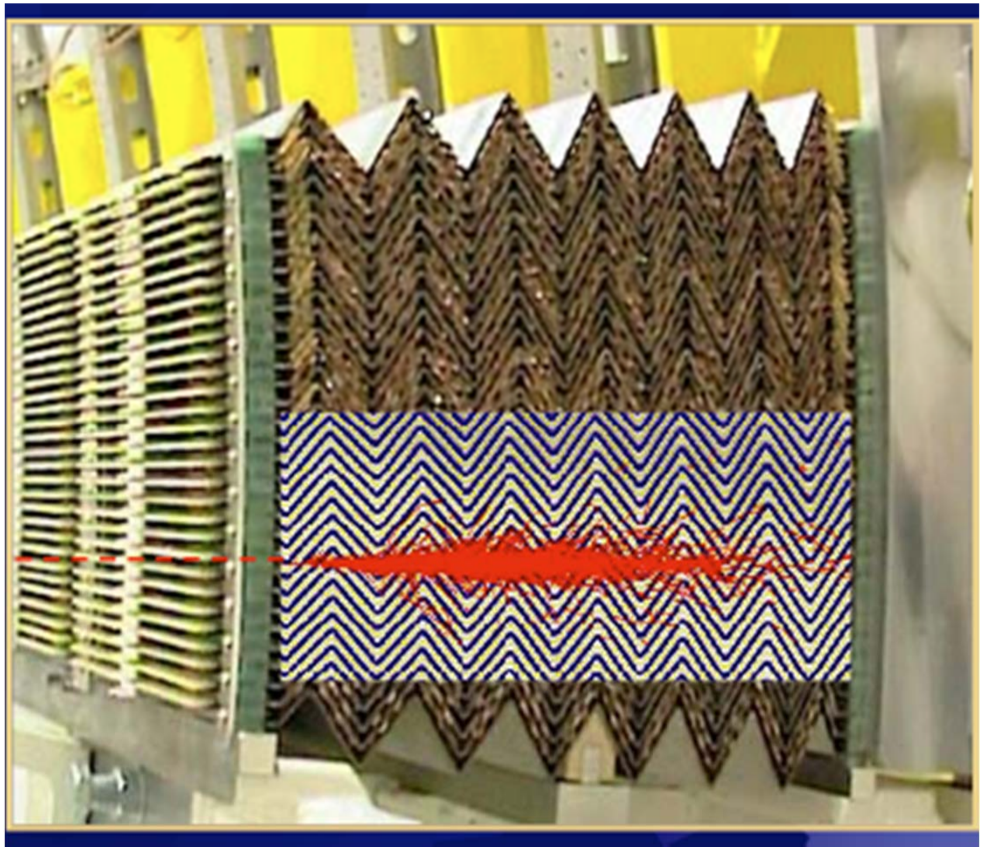
compartment 1 : 4 mm strips in η direction
compartment 2 : ~ 4 x 4 cm^2
compartment 3 : ~ 8 x 4 cm^2 in η x ϕ

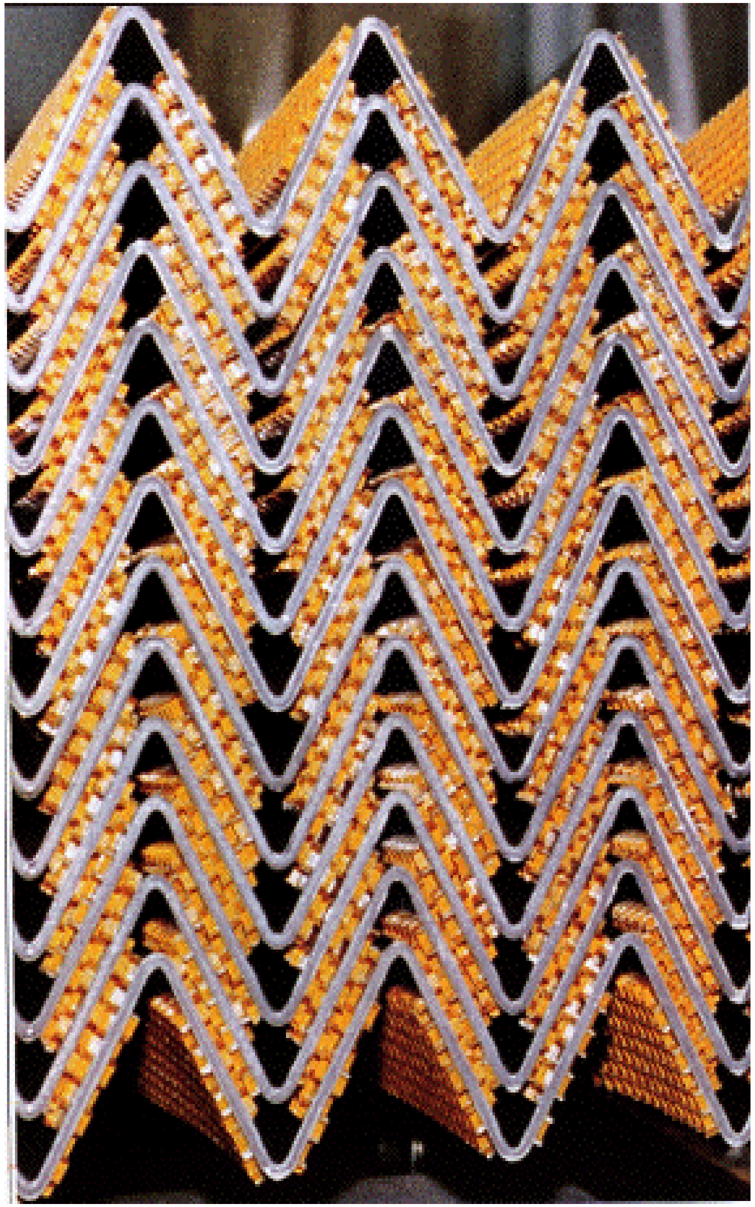
Total:
~ 200 000 channels

Readout: warm preamps + 3-gain shapers (t_p ~ 40 ns) + 40 MHz analog pipeline + 12-bit ADC



Accordion barrel





2 π detector with no cracks or gaps, no cables inside the detector

ATLAS LAr EM Calorimetry

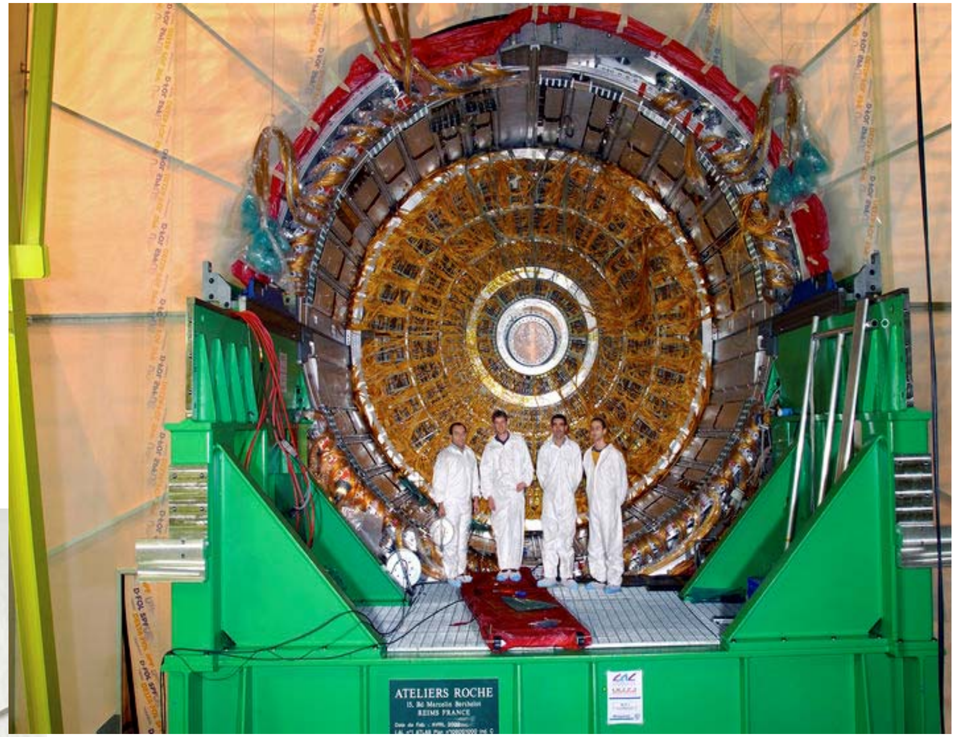
- 1024 accordion absorber plates
- 32 identical modules
- $\eta < 1.7$

Completely stacked series LAr EM barrel module at Saclay

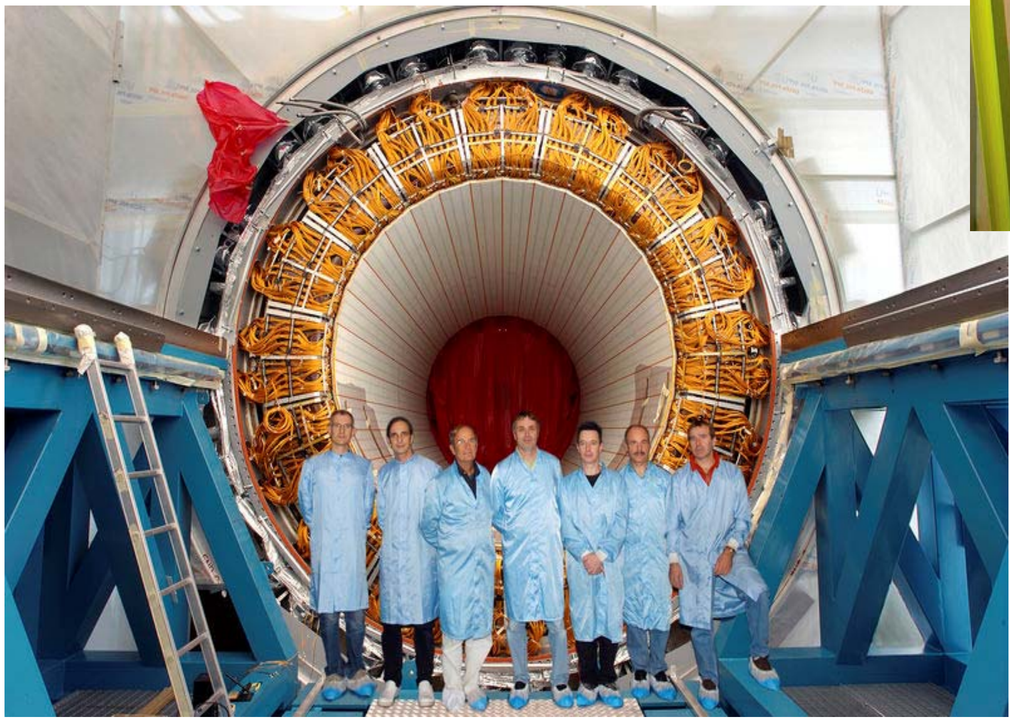
- Inner + Outer wheel
- 768 (256) accordion absorbers/wheel
- 8 identical modules/wheel
- $1.375 < \eta < 3.2$

Series LAr EM end-cap module during stacking at CPPM Marseille

ATLAS LAr EM Calorimetry



The final cold tests of the barrel EM have been done over summer 2004

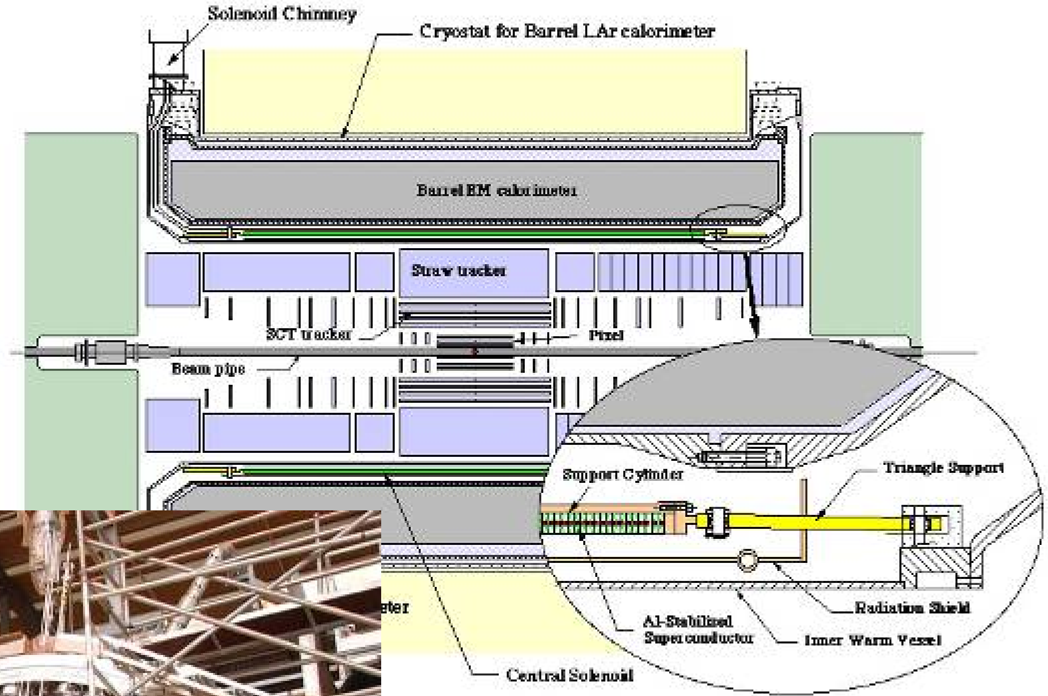


The first of the two LAr end-cap EM calorimeter wheels inserted in the cryostat

ATLAS Central Solenoid

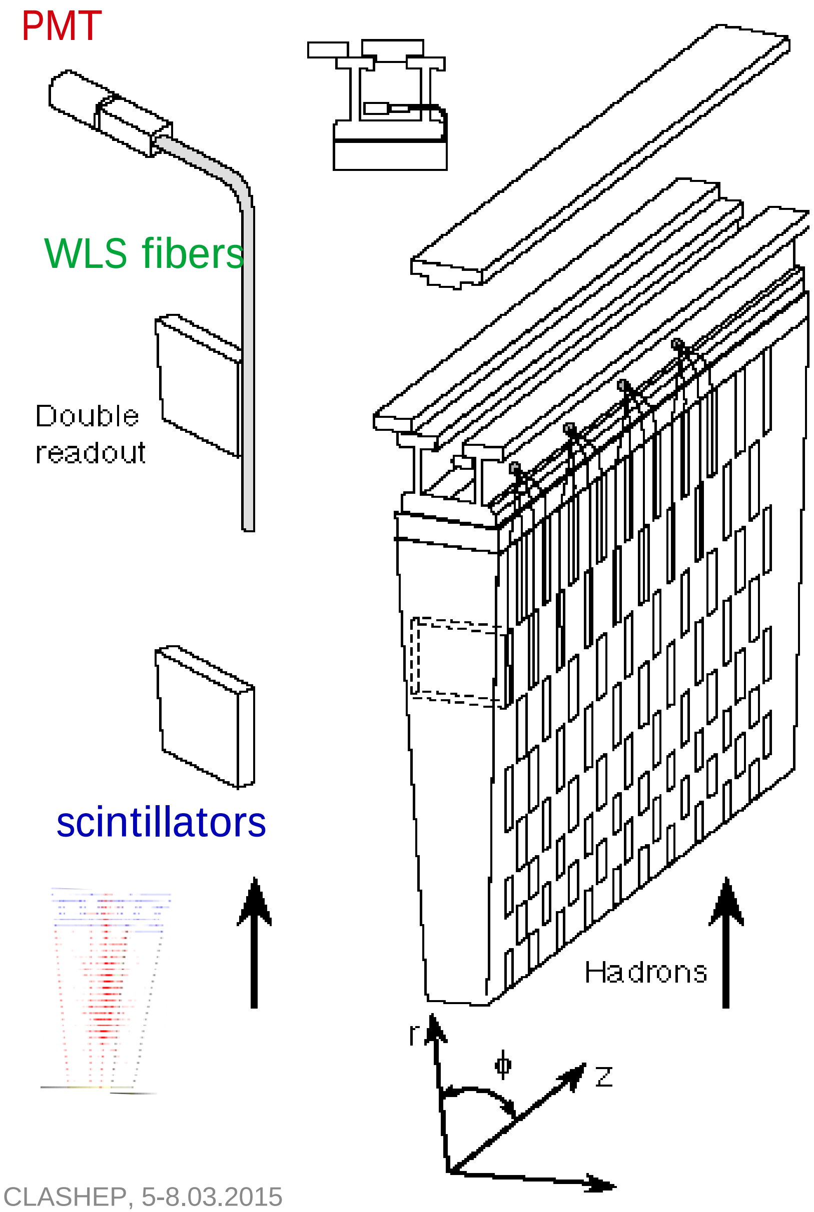
2T field with a stored energy of 38 MJ

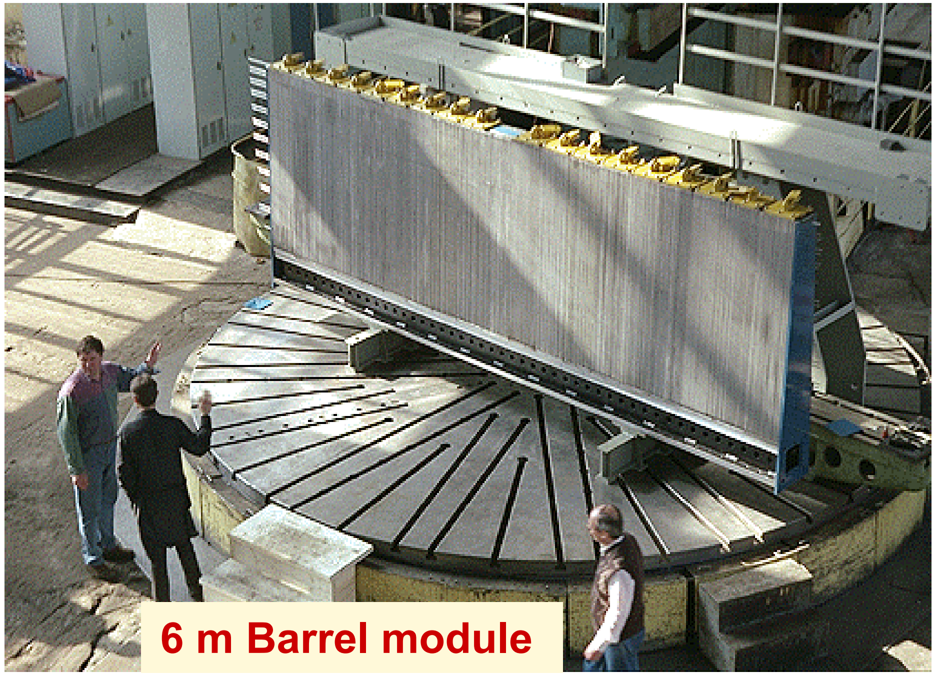
Integrated design within the barrel LAr cryostat



The solenoid has been inserted into the LAr cryostat at the end of February 2004, and it was tested at full current (8 kA) during July 2004

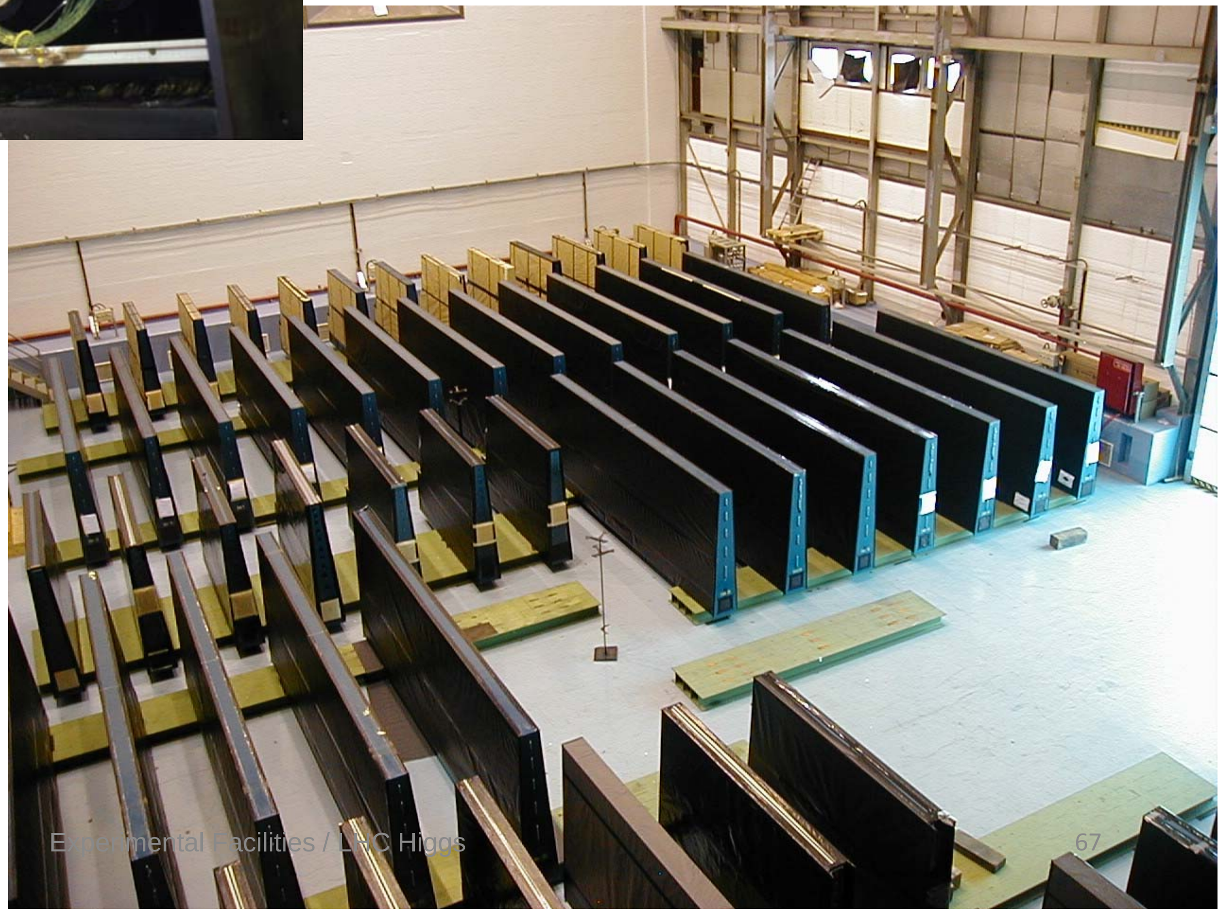
ATLAS Tile Calorimeter



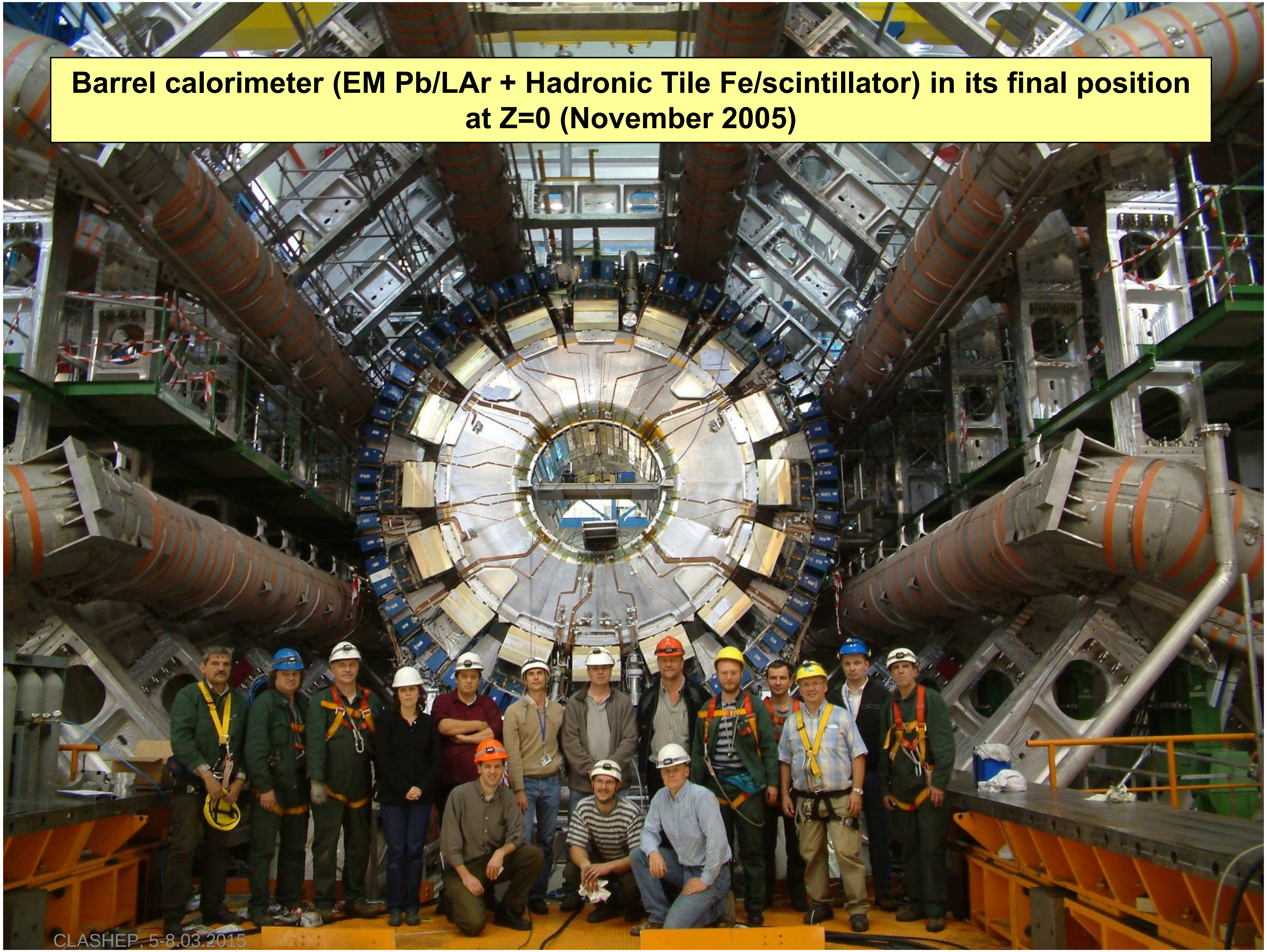


Wavelength-shifting readout fibres grouped to define the pointing cell structure

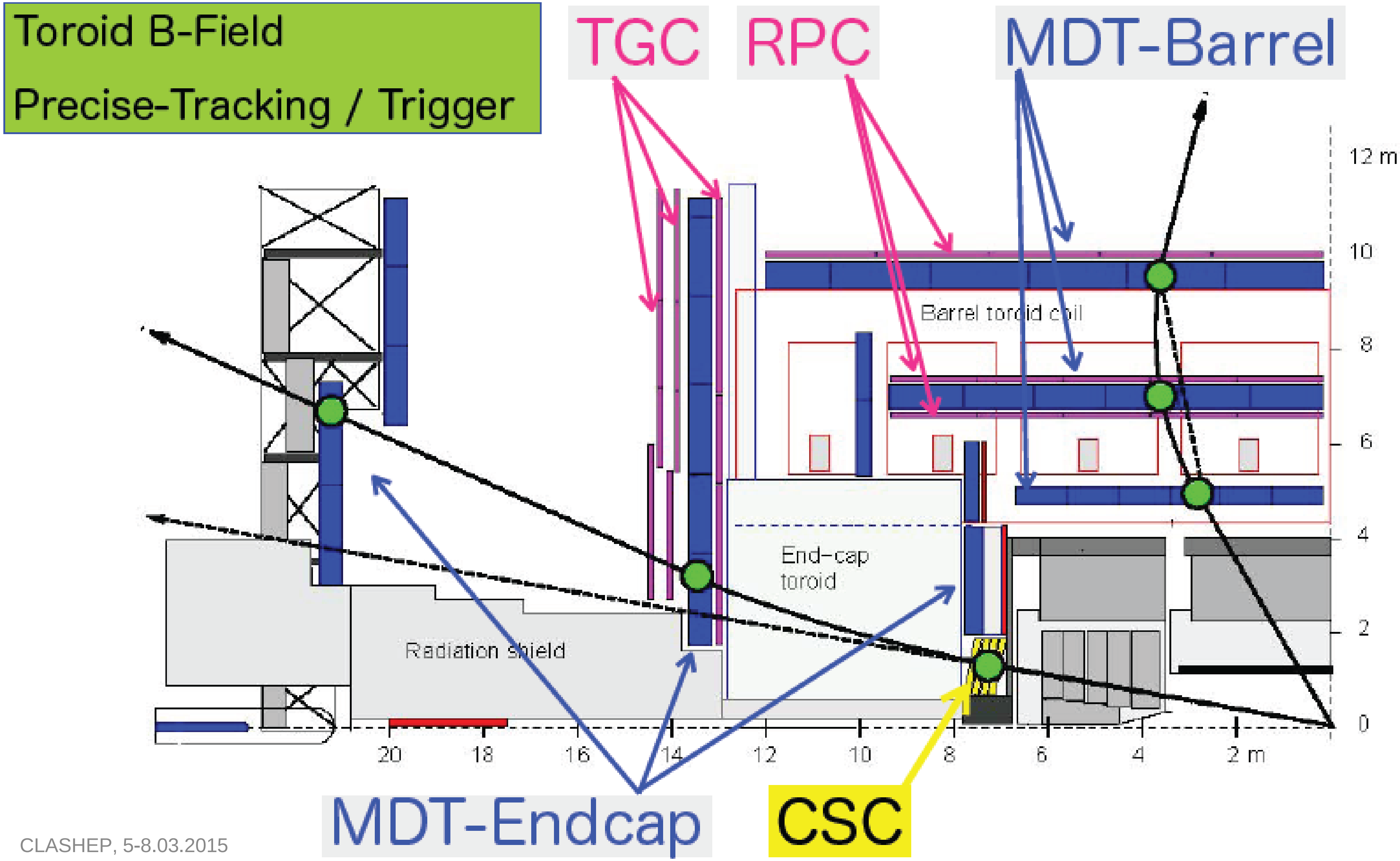
A lot of modules ready for installation (2001)



End of October 2004 the cryostat was transported to the pit, and lowered into the cavern

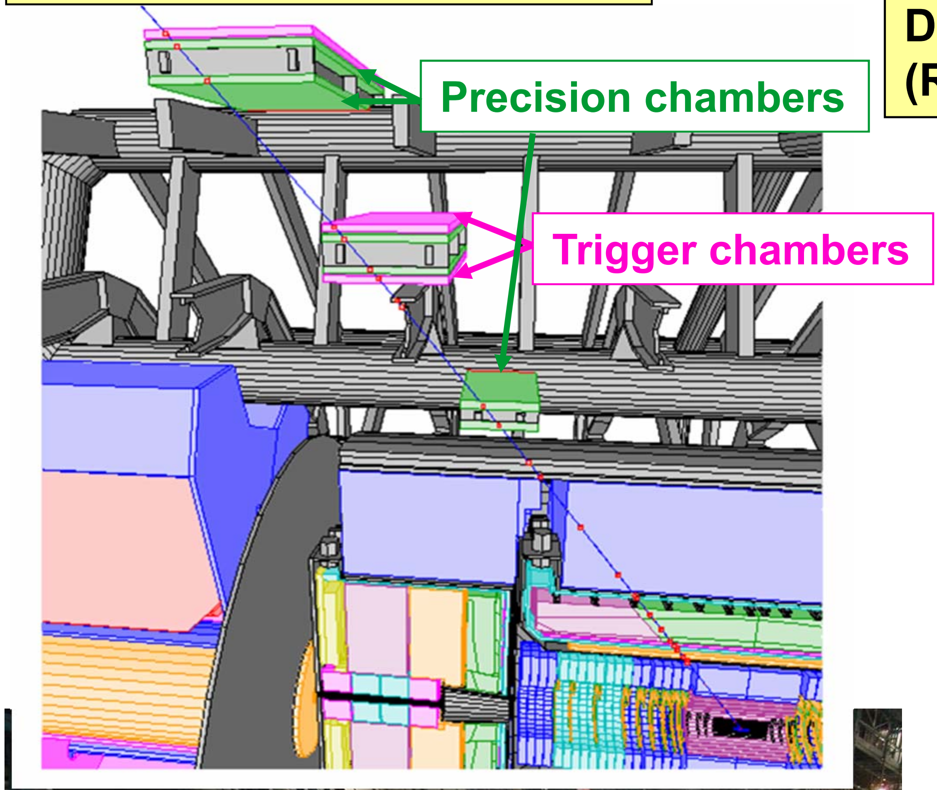

Barrel calorimeter (EM Pb/LAr + Hadronic Tile Fe/scintillator) in its final position at Z=0 (November 2005)

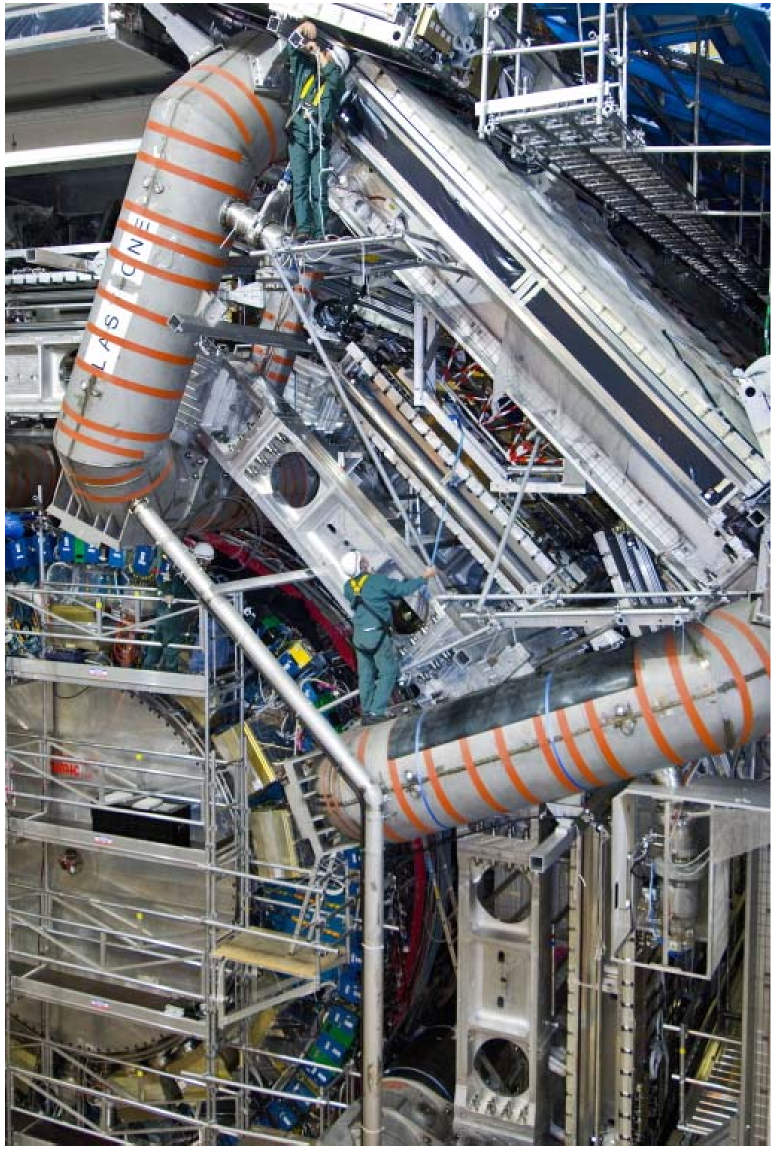
ATLAS Muon System



Muon Spectrometer

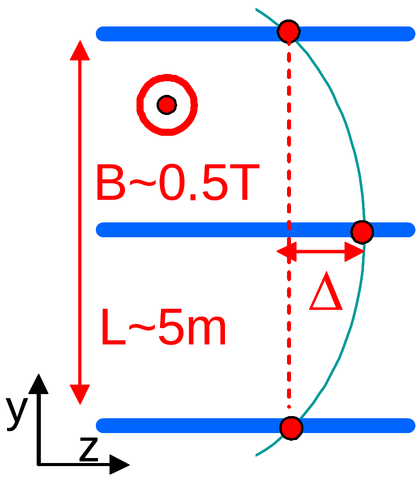
~ 600 barrel precision chambers (Monitored Drift Tubes), ~ 500 barrel trigger chambers (Resistive Plate Chambers)

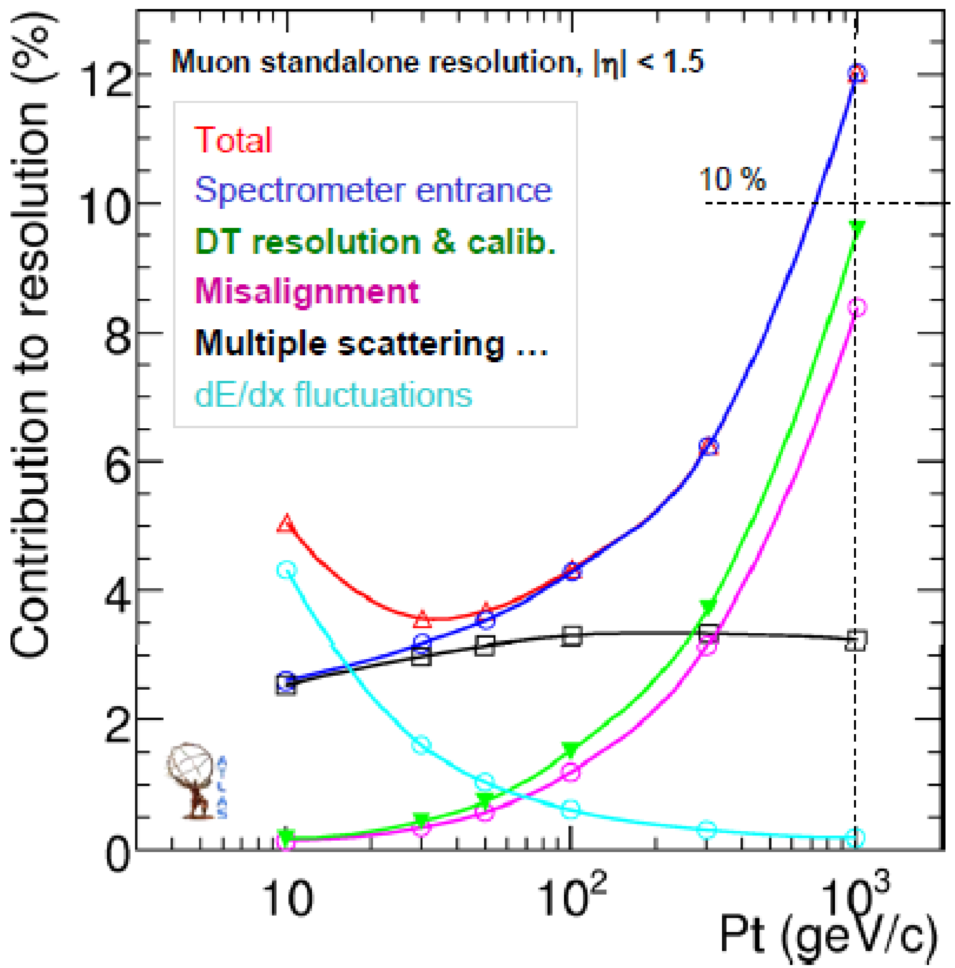




ATLAS Muon Spectrometer:
E_{μ}~ 1 TeV $\Rightarrow$ Δ~500 μm

- σ/p ~10% $\Rightarrow$ $\delta\Delta$~50 μm
- alignment accuracy to ~30 mm

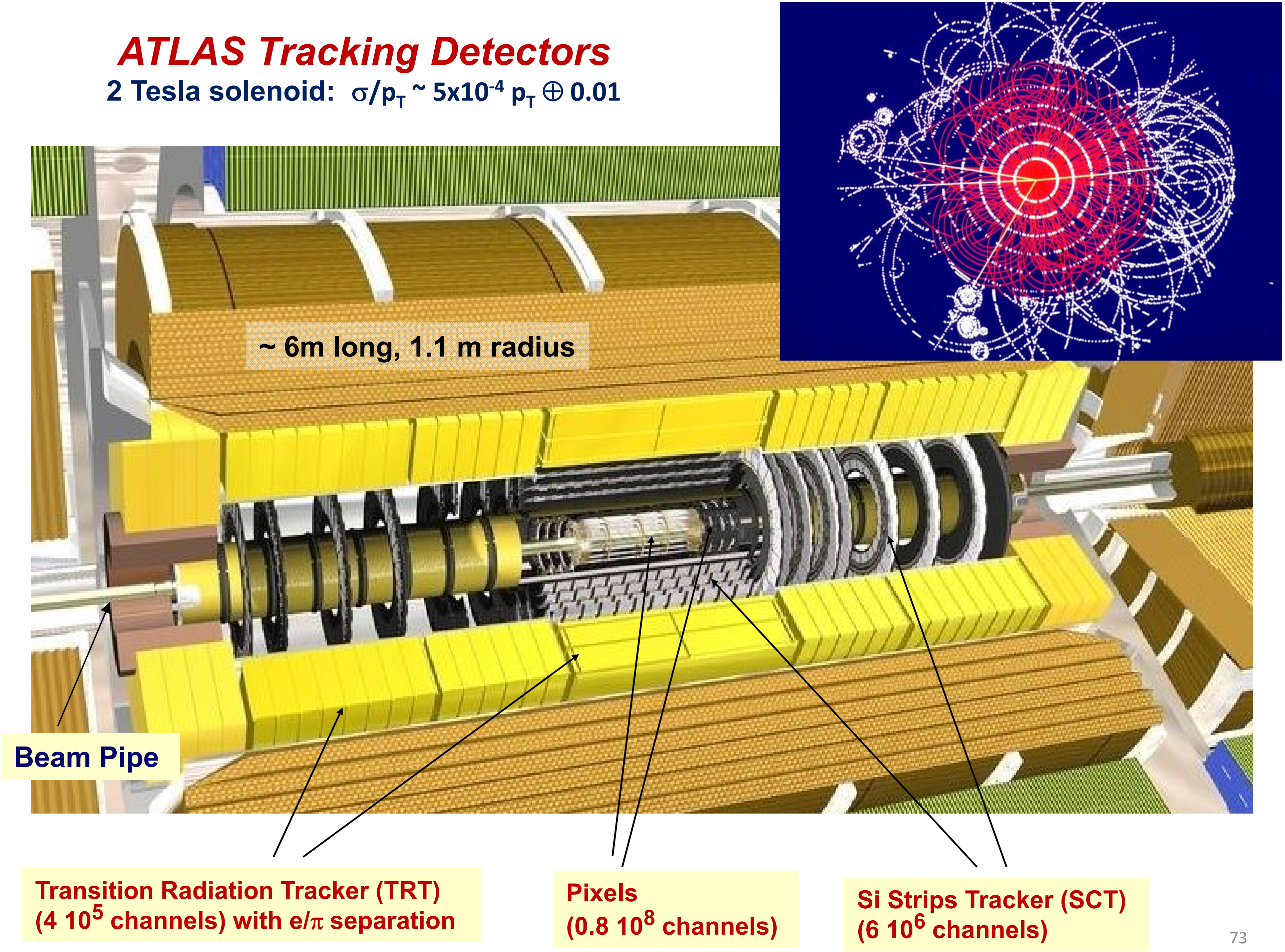




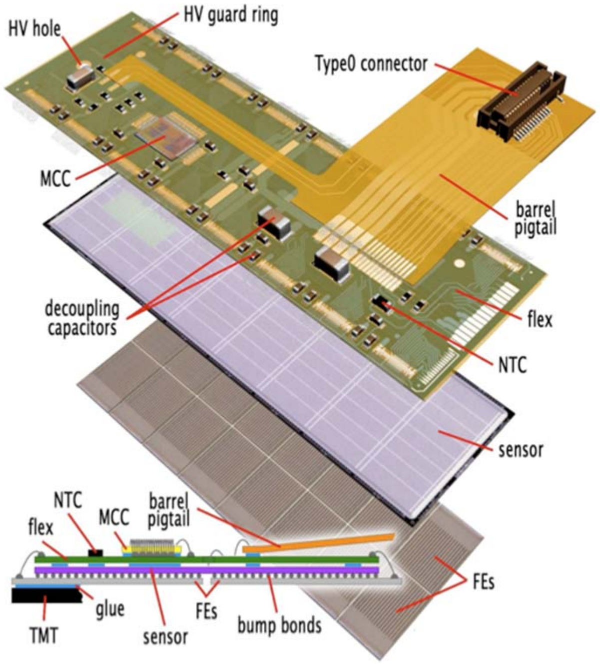
~ 1800 Hall probes to measure B-field to 0.1%, thousands of temperature probes, etc.

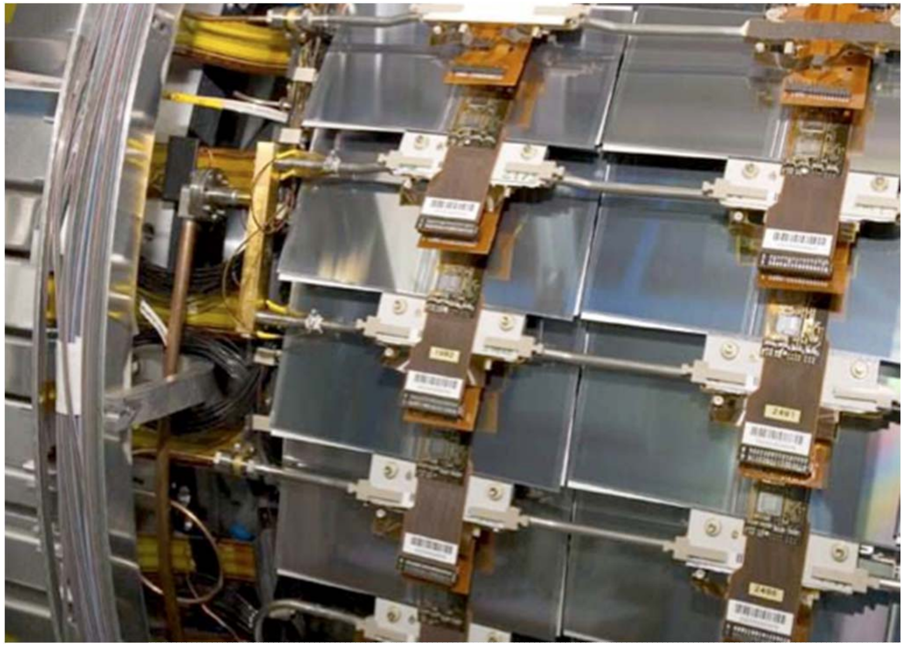
ATLAS Tracking Detectors

2 Tesla solenoid: $\sigma/p_T \sim 5\mathrm{x}10^{-4}\, p_T \oplus 0.01$



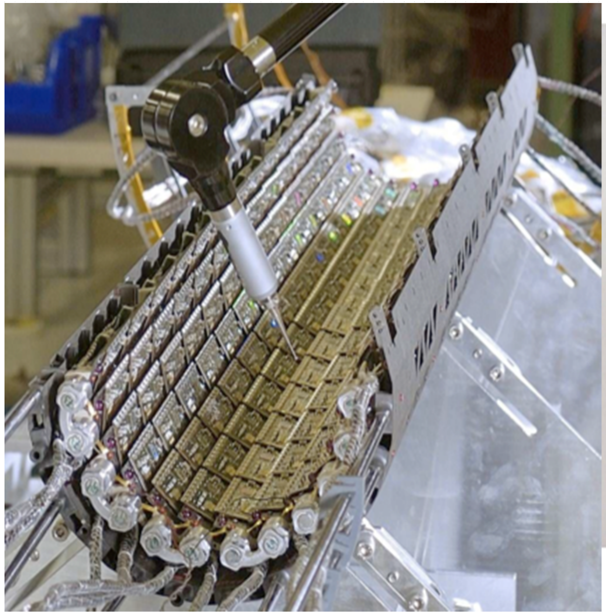
ATLAS Inner Detector Silicon-sensors

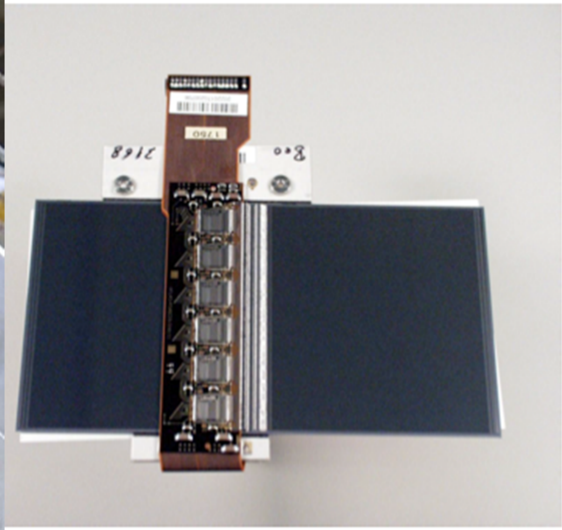


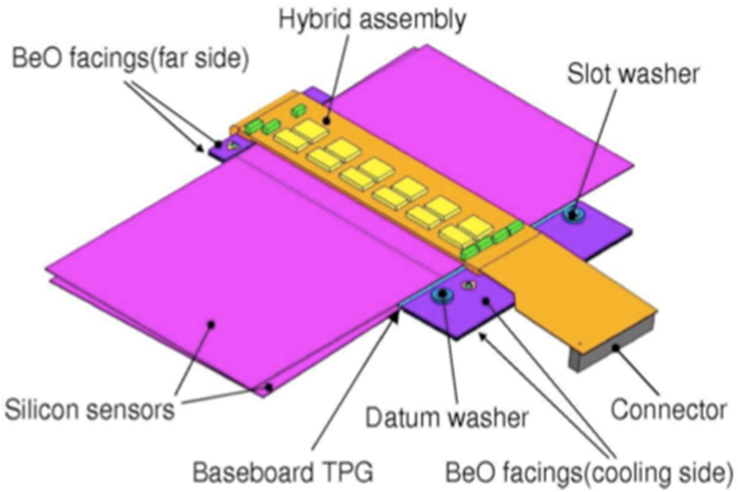


1744 Pixel modules, pixels 50x400 μm^2

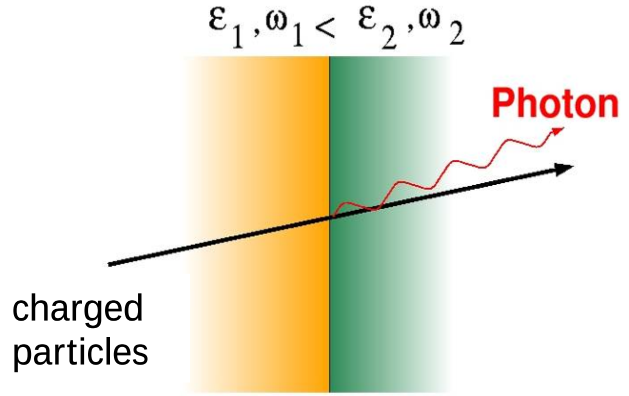
4088 SCT modules, 80 μm micro-strips



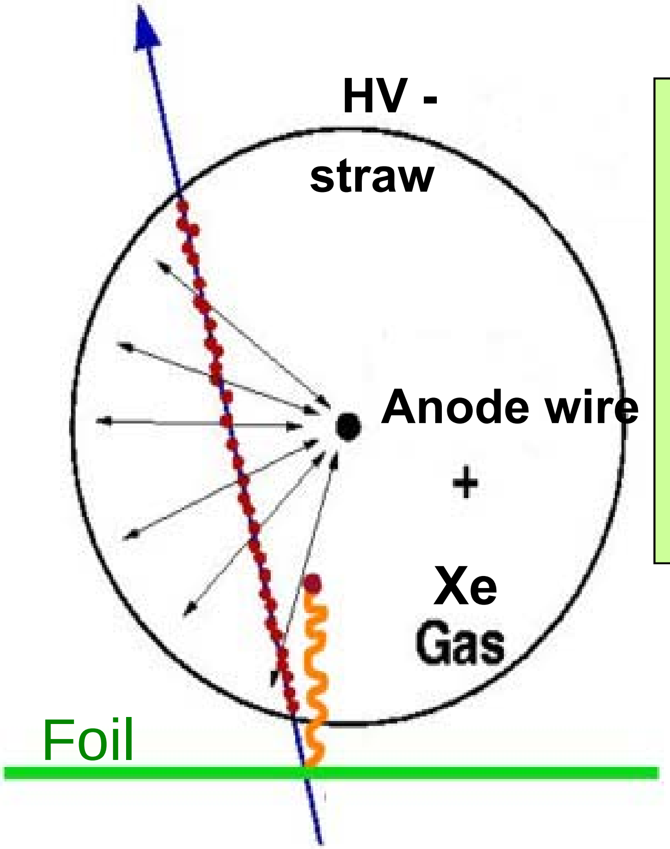




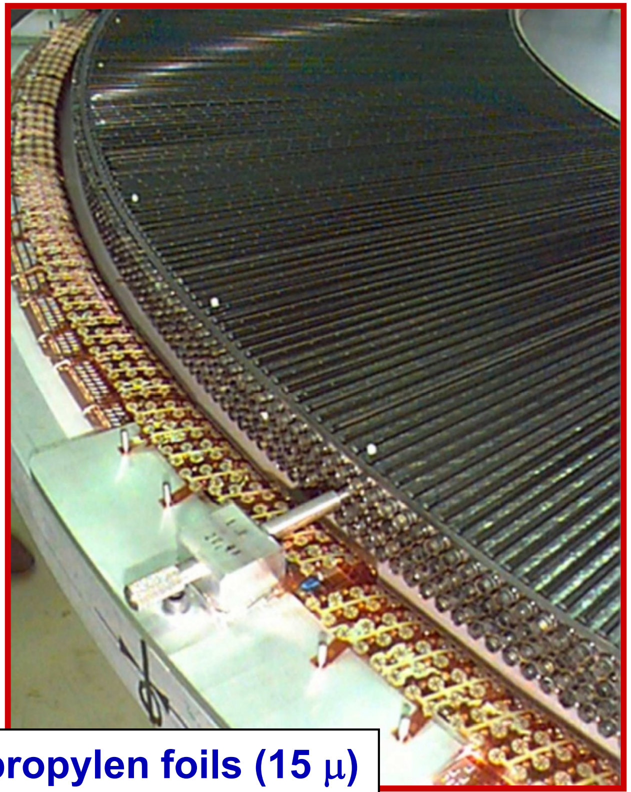
The Transition Radiation detector (TRT)



Transition radiation is emitted whenever a relativistic charged particle traverses the border between two media with different dielectric constants.
TR intensity is proportional to the particle γ-factor
$\rightarrow$ for a given particle momentum p, electrons emit more TR than pions $\rightarrow$ TR detectors used for particle identification



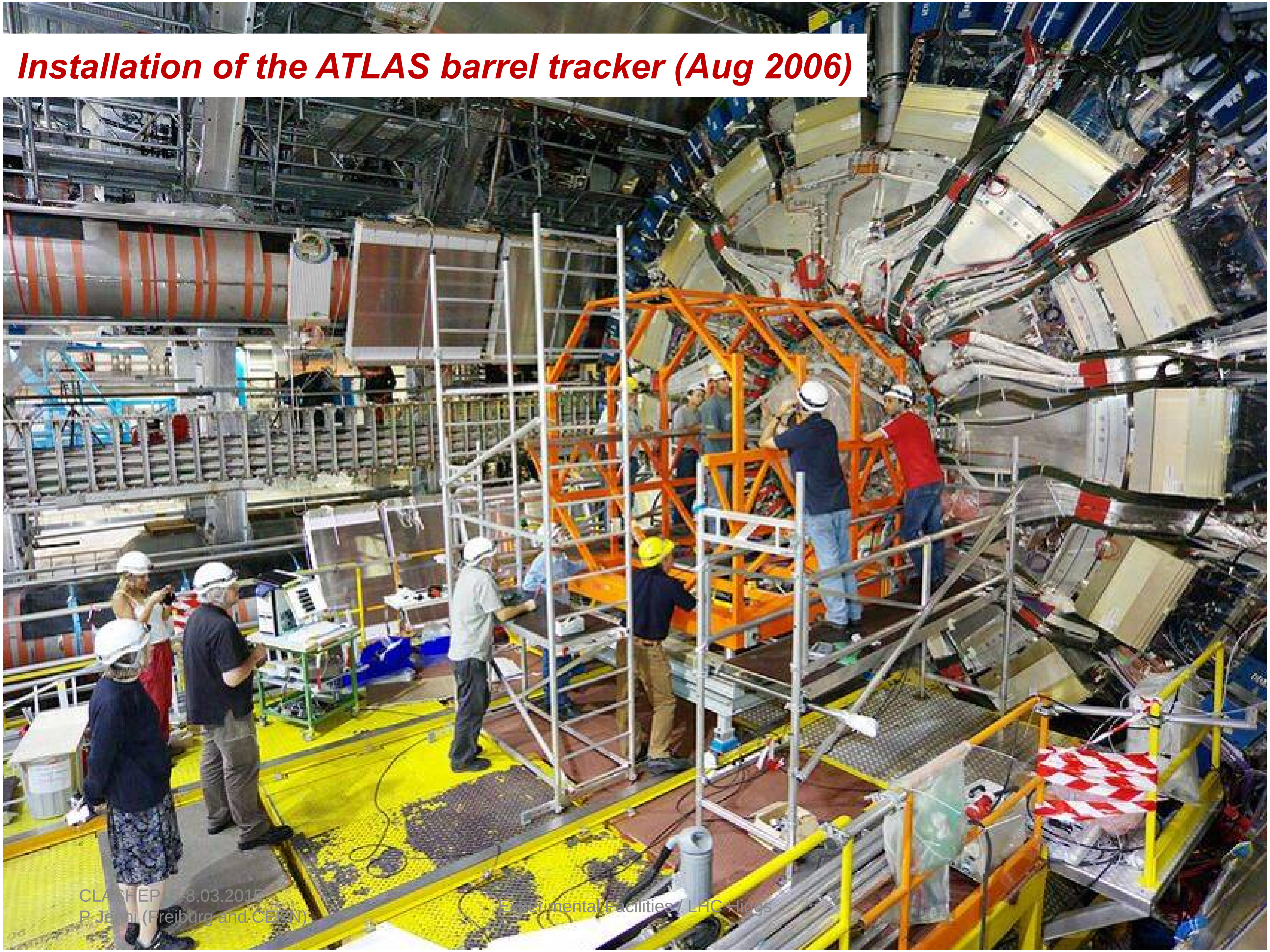
- **Energy of TR photons (proportional to ε_1-ε_2): ~ 10-30 keV (X-rays)**
- **Many crossings of polypropylene foils (radiator) to increase TR photons**
- **Xenon as active gas for high X-ray absorption**

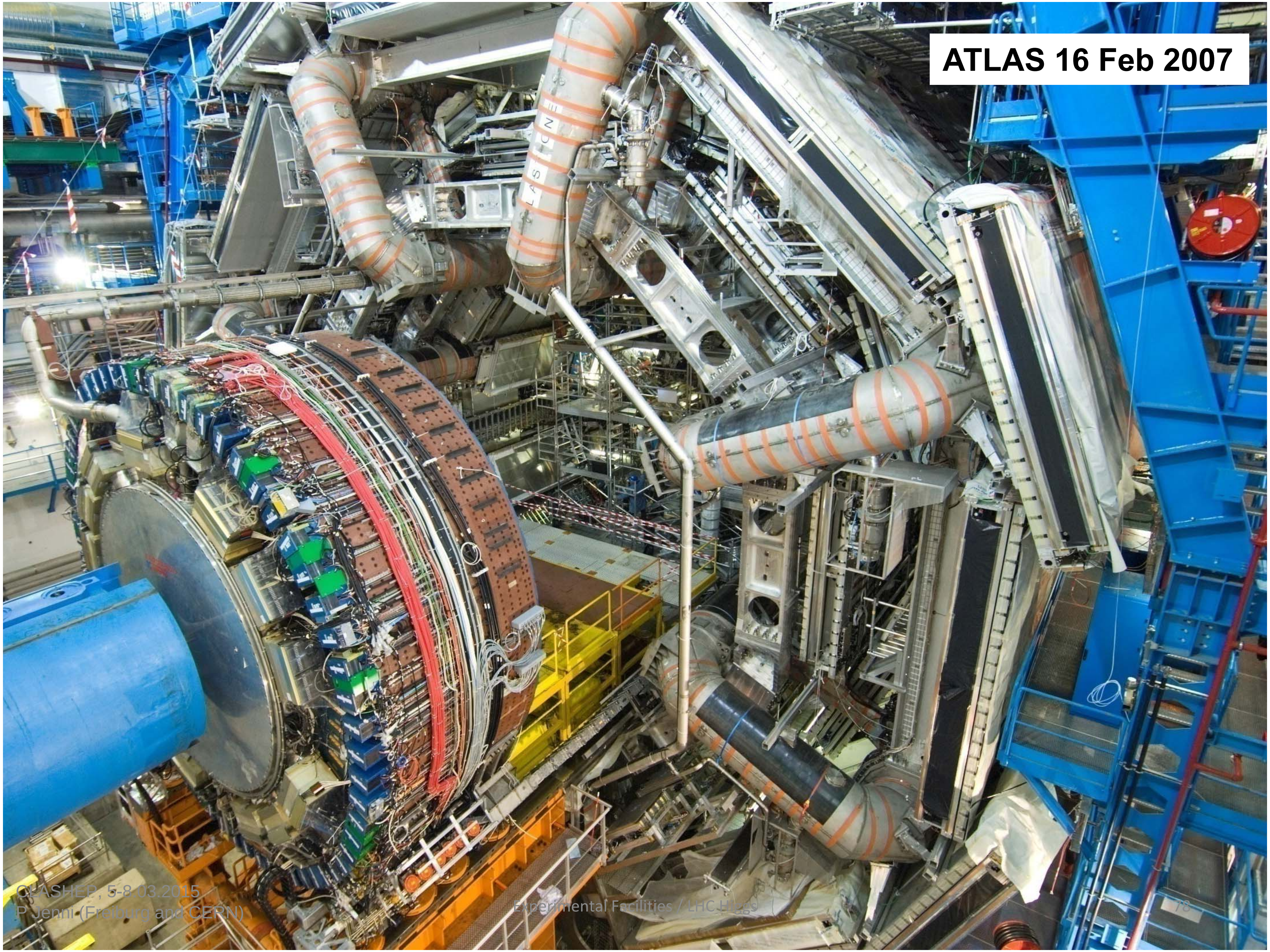


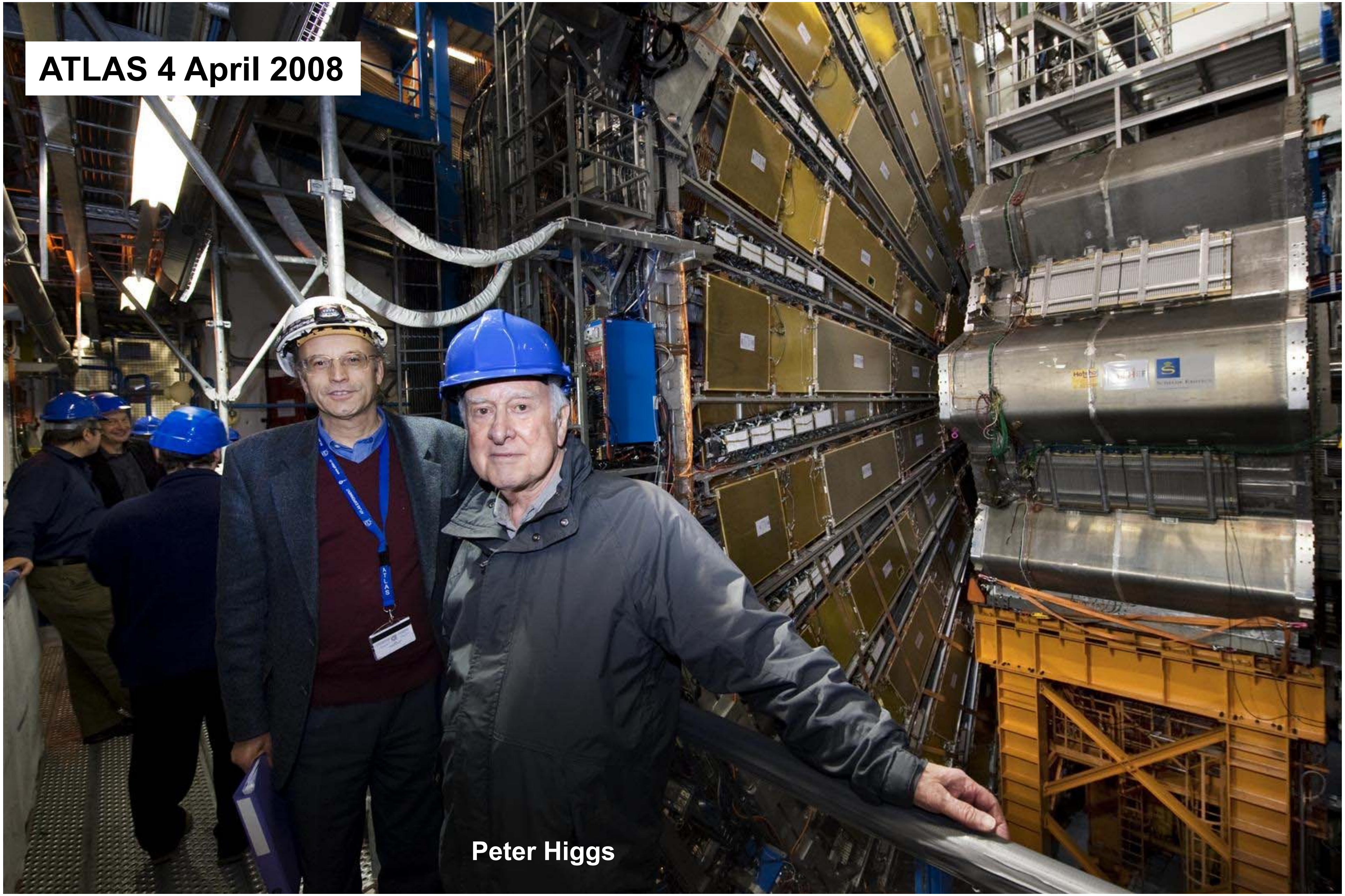
Radiator: Polypropylen foils (15 μ) interleaved with straws

End of February 2006 the barrel SCT was inserted into the barrel TRT

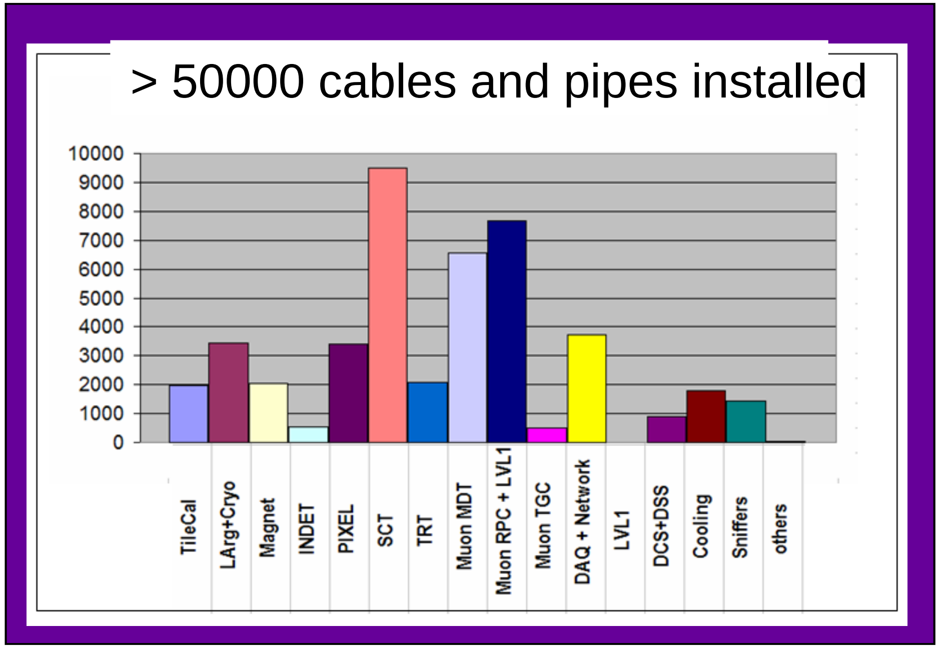
Installation of the ATLAS barrel tracker (Aug 2006)

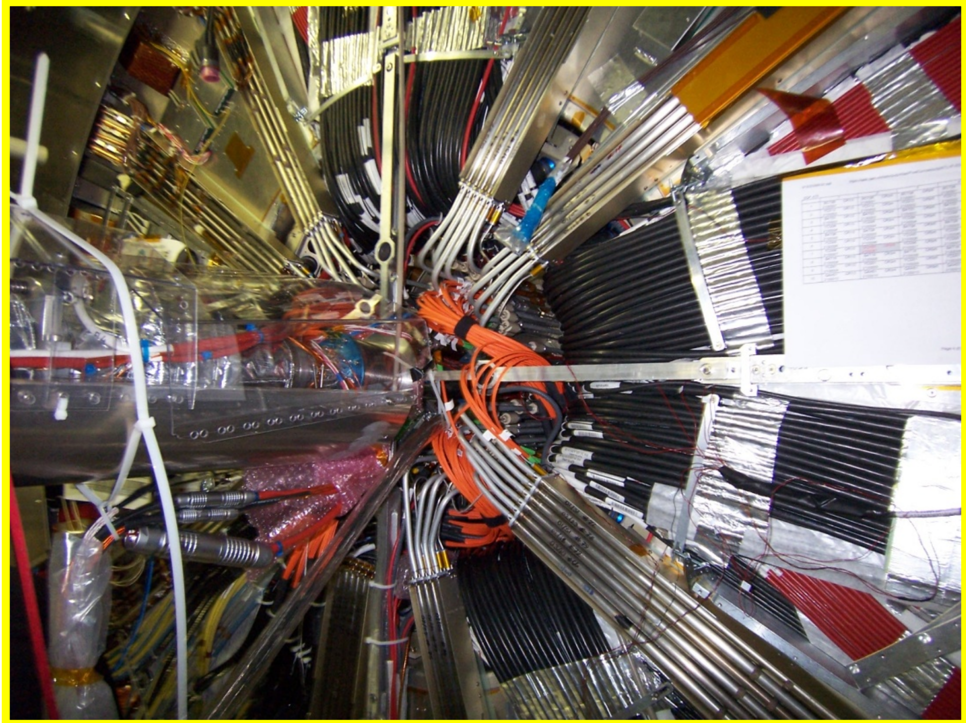


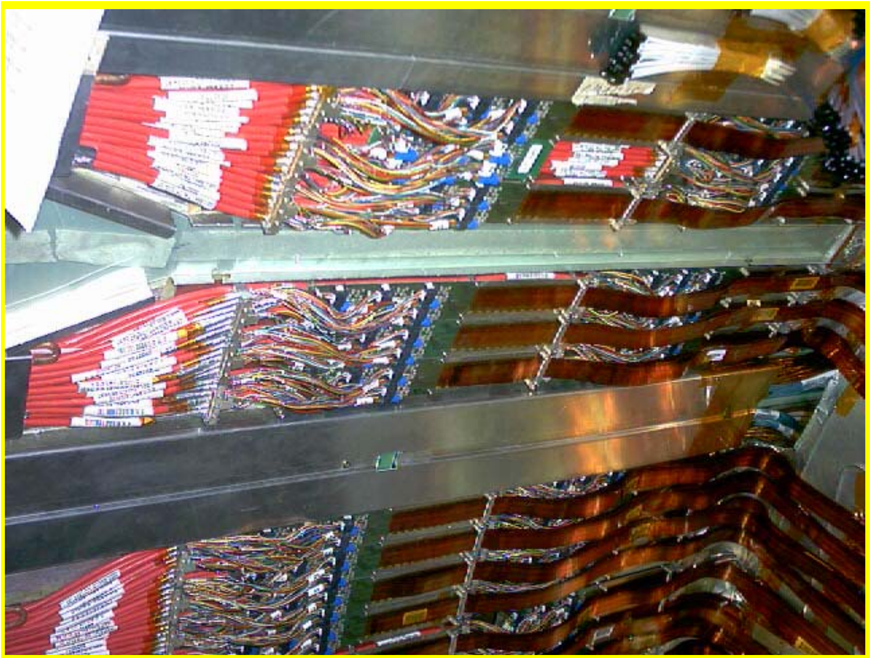

ATLAS 16 Feb 2007


ATLAS 4 April 2008
Peter Higgs

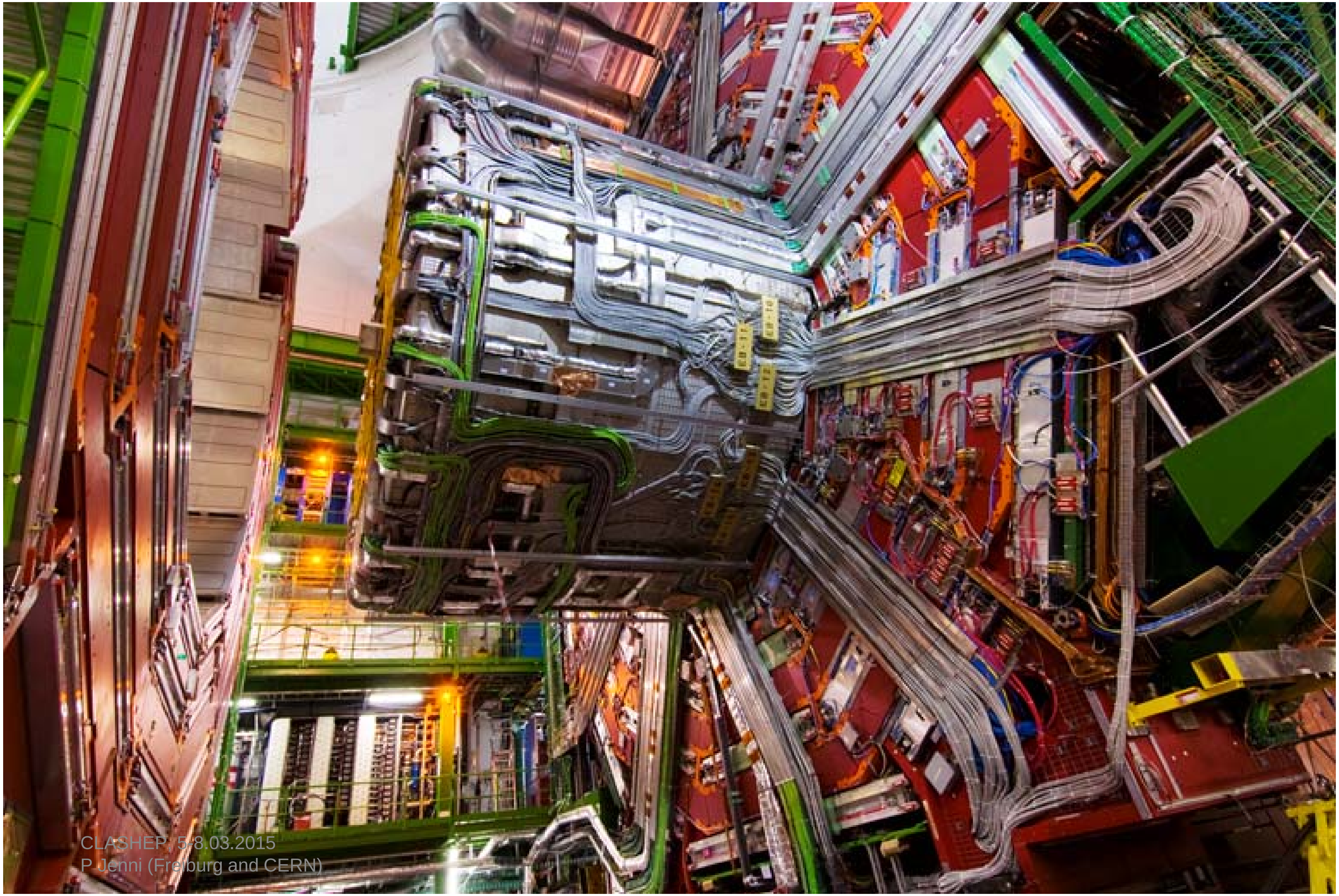
A lot of cables and pipes (ATLAS)

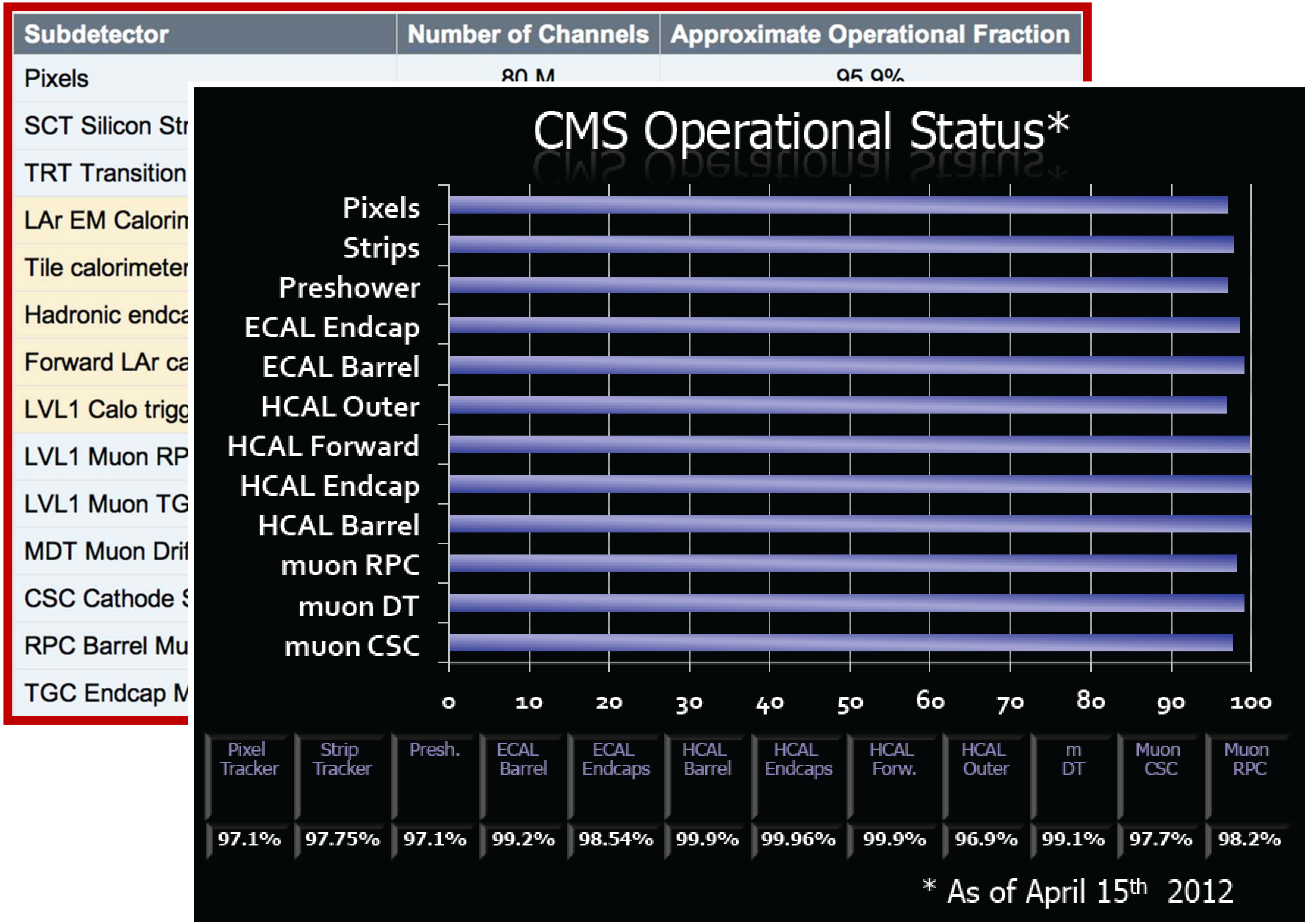






Cables and services in CMS




Subdetector
Number of Channels
Approximate Operational Fraction
Pixels
80 M
95.9%
SCT Silicon Str
TRT Transition
LAr EM Calorin
Tile calorimeter
Hadronic endca
Forward LAr ca
LVL1 Calo trigg
LVL1 Muon RP
LVL1 Muon TG
MDT Muon Drif
CSC Cathode S
RPC Barrel Mu
TGC Endcap M
CMS Operational Status*
Pixels
Strips
Preshower
ECAL Endcap
ECAL Barrel
HCAL Outer
HCAL Forward
HCAL Endcap
HCAL Barrel
muon RPC
muon DT
muon CSC
0 10 20 30 40 50 60 70 80 90 100
Pixel Tracker 97.1%
Strip Tracker 97.75%
Presh. 97.1%
ECAL Barrel 99.2%
ECAL Endcaps 98.54%
HCAL Barrel 99.9%
HCAL Endcaps 99.96%
HCAL Forw. 99.9%
HCAL Outer 96.9%
m DT 99.1%
Muon CSC 97.7%
Muon RPC 98.2%
* As of April 15th 2012

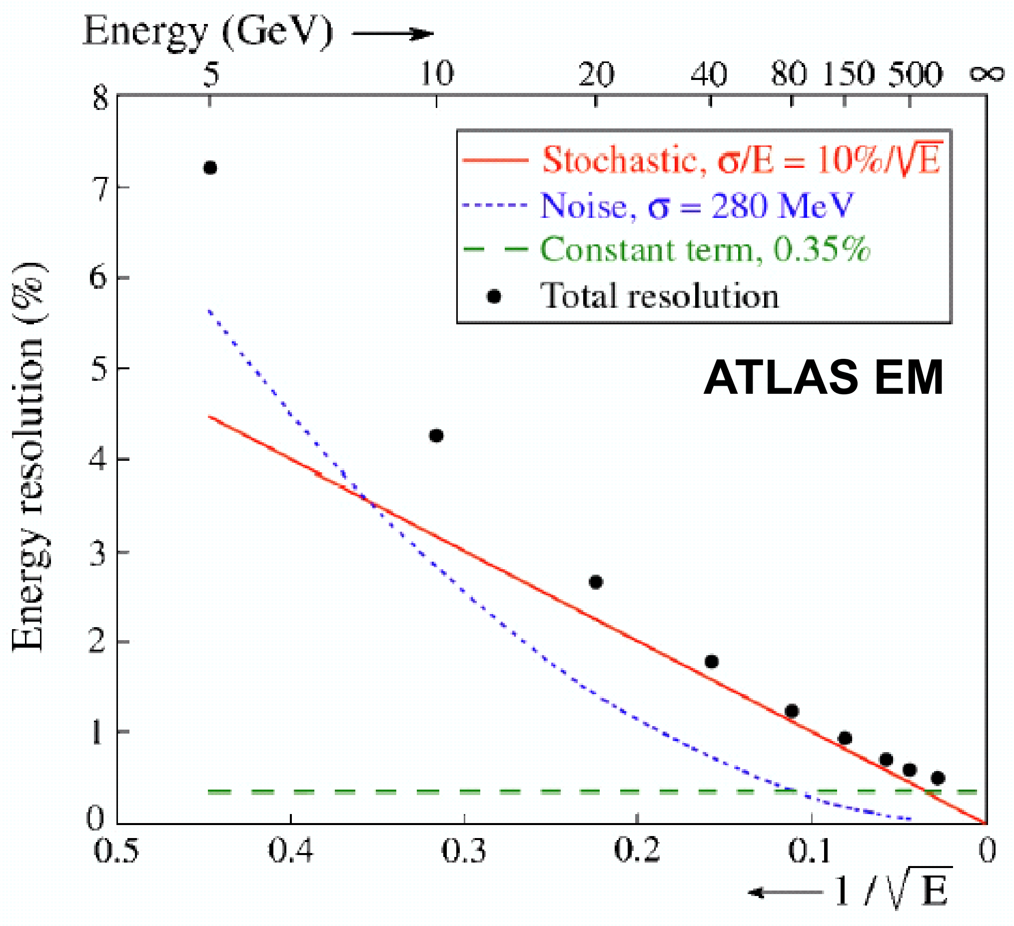
Complementary Approaches in ATLAS and CMS

	ATLAS ≡ A Toroidal LHC ApparatuS	CMS ≡ Compact Muon Solenoid
MAGNET (S)	Air-core toroids + solenoid in inner cavity (4 magnets) Calorimeters in field-free region	Solenoid Only 1 magnet Calorimeters inside field
TRACKER	Si pixels+ strips TRT $\rightarrow$ particle identification B=2T $\sigma/p_T \sim 3.8\mathrm{x}10^{-4}\, p_T \oplus 0.015$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5\mathrm{x}10^{-4}\, p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$ no longitudinal segm.
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air $\rightarrow$ $\sigma/p_T \sim 10$ % at 1 TeV standalone (~ 7% combined with tracker)	Fe $\rightarrow$ $\sigma/p_T \sim 15\text{-}30\%$ at 1 TeV standalone (5% with tracker)

Calorimeter energy resolution

Usually parametrised by

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

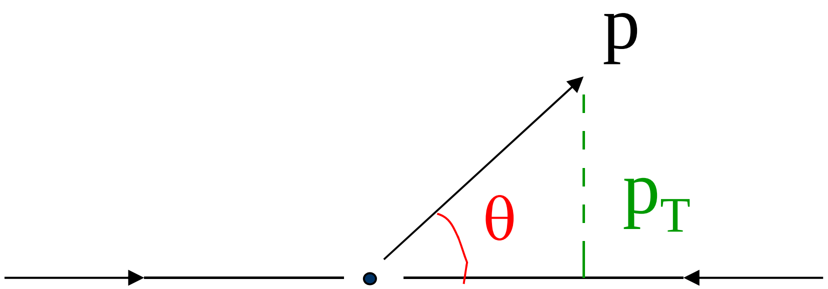


a : intrinsic resolution or stochastic term
→ given by technology choice

c : contribution of electronics noise
+ at LHC pile up noise…
→ given by electronics design

b : constant term, it contains all the imperfection
response variation versus position (uniformity), time (stability), temperature….
→ Constraints on all aspects : mechanics, electronics….

Variables used in the analysis of pp collisions

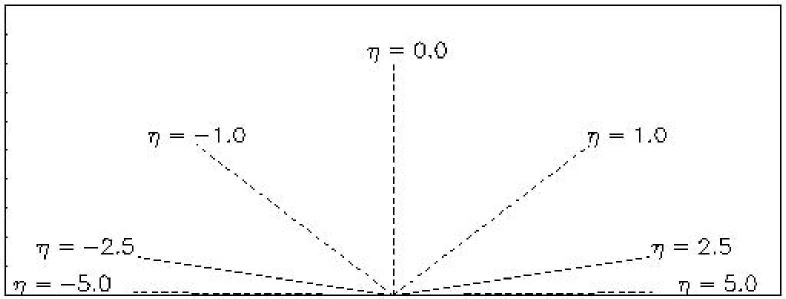


Transverse momentum
(in the plane perpendicular to the beam)

$$p_T = p \sin\theta$$

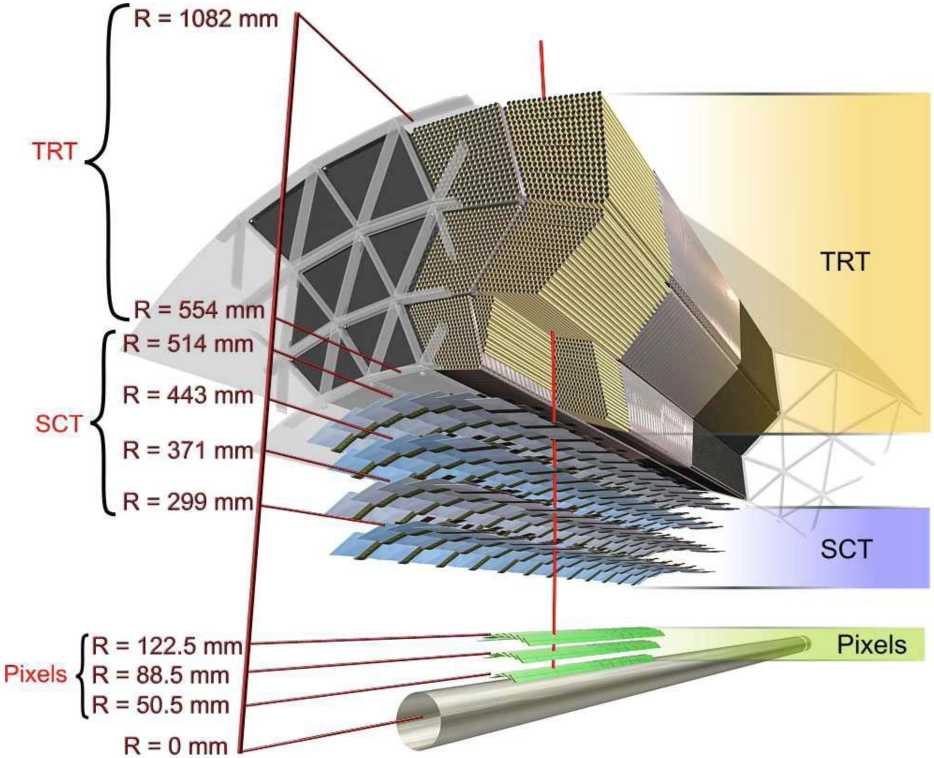
(Pseudo)-rapidity: $\eta = -\ln \tan \frac{\Theta}{2}$

$$\eta = \frac{1}{2} \ln \left(\frac{|\vec{p}| + p_L}{|\vec{p}| - p_L} \right),$$

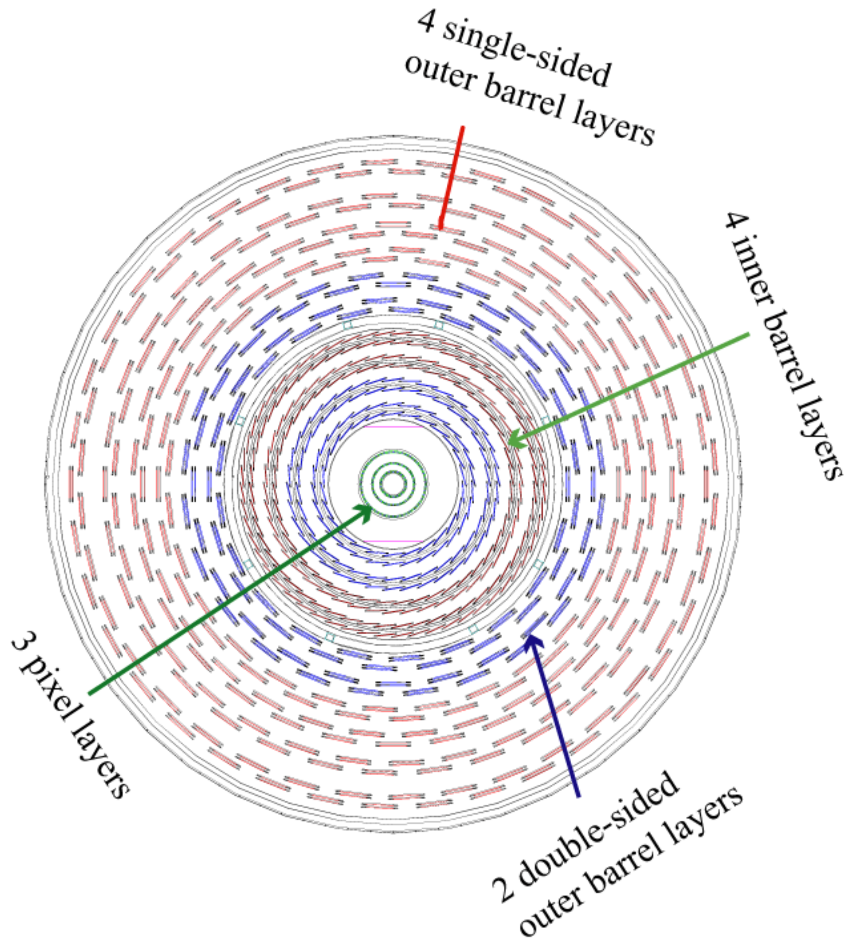


θ = 90° → η = 0
θ = 10° → η ≅ 2.4
θ = 170° → η ≅ -2.4

A critical issue in the design is the material in the inner tracker, in front of the electromagnetic calorimeter



ATLAS



CMS

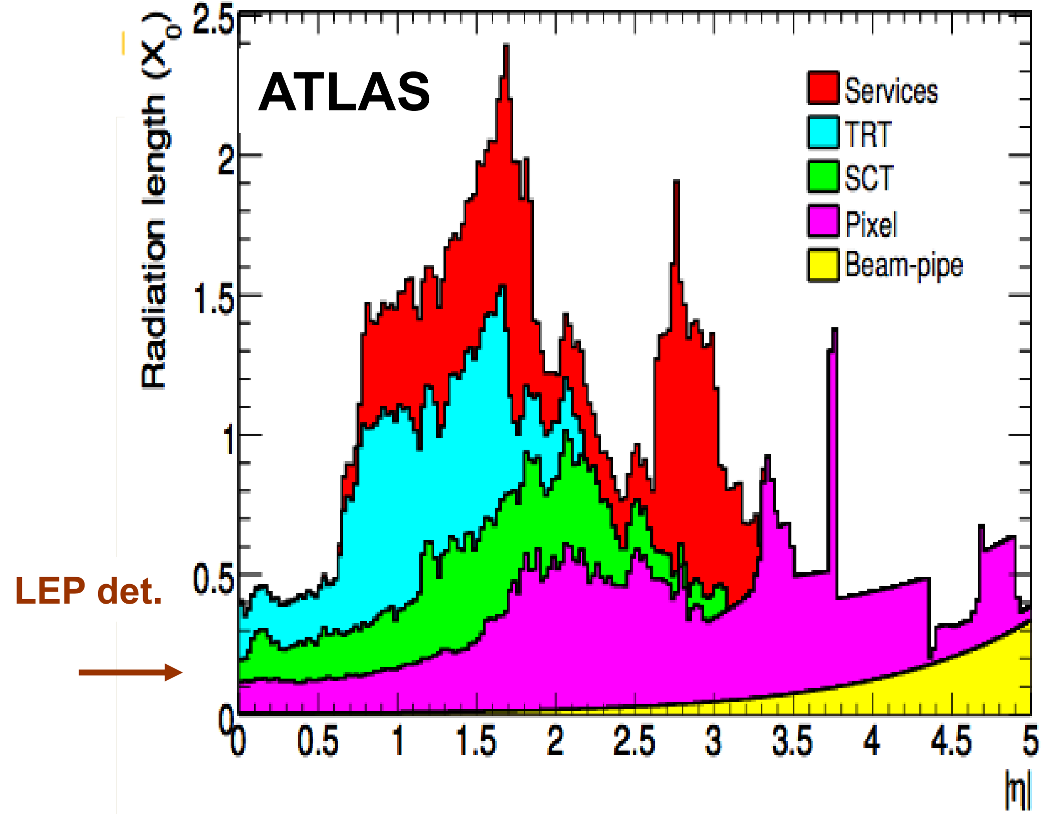
Charged Particle Interactions with Matter

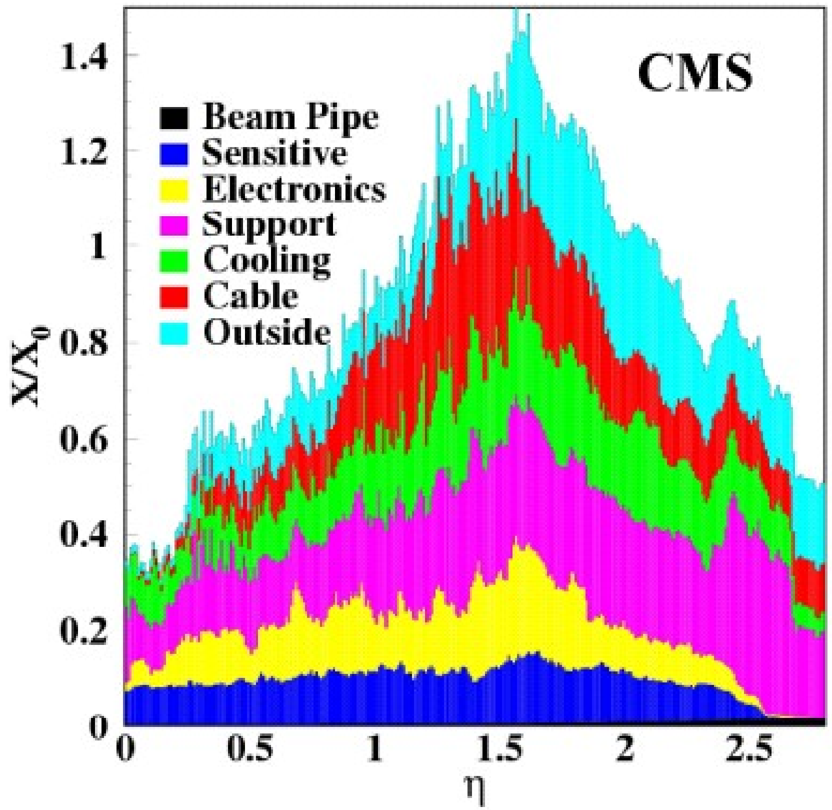
Particles are detected through their interaction with the active detector materials

Inner tracker material through planning and construction

- Energy loss by ionisation
- Bremsstrahlung
- Multiple scattering

Weight: 4.5 tons **Weight: 3.7 tons**





For ATLAS, need to add ~2 X_0 (η = 0) from solenoid + cryostat in front of EM calorimeter

Strategy toward physics

A slide from 2008, at the time of anticipating first collisions

Before data taking starts:

- **Strict quality controls of detector construction to meet physics requirements**
- **Test beams (a 15-year activity culminating with a combined test beam in 2004) to understand and calibrate (part of) detector and validate/tune software tools (e.g. Geant4 simulation)**
- **Detailed simulations of realistic detector "as built and as installed" (including misalignments, material non-uniformities, dead channels, etc.) → test and validate calibration/alignment strategies**
- **Experiment commissioning with cosmics in the underground cavern**

With the first data:

- **Commission/calibrate detector/trigger in situ with physics (min.bias, Z→ll, …)**
- **"Rediscover" Standard Model, measure it at $\sqrt{s}$ = 7 TeV (minimum bias, W, Z, tt, QCD jets, …)**
- **Validate and tune tools (e.g. MC generators)**
- **Measure main backgrounds to New Physics (W/Z+jets, tt+jets, QCD-jets,…)**

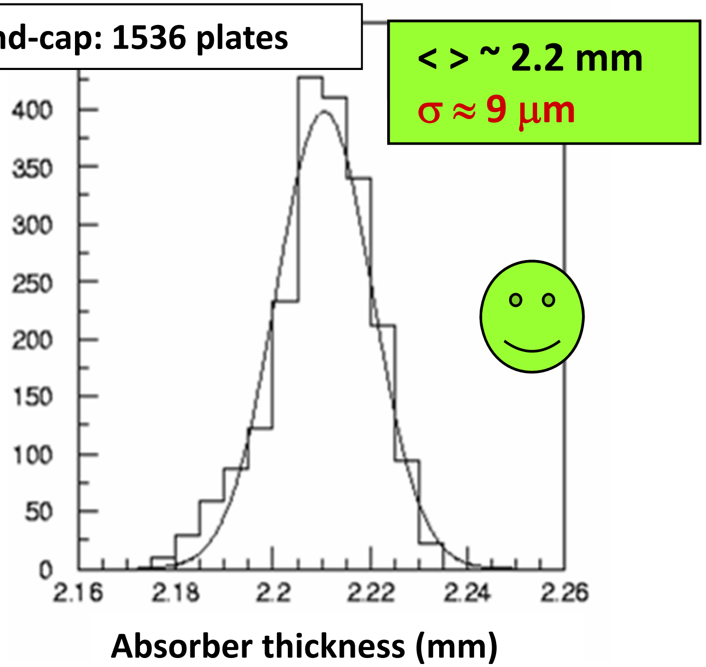
↓

Prepare the road to discoveries …

Construction example: ATLAS LAr em Accordion Calorimeter

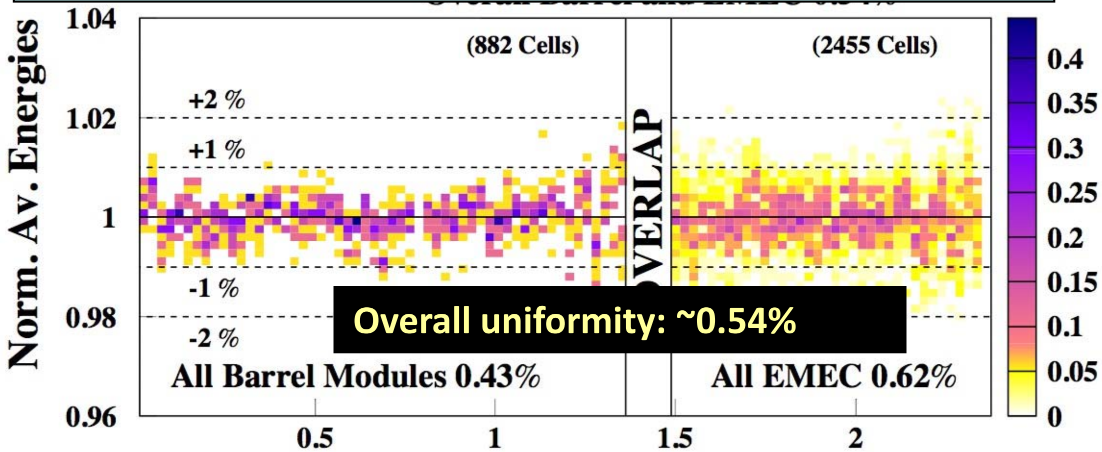
Construction quality

Thickness of Pb plates must be uniform to 0.5% (~10 μm)

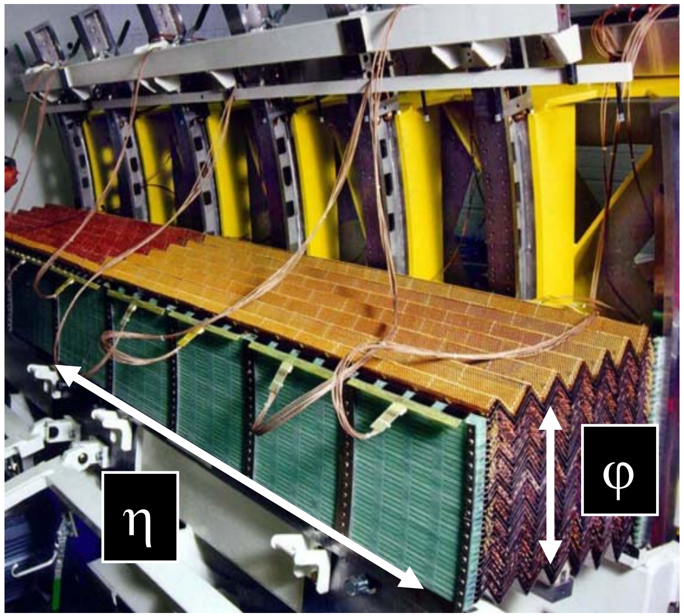


Test-beam measurements

4 (out of 32) barrel modules and 3 (out of 16) end-cap (EMEC) modules tested with beams

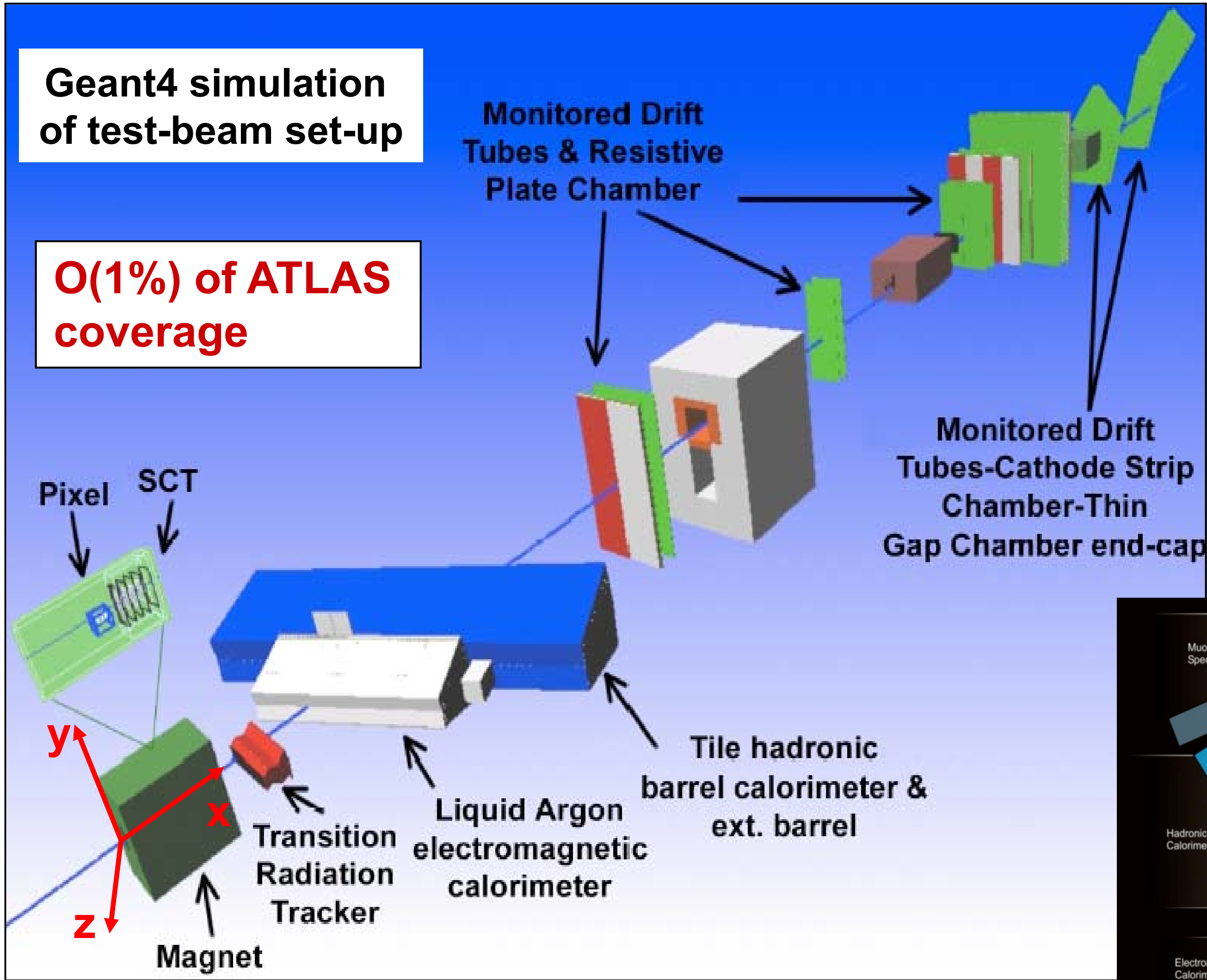


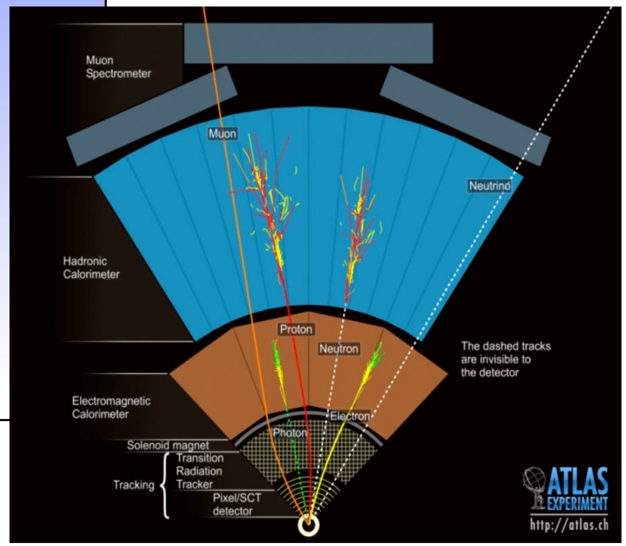
1 barrel module:
$\Delta\eta \times \Delta\varphi = 1.4 \times 0.4$
≈ 3000 channels



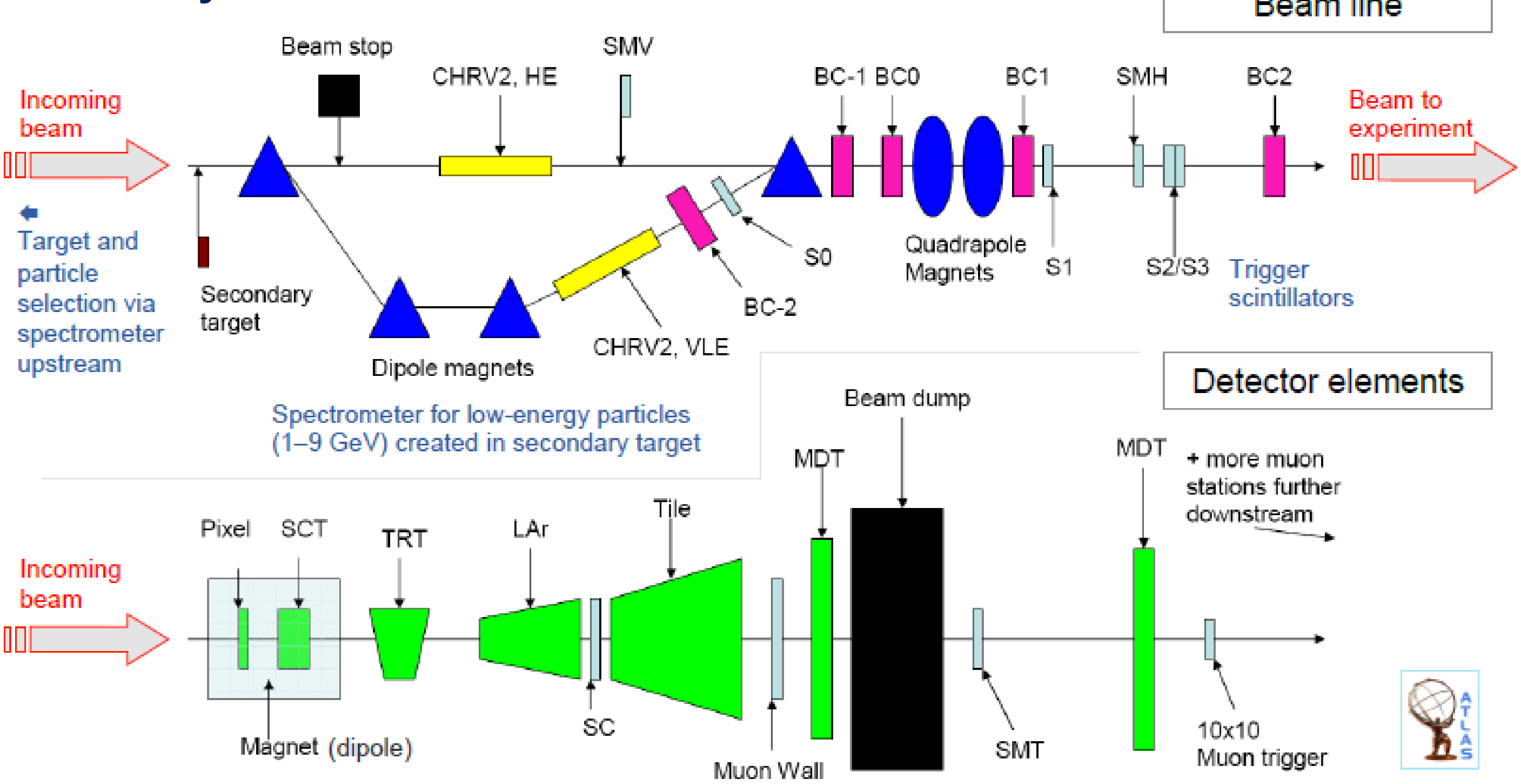
Example: 2004 ATLAS combined test beam

Full “vertical slice” of ATLAS tested in CERN H8 beam line





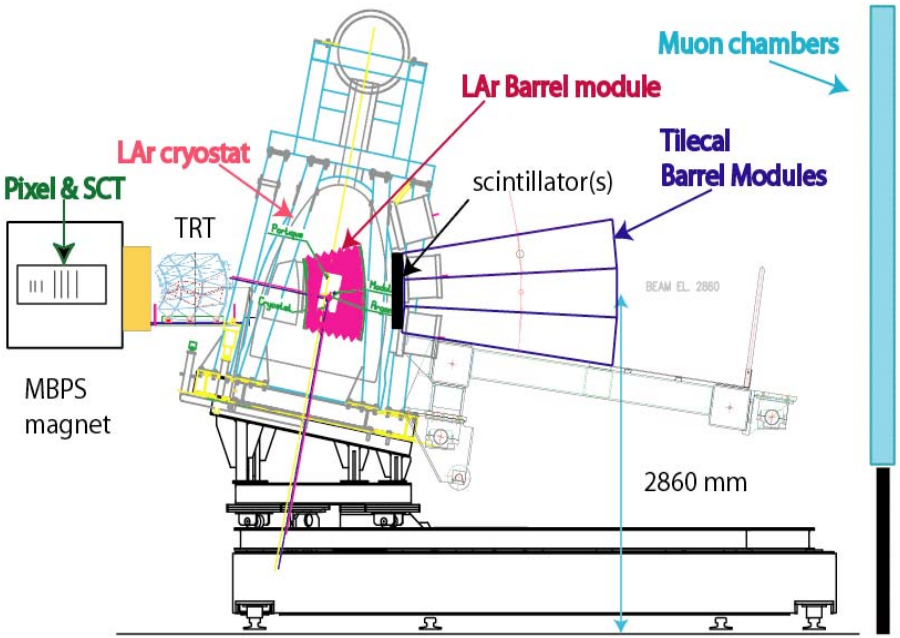
The layout of the beam



~ 90 million events collected
$e^{\pm}$, $\pi^{\pm}$ $1 \rightarrow 250$ GeV
$\mu^{\pm}$, $\pi^{\pm}$, p up to 350 GeV
γ 20-100 GeV
B-field = $0 \rightarrow 1.4$ T

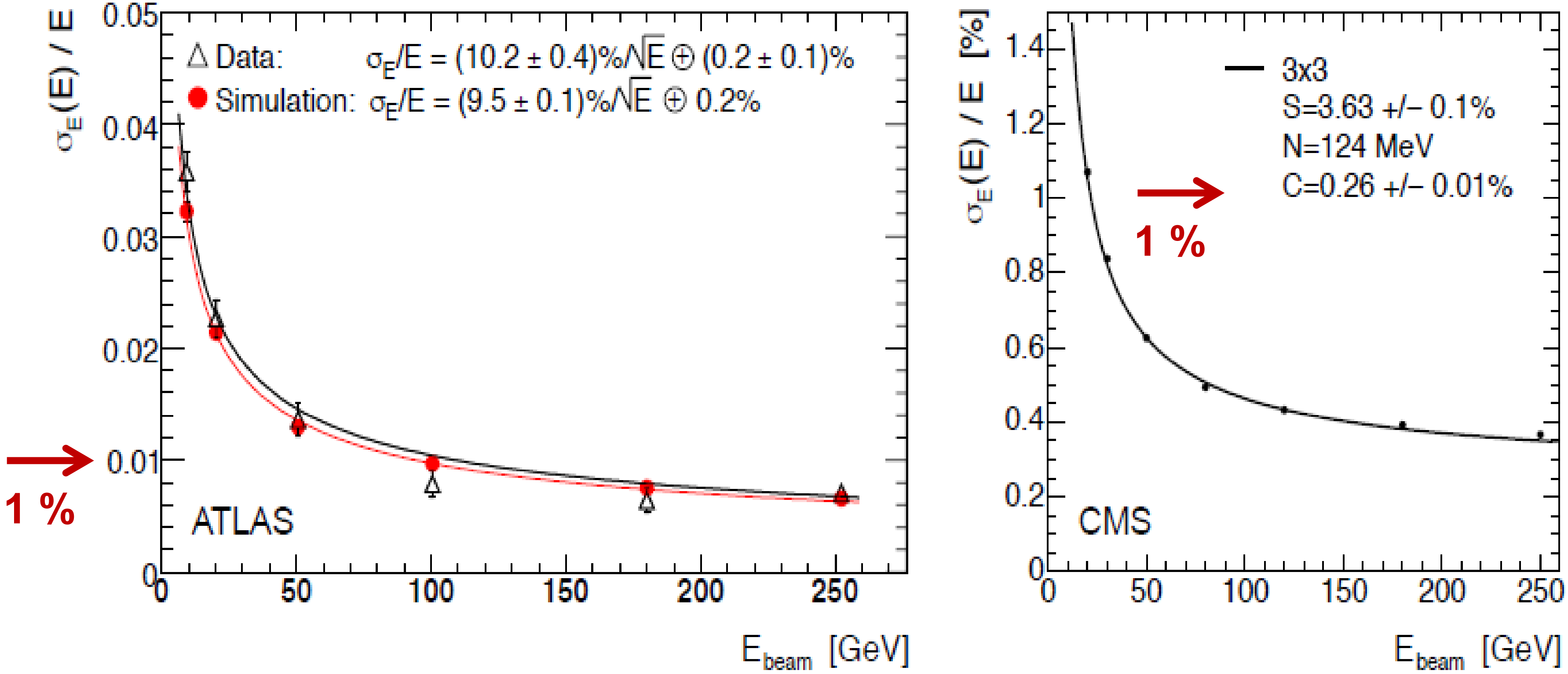
Many configurations (e.g. additional material in ID, 25 ns runs, …)

Combined test beam (H8 SPS)



All ATLAS sub-detectors (and LVL1 trigger) integrated and run together with common DAQ, monitoring, slow-control.
Data analyzed with common ATLAS software.
Gained lot of global operation experience during ~ 6 month run.

Examples of resolutions measured for electrons in ATLAS and CMS



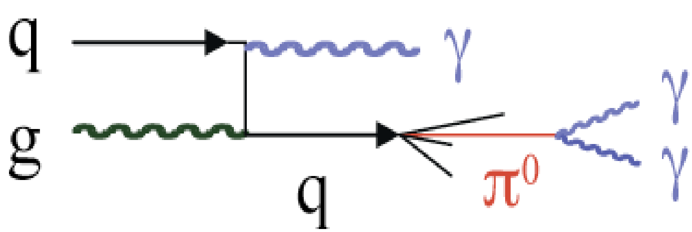
Need to be sure to identify electrons and photons

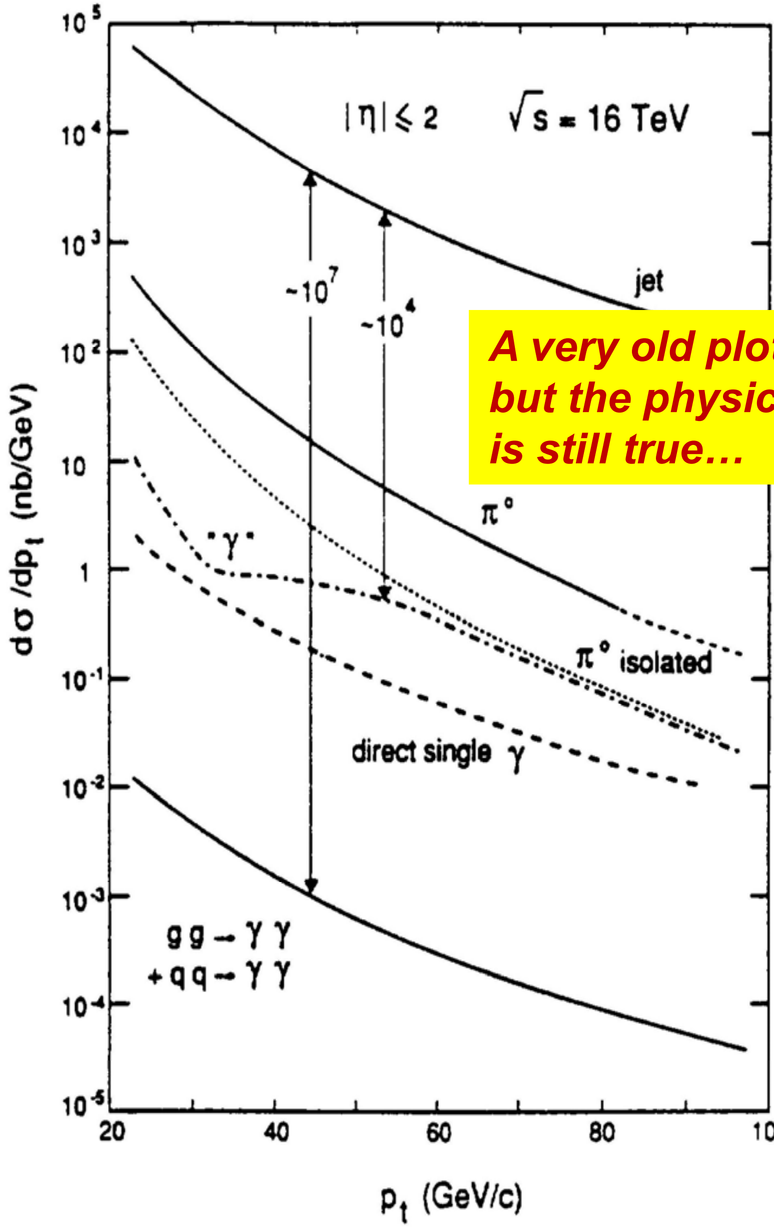
Most channels require to identify electrons and photons in their final states

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

Jet fragmentation into leading π_0 (probability 10^{-4}) represents the main source of identification errors

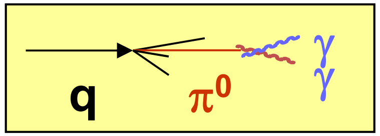
Example:





A very old plot, but the physics is still true…

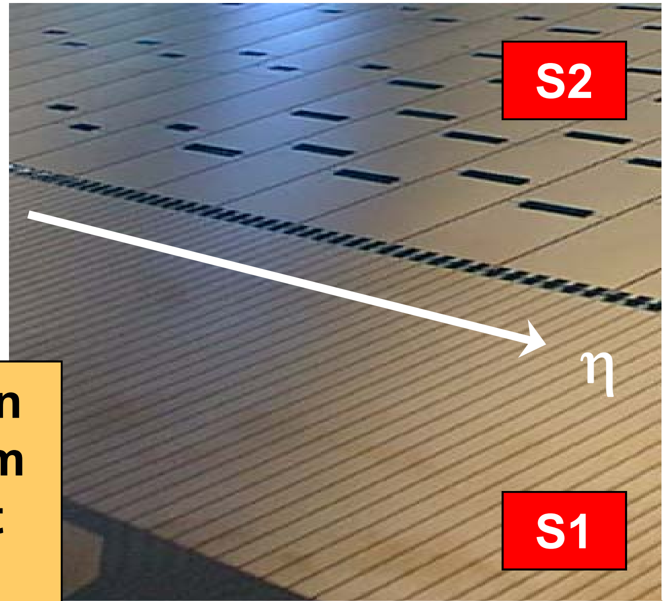
Photon identification



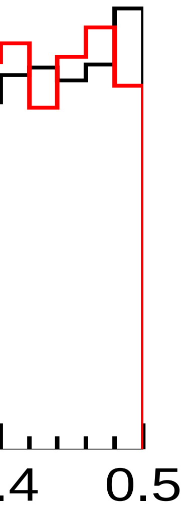
ATLAS

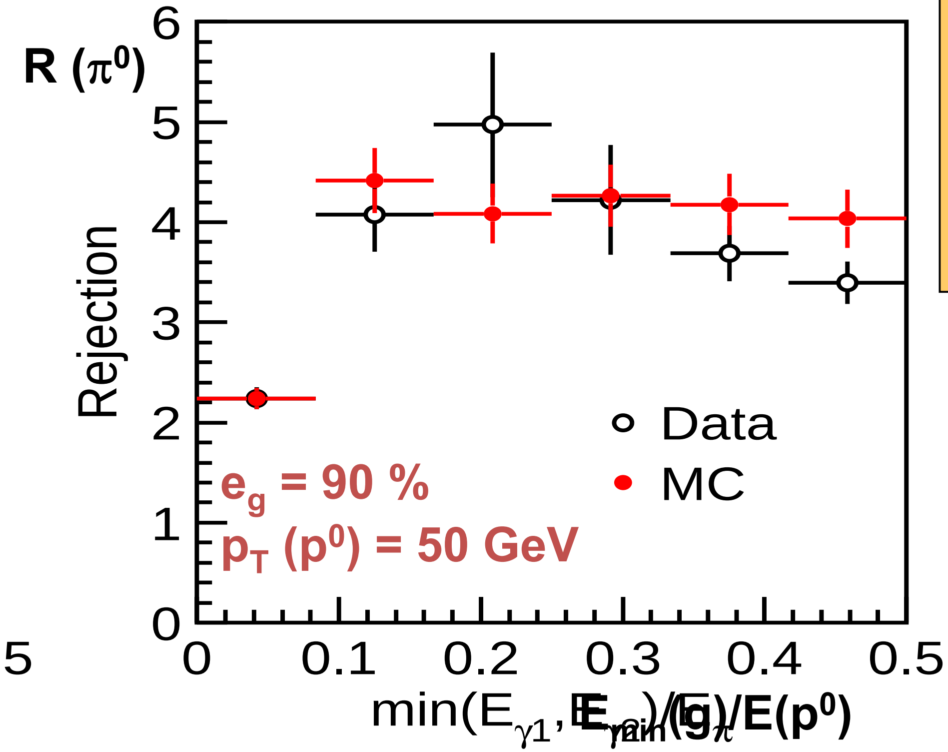
$R(\pi^0) \geq 3$ for $\varepsilon(\gamma) \sim 90\%$ needed to reject γj+jj background to $H \rightarrow \gamma\gamma$

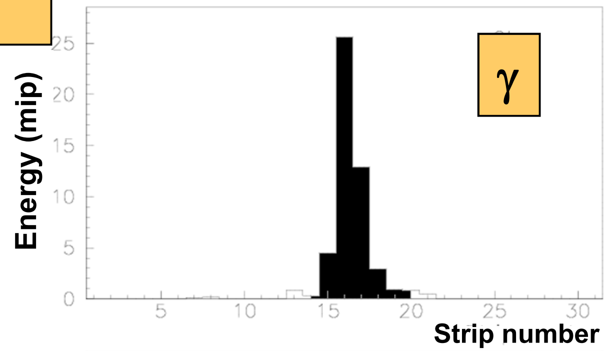
1999-2000 test-beam data collected with special photon beam

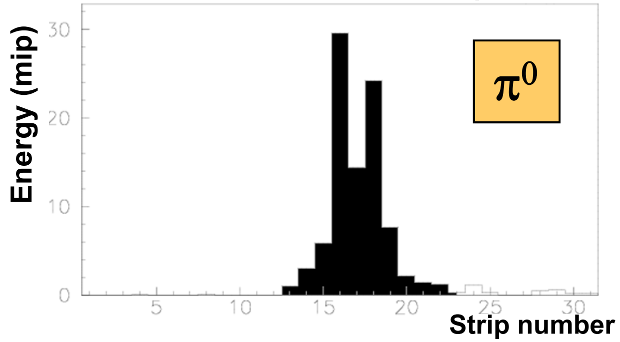


γ/π^0 separation based on 4mm η-strips in 1st calorimeter compartment







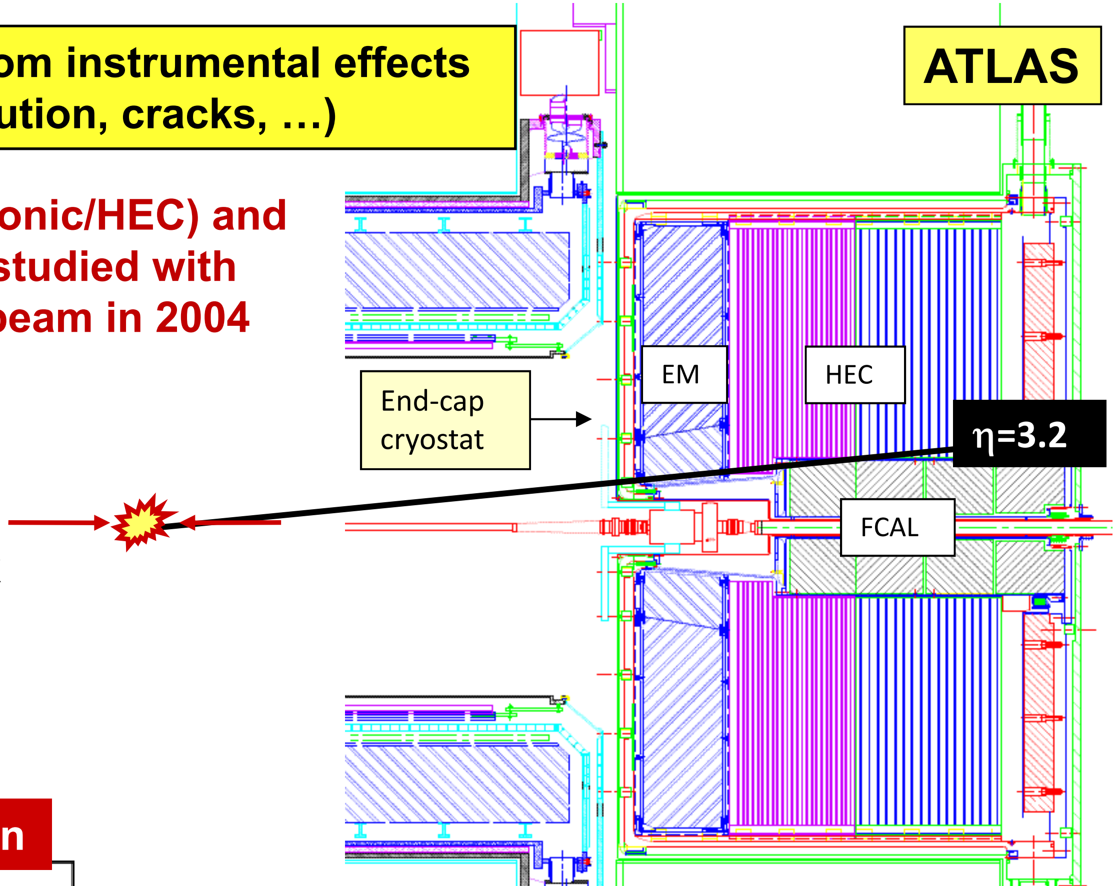


Data:	**$\langle R(\pi^0)\rangle = 3.54 \pm 0.12$**
MC:	**$\langle R(\pi^0)\rangle = 3.66 \pm 0.10$**

Background study: fake E_T^{miss} tails from instrumental effects (calorimeter non-compensation, resolution, cracks, …)

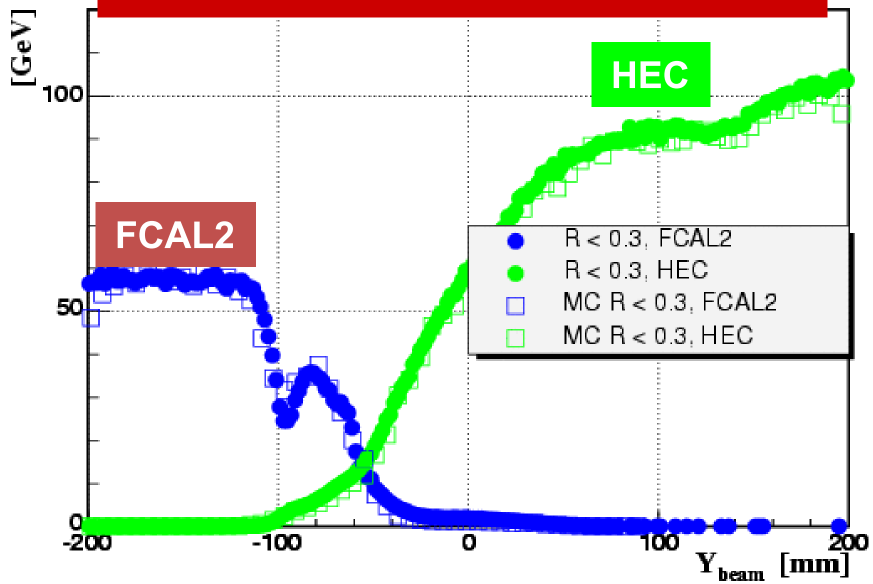
ATLAS

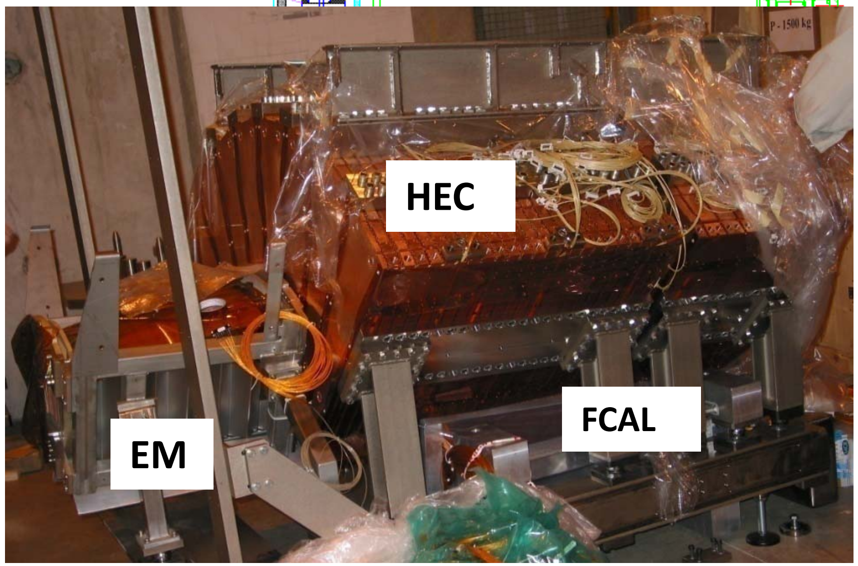
Transition between end-cap (EM, hadronic/HEC) and forward (FCAL) calorimeters at η=3.2 studied with dedicated combined test-beam in H6 beam in 2004



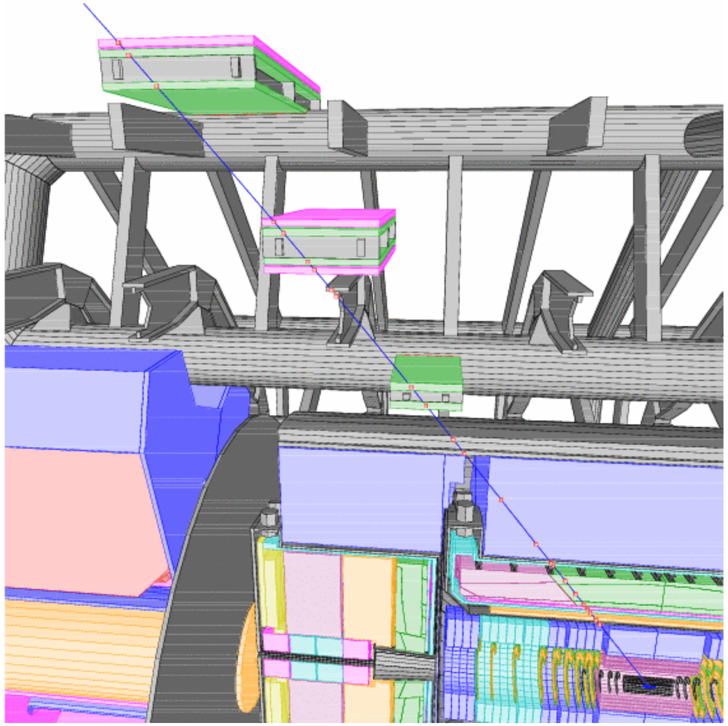
Data described well by MC in complex region with 3 different calorimeters and a lot of material

200 GeV π^- scan across transition



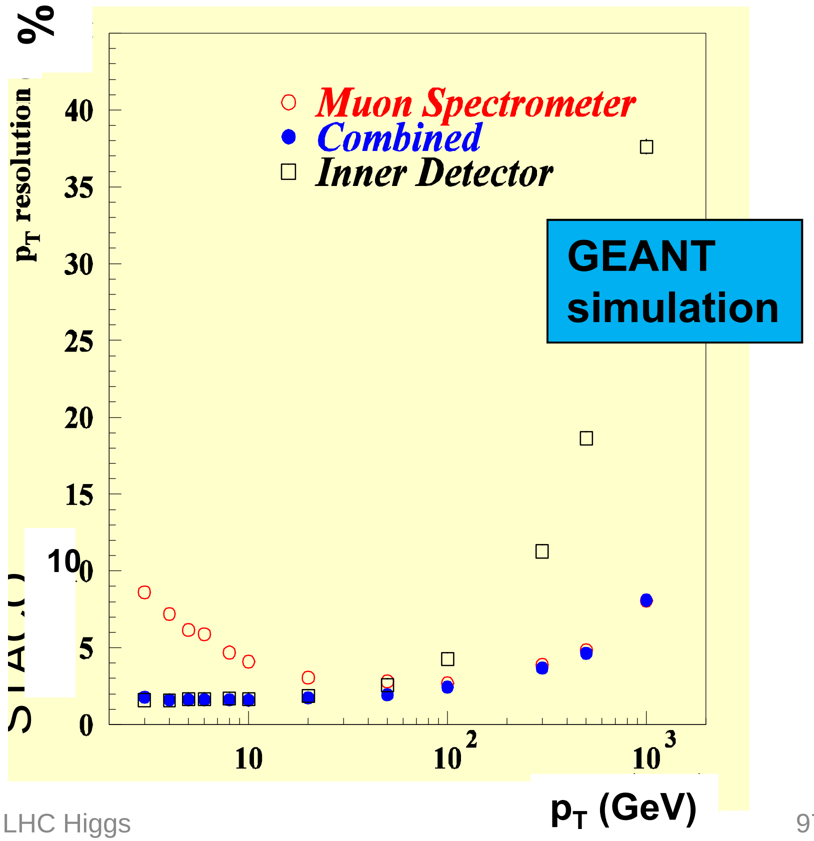


Another example : Muon Spectrometer resolution



$\sigma/p < 10\%$ for $E_\mu \sim$ TeV needed to observe a possible new resonance $X \to \mu\mu$ as "narrow" peak

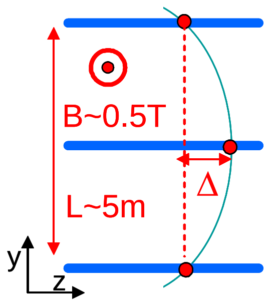
ATLAS Muon momentum resolution



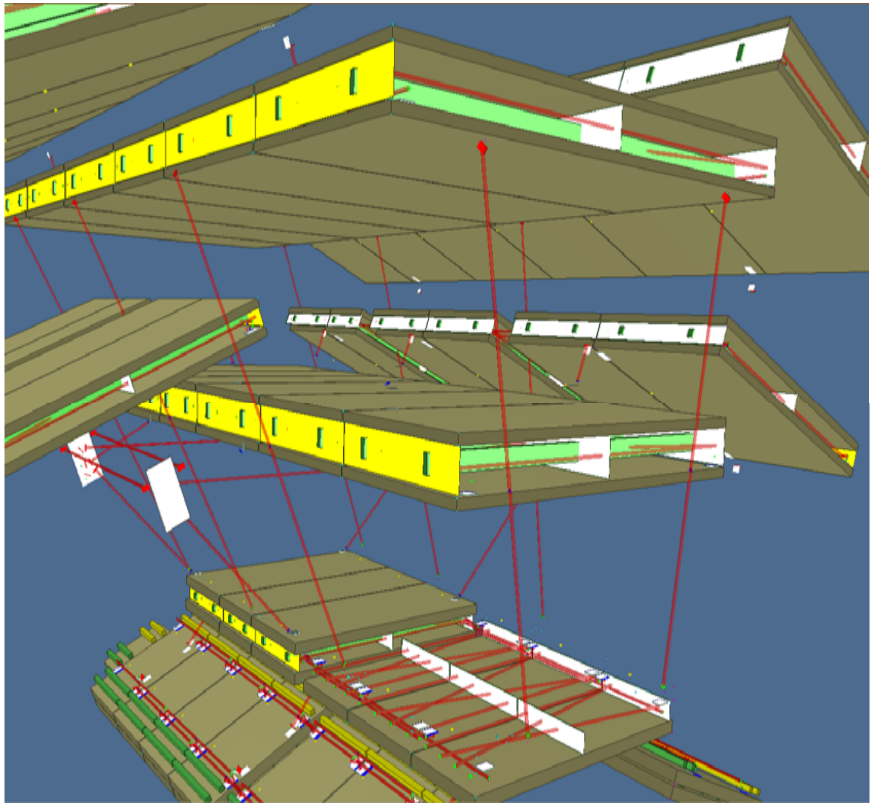
ATLAS Muon Spectrometer:
$E_\mu \sim 1$ TeV $\Rightarrow \Delta \sim 500\ \mu m$

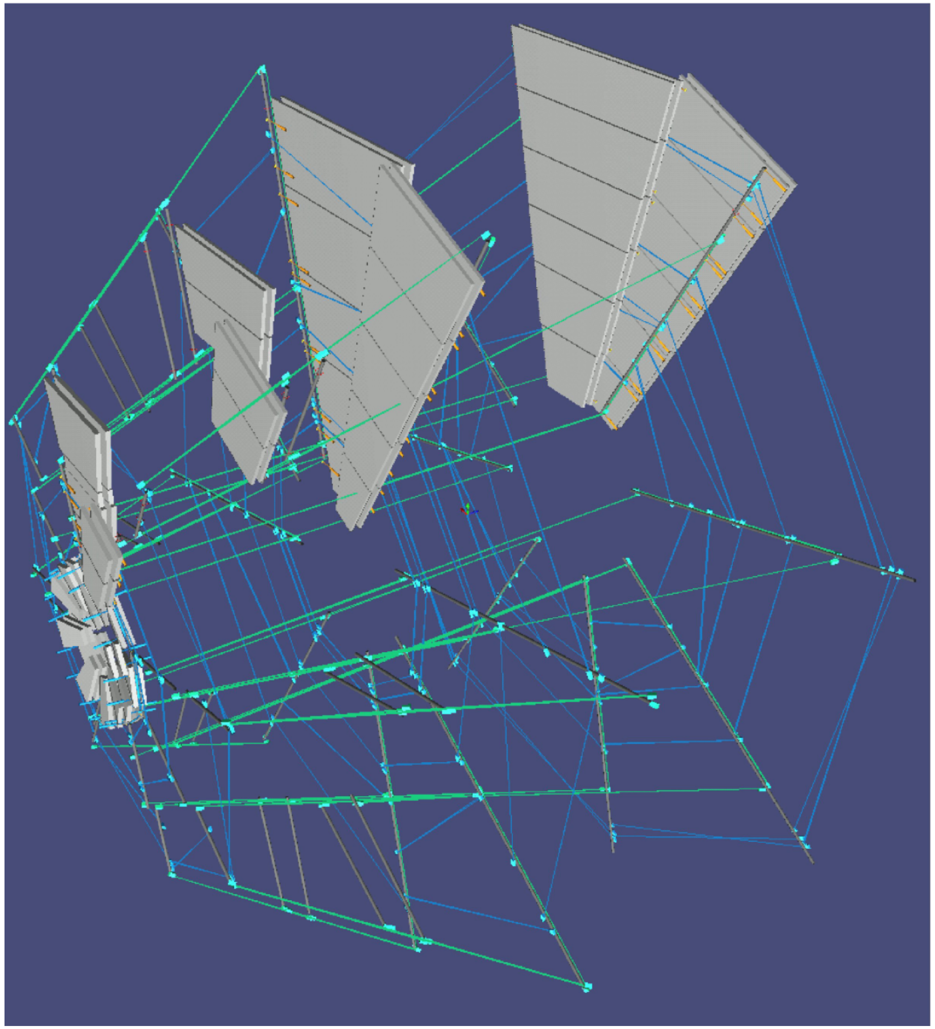
⬇

- $\sigma/p \sim 10\%$ $\Rightarrow$ $\delta\Delta \sim 50\ \mu m$
- alignment accuracy to ~30 mm



ATLAS muon spectrometer alignment system

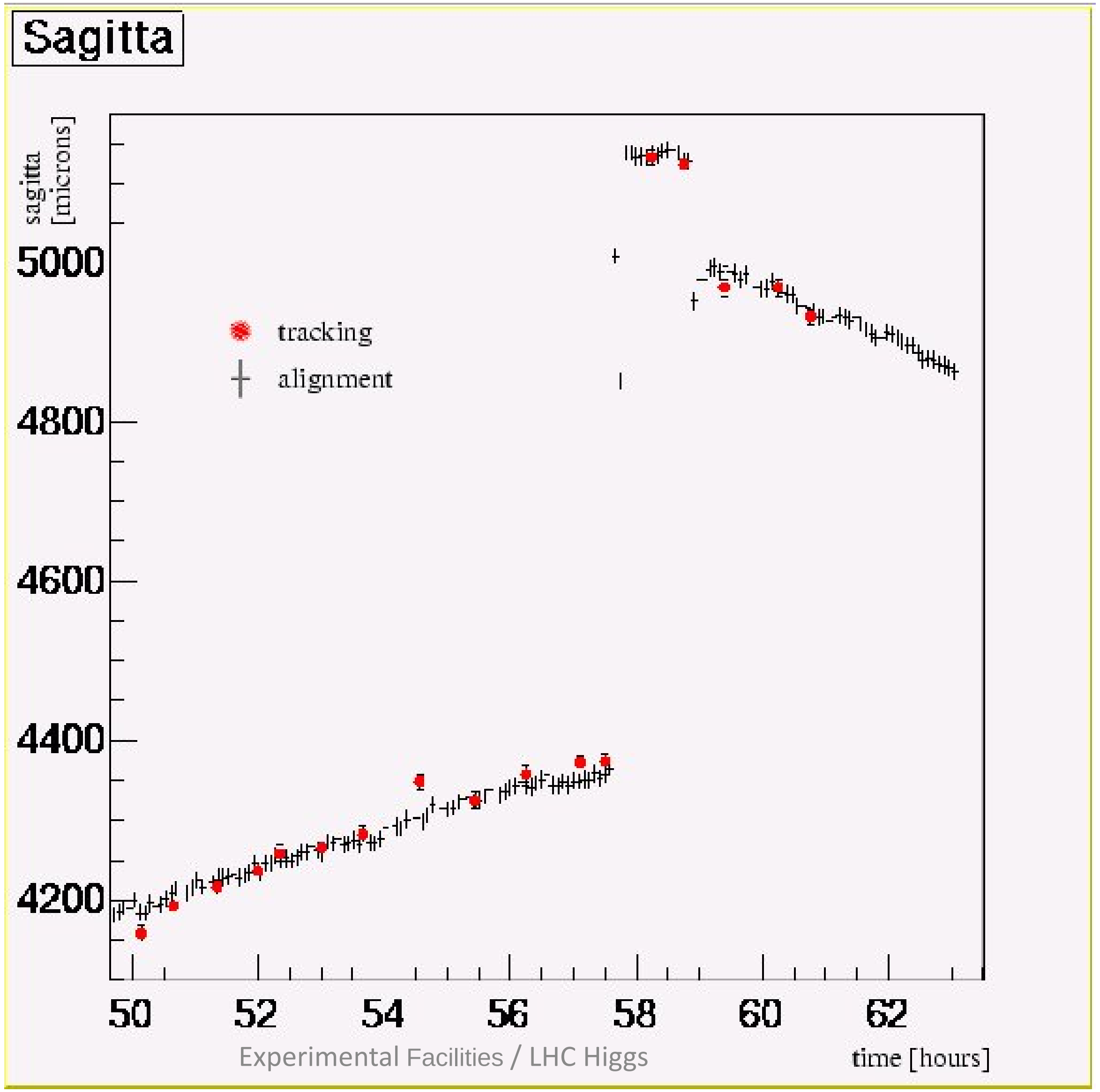




A large-scale system test facility for alignment, mechanical, and many other system aspects, with sample series chamber station in the SPS H8 beam

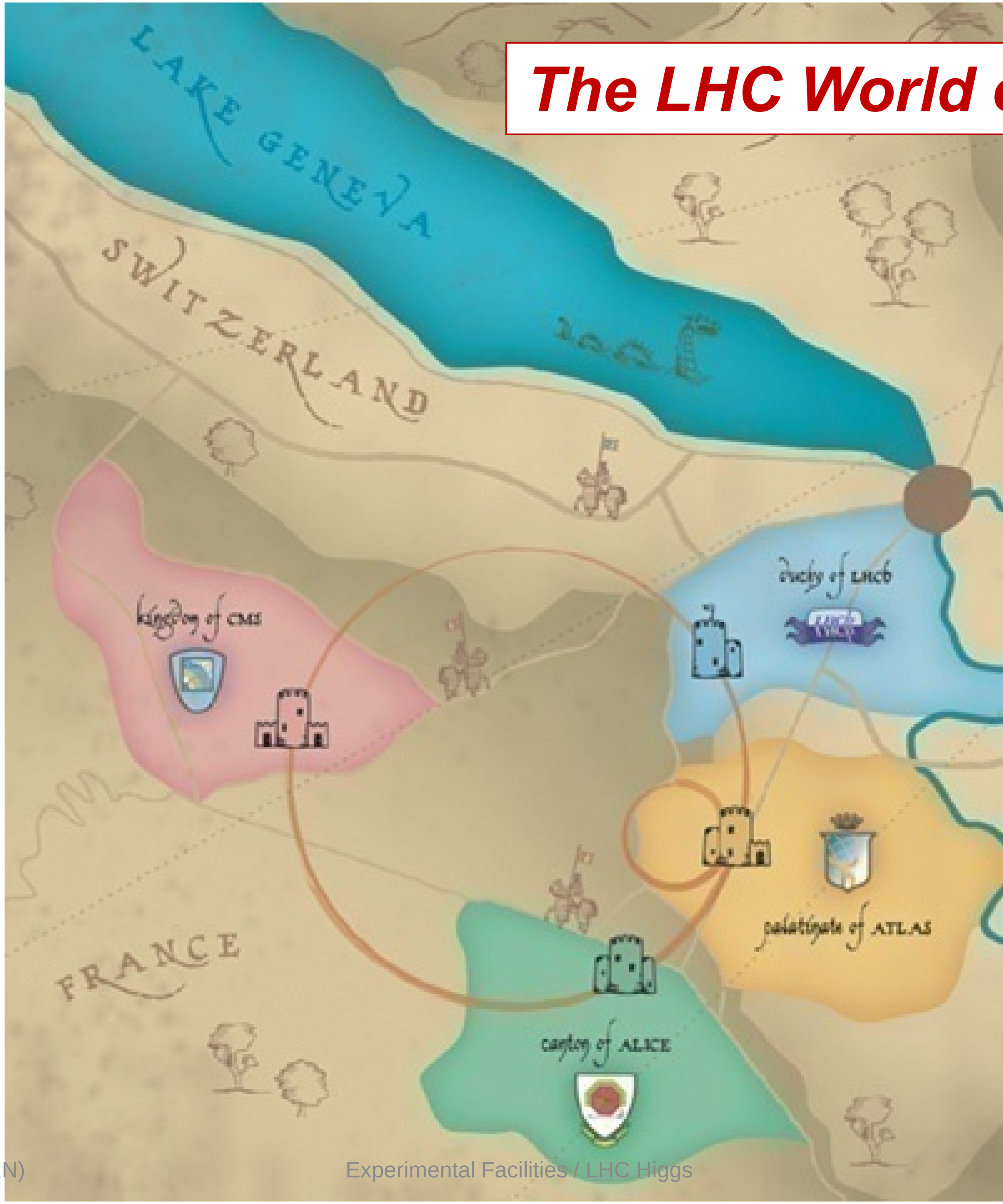
Shown in this picture is the end-cap set-up, it is preceded in the beam line by a barrel sector

Example of tracking the sagitta measurements, following the day-night variation due to thermal variations of chamber and structures, and two forced displacements of the middle chamber → movements well tracked within the required precision of ~ 10 microns



The LHC World of CERN

Plus smaller local earldoms
LHCf (point-1)
TOTEM (point-5)
Moedal (point-8)



CMS
3000 Physicists
184 Institutions
38 countries
550 MCHF

LHCb
730 Physicists
54 Institutions
15 countries
75 MCHF

ATLAS
3000 Physicists
177 Institutions
38 countries
550 MCHF

ALICE
1300 Physicists
130 Institutions
35 countries
160 MCHF

Latin America – CERN Collaboration

Involvement in LHC programme (first ICA):

Argentina (ICA '92)	**ATLAS**
Brazil (ICA '90)	**ATLAS, CMS, LHCb, ALICE**
Chile (ICA '91)	**ATLAS**
Colombia (ICA '93)	**ATLAS, CMS**
Cuba	**ALICE**
Mexico (ICA '98)	**ALICE, CMS**
Peru (ICA '93)	**ALICE (via Mexican team)**

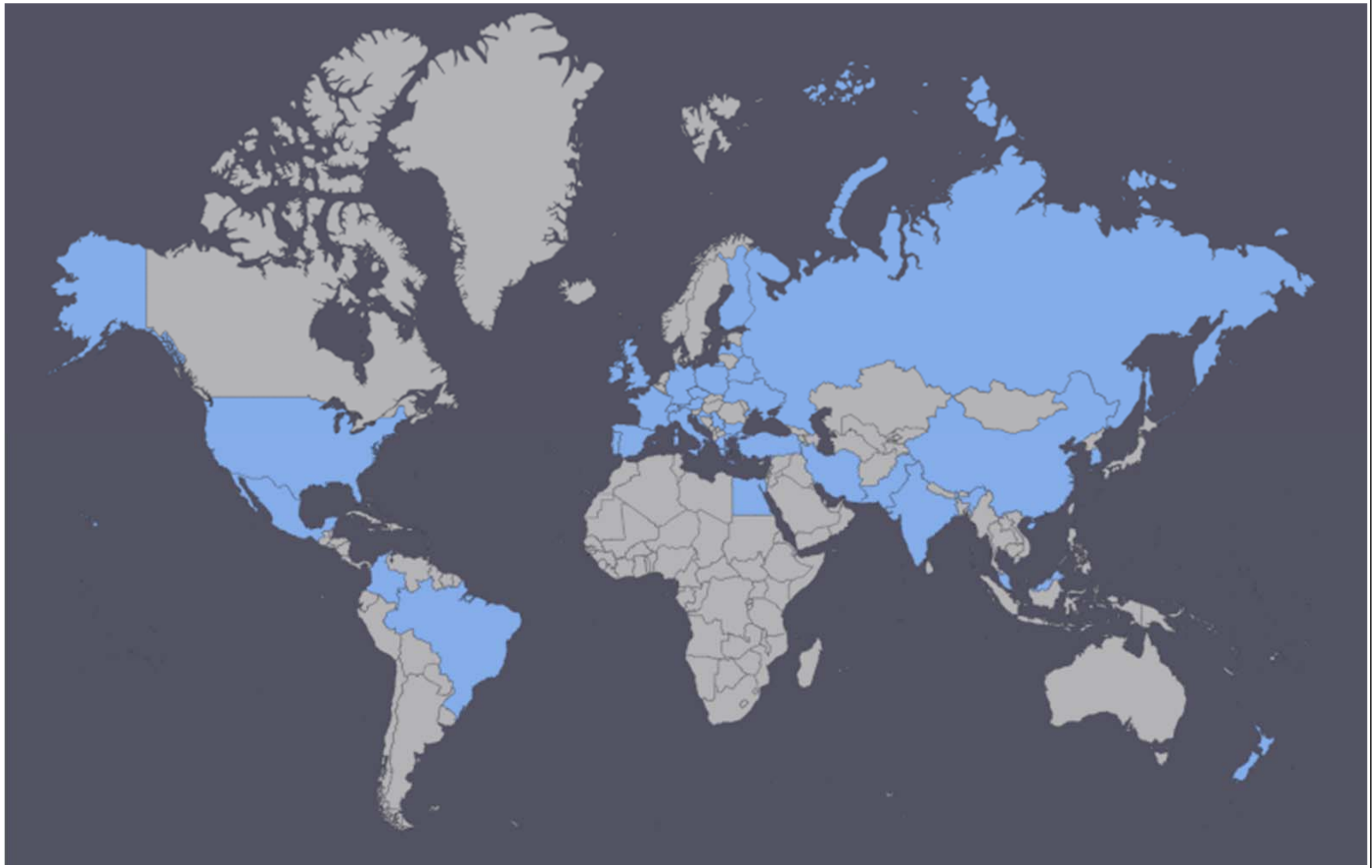
Under discussions – interests in:

Bolivia (ICA '07)	**ALICE**
Ecuador (ICA '99)	**CMS**
Venezuela	**ATLAS**

ICA: International Co-operation Agreement

180 institutes from 42 countries

Austria
Belgium
Bielorussia
Brazil
Bulgaria
CERN
China
Colombia
Croatia
Cyprus
Czech R.
Egypt
Estonia
Finland
France
Georgia
Germany
Greece
Hungary
India
Iran



Ireland
Italy
Korea
Lithuania
Malaysia
Mexico
New Zealand
Pakistan
Poland
Portugal
Russia
Serbia
Spain
Switzerland
Taipei
Thailand
Turkey
Ukraine
UK
USA
Uzbekistan

Ecuador and CERN

Current Ecuadorian institutes contributing to CMS
Escuela Politecnica Nacional (EPN)
Universidad San Francisco de Quito (USFQ)

Prof Edgar Carrera (USFQ) and summer students

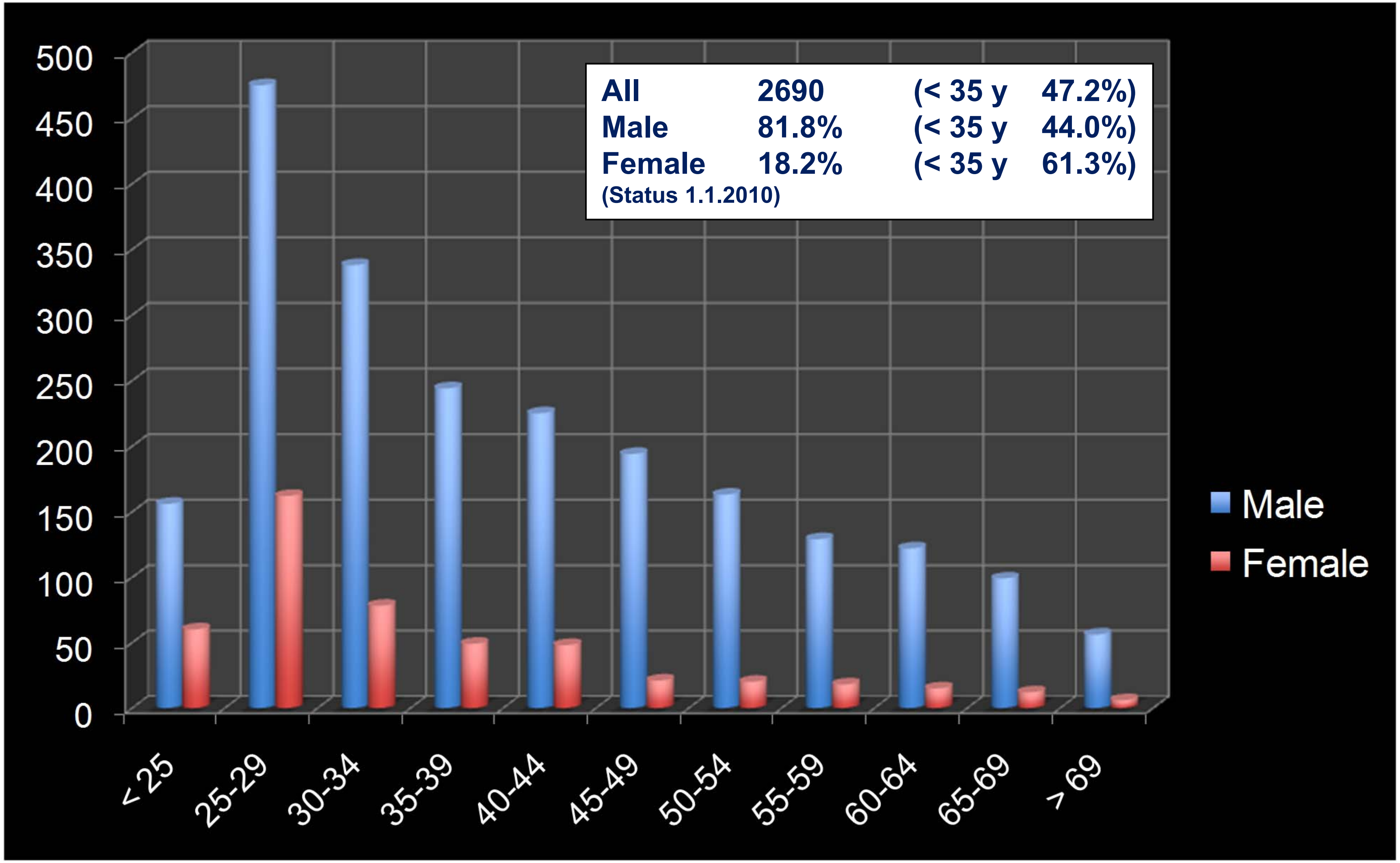
As an example:

ATLAS Collaboration

38 Countries
177 Institutions
3000 Scientific participants total
(1000 Students)

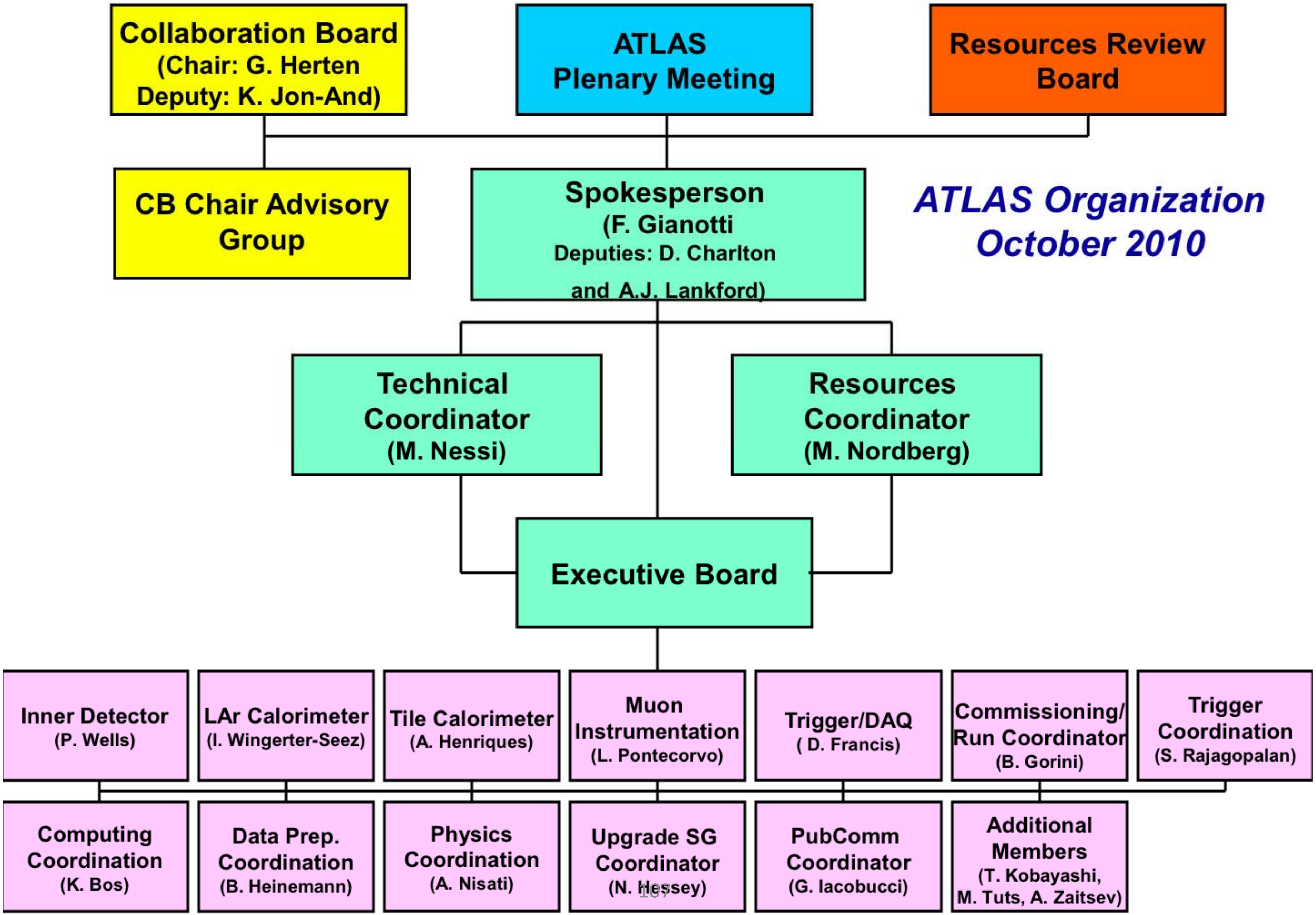
Adelaide, Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizona, UT Arlington, Athens, NTU Athens, Baku, IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, HU Berlin, Bern, Birmingham, UAN Bogota, Bologna, Bonn, Boston, Brandeis, Brasil Cluster, Bratislava/SAS Kosice, Brookhaven NL, Buenos Aires, Bucharest, Cambridge, Carleton, CERN, Chinese Cluster, Chicago, Chile, Clermont-Ferrand, Columbia, NBI Copenhagen, Cosenza, AGH UST Cracow, IFJ PAN Cracow, SMU Dallas, UT Dallas, DESY, Dortmund, TU Dresden, Dubna, Duke, Edinburgh, Frascati, Freiburg, Geneva, Genoa, Giessen, Glasgow, Göttingen, LPSC Grenoble, Technion Haifa, Hampton, Harvard, Heidelberg, Hiroshima IT, Indiana, Innsbruck, Iowa SU, Iowa, UC Irvine, Istanbul Bogazici, KEK, Kobe, Kyoto, Kyoto UE, Kyushu, Lancaster, UN La Plata, Lecce, Lisbon LIP, Liverpool, Ljubljana, QMW London, RHBNC London, UC London, Louisiana Tech, 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, LMU Munich, MPI Munich, Nagasaki IAS, Nagoya, Naples, New Mexico, New York, Nijmegen, Northern Illinois, BINP Novosibirsk, Ohio SU, Okayama, Oklahoma, Oklahoma SU, Olomouc, Oregon, LAL Orsay, Osaka, Oslo, Oxford, Paris VI and VII, Pavia, Pennsylvania, NPI Petersburg, Pisa, Pittsburgh, CAS Prague, CU Prague, TU Prague, IHEP Protvino, Rome I, Rome II, Rome III, Rutherford Appleton Laboratory, DAPNIA Saclay, Santa Cruz UC, Sheffield, Shinshu, Siegen, Simon Fraser Burnaby, SLAC, South Africa, Stockholm, KTH Stockholm, Stony Brook, Sydney, Sussex, AS Taipei, Tbilisi, Tel Aviv, Thessaloniki, Tokyo ICEPP, Tokyo MU, Tokyo Tech, Toronto, TRIUMF, Tsukuba, Tufts, Udine/ICTP, Uppsala, UI Urbana, Valencia, UBC Vancouver, Victoria, Warwick, Waseda, Washington, Weizmann Rehovot, FH Wiener Neustadt, Wisconsin, Wuppertal, Würzburg, Yale, Yerevan

Age distribution of the ATLAS population

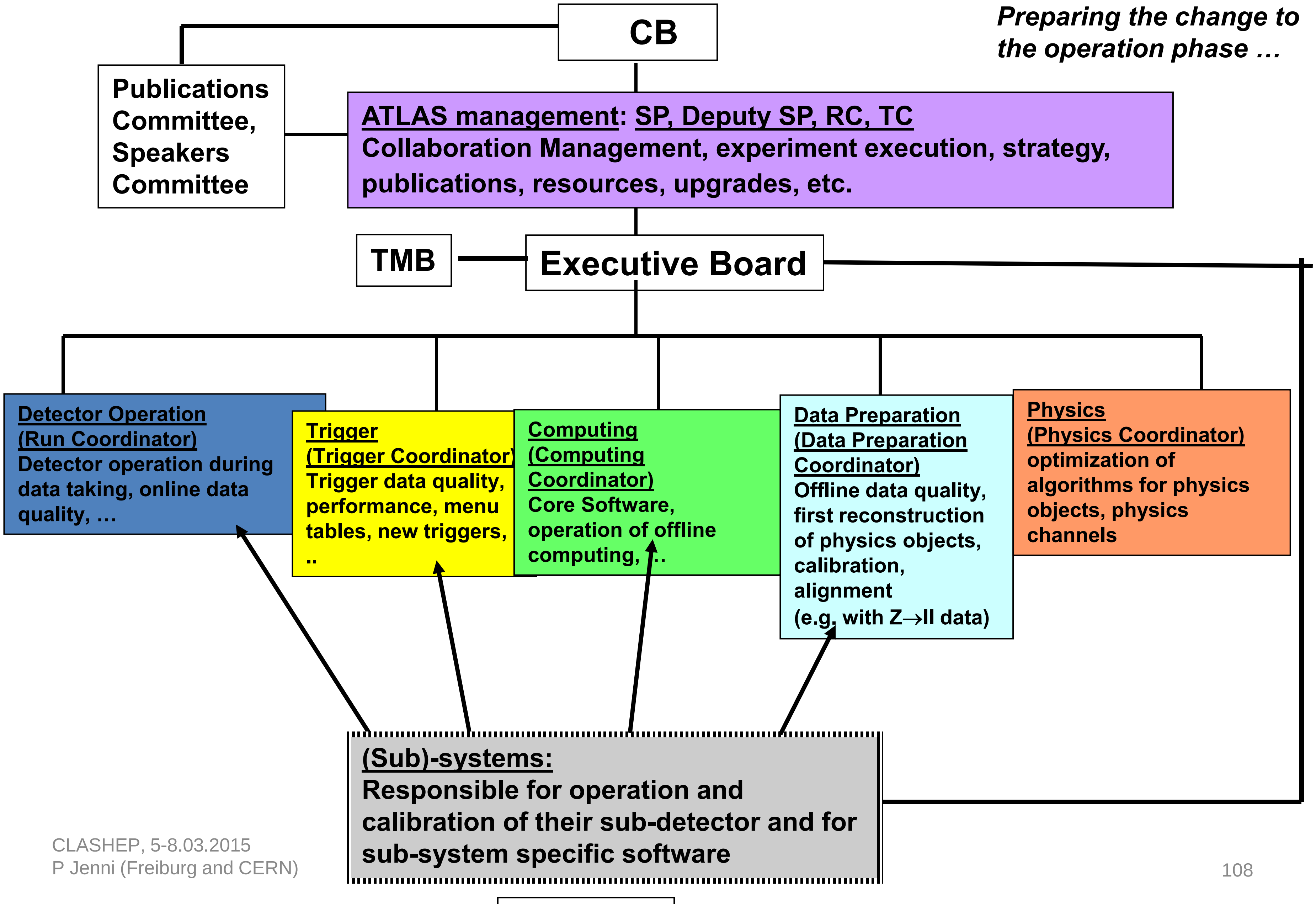


All	2690	(< 35 y	47.2%)
Male	81.8%	(< 35 y	44.0%)
Female	18.2%	(< 35 y	61.3%)

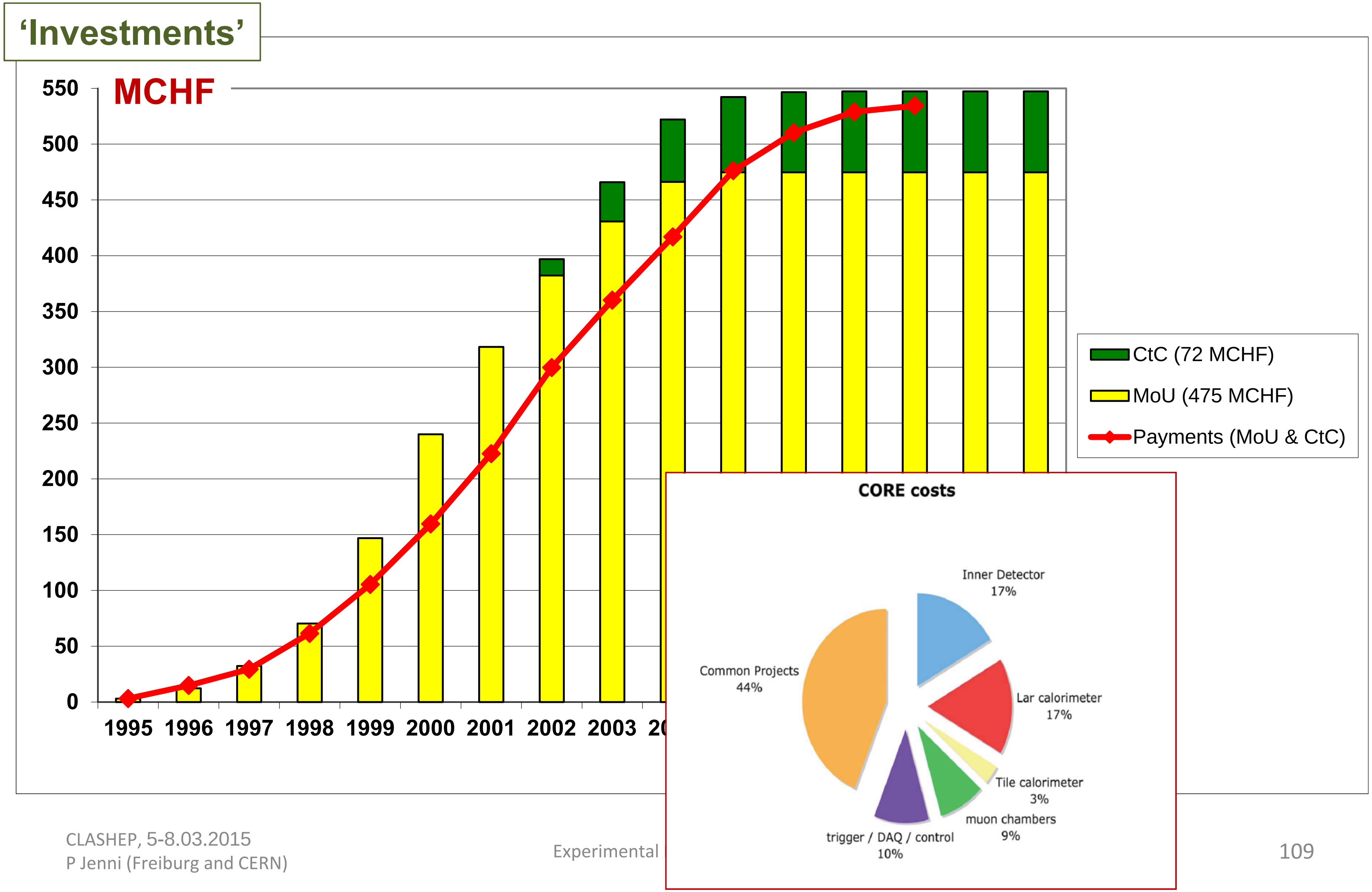
(Status 1.1.2010)


Collaboration Board
(Chair: G. Herten
Deputy: K. Jon-And)
ATLAS
Plenary Meeting
Resources Review
Board
CB Chair Advisory
Group
Spokesperson
(F. Gianotti
Deputies: D. Charlton
and A.J. Lankford)
ATLAS Organization
October 2010
Technical
Coordinator
(M. Nessi)
Resources
Coordinator
(M. Nordberg)
Executive Board
Inner Detector
(P. Wells)
LAr Calorimeter
(I. Wingerter-Seez)
Tile Calorimeter
(A. Henriques)
Muon
Instrumentation
(L. Pontecorvo)
Trigger/DAQ
(D. Francis)
Commissioning/
Run Coordinator
(B. Gorini)
Trigger
Coordination
(S. Rajagopalan)
Computing
Coordination
(K. Bos)
Data Prep.
Coordination
(B. Heinemann)
Physics
Coordination
(A. Nisati)
Upgrade SG
Coordinator
(N. Hessey)
PubComm
Coordinator
(G. Iacobucci)
Additional
Members
(T. Kobayashi,
M. Tuts, A. Zaitsev)

ATLAS example: Operation Model (Organization for LHC Exploitation)



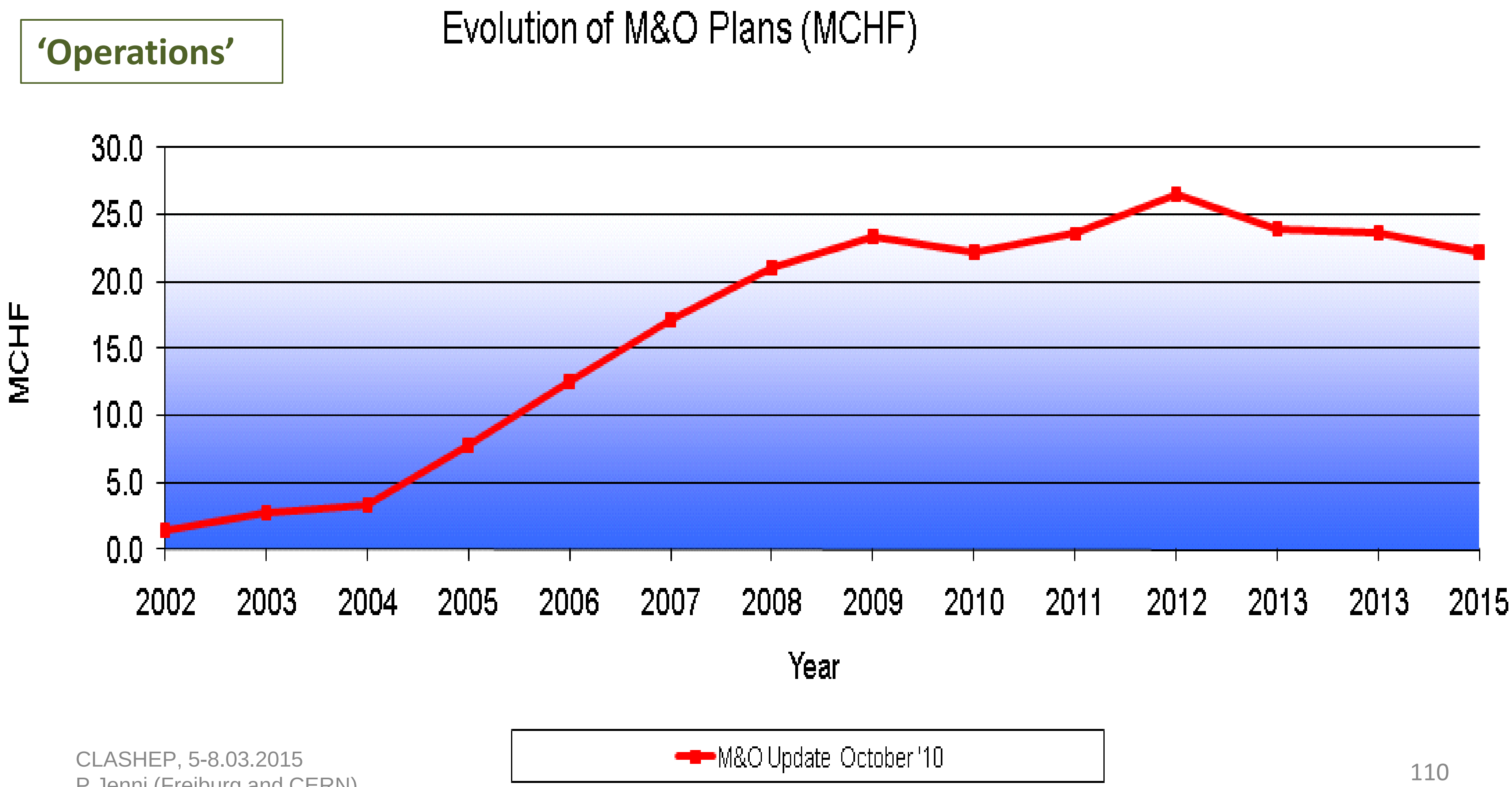
Overview of the integrated financial evolution of the 'CORE' costs of ATLAS (Construction MoU deliverables and Common Fund, Cost-to-Completion, in MCHF)



Evolution of Maintenance and Operation (M&O) costs 2002 – 2015, MCHF

M&O costs are shared between Funding Agencies according to the number of authors on scientific publications who hold a PhD (students are for 'free')

'Operations'



Since 1995 we had the Resources Review Board meetings twice a year (here all financial matters are agreed with the Funding Agency delegates, and the execution of the formal Memoranda of Understanding are monitored)