CMS

Compact Muon Solenoid

Journey to LHC Physics

CMS Summer Students 2008

Brief Physics Introduction
Design of CMS
Construction of CMS
Performance and Commissioning
Physics Prospects in First Years

T. S. Virdee
CERN/Imperial College

Unfinished Business from the Last Century

Can Physics
Be Unified ?

Can Aging
Be Postponed ?

What Secrets
Do Genes Hold ?

How Was the
Universe Born ?

How Does the
Mind Work ?

Can Robots
Be Intelligent ?

Is There Life
In Outer Space?

How Much Do We
Change the Climate?

Particle Physics

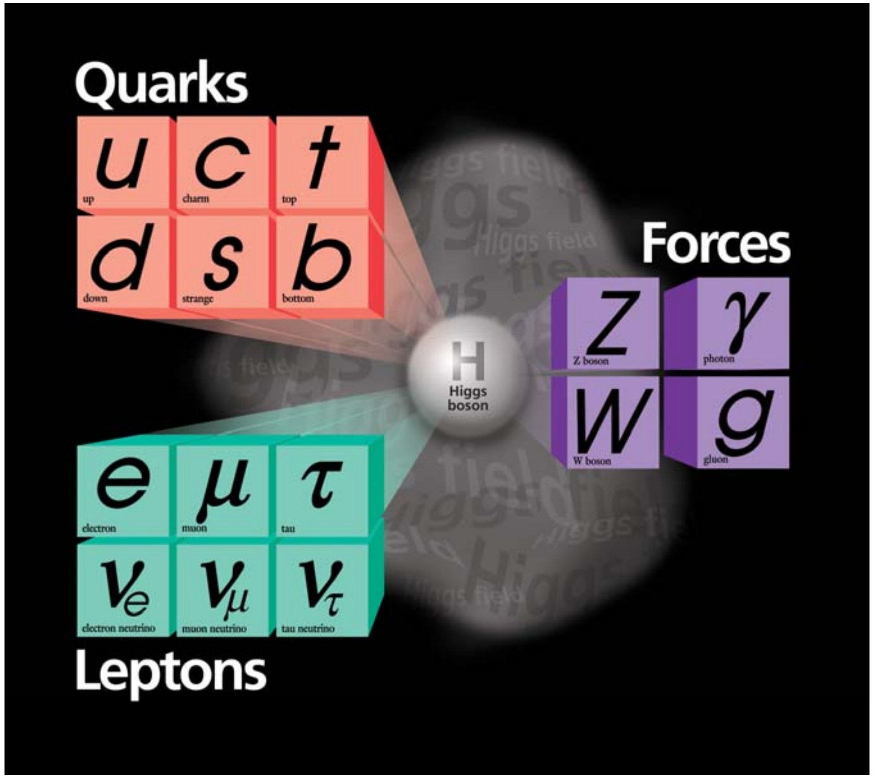
Aim to answer the two following questions:

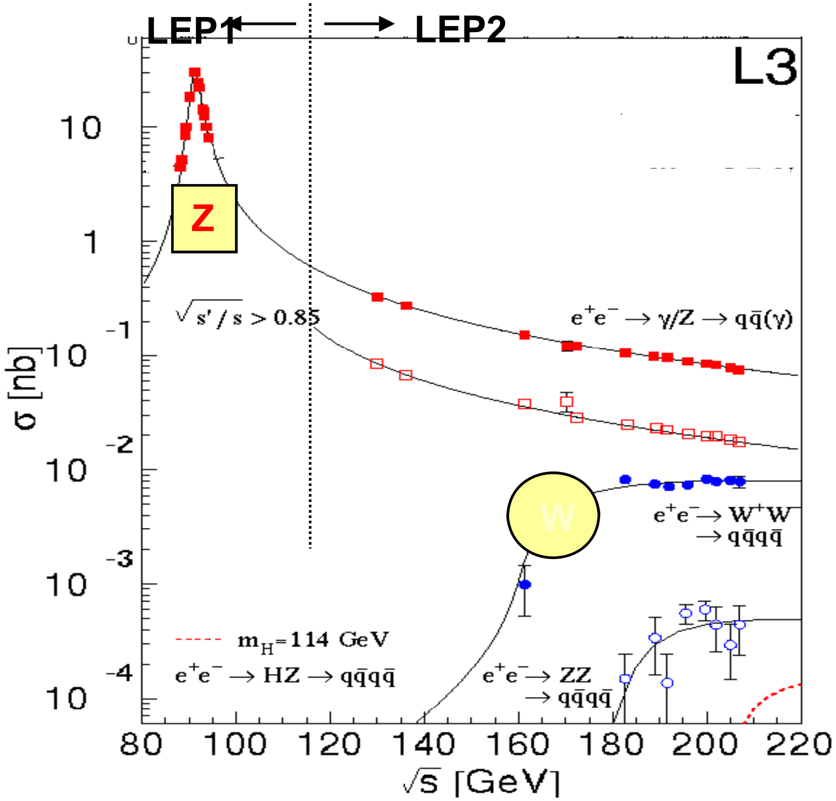
What are the elementary constituents of matter ?

What are the forces that control their behaviour at the most basic level

The Standard Model

The marriage of **Quantum Mechanics and Special Relativity**, and discovery of hundreds of particles has led to the **Standard Model of Particle Physics**





The Standard Model is a beautiful theory and arguably one that is most precisely tested
BUT we know it is not the whole truth !

Questions for the Standard Model and Beyond

LEP, SLC and the Tevatron: established that we really understand the physics at energies up to $\sqrt{s}$ ~ 100 GeV

And any new particles have masses above 200-300 GeV – and in some cases TeV.

1. SM has an unproven element: the generation of mass

Higgs mechanism ? other physics ?

Answer will be found at $\sqrt{s}$ ~ 1 TeV e.g. why $M_\gamma = 0$, $M_Z \sim 90$ GeV/c^2

2. SM without Higgs gives nonsense at LHC energies

At $\sqrt{s}$ > 1 TeV probability of $W_L W_L$ scattering > 1 !!

The SM solution: Higgs exchange cancels bad high energy behaviour.

Even if the Higgs exists, all is not 100% well with the SM alone: next question is "why is the (Higgs) mass so low"?

If SUSY is the answer, it must show up at *O*(TeV)

Recent: extra dimensions. Again, something must happen in the *O*(1-10) TeV scale if the above issues are to be addressed

Questions for the Standard Model and Beyond

3. SM is logically incomplete

Does not incorporate gravity.
Superstring theory ? ⇨ : supersymmetry, extra space-time dimensions ?

4. SM contains too many (arbitrary) parameters

Experimentally
New particles/new symmetries/new forces?

⇨Higgs boson(s), Supersymmetric particles, Z', …
Extra space-time dimensions: gravitons, micro black holes, Z' etc. ?

Requiring…..

1. Accelerators : powerful machines of accelerate particles to extremely high energies, bringing them into collision with other particles, allowing us to revisit the higher energies of our ancestral universe, to observe phenomena and particles normally no longer visible or existing in our time

2. Detectors : gigantic instruments that record the particles as they "spray" out from the collisions.

3. Computers : to collect, store, distribute and analyse the vast amount of data produced by the detectors

4. People : Only a collaboration of thousands of scientists, engineers, technicians and support staff can design, build and operate these complex "machines"

The LHC

What Type of Accelerator ?

There is something "magic" about the 1 TeV energy scale to be studied at the LHC

New Energy Domain

Search for the unexpected in an energy domain $\sqrt{s}$ > 1 TeV

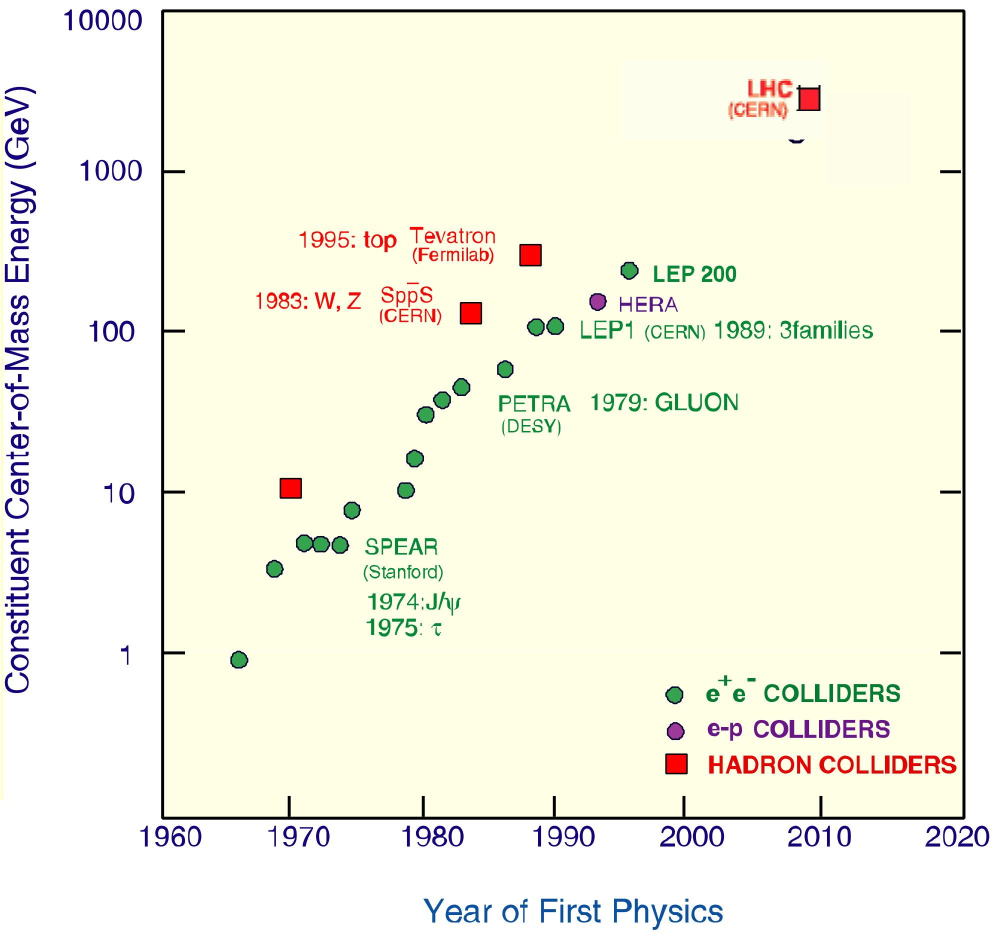
Exploratory machine required

⇨ **"Broadband"**

⇨ **hadron-hadron collider with:**

Largest possible primary energy

Largest possible luminosity



LHC Accelerator

LHC Machine is closed and is expected to be all cold (1.9 K) this month.
Collisions during last quarter of 2008

To reach the required energy in the existing tunnel, the dipoles operate at 8.3 T & 1.9 K in superfluid helium.

Ring will be emptier and colder than inter-planetary space

wrt Tevatron (USA)

Energy	x 7
luminosity	x 20

LHC Timeline

1984 Workshop on a Large Hadron Collider in the LEP tunnel, Lausanne

1987 Rubbia "Long-Range Planning Committee" recommends Large Hadron Collider as the right choice for CERN's future

1990 ECFA LHC Workshop, Aachen

1992 General Meeting on LHC Physics and Detectors, Evian les Bains

1993 Letters of Intent (ATLAS and CMS selected by LHCC)

1994 Technical Proposals Approved

1996 Approval to move to Construction (ceiling of 475 MCHF)

1998 Memorandum of Understanding for Construction Signed

1998 Construction Begins (after approval of Technical Design Reports)

2000 CMS assembly begins above ground. LEP closes

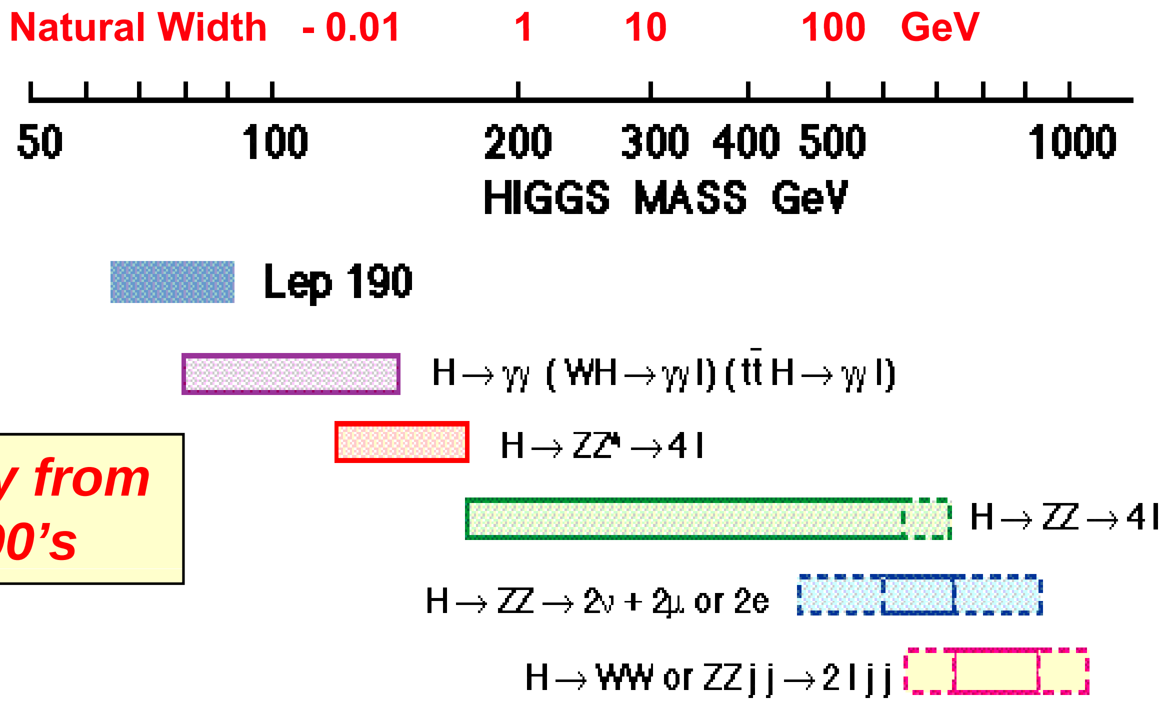
2004 CMS Underground Caverns completed

2008 CMS ready for First proton-proton Collisions

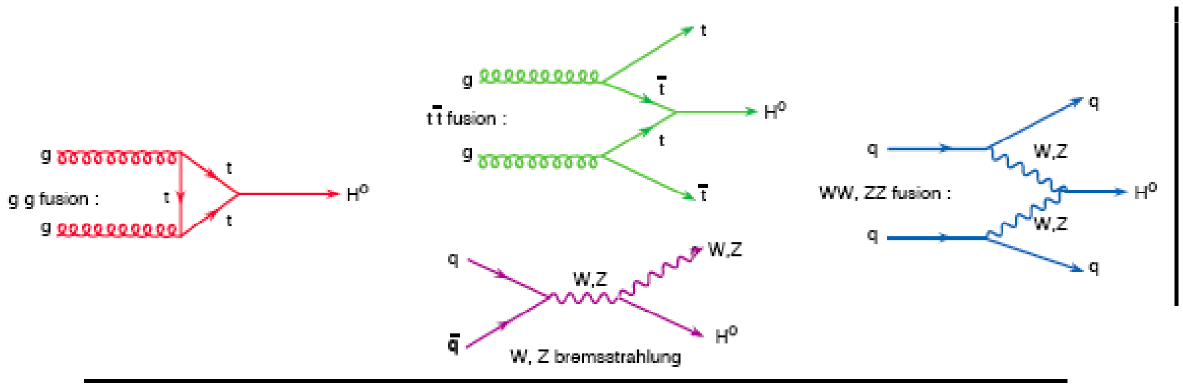
The Design of CMS

The Benchmark Reaction: SM Higgs

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



Transparency from the early 90's



(CMS) Design Criteria

Very good muon identification and momentum measurement

Trigger efficiently and measure sign of TeV muons dp/p < 10%

High energy resolution electromagnetic calorimetry

~ 0.5% @ E_T ~ 50 GeV

Powerful inner tracking systems

Momentum resolution a factor 10 better than at LEP

Hermetic calorimetry

Good missing E_T resolution

(Affordable detector)

Transparency from the early 90's

Experimental Challenge

LHC Detectors (especially ATLAS, CMS) are radically different from the ones from the previous generations

High Interaction Rate

pp interaction rate **1 billion interactions/s**
Data can be recorded for only ~10^2 out of 40 million crossings/sec
Level-1 trigger decision takes ~2-3 μs
⇨ **electronics need to store data locally (pipelining)**

Large Particle Multiplicity

~ <20> superposed events in each crossing
~ 1000 tracks stream into the detector every 25 ns
need highly granular detectors with good time resolution for low occupancy
⇨ **large number of channels (~ 100 M ch)**

High Radiation Levels

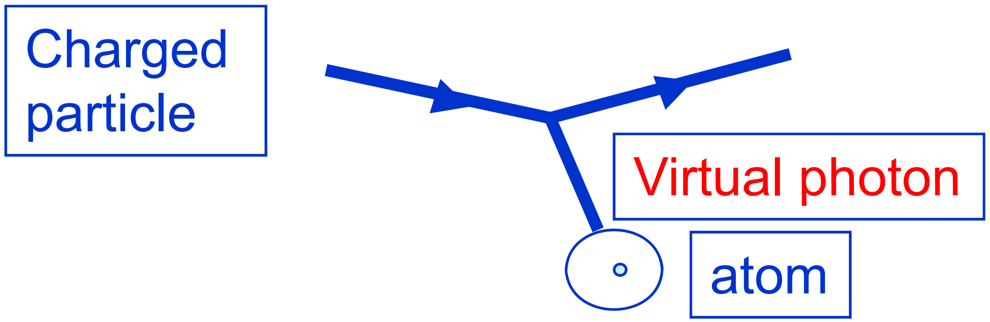
⇨ **radiation hard (tolerant) detectors and electronics**

Particle Detection

To detect particles energy must be transferred to the detecting medium

Energy Loss by Charged Particles

Lose energy via interactions of virtual photons with atomic electrons

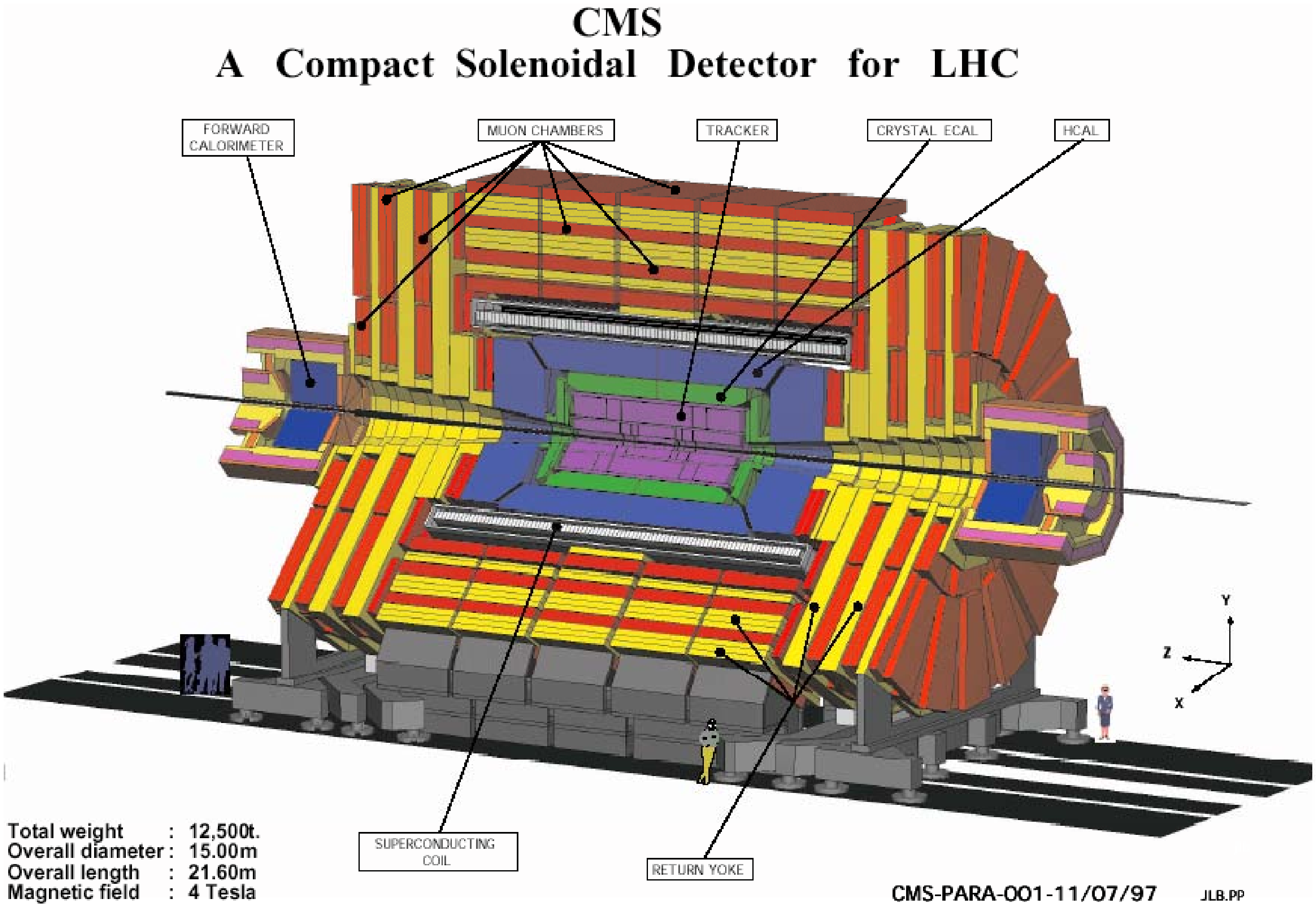


Can consider the medium as consisting of a gas of electrons

The energy transferred to the electrons causes them to be ejected from the parent atom **(ionization)** or to be excited to a higher energy state **(excitation)**

Particle detection is based on one or both of these processes

The CMS Detector

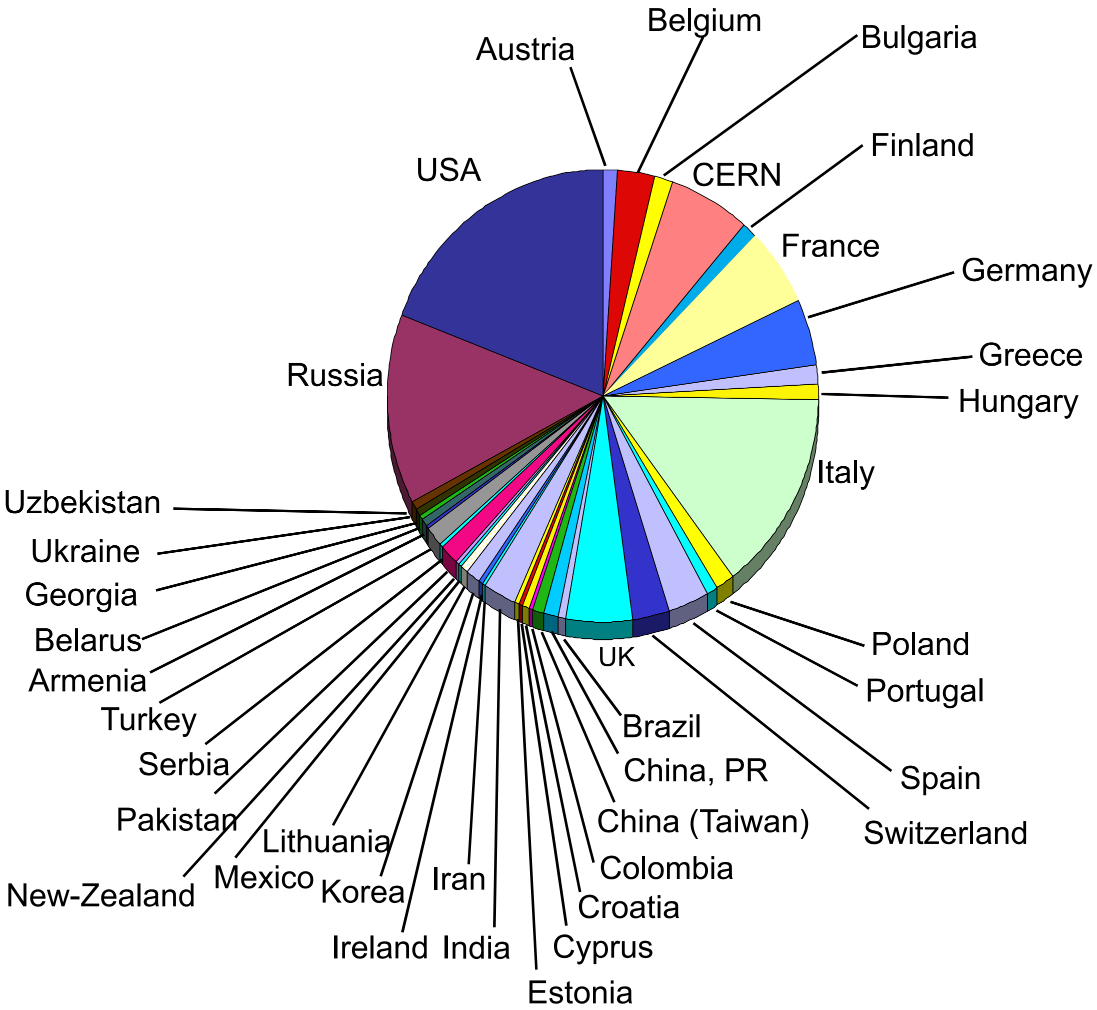


The CMS Collaboration

	Number of Laboratories
Member States	59
Non-Member States	67
USA	49
Total	175

	# Scientific Authors
Member States	1084
Non-Member States	503
USA	723
Total	2310

Associated Institutes	
Number of Scientists	62
Number of Laboratories	9



2310 Scientific Authors
38 Countries
175 Institutions

Construction of CMS

Assembly of CMS

A. Herve
From '92 CMS LoI Presentation

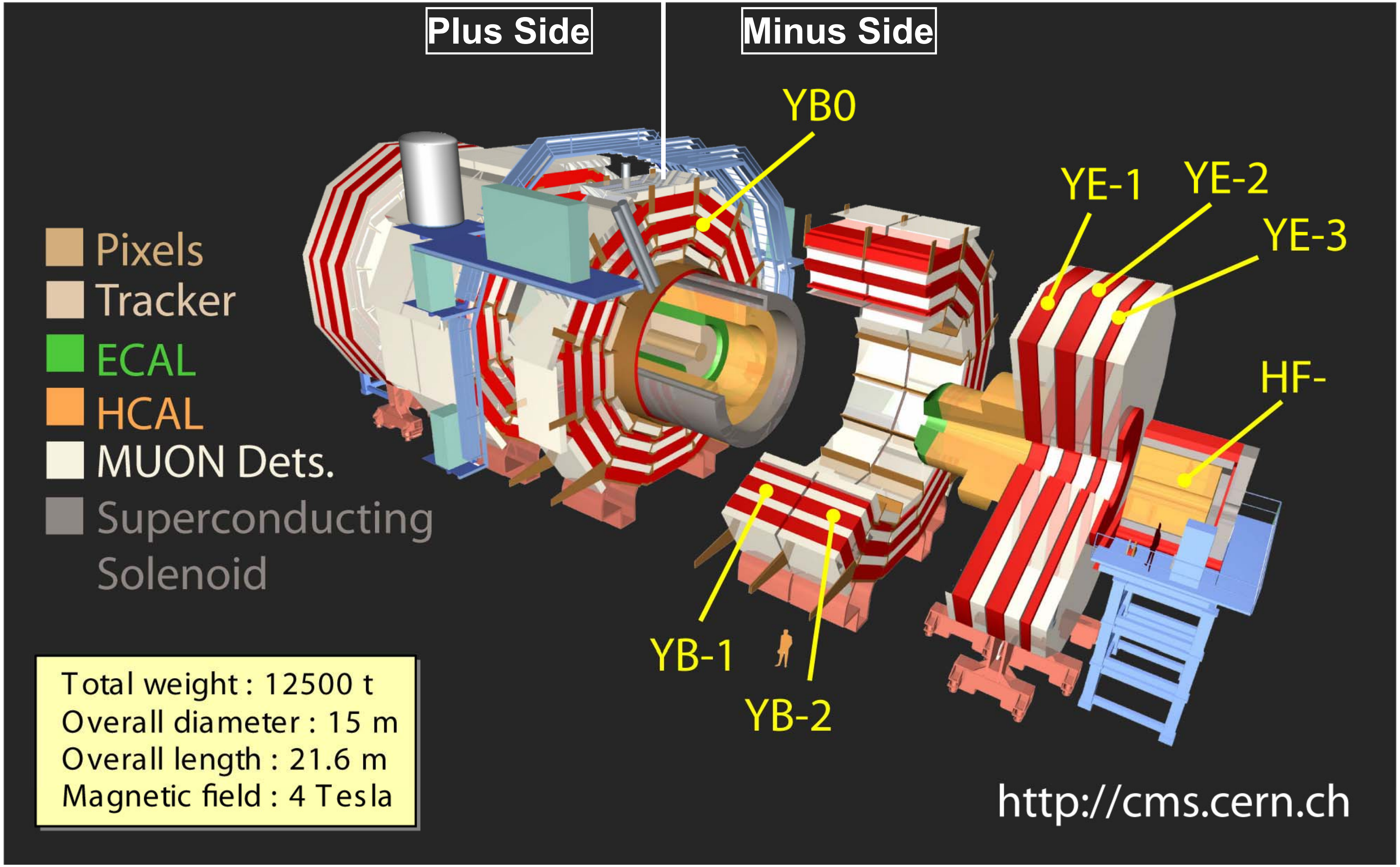
Surface Hall

The CMS magnet will be assembled and tested in the surface Hall
The muon detector will be mounted on the magnet
This necessitates a hall of 94 m x 23 m x 23 m

Underground Cavern

The modular CMS detector allows an easy transfer to and installation in the underground cavern
The size (L = 60 m, Ø = 26 m) is chosen such that an easy access for maintenance is possible

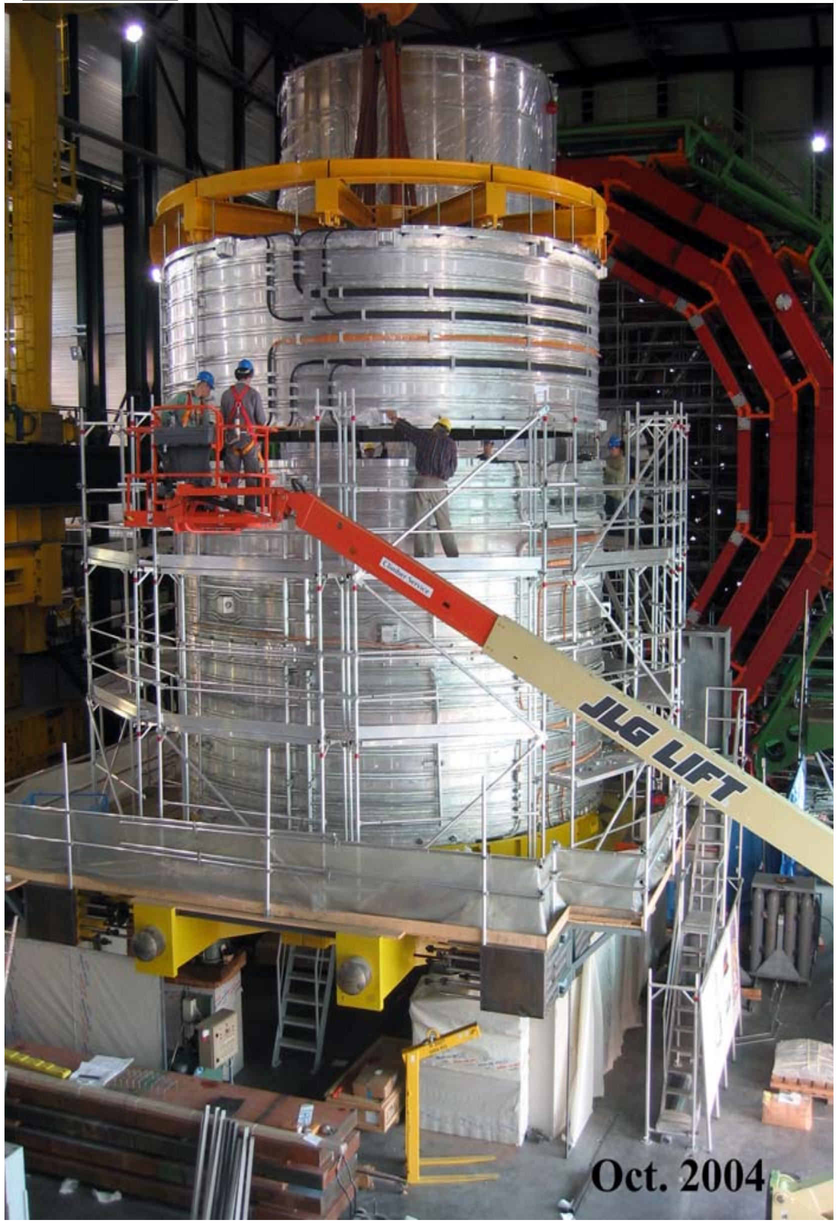
Exploded View of CMS



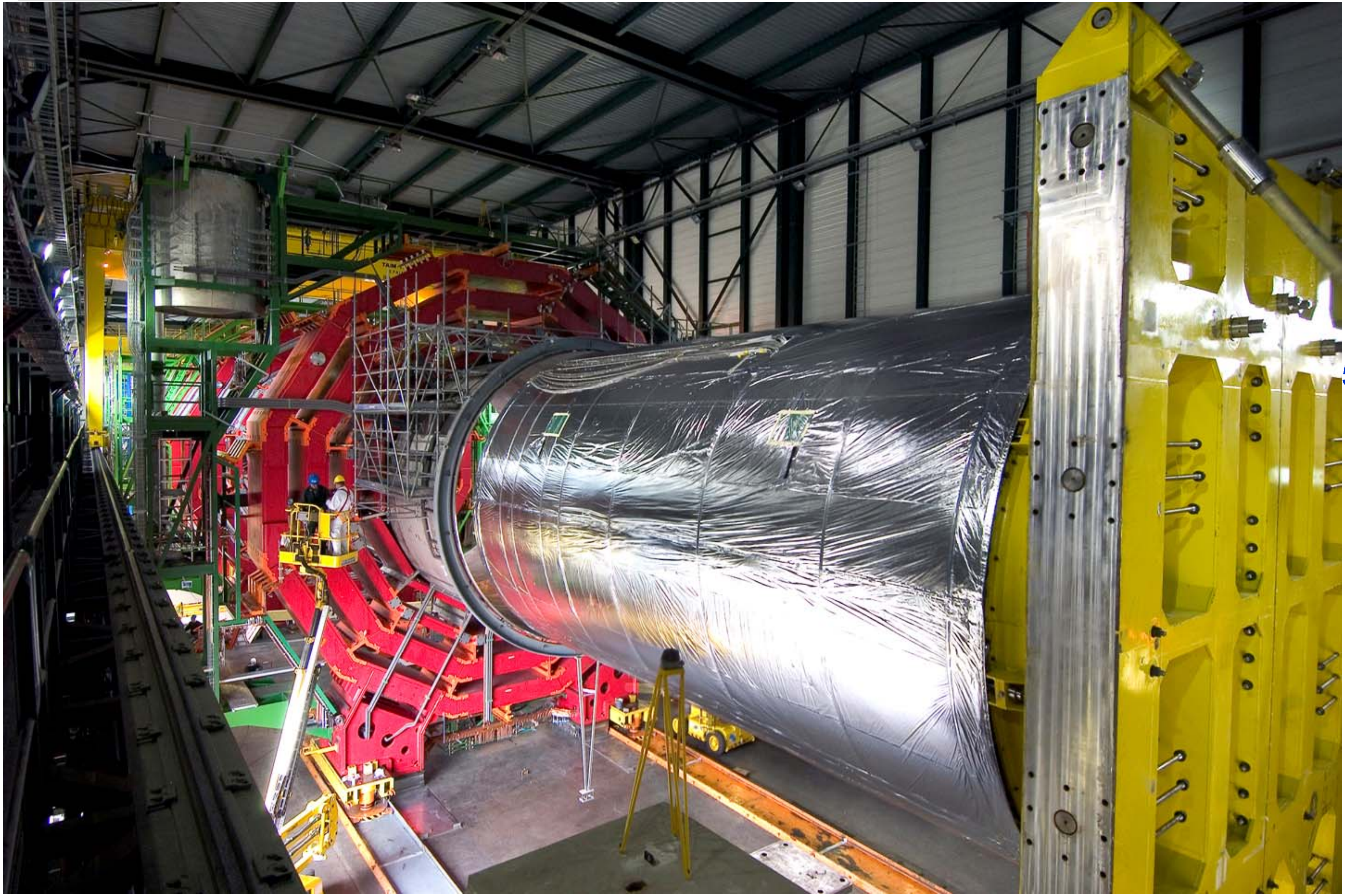
CMS Site at Point 5 (Cessy) in 2000

Assembly of Iron Yoke

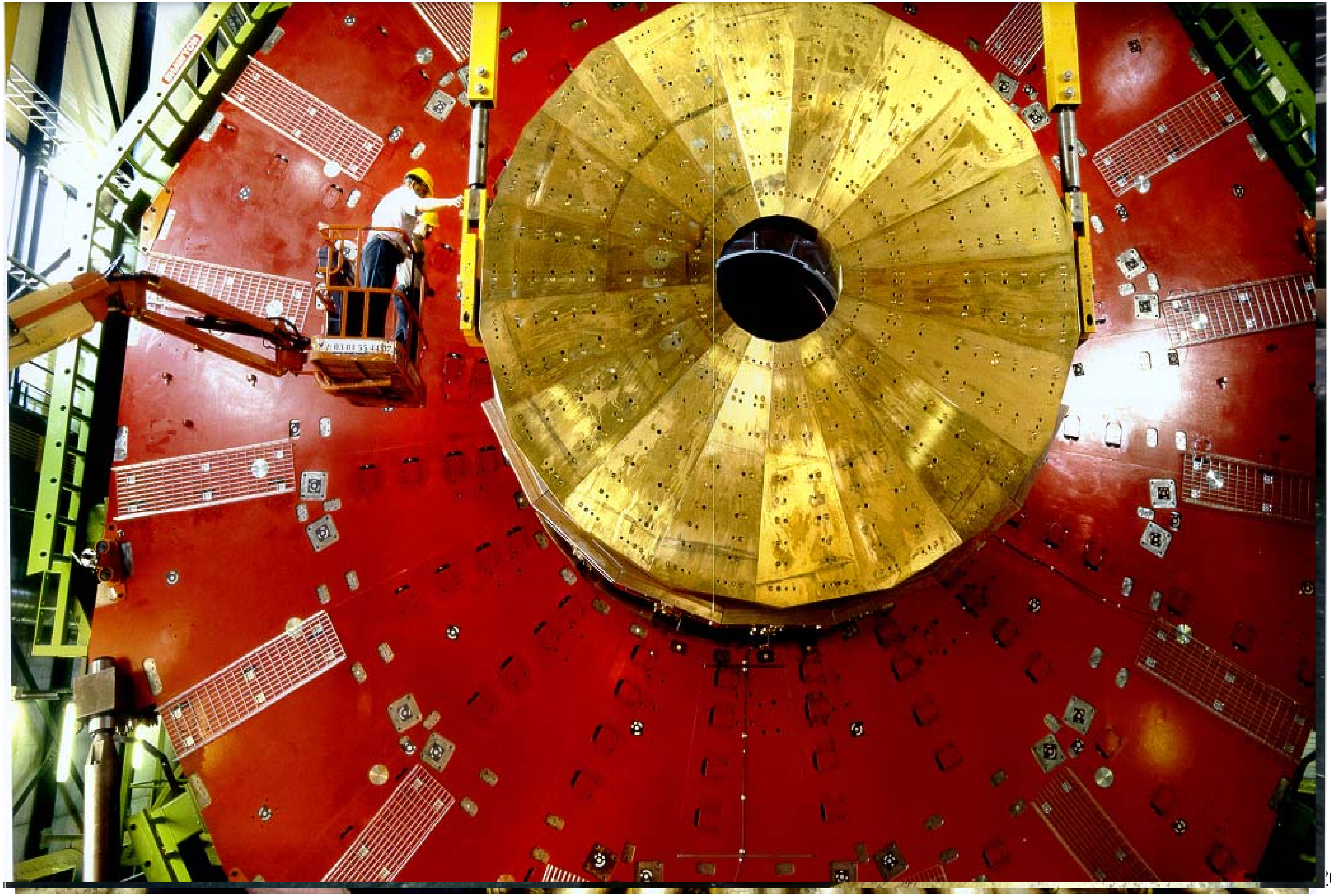
Assembly of the Coil



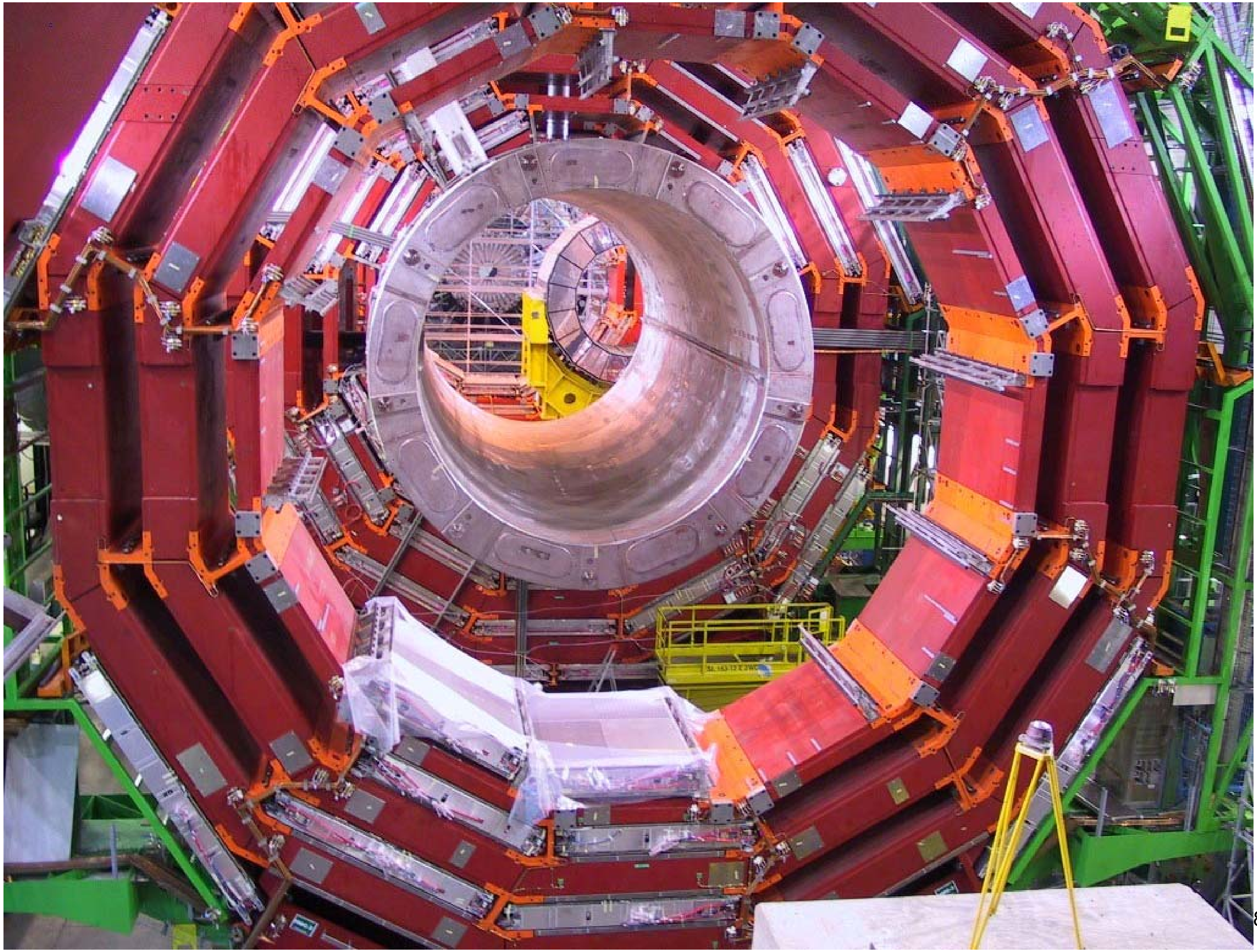
Assembly of the Coil



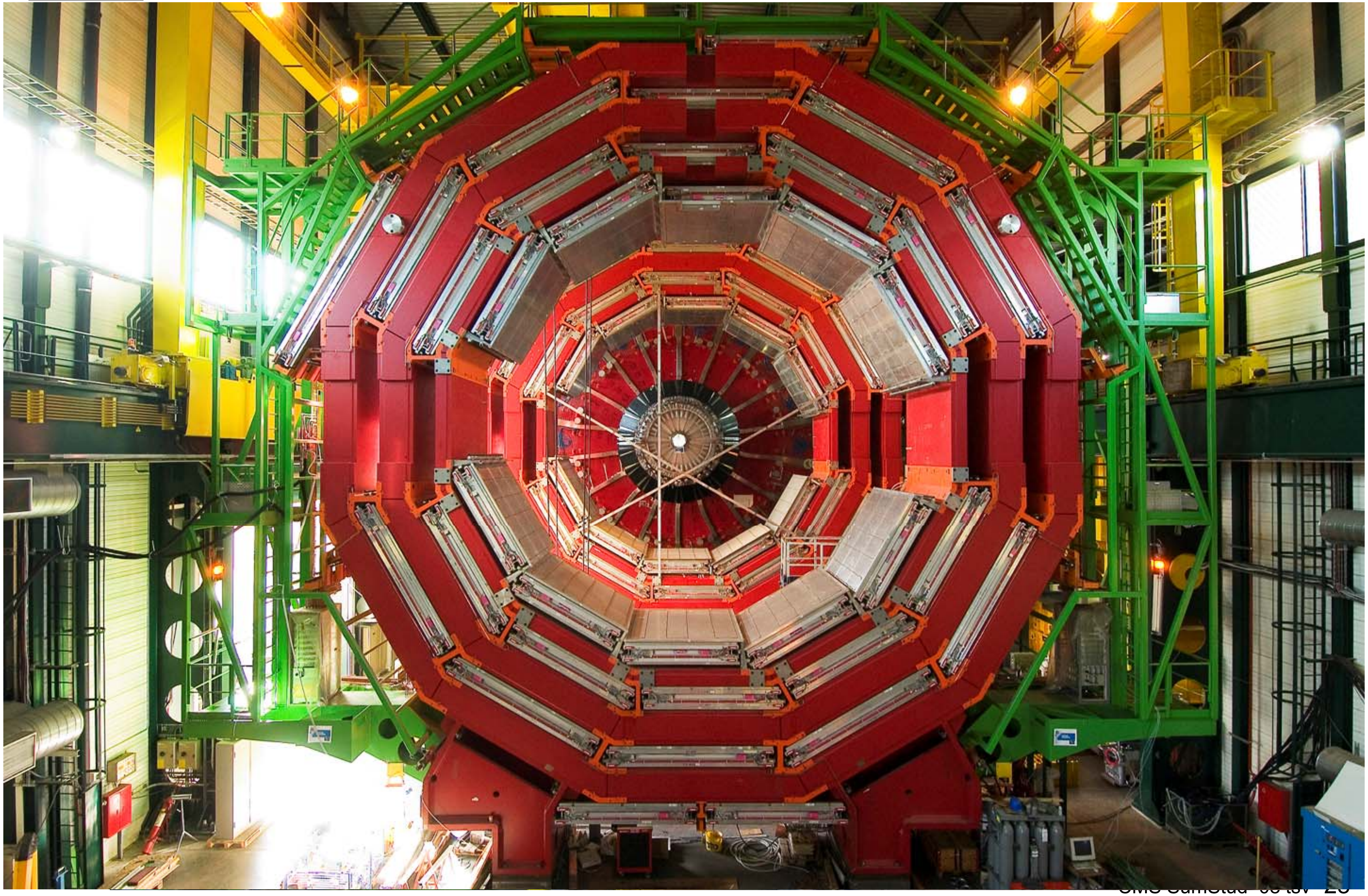
HCAL Endcap
Swords to Ploughshares !



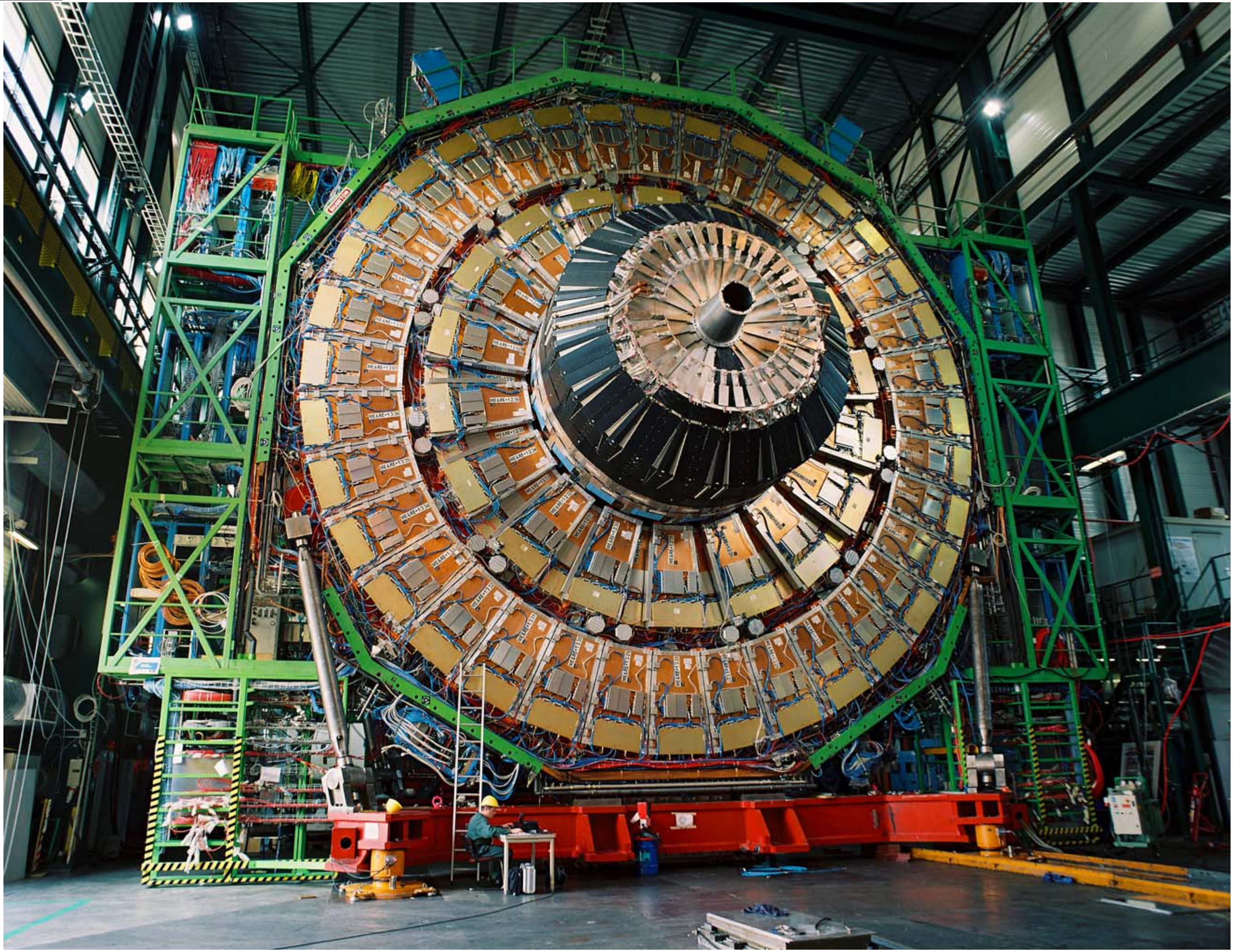
CMS Surface Hall in Feb 2006



Surface Hall: Barrel Muons



Surface Hall: Endcaps



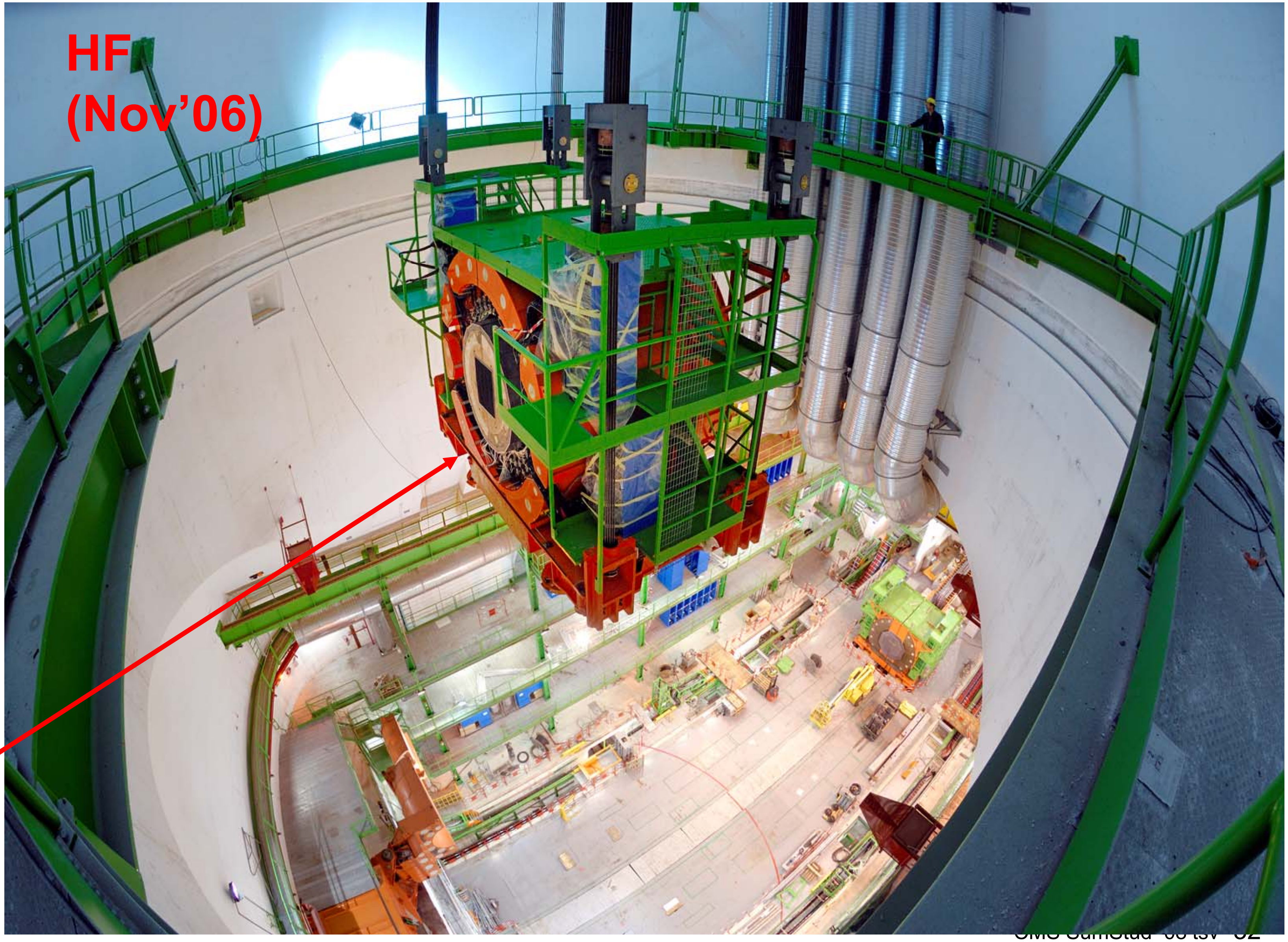
Experiment Cavern

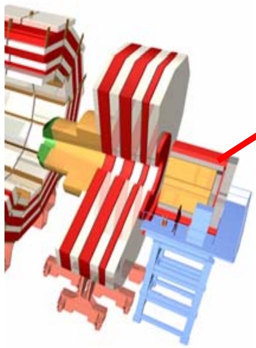
2003

2004

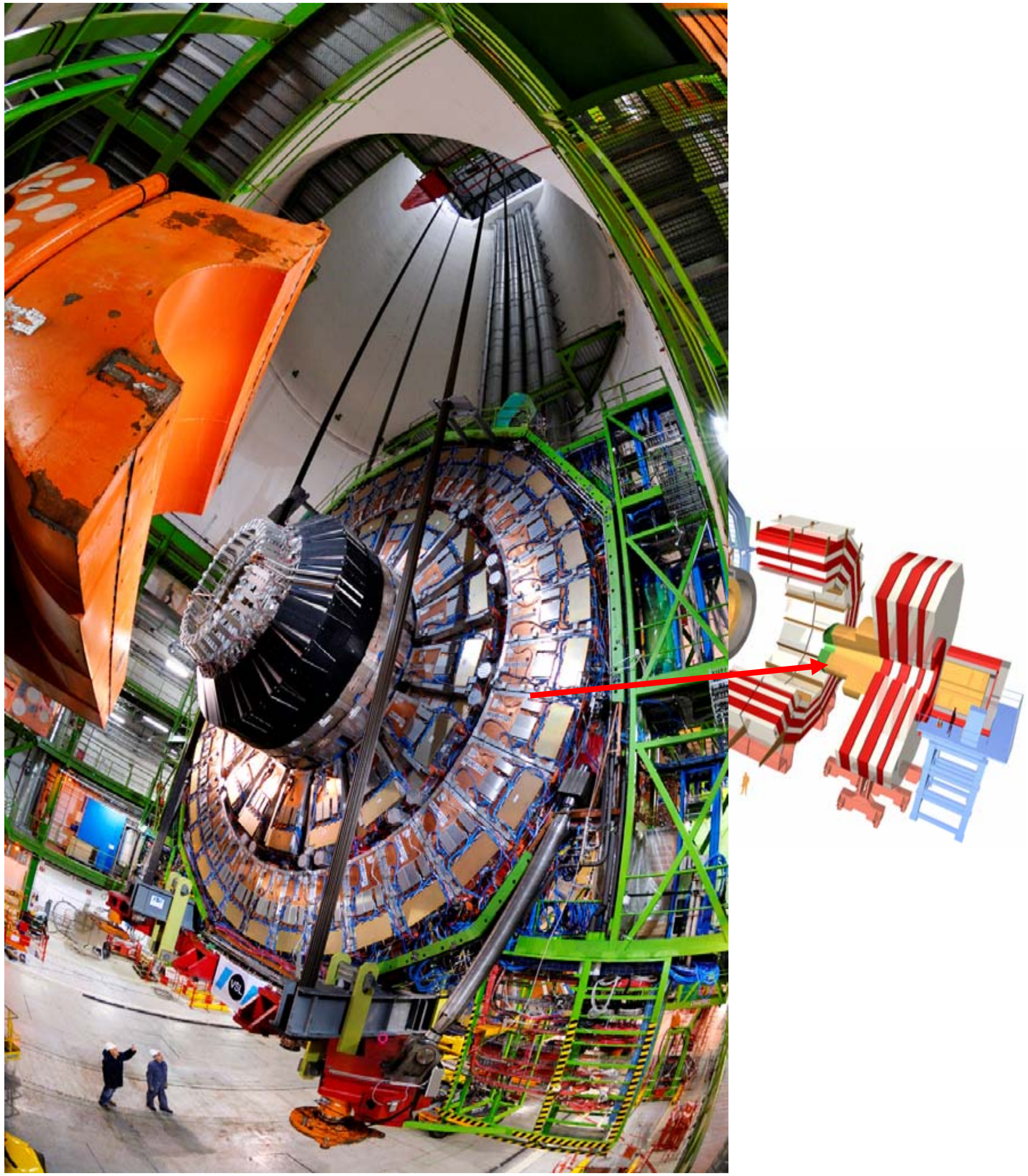
Safety: Foam Test

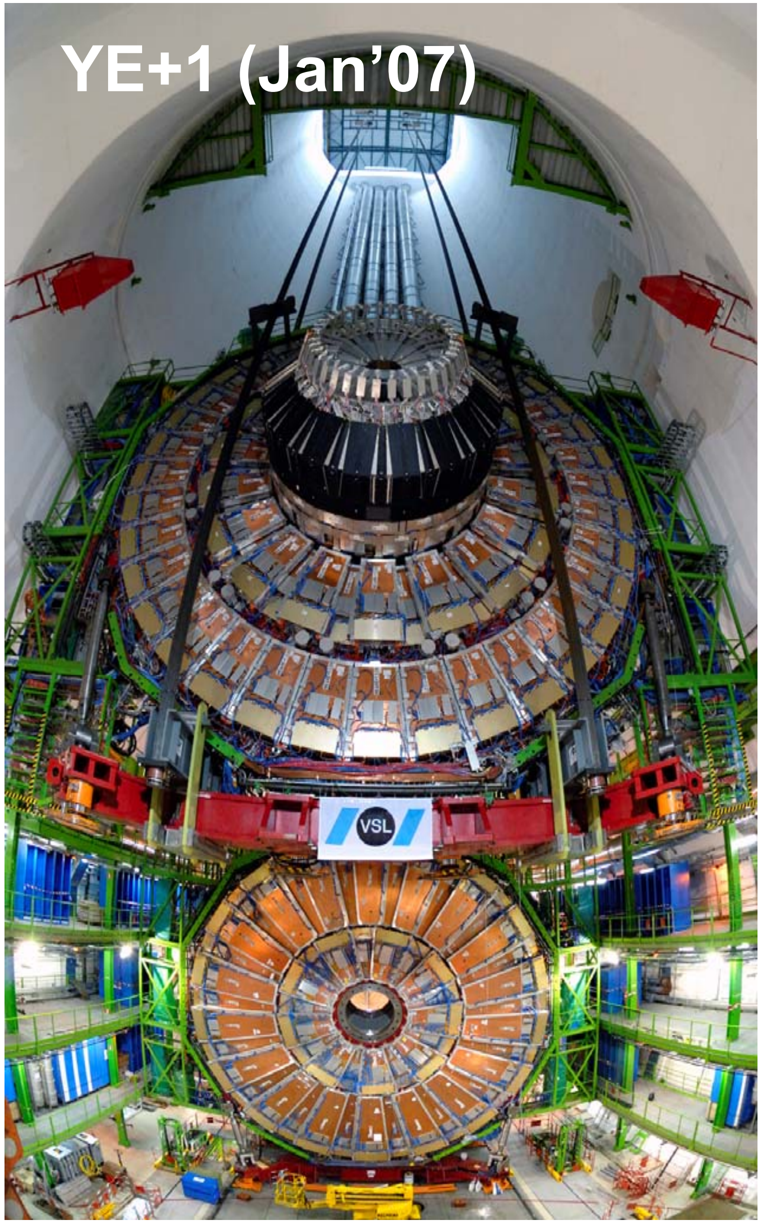
Lowering of Heavy Elements



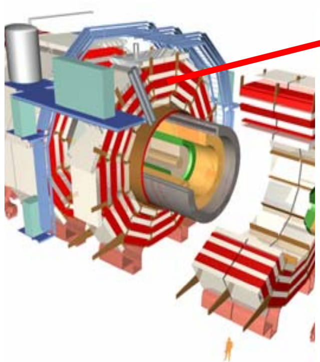


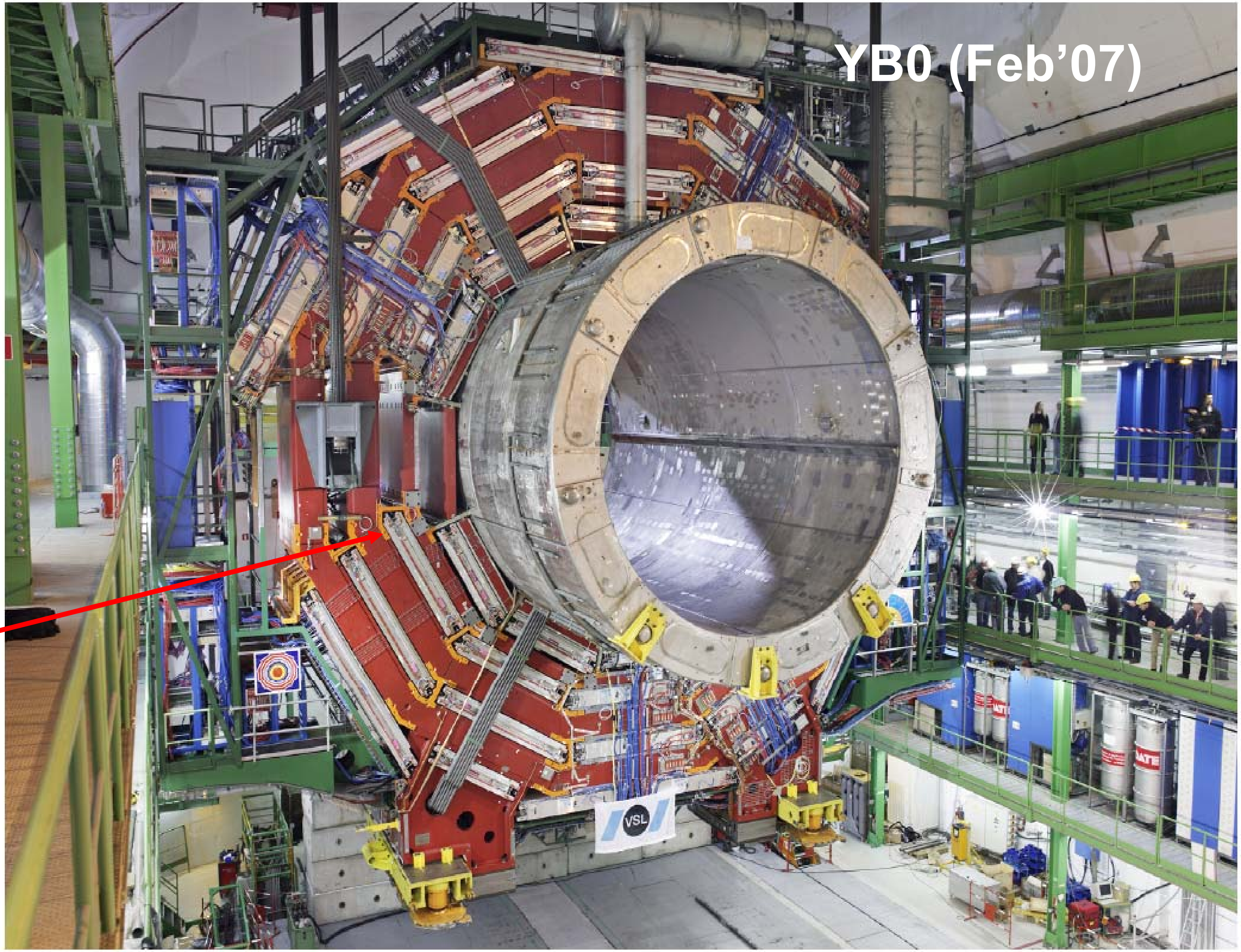
Lowering of Heavy Elements



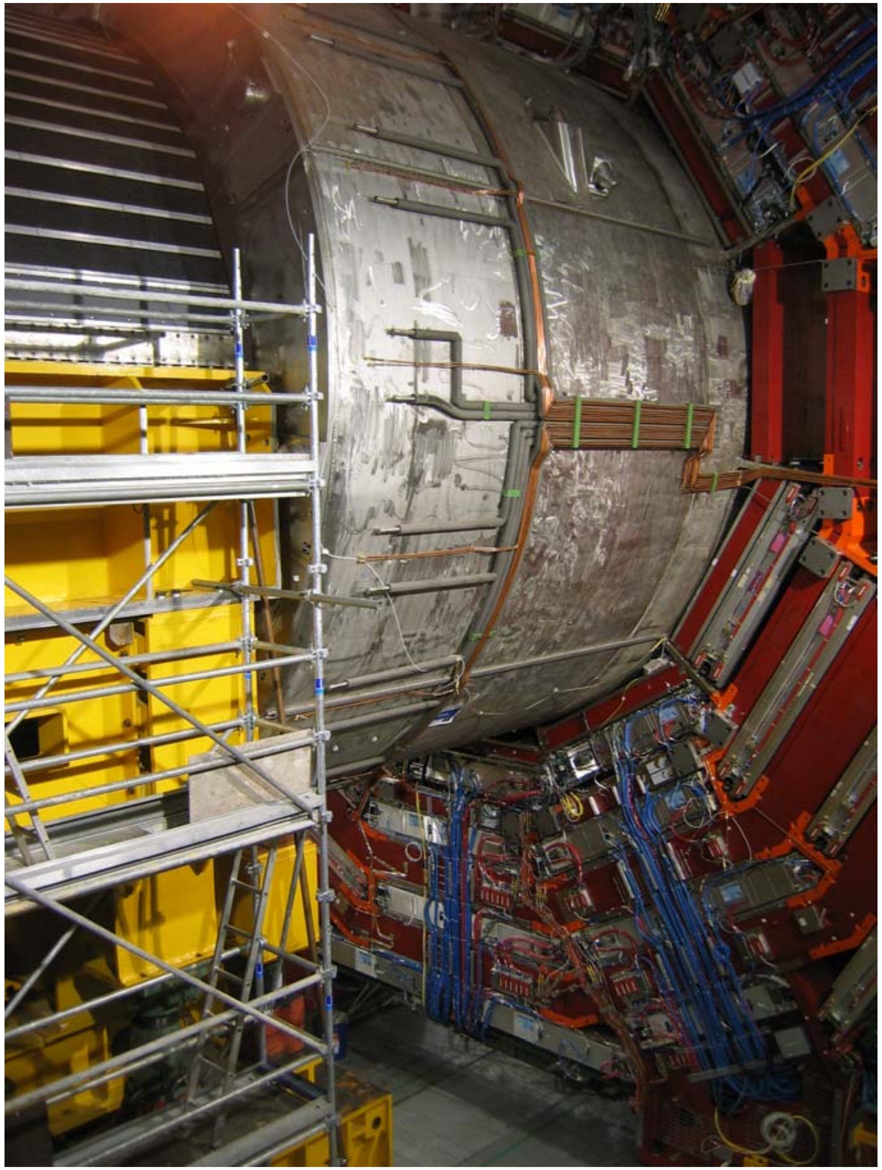


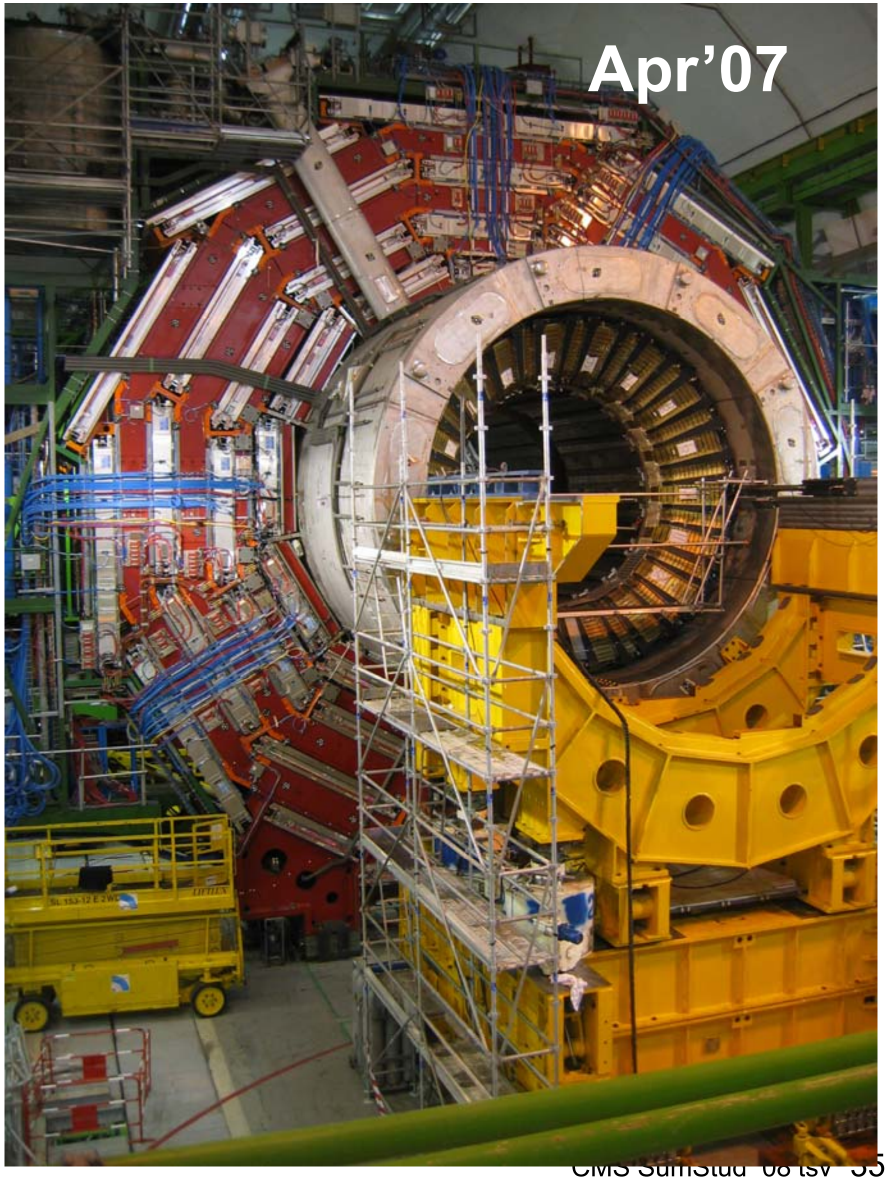
Lowering of Heavy Elements



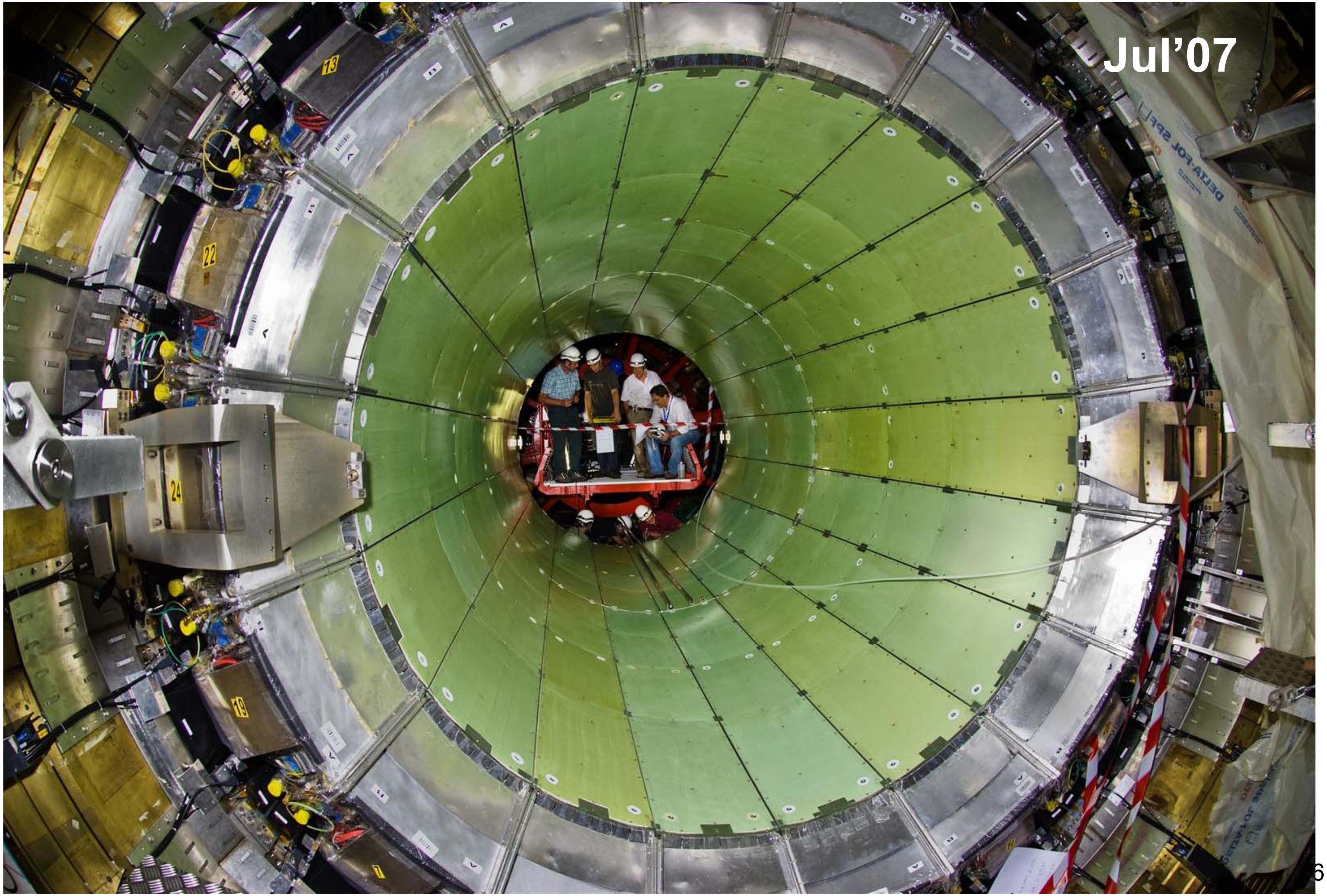


Insertion of HCAL Barrel

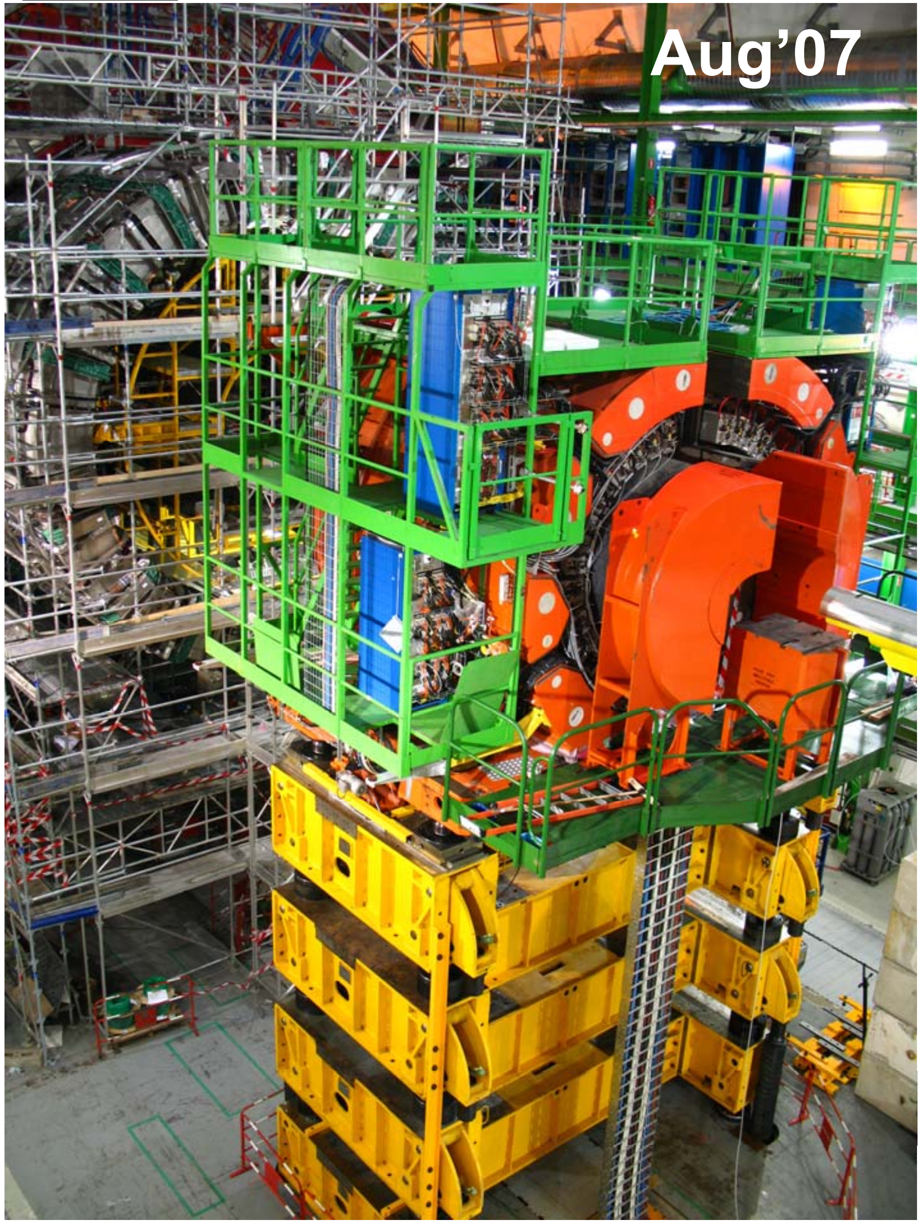


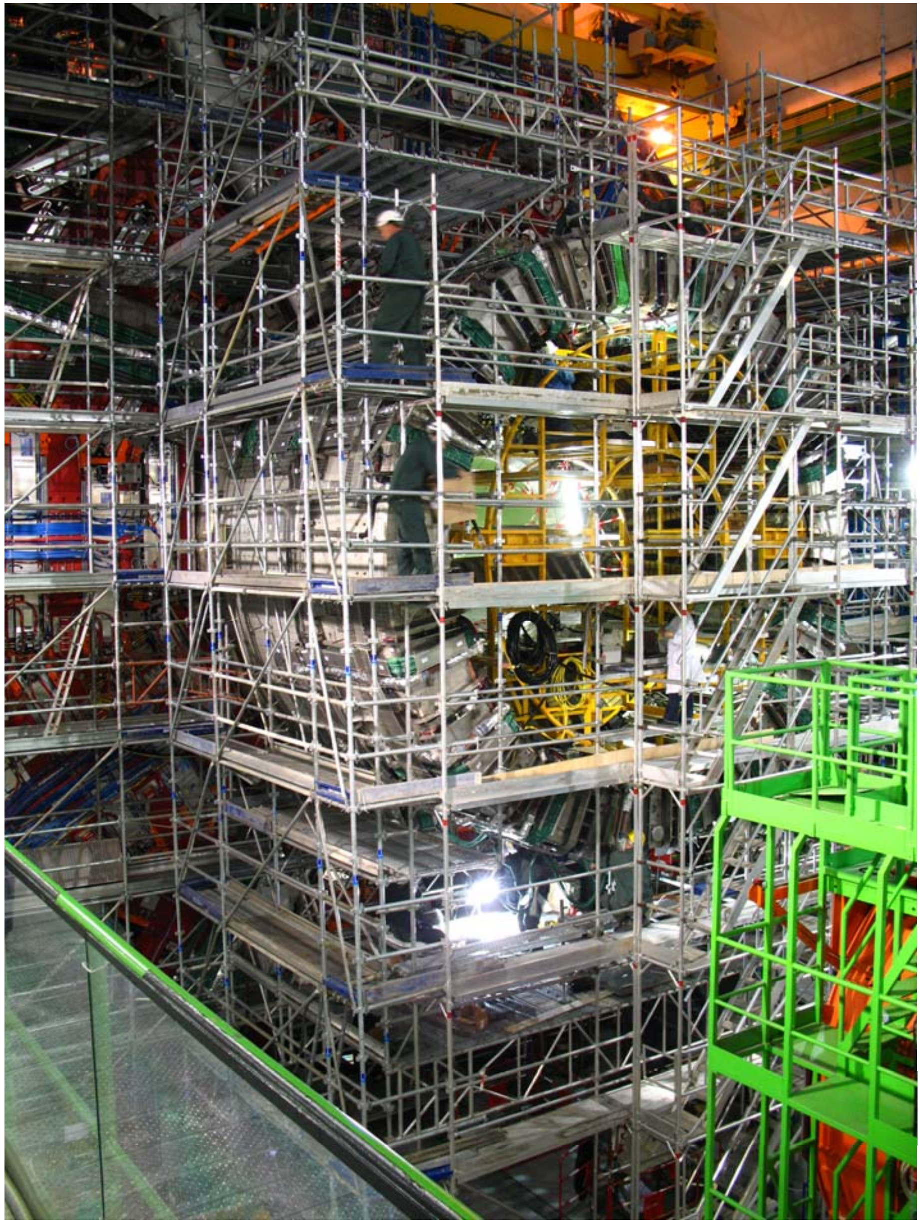


Insertion of Barrel ECAL

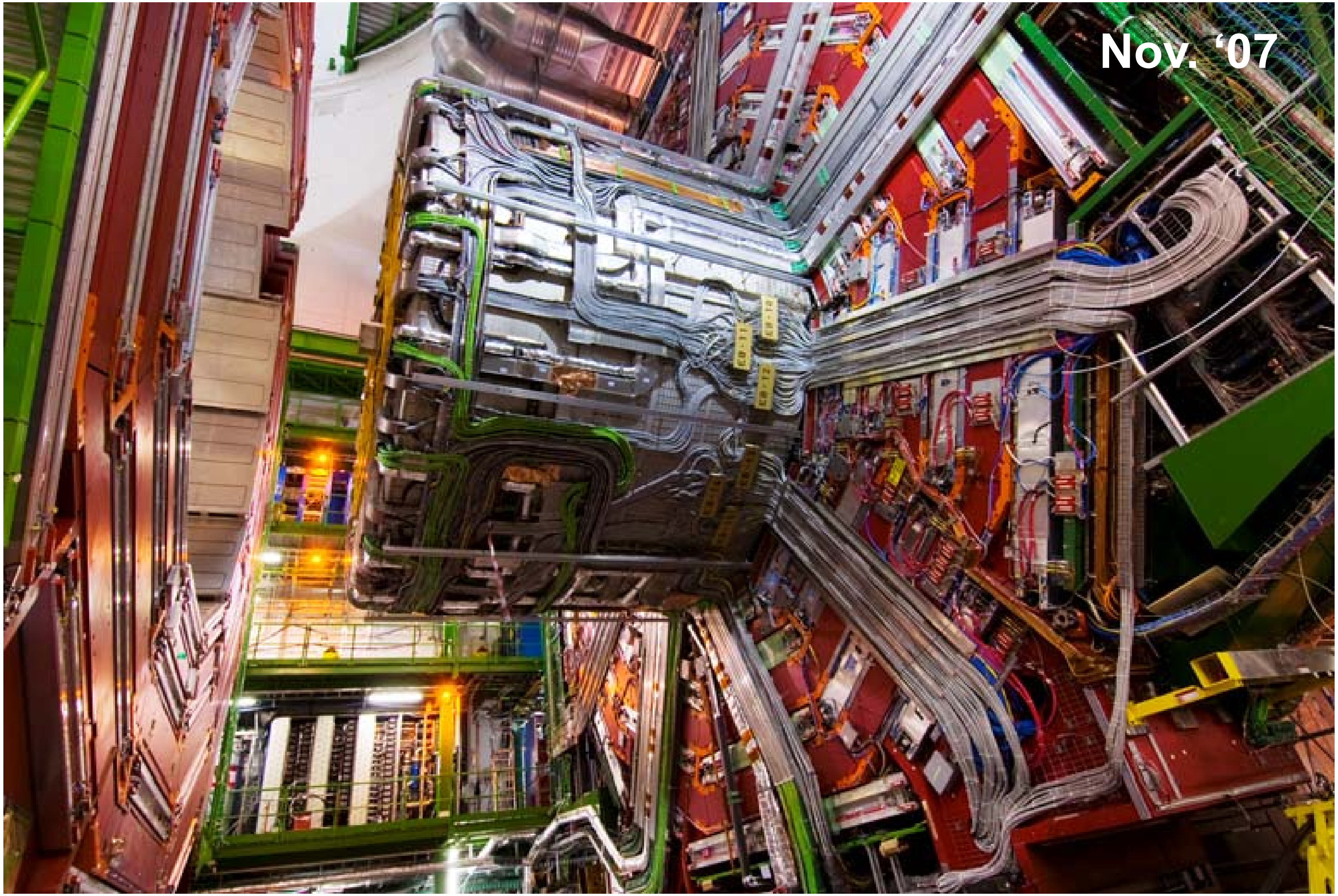


Raising of HF & YB0 Services

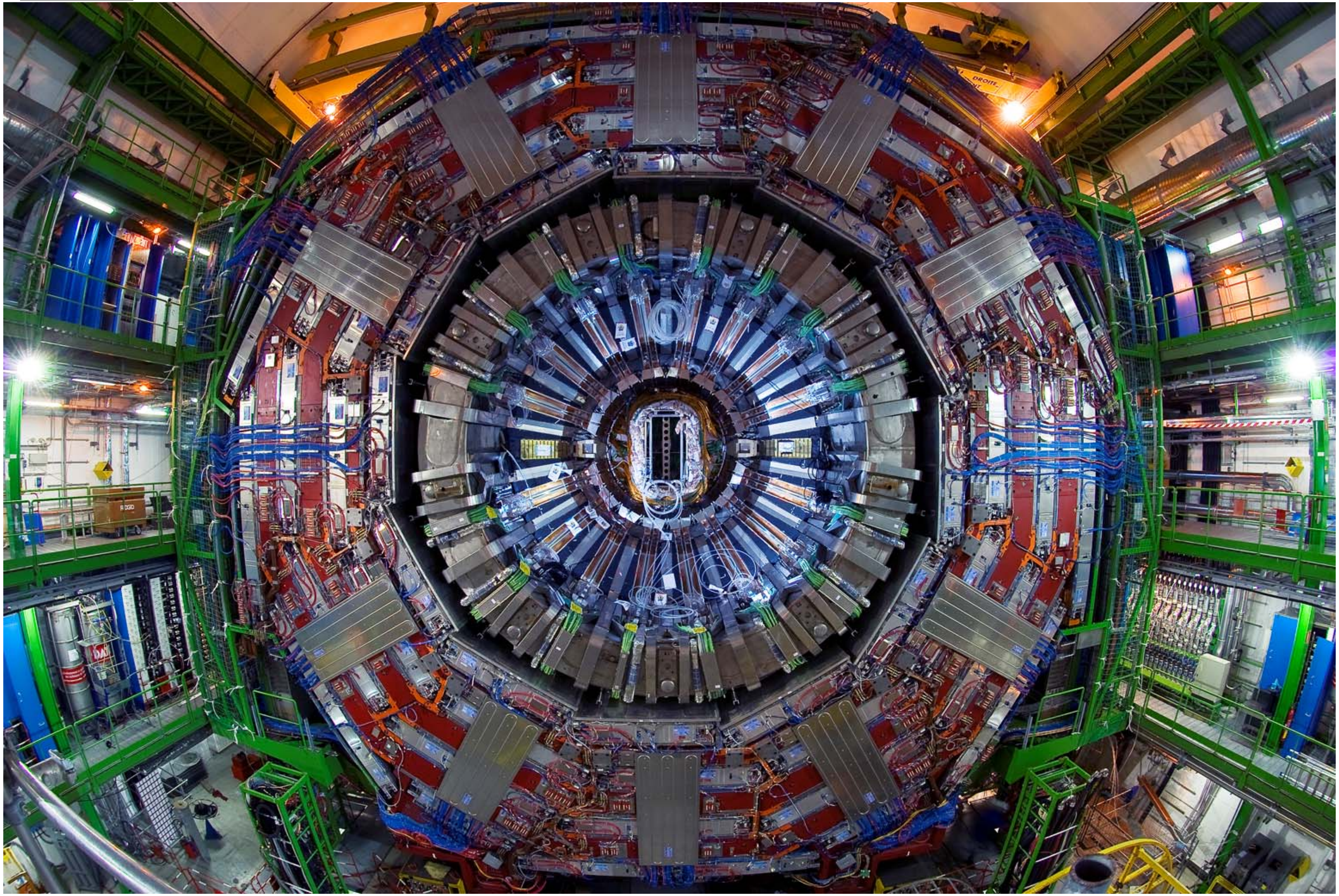




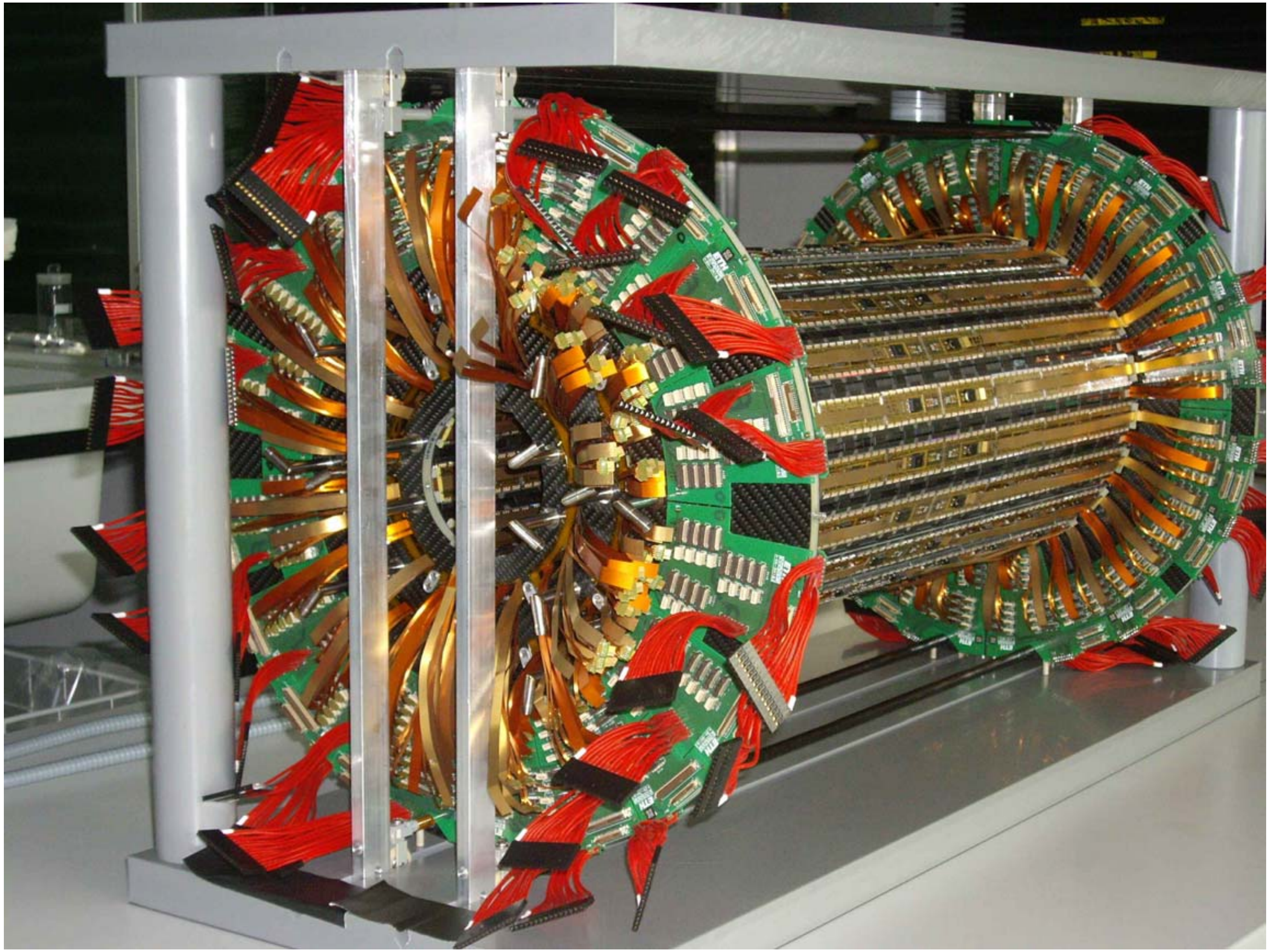
Completion of Services on YB0



Insertion of the Inner Tracker



The Pixels Detector



ECAL Endcap


Dee 1
Being Prepared for Shipment

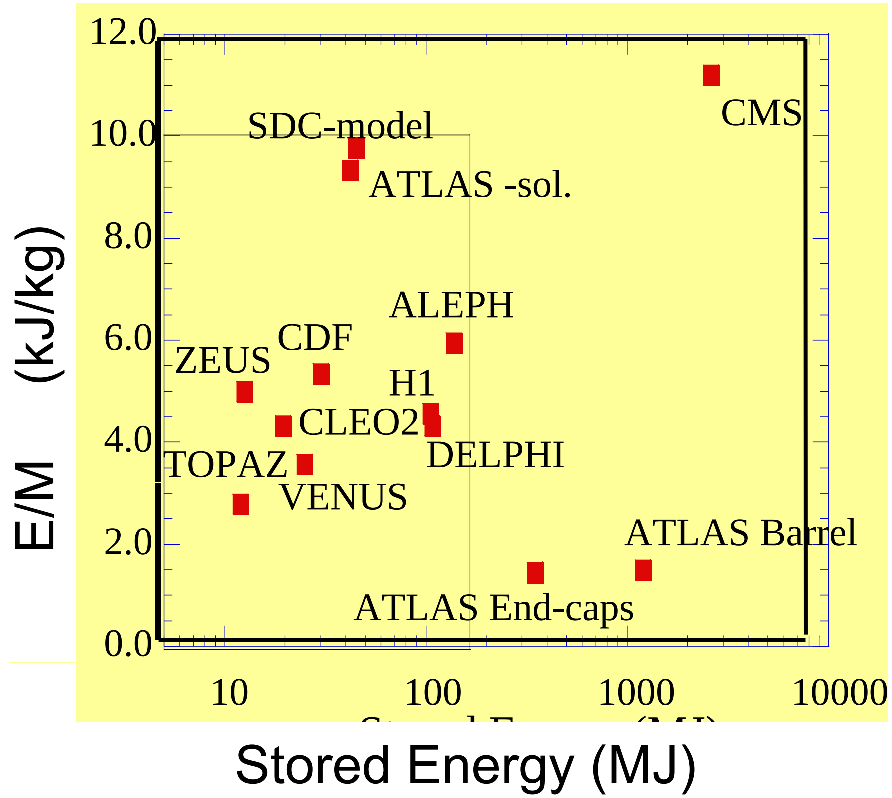

Dee 2
Photo 18 Jun
Finishing Commissioning


Dee 3
Photo 20 Jun
Starting Commissioning


Dee 4
Photo 23 May
Now Inserting vfe/fe cards

Extreme Engineering
CMS Superconducting Solenoid

Design Goal: Measure 1 TeV/c muons with < 10% resolution



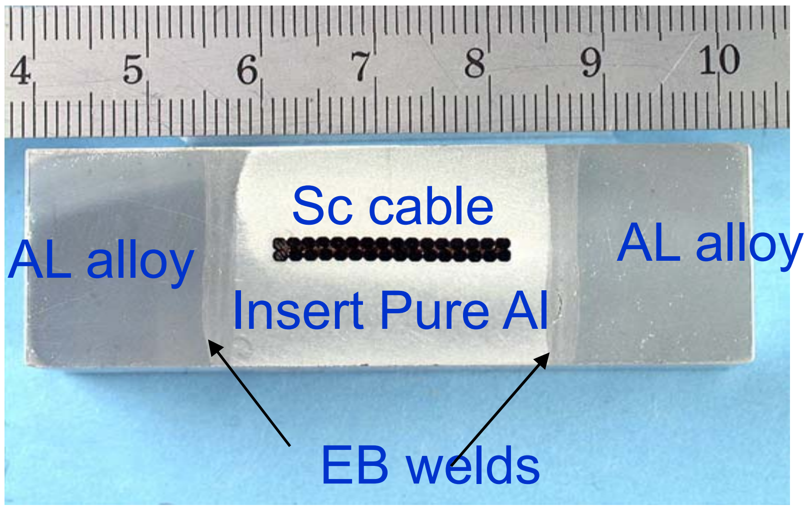
Key Features

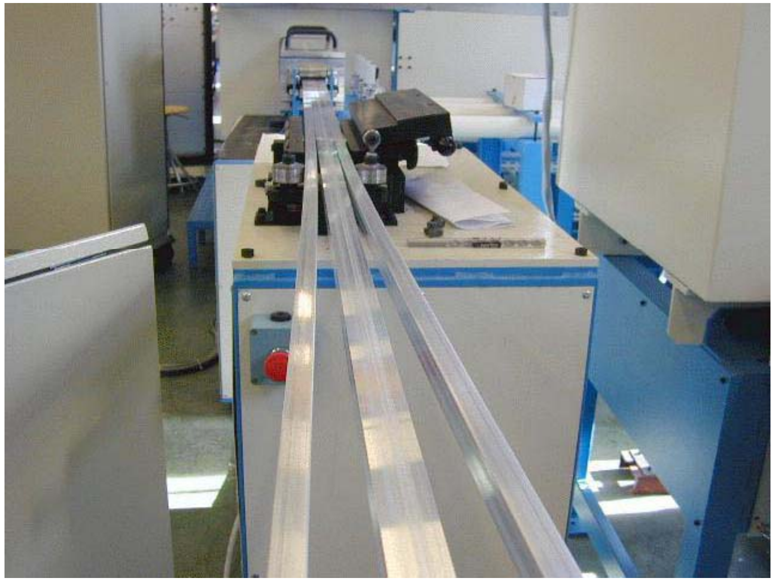
As ALEPH

- Passive protection by Quench-Back effect
- Al stabilized NbTi conductor (insert of CMS)
- Indirectly cooled at 4.5 K by thermo siphon circuits
- Inner winding vacuum impregnated with epoxy resin

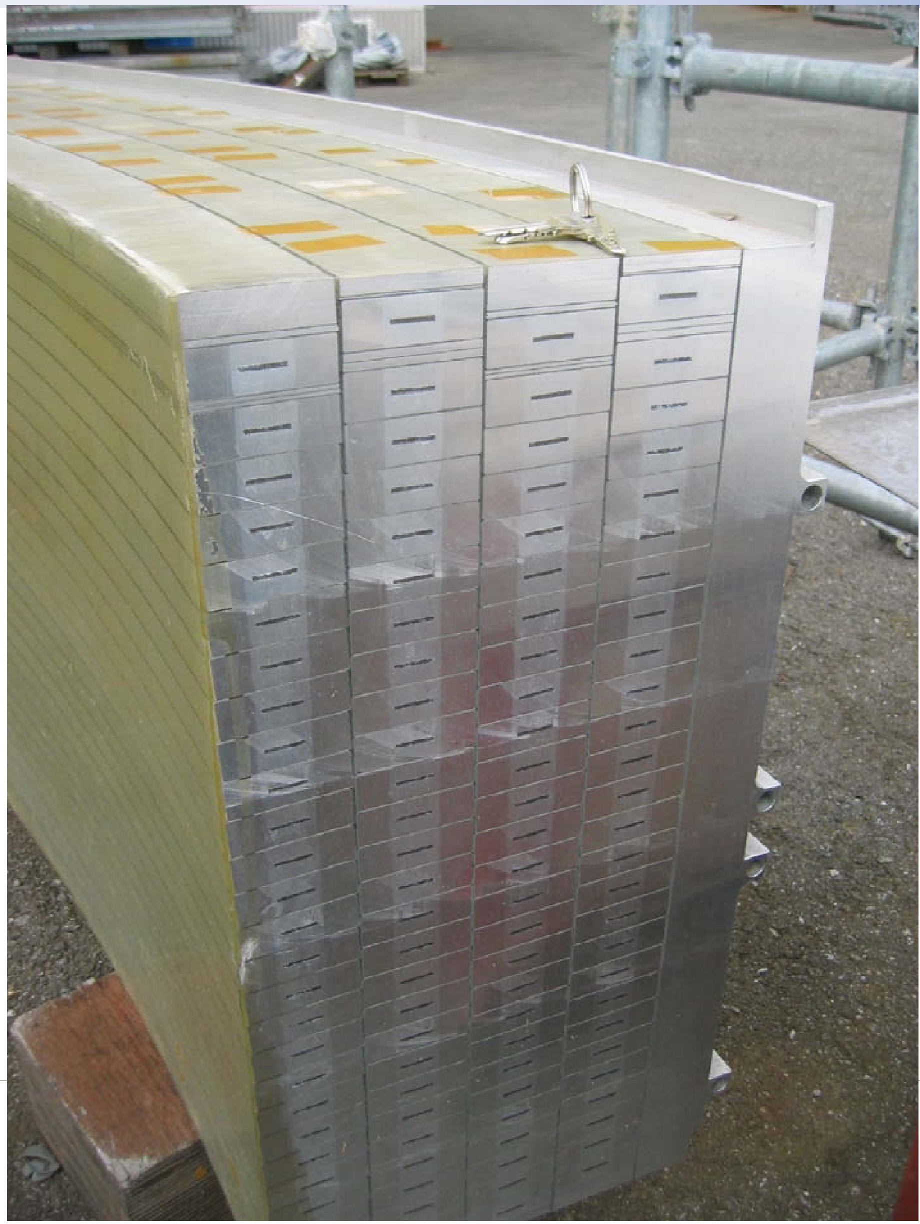
Improvements from ALEPH

- Mechanically reinforced conductor (to contain magnetic forces)
- 4 Layers (because of needed Ampere-turns)
- 5 modules (to limit unit length of conductor)





Winding of the Coil

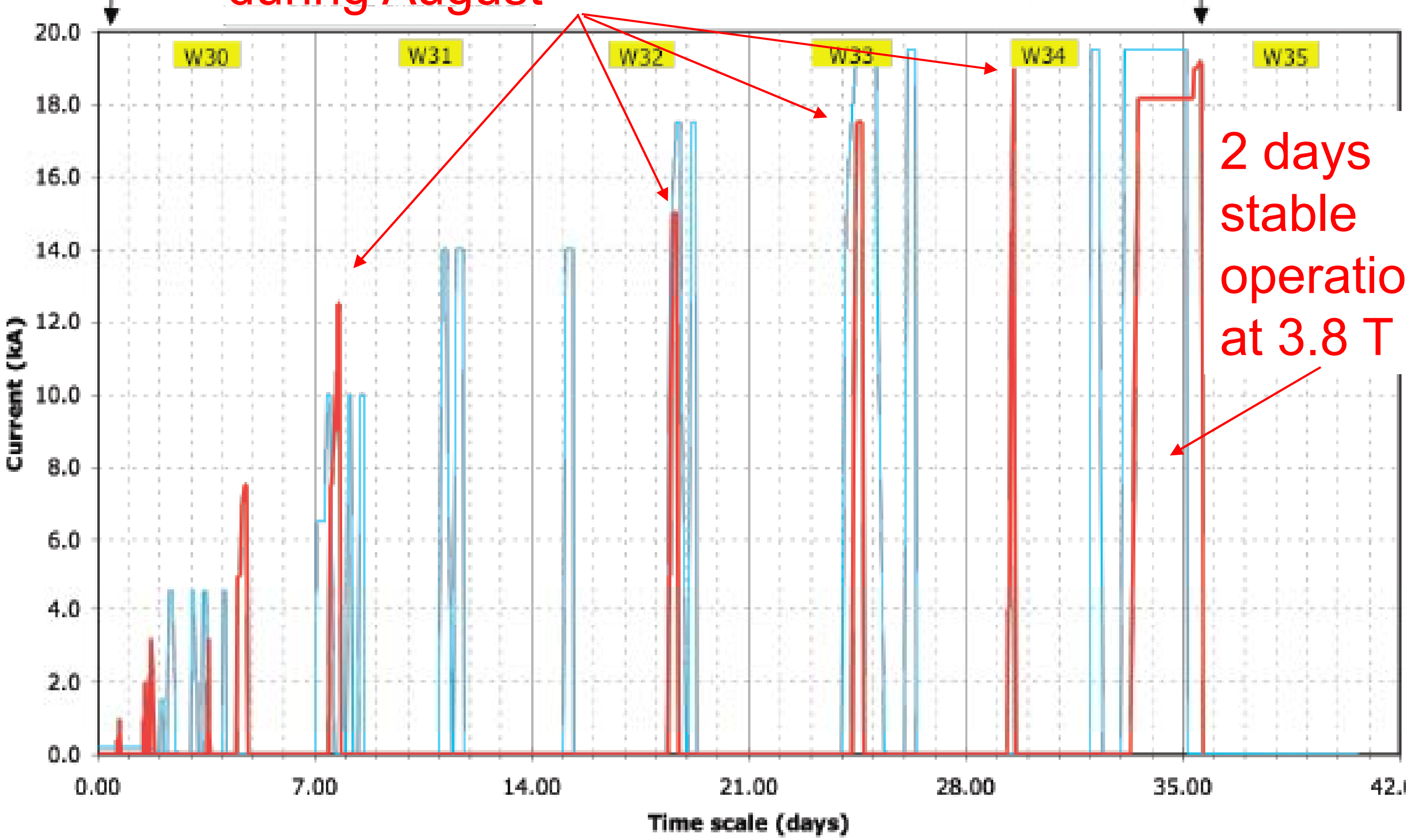


Test of the Magnet (2006)

24 July

Magnet Current Cycles achieved during August

28 August
19 kA, 4 Tesla!



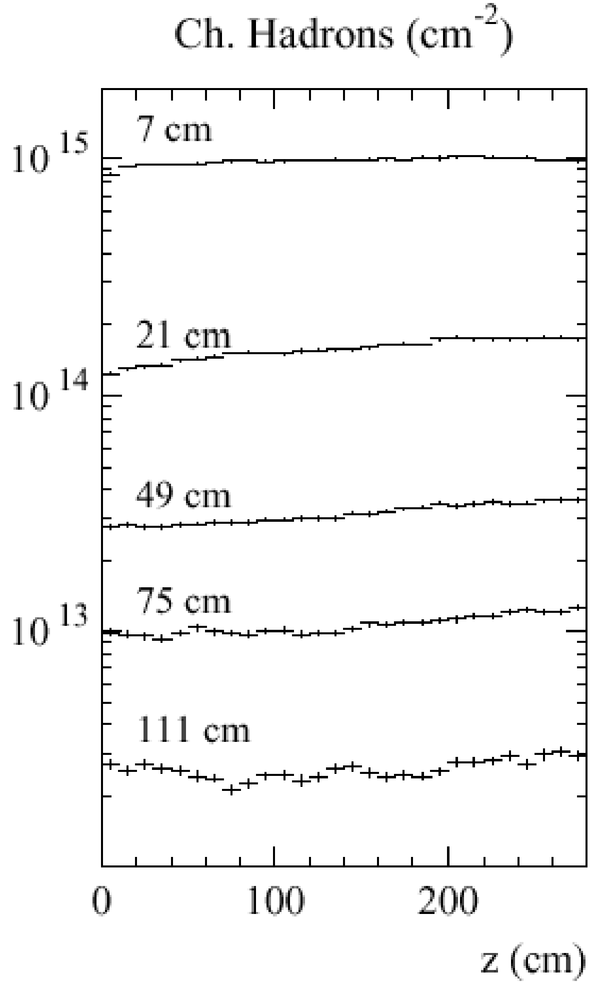
2 days stable operation at 3.8 T

Challenging Detectors

Tracking at LHC

Need factor 10 better momentum resolution than at LEP
1000 particles emerging every crossing (25ns)

Fluence over 10 years of LHC Operation



$\leq 4.10^7$ h$^\pm$/cm^2/s
pixels ($\approx 10^4$ μm^2)
occupancy $\approx 10^{-4}$

$\leq 4.10^6$ h$^\pm$/cm^2/s
Si μ-strip det.
($\approx$10 mm^2)
occupancy $\approx$ 1%

$\leq 4.10^5$ h$^\pm$/cm^2/s
Si or Gas detectors.
($\approx$1 cm^2)
occupancy $\approx$ 1%

Si Microstrips For Inner Tracking

Technologies Considered

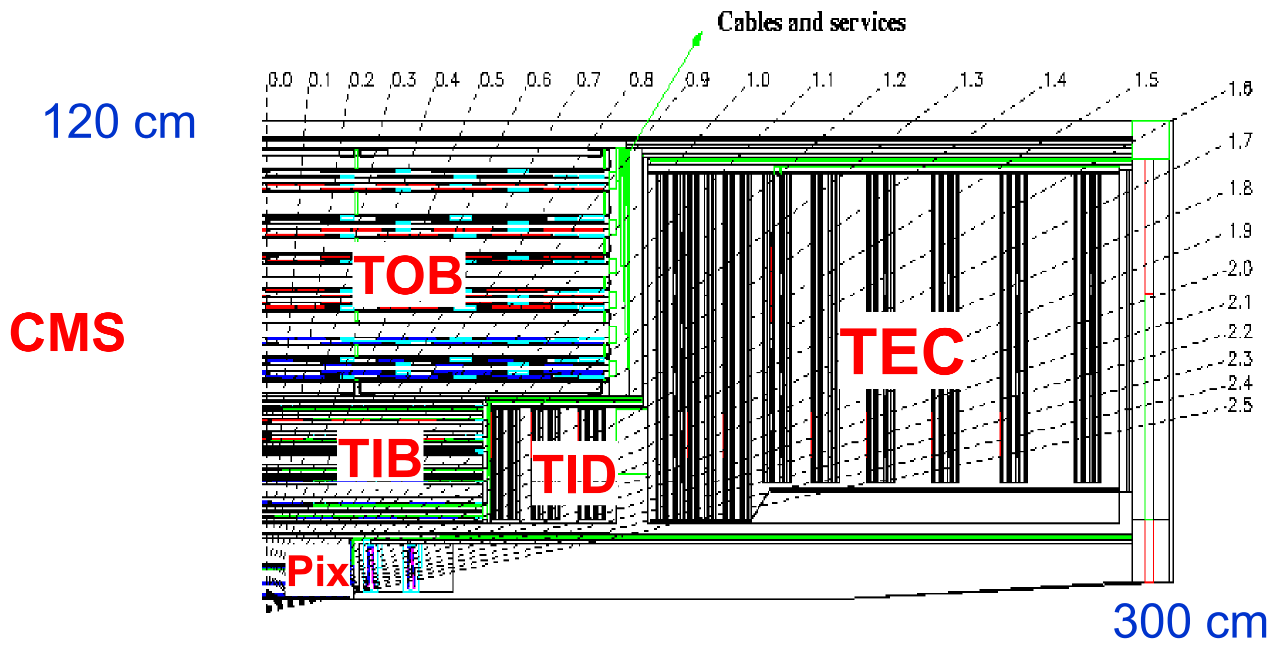
Scintillating fibres, MSGCs, Si Pixels, Si Microstrips

Si technology (ideally) suited to LHC environment

Four key developments for Si microstrip detectors

- Sensor fabrication on 6-inch instead of 4-inch wafers
- Implementation of front-end read-out chip in industry standard deep sub-micron technology
- Automation of module assembly and use of high throughput wire bonding machines
- Downwards evolution of price per unit area

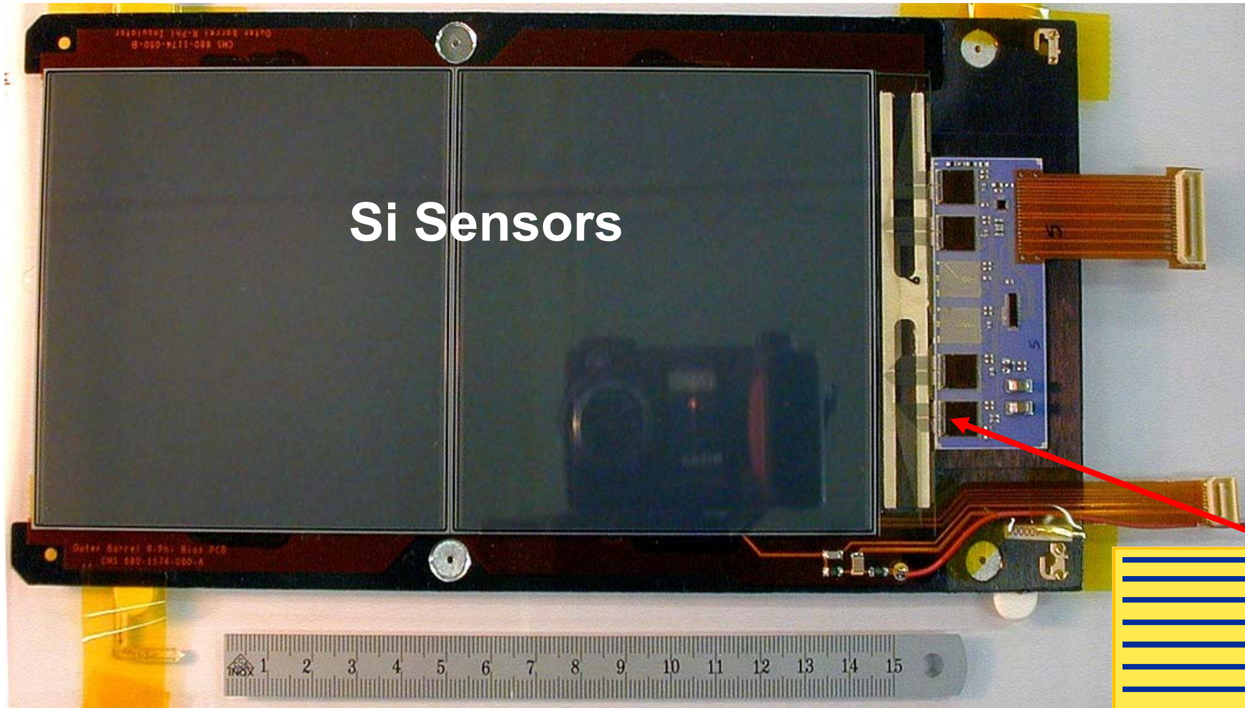
Layout of CMS Tracking



Si pixels surrounded by silicon strip detectors

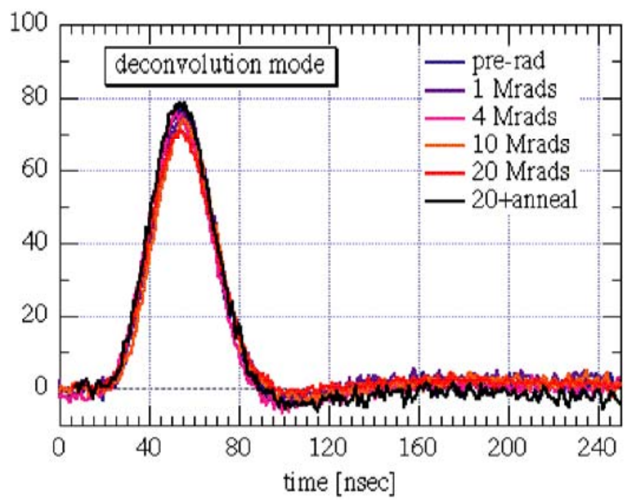
Pixels: ~ 1 m^2 of silicon sensors, 65 M pixels, 100x150 μm^2 , r = 4, 7, 11 cm
Si μstrips : 223 m^2 of silicon sensors, 10 M strips, 10 pts, r = 20 – 120 cm

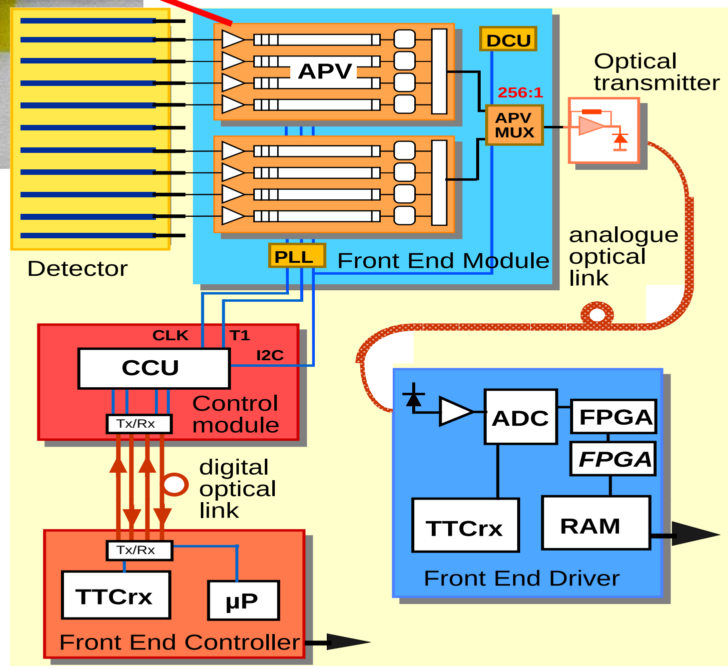
Si Modules and Electronics Chain



Ride on technology wave

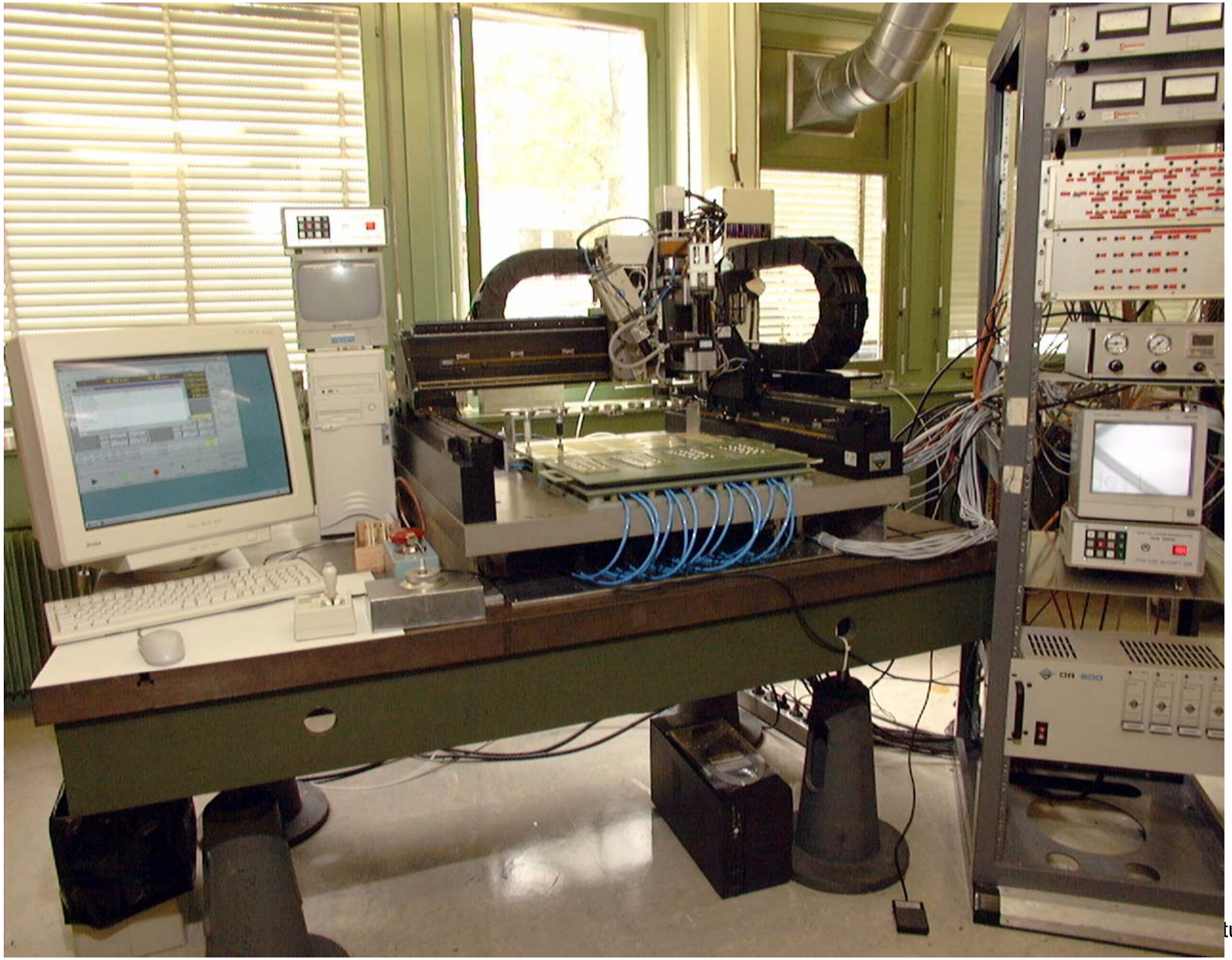
75k chips using 0.25μm technology



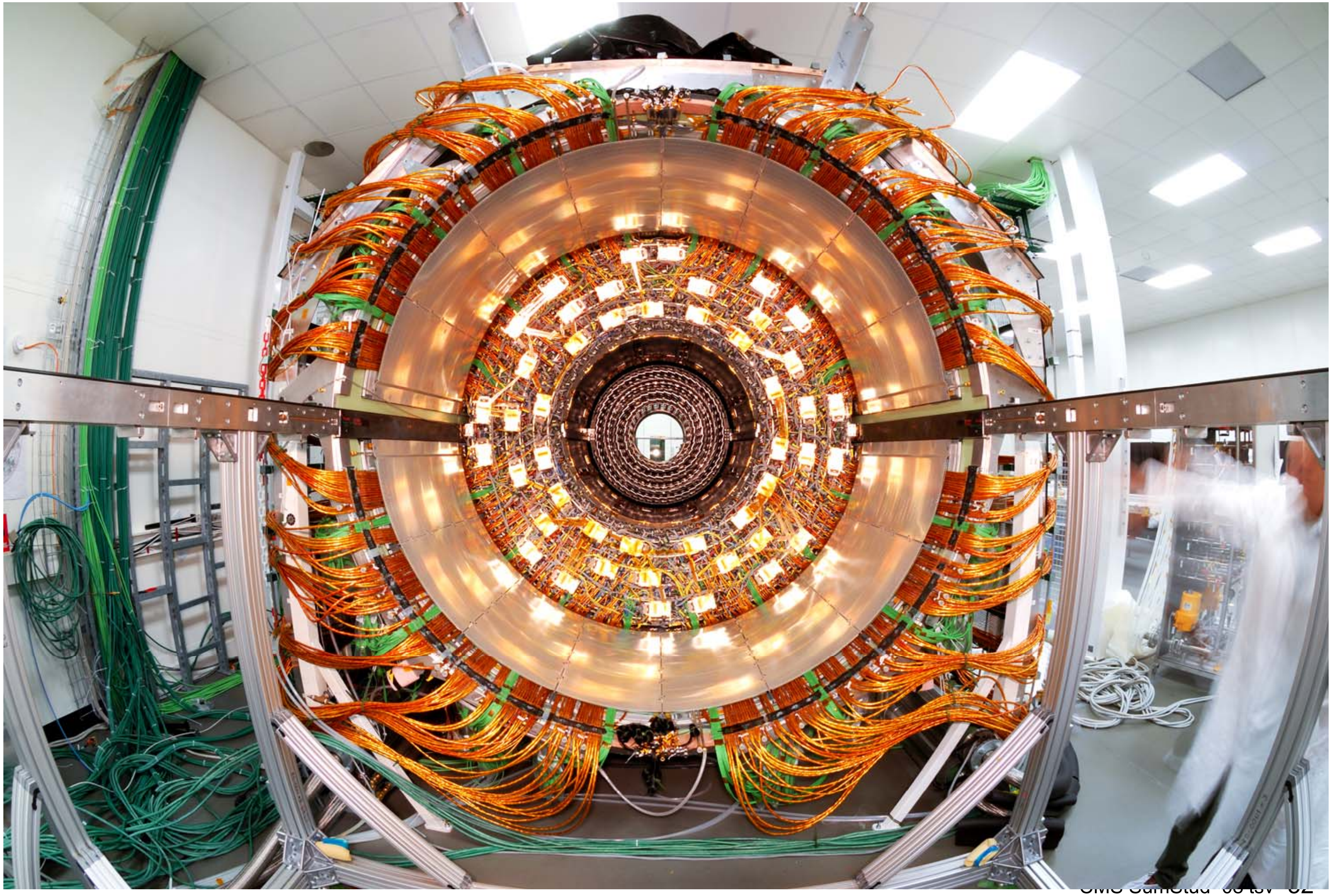


Automation in Si Module Production

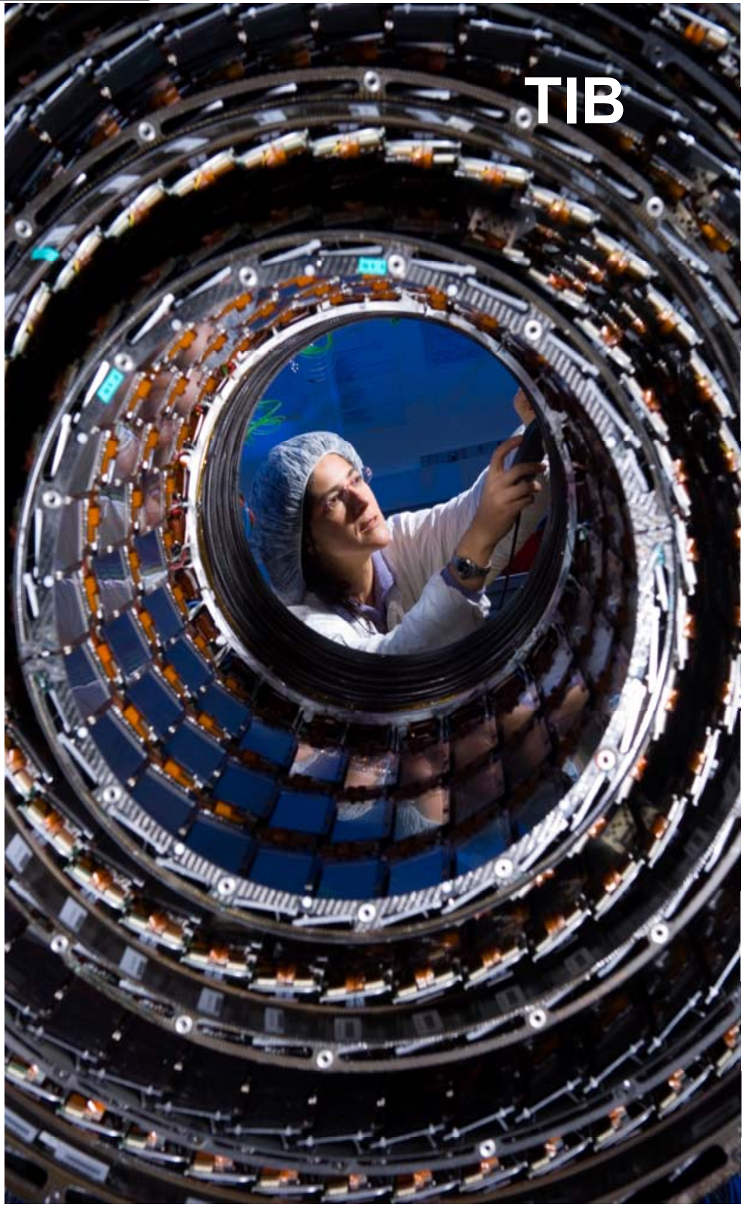
Automated module assembly and micro-bonding (17k modules)

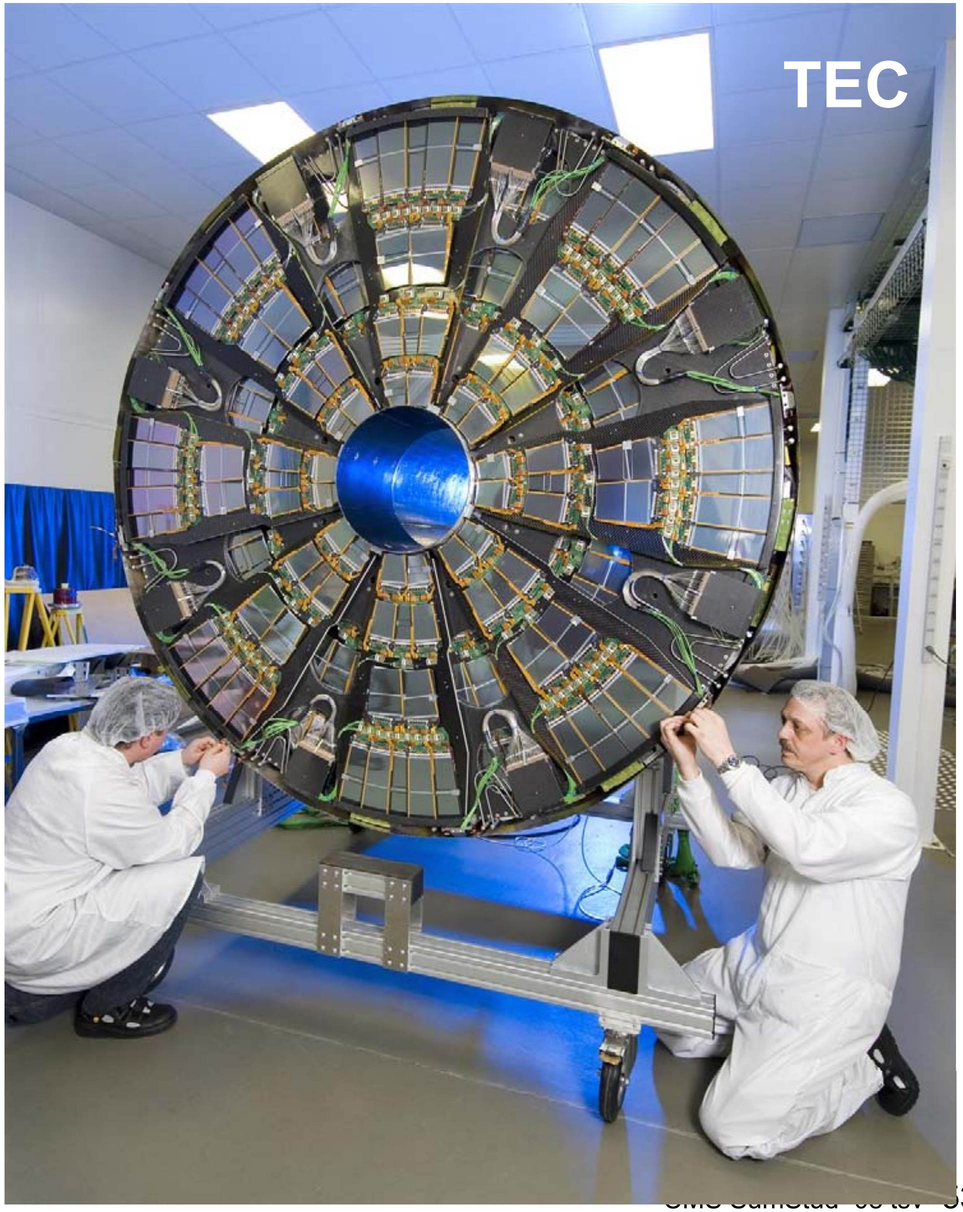


Si Tracker

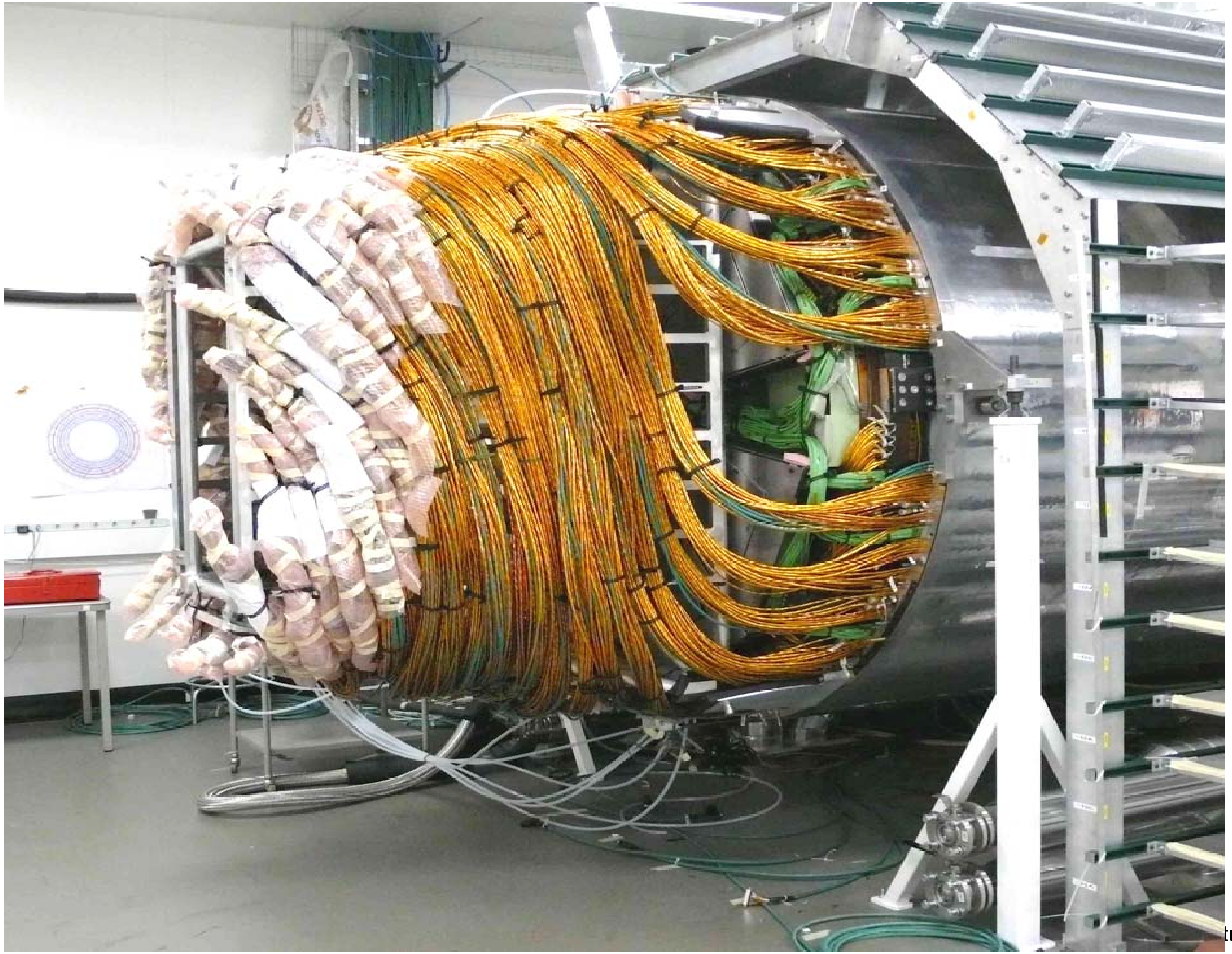


Si Tracker

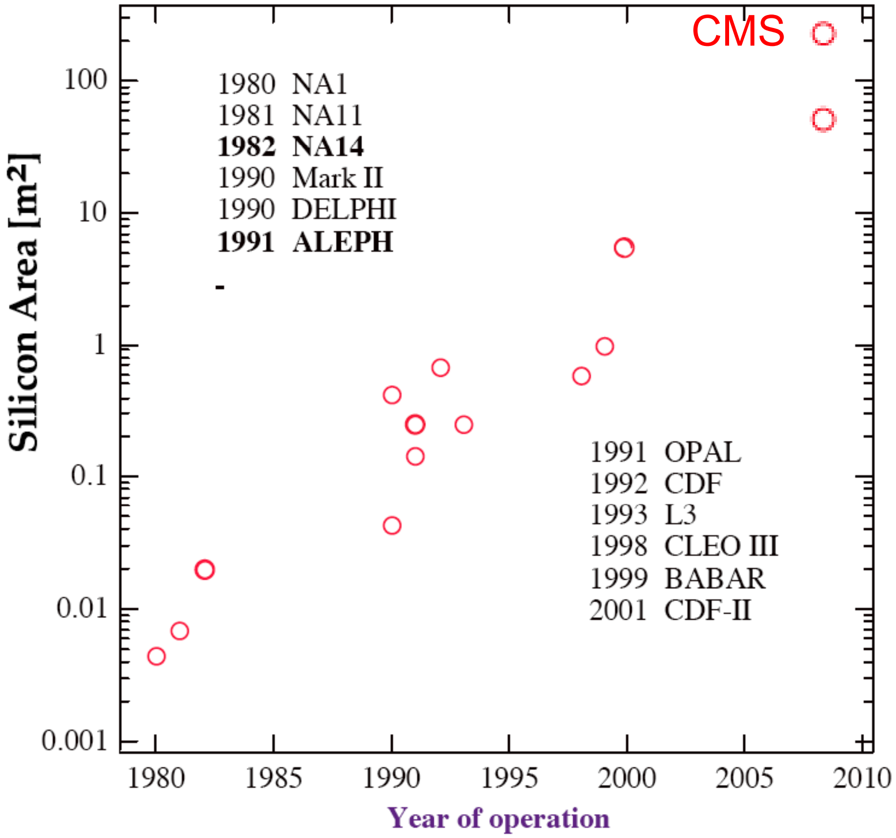


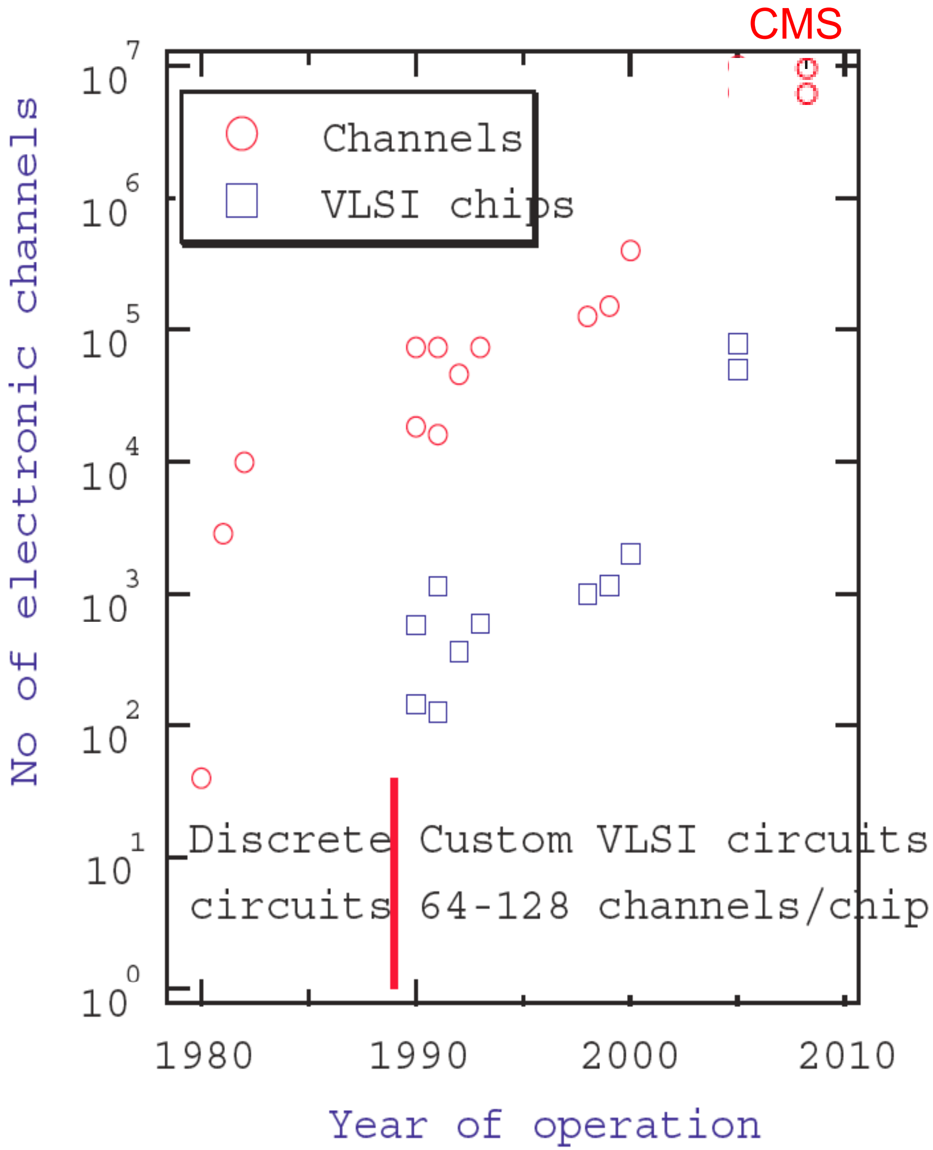


Tracker Readied for Installation



Evolution in Silicon & Electronics in High Energy Physics



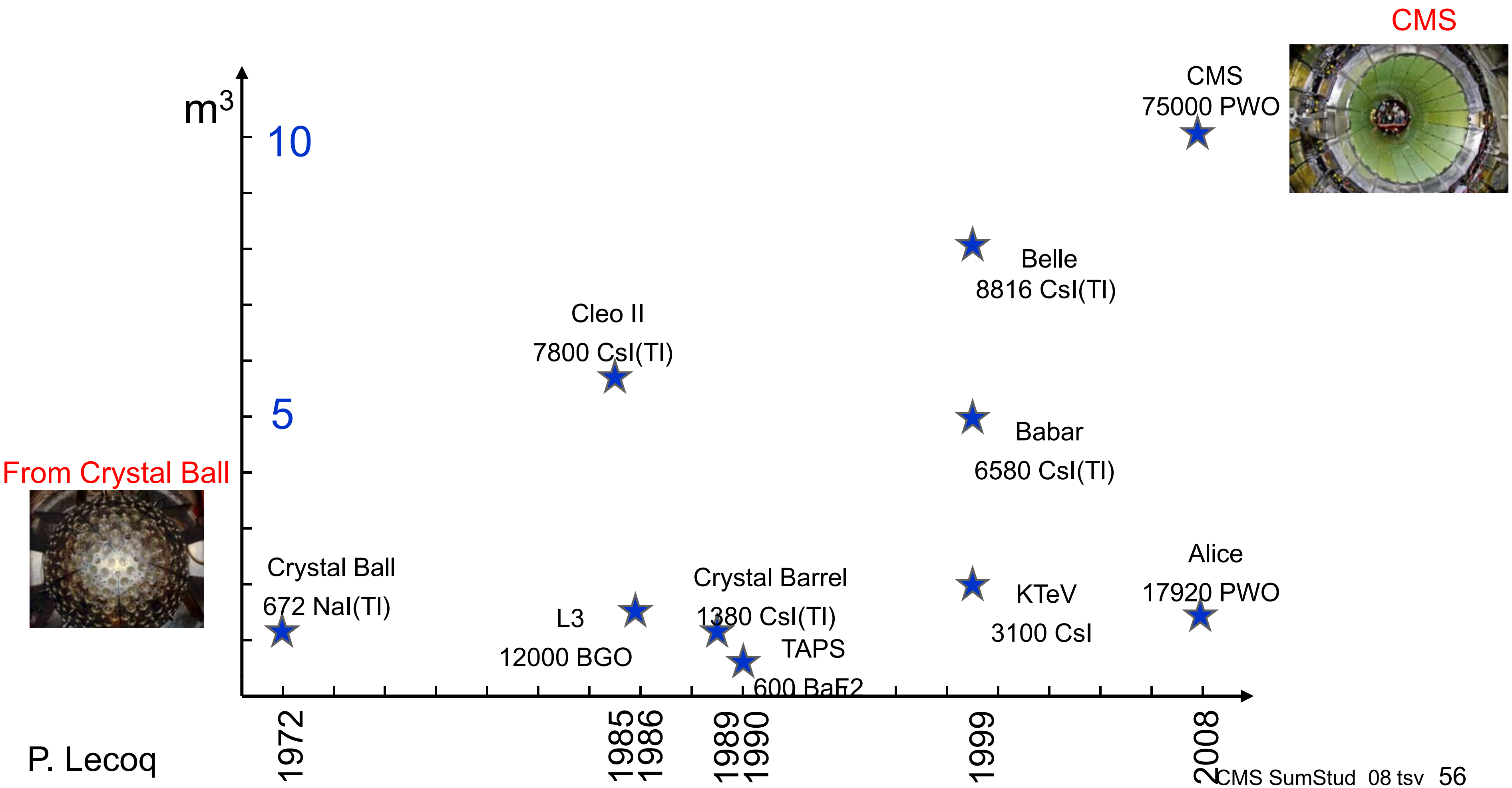


G. Hall

Lead Tungstate ECAL

Design Goal: Measure the energies of photons from a decay of the Higgs boson **to precision of ≤ 0.5%**

CMS chose scintillating crystals



P. Lecoq

Timeline for $PbWO_4$ Crystals ECAL

Idea (1993 – few yellowish cm^3 samples)

→ **R&D** (1993-1998: improve rad. hardness: purity, stoechiometry,defects)

→ **Prototyping** (1994-2001: large matrices in test beams, monitoring)

→ **Mass manufacture** (1997-2008: increase industrial capacity, QC)

→ **Systems Integration** (2001-2008: tooling, assembly)

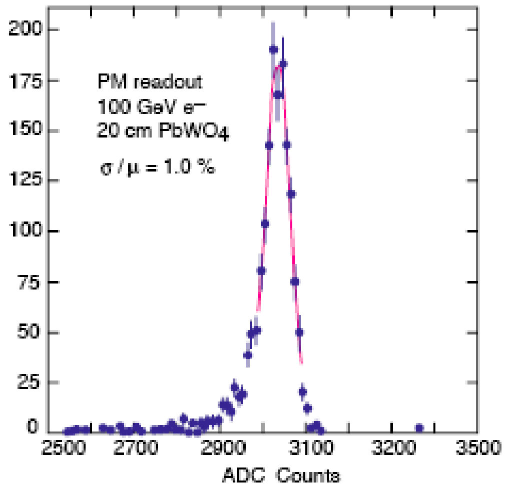
→ **Installation and Commissioning** (2007-2008)

→ **Data Taking** (2008 onwards)

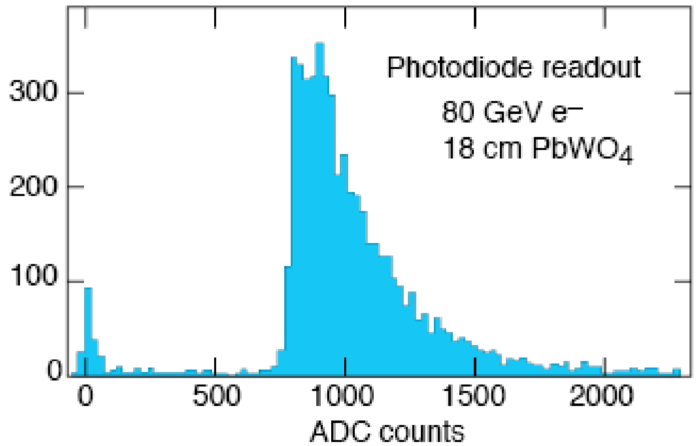
Δt ~ 15 years !!!

Choice of the Photodetector

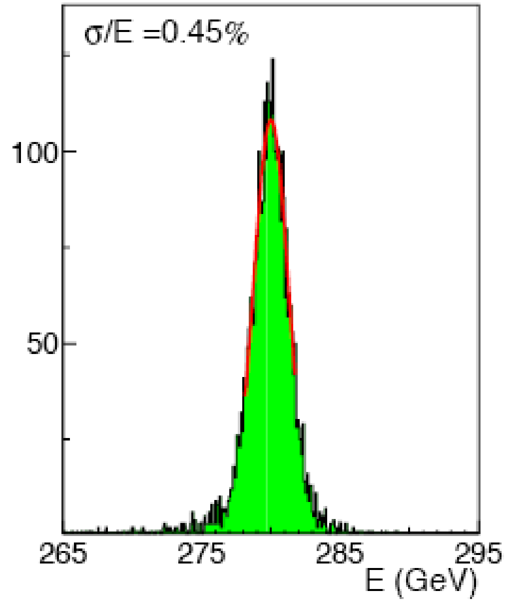
Photomultiplier Readout



Si Photodiode Readout

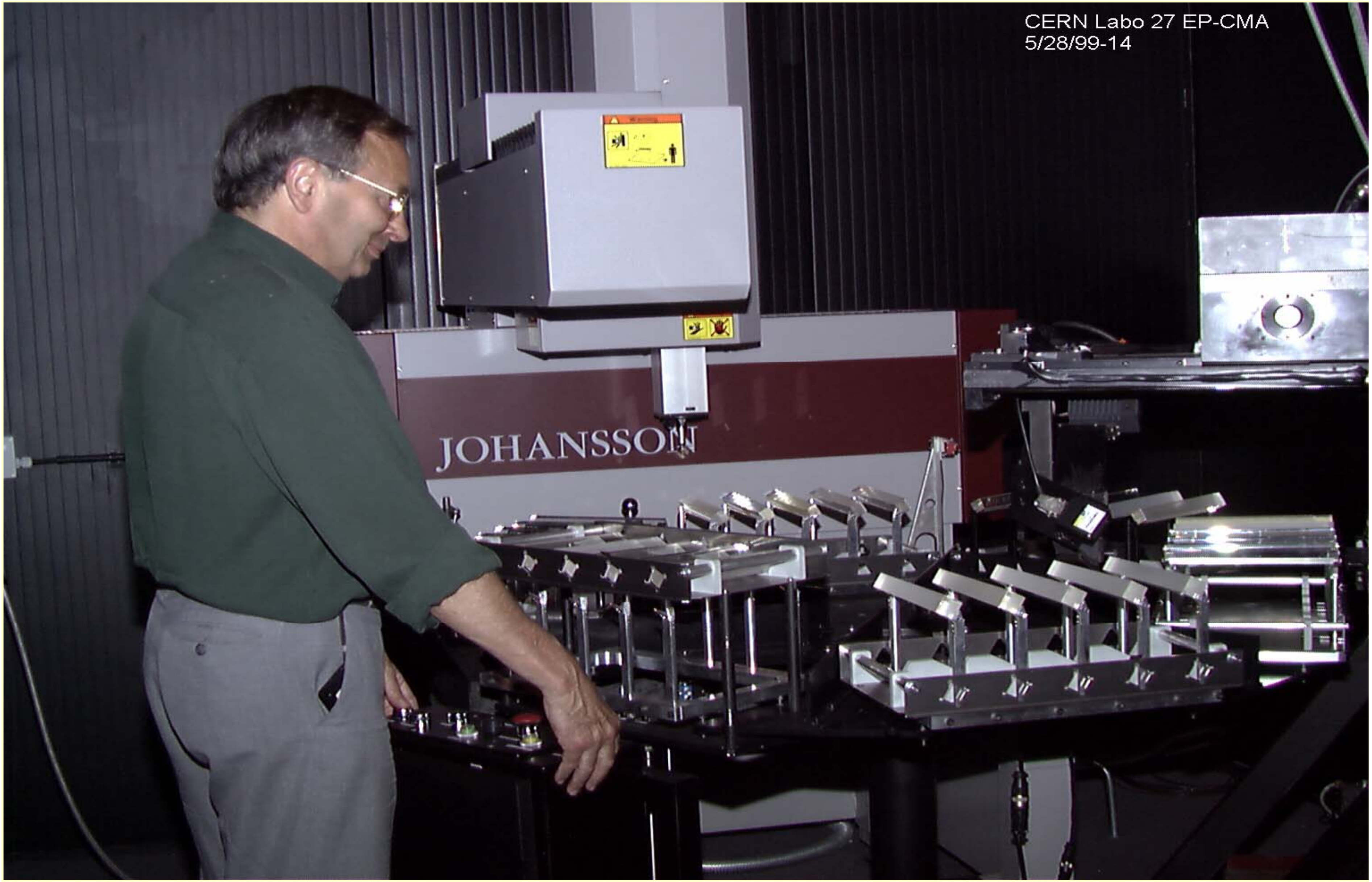


Avalanche Photodiode Readout

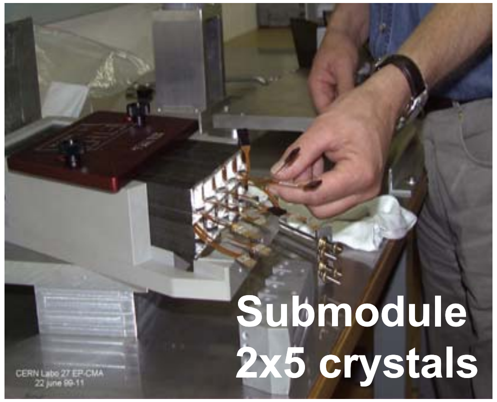


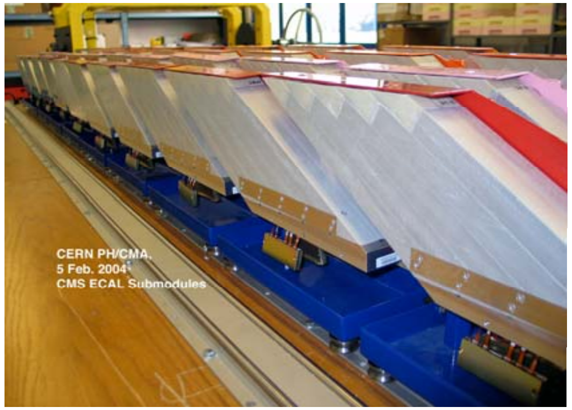
Transparency from 1993

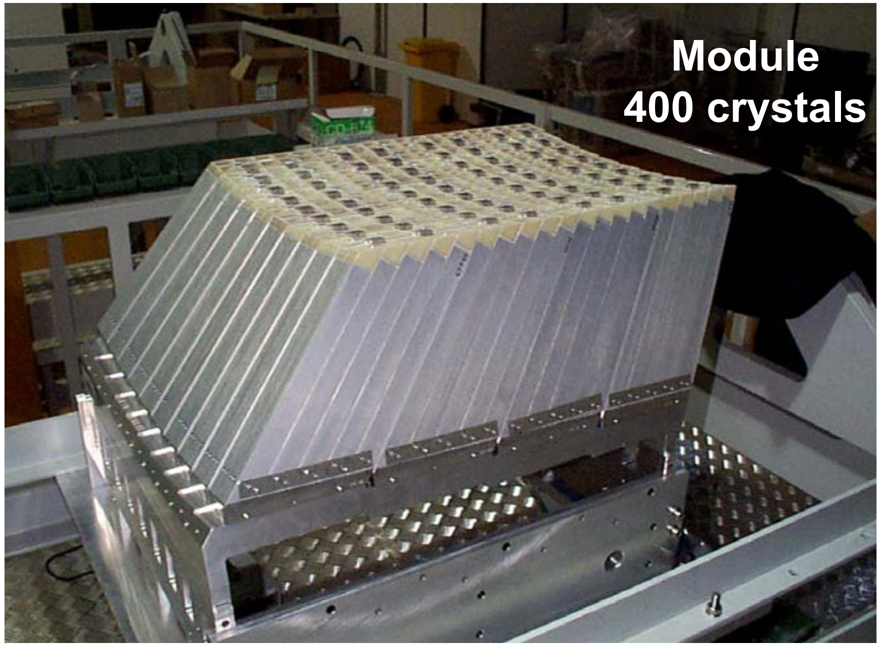
Crystals Production

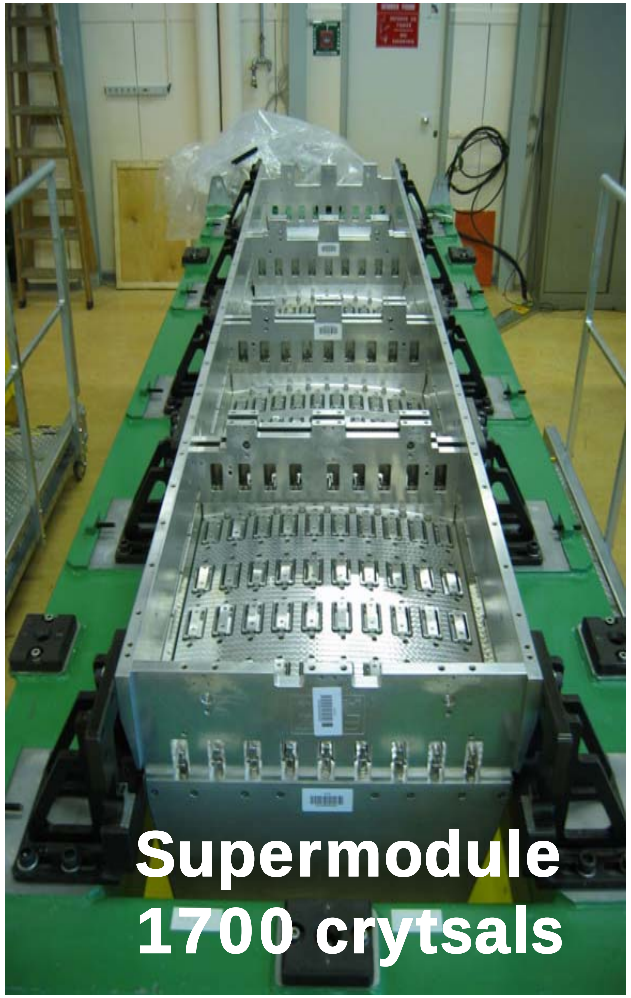


Assembly of ECAL





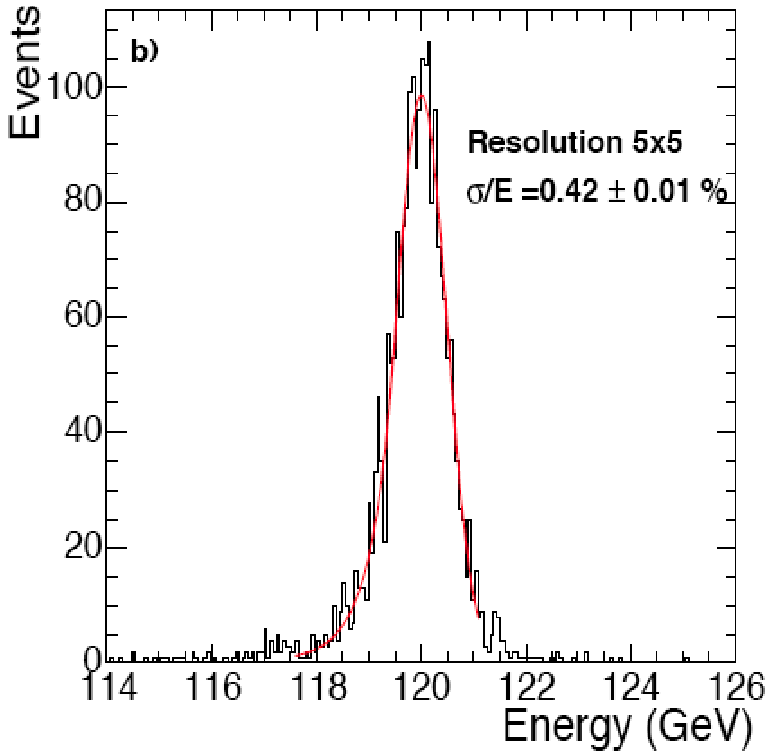




Total 36 Supermodules

ECAL: Assembly and Performance

Response to high energy electrons

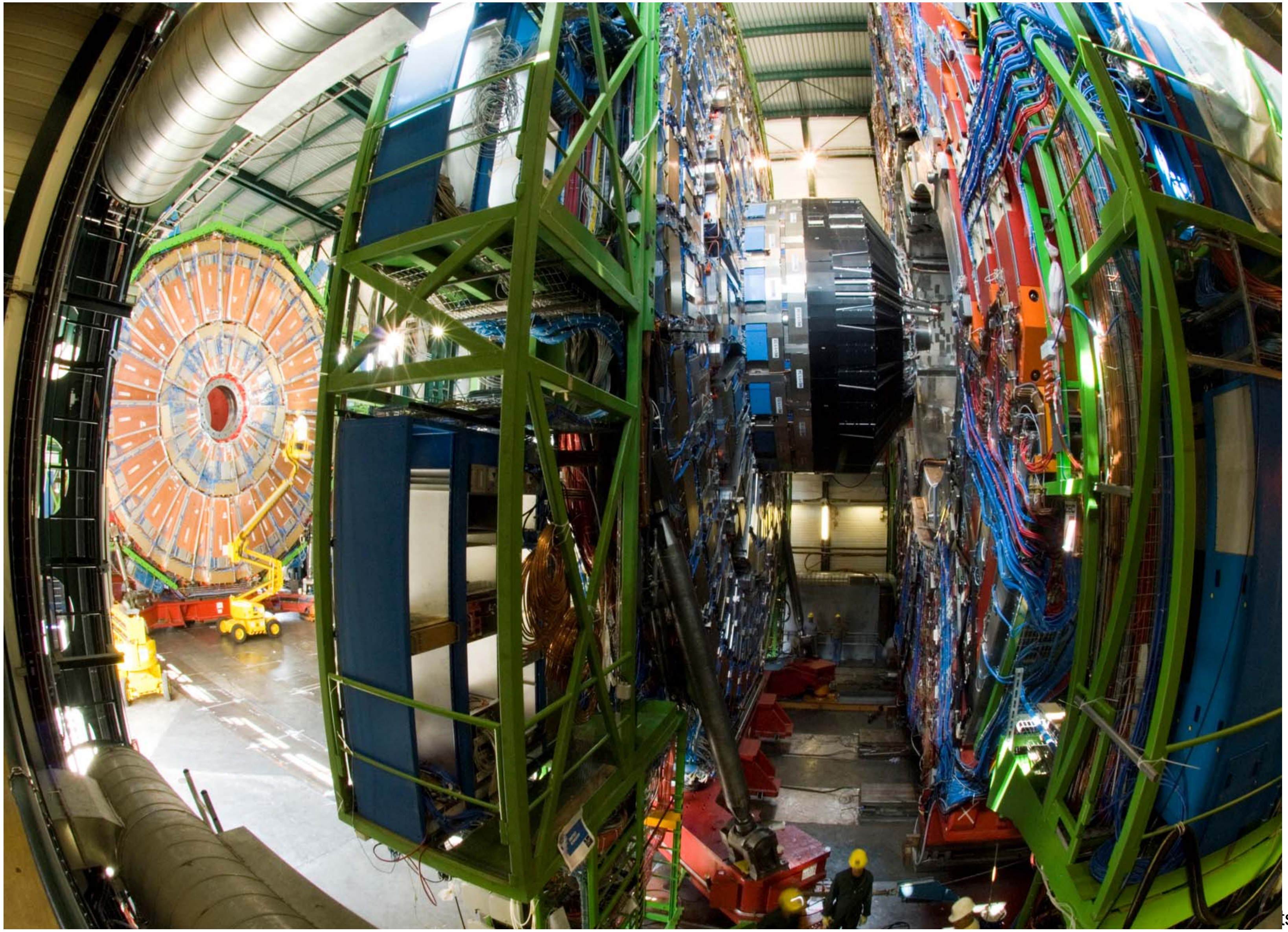


Temperature Stability: ≤ 0.1 °C

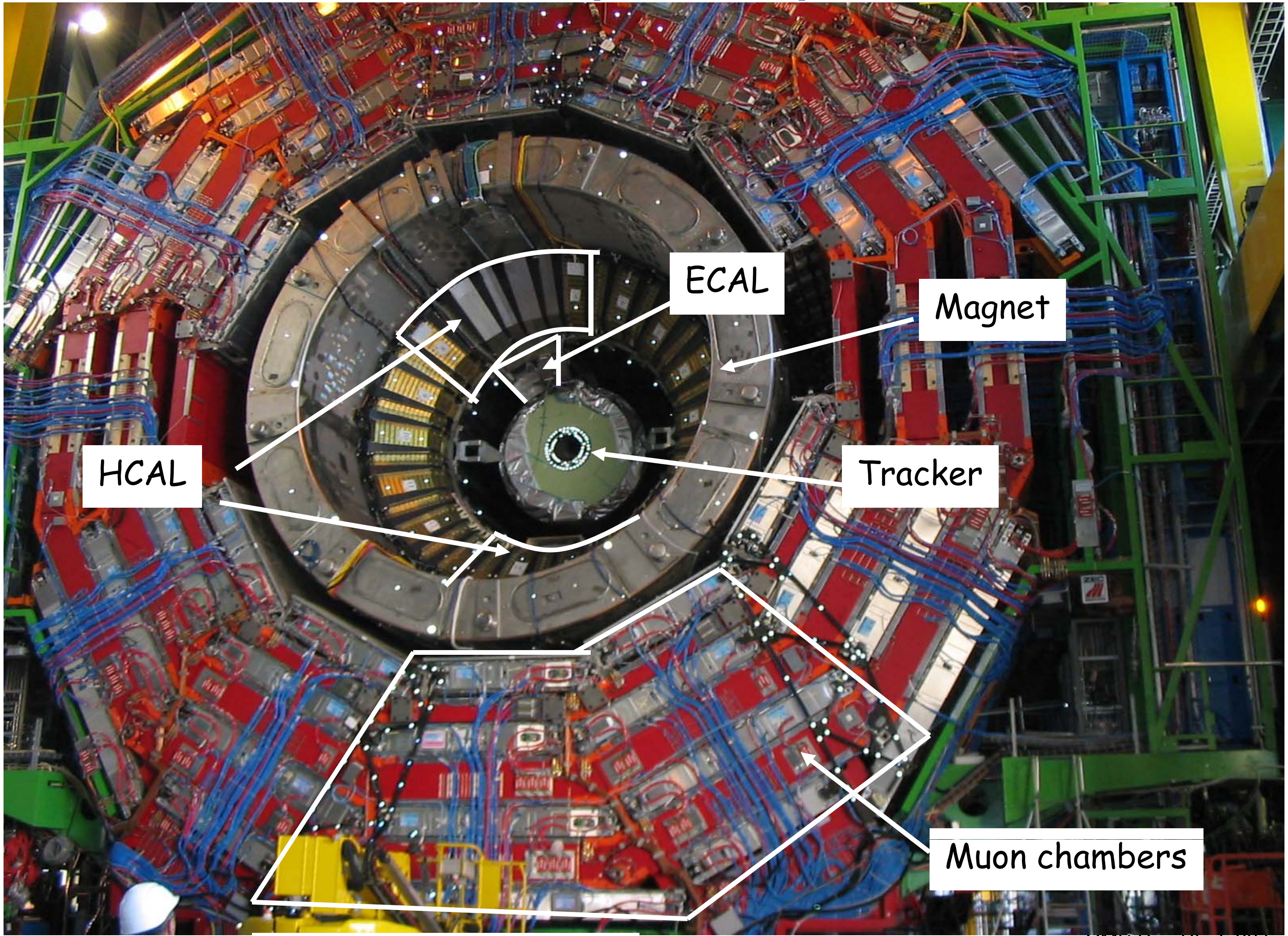
Light response stability: ≤ 0.1%

Performance and Commissioning

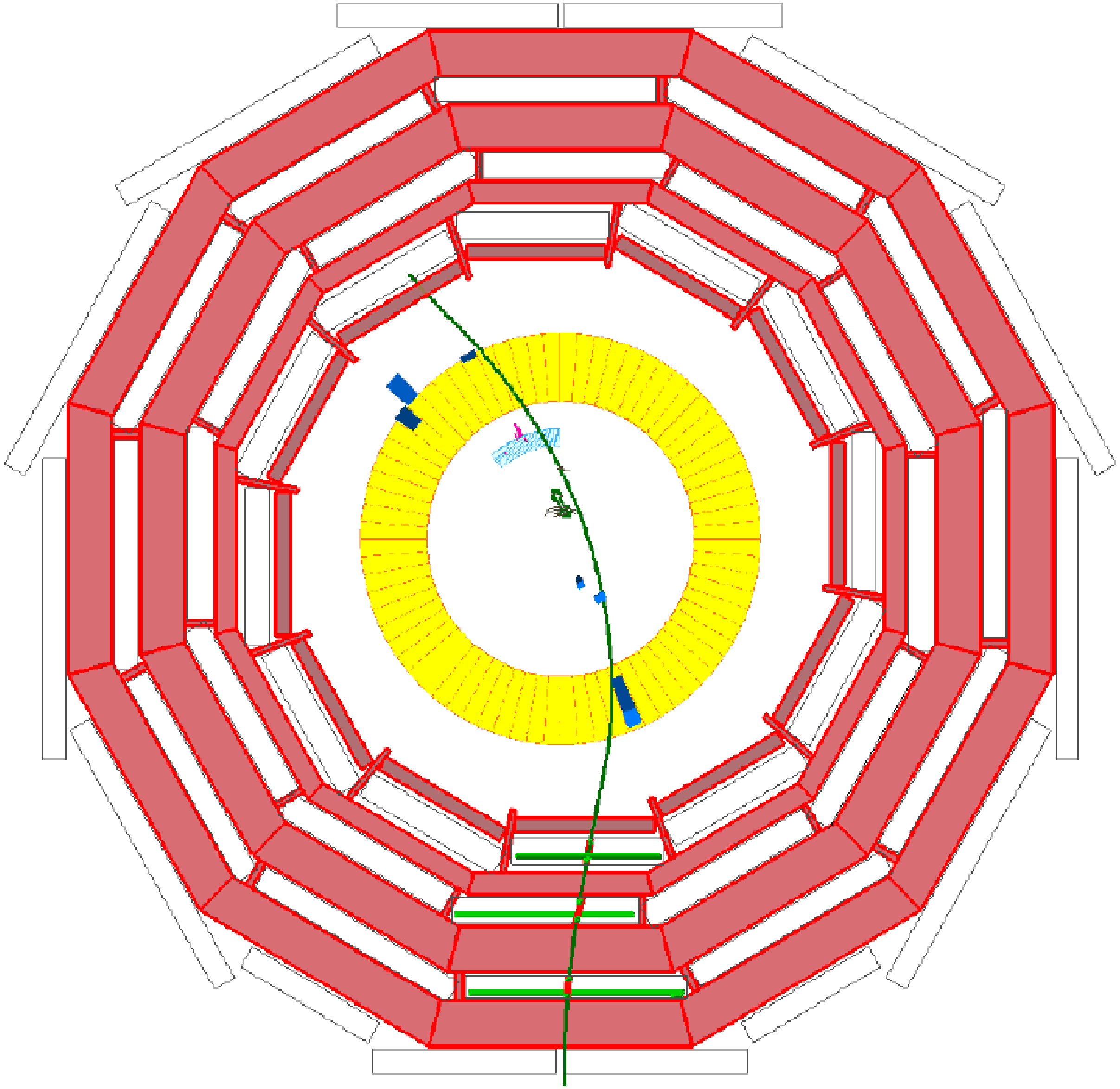
First Closure of the CMS Experiment (2006)



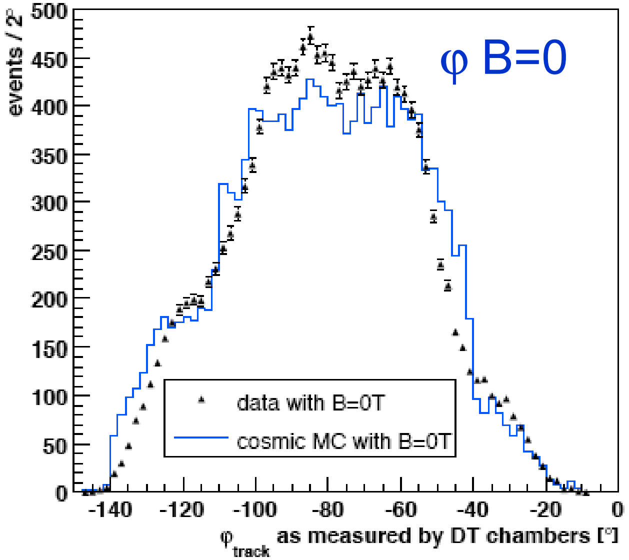
Magnet Test & Cosmic Challenge (MTCC)

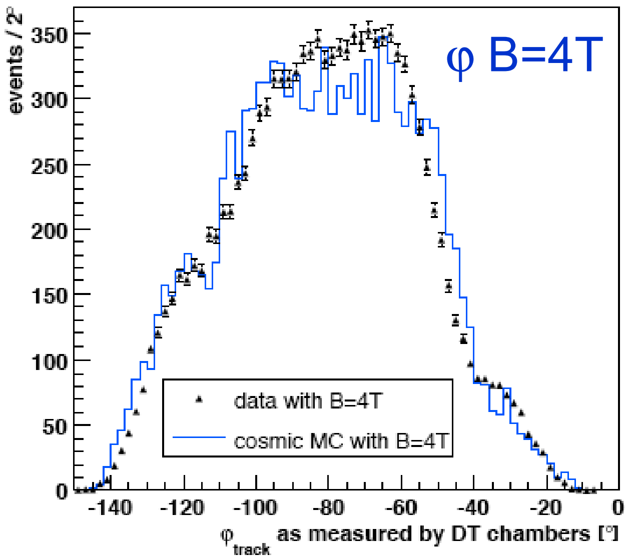


Run 2605 / Event 3981/ B 3.8 T/27.08.06)

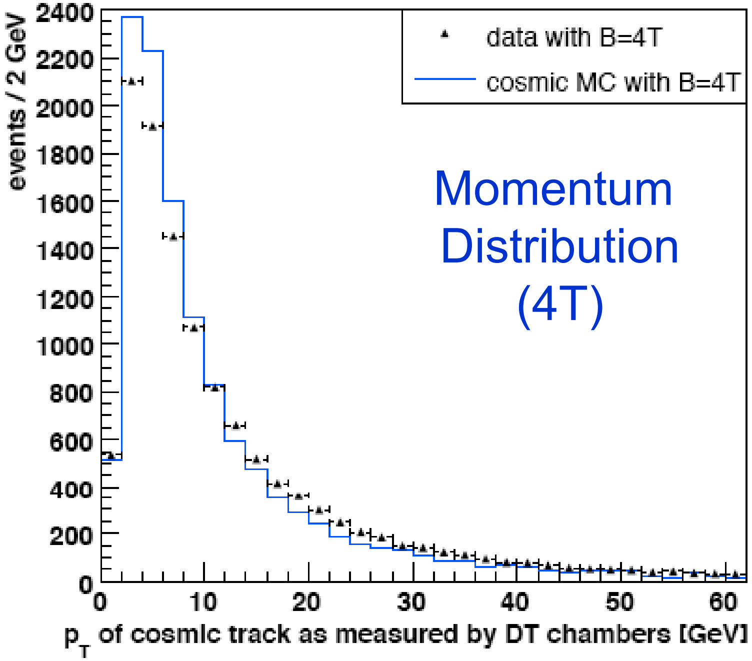


Analysis: Data in Muon DTs





Azimuthal distribution measured by DTs.



Cosmic muons data normalised to Monte Carlo simulation

Reasonable agreement between data and simulation.

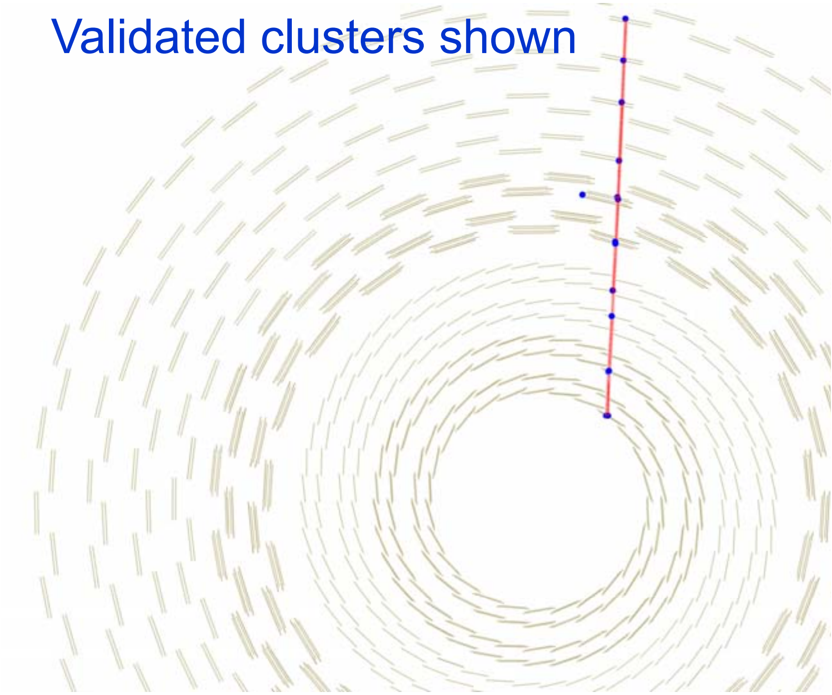
Almost every aspect of final CMS from detector to CMSSW had to work to produce these plots.

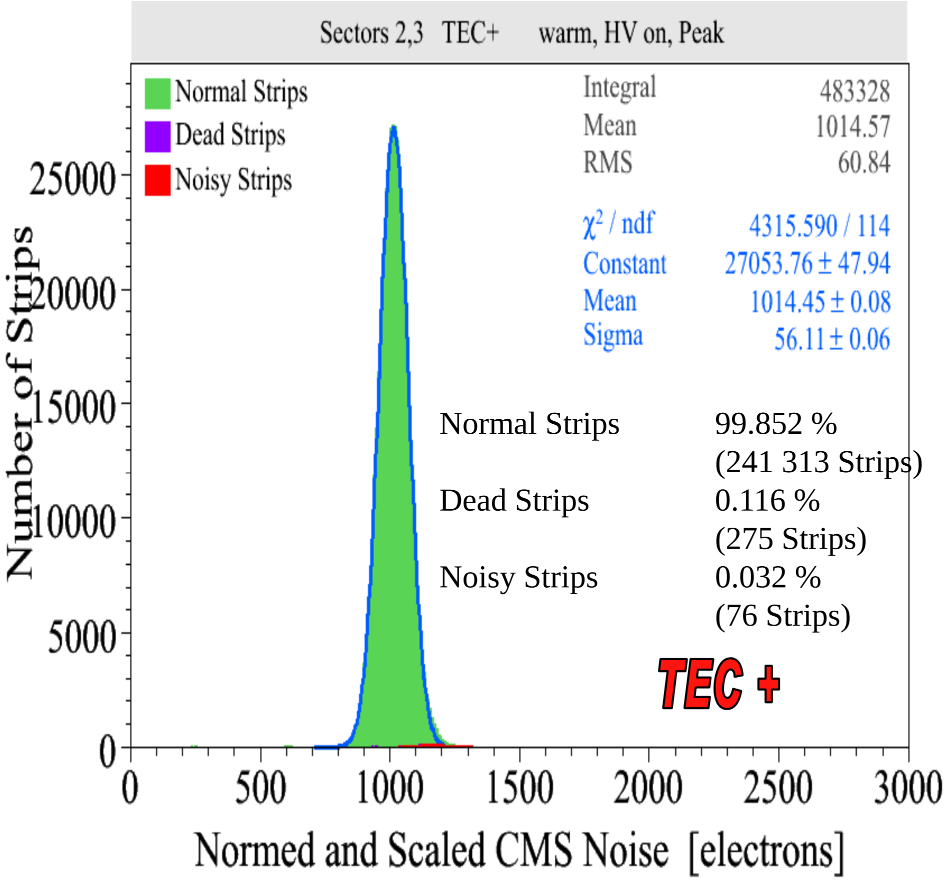
Cosmics in the Tracker (Bat 186)

Example of Performance

A cosmic at -15°C

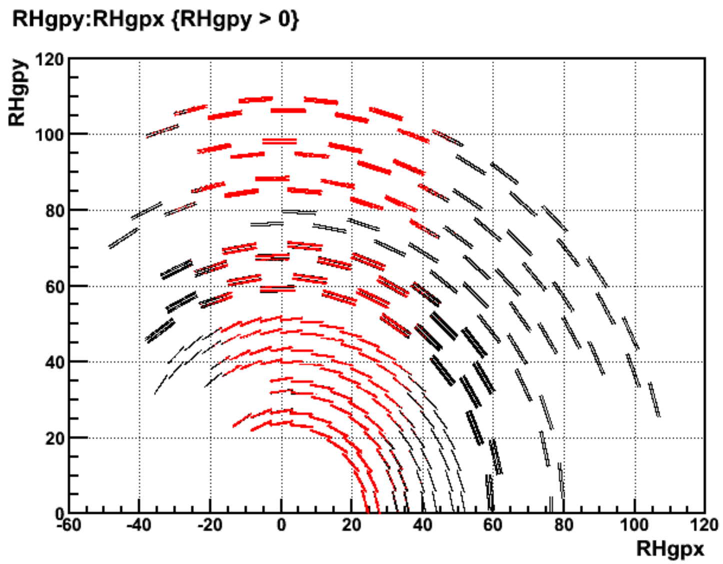
Validated clusters shown

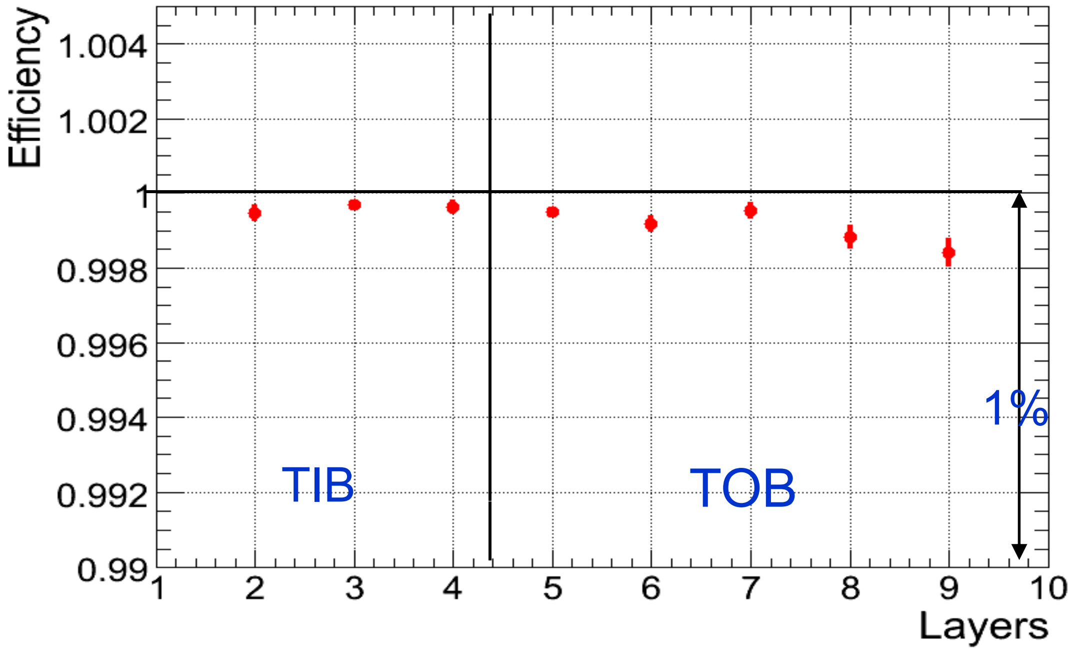


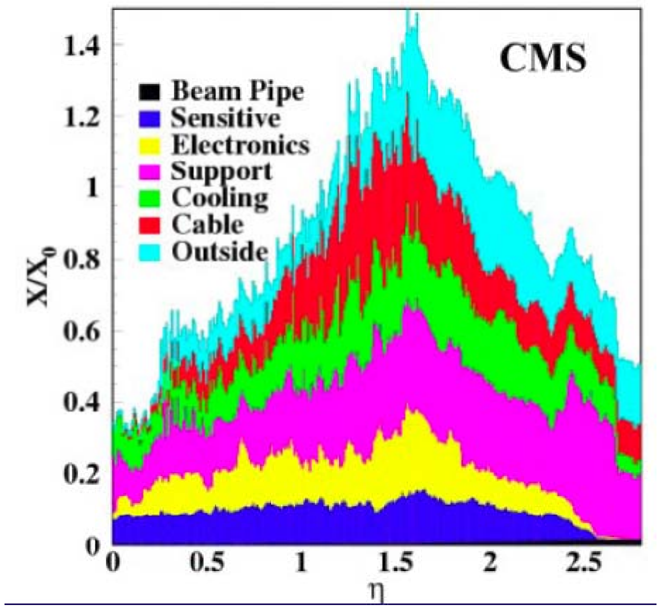


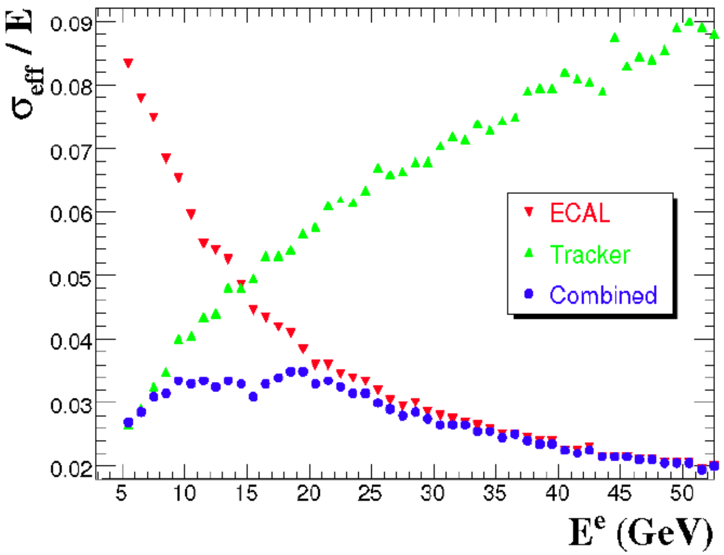
- **The Quality of the CMS Tracker is Excellent:**
- Dead or Noisy Strips < 3 / 1000
- Signal: Noise > 25:1 in Peak Readout Mode
- Enormous experience gained in operating the Tracker at TIF

Performance of the Tracker



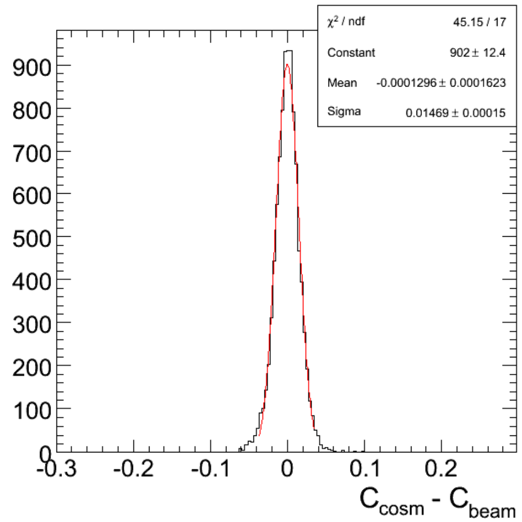


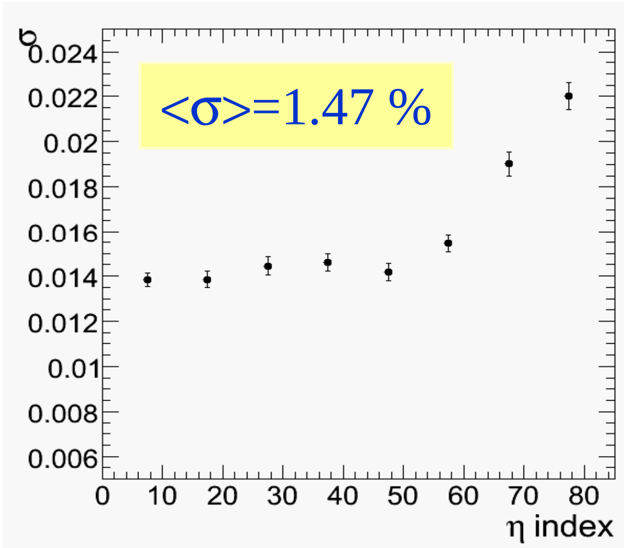




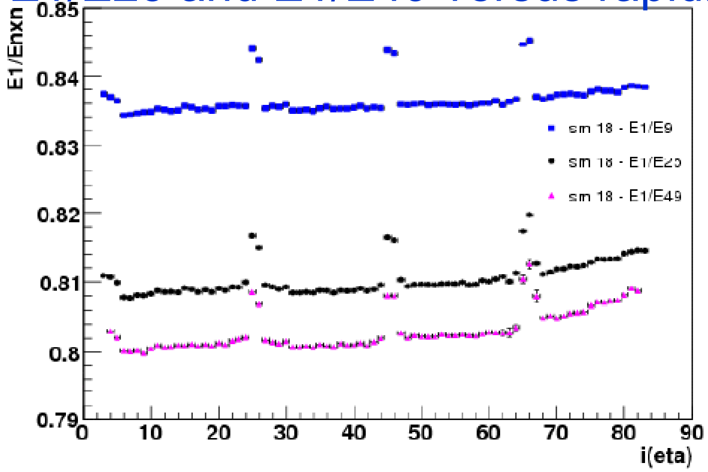
Barrel ECAL: Calibration & Test Beam

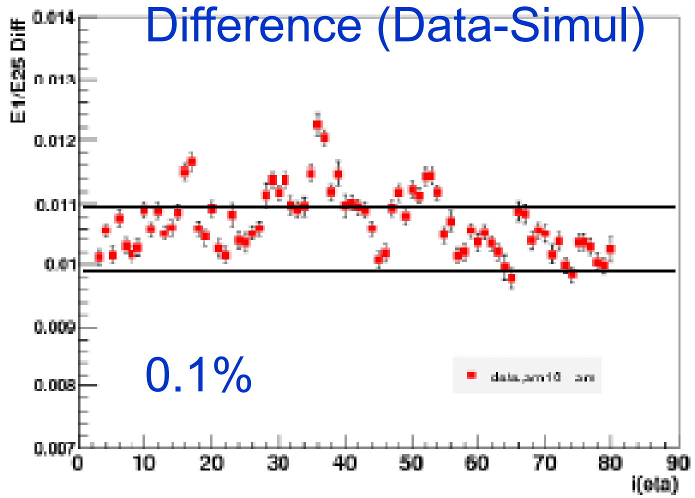
All SMs recorded cosmics for 1 week ⇒ crystal inter-calibration of ~ 1.5%.





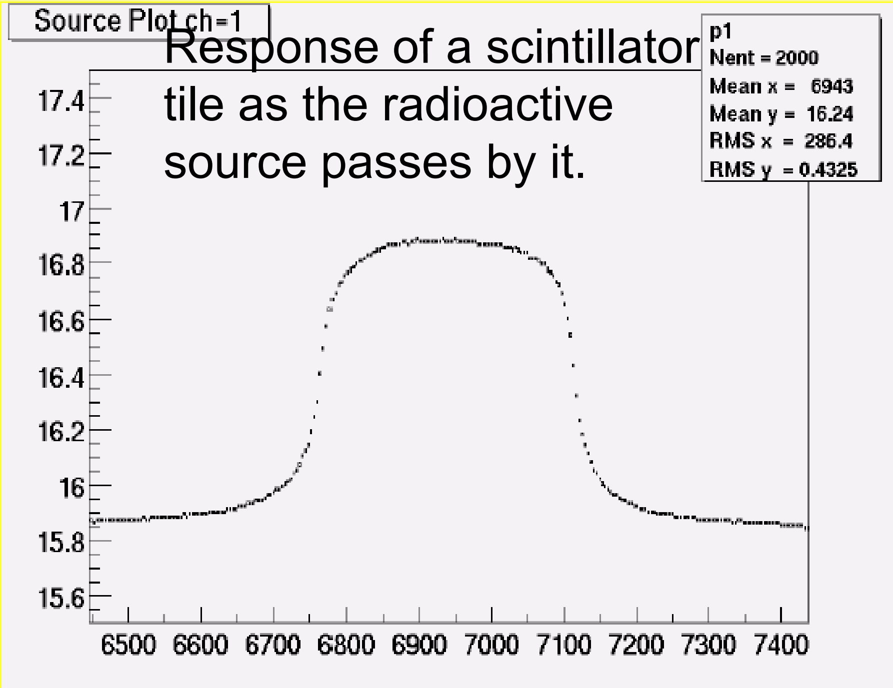
Test Beam: Containment ratios E1/E9, E1/E25 and E1/E49 versus rapidity.





Barrel HCAL: Calibration

Each scintillator tile in every layer is calibrated with a moving wire ^{60}Co 5mCi source.



Test Beam

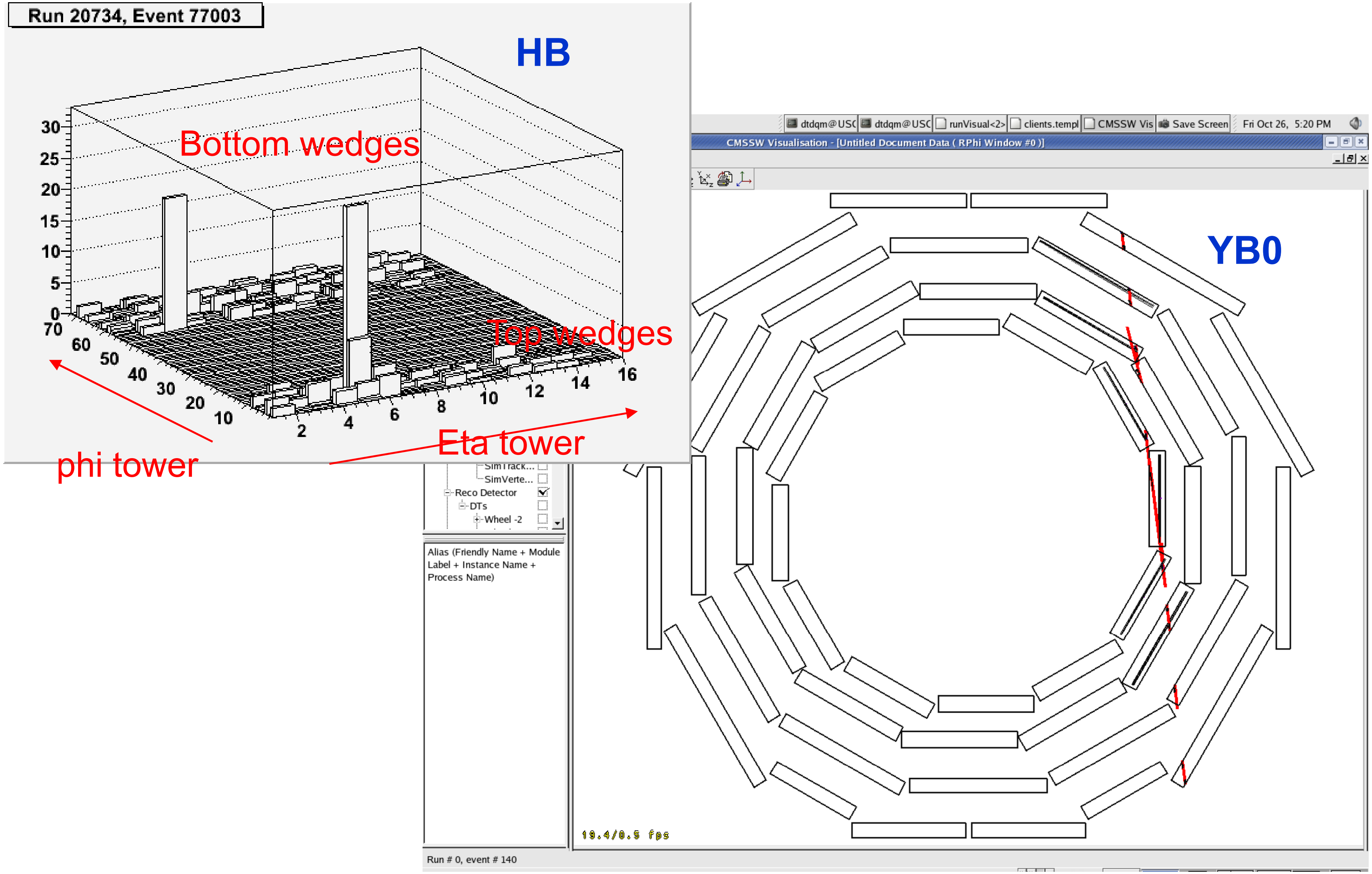
HCAL Resolution

$\sigma/E \sim 97\%/\sqrt{E} \oplus 8\%$

HB/HE pre-calibration to ~ 4%

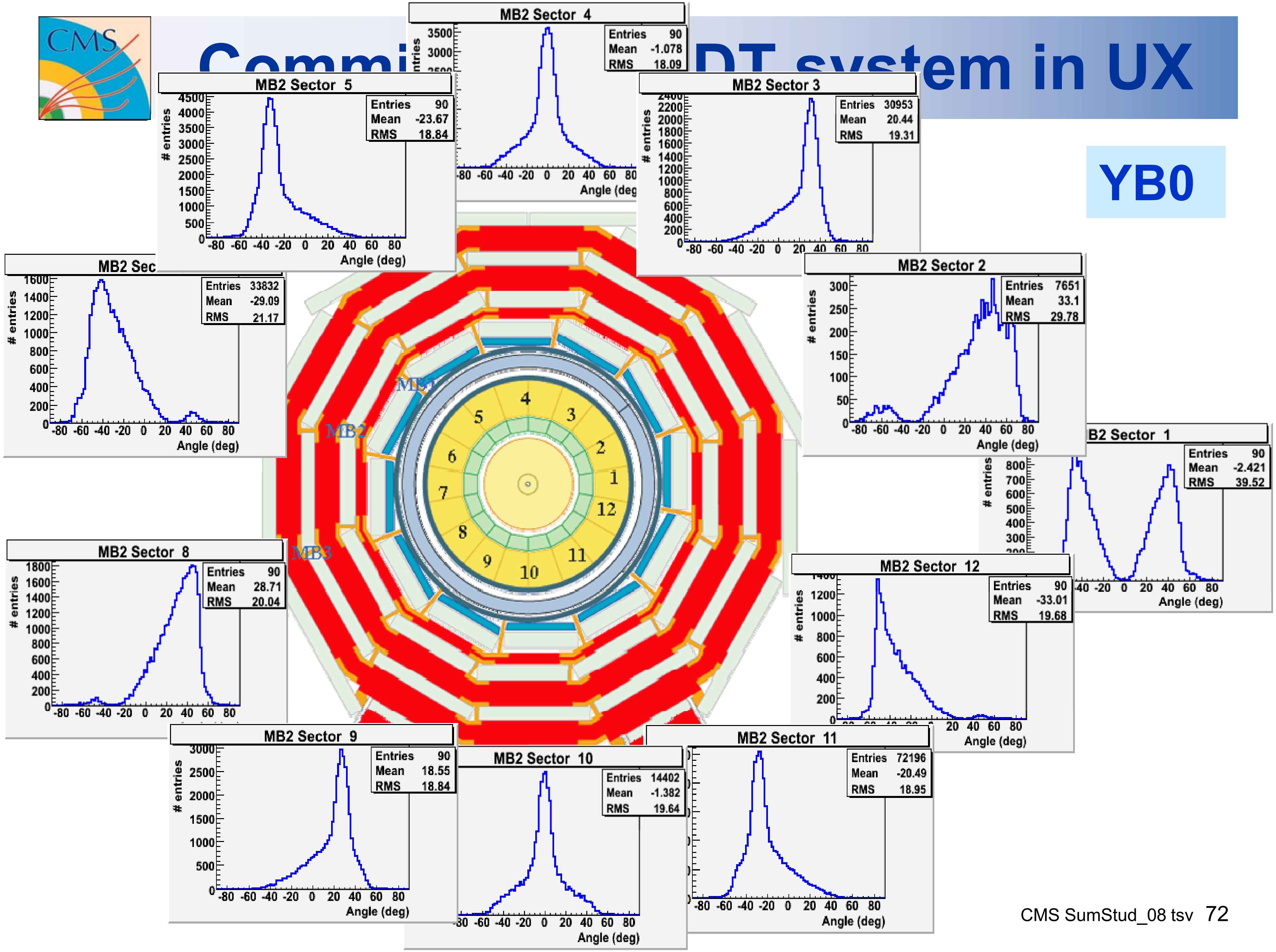
HF pre-calibration to ~ 5%

UX Commissioning: HB and DTs

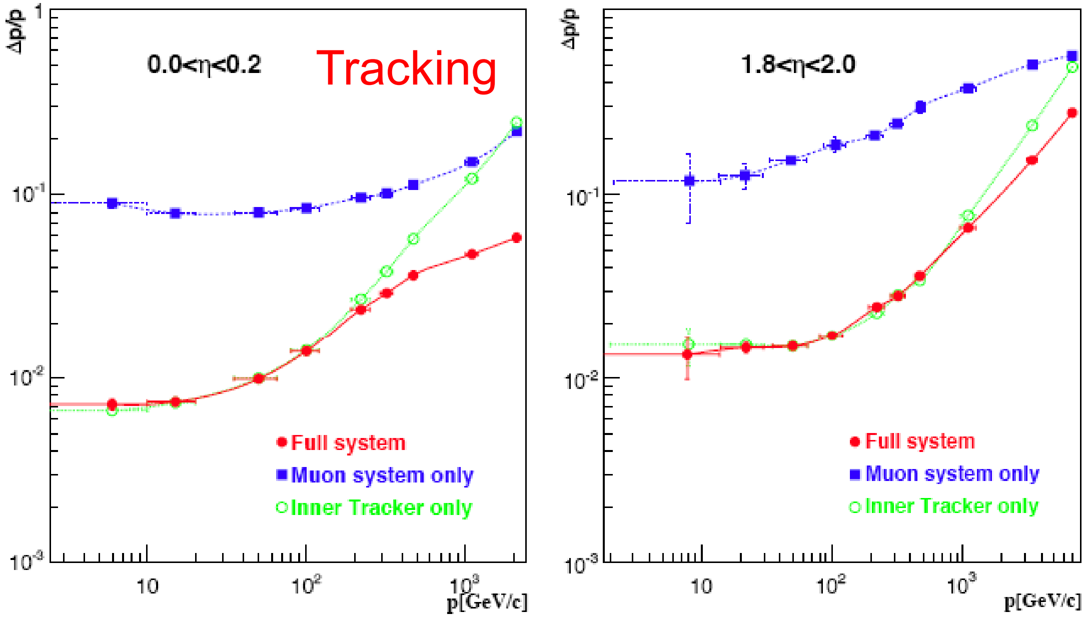


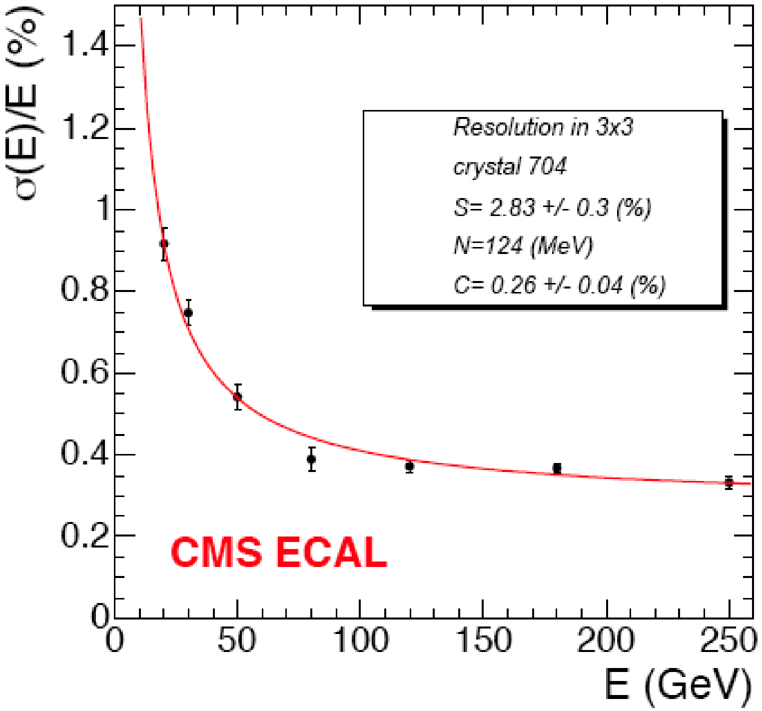
Commi… DT system in UX

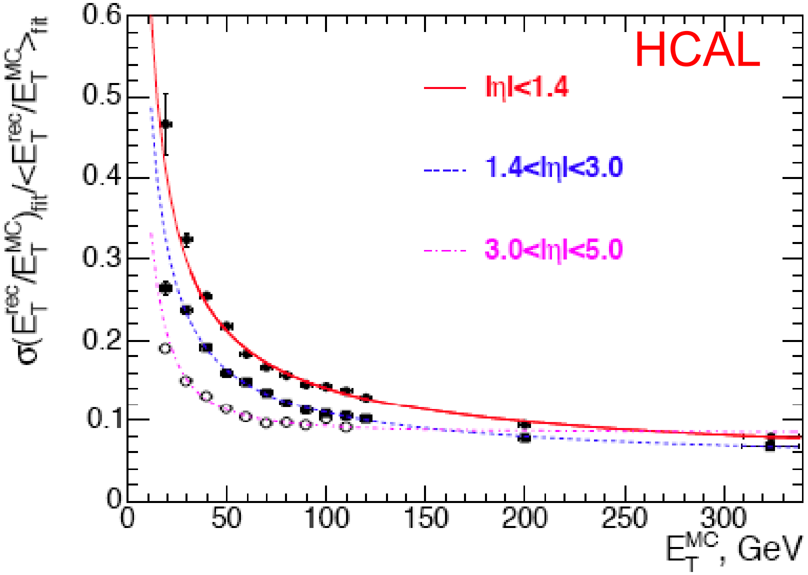
YB0

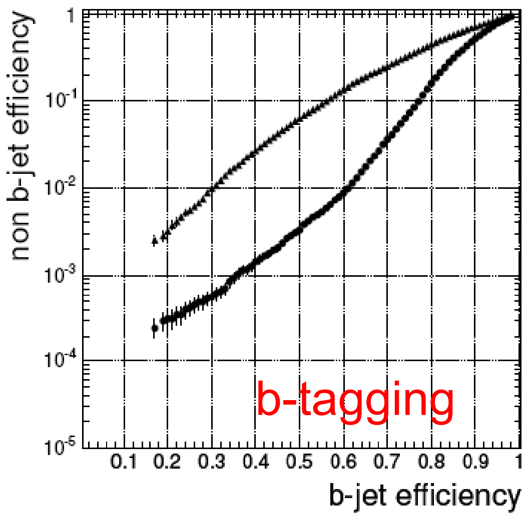


Performance of CMS: Overview



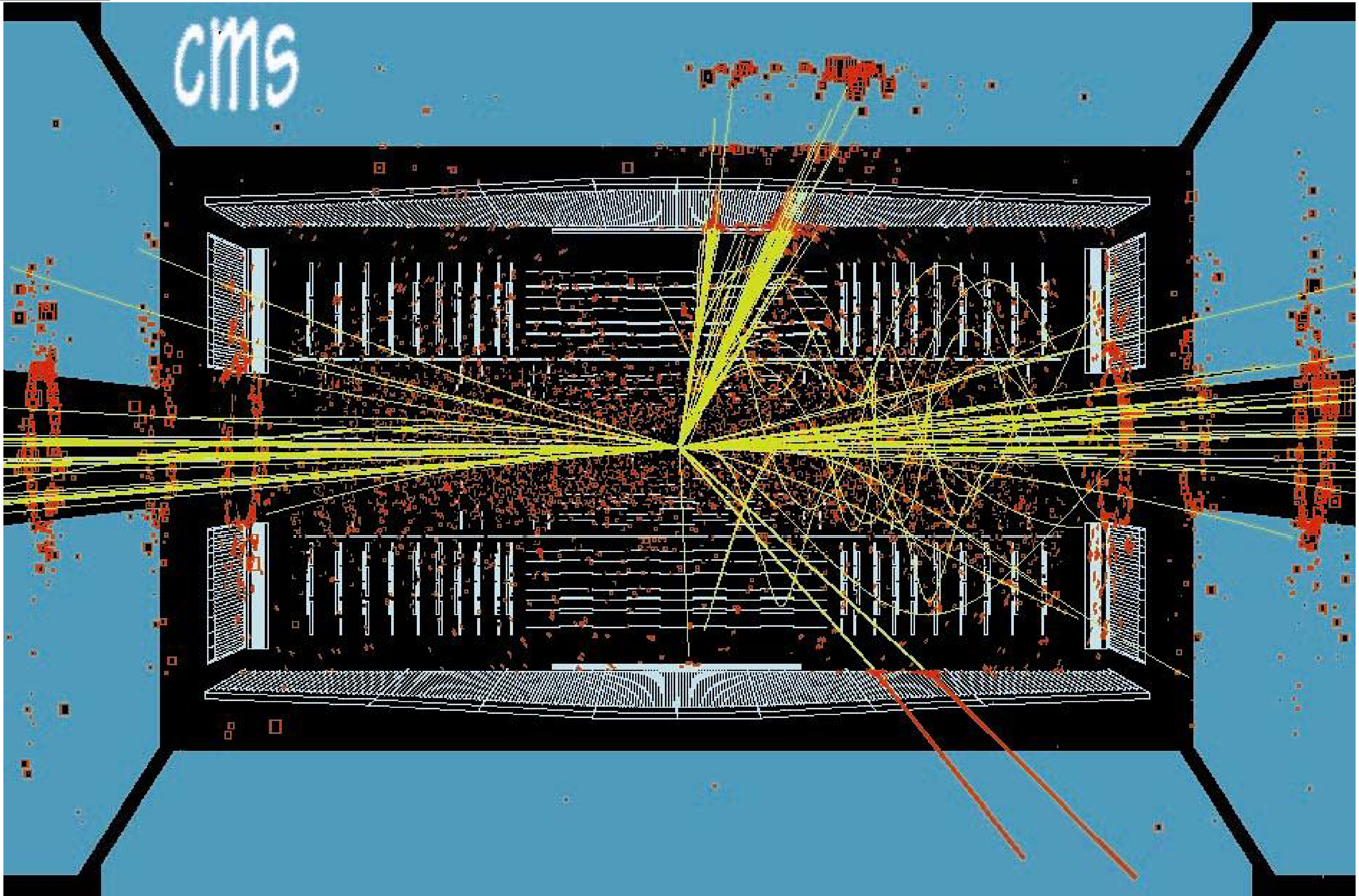






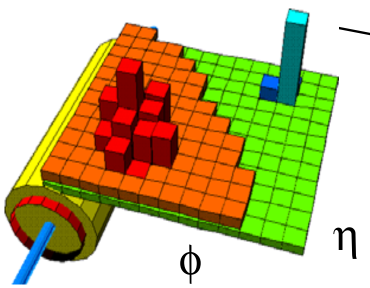
Trigger and Data Acquisition

Selection of Interesting Events



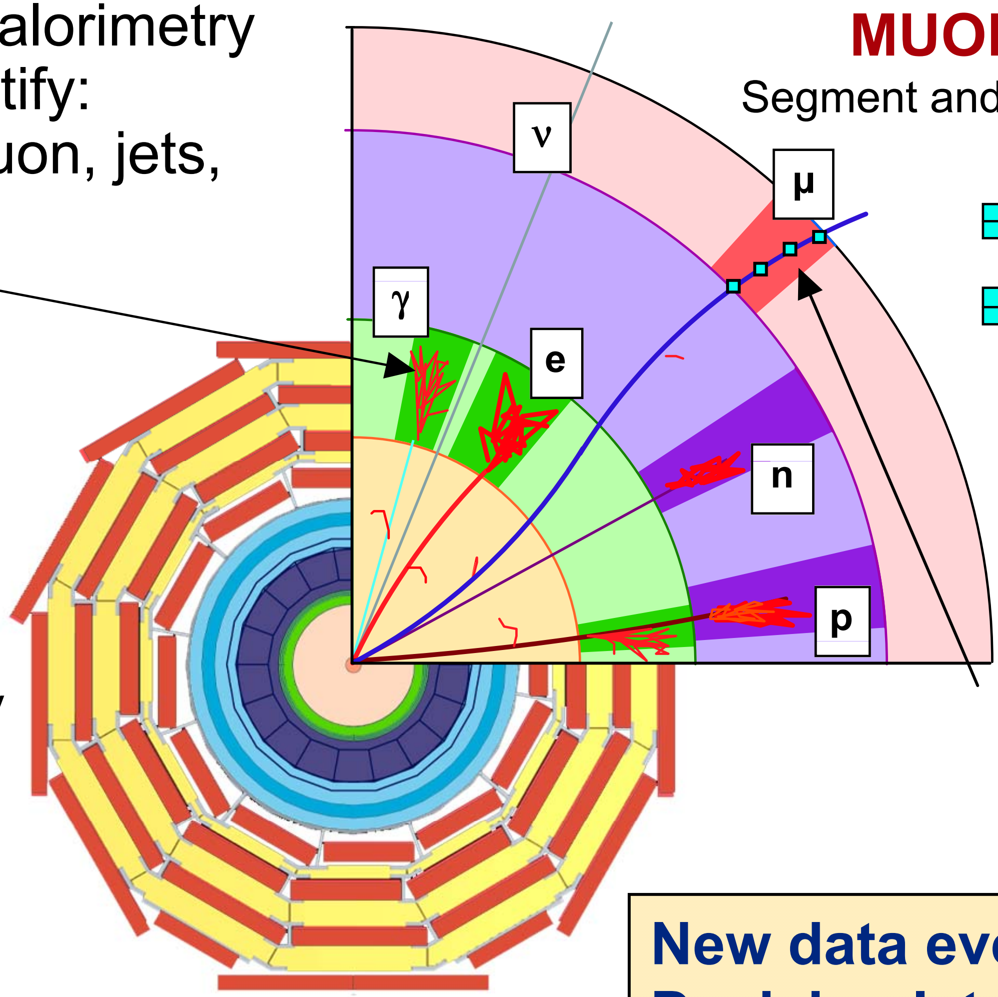
Level-1 Trigger

Use prompt data (calorimetry and muons) to identify:
High p_t electron, muon, jets, missing E_T



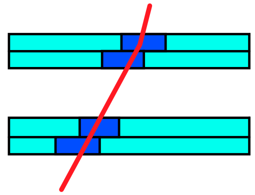
CALORIMETERs

Cluster finding and energy deposition evaluation



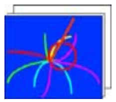
MUON System

Segment and track finding



New data every 25 ns
Decision latency ~ µs

Data Acquisition



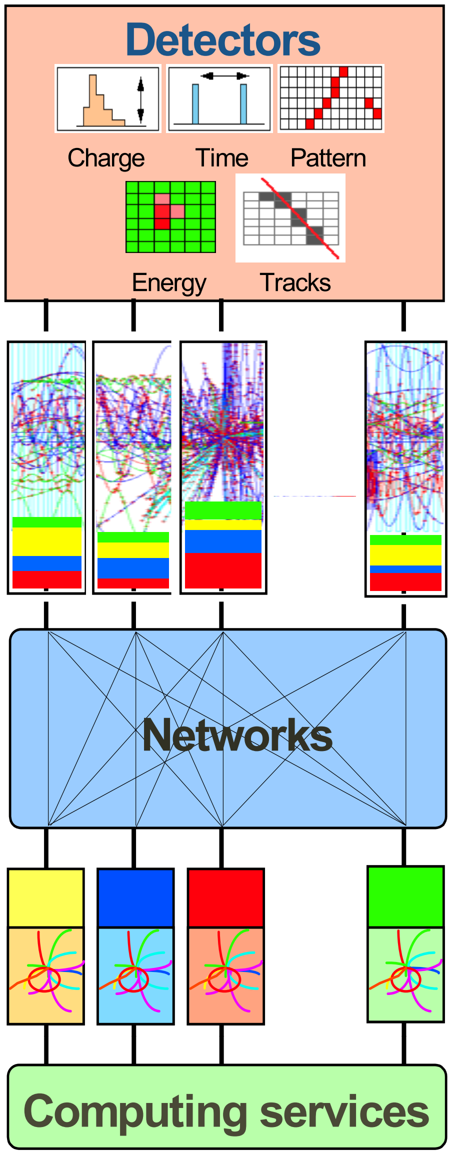
40 MHz
COLLISION RATE

100 kHz
LEVEL-1 TRIGGER

1 Terabit/s
(50000 DATA CHANNELS)

500 Gigabit/s

Gigabit/s SERVICE LAN



16 Million channels
3 Gigacell buffers

1 Megabyte EVENT DATA

200 Gigabyte BUFFERS
500 Readout memories

EVENT BUILDER. A large switching network (512+512 ports) with a total throughput of approximately 500 Gbit/s forms the interconnection between the sources (Readout Dual Port Memory) and the destinations (switch to Farm Interface). The Event Manager collects the status and request of event filters and distributes event building commands (read/clear) to RDPMs

5 TeraIPS

EVENT FILTER. It consists of a set of high performance commercial processors organized into many farms convenient for on-line and off-line applications. The farm architecture is such that a single CPU processes one event

Petabyte ARCHIVE

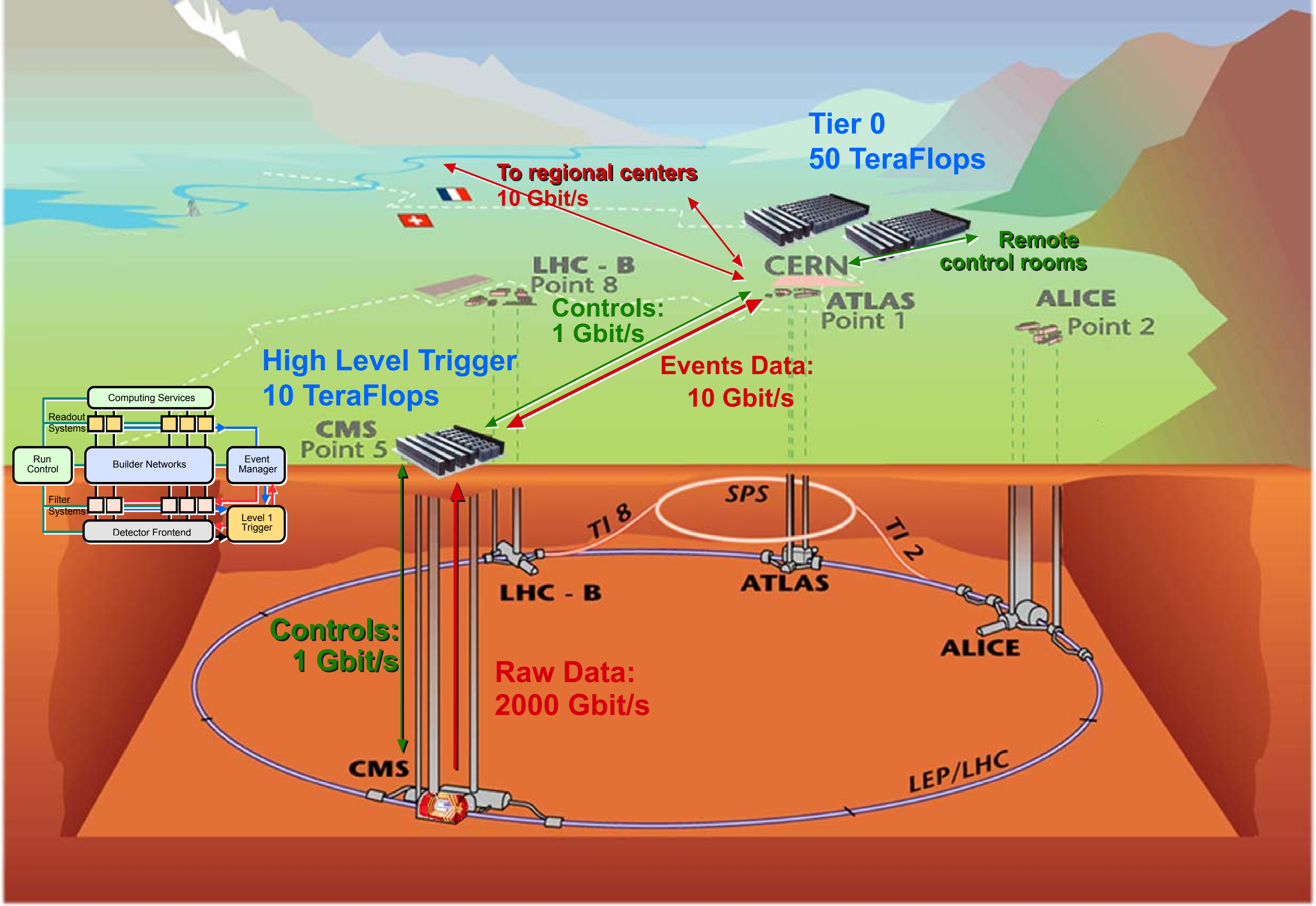
High Level Trigger

- Boundary conditions:
  - **Code** runs in a single processor, **which analyzes one event at a time**
  - **HLT has access to** full event data **(full granularity and resolution)**
  - **Only limitations:**
    - CPU time
    - Output selection rate (~10^2 Hz)
    - Precision of calibration constants
  - **Main requirements:**
    - Satisfy physics program (see later): high efficiency
    - Selection must be inclusive (to discover the unpredicted as well)
    - Must not require precise knowledge of calibration/run conditions
    - Efficiency must be measurable from data alone
    - All algorithms/processors must be monitored closely

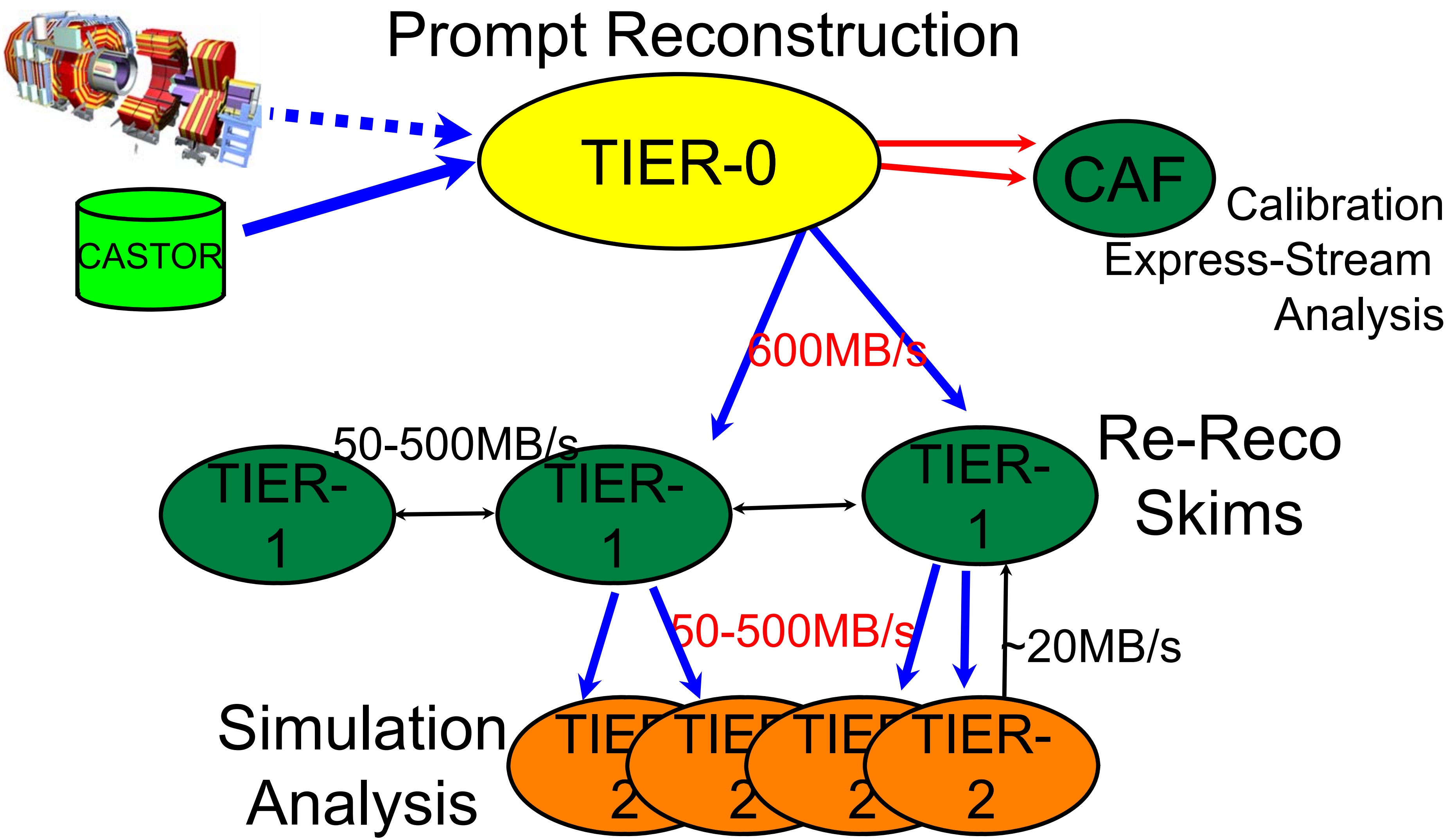
Commissioning Software and Computing Infrastructure

Computing, Software and Analysis Challenges
e.g. CSA08 in May (100% of 2008 Operation)

CMS data flow and on(off) line computing

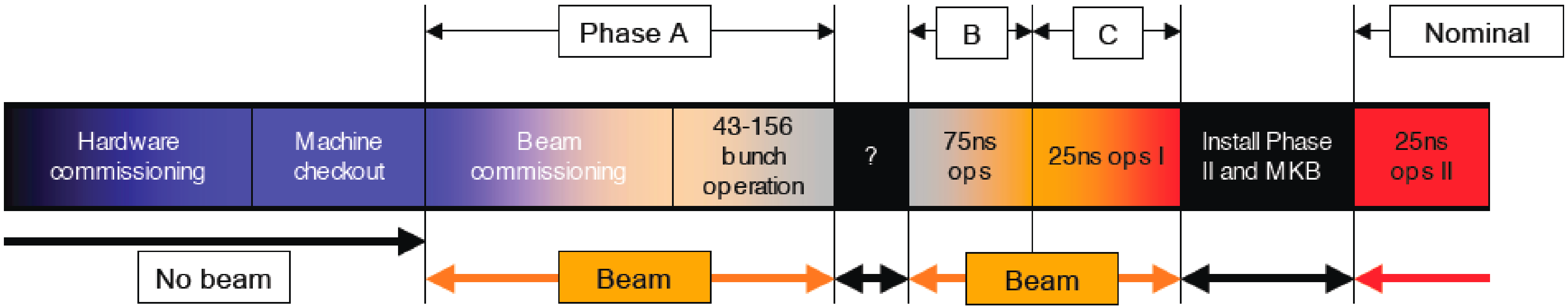


Computing WorkFlow



Preparation for Physics

Expectations of Luminosity Buildup



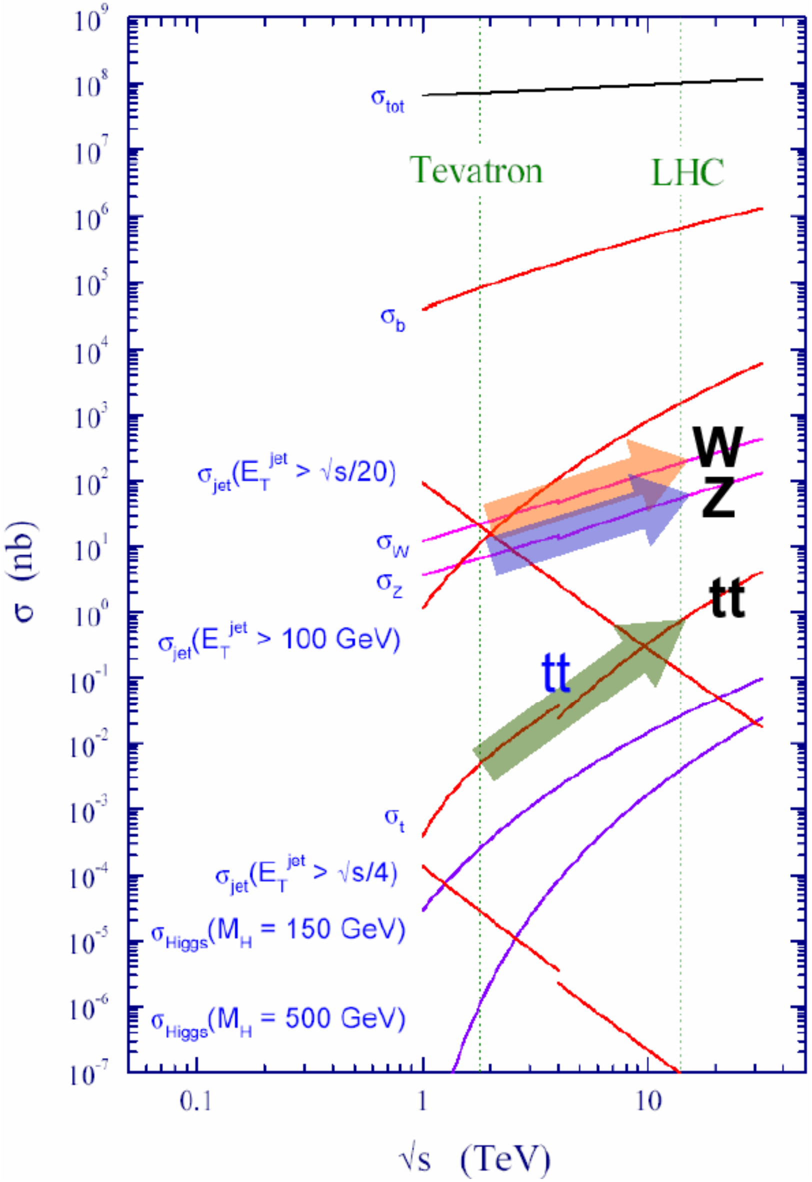
Parameter	Phase A	Phase B	Phase C	Nominal
k / no. bunches	43-156			
Bunch spacing (ns)	2021-566			
N (10^{11} protons)	0.4-0.9			
Crossing angle (μrad)	0			
$\sqrt{(\beta^*/\beta^*_{nom})}$	2			
σ* (μm, IR1&5)	32			
L ($cm^{-2}s^{-1}$)	$6\times10^{30}-10^{32}$			
Year (?)	2008			

Bunches	β*	I_b
1 x 1	18	10^{10}
43 x 43	18	3×10^{10}
43 x 43	4	3×10^{10}
43 x 43	2	4×10^{10}
156 x 156	4	4×10^{10}
156 x 156	4	9×10^{10}
156 x 156	2	9×10^{10}

Early Physics Programme

- **Prior to beam: early detector commissioning**
  - Readout & trigger tests, runs with all detectors (cosmics, test beams)
- **Early beam, up to $10pb^{-1}$:**
  - Detector synchronization, alignment with beam-halo events, minimum-bias events. Earliest in-situ alignment and calibration
  - Commission trigger, start "physics commissioning":
    - Physics objects; measure jet and lepton rates; observe W, Z, top
    - And, first look at possible extraordinary signatures…
- **Physics collisions, $100pb^{-1}$: measure Standard Model, start search**
  - 10^6 $W \to l\,\nu$ ($l = e,\mu$); 2×10^5 $Z\to ll$ ($l = e, \mu$); 10^4 $t\bar{t}\to\mu+X$
    - Improved understanding of physics objects; jet energy scale from $W \to j\,j'$; extensive use (and understanding) of b-tagging
    - Measure/understand backgrounds to SUSY and Higgs searches
  - Initial MSSM (and some SM) Higgs sensitivity
  - Early look for excesses from SUSY& Z′/jj resonances. SUSY hints (?)
- **Physics collisions, $1000pb^{-1}$: entering Higgs discovery era**
  - Also: explore large part of SUSY and resonances at ~ few TeV

LHC v/s Tevatron



Huge stats for Standard Model signals. Rates@10^{33}

~10^8 events/1fb^{-1} W (200 Hz)
~10^7 events/1fb^{-1} Z (50 Hz)
~10^6 events/1fb^{-1} tt (1 Hz)

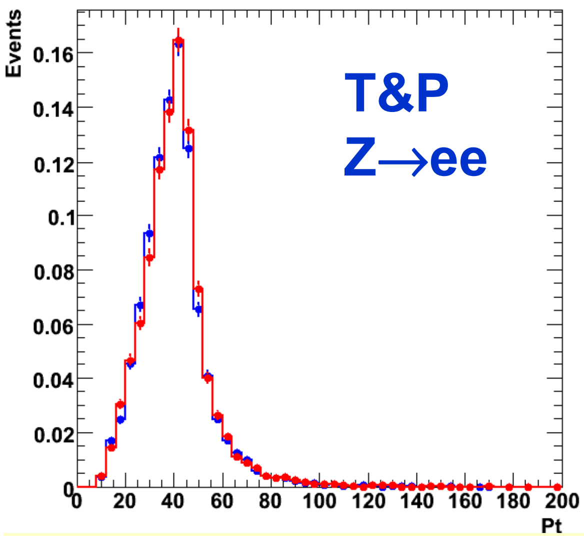
These will be used as control/ calibration samples for searches beyond the Standard Model

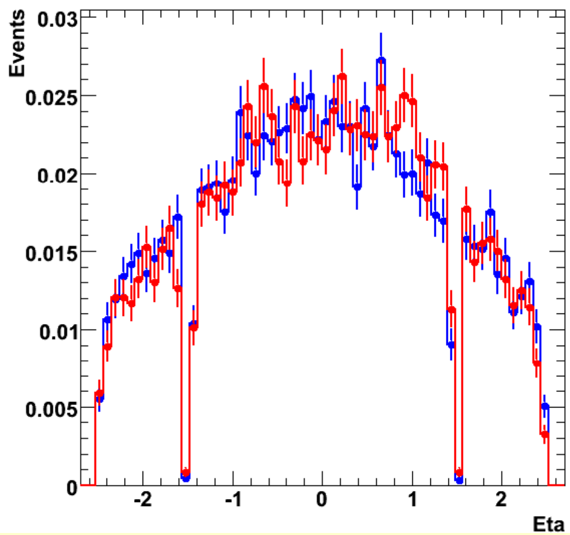
They can also be used to scrutinize the Standard Model further.

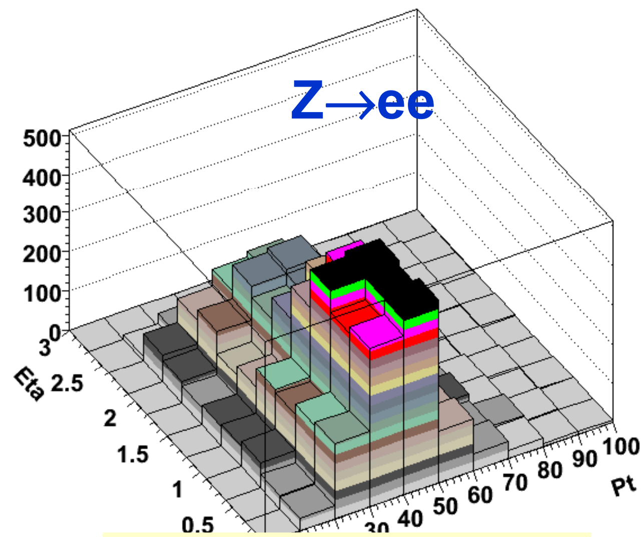
e.g. top sample is excellent for understanding lepton id. (incl. taus), jet corrections, jet energy scale, b tagging, ….

Object id/efficiency: Data Driven methods

- **Tag and Probe (T&P): identify a physics object in an unbiased way in order to study efficiencies.**
  - **One object (tag) has strict ID criteria imposed on it. Second object (probe) has looser ID criteria. Additional property that links it to the Tag object to ensure a pure sample.**
    - **$Z \to ee$ events: one tight electron (tag); the other can be a probe, provided the invariant mass of the pair is $\approx M_Z$**





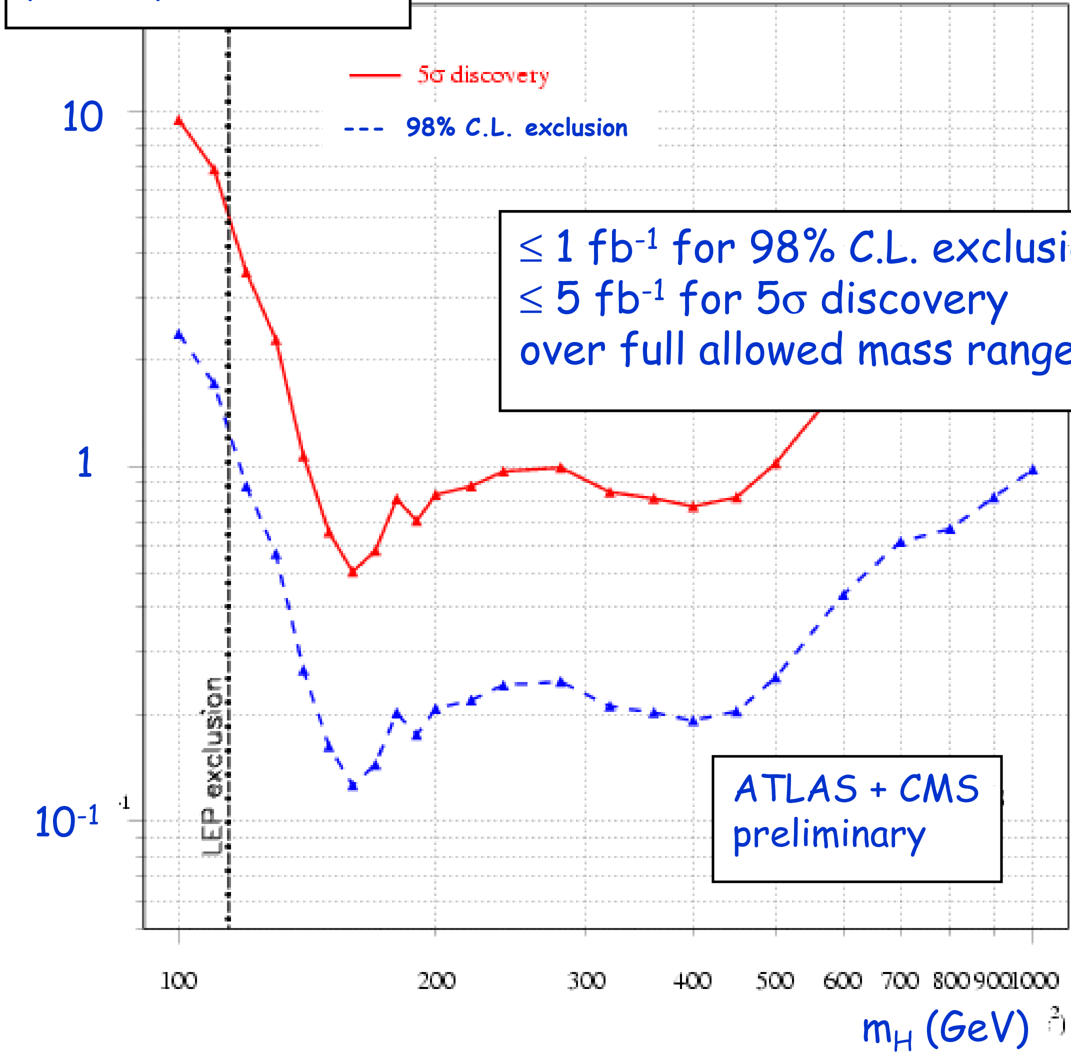


Efficiency from T&P:	**94.36±0.24**
Efficiency from MC truth:	**94.63±0.24**

} **(for 10 pb^{-1})**

SM Higgs

Needed ∫Ldt (fb^{-1})
per experiment

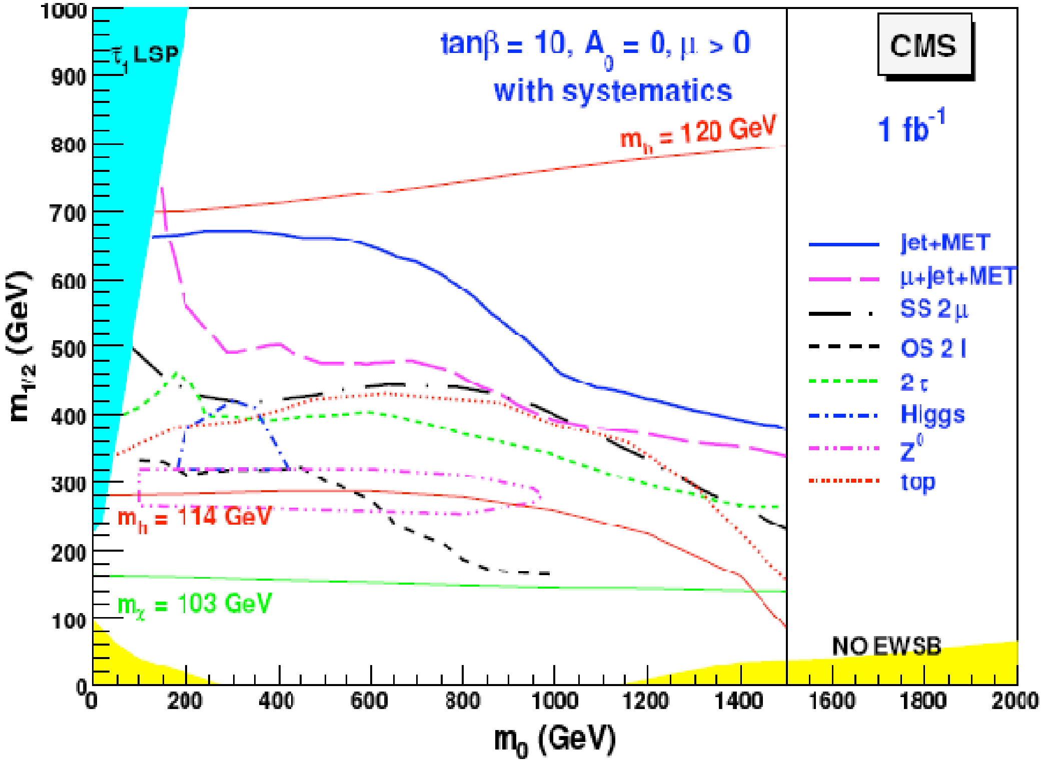


≤ 1 fb^{-1} for 98% C.L. exclusion
≤ 5 fb^{-1} for 5σ discovery
over full allowed mass range

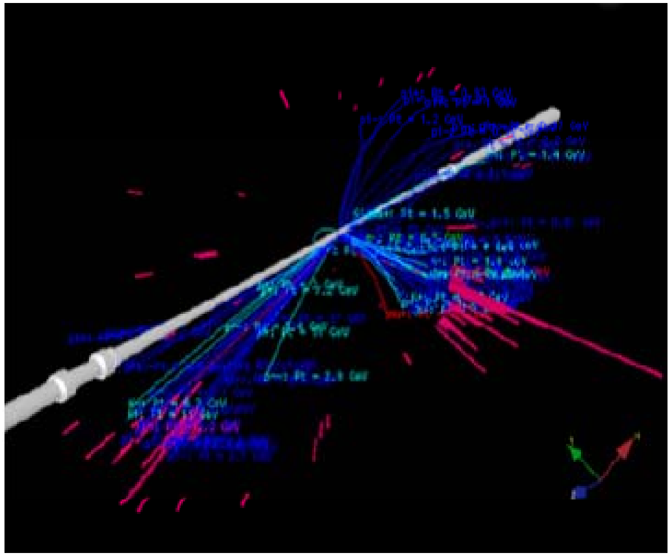
ATLAS + CMS
preliminary

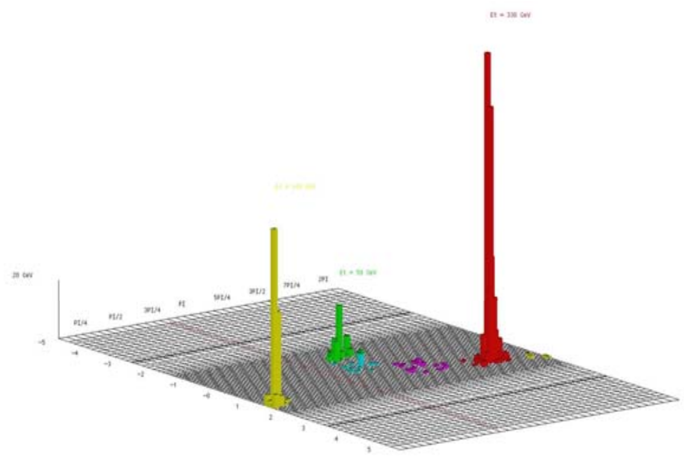
Seeking "SUSY"

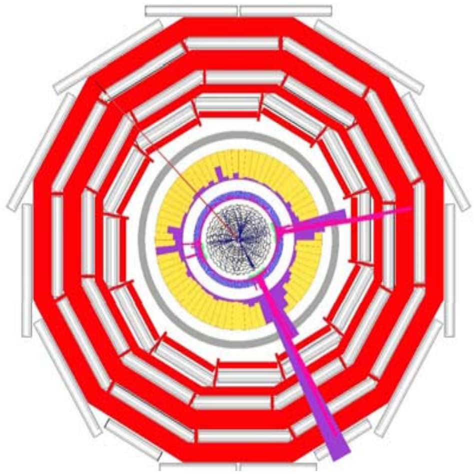
- Low-mass SUSY (M_{sp}~500GeV) accessible with O(10^{-1}) fb^{-1}. Some spectacular signatures
- Dt to discovery determined by:
  - Time to understand detector performance: E_T^{miss} tails, jet performance and energy scale, lepton id
  - Time to collect control samples -- e.g. W+jets, Z+jets, WW, top..

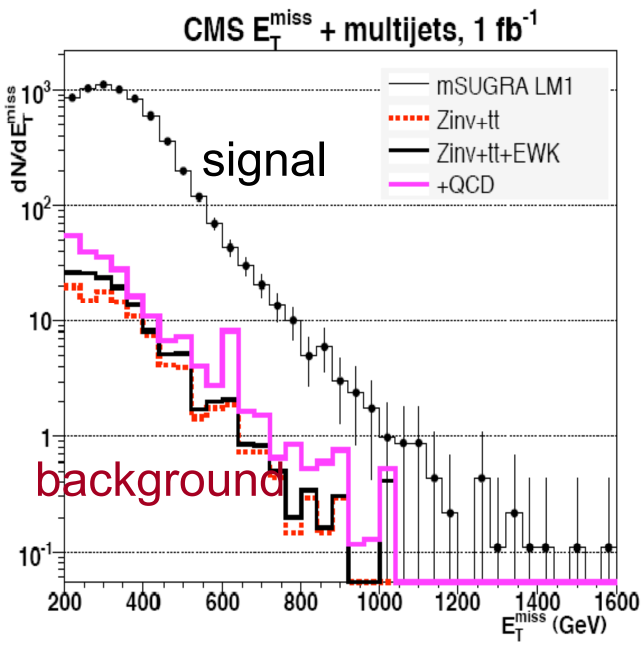


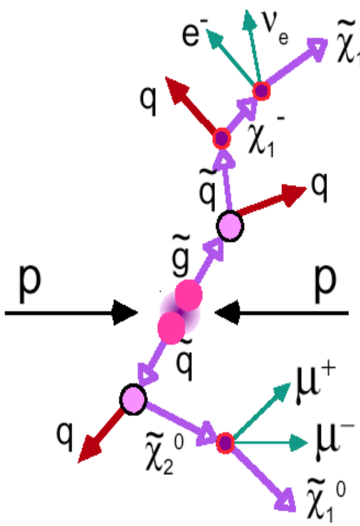
Seeking "SUSY"

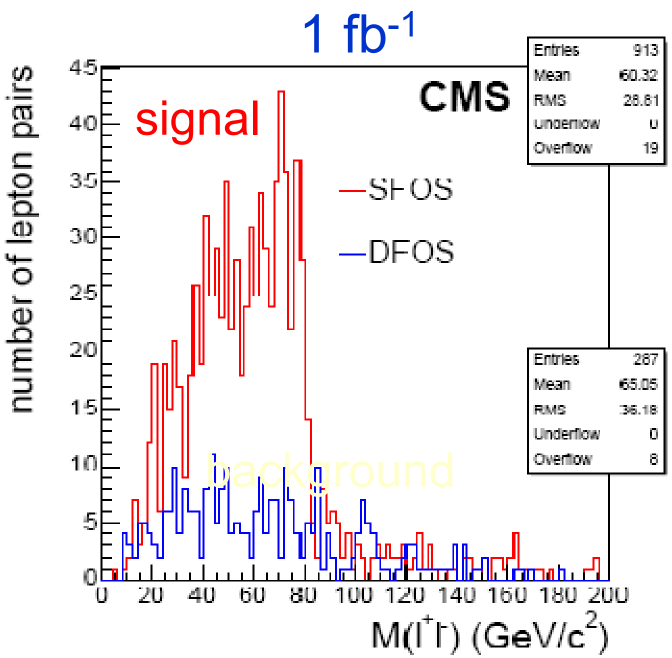






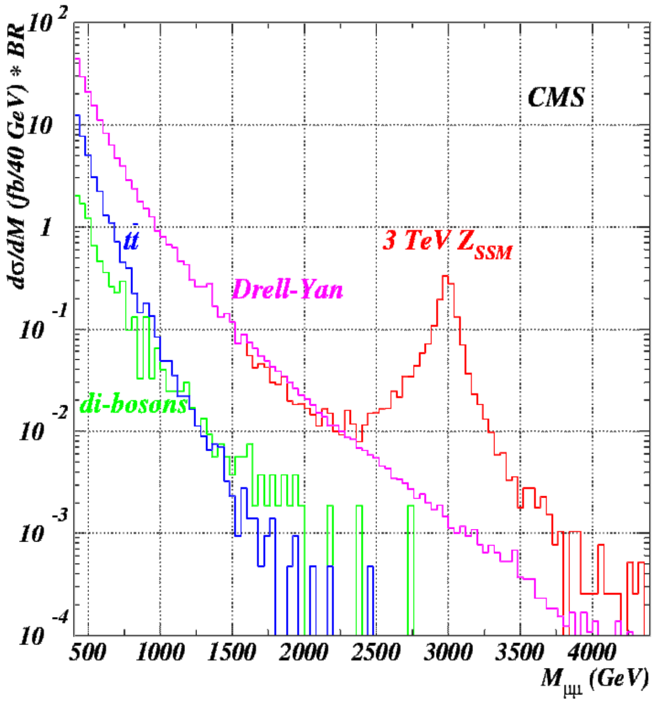


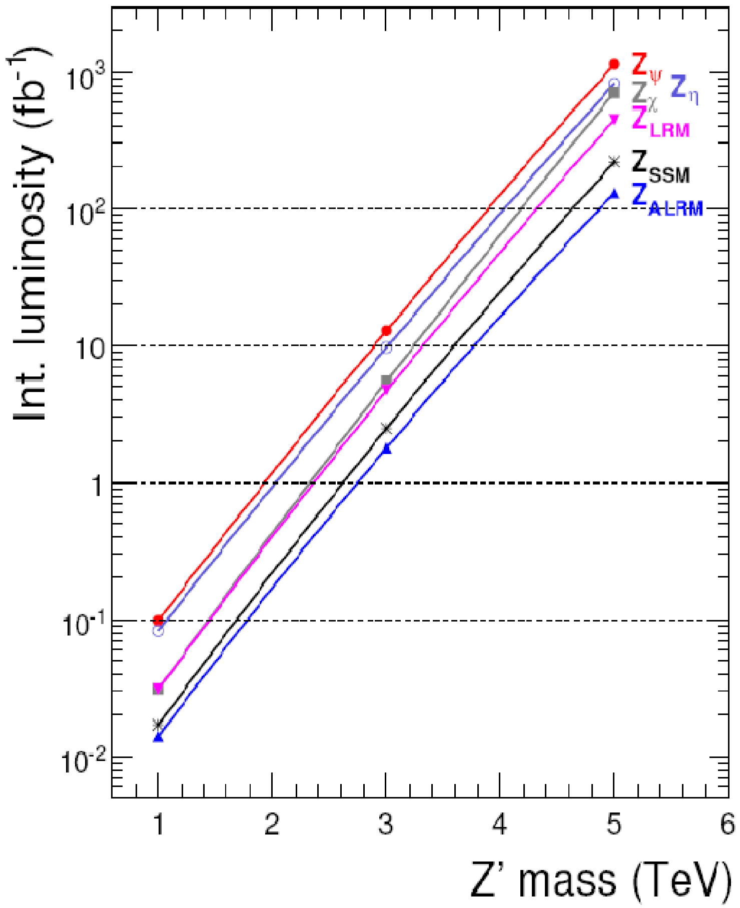




Extra Dimensions etc: Z’

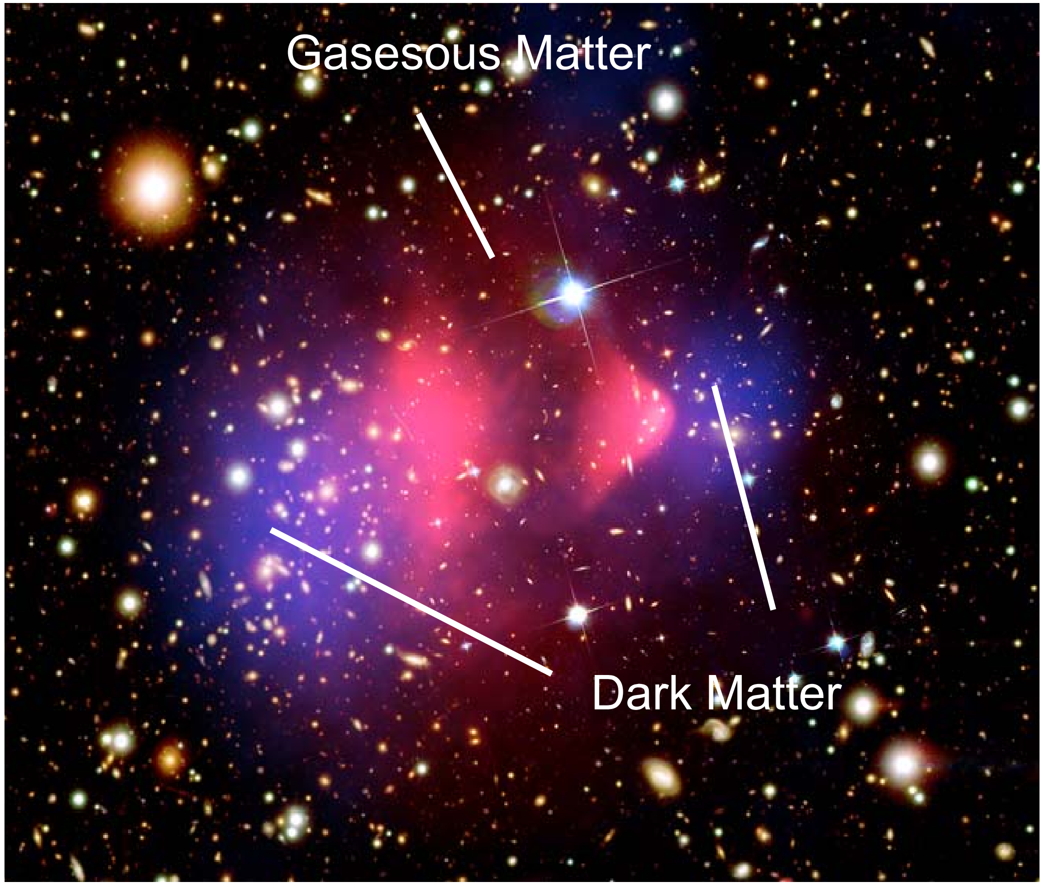
Z’→μμ production

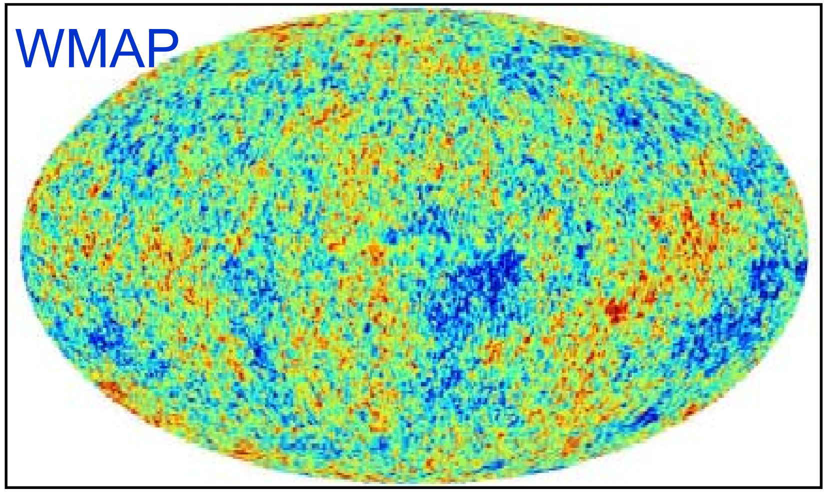




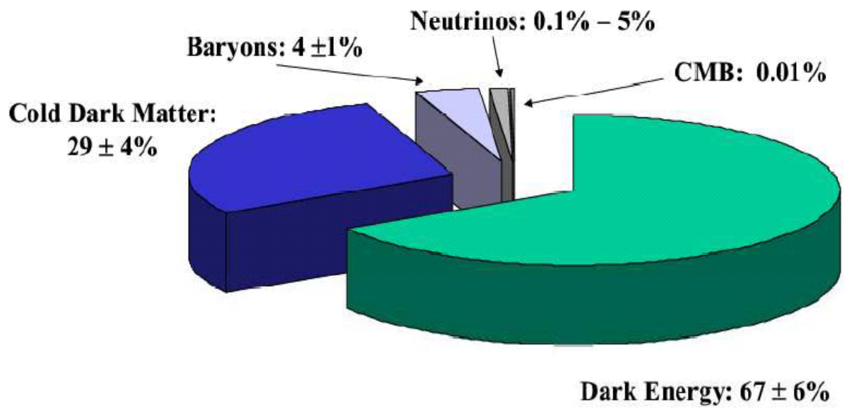
Low lumi 0.1 fb^{-1} : discovery of 1-1.6 TeV possible
High lumi 100 fb^{-1}: extend range to 3.5-4.5 TeV

The Dark Side of the Universe





Convergence Model



Lightest SUSY particle would be a prime candidate for Dark Matter

Dark Energy?
Remnant of some elementary scalar field analagous to the Higgs field?

Summary I

- **The LHC project was conceived & designed to probe the physics of the Terascale.**
- **Everything from the accelerator (its cryogenic systems, superconducting magnets,…), and the experiments (their detectors, electronics, data handling, selection of a precious few events,..) has to operate at unprecedented scales and complexity in an unprecedented environment.**
- **Their construction has required a long and painstaking effort on a global scale. They will be unparalleled scientific instruments and they are almost ready.**
- **The LHC at CERN will open a window on the "magic" 1 TeV energy scale.**
- **If indeed new physics is at the TeV-scale, CMS (and ATLAS) should find it.**

Summary II

- Construction of the CMS experiment is almost completed.
- Commissioning work already carried out gives confidence that CMS will operate with the expected performance.
- Commissioning using cosmics with more and more complete setups (complexity and functionality) going apace
- Computing, Software & Analysis: 24/7 Challenges @ 100% of 2008 conducted.
- Preparations for the rapid extraction of physics being made.

- On August CMS will be in the closed configuration; Field ON, taking cosmics, in anticipation of beam.

Summary III

We are poised to tackle some of the most profound questions in physics.

Only experiments reveal/confirm Nature’s inner secrets.

All expectations are that what we find at the LHC will reform our understanding of nature at the most fundamental level.