CMS

The CMS experiment at LHC

Compact Muon Solenoid

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University of Sofia

BPU06, Istanbul, 2006

Physics motivation

Physics motivation

- The SM is experimentally tested and confirmed with high precision
- All fundamental particles (quarks and leptons) and interaction carriers (γ, W,Z, g) are observed and
- their properties are under investigation
- However
  - ✓ One particle predicted by SM is still missing – the H-boson
  - ✓ Number of fundamental questions stay unanswered

Open Problems of SM

- The SM contains many apparently arbitrary features
  e.g. why there are 6 quarks?
- SM has a “missing element”
  i.e. mechanism to generate the observed masses of the known particles
  (Higgs mechanism)
- What is the origin of mass
  Why the Z-boson is massive whereas the related photon is massless?
- SM gives “nonsense” at very high energies
  $W_L W_L$ scattering probability becomes larger then 1 at energies above ~1 TeV
- SM is logically not complete
  Gravity is not incorporated

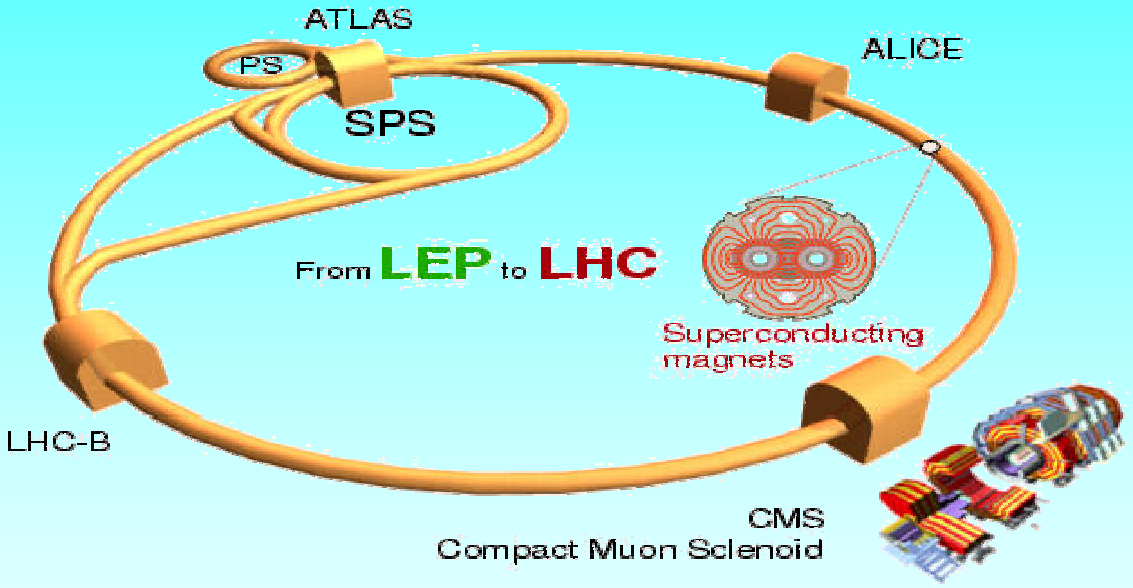
Beyond the SM

- The SM should be considered as a low energy phenomenological model
- Quest for a more fundamental theory (model) which incorporates the SM and answers the question is going on
  - ✓ GUT
  - ✓ Technicolor
  - ✓ SUSY
  - ✓ Extra Dimensions
  - ✓ Little Higgs
  - ✓ String theories
- In all of them many new features and particles are predicted
- This is so called "New Physics"

Need to
Find the Higgs
Find clues for the physics beyond the SM

The LHC program will address all these issues

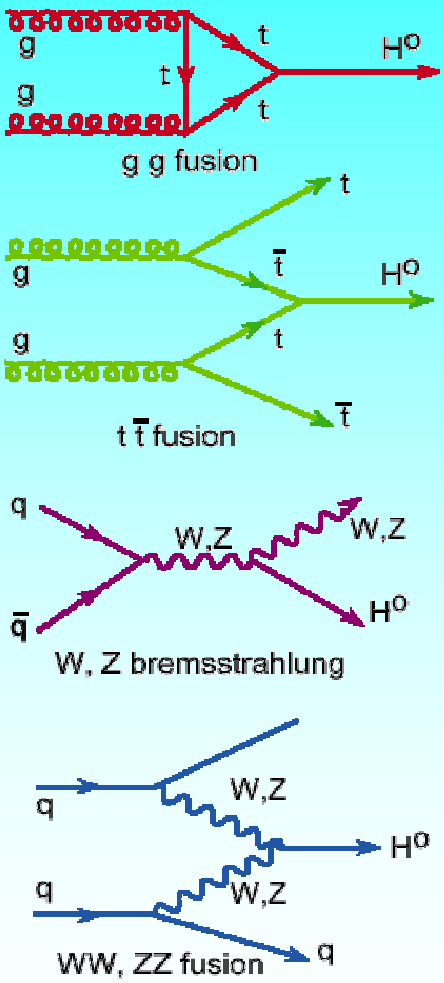
The Large Hadron Collider (LHC)



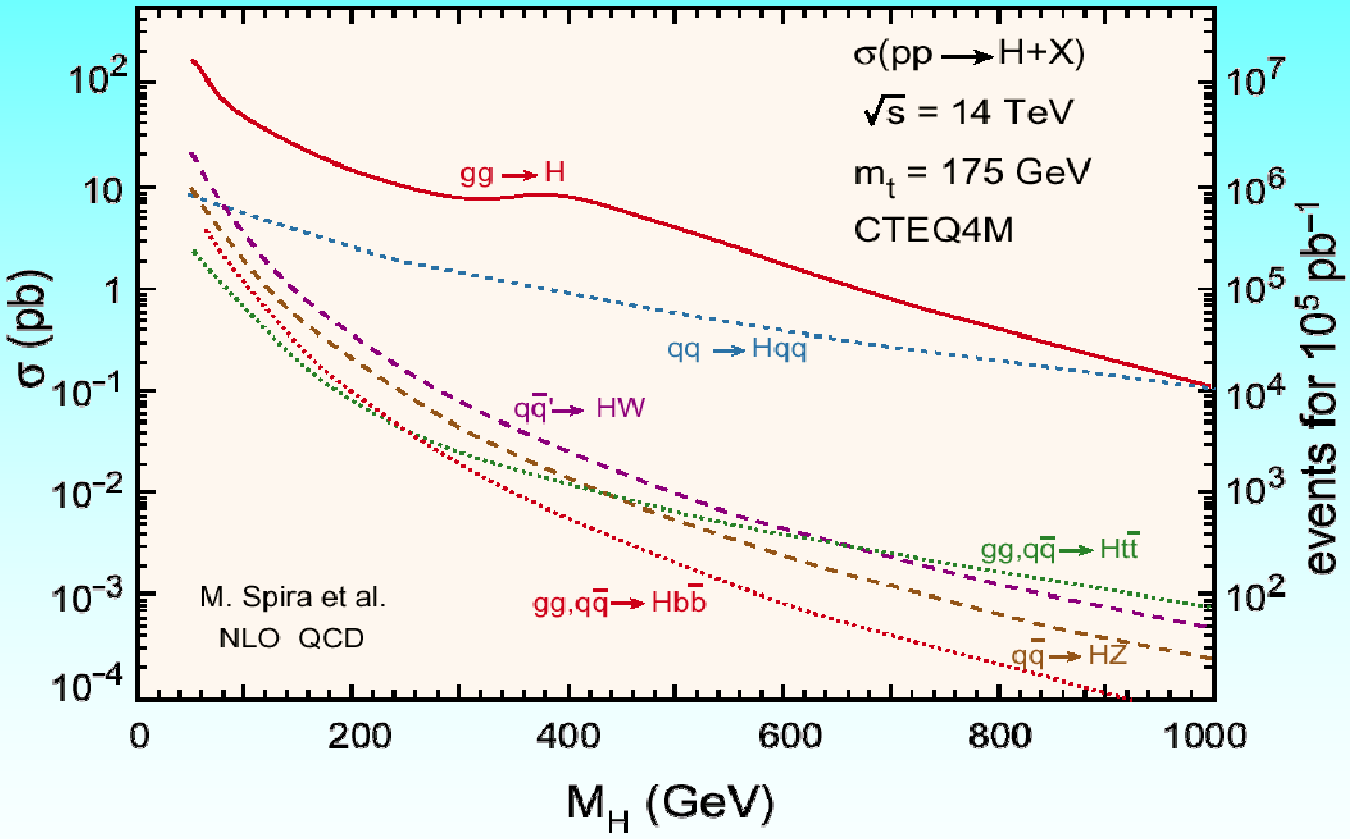
	Beams	Energy	Luminosity
LEP	e+ e-	200 GeV	10^{32} cm^{-2}s^{-1}
LHC	p p	14 TeV	10^{34}
	Pb Pb	1312 TeV	10^{27}

Detector requirements

Higgs production

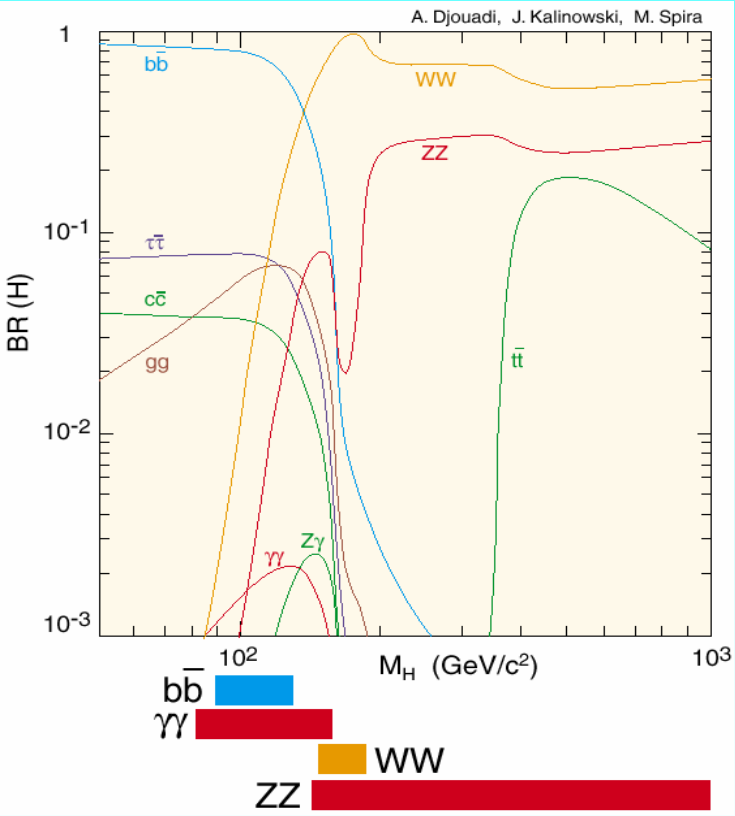


Production cross sections

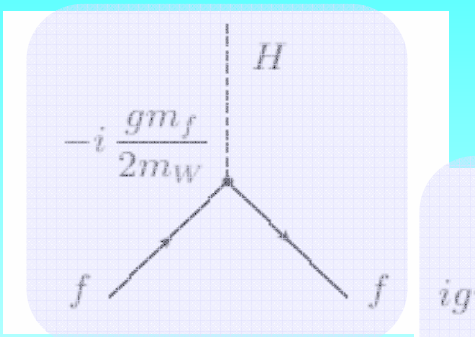


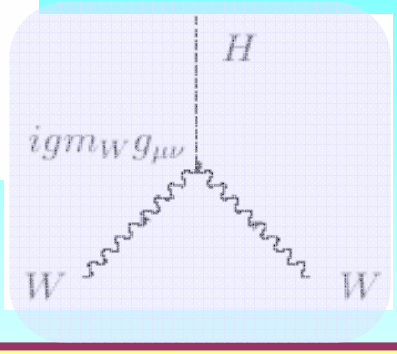
Higgs decays

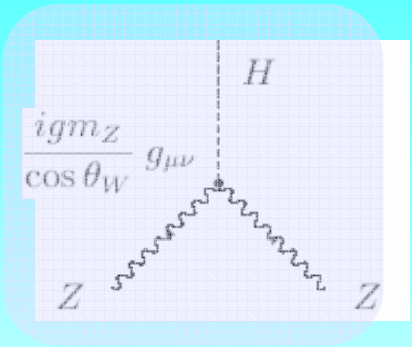
SM Higgs branching ratios



Higgs decays is proportional to the mass







Suitable search channels

80 GeV < m_H < 140 GeV H -> γγ, H -> bb
130 GeV < m_H < 700 GeV H -> ZZ(*) -> 4 ℓ (l = e, μ)
500 GeV < m_H < 1000 GeV H -> ZZ -> 2 ℓ + 2 Jets
500 GeV < m_H < 1000 GeV H -> ZZ -> 2 ℓ + 2 ν
800 GeV < m_H < 1000 GeV H -> WW-> ℓ + ν + Jets
800 GeV < m_H < 1000 GeV H -> ZZ-> 2 ℓ + 2 Jets

Supersymmetric particles

Standard Model	Supersymmetry
γ, Z^0, h^0, H^0	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$
W^+, H^+	$\tilde{\chi}_1^+, \tilde{\chi}_2^+$
$e^-, \nu_e, \mu^-, \nu_\mu, \nu_\tau$	$\tilde{e}_R^-, \tilde{e}_L^-, \tilde{\nu}_e, \tilde{\mu}_R^-, \tilde{\mu}_L^-, \tilde{\nu}_\mu, \tilde{\nu}_\tau$
τ^-	$\tilde{\tau}_1^-, \tilde{\tau}_2^-$
u, d, s, c	$\tilde{u}_R, \tilde{u}_L, \tilde{d}_R, \tilde{d}_L, \tilde{s}_R, \tilde{s}_L, \tilde{c}_R, \tilde{c}_L$
b	$\tilde{b}_1, \tilde{b}_2$
t	$\tilde{t}_1, \tilde{t}_2$

SUSY-decays

$\tilde{q} \rightarrow \tilde{\chi}_2^0\, q$

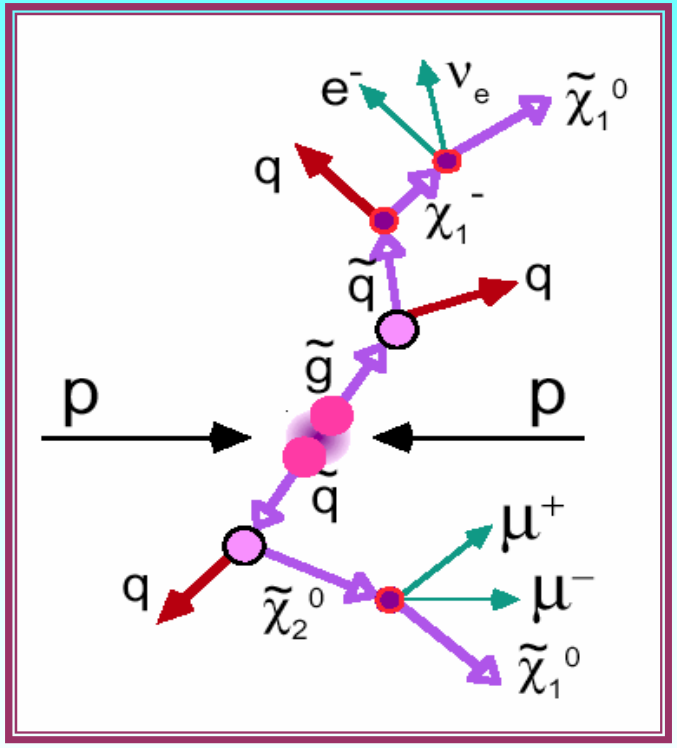
$\tilde{\mu}\, \mu$

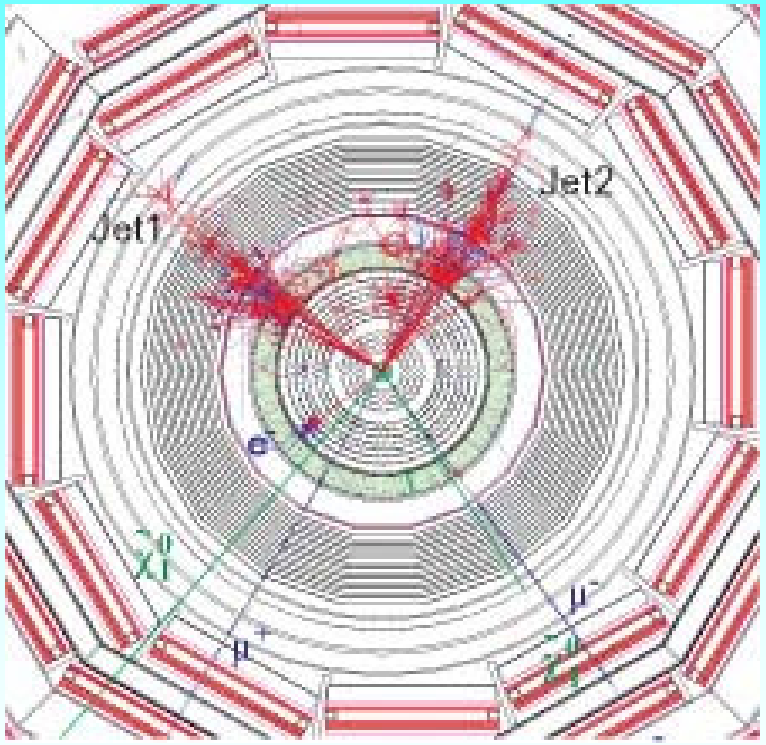
$\tilde{\chi}_1^0\, \mu$

$\tilde{g} \rightarrow q\tilde{q}$

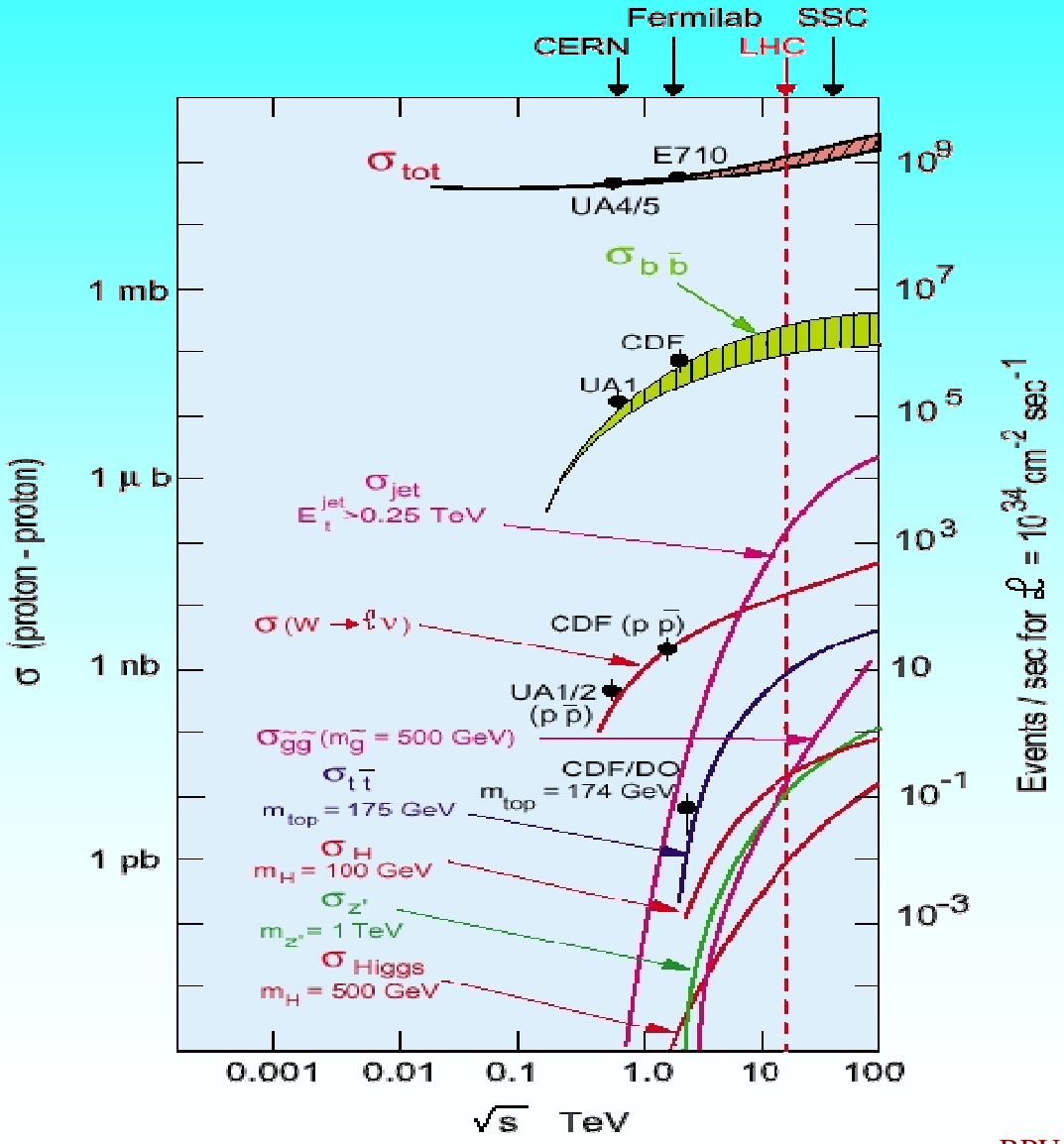
$\tilde{\chi}_1^{\pm}\, q$

$e\, \nu\, \tilde{\chi}_1^0$





pp cross-sections



Detector requirements

Very good muon identification and momentum measurement

trigger efficiently and measure sign of a few TeV muons

High energy resolution electromagnetic calorimertry

~ 0.5% @ E_T~50 GeV

Powerful inner tracking systems

factor 10 better momentum resolution than at LEP

Hermetic calorimetry

good missing E_T resolution

(Affordable detector)

Detector requirements

High Interaction Rate

pp interaction rate 10^9 interactions/s

data for only ~100 out of the 40 million crossings can be recorded per sec

Level-1 trigger decision will take ~2-3 ms

⇨ 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

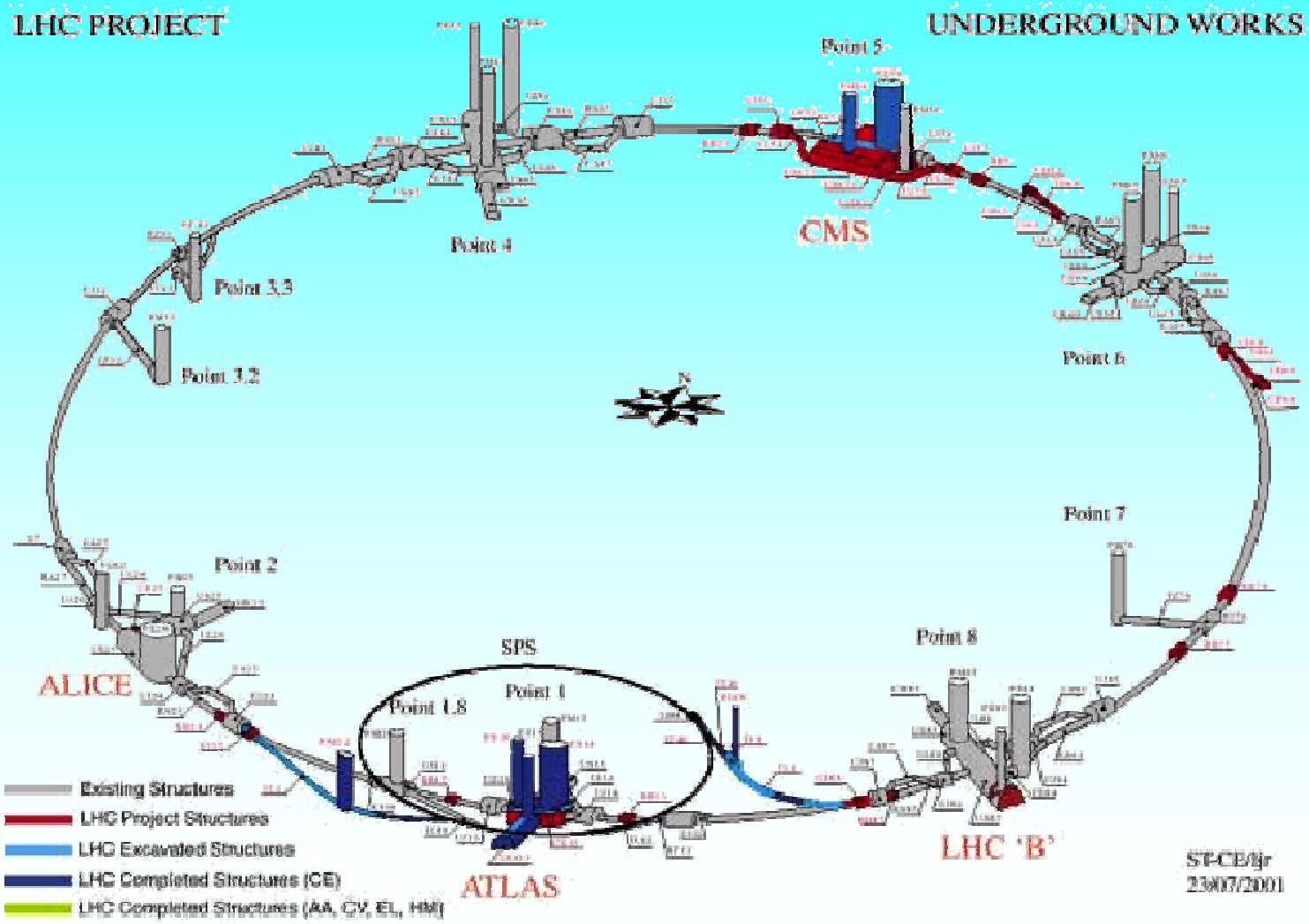
⇨ large number of channels

High Radiation Levels

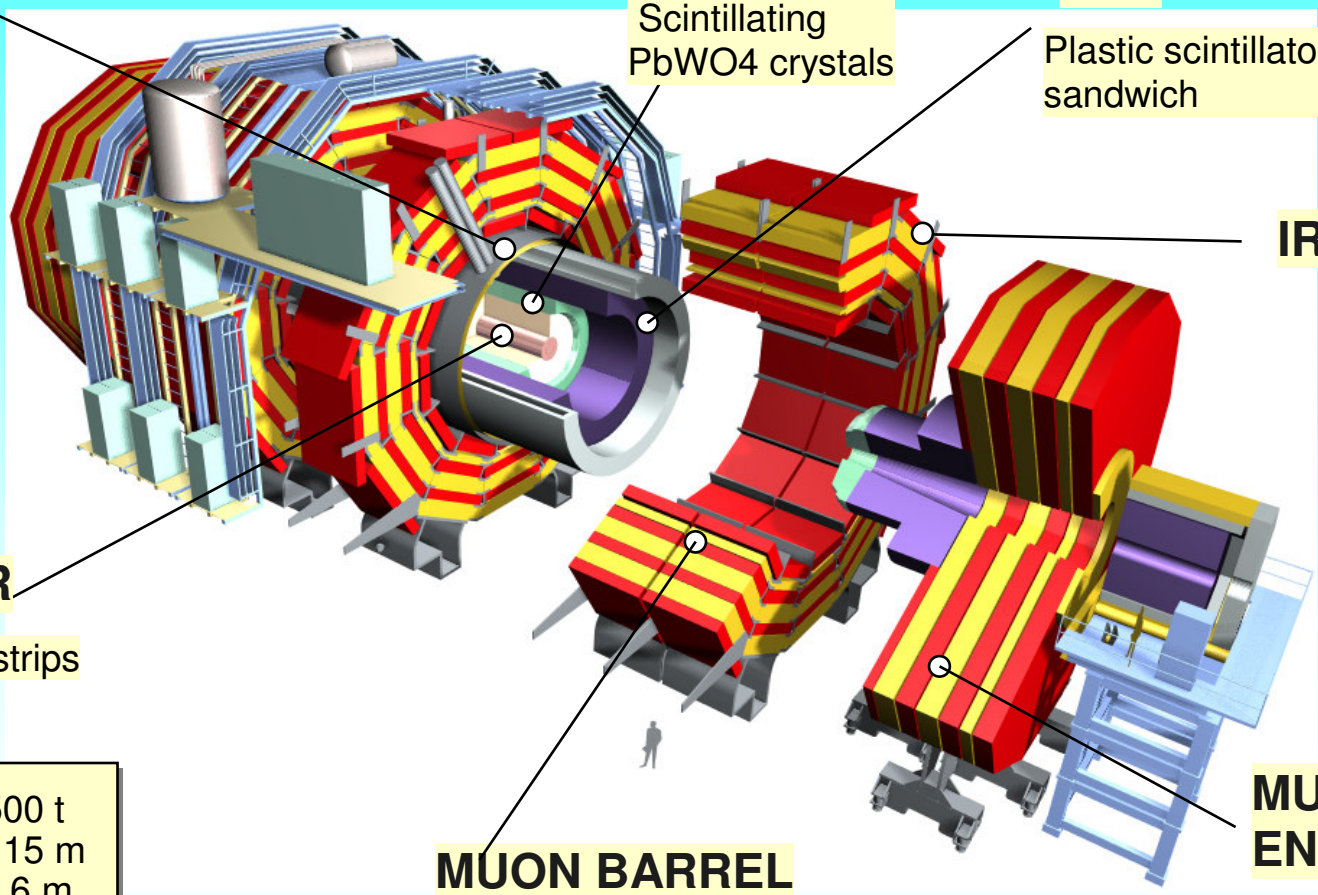
⇨ radiation hard (tolerant) detectors and electronics

The CMS detector

LHC


LHC PROJECT
UNDERGROUND WORKS
Point 5
CMS
Point 4
Point 3.3
Point 3.2
Point 6
Point 7
Point 2
ALICE
SPS
Point 1
Point 1.8
Point 8
LHC 'B'
ATLAS
Existing Structures
LHC Project Structures
LHC Excavated Structures
LHC Completed Structures (CE)
LHC Completed Structures (AA, CV, EL, HM)
ST-CE/jr
23/07/2001

The CMS detector



SUPERCONDUCTING COIL

CALORIMETERS

ECAL

Scintillating PbWO4 crystals

HCAL

Plastic scintillator/brass sandwich

IRON YOKE

TRACKER

Silicon Microstrips
Pixels

MUON ENDCAPS

Cathode Strip Chambers (**CSC**)

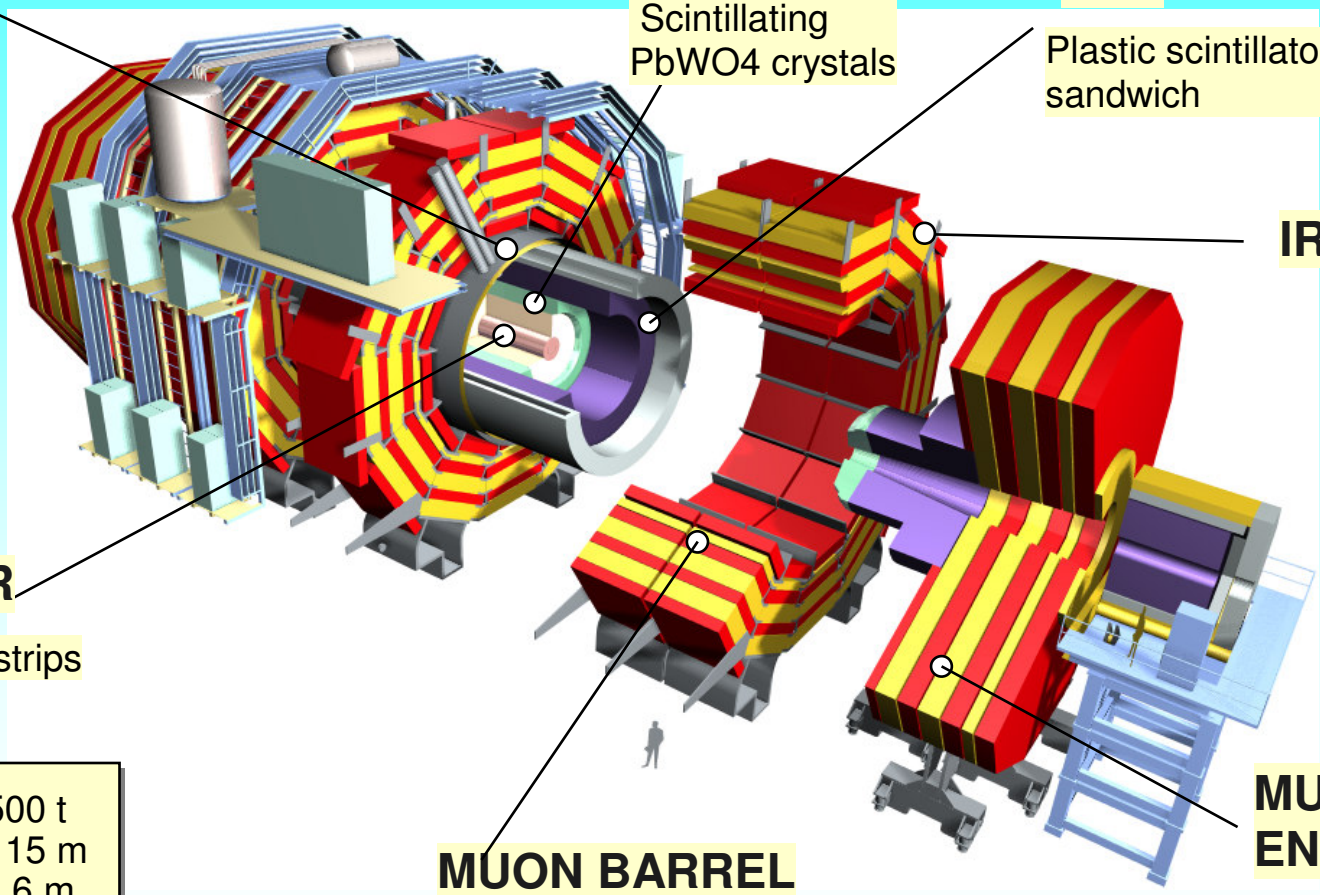
Resistive Plate Chambers (**RPC**)

MUON BARREL

Drift Tube Chambers (**DT**)

Resistive Plate Chambers (**RPC**)

Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla



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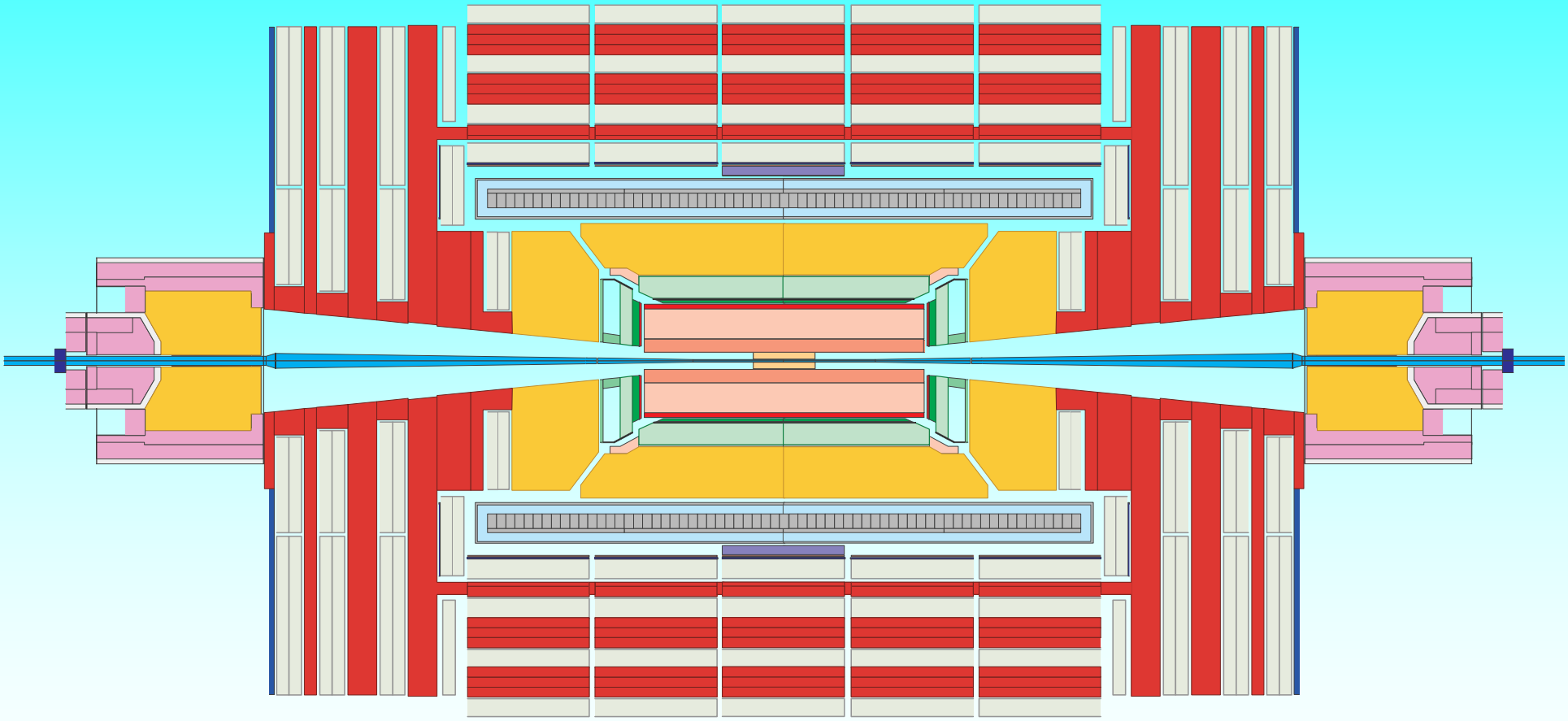
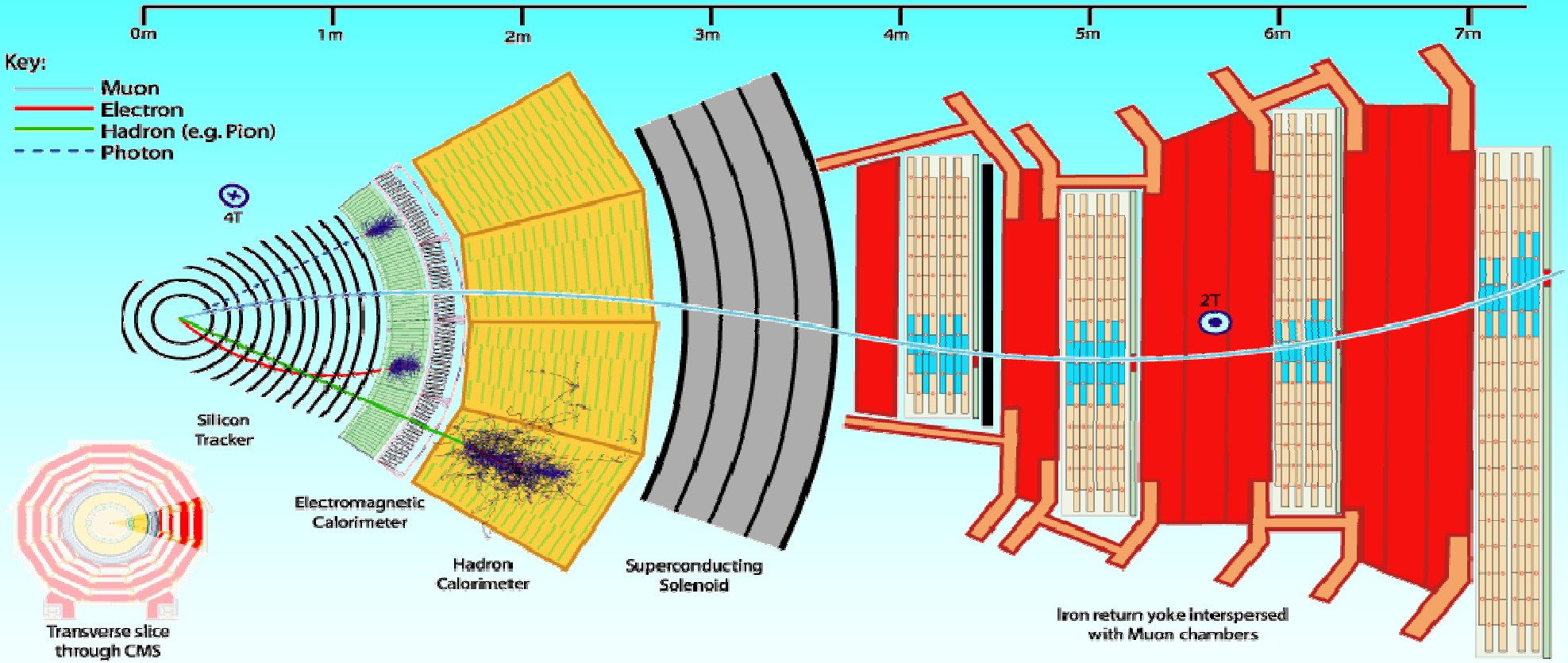
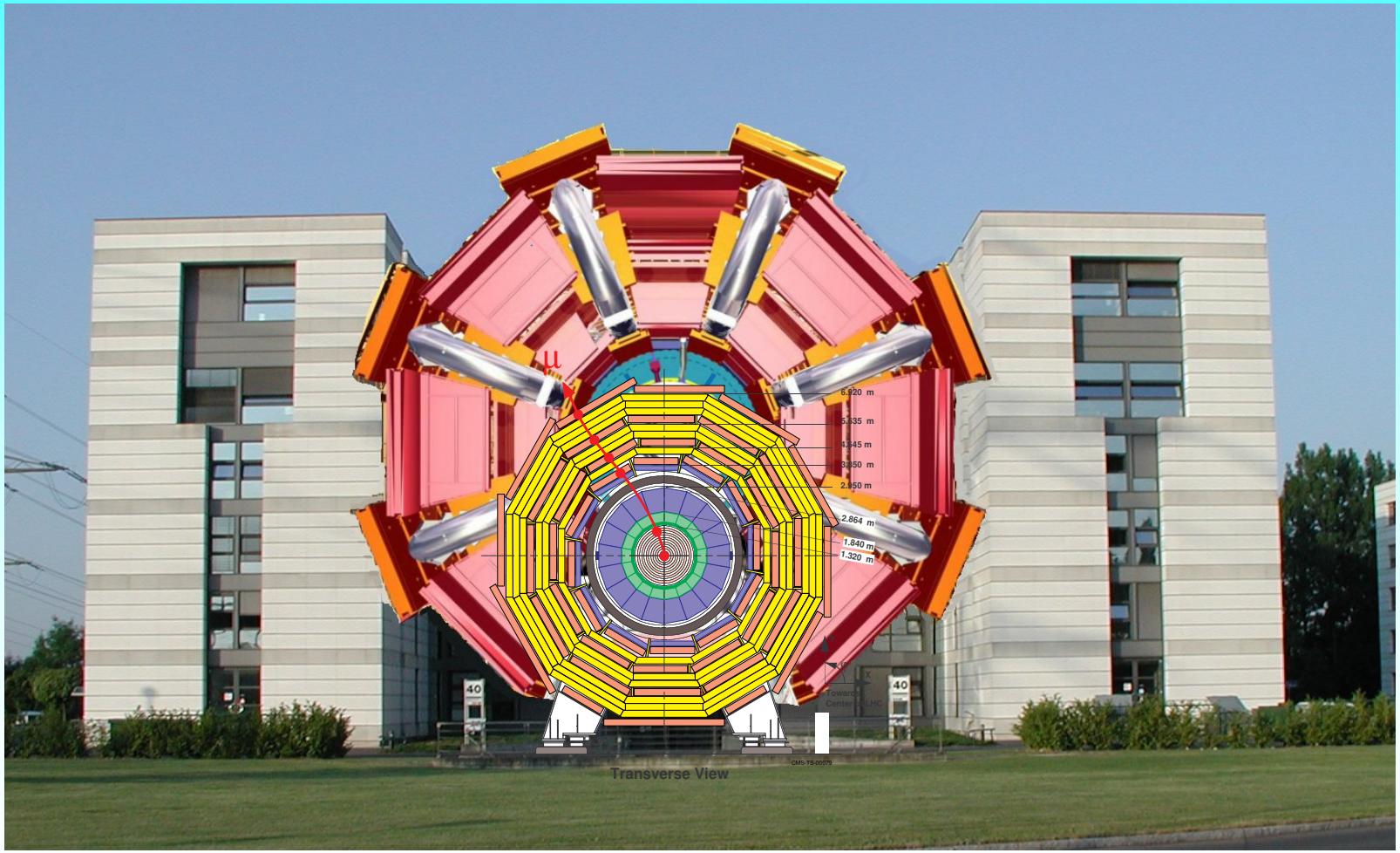
CMS Longitudinal view



CMS Detector Slice



Building 40 at CERN

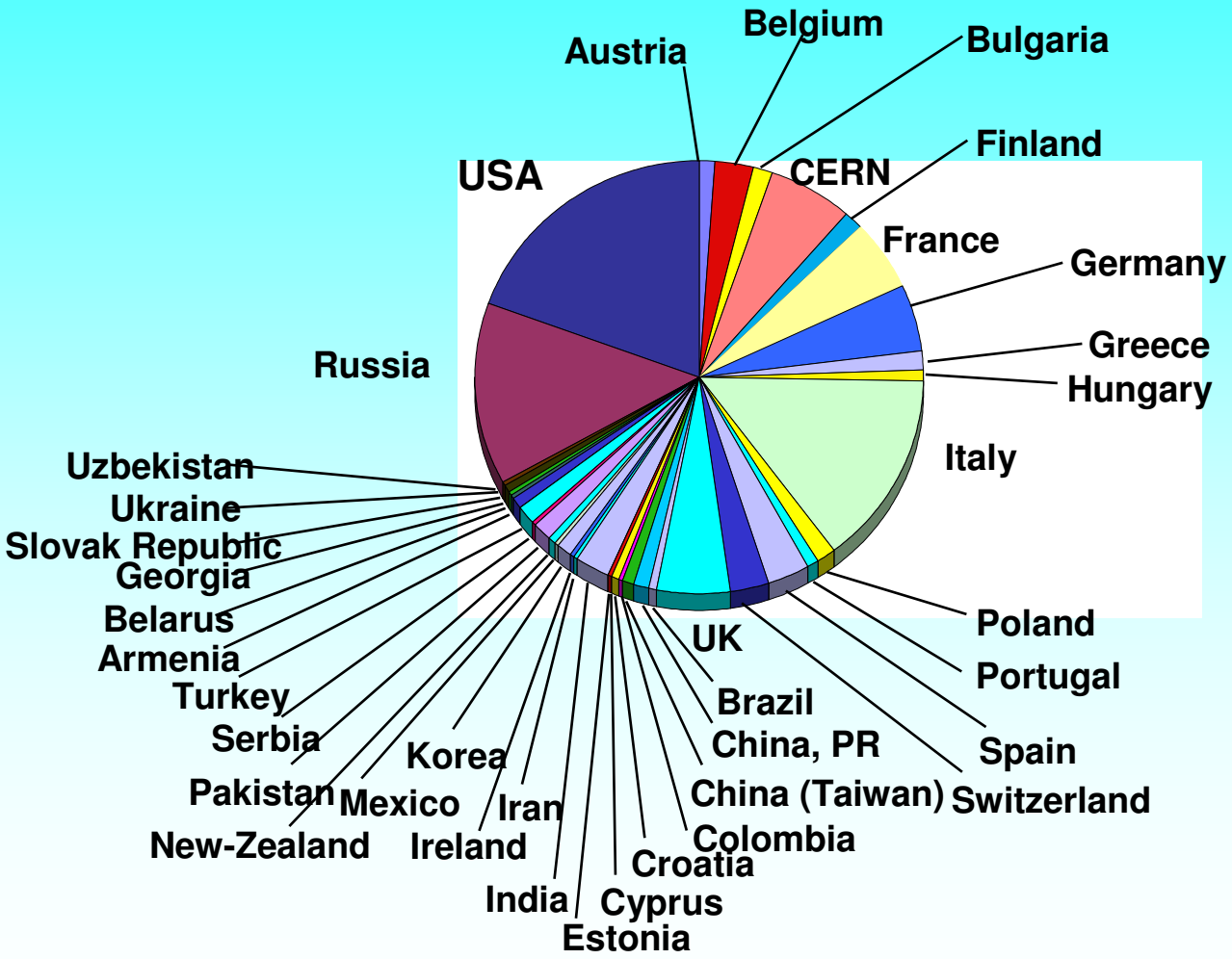


The CMS Collaboration

	Institutions
Member States	61
Non-Mem. States	64
USA	49
Total	174

	Scientists
Member States	1055
Non-Mem. States	428
USA	547
Total	2030

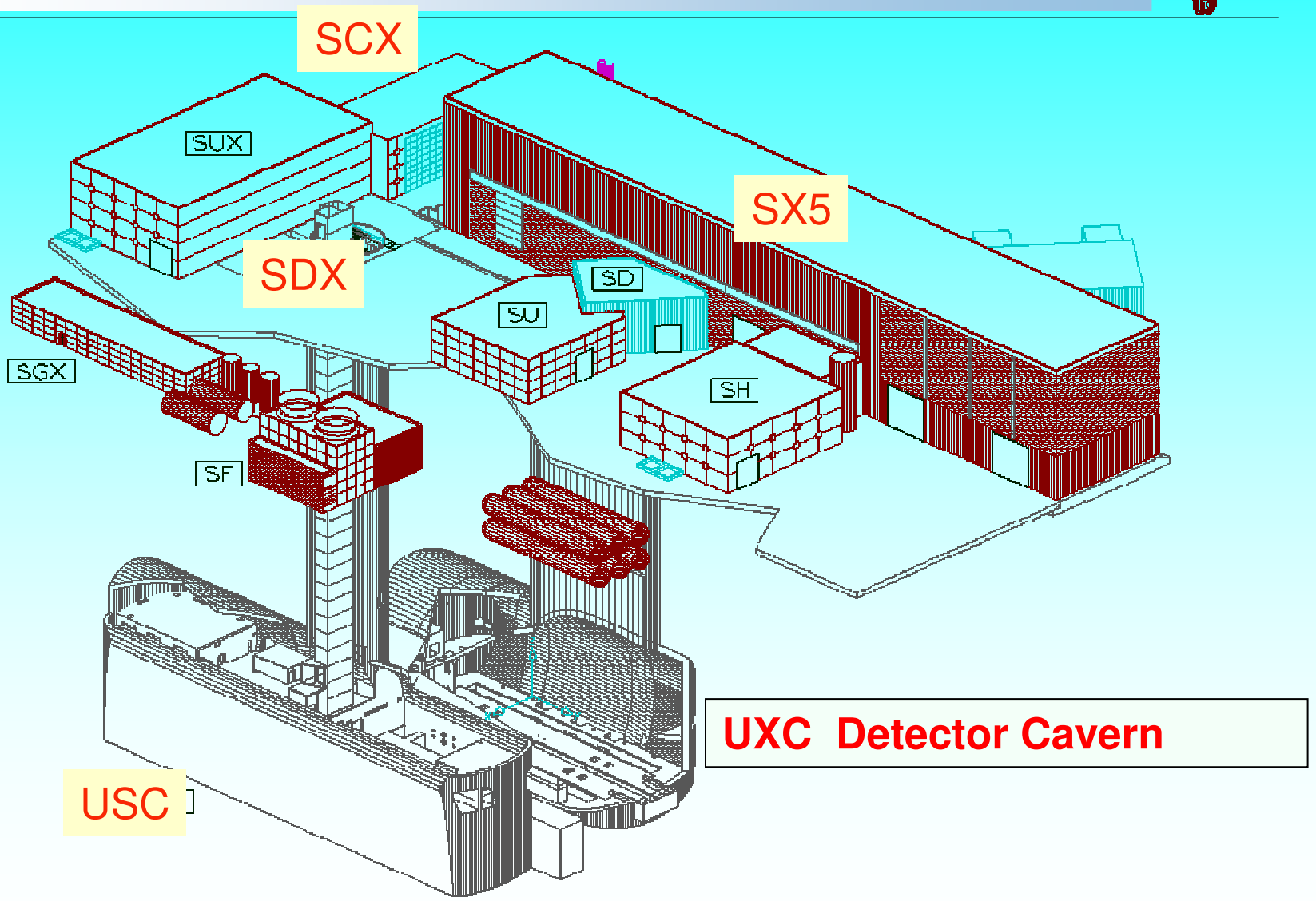
Associated Institutes	
Number of Scientists	46
Number of Laboratories	8



2030 Scientific Authors, 38 Countries, 174 Institutions

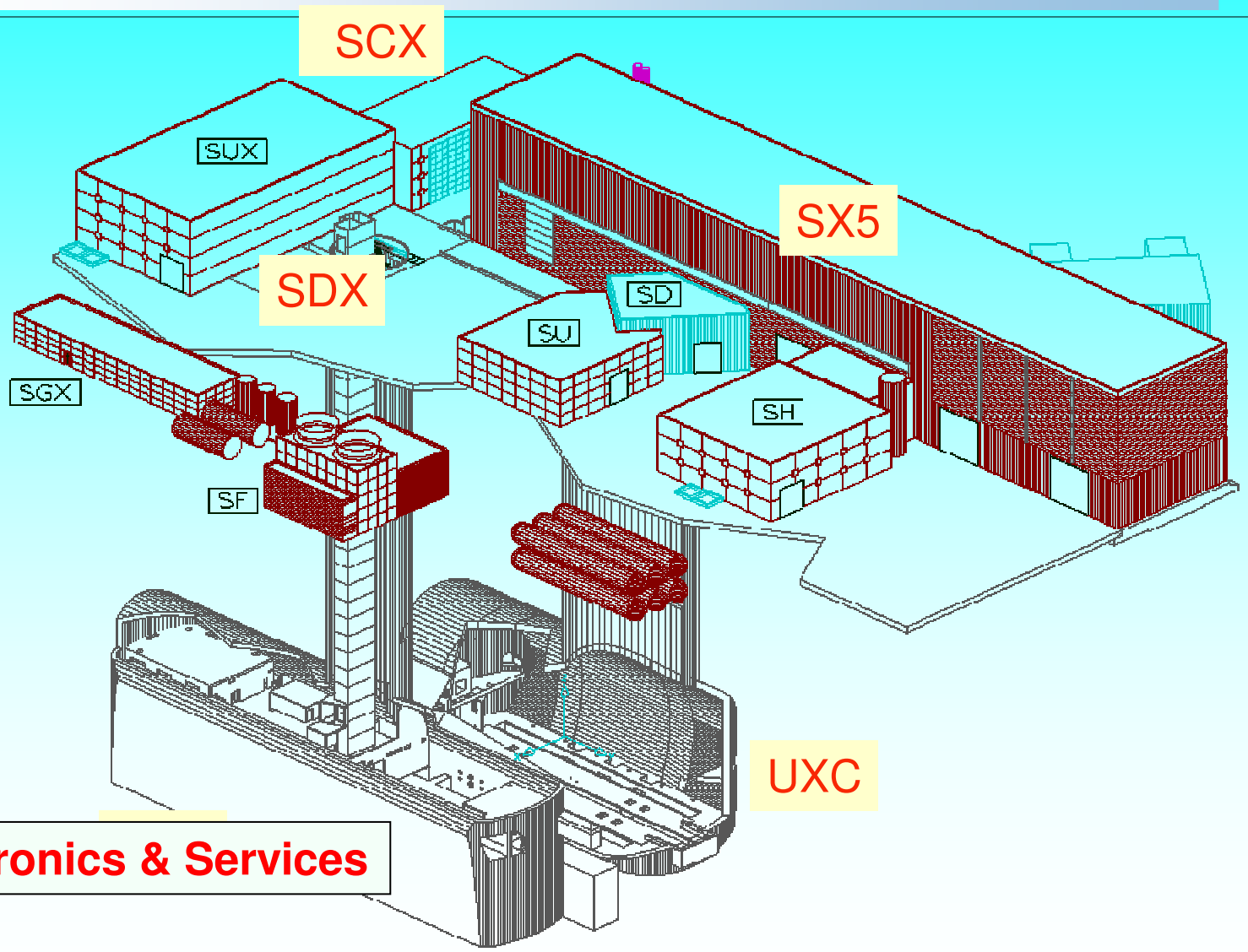
LHC Point 5

Civil Engineering Overview



Civil Engineering Overview

Civil Engineering Overview

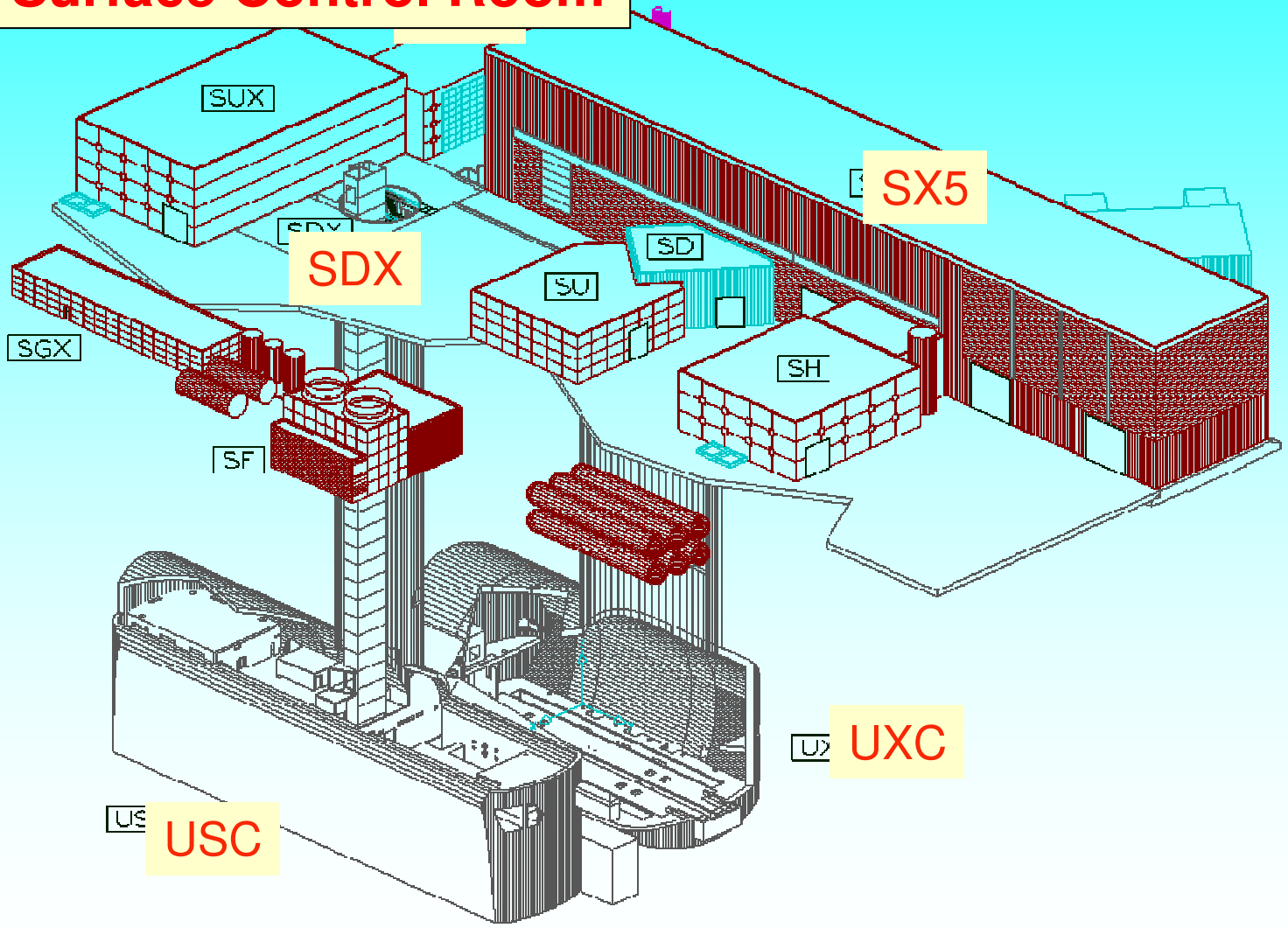


USC Electronics & Services

Civil Engineering Overview

Civil Engineering Overview

SCX Surface Control Room

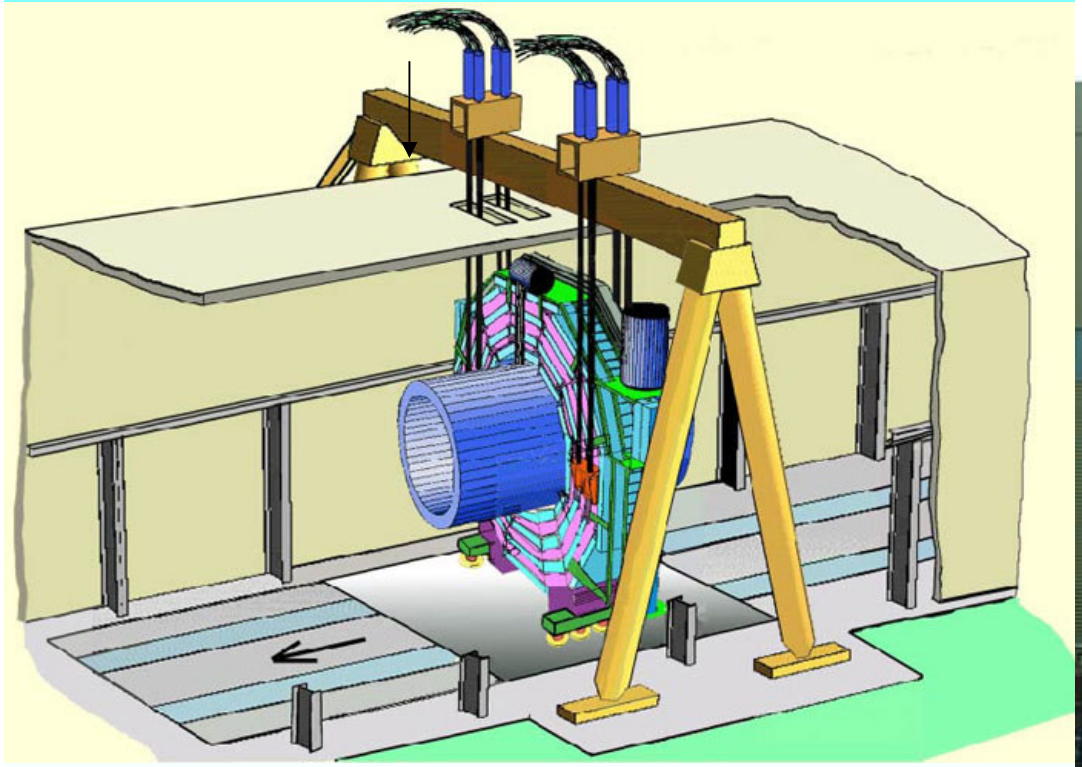


Civil Engineering Overview

1st Floor for PC farm operational 1st July

Transfer CMS Underground in 2006

Gantry installed over PX56. load test in July and start HF lowering.



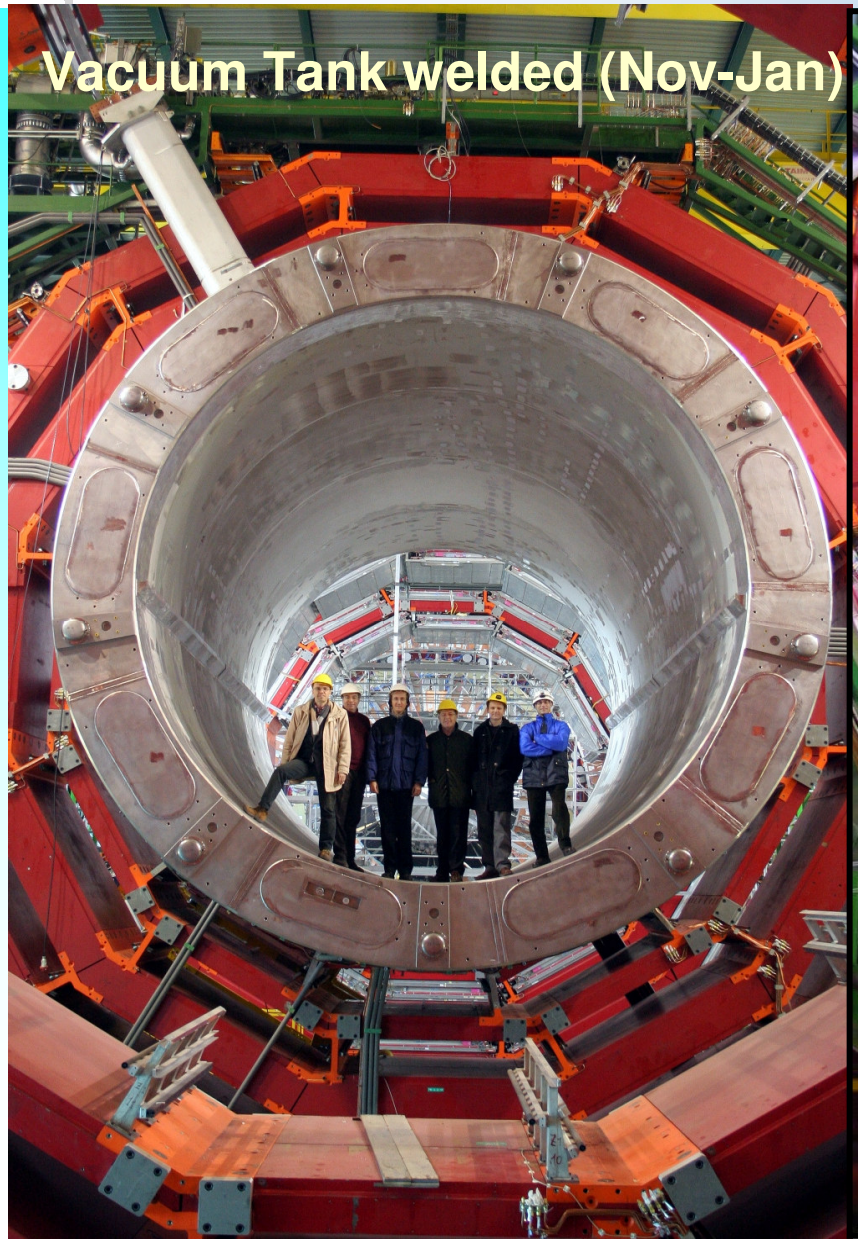
Start YB0 lowering (2000t): Nov 06

CMS Solenoid

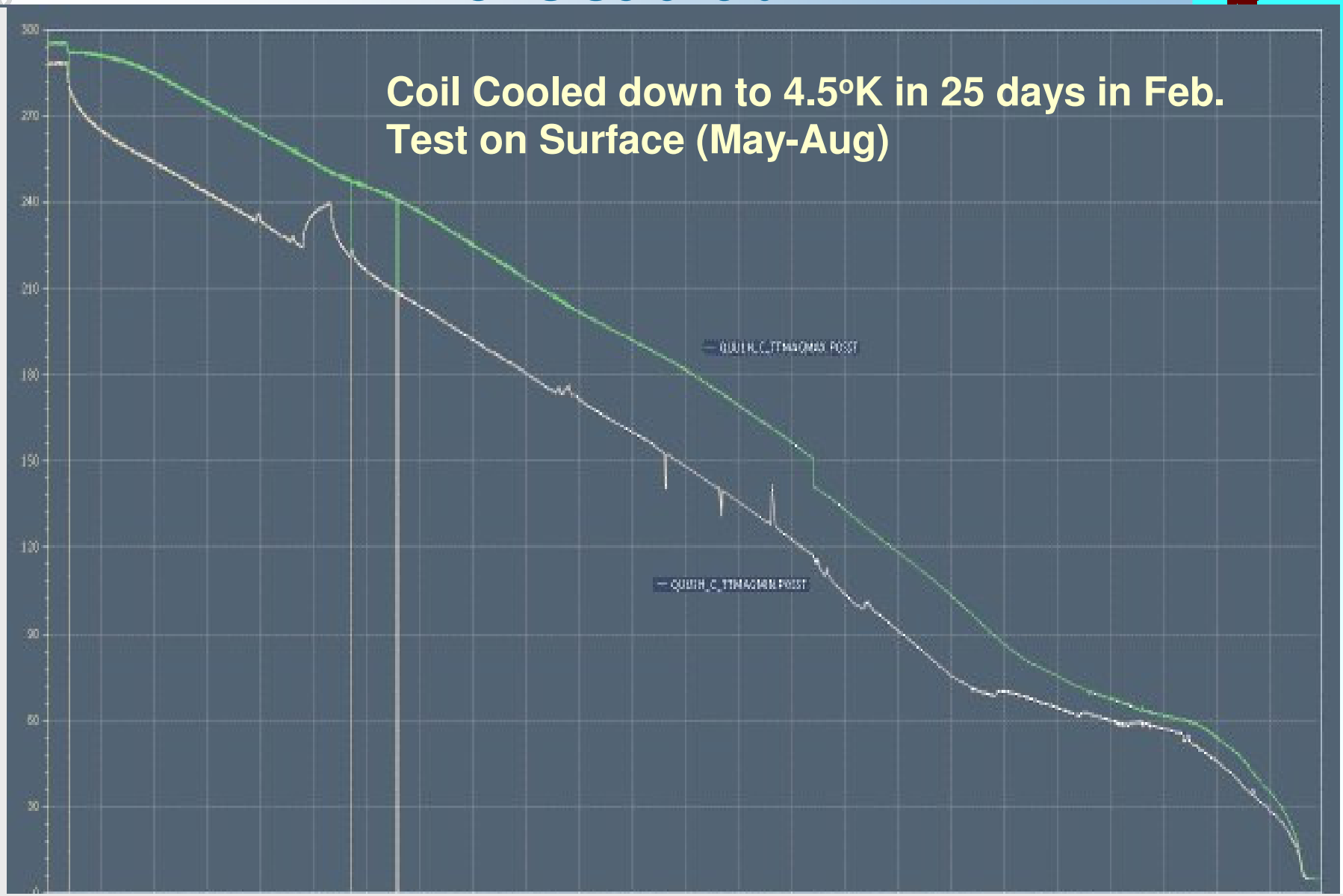
CMS Solenoid

CMS Solenoid

CMS Solenoid

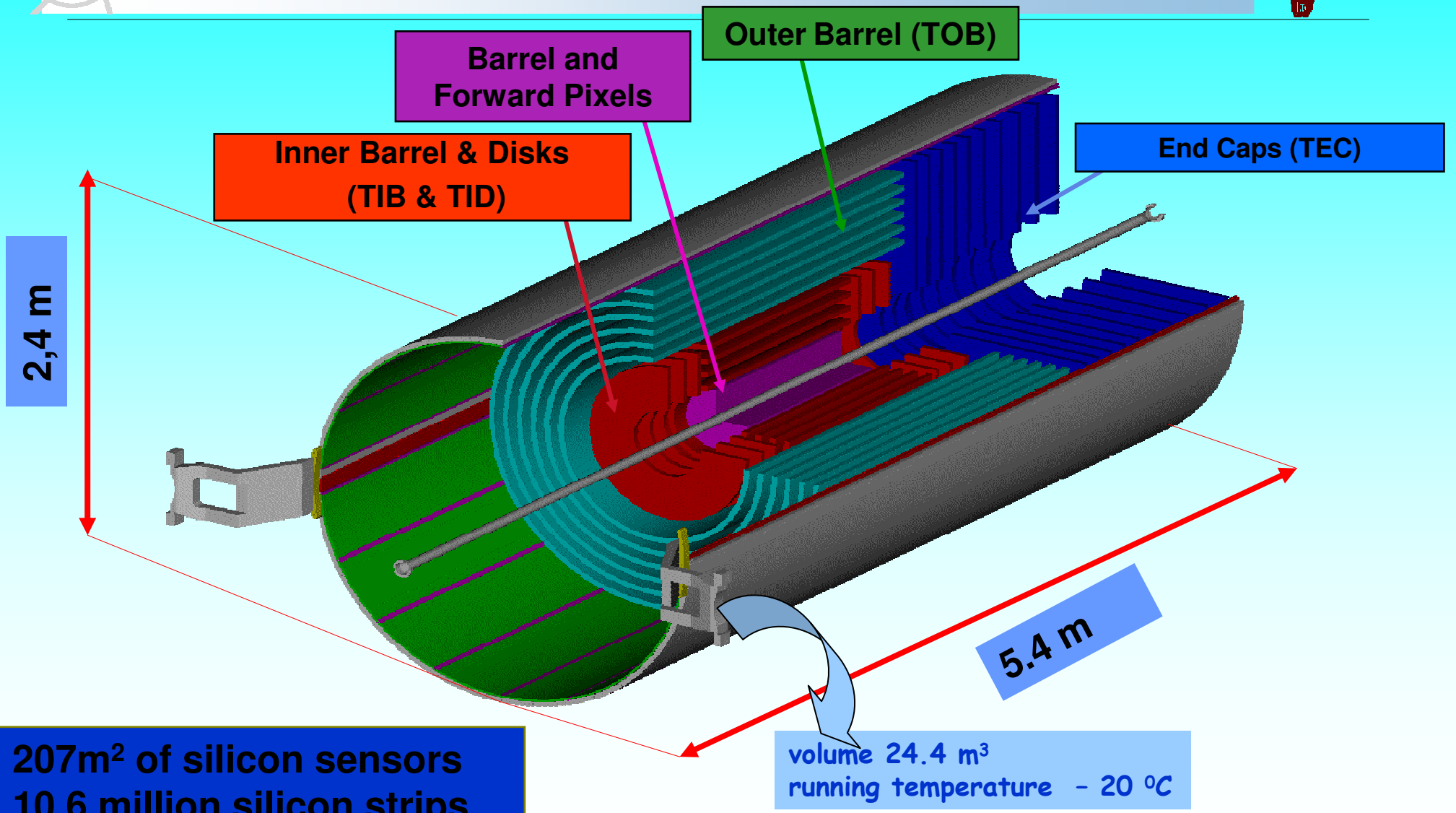


CMS Solenoid



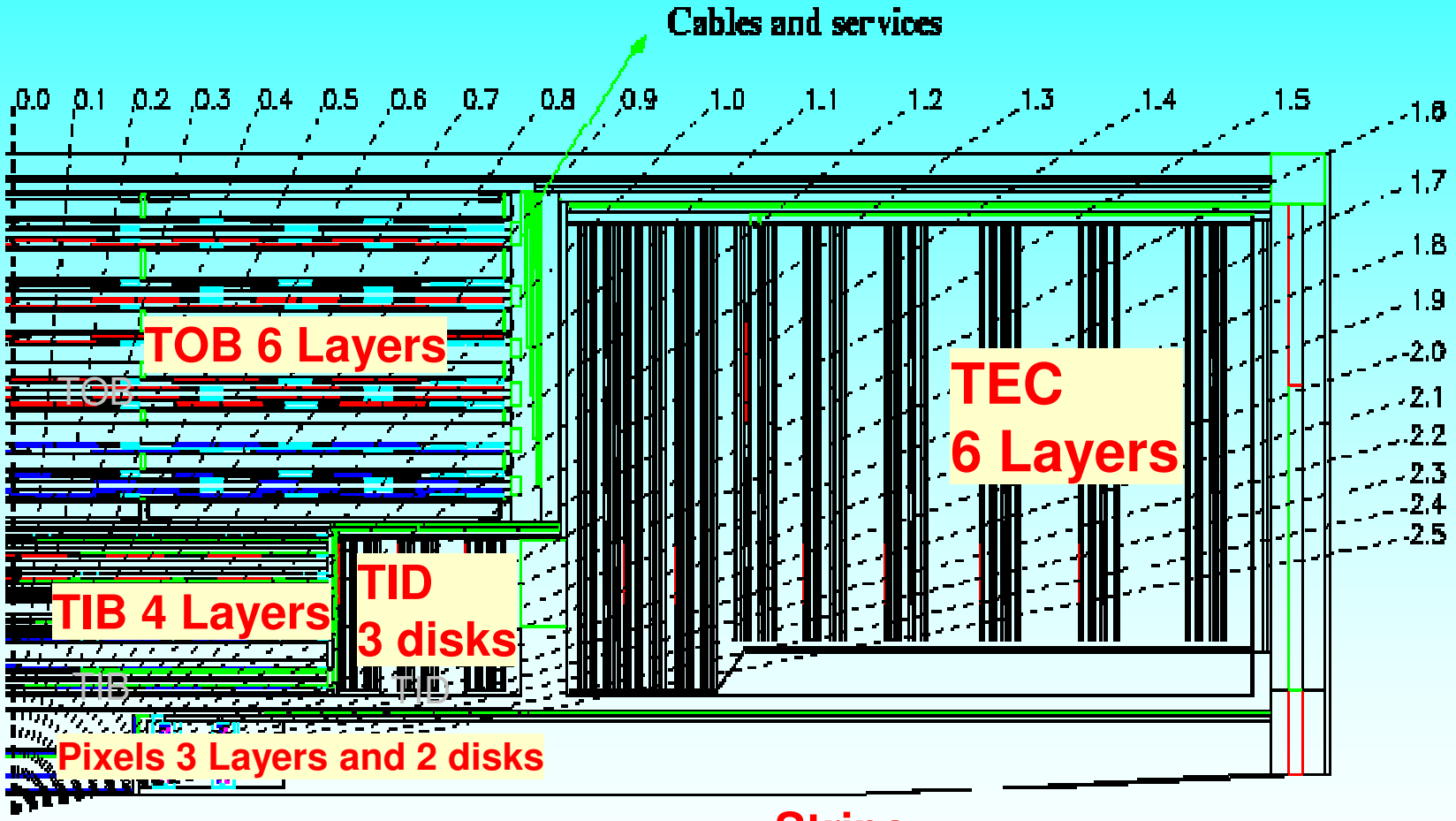
Central track detector

All Silicon Tracker



207m² of silicon sensors
10.6 million silicon strips
65.9 million pixels ~ 1.1 m²

Inner Tracker



Pixels:

100 μm x 150μm

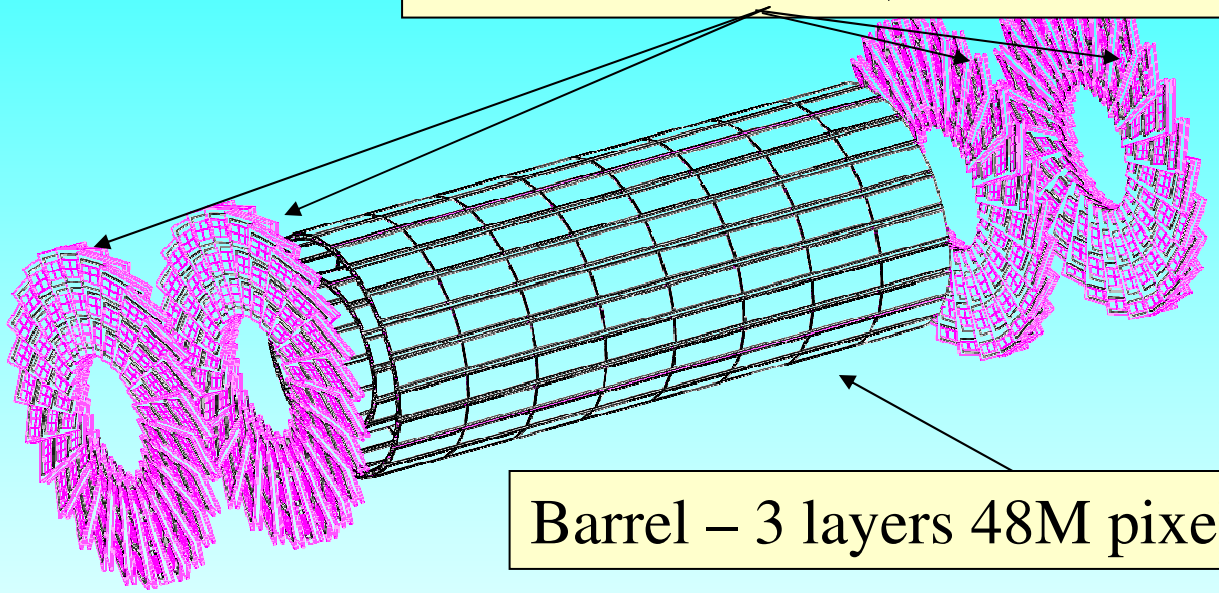
rϕ and z resolution: 15-20 μm

Strips:

Pitch: 80 μm to 180μm

Hit Resolution: 20 μm to 50μm

Pixels Design



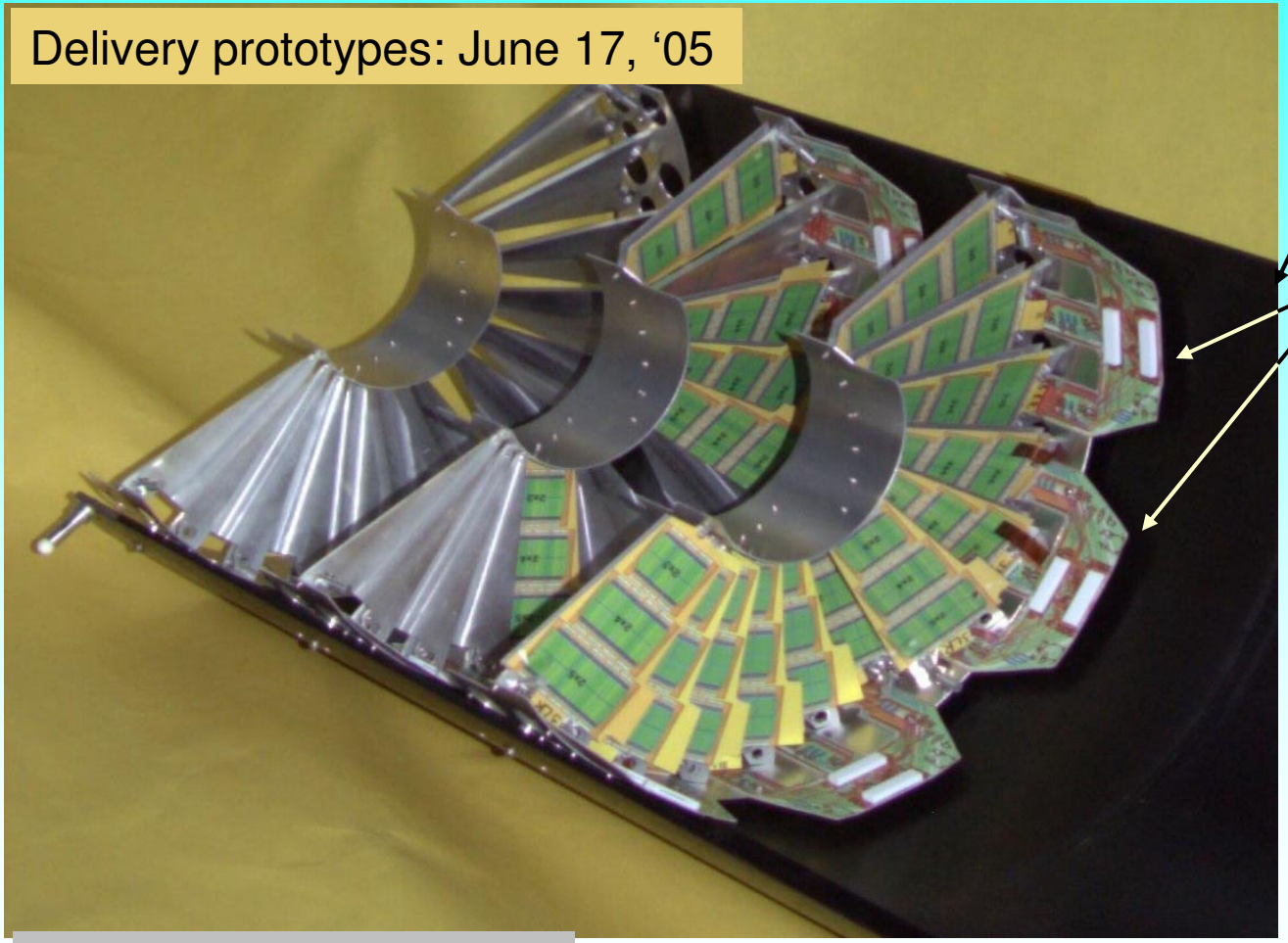
LAYERS: R = 4.3cm 7.2cm 11.0 cm → Area Barrel = 0.78 m²
Disk = 0.28 m²
Total ~ 1.1 m²

Installation +
Fluence limited
→ ΔT_{max} ~ 2 years

Cost limited !!
→ R_{max}

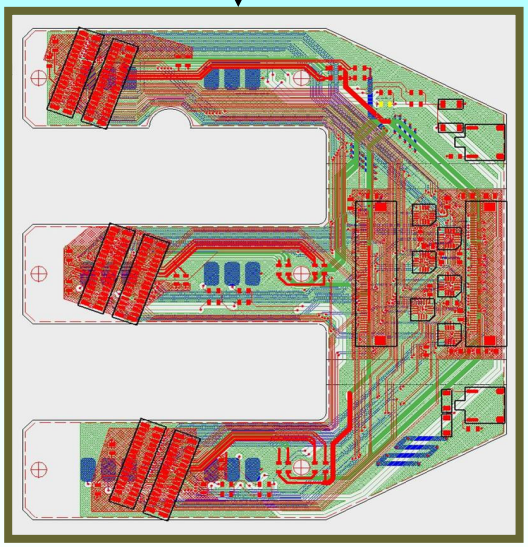
Forward Pixels

Delivery prototypes: June 17, ‘05



Service Cylinder

Adapter Board

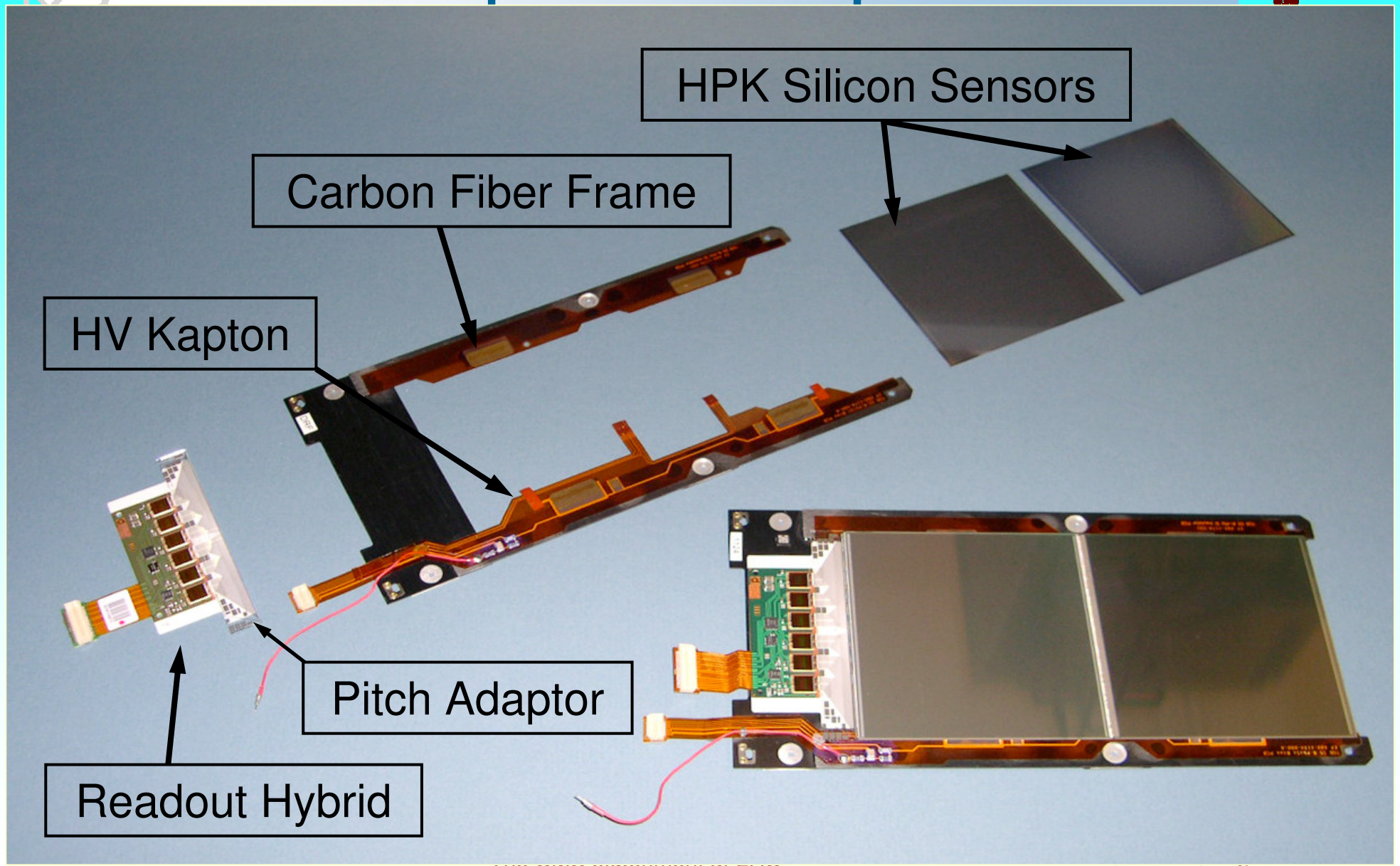


2x2 Disks
to be installed
672 Endcap Modules

Pixels Status

- Readout chip successful
  - In PSI Test beam it handled the hit rate = LHC peak luminosity
- Pre-production runs completed
  - Now fine-tuning
  - Start full production in June.
- Construction will take 1 year
- Installation for the '08 LHC physics run!
  - Commissioning module (~5% of system) to be installed for '07 pilot run to check for any unanticipated problems and study tracking and linking to the microstrip tracker.

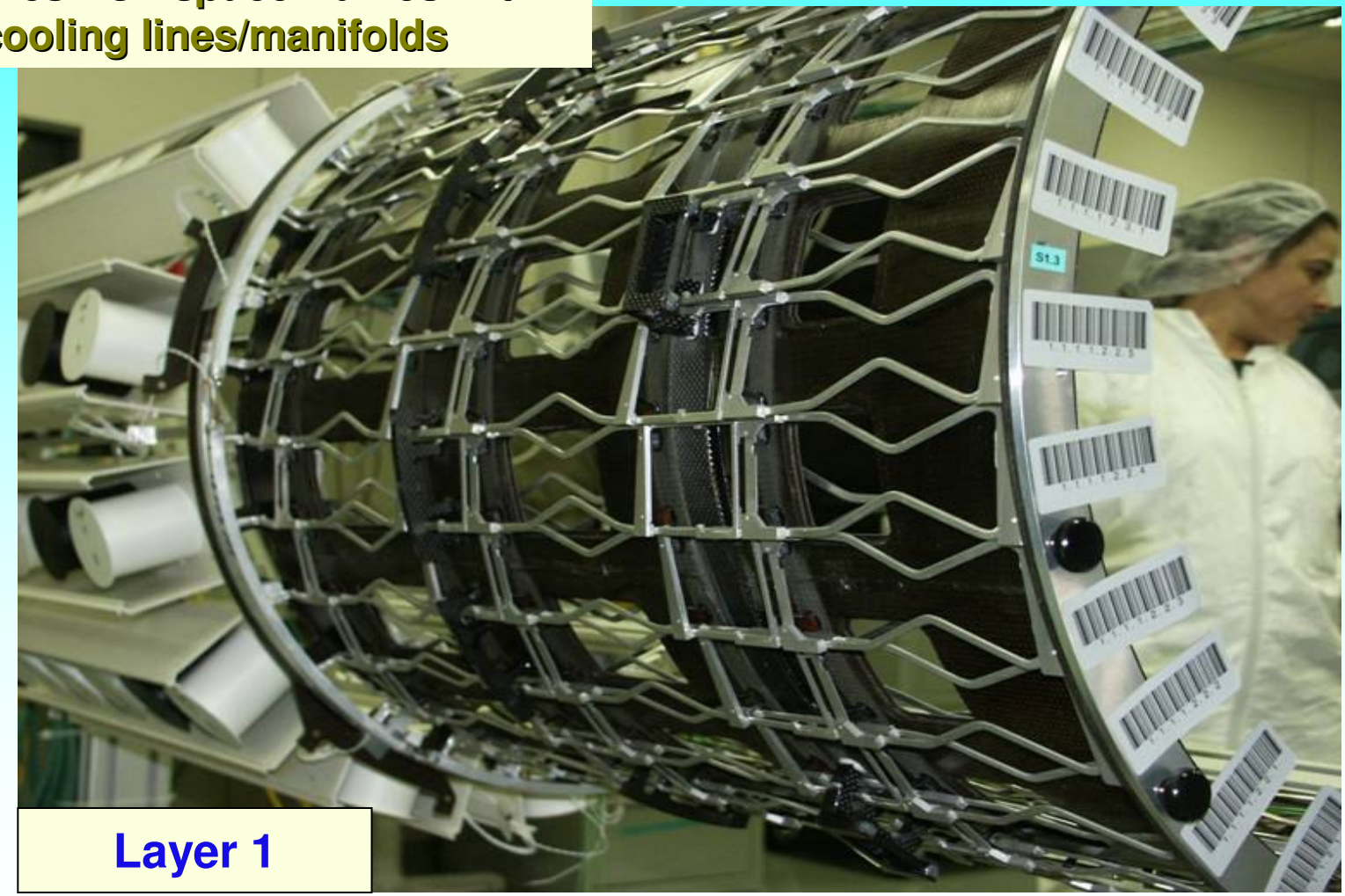
Si Strip Module Components



Tracker Inner Barrel (TIB) & Inner Disks TID)

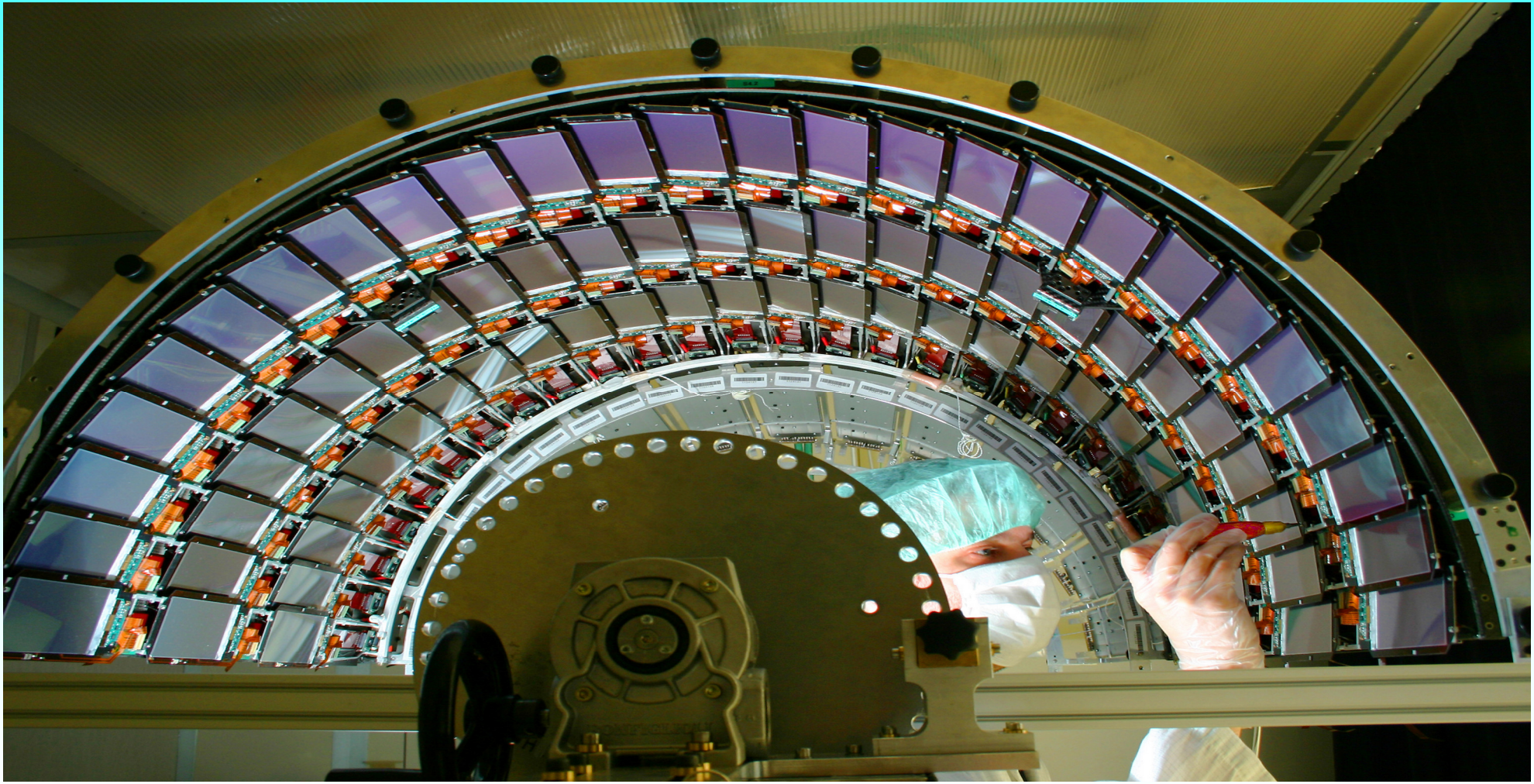
Italy

Support mechanics : CF space frames with Integrated cooling lines/manifolds

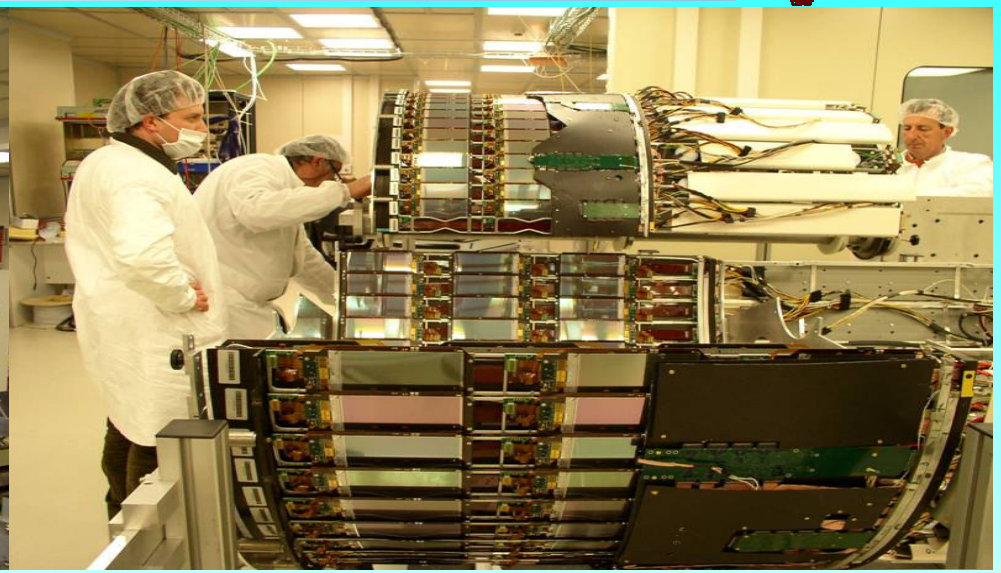


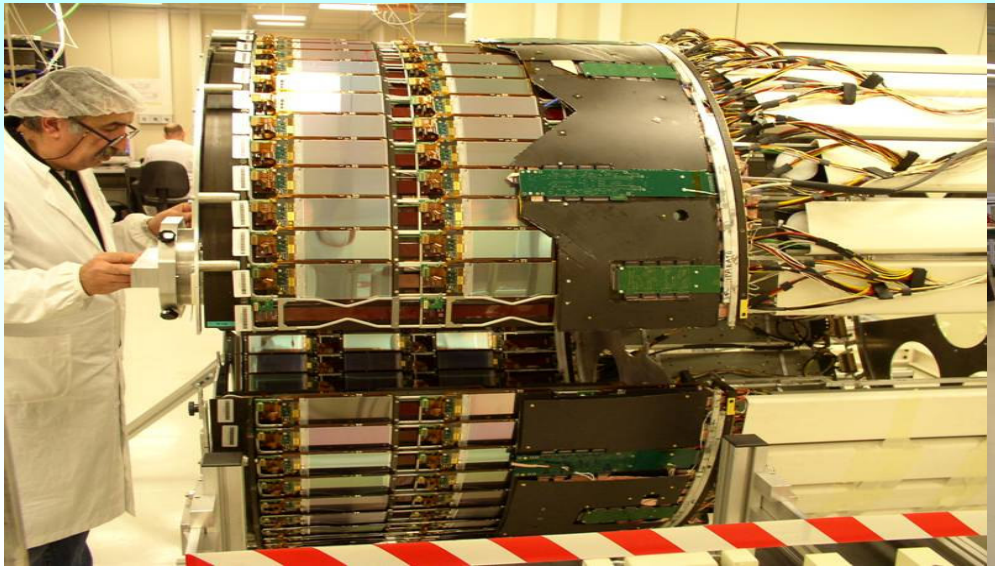
Layer 1

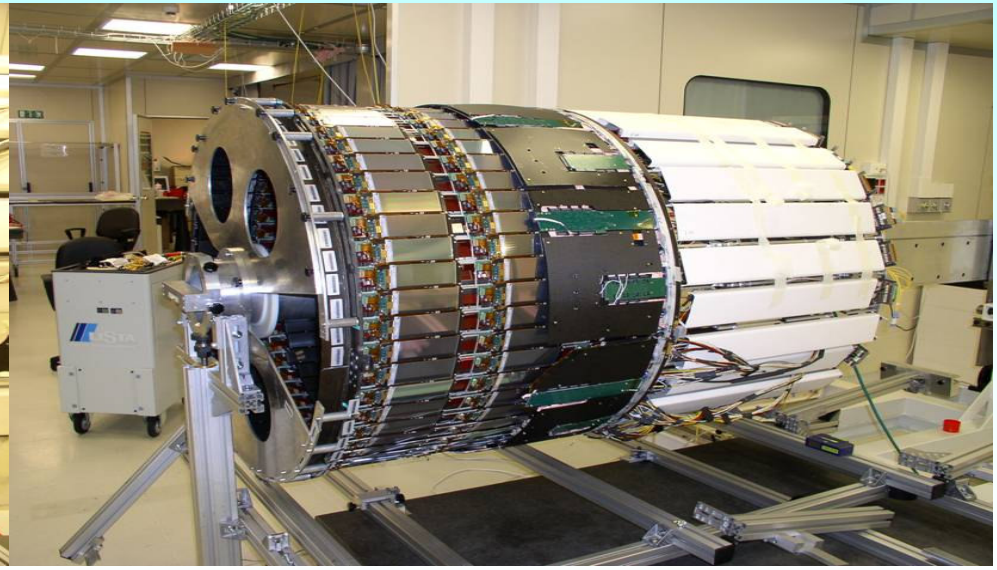
Installation of modules



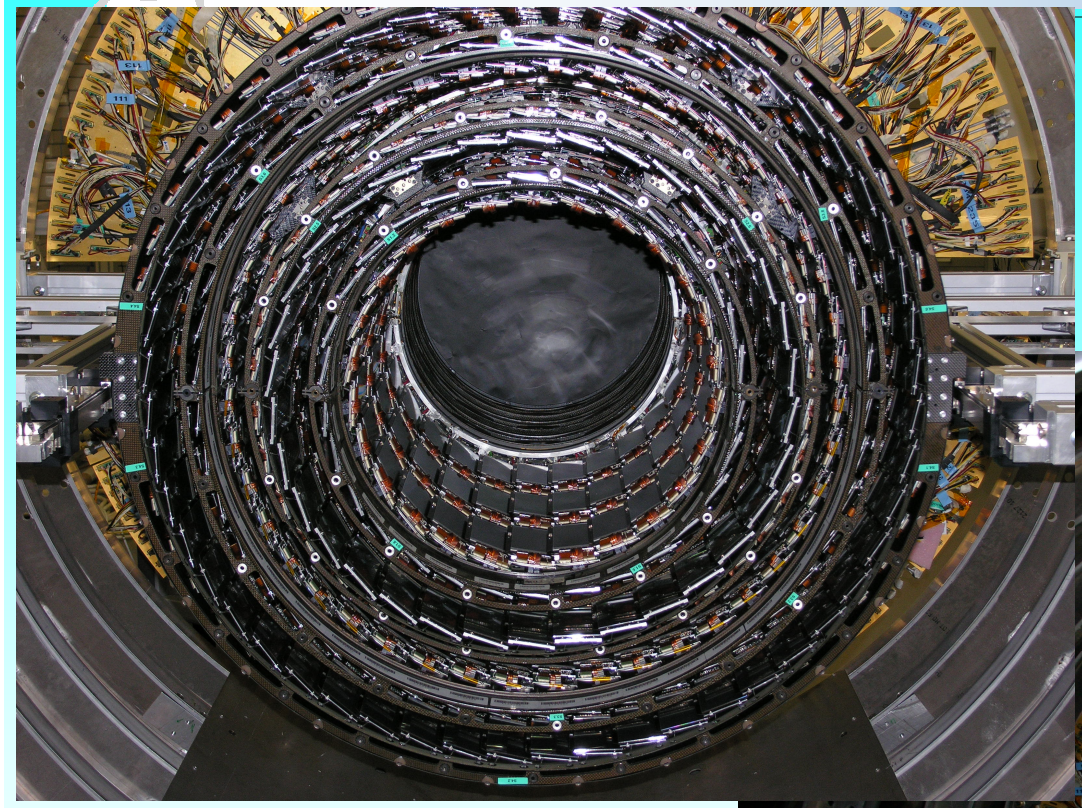
Assembly of Layer 4 (TIB+)

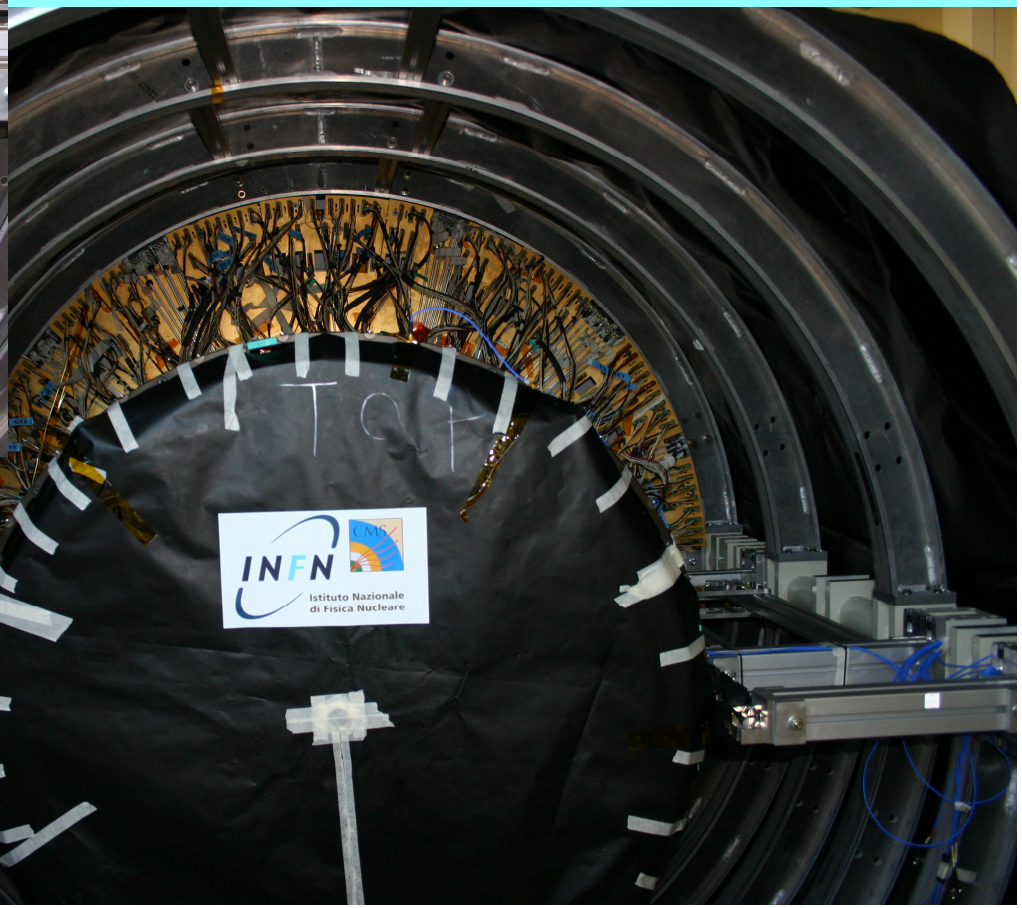






TIB

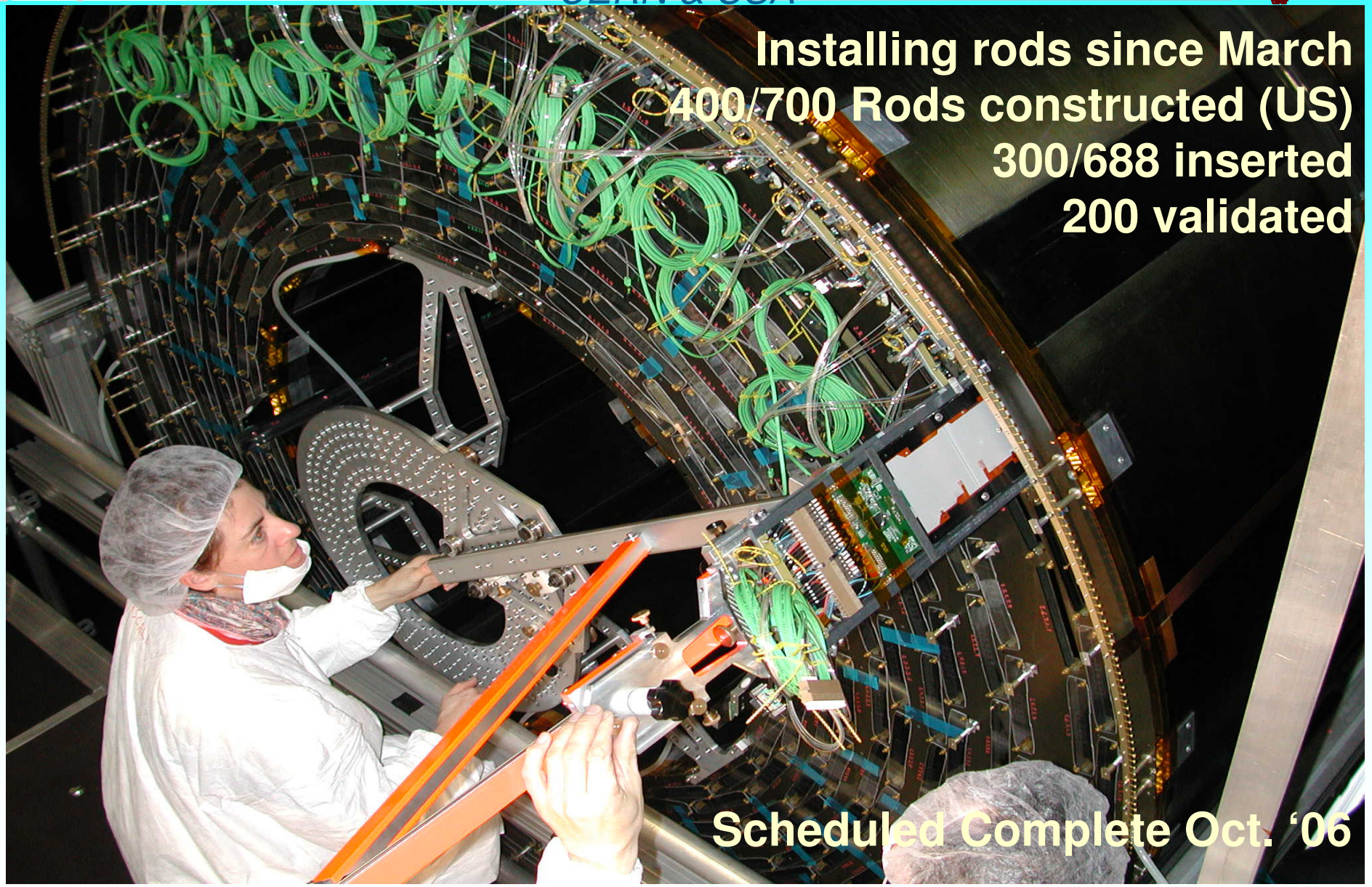





30/11/2005: TID Disk 1 is finished !

Tracker Outer Barrel (TOB)

CERN & USA

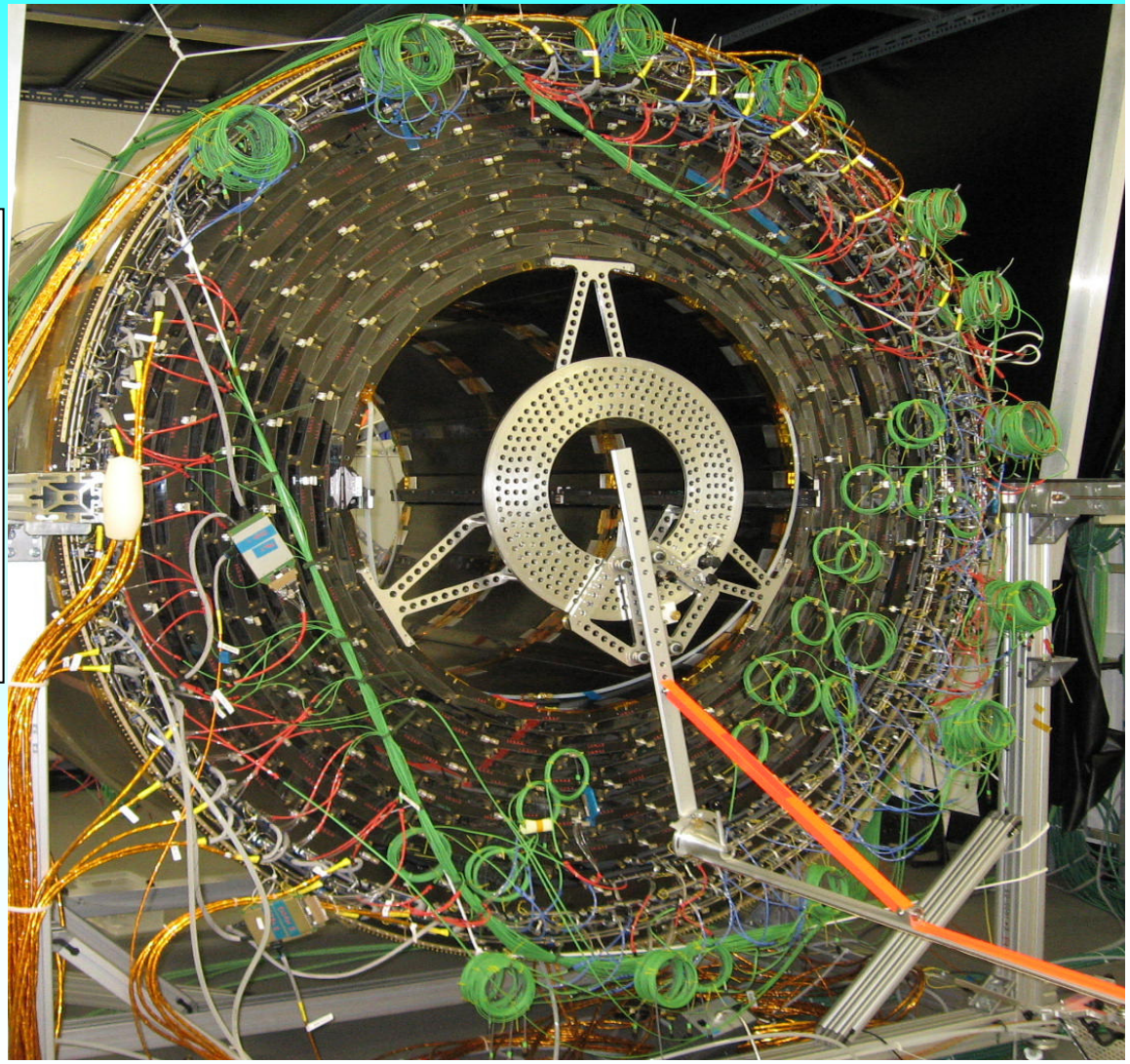


Testing the TOB

Very low noise

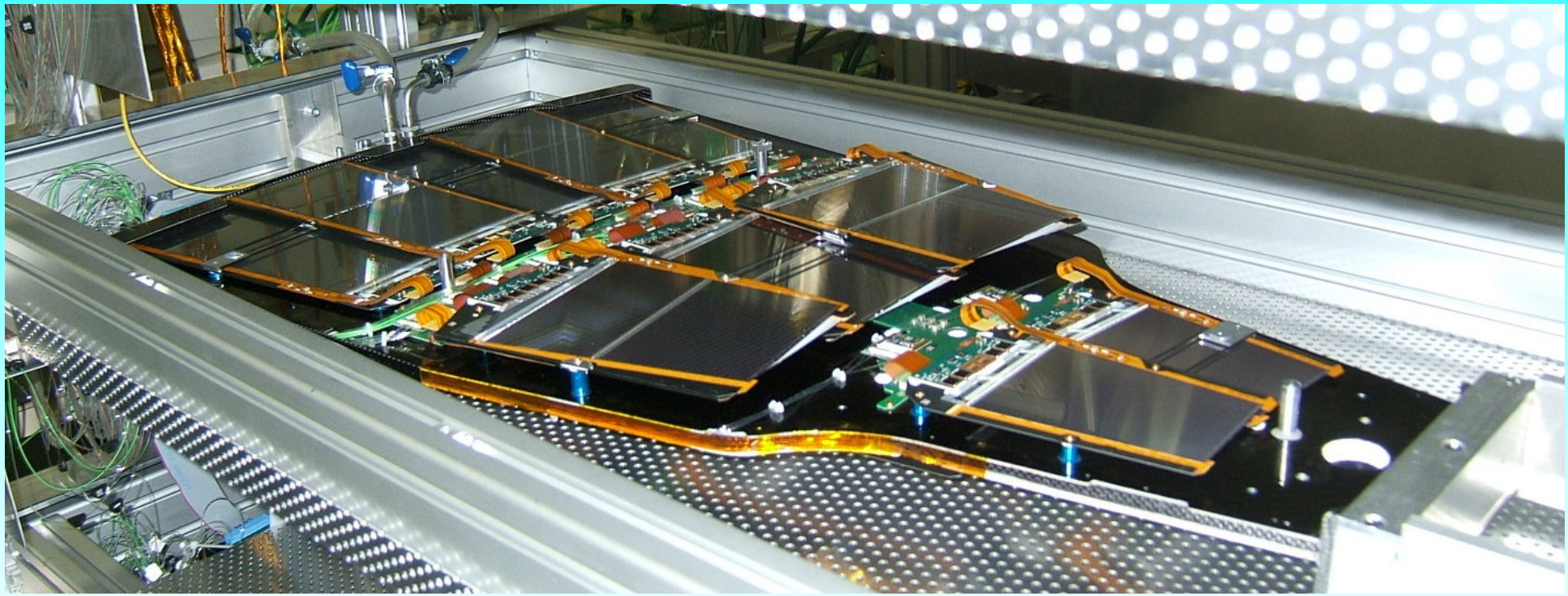
Jun06:

TOB with completed layers 5 and 6 was inserted into the tracker support tube.



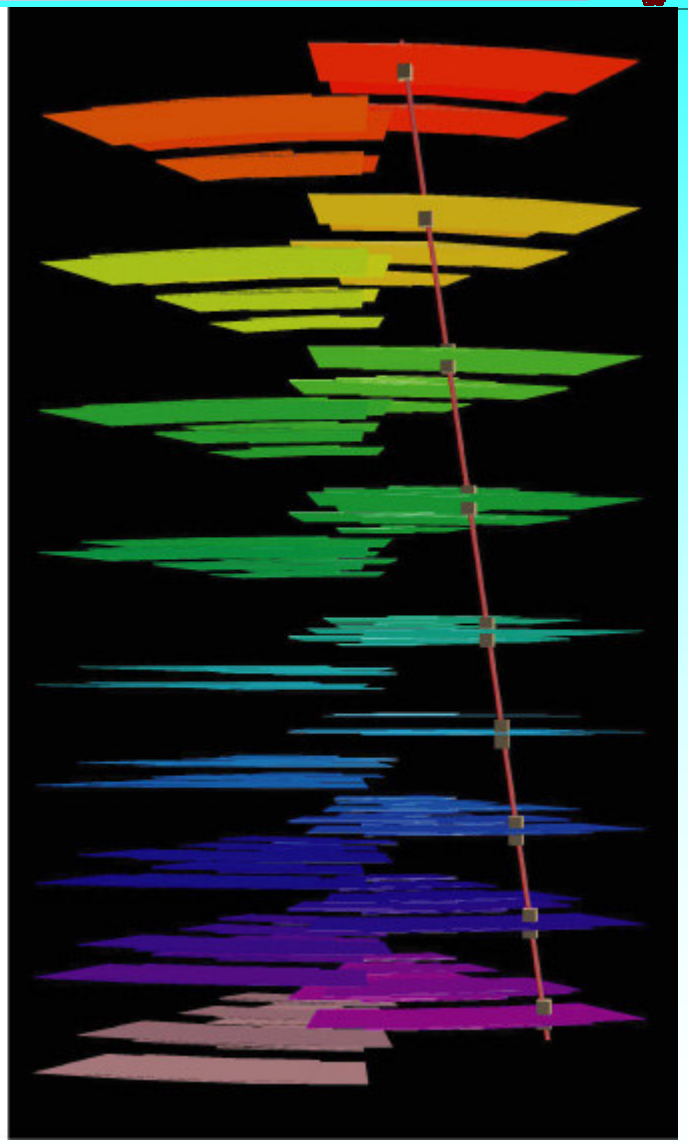
Tracker End Cap (TEC): Petals

Germany, France, Belgium…



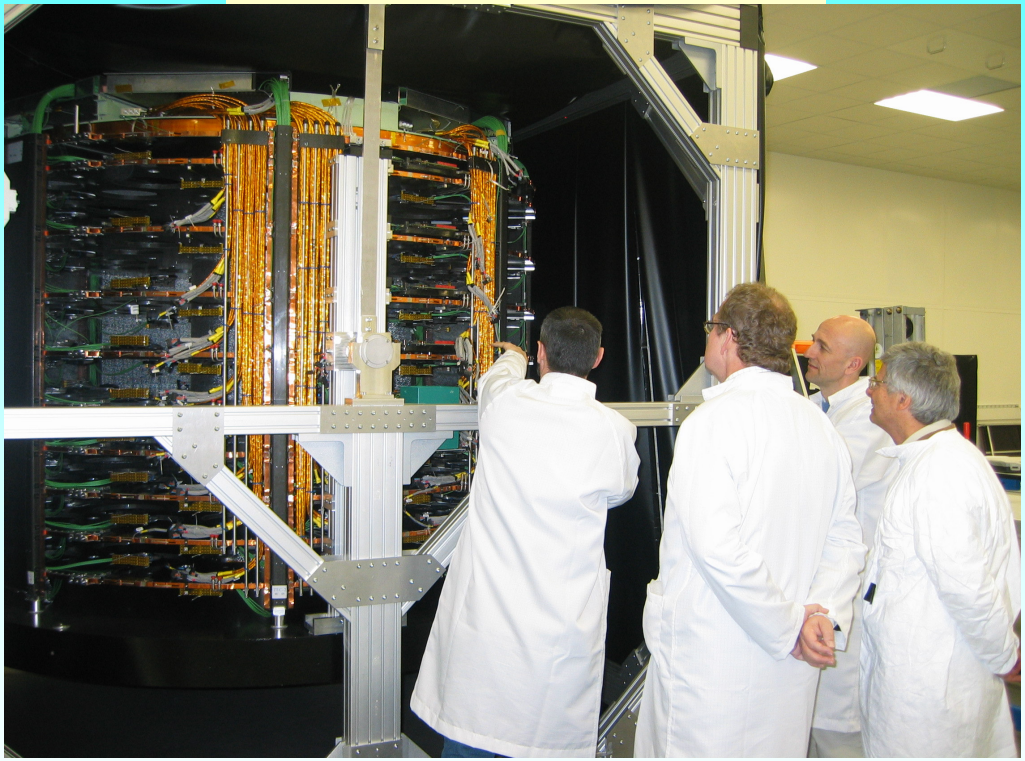
Today : 190 petals/300 (63%) ;
petals produced at a rate of 10petals/week (Fr, Ge, Be).

TEC Verification with Cosmics

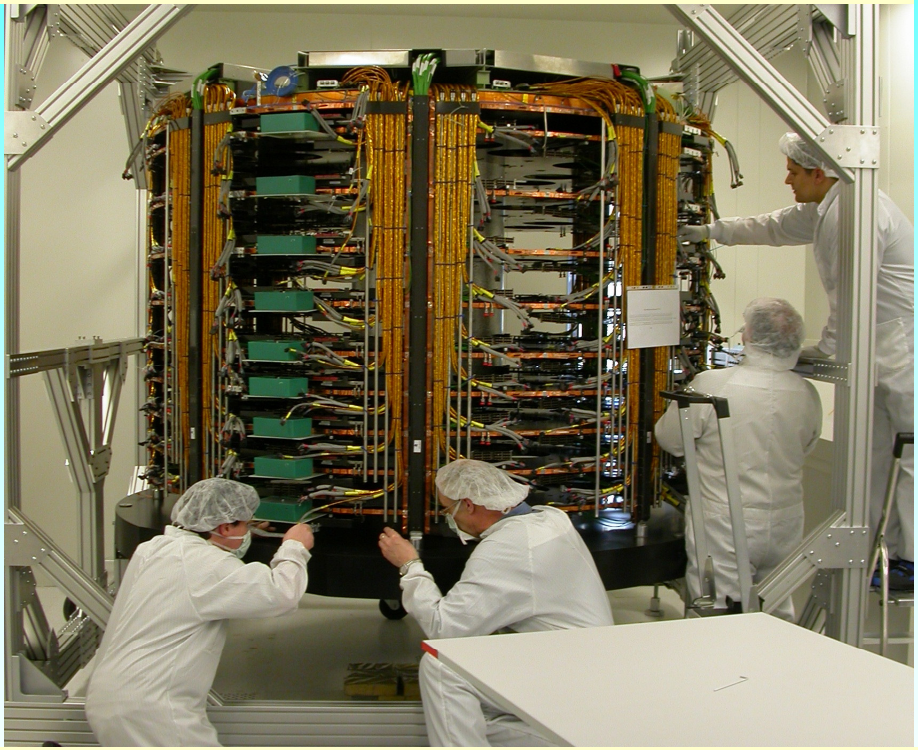


TEC: Integration

TEC- at CERN
27 petals integrated
qualification in progress

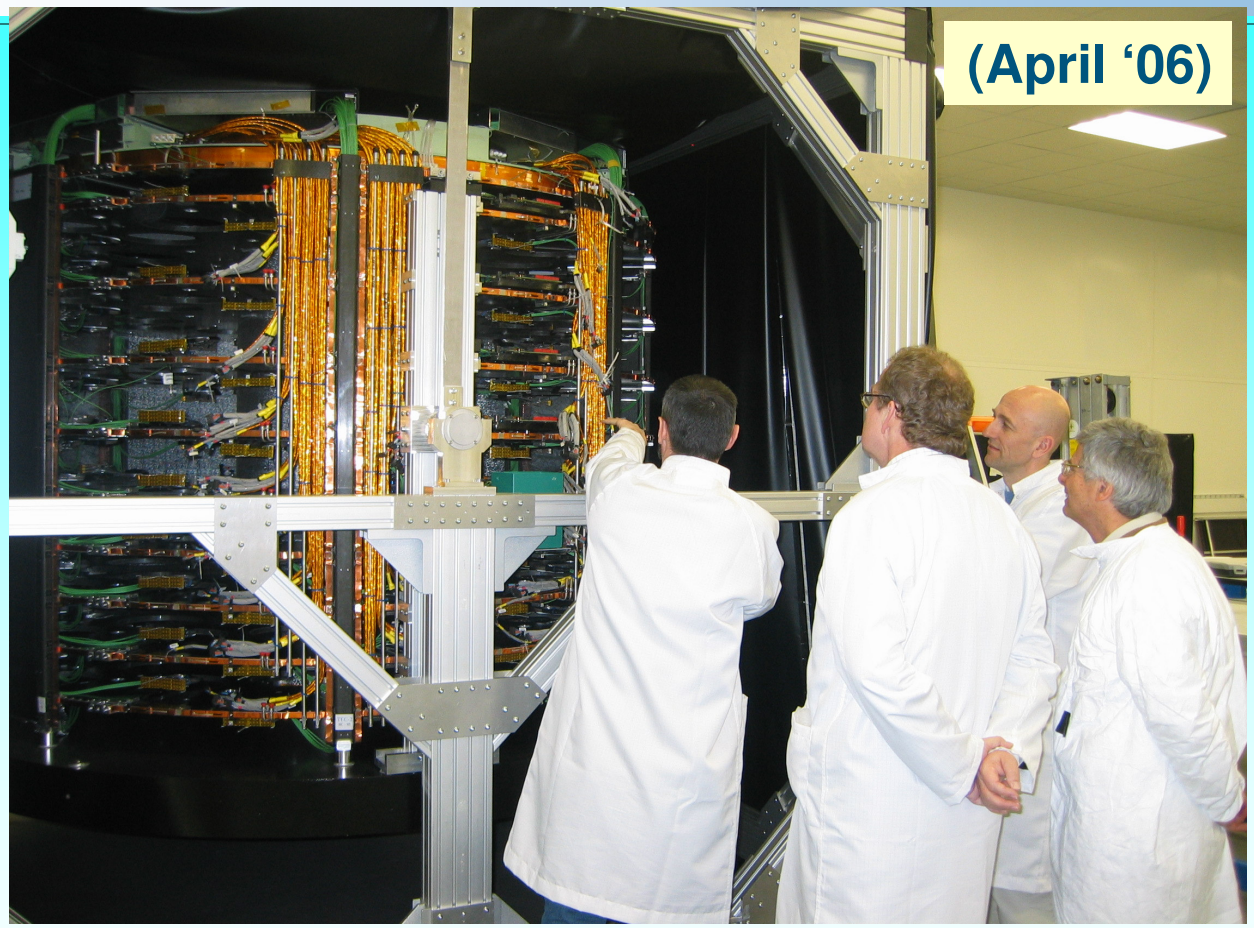


TEC+ at Aachen
54 petals integrated
1 sector of 18 fully qualified.



- Each TEC is made of 9 disks (144 petals).
- TEC+ complete: Sep06, TEC- complete: Nov06 (aim to gain 1 month)
- TIB, TOB and TEC all inside tube in Nov06.

Tracker Integration Facility

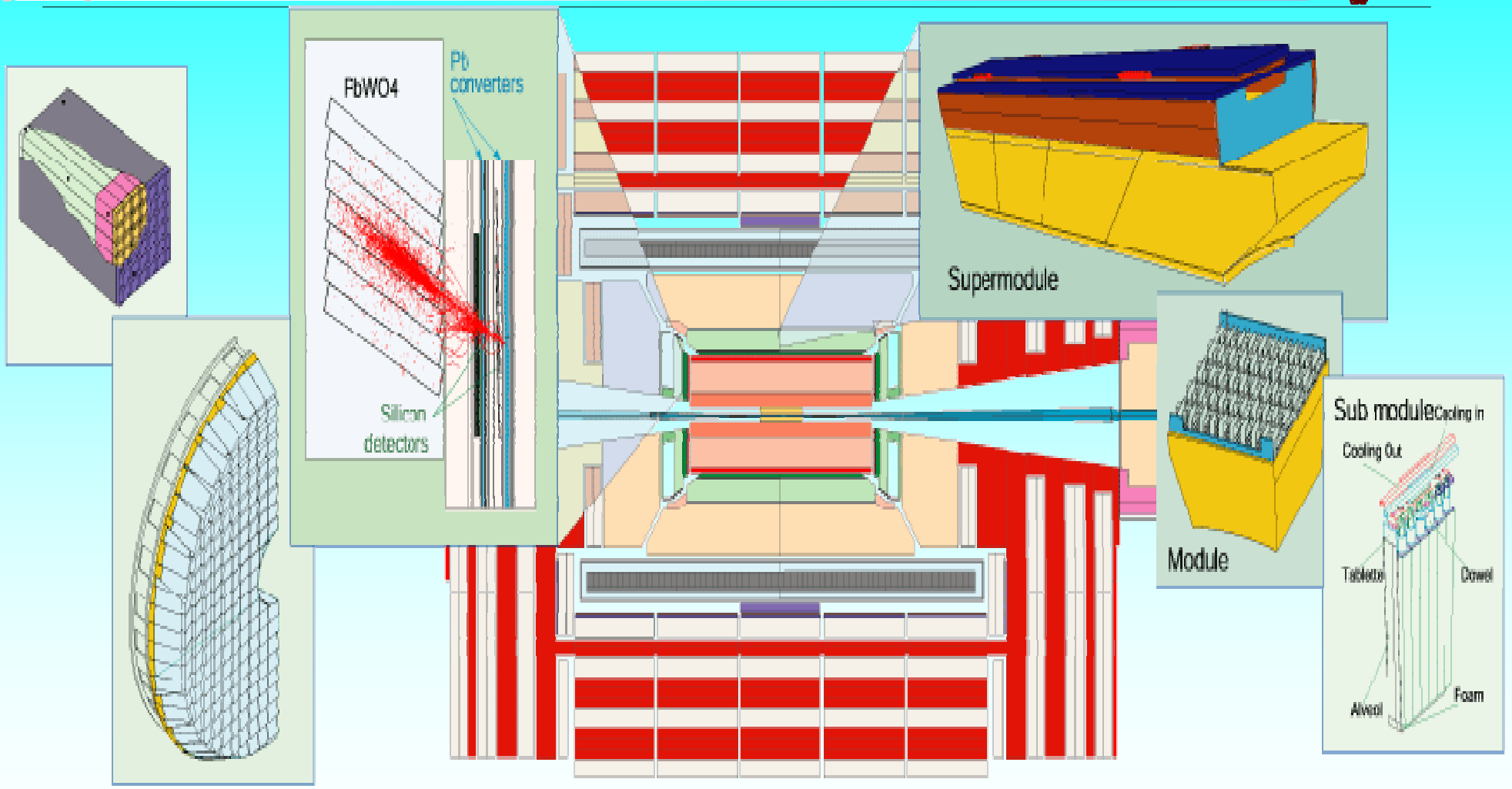


Integrate all of the Tracker at CERN (TOB, TEC & TIB) in 2006

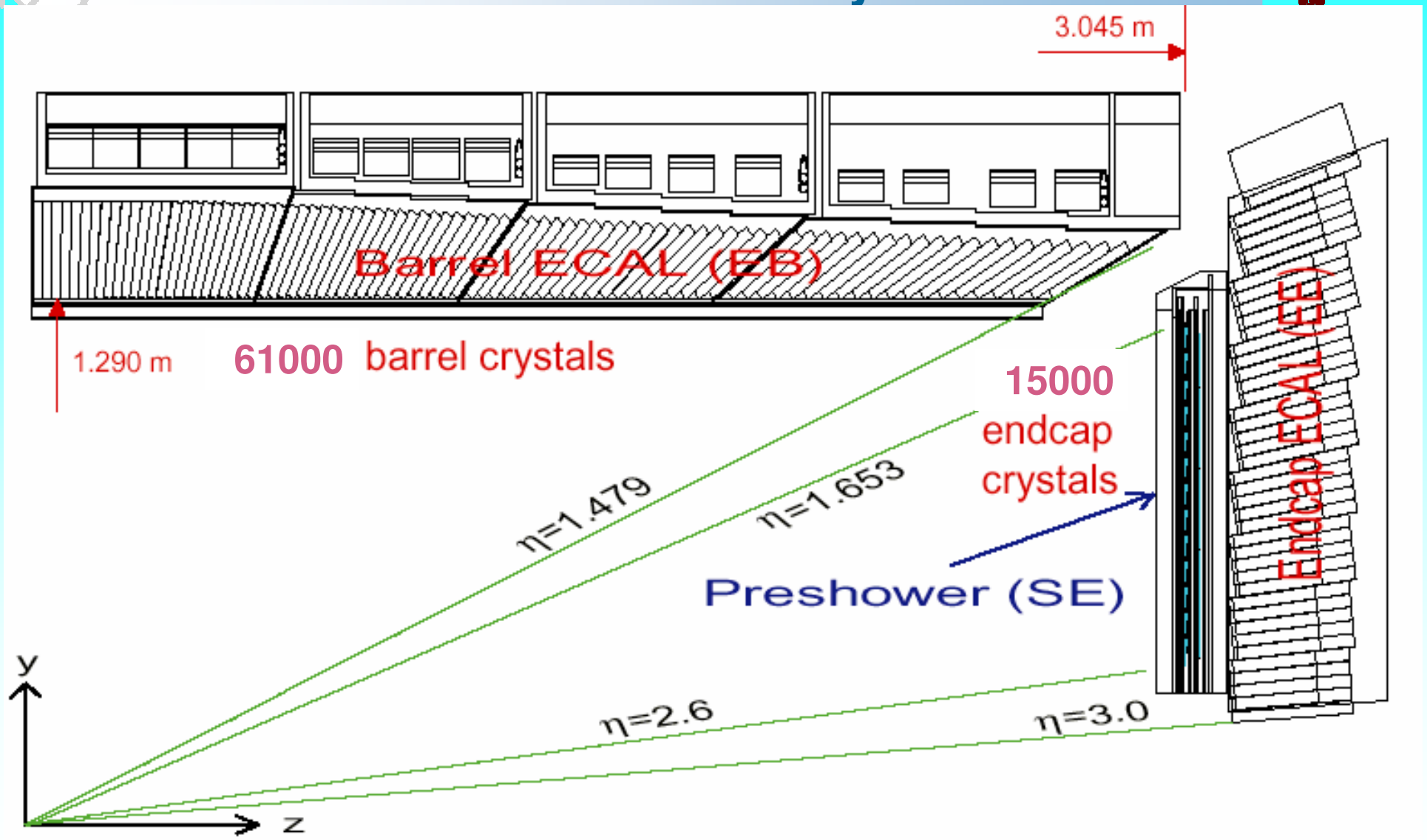
'Standard' Electronics and DAQ Systems available for 2.5 million channels!

Electromagnetic calorimeter

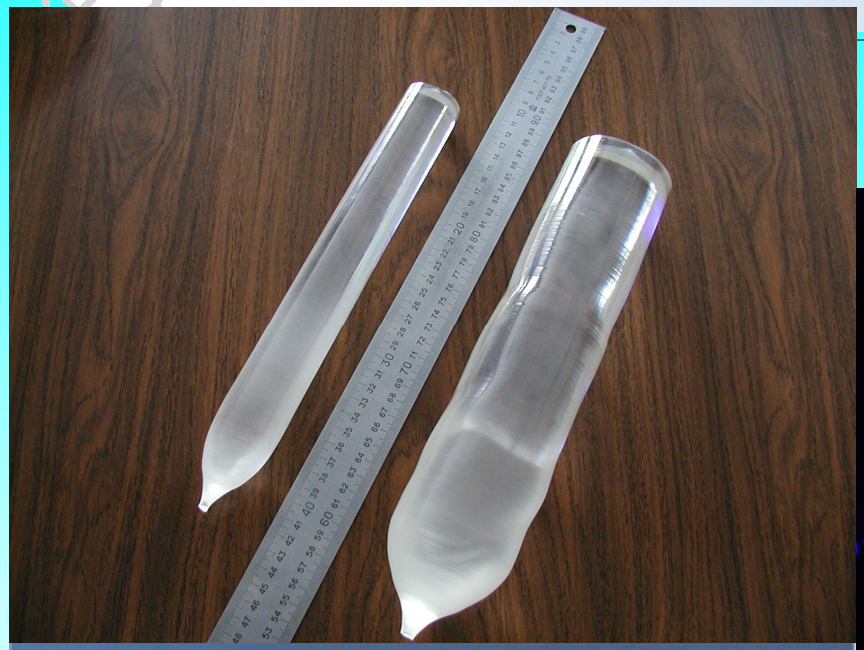
ECAL Overview

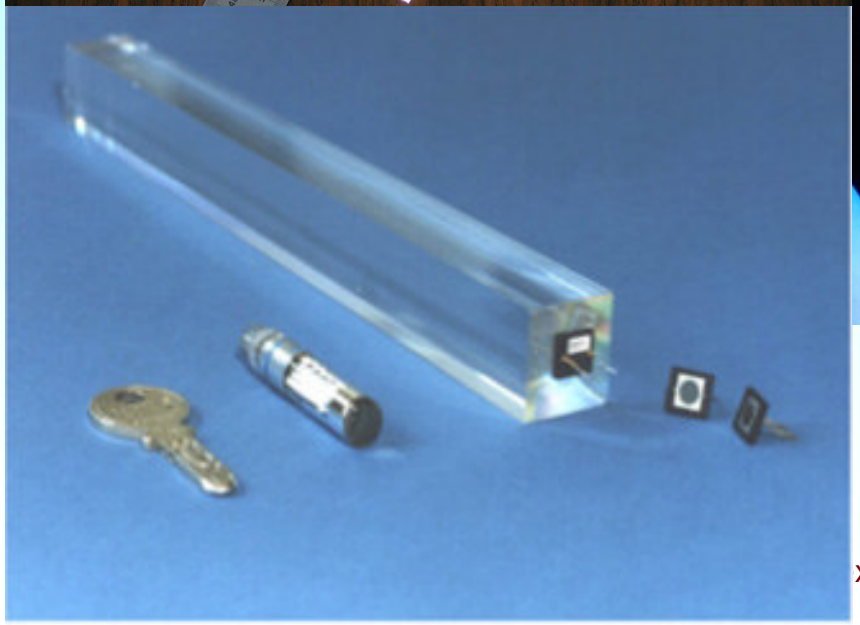


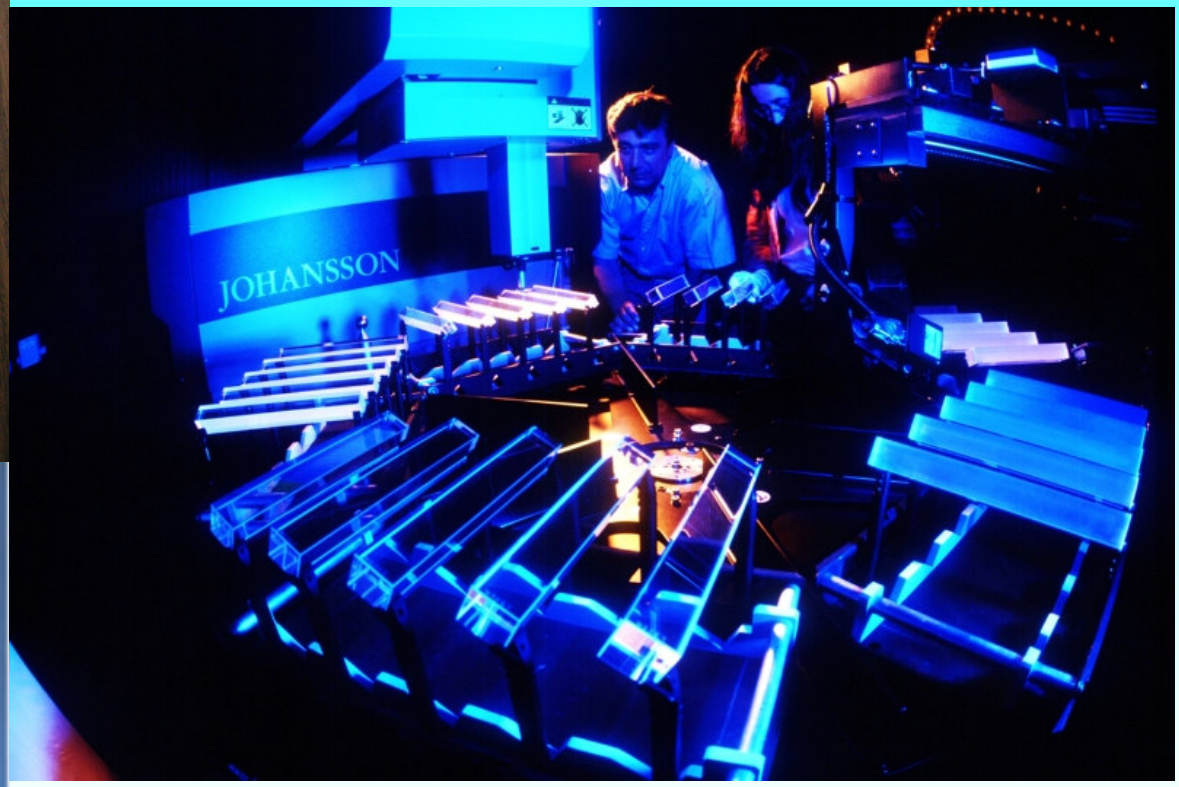
ECAL: PbWO4 Crystals



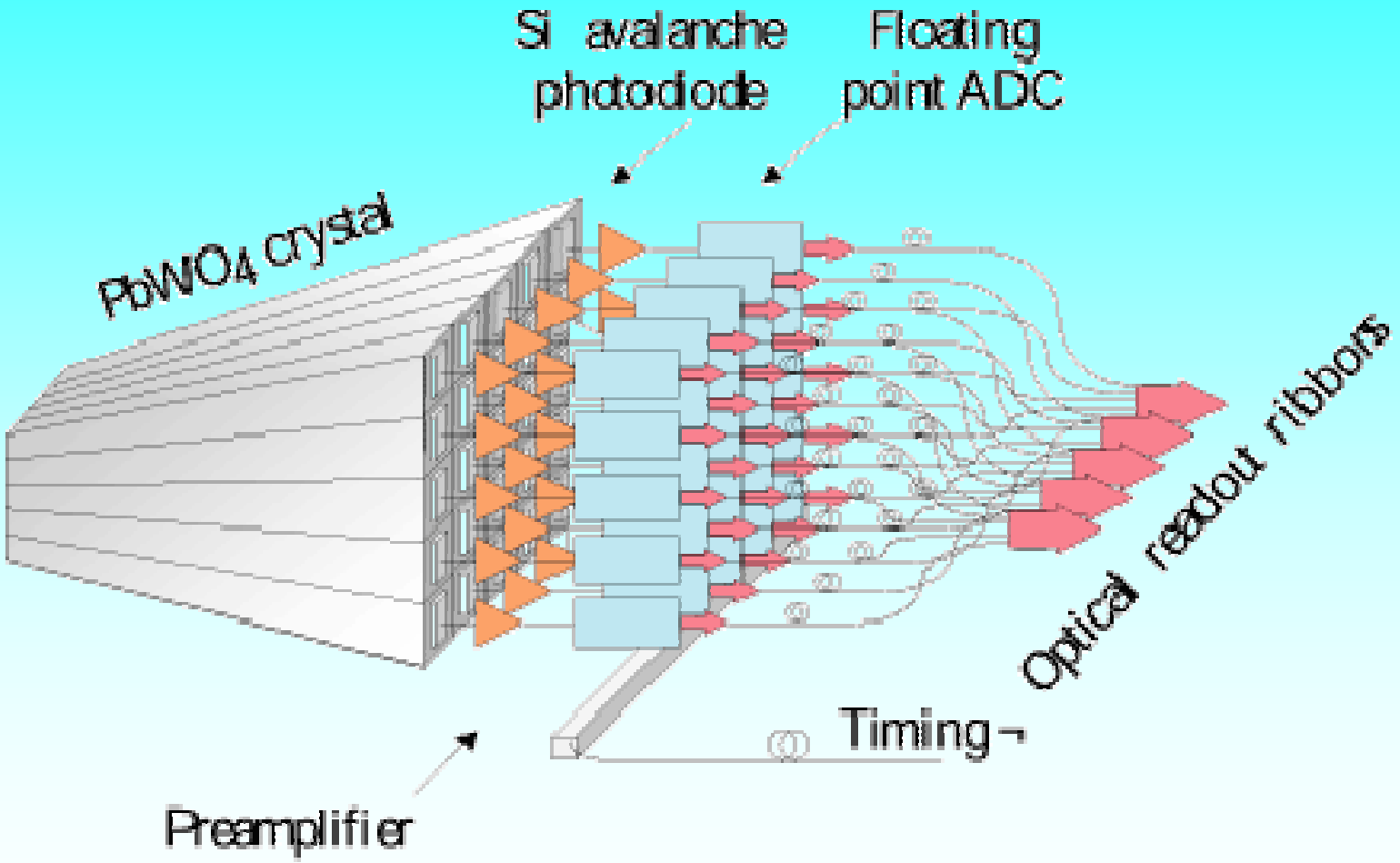
$PbWO_4$ crystals





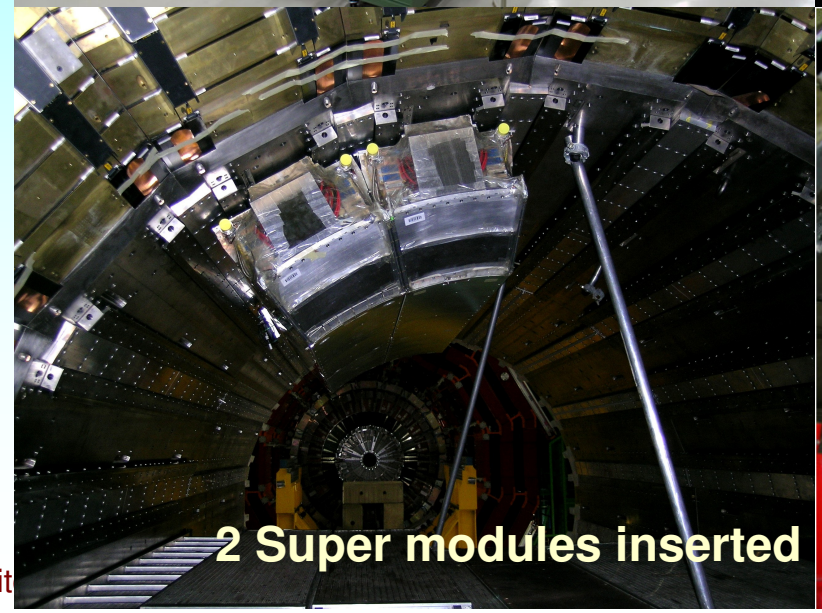


ECAL


Si avalanche photodiode
Floating point ADC
PbWO4 crystal
Optical readout ribbons
Timing
Preamplifier

ECAL module

ECAL assembly



2 Super modules inserted

27 April for magnet test

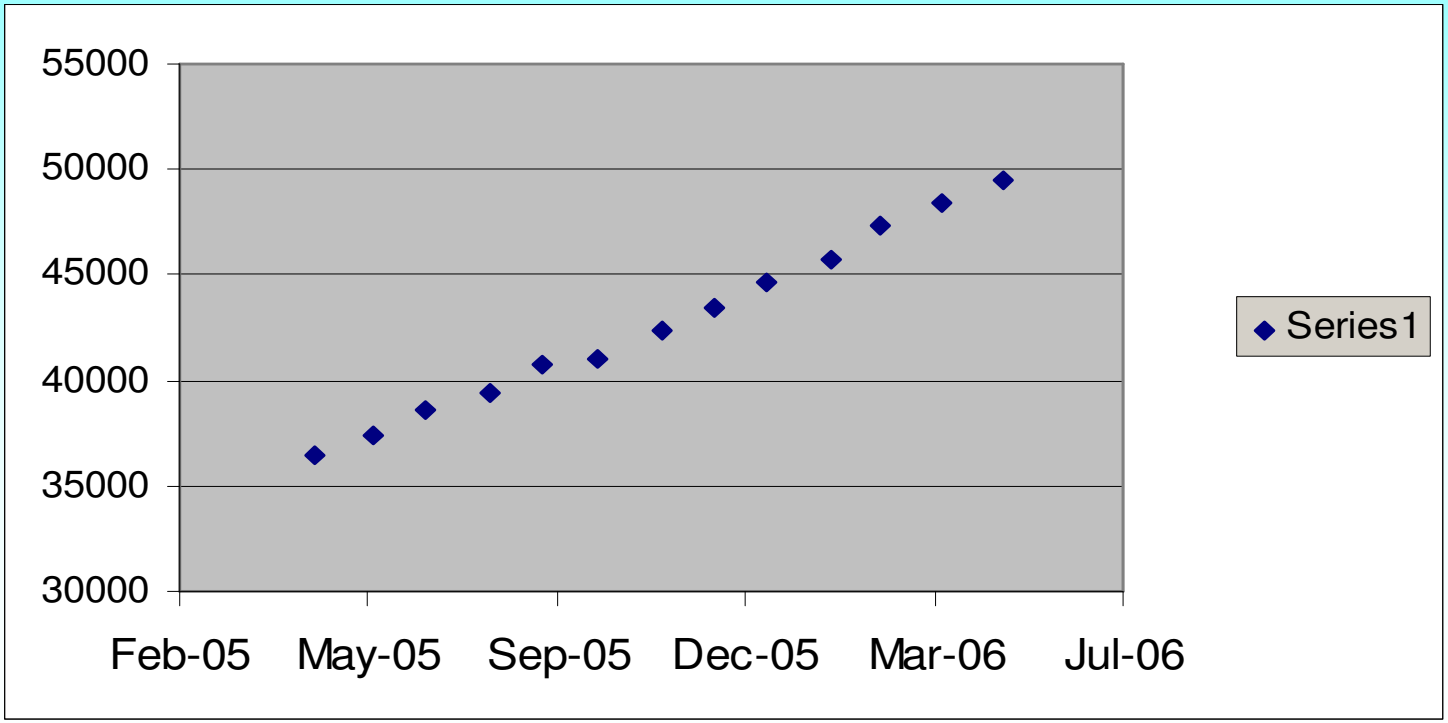
Crystals Production and ECAL Schedule

Crystals delivery determines ECAL Critical Path.

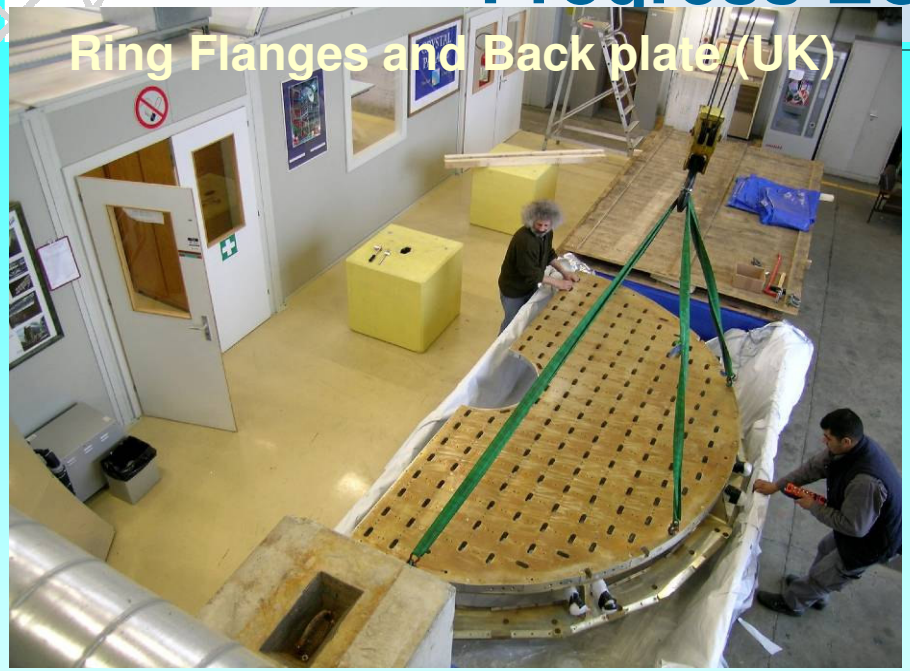
79% of usable Barrel crystals in hand (48,680/61,200).

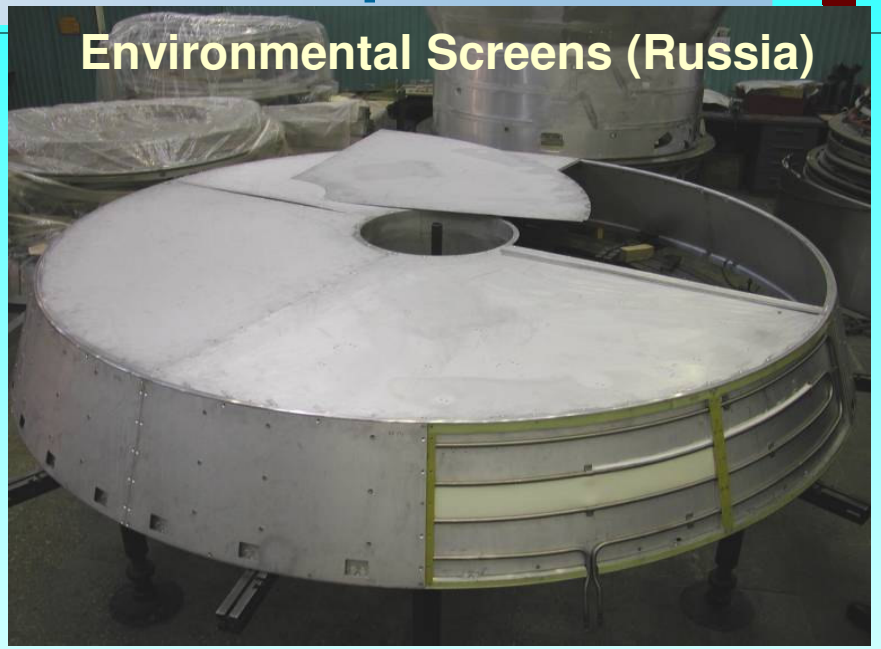
Last ECAL Barrel crystal delivered February 2007.

Last ECAL Endcap crystal delivered January 2008.



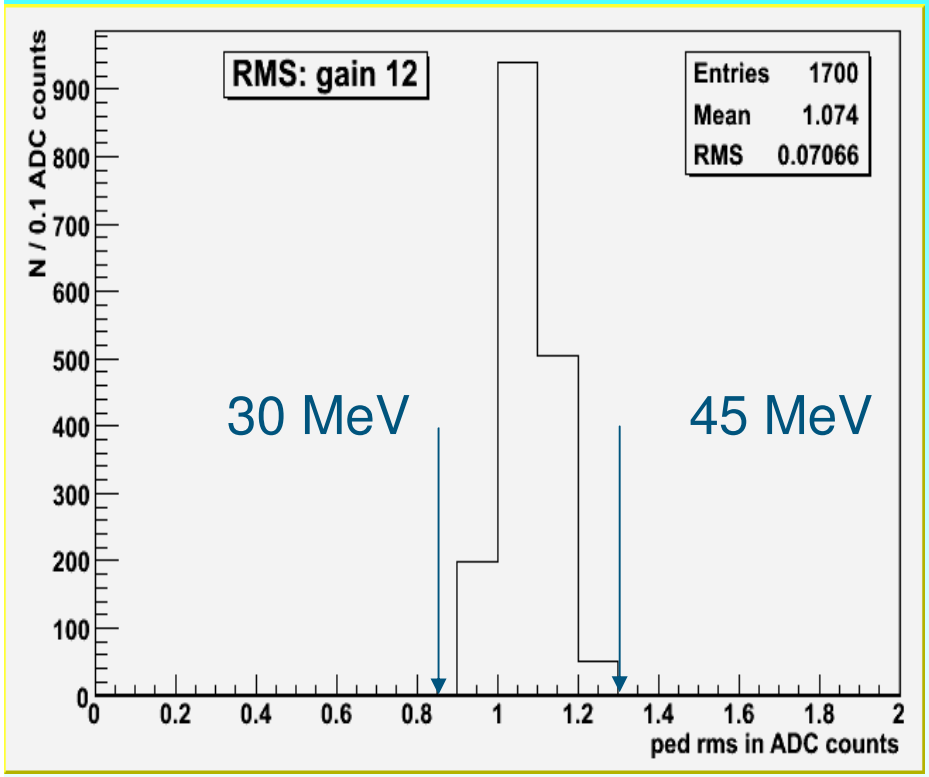
Progress ECAL Endcaps



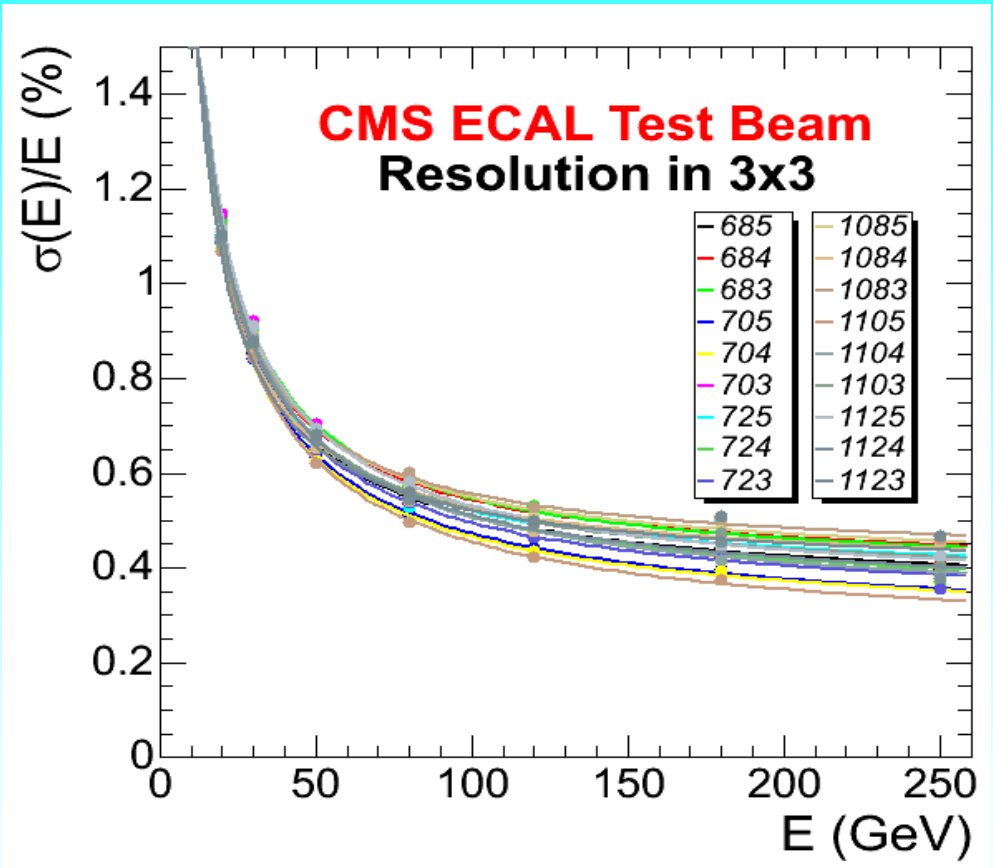


On schedule for installation end of '07

ECAL performance



Noise distribution of the 1700 channels of SM13



Energy resolution: 2004 test beam 18 crystals

Hadron calorimeter

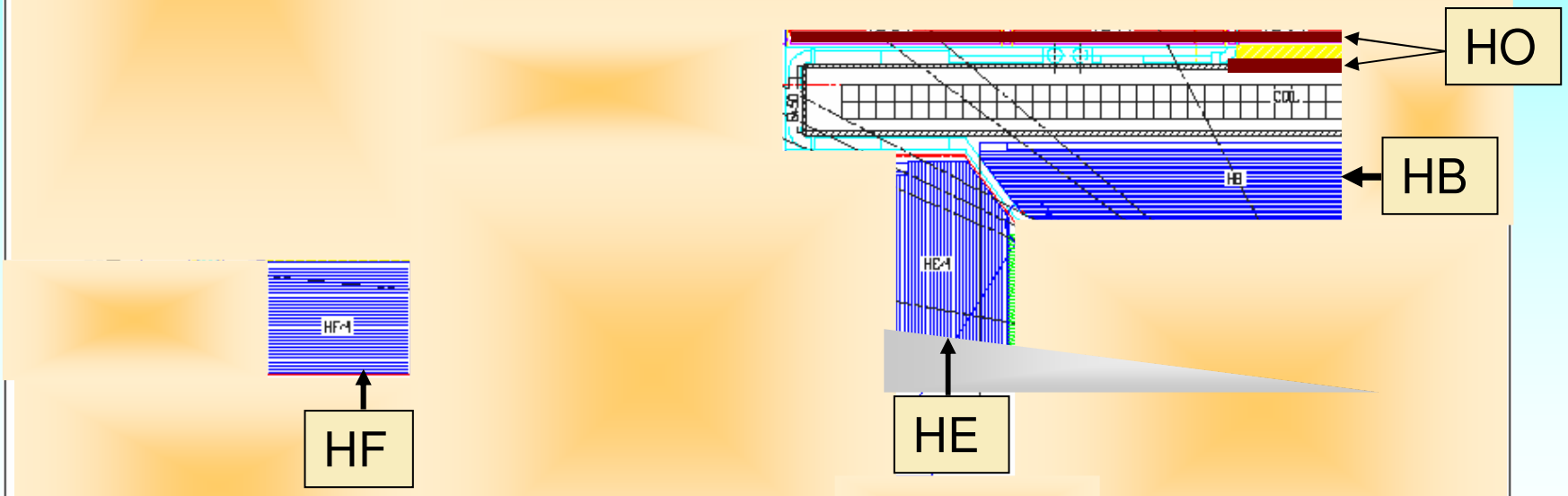
Hadronic Calorimeter: HCAL

Had Barrel: HB

Had Endcaps: HE

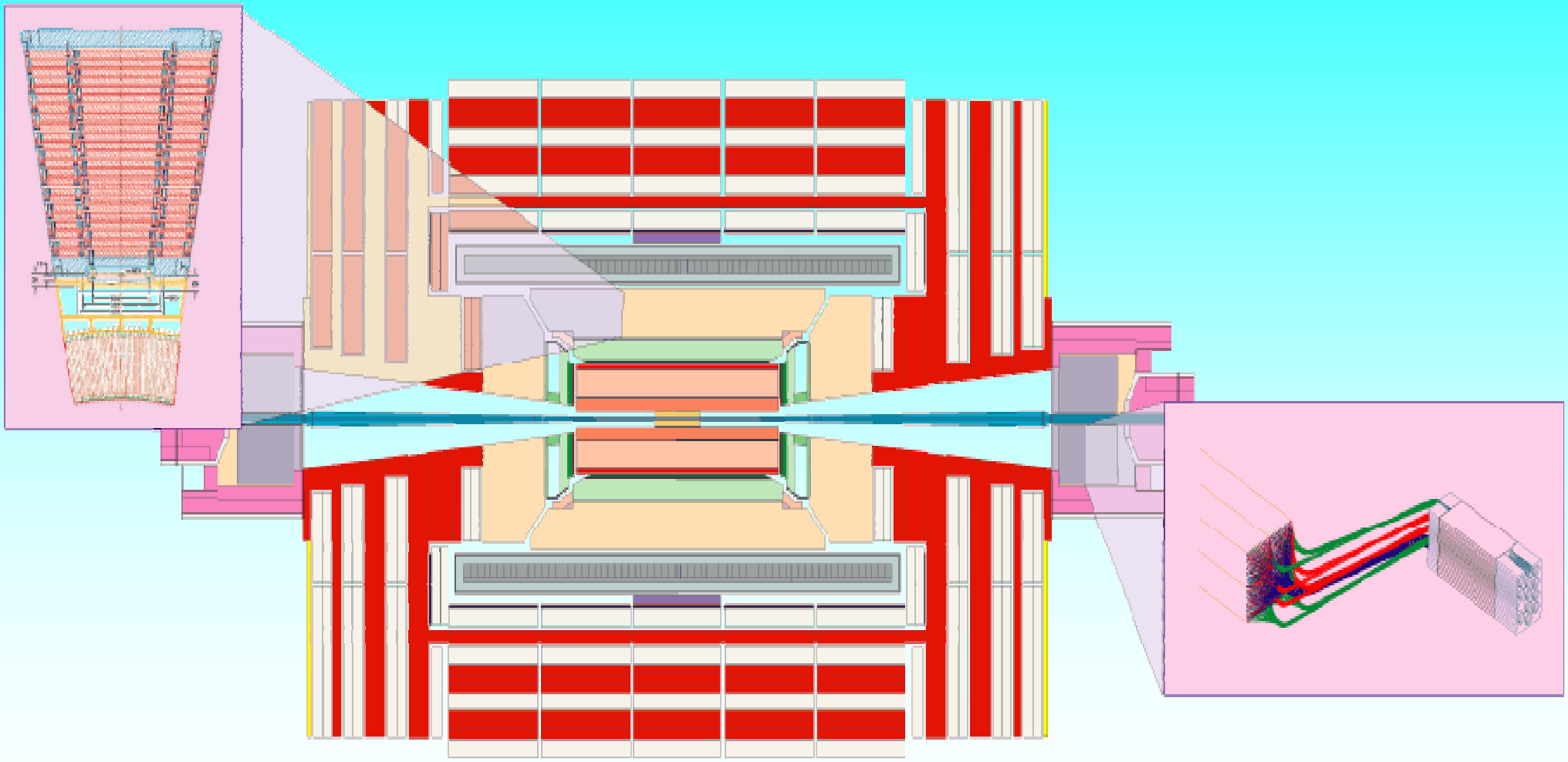
Had Forward: HF

Had Outer: HO

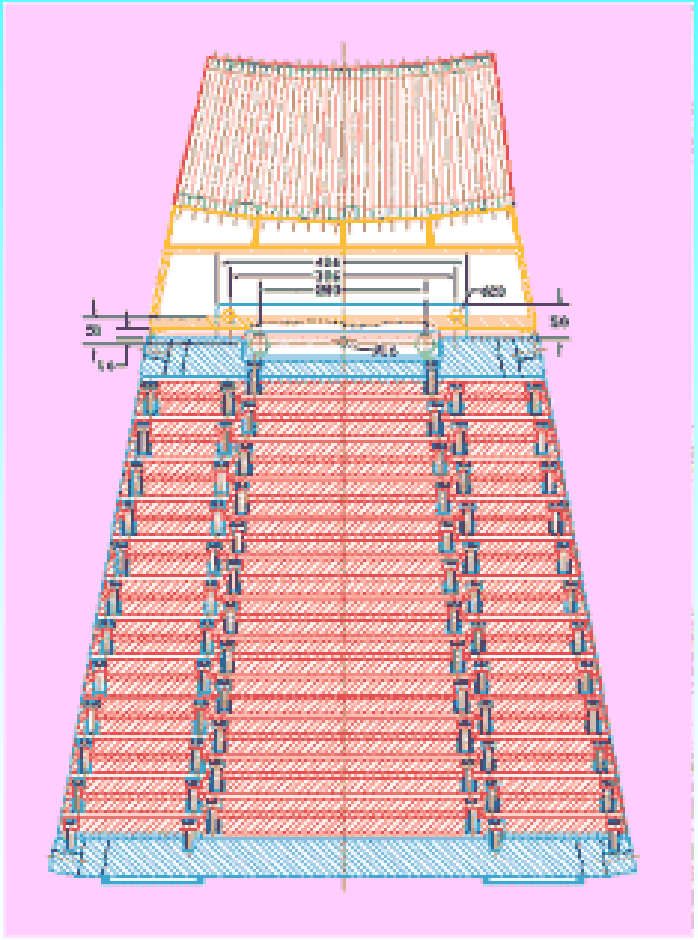


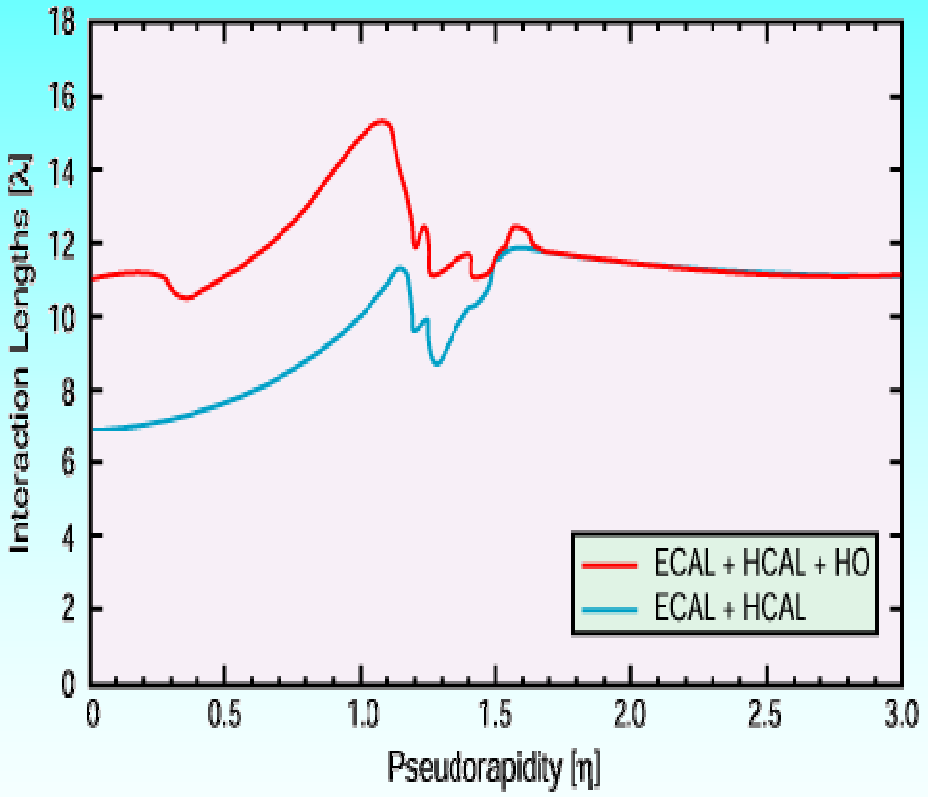
HB & HF: Brass Absorber and Scintillating tiles.
HO: Scintillator “catcher”. HF: Iron and Quartz fibers

HCAL overview

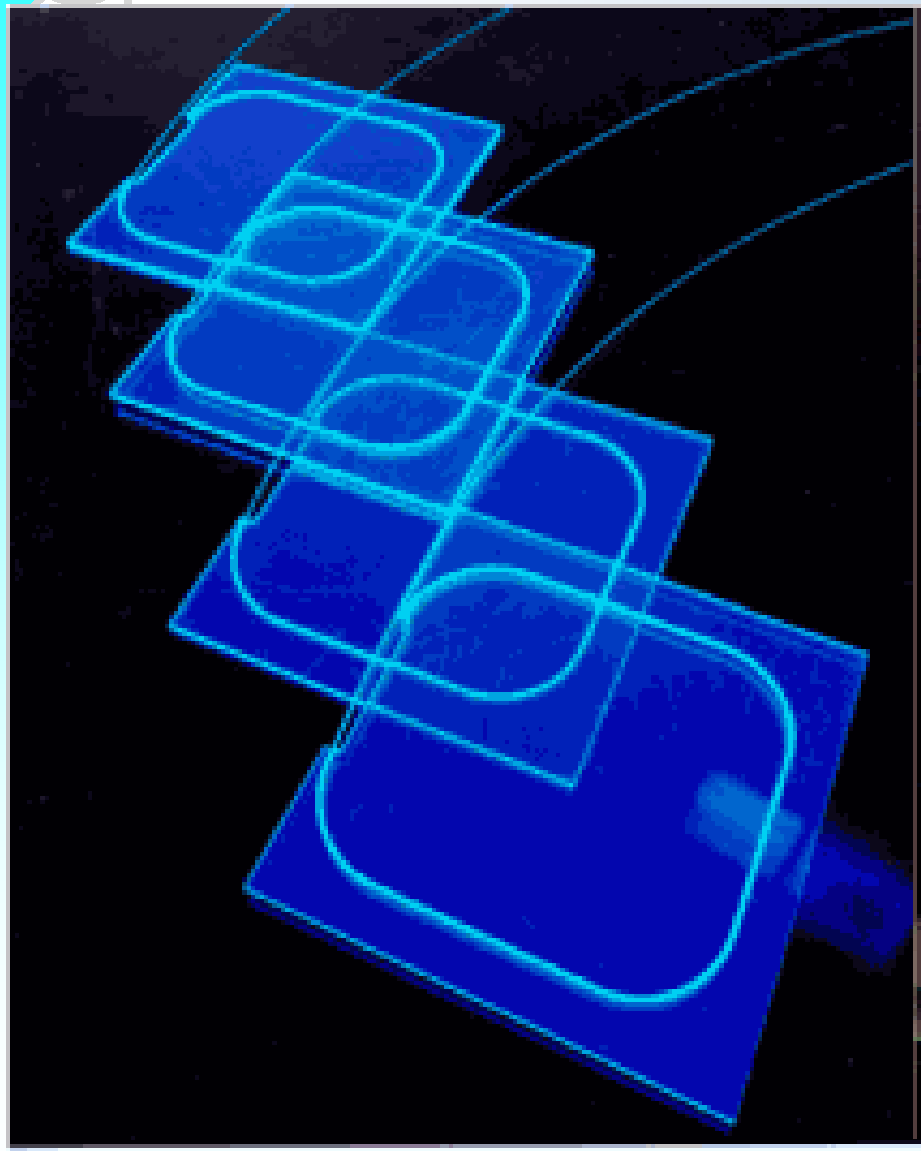


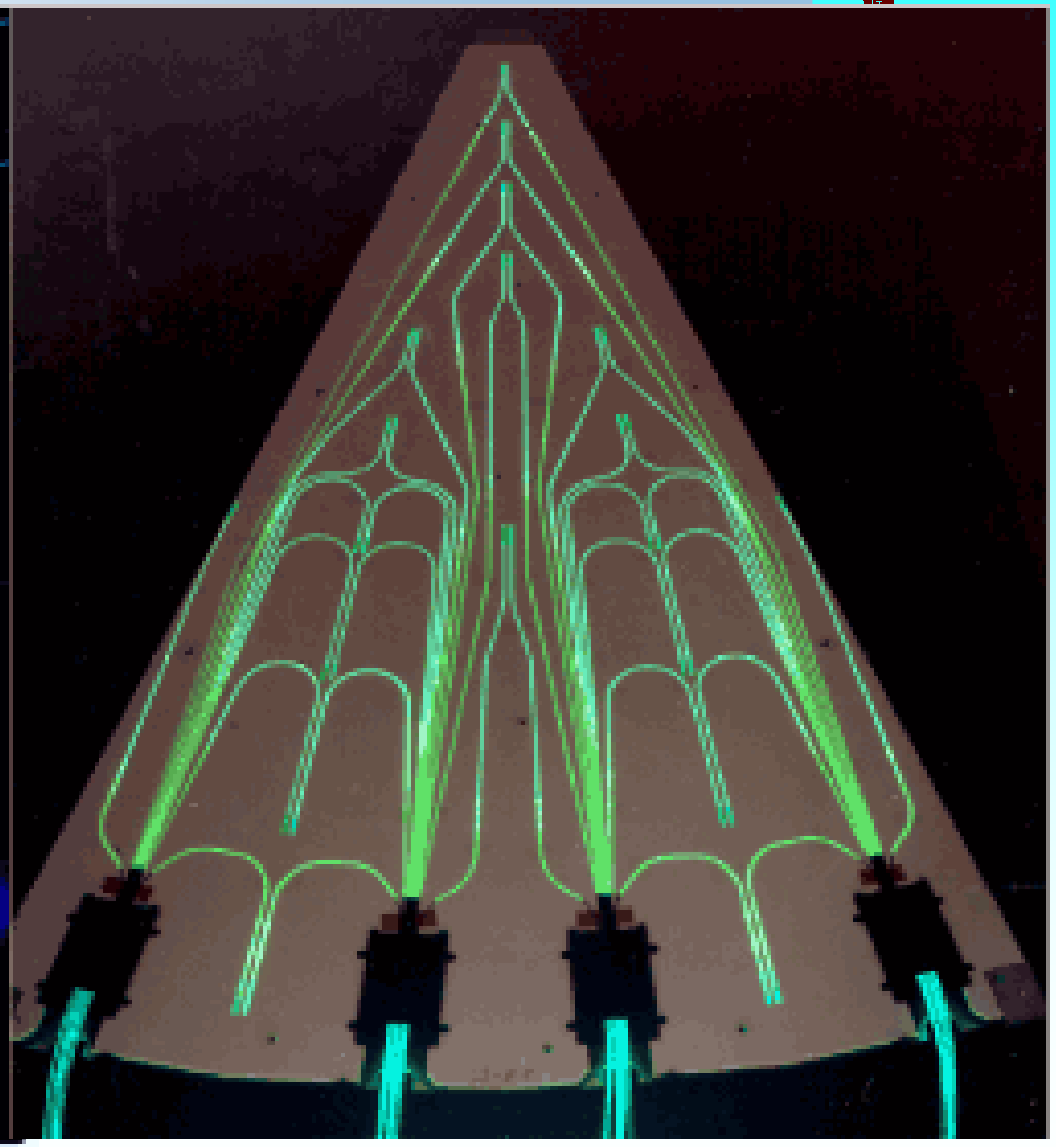
HCAL wedge



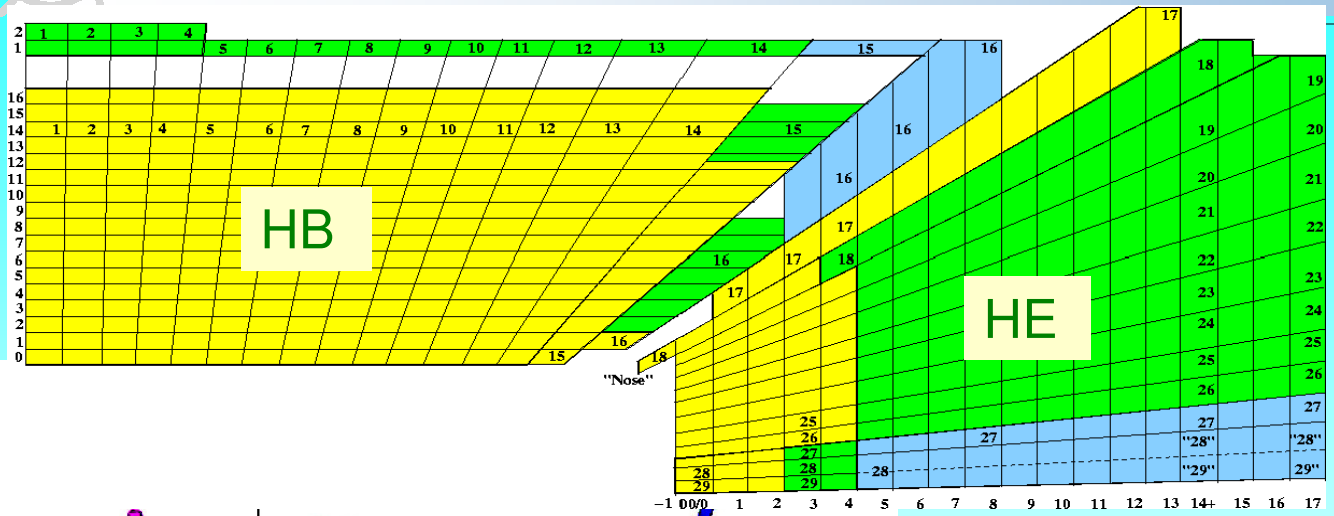

Interaction Lengths [λ]
Pseudorapidity [η]
ECAL + HCAL + HO
ECAL + HCAL
0
2
4
6
8
10
12
14
16
18
0
0.5
1.0
1.5
2.0
2.5
3.0

HCAL Scintillators

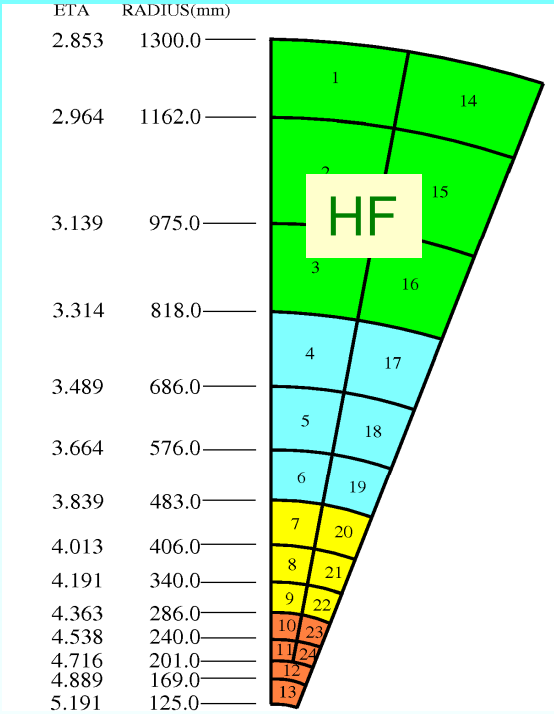


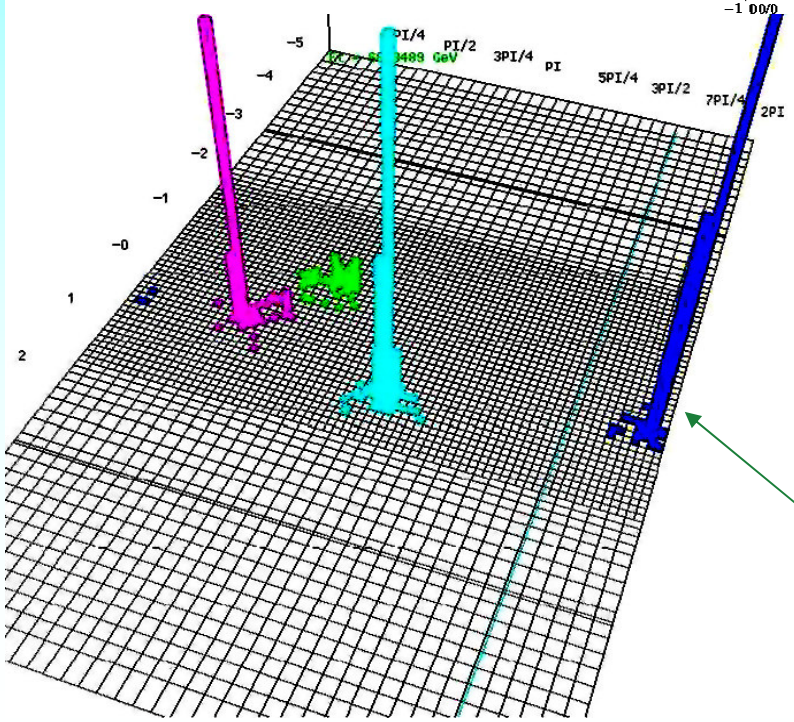


HCAL Segmentation and Coverage



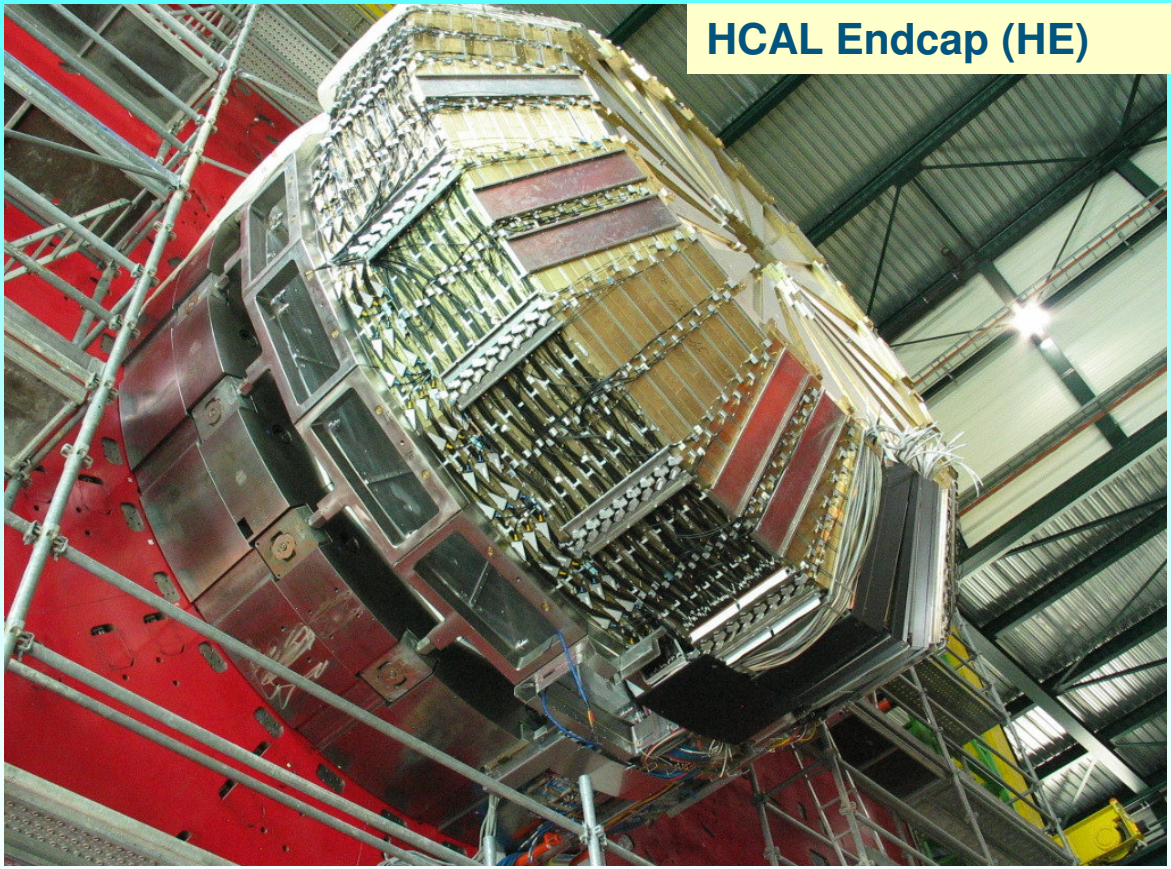
HF: 3<|η|<5
Δφ x Δη =10° x 13 η towers





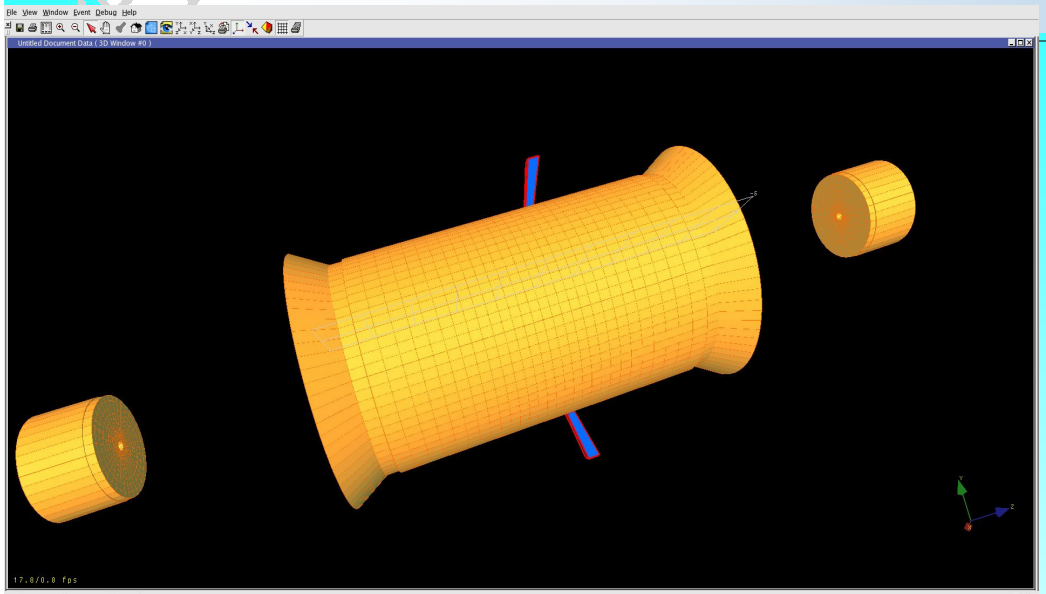
HB: |η|<1.3
HE: 1.3<|η|<3
HF: 3<|η|<5
Very Fine Granularity:
Δφ x Δη = 0.087x0.087 for |η|<1.7

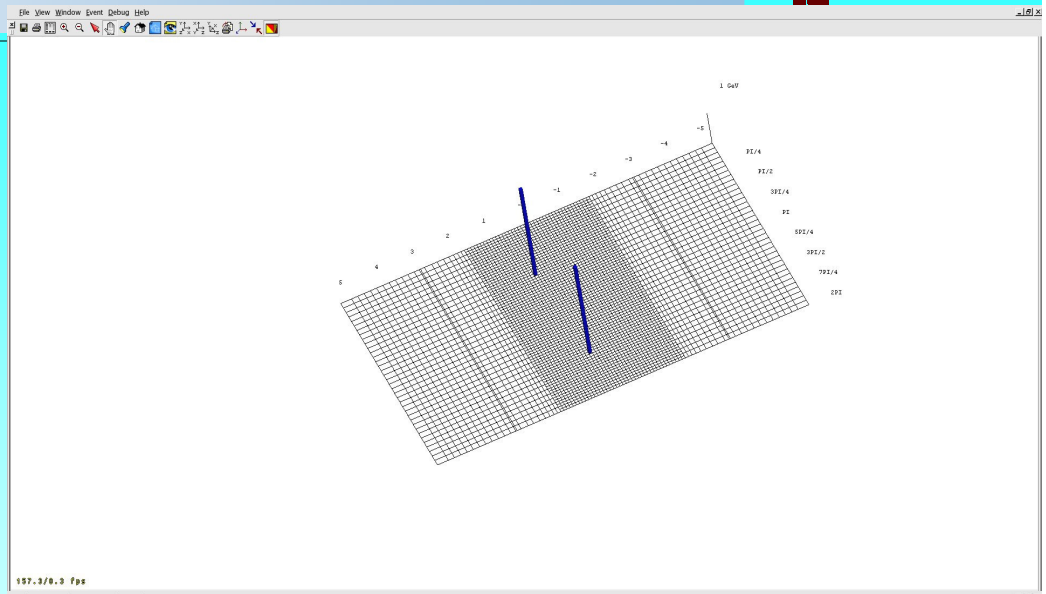
Hadron Calorimeter (HCAL) Complete

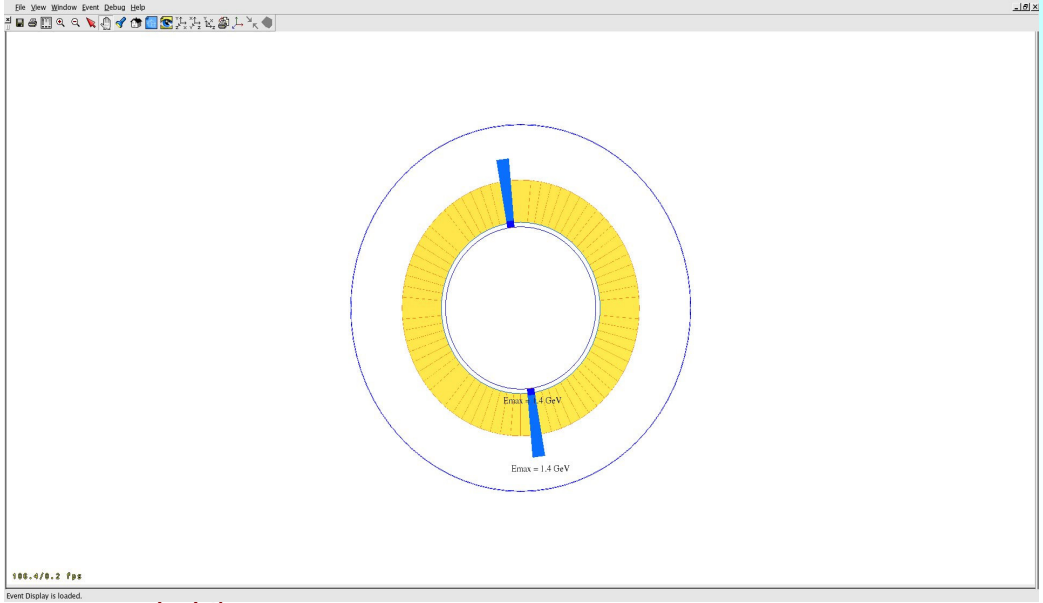


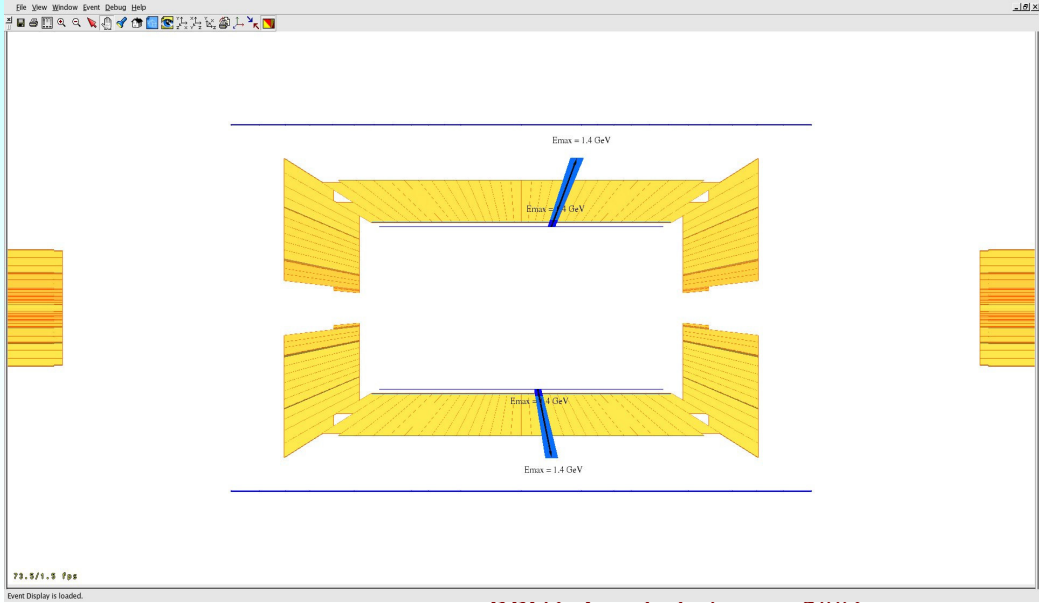
Assembly of 2 half barrels HB+ & HB- and two endcaps HE+ & HE-
completed in 03 (brass+ scint)

Cosmic's in HCAL at SX5

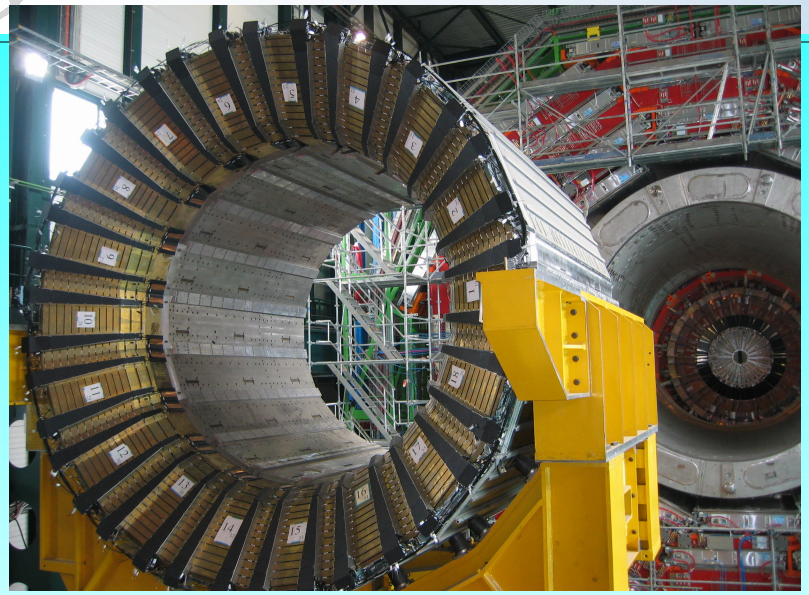






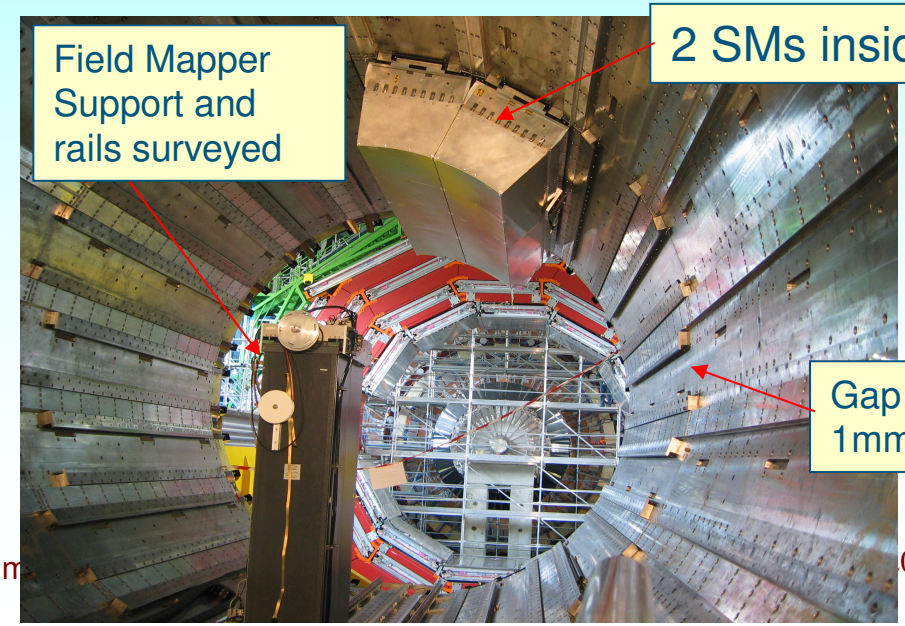


HB+ insertion complete on 3 April



Lower HB in Oct/Nov

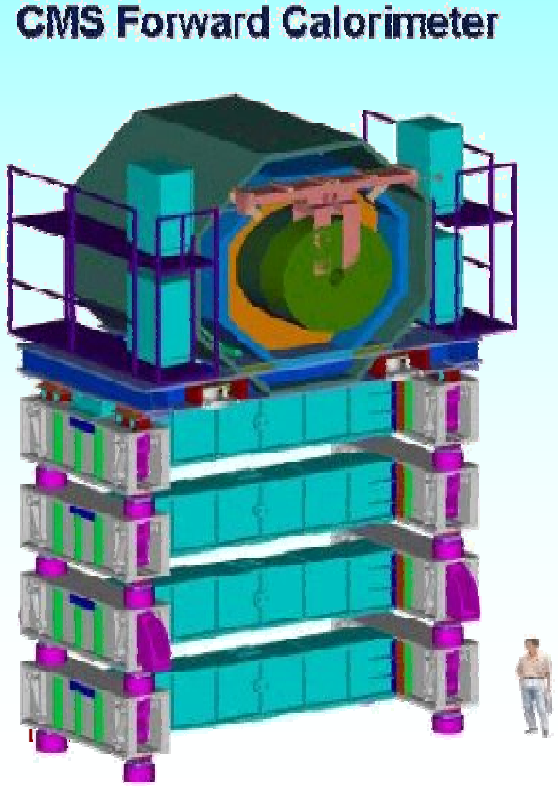
HB- insertion complete on 27 April

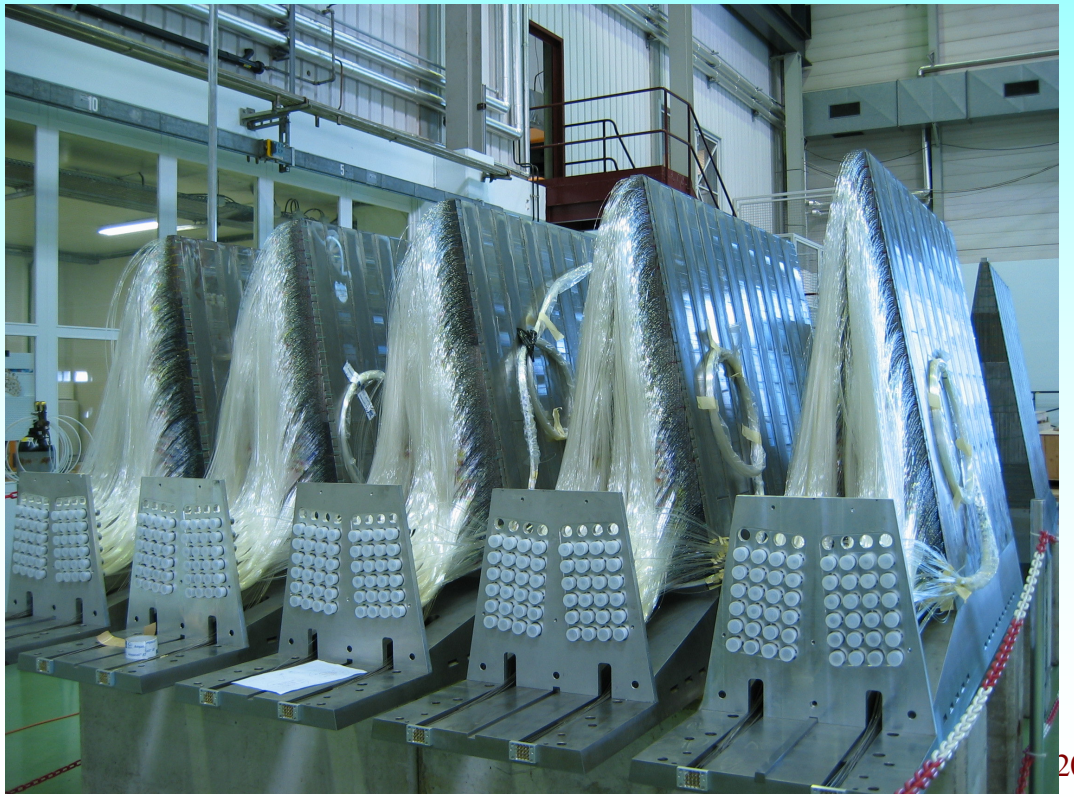


Hadronic Forward (HF) calorimeter

Steel absorbers, embedded quartz fibers // to the beam.
Fast (~10 ns) collection of Cherenkov radiation.

Coverage: $3<|\eta|<5$ $\Delta\phi$ x $\Delta\eta$ =10º x 13 η towers
Depth: 10 λ_{int}



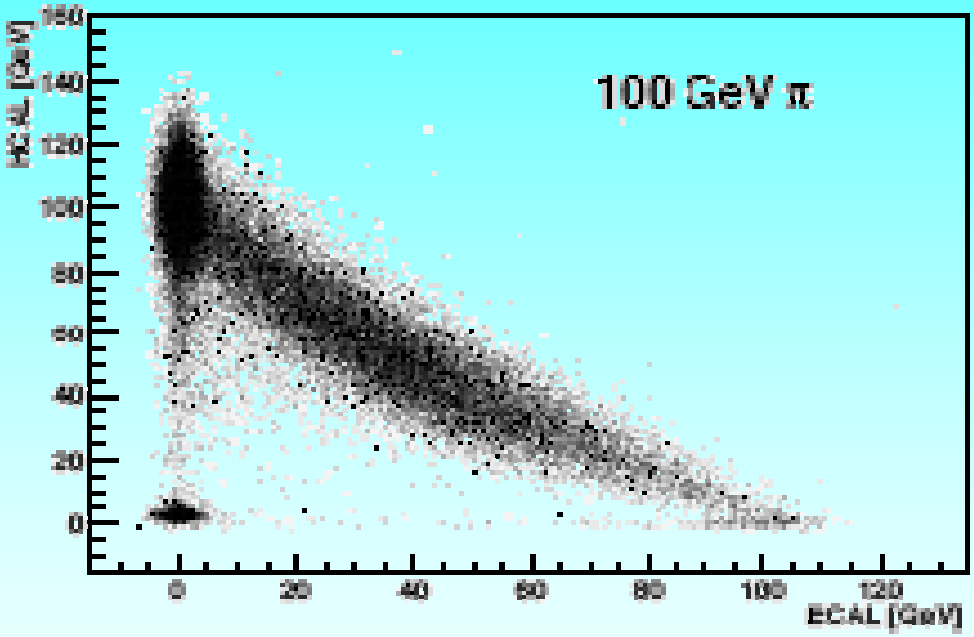


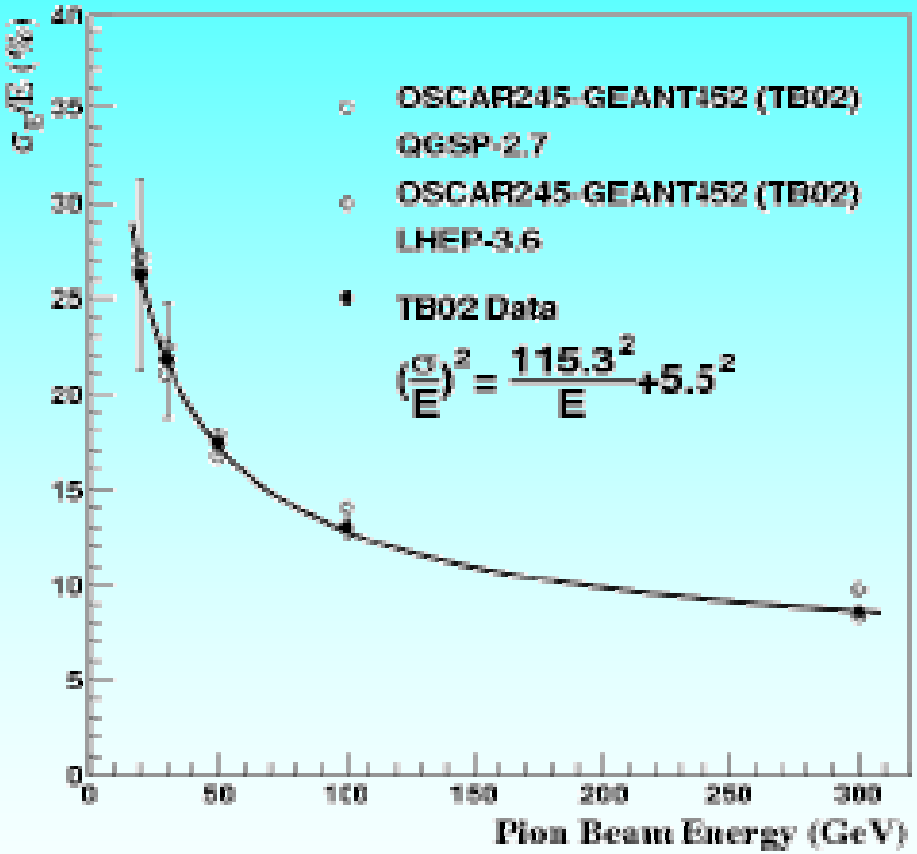
CMS: HF in Bat 186

Both have been source calibrated

Lower HF+ in September

ECAL + HCAL Energy Resolution

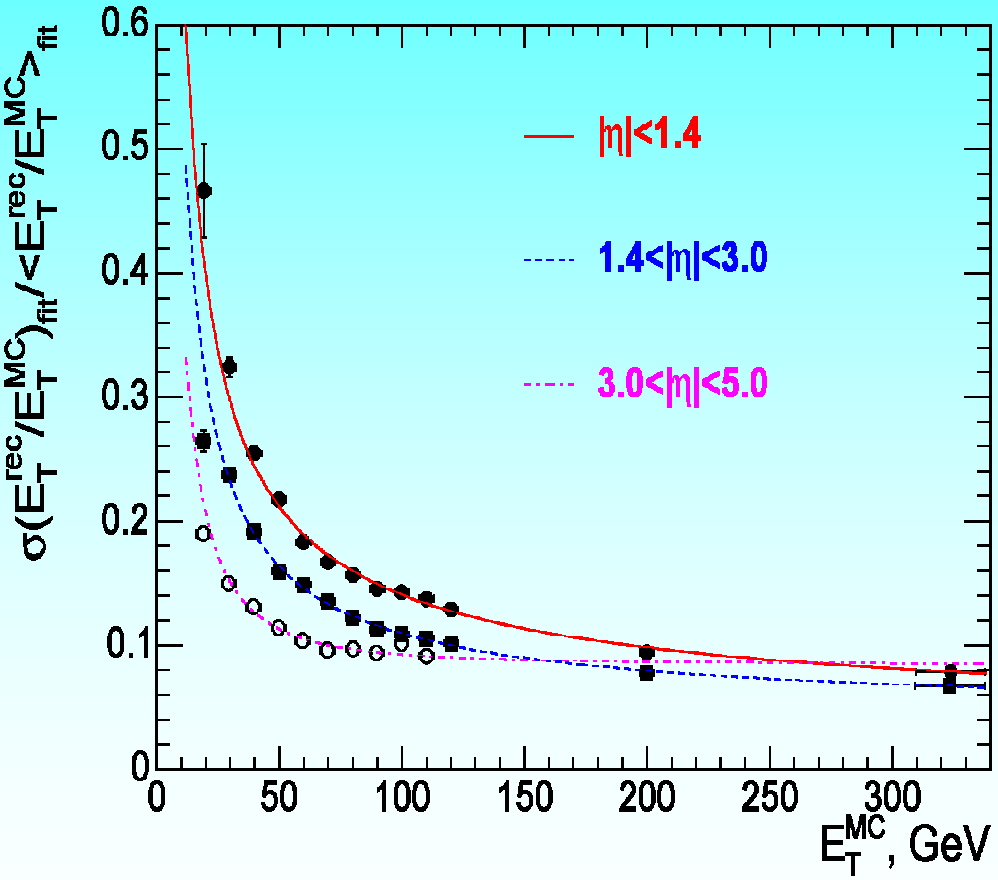




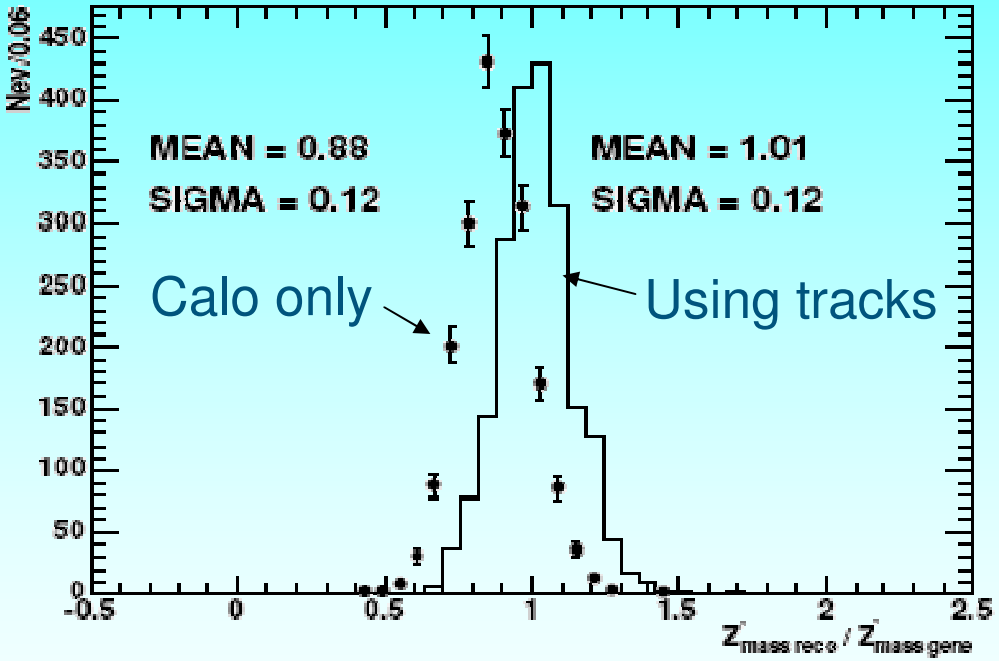
Combined Test ECAL SM + HCAL Wedge in Summer 06

Jet Reconstruction and Resolutions

Jet E_T resolution



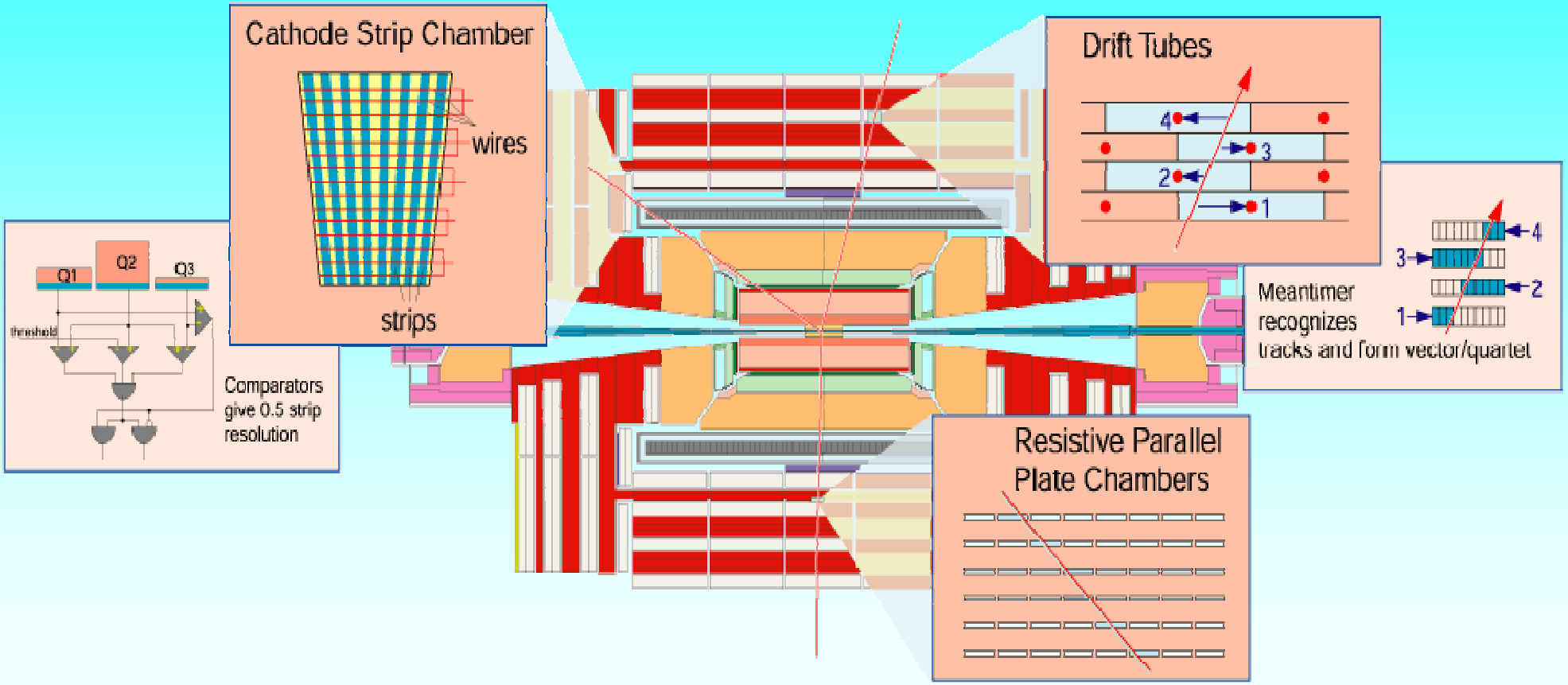
M_{jj} resolution at 120 GeV



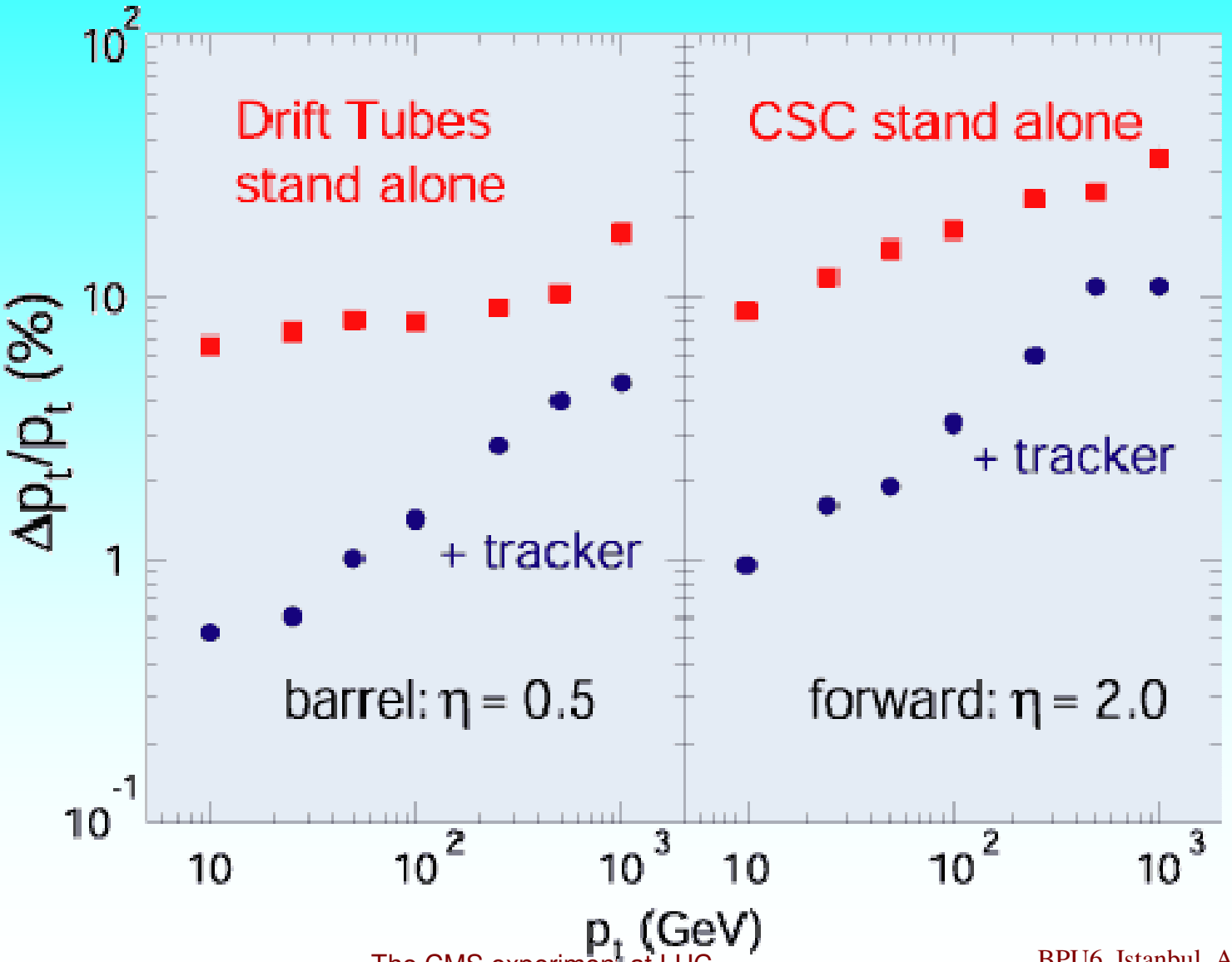
M_{jj} resolution ≤ 15%

Muon system

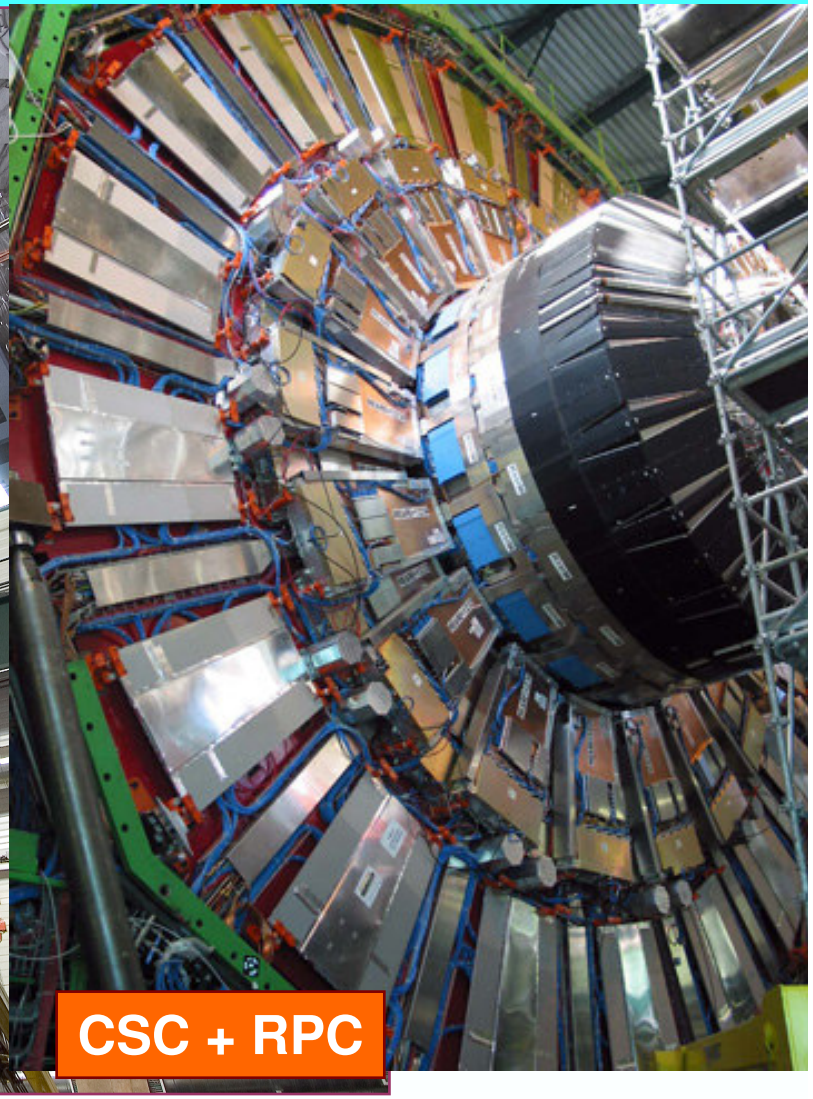
Muon system


Cathode Strip Chamber
wires
strips
Q1
Q2
Q3
threshold
Comparators
give 0.5 strip
resolution
Drift Tubes
4
3
2
1
Meantimer
recognizes
tracks and form vector/quartet
Resistive Parallel
Plate Chambers

Momentum Resolution

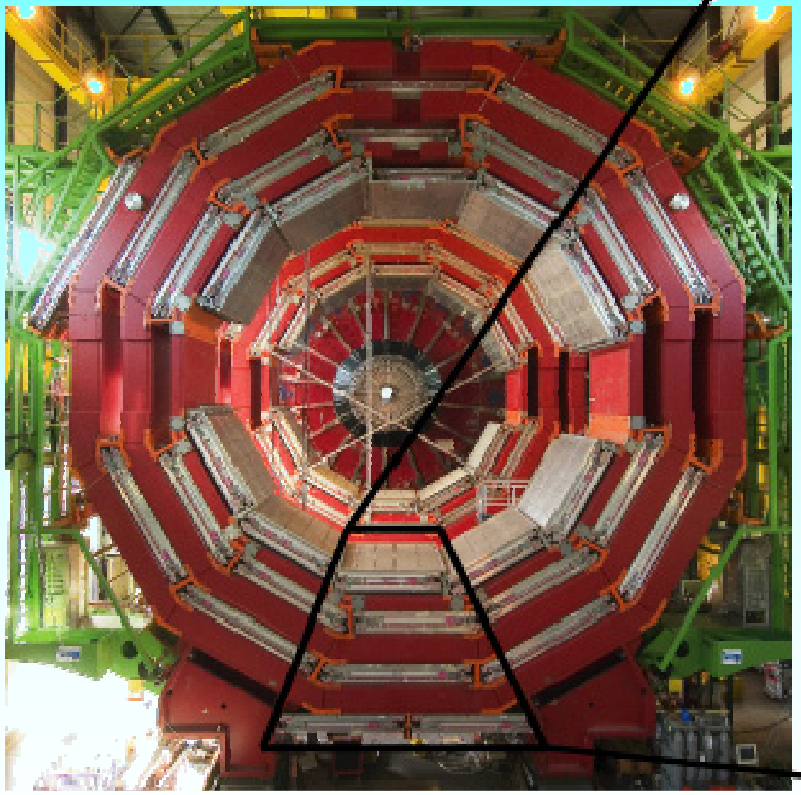


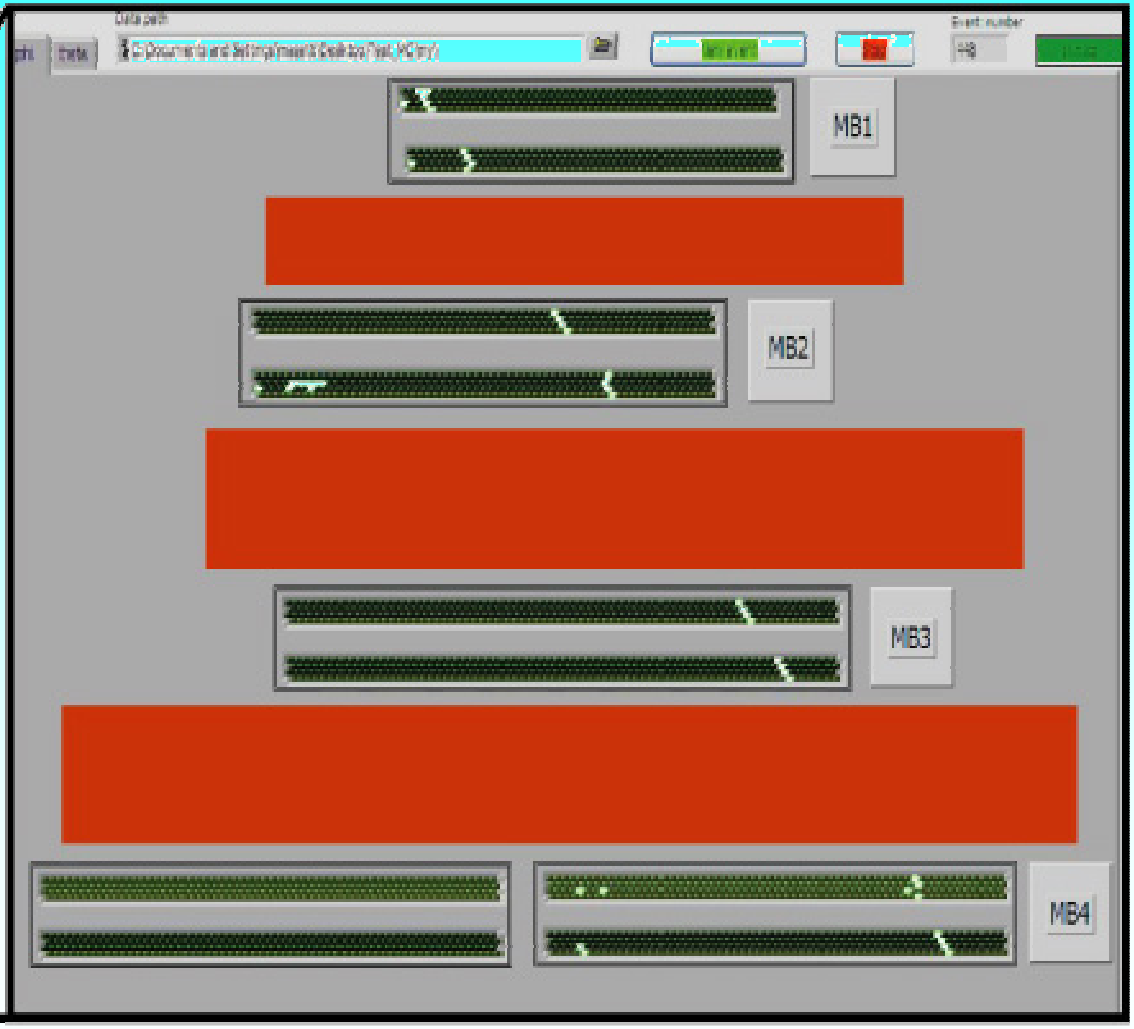
Muon system



Muon system

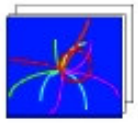
First muon event at SX5





The CMS muon system will be reviewed in next talk by B. Pavlov

Trigger and DAQ



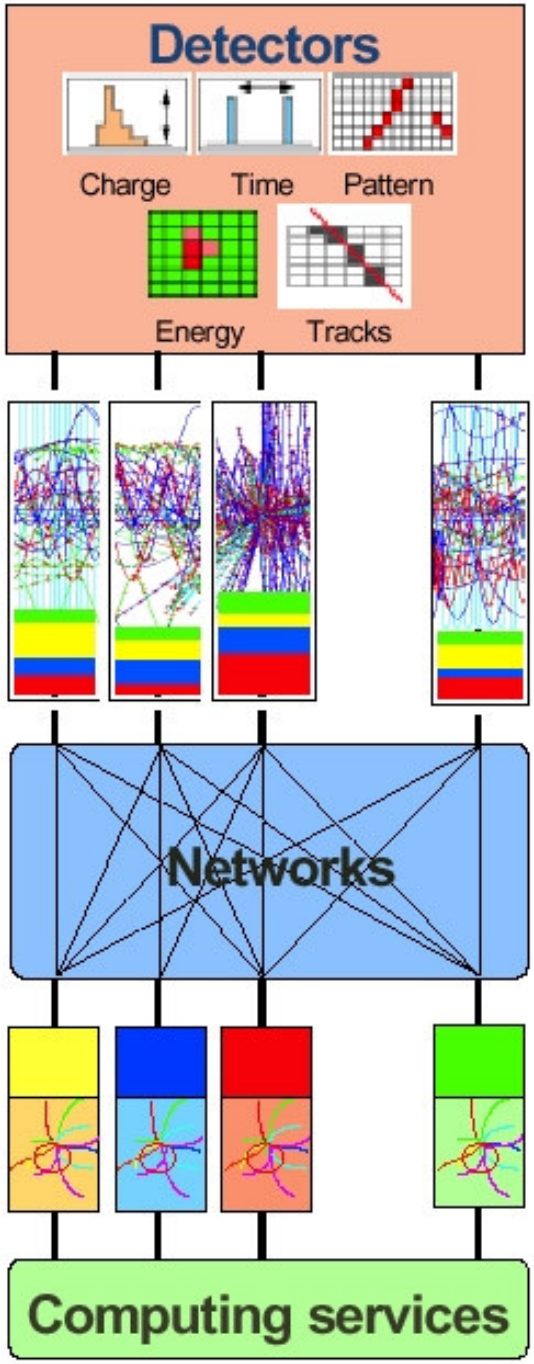
40 MHz
COLLISION RATE

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

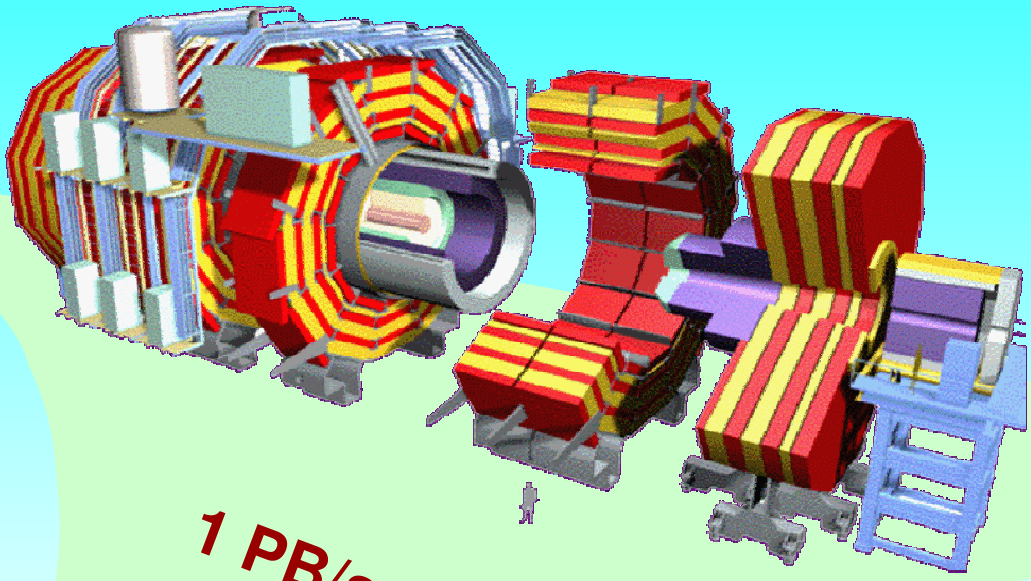
EVENT BUILDER. A large switching network (512+512 ports) with a total throughput of approximately 500 Gbit/s forms the interconnection between the sources (Readout Dual Port Memory) and the destinations (switch to Farm Interface). The Event Manager collects the status and request of event filters and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

Data processing

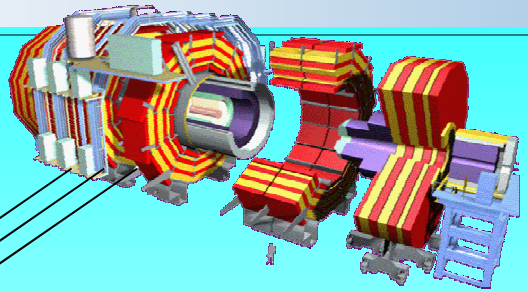


1 PB/sec

Filtering in real time:
Selection of intwresting events and data compresion

1 PB per year

LCG



Level 0

Trigger system

0.1-1.5 GB/sec

CERN computing center

Level 1

~40Gb/sec

USA

France

CERN

Italy

…

1-2.5 Gb/sec

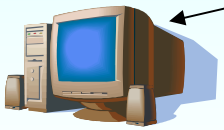
Level 2

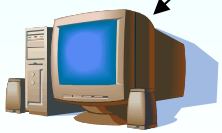
University

Laboratory

University

Level 3





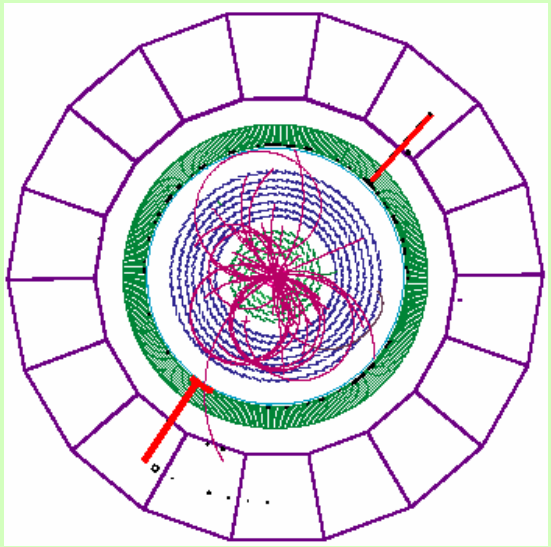
1-10 Gb/sec

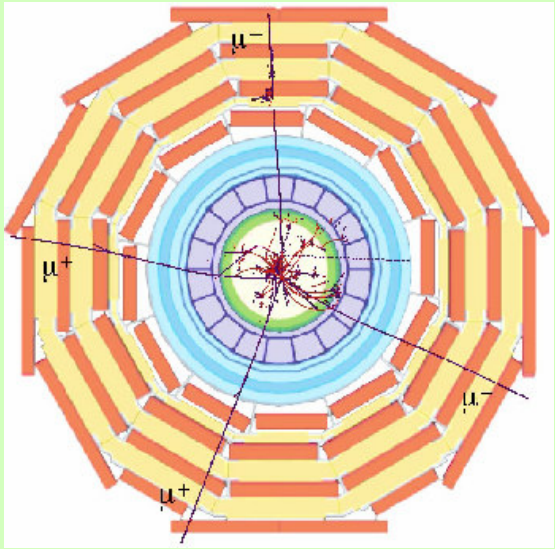
	ATLAS	CMS
MAGNET (S)	Air-core toroids + solenoid in inner cavity Calorimeters outside field 4 magnets	Solenoid Calorimeters inside field 1 magnet
TRACKER	Si pixels + strips TRD → particle identification B= 2T $\sigma/p_T \sim 5\times10^{-4}\ p_T(\text{GeV}) \oplus 0.01$	Si pixels + strips No particle identification B= 4T $\sigma/p_T \sim 1.5\times10^{-4}\ p_T\,(\text{GeV}) \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 3\%/\sqrt{E}$ no longitudinal segmentation
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air → $\sigma/p_T \sim 7$ % at 1 TeV standalone	Fe → $\sigma/p_T \sim 5\%$ at 1 TeV combining with tracker

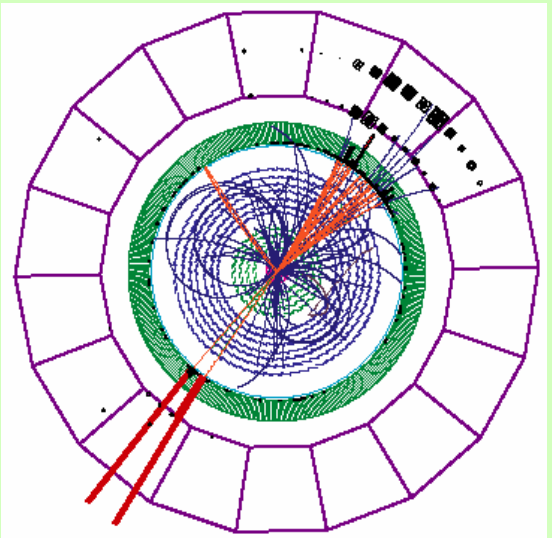
Magnet Test Cosmic Challenge

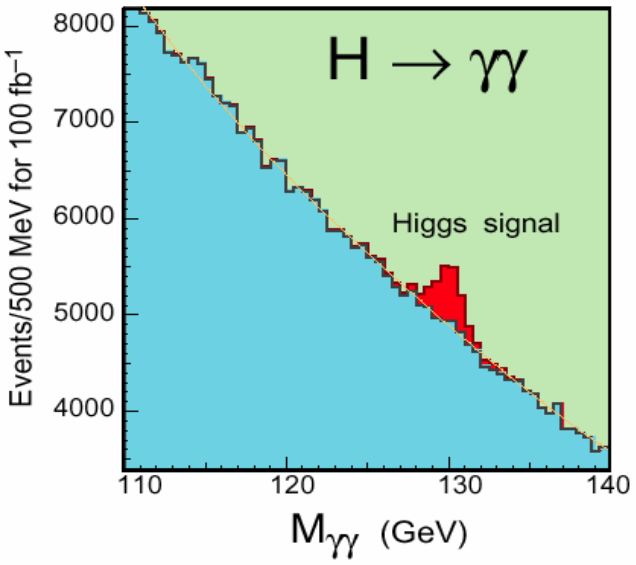
- Detector was successfully closed for first time in July
- Representatives of all systems installed (one full sector)
- Final DAQ and trigger electronics
- Magnet
  - ✓ Fast and slow discharge – well understood
  - ✓ Magnetic field of 3.95 T was reached two days ago
- Detectors
  - ✓ All detector systems are working properly
  - ✓ First cosmic events (muons) recorded with all systems
  - ✓ DAQ and Trigger – work without problems
- Goal for the next few days
  - ✓ record 10 M events at 3.8T
  - ✓ Next week – run at 4T
- End of phase I
- Phase II
- In September – measure (map) the magnetic field
- October – open detector, continue installation and start lowering

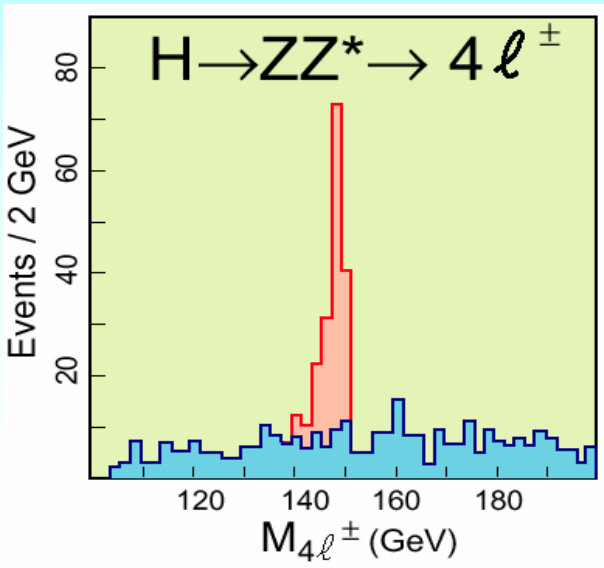
Higgs at CMS

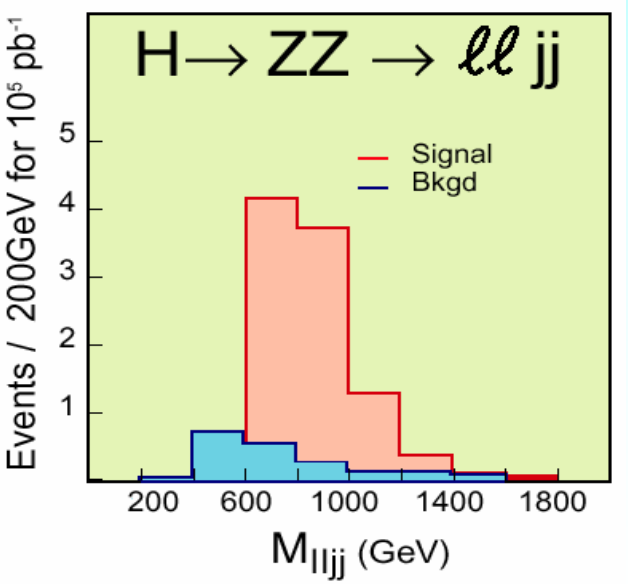



μ⁻
μ⁺
μ⁻
μ⁺

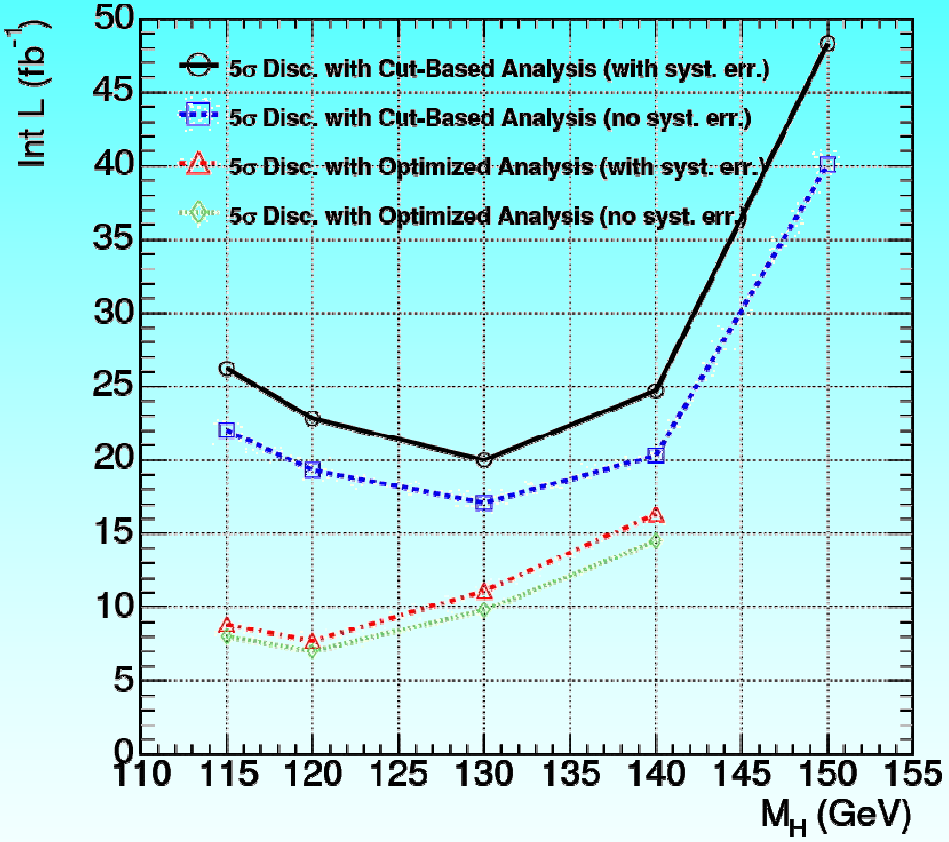


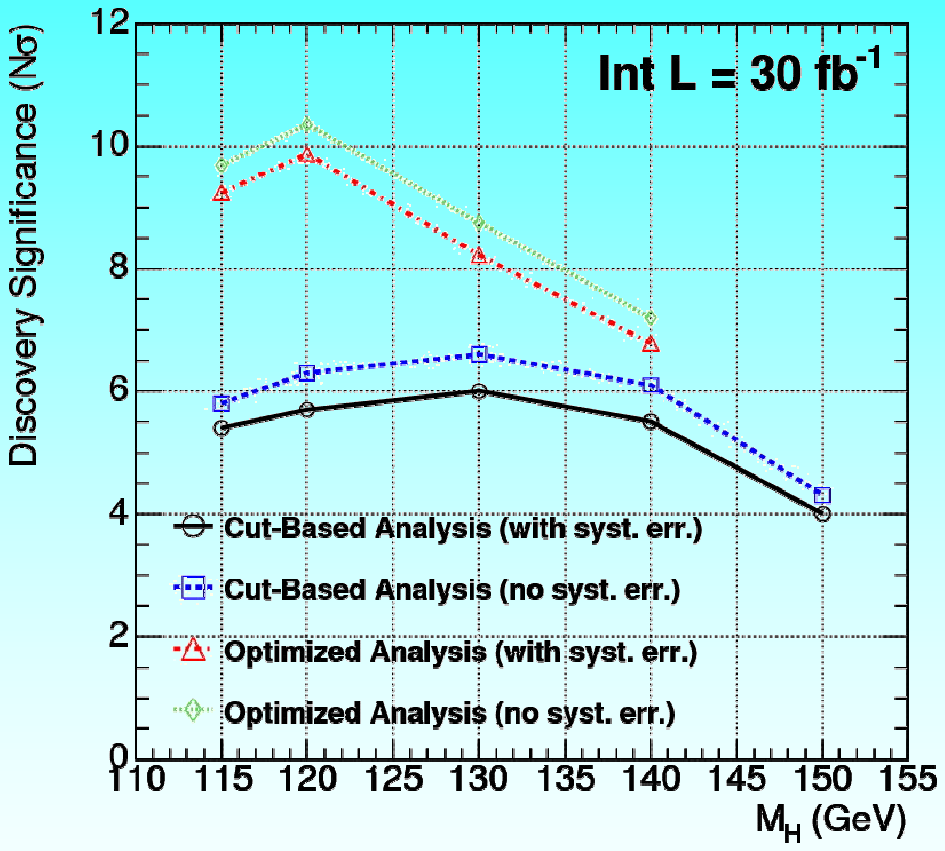

H → γγ
Higgs signal
Events/500 MeV for 100 fb⁻¹
8000
7000
6000
5000
4000
110
120
130
140
Mγγ (GeV)


H→ZZ*→ 4ℓ ±
Events / 2 GeV
80
60
40
20
120
140
160
180
M4ℓ ± (GeV)

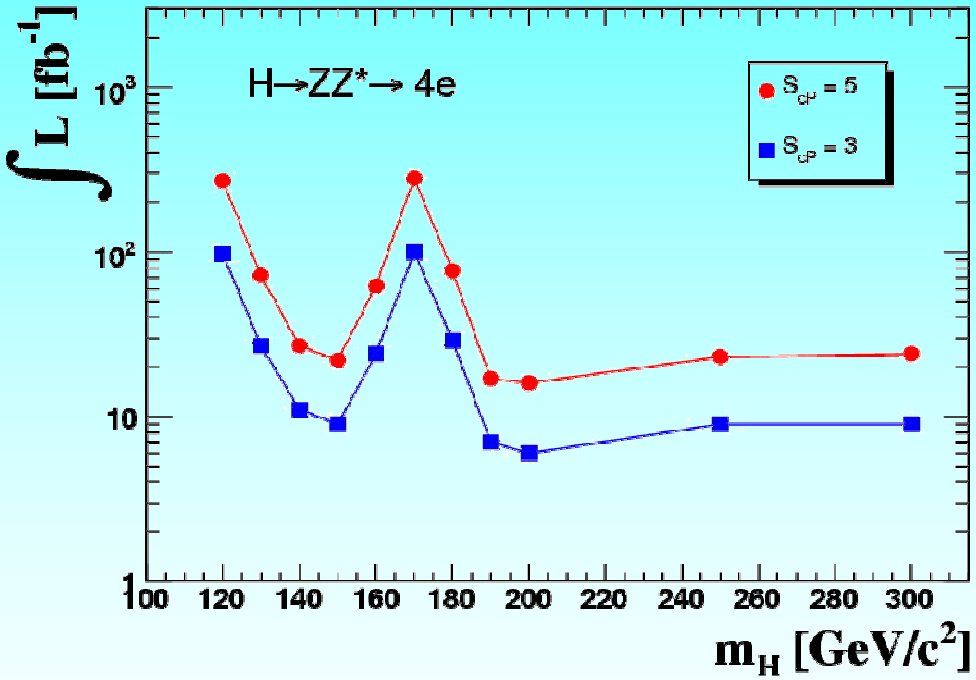

H→ ZZ → ℓℓ jj
Signal
Bkgd
Events / 200GeV for 10⁵ pb⁻¹
5
4
3
2
1
200
600
1000
1400
1800
MlIjj (GeV)

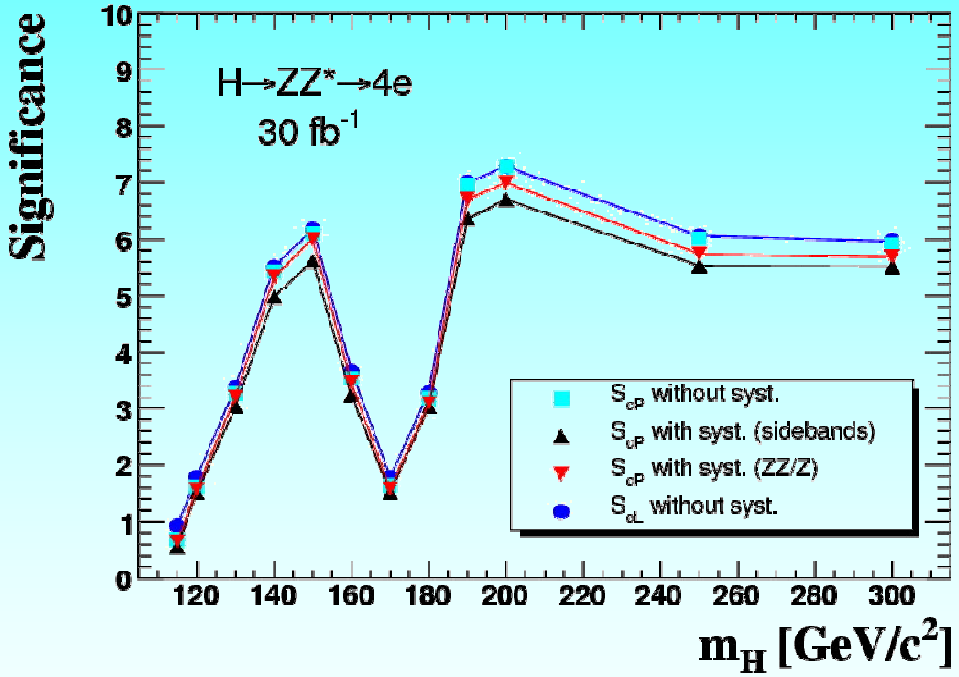
SM Higgs Boson Search H→ γγ



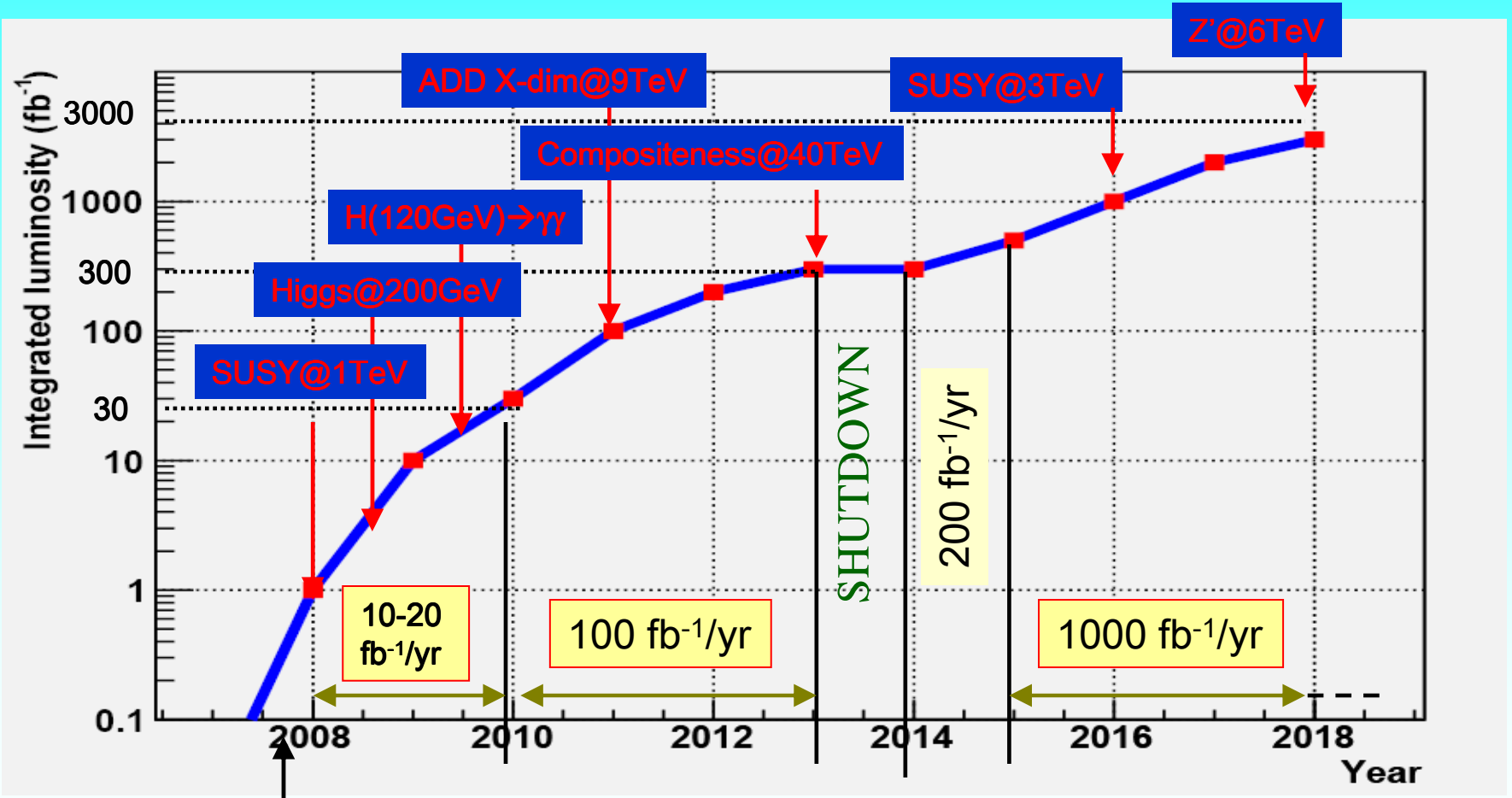


SM Higgs Boson Search



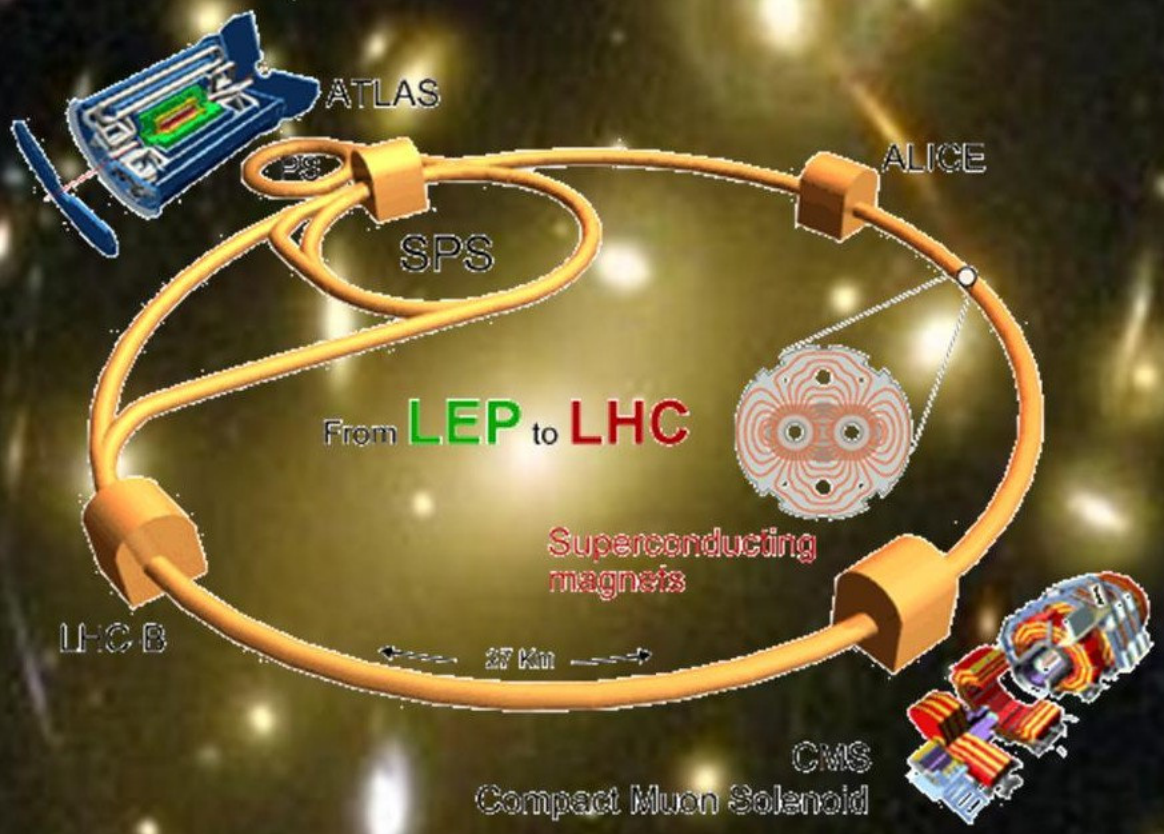


LHC Luminosity Profile



The Big Quest

for secrets of the Universe



Starts 2007

Conclusions

- Higgs is still missing
  - Symmetry Breaking in the SM (and beyond!) still not understood
  - LHC and ATLAS/CMS designed to find it
  - Numerous challenges, mostly "solved"
- Physics at the LHC will be extremely rich
  - SM Higgs (if there) in the pocket
    - Now turning to measurements of couplings, etc.
  - Supersymmetry (if there) ditto
    - Can perform numerous accurate measurements
  - Large com energy: new thresholds
    - Compositeness, new bosons, large extra dimensions within reach
  - LHC++?
- Just need to build machine/experiments.