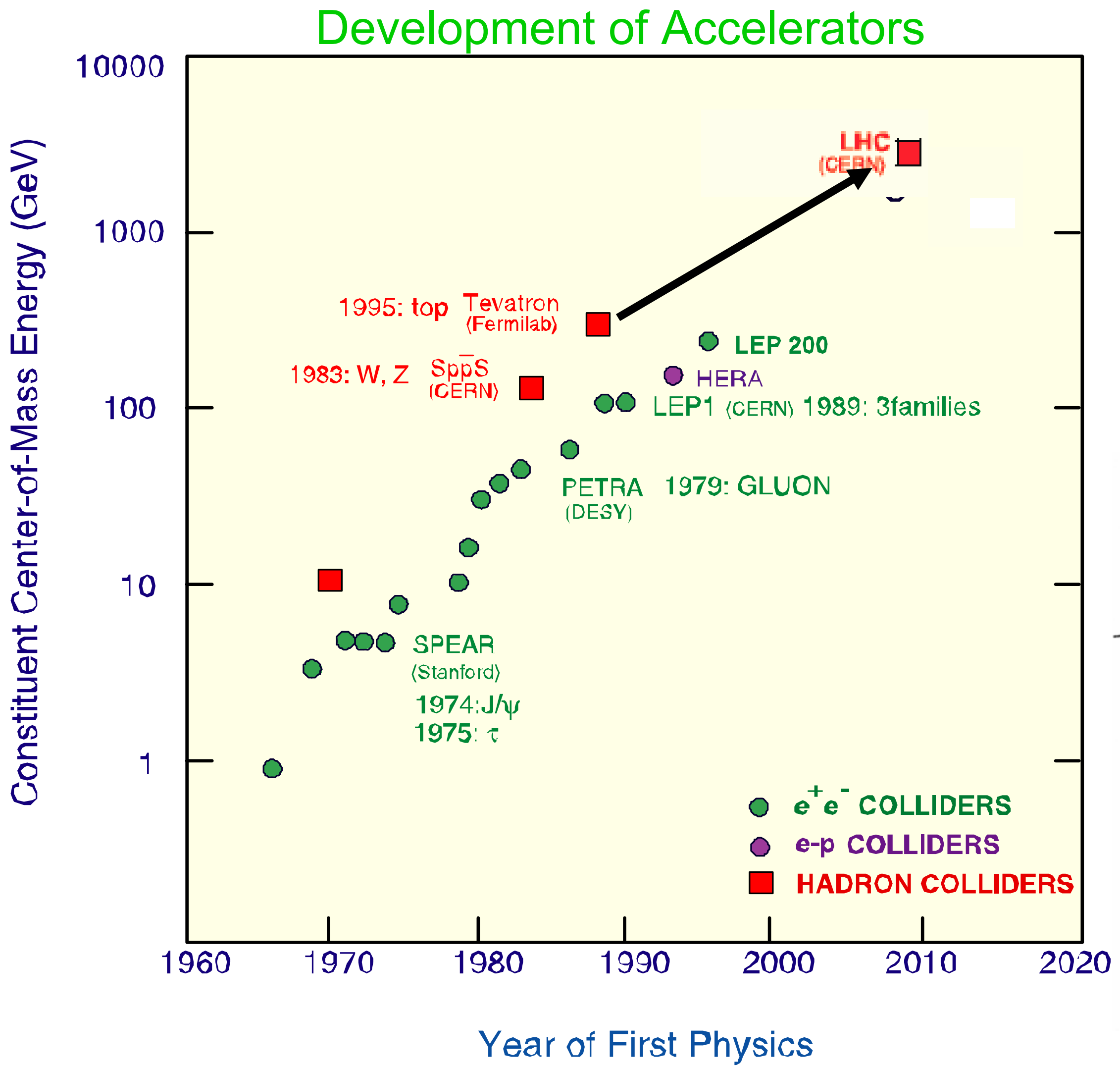
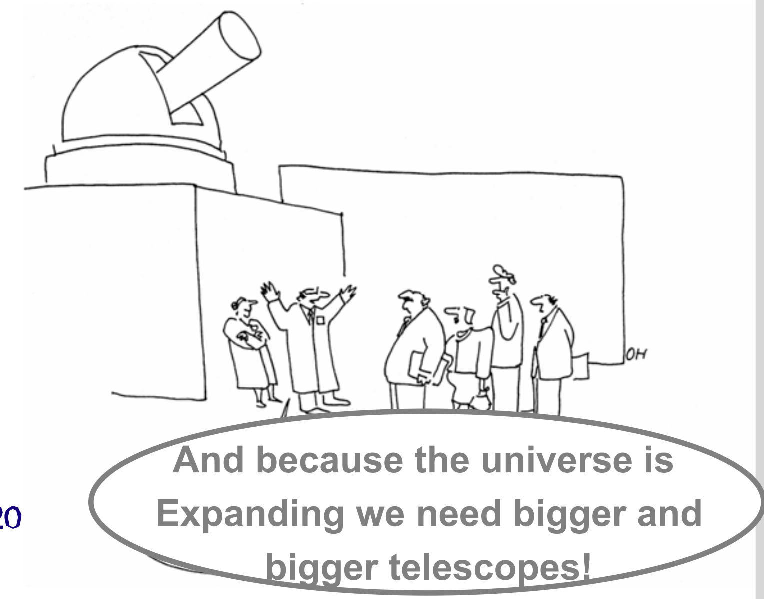


LHC: Energy 7 X
Rate 100 X
more than Tevatron !



I. THE LARGE HADRON COLLIDER

THE HISTORY

1984 Workshop for a hadron collider in the LEP-Tunnel, Lausanne

1987 Rubbia's "Long-Range Planning Committee" recommends to build, as an answer to the SSC in Texas, the Large Hadron Collider at CERN

1988 Early detector concepts

1990 Large Hadron Collider Workshop Aachen

1992 Conference on LHC physics and detectors in Evian les Bains

1993 *Letters of Intent* (ATLAS und CMS were chosen)

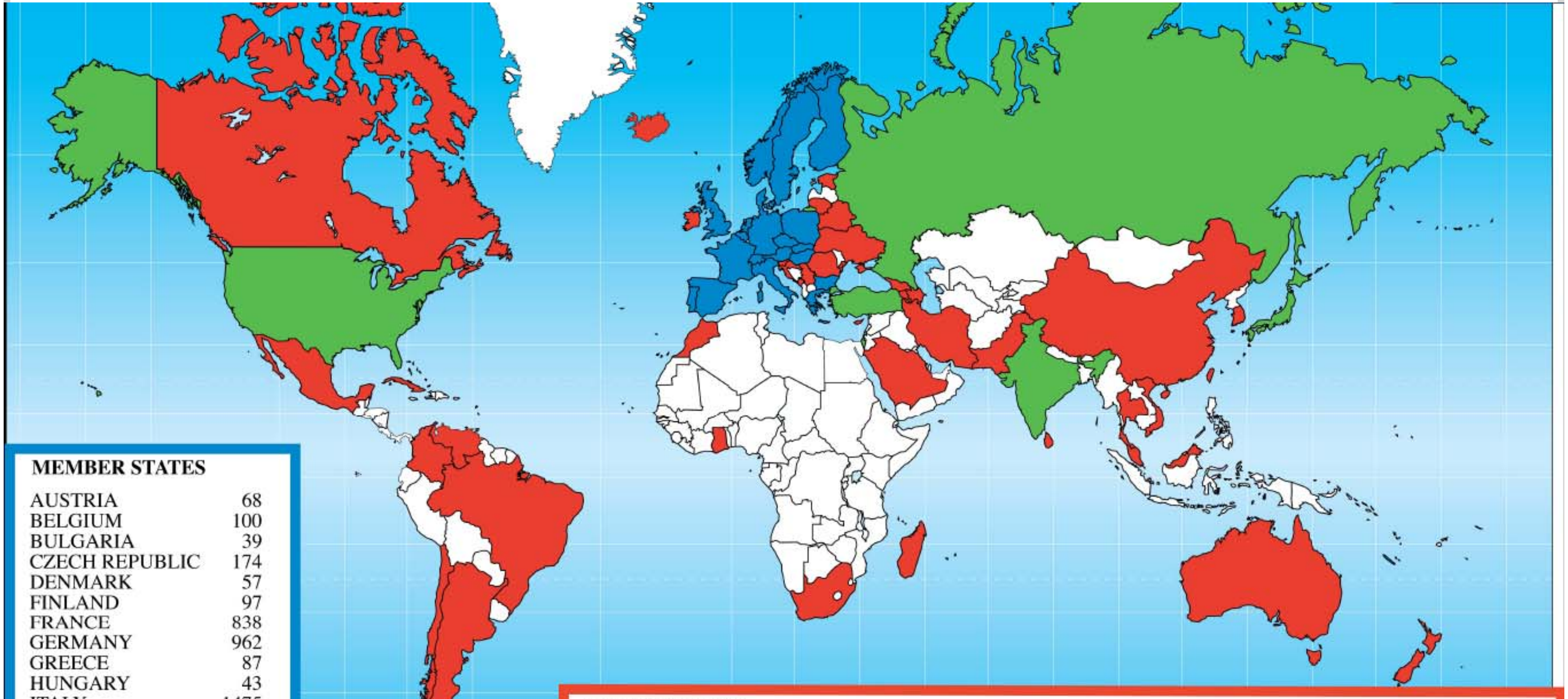
1994 Technical Design Reports

1998 Begin of construction of detector- und accelerator elements

2004 Finishing the CMS cavern

2009 LHC and Detectors operational, first Proton-Proton-collisions expected end of year

ABOUT CERN



MEMBER STATES

AUSTRIA	68
BELGIUM	100
BULGARIA	39
CZECH REPUBLIC	174
DENMARK	57
FINLAND	97
FRANCE	838
GERMANY	962
GREECE	87
HUNGARY	43
ITALY	1475
NETHERLANDS	171
NORWAY	74
POLAND	168
PORTUGAL	104
SLOVAKIA	46
SPAIN	278
SWEDEN	72
SWITZERLAND	341
UNITED KINGDOM	666

5860

OBSERVER STATES

INDIA	94
ISRAEL	57
JAPAN	192
RUSSIA	905
TURKEY	61
USA	1447

2756

OTHER STATES

ARGENTINA	10
ARMENIA	17
AUSTRALIA	15
AZERBAIJAN	4
BELARUS	18
BRAZIL	68
CANADA	127
CHILE	8
CHINA	68
COLOMBIA	12
CROATIA	22
CUBA	6
CYPRUS	7
ESTONIA	12
GEORGIA	11
GHANA	1
ICELAND	2
IRAN	13
IRELAND	10
KOREA	51
LITHUANIA	10
MADAGASCAR	1
MALAYSIA	1
MALTA	4
MEXICO	36
MONTENEGRO	1
MOROCCO	5
NEW ZEALAND	8
PAKISTAN	29
PALESTINIAN TERR.	1
ROMANIA	49
SAUDI ARABIA	2
SERBIA	15
SLOVENIA	17
SOUTH AFRICA	8
SRI LANKA	1
TAIWAN	46
THAILAND	1
UKRAINE	20
U.A.E.	4
VIETNAM	3

744

KIT Karlsruhe Institute of Technology

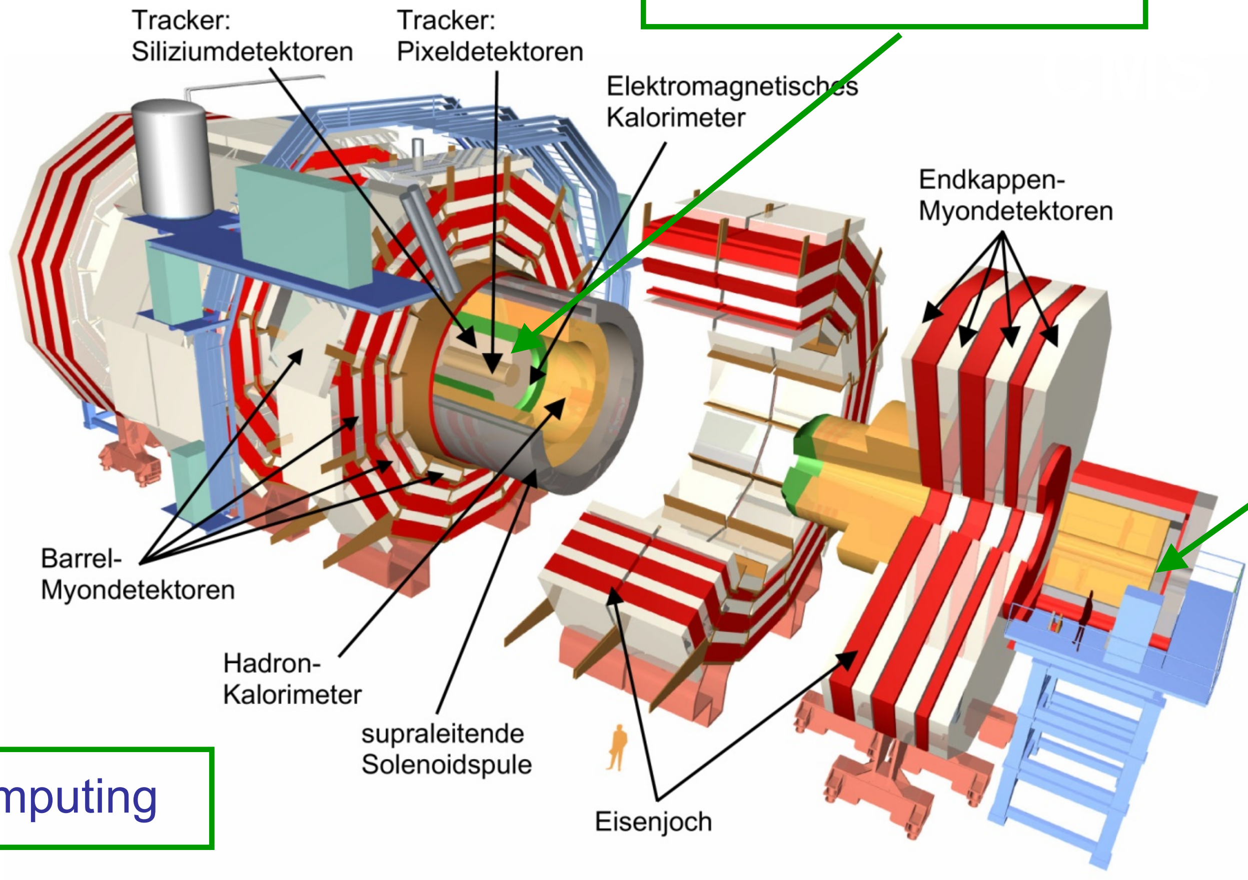
VIEW INTO THE LHC TUNNEL

- Magnetfeld von 8,3Tesla
- insgesamt 1232 Stück, 15 m lang
- 270'000 km Kabelstränge mit 6400 7μm dicken supraleitenden Filamenten
- Strom von 11'700 A
- Betriebstemperatur von 1.9 K

Operation at -271^{0}C

CONSTRUCTION OF THE ACCELERATOR

Construction of parts in institutes, assembley at CERN



Silicon Tracker

Radiation Monitor

Computing

Software / Datenanalysis

CMS-Detector:

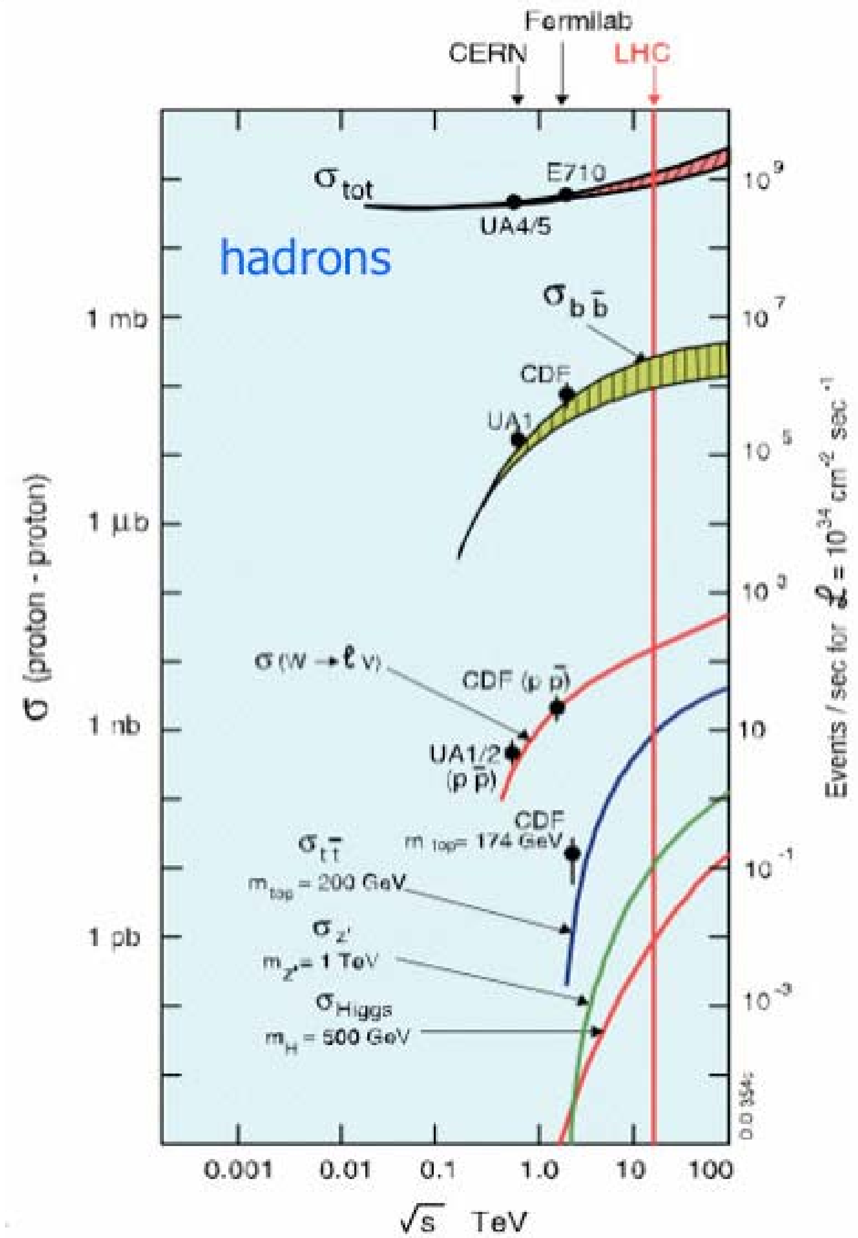
25m long, 16m high
12500 Tons
550 MSFr

CMS-Kollaboration:

2310 Scientists
38 Nations
175 Institutes

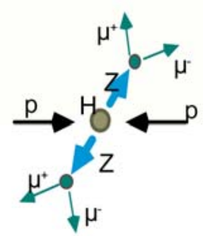
IEKP Karlsruhe: 55

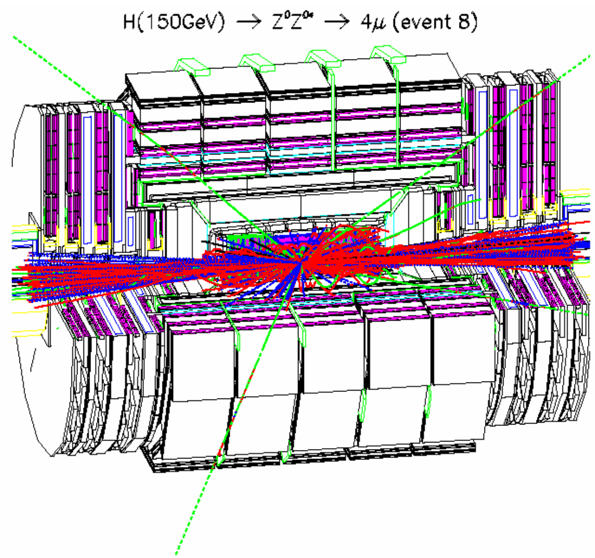
THE CHALLENGE



- **Event rates up to 800 MHz**
- **Per bunch crossing > 1000 charged tracks**
- **Very high radiation**
- **Very small cross sections**

Eg.:
To discover SM Higgs
we need 10^{14} events

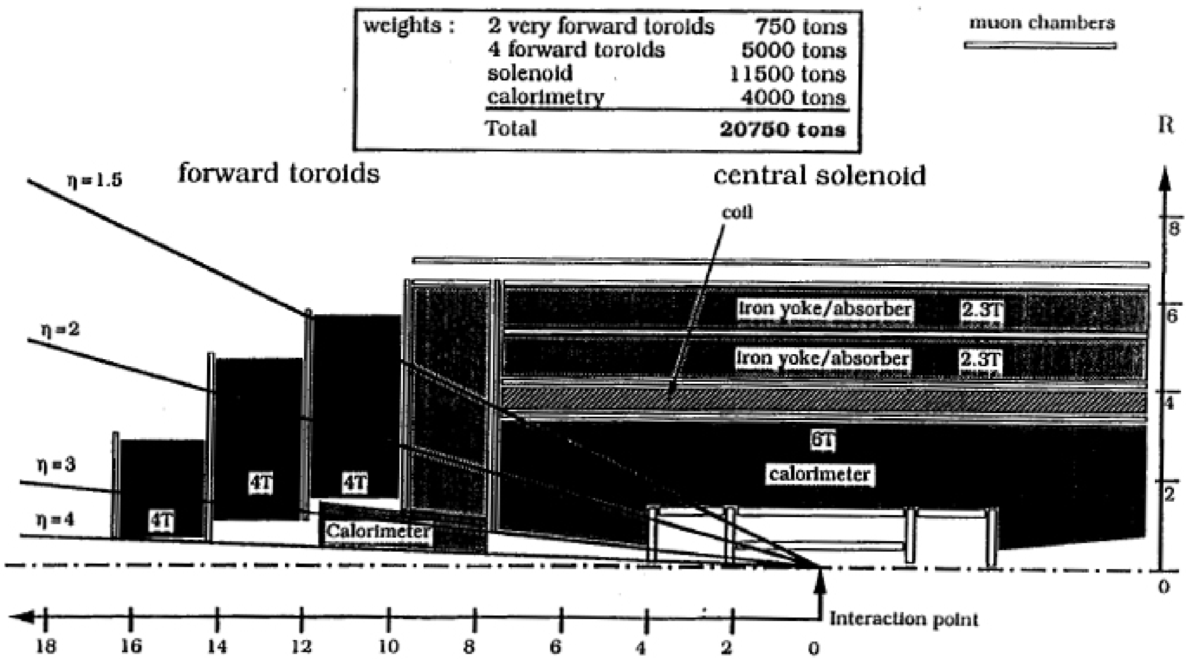


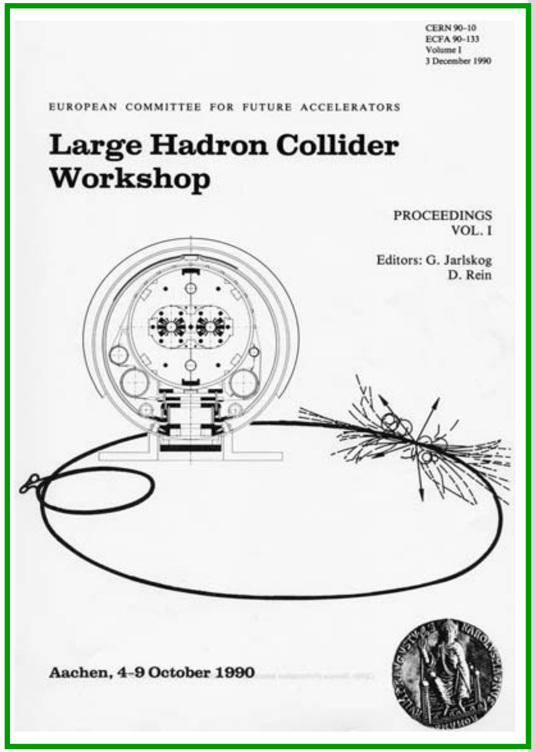


FIRST IDEAS

1987 Rubbia, Kienzle: „Iron Ball"

1988 Della Negra, Eggert: „CMS"





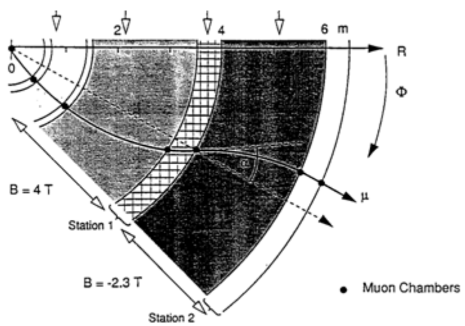
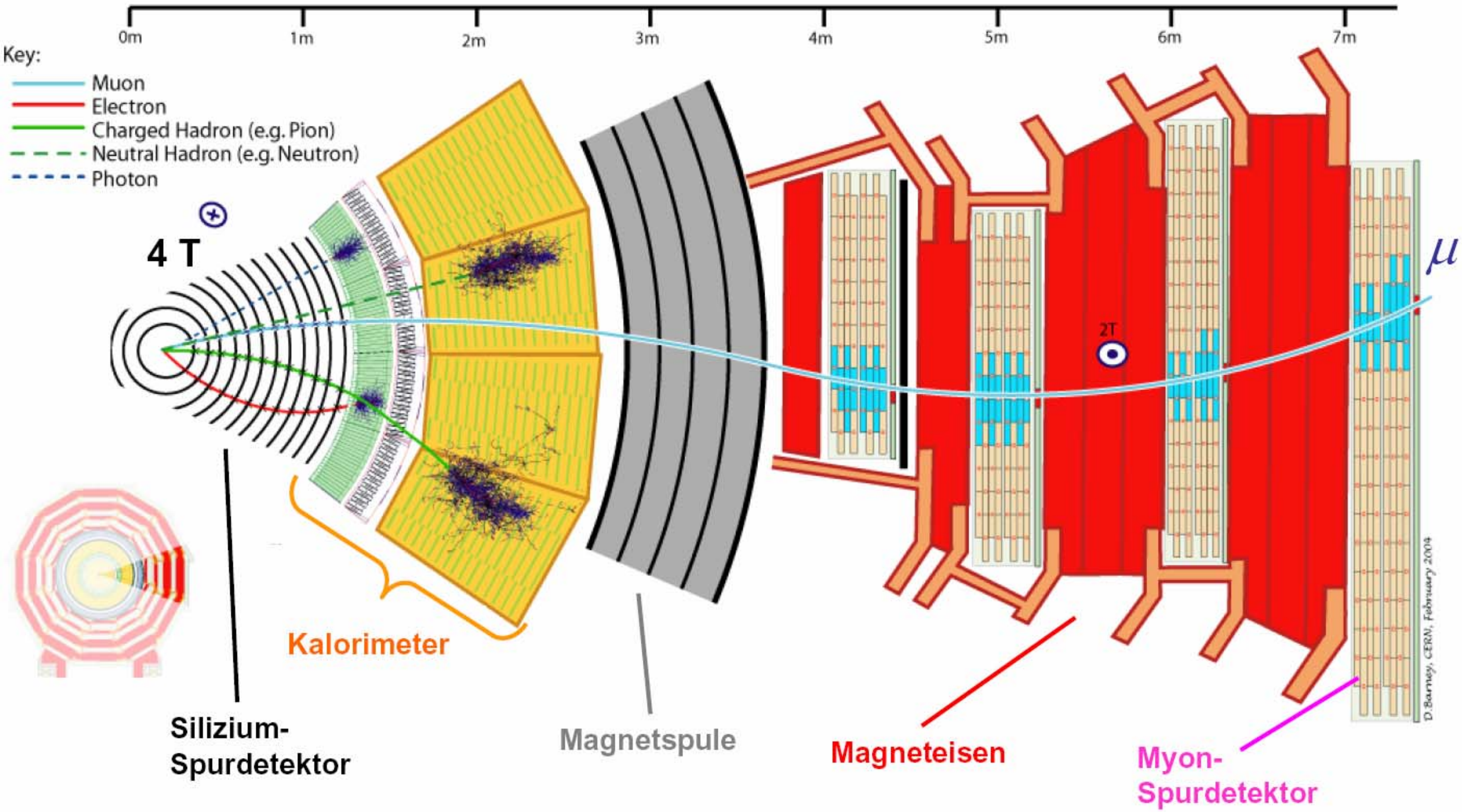
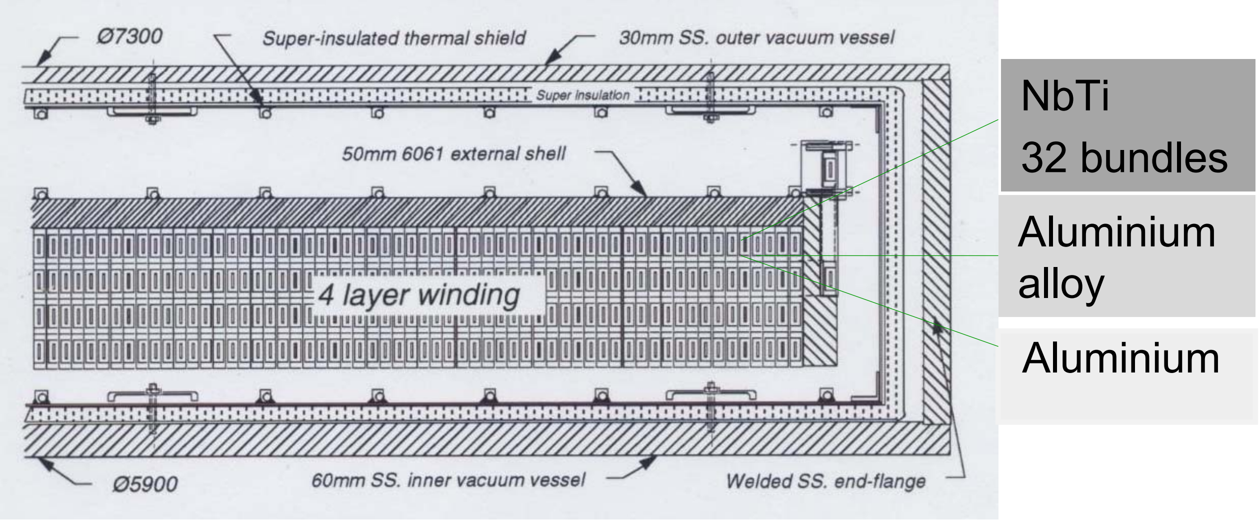


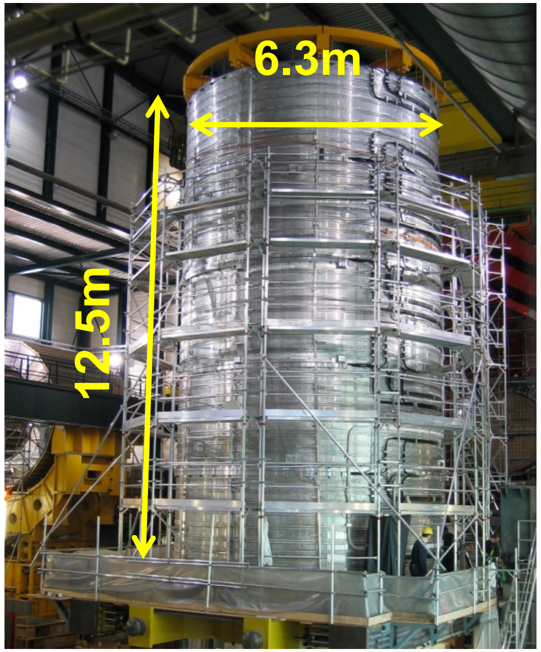
Fig. 7 Transversal view of the Compact Muon Solenoid detector.

THE DETECTOR PRINCIPLE

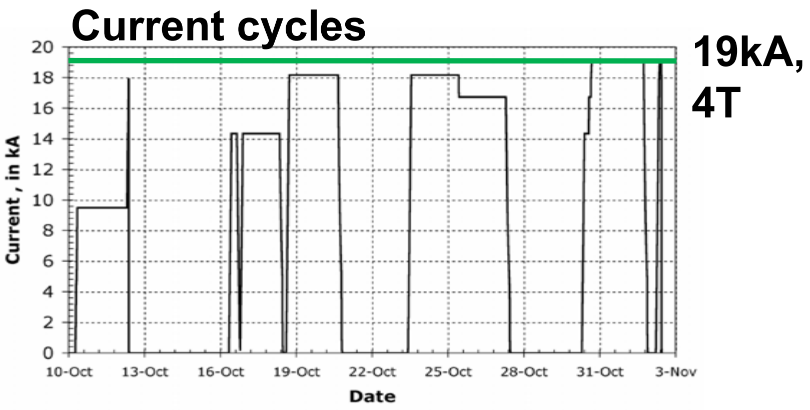


1. THE MAGNET

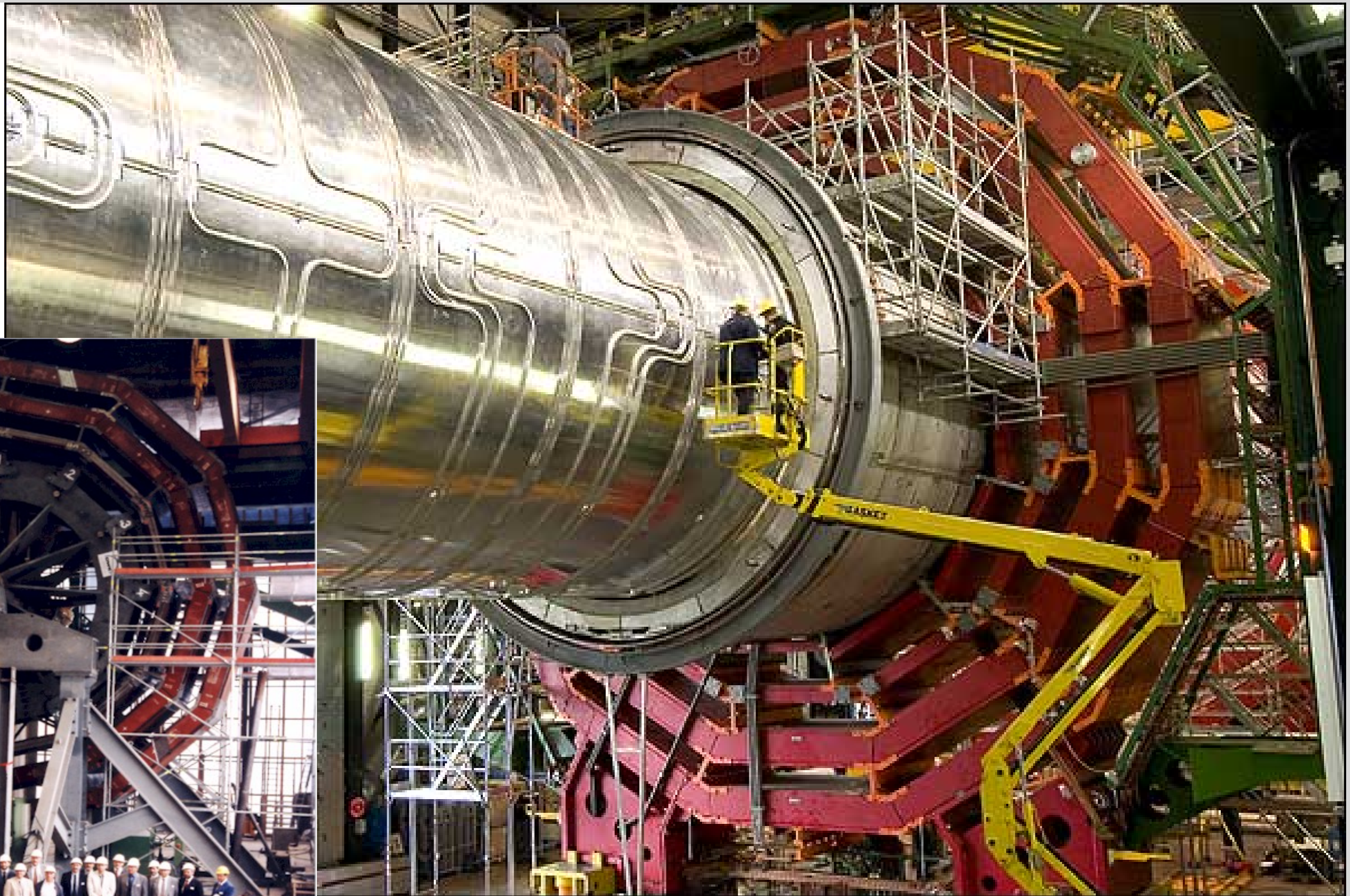


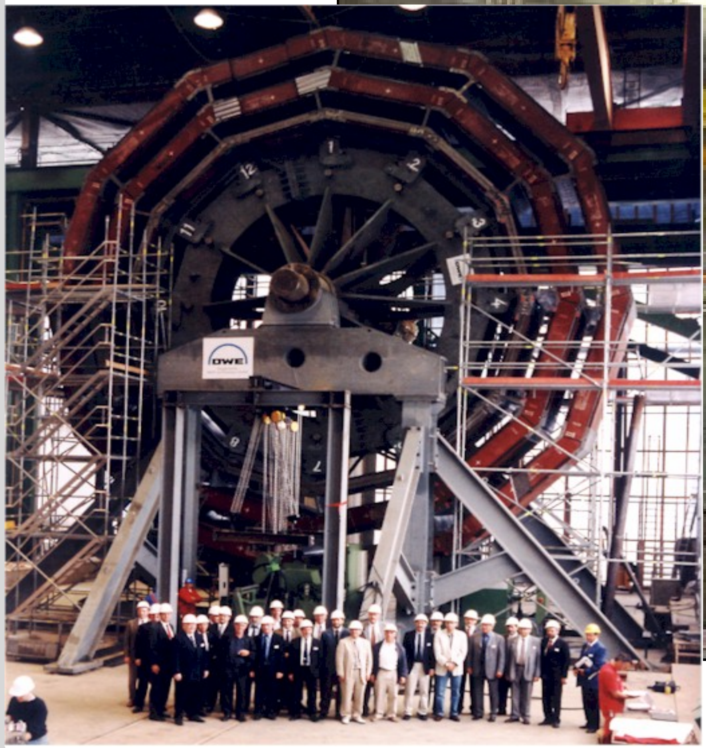


- 2112 Windings in 4 Layers
- Supra-conducting Al enforced NbTi
- 19 kA
- 220 t cold mass at 4.5K (Helium)
- Field energy 2.5 GJ
- Return yoke 10 000 t iron
- Axial force: 120 MN
- Operating field at 3.8 T
- Thickness 70 cm (1.1 λ)



Insertion of inner cryostat wall



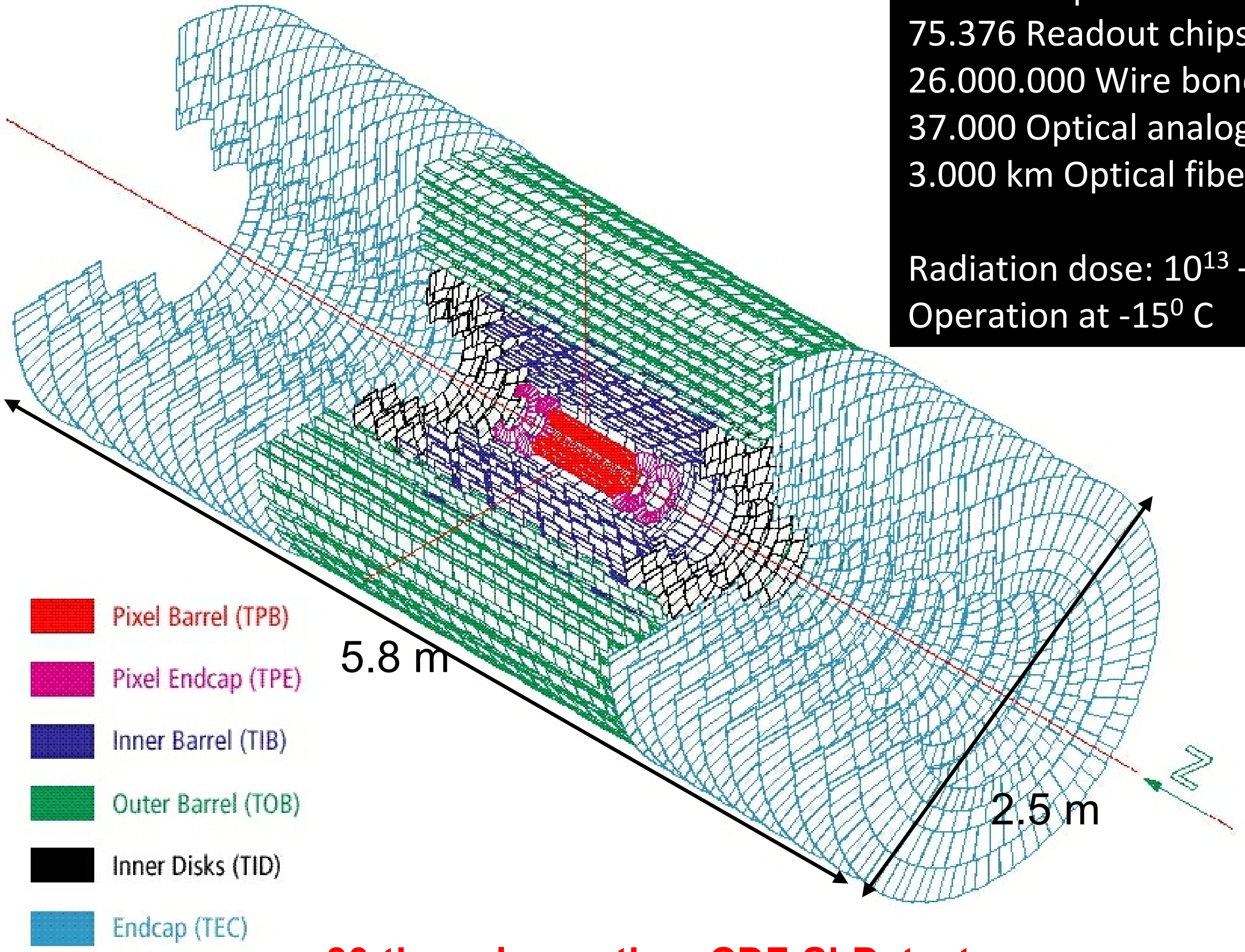


Construction of yoke at DWE-ship yard

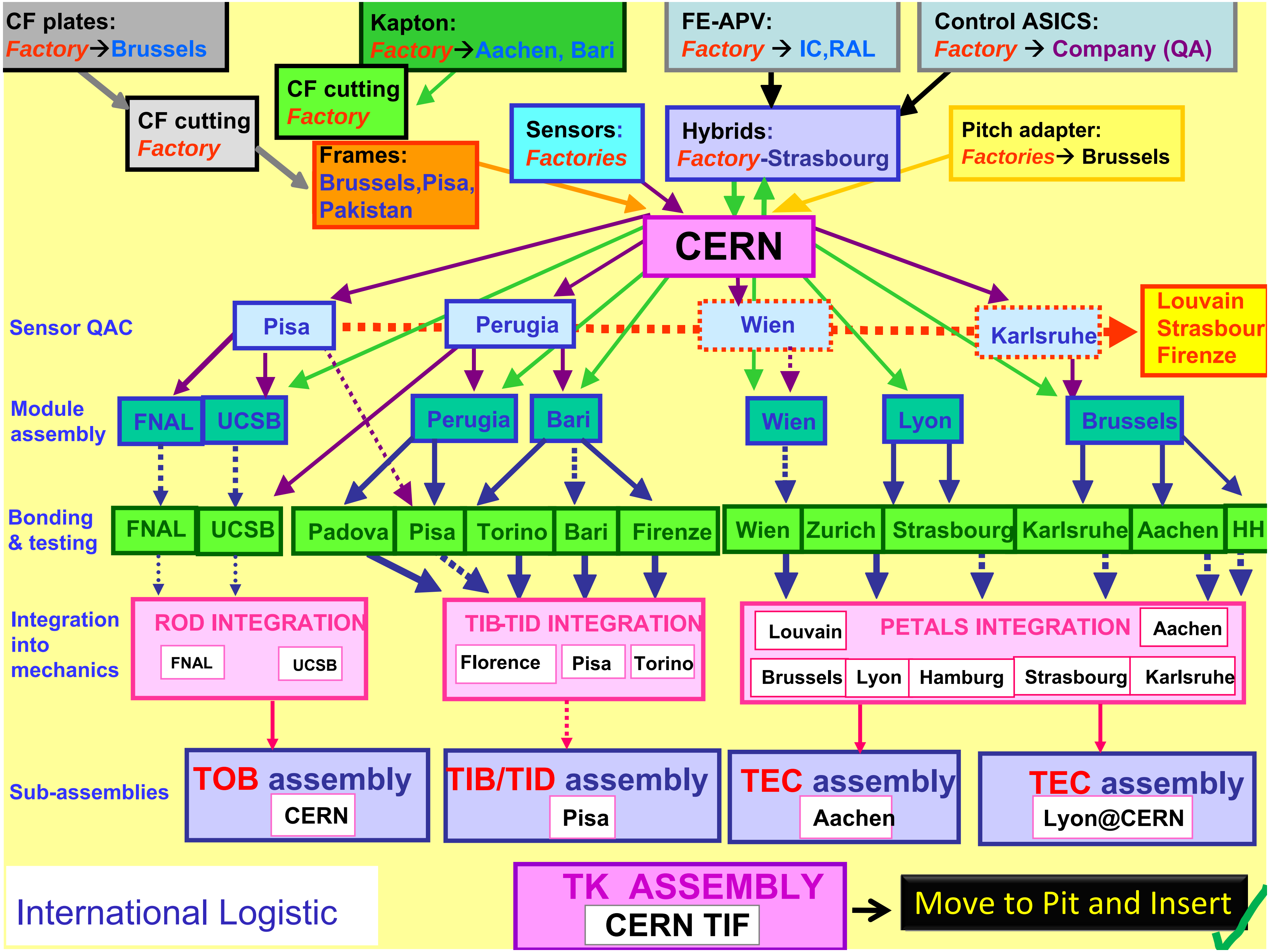
2. THE TRACKER

206 m² (Strips) + 1 m² (Pixel)
25.000 Silicon sensors
10Mio Strips
75.376 Readout chips
26.000.000 Wire bonds
37.000 Optical analogue connections
3.000 km Optical fibers

Radiation dose: $10^{13} – 10^{15}$ n_{eq} /cm²
Operation at -15⁰ C



30-times larger than CDF-Si-Detector



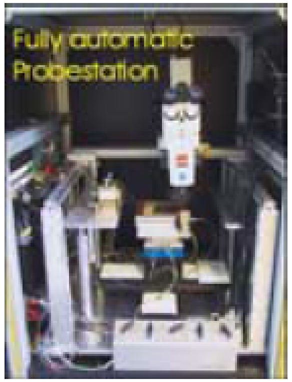
CF plates:
Factory→Brussels
Kapton:
Factory→Aachen, Bari
FE-APV:
Factory → IC,RAL
Control ASICS:
Factory → Company (QA)
CF cutting
Factory
CF cutting
Factory
Frames:
Brussels,Pisa,
Pakistan
Sensors:
Factories
Hybrids:
Factory-Strasbourg
Pitch adapter:
Factories→ Brussels
CERN
Sensor QAC
Pisa
Perugia
Wien
Karlsruhe
Louvain
Strasbour
Firenze
Module assembly
FNAL
UCSB
Perugia
Bari
Wien
Lyon
Brussels
Bonding & testing
FNAL
UCSB
Padova
Pisa
Torino
Bari
Firenze
Wien
Zurich
Strasbourg
Karlsruhe
Aachen
HH
Integration into mechanics
ROD INTEGRATION
FNAL
UCSB
TIB-TID INTEGRATION
Florence
Pisa
Torino
Louvain
PETALS INTEGRATION
Aachen
Brussels
Lyon
Hamburg
Strasbourg
Karlsruhe
Sub-assemblies
TOB assembly
CERN
TIB/TID assembly
Pisa
TEC assembly
Aachen
TEC assembly
Lyon@CERN
International Logistic
TK ASSEMBLY
CERN TIF
Move to Pit and Insert

CONTRIBUTIONS BY KARLSRUHE

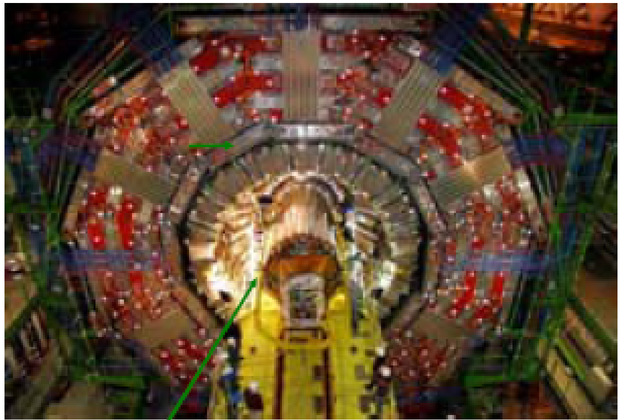
Wirebonding of 900 modules

Electronic test of modules

Precision machining of Detector supports



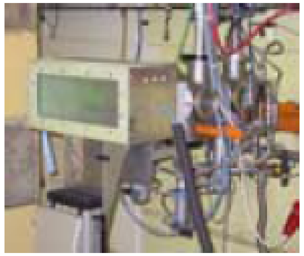
Quality controle of 8000 sensors



Insertion of tracker into CMS

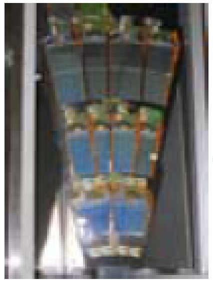
Assembly of supermodules (petals)

Pilot center for petal tests



Test of radiation hardness at cyclotron

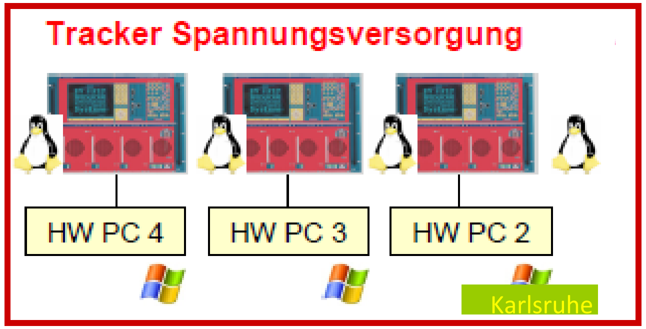
Assembly of tracker

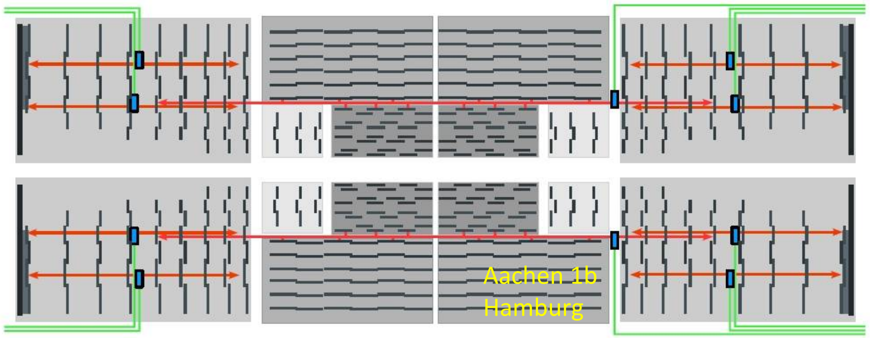


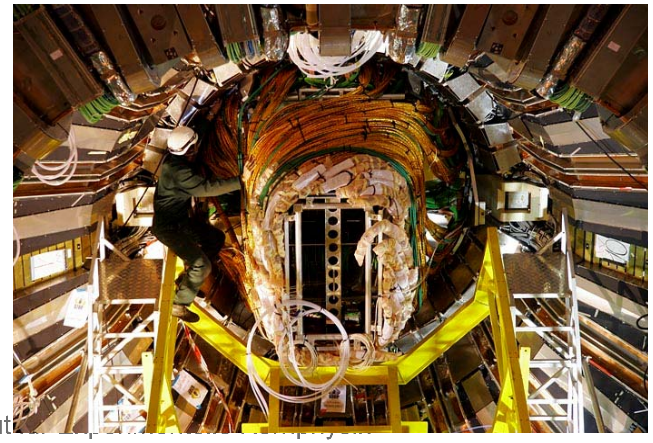
IEKP:Construction of 102 Petals for tracker (30%)

FURTHER CONTRIBUTIONS

- Detector control system
- Power supplies
- Cabling and commisioning in CMS





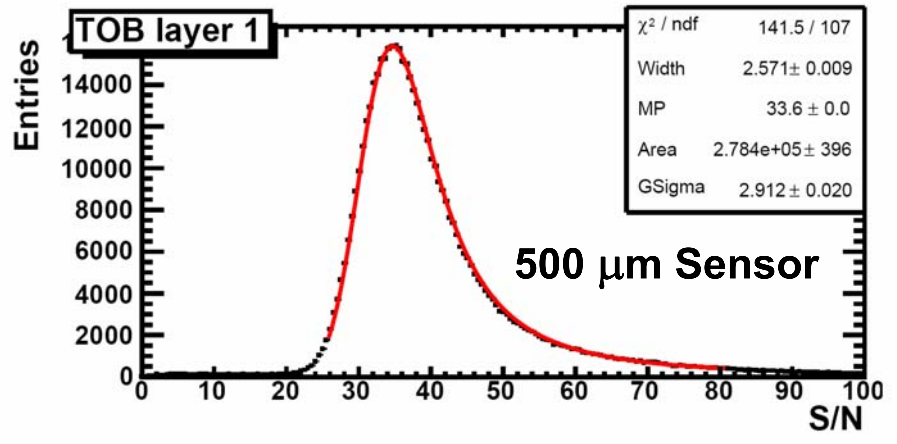


TRACKER PERFORMANCE

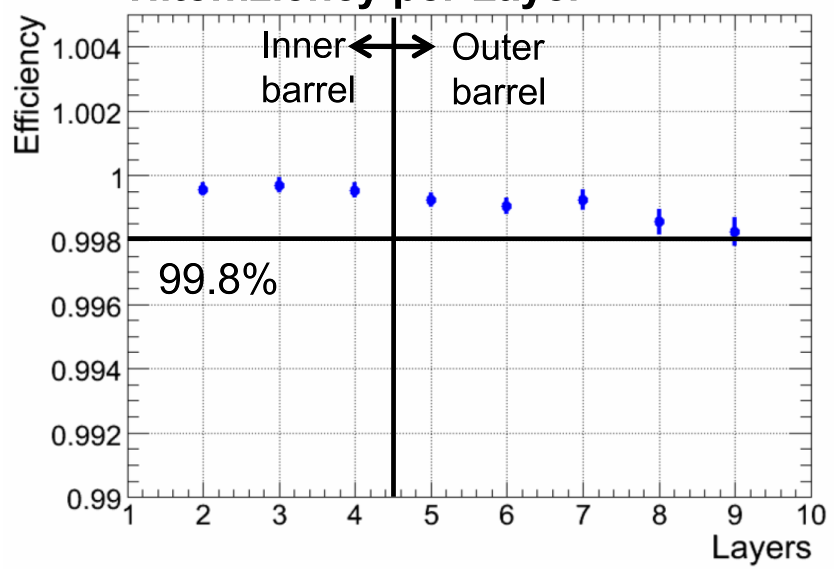
Test of Tracker:

- $-15°C < T_{cooling} < +15°C$
- 47 Million Cosmic-Triggers
- 3 tracking algorithms adapted to cosmics

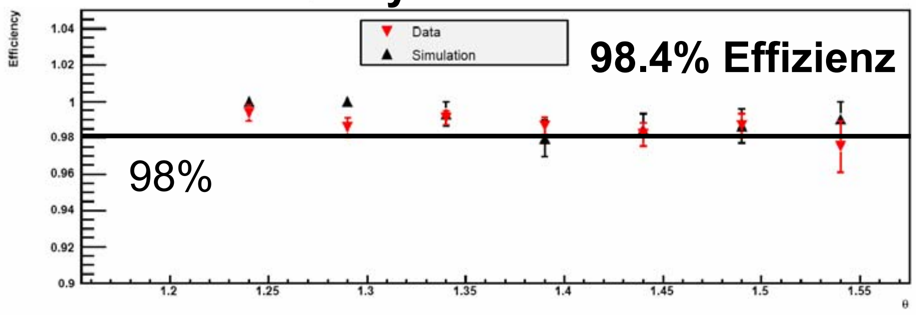
Signal / Noise (requirement: 10)



Hiteffiziency per Layer



Track efficiency in Outer Barrel vs. θ

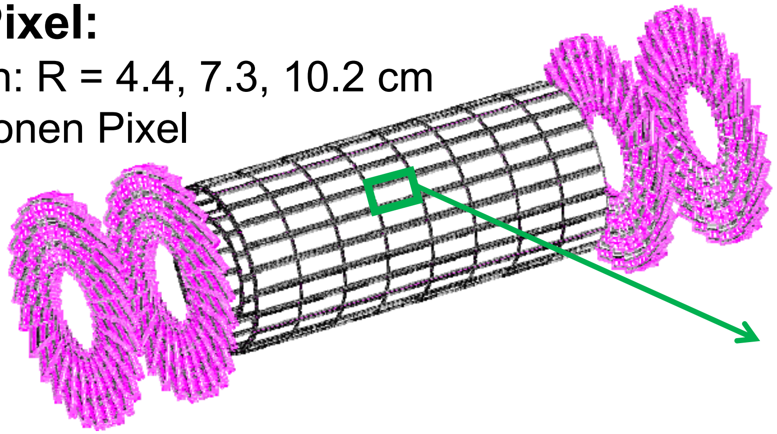


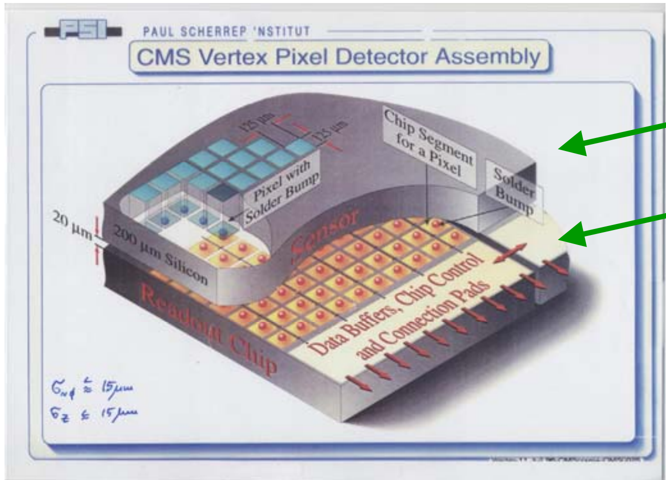
3. THE PIXEL DETECTOR

- Gute Impaktparameterauflösung für sekundäre Vertices von b- und τ-Zerfällen
- *Seeds* für Spurfindung

- **Hybrid-Technologie**
- **n+ Pixel (100 μm (r-ϕ) x 150 μm (z)) auf n-Substrat**
- Ladungsteilung zw. Pixeln wegen Lorentzwinkel (Barrel) und Geometrie (Forward) plus analoge Auslese -> **15-20 μm Ortsauflösung**

Barrel Pixel:
- 3 Lagen: R = 4.4, 7.3, 10.2 cm
- 48 Millionen Pixel





Sensor

Auslese

Chips
0.25 μm
CMOS

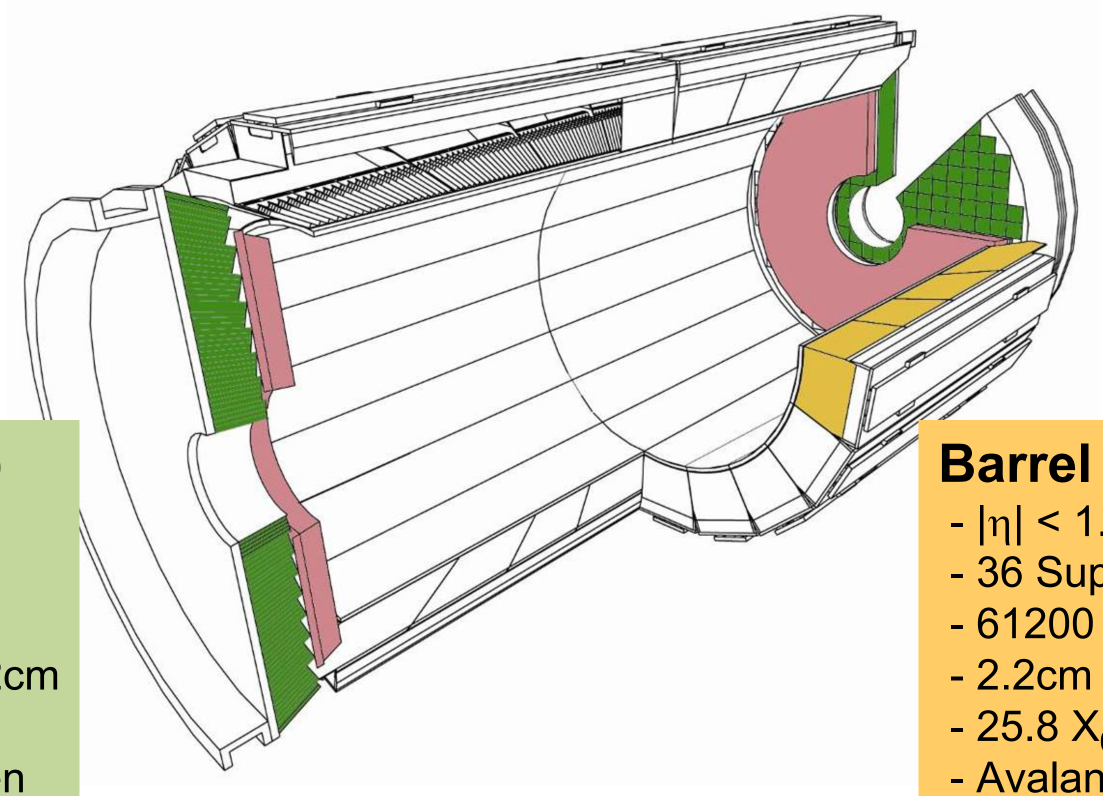
Forward Pixel:
- 2 x 2 Disks: z = $\pm$ 34.5, $\pm$ 46.5 cm
- 18 Millionen Pixel

4. THE ELECTROMAGNETIC CALORIMETER

- Benchmark-Kanal: H -> $\gamma\gamma$

- **Anforderungen:**
  - Exzellente Energieauflösung
  - Hohe Granularität
  - Strahlenresistenz
  - Schnelligkeit

Preshower zur π^0-Unterdrückung
- $1.6 < |\eta| < 2.6$
- Bleiabsorber/Siliziumstreifendetektoren
- 2 Lagen $\triangleq$ 2 X_0



Endkappen (EE)
- $1.479 < |\eta| < 3.0$
- 2 x 2 „Dees“
- 2 x 7324 Kristalle
- 2.9cm x 2.9cm x 22cm
- 24.7 X_0
- Vakuumphototrioden

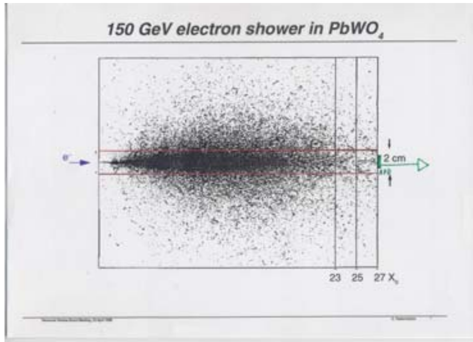
Barrel (EB)
- $|\eta| < 1.479$
- 36 Supermodule
- 61200 Kristalle
- 2.2cm x 2.2cm x 23cm
- 25.8 X_0
- Avalanche Photodioden

Bleiwolframat-Kristalle:

- Hohe Dichte: 8.28 g/cm^3
- Kurze Strahlungslänge: 0.89cm
- Kleiner Moliereradius: 2.2cm
- Schnell: 80% des Lichts wird in 25ns

- Geringe Lichtausbeute: 4.5 e$^-$ / MeV bei +18°C
- Lichtausbeute stark temperaturabhängig:
  –2.1% / °C bei +18°C
  -> T-Stabilisierung auf 0.05°C nötig!

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.8\%}{\sqrt{E\,(GeV)}}\right)^2 + \left(\frac{0.12\,GeV}{E\,(GeV)}\right)^2 + (0.3\%)^2$$




Dee 1
Commissioning (7 Jun)

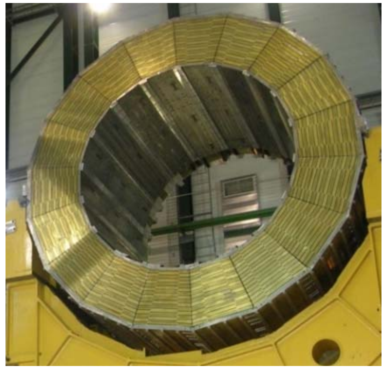

Dee 2
Start installing optical fibres (10 Jun)


Dee 3
fe boards installed (10 Jun)


Dee 4
All sc mounted (23rd May)

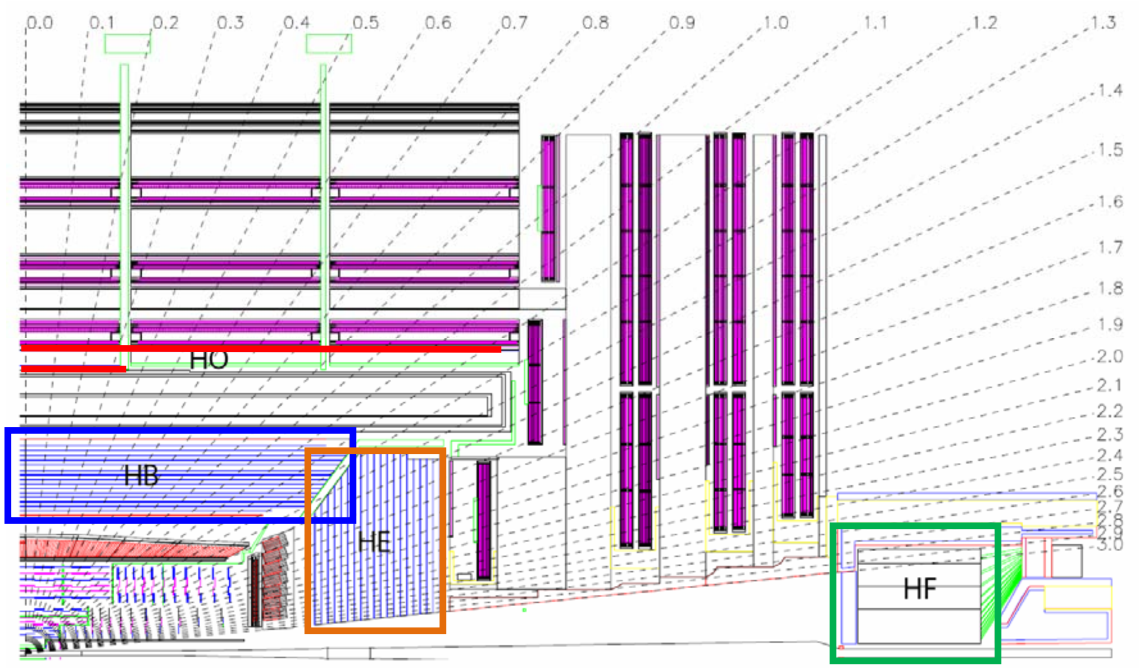
5. THE HADRON CALORIMETER

- Hauptabsorber: **Messing** (70% Cu, 30% Zn) wegen Verfügbarkeit
- Detektor: 70 000 Kacheln aus **Plastikszintillator** (Strahlenhärte, Langzeitstabilität)
- Erwartete rohe **Energieauflösung** für Pionen (Teststrahl): $\sigma/E = 120\%/\sqrt{E} + 6.9\%$



Hadron Outer (HO) Calorimeter als „Tail Catcher“

- Spule und Joch als Absorber
- 1-2 Lagen Szintillator



Hadron Barrel (HB)

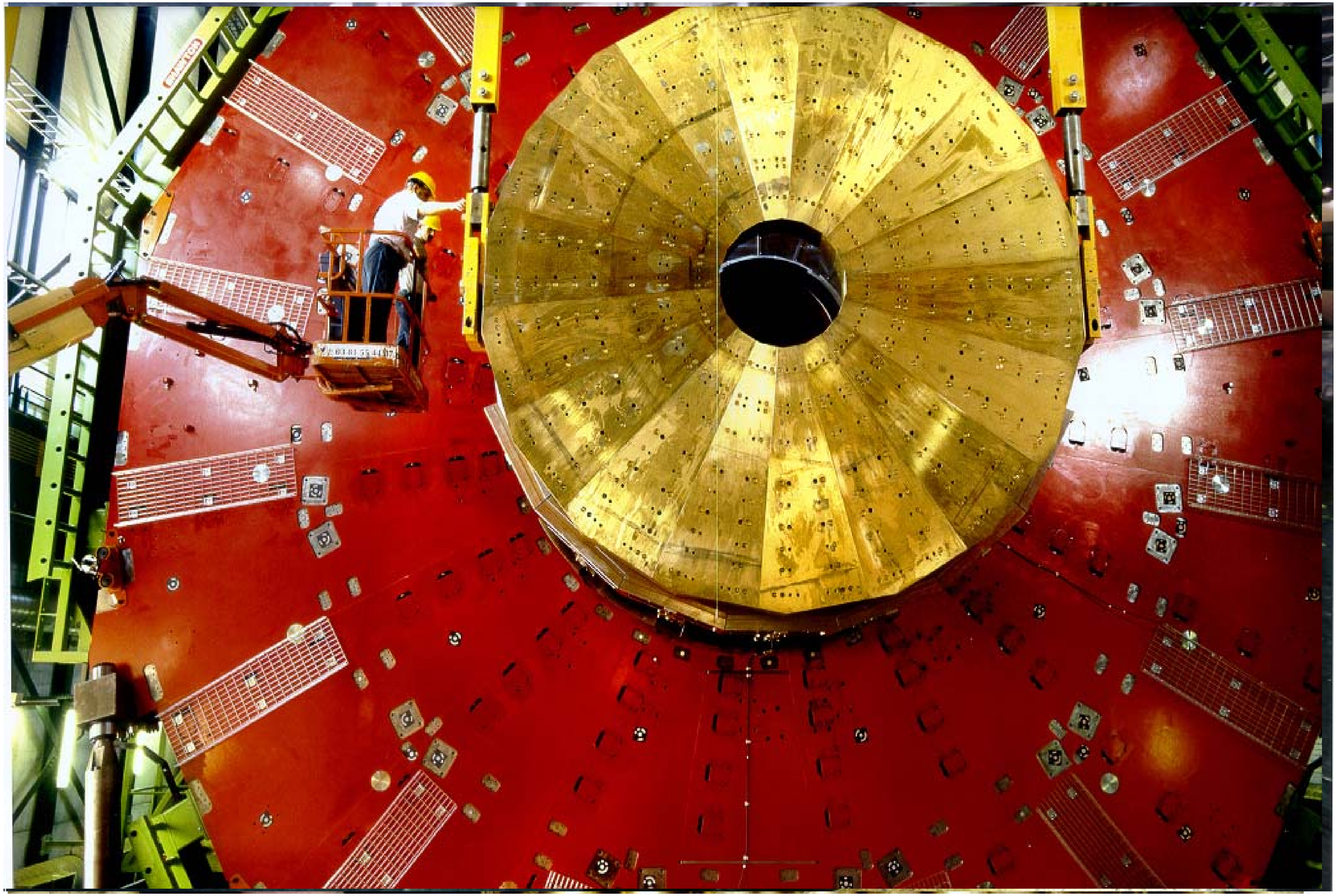
- 16 Lagen Szintillator
- 5.8 λ / $\sin\theta$

Hadron Endkappe (HE)

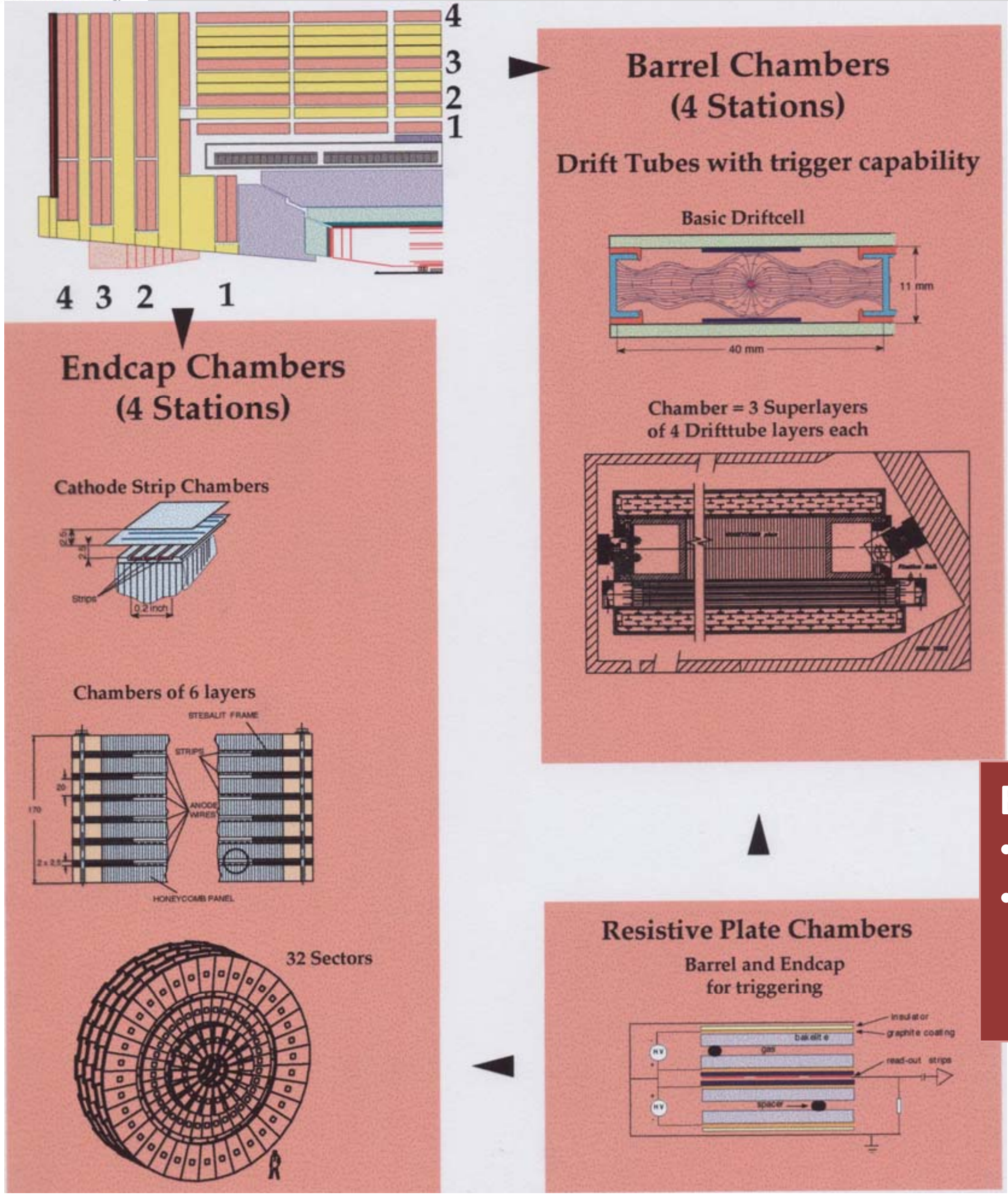
- 19 Lagen Szintillator
- 10 λ

Hadron Forward (HF)

- Dosis: 5 MGy bei $|\eta| = 5$
- Stahlabsorber
- Quartzfibern



6. THE MUON SYSTEM



Barrel ($|\eta| < 1.2$) :

- Niedrige Myon- & Untergrundrate
- B-Feld klein und im Joch verlaufend

Driftröhren

4 Lagen, 250 Kammern, 18000 m^2

Gas: 85% CO2, 15% Argon

Driftzeit: 380 ns

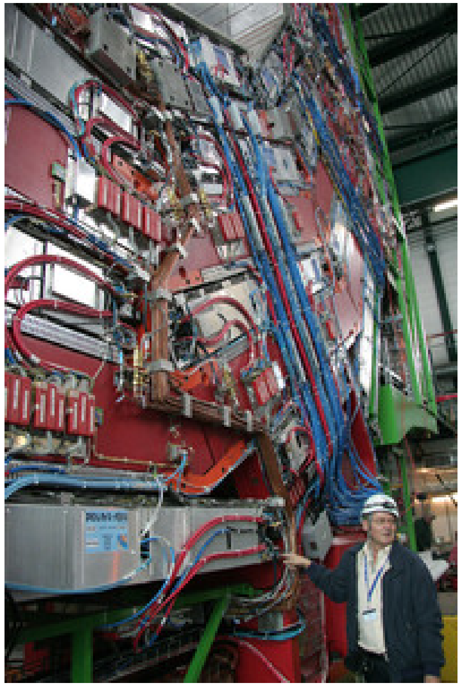
Endkappe ($0.9 < |\eta| < 2.4$) :

- Hohe Myon- & Untergrundrate: $\leq$ 1kHz/cm^2
- B-Feld groß und nicht uniform

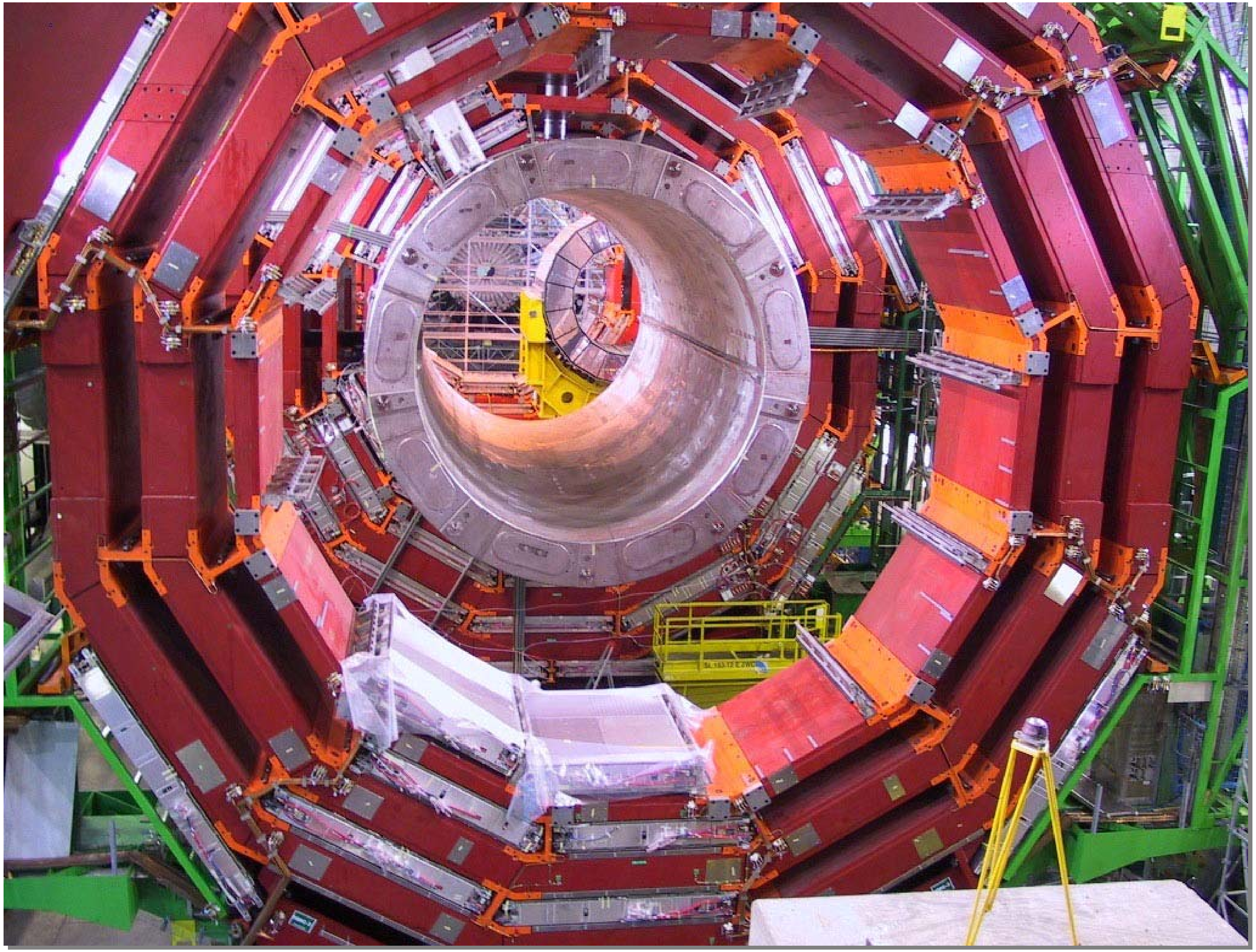
Kathodenstreifenkammern

3 - 4 Lagen, 468 Kammern, 5000m^2

CONSTRUCTION IN AACHEN

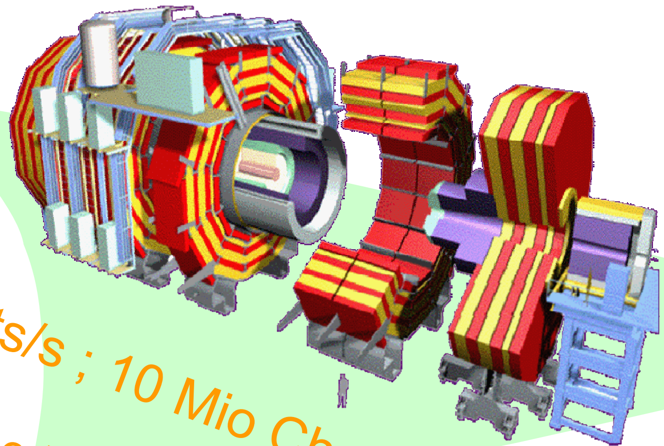


INSERTION OF MUON CHAMBERS



At CERN the World-Wide Web was invented.

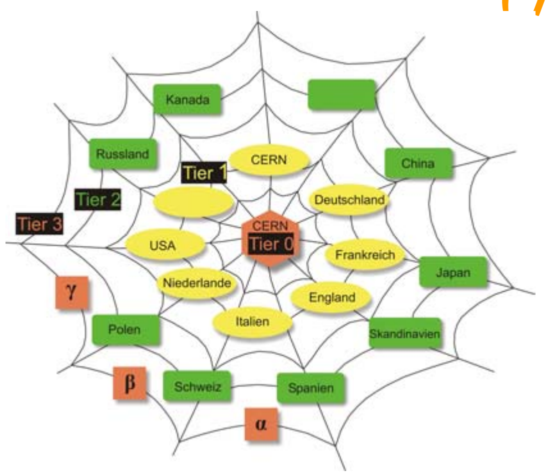
The Grid is a further evolution



40 MHz ; 10^9 Events/s ; 10 Mio Channels => **1 PetaByte/s**

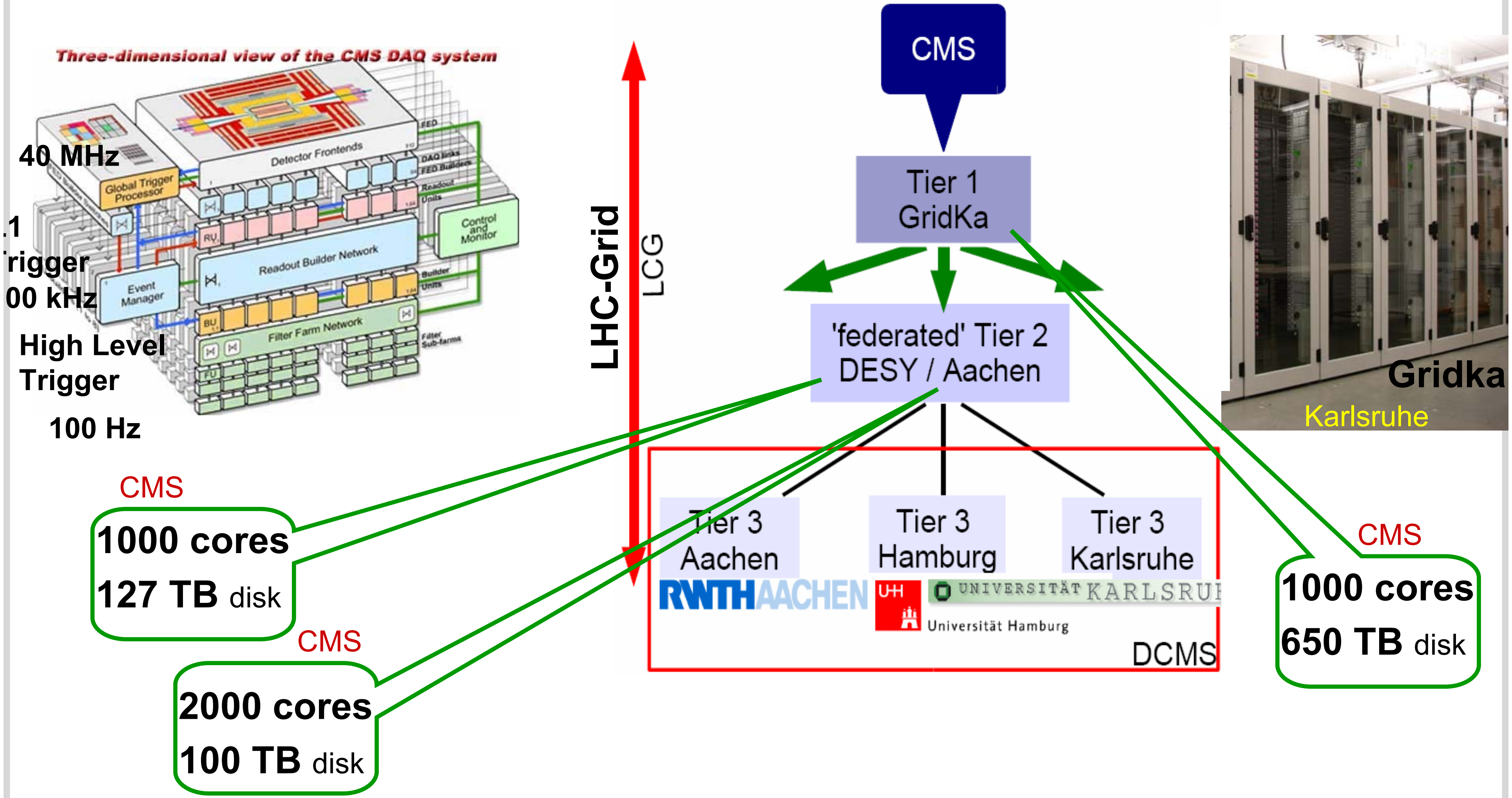
On-line Data reduction
And storage
100 Hz

~1PetaByte/Year
(1,4 Million CD)



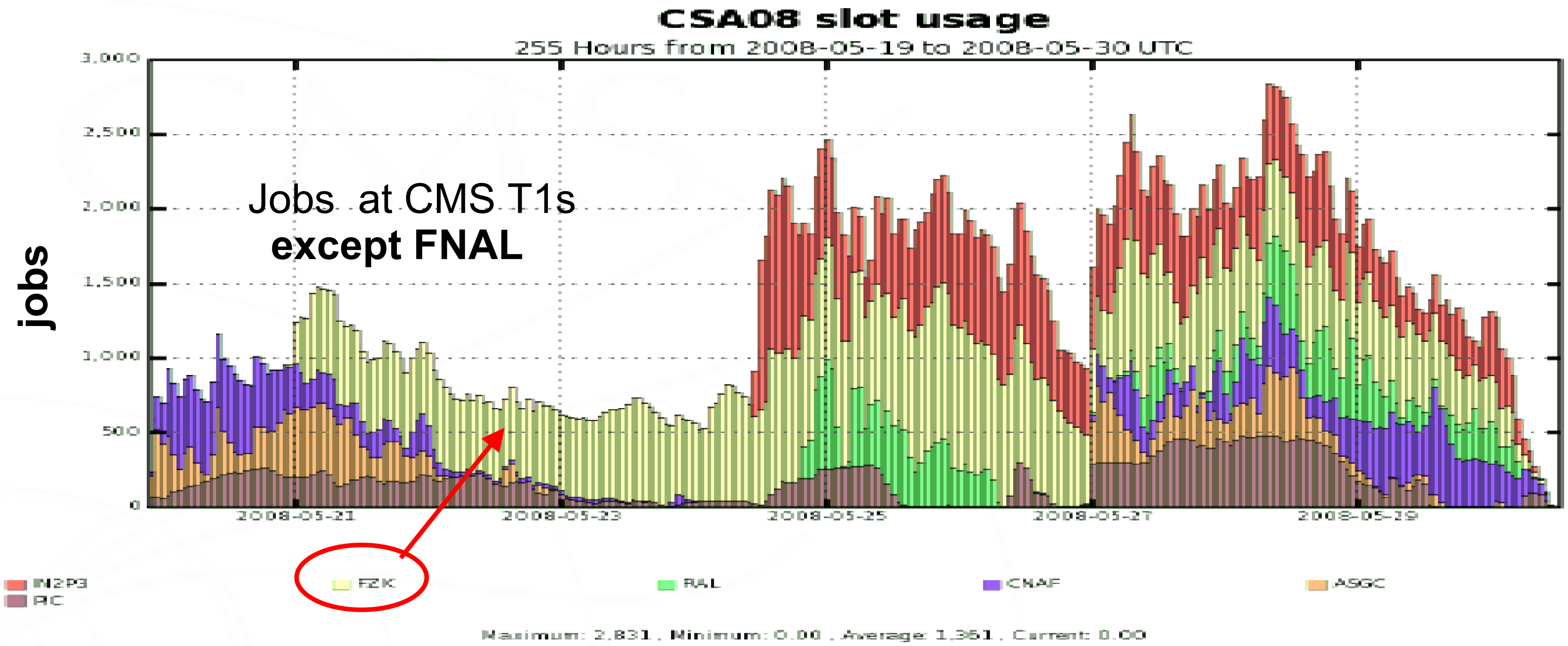
SOLUTION: THE GRID ⟶ KIT: GridKa (Tier 1)

CampusGrid (Tier 2-3)

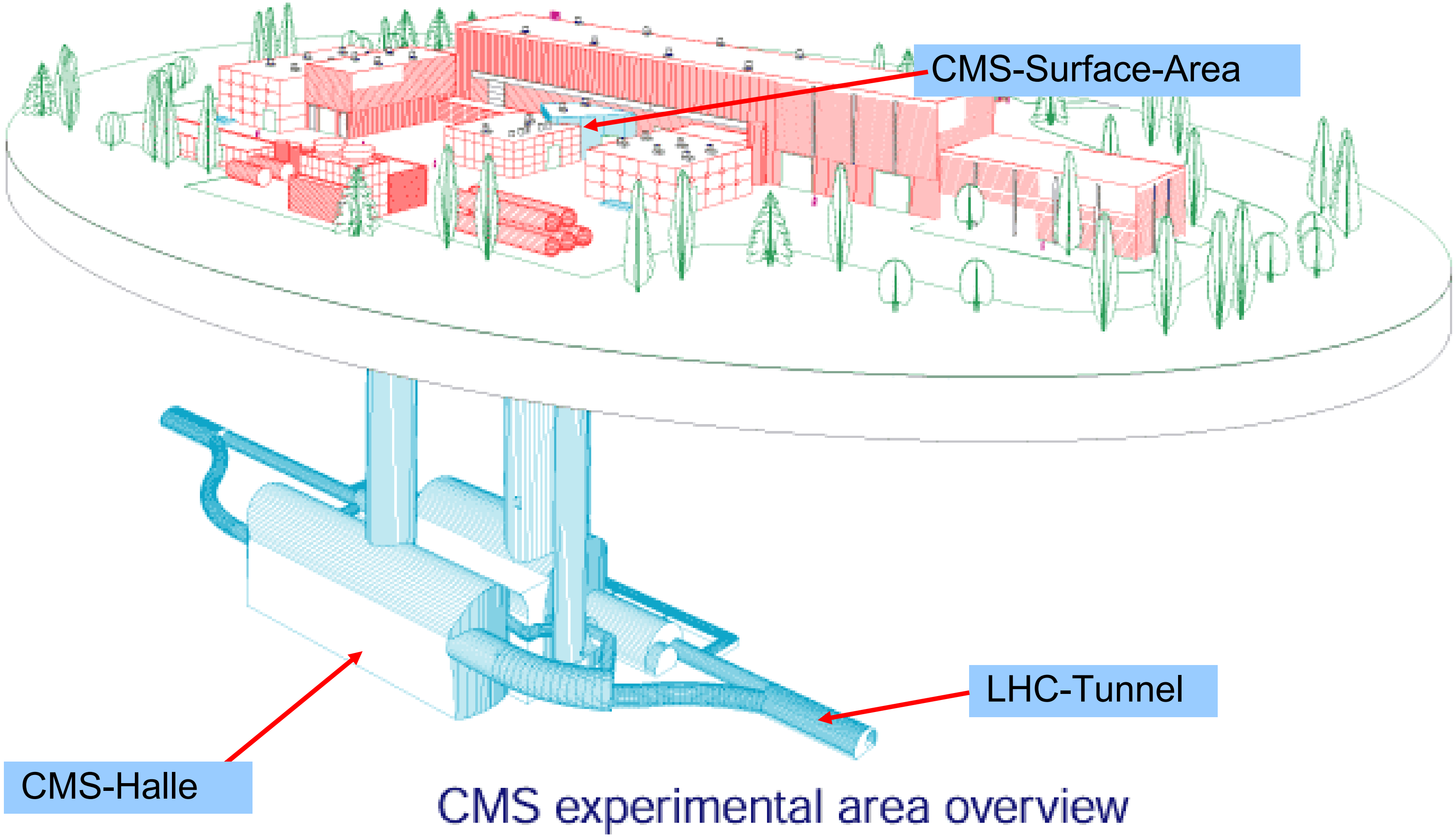

Three-dimensional view of the CMS DAQ system
40 MHz
Detector Frontends
Global Trigger Processor
Event Manager
Readout Builder Network
Filter Farm Network
Control and Monitor
High Level Trigger
100 Hz
LHC-Grid
LCG
CMS
Tier 1
GridKa
'federated' Tier 2
DESY / Aachen
Tier 3
Aachen
Tier 3
Hamburg
Tier 3
Karlsruhe
RWTHAACHEN
Universität Hamburg
DCMS
Gridka
Karlsruhe
CMS
1000 cores
127 TB disk
CMS
2000 cores
100 TB disk
CMS
1000 cores
650 TB disk

GridKa Performance, CMS

CCRC08 = LHC *computing readiness challenge* 2008



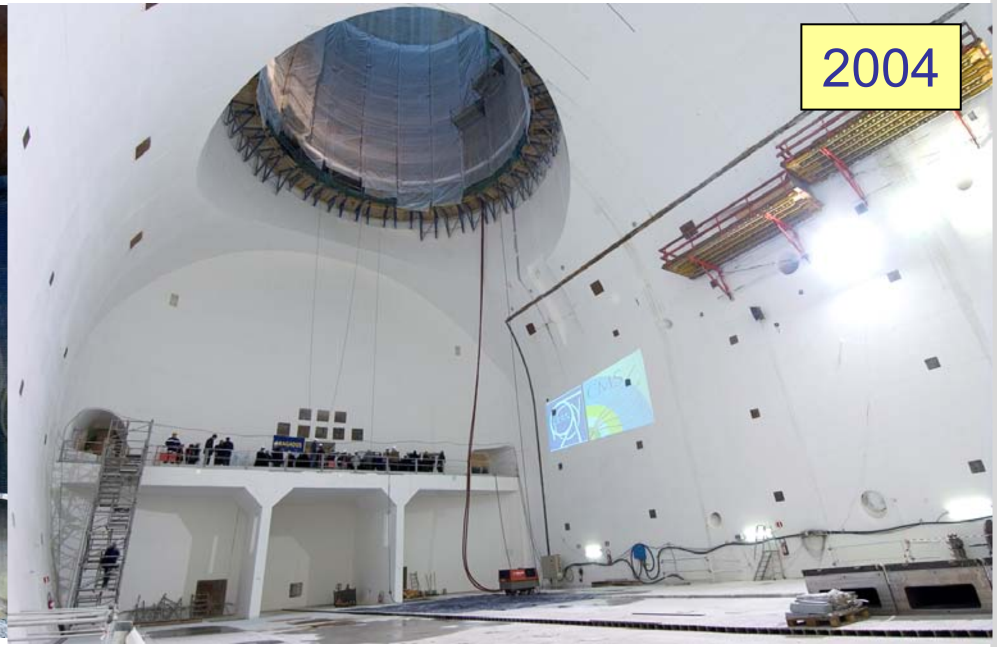
FINAL MOUNTING IN THE CAVERN



CMS ZONE IN CESSY


2002

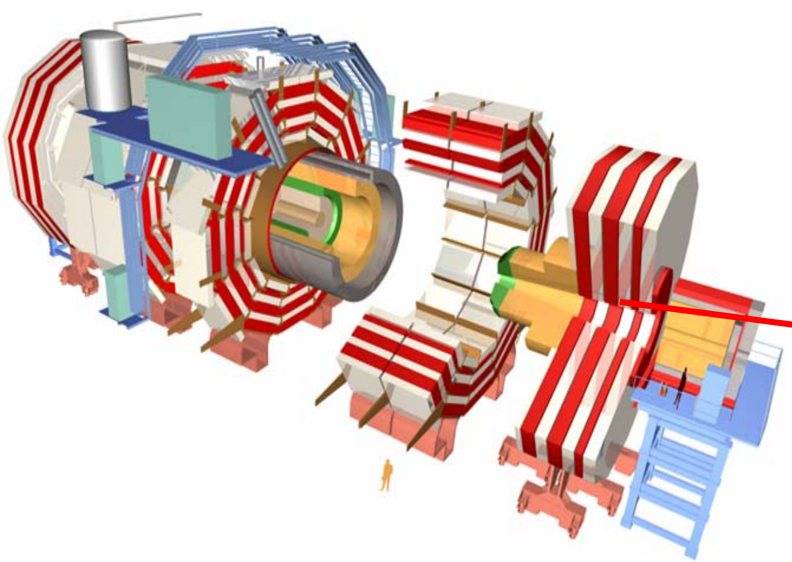

2003


2004

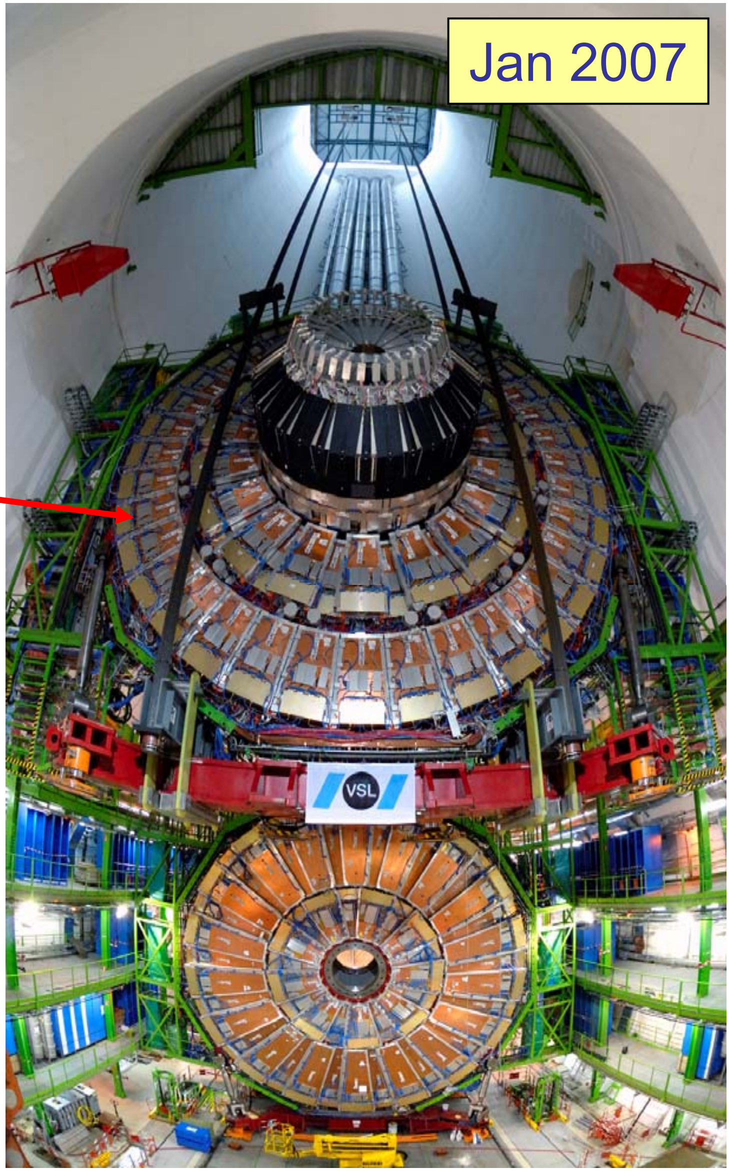
TESTS OF FIRE EXTINGUISHER

FINAL ASSEMBLY

Lowering of an End Cap

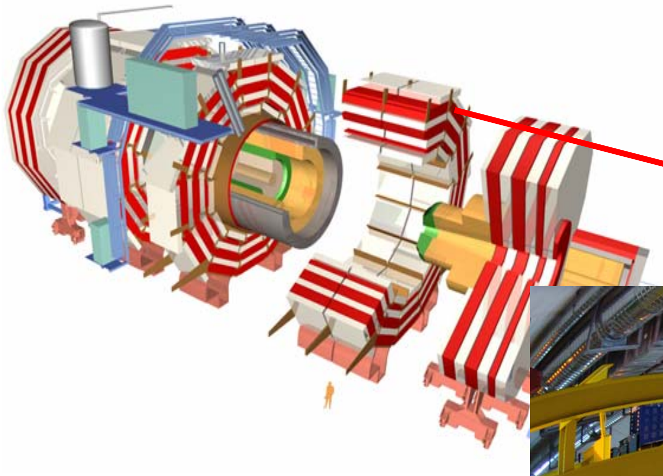


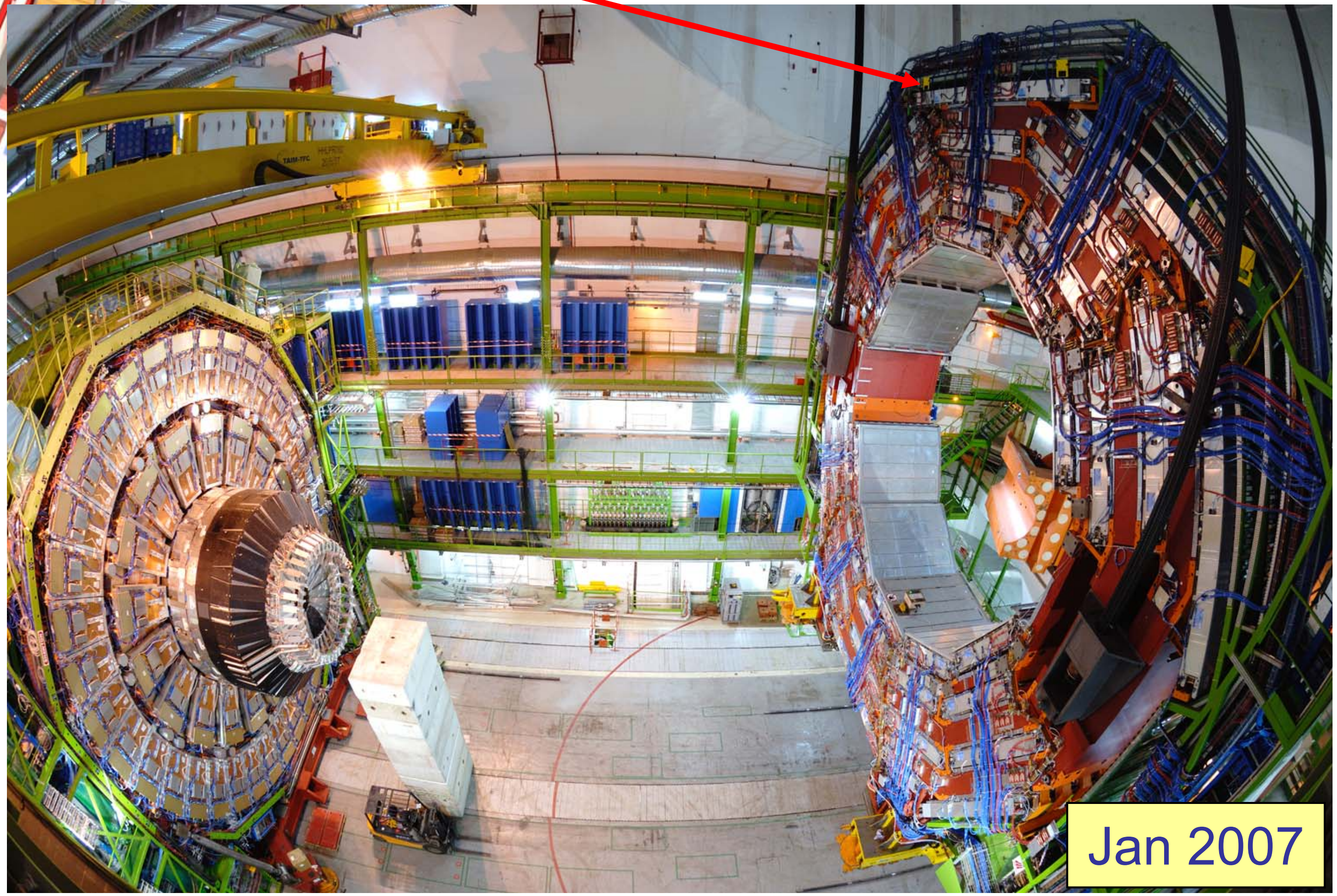
2000 ton crane



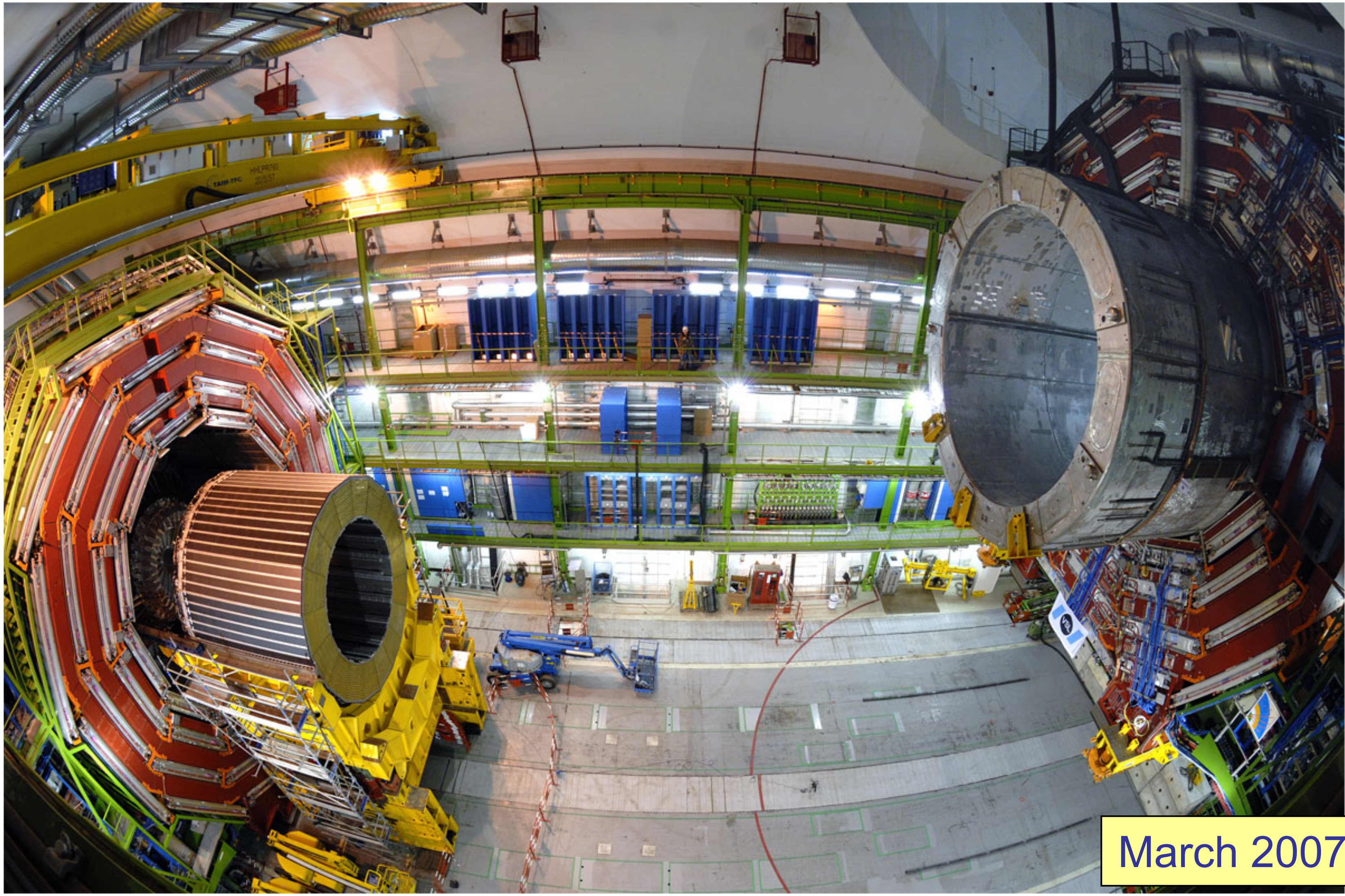
Jan 2007

Lowering of a Barrel Ring





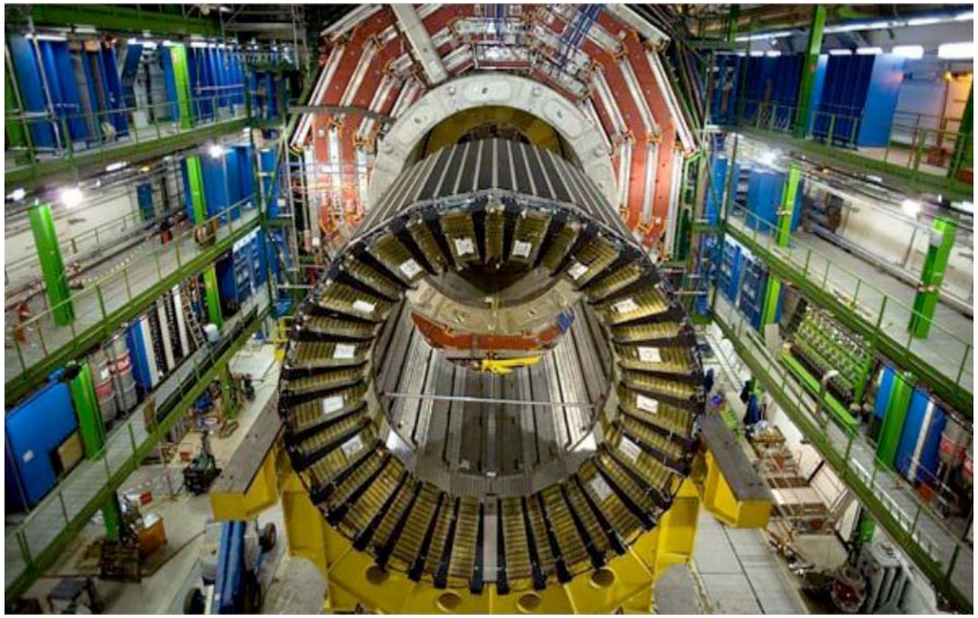
Lowering of the 1500 ton central piece

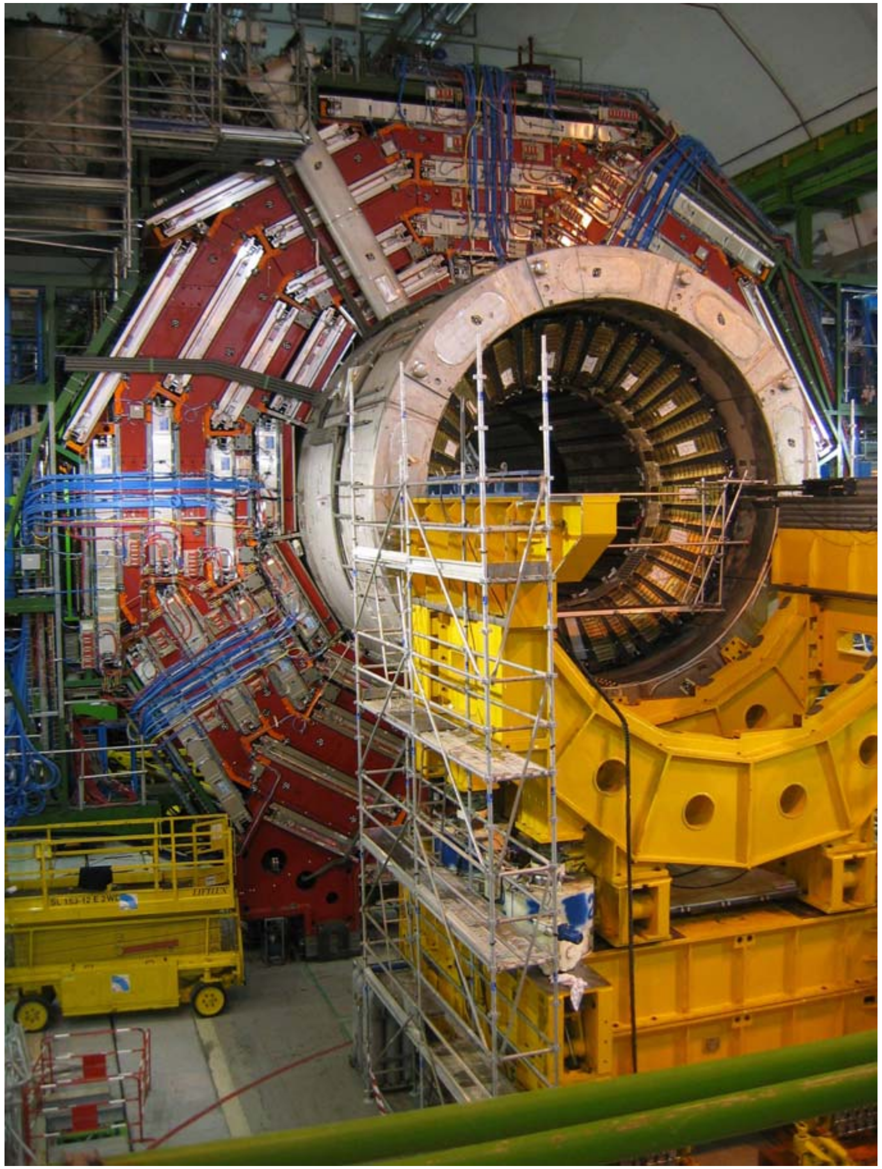


March 2007

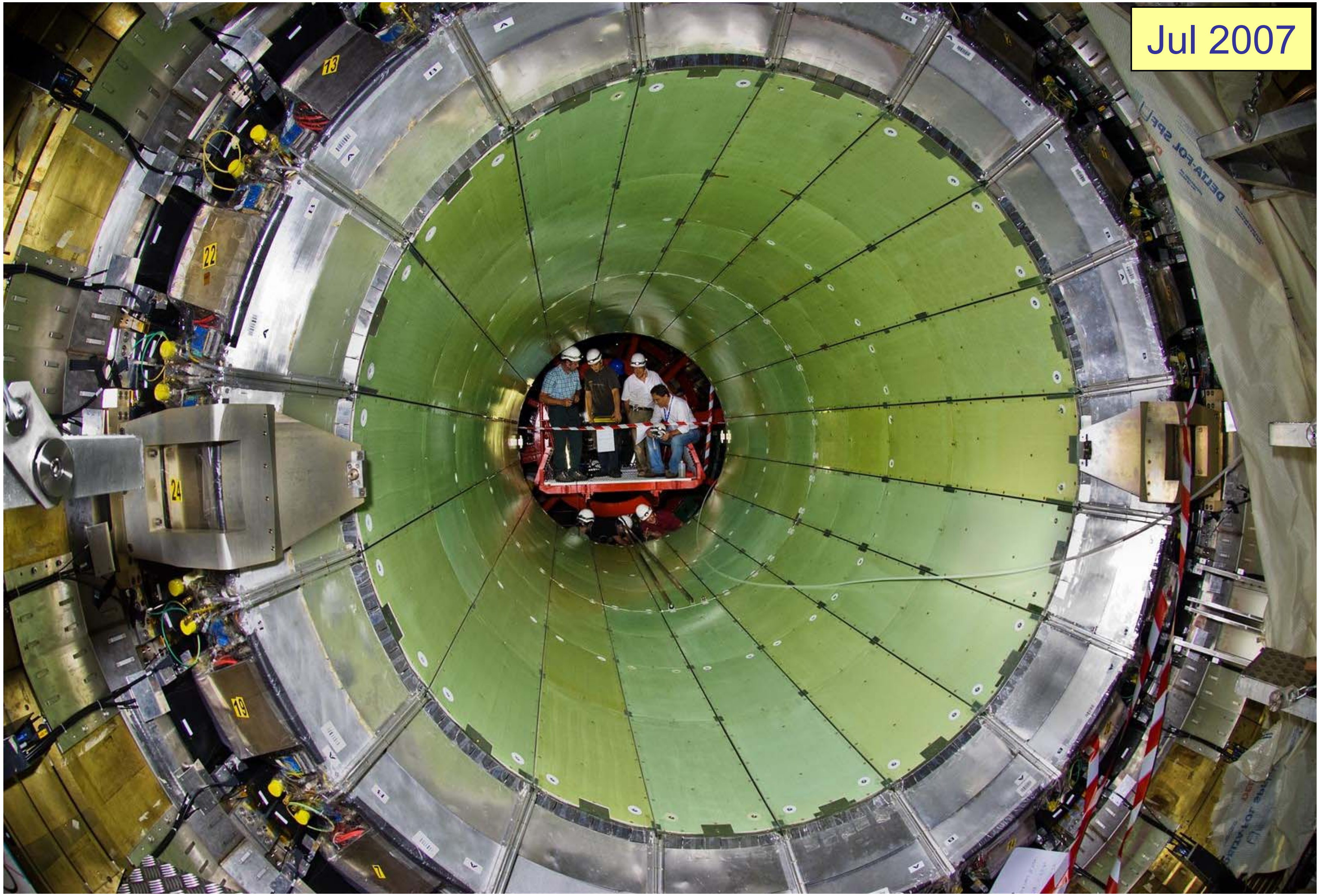
INSERTION OF THE HADRON CALORIMETER

Ap. 2007

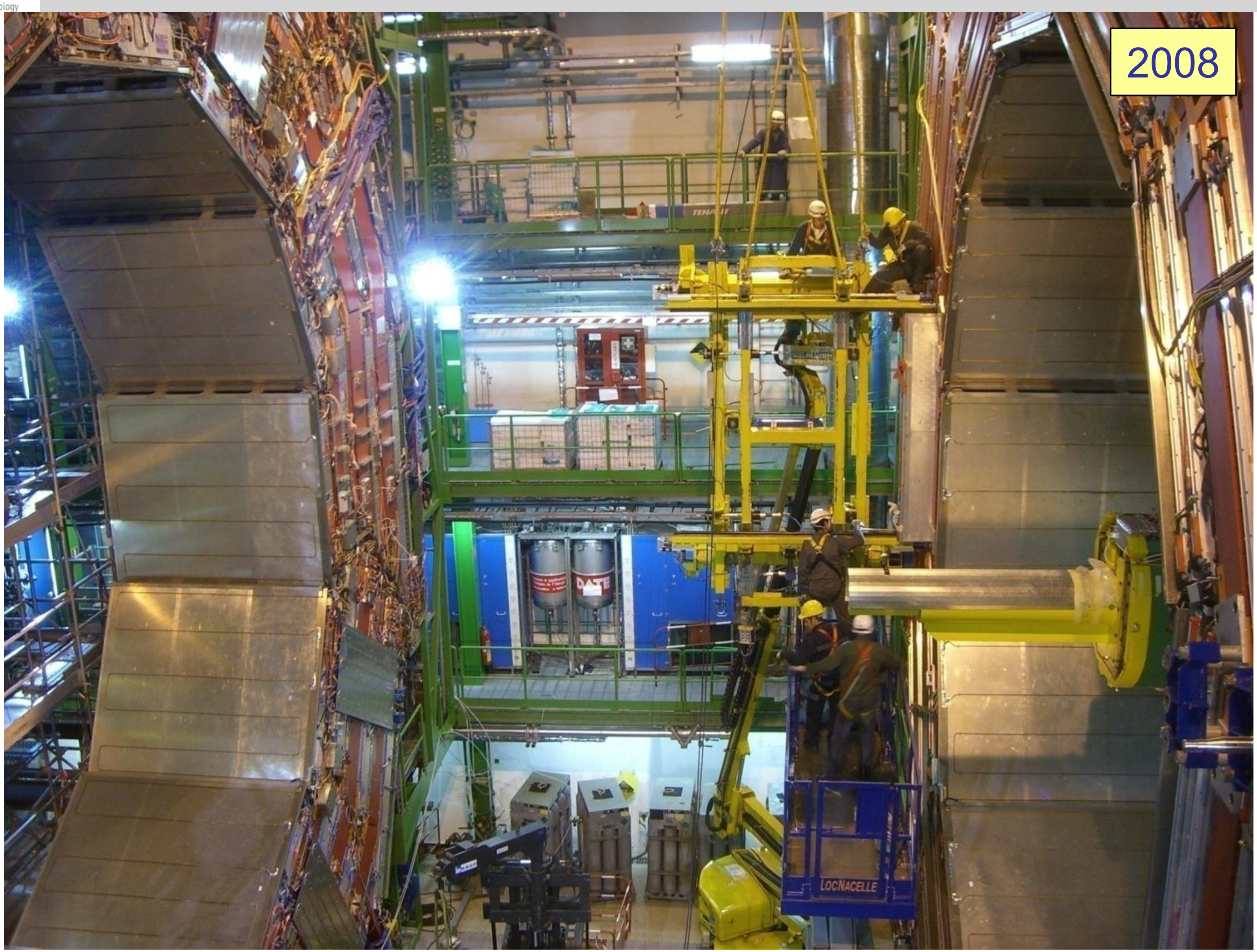




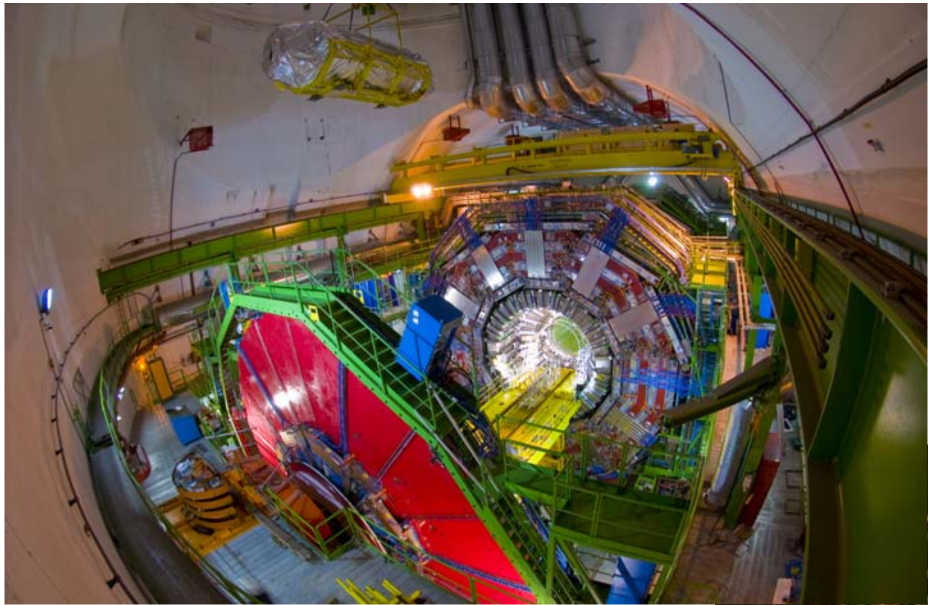
… AND THE EM CALORIMETER



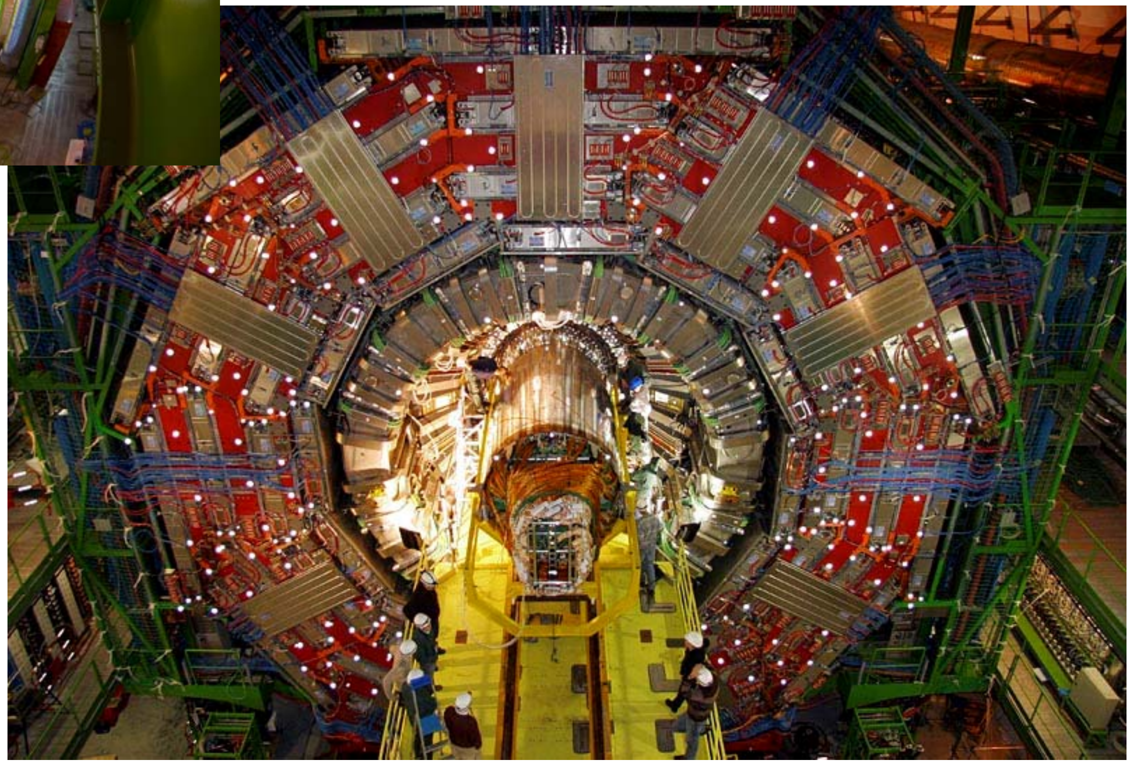
FINAL TESTS ON THE MUON SYSTEM



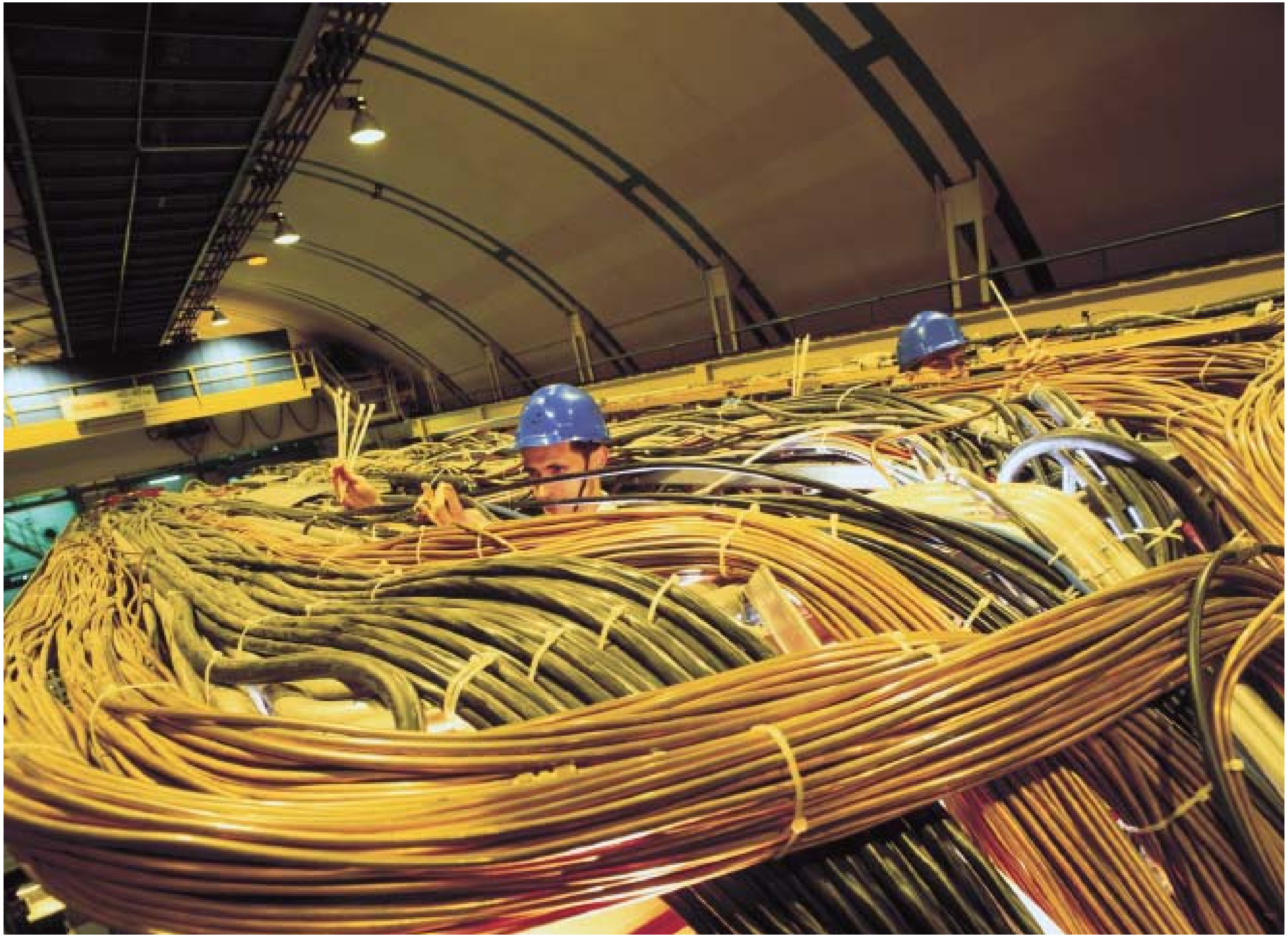
INSERTION OF THE TRACKER



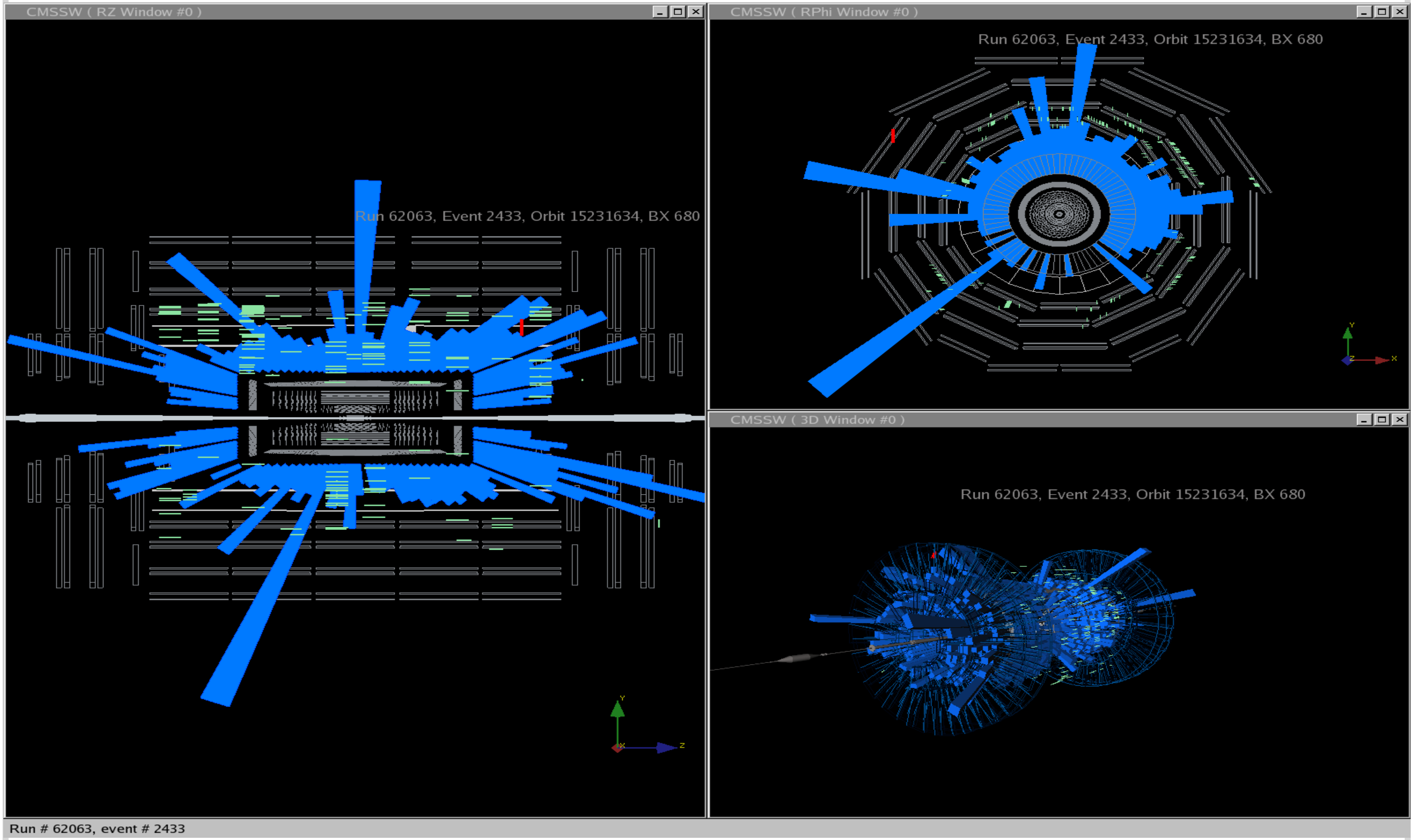
Dez. 2007



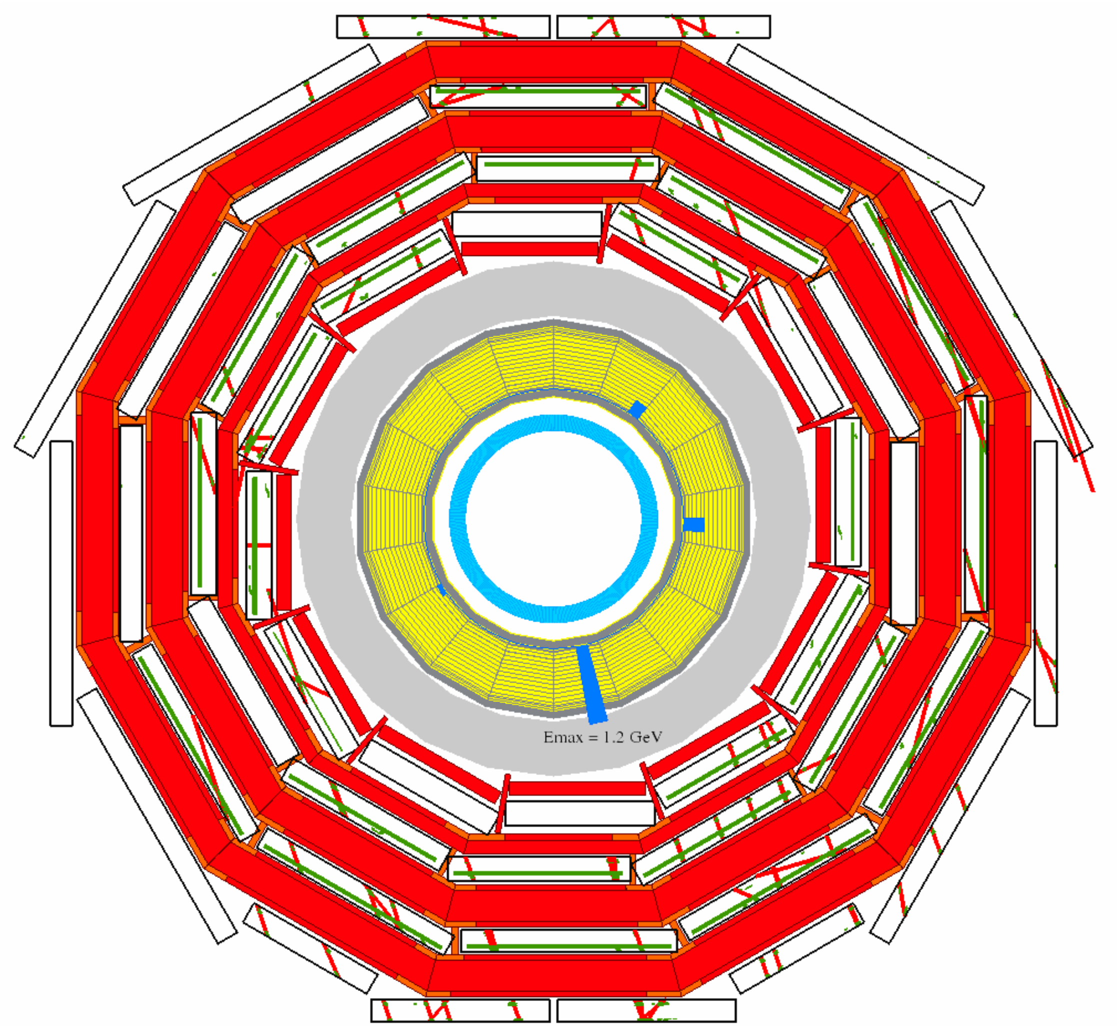
CABLES



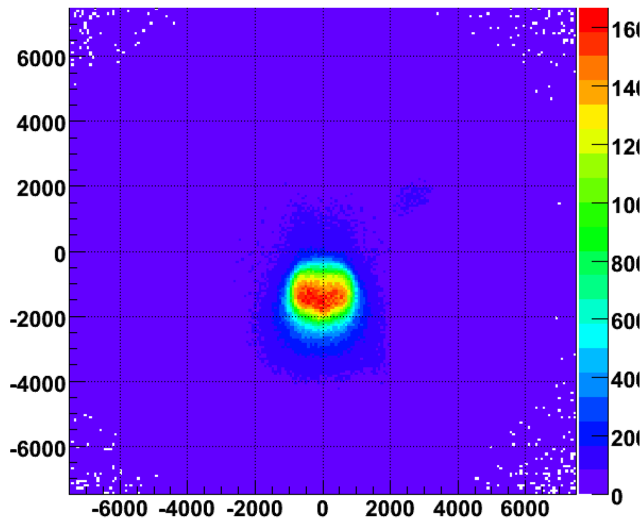
FIRST HITS IN CMS SEPT. 08



OBSERVATION OF MUON SHOWERS

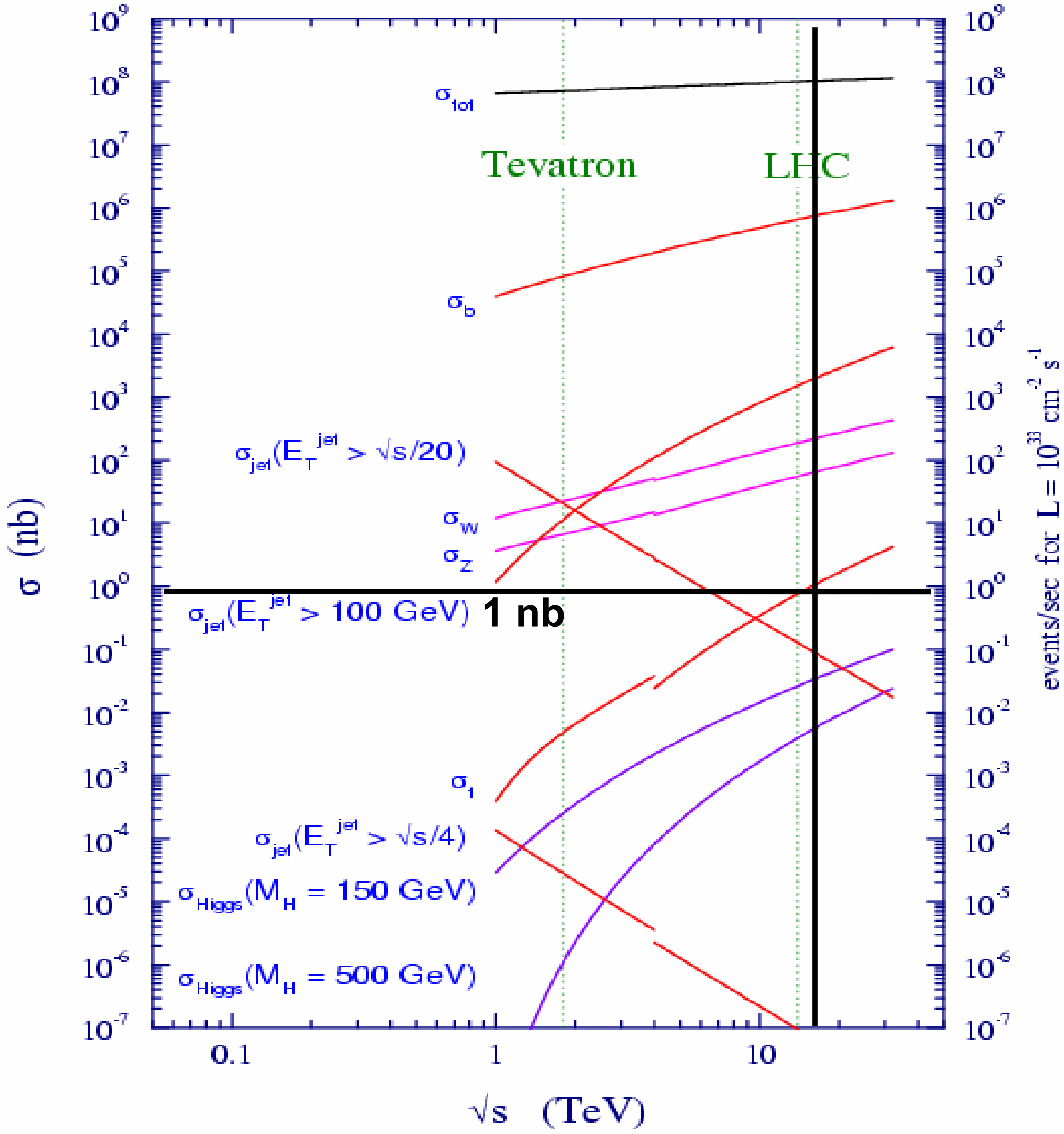


Muon tracks extrapolated to the surface



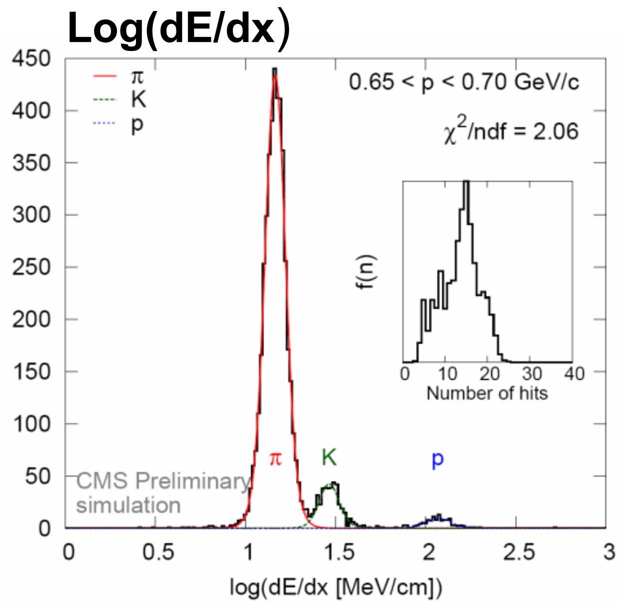
III. FIRST PHYSICS WITH CMS

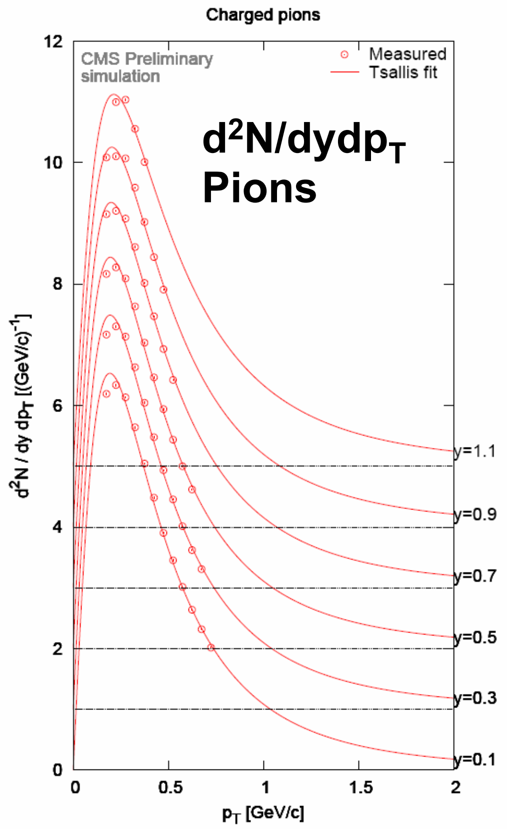
- **Hypothesis: $0 < \int L \leq 1\ fb^{-1}$ in 2010**



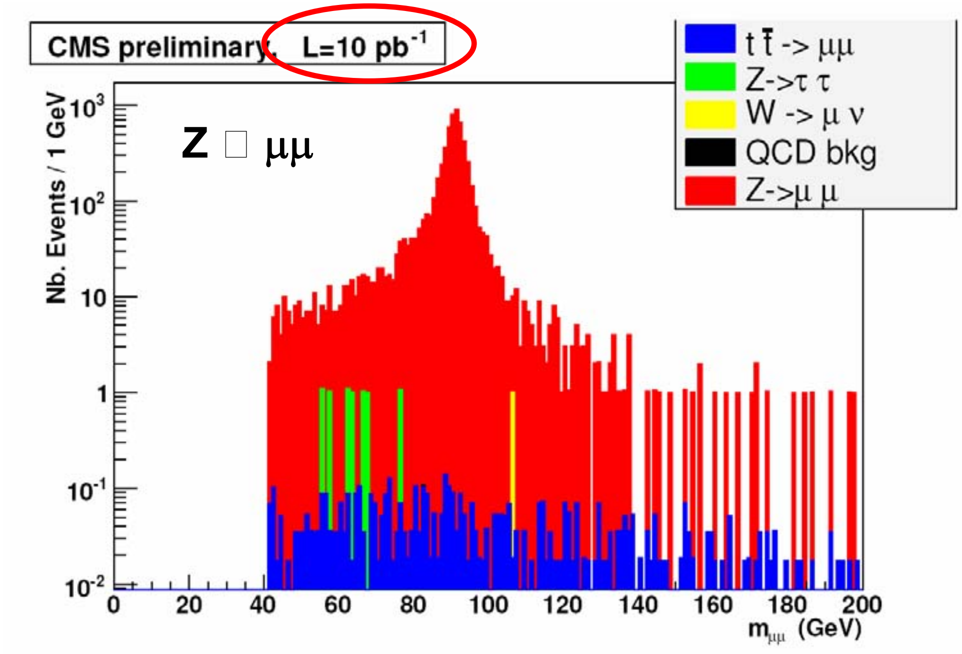
QCD STUDIES

- **Minimum Bias = inelastic soft collisions**
- **Important to know:**
  - Minimum Bias ist background for all other channels
  - Radiation dose, occupancy, …
- Minimum or zero bias trigger (≈ 1 Hz)
- p_T < 1GeV for most particles
- Separation of π, K and p through **dE/dx** in Silicon-Tracker (!)

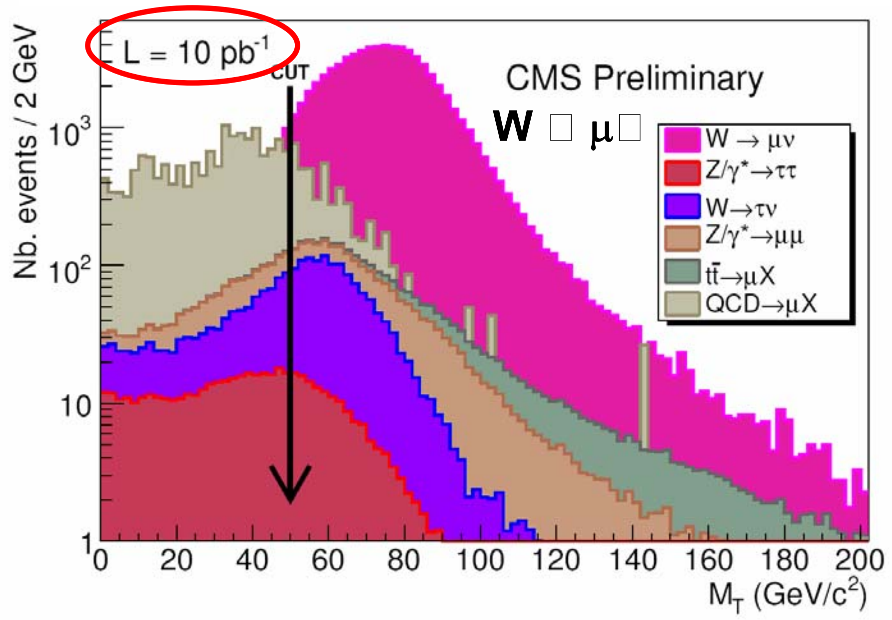




CMS PAS QCD_07_001



- W rekonstruiert aus transversaler Masse (Myon-p_T & MET)
- QCD-BG im W-Kanal aus Daten (Matrix-Methode)
- Dominanter systematischer Fehler: Impulsskala (≈ 3%)



TOP PHYSICS

Paarproduktion: σ = 830 pb in NLO □ ca. 1 Ereignis / s bei 10^{33} $cm^{-2}s^{-1}$

t □ Wb mit BR ≈ 100% □ Topologie hängt vom W-Zerfall ab

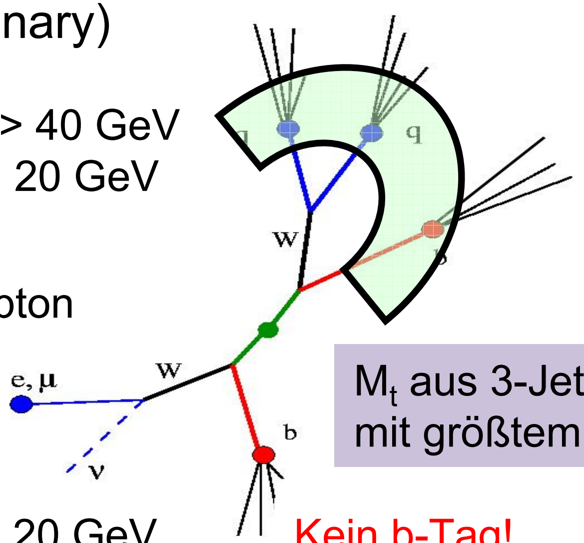
- **bb qq qq** (46%) : Kinematik rekonstruierbar, aber hoher QCD-BG und Kombinatorik
  Nützlich zur Kalibration von b-tagging und Jet-Energieskala
- **bb l□ qq** (44%) : „Goldener Kanal“ zur Massenbestimmung
- **bb l□ l□** (10%) : sehr sauber, hohes S/B, aber keine direkte Massenbestimmung

Bsp. Semi-leptonischer Kanal
(Atlas preliminary)

3 Jets mit p_T > 40 GeV
1 Jet mit p_T > 20 GeV

Isoliertes Lepton
p_T > 20 GeV

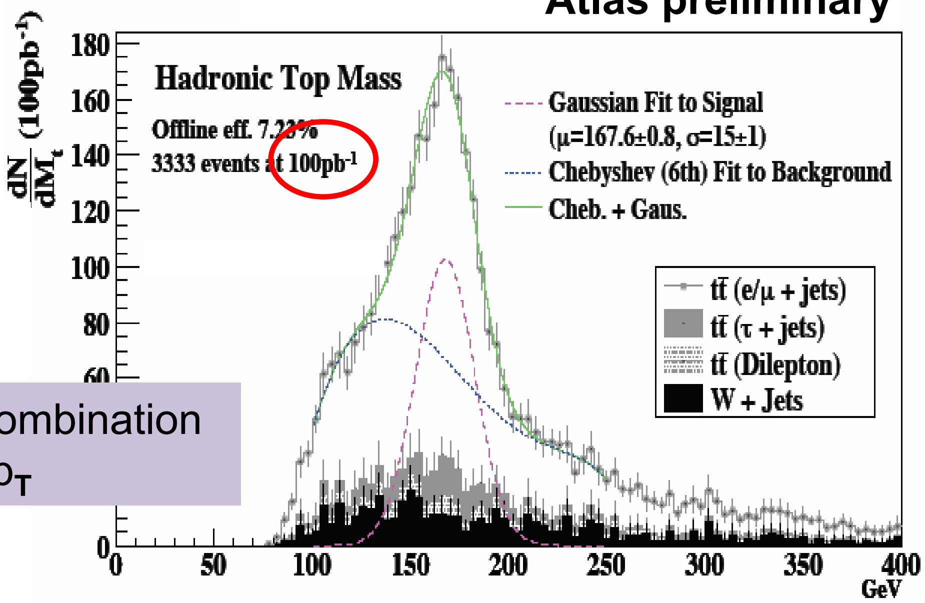
MET > 20 GeV



Kein b-Tag!

M_t aus 3-Jet-Kombination
mit größtem $\sum p_T$

Atlas preliminary

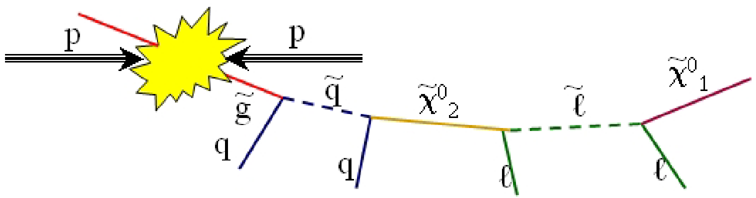


Starke Produktion von Gluinos & Squarks

Typ. Wirkungsquerschnitt @ NLO: 10 pb

CMS P-TDR (2006)
Keine K-Faktoren

Lange Zerfallsketten:



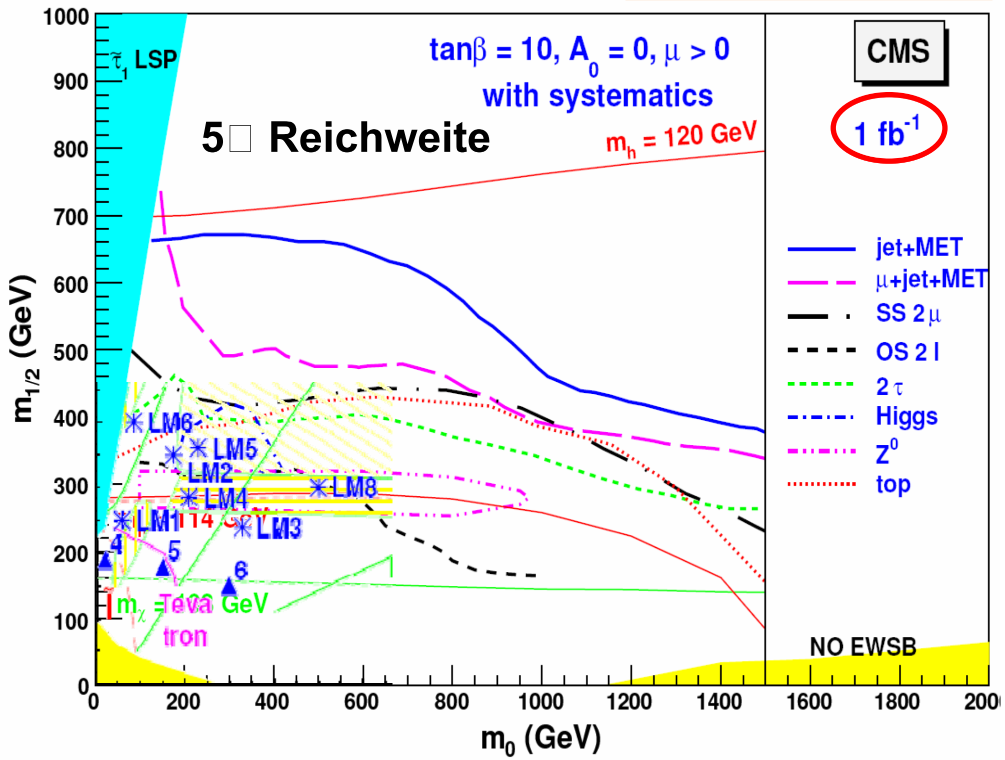
⇒ Jets + Leptonen + missing E_T

Meist minimale Modelle (mSUGRA)

Trotzdem großer Parameterraum

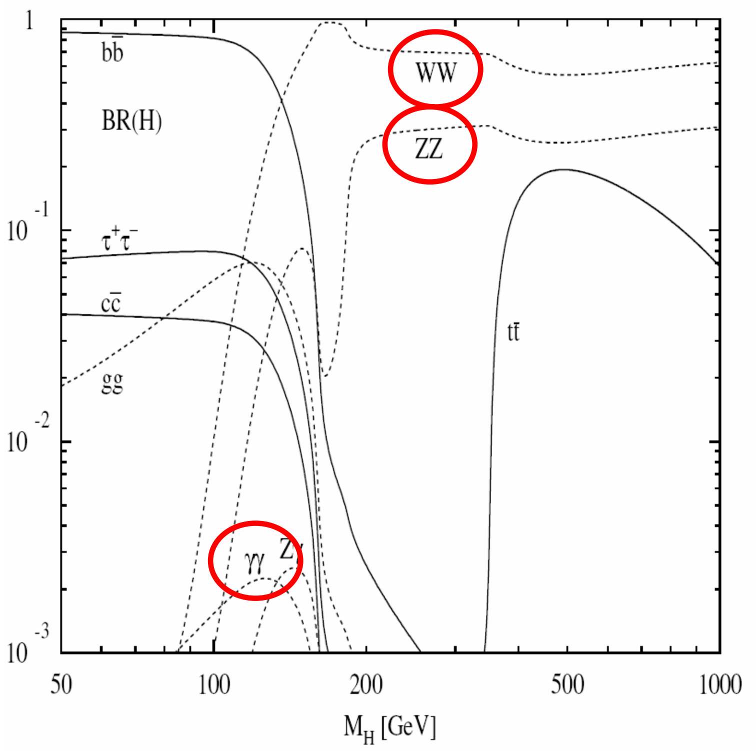
□ Wahl von Benchmark-Punkten

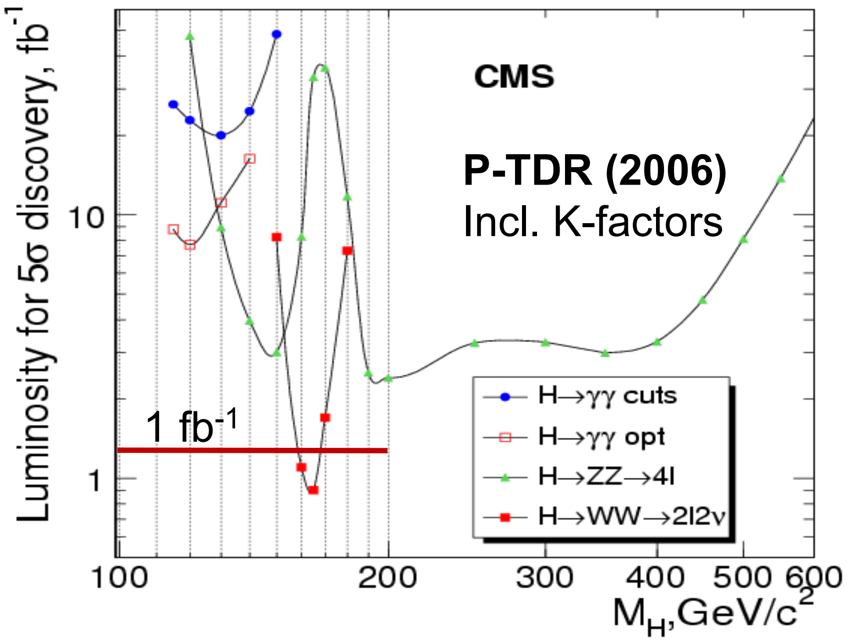
Strategie von CMS: Suche nach „Low mass“-SUSY an 10 LM-Punkte



Hohe Sensitivität inclusiver Kanäle
schon bei $1fb^{-1}$,
aber: BG muss verstanden sein!

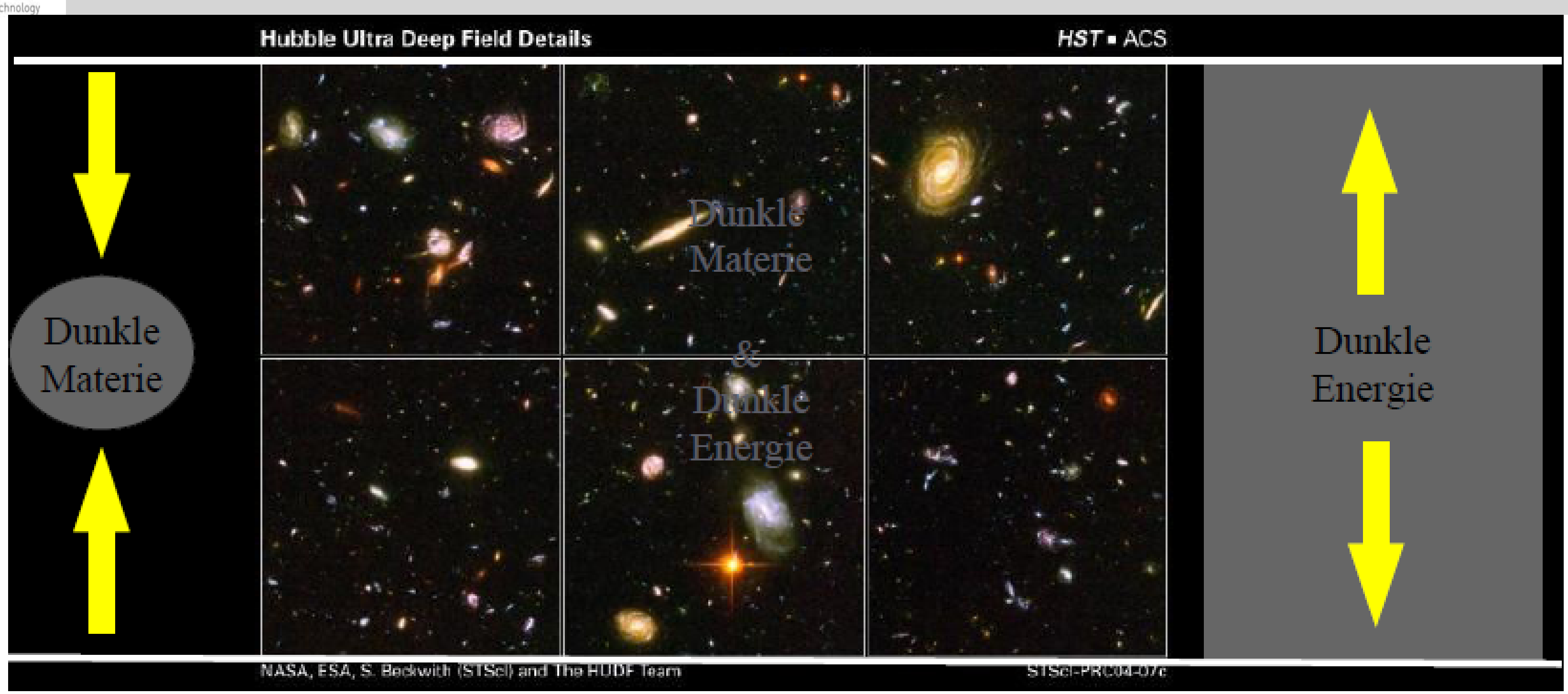
m_0 = skalare Masse an GUT- Skala
$m_{1/2}$ = Gaugino-Masse an GUT-Skala





I expect a discovery of a SM Higgs only in 3-4 years

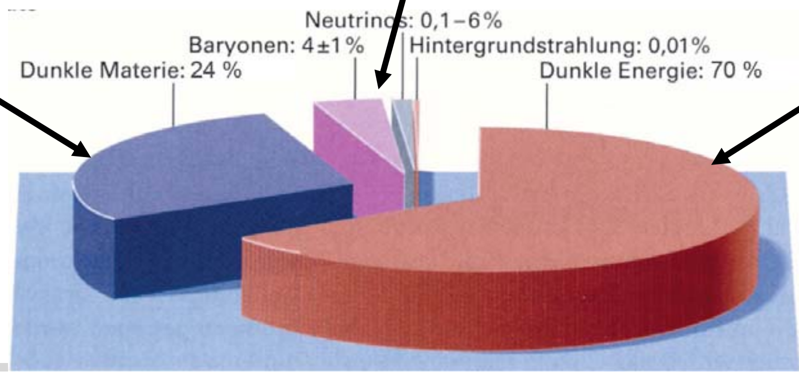
EXPLORING THE DARK UNIVERSE



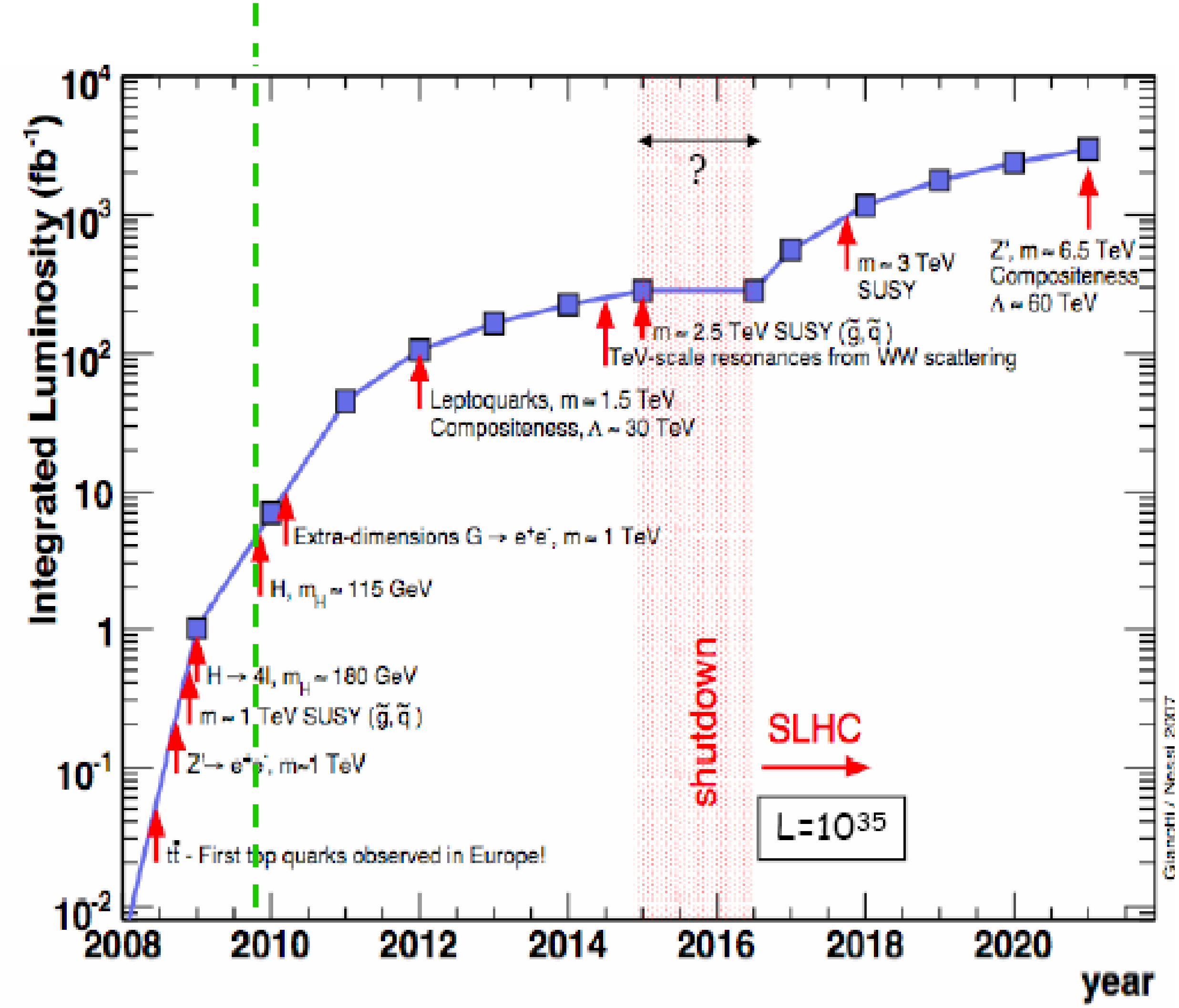
It is possible to produce Dark Matter at the LHC

Known today

Precise knowledge of the Higgs field: better understanding Of Dark Energy possible

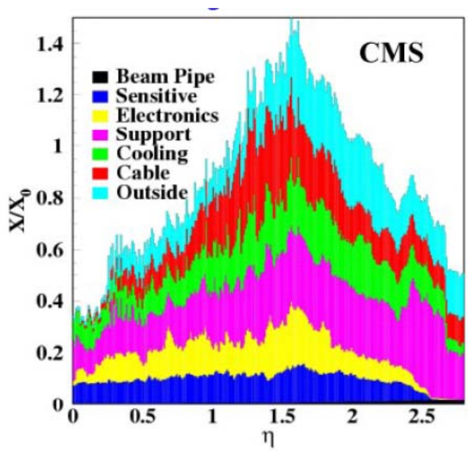


IV PLANNING THE FUTURE



Development activities in Karlsruhe on new tracker:

- Sensors
- Radiation hardness
- Cooling
- Possibly 1st level trigger



CONCLUSION

- **25 Years after first plans of the Large Hadron Collider we are ready**
- **Accelerator and detectors are most complex systems built so far**
- **We acknowledge with gratitude the support by State and government. Funding agencies and administrations need extremely high endurance**
- **Our research offers:**
  1. **Knowledge**
  2. **Developments of new technologies**
  3. **Teaching**

The Karlsruhe Team

We are looking forward to decades of exciting research


The last thing I understood was „Heureka!“
OH