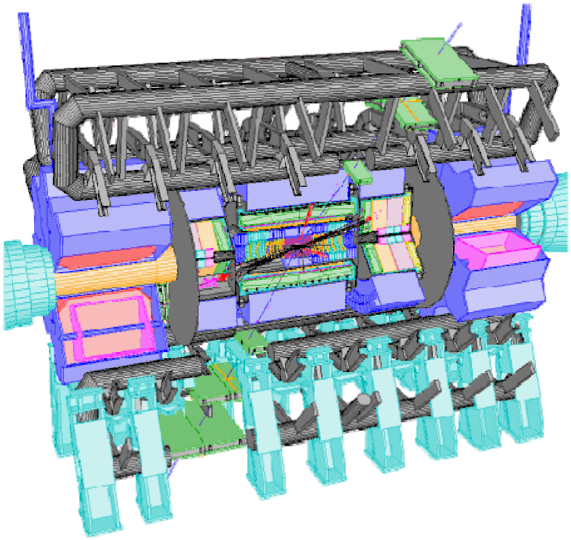
Calorimetry in Particle Physics

Lecture I



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OUTLINE - 1 -

I. Overview of Calorimetry

1. Calorimetry in Thermodynamics
2. Nuclear Radiation Detectors
3. Calorimetry in Particle Physics
4. Overview of Detection Mechanisms
5. Making of the ATLAS Lar End-caps

II. Physics of Shower Development

1. Electromagnectic showers
2. Muons traversing dense materials
3. Hadronic showers
4. Properties of the shower particles
5. Monte Carlo simulations

III. Energy Response of Calorimeters

1. Homogeneous calorimeters
2. Sampling calorimeters
3. Compensation
4. Response of Cerenkov calorimeters

OUTLINE - 2 -

IV. Fluctuations

1. Effects of fluctuations on the calorimeter performance
2. Signal quantum fluctuations
3. Sampling fluctuations
4. Instrumental effects
5. Shower leakage
6. Fluctuations in visible energy
7. Fluctuations in the electromagnetic shower content
8. Fluctuations in a compensating calorimeter
9. Off-line compensation

V. Instrumental Aspects

1. Construction principles
2. Readout of calorimeters based on light detection
3. Readout of calorimeters based on charge collection
4. Front-end signal electronics
5. Trigger processors
6. Time structure of the signals
7. Operation in a magnetic field
8. Radiation hardness

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VI. Calibration

1. Longitudinally unsegmented systems
2. Longitudinally segmented systems
3. Consequences of miscalibration
4. Offline compensation

VII. Performance of Calorimeter Systems

1. Energy resolution
2. Position and angular resolution
3. Time characteristics
4. Effects of non-compensation
5. Particle identification
6. Jets

VIII.Typical Exampels of Calorimeter Systems

1. The HERA calorimeters
2. The LHC calorimeters
3. SuperKamiokande
4. Natural calorimeters

Literature & References

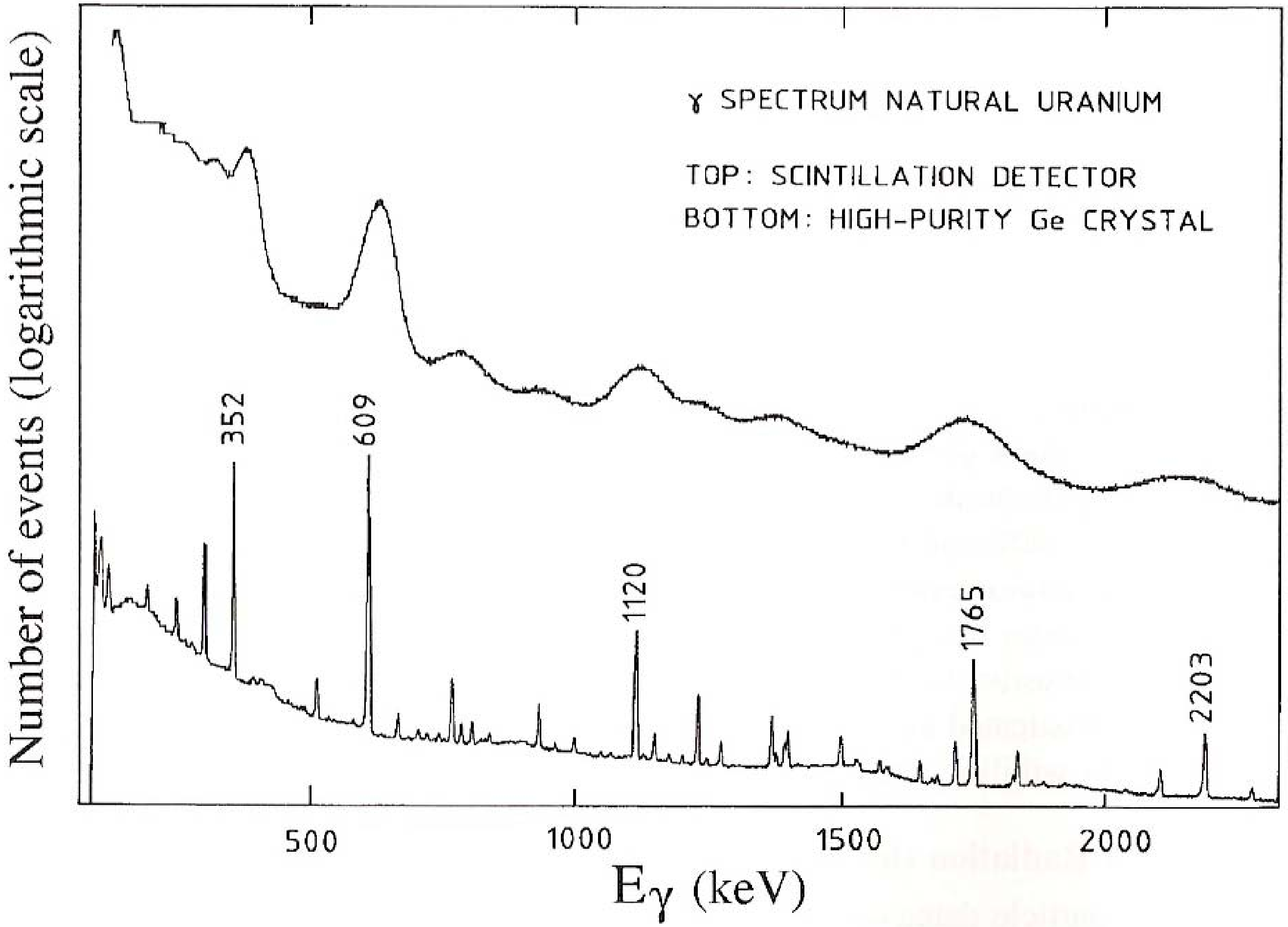
- **R.Wigmans: Calorimetry – Energy Measurement in Particle Physics, Oxford Science Publications, 1999.**
- **C.Leroy and P.G.Rancoita, Physics of cascading shower generation and propagation in matter: principles of high-energy, ultrahigh-energy and compensating calorimetry, Rep. Prog. Phys. 63 (2000) 505 - 606.**
- **C.W.Fabjan and F.Gianotti, Calorimetry for Particle Physics, CERN-EP/2003-075.**

Overview → Calorimetry in thermodynamics

- Origin of “Calorimetry“ in thermodynamics.
  - Recall experiments done in undergrad labs to determine specific heat of substances.
  - Thermally isolated boxes with substance under study.
  - Measuring device: Thermometer
- Highly sophisticated versions now in use in nuclear labs.
  - Assess amount of fissionable material.
  - E.g. ^{239}Pu produces heat of 2 mW/g.
  - Determination of amount in non-invasive manner.
- Calorimetry in particle physics:
  - Detection of particles and measurement of their properties
  - Total absorption in a block of matter
  - Determination is destructive, i.e. Particles don‘t exist after passage of device. Exception: Muons.
  - Whole particle energy converted to heat with a tiny, unmeasurable increase in temperature: 1 cal = 10^7 TeV !

Overview → Nuclear radiation detectors

- Calor particle detection in nuclear physics started after World war II with advent of scintillation counters.
  - Long known: Ionizing particles cause fluorescence e.g. in ZnS
  - Invention of photomultiplier tube (PMT): Converts individual photons into measurable electrical signals.
  - PMT made quantitative measurements of particle properties possible.
- Typical scintillators:
  - Thallium doped sodium iodide crystals {NaI(Tl)} (inorganic crystal)
  - Anthracene (organic compound, very bright scintillation, very short decay time)
  - Semiconductor crystals (lithium doped Si or Ge, highly improved energy resolution)

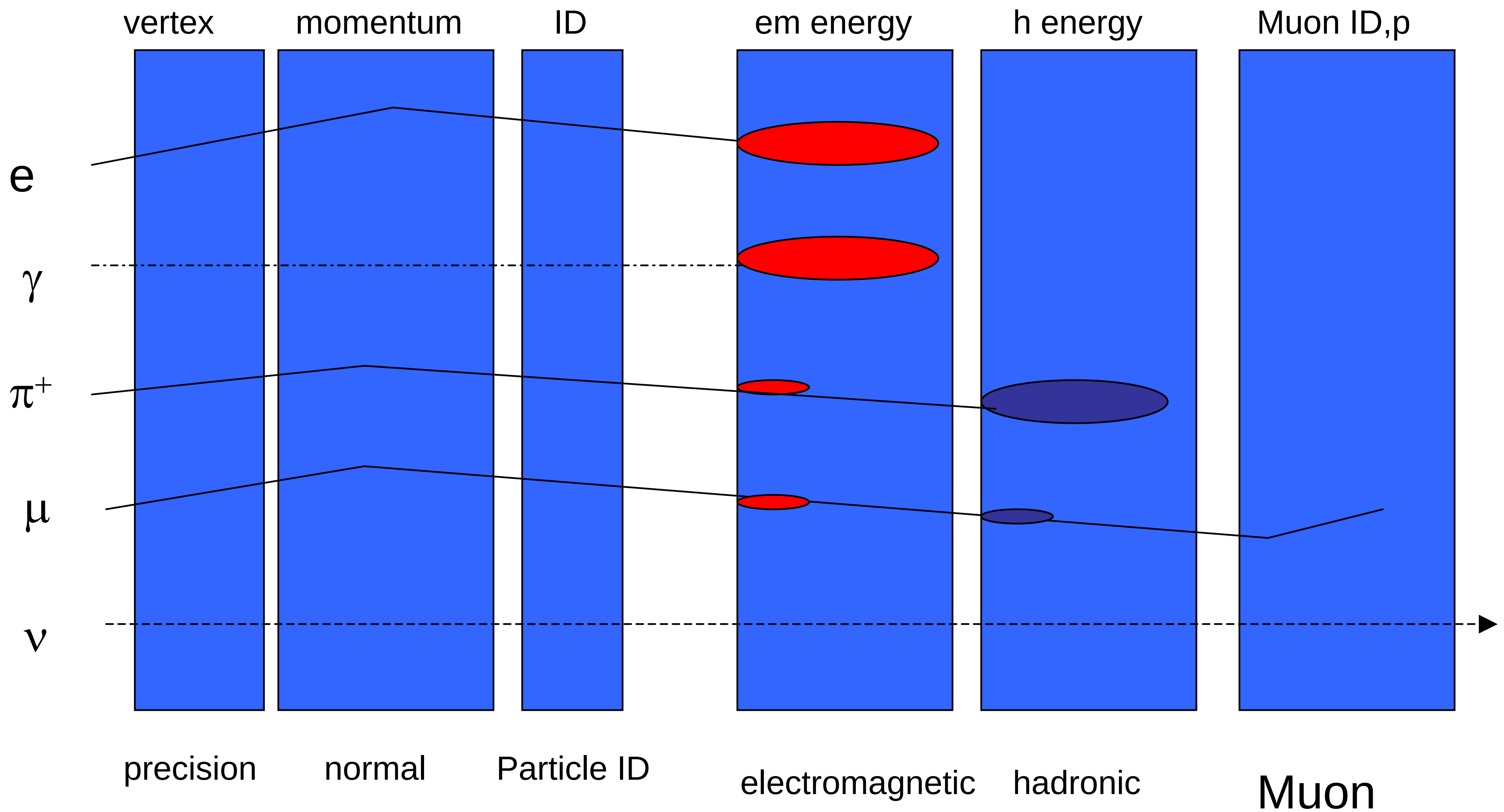


Nuclear γ-ray spectrum of decaying uranium nuclei, measured with a bismuth germanium-oxide scintillation counter (upper curve) and with a high-purity germanium crystal (lower curve)

Overview → Calorimetry in particle physics

- **Experiments in particle physics classified as**
  - **Accelerator based**
  - **Non-accelerator based**
- **Experimental particle physics studies a wide variety of phenomena at energy scales that span many orders of magnitude.**
- **Overview of the evolution of the role of calorimeters:**
  - **Shower counters**
  - **Instrumented targets**
  - **4π detectors**

The life of a particle in a detector



Tracking

Calorimeters

Muon

Tracking

Overview → Scattering experiments at accelerators

- Types of experimental set-ups in scattering experiments at accelerators:
- Fixed target geometry:
  - Beam of particles sent onto a target.
  - Most energy of the projectile transferred to the target
    Center of mass energy $E_{cm} = (2 * M * E_{beam})^{0.5}$
  - Try to measure the four-vectors of all particles produced.
  - Charged particles tracked in magnetic field: Measure momentum and charge
  - Mass measurment by ionization density
  - Difficulties with electrically neutral particles (n, γ, K^0, Λ)
- Colliding beam geometry
  - Two beams of particles collide
  - Energy available for particle production in a head-on collision is $E_{cm} = 2 * E_{beam}$
- Experimental aims
  - Try to measure the four-vectors of all particles produced.
  - Charged particles tracked in magnetic field: Measure momentum and charge
  - Mass measurment by ionization density
  - Difficulties with electrically neutral particles (n, γ, K^0, Λ)

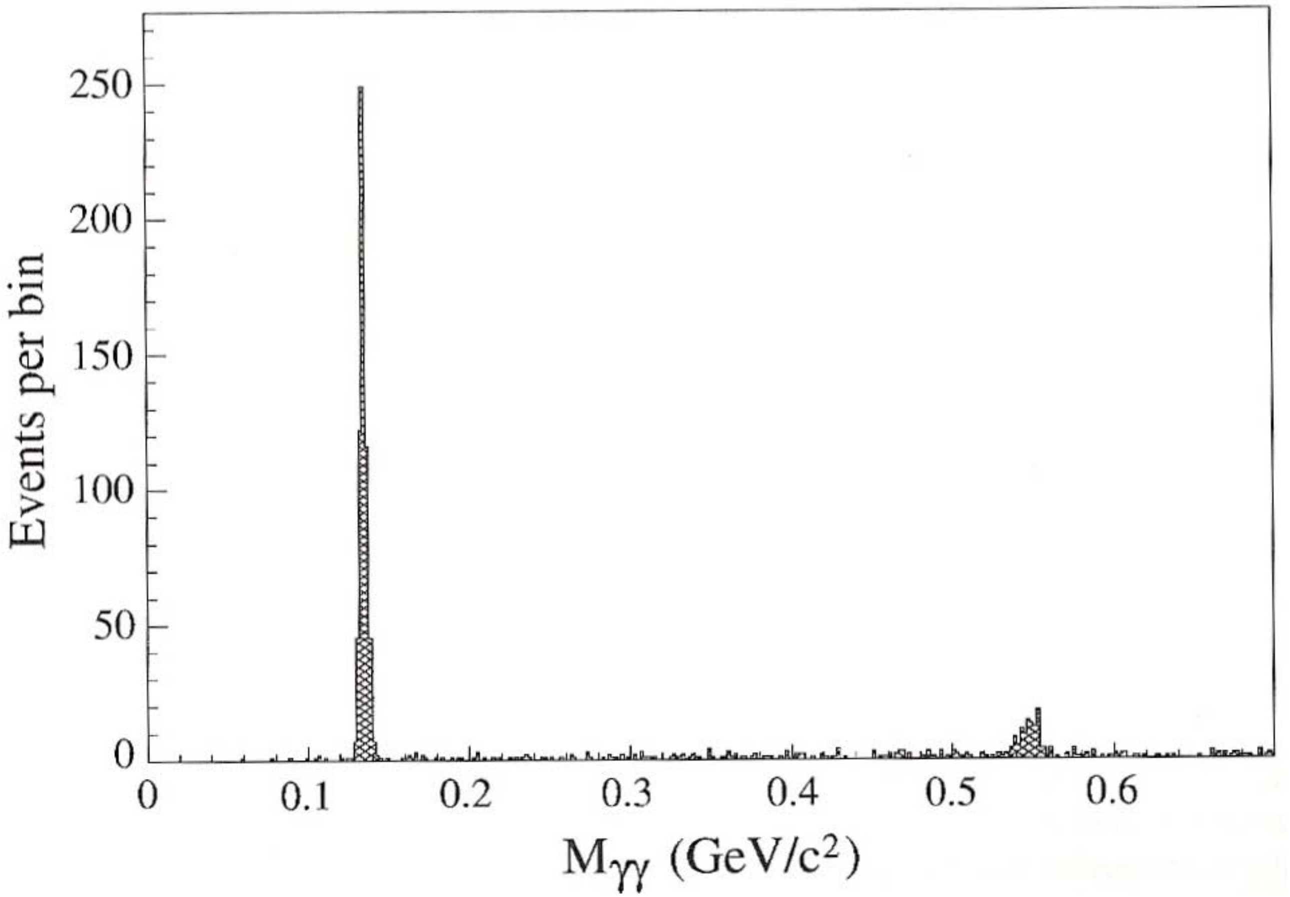
    ➔ Shower counters

Overview → Shower counters → Homogeneous / Sampling

- ‘Homogeneous‘ calorimeters:
  - Entire volume sensitive to the particles and contributing to the detector signal.
  - Absorbing particles and detecting signals done by the same materials.
- ‘Sampling‘ calorimeters
  - Function of particle absorption and signal generation by different materials
  - Dubbed ‘Passive‘ and ‘Active‘ materials
  - Passive medium typically high density materials (Fe, Cu, Pb, U)
  - Active medium forms signal through light or charge generation
  - Properties:
    - Small fraction of energy deposited in active medium
    - Energy resolution for electromagnetic particles (electrons, photons) worse
    - Relatively cheap, i.e. Suitable for very large detectors.

Overview → Shower counters → Scintillators

- **Long tradition of scintillating crystal calorimetry**
  - **‘Homogeneous‘ calorimeters:**
- **NaI(Tl):**
  - **First scintillator shower counter in particle physics**
  - **Photons measured with high efficiency and ~1% resolution**
  - **The π^0 reconstructed with high efficiency.**
  - **Disadvantage: hygroscopic**
- **Other popular scintillating crystals:**
  CsI, BaF_2, CeF_3, BGO, $PbWO_4$
- **Optimization and choice according to**
  - **Signal speed**
  - **Radiation hardness**
  - **Density**
  - **Cost ....**



$\gamma\gamma$ invariant mass spectrum measured with a CsI crystal spectrometer (KTeV).

The two peaks correspond to decaying π^0 and η mesons.

Overview → Shower counters → Cerenkov

- **Lead-glass calorimeters**
  - **‘Homogeneous‘ calorimeters**
- **Composition:**
  - **Various shapes and forms (e.g. ‘Lead-glass wall‘)**
  - **Consists of SiO_2 and PbO (up to 70%)**
- **Properties:**
  - **Transparent**
  - **High density (~ 5 g/cm^3)**
  - **No scintillation, but emits Cerenkov light when particles traverse.**
- **Performance:**
  - **Low light yield (several orders smaller than for scintillating crystals)**
  - **Energy resolution worse than for scintillating crystals**
  - **Instantaneous nature of Cerenkov light produces extremely fast signals, much faster than signals from scintillating crystals.**

Overview → Instrumented targets

- Fixed target experiments typically have separate targets and an arragement of detectors
  - to determine whether interactions were taking place in the target, and
  - to measure the properties of the reaction products in the case ofinteresting events.
- Experiments to study ‘very rare phenomena‘
  - typically combine the functions of target and detector,
  - with usually very large target masses,
  - very large instrumented targets
- Examples:
  - Neutrino interactions
  - Proton decay
  - Cosmic rays at highest energies

Overview → Instrumented targets → Neutrino exp.

- **Eamples of neutrino production**
  - **Pion, muon, kaon decays (accelerators)**
  - **Fusion of hydrogen into helium nuclei in the sun**
  - **Supernovae**
- **Neutrino cross section**
  - **very low probability of interaction with matter.**

    e.g. mean free path of typical solar ν about a lightyear in iron.
  - **cross section proportional to neutrino energy, i.e. somewhat better for accelerator ν with energies in the 100 GeV range.**

    e.g. Interaction probability in a 1000 ton target is ~1 / 109.**
  - **Need intense beams and large target masses.**
- **Features of large neutrino experiments at accelerators:**
  - **Muon spectrometer to identify muons and measure their momenta:**

    Front part of detector defined as fiducial volume of ν interactions.

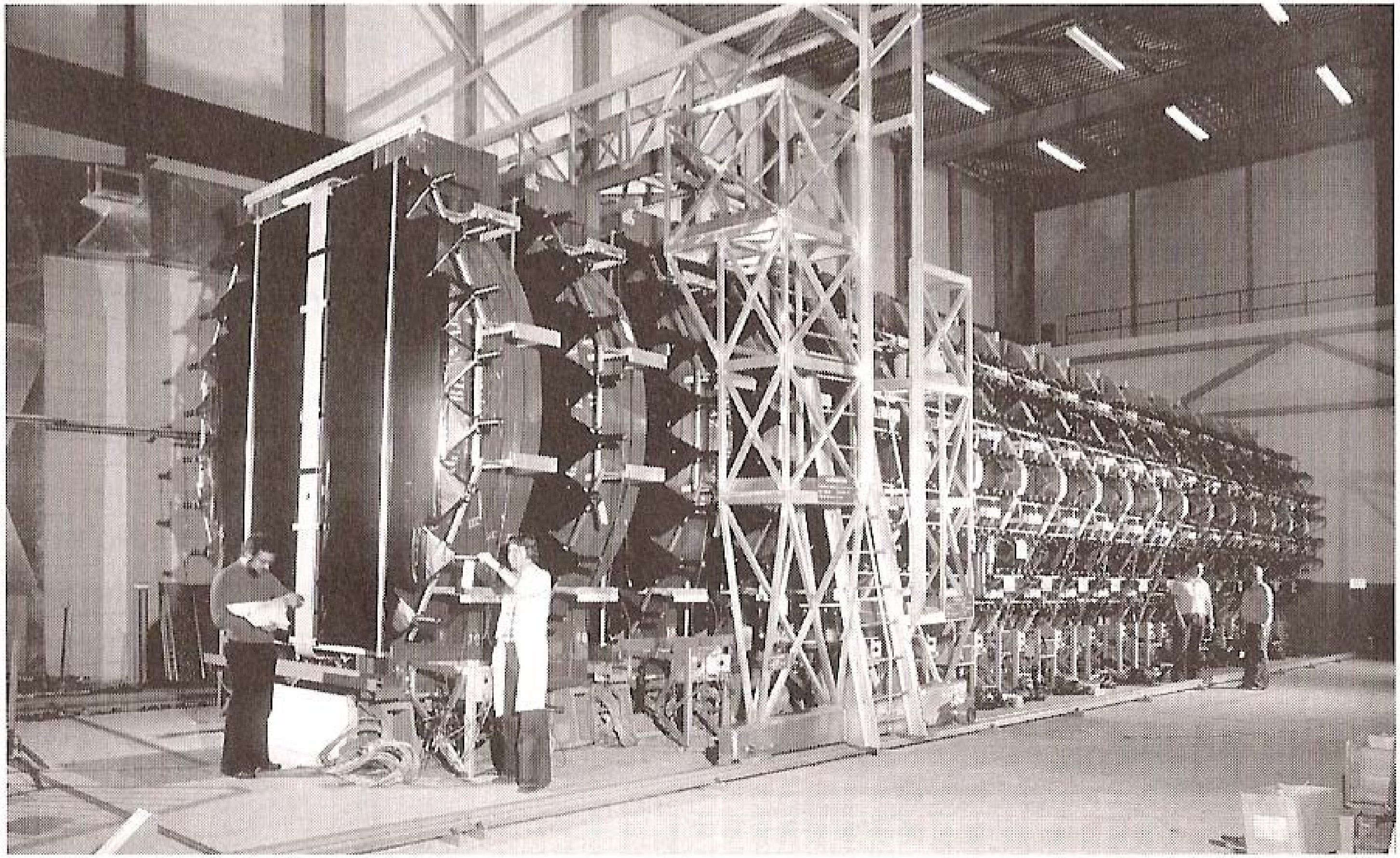
    Rear part of detector located in magnetic field. Particles there are muons.
  - **Hadrons measured by calorimeters:**

    Integration of the signals from the active layers in the fiducial volume. Measure hadronic energy by comparison with signals created by hadrons of known energy (testbeams). Typical precision: 10 %.

Overview → Instrumented targets → Neutrino exp.

Large Neutrino experiments at accelerators:

- First generation (1970s) measured nucleon structure and weak interactions
  - WA1 and CHARM at CERN, CCFRR at Fermilab
    - Target mass: ~1000 tons
    - Targets: Iron or marble slabs arranged in large slabs perpendicular to the beam, interleaved plastic or liquid scintillators, wire chambers, drift chambers, ...
- Later generations (1980/90s) specialised on more detailed aspects of ν physics, i.e. needed larger and more sophisticated detectors.
  - CHARM II, NOMAD, CHORUS at CERN
- New generation of neutrino experiments (‘long baseline experiments‘) look for ν oscillations:
  - Accelerator produced ν beam sent in direction of new superb detectors located several hundred or thousand km away. Examples:
    - CERN beam to Gran Sasso (MACRO, OPERA)
    - Fermilab beam to underground mine in Minnesota (MINOS) and to Canada (SNO)
    - KEK beam to SuperKamiokande (K2K, T2K)



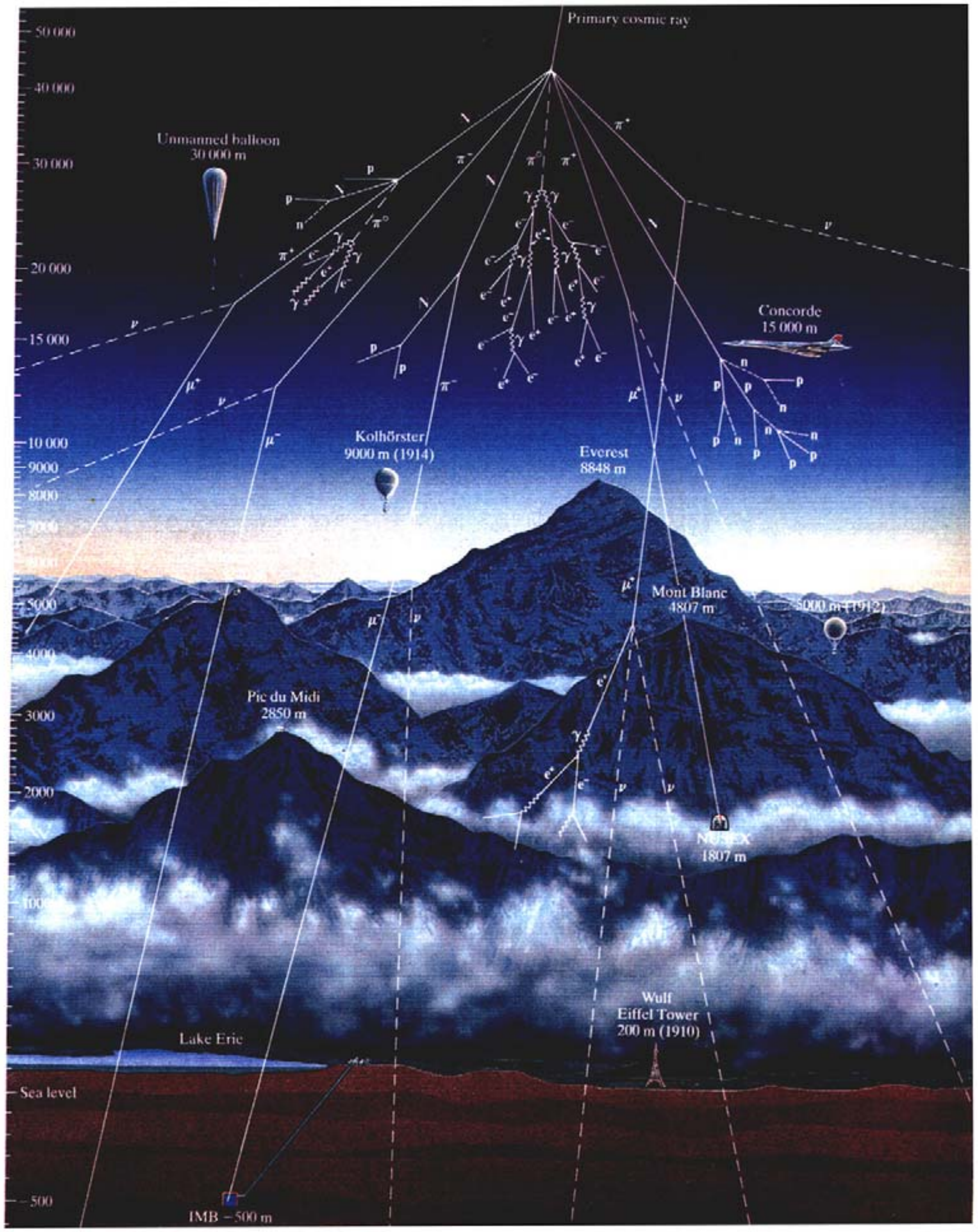
The WA1 neutrino detector combination (CERN 1976 – 1984).

Large slabs of iron interleaved with layers of plastic scintillator. Rear part of the detector (left side of picture) instrumented with wire chambers for tracking muons.

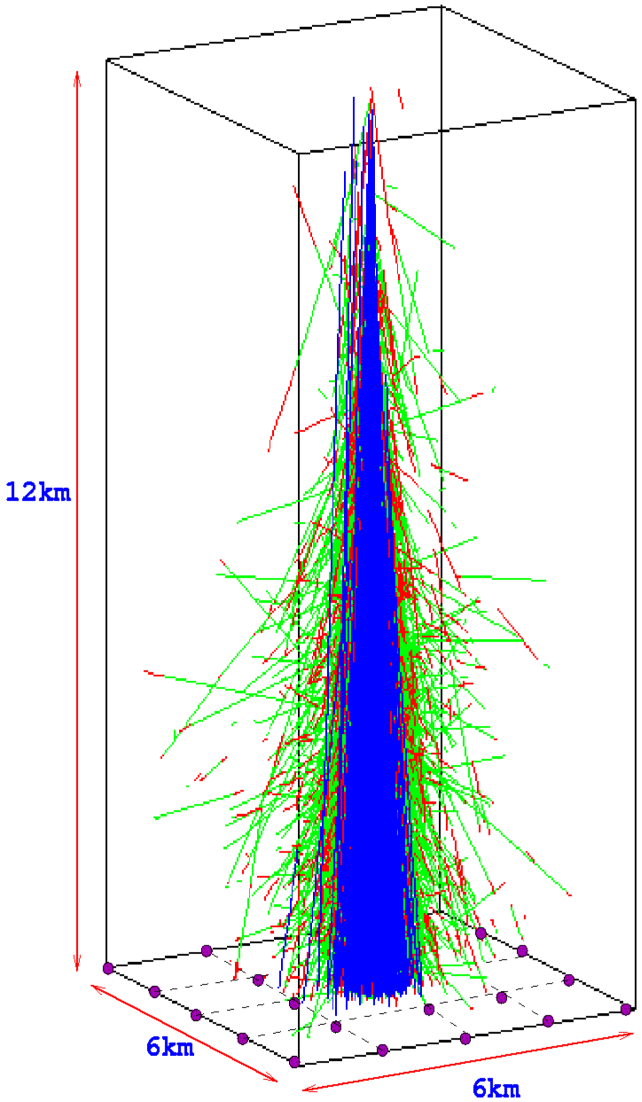
Overview → Instrum. targets → Cosmic rays / Proton decay

- Some of the goals of cosmic ray experiments:
  - Production of atmospheric ν
  - Detection of solar ν
  - Detection of ν from supernovae
  - Detection of extremely energetic (~10**19) particles entering the Earth atmosphere
- New generation of experiments operational or under construction
  - Need very large instrumented mass with large sampling calorimeters.
  - Typically on high mountain to minimze effect of atmosphere
  - Typically in deep mines, in tunnels under high mountains or deep under water or ice Goal: Minimize background.
- Search for proton decay
  - Limit on partial lifetime for decay to e+ π^0 is so far 10**32 years)
  - Need detector with 10**32 protons (300 m^3 water) to observe 1 decay / year.
- Typical detectors: Water Cerenkov calorimeters
  - High purity water viewed by large number of PMTs
  - Observe characteristic blue light emitted during the passage of relativistic charged particles through the water.
  - IMB (Ohio), SuperKamiokande (Japan) use water
  - DUMAND, NESTOR, ANTARES operate under water
  - ICECUBE emersed in ice under South Pole
  - Solar neutrino observatory (SNO) uses heavy water

Giant Air Shower in Earth's Atmosphere



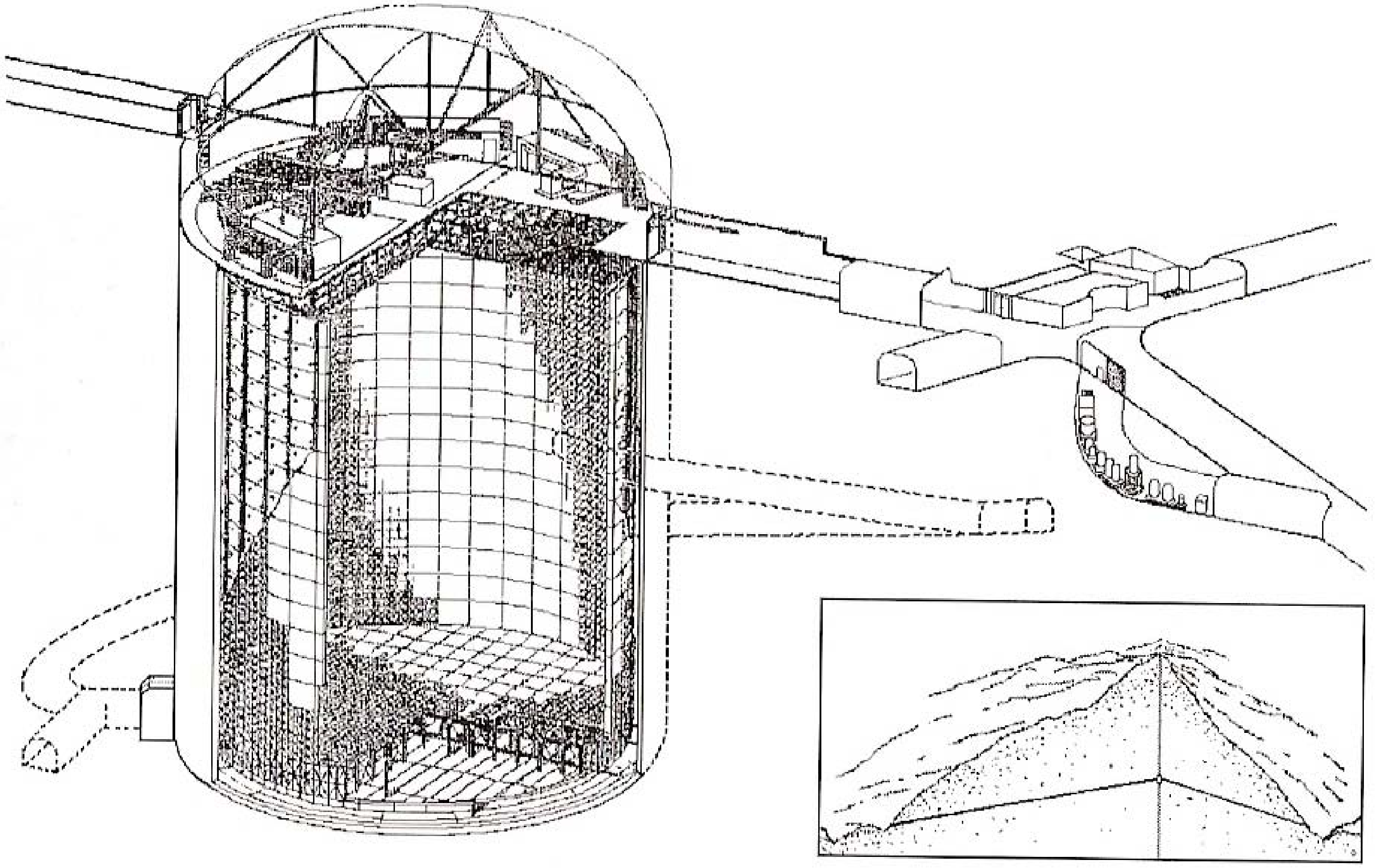
A 10^{19} eV Extensive Air Shower



100 billion particles at sea level

photons, electrons (99%), muons (1%)

● Ground Array stations



Schematic view of the SuperKamiokande detector

Overview → 4π Detectors

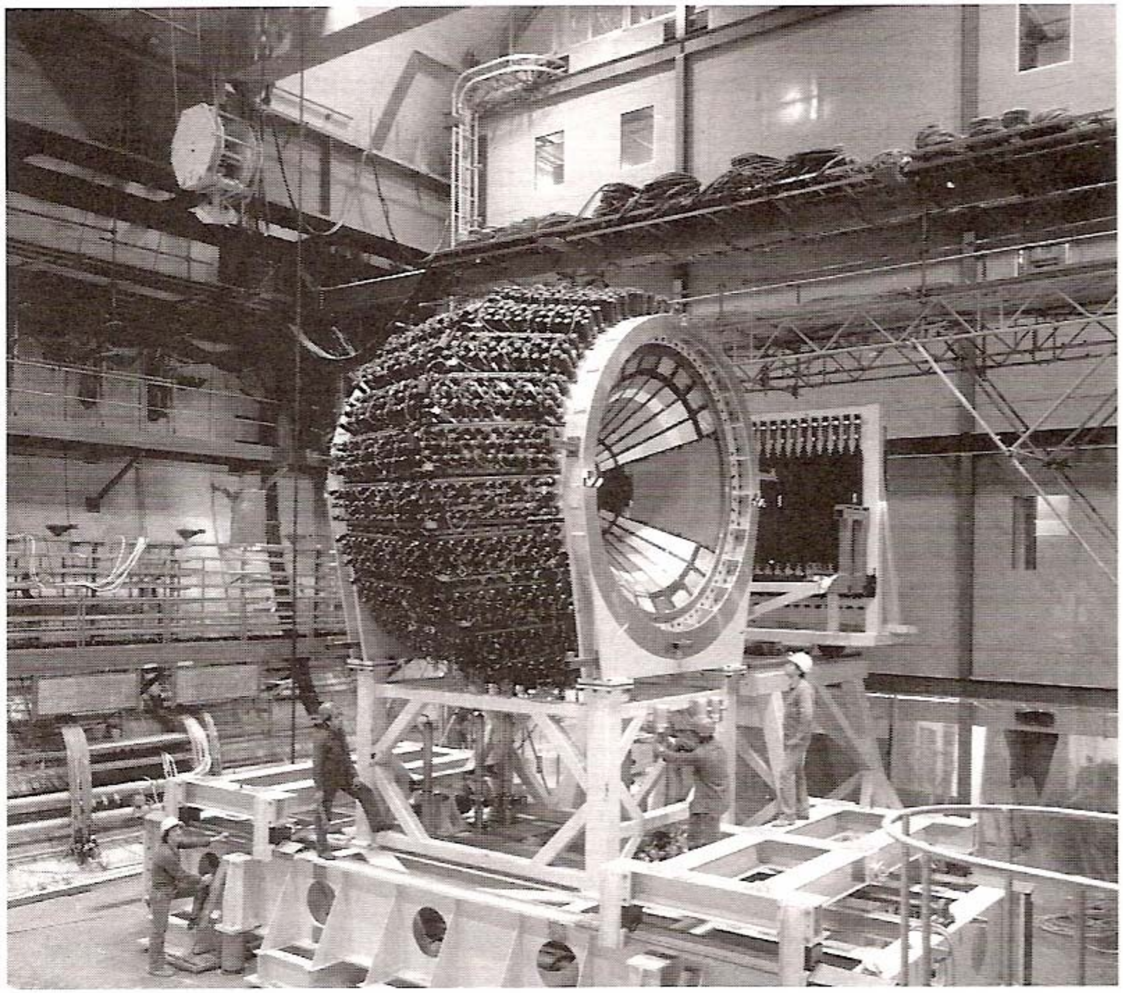
- Role of the calorimeters becomes more important at higher energies:
  - Information provided by calorimeters improves with increasing energy, while the precision of the momentum measurement of charged tracks decreases.
  - Calorimetric measurement of the four-vectors of particles possiblee due to granularity
  - Calorimetric together with tracking information allows particle identification (e / π)
- Calorimeters become more important in colliding beam geometries
  - Emphasis on measurement of more global event characteristics:

    Energy flow, missing transverse energy, production of jets
- Colliding beam facilities are now dominant source of particles
  - 1970s: e+e- colliders DORIS, SPEAR and pp collider ISR (CERN)
  - Proton – Anti-proton SppbarS (CERN): UA1 and UA2 experiments discovered the W and Z intermediate vector bosons looking at signatures like

    Energetic charged lepton in combination with missing transverse energy.
  - LEAR, LEP, LHC (CERN)
  - Tevatron (FNAL)
  - PETRA, HERA (DESY)
  - PEP, SLC (SLAC)
  - TRISTAN and B-factory (KEK)

Overview → 4π Detectors

- Experiments at colliding beam facilities
  - e+e- colliders: Calorimetry emphasized measurement of e.m. Particles and properties.
    Examples:
    Crystal Ball (SPEAR)
    CUSB and CLEO (CESR)
    Crystal Barrel (LEAR)
    ALEPH, DELPHI, L3, OPAL (LEP)
    BaBar (SLAC B-factory), BELLE (KEK B-factory)
  - Hadron colliders: Calorimetry emphasis on hermeticity, measurement of energy flow, detection of jets and on electron identification.
    Examples:
    UA1 and UA2 experiments discovered the W and Z intermediate vector bosons looking at signatures like Energetic charged lepton in combination with missing transverse energy.
    ATLAS, CMS (LHC)



UA2 calorimeter at CERN proton - anti-proton collider (1980 – 1986)

Overview → Detection Mechanisms

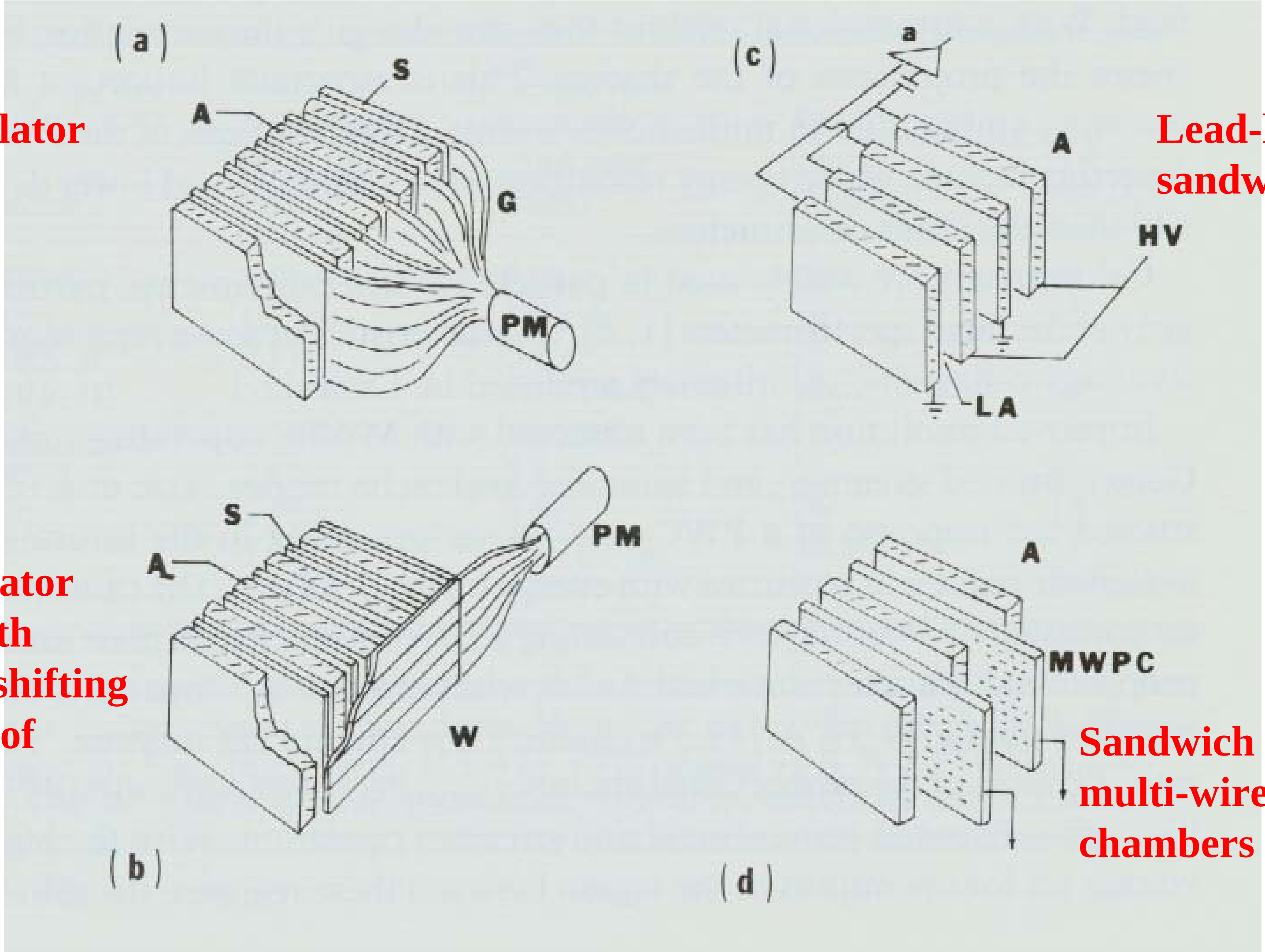
- **Scintillation**
- **Cerenkov radiation**
- **Ionization**
- **Cryogenic phenomena**

Overview → Scintillation

- Charged particles traversing matter loose energy by e.m. interaction with Coulomb fields surrounding the charged constituents of matter.
- This energy may be used for
  - ionization (see later),
  - excitation of atoms/molecules (scintillation).
- Excited states are unstable, quick return to the ground state, release of photons.
  - Timescale of this process is not uniquely defined.

    It depends on excitation energy and number of return paths open.
- Fluorescence / scintillation:
  - The emitted photons are in the visible domain.
  - Typical timescales range from micro- to picosec. Decay times of typical scintillators like BGO are several hundred nsec.
- Major inventions:
  - PMT (discussed before). New developments like Avalanche Photo Diode (APD) take care of PMT weaknesses (e.g. Magnetic field).
  - Wavelength shifters:
    - Absorb scintillation light and re-emit at a longer wavelength.
    - Advantage for hermetic calorimeters: Scintillation light can be wavelength-shifted and at the same time redirectedtowards rear end of calorimeter.
    - Price: Loss of light.

Examples of Calorimeter Read-out Schemes



Lead-scintillator sandwich

Lead-liquid argon sandwich

Lead-scintillator sandwich with wavelength-shifting bars on side of module

Sandwich of lead and multi-wire proportional chambers

Overview → Scintillation

- **Orientation of active layers:**
  - **No need to orient them perpendicular to direction of incoming particle.**
  - **Different new geometries invented:**
    - **Parallel to beam direction**
    - **Accordion shape**
    - **Tile etc**
- **Plastic optical fibers:**
  - **Consist of a polystyrene core (n-1.59)**
  - **Surrounded by one or several layers of cladding with lower values of n.**
- **Fibers used in particle physics are both source of the light and medium of transport to place where conversion to electrical signal can happen.**
- **Advantages of such optical fibers:**
  - **Possibility for perfectly hermetic calorimeter structure.**
  - **Very high sampling frequency may be obtained, leading to good energy and position resolution.**
  - **High signal speed**
  - **Fine granularity possible.**

Overview → Cerenkov radiation

- A charged particle travelling faster than the speed of light in a certain medium ($v > c / n$, n index of refraction)
  - loses energy by emitting Cerenkov radiation.
  - Radiation emitted at Cerenkov angle $\theta_C = \arccos(1 / n * \beta)$ vs. Particle direction
    Half cone with half-opening angle θ_C.
  - Visble part of the Cerenkov radiation seen as blue light.
- Emission of Cerenkov light contributes very little to energy loss of particles.
  - Charged particle with $\beta \sim 1$ looses in water 0.4 keV/cm. Ionization loss: 2100 keV/cm.
- Cerenkov effect sensitive to velocity of particles:
  - Mass determination for particles of which the momentum has been determined.
  - Useful to separate electrons, pions, kaons, protons, deuterons from each other.
  - Realized for various devices: Threshold, differential, ring imaging Cerenkov counters.
- Cerenkov light is instantaneous:
  - Used for experiments in which ultimate signal speed is required.

Overview → Ionization

- Charged particles traversing matter may ionize the atoms of this matter:
  - Electrons are released from their Coulomb field leaving behind ionized atoms.
  - Collection of liberated electrons is signal producing technique in various detectors
  - Electrons may or may not be amplified.
- Ionization chambers based on liquid media:
  - No amplification.
  - An electric field apllied over the liquid gap separates electrons and ions.
  - Electrons collected at Anode, ions at cathode.
  - Mean free path of electrons should be long, therefore use noble liquids where all electron shells are filled, no capture of electrons.
  - Very stringent purity standards. Contamination by electro-negative substances have to be kept below 1 ppm level.
- Calorimeters based on noble liquids:
  - Pioneered with liquid argon (LAr).
  - LAr cheap, available in large quantities, purity levels can easily be maintained.
- Examples of operating LAr calorimeters:
  - D0 at Tevatron (FNAL)
  - H1 at HERA (DESY)
  - ICARUS (homogeneous LAr calorimeter) Gran Sasso

Overview → Ionization

- **Other noble liquids:**
  - **Krypton (LKr) and xenon (LXe) much more expensive**
  - **Special advantages like higher density or higher Zvalue.**
  - **LXe is very good scintillator**
- **Noble liquids are very radiation hard**

Overview → Ionization

- **Ionization calorimeters with gaseous media:**
  - **Electrons undergo considerable multiplication resulting in an avalanche.**
  - **Multiplication process works best in the vicinityof the anode.**

    Anode often made of very thin wires (30 μm).
- **Wire chambers operate in variety of modes:**
  - **Depends on gas mixture and voltage applied across gap**
  - **Proportional mode, streamer mode, Geiger mode, ...**
  - **Time needed for charge to arrive at anode provide information about spatial coordinates of particle. Principle of drift chambers.**
  - **Large number of calorimeter systems rely on wire chambers.**
- **Solid state devices measure ionization charge:**
  - **Semiconductor crystals (Si, Ge and GaAs) used as particle detectors**
  - **Outer shell atomic levels exhibit band structure: valence band and conduction band separated by an energy gap.**
  - **Ionizing particle excites electrons from valence into conduction band, leaving hole in valence band.**
  - **Electron-hole pairs collected by an electric field.**
  - **Very little energy is required to produce electron-hole pair (3.6 eV in Si, 46 eV in LAr)**

Overview → Cryogenic phenomena

- **Highly specialized calorimetric detectors study phenomena at boundary of particle physics and astrophysics. Need precise measurements of small energy deposits. Exploit phenomena at very low temperatures:**
  - **Dark matter**
  - **Solar neutrinos**
  - **Magnetic monopoles ....**
- **Phenomena:**
  - **Cooper pairs are broken by phonon absorption**
  - **Specific heat for dielectric crystals and for superconductors decreases to very small values at very low temperatures.**
  - **Some materials change properties (e.g. magnetization), thereby provide detector signals.**
- **Mostly R&D efforts:**
  - **Bolometers**
  - **Superconducting tunnel junctions**
  - **Superheated superconducting granules**

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- Mostly R&D efforts:
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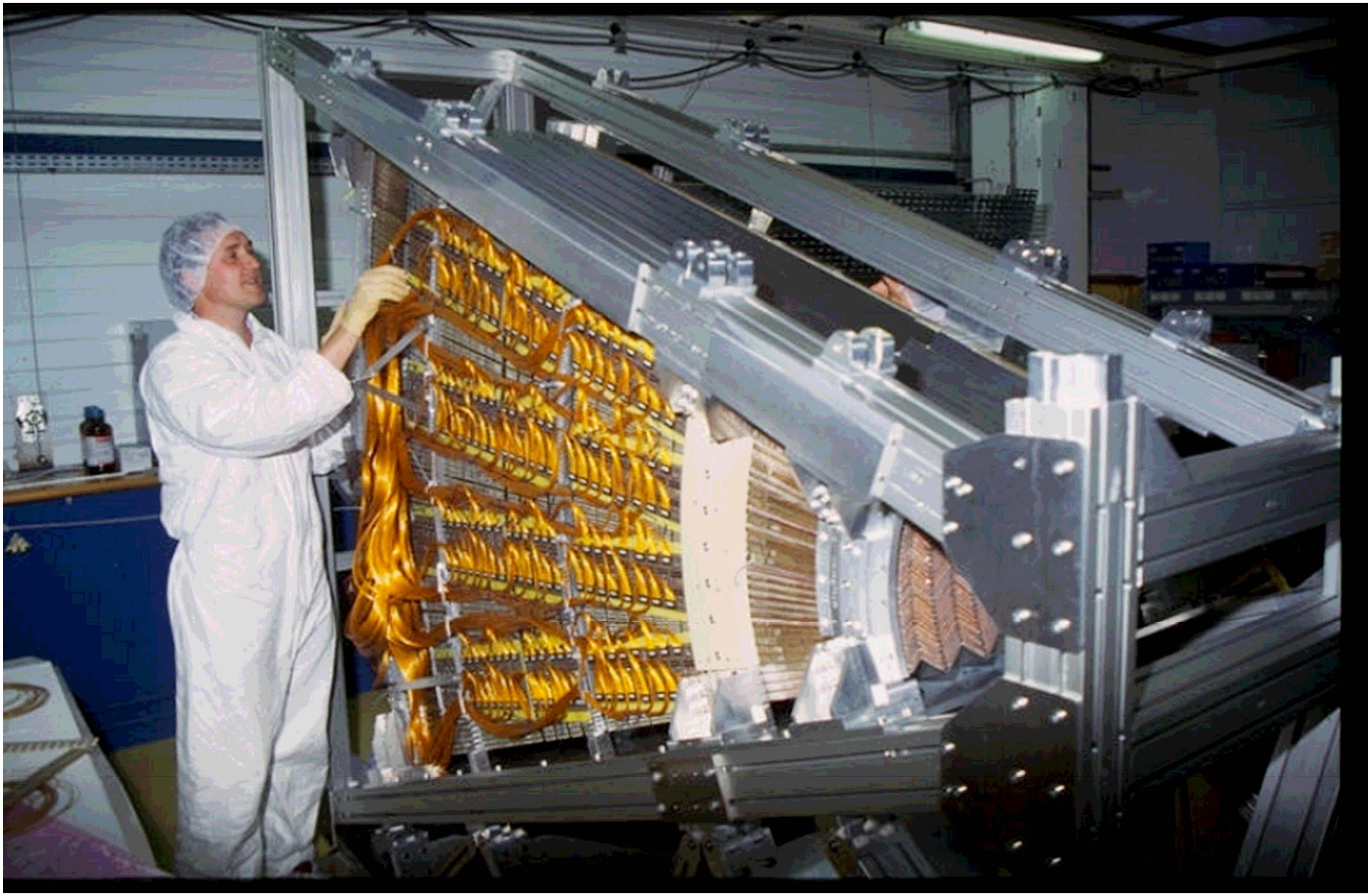
ATLAS End-Cap Calorimeter

- **ATLAS and CMS are the two general purpose experiments at the LHC**

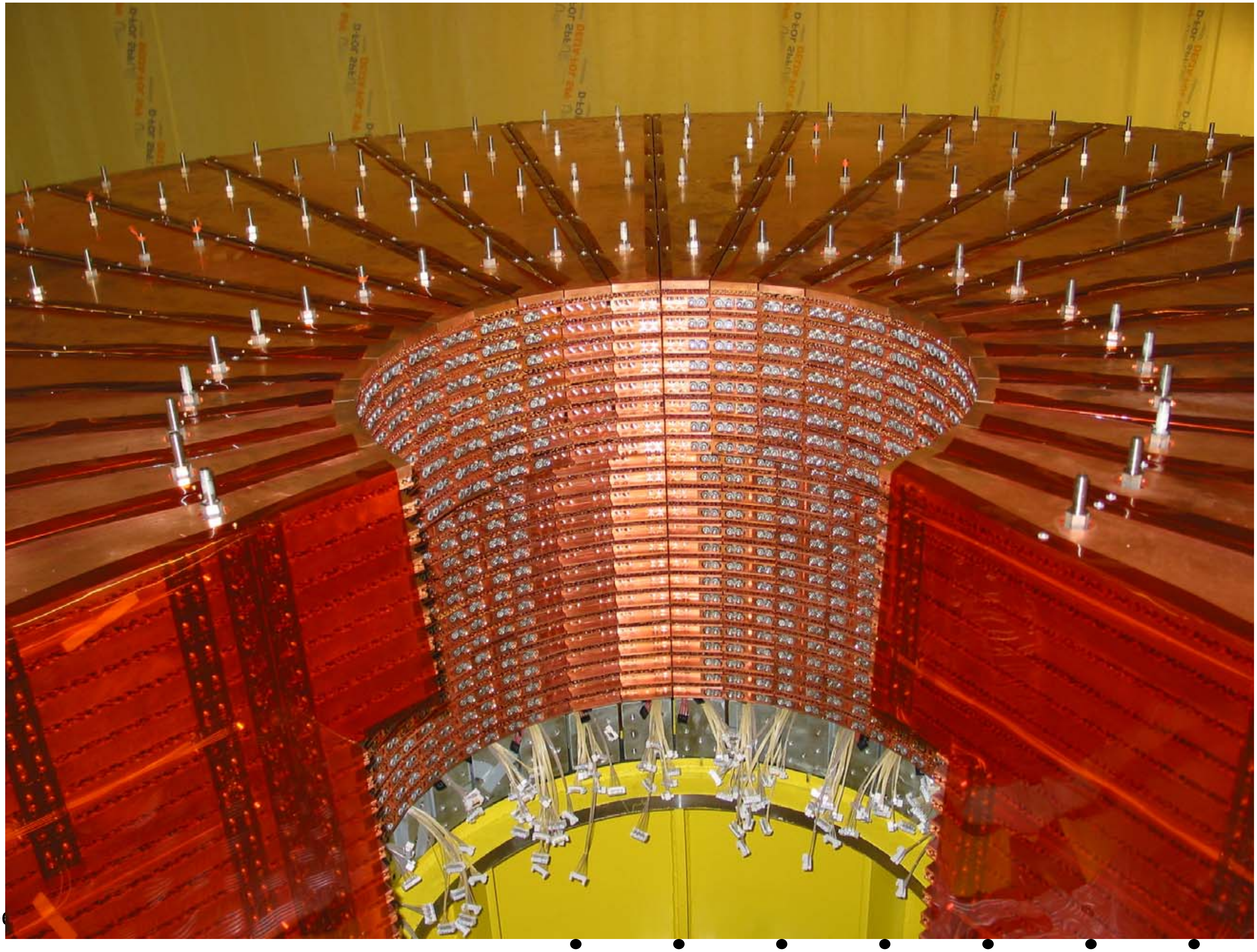
- **The ATLAS Calorimeter consists of one Barrel and two end-cap calorimeters.**
- **Each calorimeter is made of an inner shell of LAr calorimetry and an outer shell of tile calorimetry.**
- **More detailed discussion later.**
- **Here some pictures of the LAr end-caps.**
- **Each LAr end-cap cryostat houses three different calorimeter types:**
  - **An e.m. calorimeter wheel (EMEC) with a presampler in front,**
  - **Two hadronic calorimeter wheels (HEC)**
  - **A forwad calorimeter (FCAL)**

EMEC Module

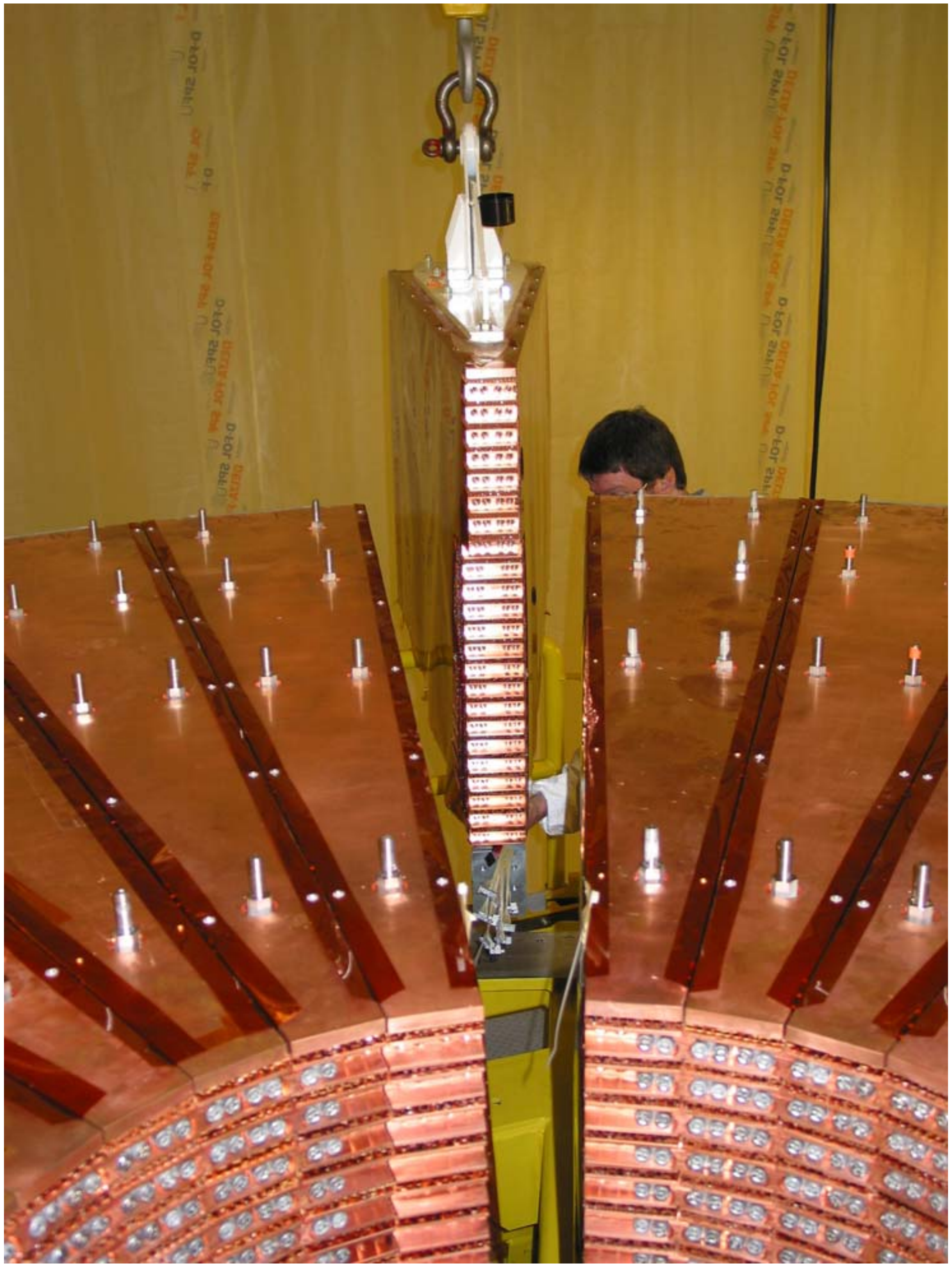


A single LAr HEC Module

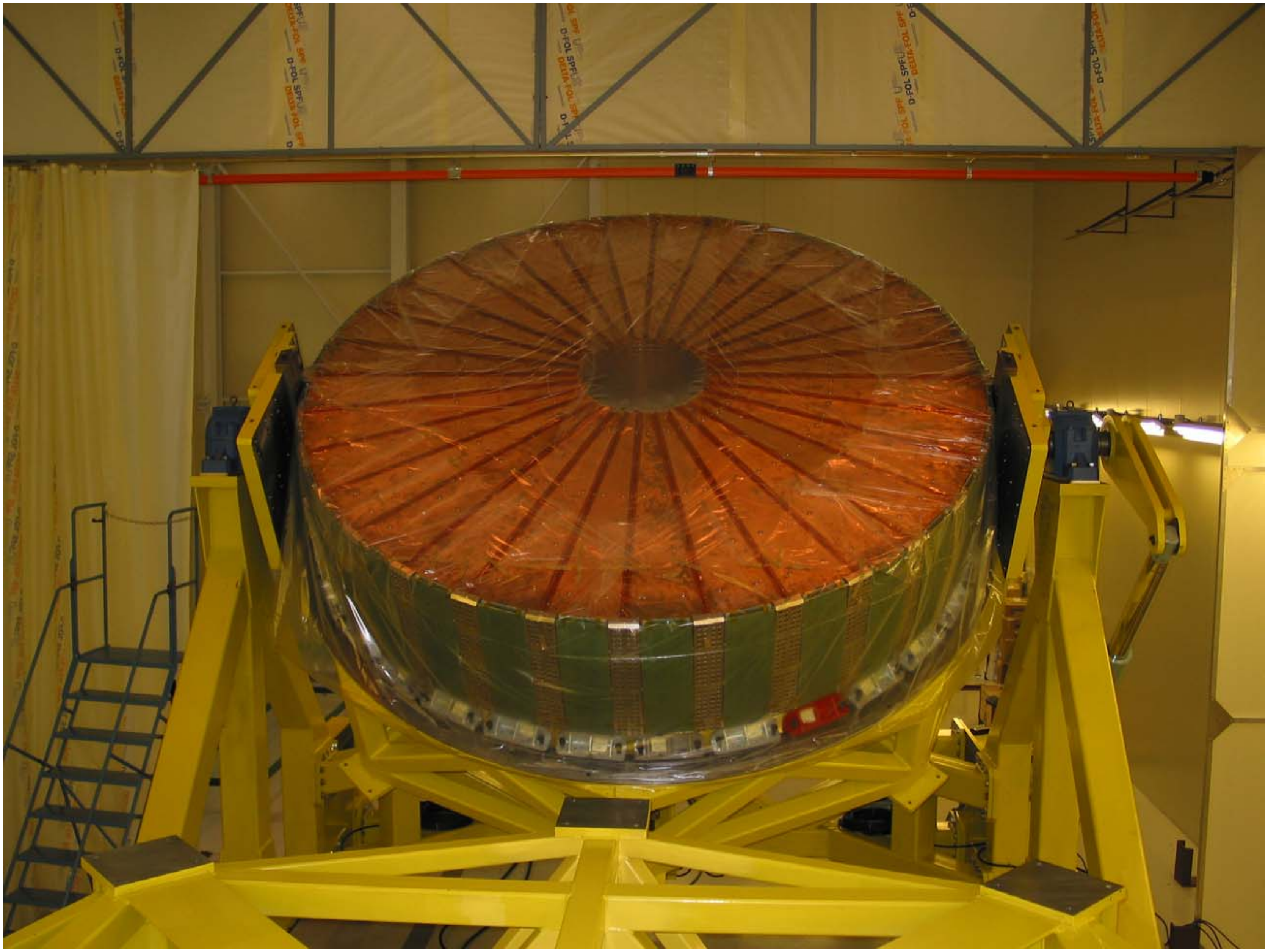
A HEC Wheel partially assembled



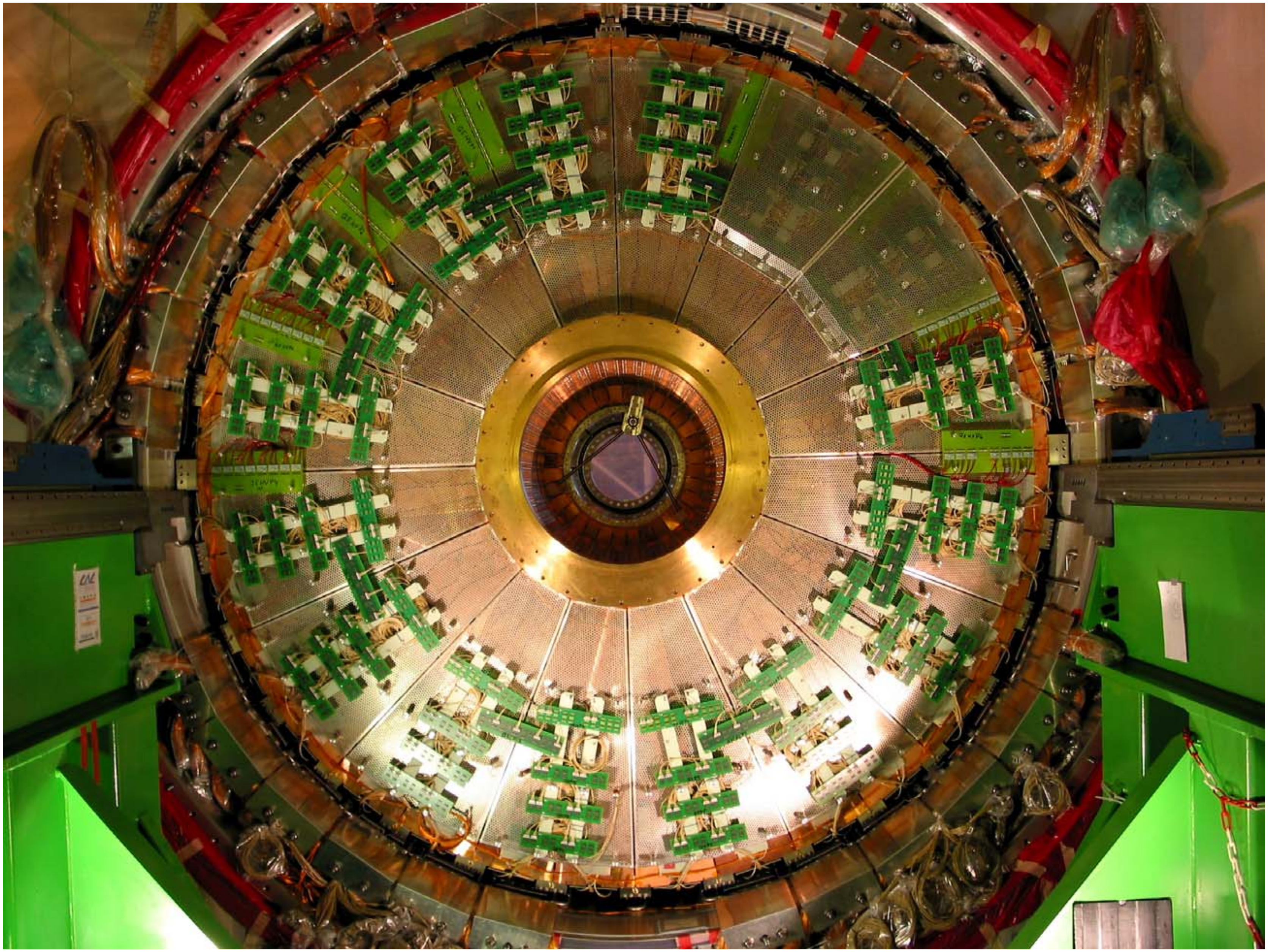
The last module (of 32) for a HEC wheel



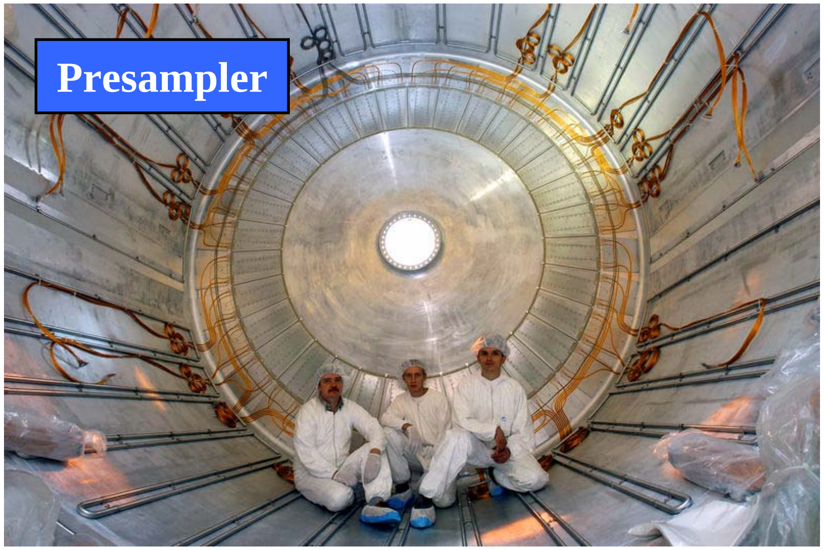
HEC Wheel fully assembled, before rotation

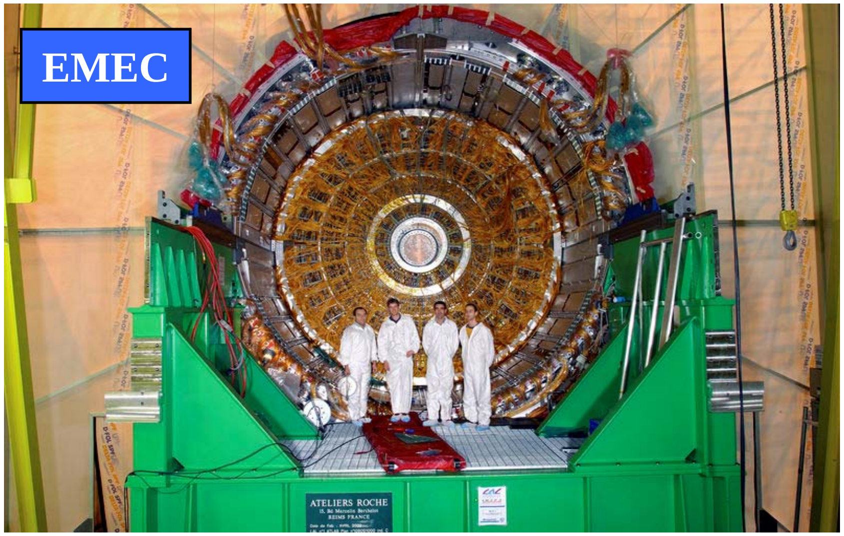


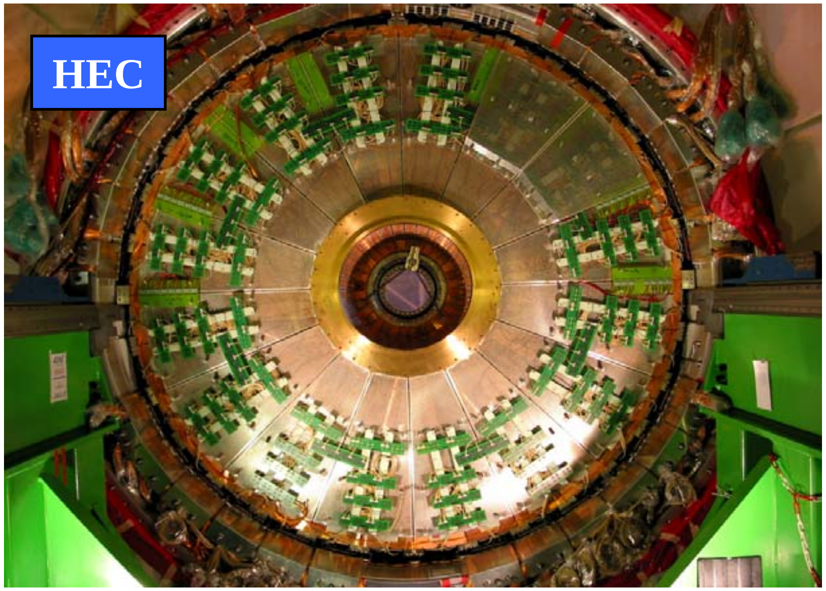
HEC Wheel rotated and inserted into the cryostat

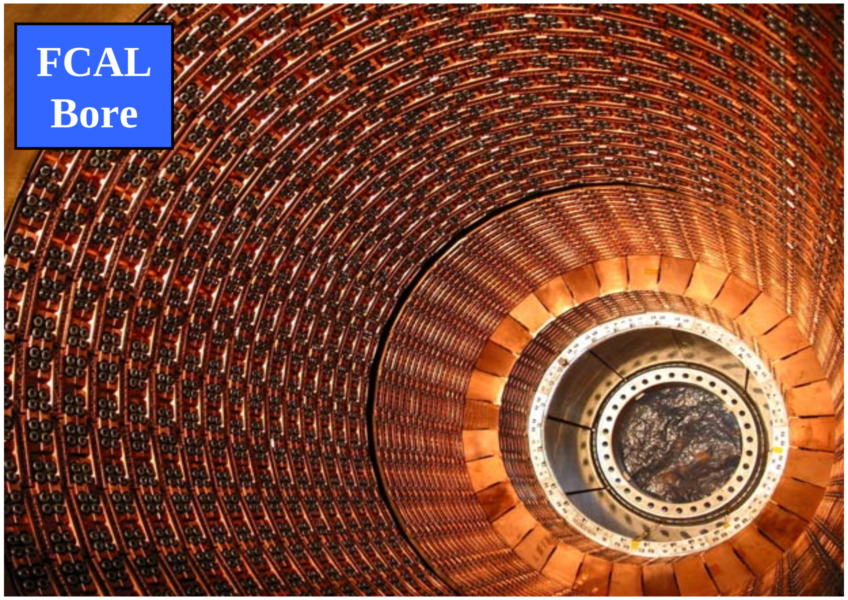


ATLAS LAr END-CAP Integration

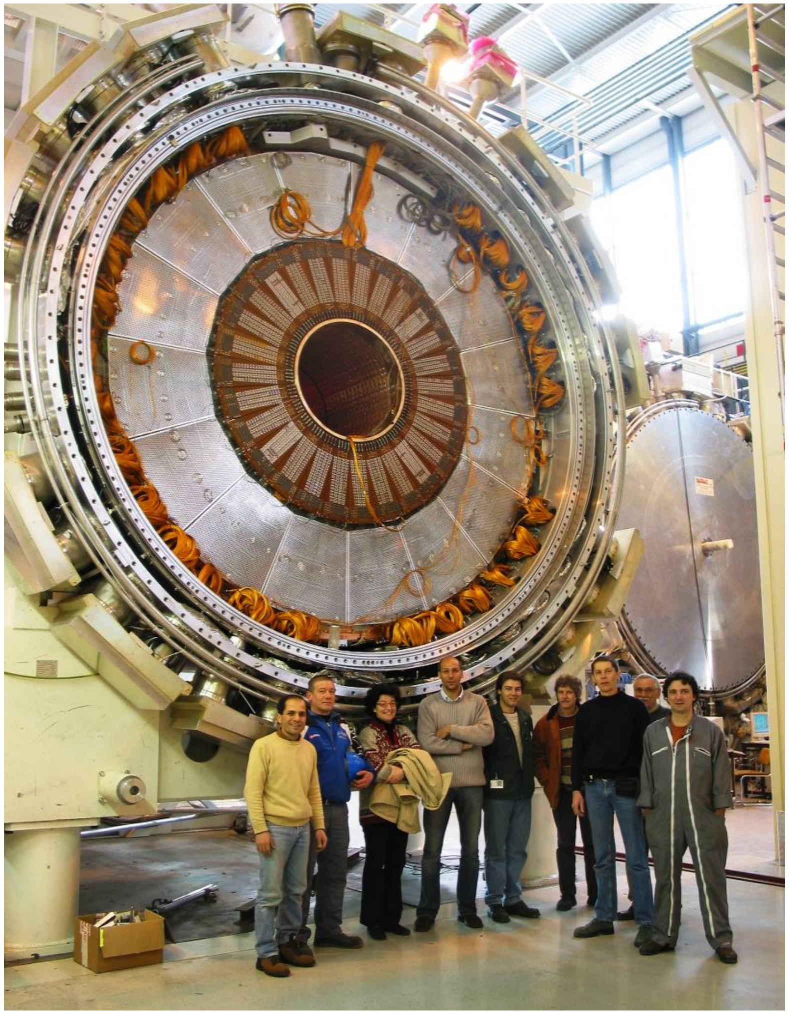






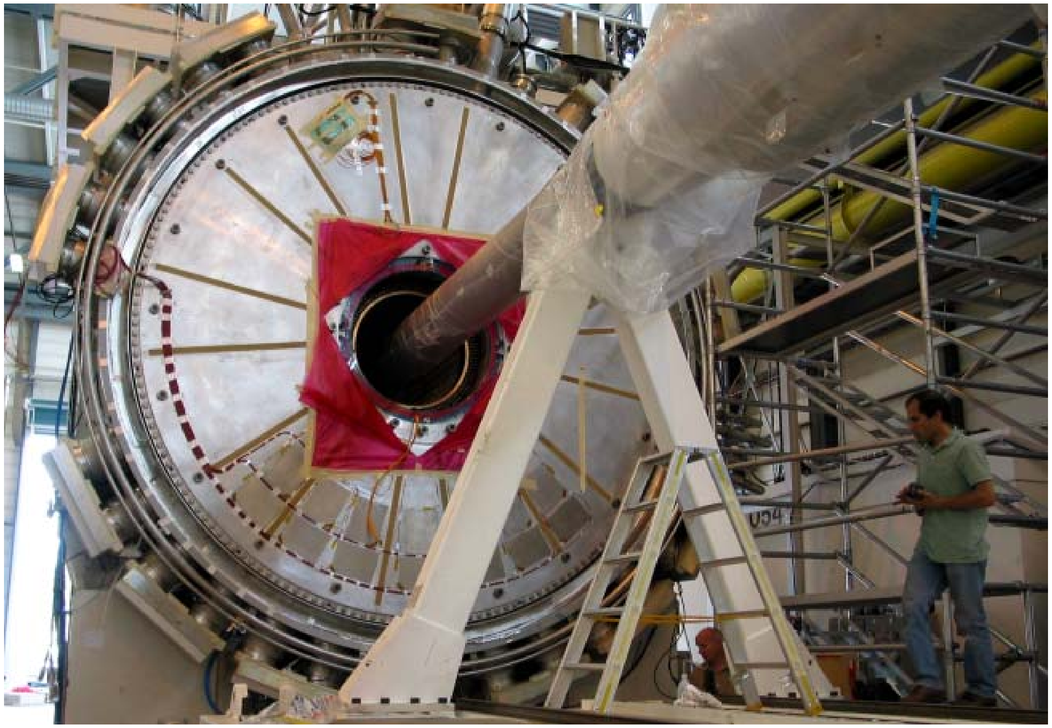


ATLAS LAr END-CAP Final Integration

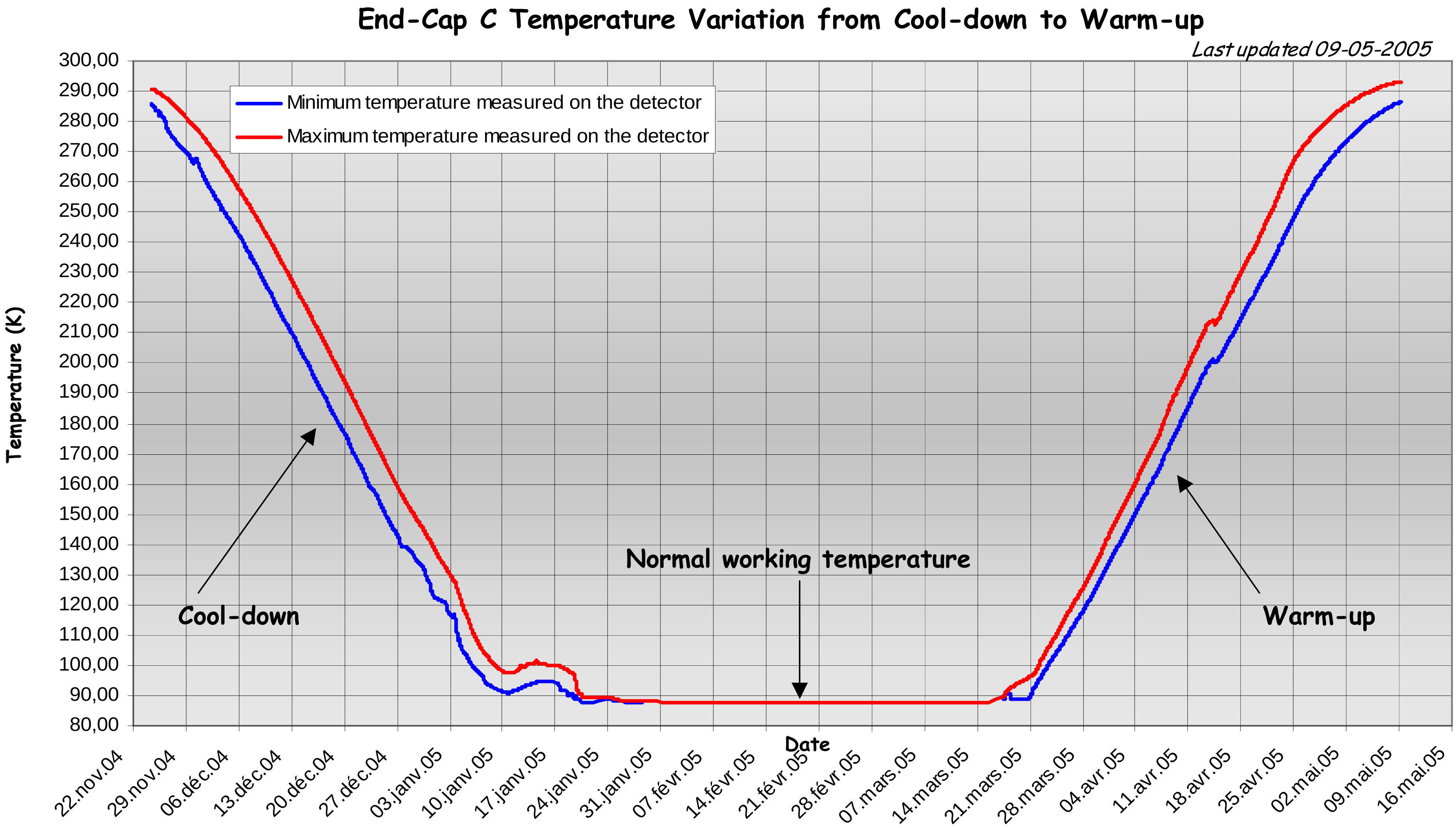


LAr End-Cap A before closure

FCAL A insertion



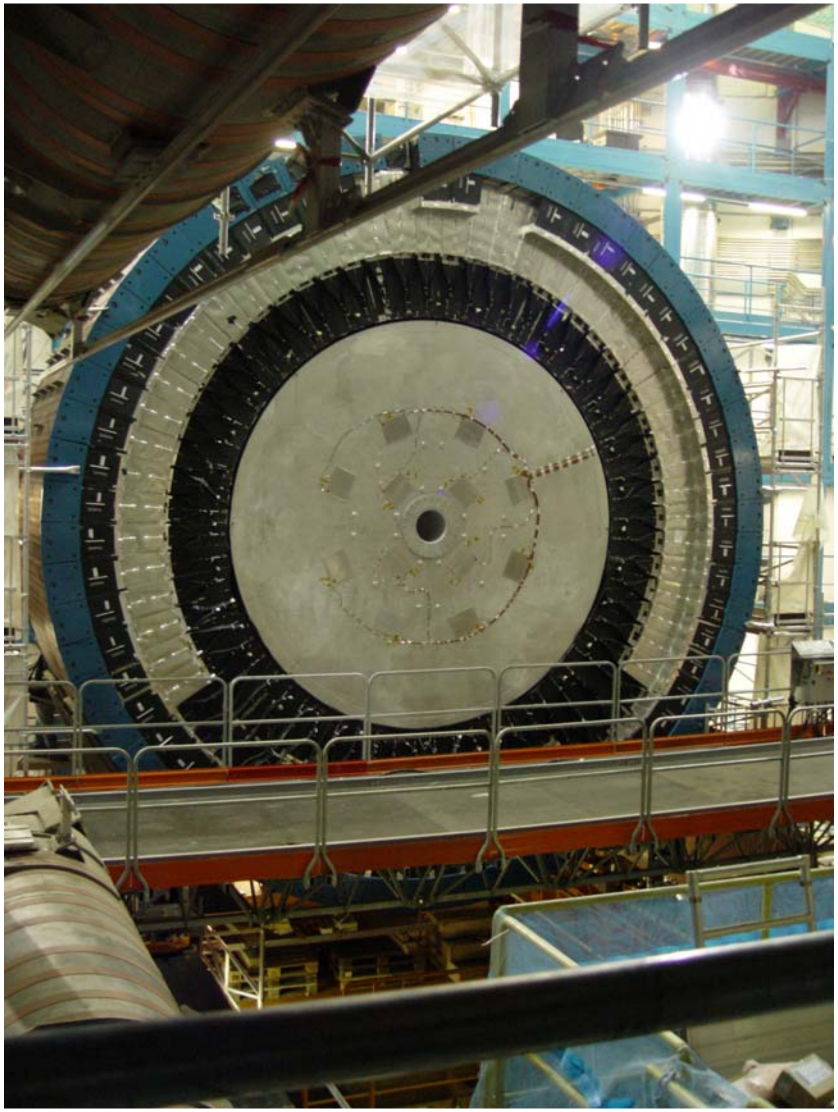
ATLAS LAr END-CAP Cool-down / Warm-up



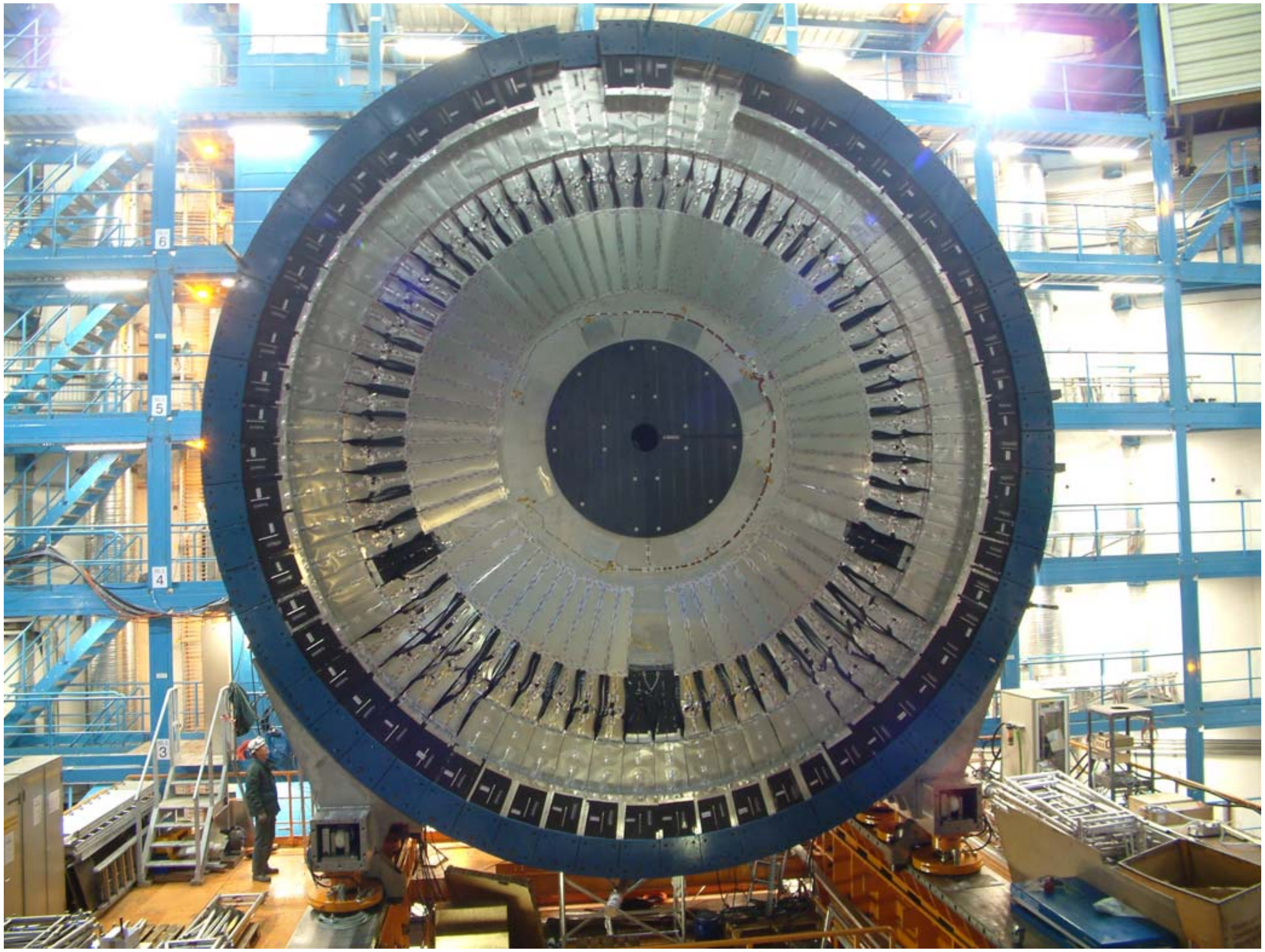
ATLAS LAr END-CAP Transport to Point 1

ATLAS LAr END-CAP in Surface Building

ATLAS LAr END-CAP Lowering into Pit



ATLAS END-CAP Calorimeter Frontside



ATLAS END-CAP Calorimeter Backside