The ATLAS Experiment at the CERN Large Hadron Collider

A 30 minute tour

Peter Krieger

University of Toronto

The Standard Model of Particle Physics

$$\mathbf{SU}(3)_{\mathbf{C}} \times \mathbf{SU}(2)_{\mathbf{L}} \times \mathbf{U}(1)_{\mathbf{Y}}$$

$$\begin{pmatrix} \mathbf{e} \\ \nu_{\mathbf{e}} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \mu \\ \nu_{\mu} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \tau \\ \nu_{\tau} \end{pmatrix}_{\mathbf{L}}$$

$$\begin{pmatrix} \mathbf{u} \\ \mathbf{d} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \mathbf{c} \\ \mathbf{s} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \mathbf{t} \\ \mathbf{b} \end{pmatrix}_{\mathbf{L}}$$

$$\gamma$$

$$\mathbf{W}^{\pm}, \mathbf{Z}^{0}$$

Higgs $\mathbf{H}^{0}$

$$\mathbf{g}$$

Consistent with all existing experimental data

BUT

- **No Higgs yet**
- **19 free parameters (masses, couplings etc)**
- **three (?) generations of fundamental fermions**
- **Hierarchy problem (need Supersymmetry)**
- **Charge ratios of quarks and leptons (GUTs)**
- **No gravity (need string theory ?)**

A Number candidates for physics beyond the SM

Expected mass scale for new physics ~ 1 TeV

Beyond the Standard Model

Hierarchy problem: there are two fundamental energy scales that we know of: the electroweak scale and the Planck scale: $M_{EW} / M_{planck} \approx 10^{-17}$

Naturalness problem: radiative corrections to the mass of a fundamental scalar (e.g. the Higgs) scale like Λ^2 where Λ is the energy scale to which the theory remains valid. This yields a fine-tuning problem for the Higgs mass unless:

a) There is new physics at the ~ TeV energy scale

Could be gravity if there are extra dimensions

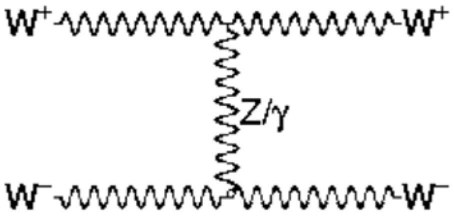
b) There is some symmetry protecting the Higgs mass against large radiative corrections (Supersymmetry)

If the Higgs is not discovered with a mass < 800 GeV, expect the dynamics of WW, ZZ scattering to reveal new physics at this energy scale

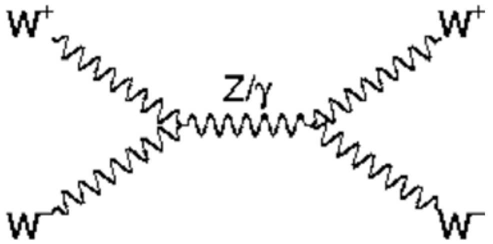
We *MUST* see something at LHC energies

Vector Boson Scattering

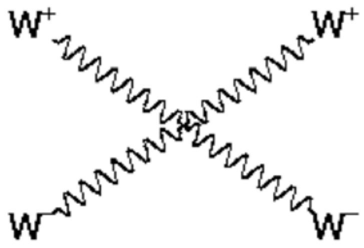
(a)



(b)

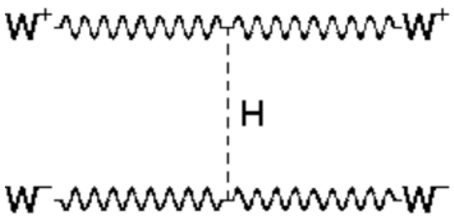


(c)

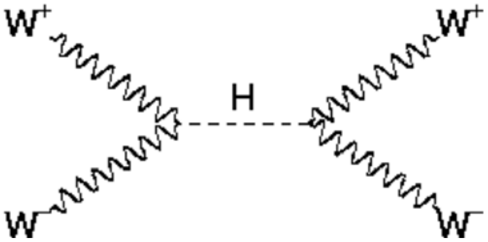


Cross-section grows with $s \equiv E_{CM}^2$. Eventually violates unitarity (probability) unless there are additional processes. Need to add

(d)

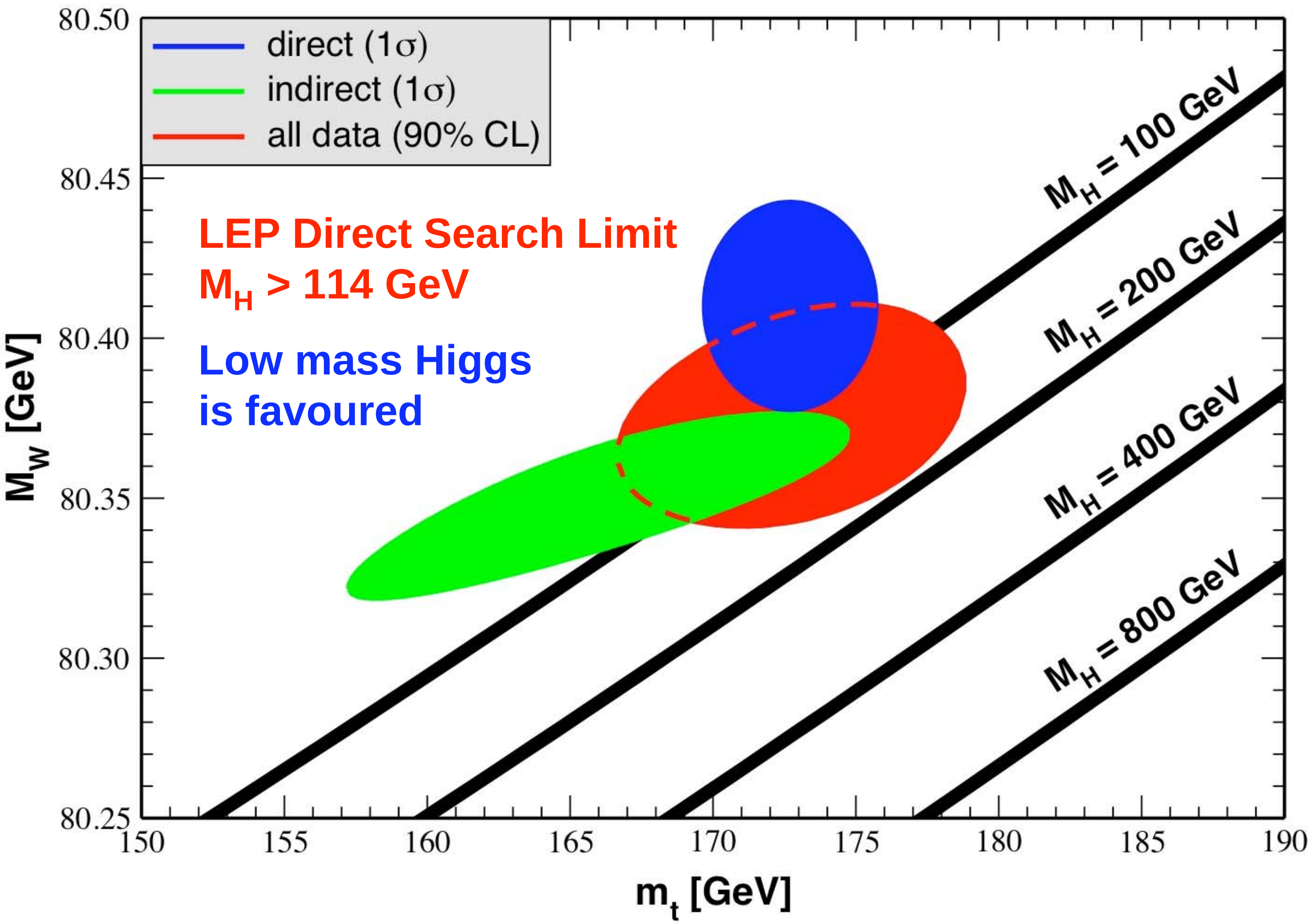


(e)



with $M_H \leq 1\,TeV$

Constraints on the Higgs Mass



LEP Direct Search Limit
$M_H > 114$ GeV

Low mass Higgs is favoured

Supersymmetry

Each SM boson (fermion) has a fermionic (bosonic) supersymmetric partner with IDENTICAL MASS and Standard Model COUPLINGS

leptons **sleptons**

$$\begin{pmatrix} \mathbf{e} \\ \nu_{\mathbf{e}} \end{pmatrix} \begin{pmatrix} \mu \\ \nu_{\mu} \end{pmatrix} \begin{pmatrix} \tau \\ \nu_{\tau} \end{pmatrix} \leftrightarrow \begin{pmatrix} \tilde{\mathbf{e}} \\ \tilde{\nu}_{\mathbf{e}} \end{pmatrix} \begin{pmatrix} \tilde{\mu} \\ \tilde{\nu}_{\mu} \end{pmatrix} \begin{pmatrix} \tilde{\tau} \\ \tilde{\nu}_{\tau} \end{pmatrix}$$

$$\begin{pmatrix} \mathbf{u} \\ \mathbf{d} \end{pmatrix} \begin{pmatrix} \mathbf{c} \\ \mathbf{s} \end{pmatrix} \begin{pmatrix} \mathbf{t} \\ \mathbf{b} \end{pmatrix} \leftrightarrow \begin{pmatrix} \tilde{\mathbf{u}} \\ \tilde{\mathbf{d}} \end{pmatrix} \begin{pmatrix} \tilde{\mathbf{c}} \\ \tilde{\mathbf{s}} \end{pmatrix} \begin{pmatrix} \tilde{\mathbf{t}} \\ \tilde{\mathbf{b}} \end{pmatrix}$$

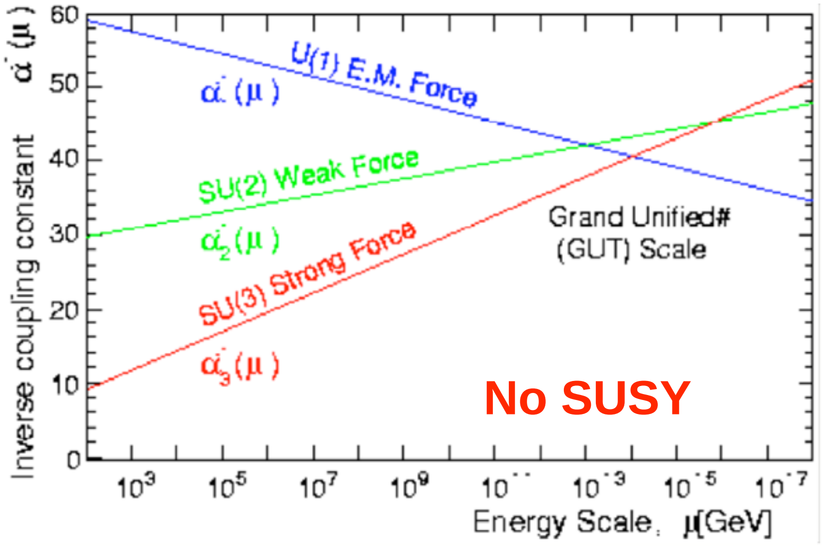
quarks **squarks**

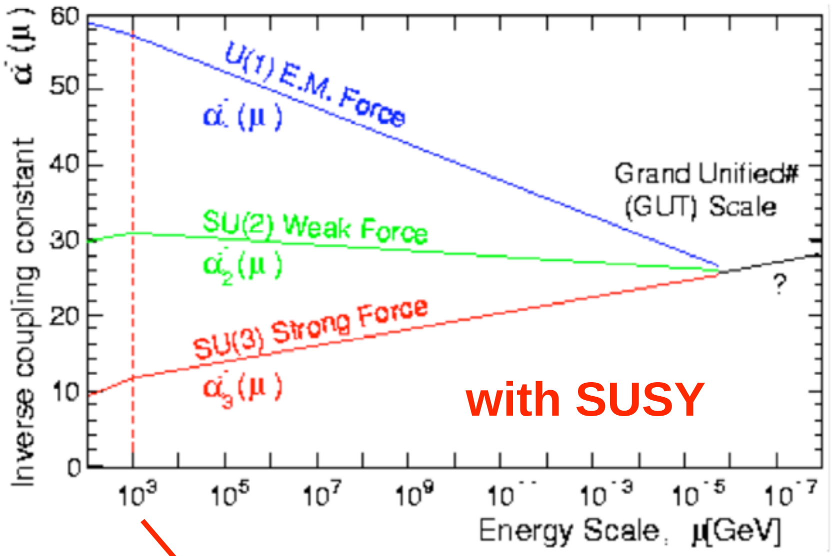
gauginos		**higgsinos**		**gluinos**	
$\mathbf{W}^{\pm}$	$\tilde{\mathbf{W}}^{\pm}$	$\mathbf{h}^{0}$	$\tilde{\mathbf{h}}^{0}$	$\mathbf{g}$	$\tilde{\mathbf{g}}$
$\mathbf{Z}^{0}$	$\tilde{\mathbf{Z}}^{0}$	$\mathbf{H}^{0}$	$\tilde{\mathbf{H}}^{0}$		
γ	$\tilde{\gamma}$	$\mathbf{A}^{0}$	$\tilde{\mathbf{A}}^{0}$		
		$\mathbf{H}^{\pm}$	$\tilde{\mathbf{H}}^{\pm}$		

Obviously we do not see such particles. So we say SUSY is a *broken symmetry*. However, most motivations for SUSY require a mass scale of less than about 1 TeV

Force Unification with and without SUSY

Weak-scale SUSY seems to allow for force unifications at high energy (running of coupling constants with energy):





Assumes a TeV scale SUSY particle mass spectrum

R-parity

R-Parity is a quantum number which distinguishes SM and supersymmetric particles

$$\mathbf{R} = (-1)^{3(\mathbf{B}-\mathbf{L})+2\mathbf{S}}$$

Most supersymmetric models assume R-Parity Conservation

This has two important consequences:

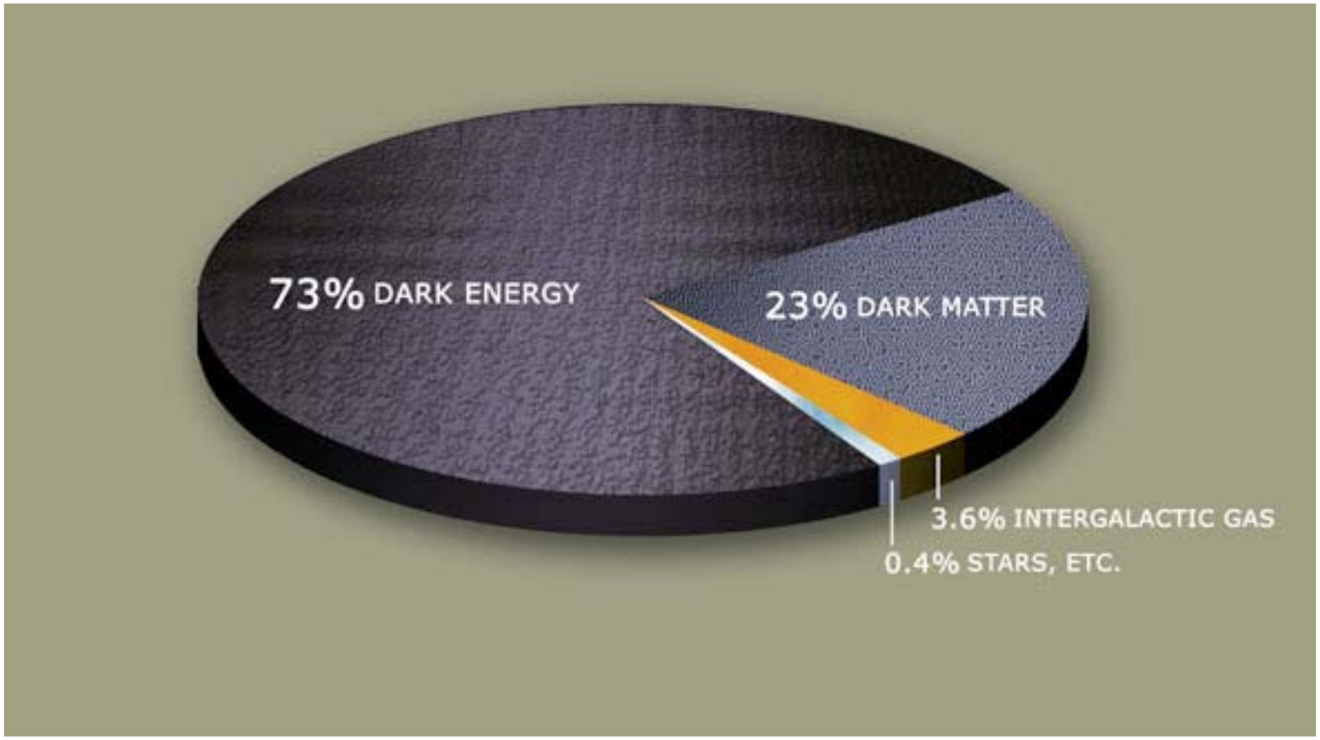
Supersymmetric particles must be produced in pairs

There must be some Lightest Supersymmetric Particle or LSP

This LSP is usually the lightest neutralino $\tilde{\chi}_1^0$ which can be a good Cold Dark Matter candidate.

This leads to an experimental signature of large transverse missing energy. In the case of pair production of squarks and gluinos at the LHC, the standard signature is *jets + missing energy*

Cosmological Issues

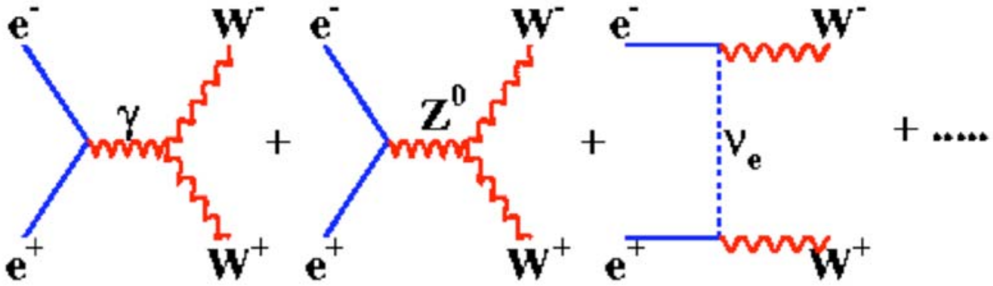


Evidence is that dark matter is predominantly “cold”, e.g. non-relativistic. Popular candidate is the WIMP (Weakly Interacting Massive Particle). The LSP can be a very good candidate for this.

Some Basic Collider Physics

How does one calculate the rate for some physics process at a collider ?

$\mathcal{M}$ = sum of all contributing processes, here for $e^+e^- \rightarrow W^+W^-$



Define cross-section $\sigma \propto |\mathcal{M}|^2$ units of (length)^2

Define luminosity $\mathcal{L} \approx N \frac{f}{A}$

bunch crossing frequency

~ cross-sectional size of the beams

~Number of particle bunches times numbers of particles in each bunch

Instantaneous production rate $N = \mathcal{L}\,\sigma$

Hadron Colliders vs Electron Positron Colliders

Bending a charged particle in a magnetic field costs energy emitted in the form of synchrotron radiation:

$$\Delta E = \frac{4\pi}{3} \bullet \frac{e^2\beta^2\gamma^4}{\rho} \propto \frac{1}{m^4} \quad \text{or} \quad E^4$$

For fixed radius machine (i.e. in the LEP tunnel at CERN with ρ = 6.28km) synchrotron radiation loss for protons is less that that for electrons by the amount

$$\left(\frac{m_e}{m_p}\right)^4 \approx 10^{-13}$$

Cannot (feasibly) build electron synchrotrons of arbitrarily high energy. Need either:

- ✓ hadron collider
- ✓ linear electron positron collider

The Large Hadron Collider at CERN

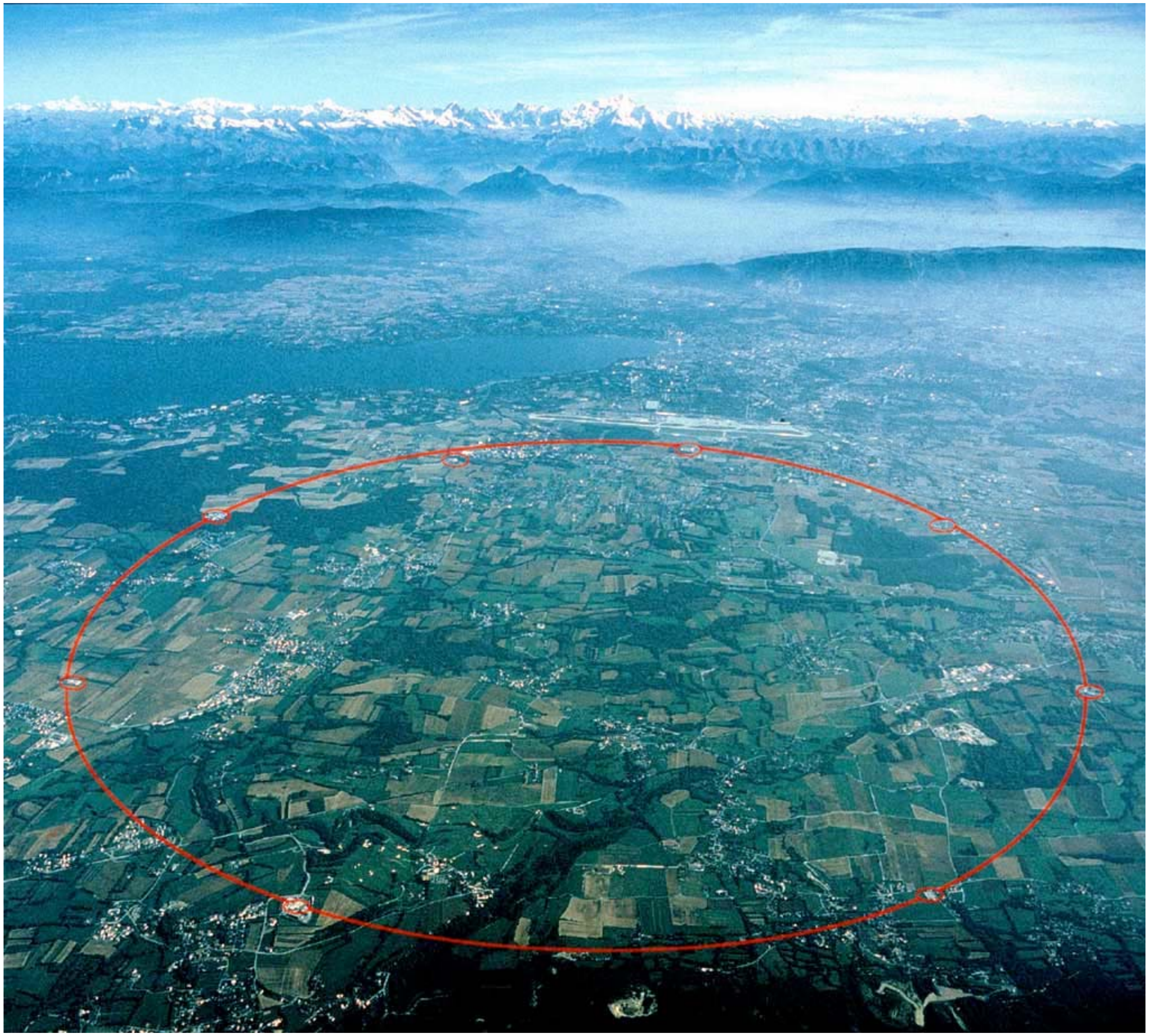
Proton-proton collider installed into the 27km circumference LEP ring at CERN in Geneva Switzerland:

- ➢ pp centre-of-mass energy of 14 TeV
- ➢ constituent centre-of-mass energies ~ 1-2 TeV
- ➢ luminosity of 10^{33} $cm^{-2}s^{-1}$ (low luminosity)
  10^{34} $cm^{-2}s^{-1}$ (high luminosity)
- ➢ proton bunch spacing of 25 ns (40MHz collision frequency)

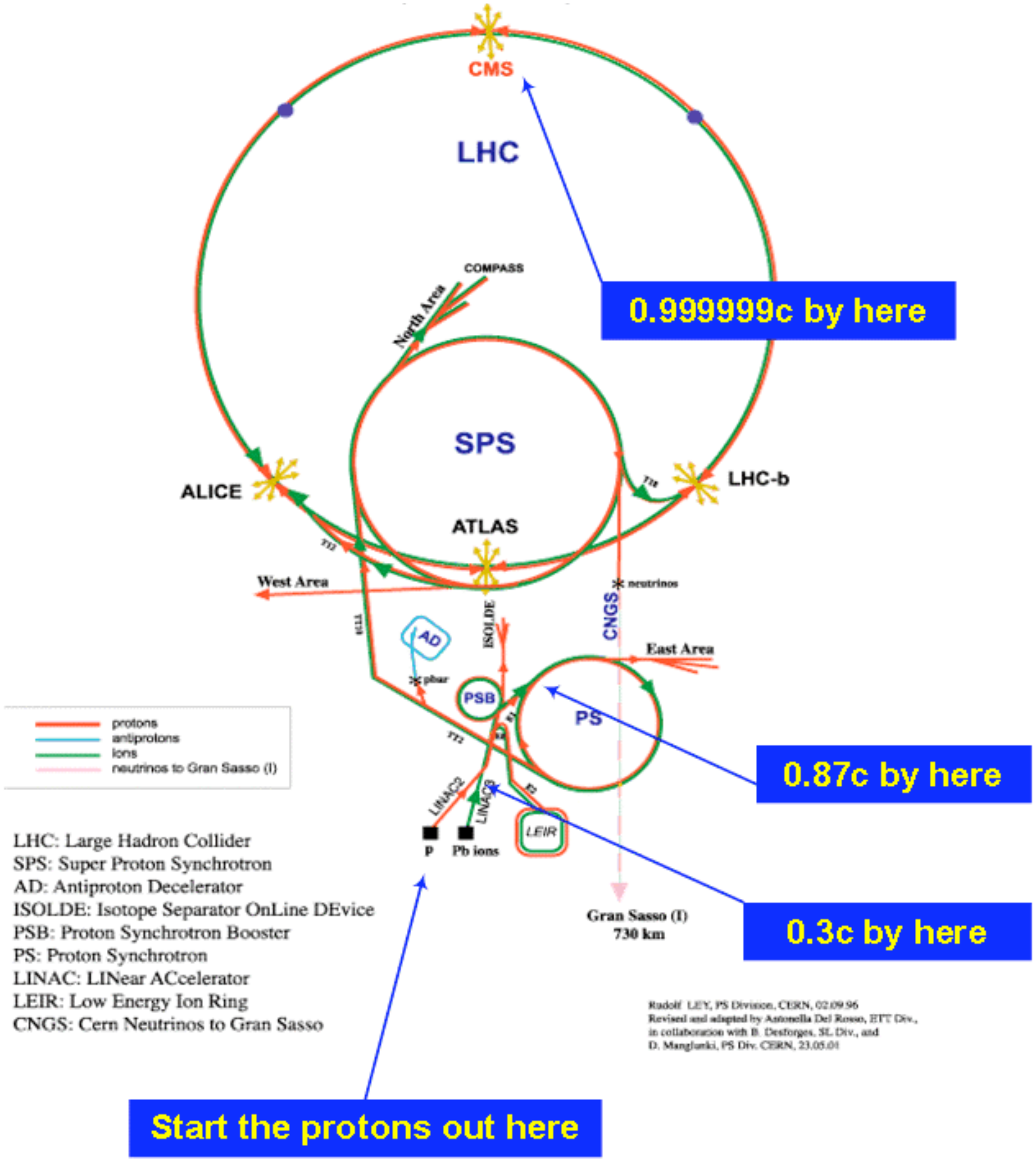
Physics goals: whatever TeV-scale physics is there to be discovered

- Higgs boson
- Supersymmetry
- Extra dimensions
- Extended gauge theories
- Compositeness
- Low-scale gravity

CERN Aerial View



LHC Accelerator Chain



LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso

Rudolf LEY, PS Division, CERN, 02.09.96
Revised and adapted by Antonella Del Rosso, ETT Div.,
in collaboration with B. Desforges, SL Div., and
D. Manglunki, PS Div. CERN, 23.05.01

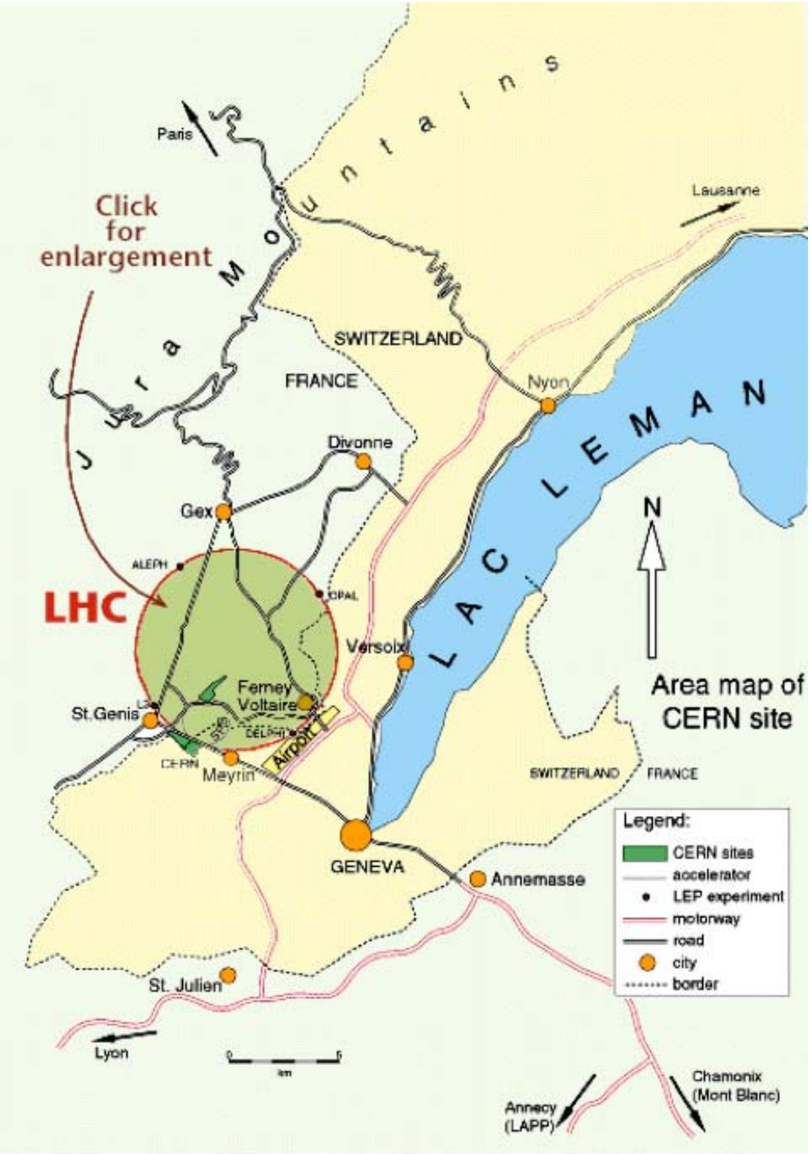
0.999999c by here

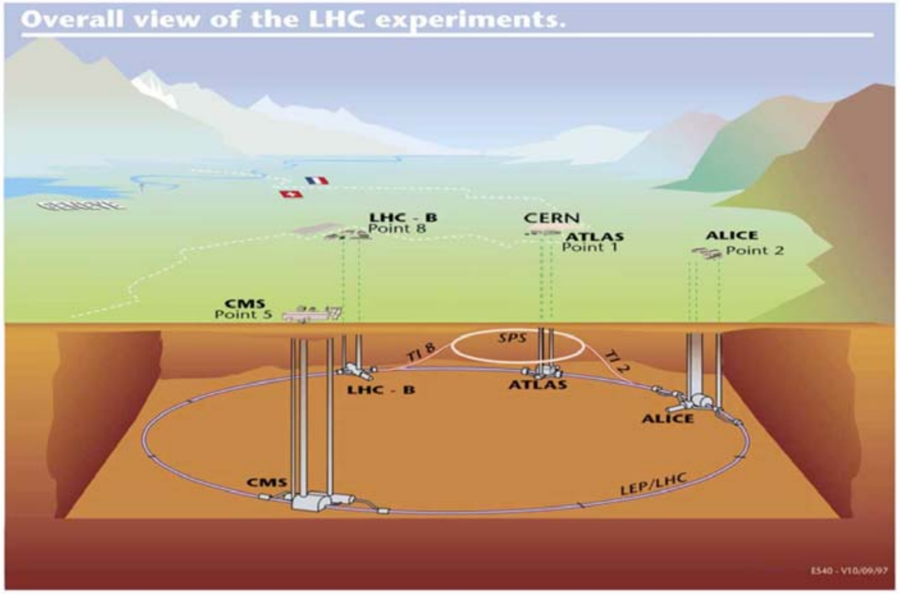
0.87c by here

0.3c by here

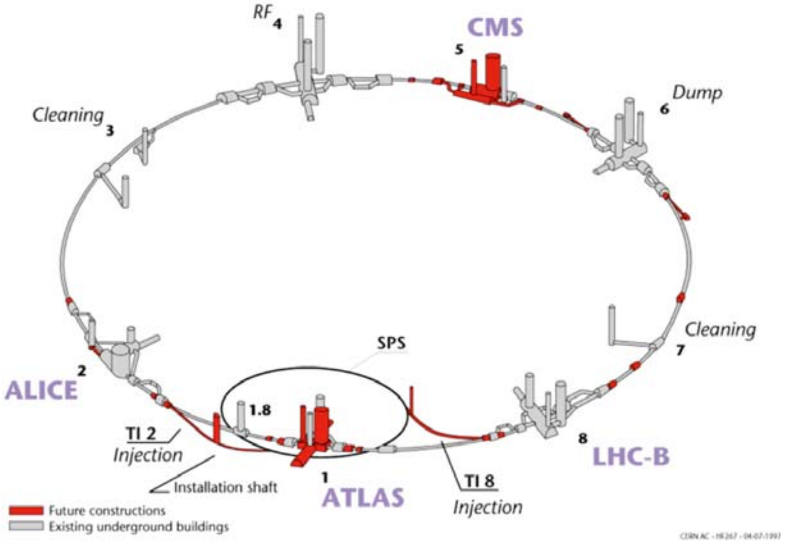
Start the protons out here

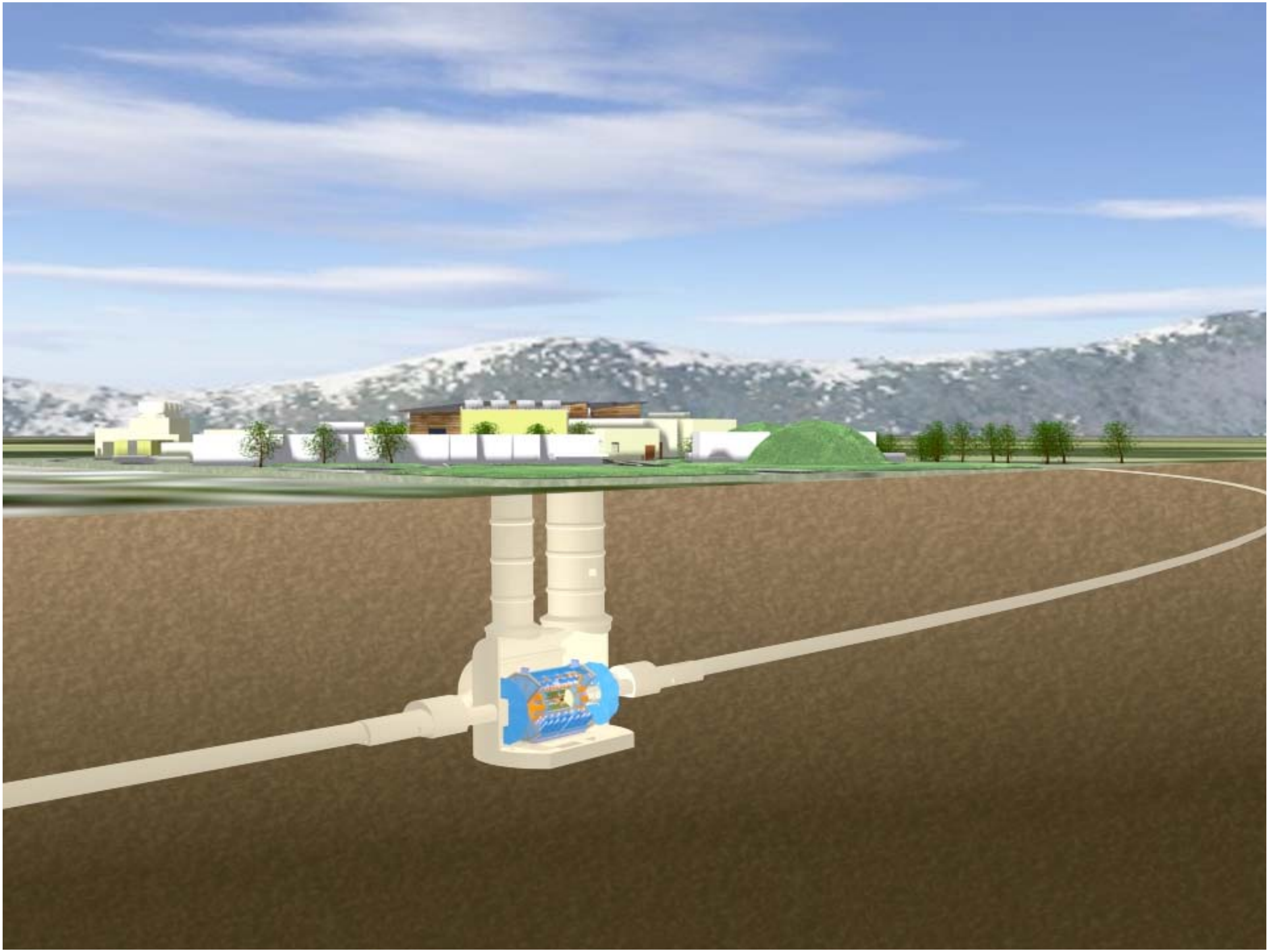
The CERN Large Hadron Collider



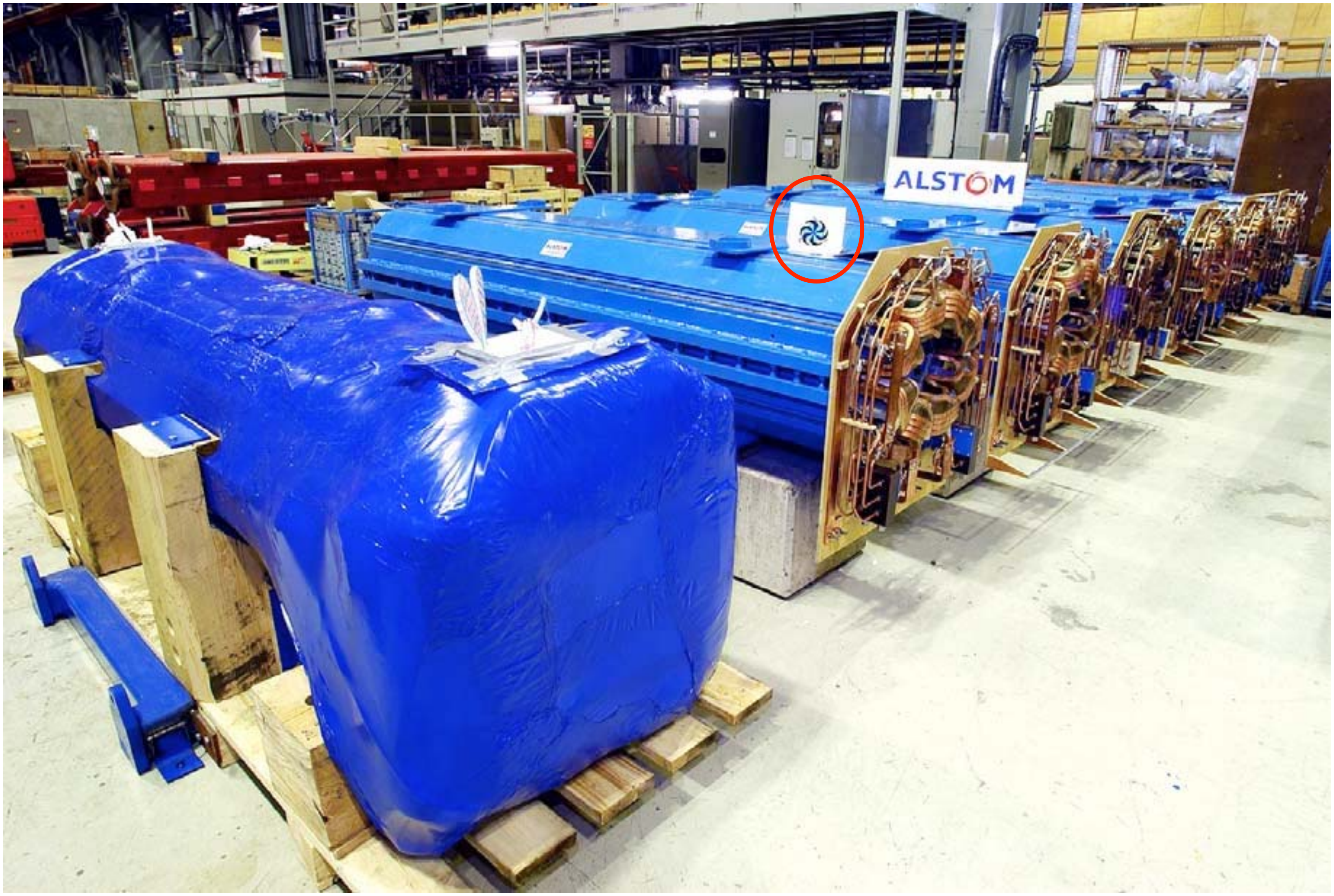


Layout of the LEP tunnel including future LHC infrastructures.

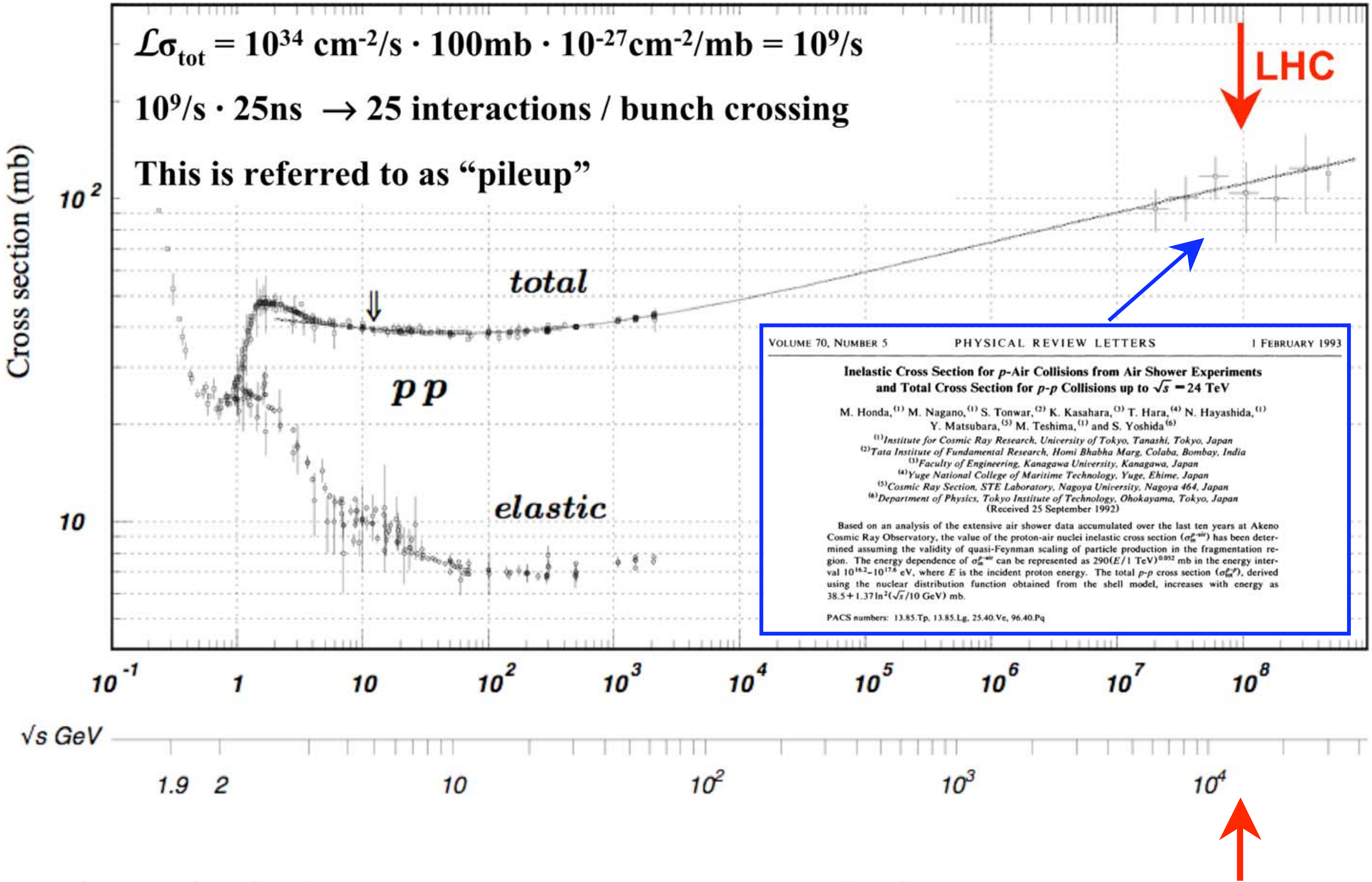




Quadrupole Magnets from Canada



The proton-proton total cross-section



$\mathcal{L}\sigma_{tot} = 10^{34}\ \mathrm{cm^{-2}/s} \cdot 100\mathrm{mb} \cdot 10^{-27}\mathrm{cm^{-2}/mb} = 10^9/\mathrm{s}$

$10^9/\mathrm{s} \cdot 25\mathrm{ns}$ → 25 interactions / bunch crossing

This is referred to as "pileup"

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Inelastic Cross Section for *p*-Air Collisions from Air Shower Experiments and Total Cross Section for *p*-*p* Collisions up to $\sqrt{s} = 24$ TeV

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Y. Matsubara,(5) M. Teshima,(1) and S. Yoshida(6)
(1)*Institute for Cosmic Ray Research, University of Tokyo, Tanashi, Tokyo, Japan*
(2)*Tata Institute of Fundamental Research, Homi Bhabha Marg, Colaba, Bombay, India*
(3)*Faculty of Engineering, Kanagawa University, Kanagawa, Japan*
(4)*Yuge National College of Maritime Technology, Yuge, Ehime, Japan*
(5)*Cosmic Ray Section, STE Laboratory, Nagoya University, Nagoya 464, Japan*
(6)*Department of Physics, Tokyo Institute of Technology, Ohokayama, Tokyo, Japan*
(Received 25 September 1992)

Based on an analysis of the extensive air shower data accumulated over the last ten years at Akeno Cosmic Ray Observatory, the value of the proton-air nuclei inelastic cross section ($\sigma_{in}^{p\text{-air}}$) has been determined assuming the validity of quasi-Feynman scaling of particle production in the fragmentation region. The energy dependence of $\sigma_{in}^{p\text{-air}}$ can be represented as $290(E/1\ \mathrm{TeV})^{0.052}$ mb in the energy interval $10^{16.2}$–$10^{17.6}$ eV, where E is the incident proton energy. The total *p*-*p* cross section ($\sigma_{tot}^{p\text{-}p}$), derived using the nuclear distribution function obtained from the shell model, increases with energy as $38.5 + 1.37\ln^2(\sqrt{s}/10\ \mathrm{GeV})$ mb.

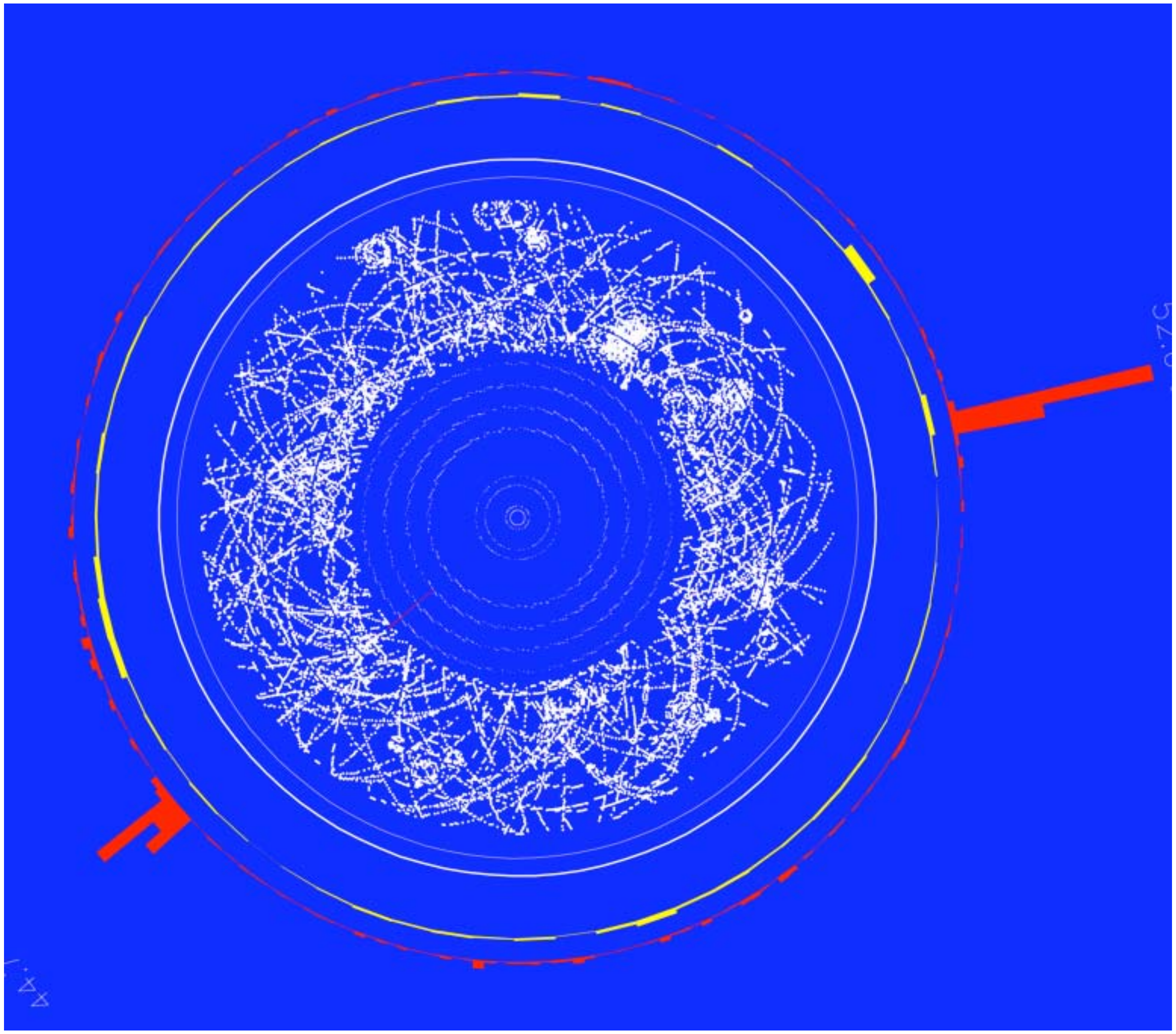
PACS numbers: 13.85.Tp, 13.85.Lg, 25.40.Ve, 96.40.Pq

Min-Bias Events at High Luminosity (10^{34} $cm^{-2}s^{-1}$)

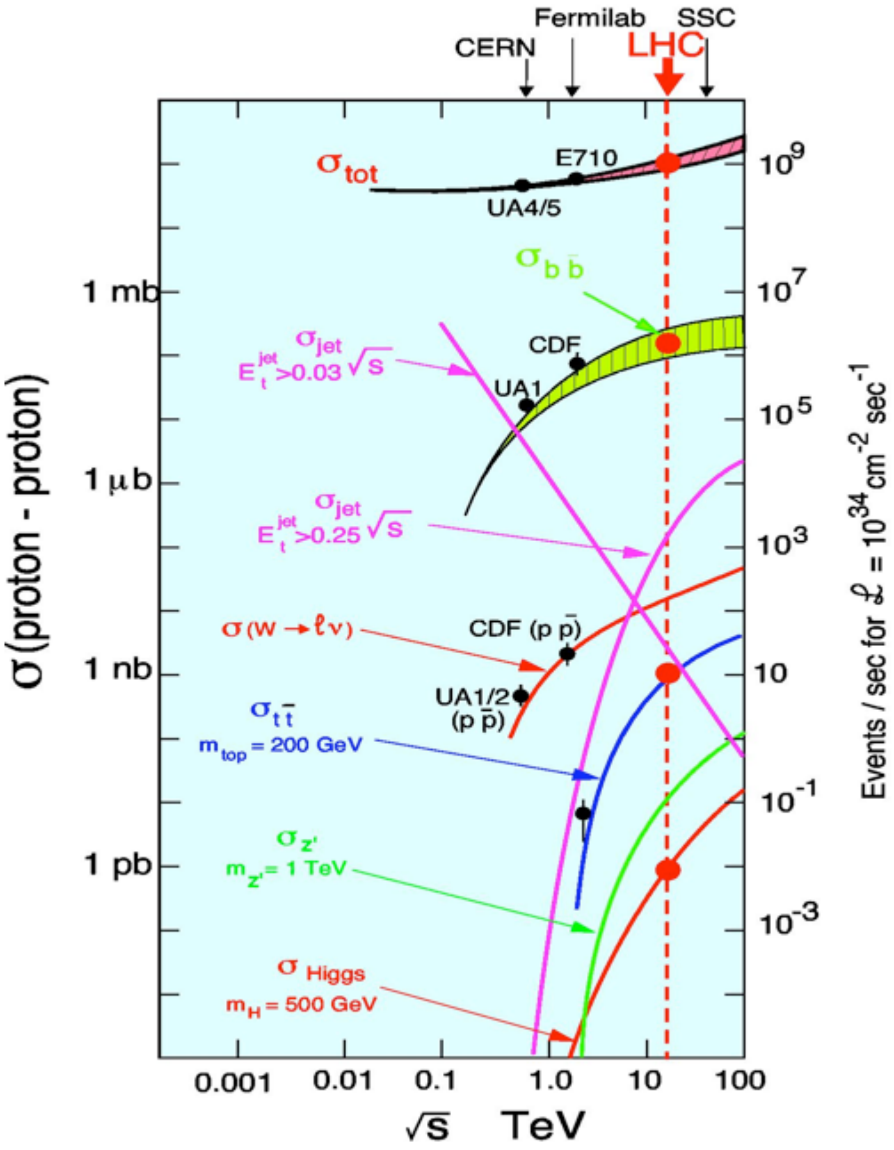
High event rate results in large detector occupancies

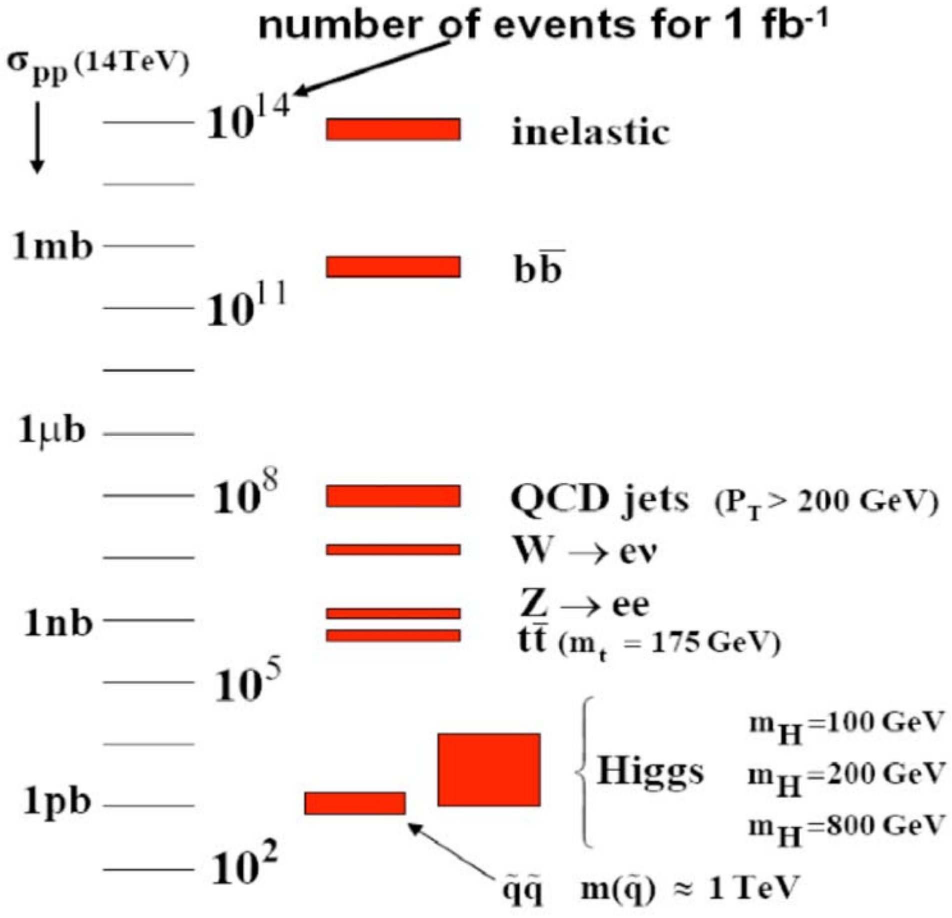
High charged particle multiplicity visible in tracking detector

ATLAS H→γγ

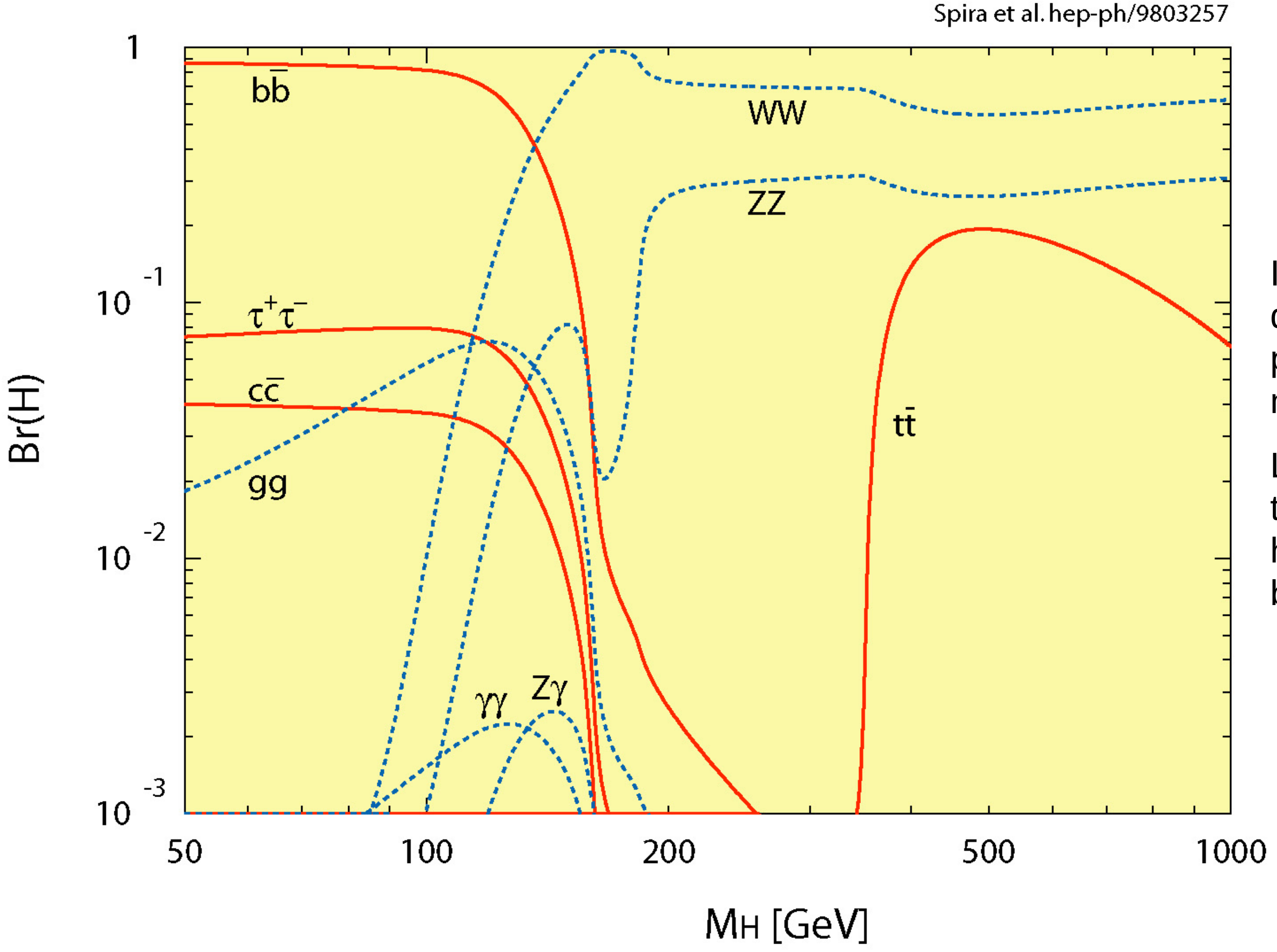


Production cross-sections at the LHC





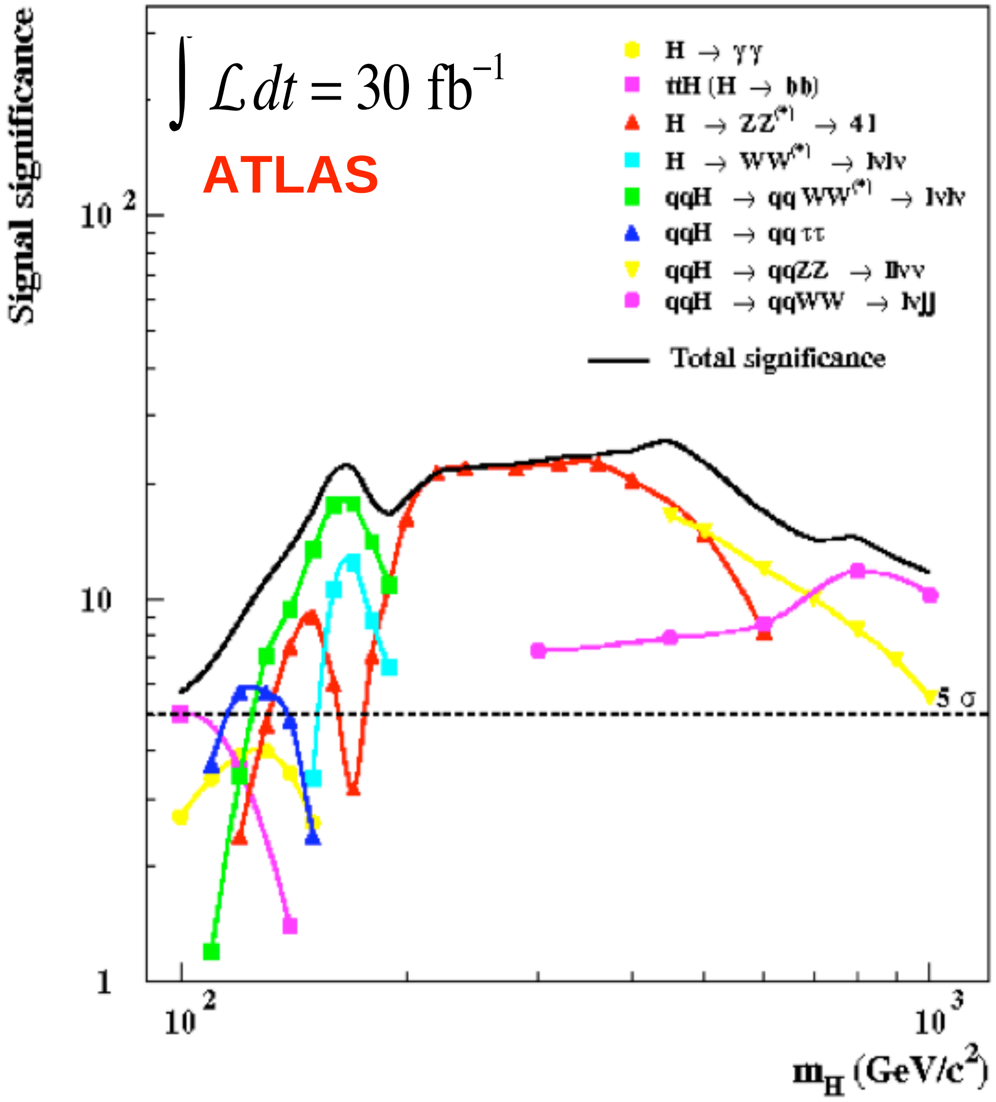
Higgs Branching Fractions vs M_H



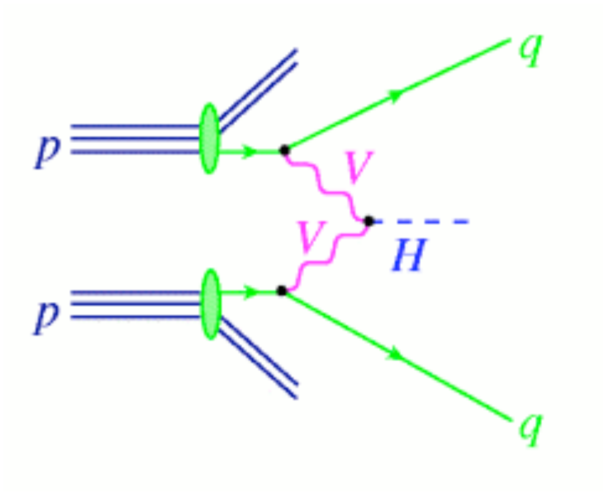
In terms of discovery potential, MH matters a lot.

Low mass is tricky due to huge QCD backgrounds.

Higgs Discovery Significance at ATLAS

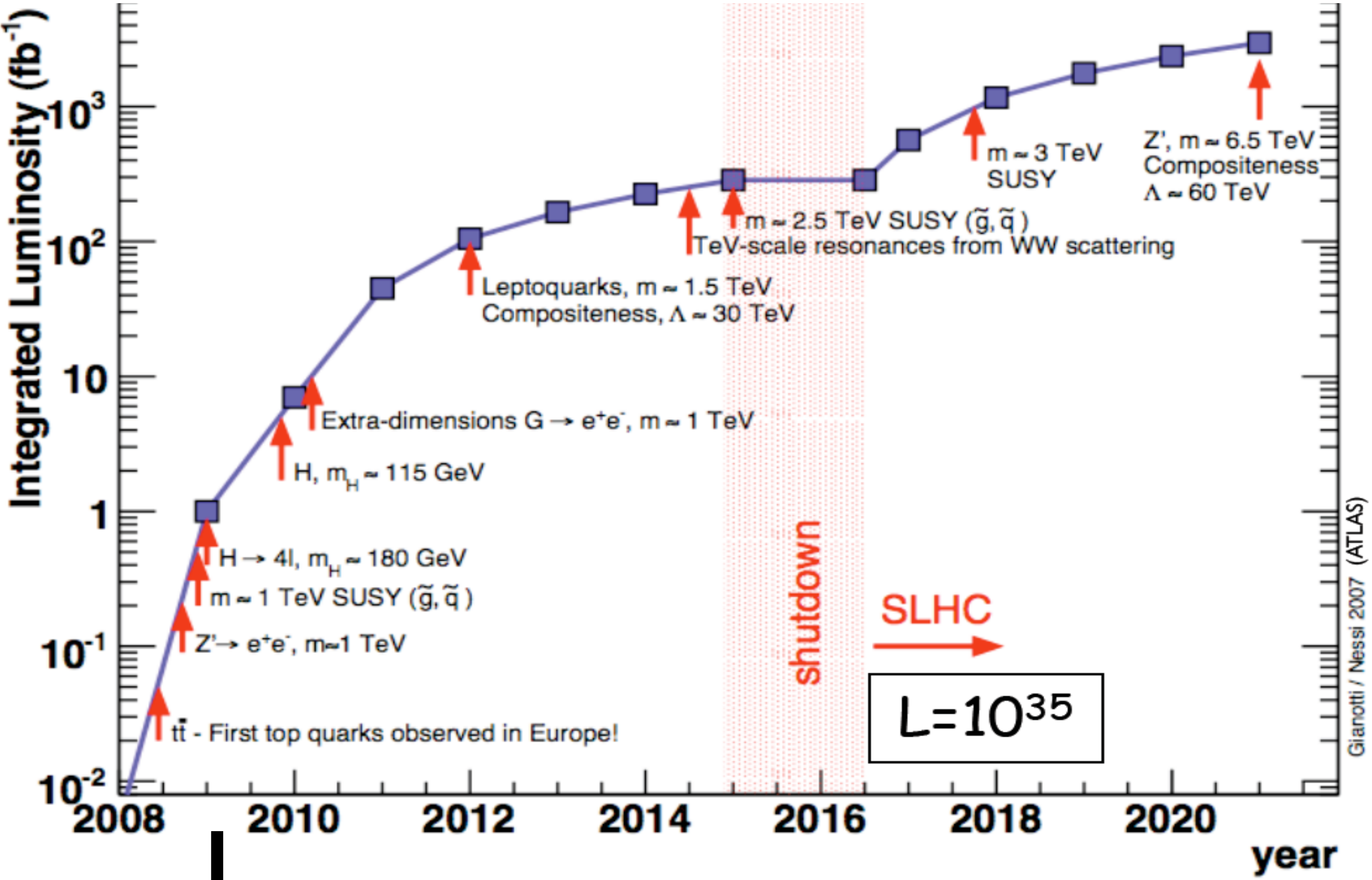


Vector boson fusion important in the low mass region



for example, VBF $H \to \tau^+\tau^-$

LHC luminosity profile and physics reach

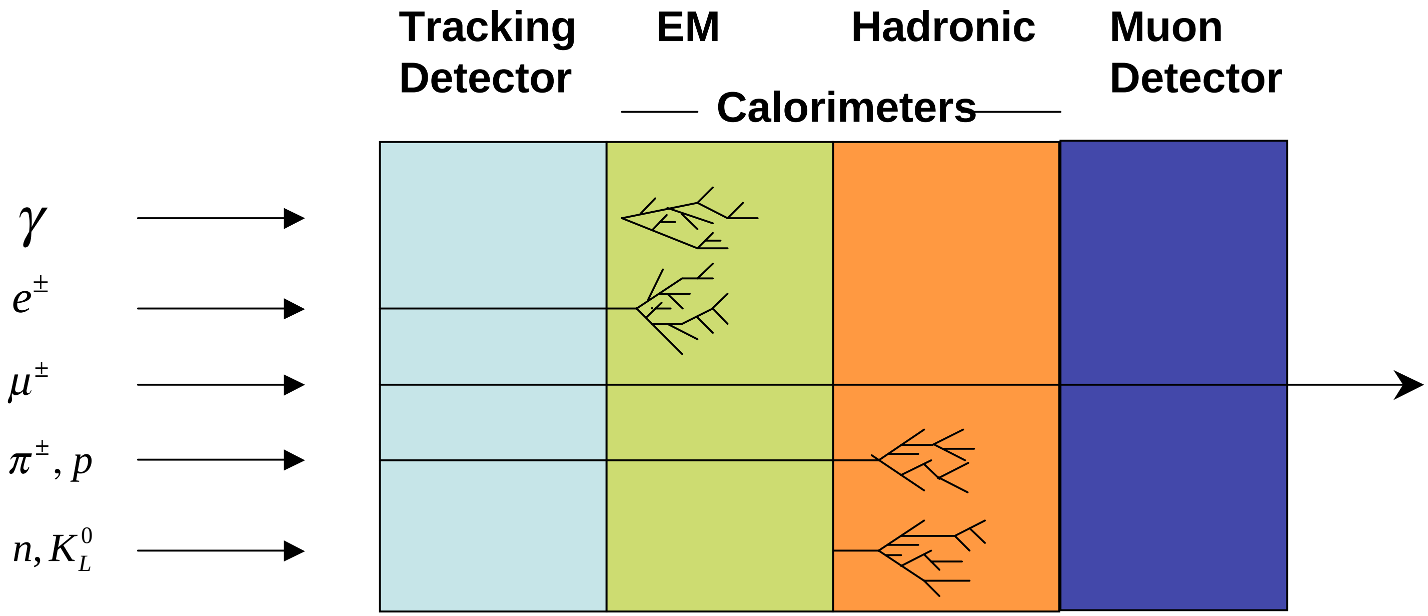


early physics

O($1fb^{-1}$)

Collider Detectors

Events reconstructed based on particles stable enough to be detected



Charged particle momentum, particle ID

$e^{\pm}, \gamma$

muons

-------Hadrons, jets----------

Calorimeters vs Magnetic Spectrometers

A calorimeter measures particle / jet energies via total energy deposition in the device e.g. absorption of entire particle / jet energy through a showering process (EM or hadronic).

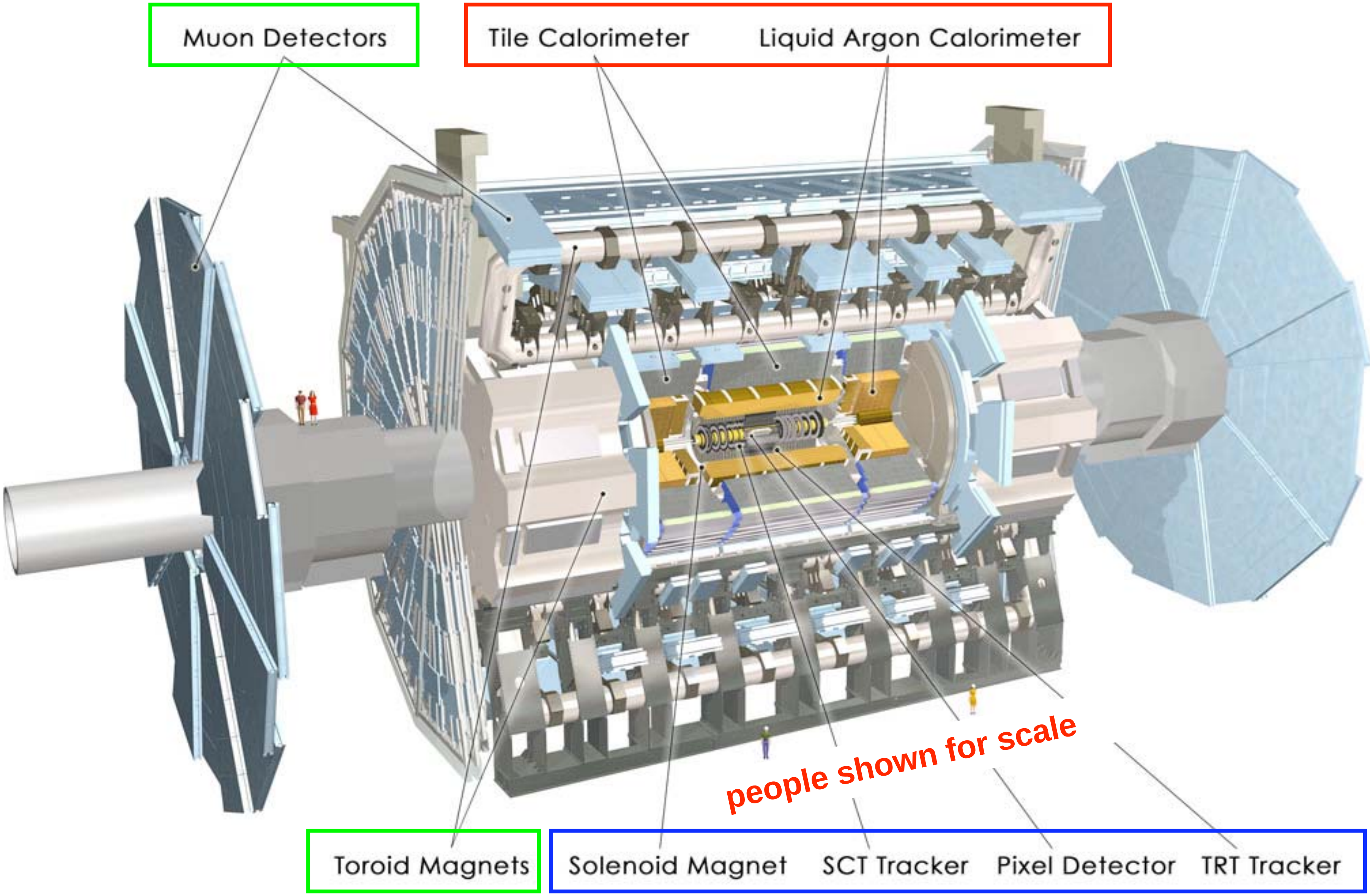
Magnetic spectrometers measure particle momenta via curvature in a known magnetic field (usually solenoidal, but also toroidal in the case of the ATLAS muon spectrometer).

For a given design, the depth of a calorimeter capable of providing full containment of high energy particles scales like ln(E).

For a magnetic spectrometer, the resolution $\Delta p/p$, for a given detector size, scales like sqrt(E). Magnetic spectrometers must get larger at higher energies, to achieve the same momentum resolution.

In ATLAS, most of the detector volume is occupied by the muon spectrometer.

The ATLAS Detector


Muon Detectors

Tile Calorimeter

Liquid Argon Calorimeter

Toroid Magnets

Solenoid Magnet

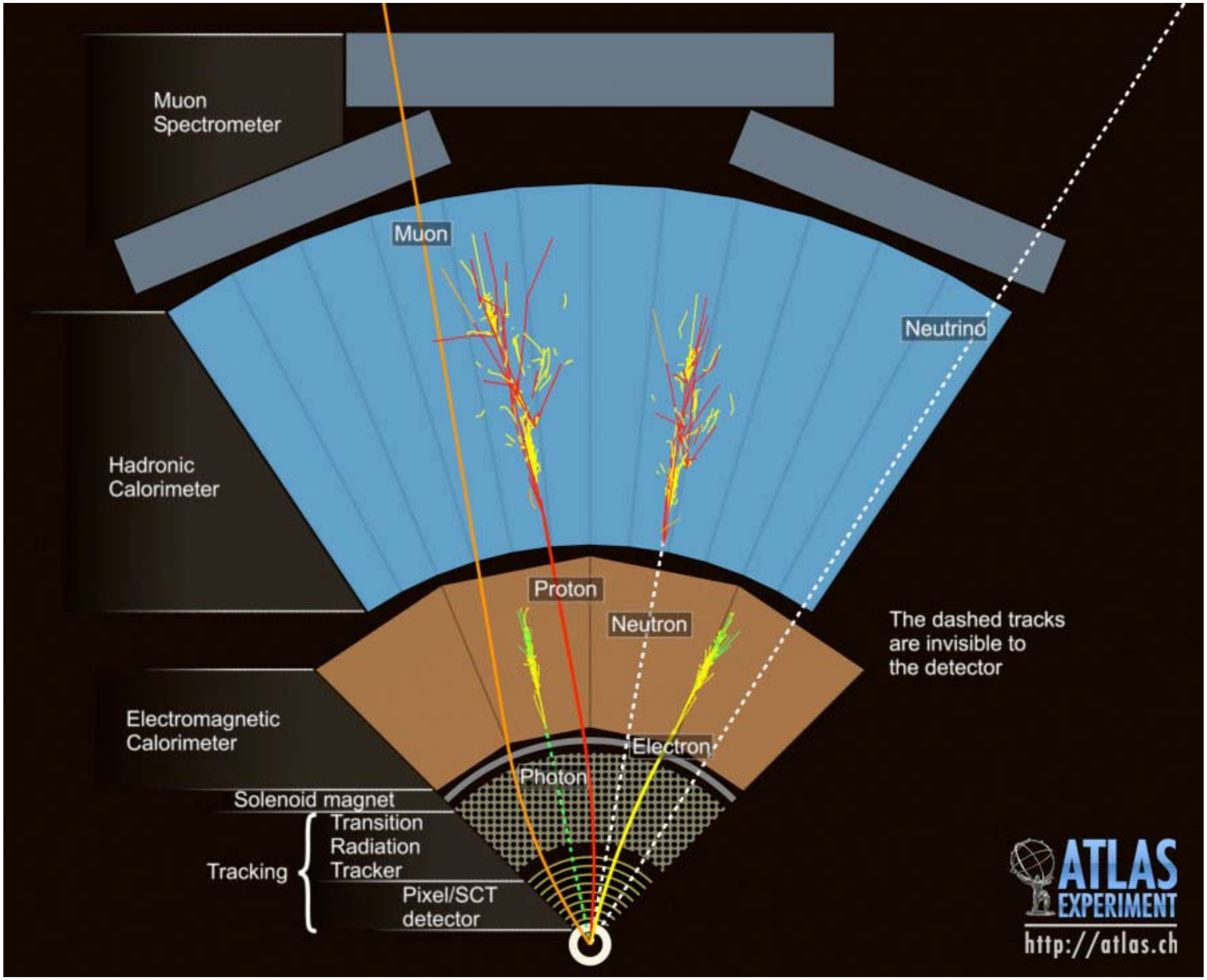
SCT Tracker

Pixel Detector

TRT Tracker

people shown for scale

ATLAS Event Slice



The dashed tracks are invisible to the detector

The ATLAS Canada Collaboration

Alberta
Carleton
Montreal
McGill   Simon
Fraser Regina
Toronto
TRIUMF
UBC
Victoria
York

42 University/Lab Physicists
150 People, including engineers, technicians and students

20 Undergraduate students
60 Graduate Students
20 Postdocs

Focus has been on LAr Calorimetry

Four NSERC funded projects:

Hadronic Endcap Calorimeter

Hadronic Forward Calorimeter

Endcap Signal Cryogenic Feedthroughs

Front-End Board Electronics

Other Important Activities

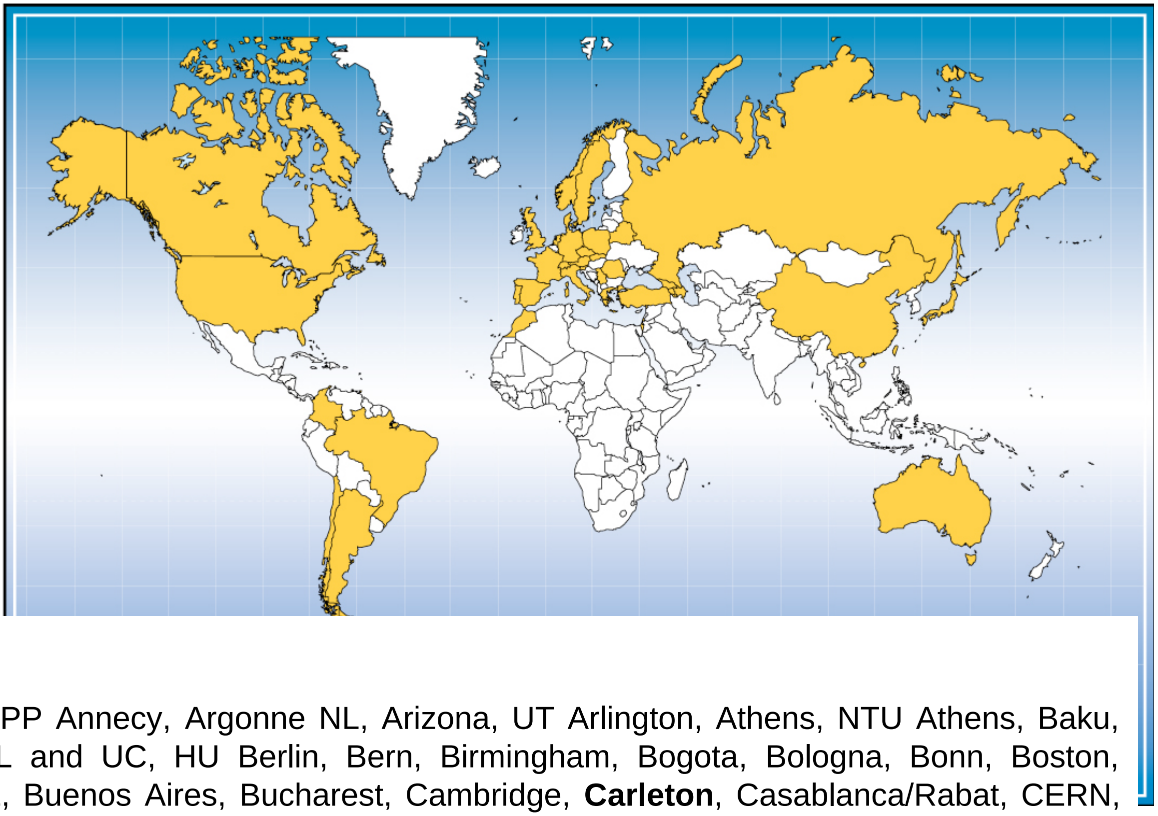
High Level Trigger
ATLAS Computing
TRT Electronics
ATLAS Upgrades (SLHC)
Beam Conditions Monitors
Beam Testing / Analysis
Calorimeter Calibration
Physics Studies / Analysis
Radiation Hardness Studies
Pixel Testing and Assembly

ATLAS Collaboration

(Status October 2007)

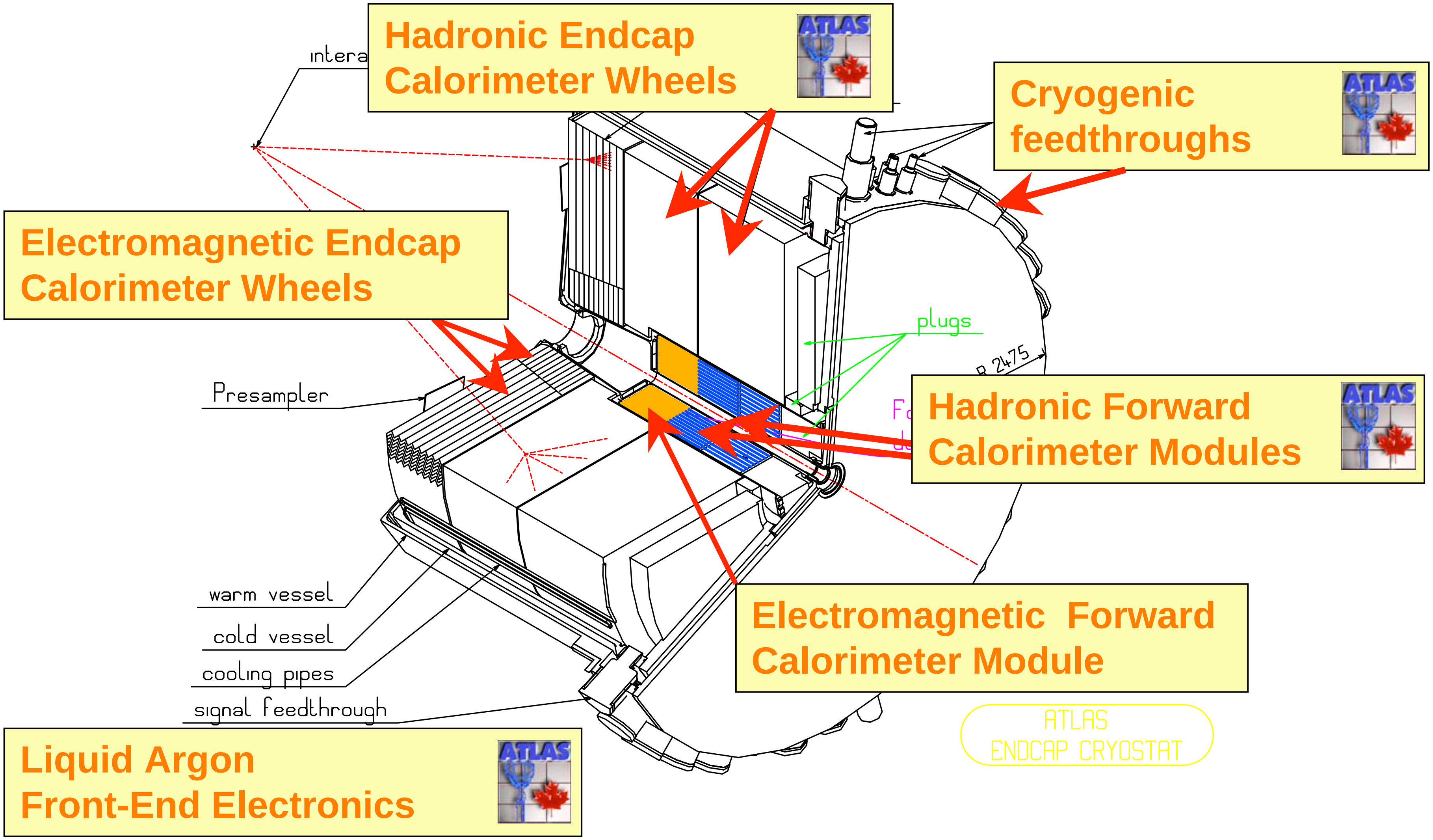
37 Countries
167 Institutions
2000 Scientific Authors total
(1600 with a PhD)

CANADA: ~ 4% of collaboration



Albany, **Alberta**, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizona, UT Arlington, Athens, NTU Athens, Baku, IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, HU Berlin, Bern, Birmingham, Bogota, Bologna, Bonn, Boston, Brandeis, Bratislava/SAS Kosice, Brookhaven NL, Buenos Aires, Bucharest, Cambridge, **Carleton**, Casablanca/Rabat, CERN, Chinese Cluster, Chicago, Chile, Clermont-Ferrand, Columbia, NBI Copenhagen, Cosenza, AGH UST Cracow, IFJ PAN Cracow, DESY, Dortmund, TU Dresden, JINR Dubna, Duke, Frascati, Freiburg, Geneva, Genoa, Giessen, Glasgow, Göttingen, LPSC Grenoble, Technion Haifa, Hampton, Harvard, Heidelberg, Hiroshima, Hiroshima IT, Indiana, Innsbruck, Iowa SU, Irvine UC, Istanbul Bogazici, KEK, Kobe, Kyoto, Kyoto UE, Lancaster, UN La Plata, Lecce, Lisbon LIP, Liverpool, Ljubljana, QMW London, RHBNC London, UC London, Lund, UA Madrid, Mainz, Manchester, Mannheim, CPPM Marseille, Massachusetts, MIT, Melbourne, Michigan, Michigan SU, Milano, Minsk NAS, Minsk NCPHEP, **Montreal**, **McGill Montreal**, FIAN Moscow, ITEP Moscow, MEPhI Moscow, MSU Moscow, Munich LMU, MPI Munich, Nagasaki IAS, Nagoya, Naples, New Mexico, New York, Nijmegen, BINP Novosibirsk, Ohio SU, Okayama, Oklahoma, Oklahoma SU, Oregon, LAL Orsay, Osaka, Oslo, Oxford, Paris VI and VII, Pavia, Pennsylvania, Pisa, Pittsburgh, CAS Prague, CU Prague, TU Prague, IHEP Protvino, **Regina**, Ritsumeikan, UFRJ Rio de Janeiro, Rome I, Rome II, Rome III, Rutherford Appleton Laboratory, DAPNIA Saclay, Santa Cruz UC, Sheffield, Shinshu, Siegen, **Simon Fraser Burnaby**, SLAC, Southern Methodist Dallas, NPI Petersburg, Stockholm, KTH Stockholm, Stony Brook, Sydney, AS Taipei, Tbilisi, Tel Aviv, Thessaloniki, Tokyo ICEPP, Tokyo MU, **Toronto**, **TRIUMF**, Tsukuba, Tufts, Udine/ICTP, Uppsala, Urbana UI, Valencia, **UBC Vancouver**, **Victoria**, Washington, Weizmann Rehovot, FH Wiener Neustadt, Wisconsin, Wuppertal, Yale, Yerevan

Canadian Contributions to ATLAS LAr Calorimeter



Hadronic Endcap Calorimeter Wheels

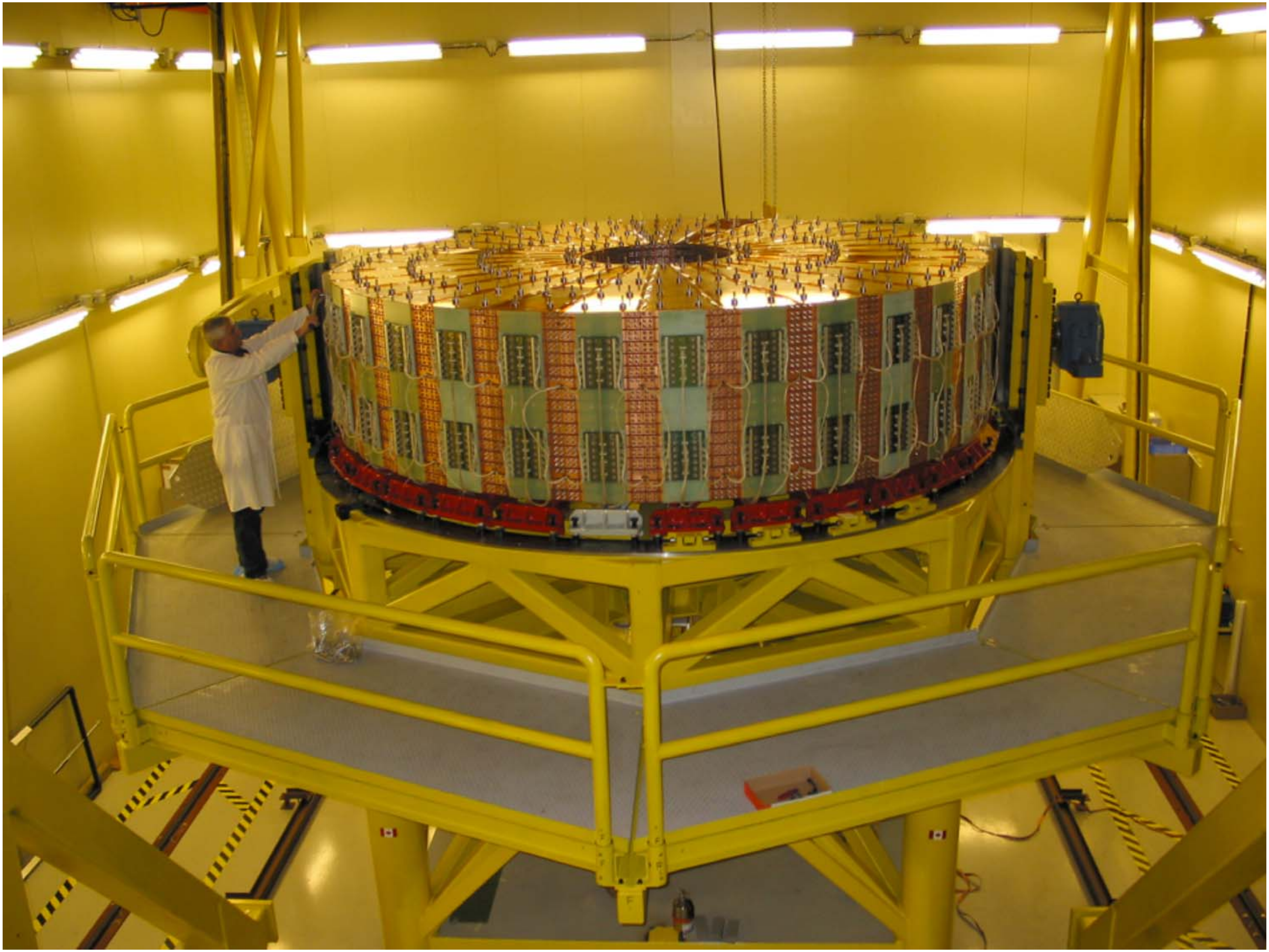
Cryogenic feedthroughs

Electromagnetic Endcap Calorimeter Wheels

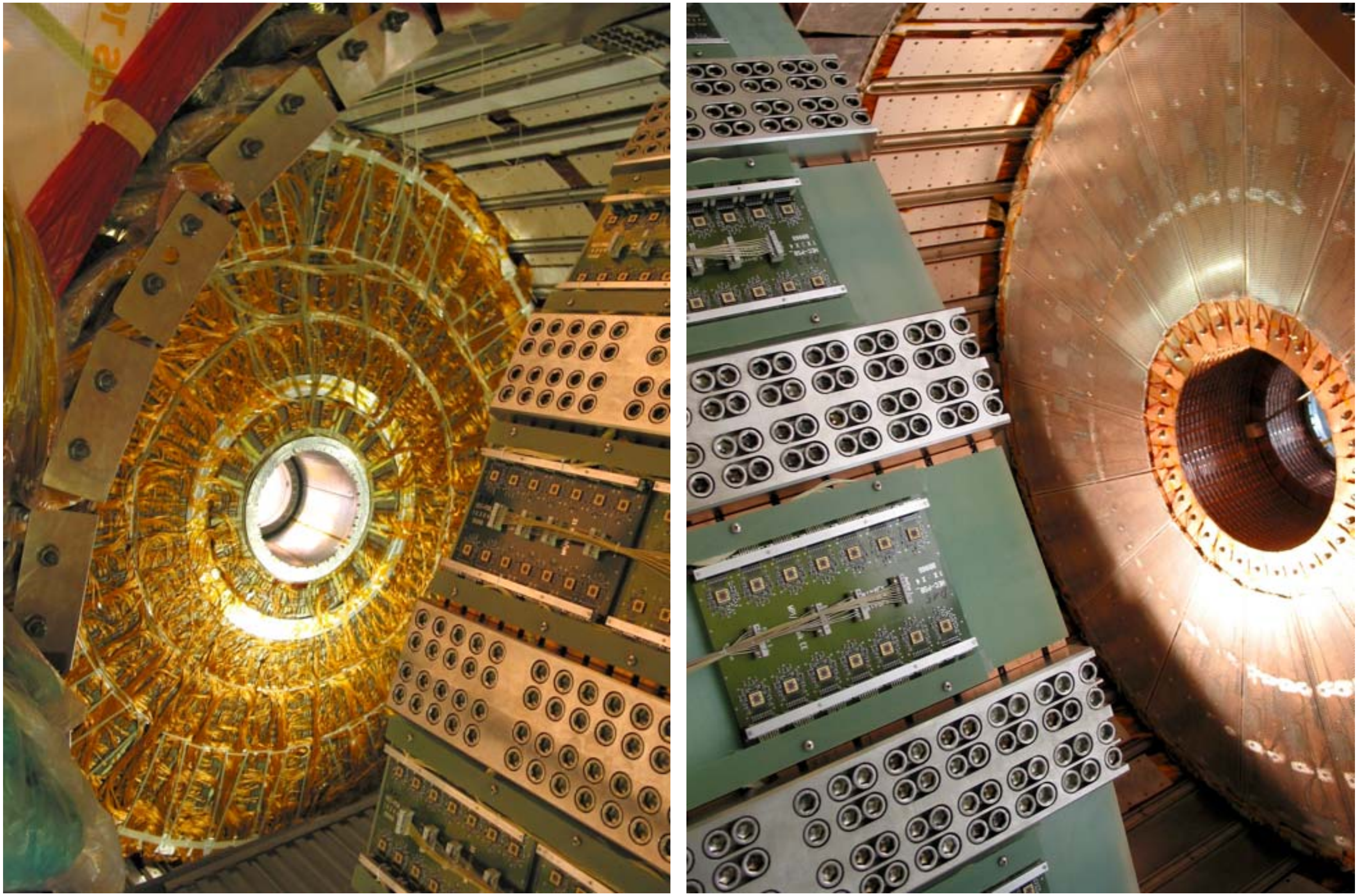
Hadronic Forward Calorimeter Modules

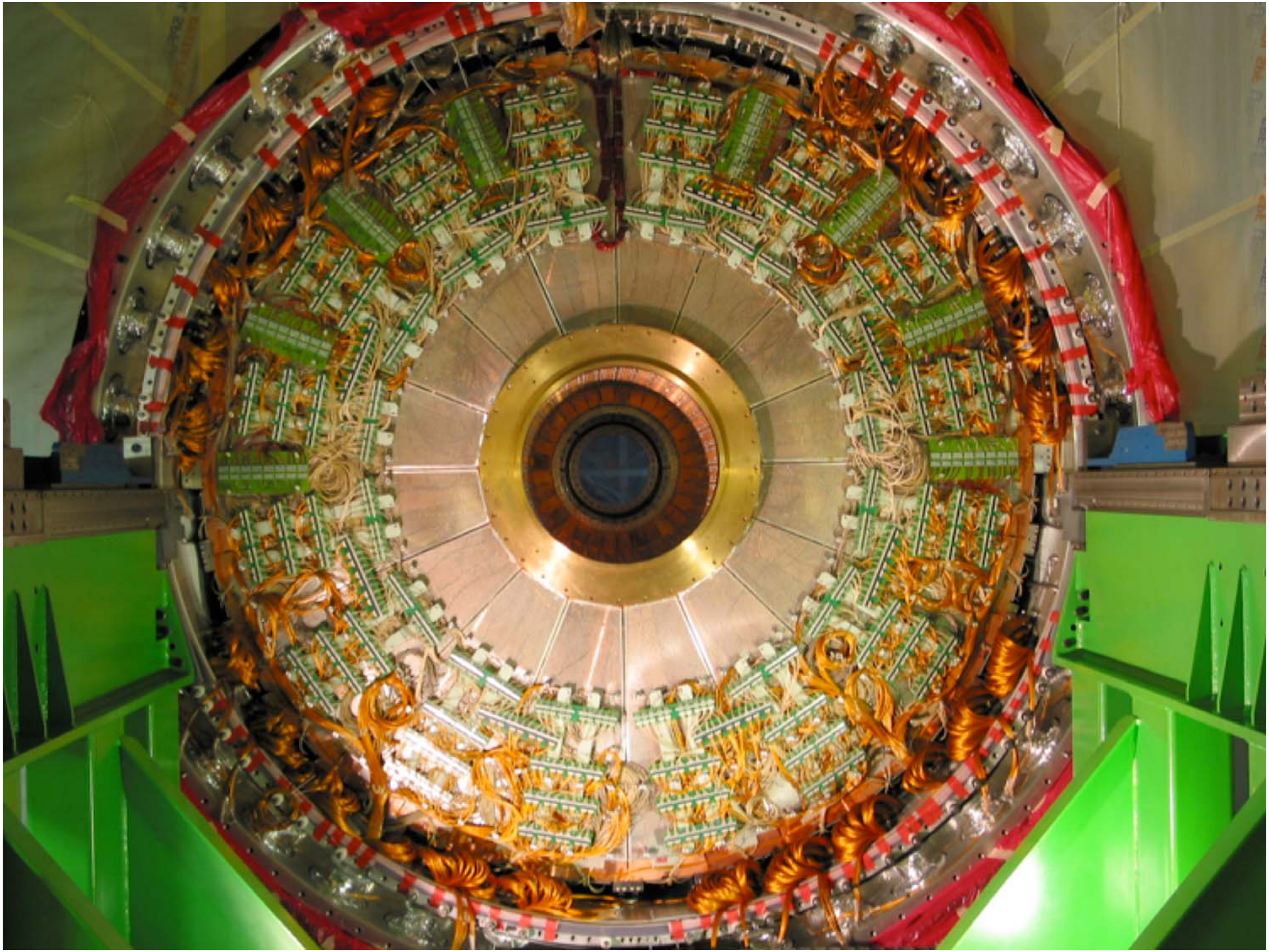
Electromagnetic Forward Calorimeter Module

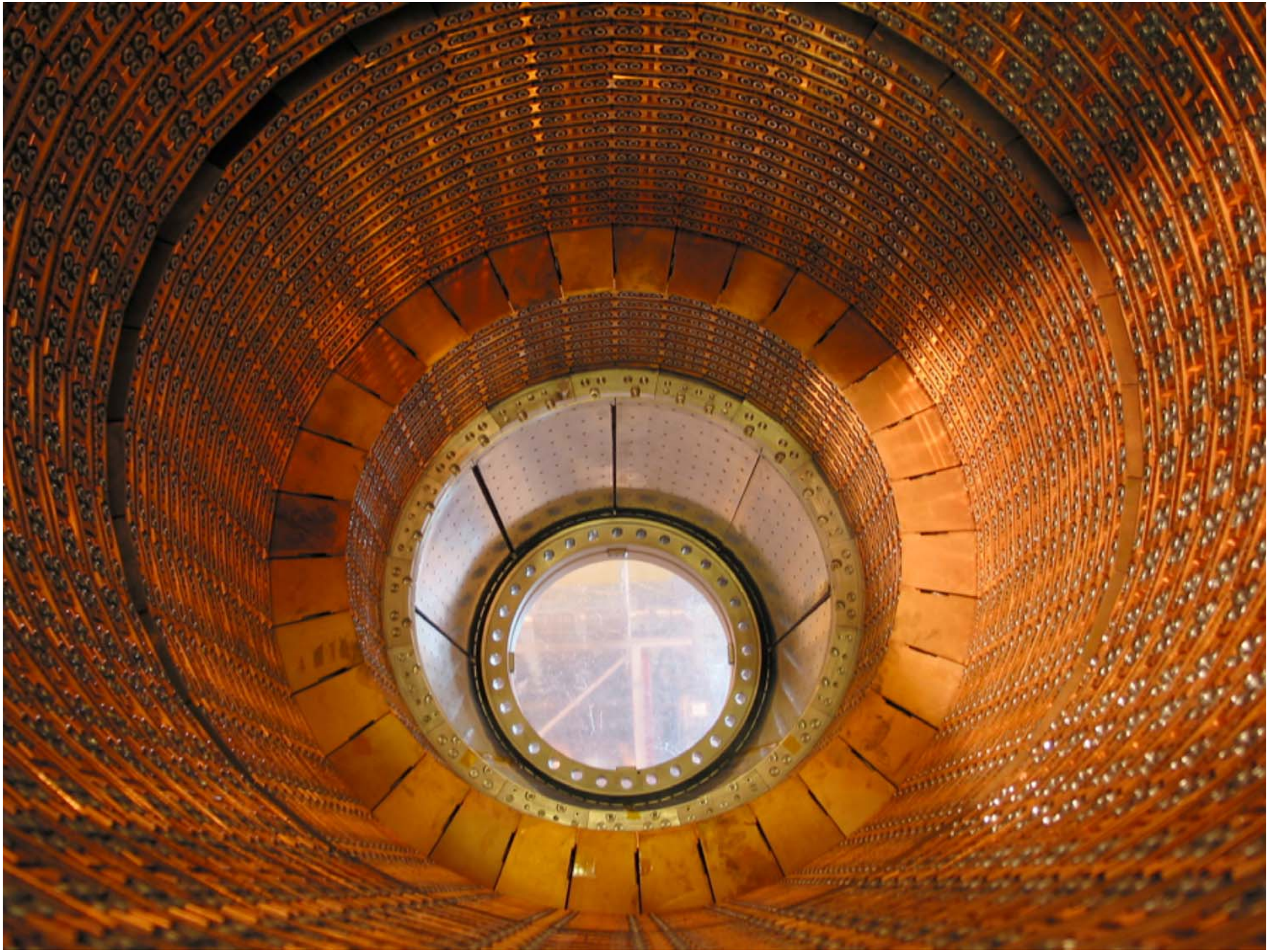
Liquid Argon Front-End Electronics



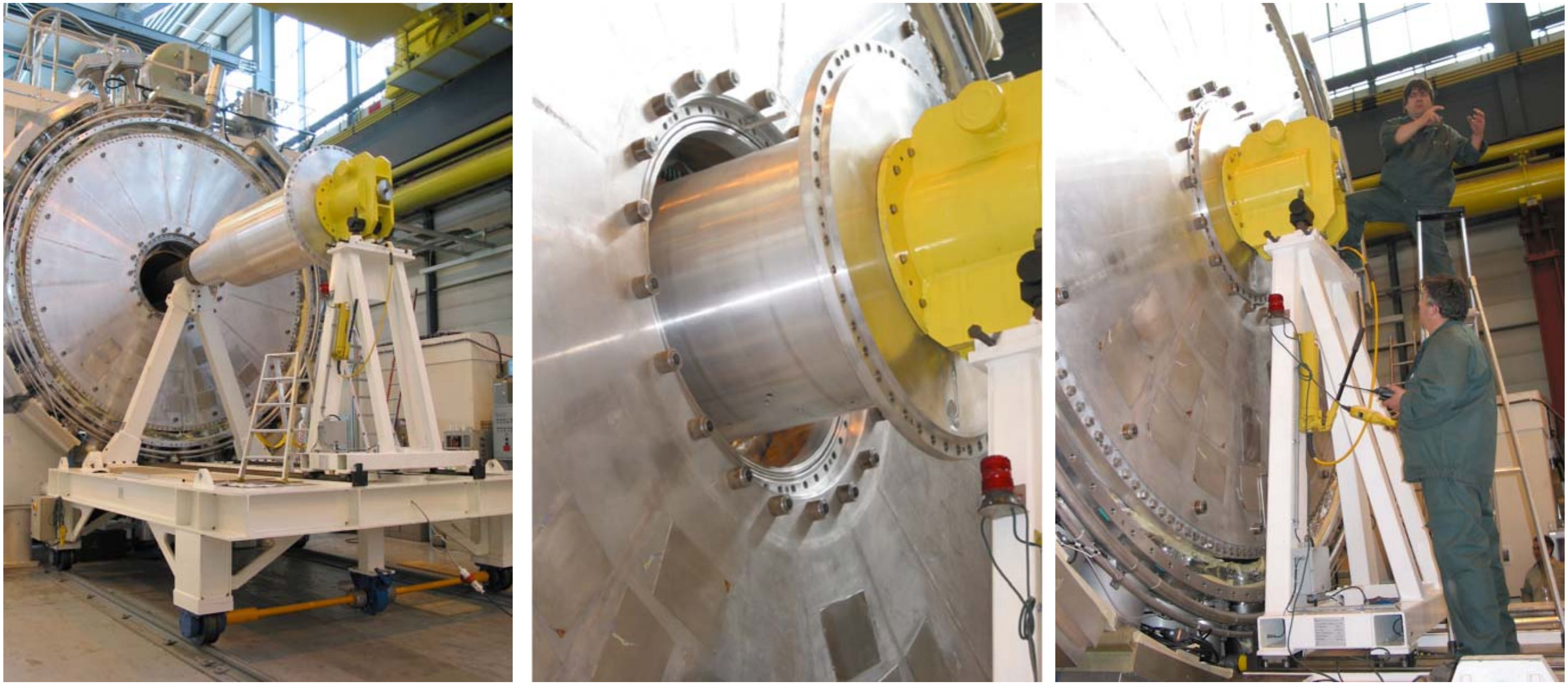
Insertion of HEC Wheels into Endcap Cryostat



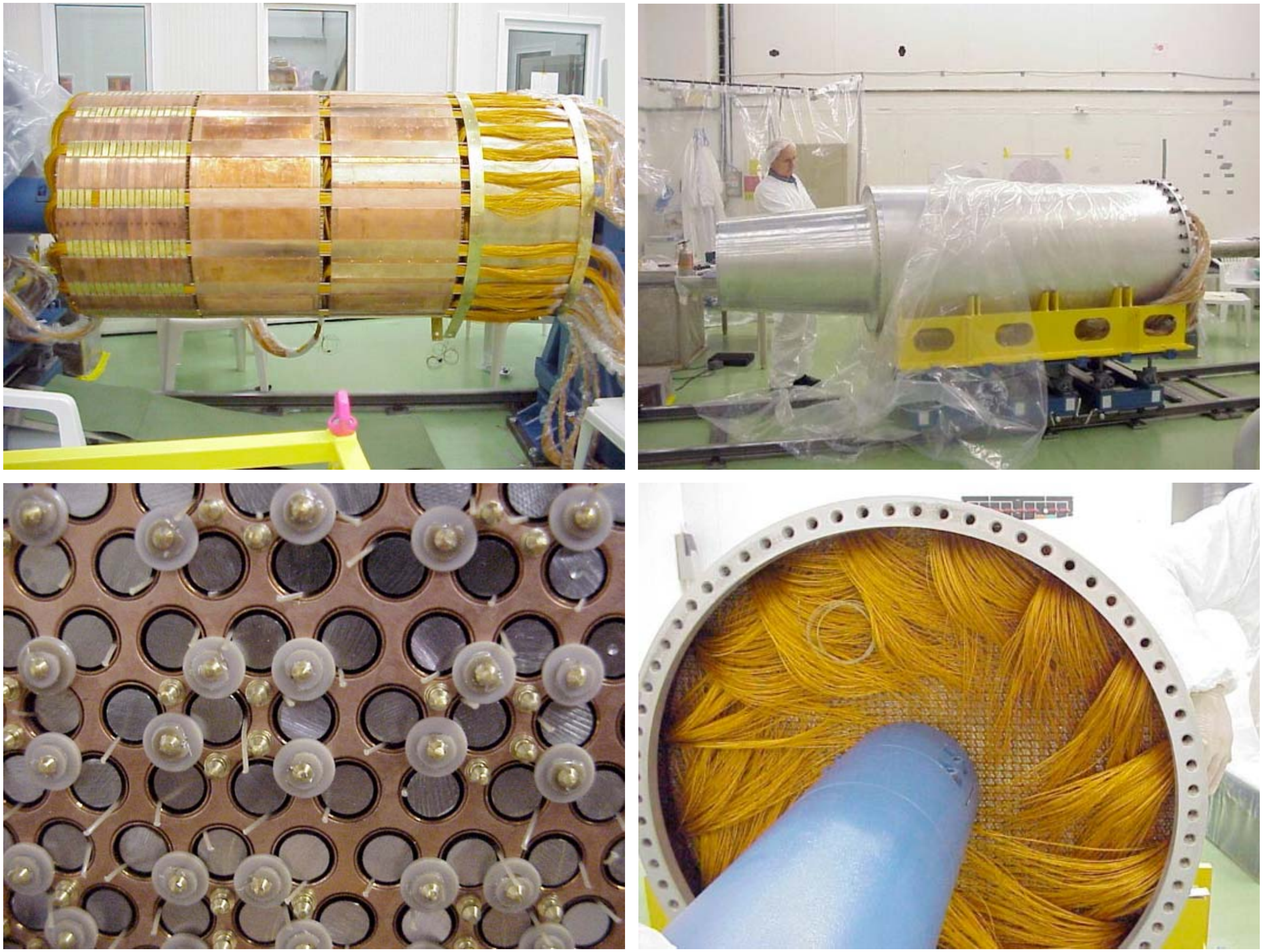




Insertion of the Forward Calorimeter



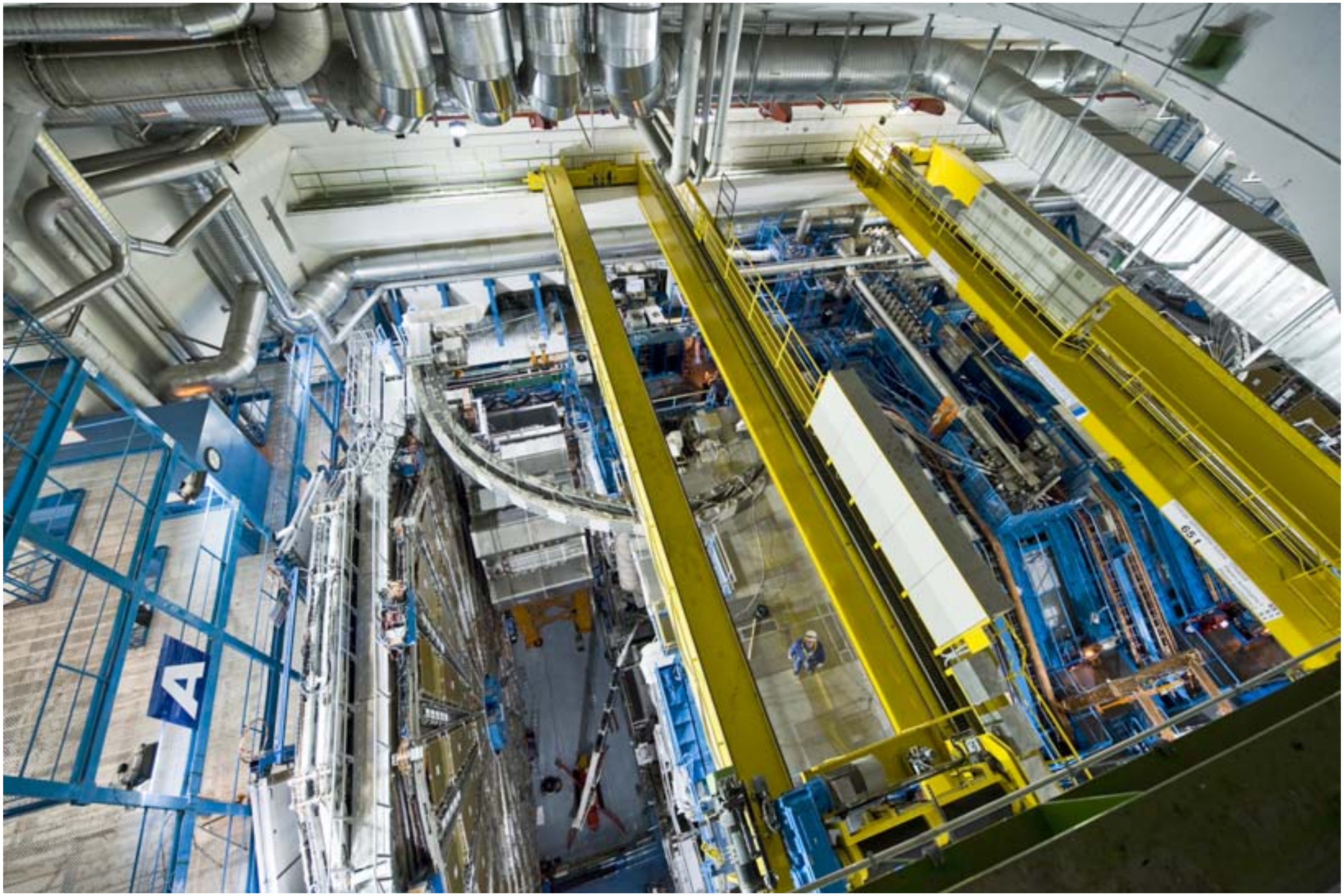
The ATLAS Forward Calorimeter

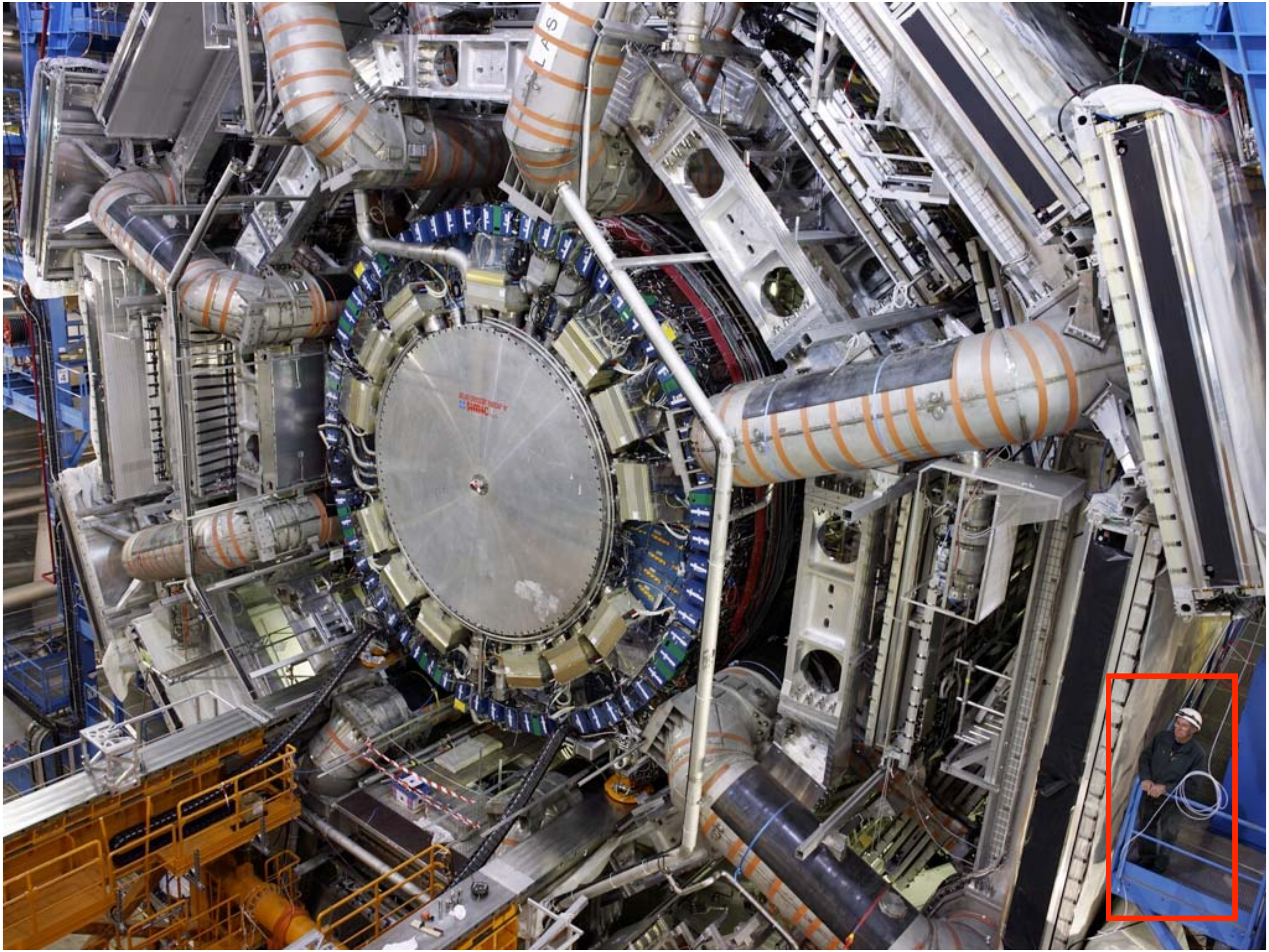


The ATLAS Cavern, June 2003

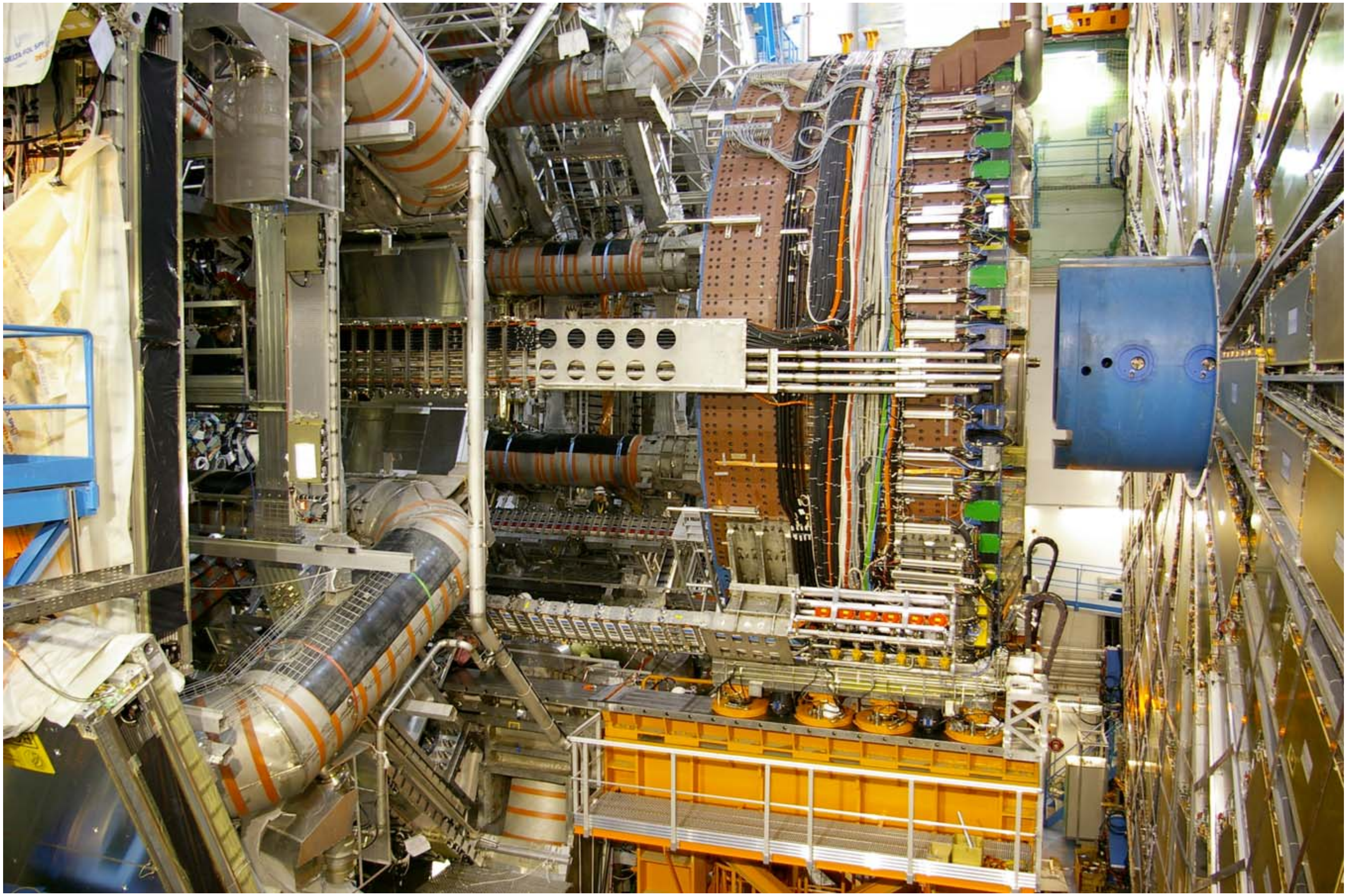
The ATLAS Cavern June 2004

ATLAS Cavern February 2008

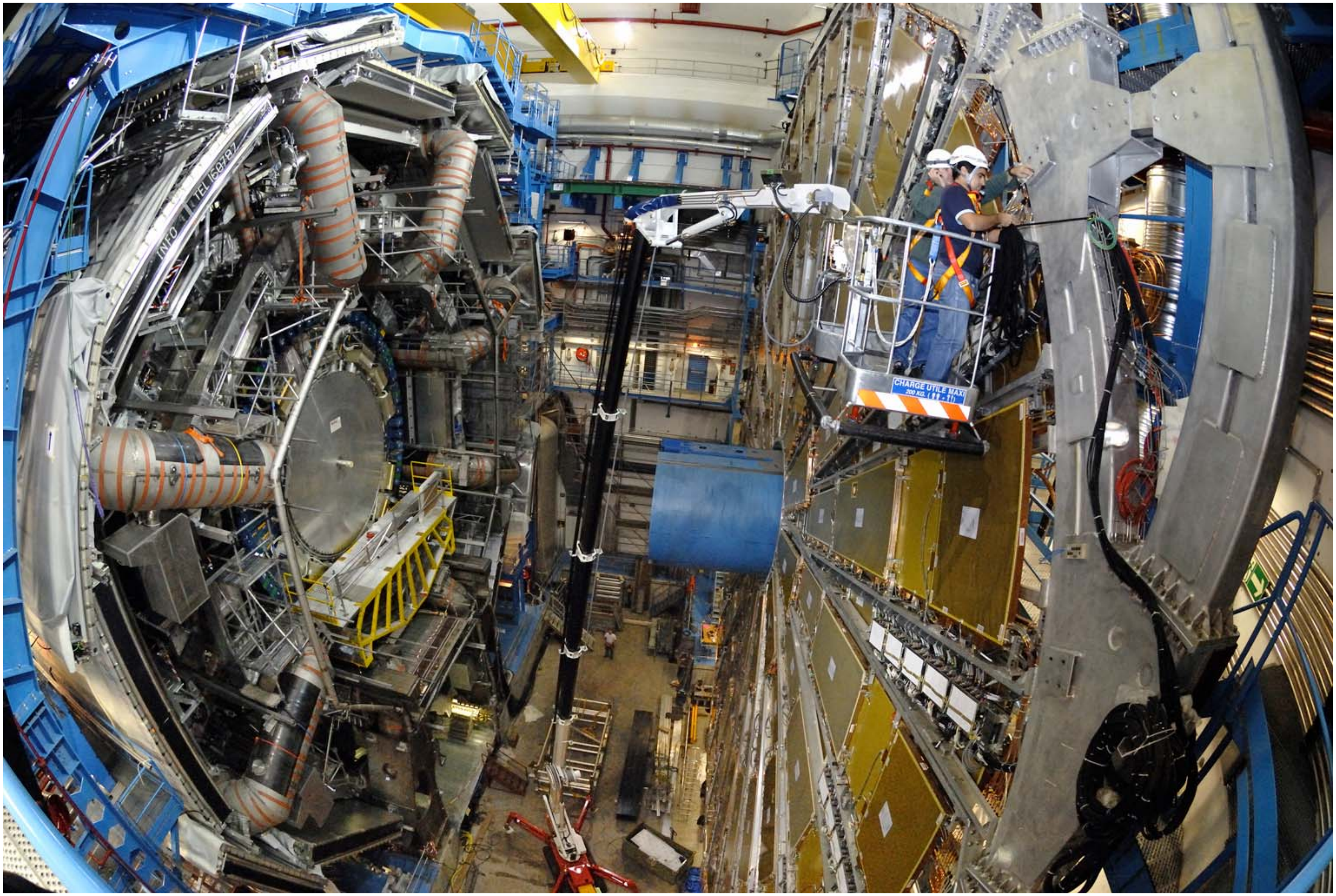




ATLAS Detector (Endcap Calorimeter Out)

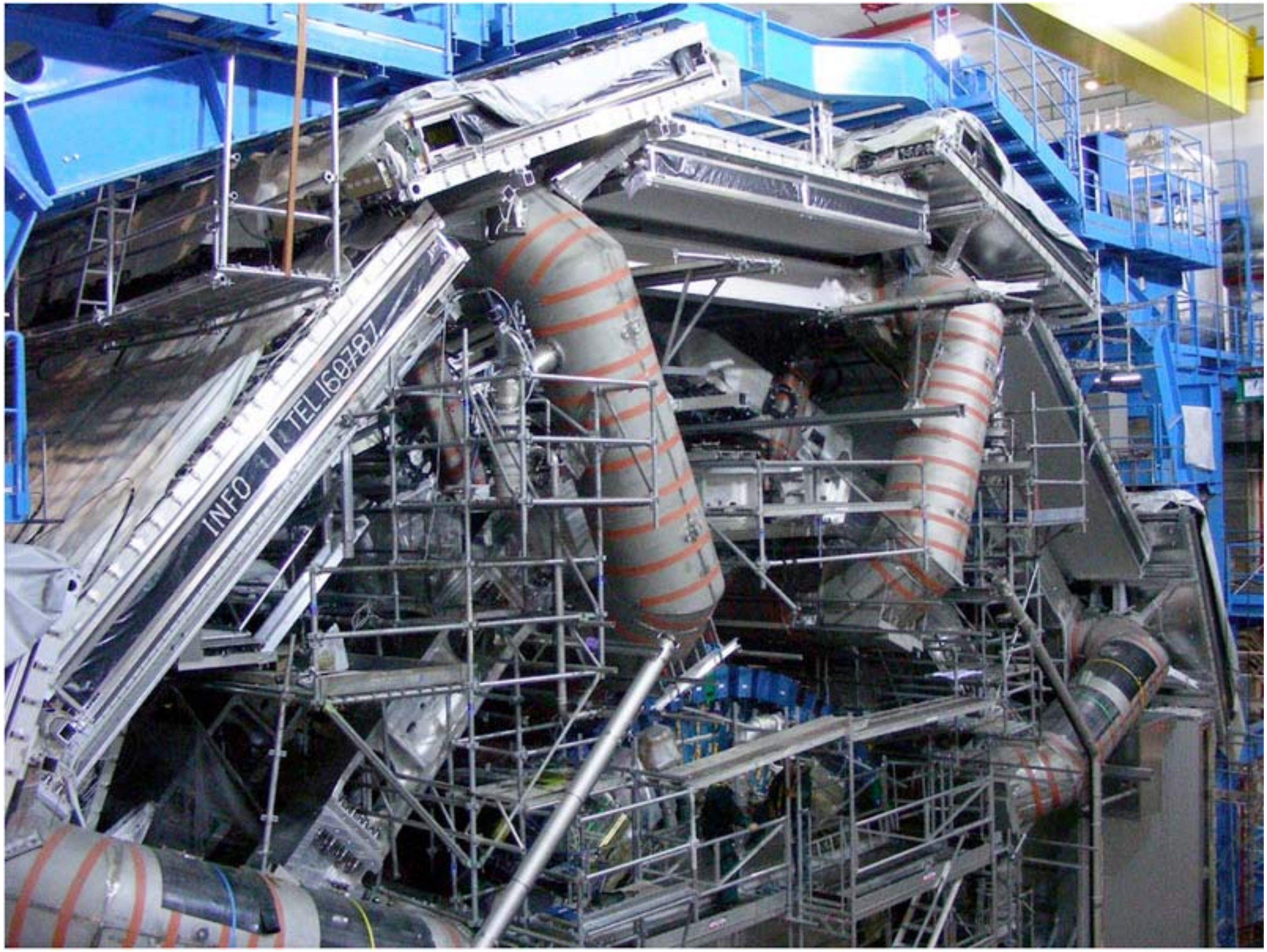


Muon Big Wheel Installation (Sept 2006)

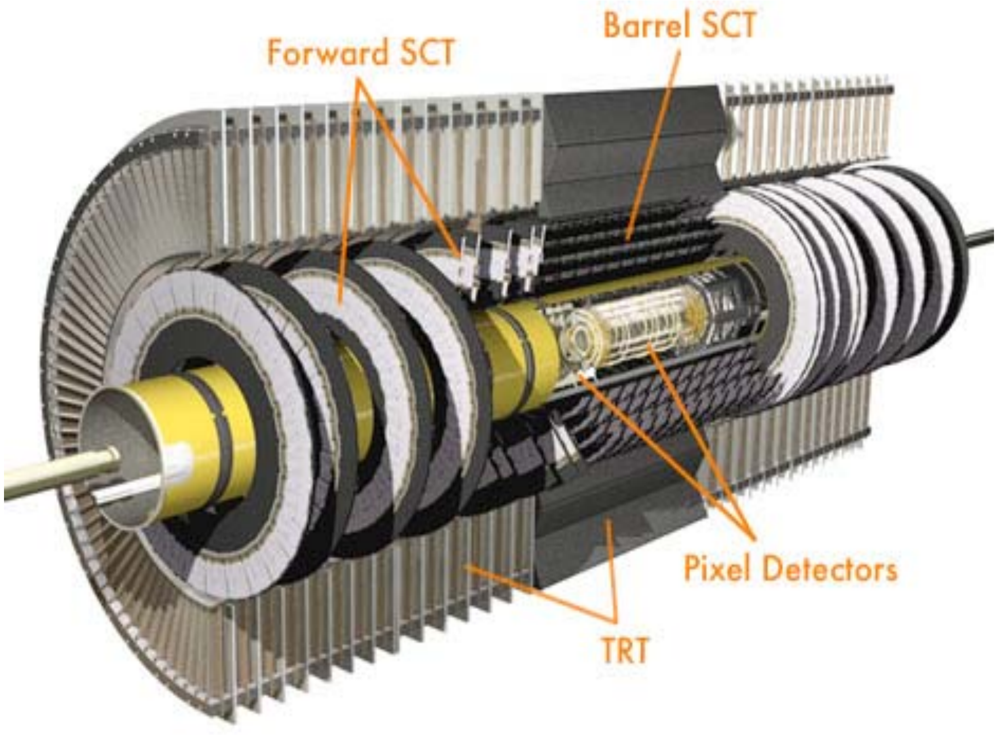


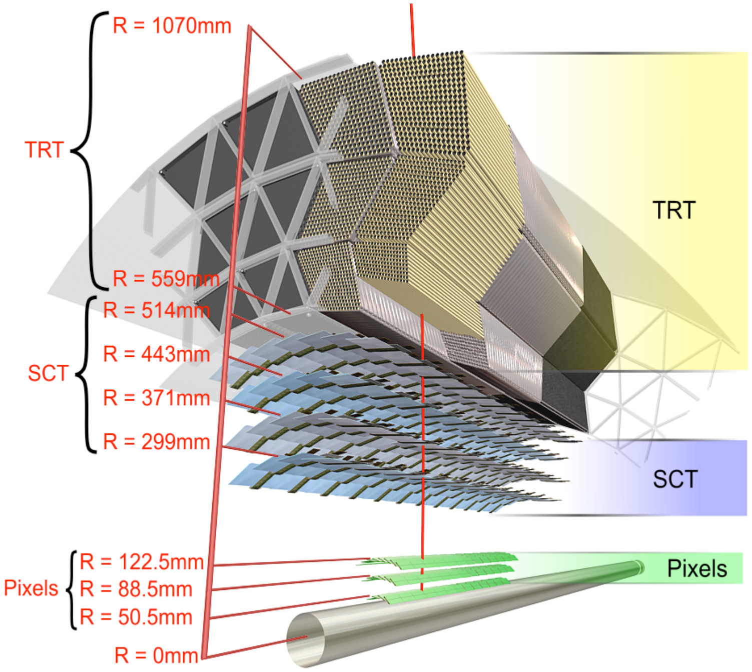
Muon System Installation

Muon Chambers



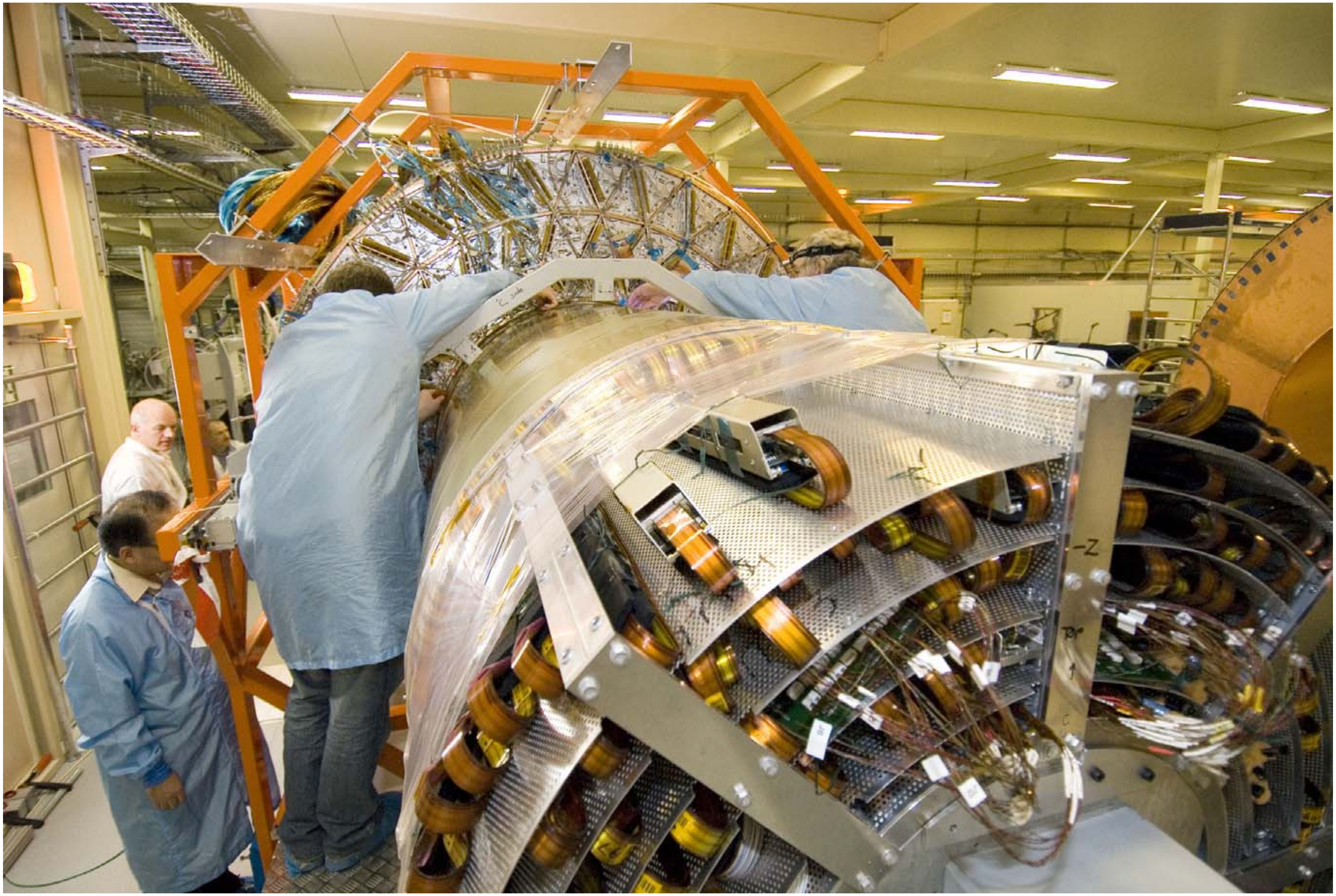
The ATLAS Inner Detector



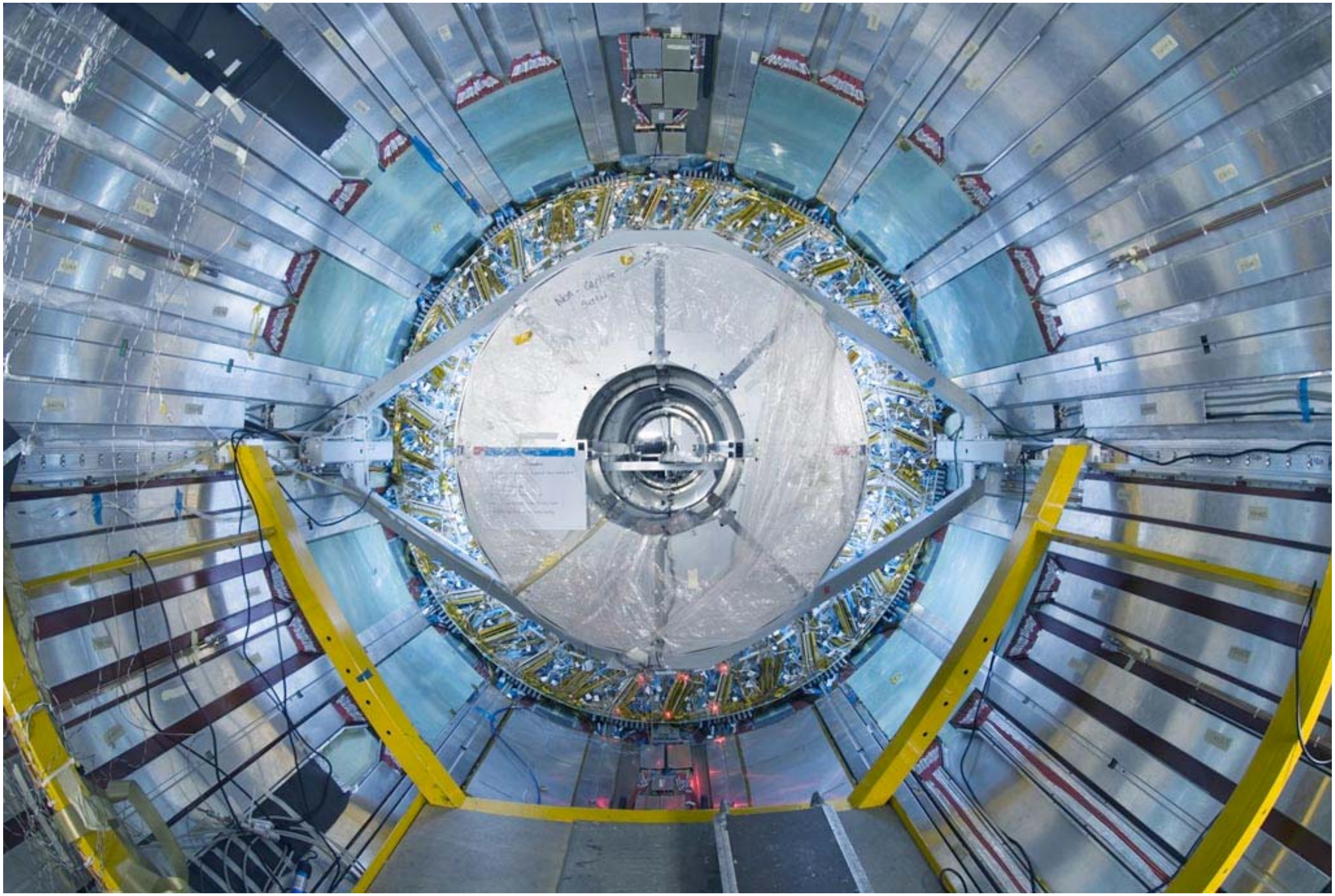


- Detector components installed in 4 steps
- Barrel SCT + TRT
- 2 End-Caps SCT + TRT
- Full pixel detector + Be beam pipe

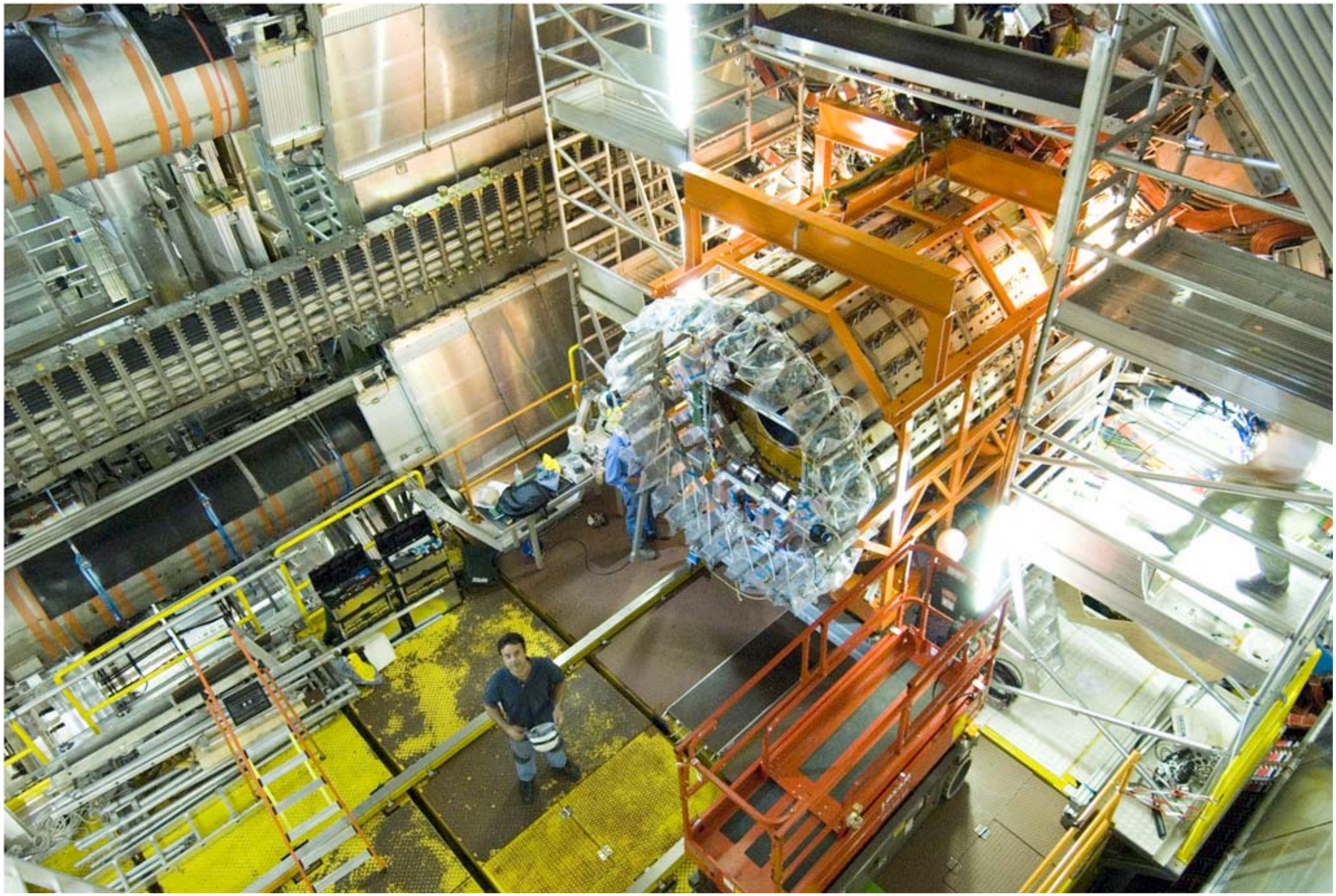
Installation of SCT into TRT



Inner Detector Barrel Installed in ATLAS



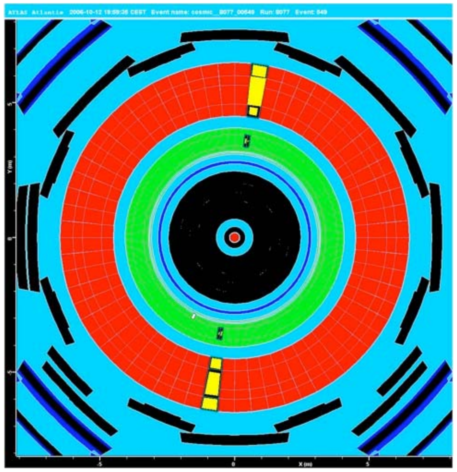
Inner Detector Endcap Installation May 2007



ATLAS Commissioning: Timeline

1: Combined
Beam Tests

2: Detector Installation,
Cosmic Ray Commissioning



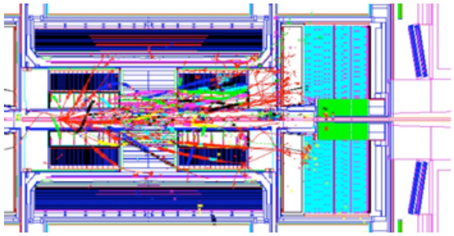
2.5: Spring ’08: Global cosmic run

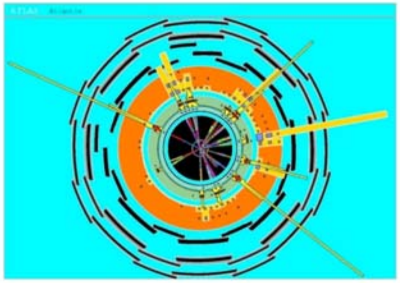
3: Single beam

4: First LHC collisions

5: First Physics

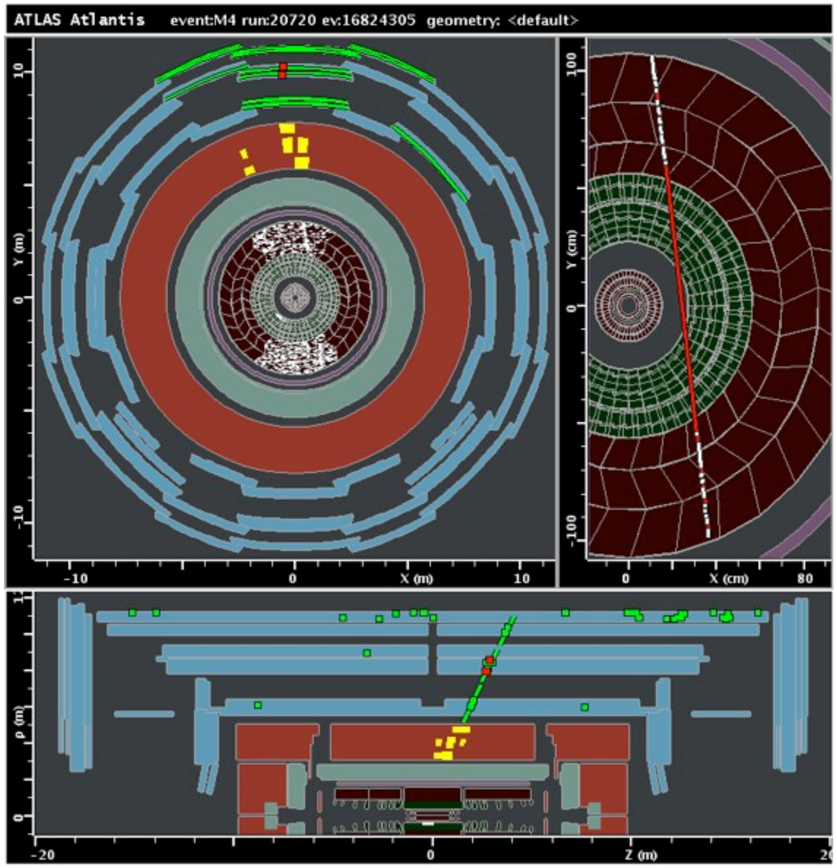
2004 2005 2006 **2007** ***2008***

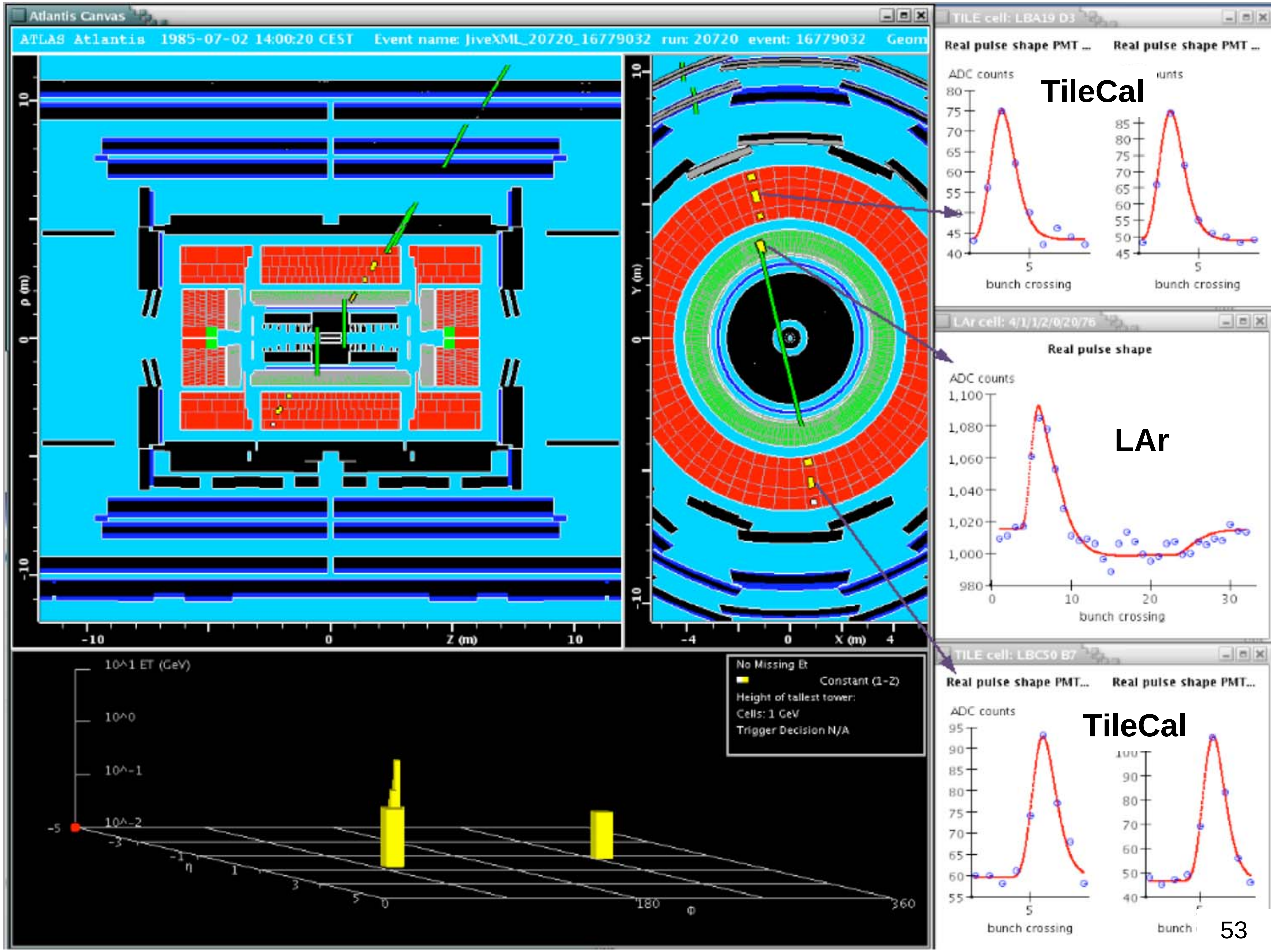




Running ATLAS: Main Control Room

Commissioning with Cosmic Ray Events





ATLAS Atlantis 1985-07-02 14:00:20 CEST Event name: JiveXML_20720_16779032 run: 20720 event: 16779032 Geom

No Missing Et

Constant (1-2)

Height of tallest tower:

Cells: 1 GeV

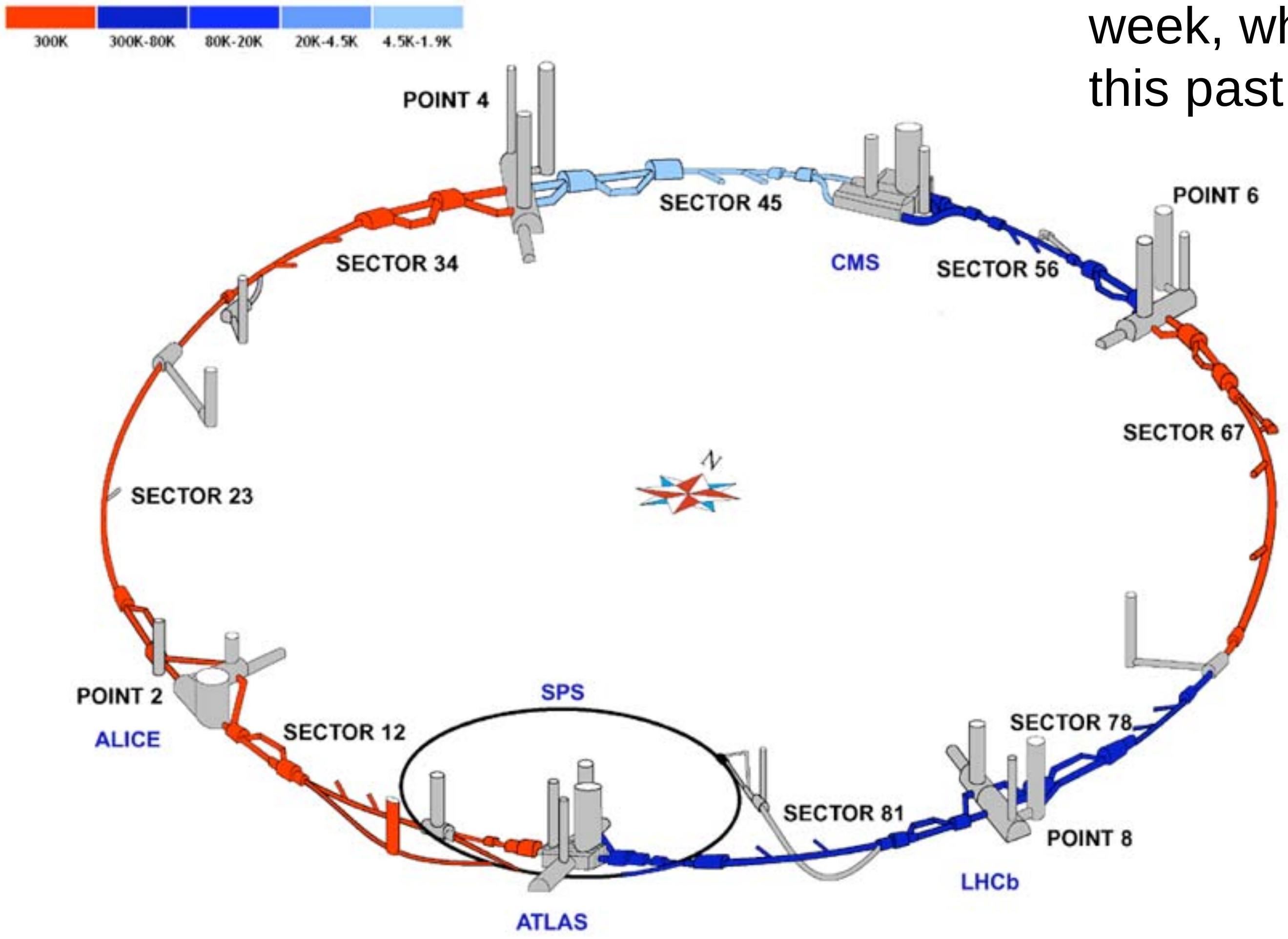
Trigger Decision N/A

TileCal

LAr

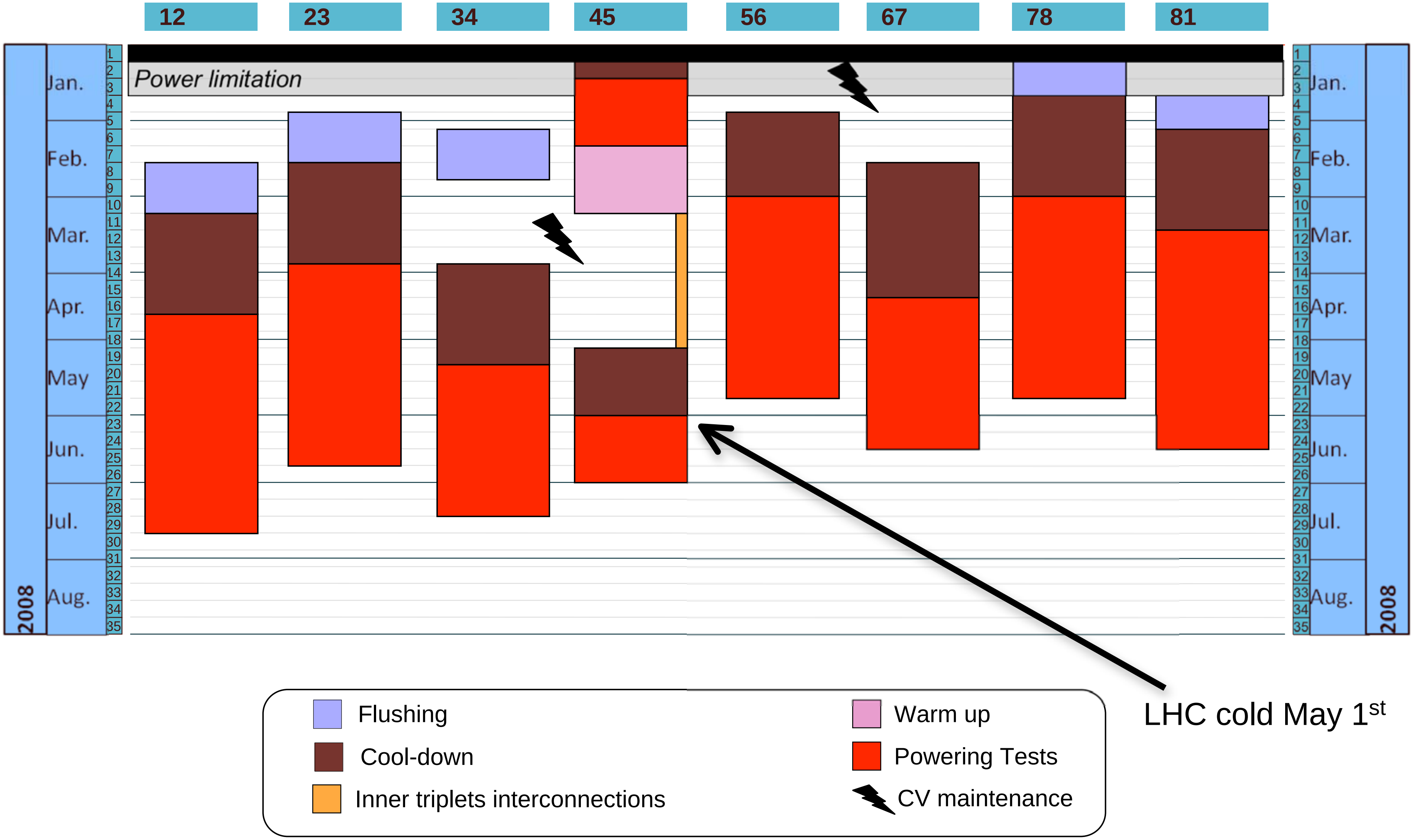
TileCal

LHC Cooldown Status February 2008



Presented during the most recent ATLAS week, which took place this past week.

Current LHC Schedule



LHC cold May 1^{st}

Summary

The LHC Experimental programme represents the largest international scientific collaboration even undertaken.

The work of thousands of people over the past two decades is about to come to fruition.

This promised to be an exciting and rewarding period, and one that will likely set the direction taken in both the experimental and theoretical sides of the fields for the next few decades.