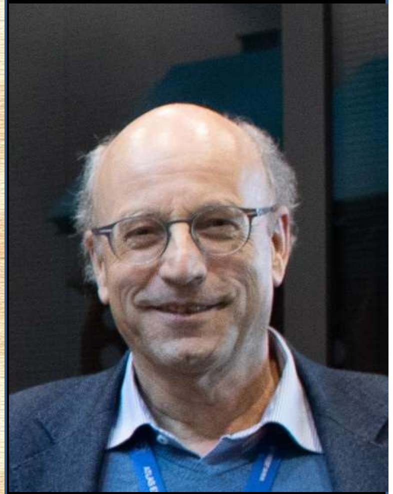
African School of Fundamental Physics and Applications

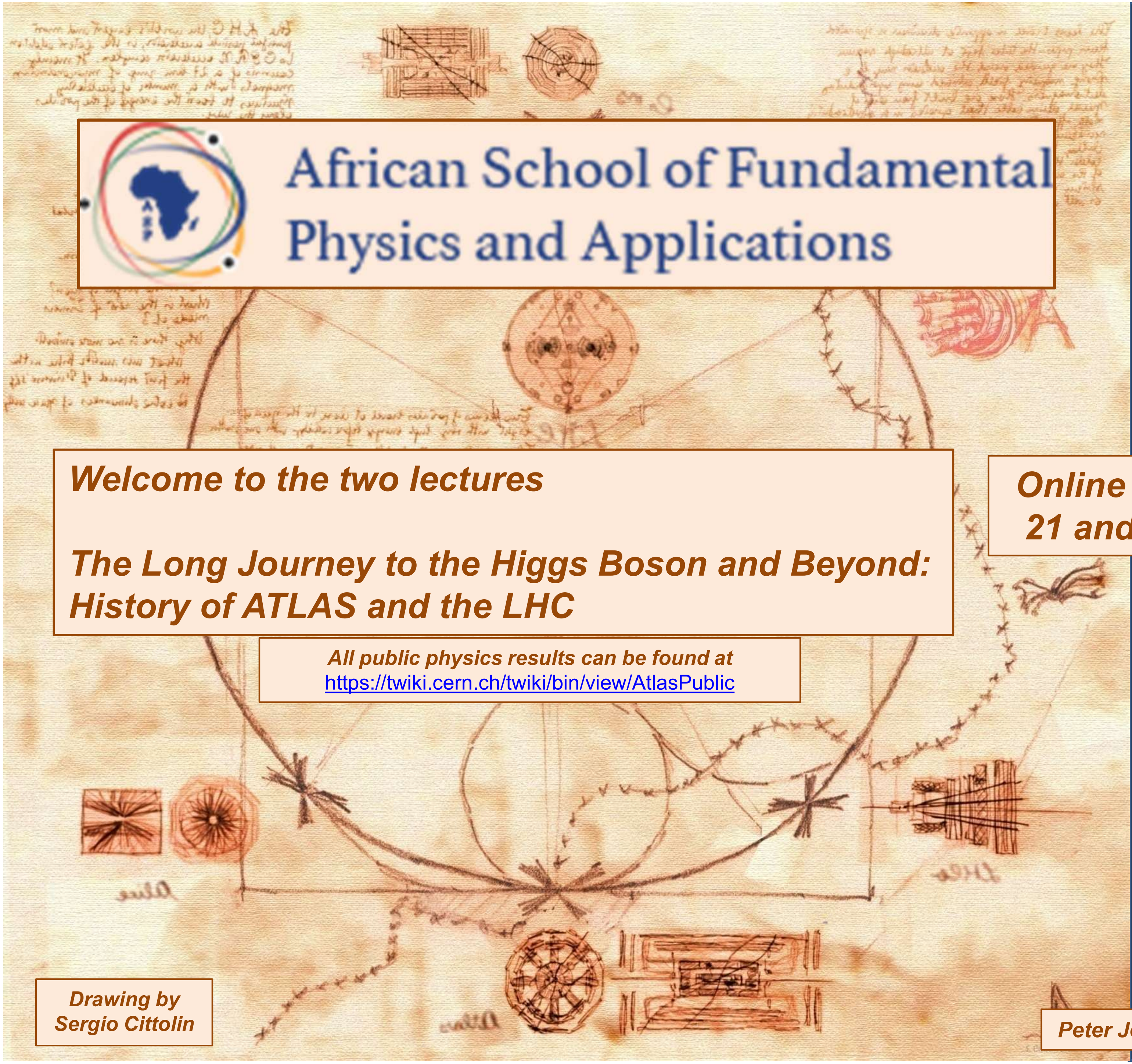


Welcome to the two lectures

The Long Journey to the Higgs Boson and Beyond: History of ATLAS and the LHC

All public physics results can be found at
https://twiki.cern.ch/twiki/bin/view/AtlasPublic

Online lecture series
21 and 28 July 2020



Drawing by Sergio Cittolin

Peter Jenni, Freiburg and CERN

A few things about me …

I am Swiss, borne in 1948, and studied physics at the University of Bern and the Swiss Federal Institute of Technology (ETHZ) with a PhD in physics in 1976

I was fascinated by experimental particle physics from when I started university, a few months as summer student at CERN in the early 1970s confirmed that, and this remained so since more than 50 years

I worked at most accelerators and colliders at CERN, namely in the early years

- **1972/3 at the Synchro-Cyclotron as a student**
- **1974/6 at the Proton Synchrotron as a Fellow and PhD student**
- **1976/7 at the Intersecting Storage Rings (ISR) as ETHZ Research Associate**

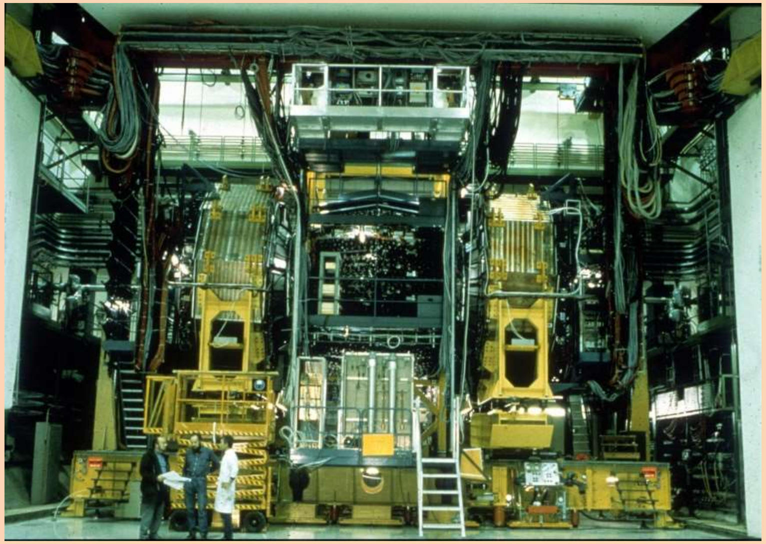
Two pictures from 1976 and 1977, working on the detector of the experiment R702 at the ISR

During 1978/9 I was a Research Associate at the Stanford Linear Accelerator Center (SLAC) in California in the group of Burton Richter, getting experience with the Mark-II experiment at the e+e- collider SPEAR

Back in Europe, I became a CERN staff and was fully involved in the CERN proton-antiproton collider experiment UA2, and its upgrade UA2' (1980-1991)

I worked directly on the jet and W/Z discoveries, and the search for new physics, but also on all calorimeter aspects of this experiment

Enjoying to work also as a Project Leader hands-on on the calorimeter upgrade for the UA2' detector (1985)



Since the 1980s, in parallel with, and motivated by the success of, the CERN p-pbar Collider I engaged enthusiastically into physics and detector discussions for a far future hadron collider in the LEP tunnel, the Large Hadron Collider (LHC)

I will talk about that in the lectures, with pictures there; in short the LHC became my main activity from 1989 onwards, first as informal spokesperson of a proto-Collaboration, and then after the formal approval of the ATLAS project in 1995 I was Spokesperson for it until 2009

Even though I am now formally retired as CERN staff since 2013, I am still fully involved in the ATLAS Collaboration, now with a host affiliation as an honorary professor with the University of Freiburg

I have been, and still am, involved in many international committees on several continents helping to shape the future of particle physics in the world

The greatest motivation for that remains for me to help building up a science future for all talents from everywhere

Physics Schools are a perfect opportunity to share the enthusiasm for fundamental science, and I am very happy to contribute again a little to the great initiative of Ketevi Assamagan with the ASP series

The Long Journey to the Higgs Boson and Beyond: History of ATLAS and the LHC

African School of Fundamental Physics and Applications

The plan:

A bit about the history of the LHC and its experiments (and recalling previous hadron colliders, their experiments, and their physics highlights)

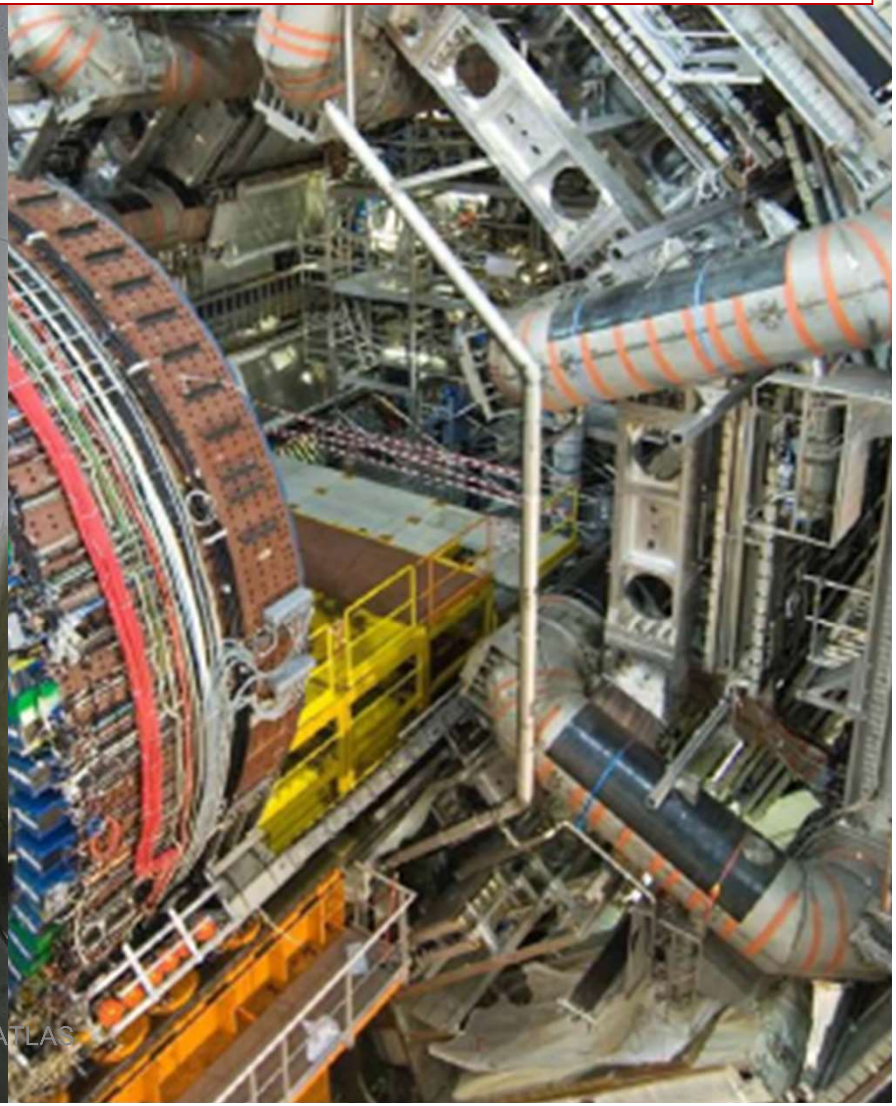
*It will be limited to the high-energy frontier and physics highlights establishing the Standard Model **

(I): History
- *Examples of technical challenges*
- *Testing/Commissioning the detector*

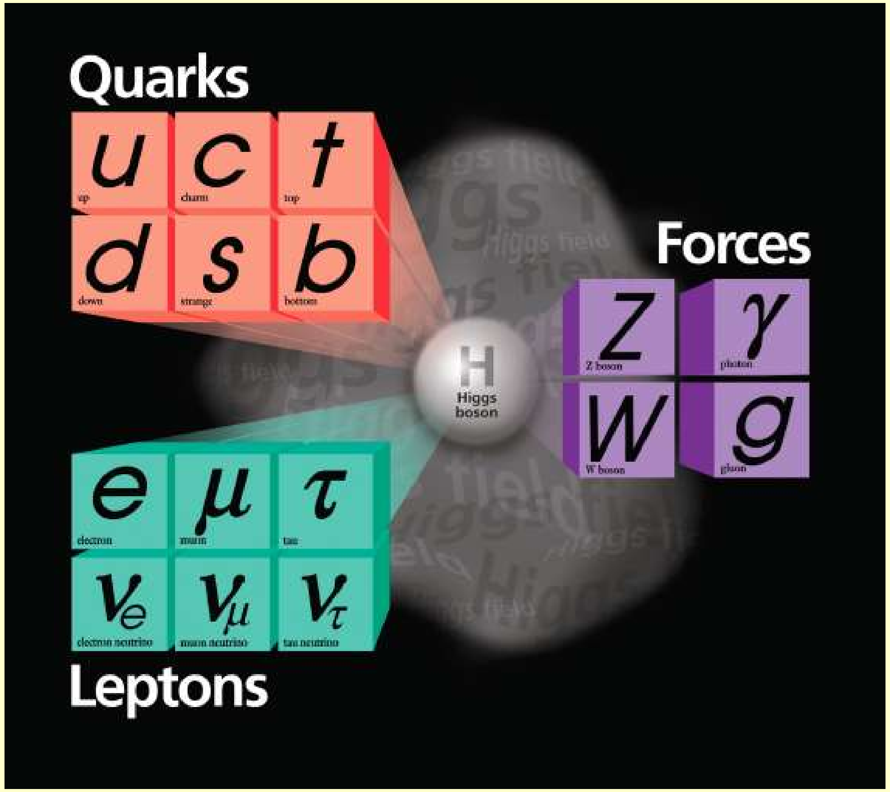
(II): Some ATLAS physics highlights results
- *Standard Model*
- *Higgs boson*
- *Beyond the SM searches*

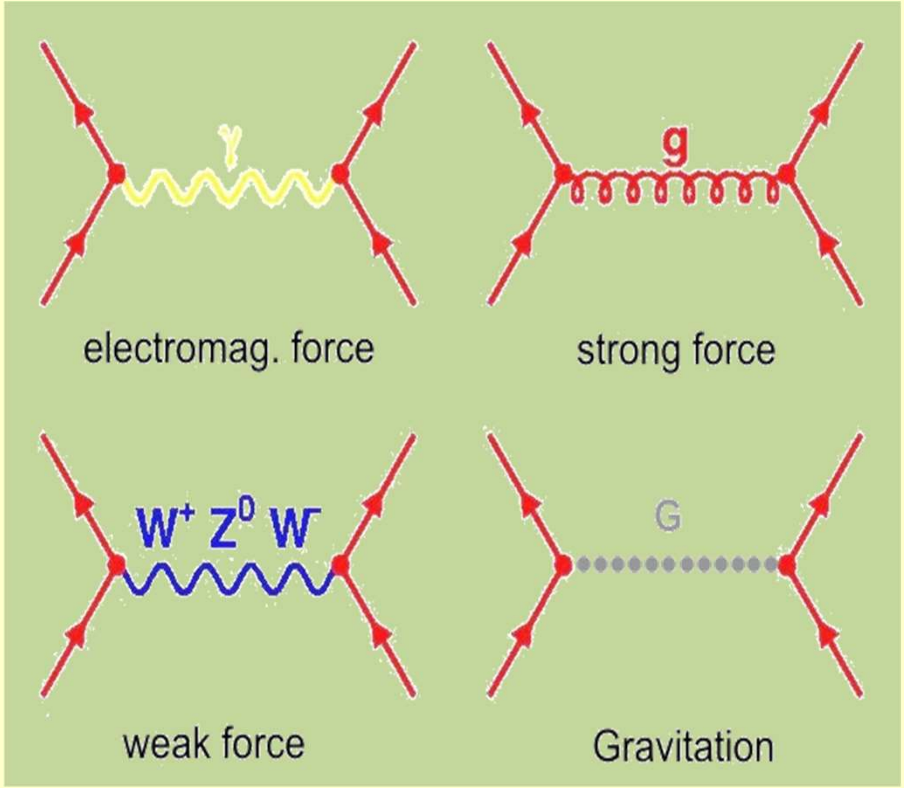
** Leaving aside flavour physics and heavy ion physics, which are also very important and successful parts of the LHC programme*

The Large Hadron Collider project is a global scientific adventure, which was initiated more than 35 years ago, combining the accelerator, the experiments, a worldwide computing grid, and with lots of motivation from our theory colleagues



The Standard Model of Particle Physics



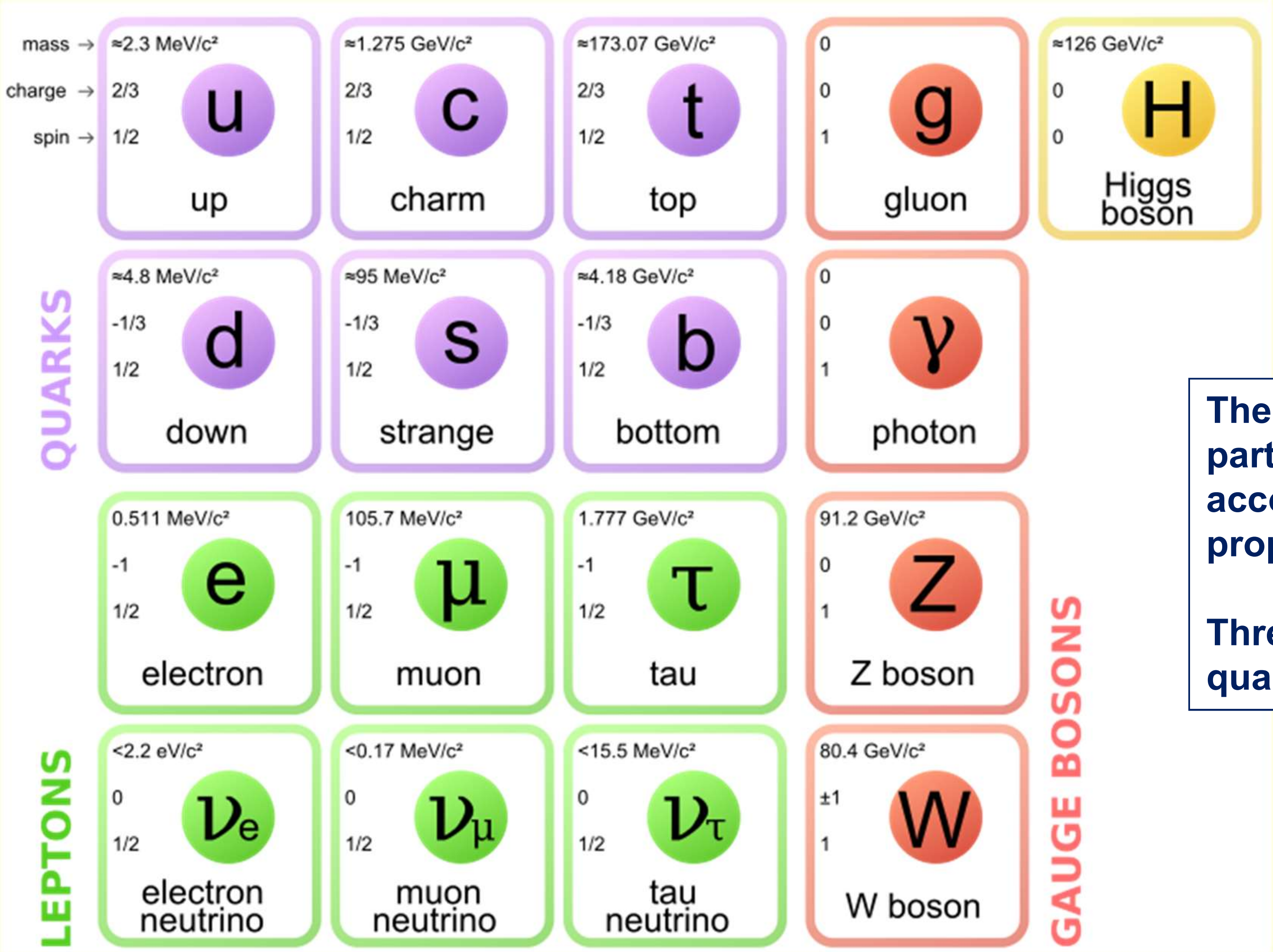


(i) Constituents of matter: quarks and leptons

(ii) Four fundamental forces
(described by quantum field theories, except gravitation)

(iii) The Brout-Englert-Higgs field (problem of mass, broken symmetry)

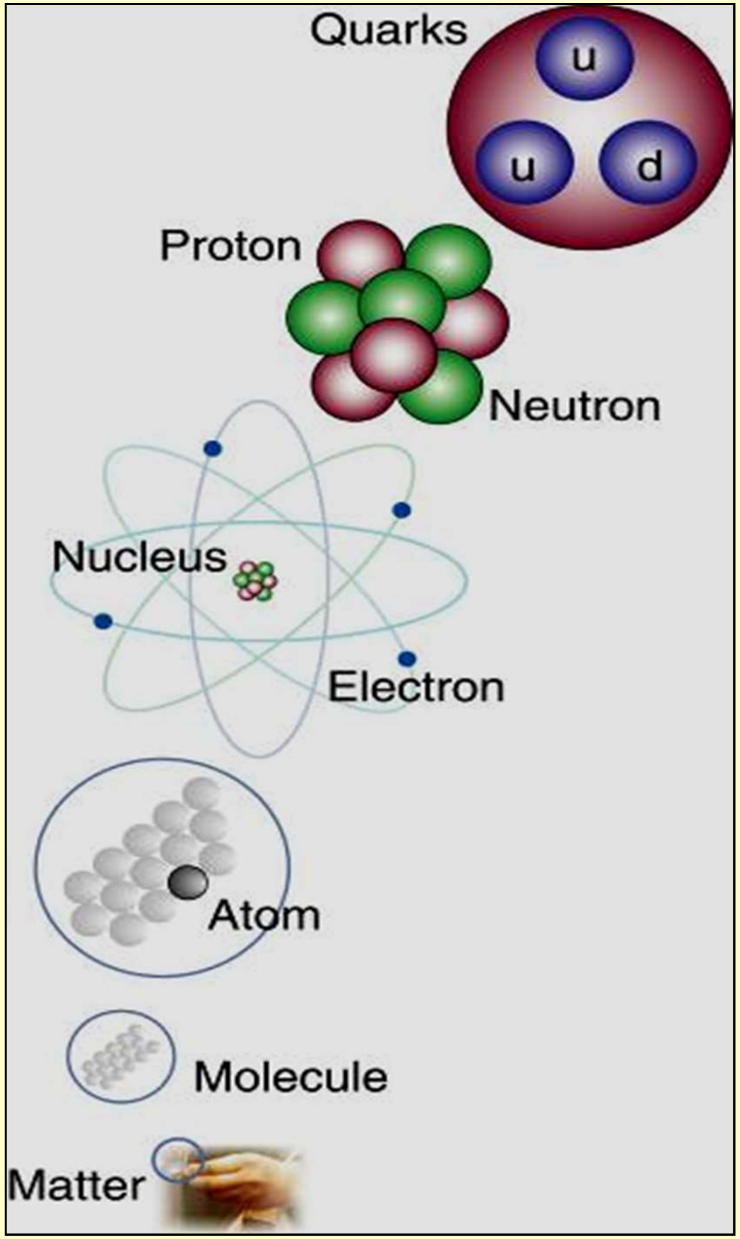
Standard Model of Elementary Particles



The elementary particles arranged according to their properties

Three families of quarks and leptons

← ***Fermionen*** → ← ***Bosonen*** →



The protons, neutrons, and many others like pions, kaons … are not elementary particles

They are objects that are composed of quarks, bound together by the strong force mediated by the gluons

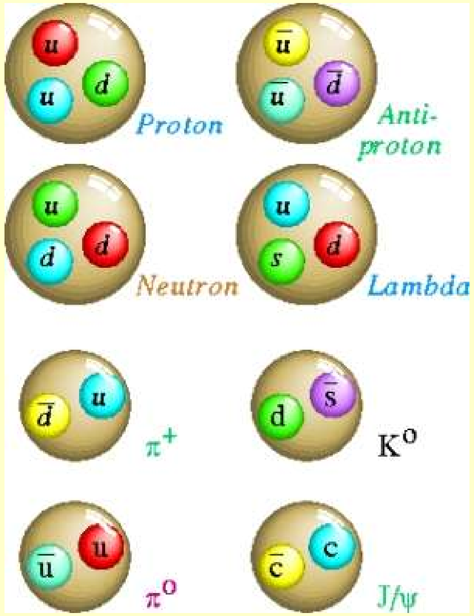
Their mass is mainly due to the 'binding energy' holding them together …

Quark Model 1964

Murray Gell-Mann
George Zweig

M. Gell-Mann
Nobel Prize 1969

G Zweig



Some of the Pioneers of the Standard Model of Particle Physics…

Quark Model:
Murray Gell-Mann, George Zweig

interaction		group	dim.	particles	source	coup-ling
electromagnetic	QED	U(1)	1	γ	charge	e
weak	QFD	SU(2)	3	W^+W^-Z	flavour	g_w
strong	QCD	SU(3)	8	gluons	colour	g_s

But please don't forget all the experimentalists who established step by step the SM as a reality … !

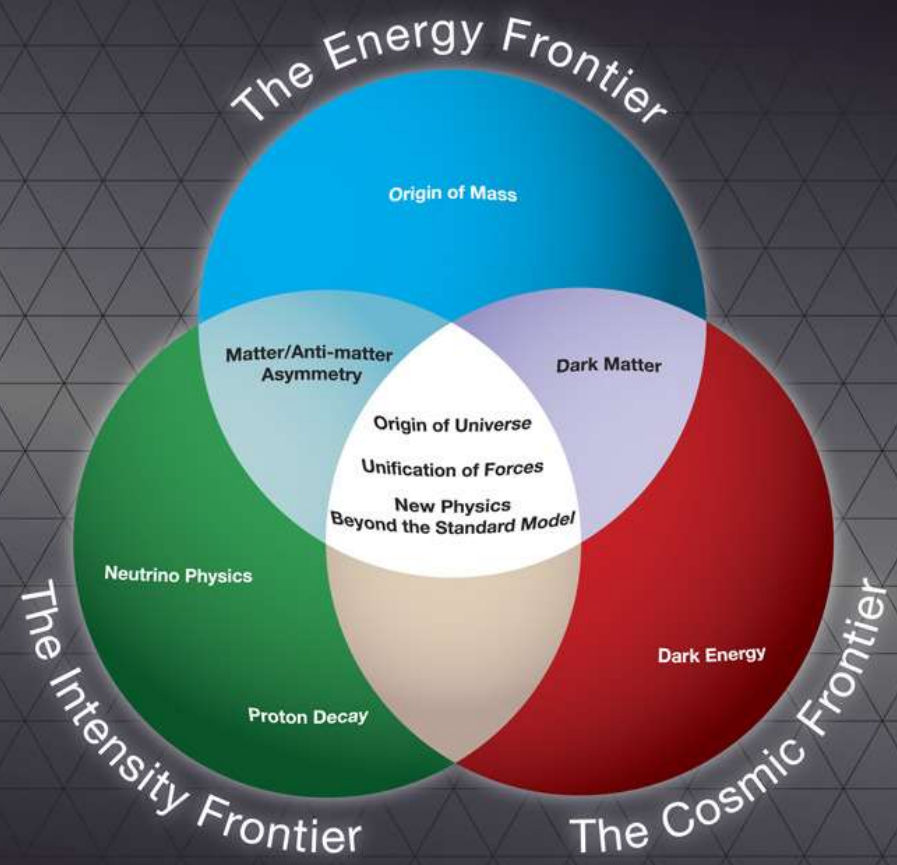
Scalar fields can generate mass:
Robert Brout, François Englert, Peter Higgs, Gerald Guralnik, Carl Hagen, Tom Kibble

Gauge theory of the weak interaction:
Sheldon Glashow, Abdus Salam, Steven Weinberg

Gauge theory of the strong interaction, asymptotic freedom:
David Gross, David Politzer, Frank Wilczek

The famous three pillars of particle physics

The LHC addresses in first place the Energy Frontier and major parts of the Intensity Frontier

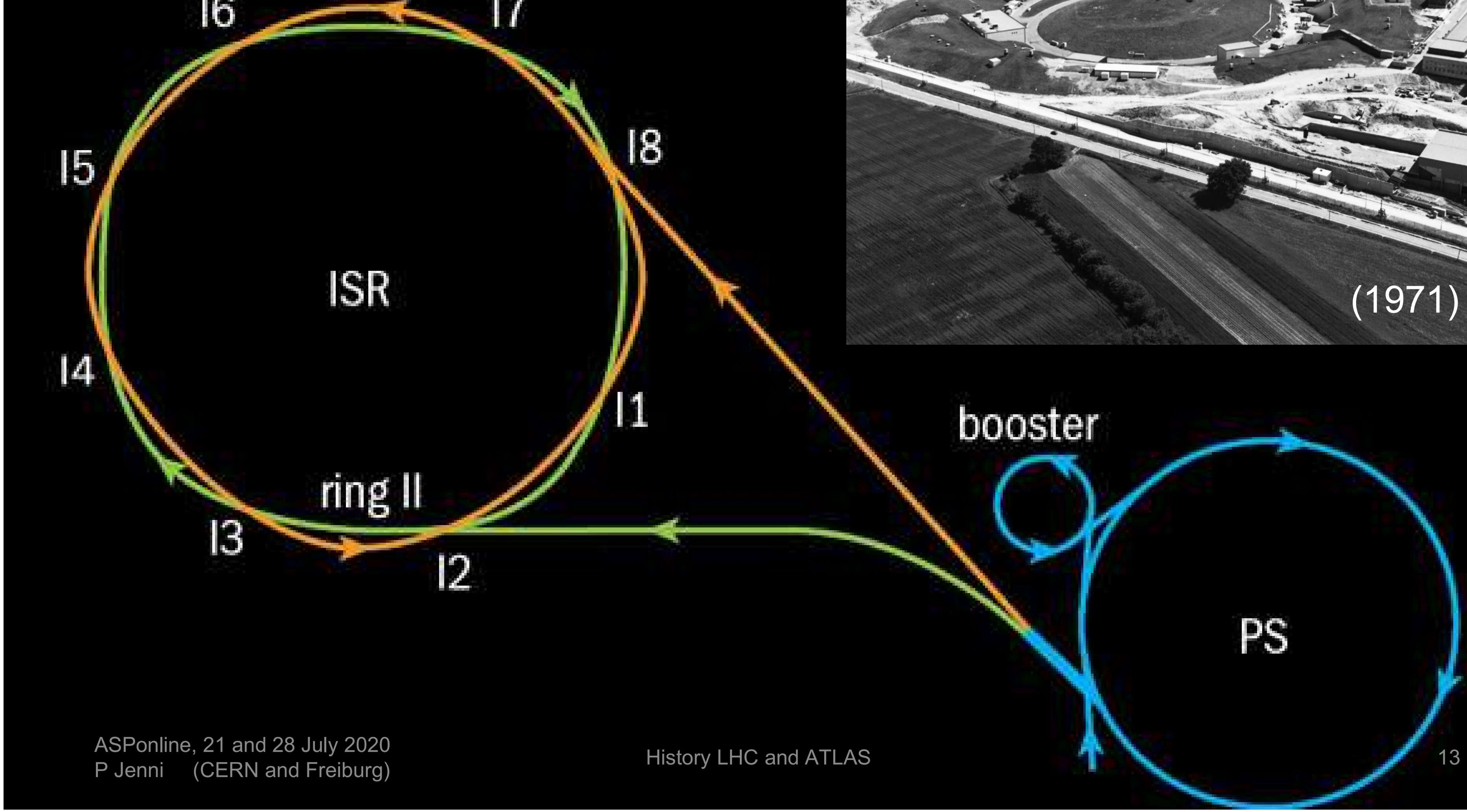


But, before talking about the LHC, let's step back and recall a bit the evolution and a few highlights (restricting myself to SM results) of the previous generations of hadron colliders at the high energy frontier, namely the

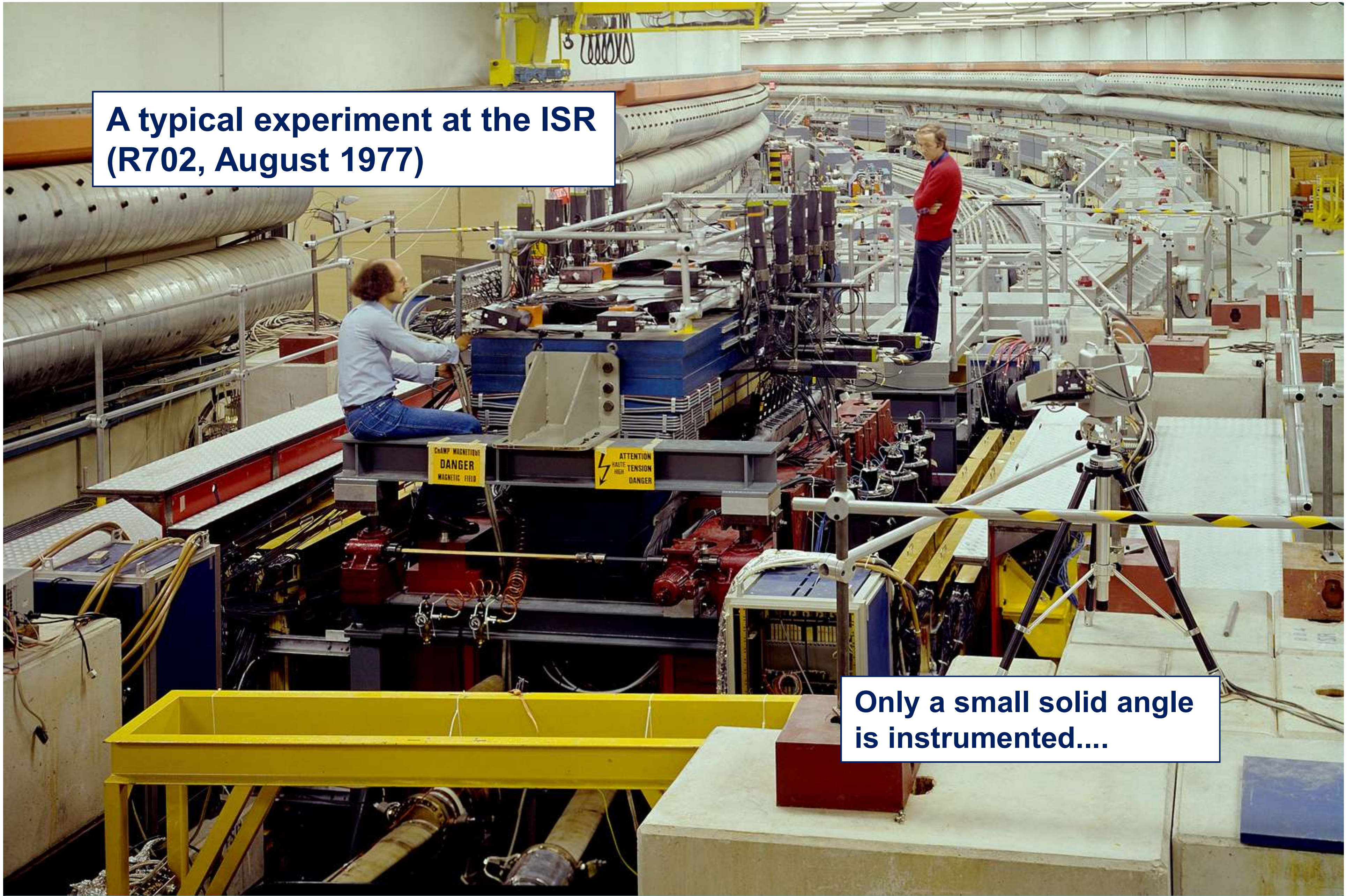
- ***CERN Intersection Storage Ring (ISR)***
- ***CERN SPS proton – antiproton Collider***
- ***Fermilab proton – antiproton Collider***

Intersecting Storage Ring ISR 1971-1984

(Circumference of 942 m, up to 63 GeV collision energy, achieved a peak luminosity 1.4 x $10^{32}cm^{-2}s^{-1}$, well above the design)



A typical experiment at the ISR (R702, August 1977)



Only a small solid angle is instrumented....

The other comment here, valid in general for the ISR: a few years earlier, the experiments could have made nice discoveries …

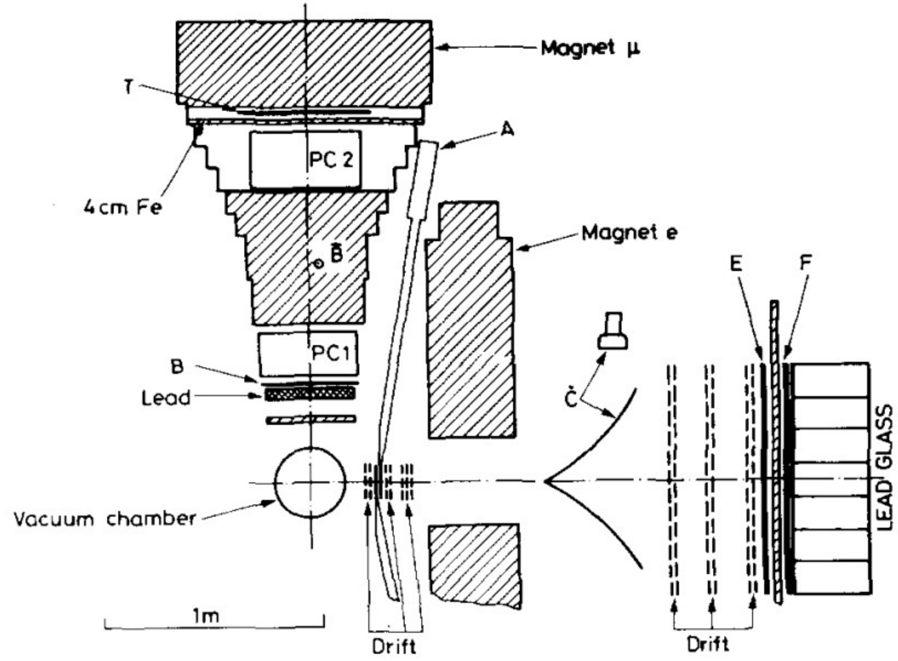


Fig. 1. View of the apparatus transverse to the beams. A second complete electron spectrometer (not shown) is placed symmetrically to the left.

A.G. Clark et al. / Electron pair production at the ISR 45

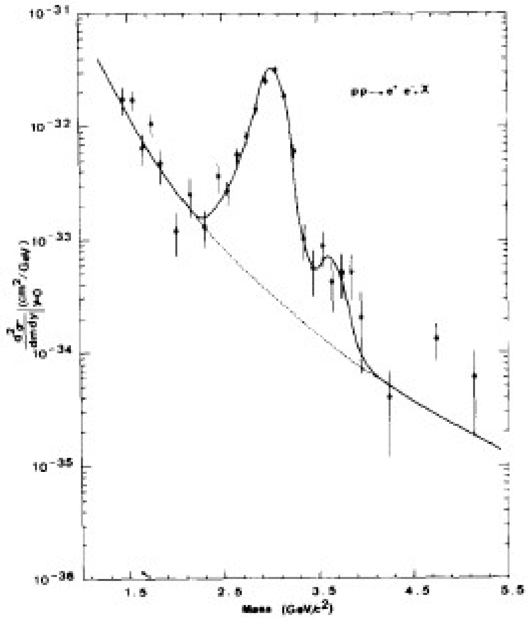
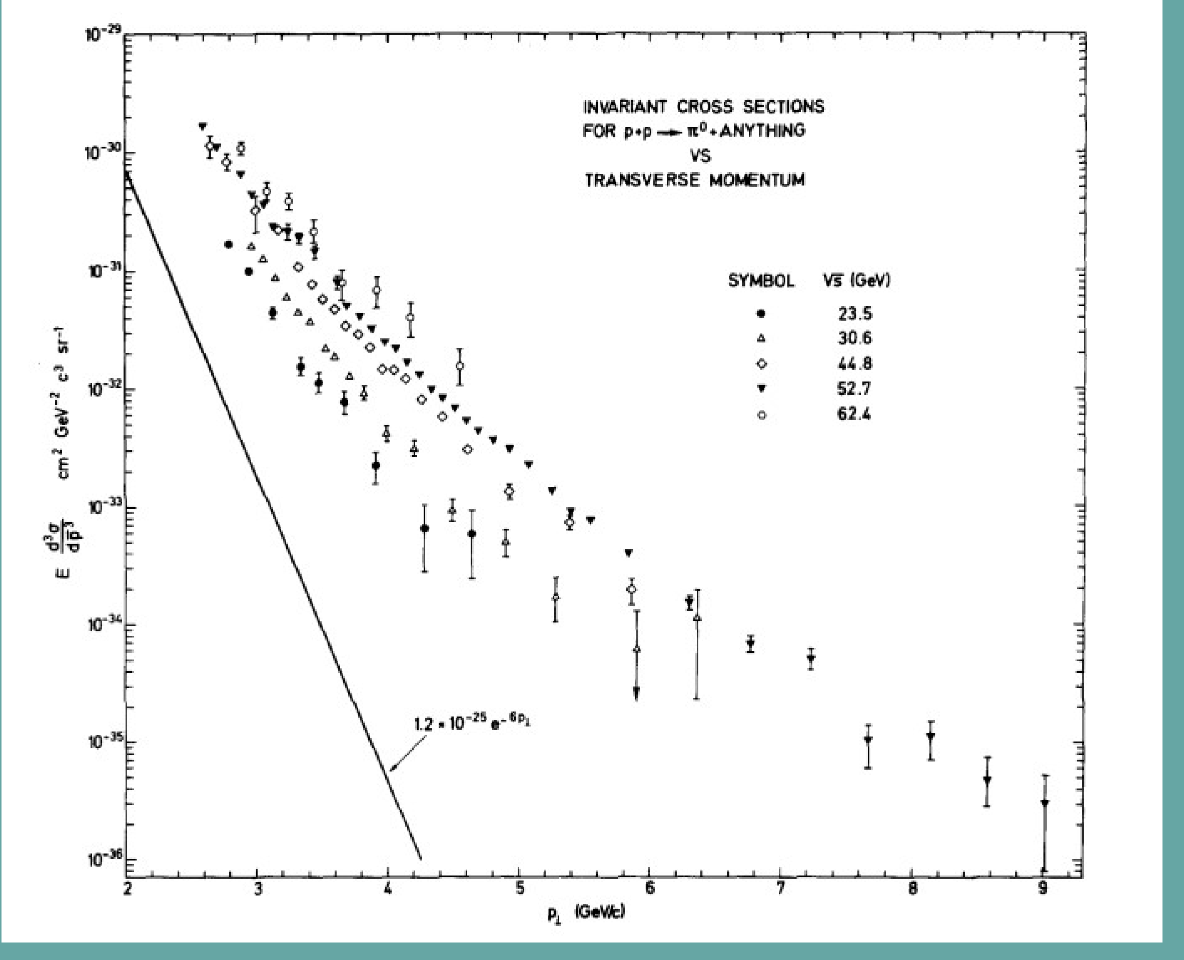
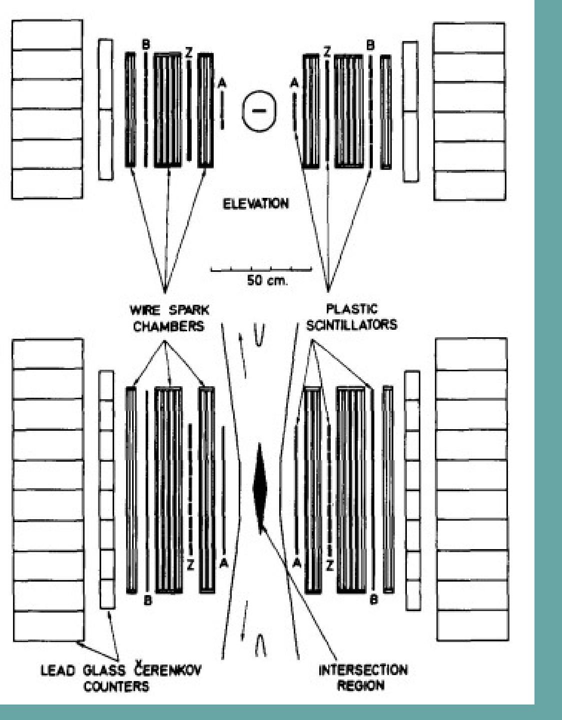


Fig. 12. The cross section $(d^2\sigma/dmdy)_{y=0}$ for inclusive electron pair production is displayed as a function of the pair mass. The line is the result of the fit described in subsect. 4.2.

R702, Nucl. Phys. B 142 (1978) 29

The pioneering legacy result from the ISR:
Large transverse momentum phenomena became evident, characteristic of parton scattering at hadron colliders

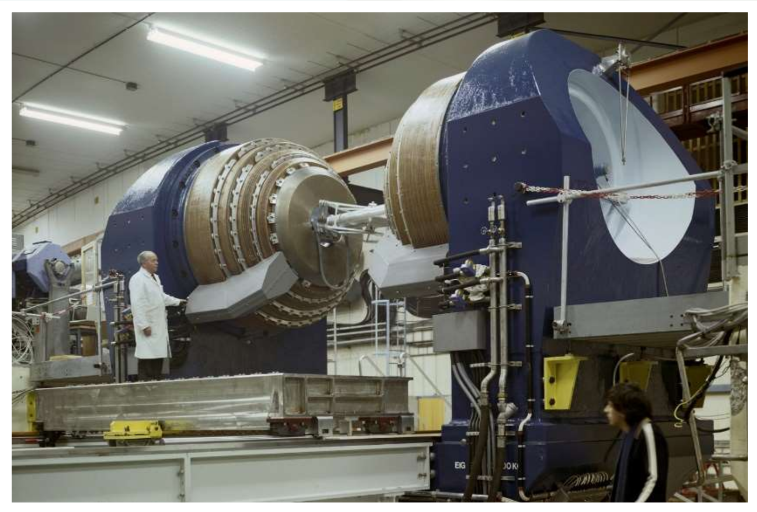


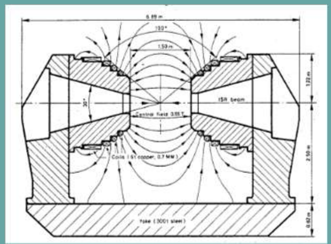


Phys. Lett. B 46 (173) 471

Observed by 3 experiments, shown is the 1973 inclusive π^o cross-section at 90º by R103 in 1973

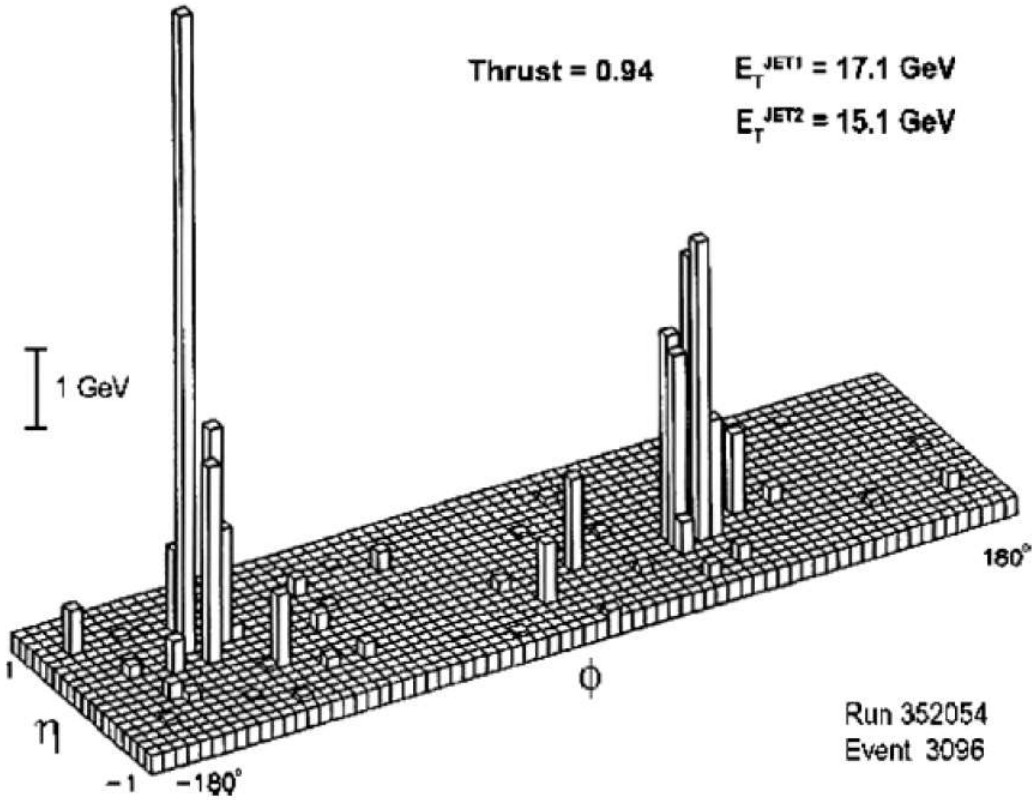
The last generation detectors, here the Axial Field Spectrometer R807/8, were closer to general purpose collider detectors as we know them now





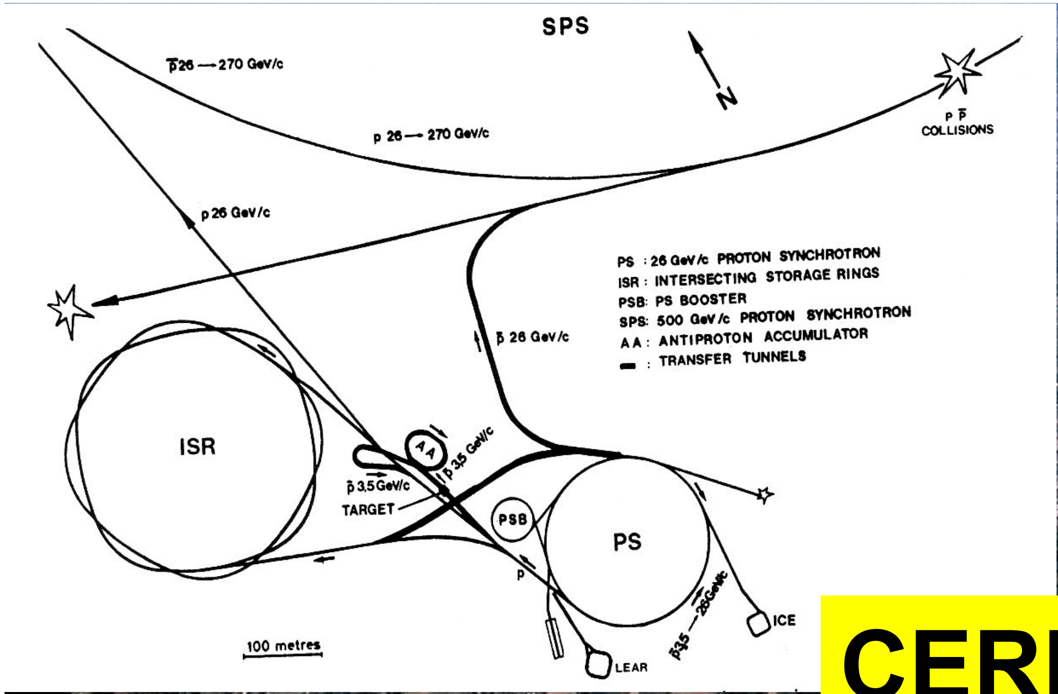
AFS approaching 4π coverage, with a Uranium-scintillator calorimeter

When the ISR closed down 1983/4, evidence for two-jet events became clear...

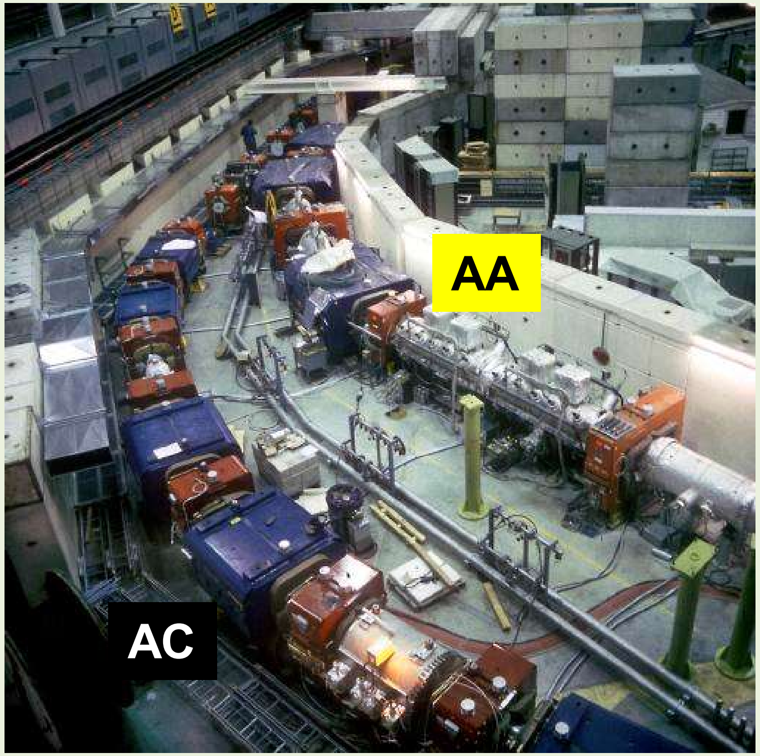


A 'lego plot' from the AFS experiment showing the two-jet in the calorimeter energy map

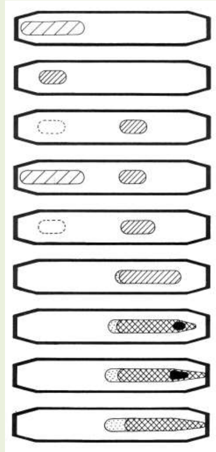
… but by then the focus of attention for hard scattering had already turned to the CERN SPS proton-antiproton collider with its higher energy



CERN SPS $p\bar{p}$ Collider



The crucial challenge was to stack as much as possible antiprotons over many hours to reach high luminosities



A view of the CERN SPS, 450 GeV

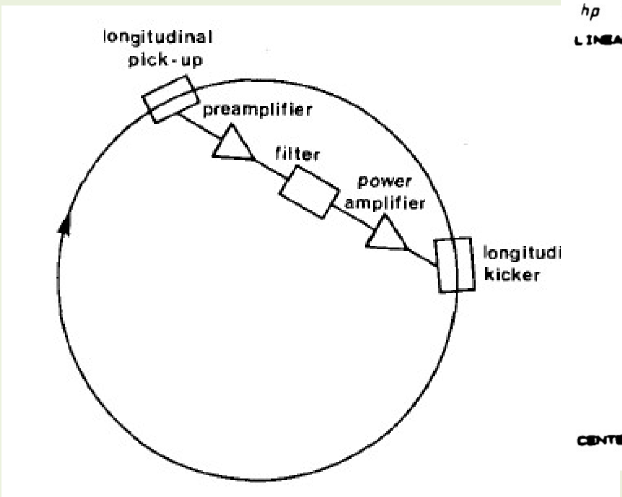
The CERN Antiproton Accumulator (AA) 3.5 GeV large-aperture ring for antiproton storage and cooling, and the Antiproton Collector (AC) added for the second phase

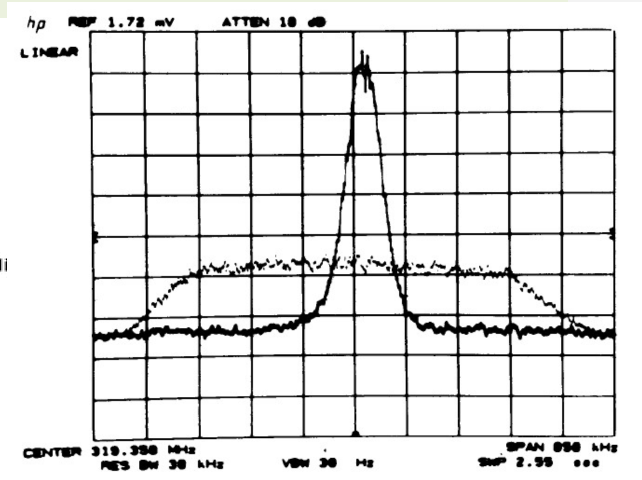
Simon van der Meer 1925 – 2011

Nobel Prize in 1984 for the contributions that led to the discoveries of the W and Z

(shared with Carlo Rubbia)

Van der Meer's crucial contribution was the stochastic cooling for accumulating enough anti-protons in conditions to be accelerated later in the SPS together with protons to provide the 630 GeV collisions needed to discover the W and Z





CERN SPS Proton-Antiproton Collider operation (1981 – 1990)

Year	Collision Energy (GeV)	Peak luminosity (cm^{-2} s^{-1})	Integrated luminosity (cm^{-2})
1981	546	$\sim 10^{27}$	2.0×10^{32}
1982	546	5×10^{28}	2.8×10^{34}
1983	546	1.7×10^{29}	1.5×10^{35}
1984-85	630	3.9×10^{29}	1.0×10^{36}
1987-90	630	$\sim 2 \times 10^{30}$	1.6×10^{37}

Unambiguous jets

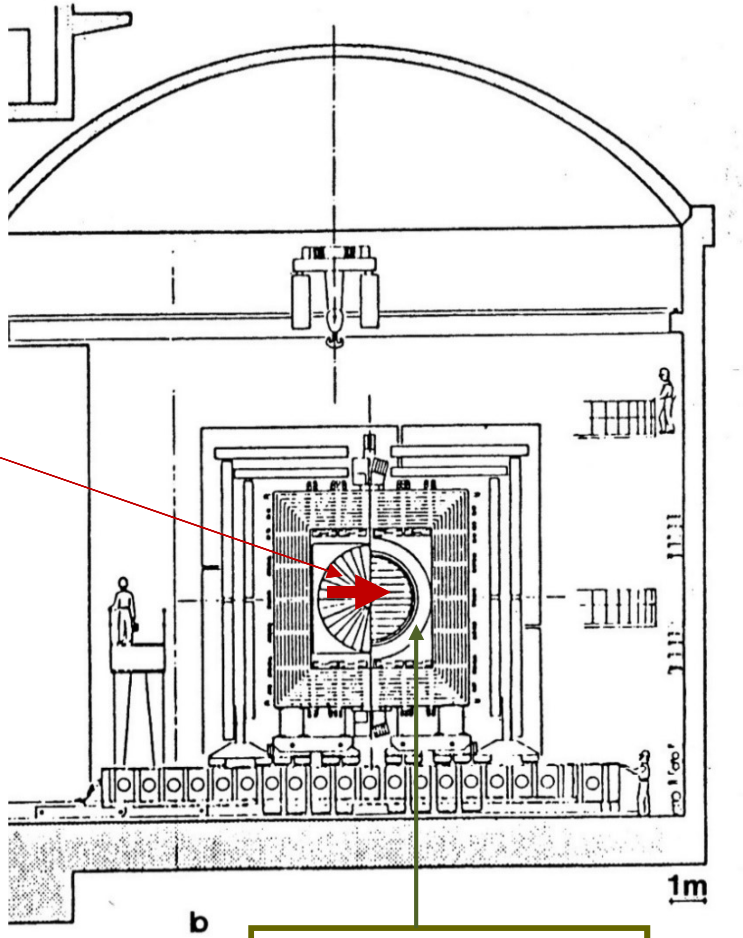
W discovery

Z discovery

Searches for top, SUSY, and m_W measurements, B^o – B^o mixing

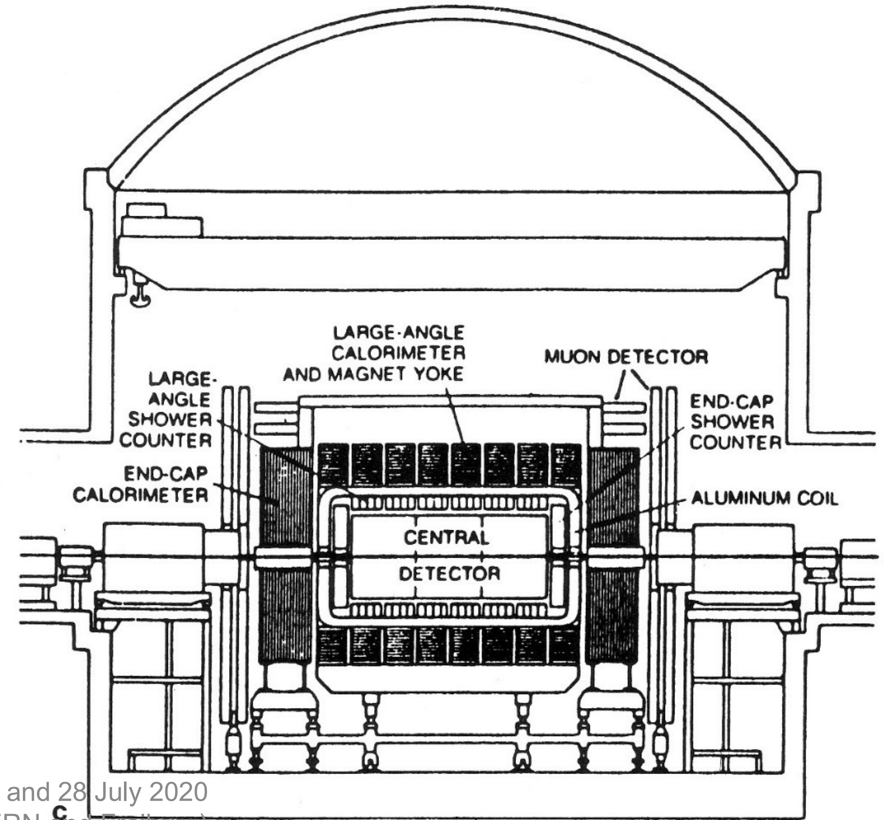
The UA1 detector, pioneering a first hermetic hadron collider detector approach at the CERN $p\bar{p}$ Collider (January 1981)

Magnetic field direction



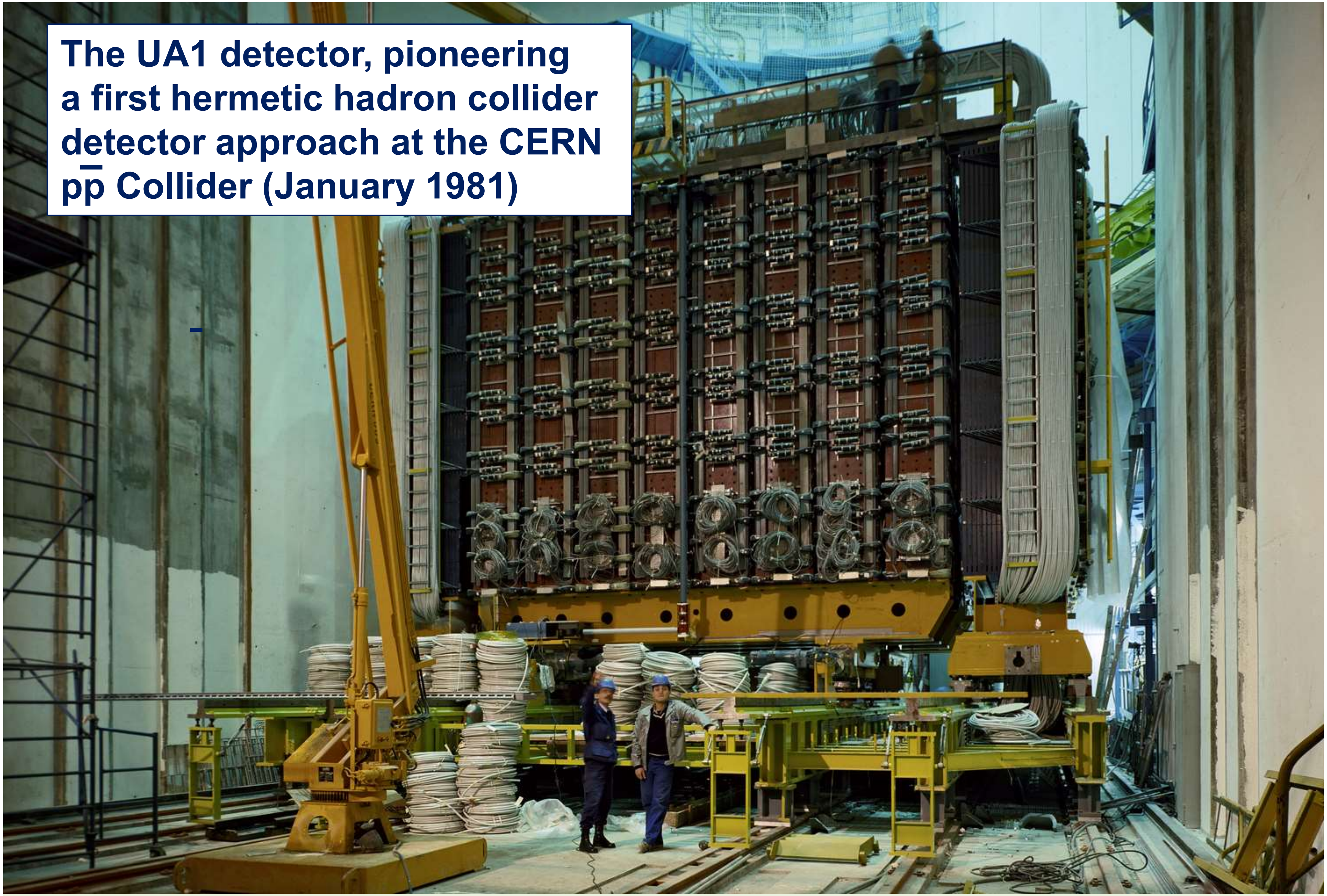
b

Central electromagnetic calorimeter

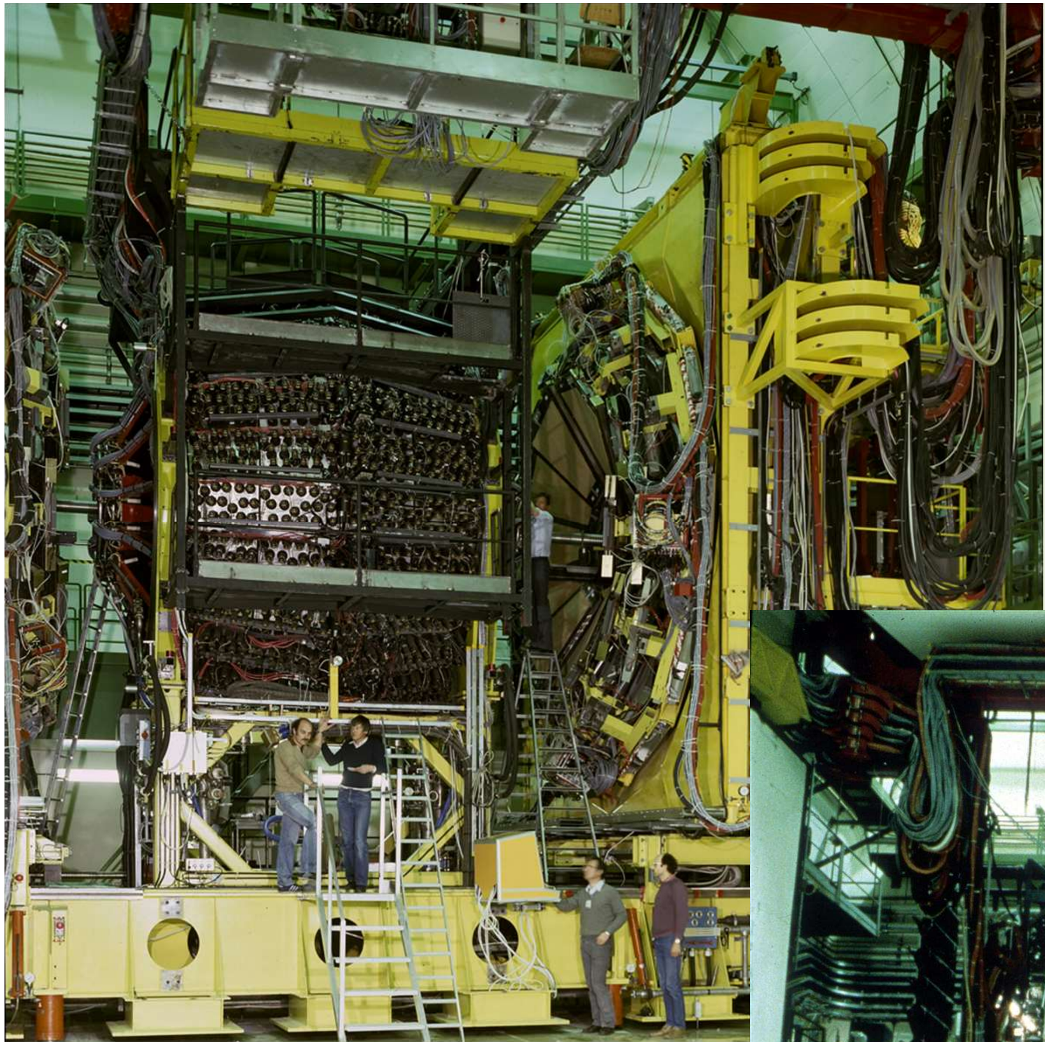


c

The UA1 detector, pioneering a first hermetic hadron collider detector approach at the CERN $p\bar{p}$ Collider (January 1981)

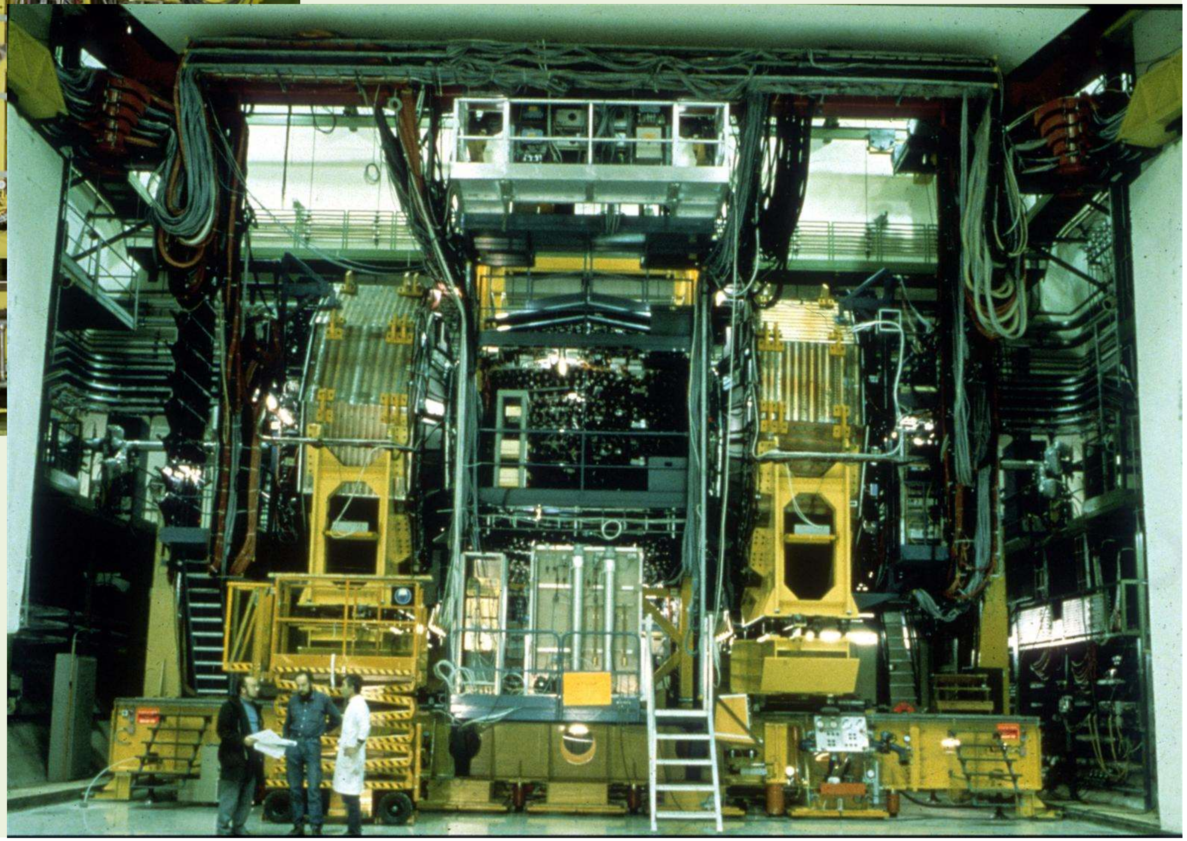


The UA2 detector
(‘highly’ segmented, central calorimeter with pointing cells, but no muon detection)



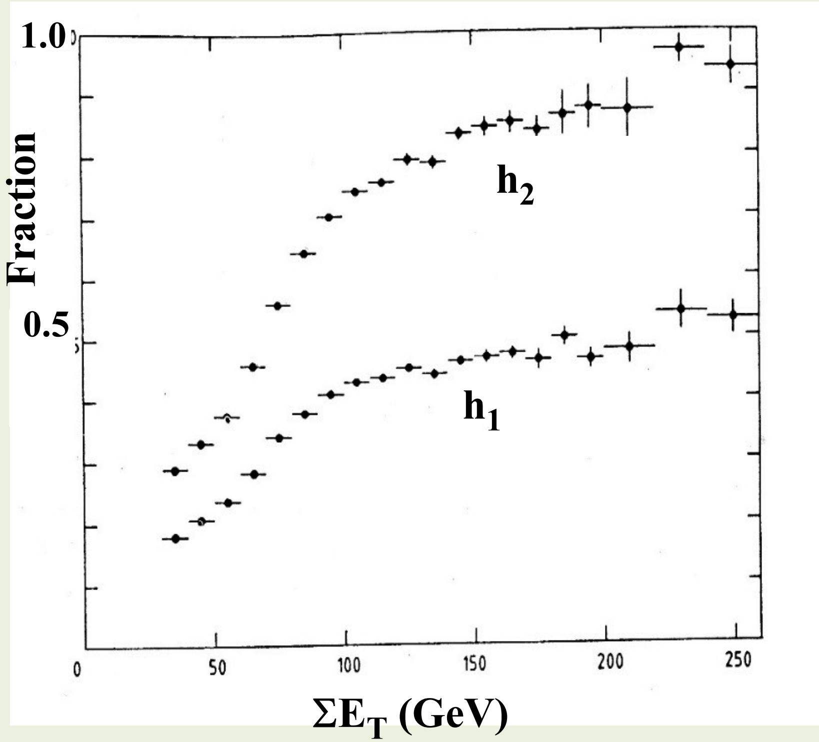
UA2 1981-85
(toroid forward magnets)

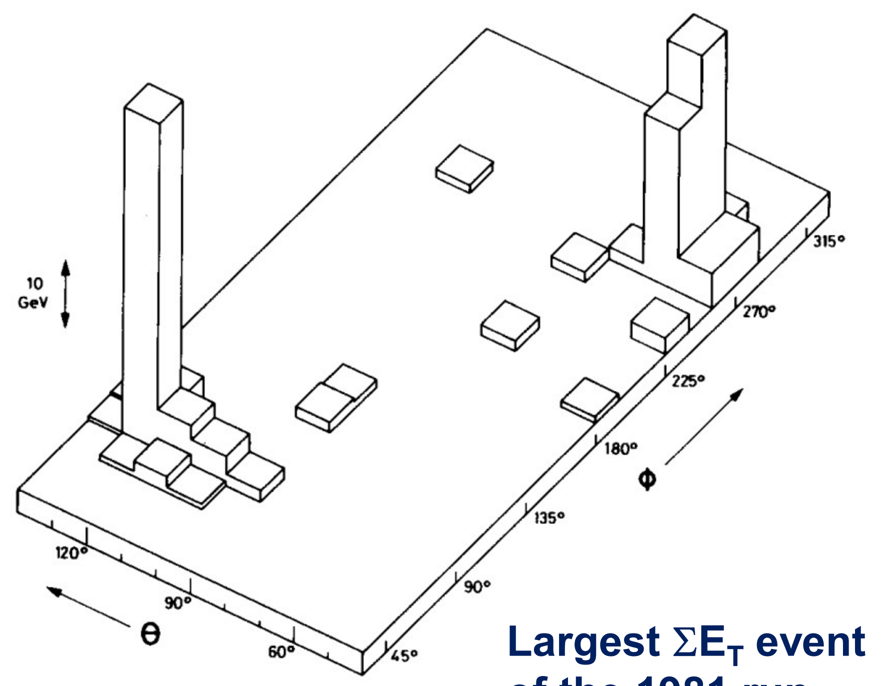
UA2’ 1987-90
(fully non-magnetic, upgraded with new hermetic end-cap calorimeters for ET_{miss} …)



Emergence of two-jet processes in UA2 events with large transverse energy in the central calorimeter

UA2, Phys. Lett. B 118 (1982) 203





Largest ΣE_T event of the 1981 run

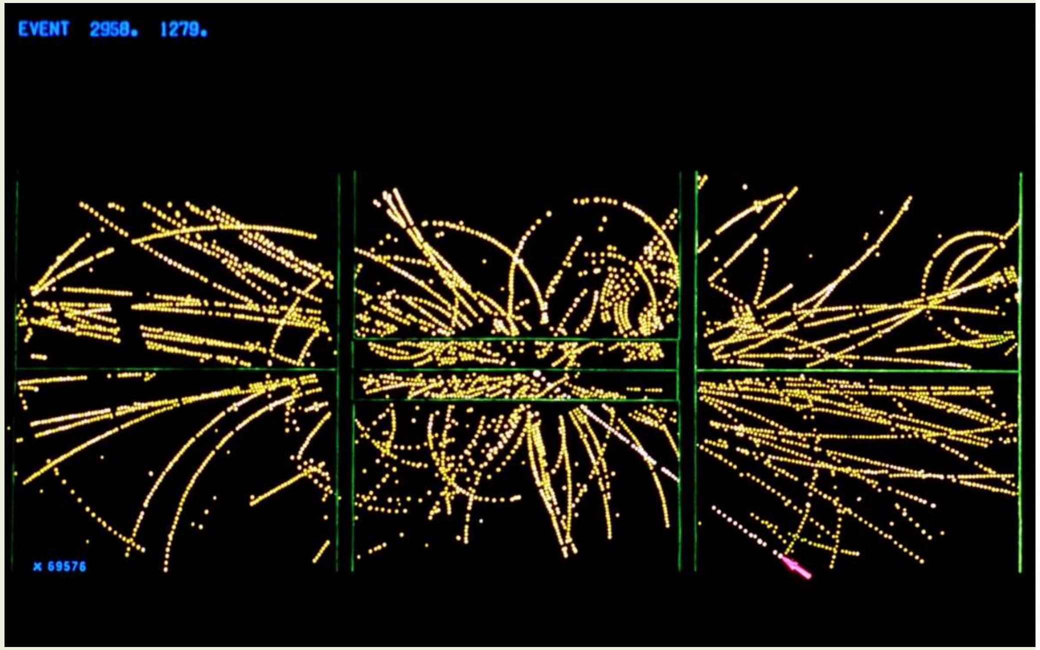
$$h_1 = \frac{E_T^{\,1}}{\Sigma E_T}$$ fraction of total E_T carried by leading cluster

$$h_2 = \frac{E_T^{\,1} + E_T^{\,2}}{\Sigma E_T}$$ fraction of total E_T carried by the two leading clusters

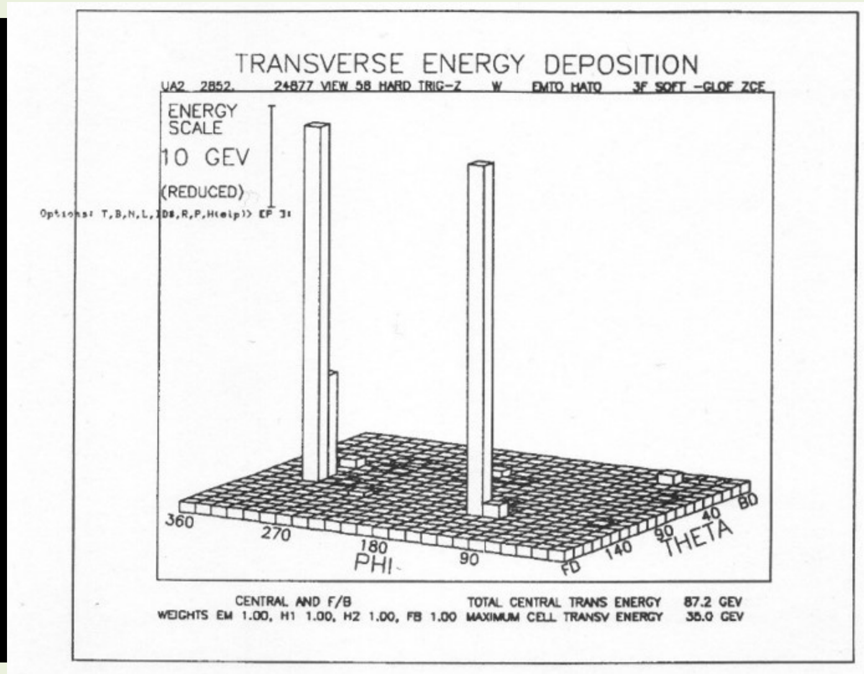
At that time: jet = cluster = adjacent cells above a threshold

W and Z boson discovery (1982/3)

W discovery press conference 25 January 1983 with Rubbia, van der Meer, Schopper, Gabathuler, Darriulat



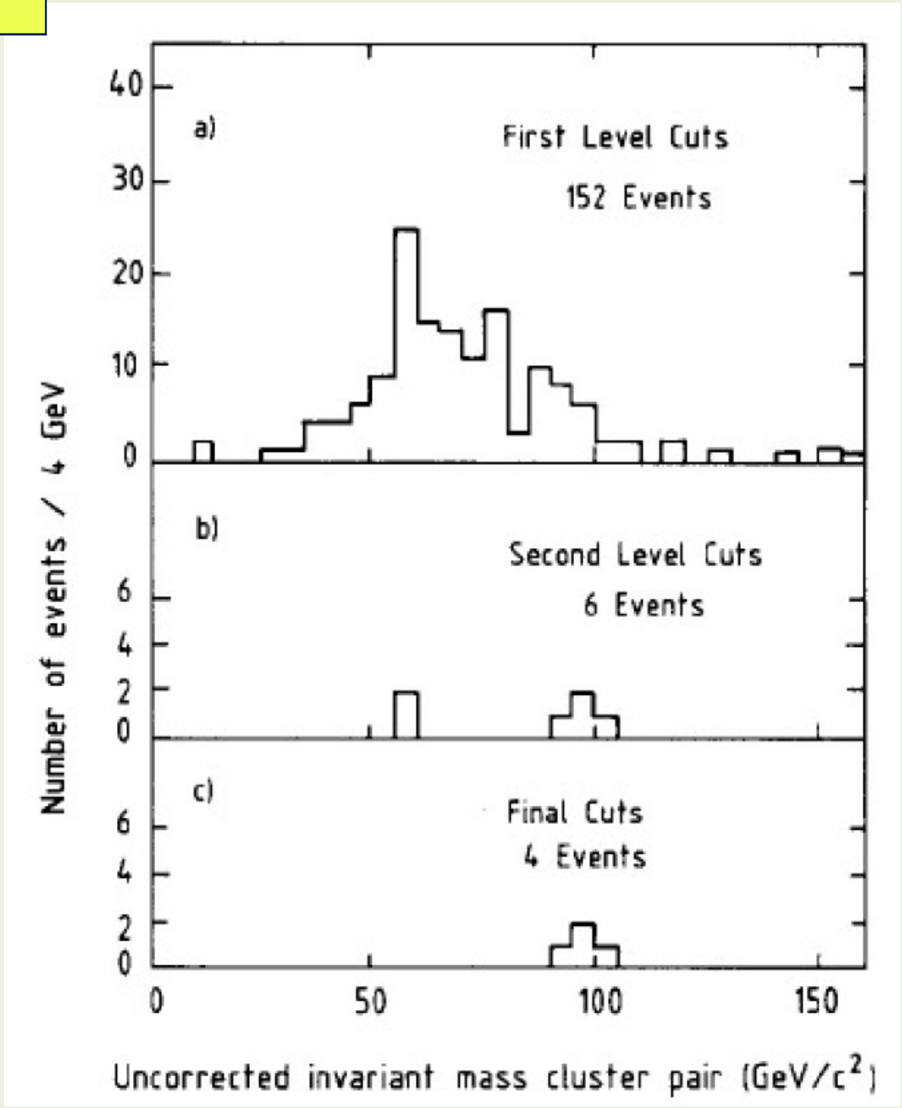
UA1 W → eν event, the arrow points to the electron, 1982



UA2 online display of a Z → ee event, 1983

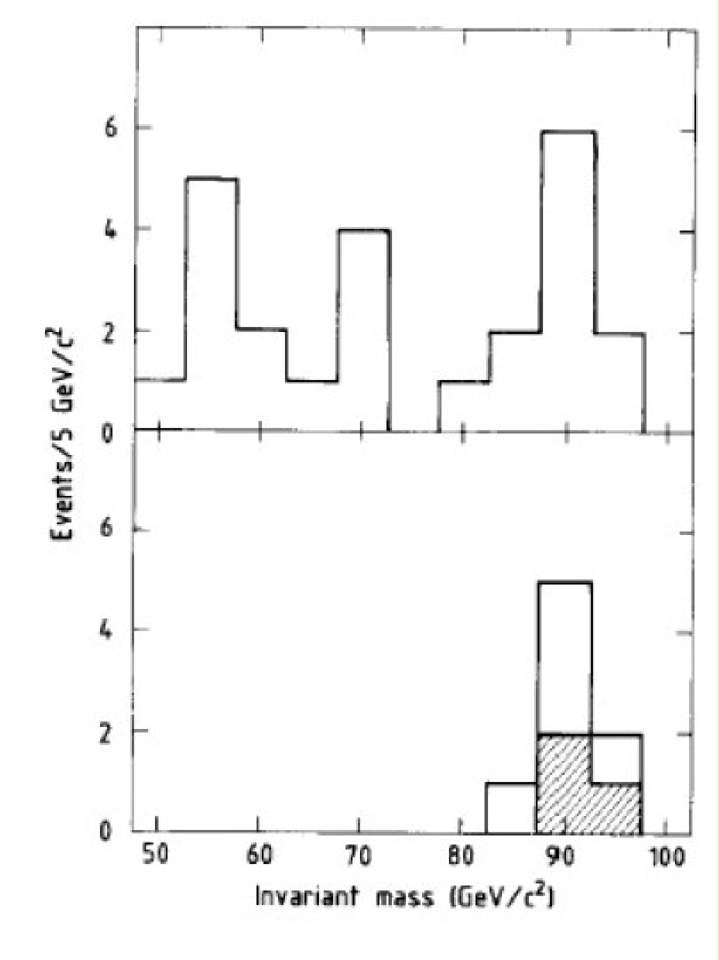
Z^o

UA1



UA1, Phys. Lett. B 126 (1983) 398

UA2



The Z → ee results presented in May and June 1983 at CERN

UA2, Phys. Lett. B 129 (1983) 130

At the end of the CERN proton-antiproton collider, the first ‘precise’ measurement of the W mass by UA2

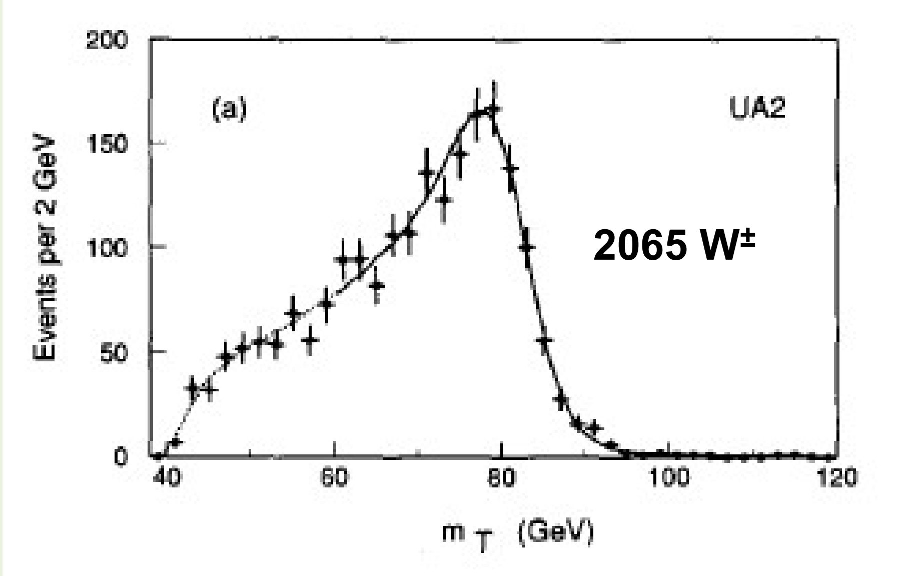
Exploit a precise measurement of the ratio $r = m_W / m_Z$ to avoid the the calorimeter calibration uncertainty and use the precise measurement for m_Z from LEP and SLD
(direct m_W fit 80.84 ± 0.22 GeV ±1% calibration)

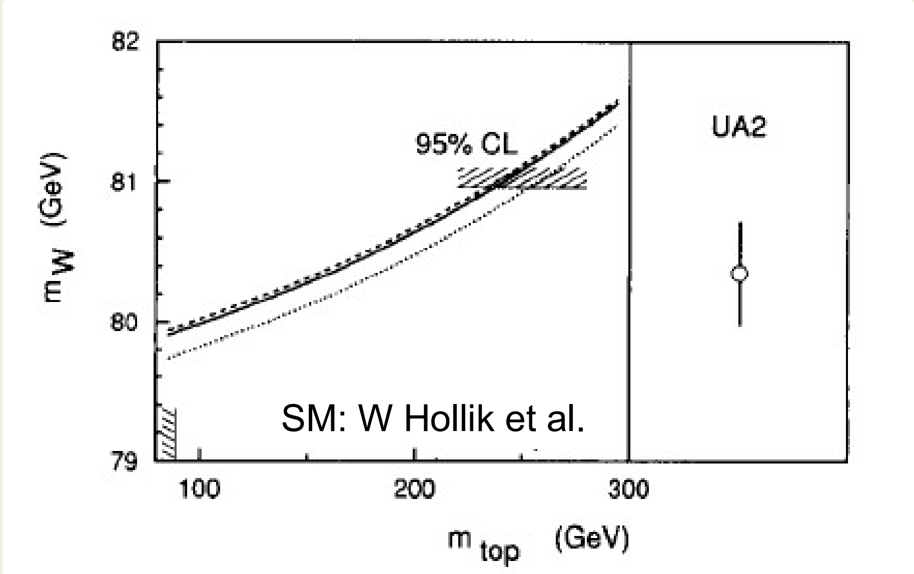
$r = 0.8813 \pm 0.0036 \pm 0.0019$

yielding $m_W = 80.35 \pm 0.33 \pm 0.17$ GeV

This gave a bound on the mass of the top quark in the frame of the Standard Model, five years before the top quark discovery at Fermilab

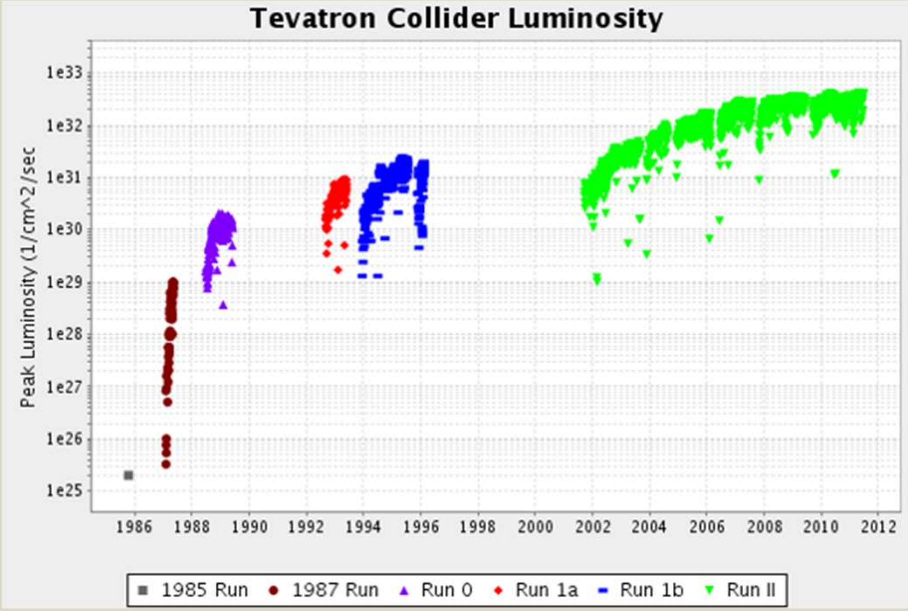
$m_{top} = 160^{+50}_{-60}$ GeV





Tevatron, CDF and DØ: a Legacy Impact on the SM

Tevatron proton-antiproton Collider run and performance history

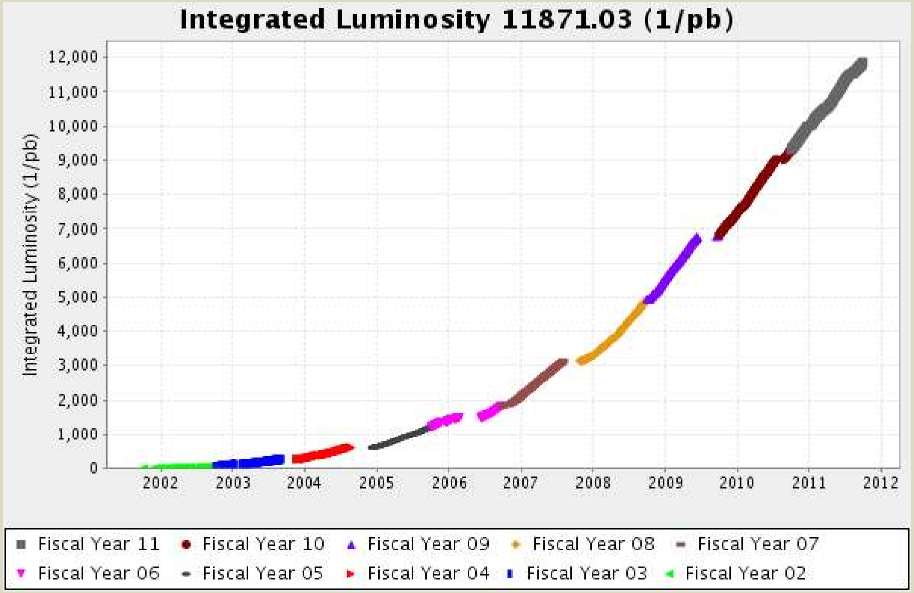


<u>Run 0</u> (1987 – 1988):

1.8 TeV, CDF only, 4 pb^{-1}

<u>Run I</u> (1992 – 1996):

1.8 TeV, CDF+DØ: 120 pb^{-1}

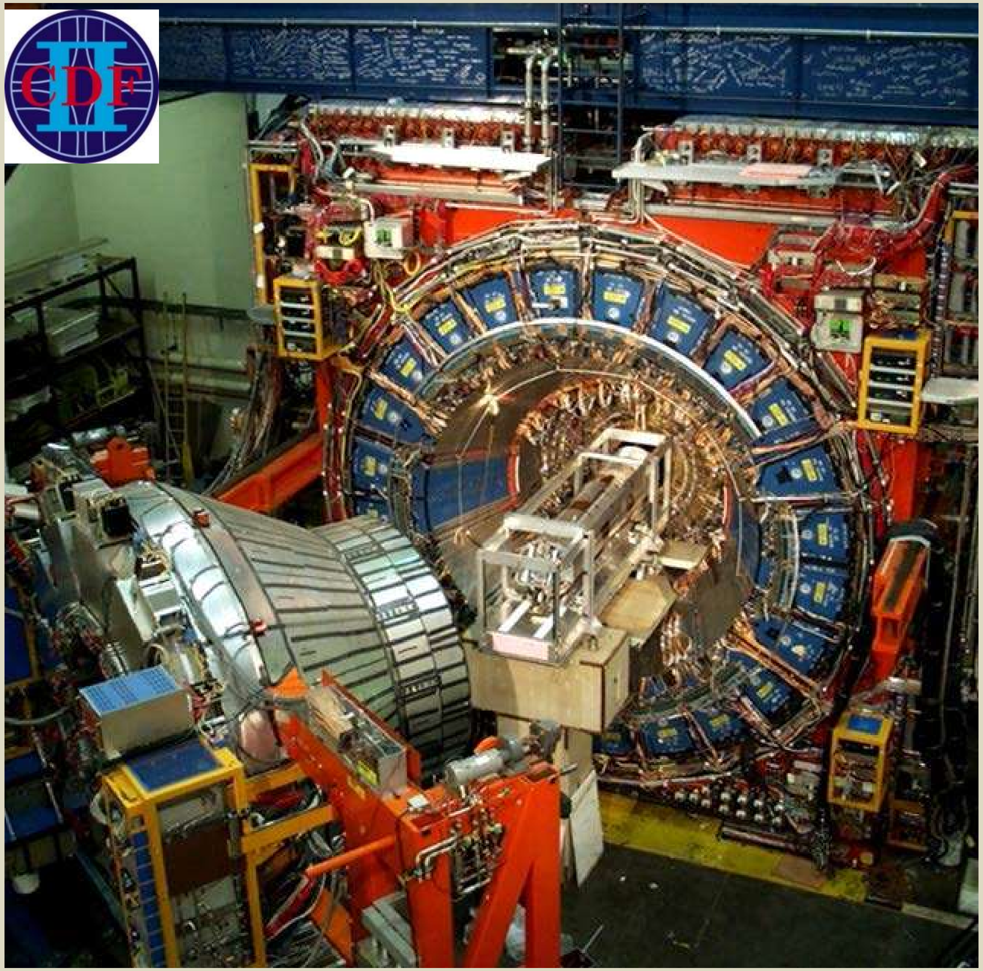


<u>Run II</u> (2001 – 2011):

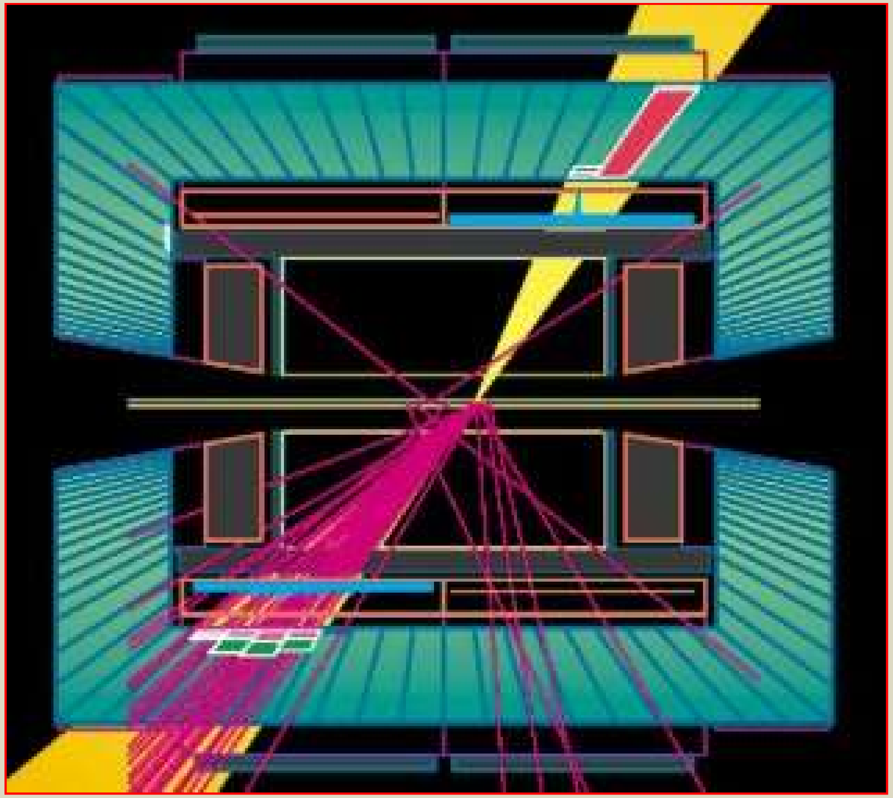
1.96 TeV, 12 fb^{-1}

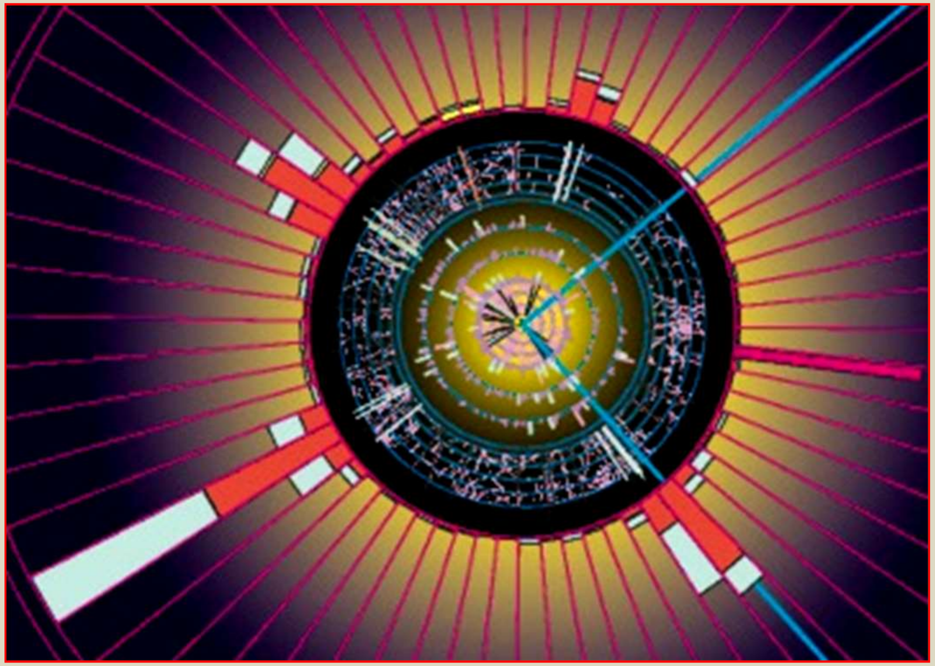
→ Great performance with added Main Injector, Recycler Ring …

The initial detectors (Run I) already were designed as general-purpose experiments, with a complexity and sophistication well beyond what has been done before. (Shown are pictures for the Run II detectors.)

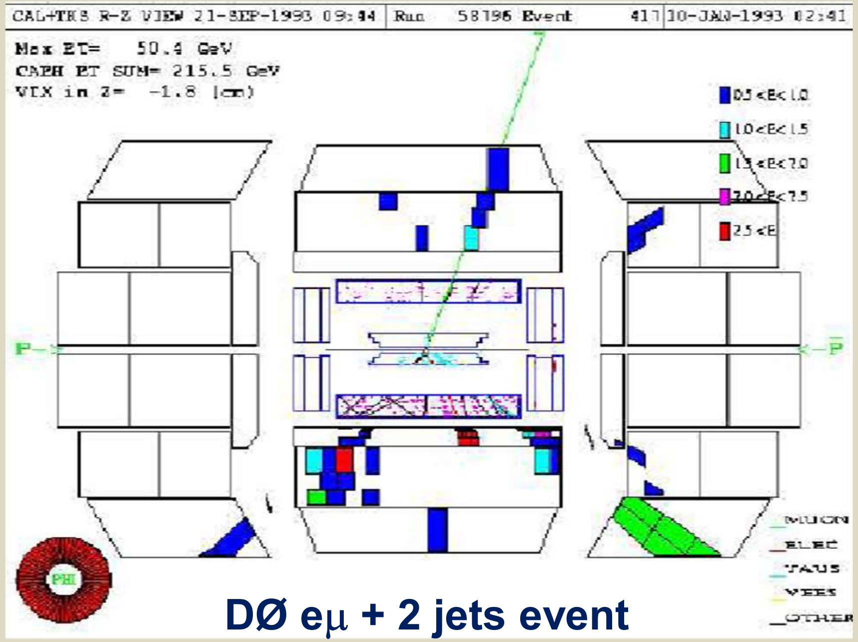


The CDF and D0 Collaborations pioneered many of the modern analysis methods that are now used and further developed at LHC

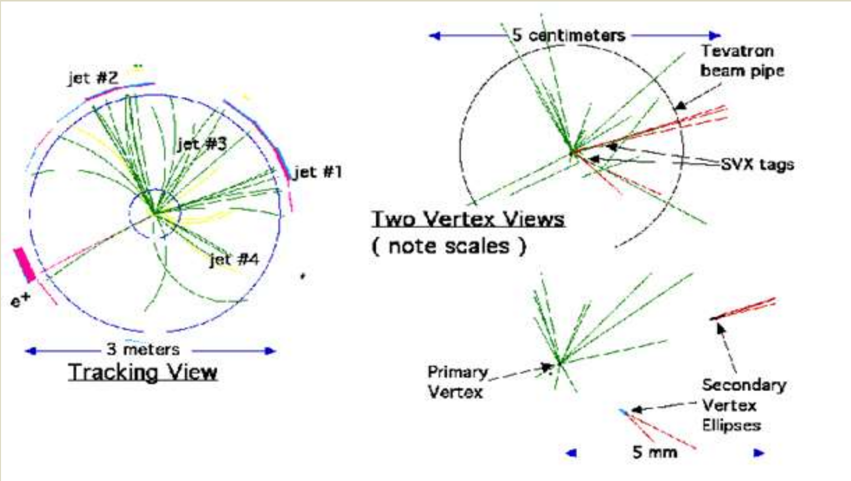




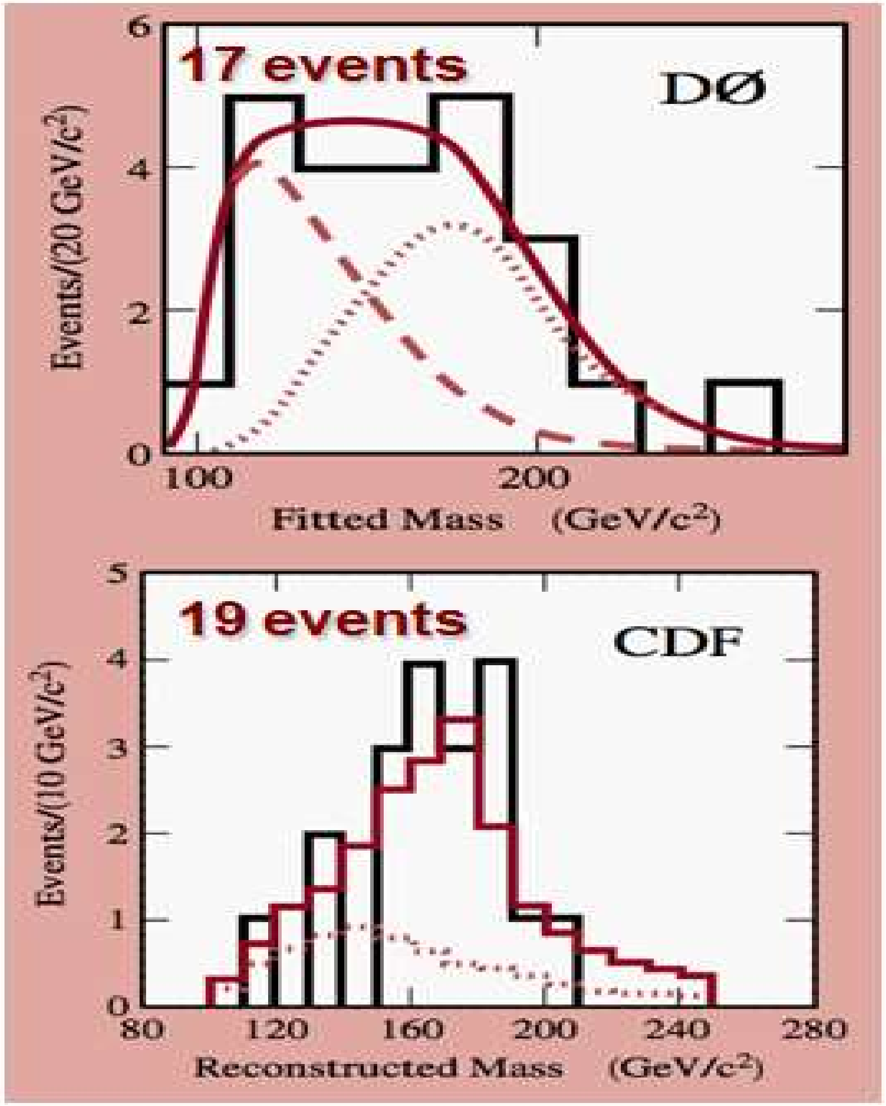
Top quark discovery: Major step establishing the Standard Model
(CDF and DØ, 24th February 1995 papers submitted, 2nd March 1995 joint seminar)



DØ eμ + 2 jets event



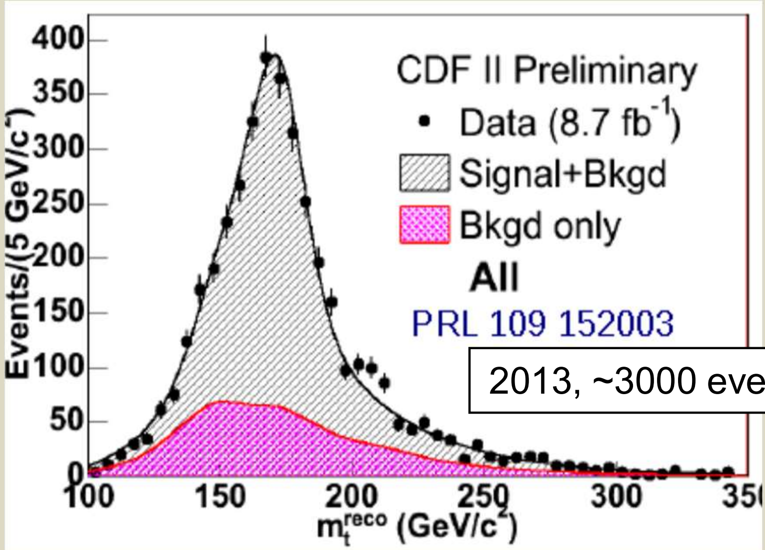
CDF secondary vertices b-jet event



1995, CDF and DØ experiments, Fermilab

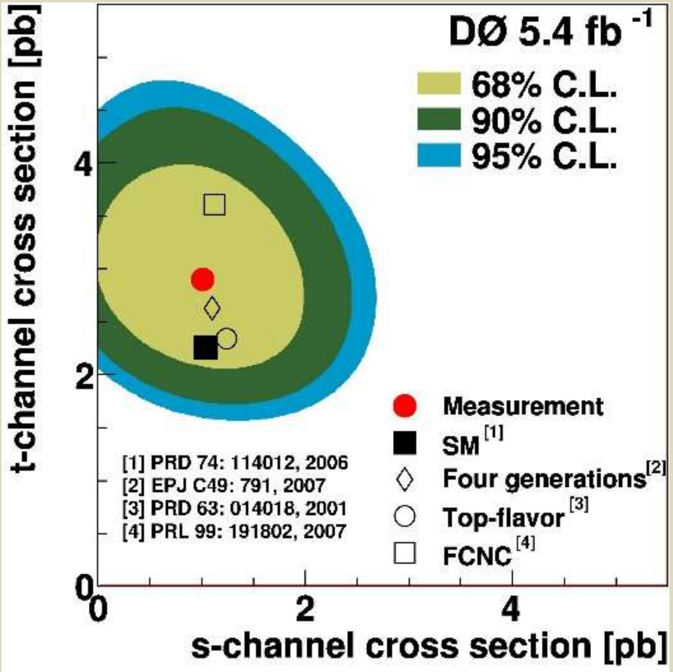
CDF Phys. Rev. Lett. 74 (1995) 2626
D0 Phys. Rev. Lett. 74 (1995) 2632

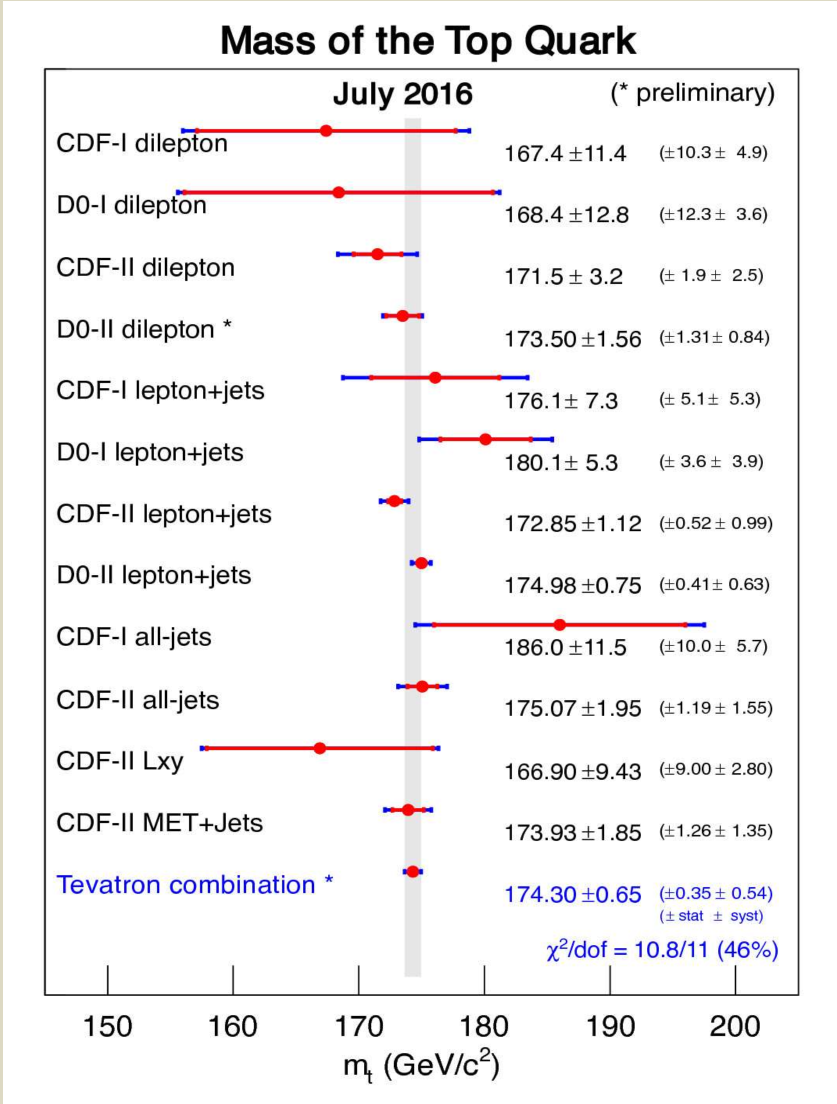
A very rich harvest of top physics followed, just a few examples…



2013, ~3000 events

Single t production discovered 2009, thanks to sophisticated MV methods





Collision energy

Tevatron ($p\bar{p}$)

1.96 TeV

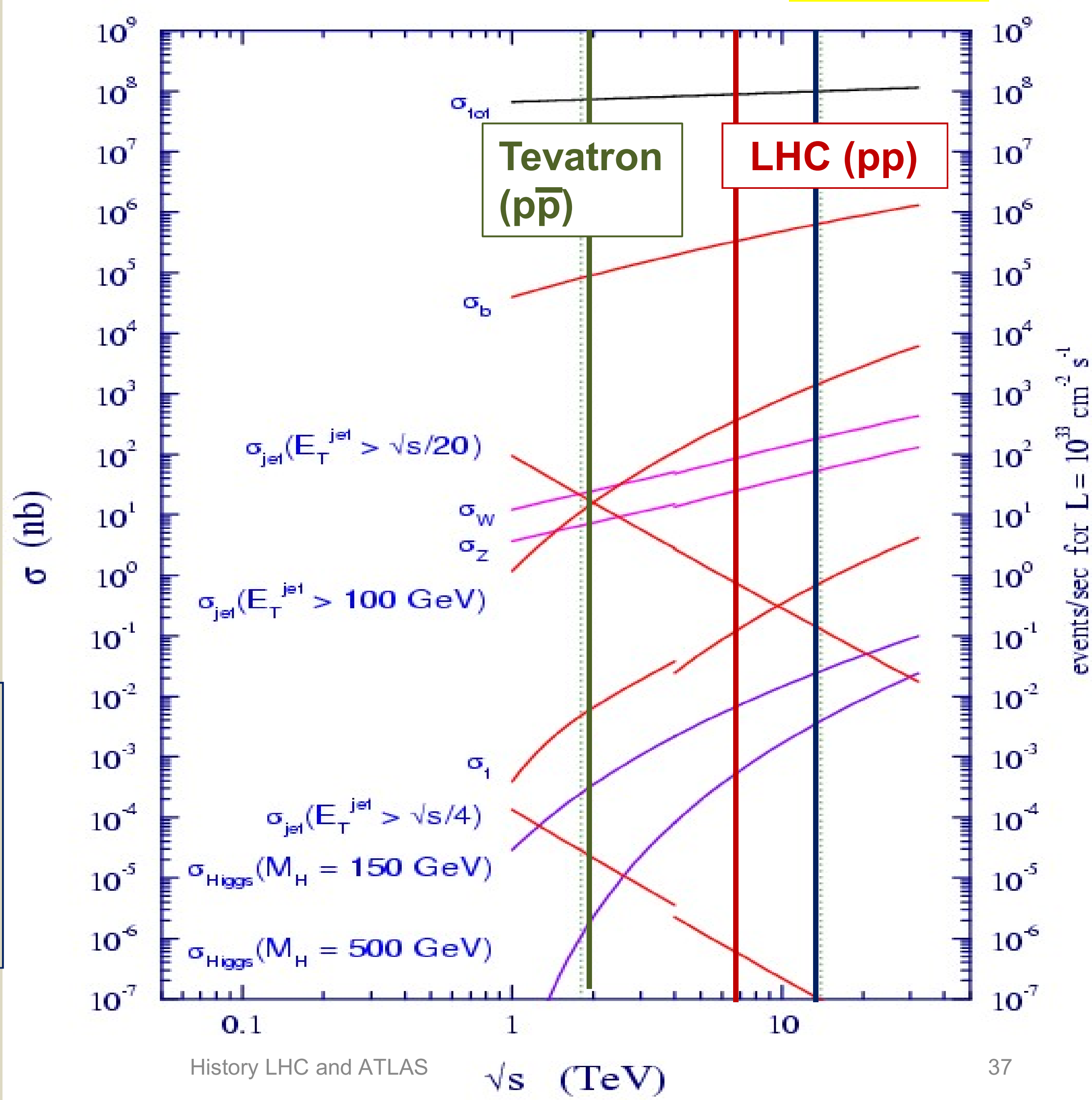
LHC (pp)

initially 7 TeV
Run 1+2 13 TeV
design 14 TeV

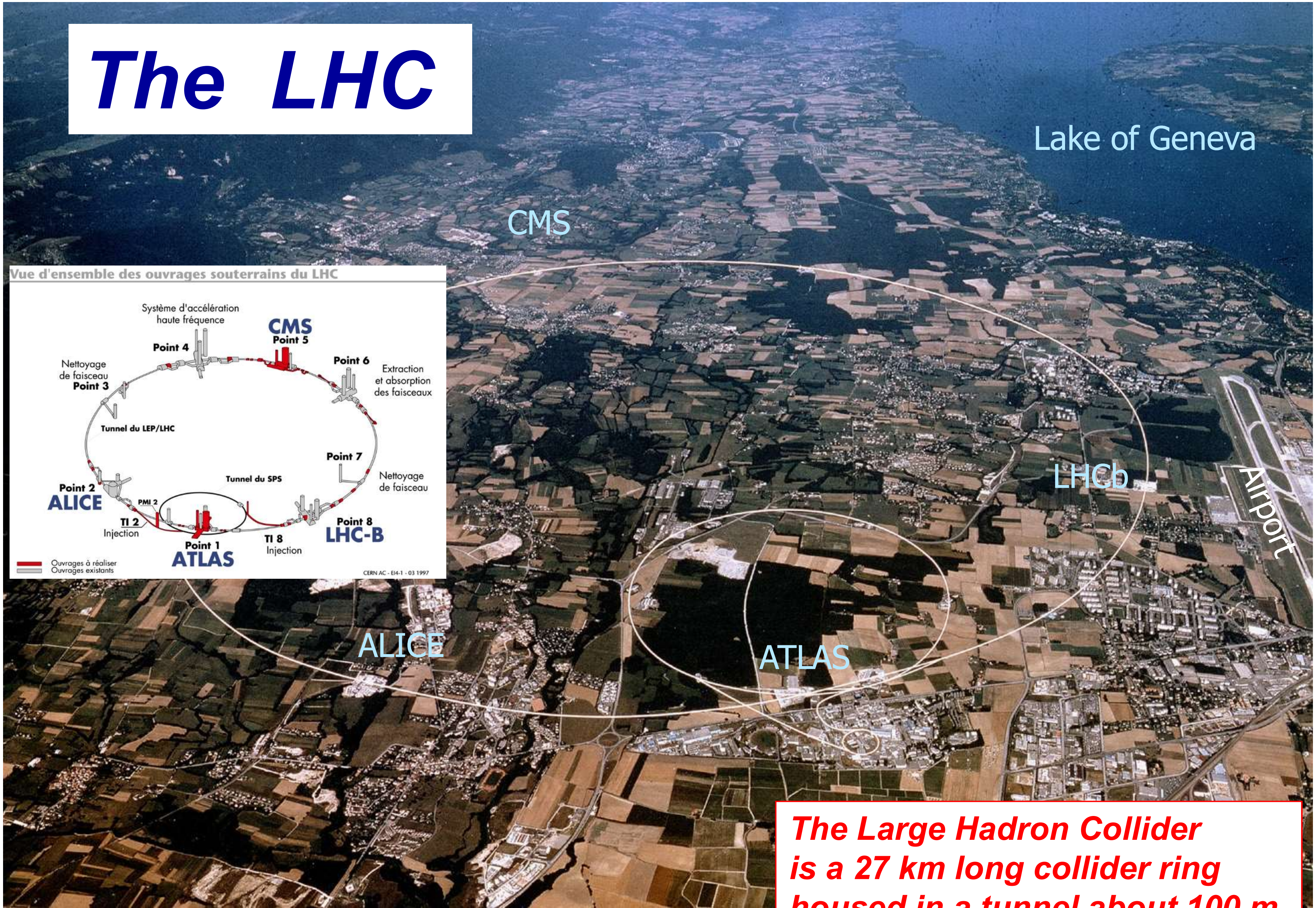
The other key parameter for setting the road map for discoveries is the integrated luminosity

$$N_{events} = \sigma \int L \, dt$$

Some bench-mark cross-sections **~ 1990 !**

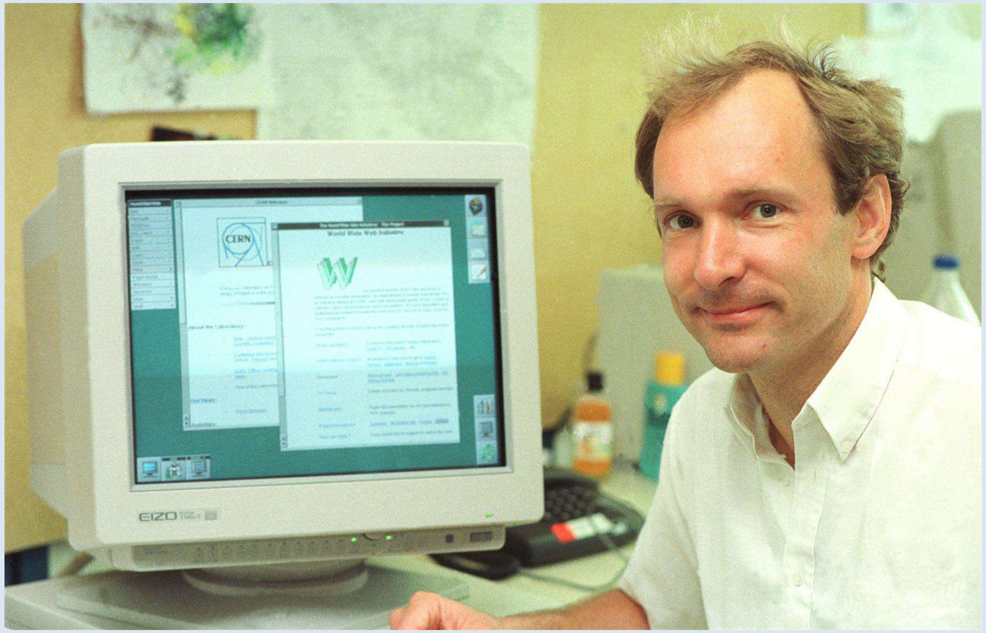


The LHC



The Large Hadron Collider is a 27 km long collider ring housed in a tunnel about 100 m underground near Geneva

The first picture on the Web in 1992 !



Tim Berners-Lee
(pictured July 1994)

Sir Tim Berners-Lee and CERN DG Fabiola Gianotti (12^{th} March 2019)

How the LHC came to be …

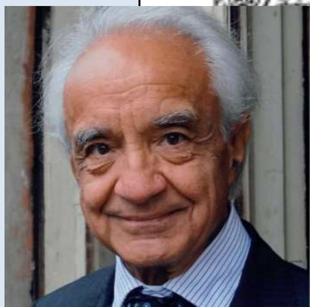
Some very early key dates

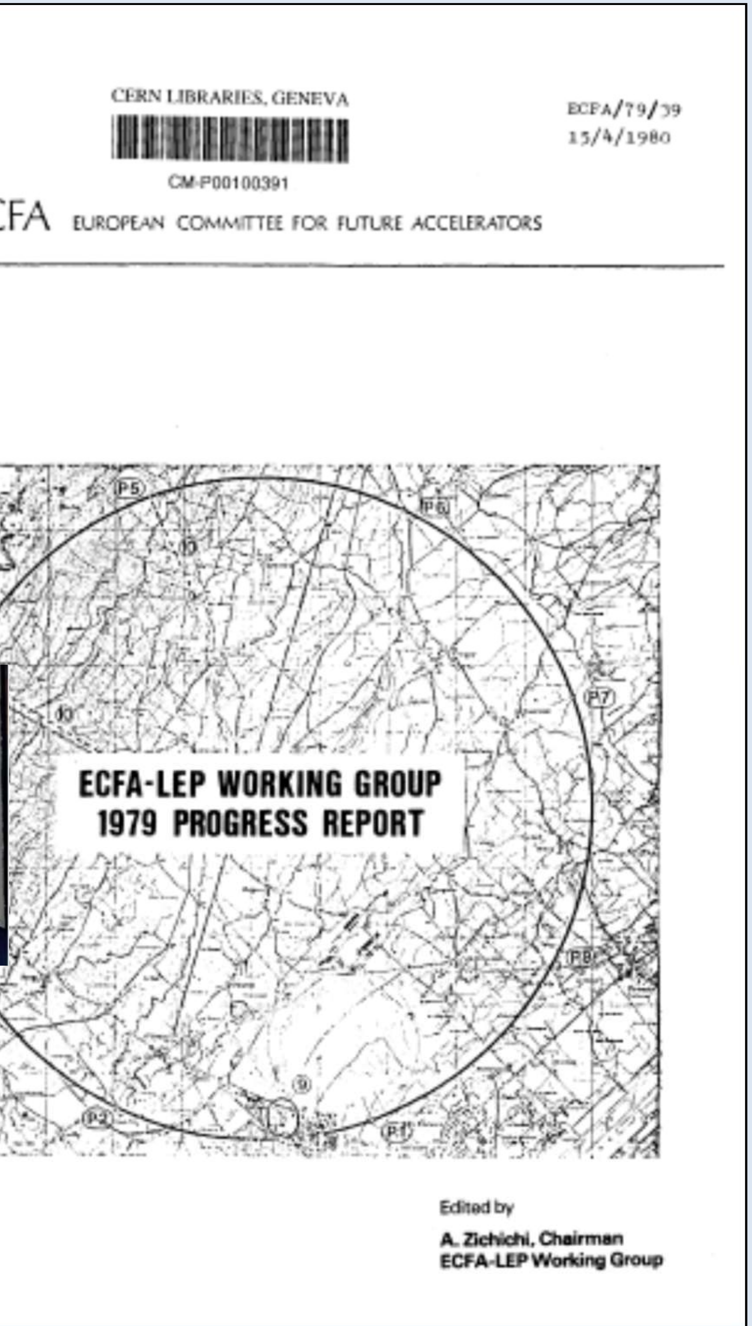
1977 The community talked about the LEP project, and it was already mentioned that a new tunnel could also house a hadron collider in the far future

1979 LEP White Book:

ECFA-LEP Working Group 1979 chaired by A Zichichi

‘Tunnel with 27 km circumference and a diameter of 5 m, with a view to the replacement of LEP at the end of its activities by a proton-proton Collider using cryogenic magnets’





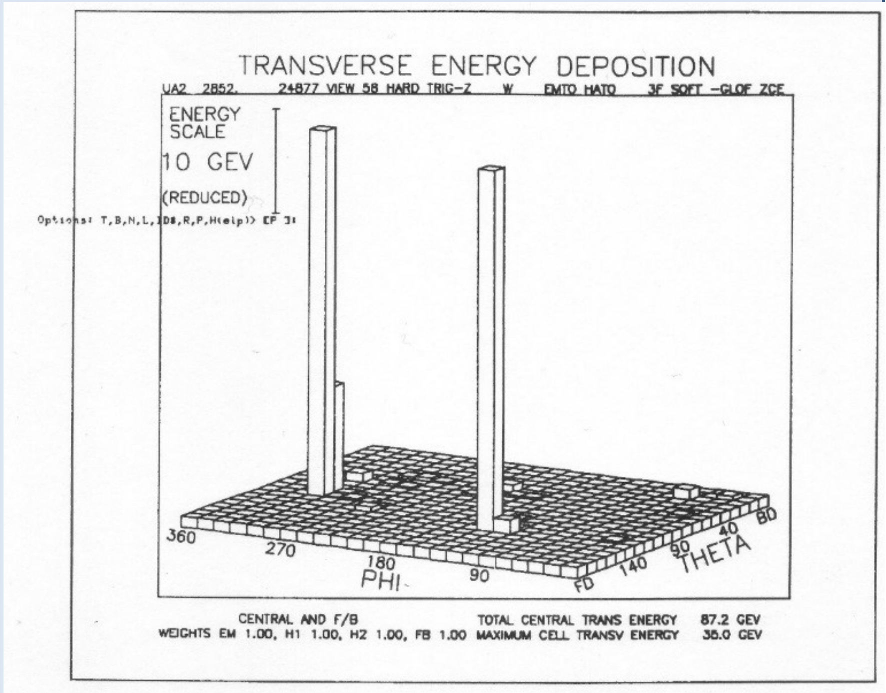
1981 **LEP was approved with a large and long (27 km) ring tunnel**

1983 **The early 1980s were crucial**

The real belief that a 'dirty' hadron collider can actually do great discovery physics came from UA1 and UA2 with their W and Z boson discoveries at CERN

Herwig Schopper
CERN DG 1981 - 1988

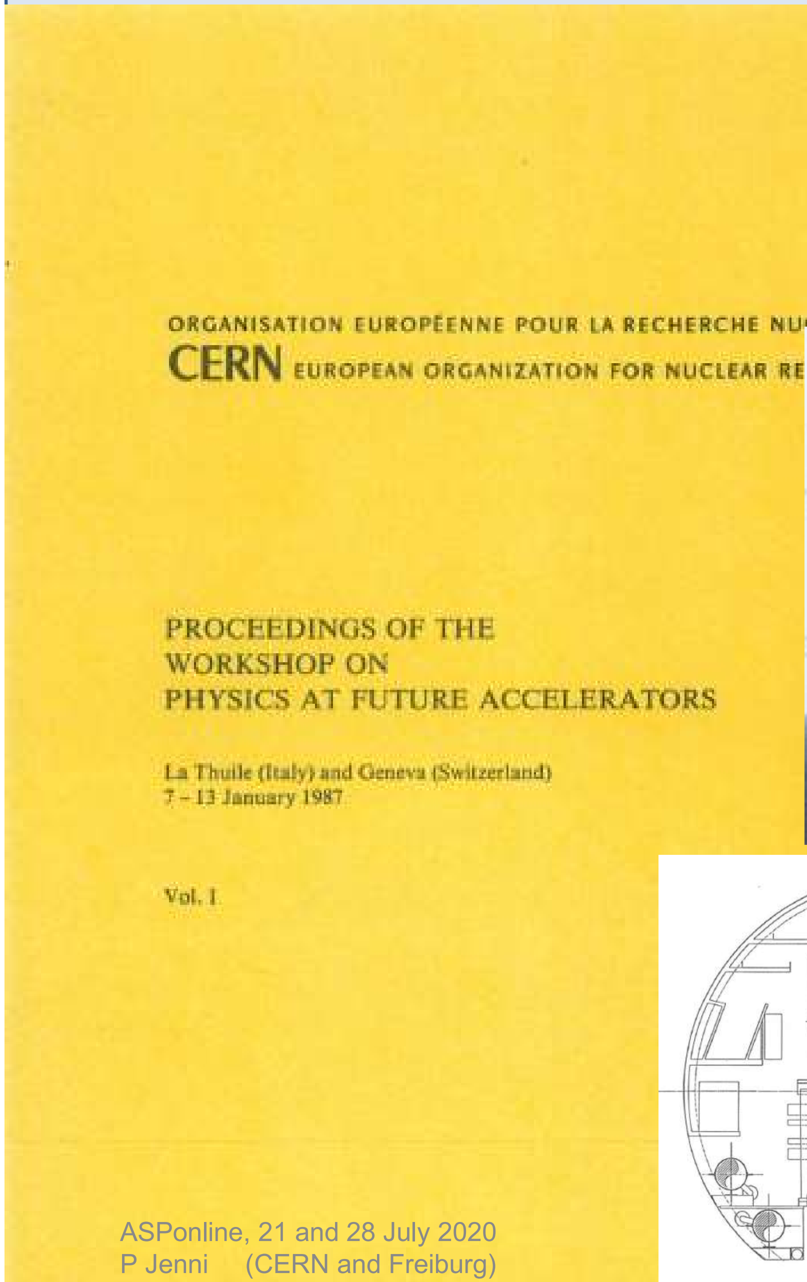
1984 For the community it all started with the CERN - ECFA Workshop in Lausanne on the feasibility of a hadron collider in the future LEP tunnel



A very early Z → ee online display from one of the detectors (UA2)

La Thuile 7 – 13 January 1987

(Carlo Rubbia’s Long Range Planning Committee)


CERN 87-07
Vol. I
4 June 1987

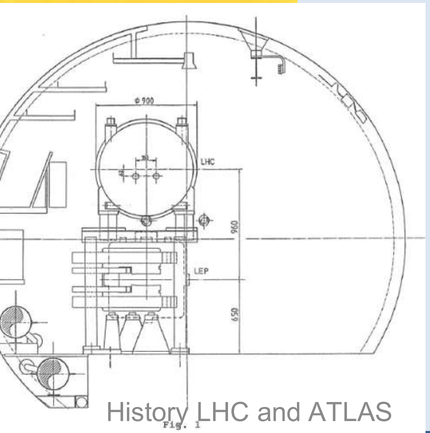
ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUC

CERN EUROPEAN ORGANIZATION FOR NUCLEAR RE

PROCEEDINGS OF THE
WORKSHOP ON
PHYSICS AT FUTURE ACCELERATORS

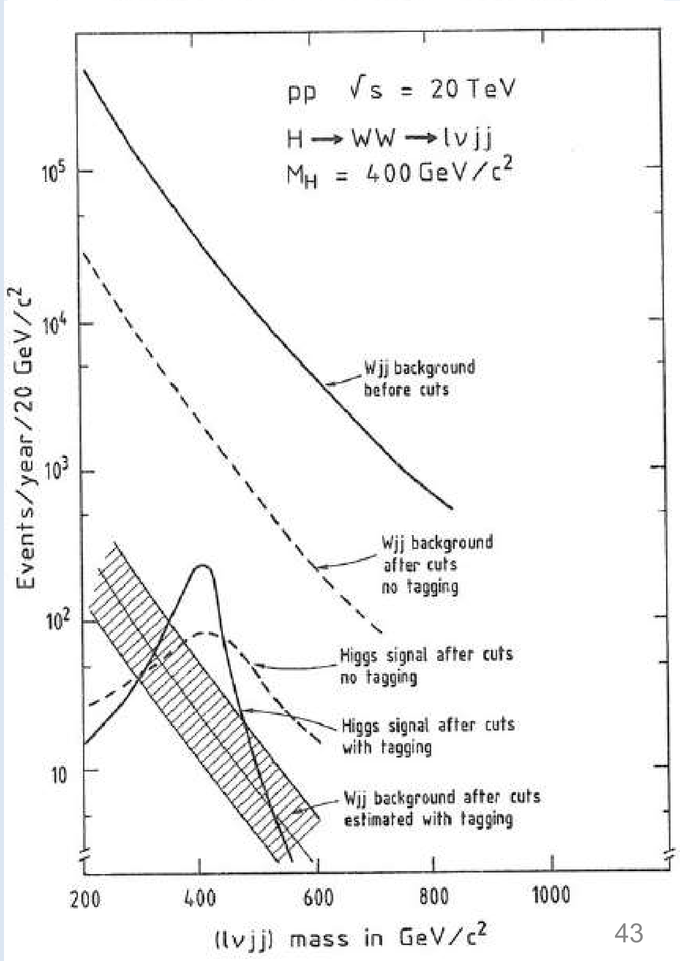
La Thuile (Italy) and Geneva (Switzerland)
7 – 13 January 1987

Vol. I

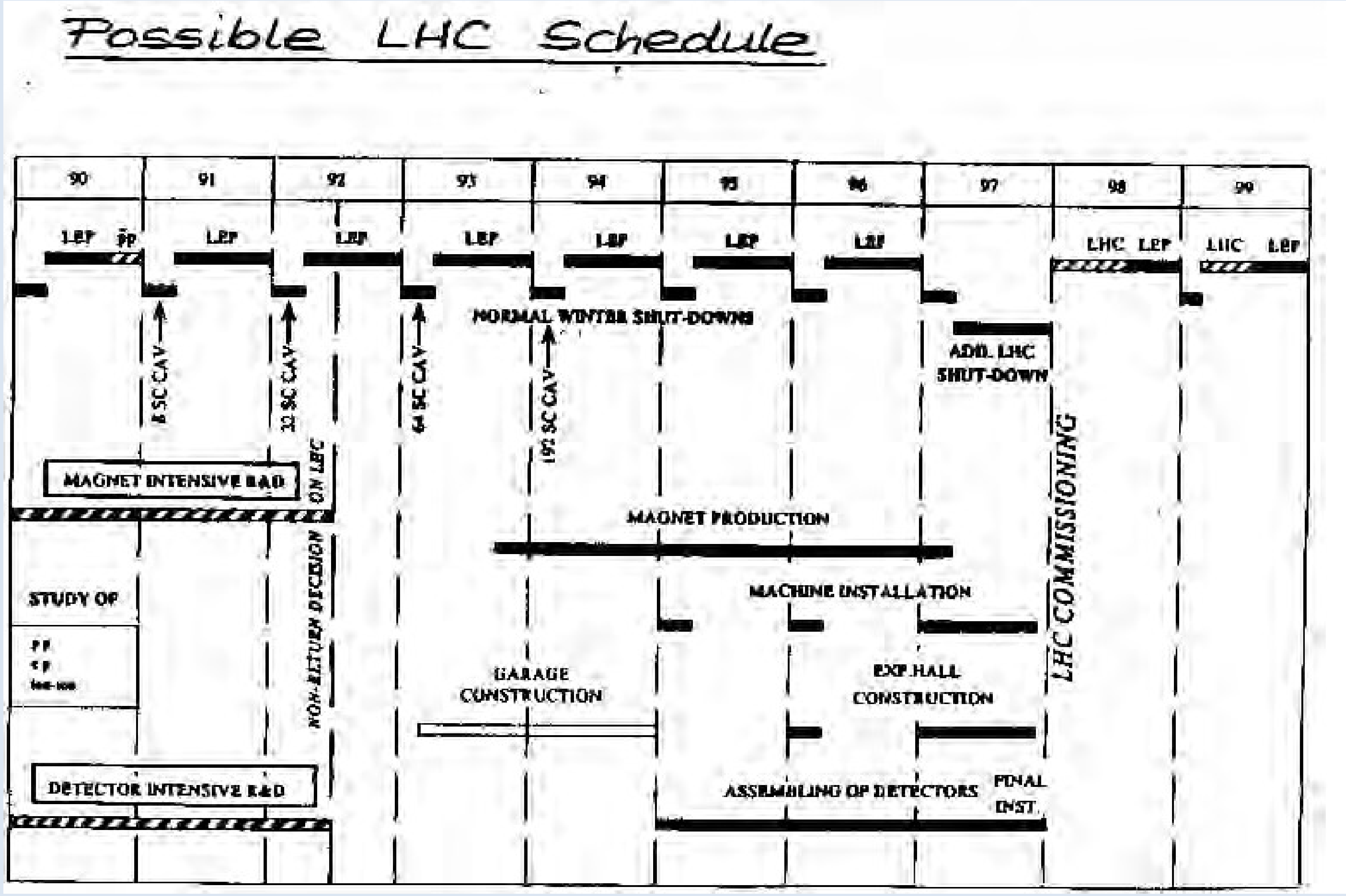


Collider parameters

Machine		$\sqrt{s}$ (TeV)	L ($cm^{-2} s^{-1}$)
LHC	pp	16	$10^{33} \rightarrow 10^{34}$
	ep	1.3	10^{32}
		1.8	10^{31}
CLIC	e^+e^-	2	$10^{33} \rightarrow 10^{34}$



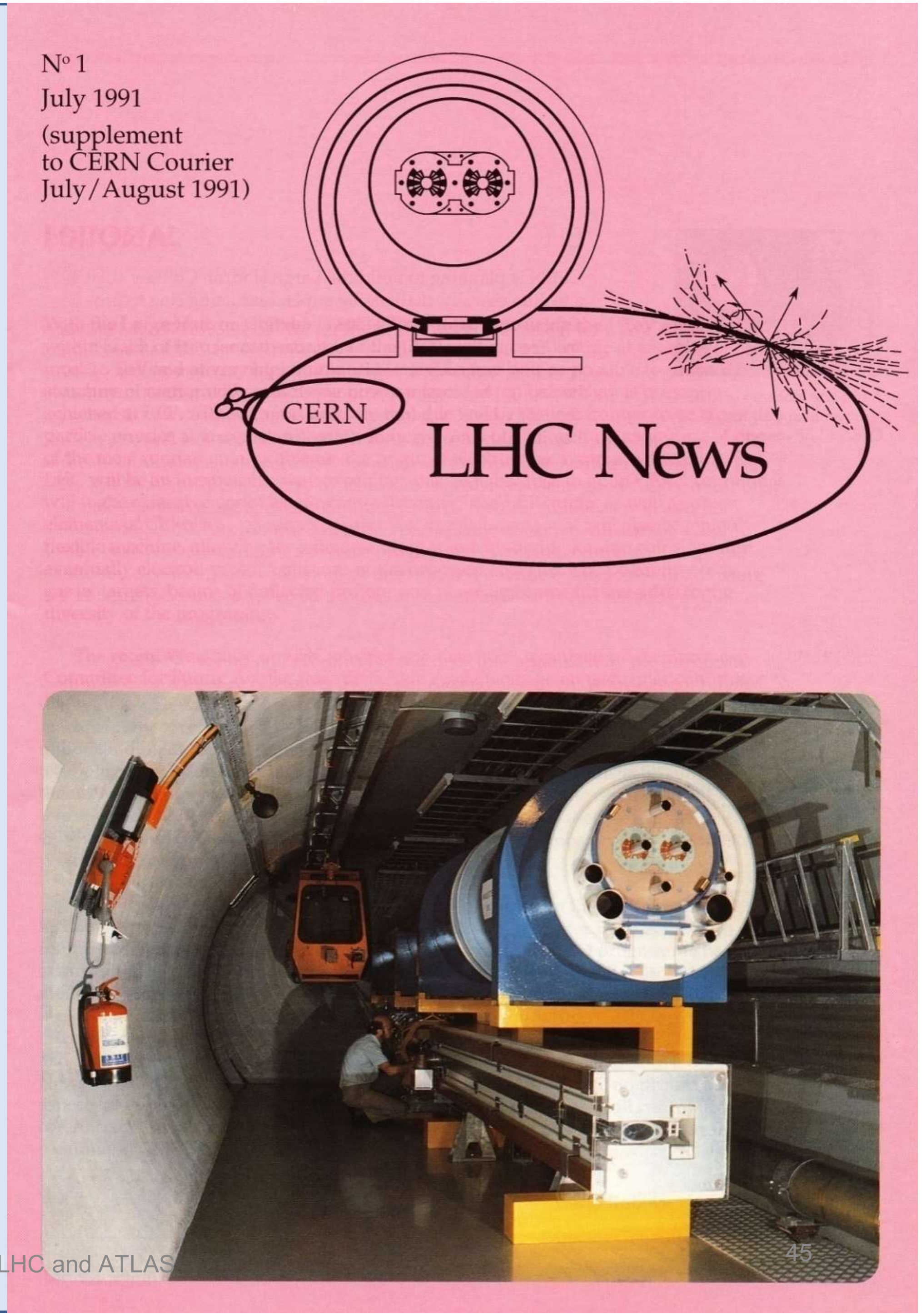
From a very early talk about the LHC, must have been around 1987 …



1991 December CERN Council:
'LHC is the right machine for advance of the subject and the future of CERN' (thanks to the great push by DG C Rubbia)

1993 December proposal of LHC with commissioning in 2002

Minister Boris Saltykov and DG Carlo Rubbia signing an updated Cooperation Agreement Russia and CERN (28 June 1993)



1994 In order to have any chance at all of approval, the idea of a staged construction was worked out by the then new CERN DG Chris Llewellyn-Smith

June 1994 Council:

Staged construction was proposed, but some countries could not yet agree, so the Council session vote was suspended until

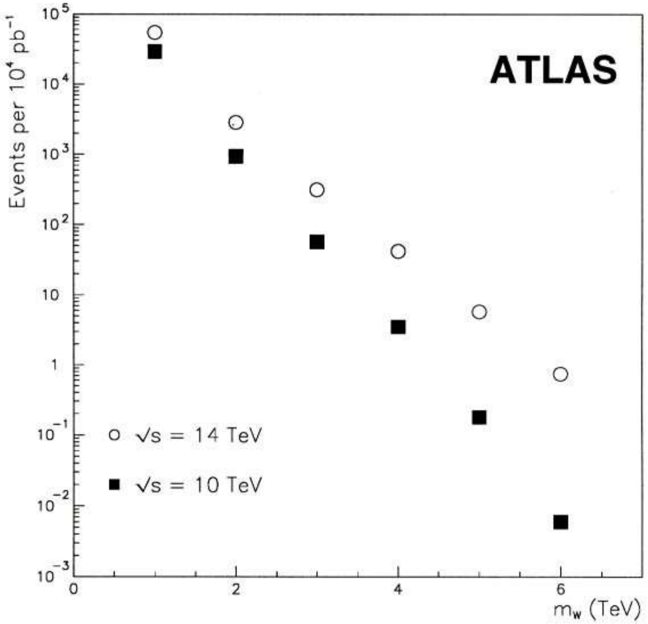
16 December 1994 Council:

Two-stage construction of LHC was approved

ATLAS provided comparisons between 10 and 14 TeV…
→ worthwhile to start with

Search for new, heavy, gauge bosons

Number of W' decays into eν or μν for 10^4 pb^{-1}



The accessible mass range is affected by both the lower energy and luminosity

The two-stage approval of LHC was understood to be modified in case sufficient CERN non-member state contributions would become available

A lot of LHC campaigns and negotiations took place in the years 1995 - 1997, including also the experiments

Japan, Russia, JINR, India, Canada and the USA were agreeing in that phase to contribute to the LHC

(Israel contributed all along to the full CERN programme and LHC)

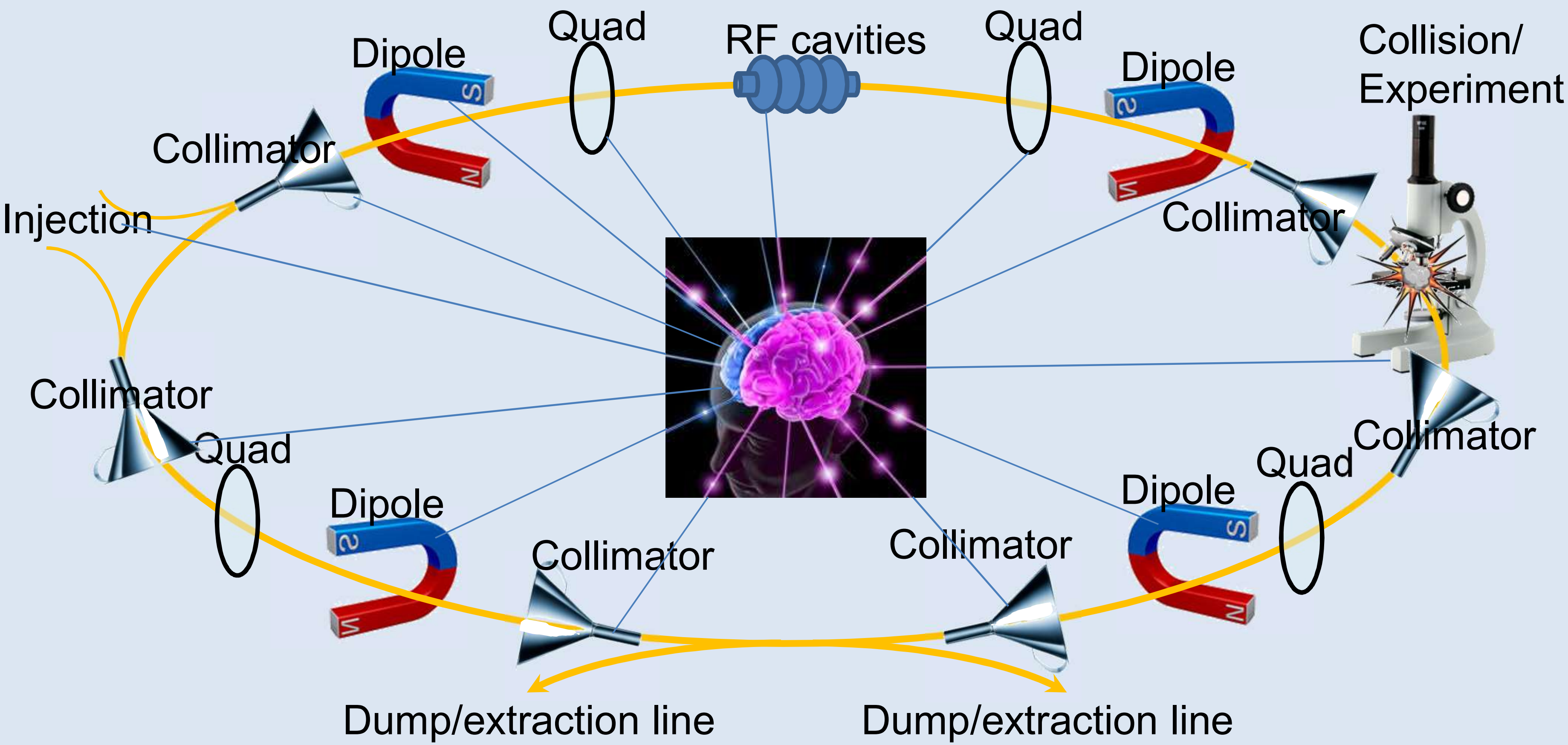
1996

December Council approved finally the single-stage 14 TeV LHC for completion in 2005

Signature of the Japan-CERN agreement on 1st June 1995

(K Yosana – Japanese Minister, H Curien – Council President, C Llewellyn-Smith – CERN DG, with the famous Daruma doll)

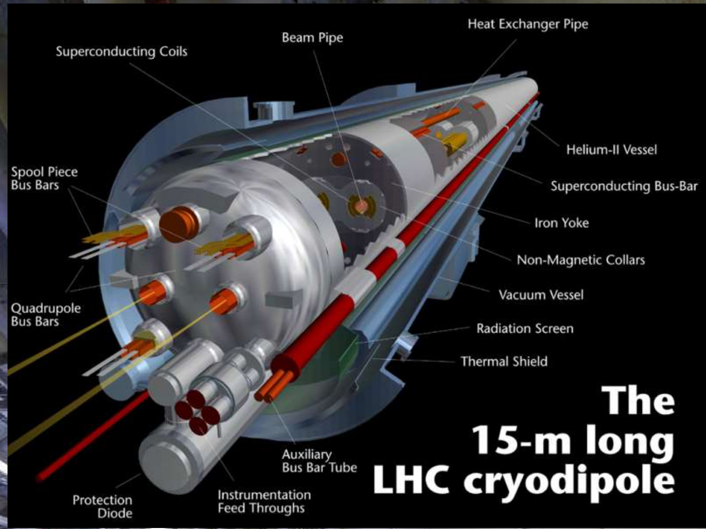
Pedagogical sketch of a hadron collider



Goal: producing the highest number of collisions at the highest energy, in the safest way…

The most challenging components were the 1232 high-tech superconducting dipole magnets

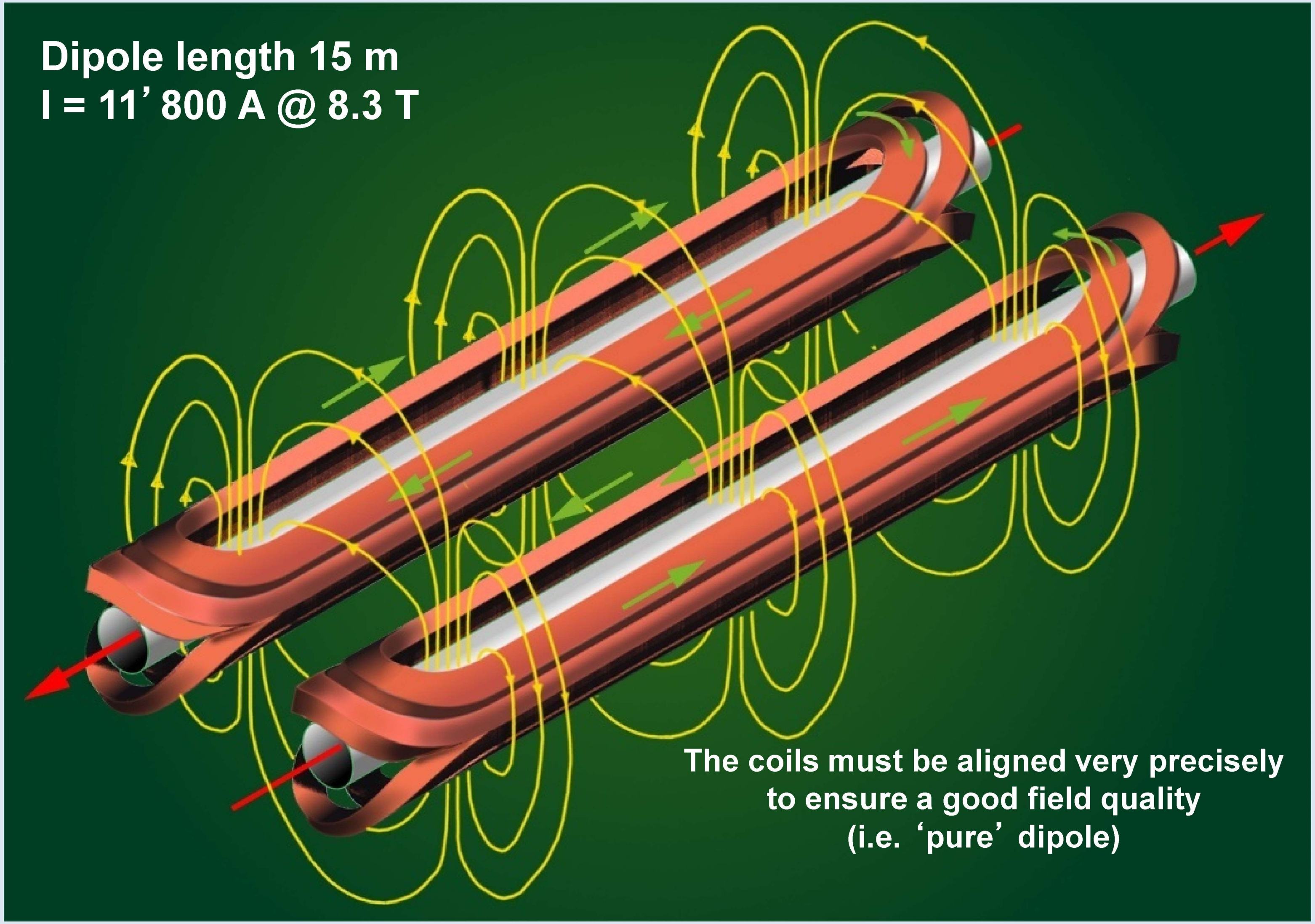
Magnetic field:	8.4 T
Operation temperature:	1.9 K
(120 tons of superfluid Helium)	
Dipole current:	11700 A
Stored energy:	7 MJ
Dipole weight:	34 tons
7600 km of Nb-Ti superconducting cable	



p(TeV) = 0.3 B(T) R(km)

LHC Construction Project Leader Lyndon Evans

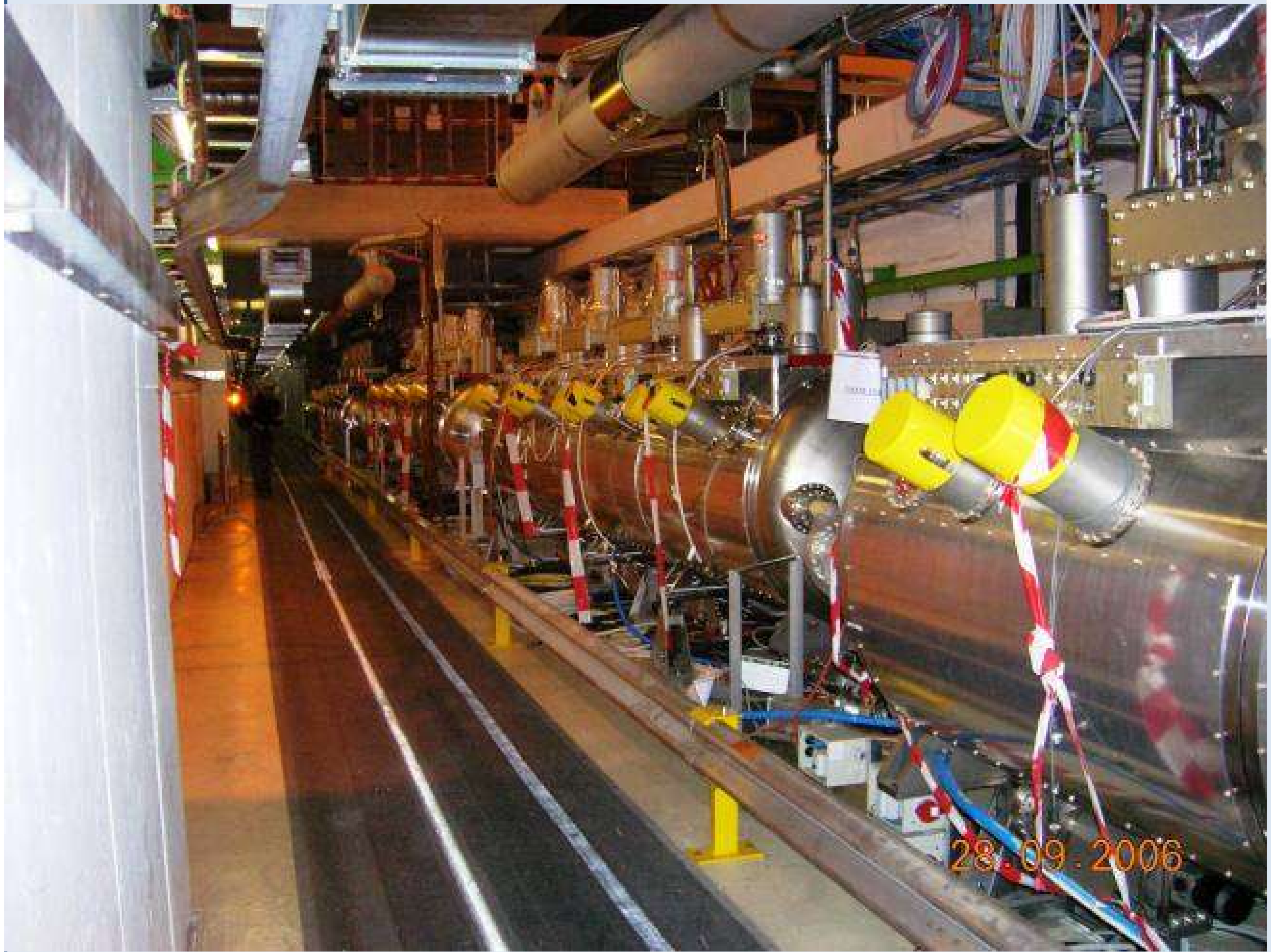
Coils in the LHC dipoles

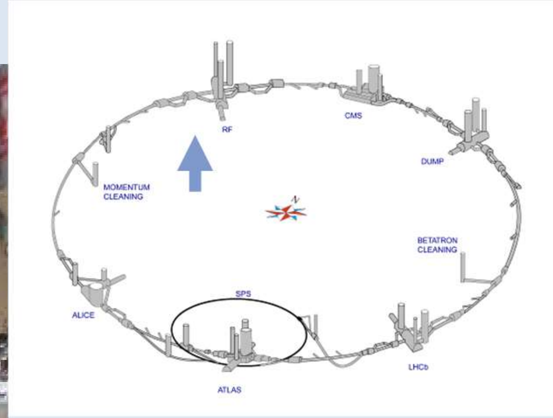


Descent of the last dipole magnet, 26 April 2007

30'000 km underground transports at a speed of 2 km/h!

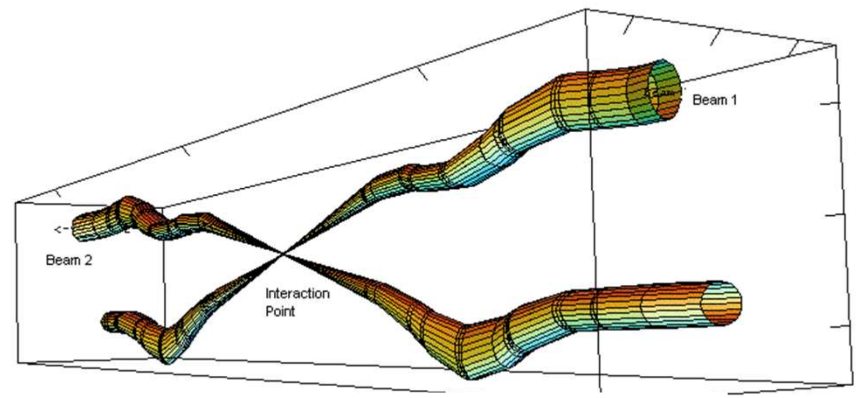
The LHC beams are accelerated by superconducting Radio-Frequency (RF) cavities





Note: The acceleration is not such a big issue in pp colliders (unlike in ring e^+e^- colliders), because of the ~ $1/m^4$ dependance of the synchrotron radiation energy losses [~ E^4_{beam}/Rm^4]

Special quadrupole magnets ('Inner Triplets') are focussing the particle beams to reach highest densities ('luminosity') at their interaction point in the centre of the experiments

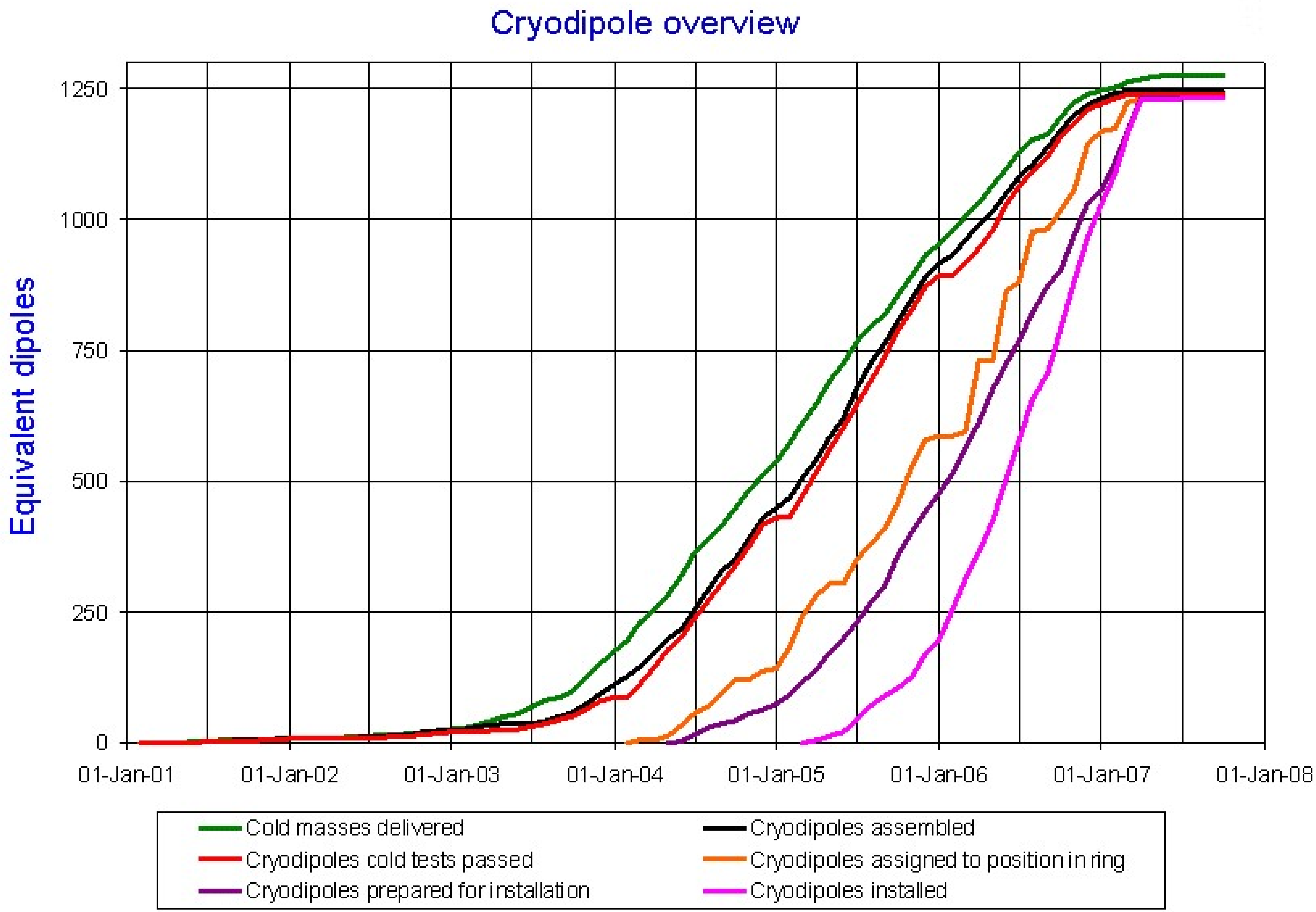


Relative beam sizes around the collision point

LHC Progress Dashboard

History of the dipole magnet construction and installation

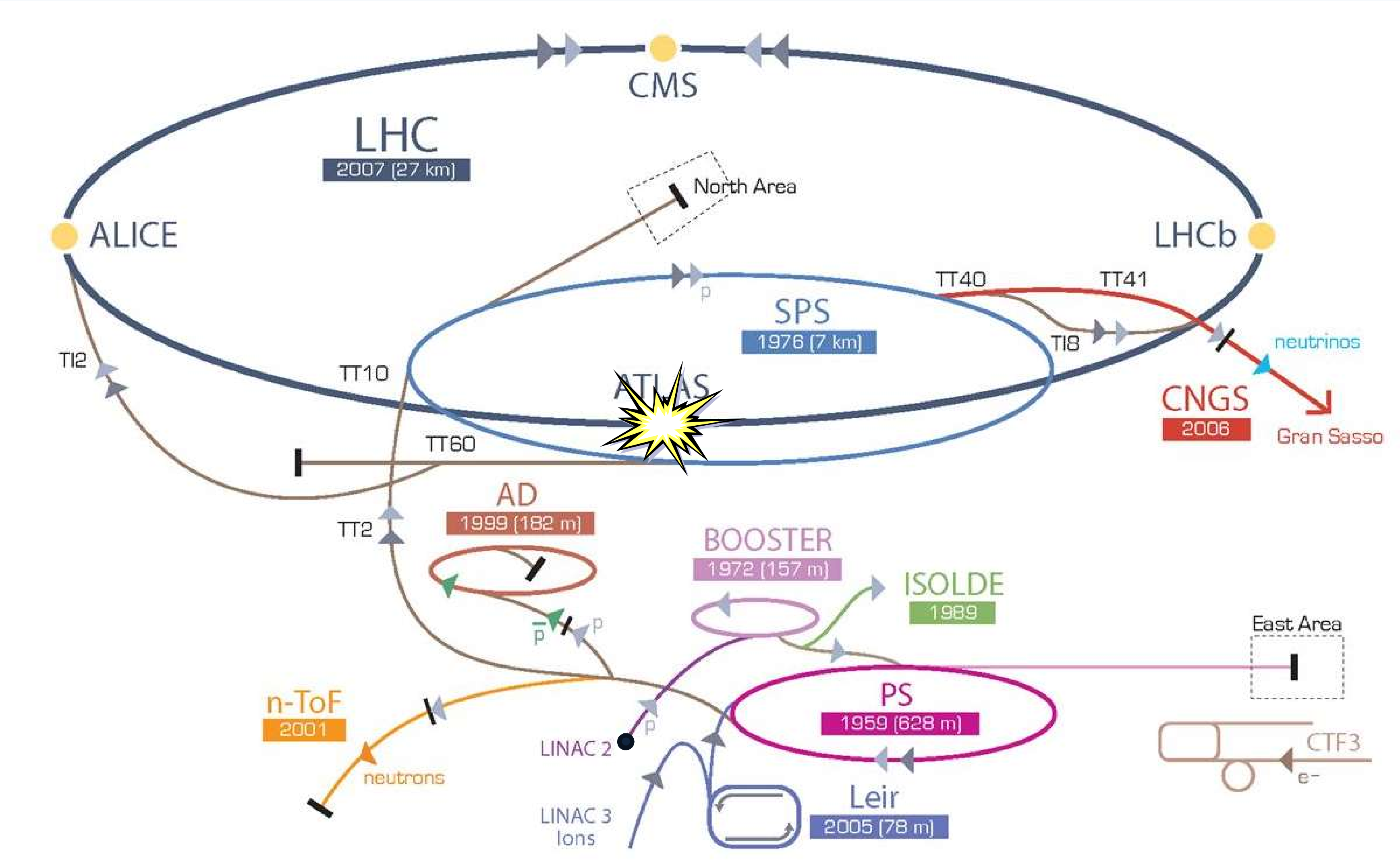
Accelerator Technology Department



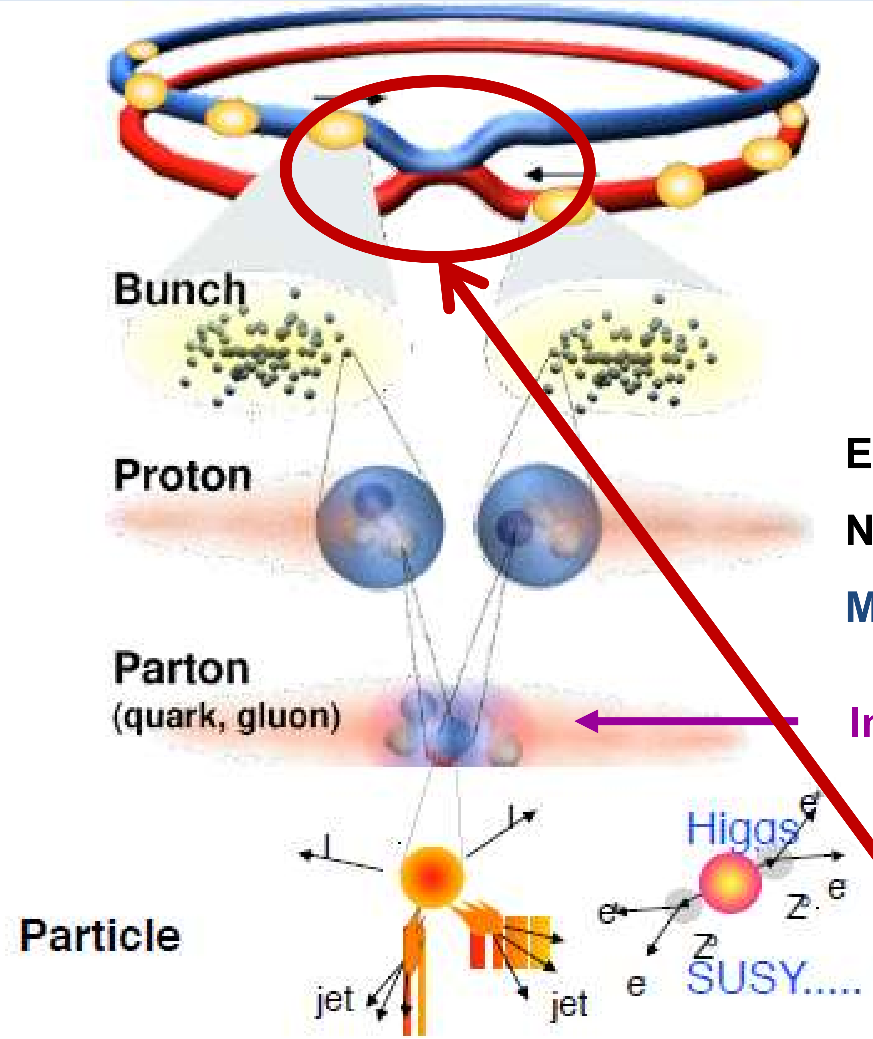
Updated 30 September 2007

Data provided by D. Tommasini AT-MCS, L. Bottura AT-MTM

CERN's particle accelerator chain



Collisions at the LHC



Proton - Proton	2808 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV ($7x10^{12}$ eV)
Luminosity	$10^{34} cm^{-2} s^{-1}$
Crossing rate	40 MHz

Event rate:

$N = L \times \sigma$ (pp) $\approx$ 10^9 interactions/s

Mostly soft (low p_T) events

Interesting hard (high-p_T) events are rare

New physics rate $\approx$ .00001 Hz

Event selection:
1 in 10,000,000,000,000

→ Interesting events are very, very rare
→ One needs highly sophisticated instruments to find them

Arguing after the mid-1980s of being ambitious and design a general purpose detector …

A very simplified summary:

detector signature	accessible physics process
$\mu^\pm$	$H \to ZZ \to 4\mu^\pm$ $Z' \to \mu^+\mu^-$ (σ_m ?)
$\mu^\pm$, jets, $\not{p}_T$	add: $H \to ZZ \to \mu^+\mu^-\nu\bar{\nu}$ $W' \to \mu^\pm\nu$ compositeness $\tilde{q}, \tilde{g}$ (direct decays) jet spectroscopy
e, $\mu^\pm$, jets, $\not{p}_T$ (non-)magnetic central part (reduced tracking)	add: 4× rate $H \to ZZ \to 4e^\pm$ 2× rate $H \to ZZ \to e^+e^-\nu\bar{\nu}$ 2× rate Z', W' $\tilde{q}, \tilde{g}$ (also cascade decays) mass resolution eμ heavy Q, L $H \to \gamma\gamma$
$e^\pm$, $\mu^\pm$, $\tau^\pm$, jets, $\not{p}_T$ full momentum and tracking	add: more redundancy and cross-checks on above, H^+, SUSY-H, heavy flavour tags

Lepton detection at LHC is crucial. Small rates are expected for many potential signals

⇒ detection of e and μ

Muons are relatively easy to identify but hard to measure well

(precise μ measurements may mean hundreds of MCHF)

Electrons are relatively easy to measure but hard to identify at 10^{34}

(radiation-hard inner detector)

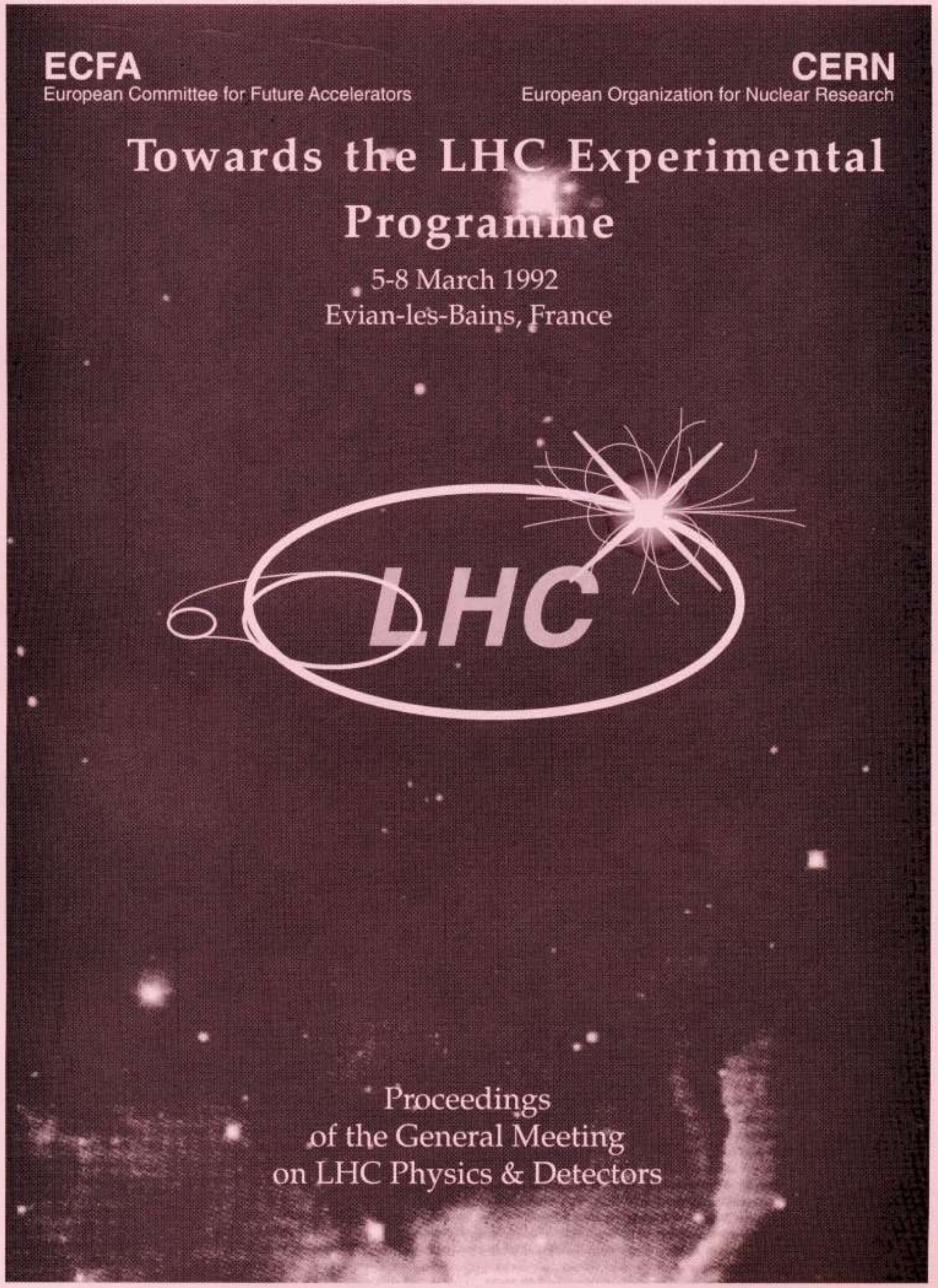
Lepton isolation criteria are also important to reject backgrounds from heavy flavour decays

March 1992

Evian Meeting with EoI presentations

ASCOT	pp	Norton
CMS	pp	Della Negra / Desportes
EAGLE	pp	PJ
L3+1	pp	Ting / Pauss

LHC Beauty Collider	Schlein
B extracted beam	Carboni
B gas jet	Nakada
Neutrino at LHC	Vannucci
LHC HI	Schukraft
DELPHI LHC HI	Jarlskog



The birth of ATLAS

March 1992 – Summer 1992

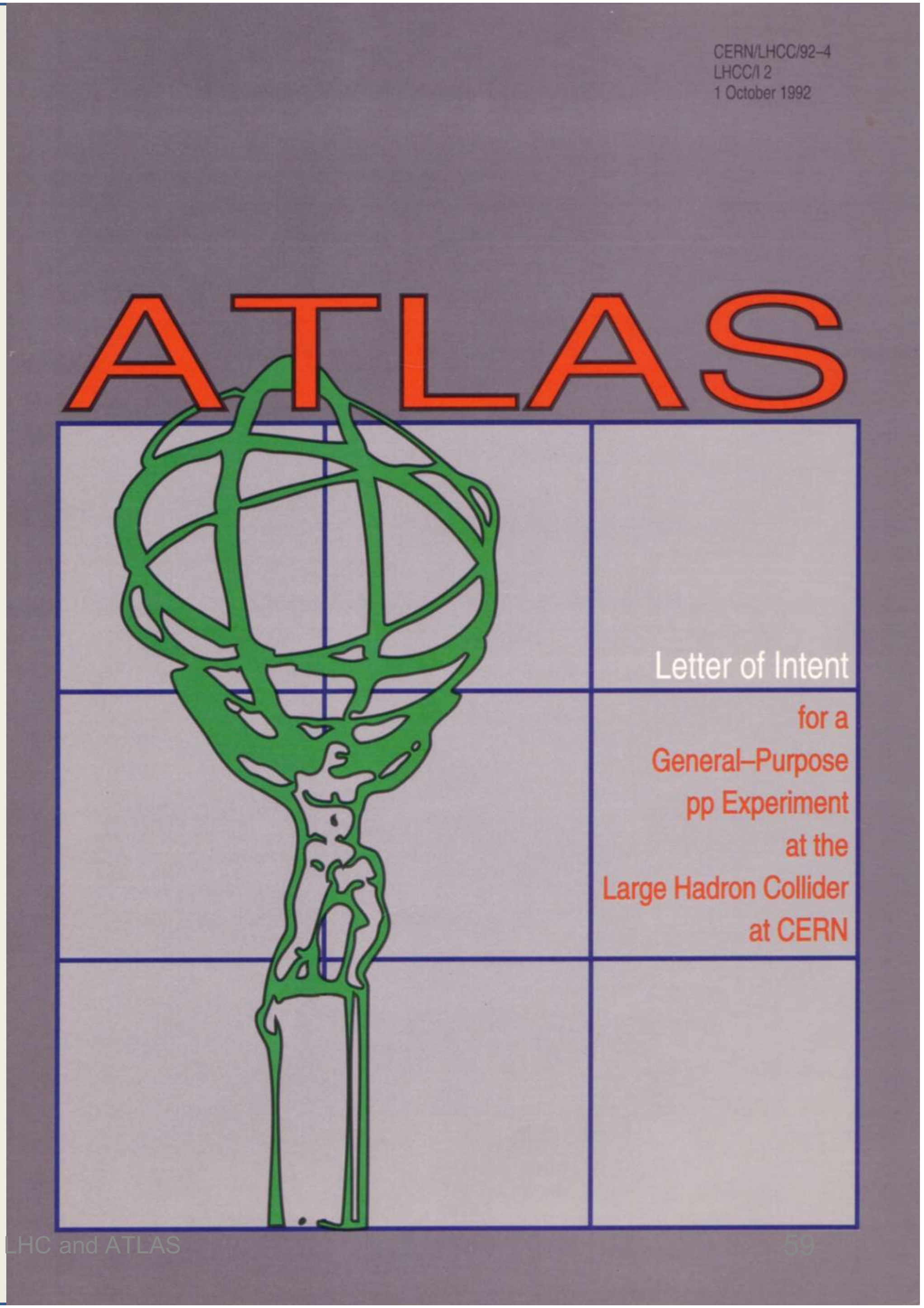
Merging of ASCOT and EAGLE

September 1992: Decision on the name taken in vote at the Collaboration Board based on many names suggested by Collaboration members

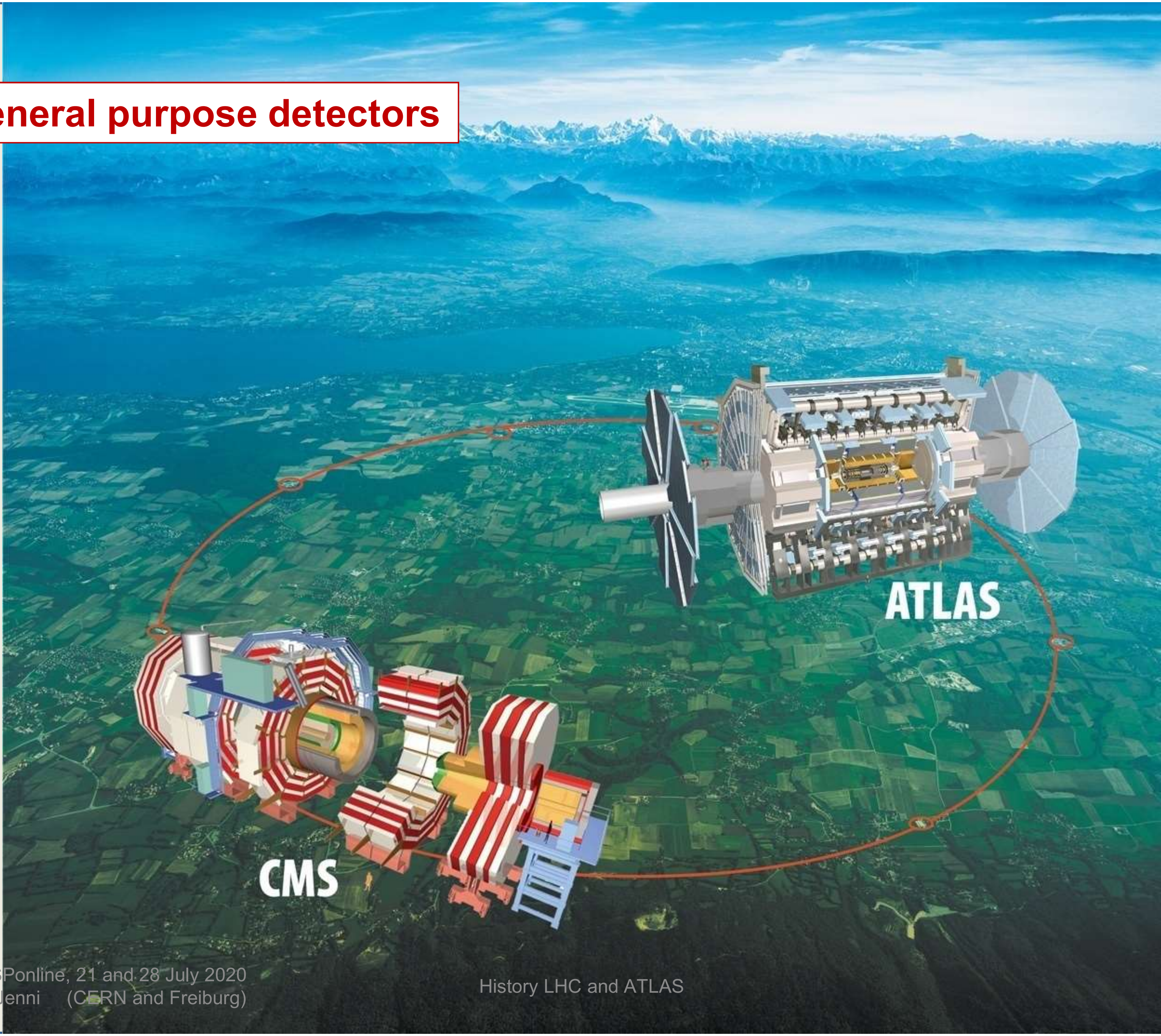
1st October 1992

ATLAS LoI submitted to the LHCC

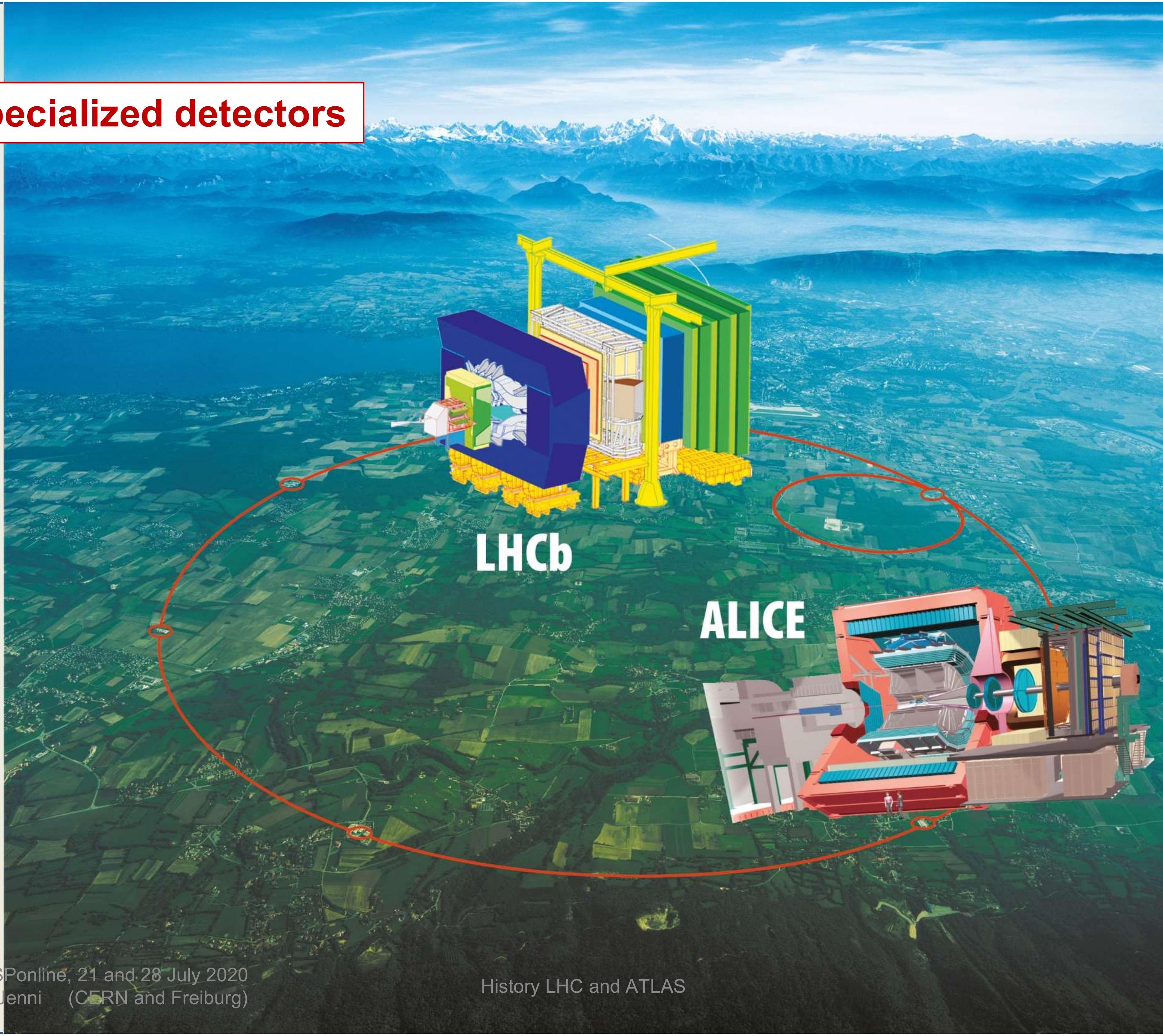
'Official birth of the ATLAS Collaboration'



General purpose detectors



Specialized detectors

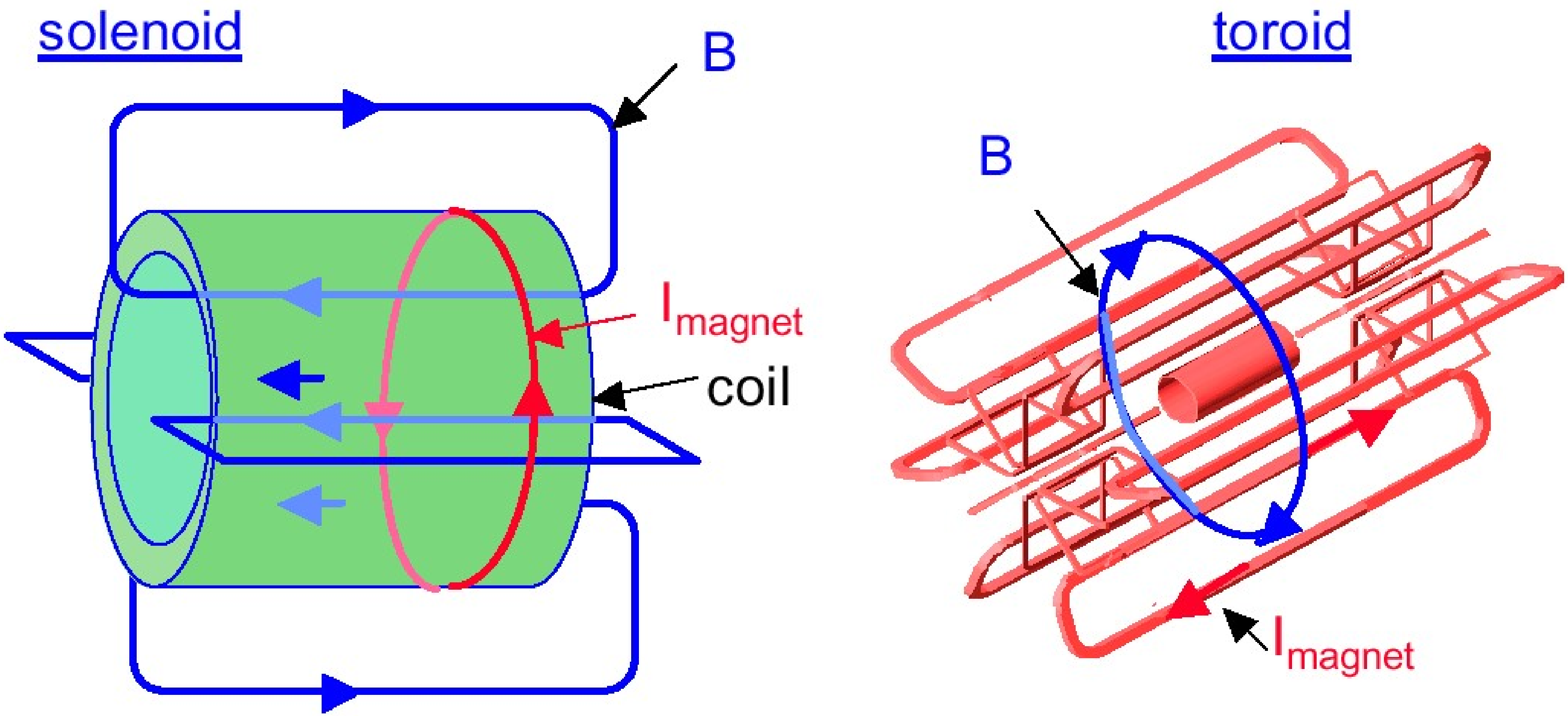


Complementary Approaches in ATLAS and CMS

	ATLAS ≡ A Toroidal LHC ApparatuS	CMS ≡ Compact Muon Solenoid
MAGNET (S)	Air-core toroids + solenoid in inner cavity (4 magnets) Calorimeters in field-free region	Solenoid Only 1 magnet Calorimeters inside field
TRACKER	Si pixels+ strips TRT $\rightarrow$ particle identification B=2T $\sigma/p_T \sim 3.8\times10^{-4}\ p_T \oplus 0.015$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5\times10^{-4}\ p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$ no longitudinal segm.
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air $\rightarrow$ $\sigma/p_T \sim 10$ % at 1 TeV standalone (~ 7% combined with tracker)	Fe $\rightarrow$ $\sigma/p_T \sim$ 15-30% at 1 TeV standalone (5% with tracker)

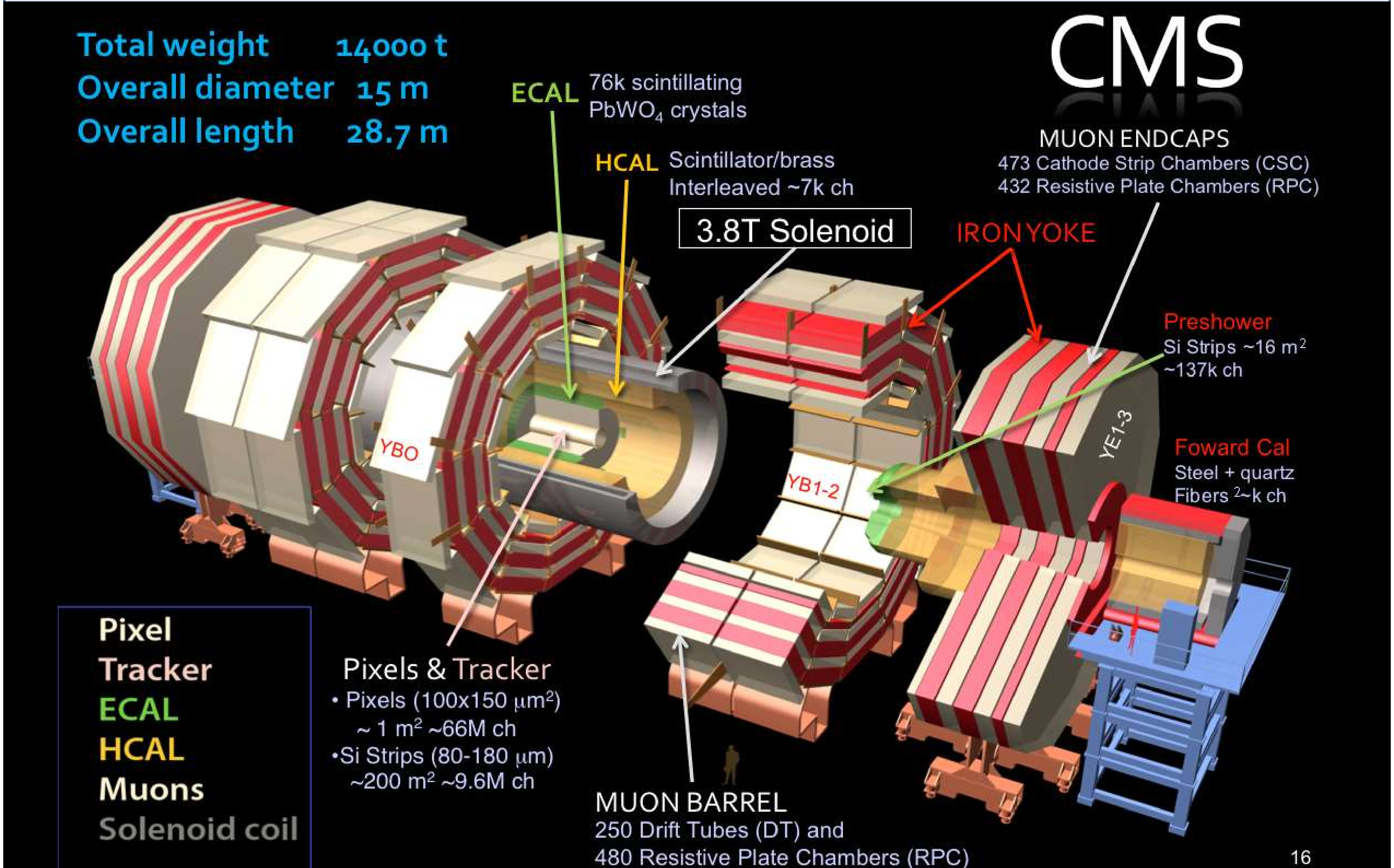
Magnetic fields

Magnetic field configurations:

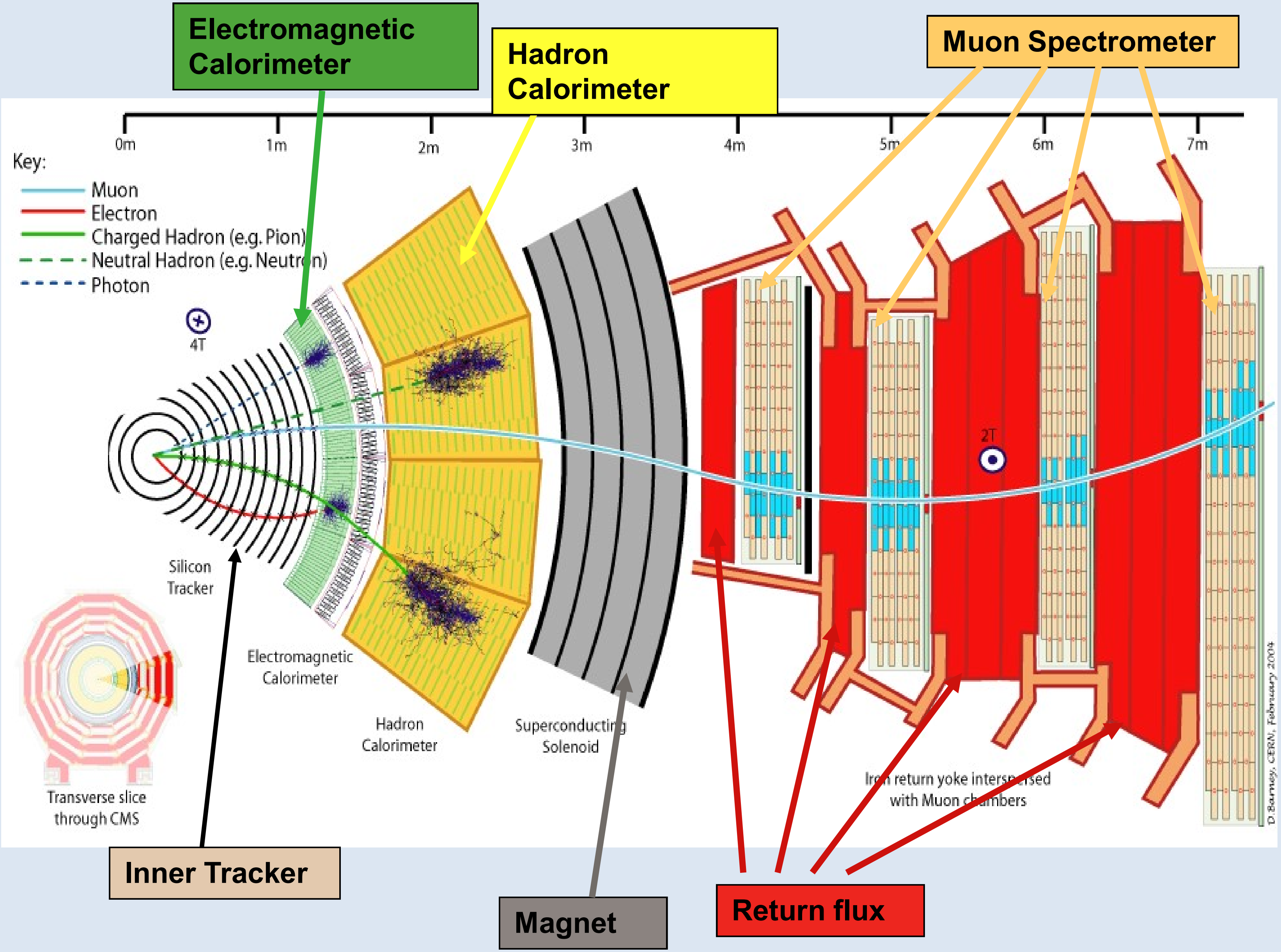


From C.Joram

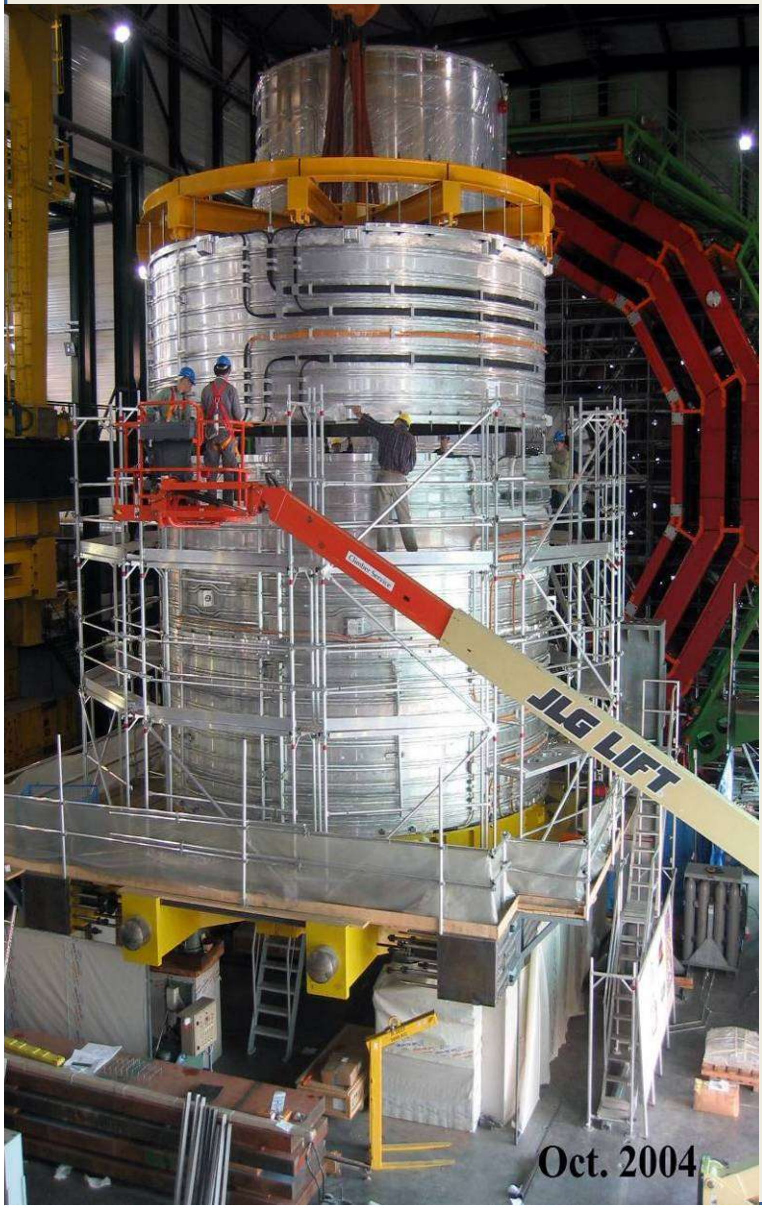
Exploded View of CMS



Main components of the CMS detector



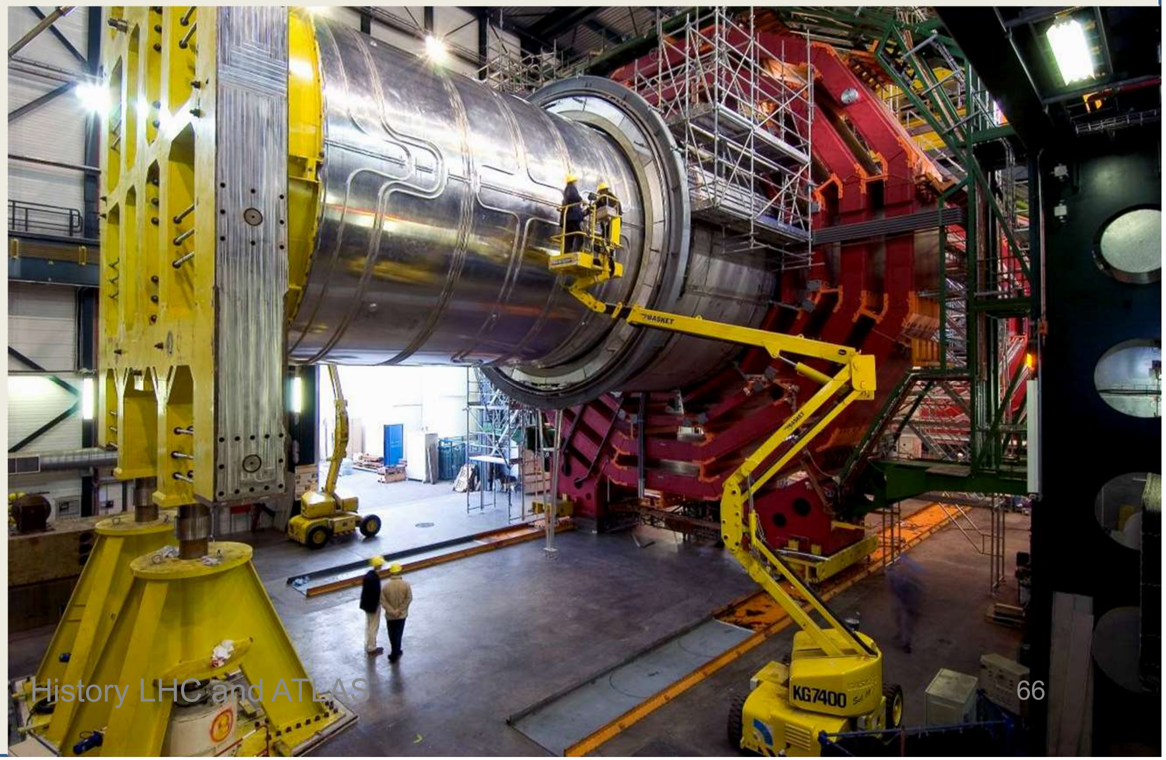
An Example of an Engineering Challenge: CMS Solenoid



CMS solenoid:

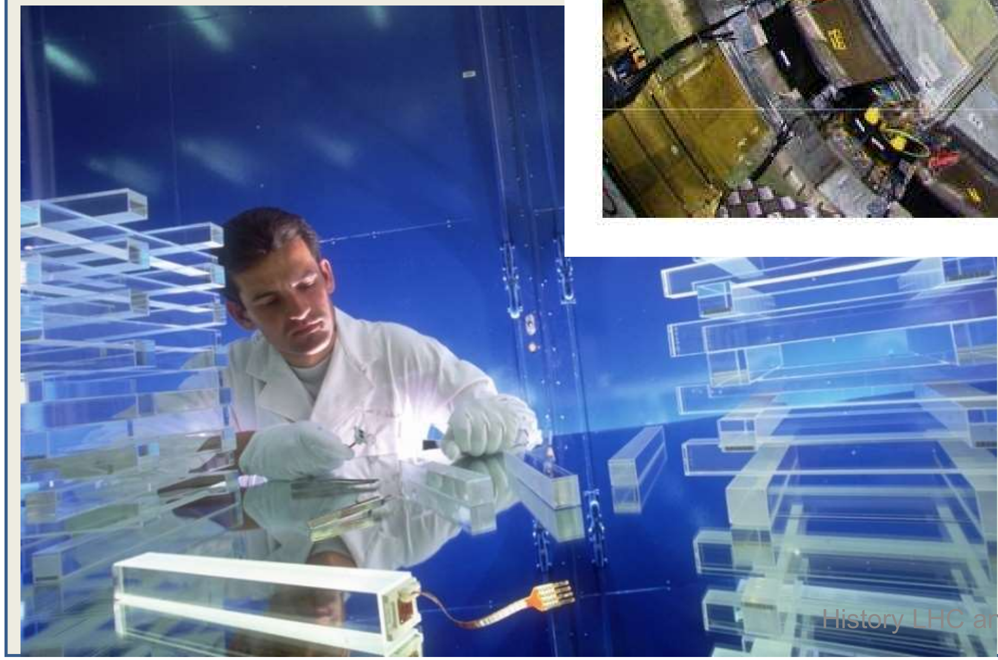
Magnetic length	12.5 m
Diameter	6 m
Magnetic field	4 T
Nominal current	20 kA
Stored energy	2.7 GJ

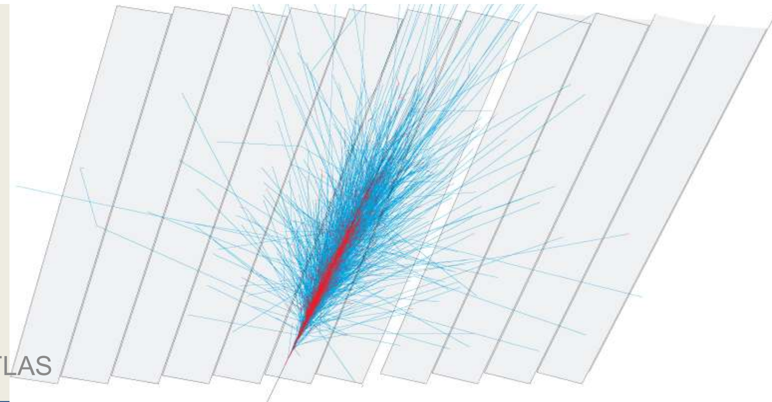
Tested at full current in Summer 2006



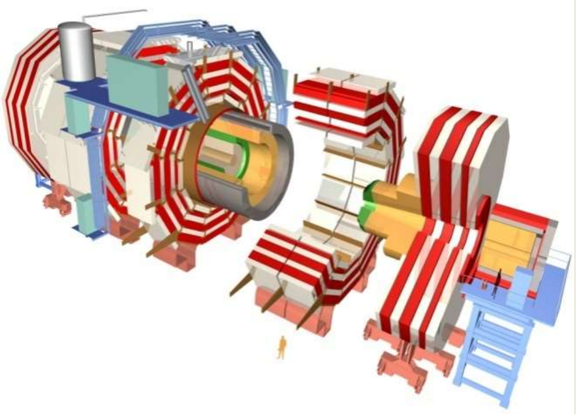
CMS Electron and Photon calorimeter: 76 000 $PbW0_4$ crystals

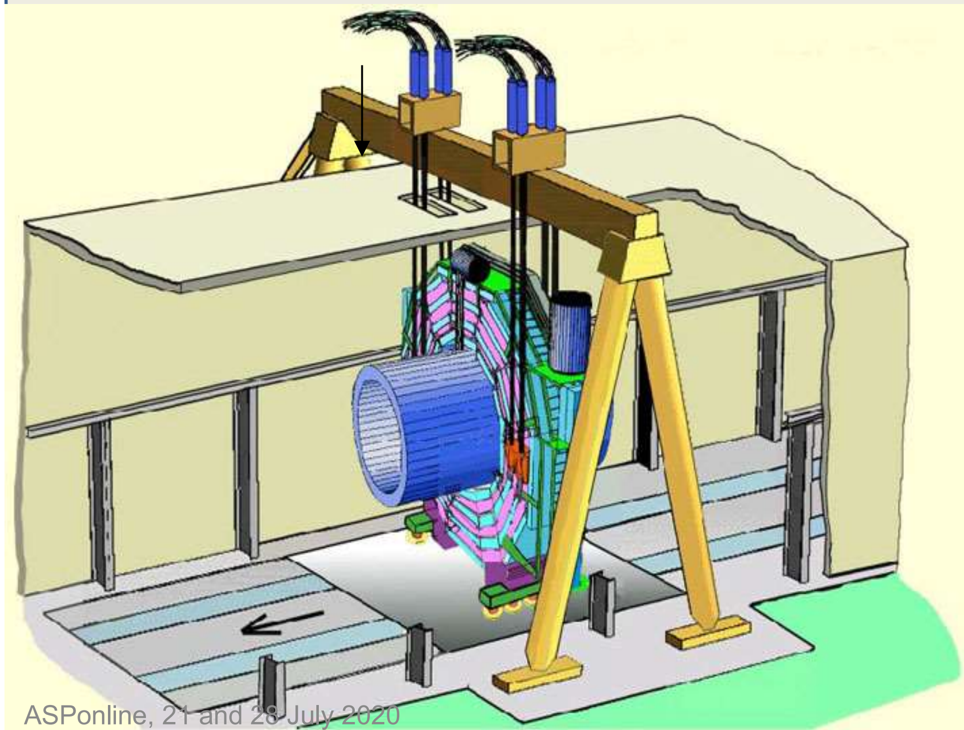
End-cap was on the critical path for many years, but it was completed just in time before final closure, a major achievement by CMS

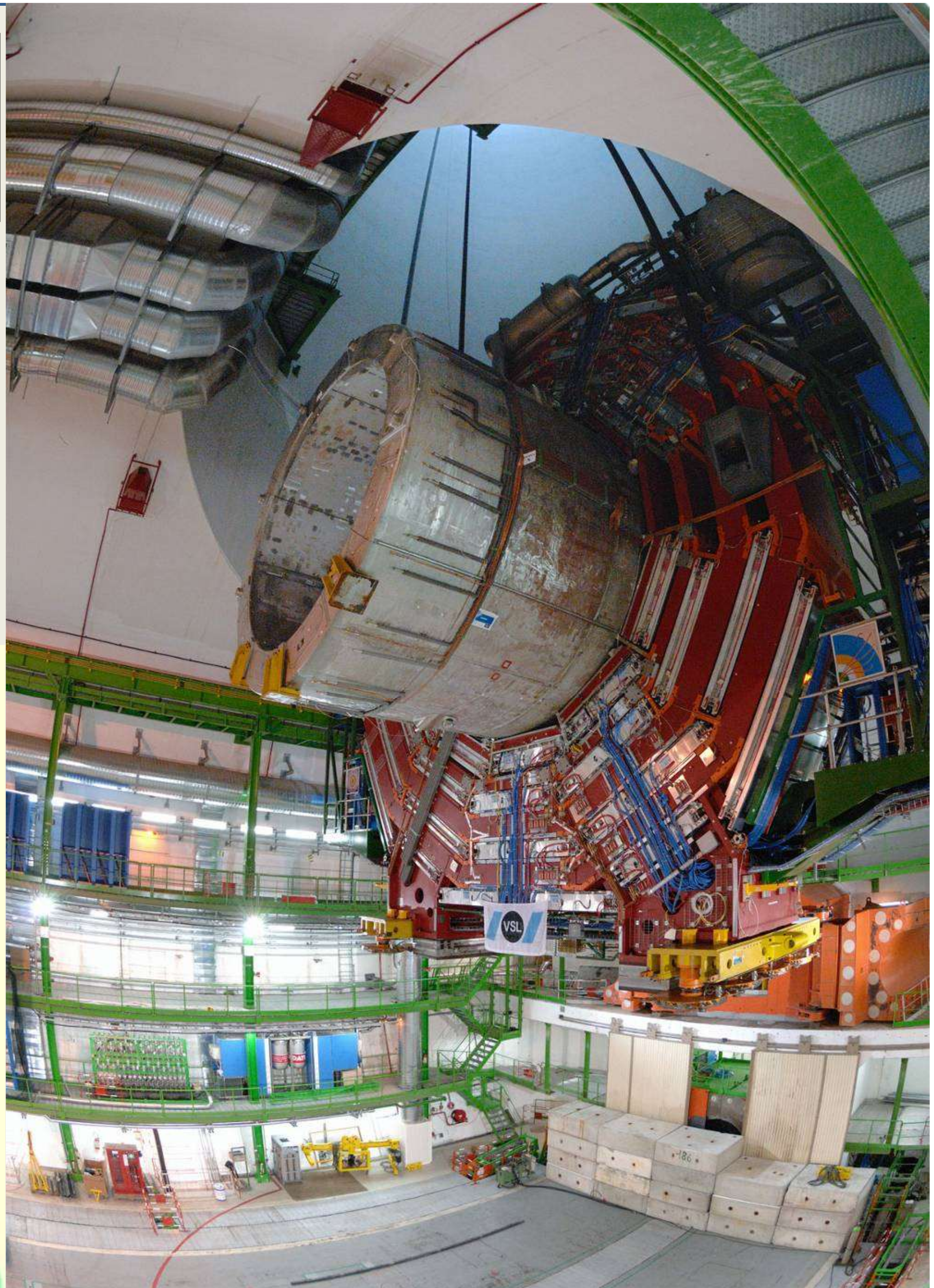




The central, heaviest slice (2000 tons) with the solenoid magnet, lowered into the underground cavern in Feb. 2007

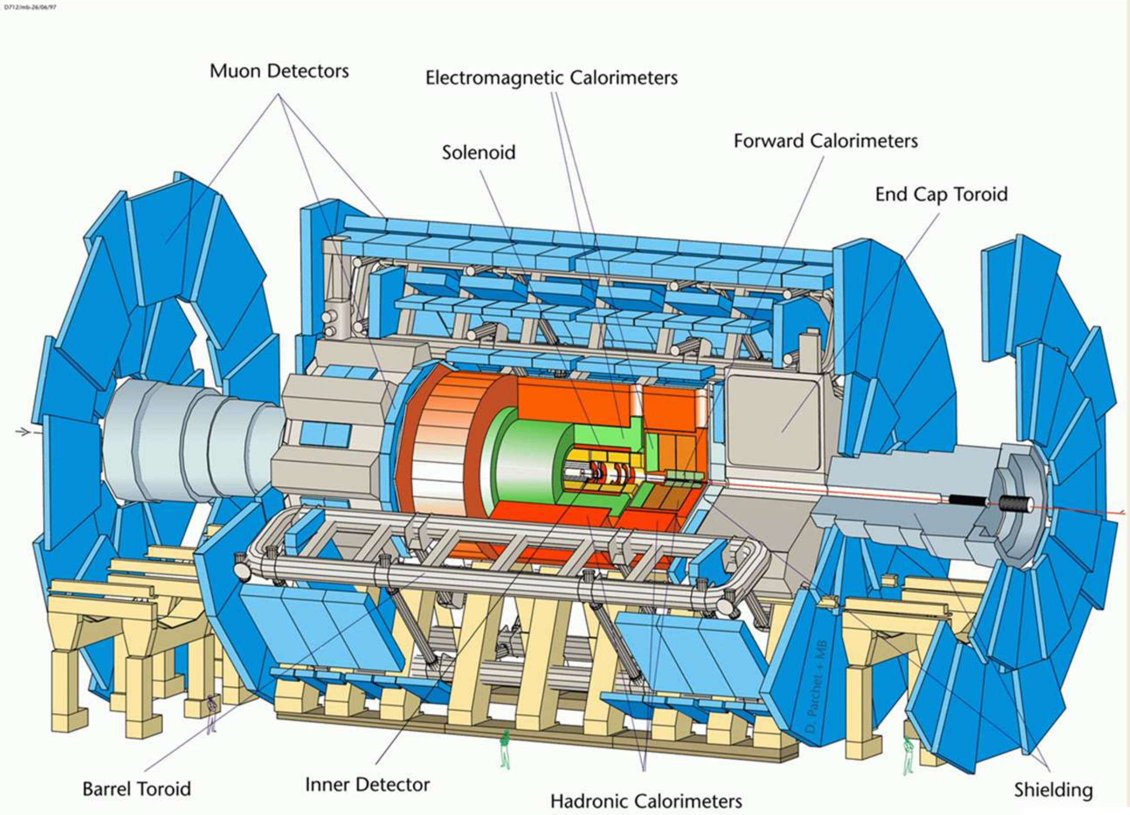






In total 15 slices were installed in this way

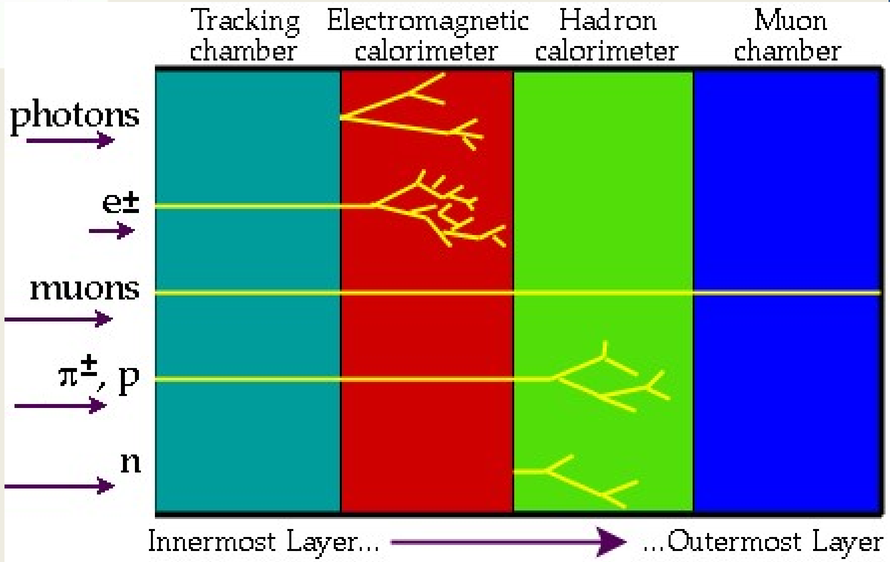
CMS before closure 2008



ATLAS

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~ 10^8 electronic channels
~ 3000 km of cables

- **Tracking ($|\eta|<2.5$, B=2T) :**
  - -- Si pixels and strips
  - -- Transition Radiation Detector (e/π separation)
- **Calorimetry ($|\eta|<5$) :**
  - -- EM : Pb-LAr
  - -- HAD: Fe/scintillator (central), Cu/W-LAr (fwd)
- **Muon Spectrometer ($|\eta|<2.7$) :**
  - -- air-core toroids with muon chambers



ATLAS Collaboration

(Status October 2019)

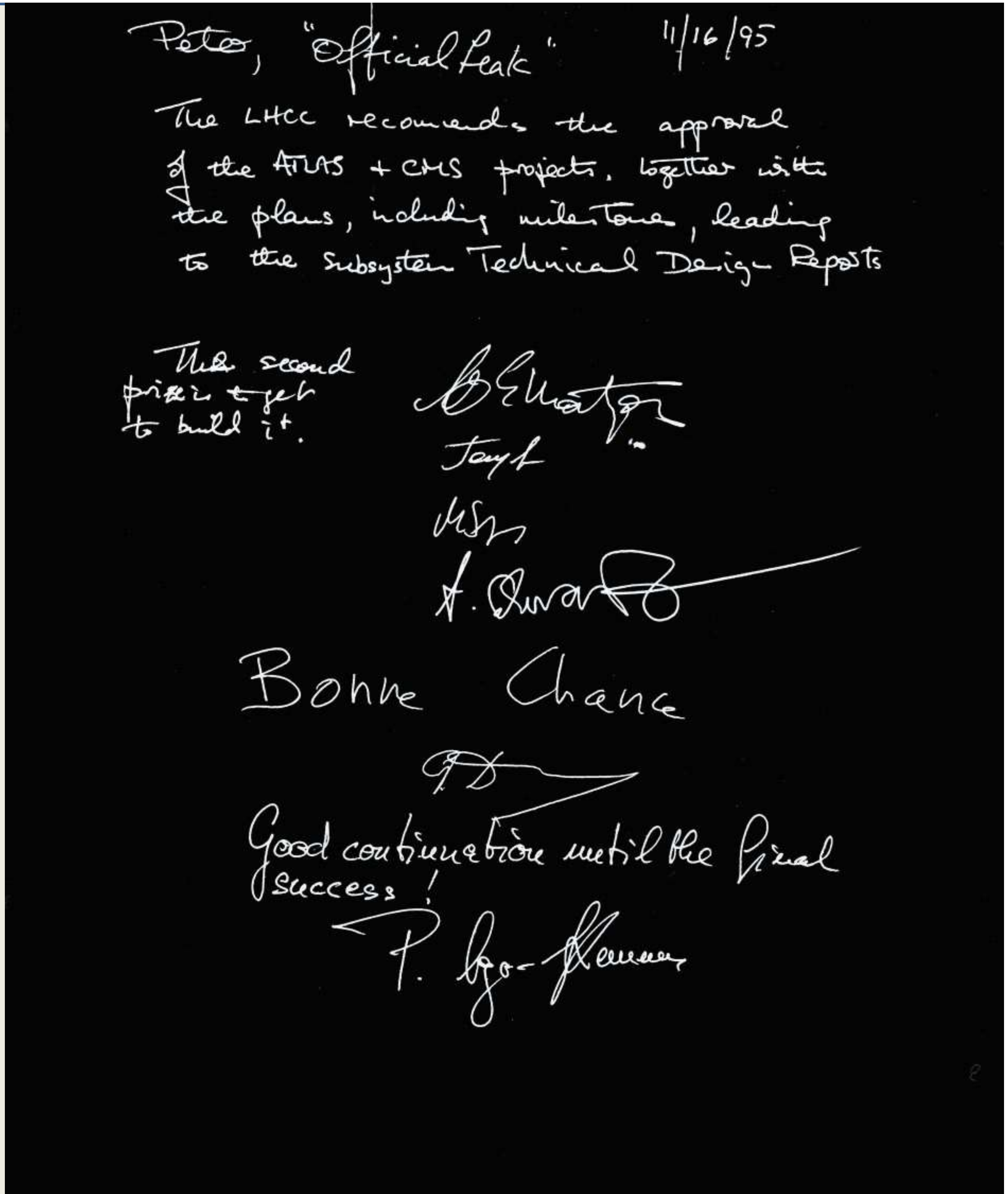
38 Countries
183 Institutions
2900 Scientific authors total
(1000 Students)

(Plus 8 Associated Technical Institutes)

Adelaide, Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizo… a, UT Arlington, UT Austin, Athens,
NTU Athens, Baku, IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, HU Berli… Birmingham, UAN Bogota, Bologna,
Bonn, Boston, Brandeis, Brazil Cluster, Bratislava/SAS Kosice, Brookhaven NL, Bu… charest, Cambridge, Carleton, CERN,
China IHEP-NJU-THU, China USTC-SDU-SJTU, Chicago, Chile, Clermo… NBI Copenhagen, Cosenza,
AGH UST Cracow, IFJ PAN Cracow, SMU Dallas, UT Dallas, NCSR De… TU Dresden, JINR Dubna, Duke,
Edinburgh, Frascati, Freiburg, Geneva, Genoa, Giessen, Glasgow… nion Haifa, Harvard, Heidelberg,
Hiroshima IT, Hong Kong, NTHU Hsinchu, Indiana, Innsb… anbul Bogazici, KEK, Kobe, Kyoto,
Kyoto UE, Kyushu, Lancaster, UN La Plata, Lecce, L… W London, RHBNC London, UC London,
Louisiana Tech, Lund, UA Madrid, Mainz, Man… usetts, MIT, Melbourne, Michigan, Michigan SU,
Milano, Minsk NAS, Minsk NCPHEP, Mo… rocco, FIAN Moscow, ITEP Moscow, MEPhI Moscow,
MSU Moscow, LMU Munich, MPI M… ples, New Mexico, New York, Nijmegen, Northern Illinois,
BINP Novosibirsk, Ohio SU, Okayama, … Olomouc, Oregon, LAL Orsay, Osaka, Oslo, Oxford, LPNHE Paris VI
and VII, Pavia, Pennsylvania, NPI Peters… gh, CAS Prague, CU Prague, TU Prague, IHEP Protvino, Rome I, Rome II,
Rome III, Rutherford Appleton Laborat… y, Santa Cruz UC, Sheffield, Shinshu, Siegen, Simon Fraser Burnaby, SLAC,
South Africa, Stockholm, KTH Stockhol… y Brook, Sydney, Sussex, AS Taipei, Tbilisi, Tel Aviv, Thessaloniki, Tokyo ICEPP,
Tokyo MU, Tokyo Tech, Tomsk, Toronto, Trento, TRIUMF, Tsukuba, Tufts, Udine/ICTP, Uppsala, UI Urbana, Valencia, UBCVancouver,
Victoria, Warwick, Waseda, Washington, Weizmann Rehovot, FH Wiener Neustadt, Wisconsin, Wuppertal, Würzburg, Yale, Yerevan

Similar world-spanning Collaboration for CMS

For the experiments it was a long way convincing the LHCC, but finally, on 16th November 1995, our referees were happy, and Hugh Montgomery, ATLAS main referee at that time, gave us the following 'official leak' from the committee…


Peter, "Official Leak" 11/16/95

The LHCC recommends the approval of the ATLAS + CMS projects, together with the plans, including milestones, leading to the Subsystem Technical Design Reports

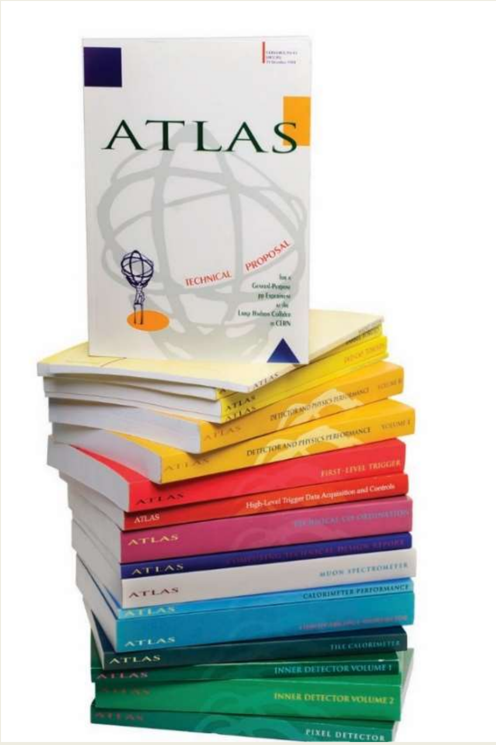
The second prize to get to build it.

Bonne Chance

Good continuation until the final success!

The LHCC recommendations meant in particular that ATLAS and CMS could now proceed in developing their series of Technical Design Reports

From 1996 onwards ATLAS entered the phase of producing Technical Design Reports for all its systems



The formal construction approval was then given with the approval of the first TDRs, namely for the calorimeters
(Note: same timeline and conditions for CMS)

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
Laboratoire Européen pour la Physique des Particules
European Laboratory for Particle Physics

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E-mail: Christopher.Llewellyn.Smith@cern.ch

Our Ref. DG/mnd/2540

Dr Peter Jenni
PPE Division
CERN

Geneva, 1st July 1997

Dear Peter,

Following the thorough discussion of the status of ATLAS and CMS by Council and its Committees two weeks ago, the way is now open for construction to begin. I am therefore pleased to inform you that I have decided to *i)* set the cost ceiling for ATLAS at 475 MCHF (1995 prices) and *ii)* approve the TDR of the ATLAS calorimeters on the following basis formulated by the LHCC and endorsed by the Research Board at its meeting on 12th June:

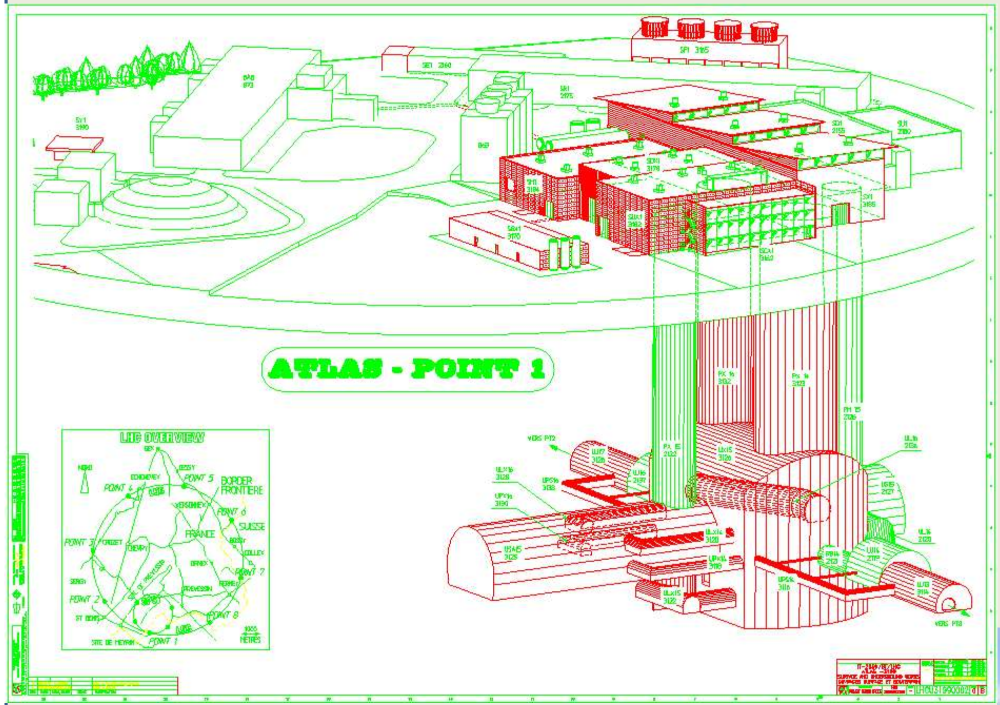
*"The LHCC **recommends general approval** of the ATLAS Calorimetry Technical Design Report describing design, performance, construction, and installation in 2004. The review **identified some concerns** in limited areas, which require resolution (LHCC 97–27). The LHCC considers that the schedules and milestones given in the TDR are reasonable, and these will be used by the committee to measure and regulate the future progress of the project."*

Yours sincerely,

Chris

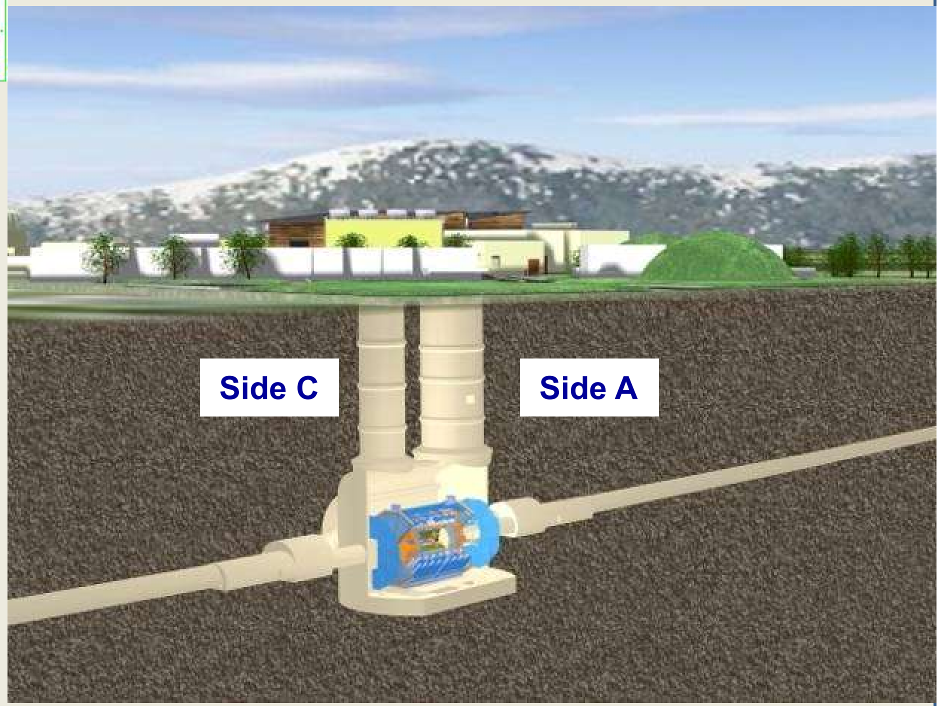
Chris Llewellyn Smith

cc: L Foà
E Iarocci



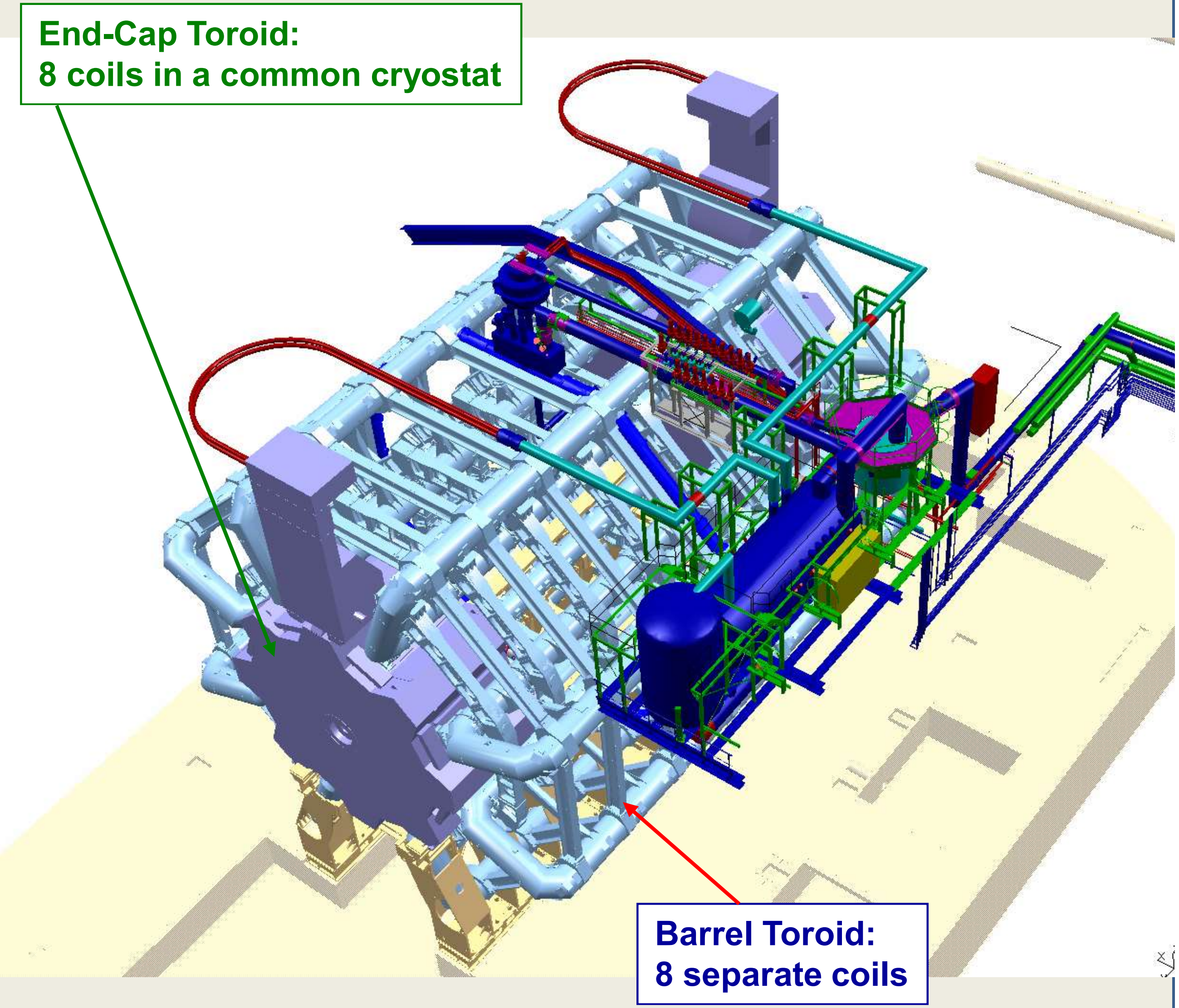
The Underground Cavern at Point-1 for the ATLAS Detector
(excavation started in 1998)

Length = 55 m
Width = 32 m
Height = 35 m



LHC Point 1 - UX 15 Cavern - Concrete walls 6th lift - 20-02-2003 - CERN ST-CE

ATLAS Toroid Magnet System



Barrel Toroid parameters

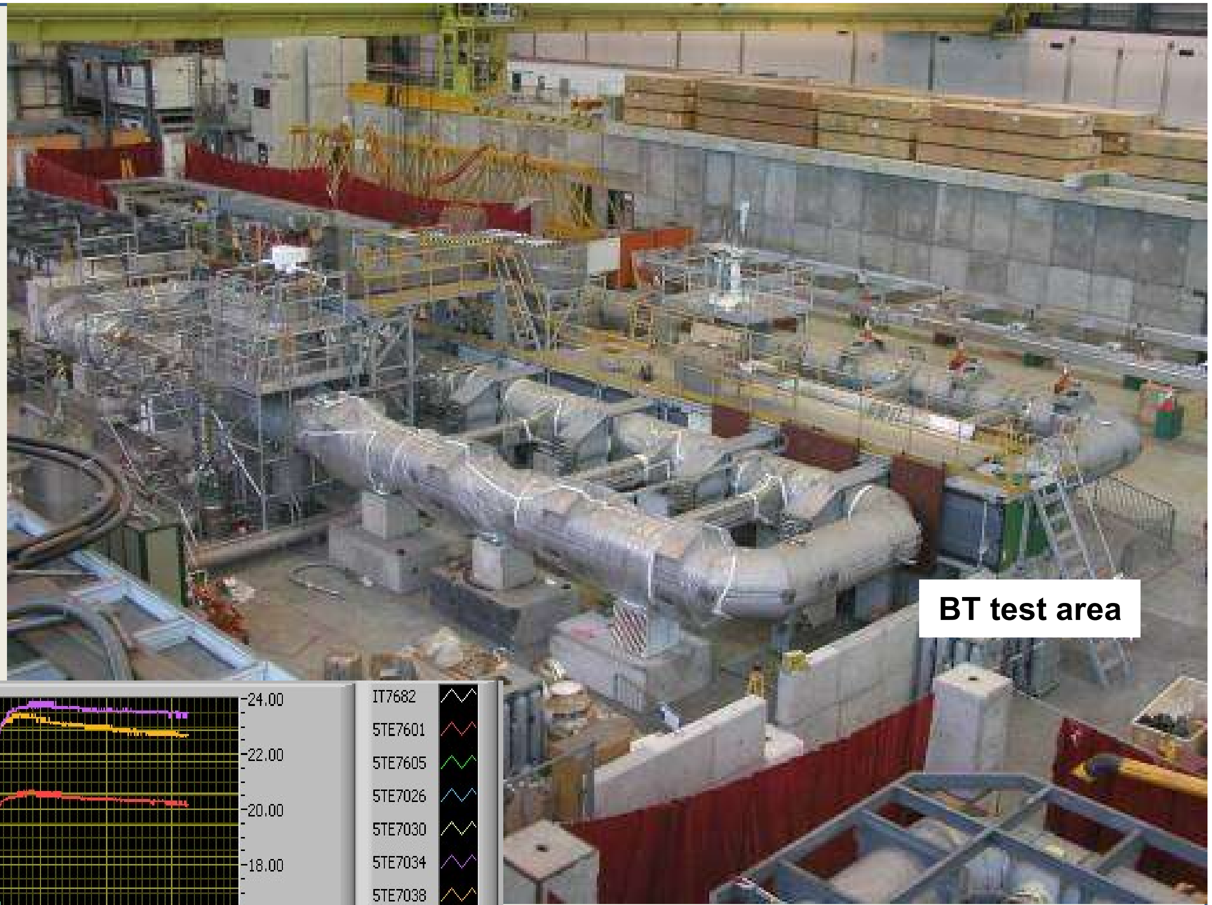
25.3 m length
20.1 m outer diameter
8 coils
1.08 GJ stored energy
370 tons cold mass
830 tons weight
4 T on superconductor
56 km Al/NbTi/Cu conductor
20.5 kA nominal current
4.7 K working point

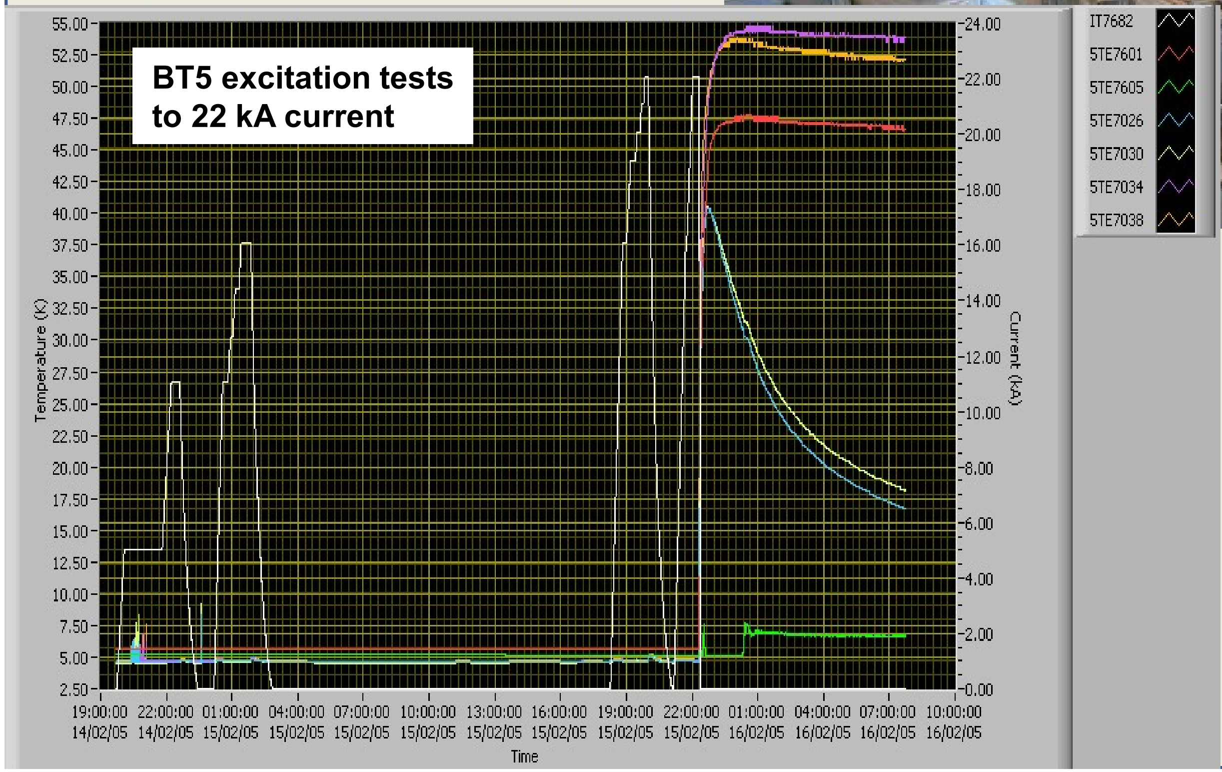
End-Cap Toroid parameters

5.0 m axial length
10.7 m outer diameter
2x8 coils
2x0.25 GJ stored energy
2x160 tons cold mass
2x240 tons weight
4 T on superconductor
2x13 km Al/NbTi/Cu conductor
20.5 kA nominal current
4.7 K working point

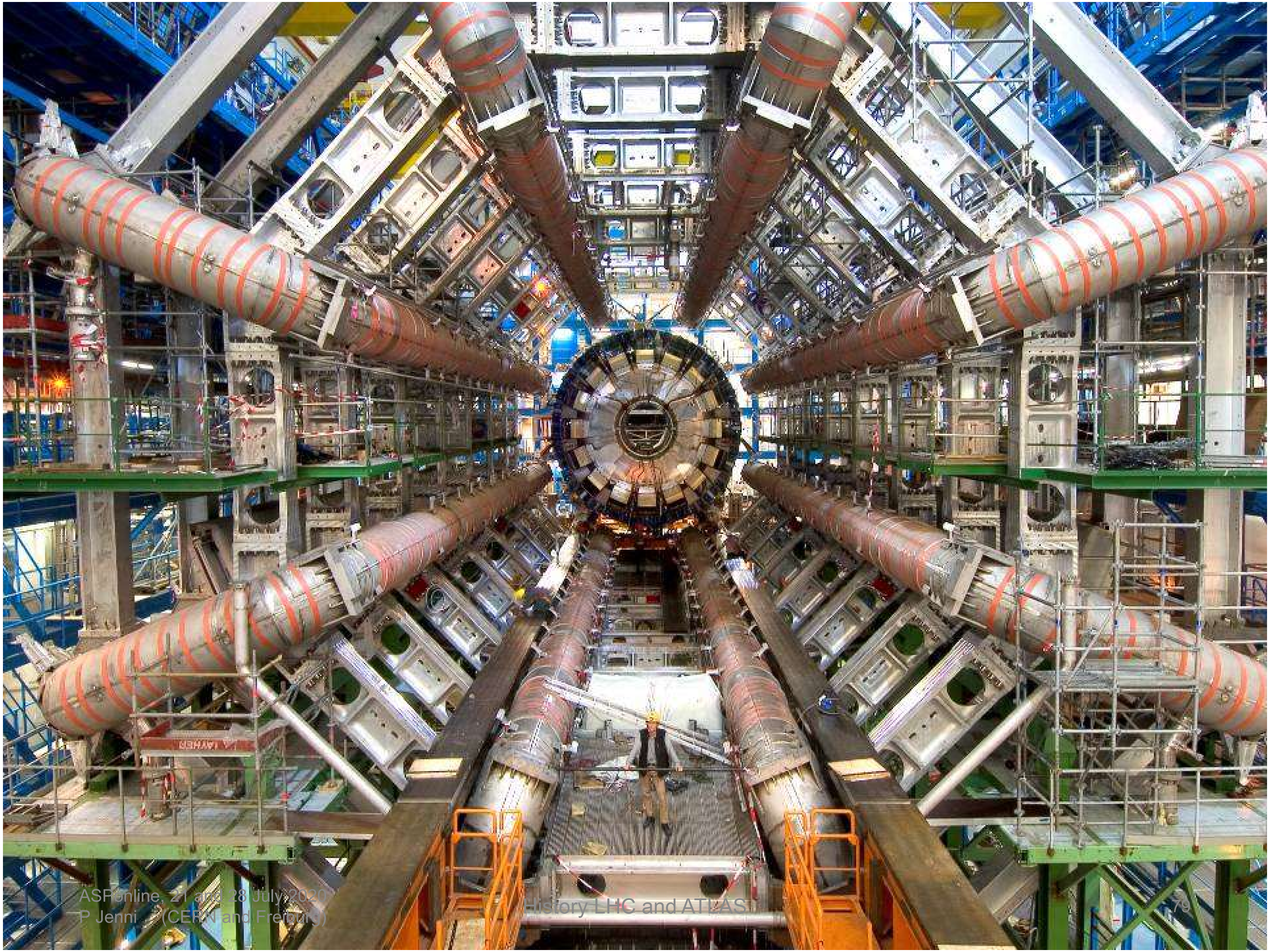
ATLAS Barrel Toroid construction

Series integration and tests of the 8 coils at the surface were finished in June 2005



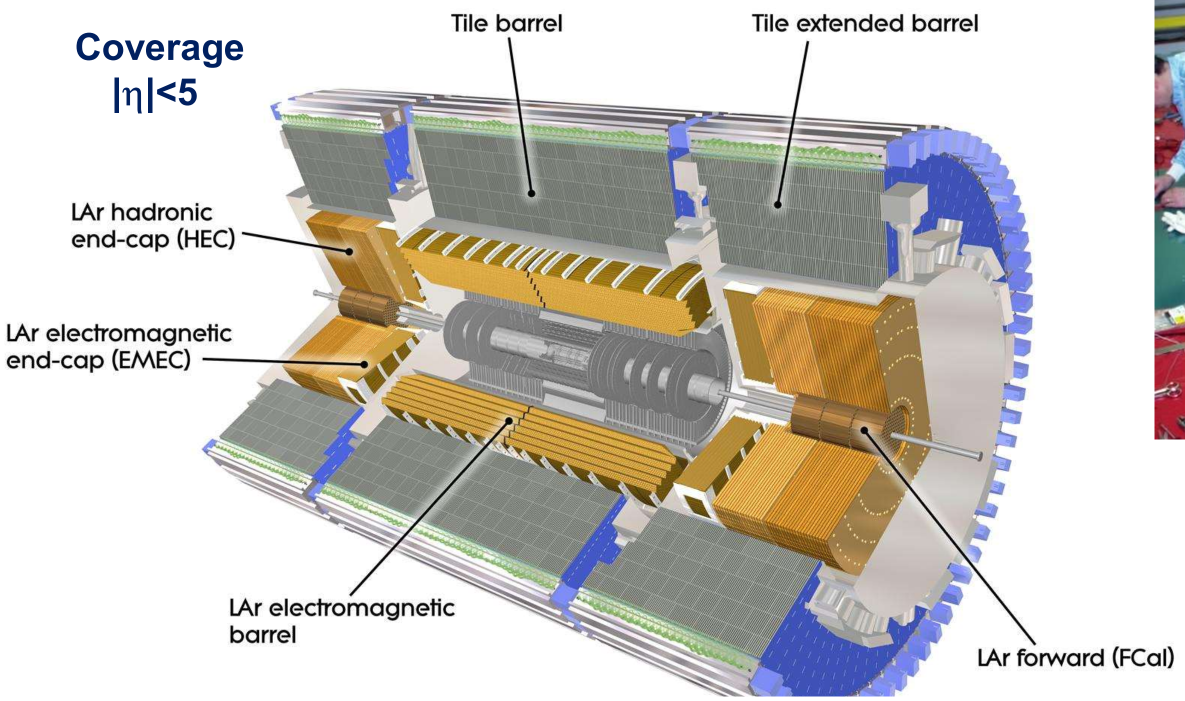


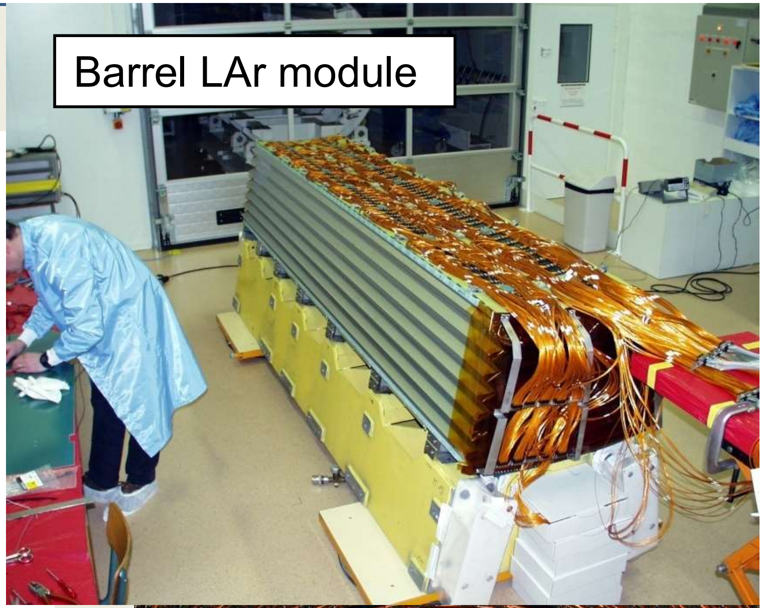
First Barrel Toroid coil on its way to Point-1 (21-10-2004)

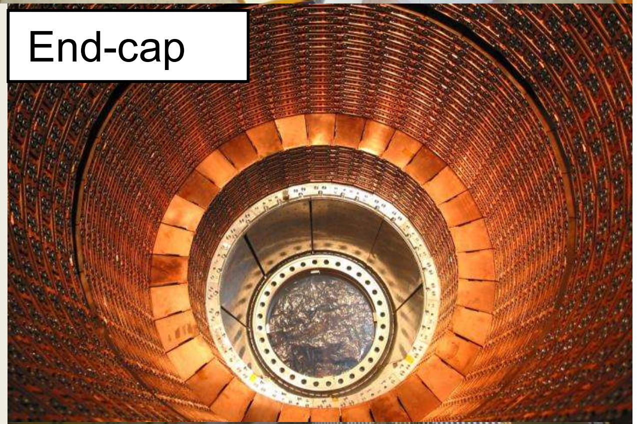


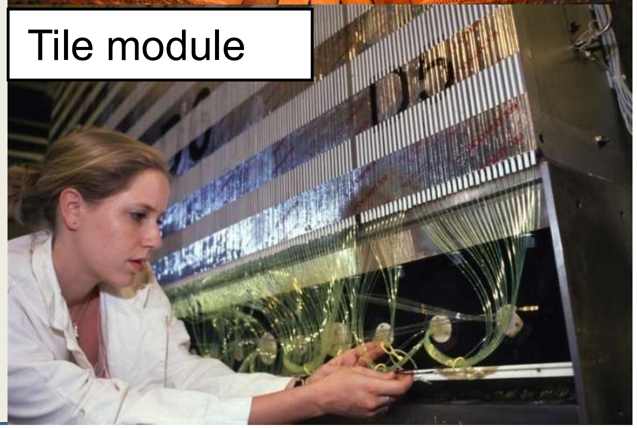
ATLAS Calorimetry

Coverage
|η|<5





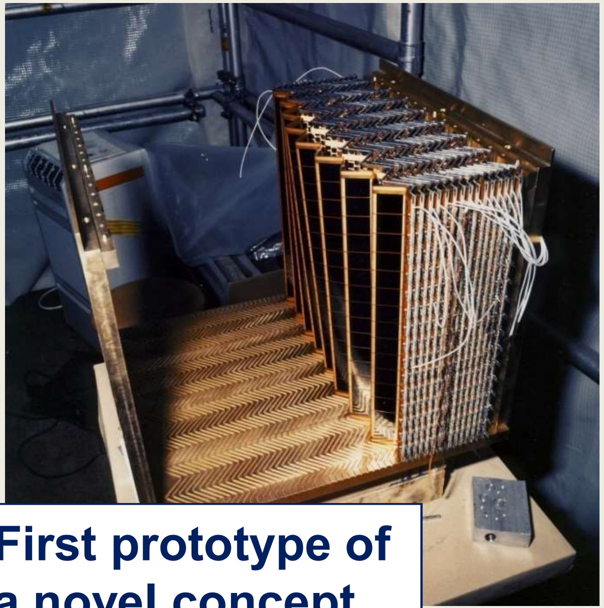




Electromagnetic Calorimeter
barrel, end-cap: Pb-LAr
~10%/√E energy resolution e/γ
180'000 channels: longitudinal segmentation

Hadron Calorimeter
barrel Iron-Tile, EC/Fwd Cu/W-LAr (~20'000 channels)
σ/E ~ 50%/√E $\oplus$ 0.03 pion (10 λ)

Trigger for e/γ , jets, missing E_T



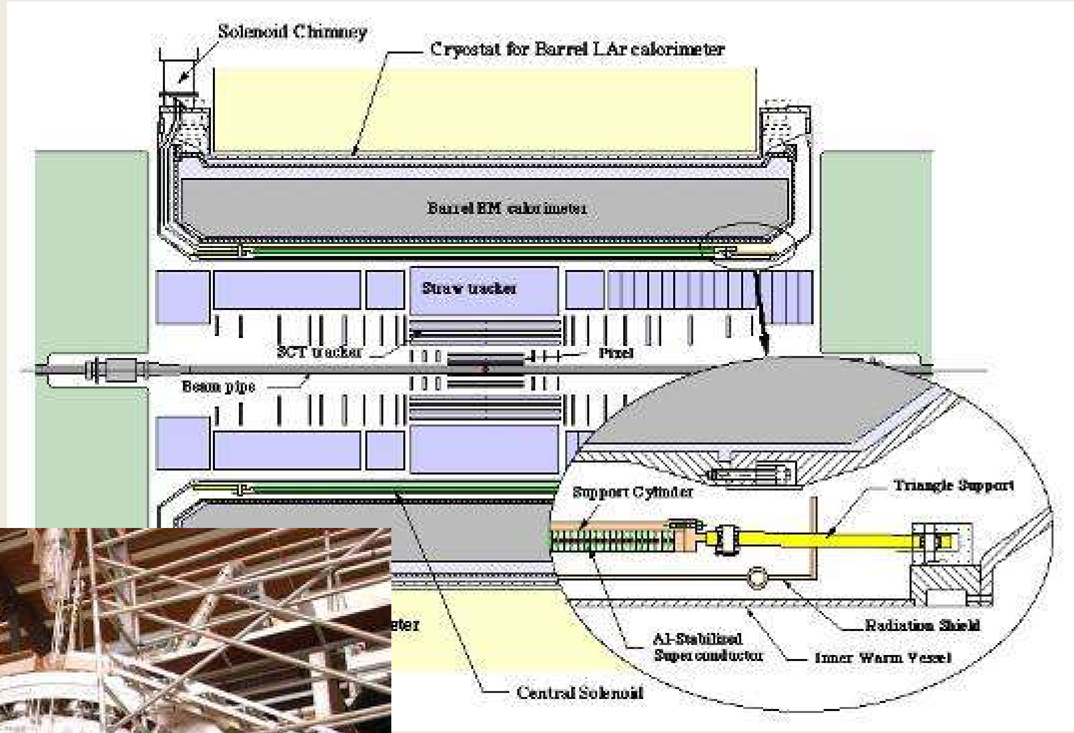
First prototype of a novel concept ('accordion') 1990

LAr EM Calorimeter construction 1999 - 2004

ATLAS Central Solenoid

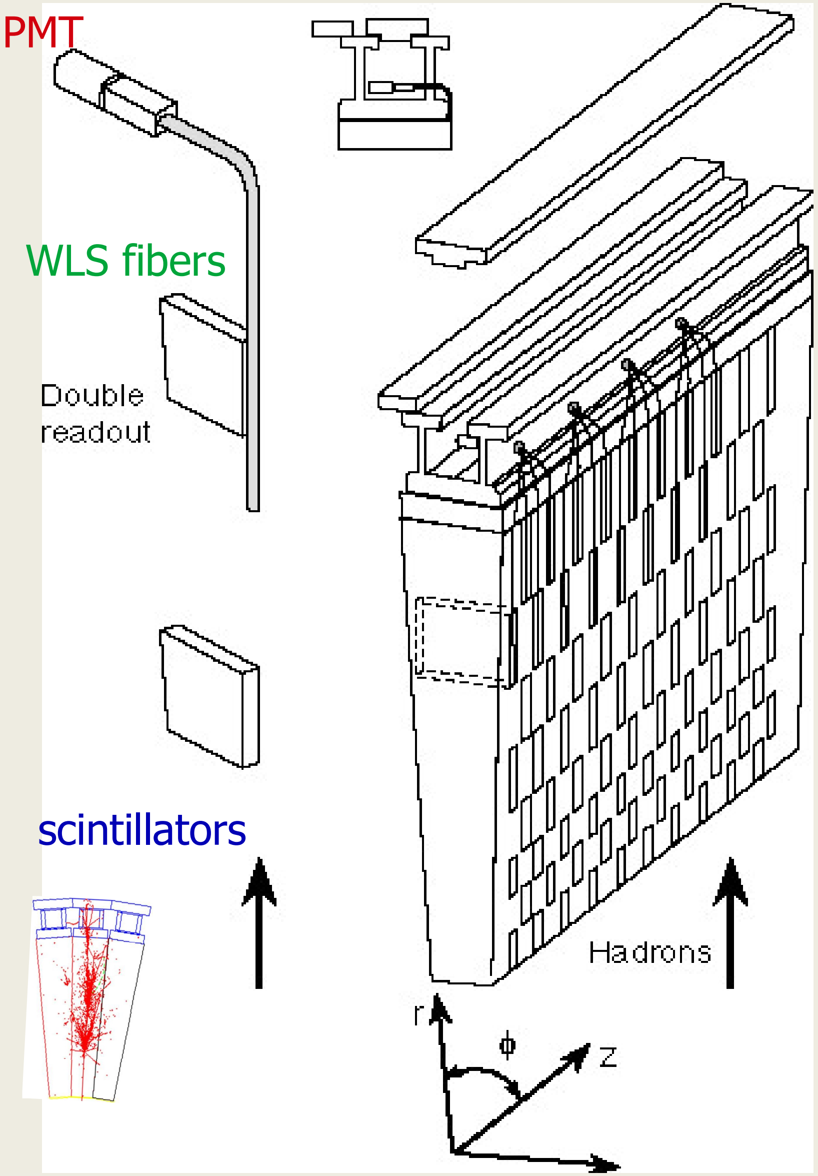
2T field with a stored energy of 38 MJ

Integrated design within the barrel LAr cryostat

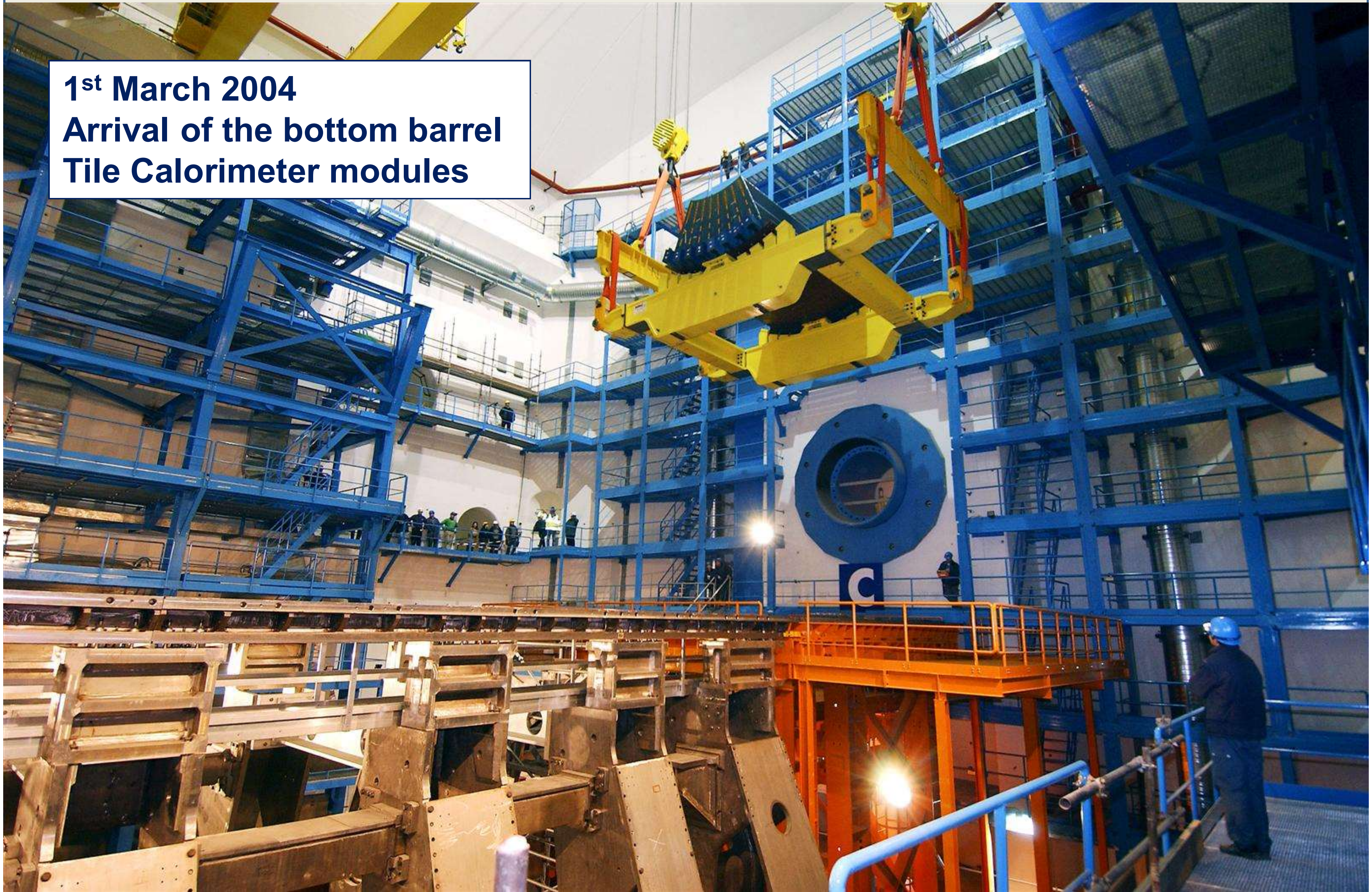


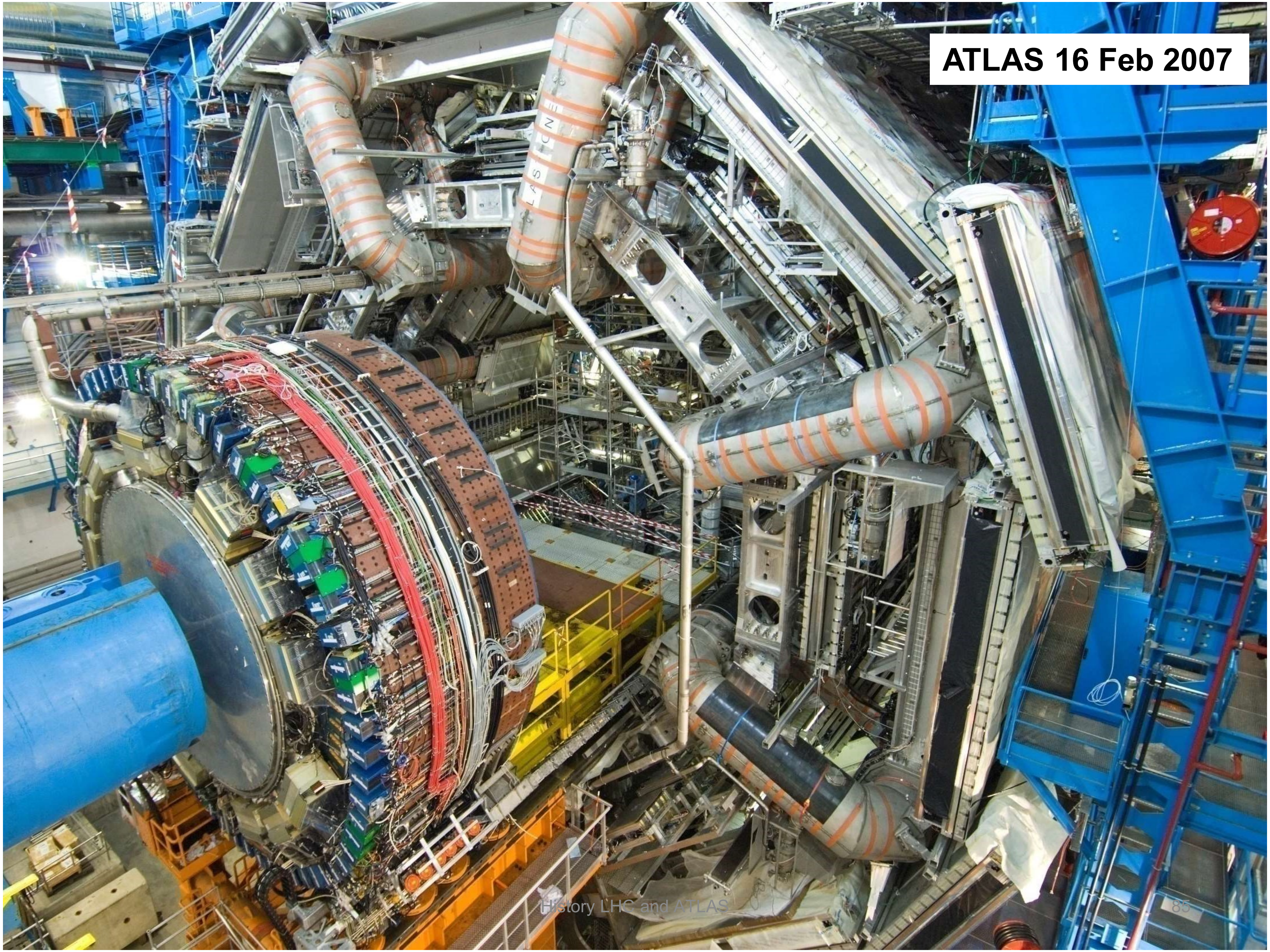
The solenoid has been inserted into the LAr cryostat at the end of February 2004, and it was tested at full current (8 kA) during July 2004

ATLAS Tile Calorimeter



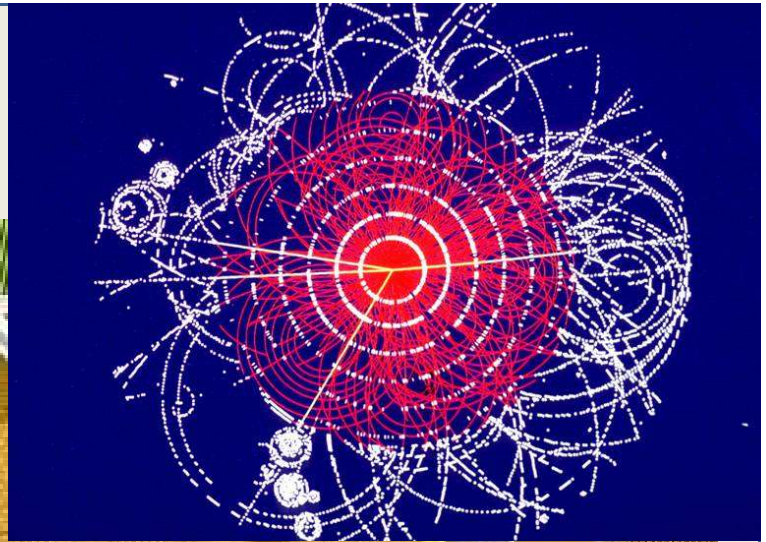
1st March 2004
Arrival of the bottom barrel Tile Calorimeter modules

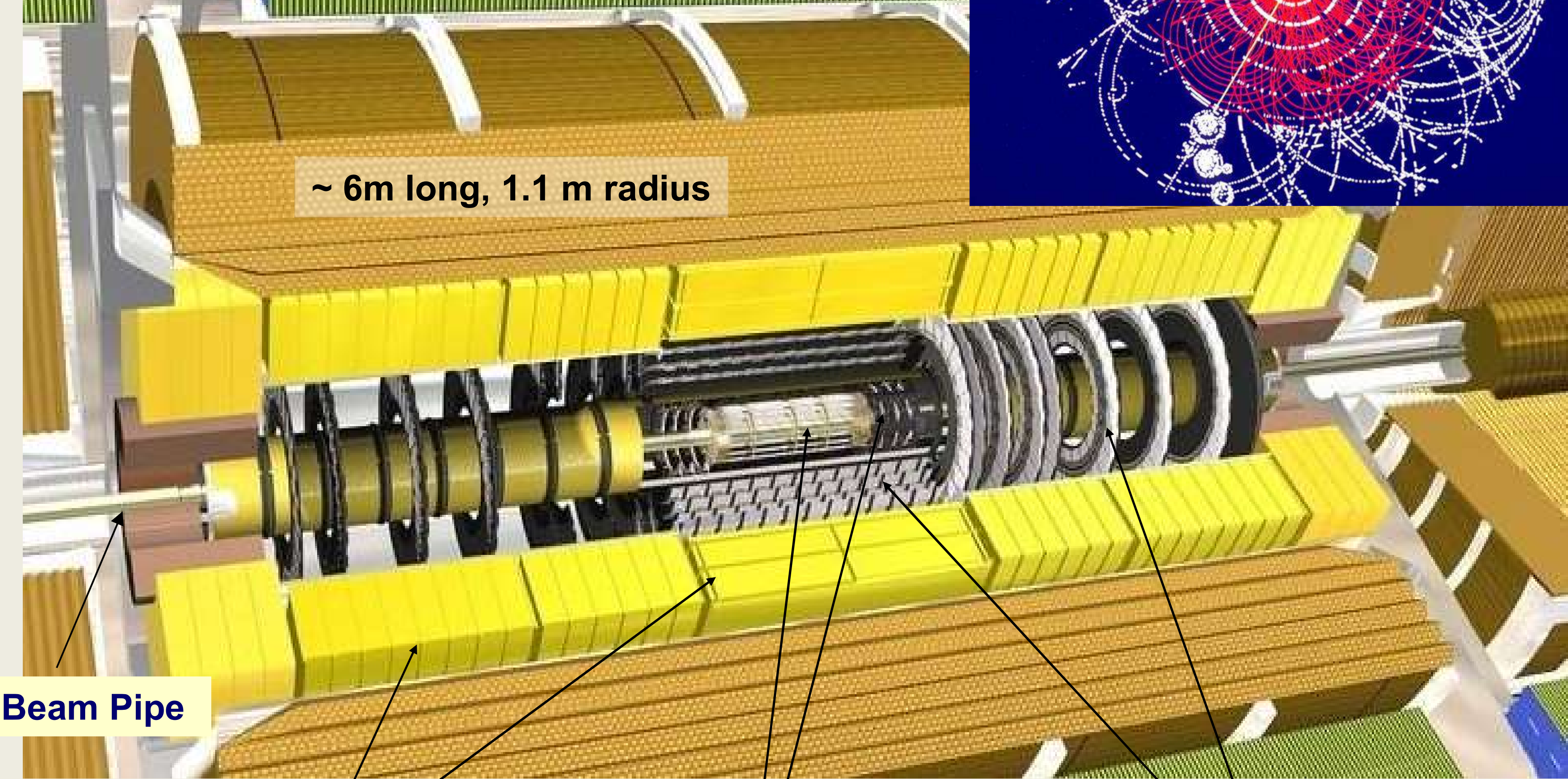



ATLAS 16 Feb 2007

ATLAS Tracking Detectors

2 Tesla solenoid: $\sigma/p_T \sim 5\times10^{-4}\, p_T \oplus 0.01$





Beam Pipe

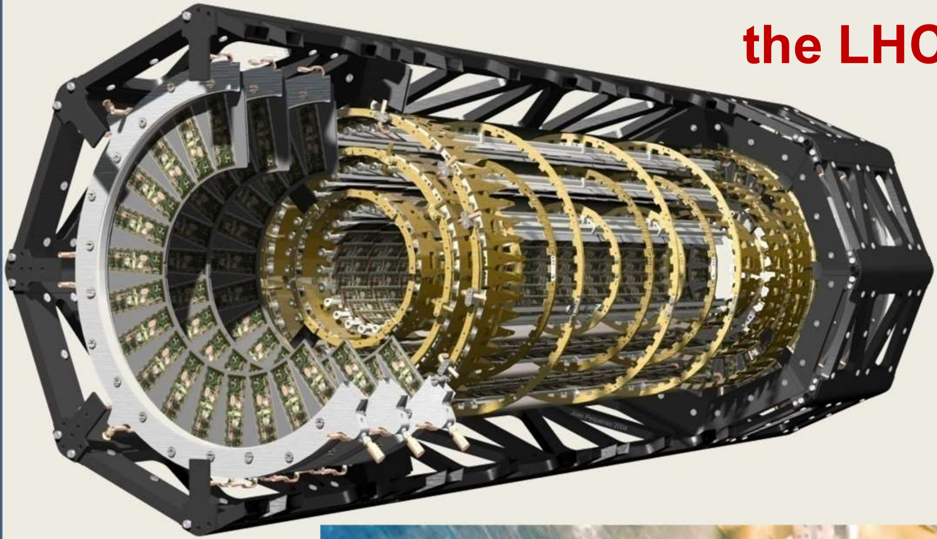
Transition Radiation Tracker (TRT)
($4\ 10^5$ channels) with e/π separation

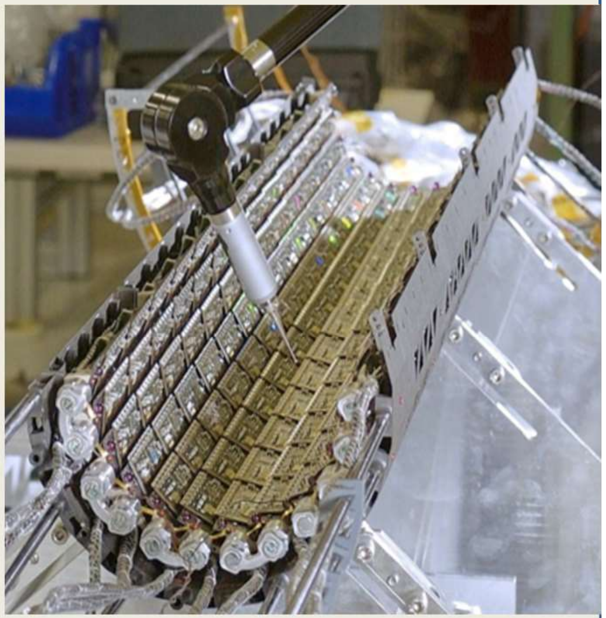
Pixels (initial)
($0.8\ 10^8$ channels)

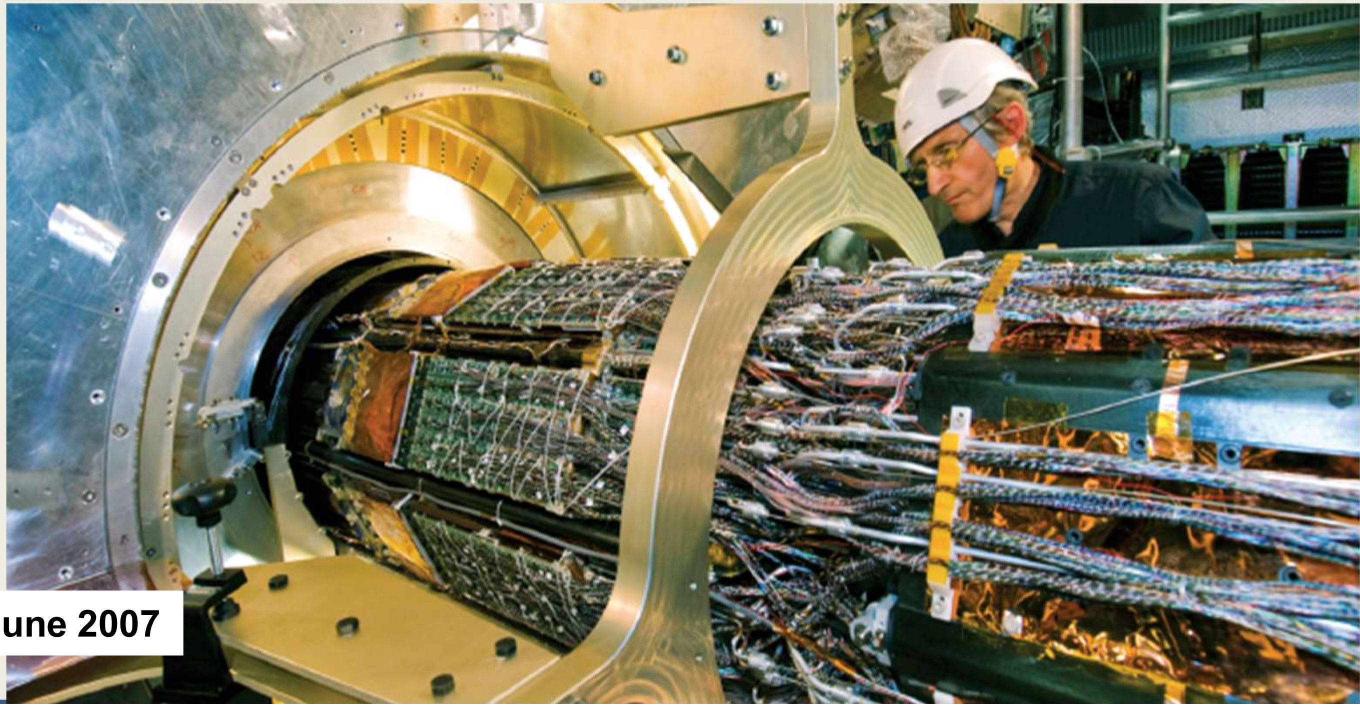
Si Strips Tracker (SCT)
($6\ 10^6$ channels)

A forth layer at very small radius has been added as Phase-0 upgrade for Run-2

The Pixel tracker is a particularly high-tech device close around the LHC beam pipe

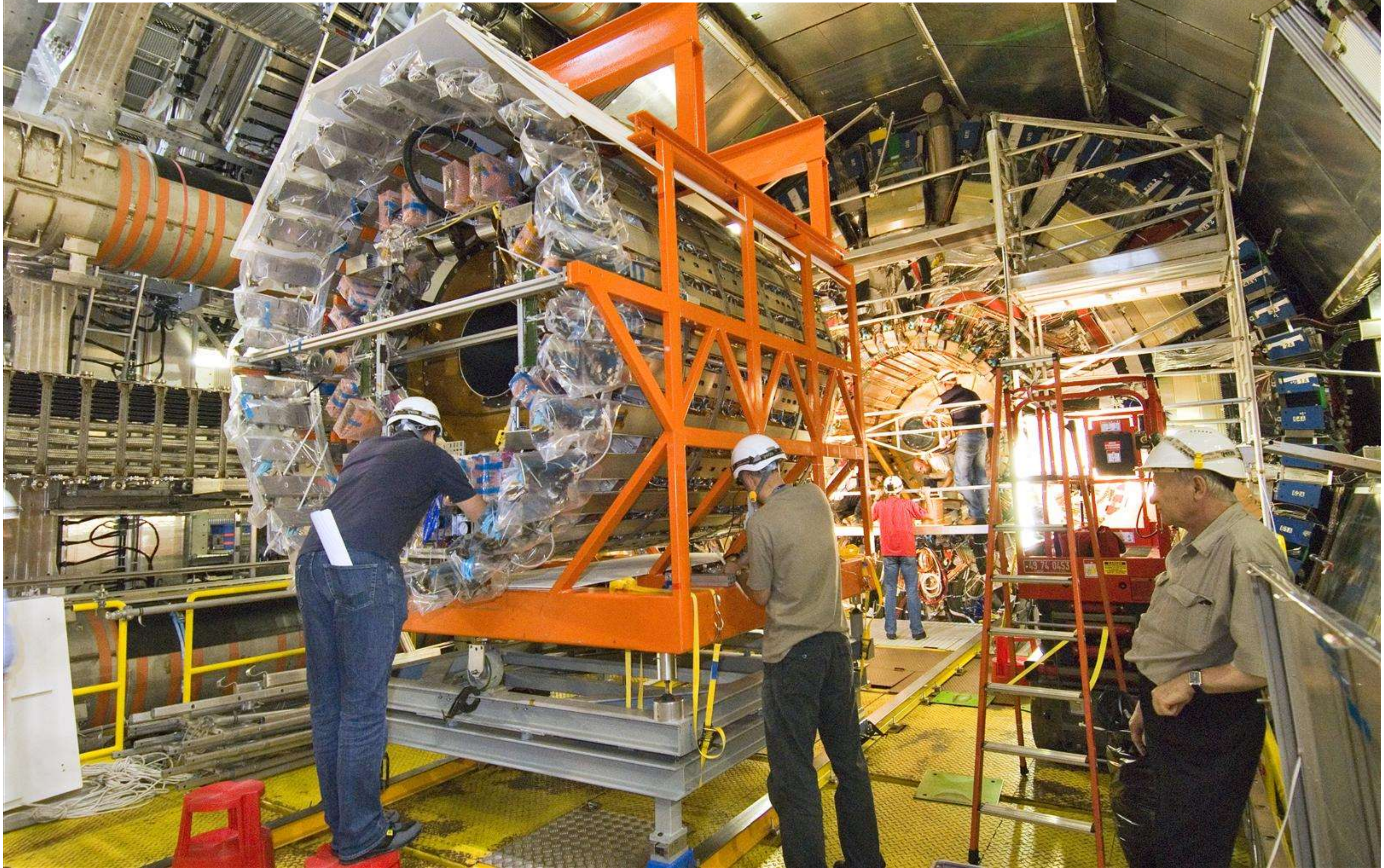






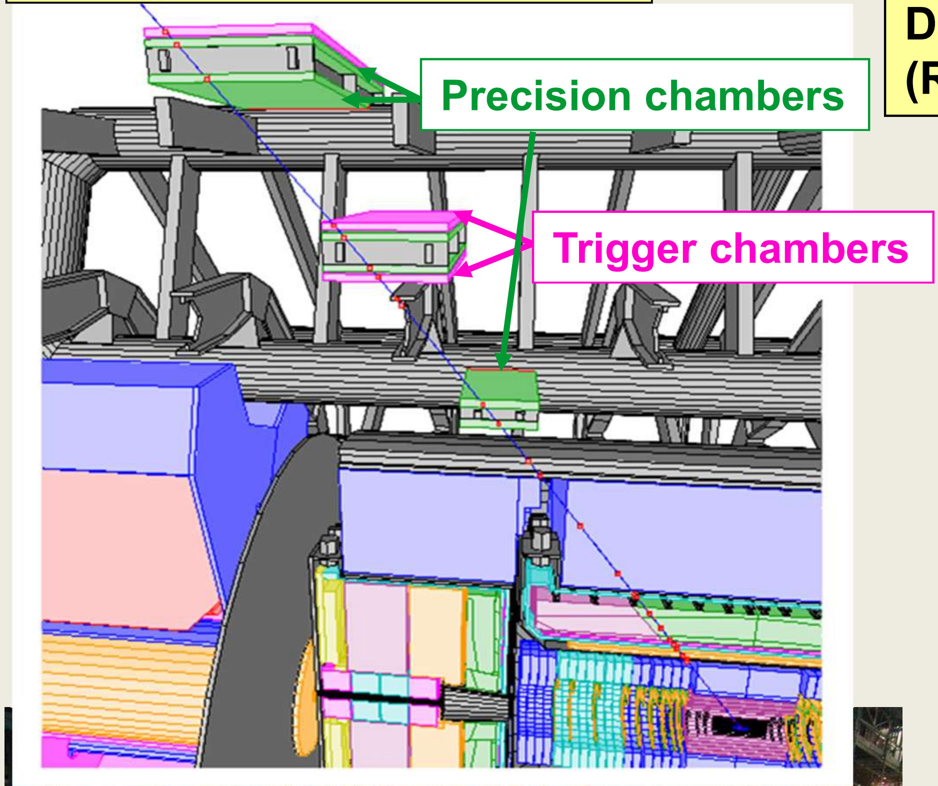
Insertion in June 2007

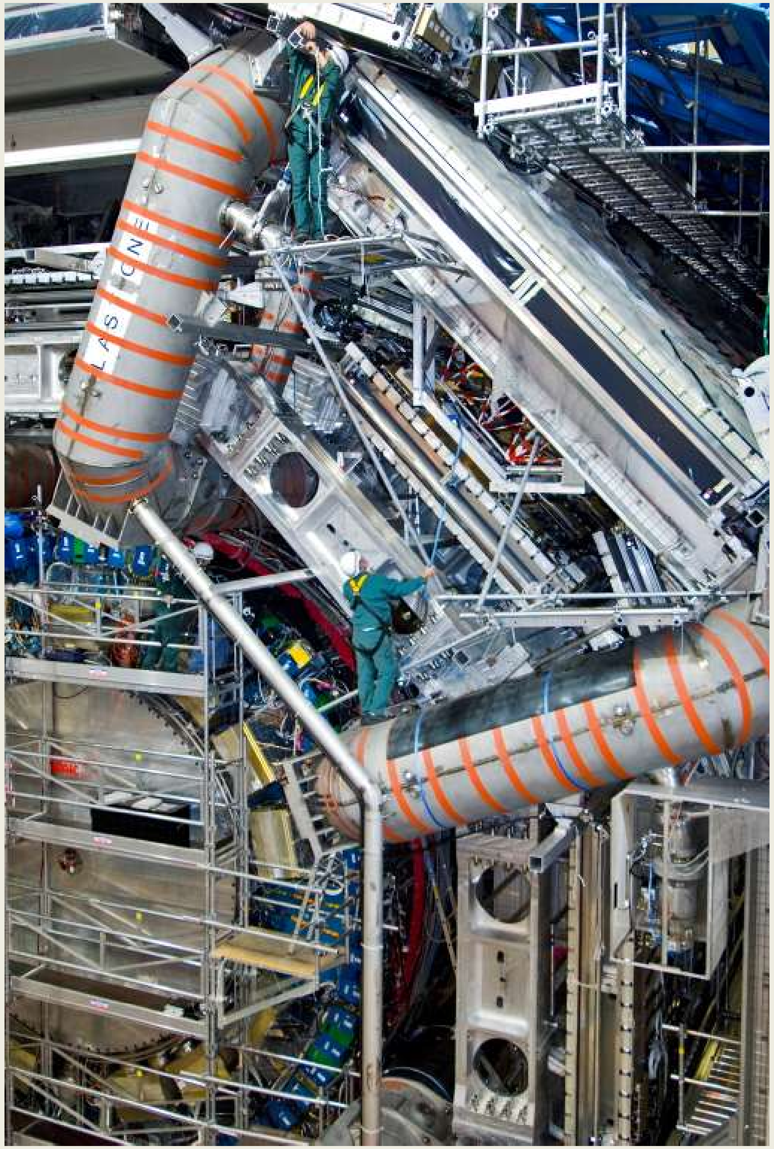
Installation of the first ATLAS end-cap tracker (May 2007)



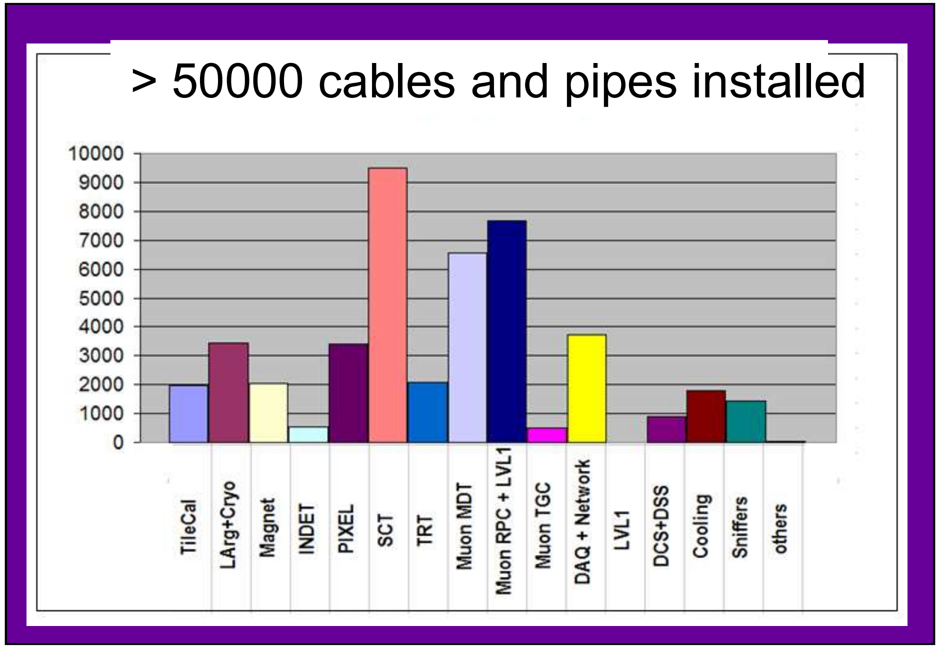
Muon Spectrometer

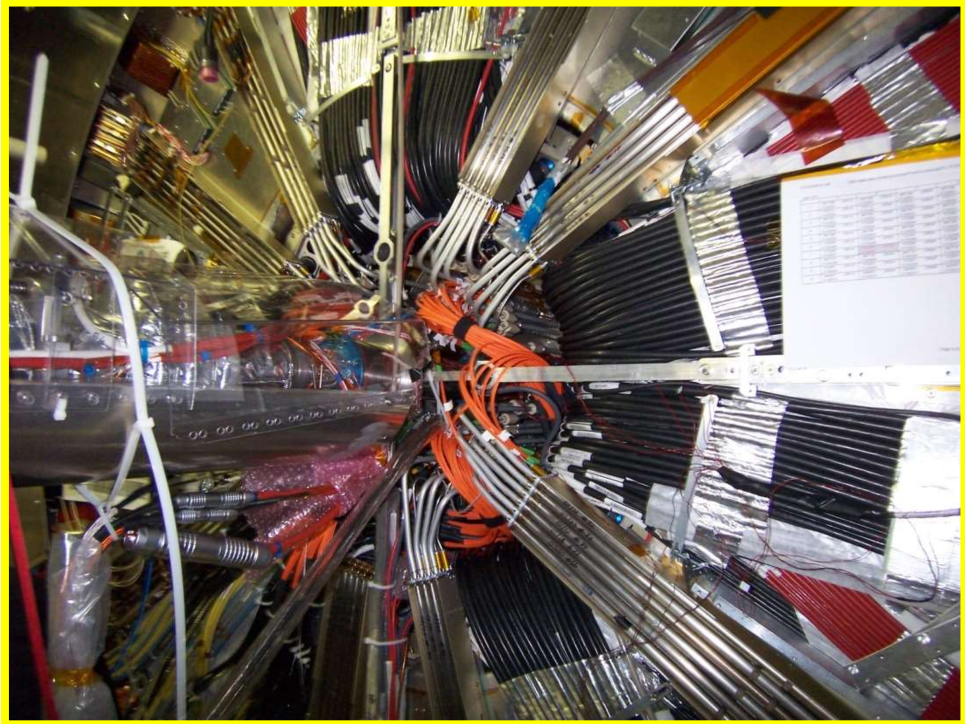
~ 600 barrel precision chambers (Monitored Drift Tubes), ~ 500 barrel trigger chambers (Resistive Plate Chambers)

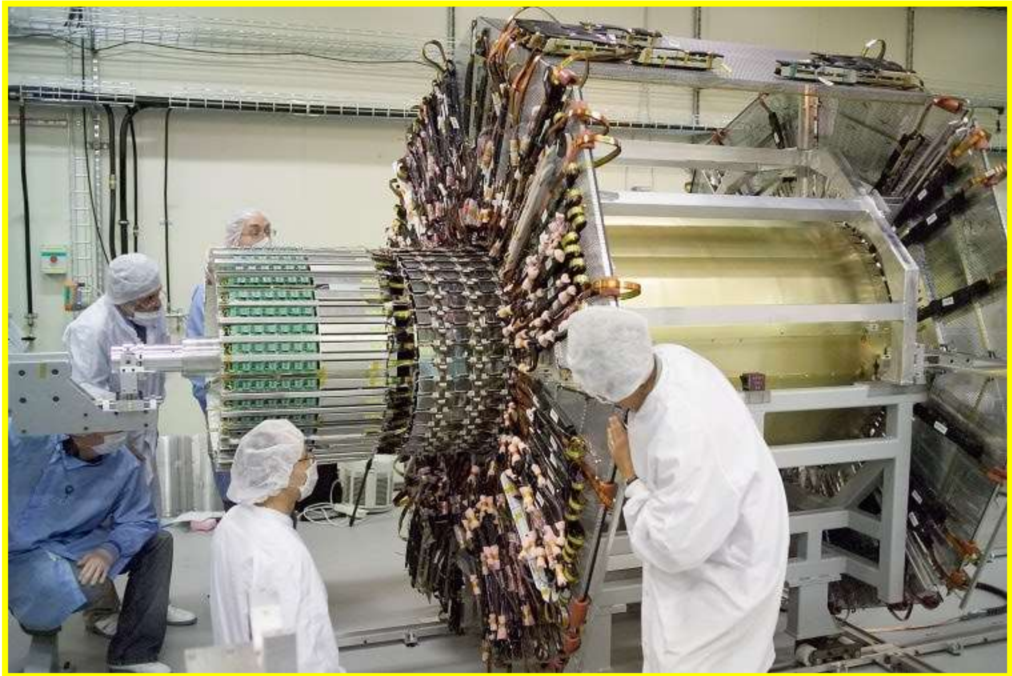


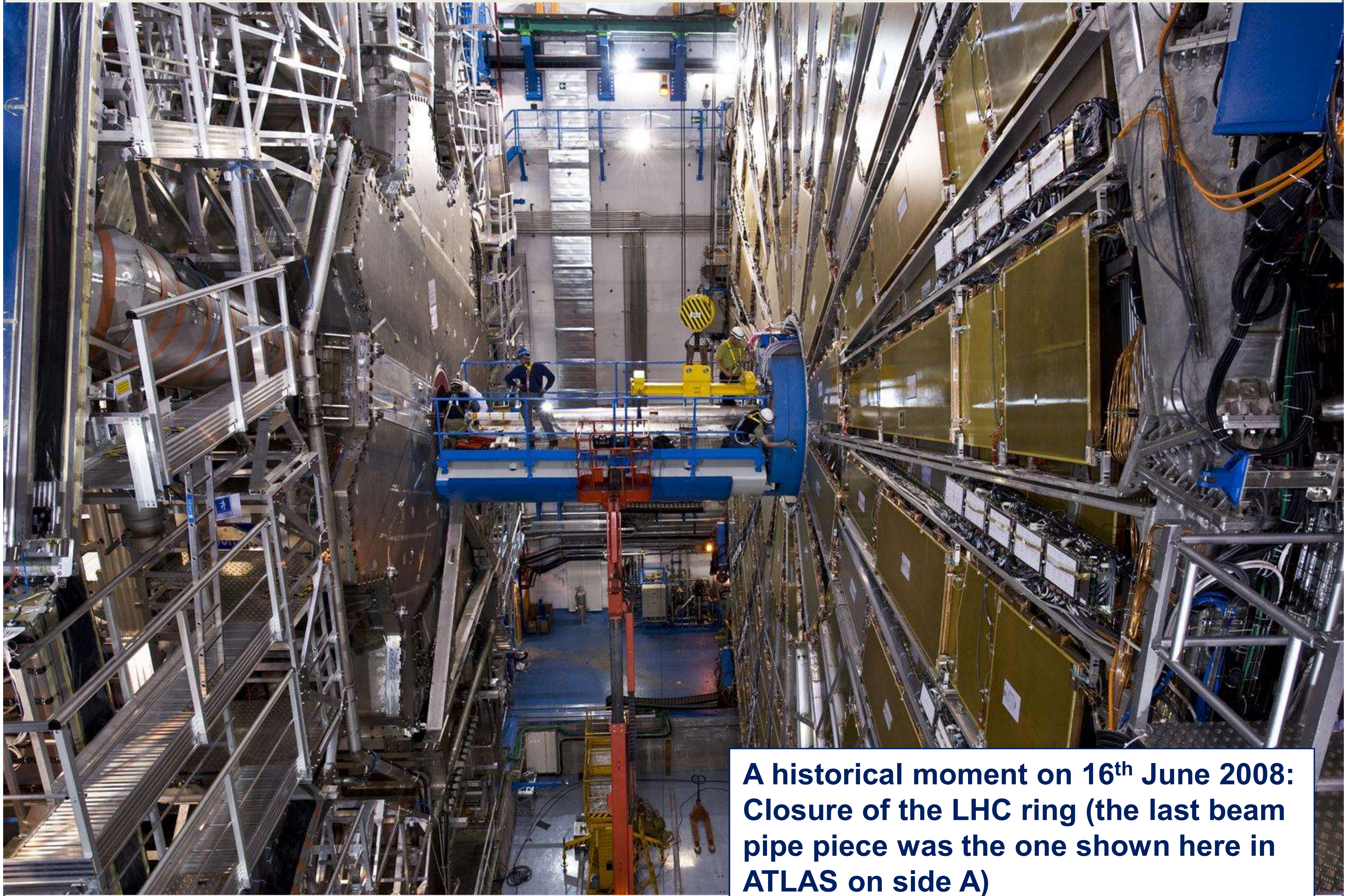


A lot of cables and pipes (ATLAS)





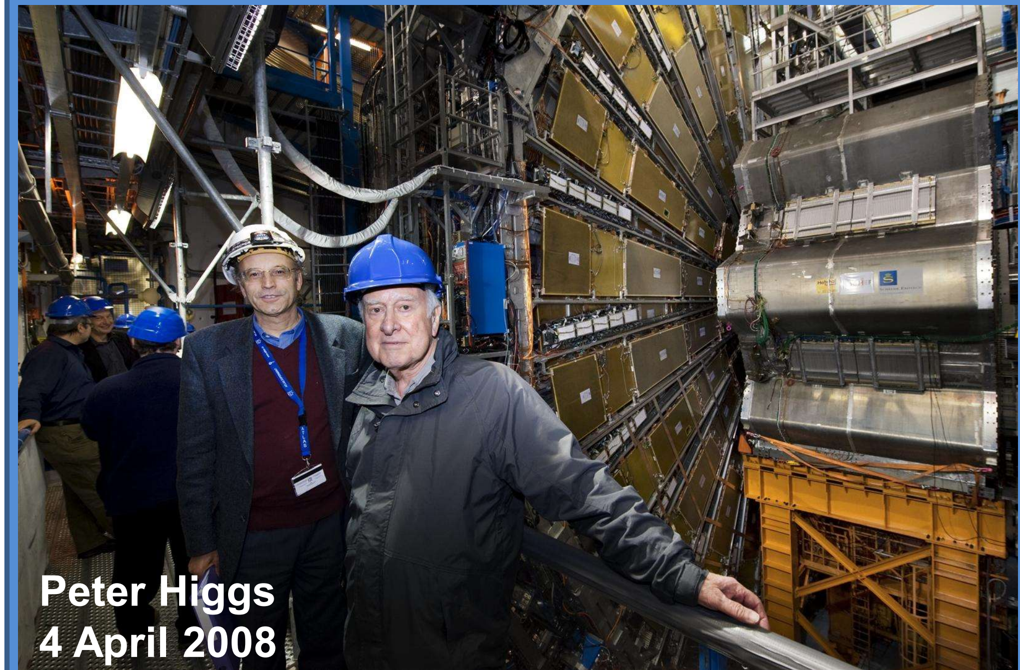




A historical moment on 16th June 2008: Closure of the LHC ring (the last beam pipe piece was the one shown here in ATLAS on side A)

Famous visitors in ATLAS and CMS

Francois Englert
6 Dec 2007



Peter Higgs
4 April 2008

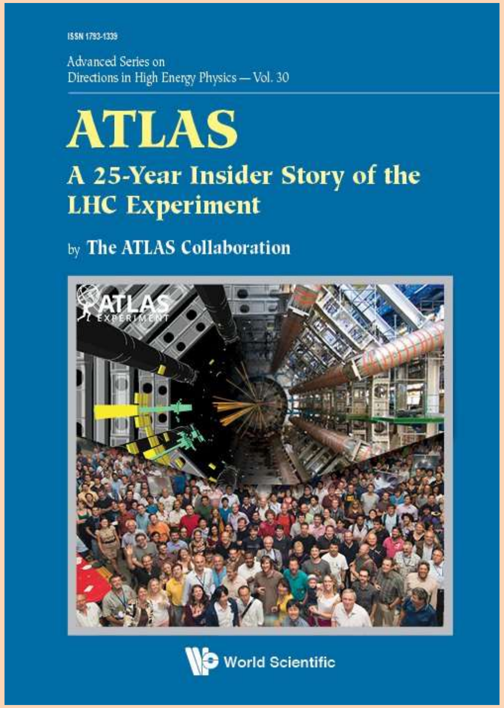
Steven Weinbeg
7 July 2009

Some resources on the web available in open access:

The evolution of hadron collider experiments
Paul Grannis and Peter Jenni, Physics Today 66, 6, 38 (2013)
http://dx.doi.org/10.1063/PT.3.2010

Journey in the Search for the Higgs Boson
The ATLAS and CMS experiments
M Della Negra, P Jenni, T S Virdee, Science 338, 1560 (2012)
http://www.sciencemag.org/content/338/6114/1560.full.html

The ATLAS experiment
Monica L Dunford and Peter Jenni, Scholarpedia 99(10):32147)
http://www.scholarpedia.org/article/The_ATLAS_experiment



The whole ATLAS book about its history and early results freely available:
https://www.worldscientific.com/worldscibooks/10.1142/11030

Podcast of a long interview with me about LHC and ATLAS:
http://omegataupodcast.net/?fbclid=IwAR3UlgfJ1mZslukY1UKFobOB2U7uuH4c2IG42qspkjOy7P80EXzYxZqJKPA