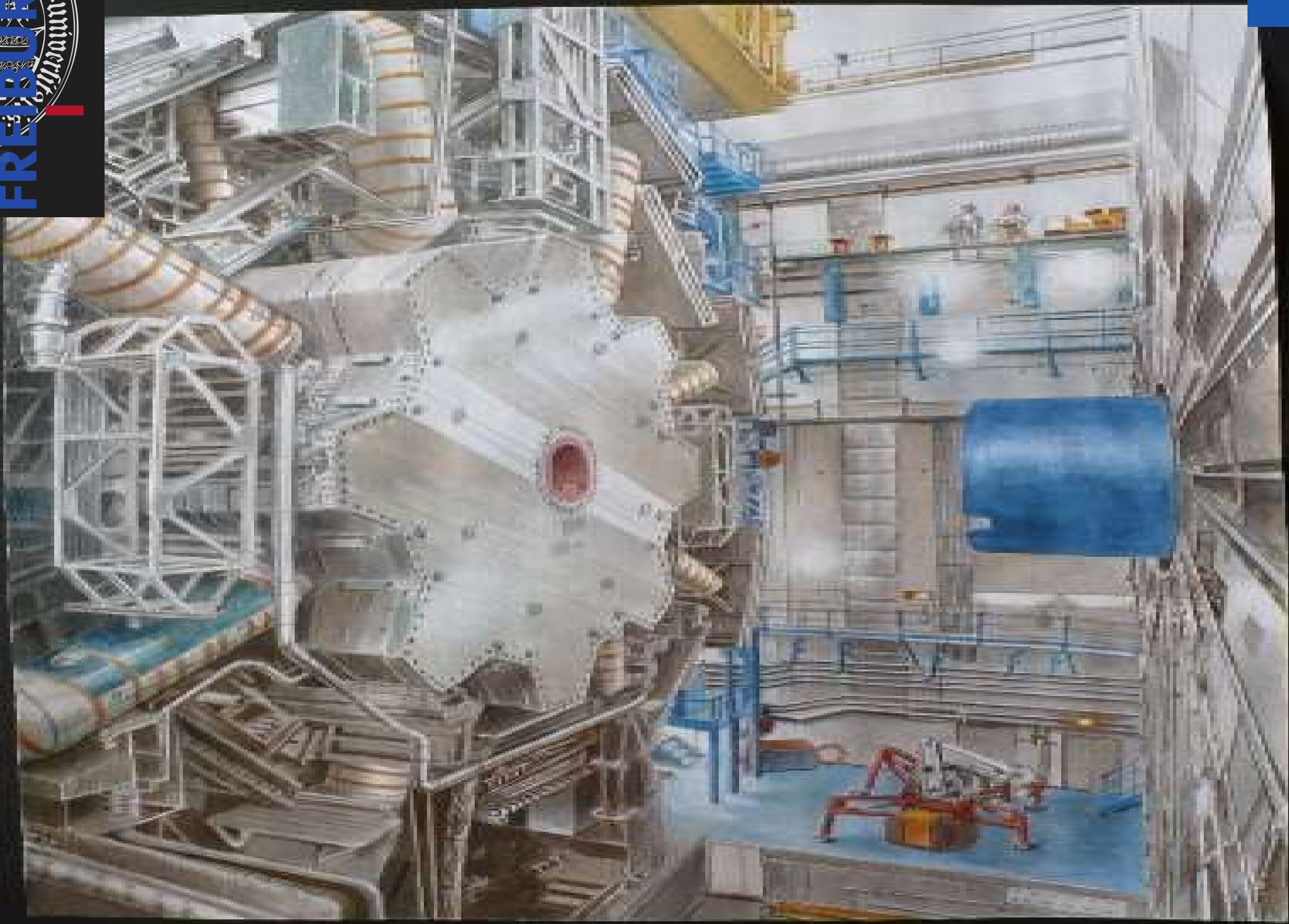
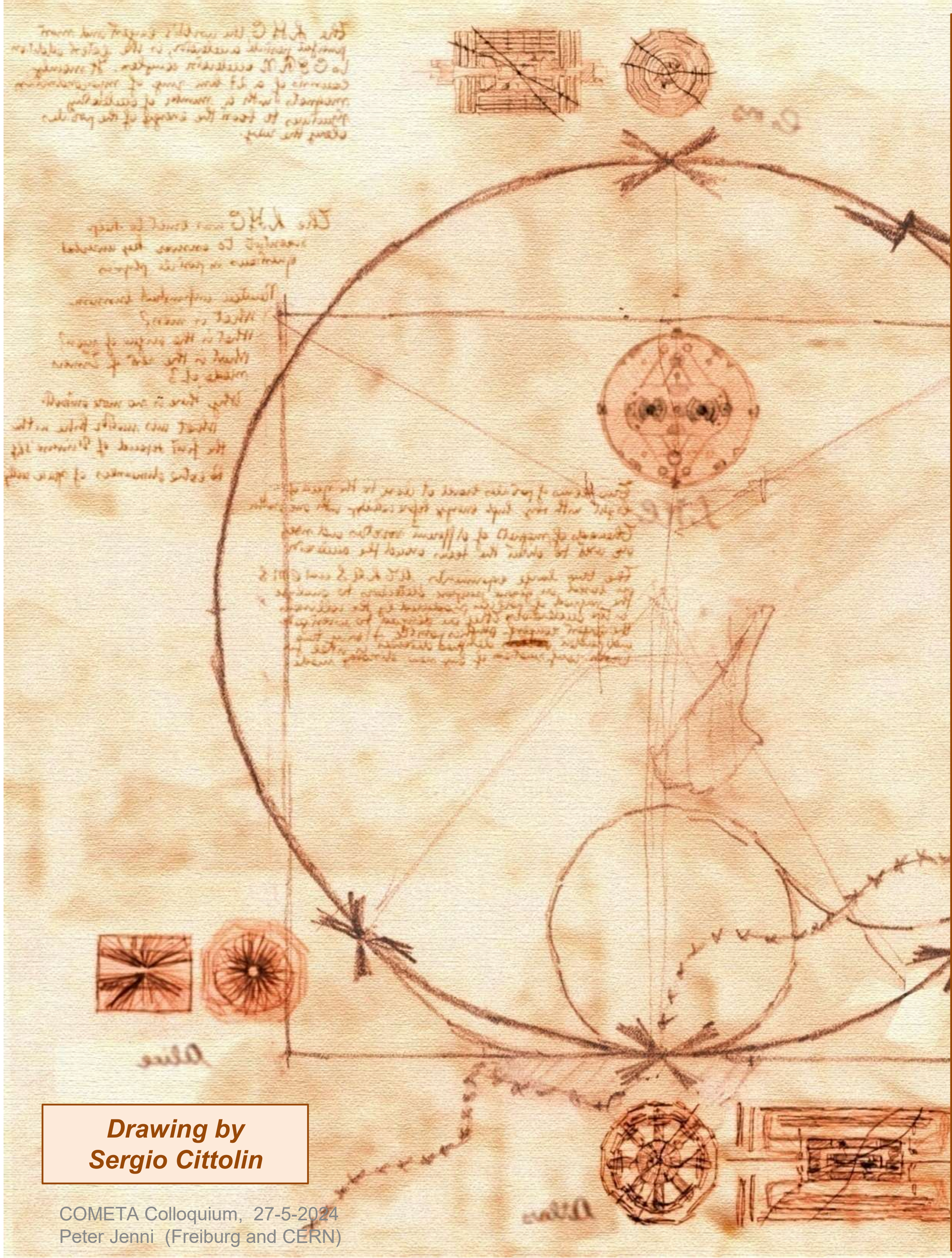


The Long Journey to the Discovery of the Higgs Boson

Peter Jenni
Albert-Ludwigs-Universität Freiburg and CERN
COMETA Colloquium, 27 May 2024



Drawing by
Sergio Cittolin

Selected historical flashbacks to hadron collider experiments on the way to the LHC energy frontier

The plan is to comment a bit on:

- Setting the historical context for a hadron collider
- Recall the early LHC project history
- Some major milestones leading to ATLAS and CMS as they are now, with ATLAS as showcase
  - prehistory, path to approval
  - construction highlights
  - financial framework

Disclaimer:

- The Higgs boson physics results have of course been covered by many seminars and talks, and you know the analyses much better than me!
- LHCb, ALICE, LEP experiments, all very beautiful, are outside the scope of this talk

How the LHC came to be …

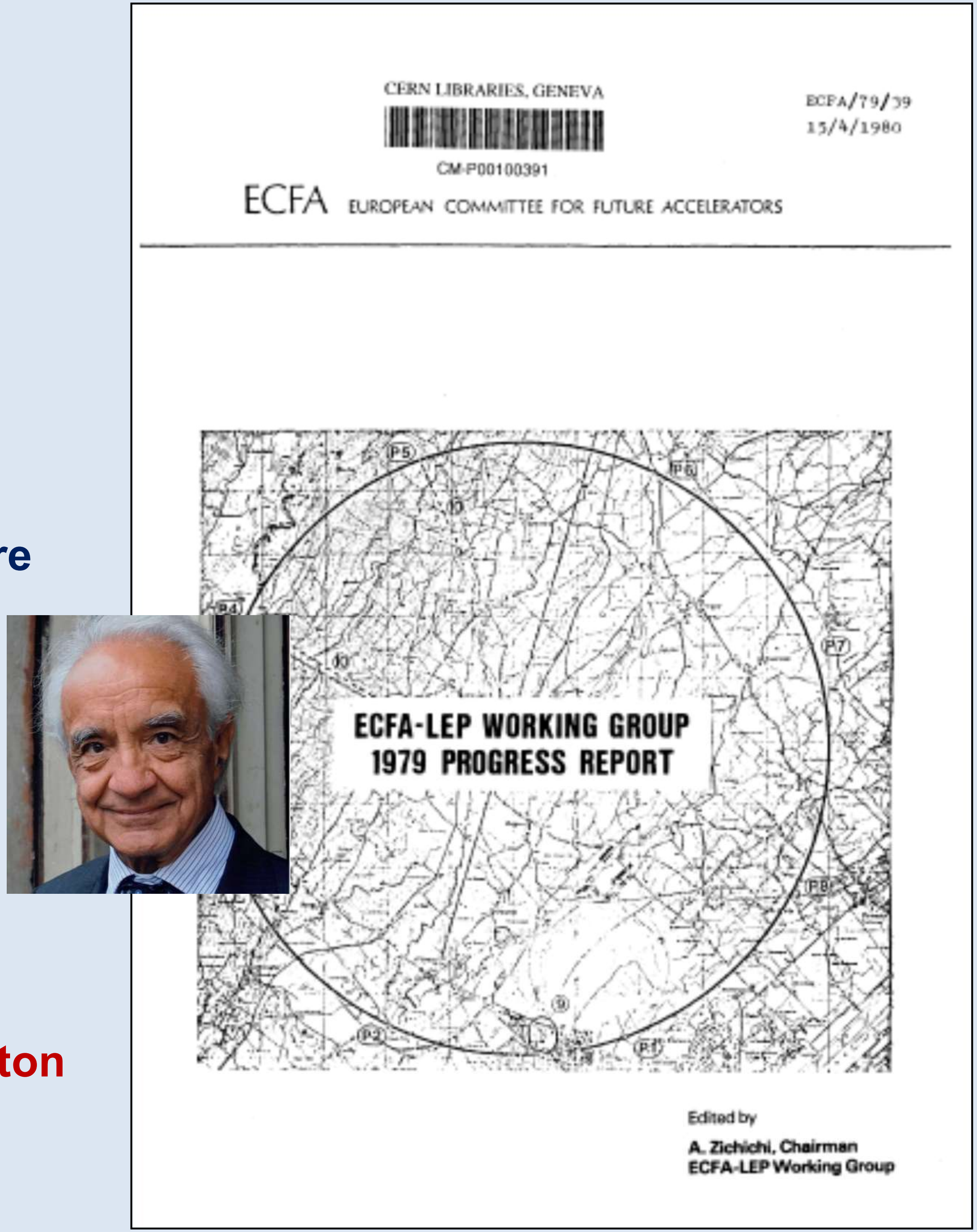
Some very early key dates

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’



CERN LIBRARIES, GENEVA

CM-P00100391

ECFA/79/39
15/4/1980

ECFA EUROPEAN COMMITTEE FOR FUTURE ACCELERATORS

ECFA-LEP WORKING GROUP
1979 PROGRESS REPORT

Edited by
A. Zichichi, Chairman
ECFA-LEP Working Group

Hadron Colliders and their experiments have more than 50 years history by now, and each project had very major impacts on the following one

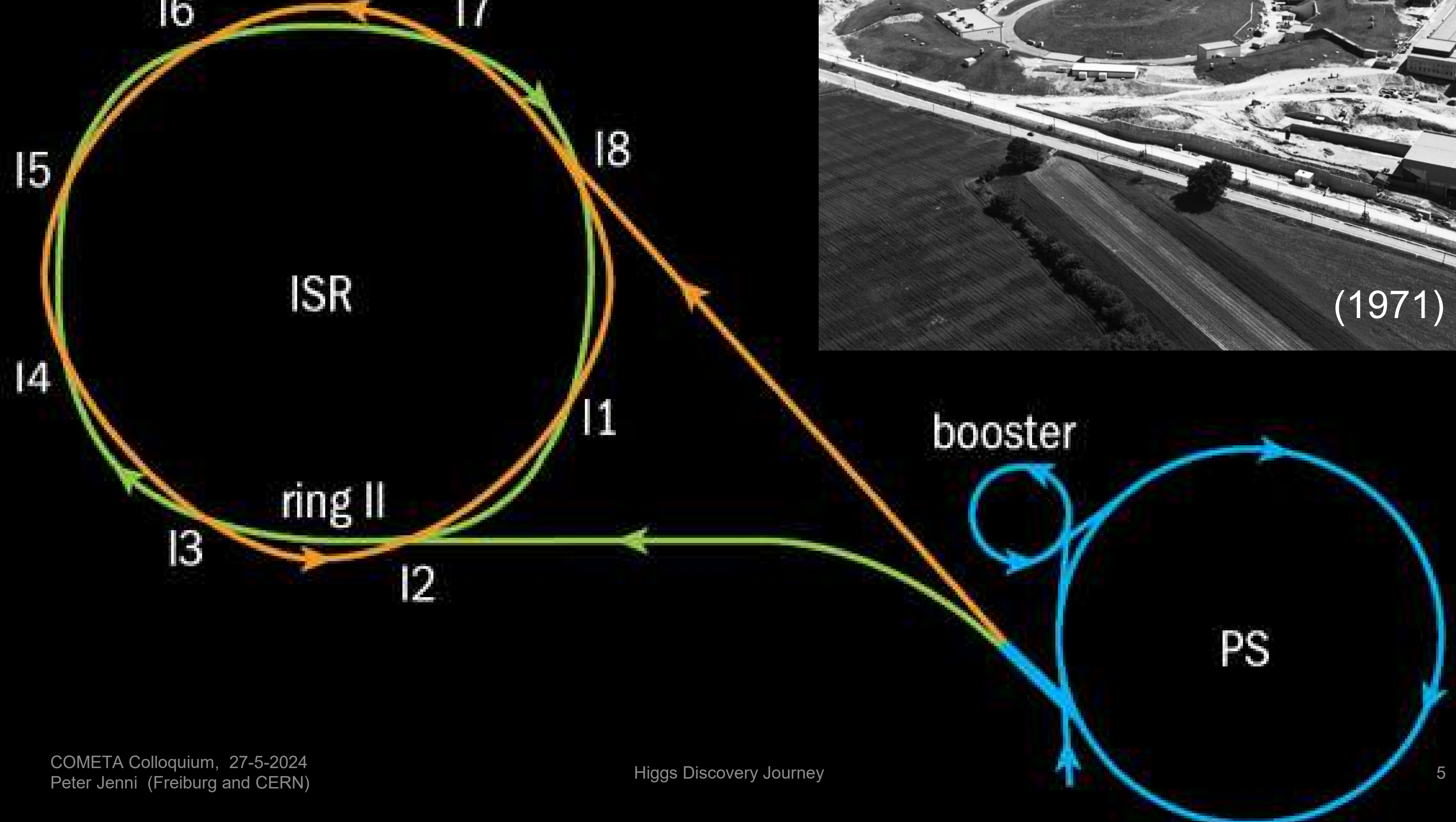
Some key dates and (max) collision energies to remember

Intersecting Storage Rings (ISR) at CERN	operated 1971-1984	63 GeV
CERN SPS pbar-p Collider	operated 1981-1990	630 GeV
Tevatron pbar-p Collider at FNAL	operated 1987-2011	2 TeV
LHC at CERN	operating since 2009	14 TeV
Superconducting Super Collider (SSC) in Texas	project abandoned 1993	40 TeV

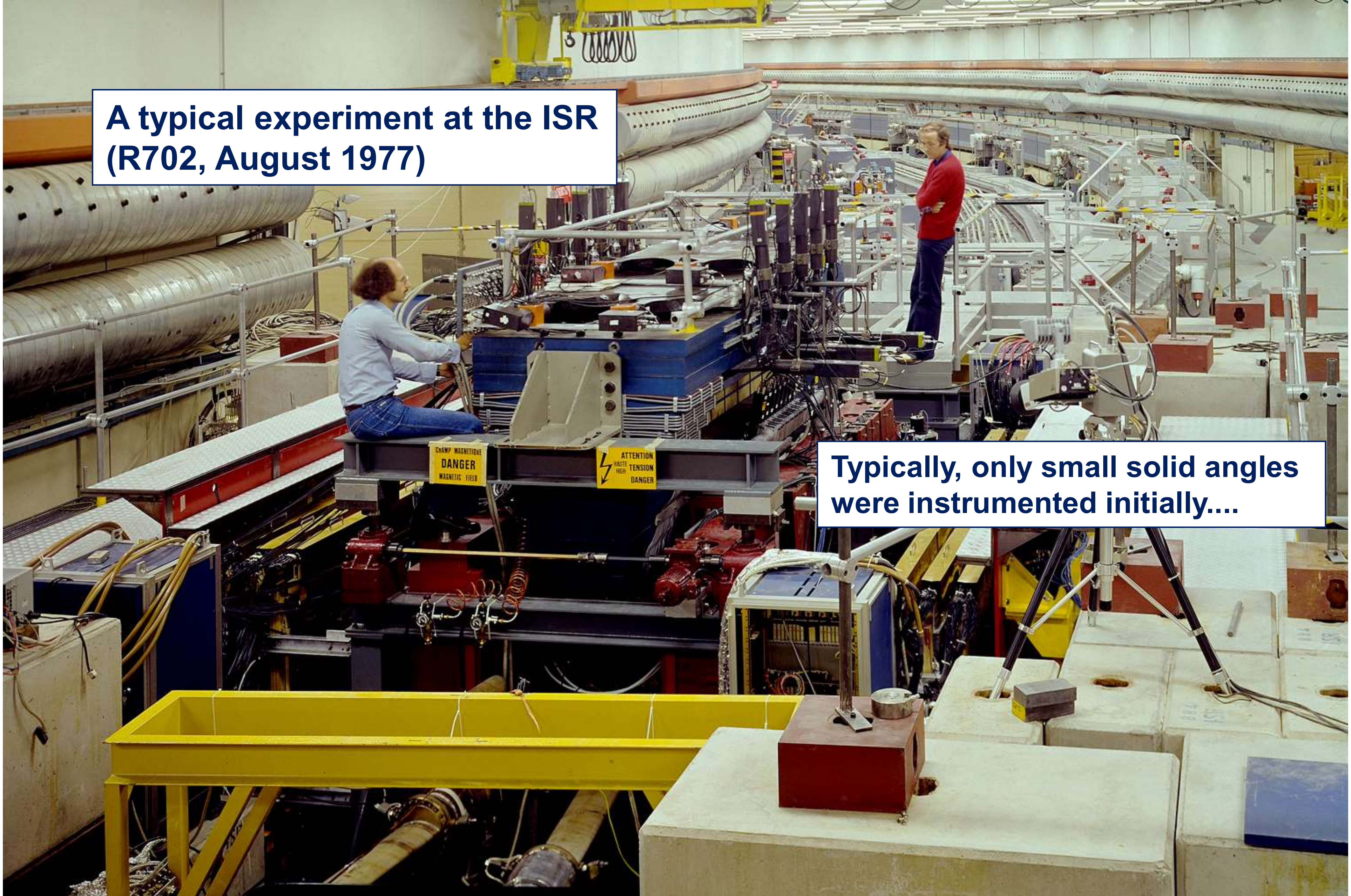
CERN Courier feature article,
50 years of hadron colliders,
Lyn Evand and PJ, January 2021

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)



Typically, only small solid angles were instrumented initially....

Burton Richter's experiment: search for open charm in pp by oppositely charged eμ events (from semi-leptonic decays of charmed meson pairs)

Typically, only small solid angles were instrumented initially....

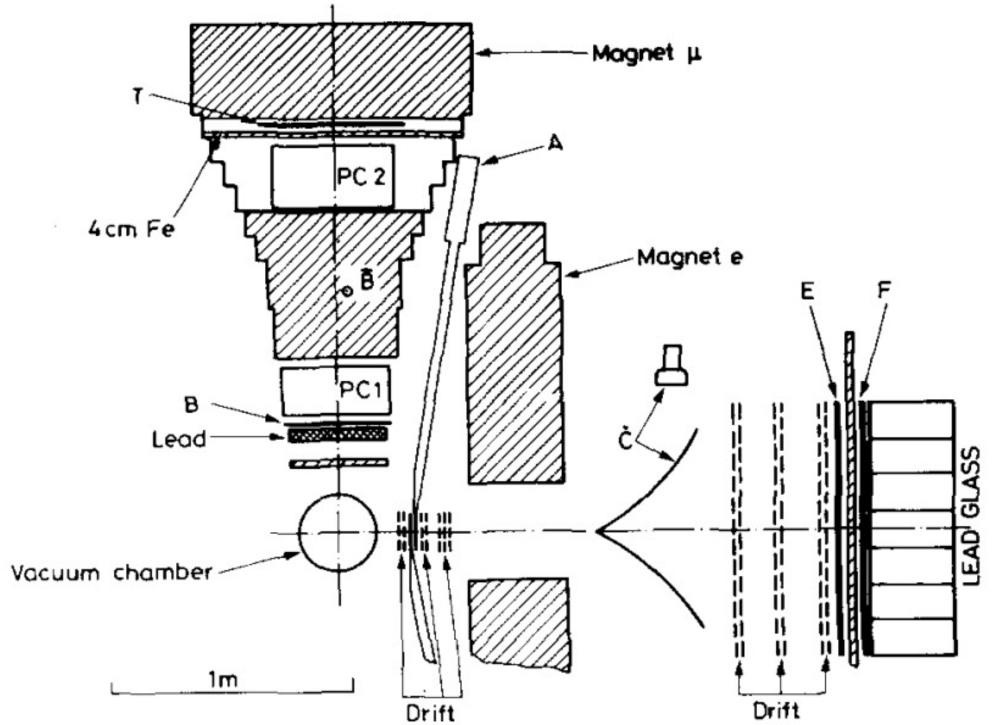
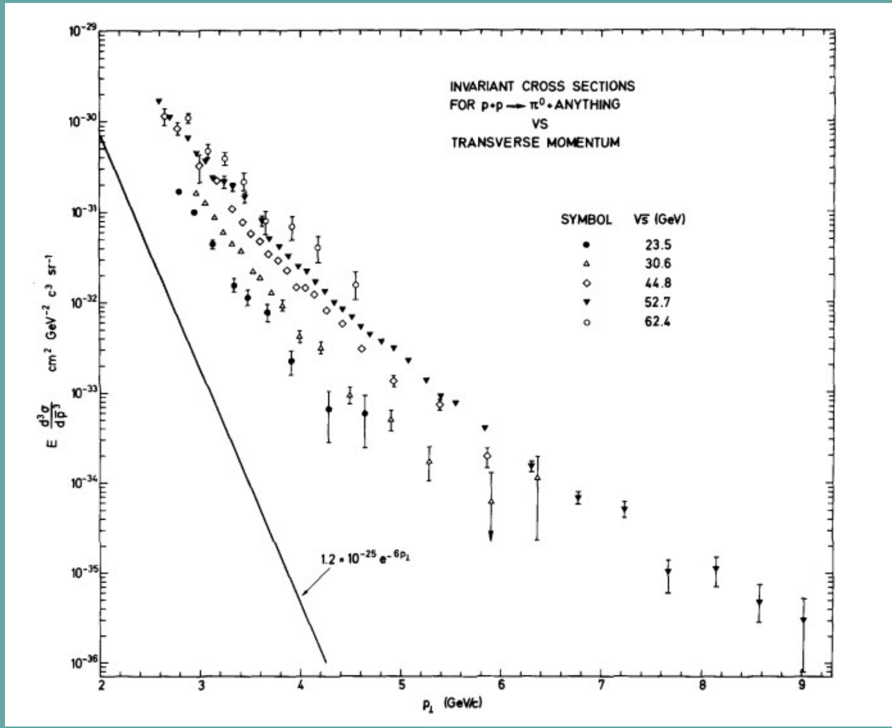


Fig. 1. View of the apparatus transverse to the beams. A second complete electron spectrometer (not shown) is placed symmetrically to the left.

Burton Richter in 1977 with the future CERN DG Christopher Llewellyn Smith

The pioneering legacy result from the ISR:

Large transverse momentum phenomena became evident, characteristic of parton scattering at hadron colliders

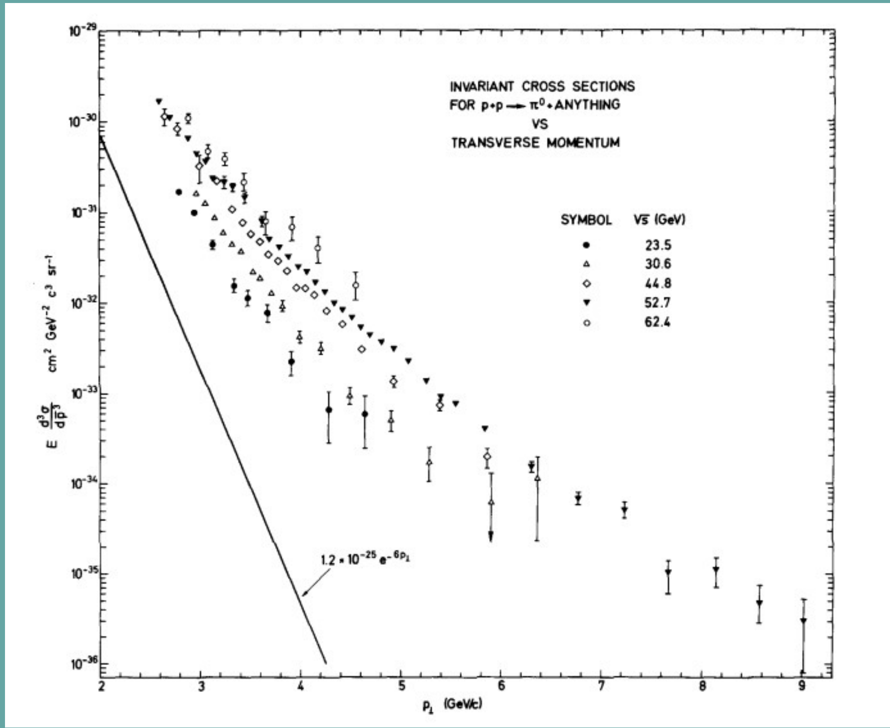


Observed by 3 experiments, shown are the 1973 inclusive π^o cross-sections at 90^o by R103 in 1973

Phys. Lett. B 46 (1973) 471

The pioneering legacy result from the ISR:

Large transverse momentum phenomena became evident, characteristic of parton scattering at hadron colliders



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

Phys. Lett. B 46 (1973) 471

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

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

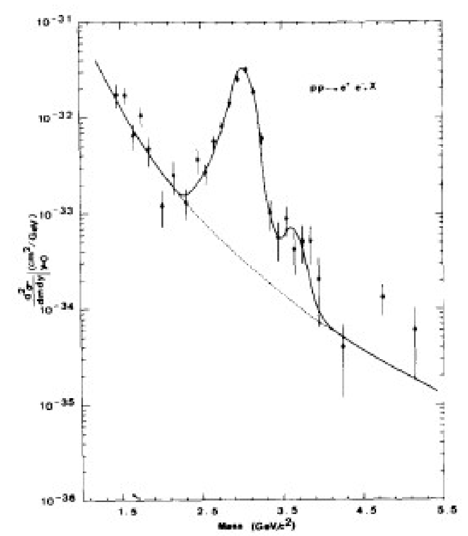


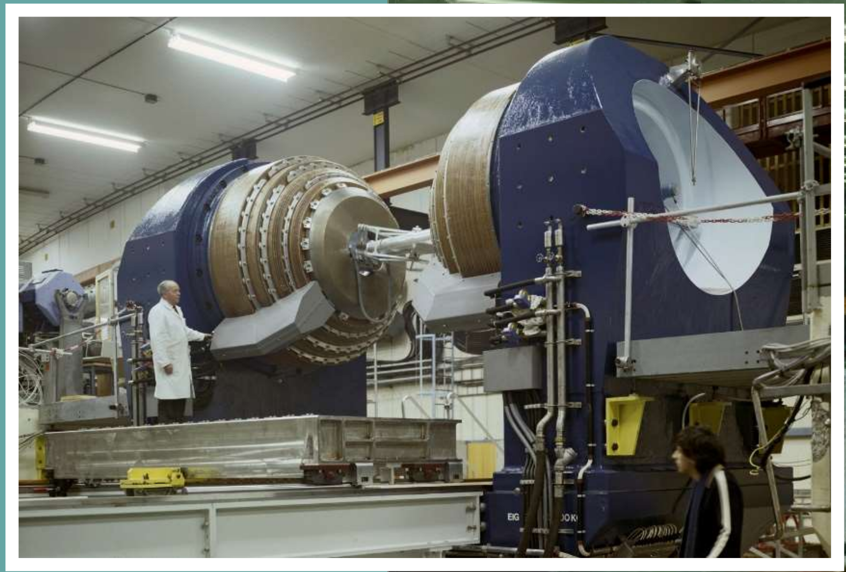
Fig. 12. The cross section $(d^2\sigma/dmdy)_{y=0}$ for inclusive electron pair production is displayed as a function of the pair mass. The line is the result of the fit described in subsect. 4.2.

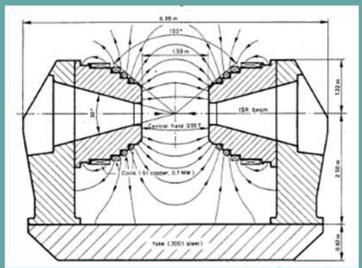
J/Ψ and Ψ' peaks from decays into e+e- pairs from R702 in 1978

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

The J/Ψ discovery of SLAC and Brookhaven of 1974 ('November revolution') was missed because of initially lacking low mass electron triggers, slow DAQ, and limited solid angle coverage …

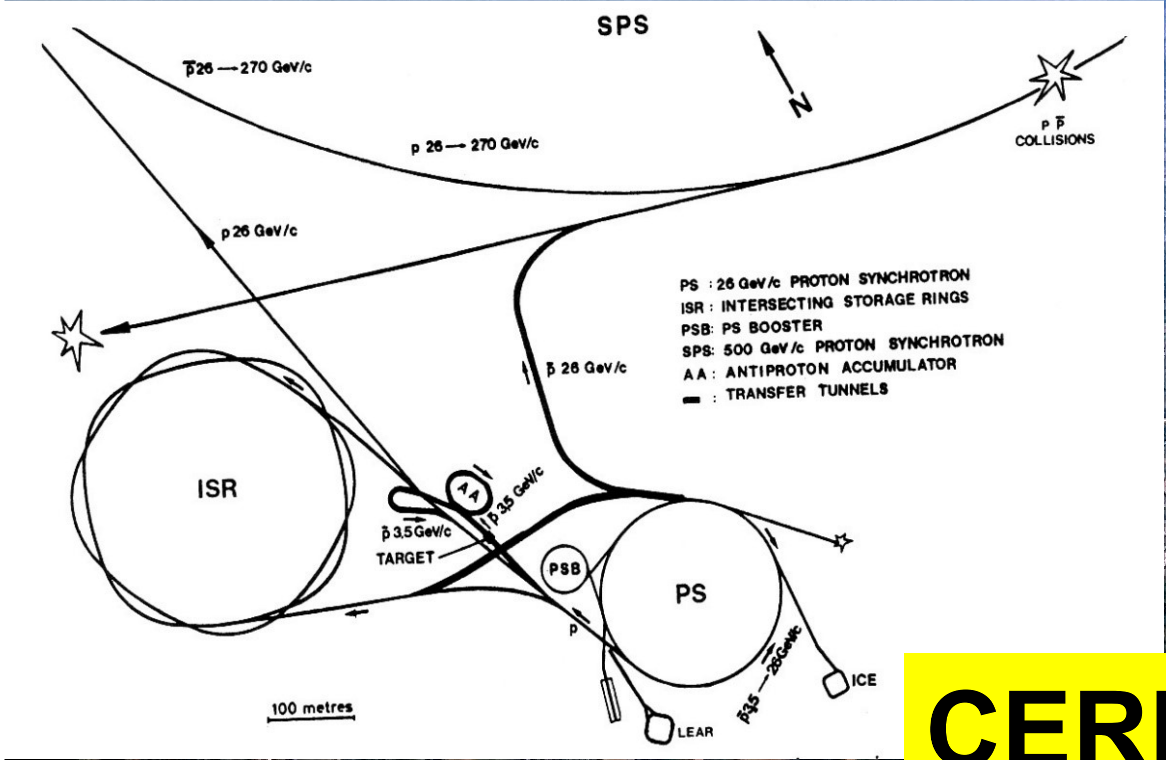
The last generation detectors, here the Axial Field Spectrometer R807/8, were closer to general purpose collider detectors as we know them now





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

CERN SPS $p\bar{p}$ Collider



1981 - 1990

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}

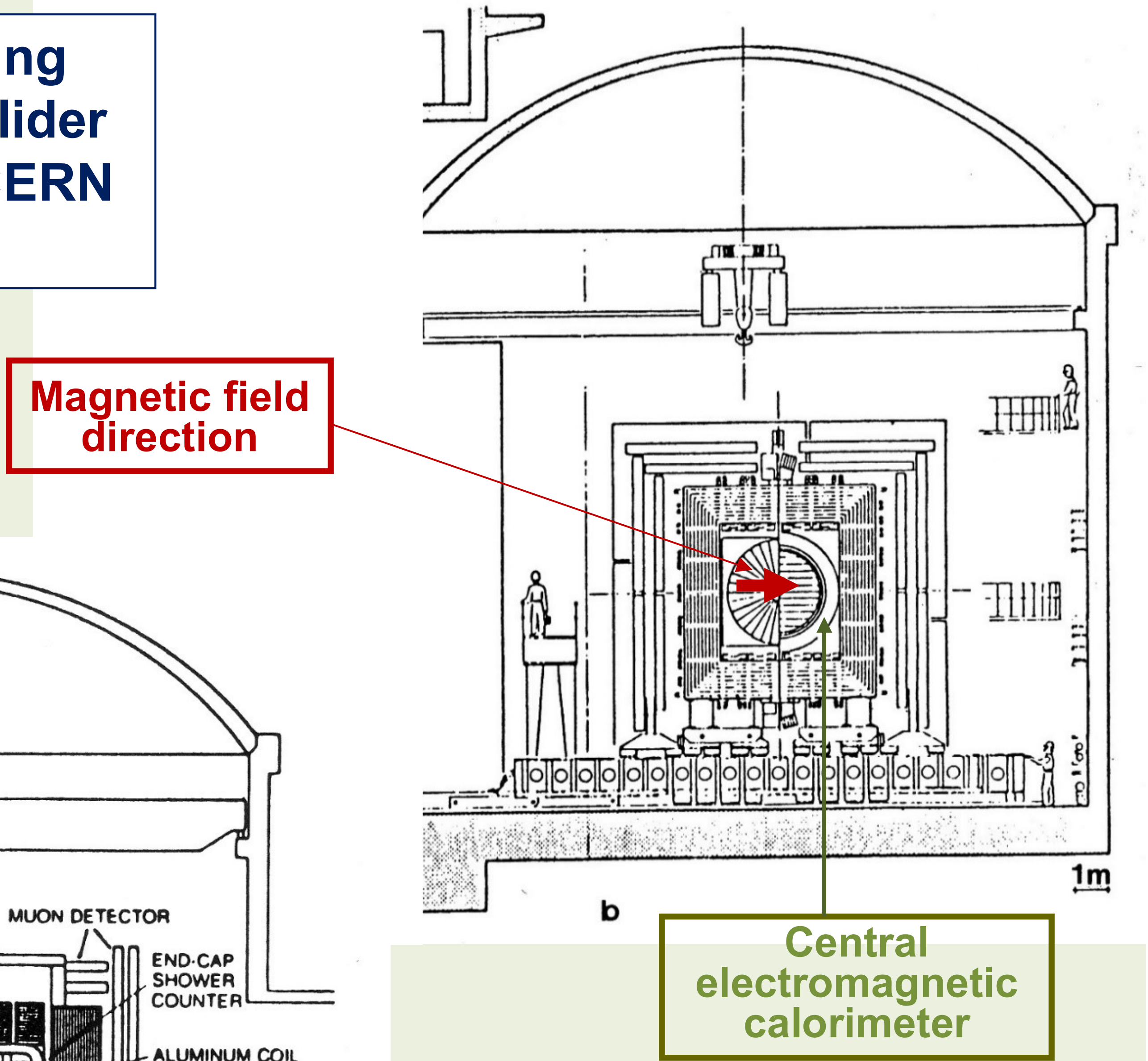
Unambiguous jets

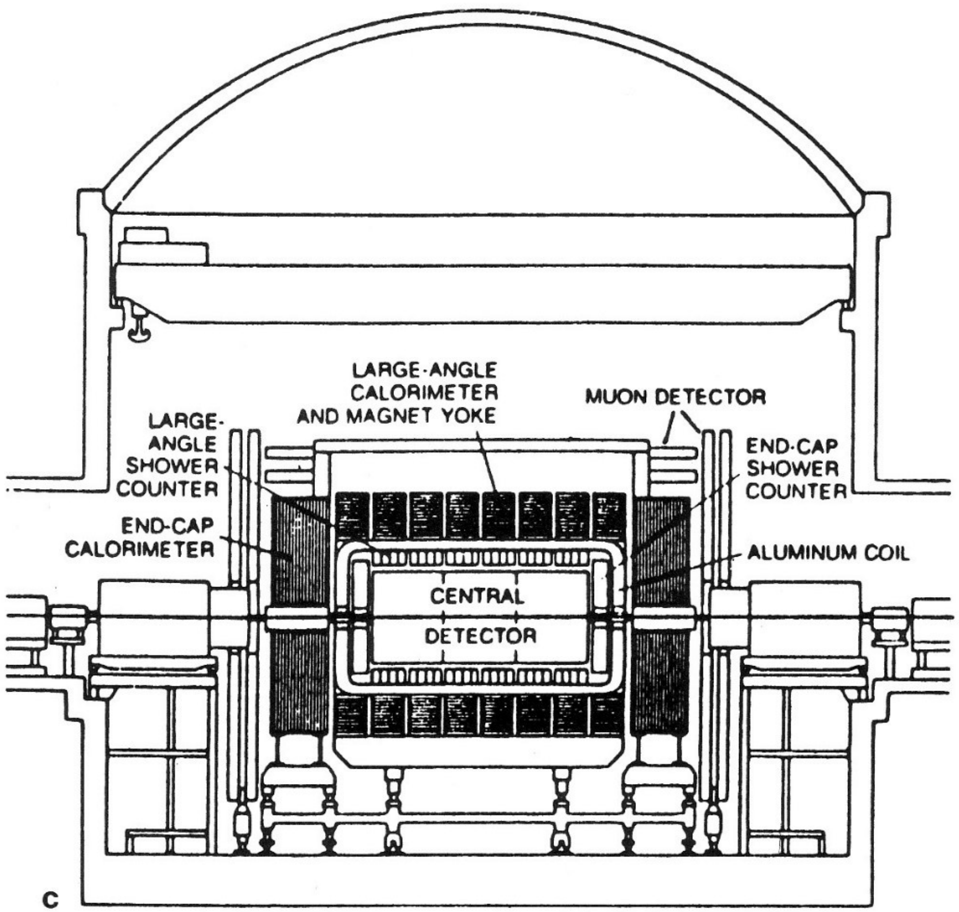
W discovery

Z discovery

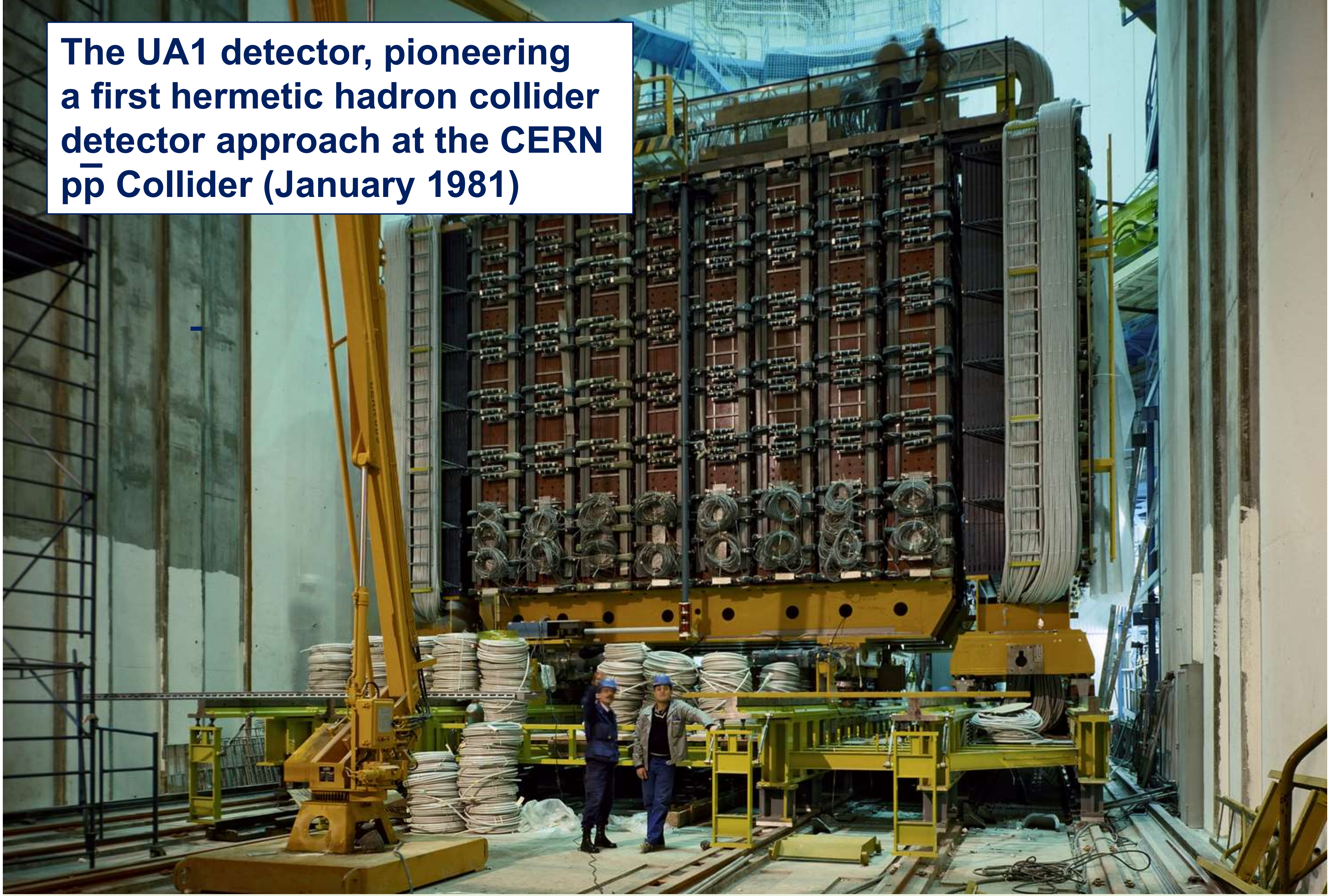
Searches for top, SUSY, and m_W measurements, $B^o - B^o$ mixing

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

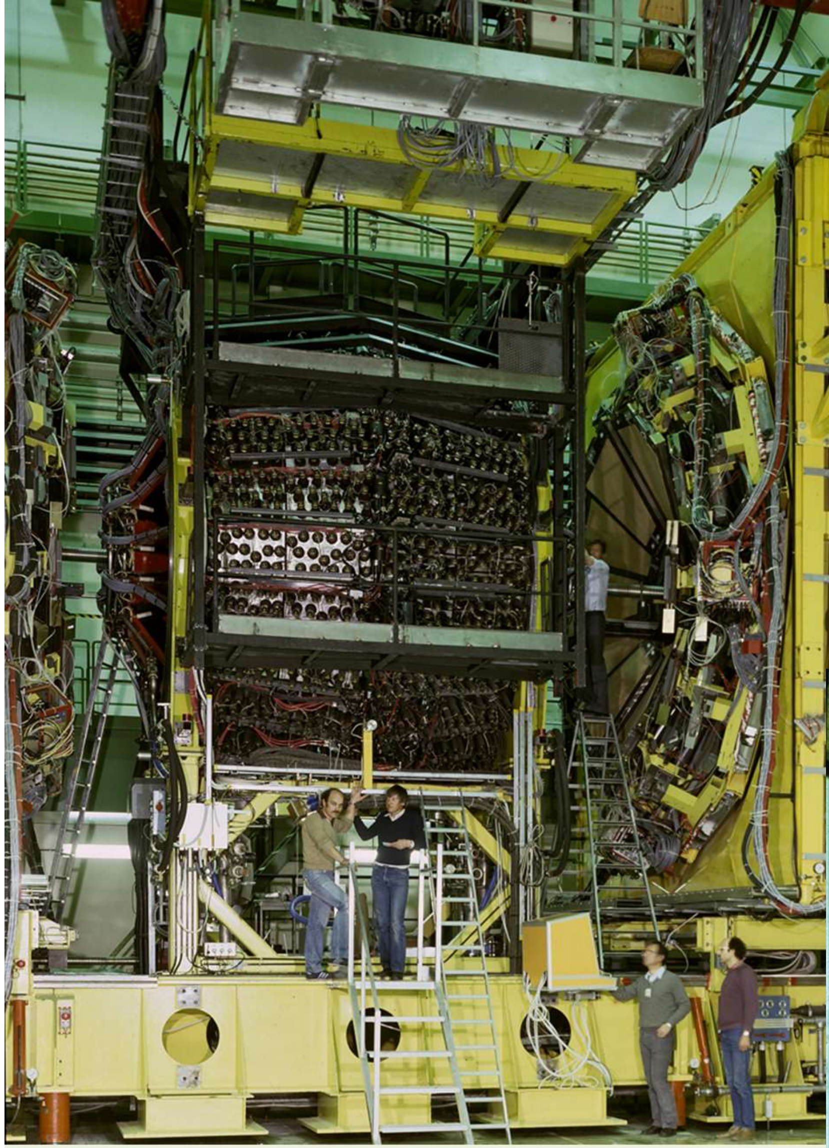




The UA1 detector, pioneering a first hermetic hadron collider detector approach at the CERN $p\bar{p}$ Collider (January 1981)

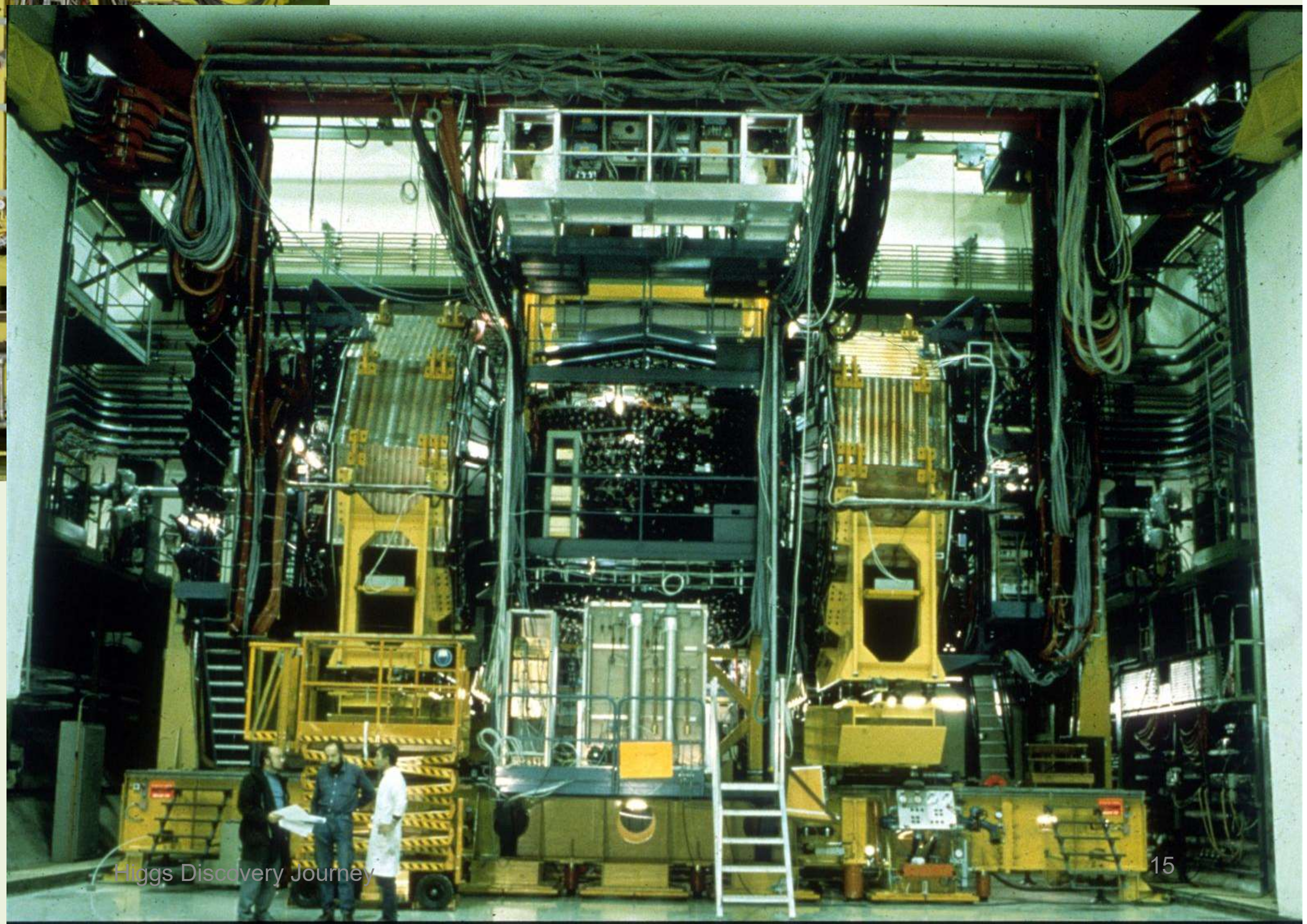


The UA2 detector
('highly' segmented, central calorimeter with pointing cells, but no muon detection)



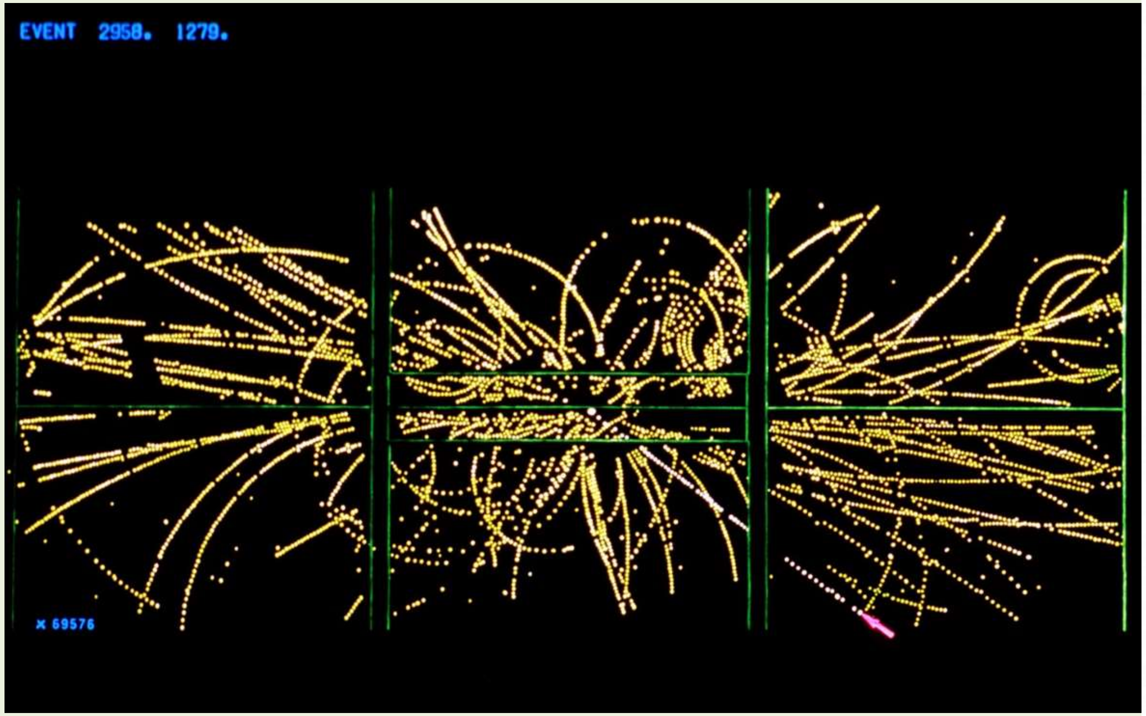
UA2 1981-85
(toroid forward magnets)

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

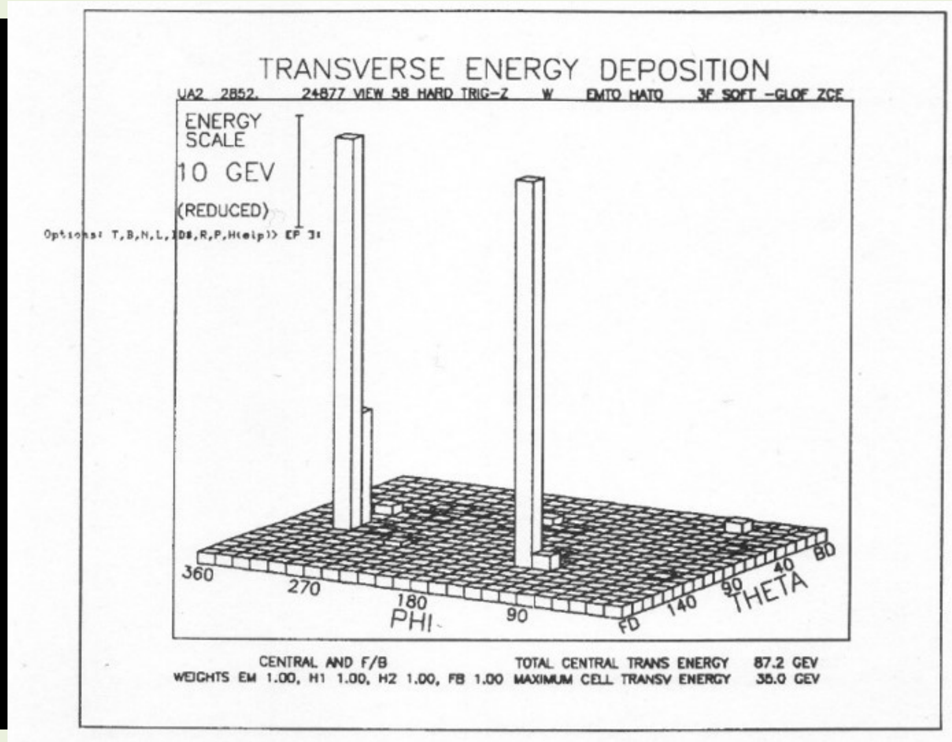


W and Z boson discovery (1982/3)

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

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)

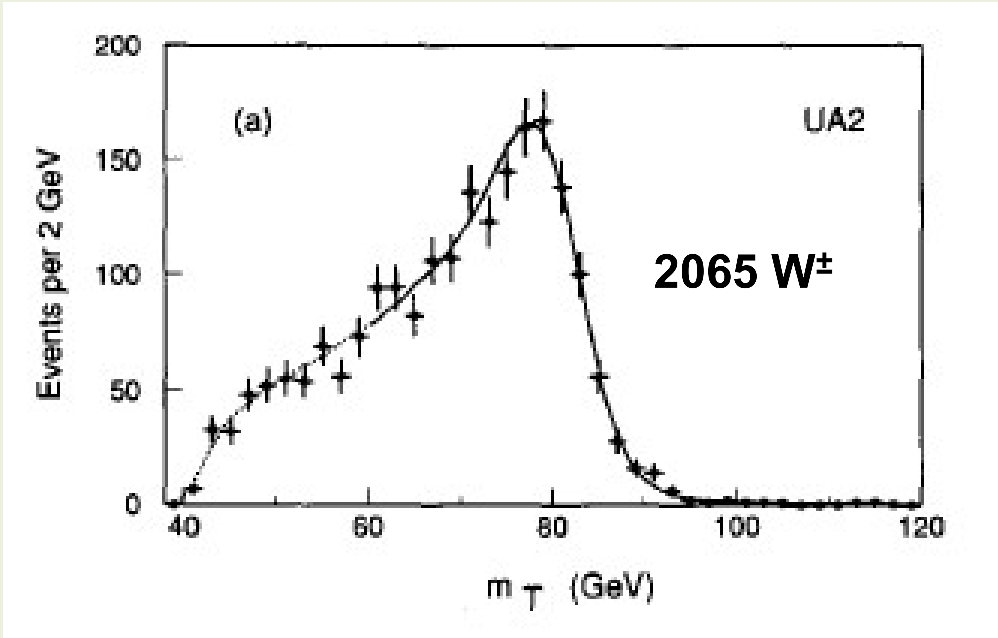
$r = 0.8813 \pm 0.0036 \pm 0.0019$

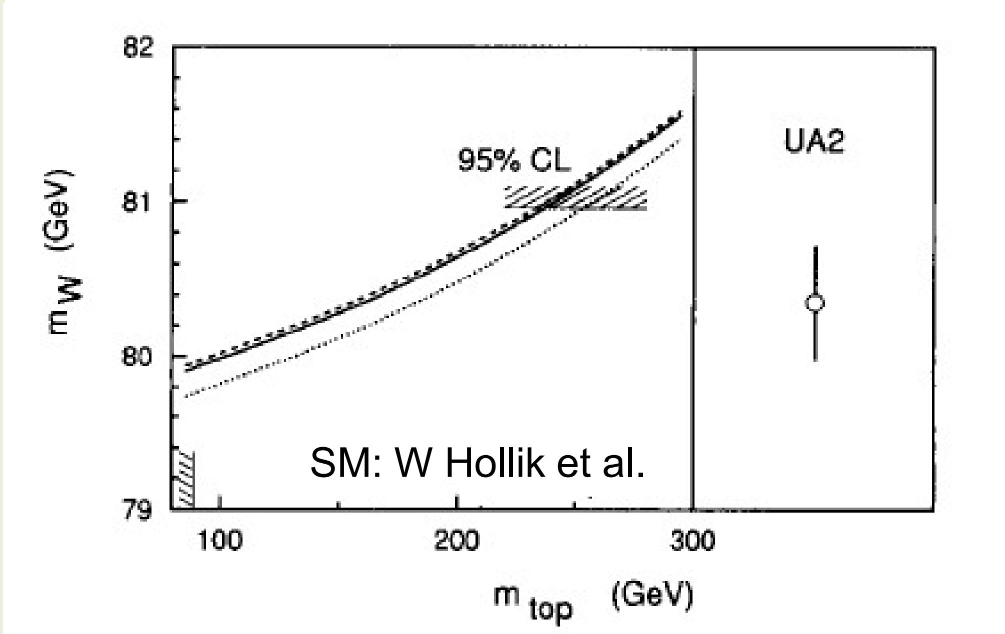
yielding $m_W = 80.35 \pm 0.33 \pm 0.17$ GeV

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

Phys. Lett. B276 (1992) 354-364





COMETA Special:

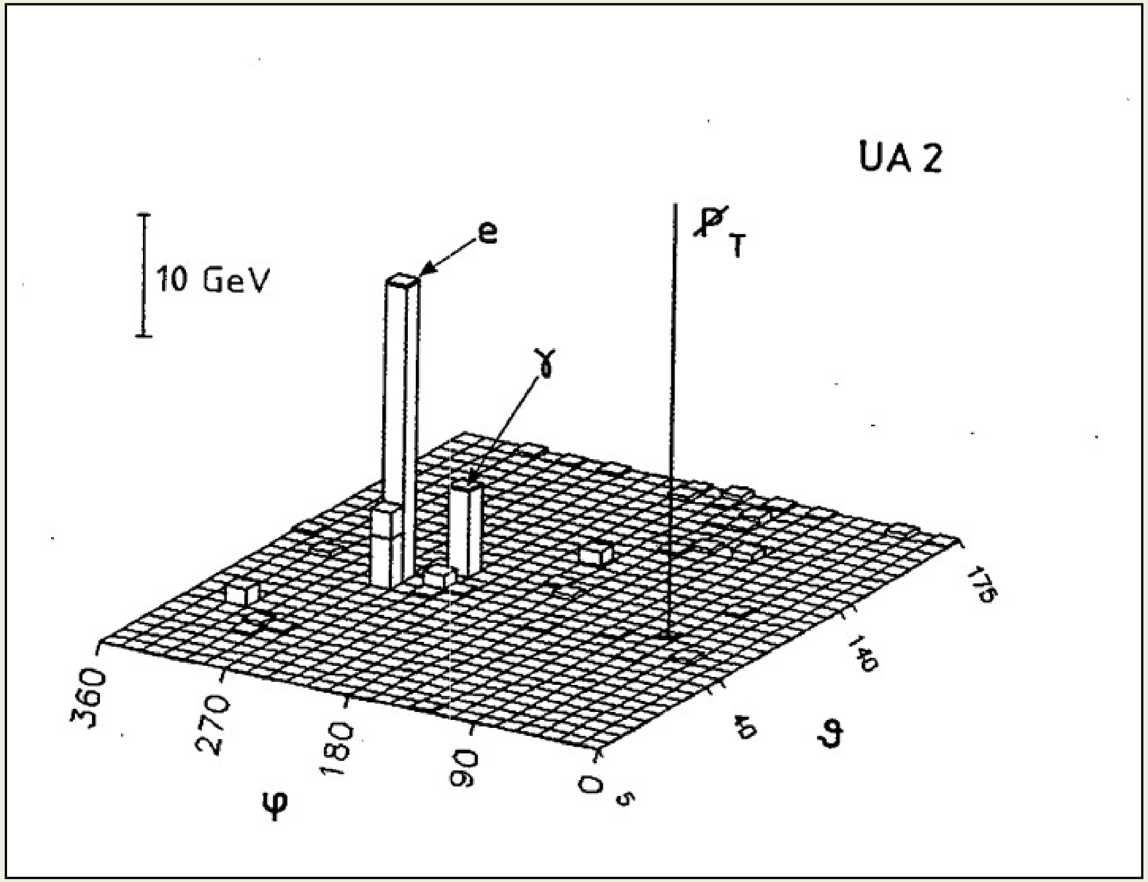
At the end of the CERN proton-antiproton collider, also the first observation of Wγ boson pair production was published by UA2

16 eνγ + X events observed, with a background of 6.8 ± 1.0

First constraints on the WWγ coupling

6. CONCLUSIONS

A first direct measurement of the coupling of the W boson to the photon has been performed at the CERN $\bar{p}p$ collider. The parameter κ has been measured to be $1^{+2.6}_{-2.2}$ with $-3.5 < \kappa < 5.9$ as its 95% confidence limits. The parameter λ has been measured to be $0^{+1.7}_{-1.8}$ with $-3.6 < \lambda < 3.5$ as its 95% confidence limits. The measurements do not depend on any cutoffs or regularization schemes and are in good agreement with expectations from the Standard Model.



Phys. Lett. B277 (1992) 194-202

Tevatron Collider, CDF and DØ experiments: a legacy inpact on the SM (Fermilab, near Chicago, US, 1987 – 2011): 2 TeV, 6.3 km circumference)

Tevatron proton-antiproton Collider run and performance history

<u>Run 0</u> (1987 – 1988):

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

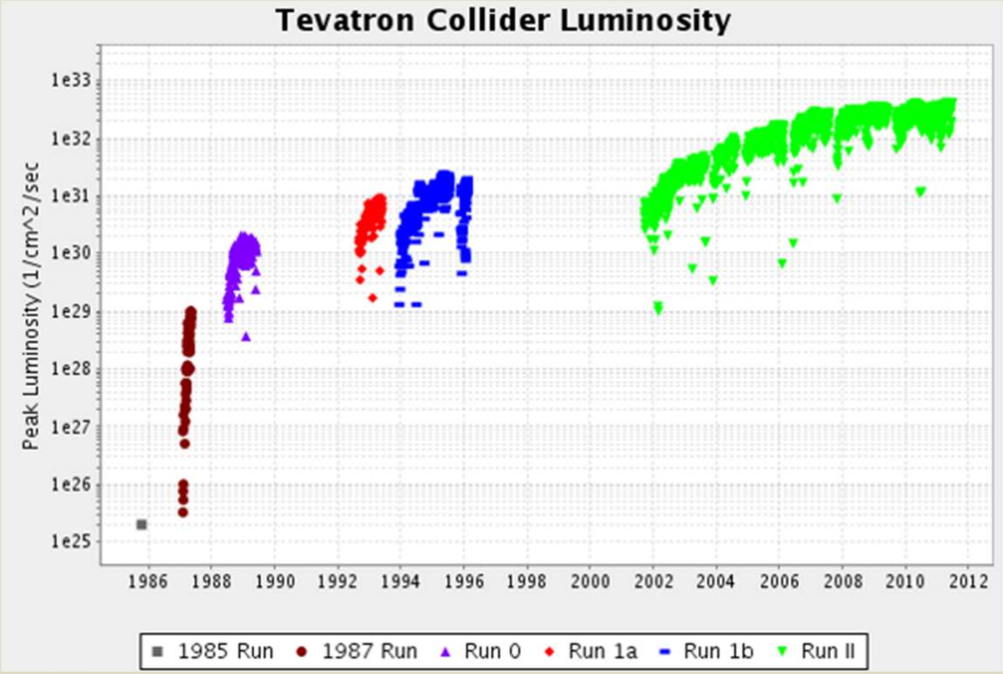
<u>Run I</u> (1992 – 1996):

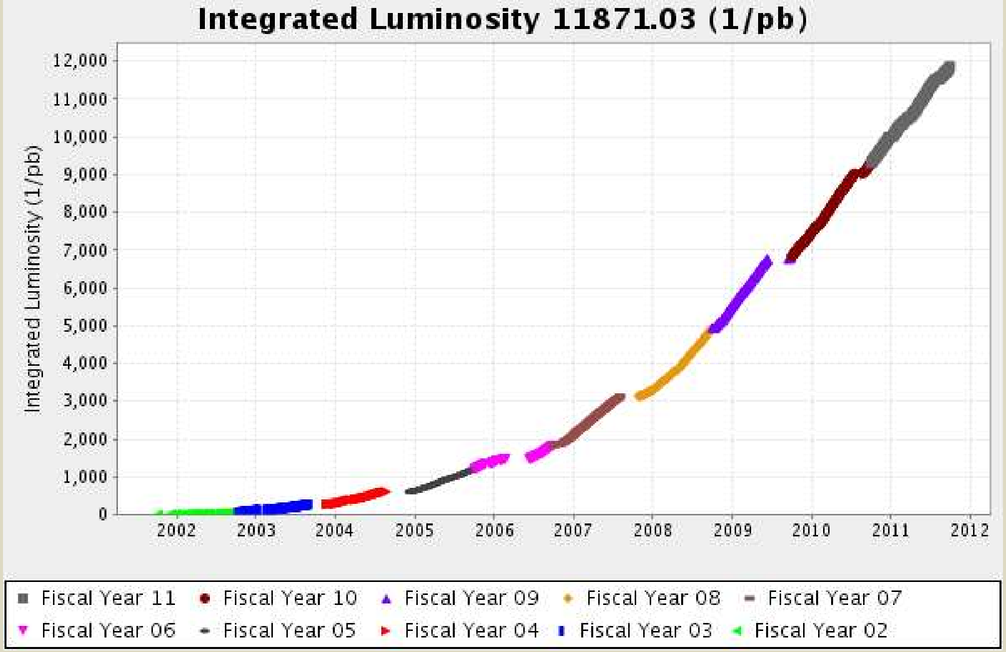
1.8 TeV, CDF+DØ: 120 pb^{-1}

<u>Run II</u> (2001 – 2011):

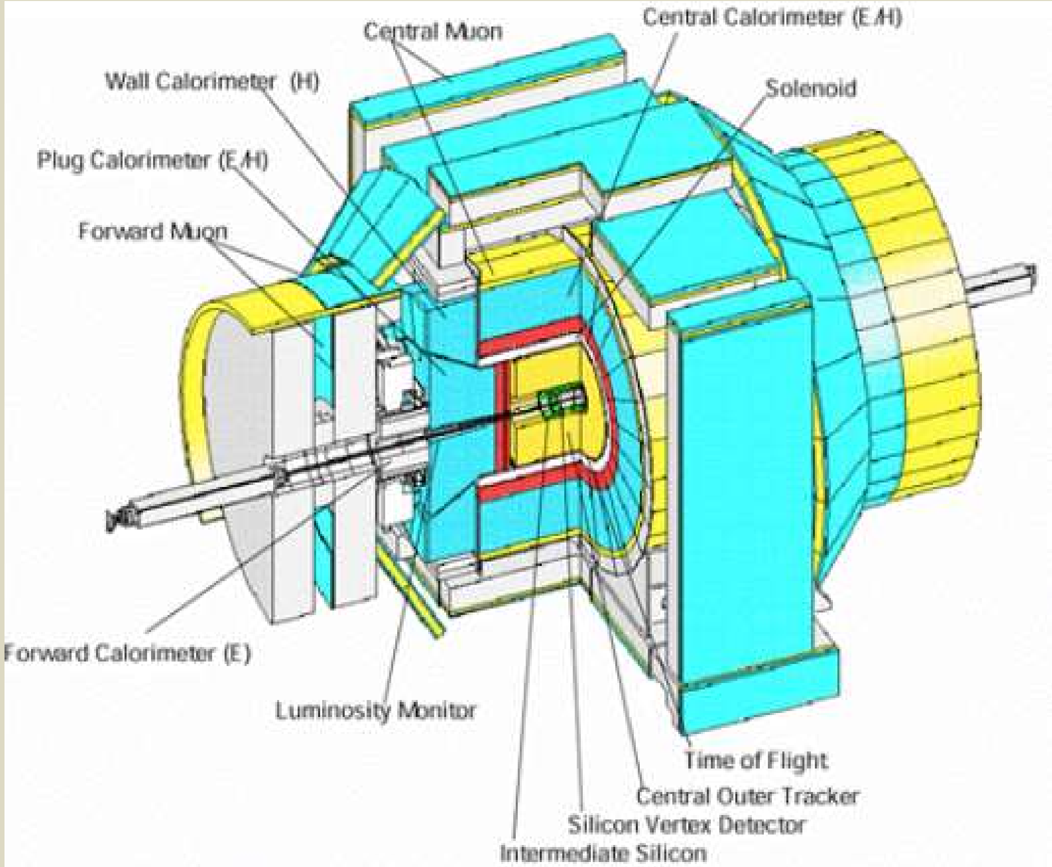
1.96 TeV, 12 fb^{-1}

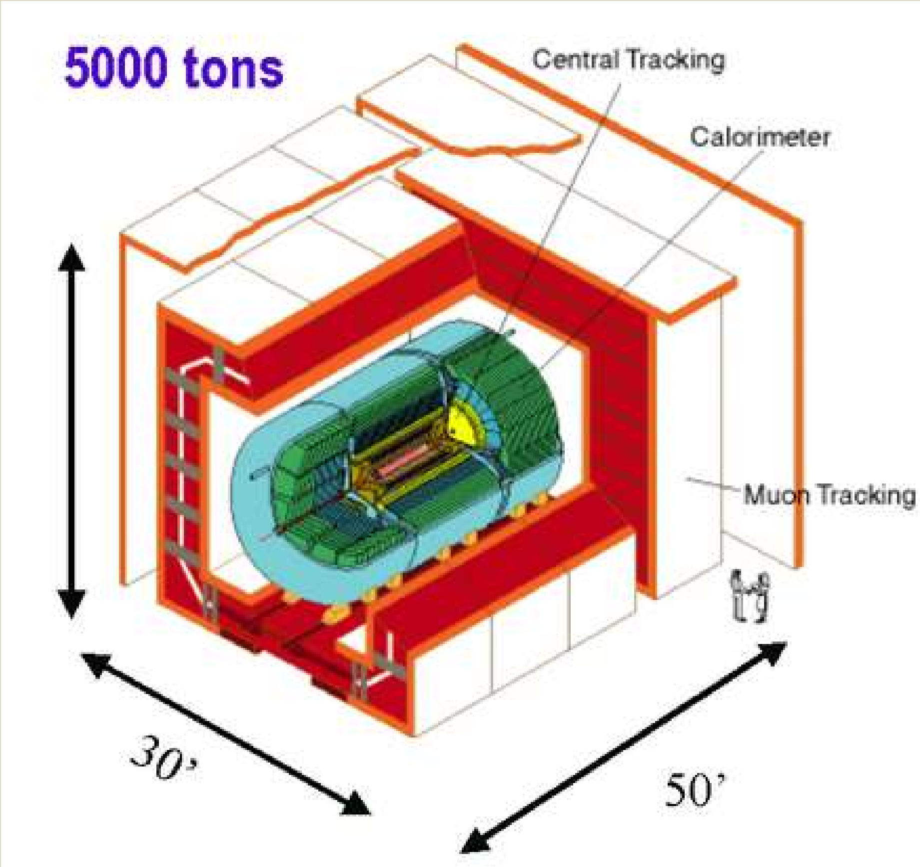
→ Great performance with added Main Injector, Recycler Ring …





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 drawings for the Run II detectors.)

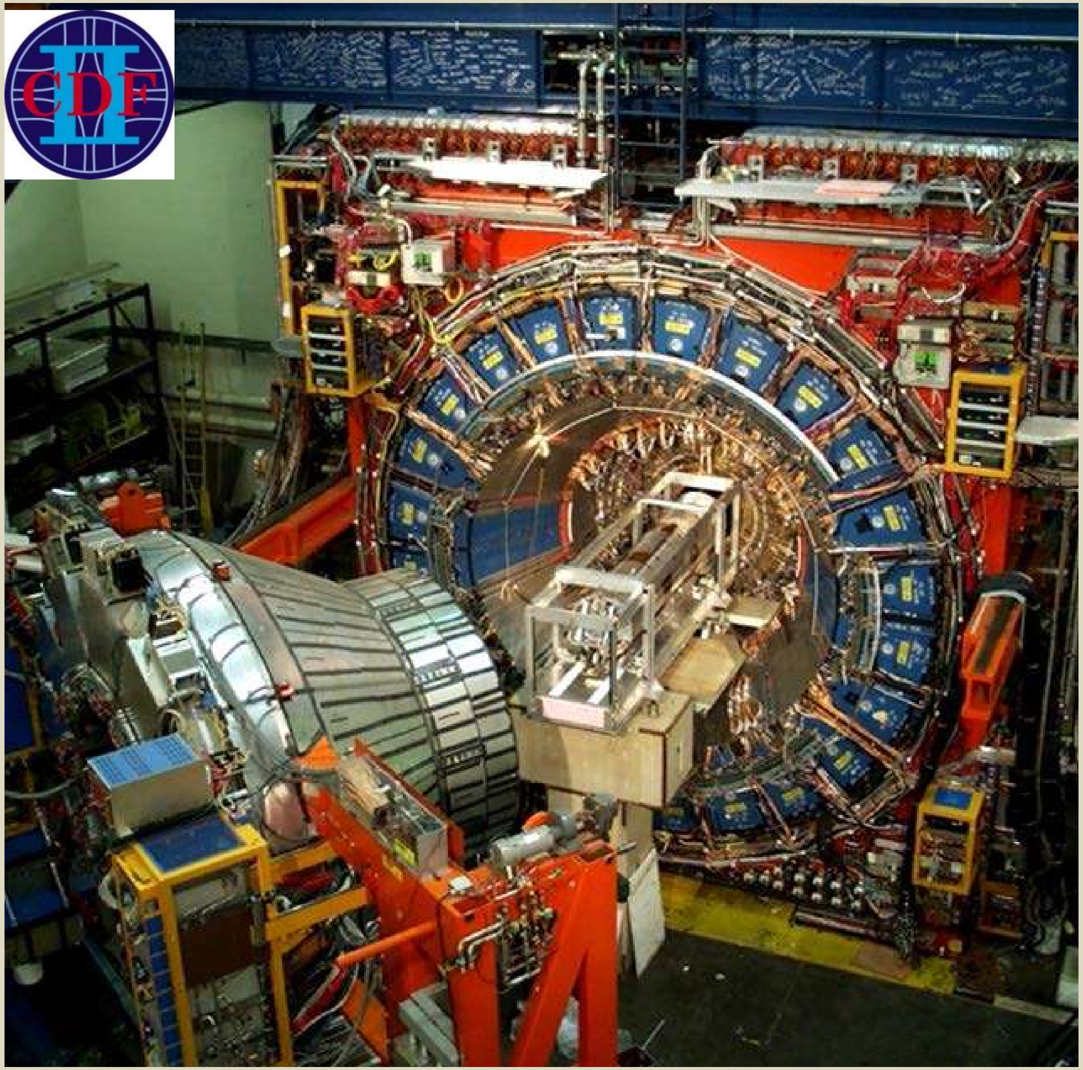




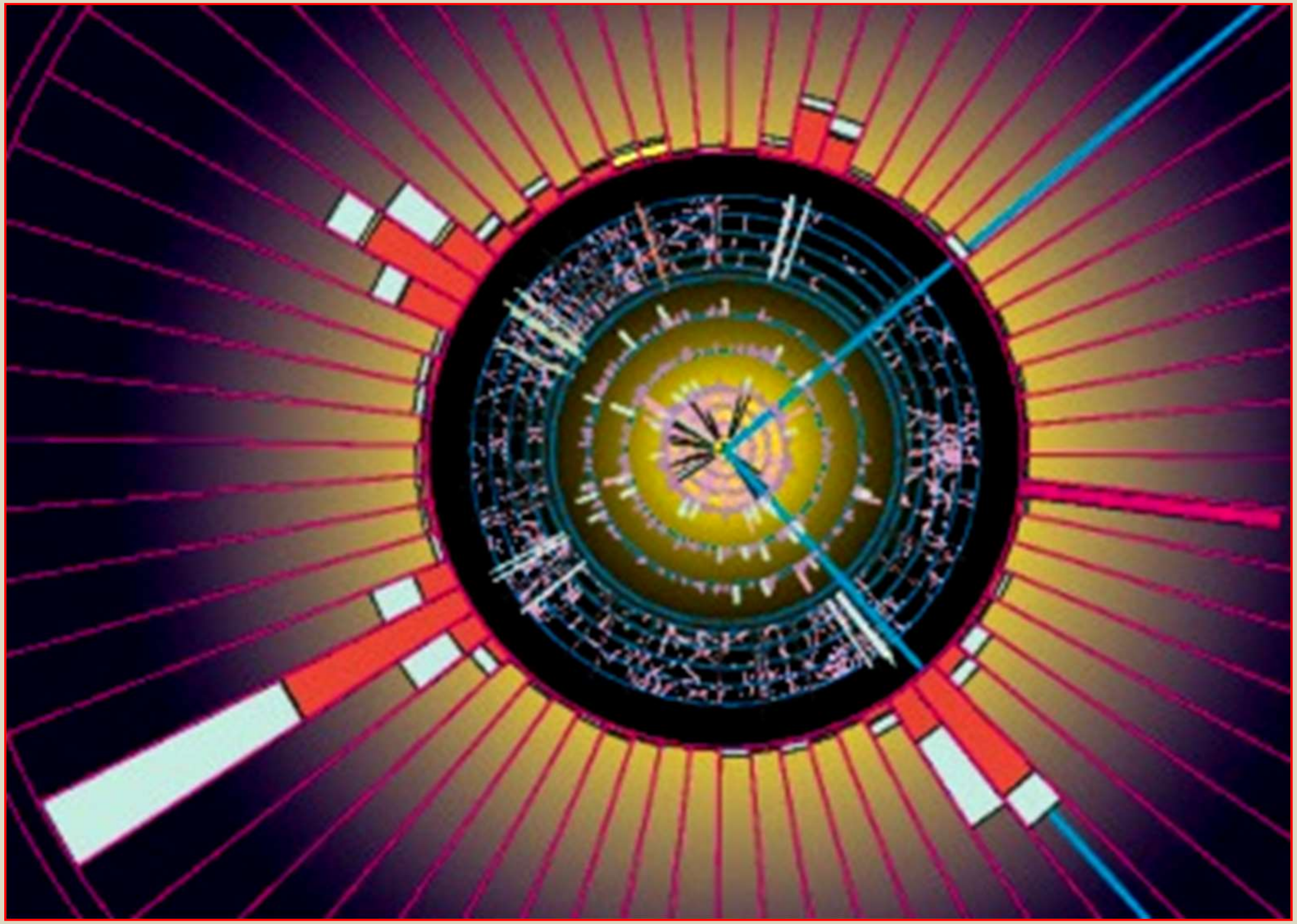
CDF

DØ

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.)

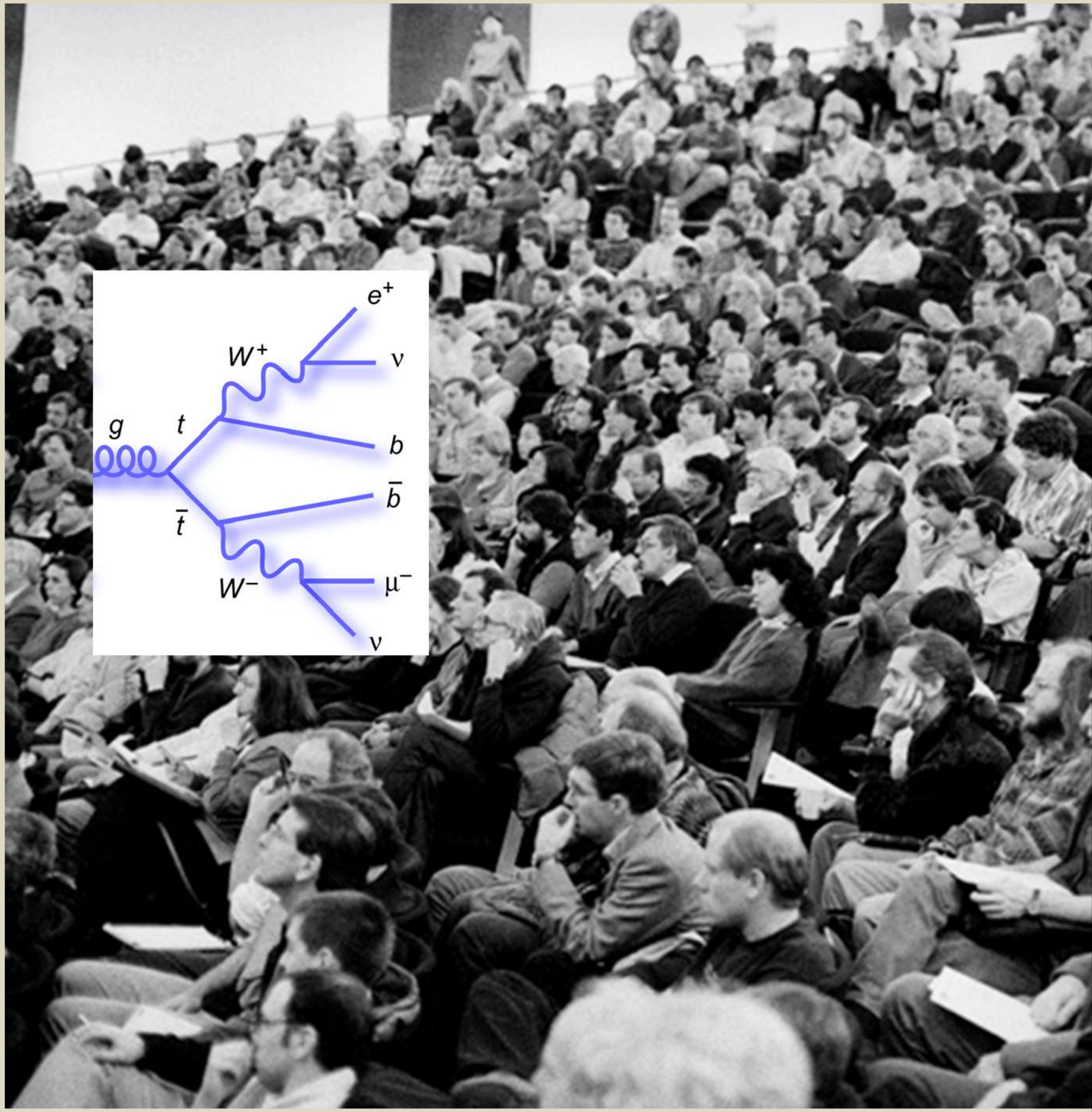


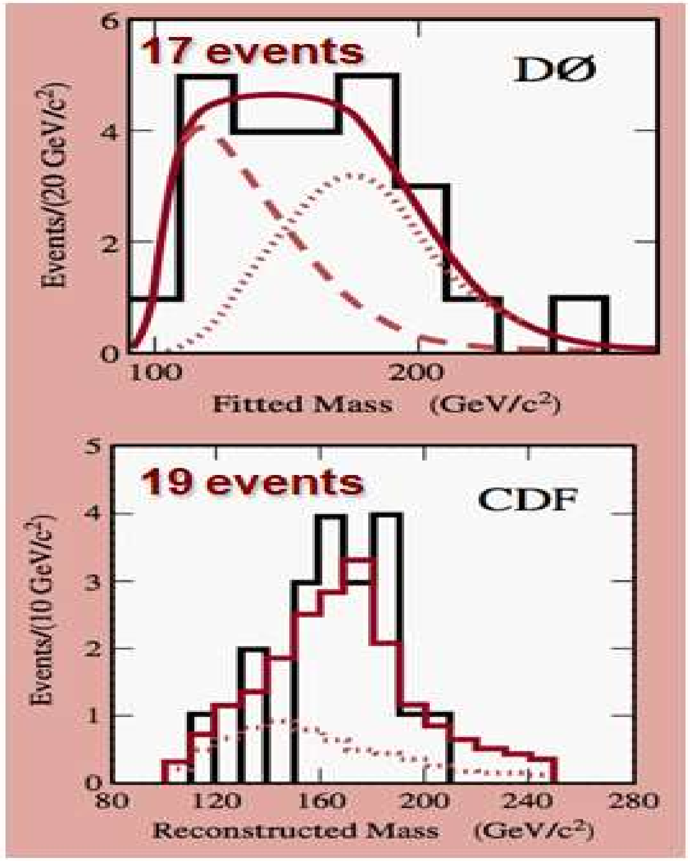
The CDF and D0 Collaborations pioneered many of the modern analysis methods that are now used and much further developed at LHC



As an example: D0 Run II event display of a top-antitop candidate event

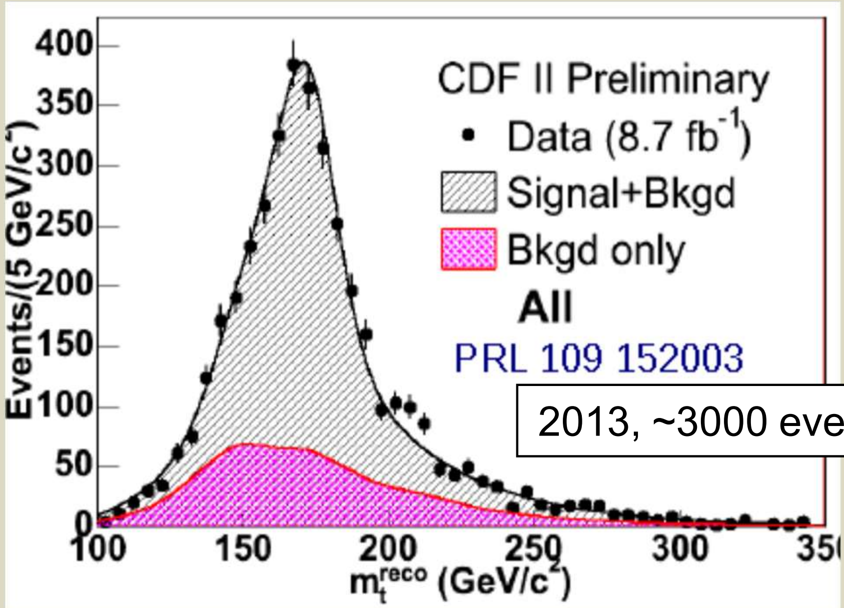
Top quark discovery: Major step establishing the Standard Model
(CDF and DØ, 24th February 1995 papers submitted, 2nd March 1995 joint seminar)





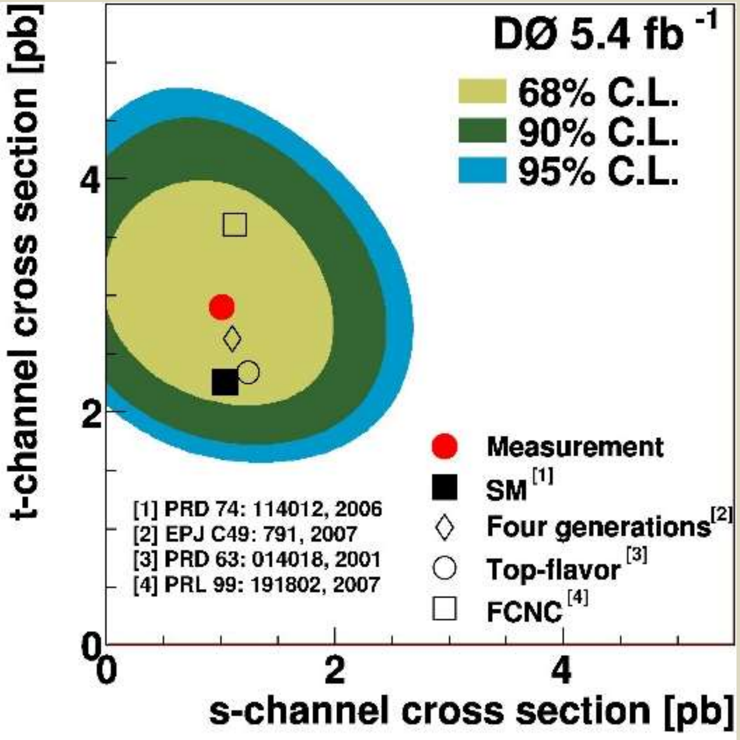
1995, CDF and DØ experiments, Fermilab

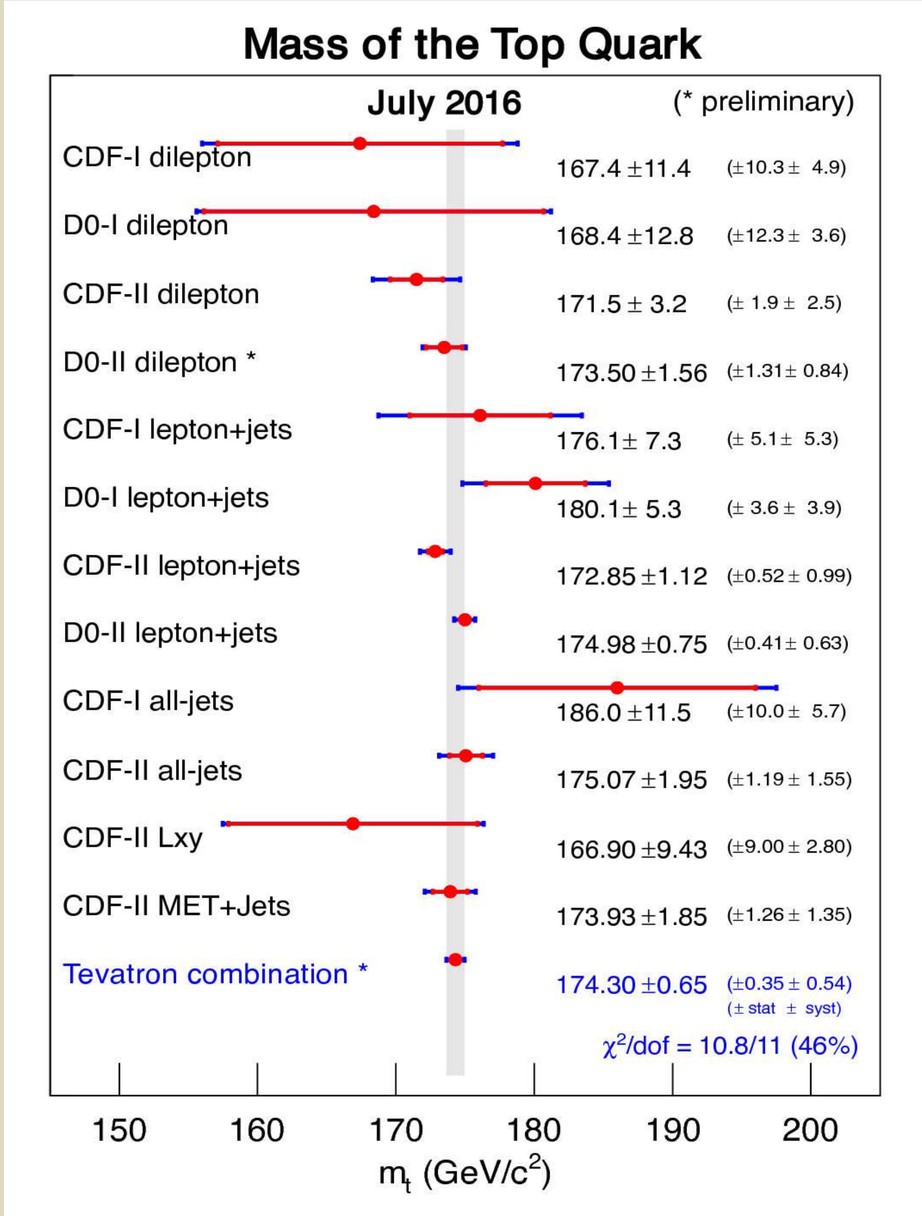
A very rich harvest of top physics followed, just a few examples…



2013, ~3000 events

Single t production discovered 2009, thanks to sophisticated MV methods

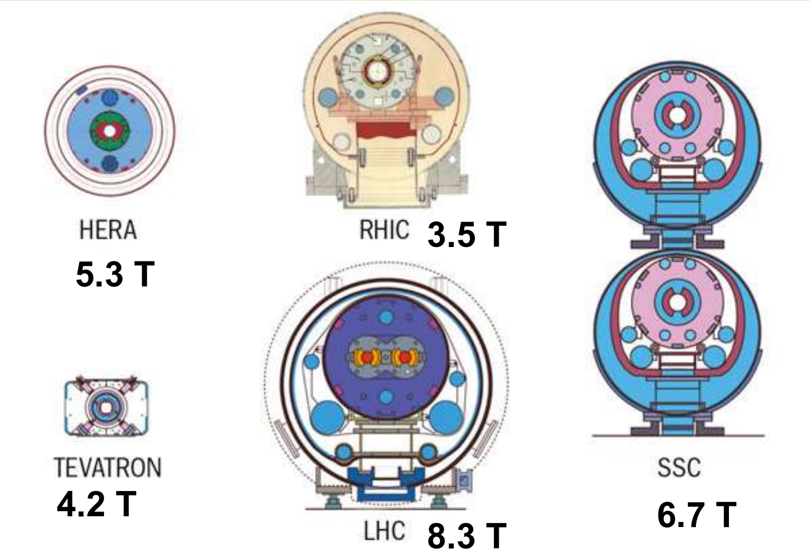


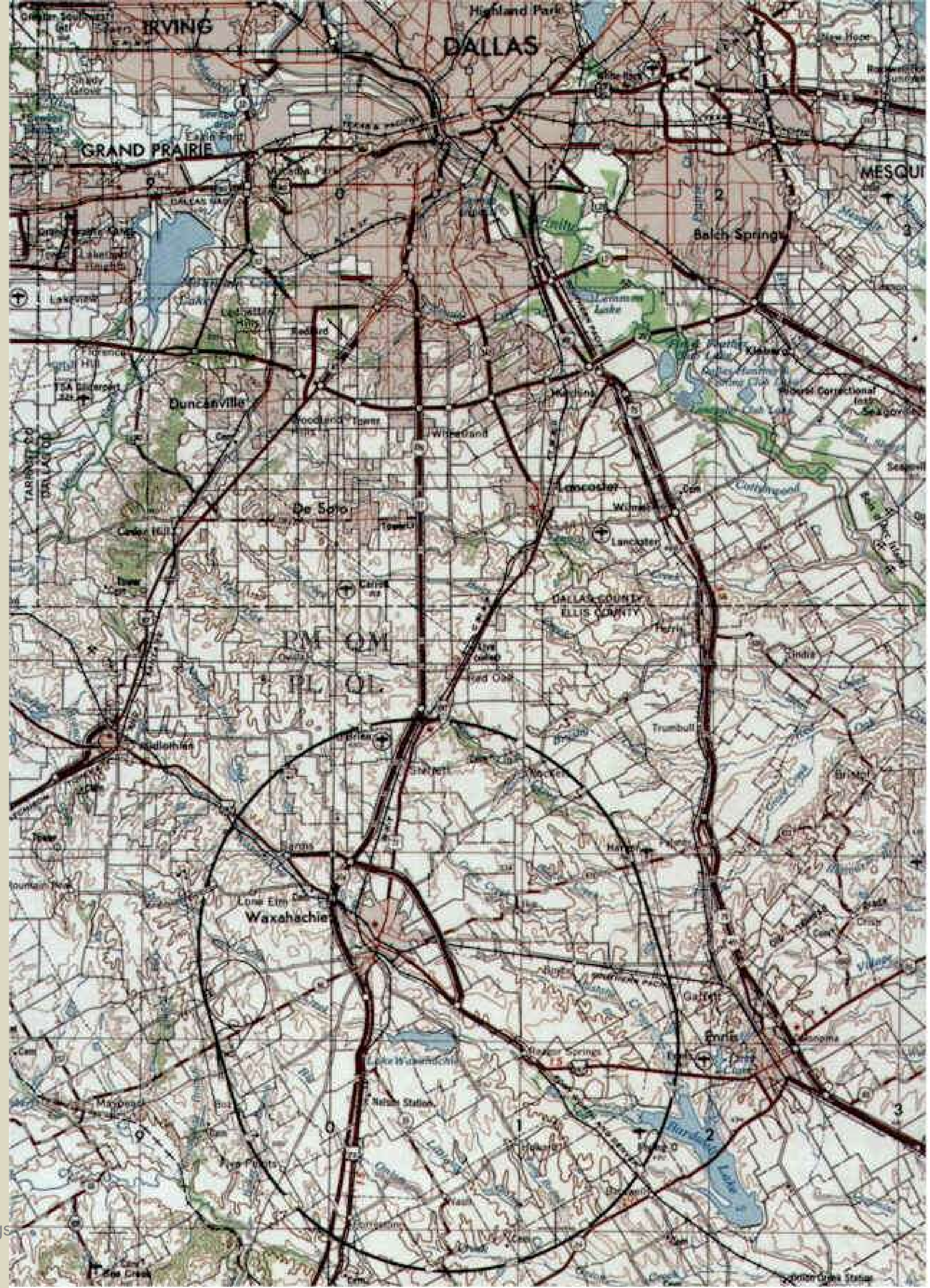


The largest hadron collider that was started, but never finished …

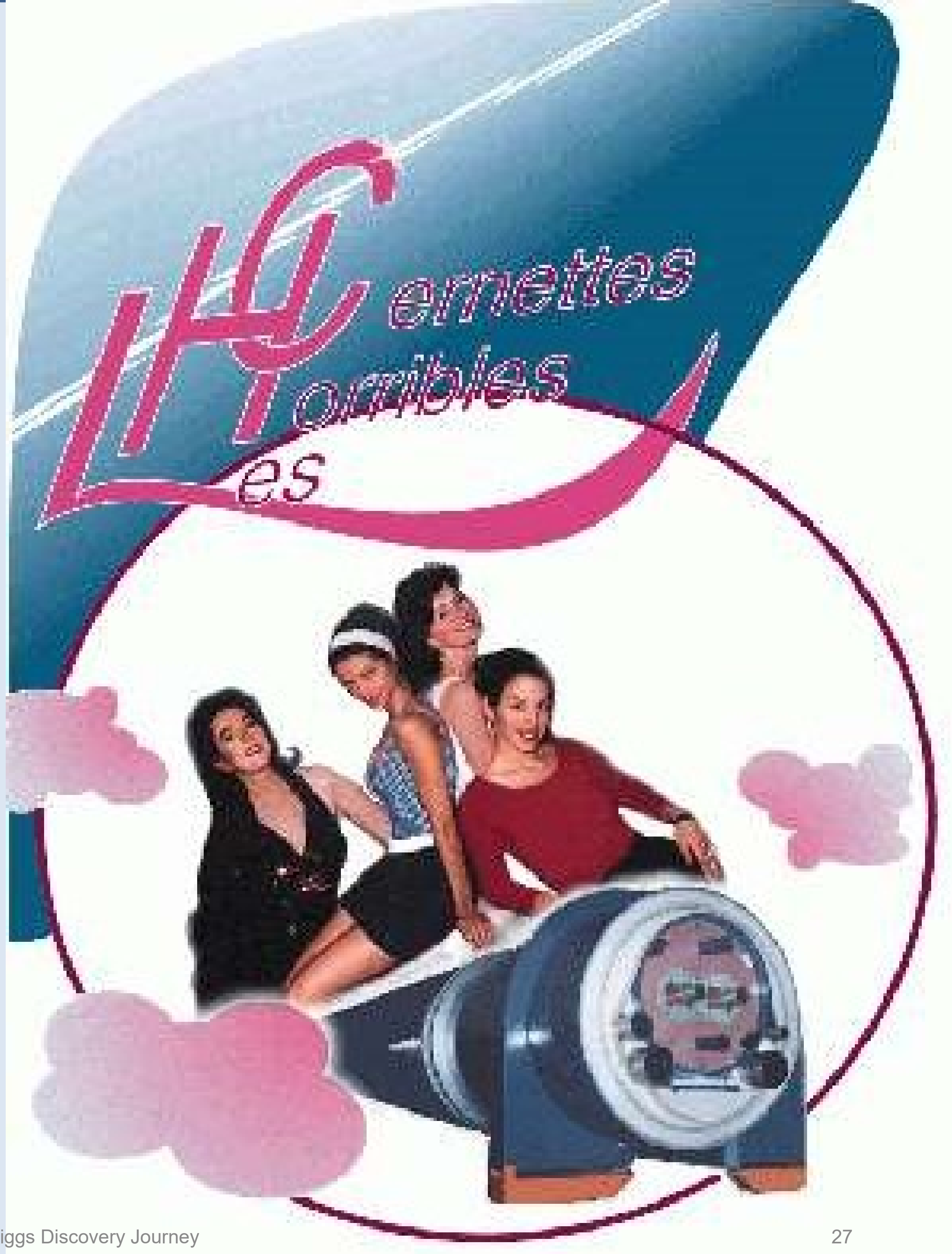
Superconducting Super Collider (SSC)

Circumference	87.1 km
(tunnel at cancellation	~23 km)
Beam energy	20 TeV
Dipole field	6.7 Tesla
Start of the project	~ 1983
Cancellation by Congress	Oct 1993





The first picture on the Web in 1992 !



But focus back now on the LHC and ATLAS history

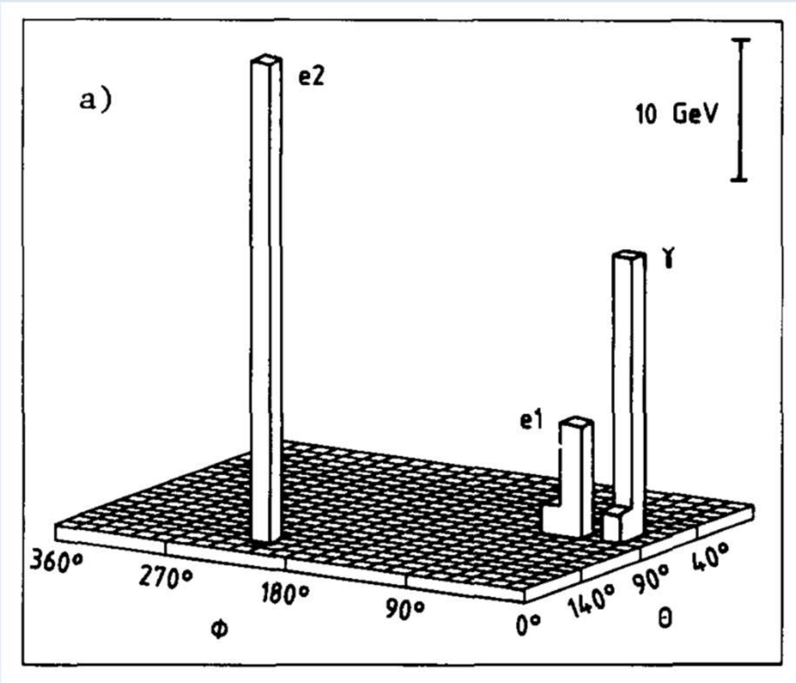
1981 LEP was approved with a large and long (27 km) ring tunnel

Herwig Schopper
CERN DG 1981 – 1988
(Happy birthday,
100 years on 28 February !)

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

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



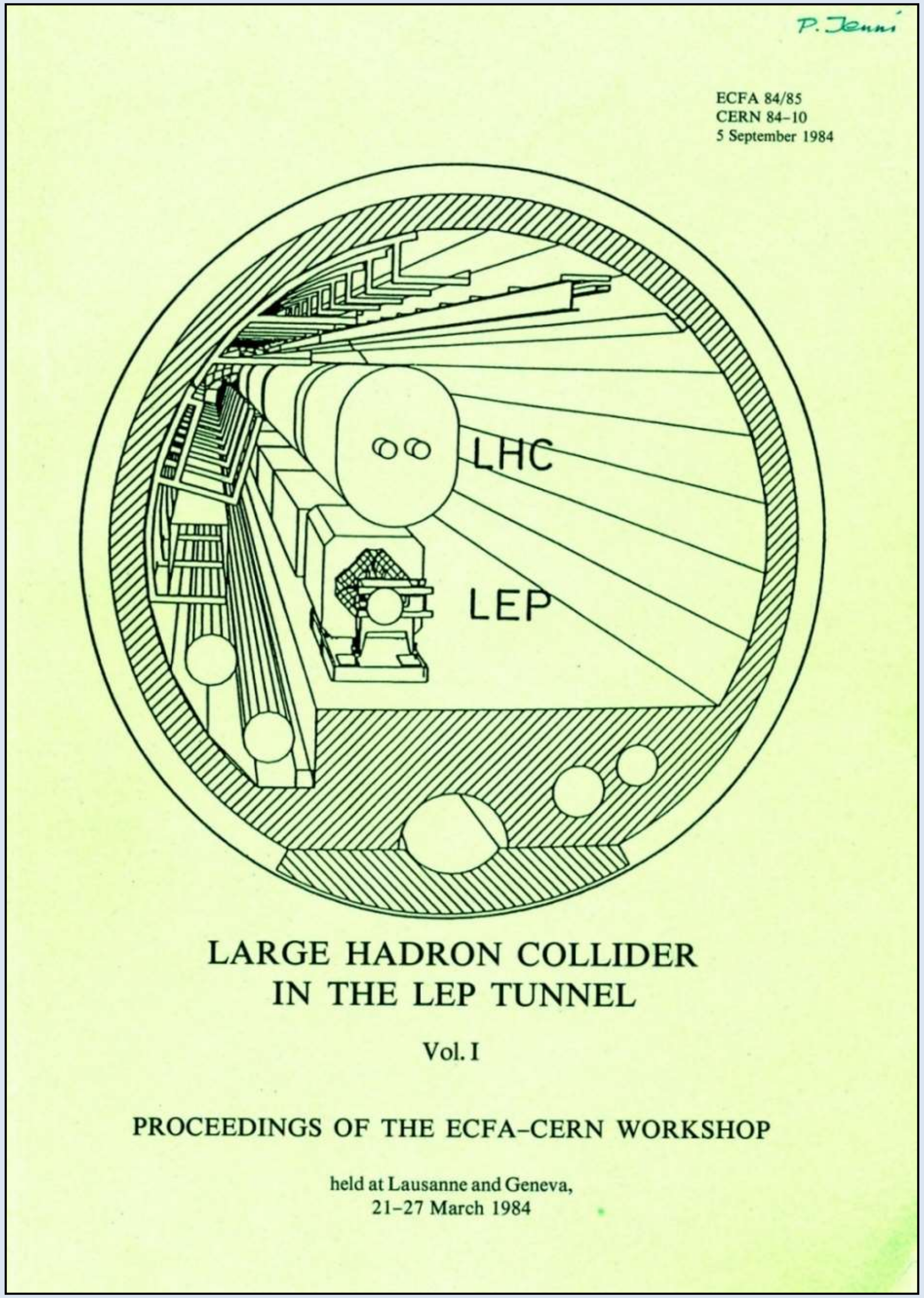
1984 For the community it all started with the CERN - ECFA Workshop in Lausanne on the feasibility of a hadron collider in the future LEP tunnel

Giorgio Brianti was leading the LHC machine studies until 1993

1986 LAA R&D on new detector technologies started, later followed by the DRDC

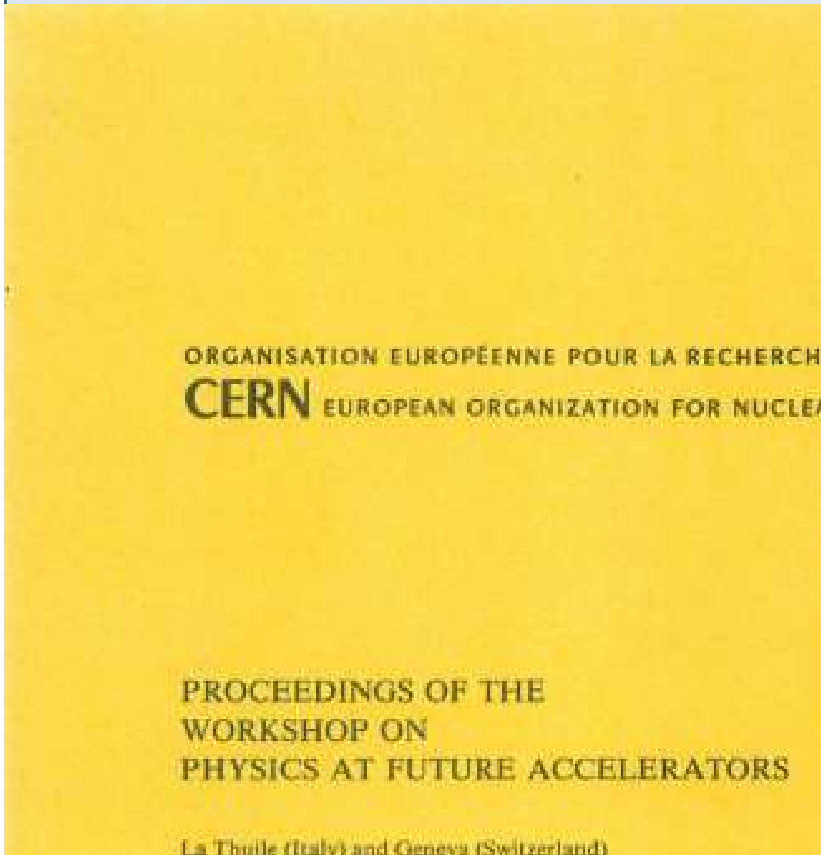
1987 La Thuile Workshop

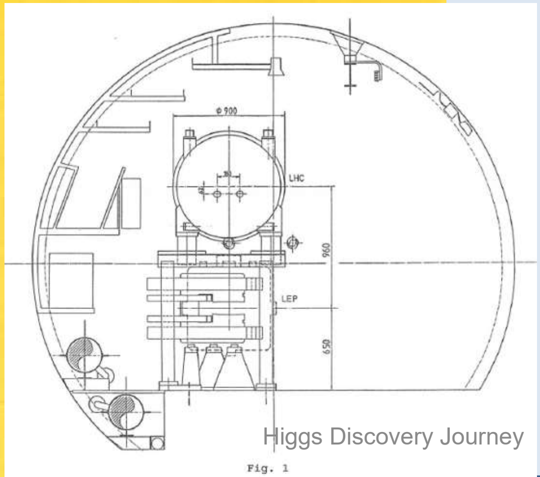
Many LHC colleagues were already involved in this WS set up by Carlo Rubbia as part of the Long Range Planning Committee



La Thuile 7 – 13 January 1987

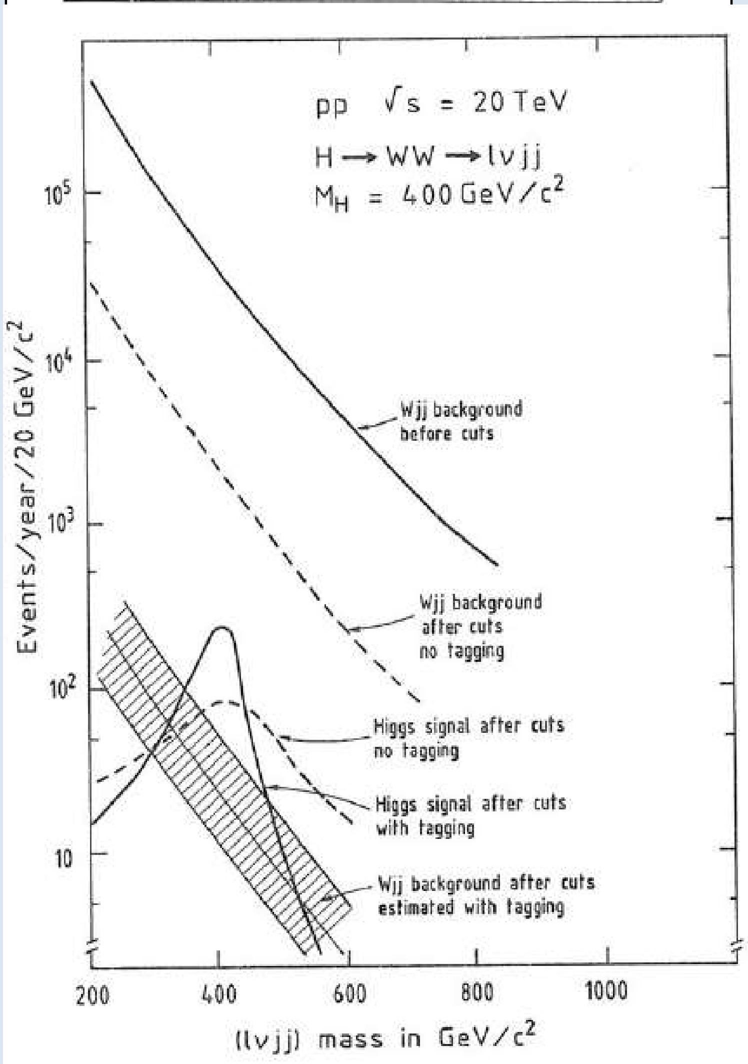
(Carlo Rubbia's Long Range Planning Committee)





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	$10^{33} \rightarrow 10^{34}$



Arguing around 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 $e\mu$ 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

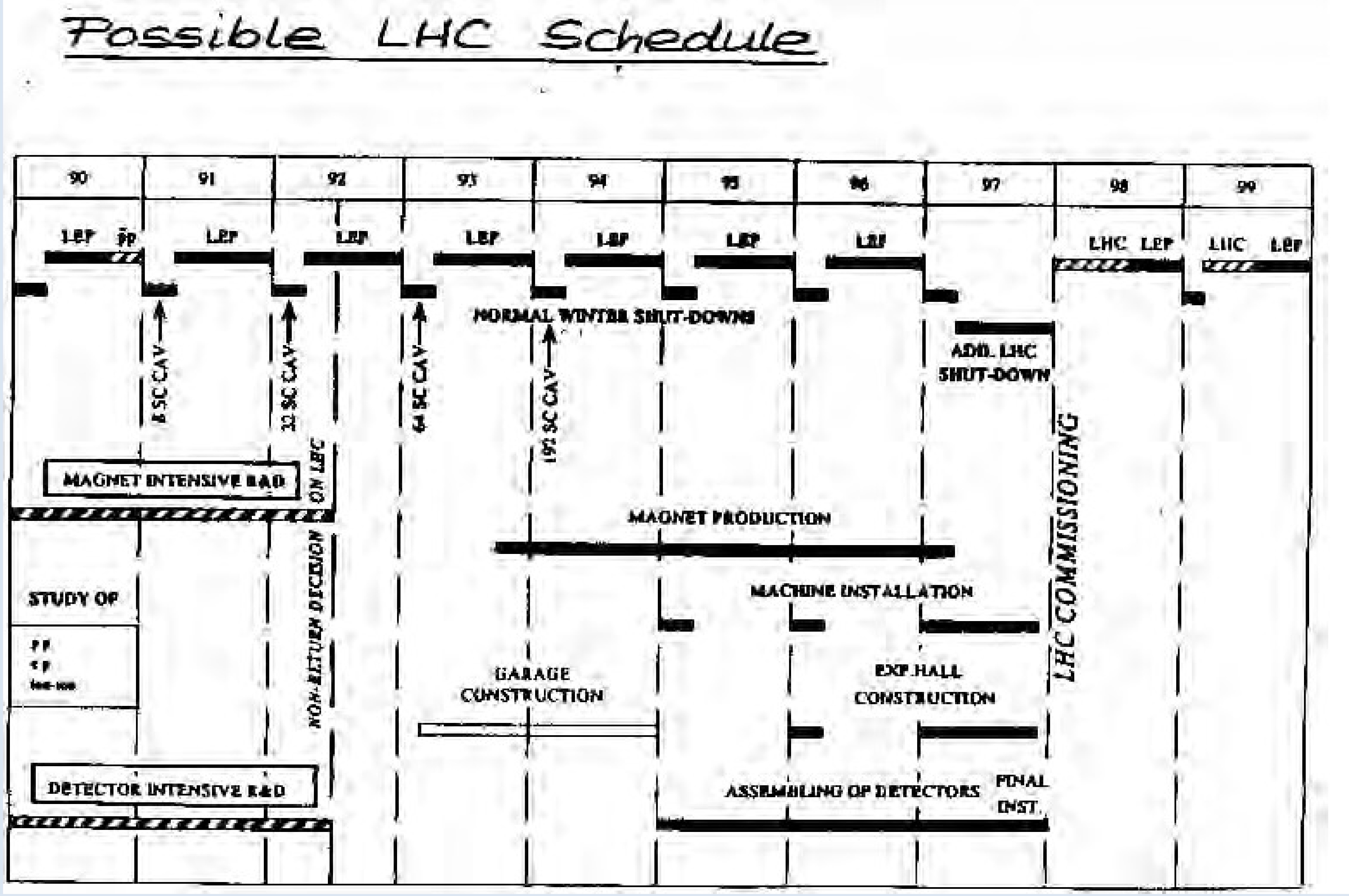
(precise μ measurements may mean hundreds of MCHF)

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 back-grounds from heavy flavour decays

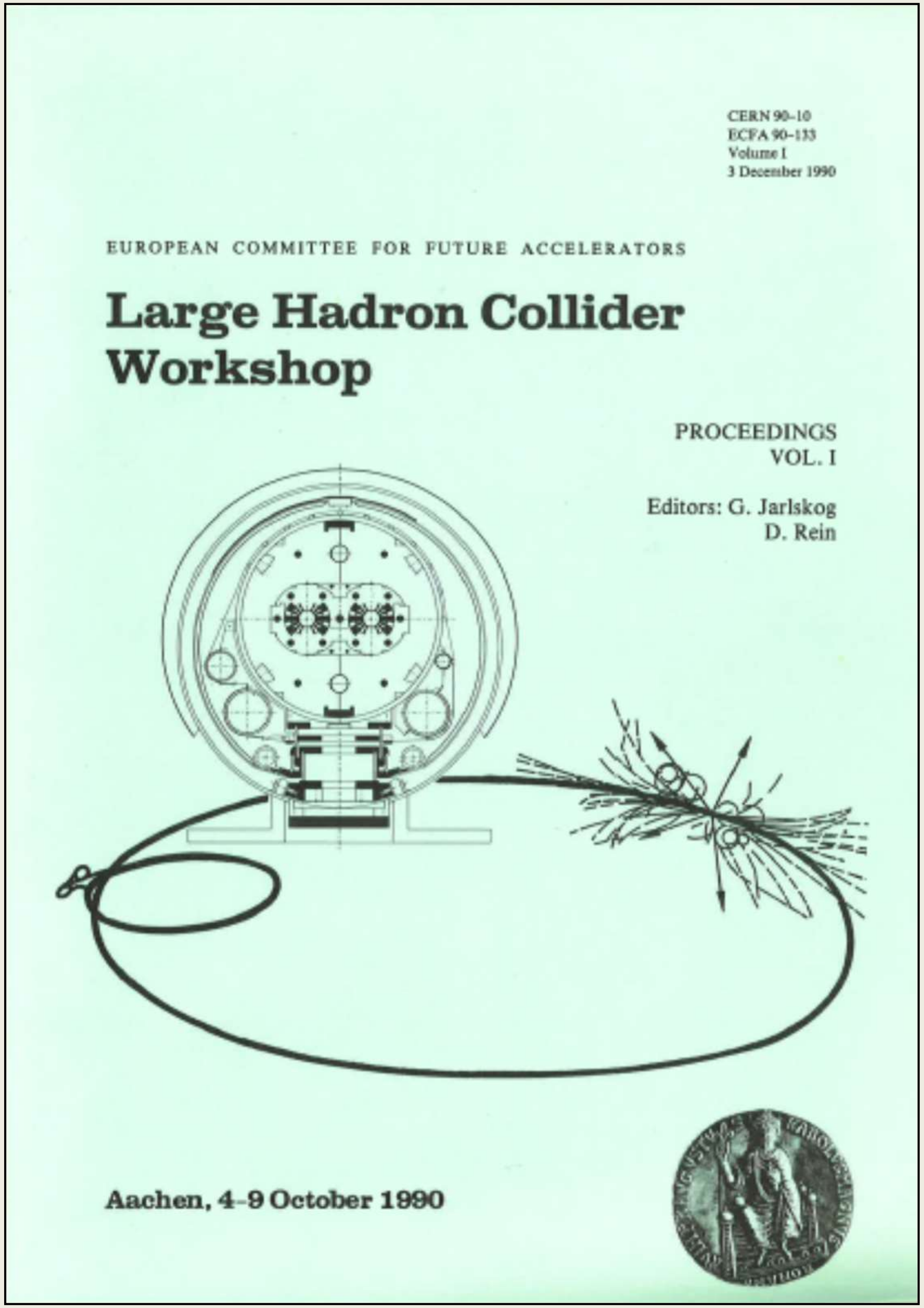
From an early talk about the LHC, must have been around 1986/7 …



1989 ECFA Study Week in Barcelona for LHC instrumentation
(forming of first proto-Collaboration)

1990 Large Hadron Collider Workshop Aachen (CERN - ECFA)
(First serious R&D results and detailed realistic Monte Carlo studies, first ideas of detector concepts)

1992 CERN – ECFA meeting 'Towards the LHC Experimental Programme' in Evian



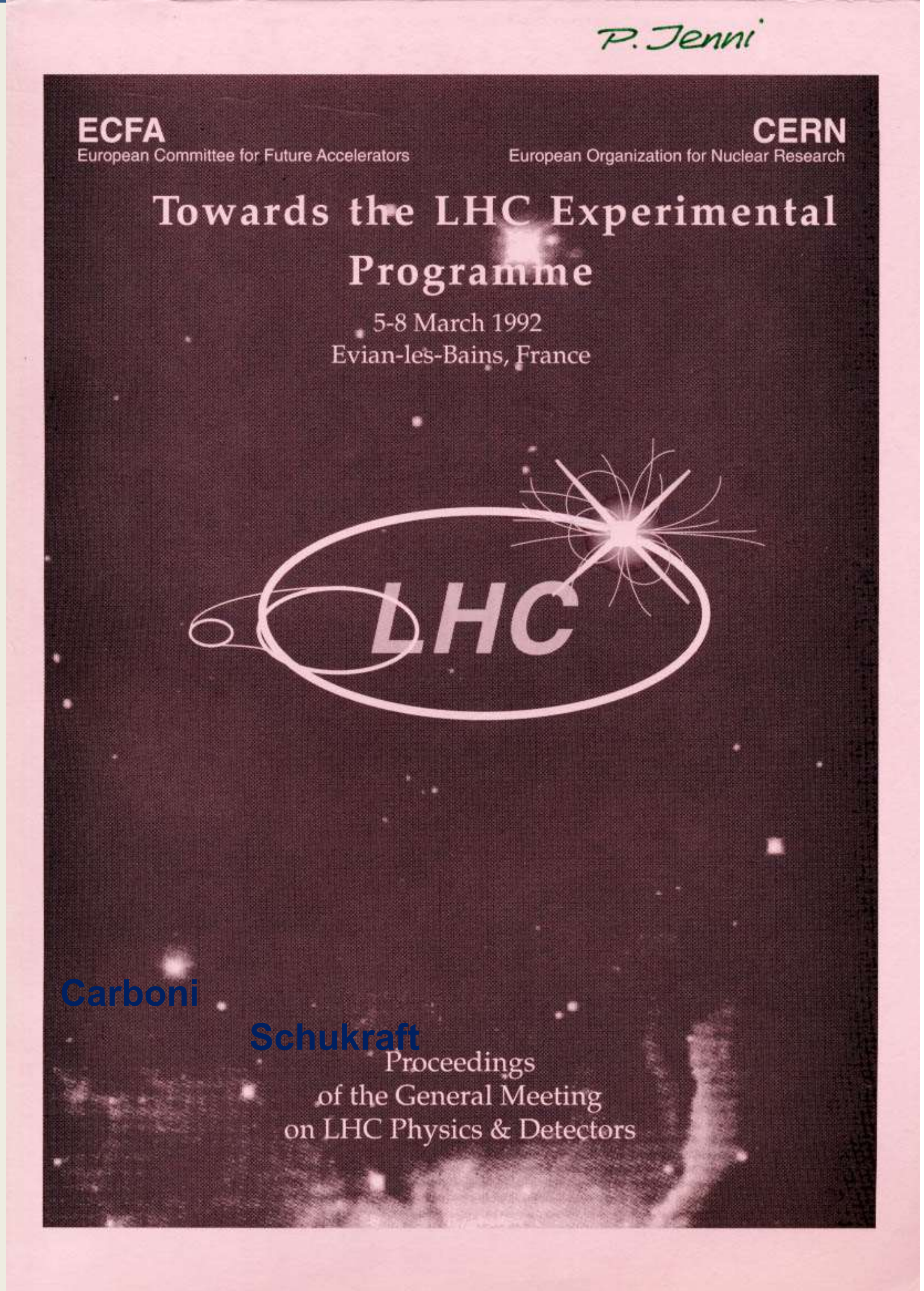
1989 ECFA Study Week in Barcelona for LHC instrumentation
(forming of first proto-Collaboration)

1990 Large Hadron Collider Workshop Aachen (CERN - ECFA)
(First serious R&D results and detailed realistic Monte Carlo studies, first ideas of detector concepts)

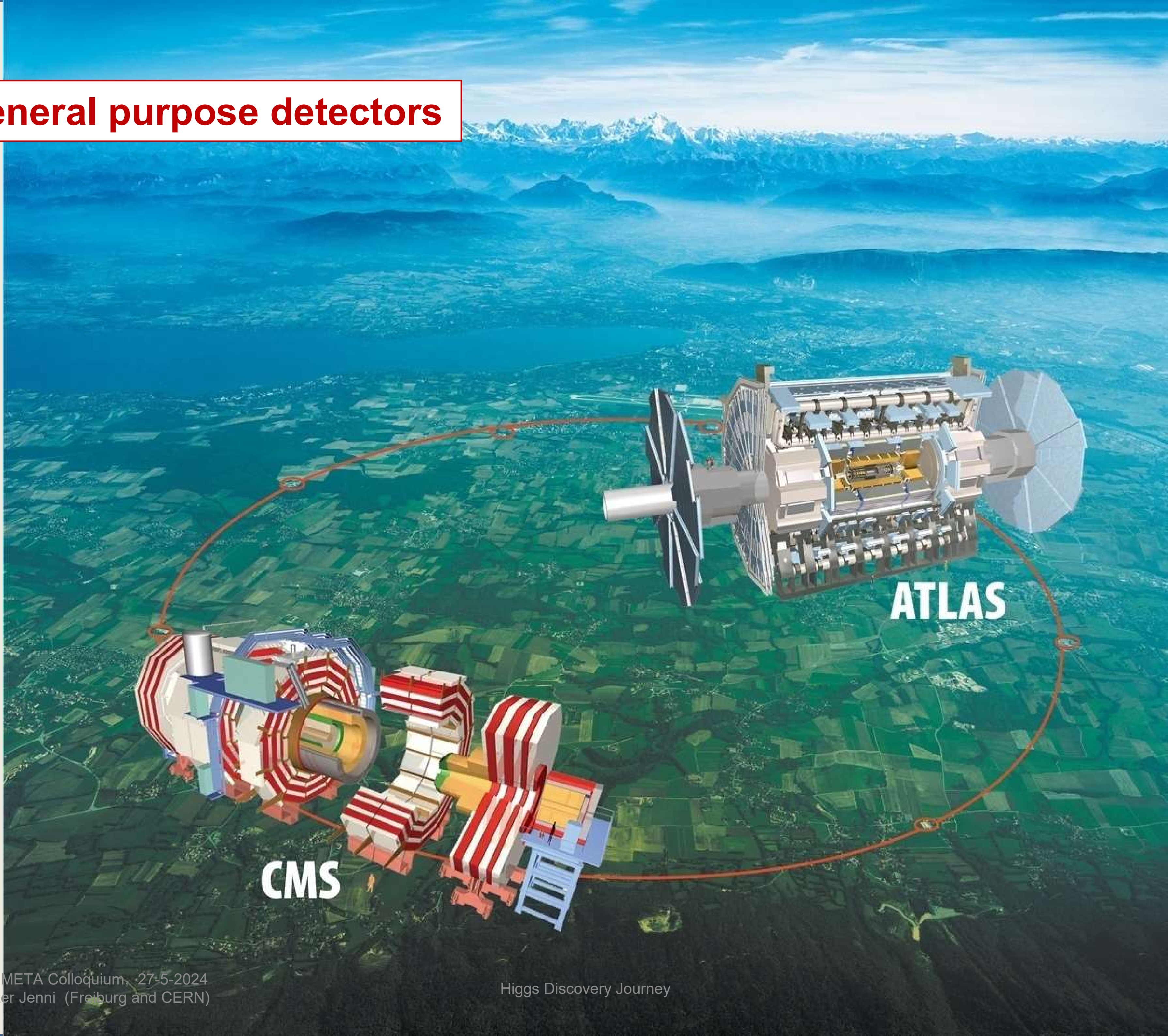
1992 CERN – ECFA meeting ‘Towards the LHC Experimental Programme’ in Evian

Four general purpose experiments:
(ASCOT, CMS, EAGLE, and L3+1)

Six other experiments:
(LHC Beauty Collider, B extracted beam, B gas jet, Neutrino at LHC, LHC HI, and DELPHI LHC HI)



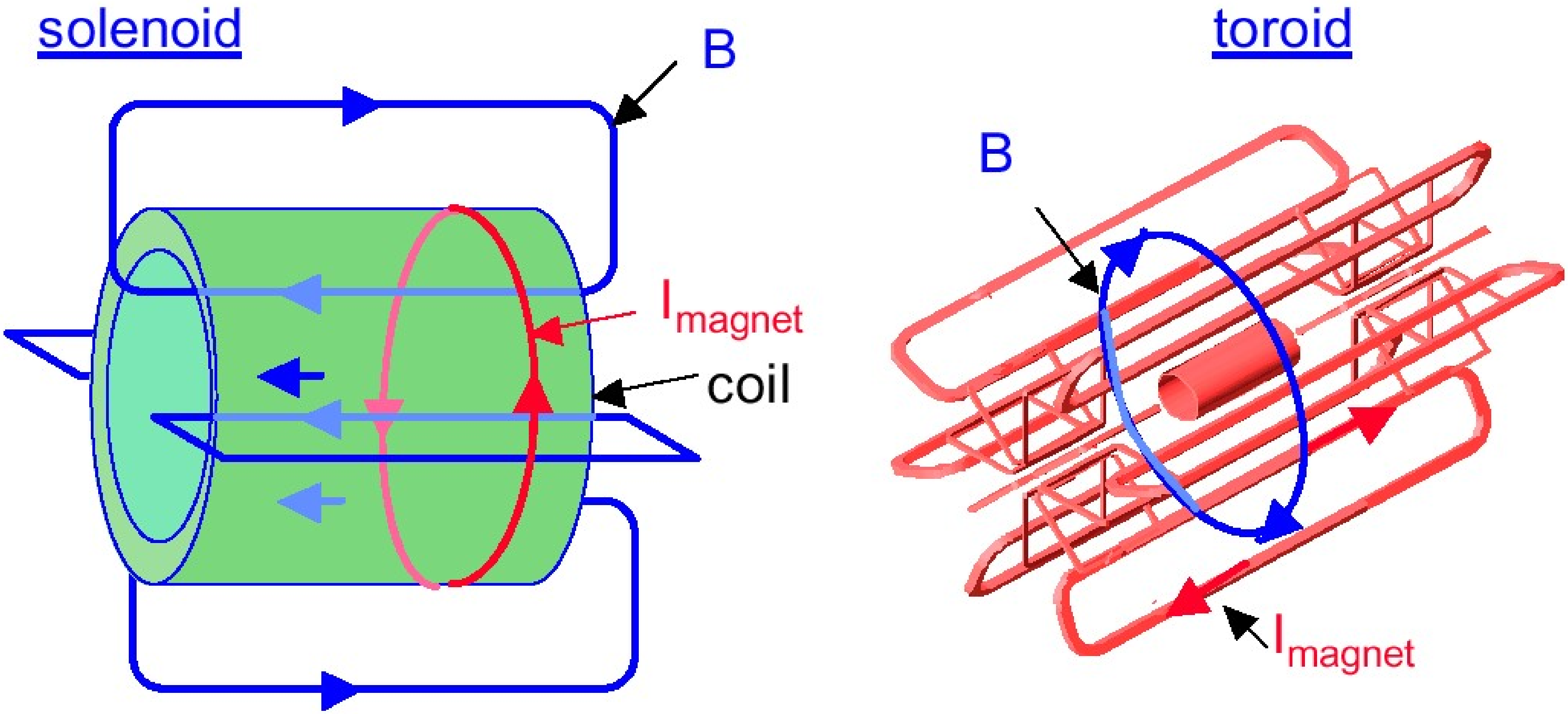
General purpose detectors



Complementary Approaches in ATLAS and CMS

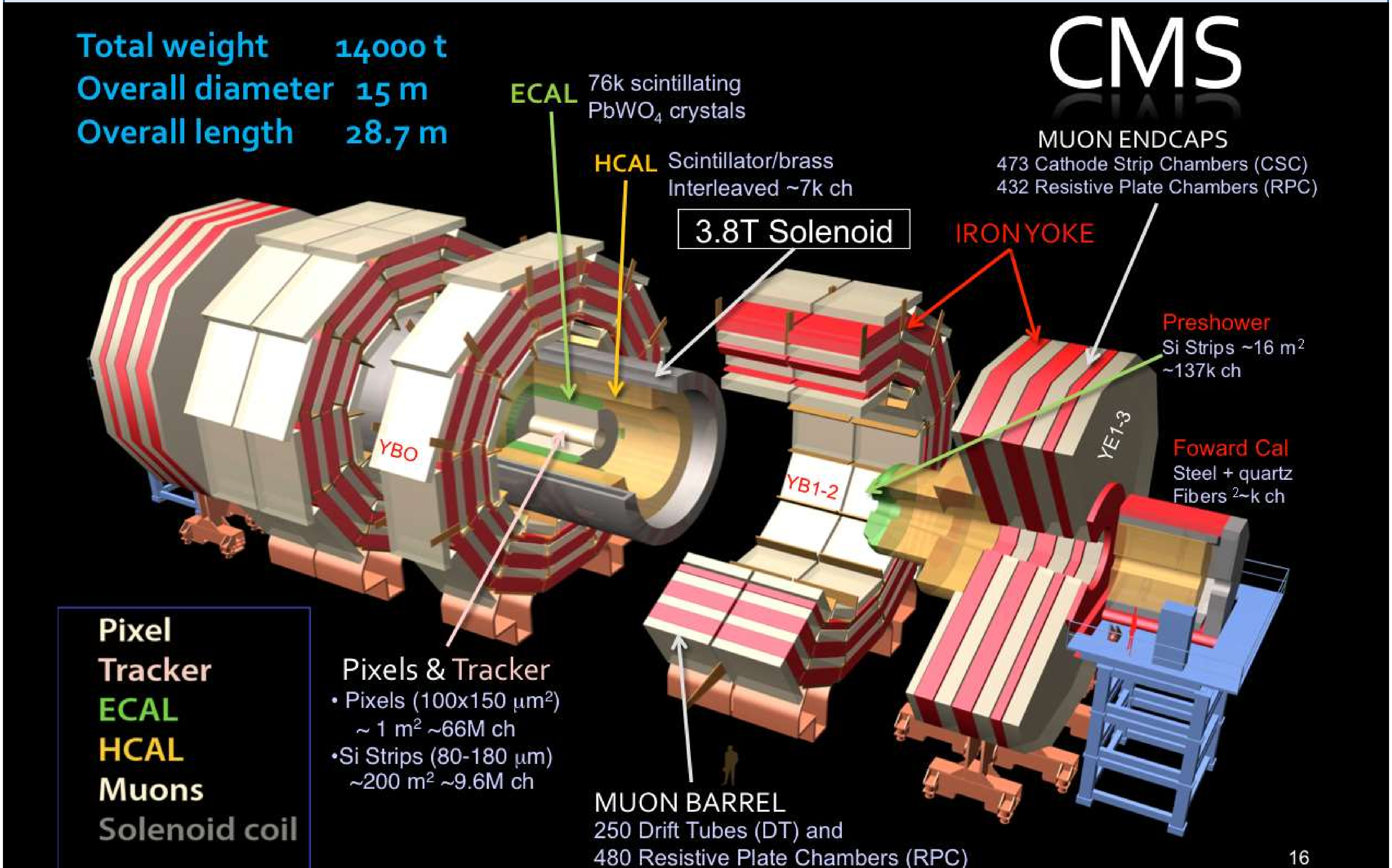
	ATLAS ≡ A Toroidal LHC ApparatuS	CMS ≡ Compact Muon Solenoid
MAGNET (S)	Air-core toroids + solenoid in inner cavity (4 magnets) Calorimeters in field-free region	Solenoid Only 1 magnet Calorimeters inside field
TRACKER	Si pixels+ strips TRT $\rightarrow$ particle identification B=2T $\sigma/p_T \sim 3.8\text{x}10^{-4}\ p_T \oplus 0.015$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5\text{x}10^{-4}\ p_T \oplus 0.005$
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 $\rightarrow$ $\sigma/p_T \sim 15\text{-}30\%$ at 1 TeV standalone (5% with tracker)

Magnetic field configurations:

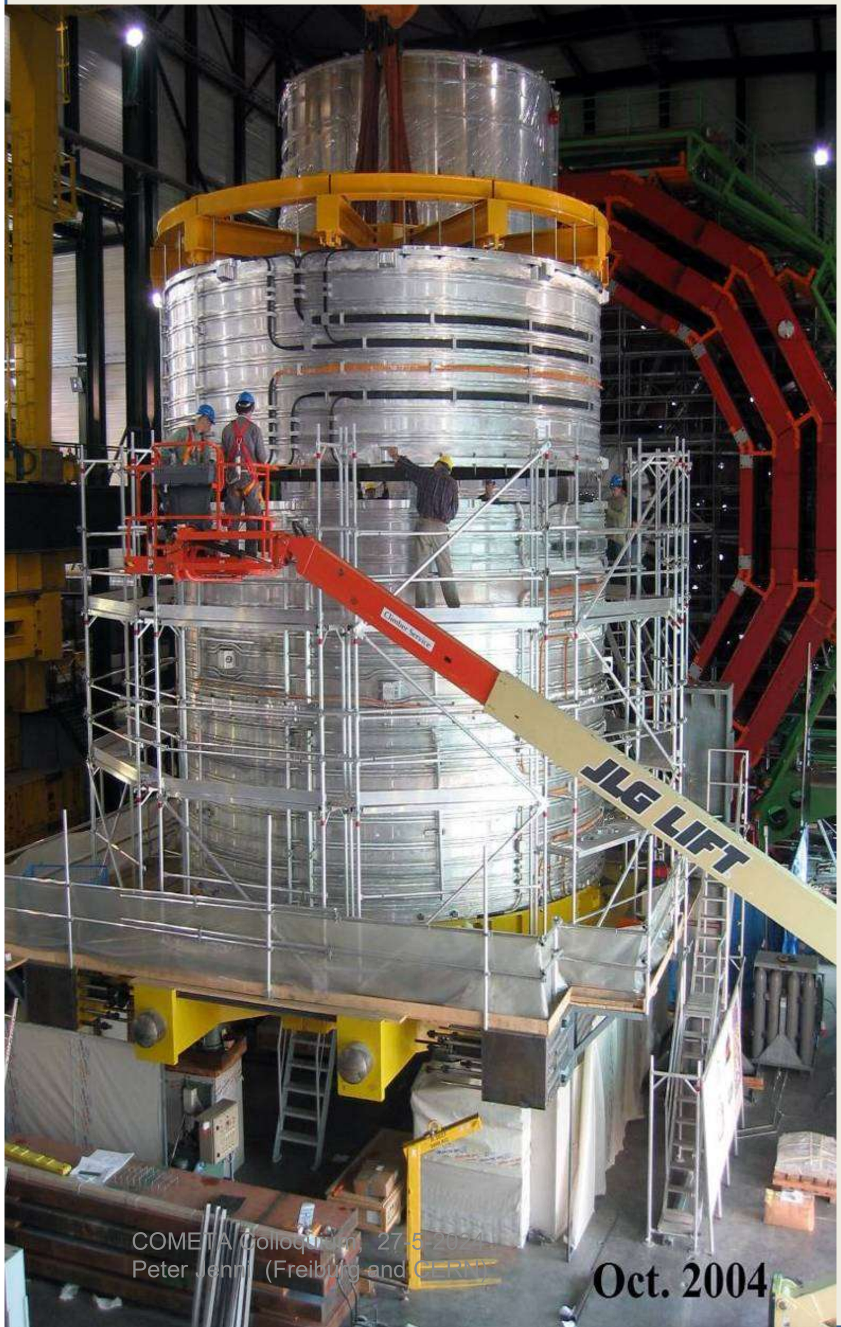


From C.Joram

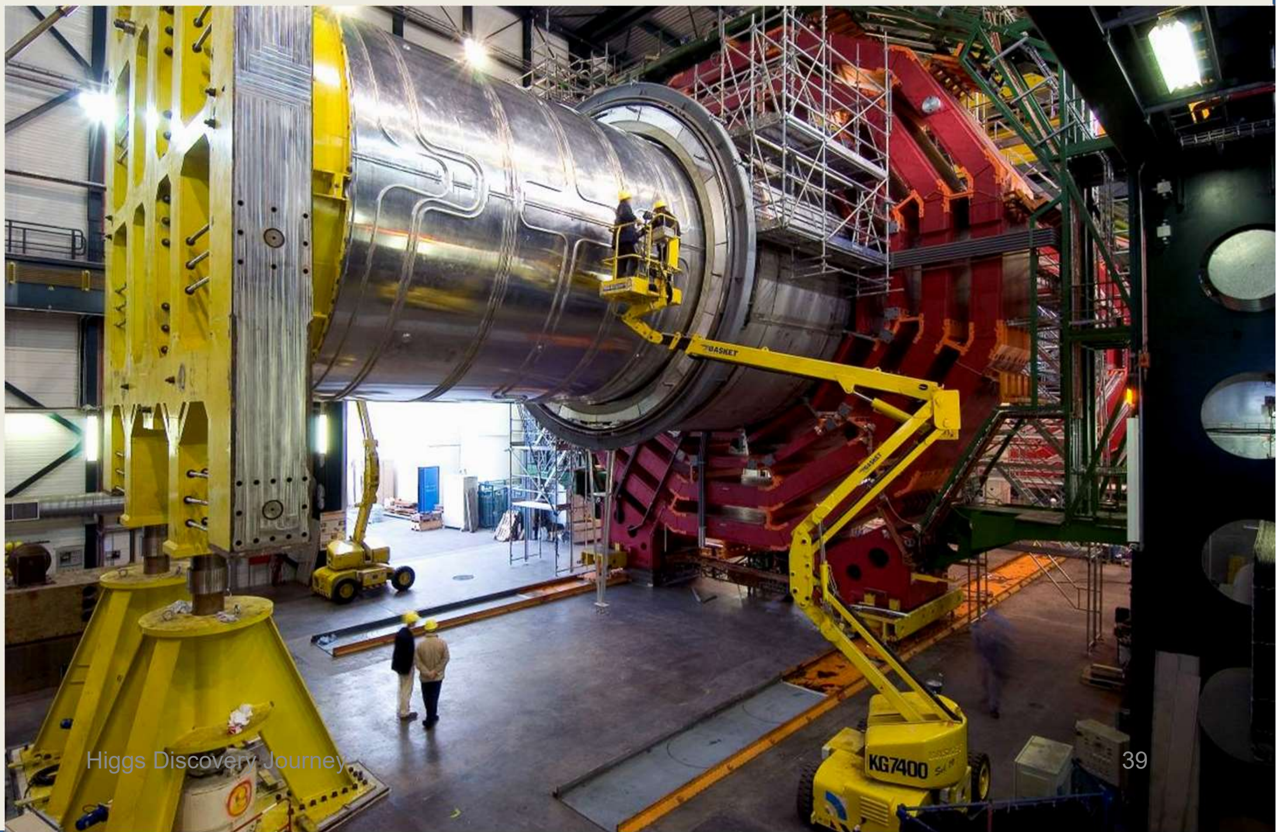
Exploded View of CMS



An Example of an Engineering Challenge: CMS Solenoid

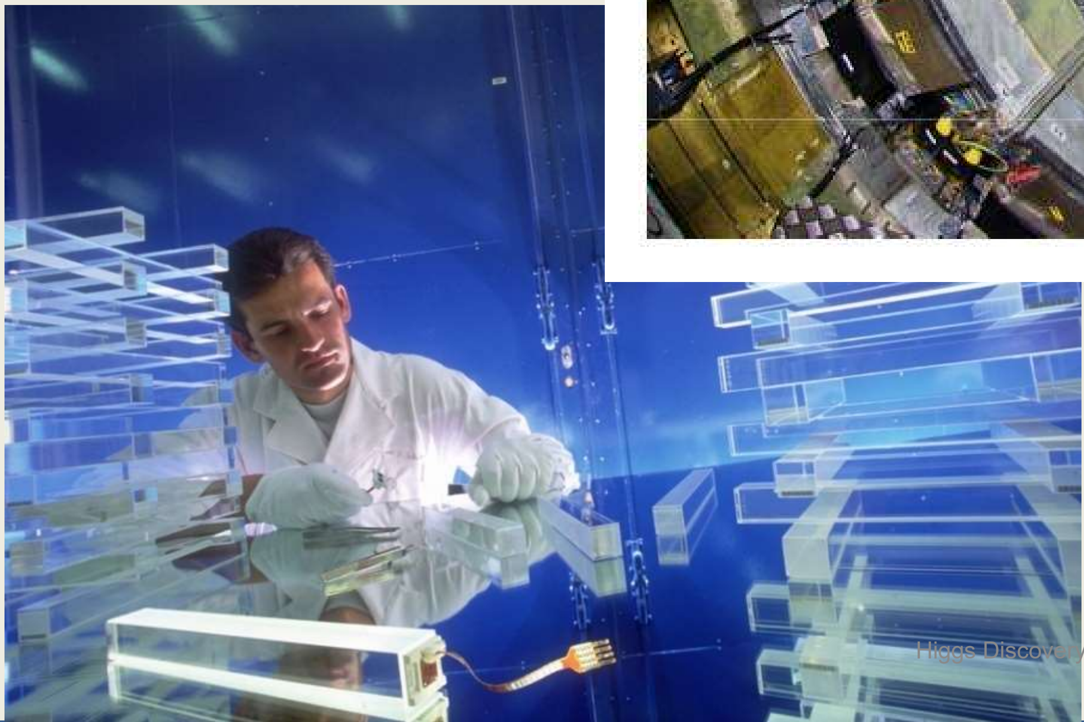


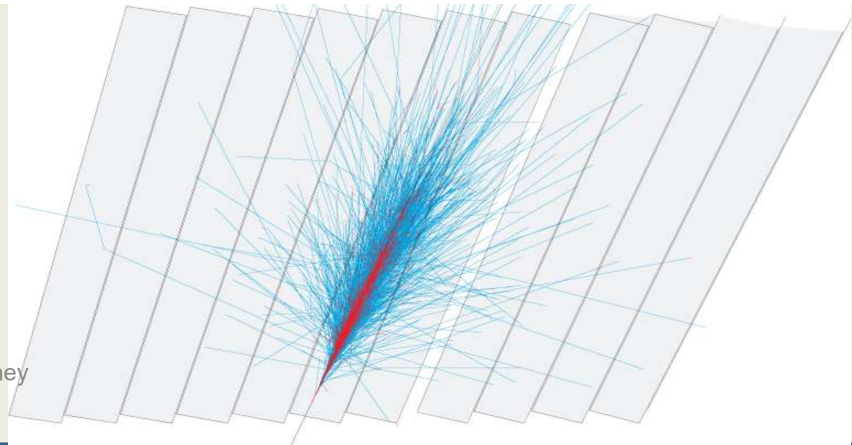
<u>CMS solenoid:</u>	
Magnetic length	**12.5 m**
Diameter	**6 m**
Magnetic field	**4 T**
Nominal current	**20 kA**
Stored energy	**2.7 GJ**
Tested at full current in Summer 2006	



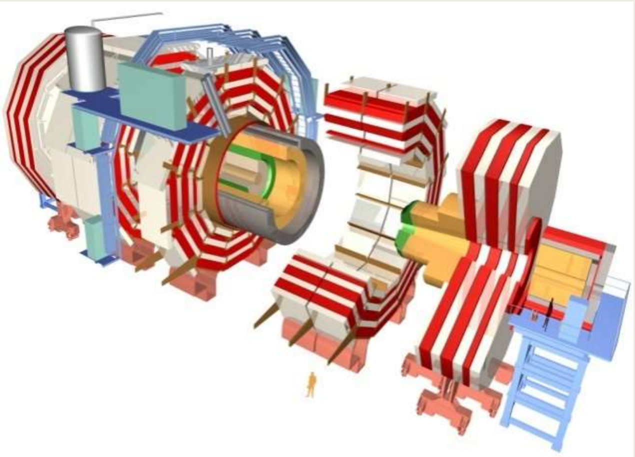
CMS Electron and Photon calorimeter: 76 000 $PbW0_4$ crystals

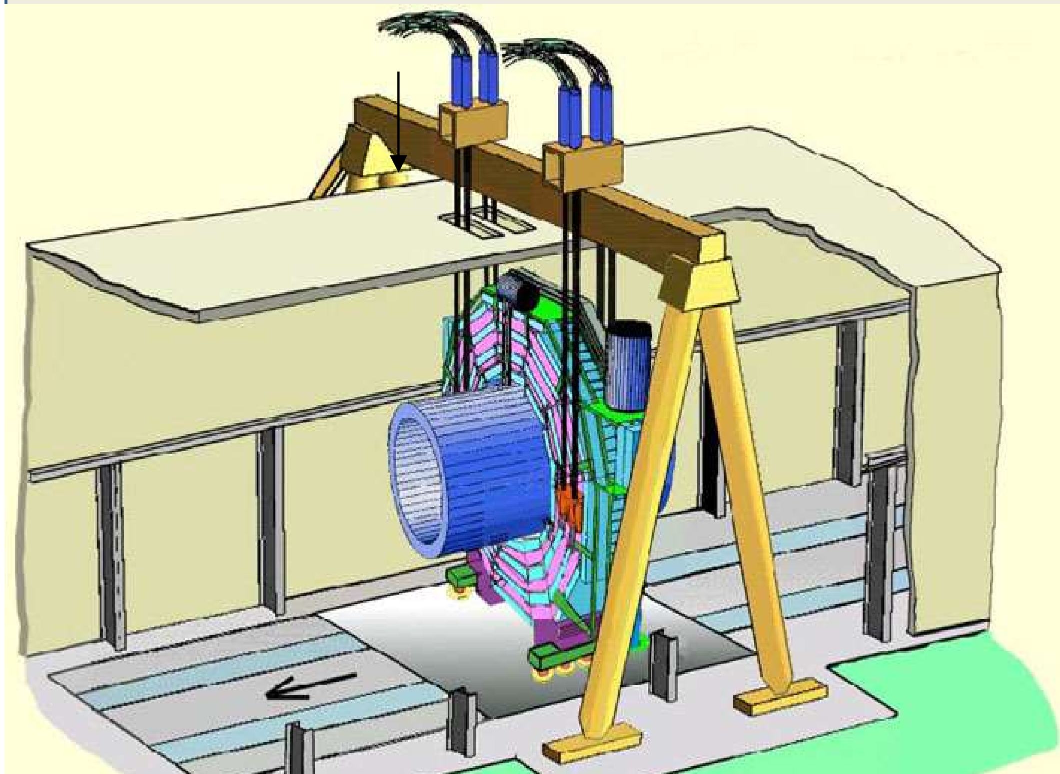
End-cap was on the critical path for many years, but it was completed just in time before final closure, a major achievement by CMS

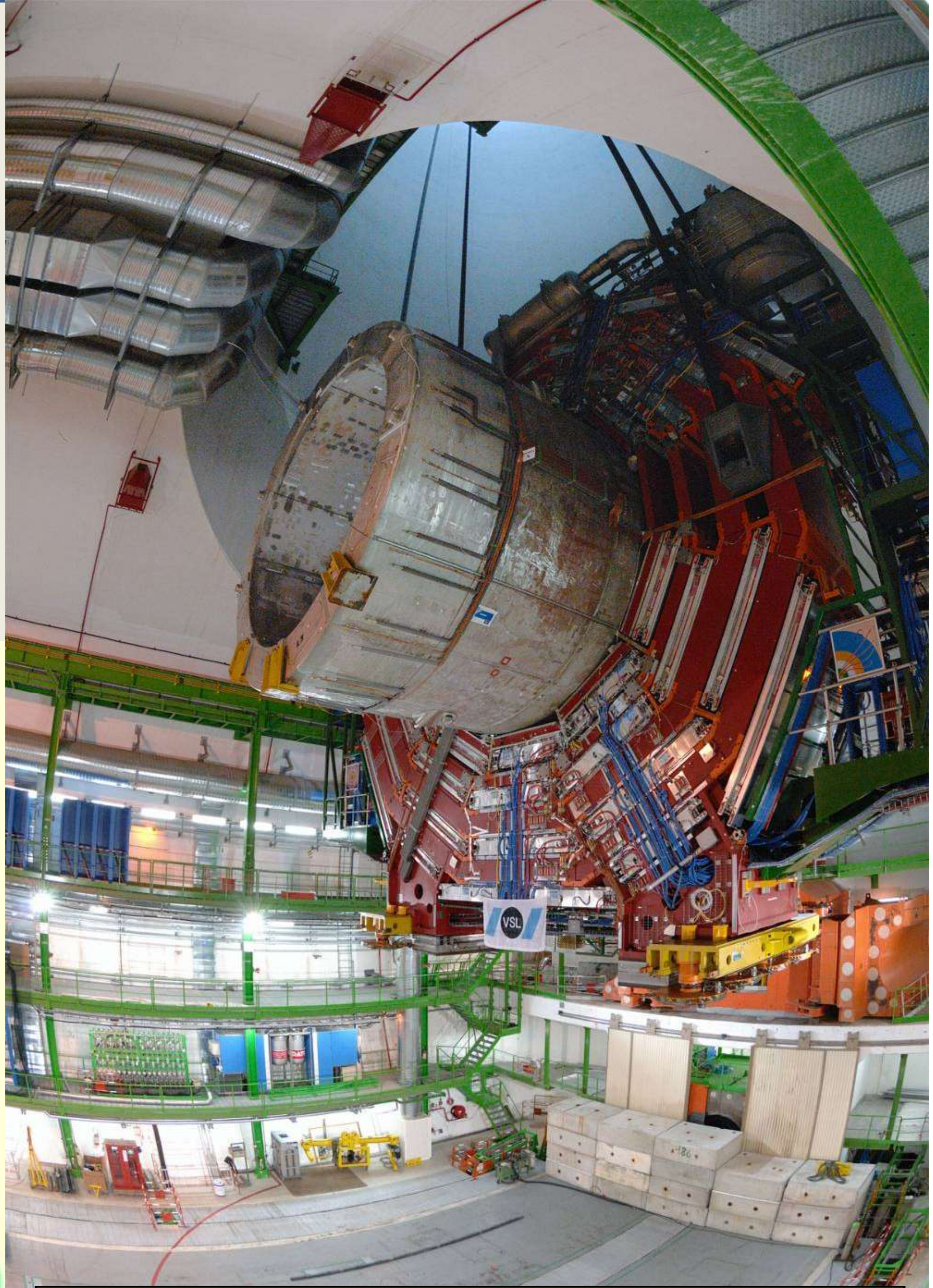




The central, heaviest slice (2000 tons) with the solenoid magnet, lowered into the underground cavern in Feb. 2007







In total 15 slices were installed in this way

CMS before closure 2008

The birth of ATLAS

March 1992 – Summer 1992

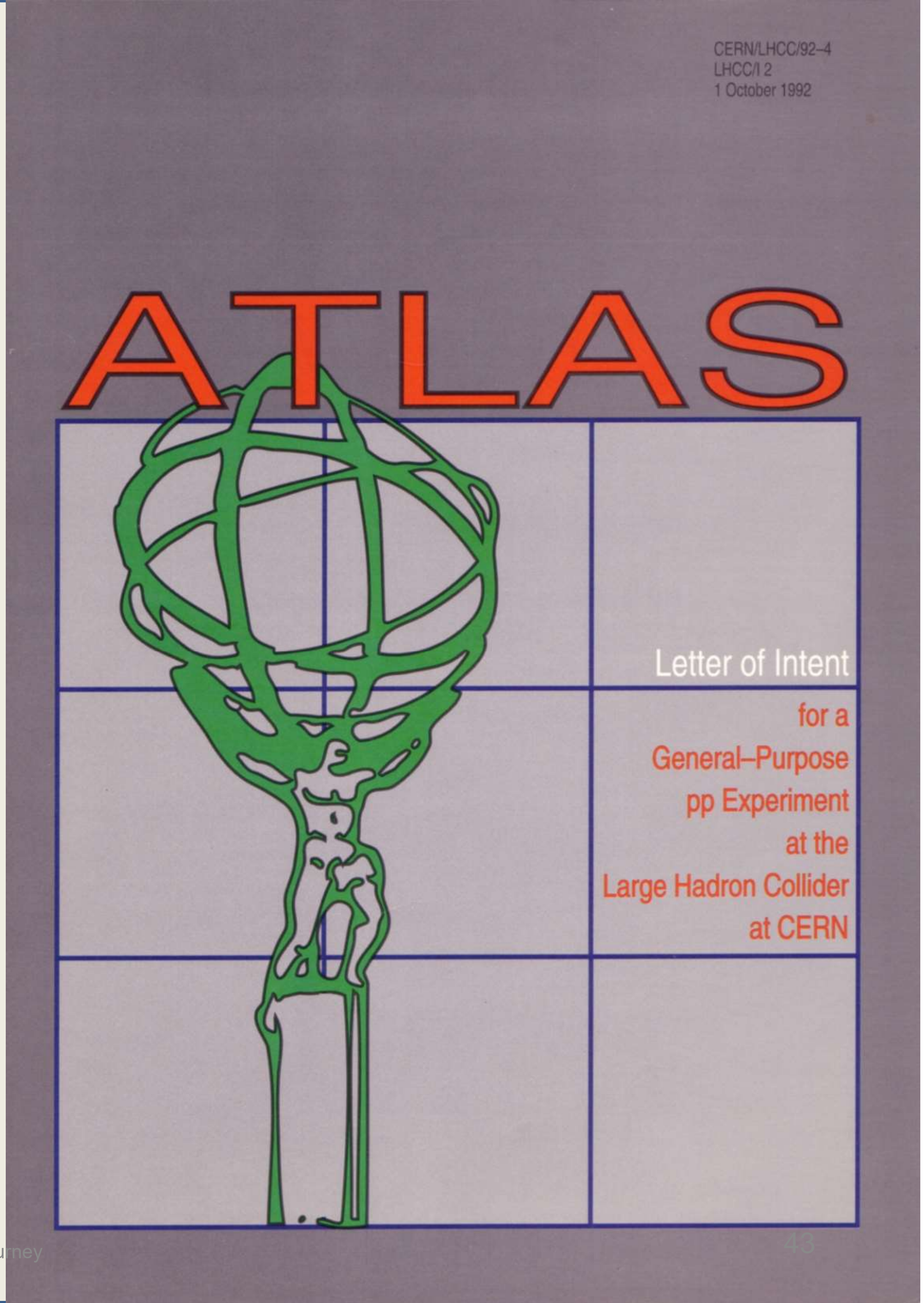
Merging of ASCOT and EAGLE

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

1st October 1992

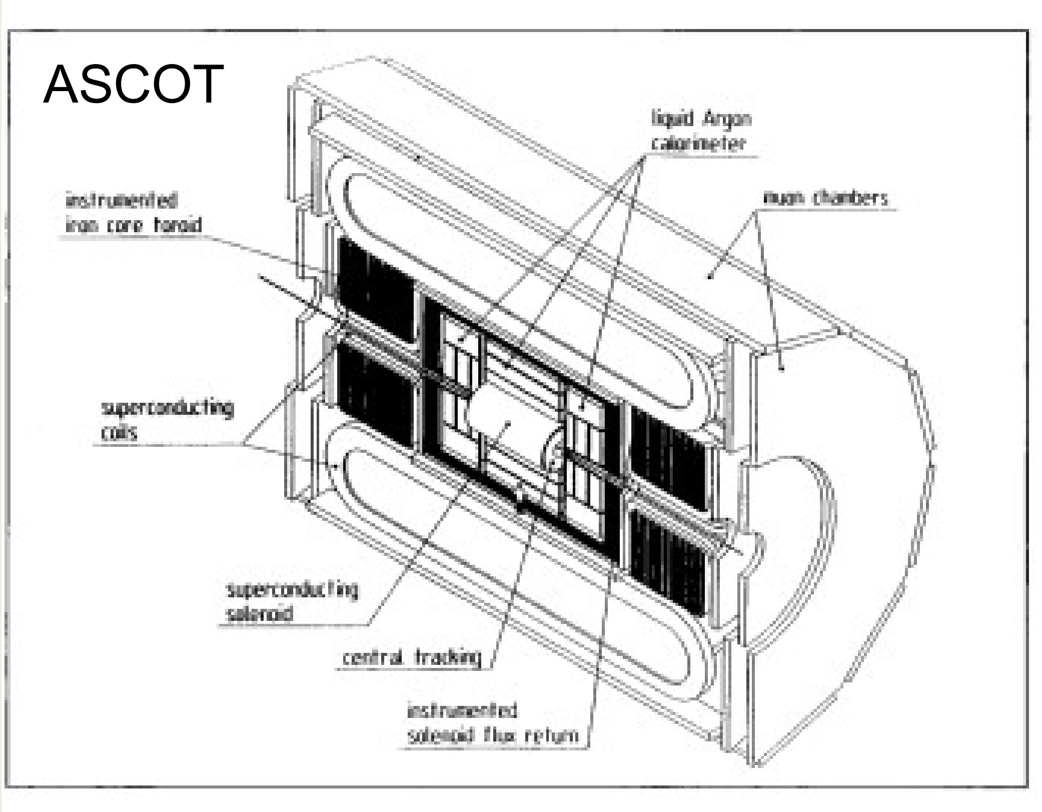
ATLAS LoI submitted to the LHCC

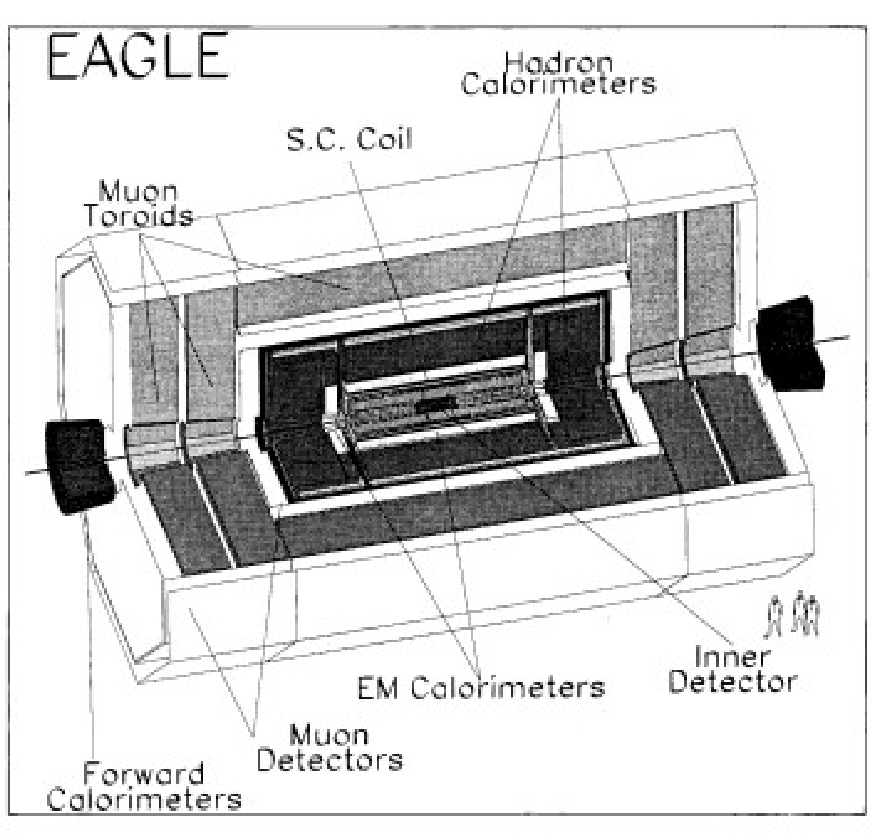
'Official birth of the ATLAS Collaboration'



The ASCOT and EAGLE proto-collaborations both presented detector concepts with a toroid magnet configuration for the muon spectrometer at the Evian meeting

From their Expressions of Interest





ASCOT with a superconducting air-core barrel and warm iron end cap toroids

EAGLE with warm iron barrel and end cap toroids

The ATLAS LoI presentation to the LHCC on 5th Nov 1992

ATLAS

Letter of Intent for a General-Purpose pp Experiment at the LHC

Introduction and overview

- general concept
- magnet systems
- integration and radiation
- costs

Detector subsystems, R&D and expected performance

- calorimetry
- inner detector
- muon detector
- trigger and DAQ

Physics performance

ATLAS
Collaboration

Alberta, Alma Ata, NIKHEF Amsterdam, LAPP Annecy, Athens, NTU Athens, UA Barcelona, Bern, Birmingham, Bratislava, Cambridge, CERN, Clermont-Ferrand, NBI Copenhagen, Cosenza, INP Cracow, IPNT Cracow, Debrecen, Dortmund, JINR Dubna, Edinburgh, Florence, Frascati, Freiburg, Geneva, Glasgow, ISN Grenoble, Technion Haifa, Hamburg, Heidelberg, SEFT Helsinki, Innsbruck, Jena, Kobe, Kosice, Lancaster, Lisbon, Liverpool, QMW London, RHBNC London, UC London, Lund, UA Madrid, Mainz, Manchester, Mannheim, CPPM Marseille, Melbourne, Milano, Montreal, ITEP Moscow, Lebedev Moscow, MEPhI Moscow, MSU Moscow, Munich, MPI Munich, Nijmegen, LAL Orsay, Oslo, Oxford, Paris VI and VII, Pavia, Pisa, Prague, IHEP Protvino, COPPE Rio de Janeiro, Rome I and II, Rutherford Appleton Laboratory, DAPNIA Saclay, CST Saratov, Sheffield, Siegen, LITMO St. Petersburg, NPI St. Petersburg, Stockholm, MSI Stockholm, Ansto Sydney, Tel-Aviv, Tokyo, Uppsala, Valencia, UBC Vancouver, Victoria, Vienna, Warsaw, Weizmann Rehovot, Wuppertal

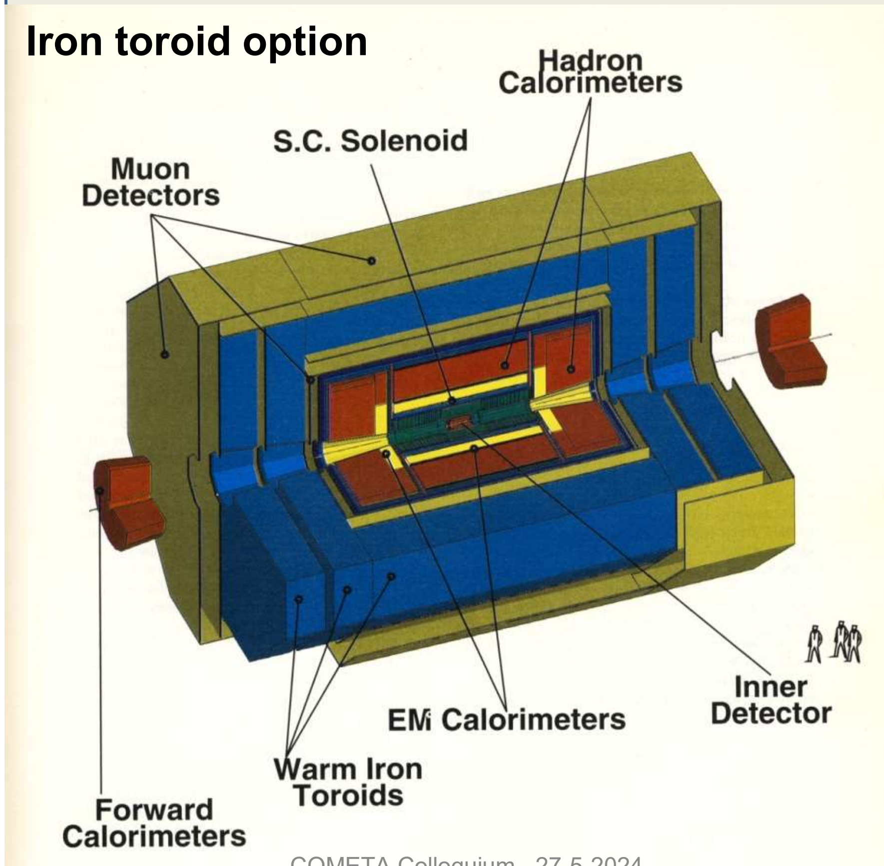
(88 Institutions with about 850 authors on LoI)

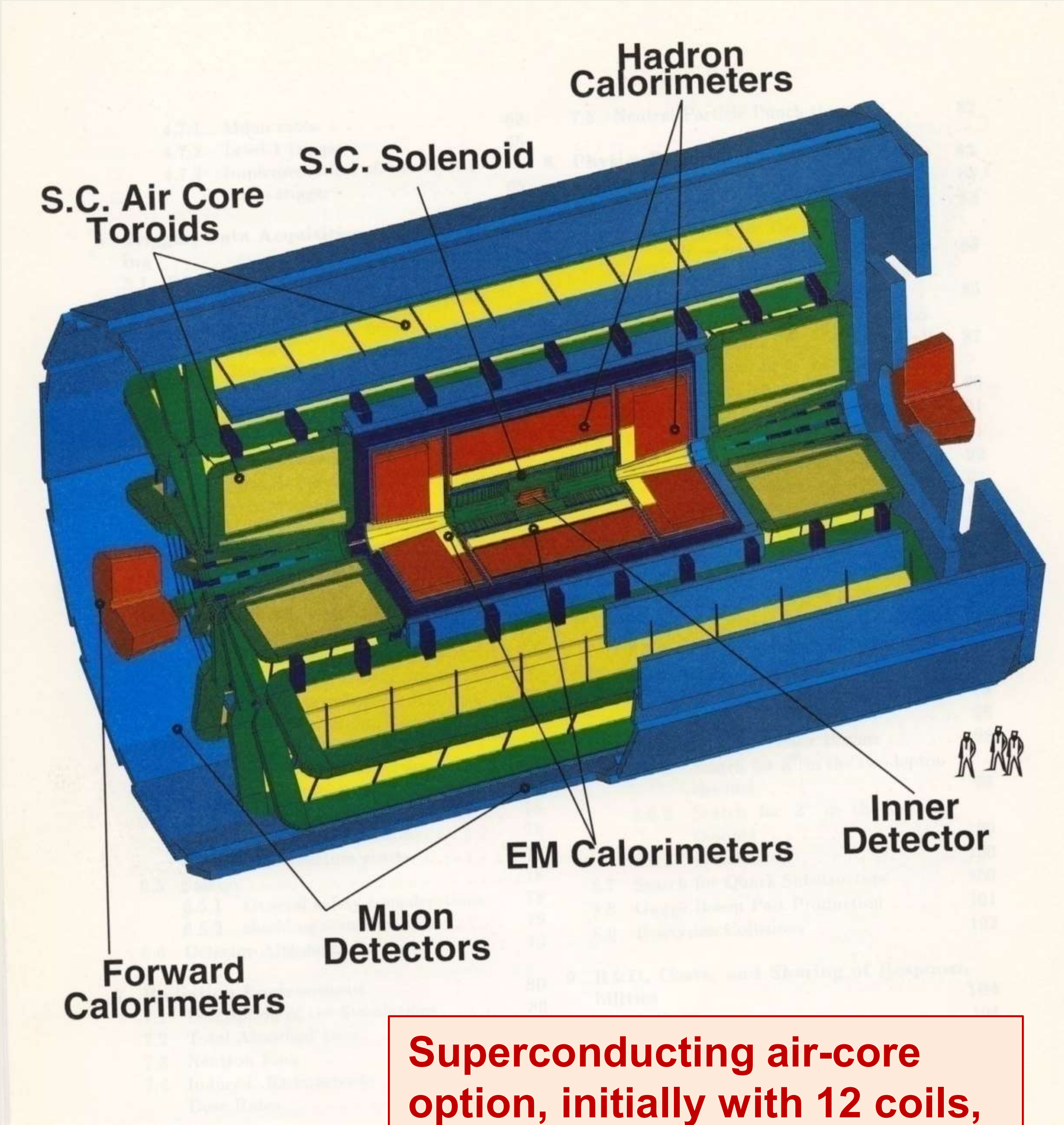
Spokespersons: F. Dydak and P. Jenni

From the Letter of Intent

The LoI still had two toroid options, one full iron and one all superconducting air-core

Shortly after ATLAS decided for the *superior air-core magnet*

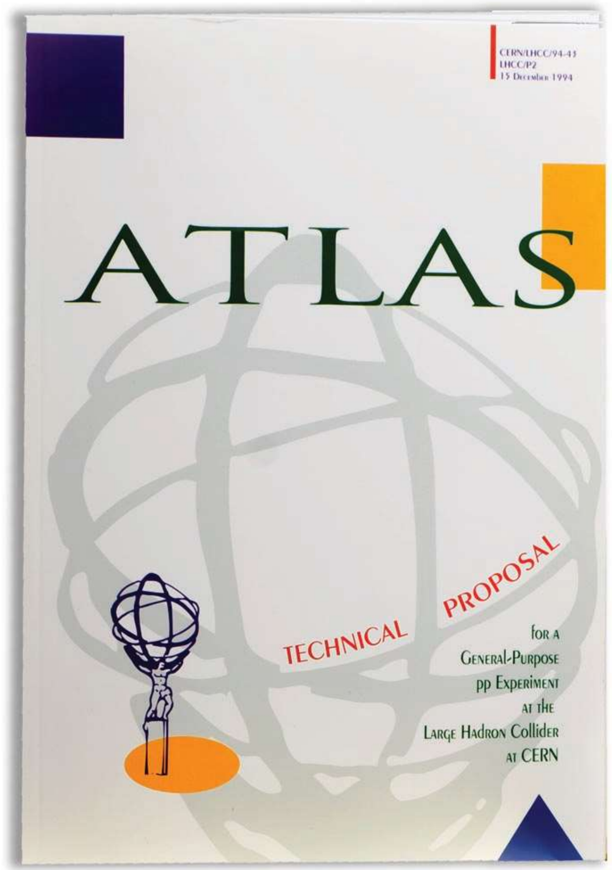




Superconducting air-core option, initially with 12 coils, then redesigned with 8 coils (mainly for cost reductions)

ATLAS was then (June 1993) invited by LHCC to work out a Technical Proposal

(Submitted on 15th December 1994, presented on 19th January 1995)



ATLAS Collaboration

(Status: Technical Proposal, 15 December 1994)

Alberta, Alma Ata, NIKHEF Amsterdam, LAPP Annecy, Argonne NL, Arizona, Arlington UT, Athens, NTU Athens, Baku, UA Barcelona, Berkeley LBL and UC, Bern, Birmingham, Bonn, Boston, Brandeis, Bratislava, Brookhaven NL, IAP Bucharest, Cambridge, Carleton/CRPP, CERN, Chicago, Clermont-Ferrand, Columbia, NBI Copenhagen, Cosenza, INP Cracow, FPNT Cracow, Dortmund, JINR Dubna, Duke, Edinburgh, Florence, Frascati, Freiburg, Fukui, Geneva, Genoa, Glasgow, ISN Grenoble, Technion Haifa, Hamburg, Harvard, Hawaii, Heidelberg, SEFT Helsinki, Hiroshima IT, Hiroshima, Indiana, Innsbruck, Irvine UC, Istanbul Bogazici, Jena, KEK, Kobe, Kosice, Kyoto UE, Lancaster, Lecce, Lisbon, Liverpool, QMW London, RHBNC London, UC London, Lund, UA Madrid, Mainz, Manchester, Mannheim, CPPM Marseille, MIT, Melbourne, Michigan SU, Milano, Minsk, Montreal, ITEP Moscow, Lebedev Moscow, MEPhI Moscow, MSU Moscow, Munich LMU, MPI Munich, Naples, Naruto UE, Nijmegen, Northern Illinois, BINP Novosibirsk, LAL Orsay, Oslo, Oxford, Paris VI and VII, Pavia, Pennsylvania, Pisa, Pittsburgh, CAS Prague, CU Prague, TU Prague, IHEP Protvino, COPPE Rio de Janeiro, Rochester, Rockefeller, Rome I, Rome II, Rome III, Rutherford Appleton Laboratory, DAPNIA Saclay, Santa Cruz UC, Sheffield, Shinsu, Siegen, Southern Methodist, IFMO St. Petersburg, NPI St. Petersburg, Stockholm, KTH Stockholm, Ansto Sydney, Tbilisi AS, Tbilisi SU, Tel-Aviv, Thessaloniki, Tokyo CU, Tokyo ICEPP, Tokyo MU, Tokyo AT, Toronto, TRIUMF, Tufts, Uppsala, Urbana UI, Valencia, UBC Vancouver, Victoria, Washington, Weizmann Rehovot, Wisconsin, Wuppertal, Yerevan

(140 Institutions with about 1500 authors)

From the TP presentation

But again, we were too expensive!

→ Another round of cost reduction: the famous 'Pilcher' Task Force for global descoping

A major ingredient was:

'Reduction of detector dimensions and magnetic fields, leading to an adequate safety margin in the cavern size'

ATLAS Internal Note
Gen-No-014
24th November 1995

Report of the Global Descoping Task Force

Abstract

The work and recommendations of the ATLAS Global Descoping Task Force are presented. The revised configuration is believed to be one which retains good integrated physics performance of the detector and reduces the cost by 24.8 MCHF.

1

But again, we were too expensive!

→ Another round of cost reduction: the famous ‘Pilcher’ Task Force for global descoping

A major ingredient was:

‘Reduction of detector dimensions and magnetic fields, leading to an adequate safety margin in the cavern size‘

HOWEVER, AS WE SEE NOW WITH THE BENEFIT OF HINDSIGHT:

It was crucial to resist as much as possible to major descoping of specific detector systems, like for example the granularity of the calorimeters

Thanks to this ATLAS can exploit now with - at the time - unforeseen advanced analysis methods a lot of physics well beyond the initial dreams …

ATLAS Internal Note
Gen-No-014
24th November 1995

Report of the Global Descoping Task Force

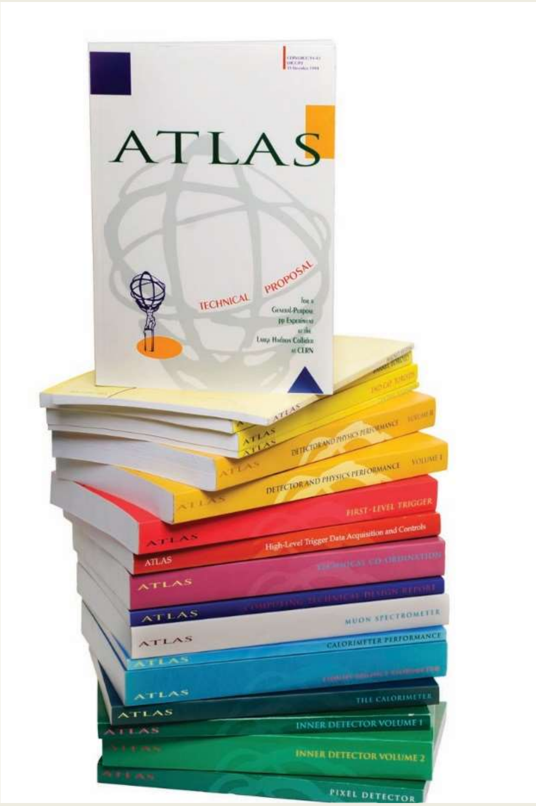
Abstract

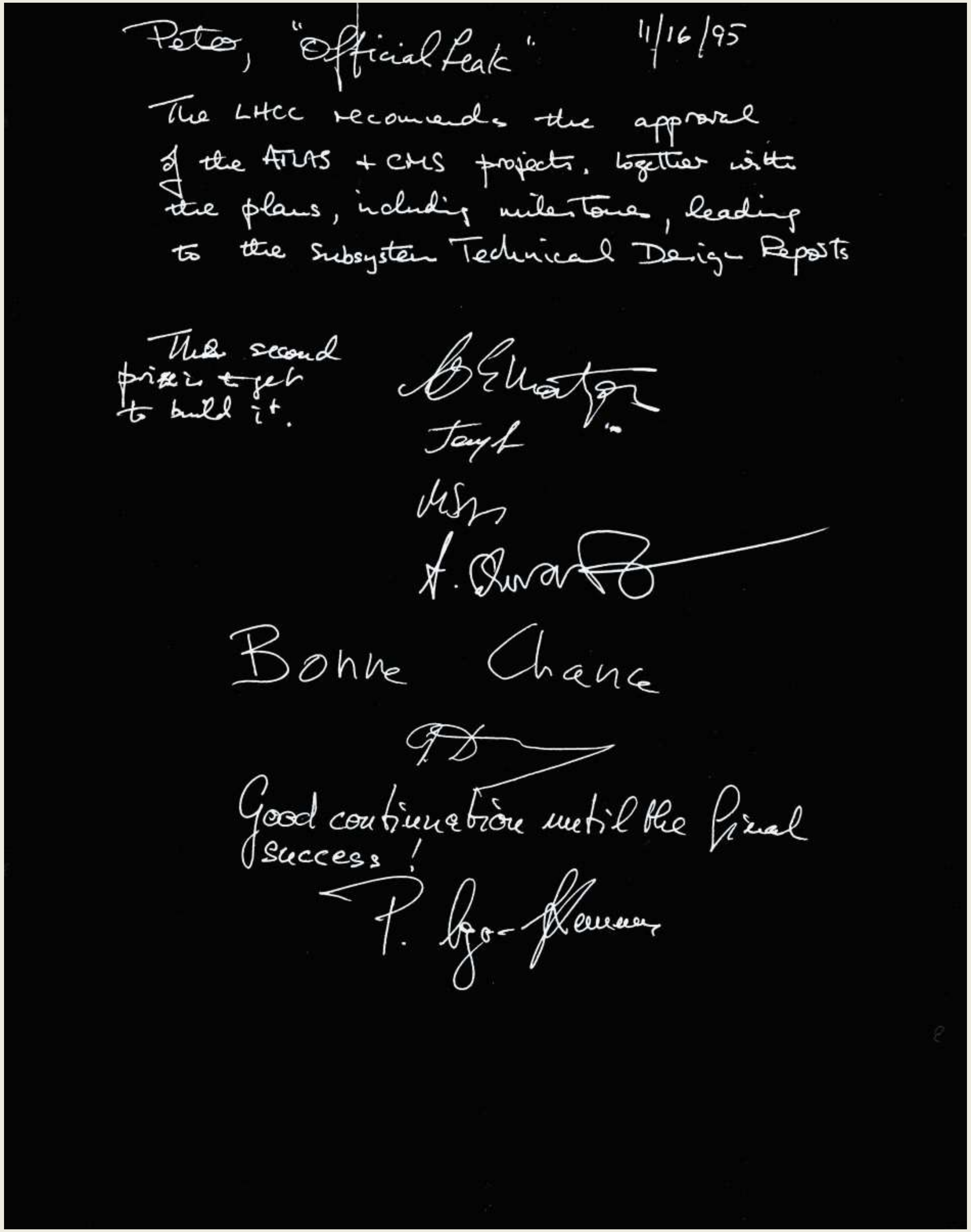
The work and recommendations of the ATLAS Global Descoping Task Force are presented. The revised configuration is believed to be one which retains good integrated physics performance of the detector and reduces the cost by 24.8 MCHF.

1

The Technical Proposal evaluations concluded by the end of 1995

It was a long way to convincing the LHC Experiment Committee (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 recomends the approval of the ATLAS + CMS projects, together with the plans, including milestones, leading to the subsystem Technical Design Reports

The second prize is to get to build it.

Bonne Chance

Good continuation until the final success!

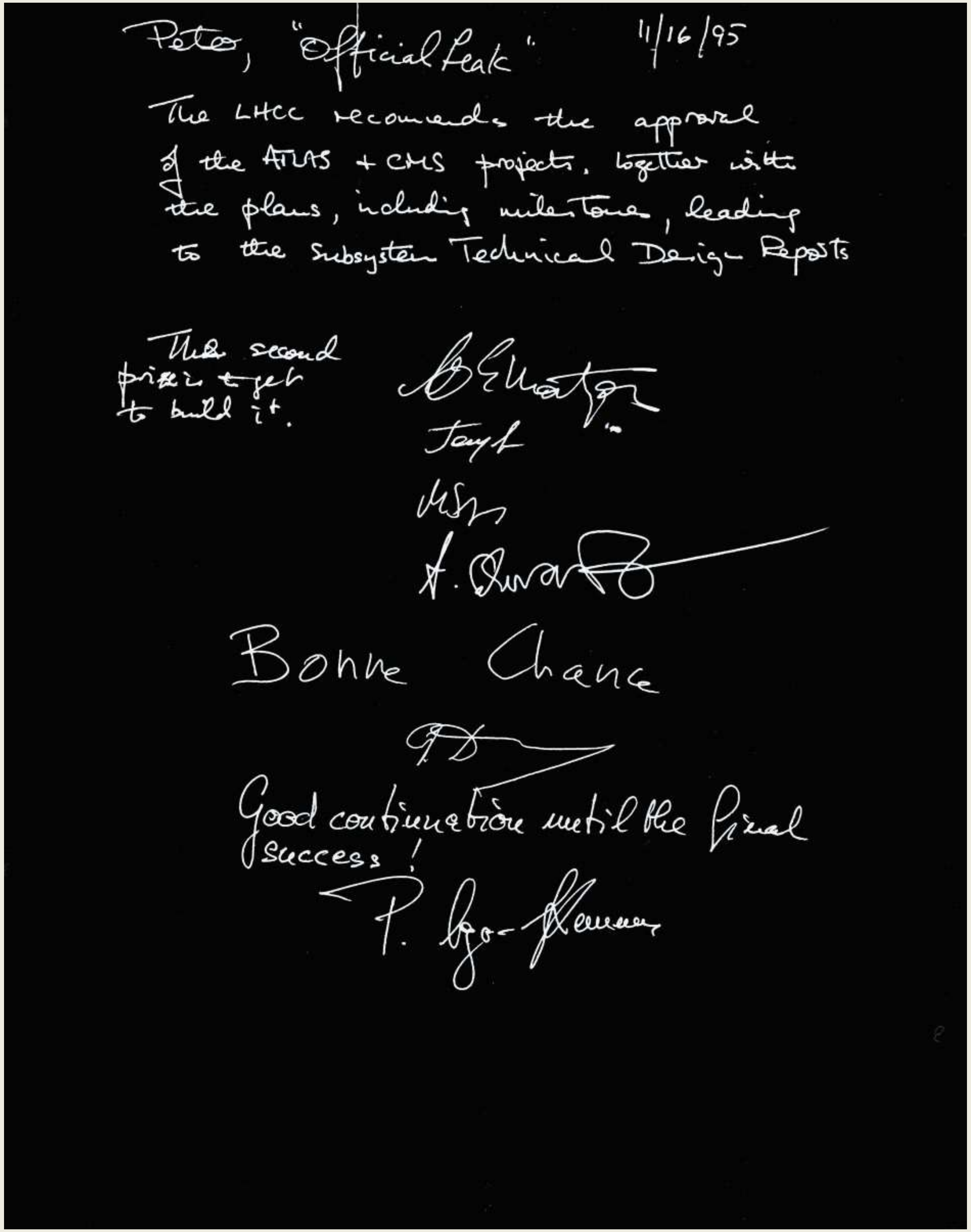
The Technical Proposal evaluations concluded by the end of 1995

It was a long way to convincing the LHC Experiment Committee (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…

ATLAS (and CMS) were invited then to work out Technical Design Reports for the various Sub-systems

ATLAS: 17 volumes in total over the years !

TDR	Pages	Titles	Date
1	178	*Calorimeter Performance*	1996-12-15
2	606	*Liquid Argon Calorimeter*	1996-12-15
3	330	*Tile Calorimeter*	1996-12-15
4	256	*Inner Detector Vol 1*	1997-04-30
5	898	*Inner Detector Vol 2*	1997-04-30
6	101	*Magnet System*	1997-04-30
7	208	*Barrel Toroid*	1997-04-30
8	282	*End-Cap Toroids*	1997-04-30
9	85	*Central Solenoid*	1997-04-30
10	513	*Muon Spectrometer*	1997-05-31
11	317	*Pixel Detector*	1998-05-31
12	500	*First-Level Trigger*	1998-06-30
13	598	*Technical Coordination*	1999-01-31
14	458	*Detector and Physics Performance Vol 1*	1999-05-25
15	506	*Detector and Physics Performance Vol 2*	1999-05-25
16	370	*High-Level Trigger Data Acquisition and Controls*	2003-06-30
17	234	*Computing*	2005-03-18
Total	**6440**	**pages**	


Peter, "official leak" 11/16/95

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

The second prize is to get to build it.

Bonne Chance

Good continuation until the final success!

The Technical Proposal evaluations concluded by the end of 1995

It was a long way to convincing the LHC Experiment Committee (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…

ATLAS (and CMS) were invited then to work out Technical Design Reports for the various Sub-systems

ATLAS: 17 volumes in total over the years !

TDR	Pages	Titles	Date
1	178	*Calorimeter Performance*	1996-12-15
2	606	*Liquid Argon Calorimeter*	1996-12-15
3	330	*Tile Calorimeter*	1996-12-15
4	256	*Inner Detector Vol 1*	1997-04-30
5	898	*Inner Detector Vol 2*	1997-04-30
6	101	*Magnet System*	1997-04-30
7	208	*Barrel Toroid*	1997-04-30
8	282	*End-Cap Toroids*	1997-04-30
9	85	*Central Solenoid*	1997-04-30
10	513	*Muon Spectrometer*	1997-05-31
11	317	*Pixel Detector*	1998-05-31
12	500	*First-Level Trigger*	1998-06-30
13	598	*Technical Coordination*	1999-01-31
14	458	*Detector and Physics Performance Vol 1*	1999-05-25
15	506	*Detector and Physics Performance Vol 2*	1999-05-25
16	370	*High-Level Trigger Data Acquisition and Controls*	2003-06-30
17	234	*Computing*	2005-03-18
Total	**6440**	**pages**	

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

Professor C H Llewellyn Smith
Director General
CH - 1211 Geneva 23, Switzerland
Telephone Direct: (41.22) 767 23 00
Secretary: (41.22) 767 35 96
Fax: (41.22) 767 89 95
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

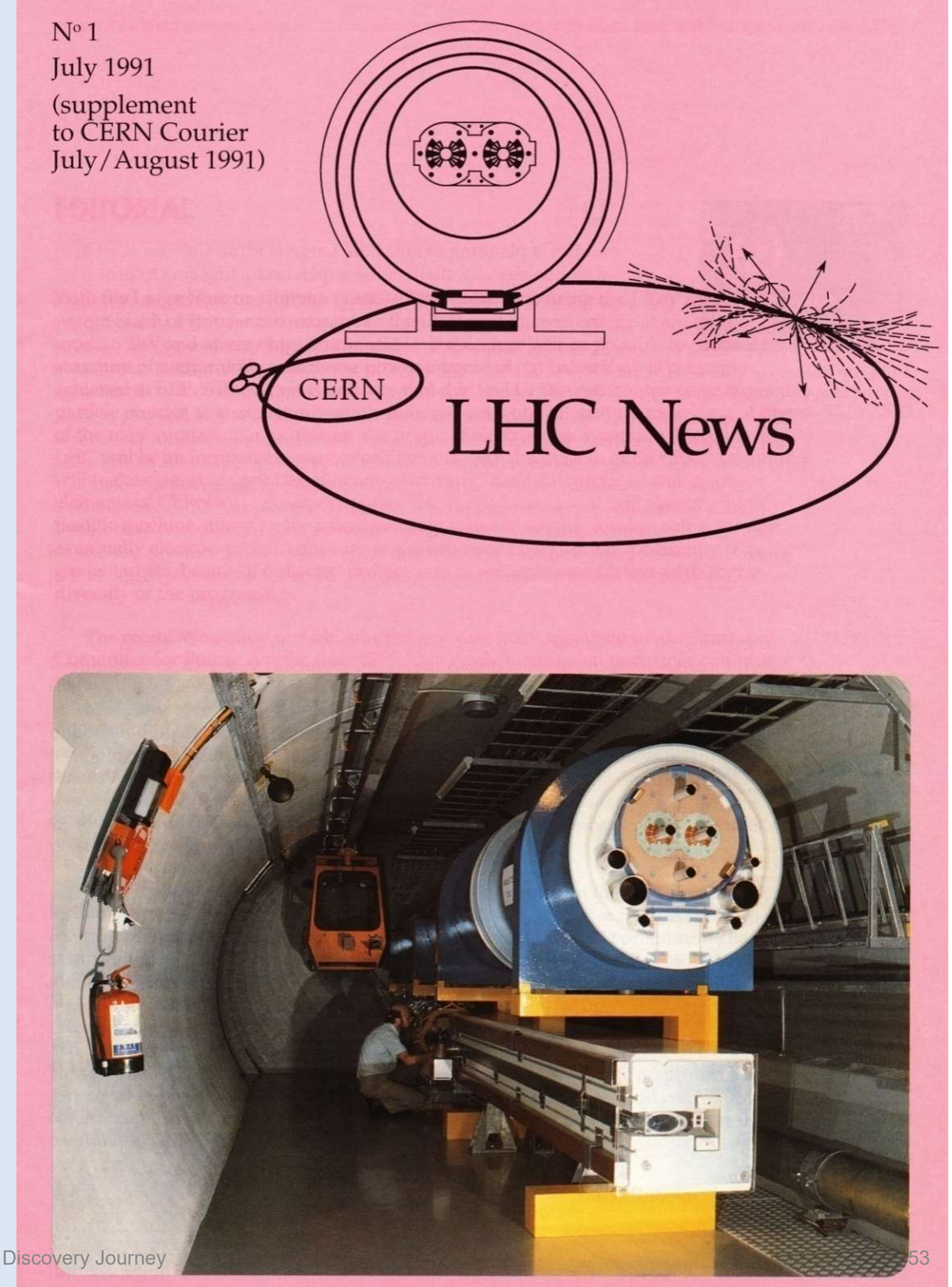
The formal construction approval was then given with the approval of the first TDRs (1 July 1997)

In the meantime, on the LHC machine side…

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

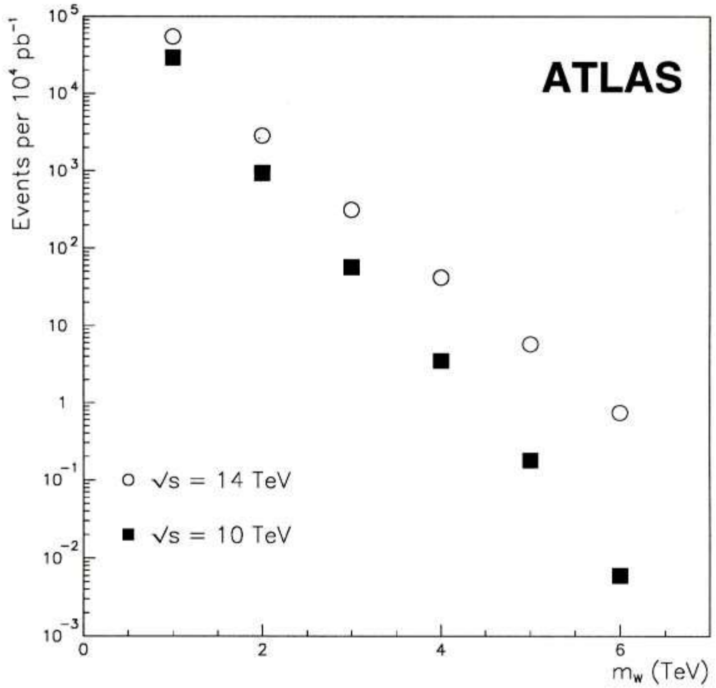
16 December 1994 Council:

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

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 US-CERN agreement on 19th December 1997: R Eisenstein (NSF), C Llewellyn Smith (CERN DG), M Krebs (DOE)

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)

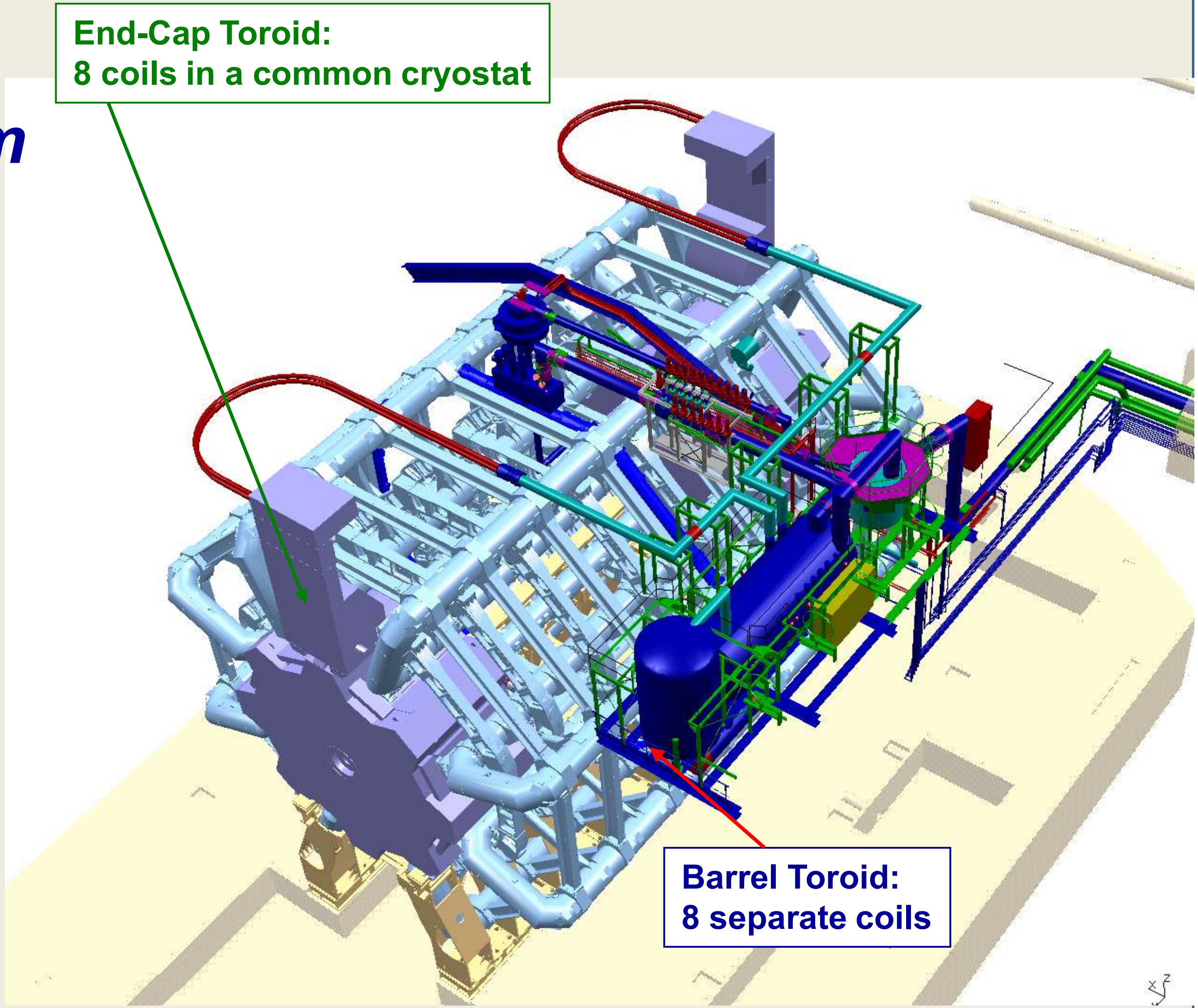
1996

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

Delivery of the last dipole for the LHC injection lines from Russia (15th June 2001), with L Maiani and A Skrinsky in the centre

Few examples of the many technical challenges for the ATLAS detector construction

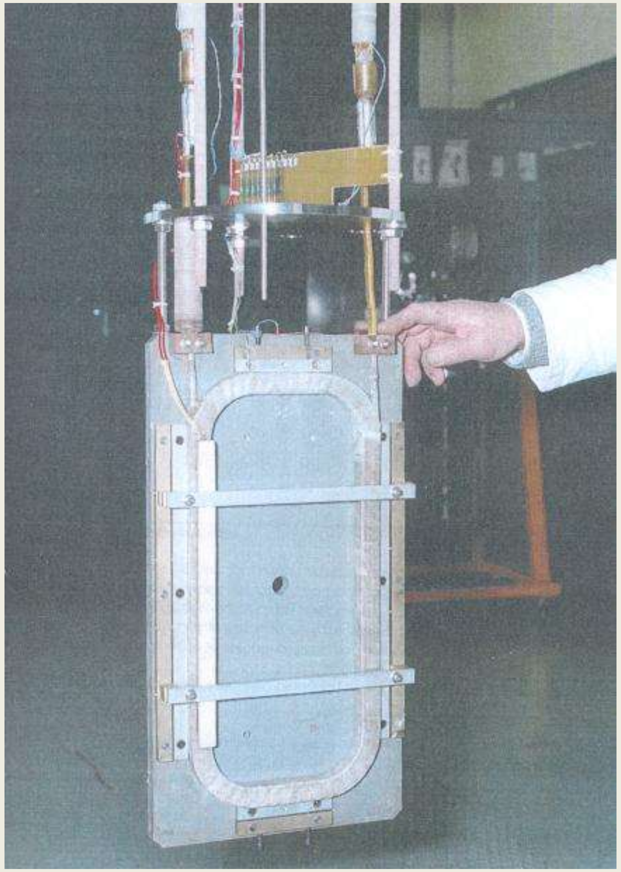
ATLAS Toroid Magnet System



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

From small to big:
Important first steps towards the ATLAS Barrel Toroid



Micro-B coil (Saclay R&D)

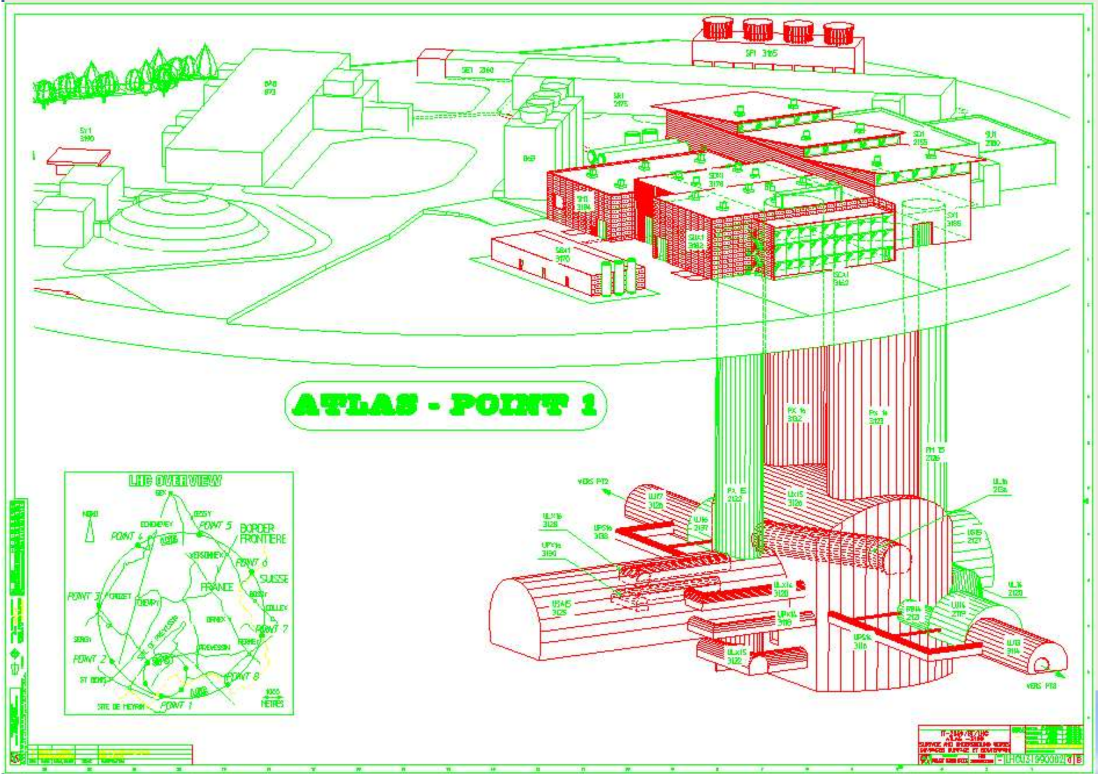
The ATLAS Race-Track coil at Saclay (tests ~1995, picture 1999)

Barrel Toroid coil integration and testing in Hall 180

Series integration and tests of the 8 coils at the surface from 2001 until in June 2005

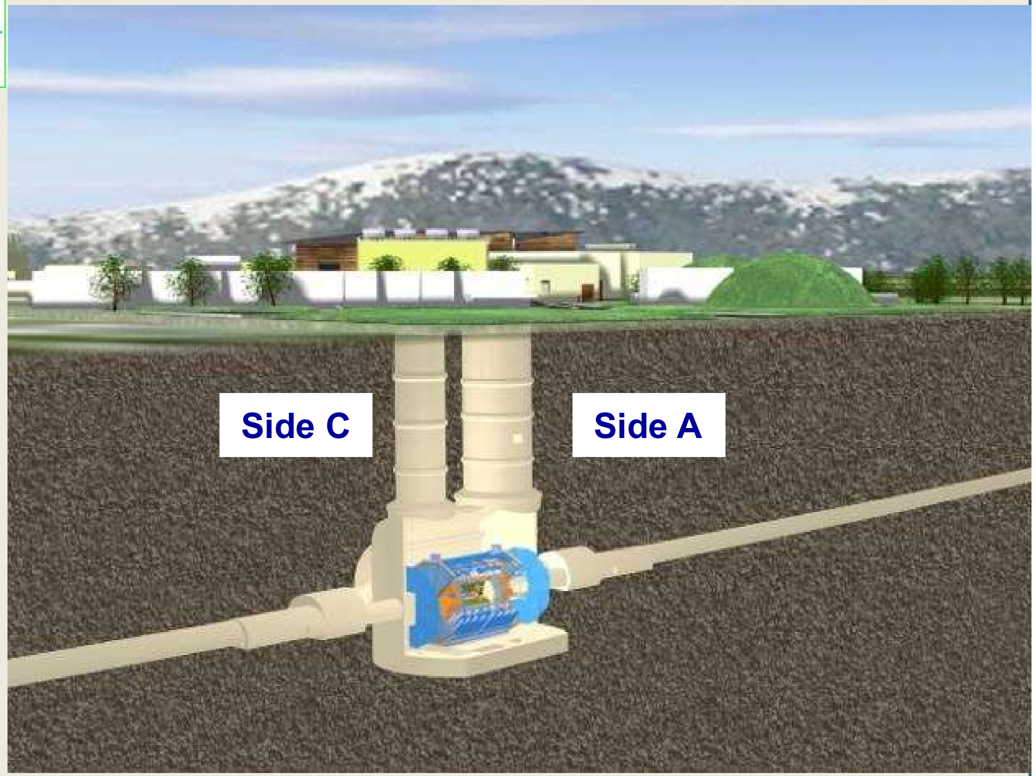
BT5 excitation tests to 22 kA current

November 2003



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

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



Point-1 Civil Engineering 1998-2003
(underground cavern 56 x 32 x 35 m^3)

Formal inauguration of the point-1 cavern on 4th June 2003

Daniel Fournier   5 January 1990

An approach to high granularity, fast Liq Ar calorimetry using an ‘accordeon’ structure

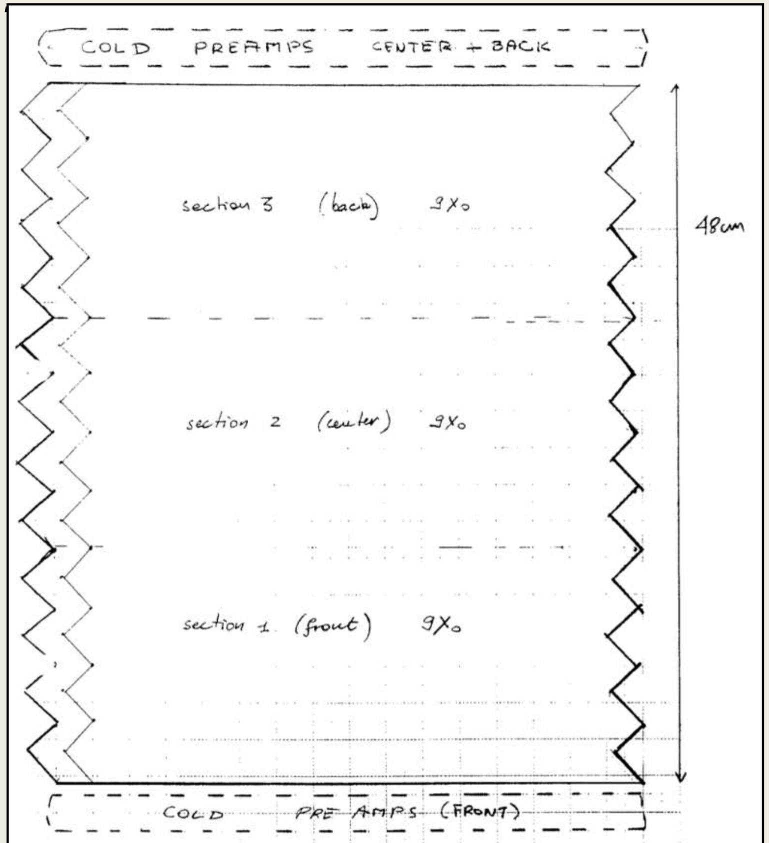


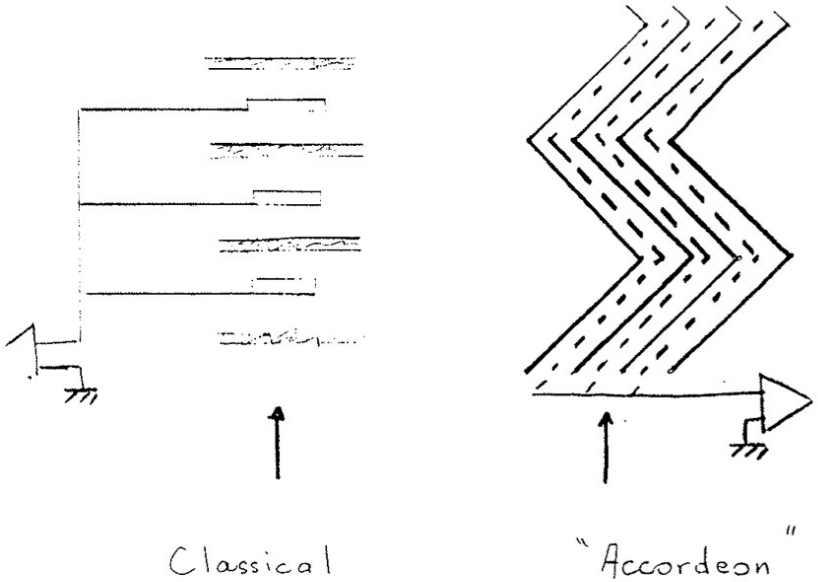
Fig 1 The test calorimeter (scale 1:2.5) (top view)

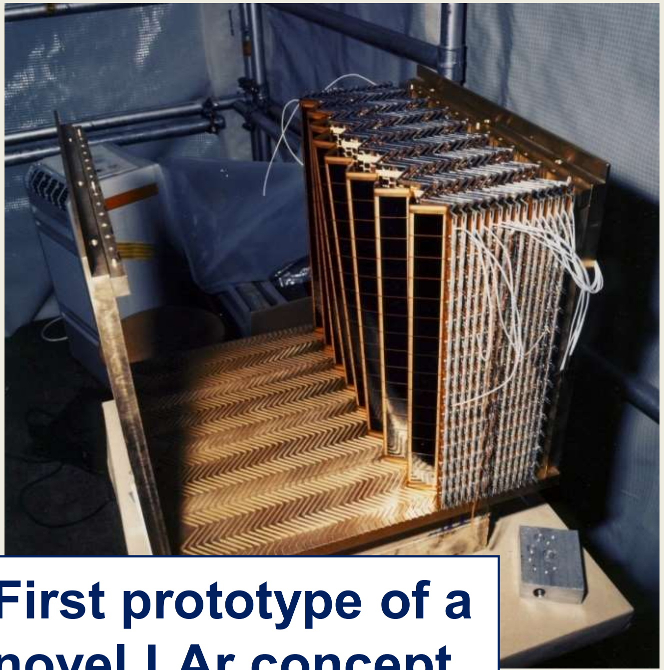
D.Fournier 5-jan-90

An approach to high granularity, fast Liq Ar calorimetry using an "accordeon" structure

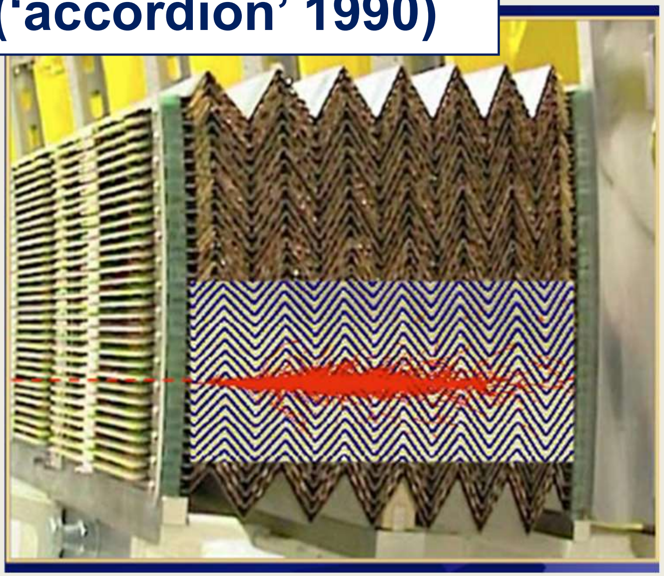
1)BASIC IDEA

In the conventionnal approach of liquid argon calorimetry parallel electrodes are connected in parallel(or in serie in the ES transformer approach) to form a tower. Instead one consider here a scheme in which the converter plates and electrodes are at +- 45 degrees ,thus making an "automatic" connection of the elements forming a tower.
In this situation the incident particle makes an angle of 45 degrees with the converter plates.To first order resolution similar to the standard case is recovered by choosing converter plates thinner by sqrt(2).





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

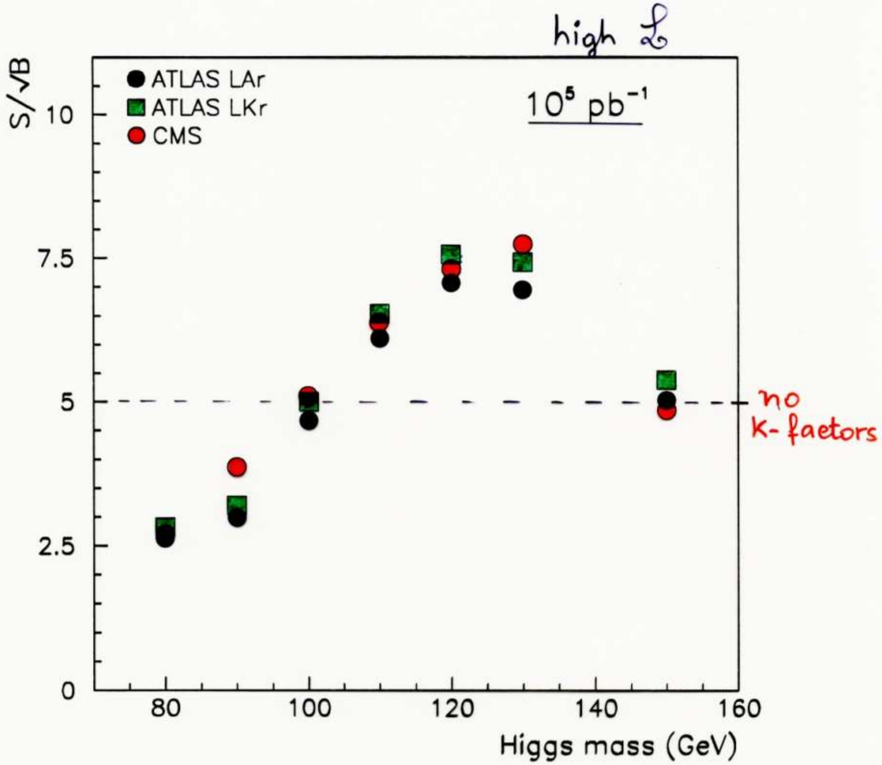


LAr EM calorimeter construction 1999 - 2004

We had quite some intense discussions within the Collaboration and with the LHCC about performance issues in the 1990s, here as example on the EM resolution…

H → γγ SIGNIFICANCE

LKr : ~ 7 % better than LAr



CMS : à la ATLAS : no K-factors
jet bckgr. included
etc.

low ℒ : CMS ~ 20 % better than ATLAS LAr
~ 12 % Lkr

H → γγ m_H = 100 GeV

Contributions to σ_m

high ℒ

	LAr (MeV)	LKr (MeV)	
SAMPLING TERM	900	687	←
CONSTANT TERM (0.7 %)	490	490	
PILE-UP ⊕ NOISE	500	390	←
VERTEX	400	403	
TOTAL ⊕ high ℒ	1250 ± 30	1040 ± 30	20 % ± 4 %
TOTAL low ℒ	1050 ± 30	860 ± 30	
Mass bin ε ≈ 80 % (high ℒ)	3430	3080	~ 11 %

Gain in $S/\sqrt{B}$ ≈ 7 %

Original slides from F. Gianotti

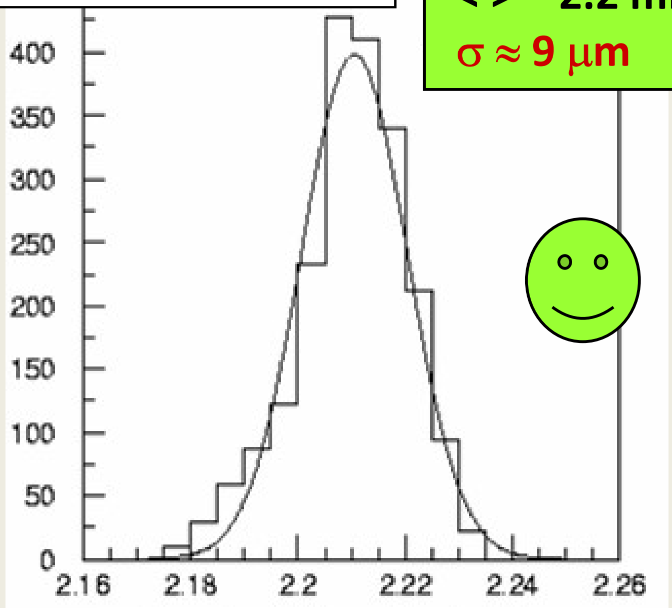
An example of constant quality checks (done on all ATLAS components, here shown for the LAr EM calorimeter)

Construction quality

Thickness of Pb plates must be uniform to 0.5% (~10 μm)

End-cap: 1536 plates

< > ~ 2.2 mm
$\sigma \approx 9$ μm

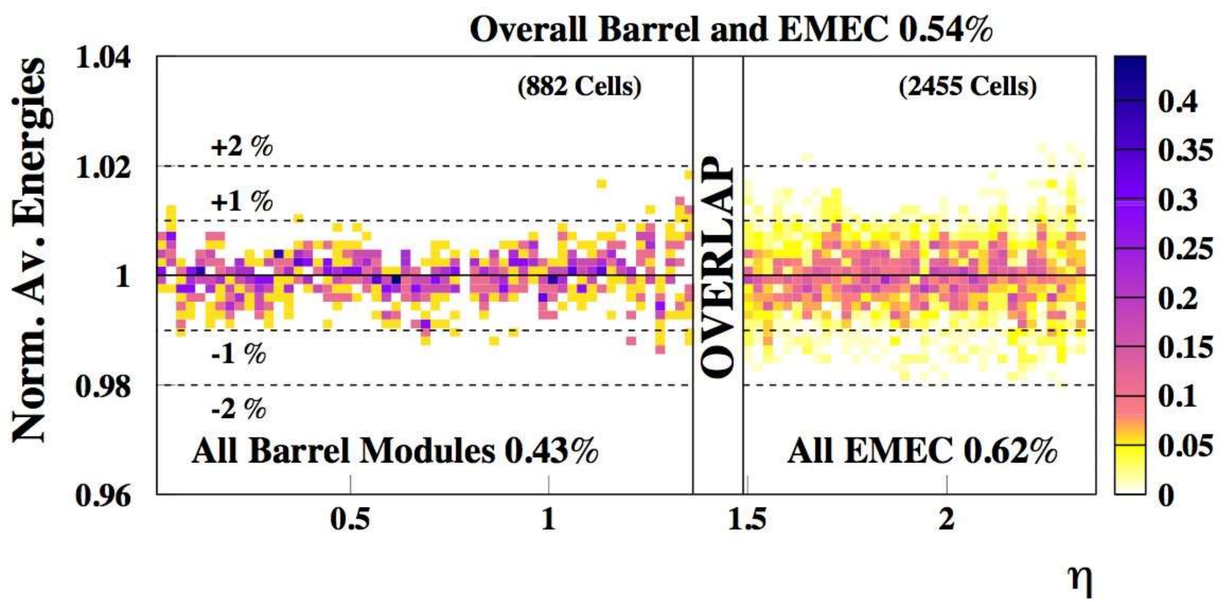


Absorber thickness (mm)

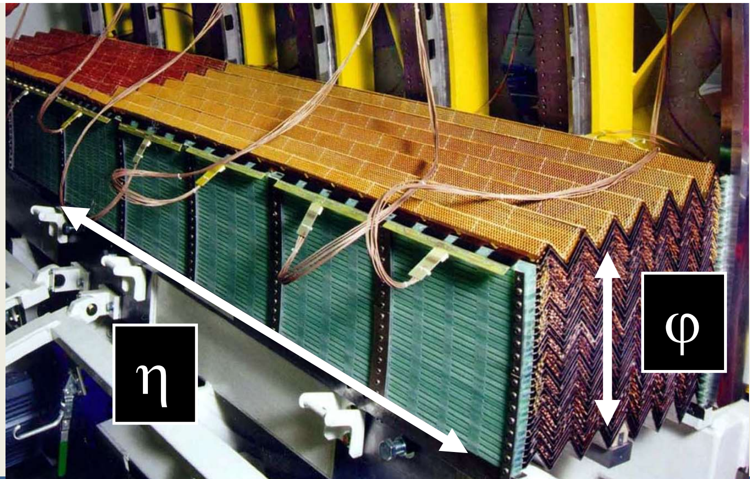
Test-beam measurements

4 (out of 32) barrel modules and 3 (out of 16) end-cap (EMEC) modules tested with beams

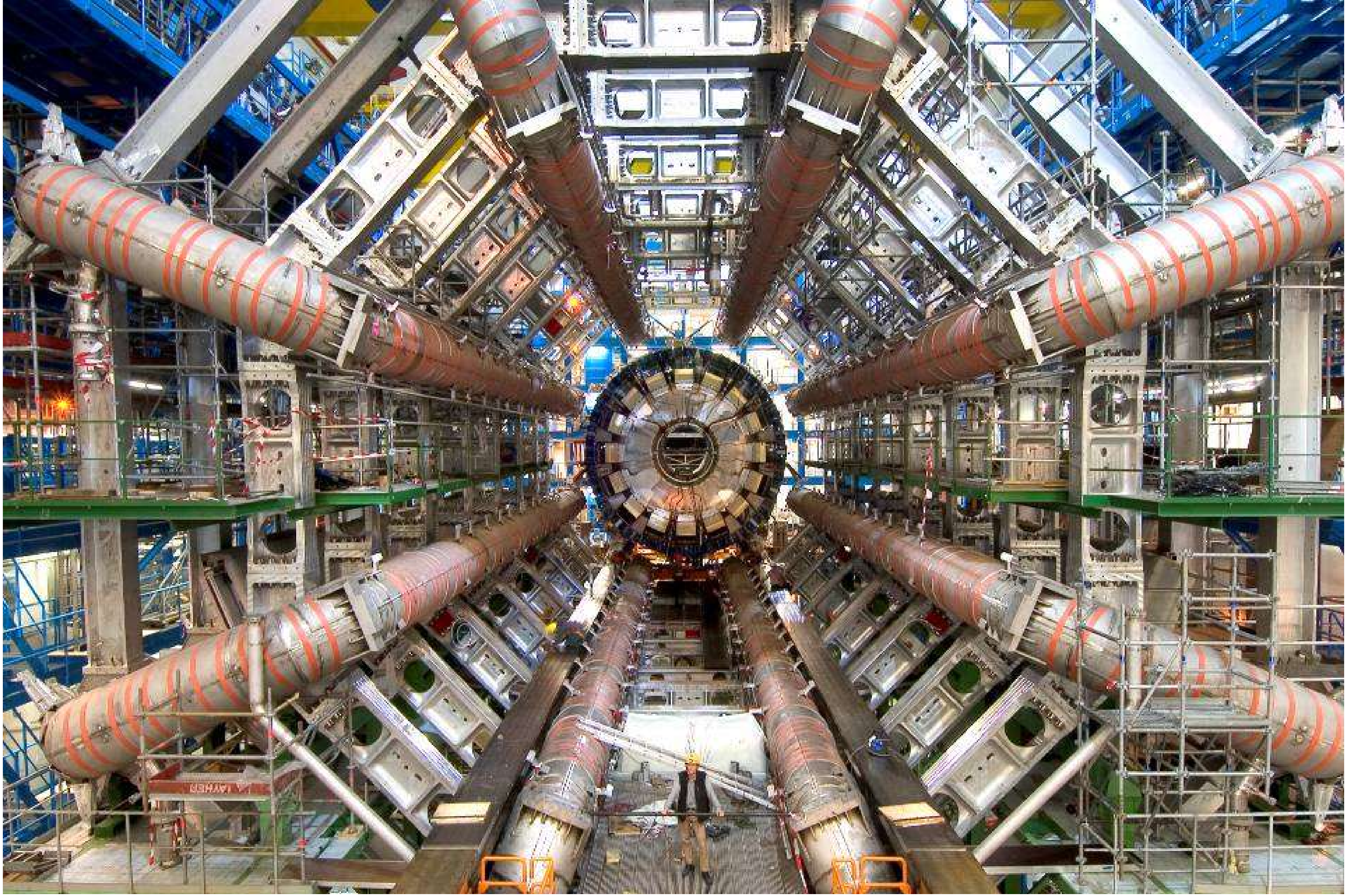
Scans with 120-245 GeV electrons (all 7 tested modules)



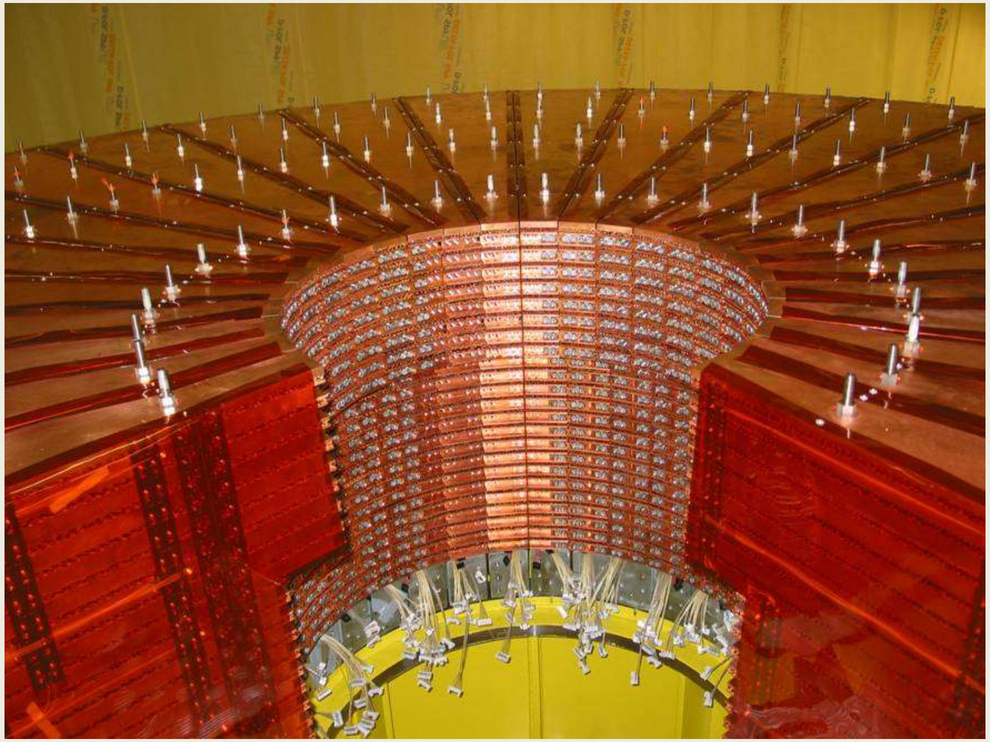
1 barrel module:
$\Delta\eta \times \Delta\varphi = 1.4 \times 0.4$
≈ 3000 channels

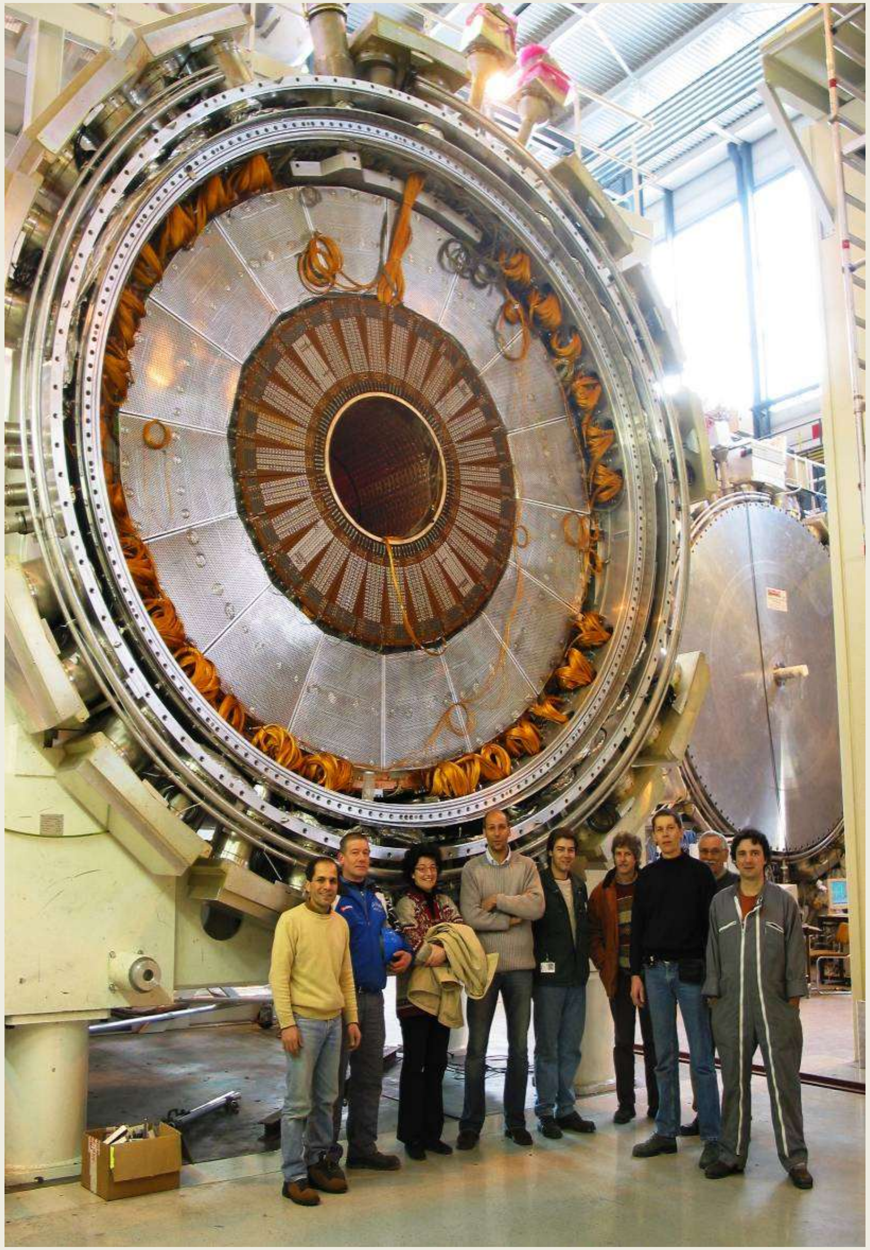


Insertion of the solenoid into the LAr EM calorimeter barrel cryostat



Barrel toroid and barrel calorimeter (plus solenoid) installations 2004-2005





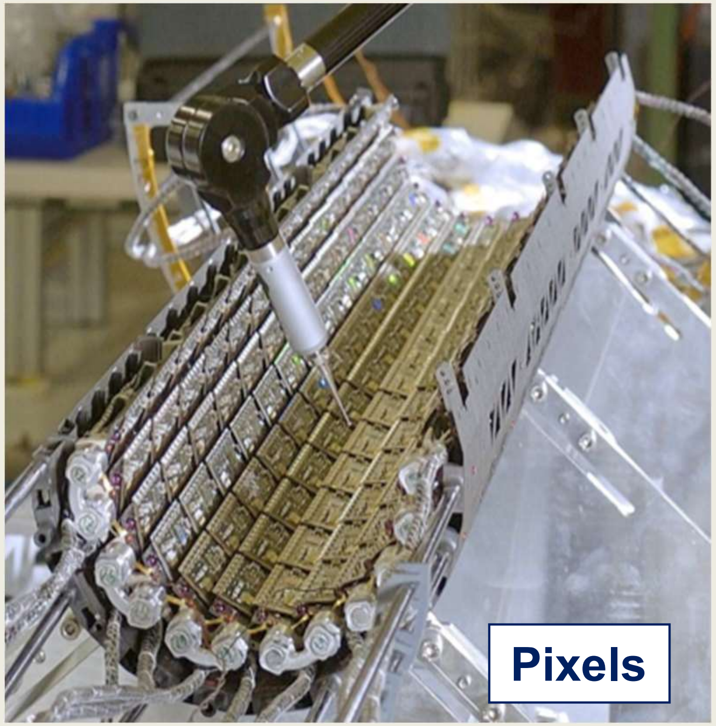
LAr hadronic End-Cap Calorimeters (pictures show stacking 2000, wheel assembly 2003 and cryostat before closing 2005)

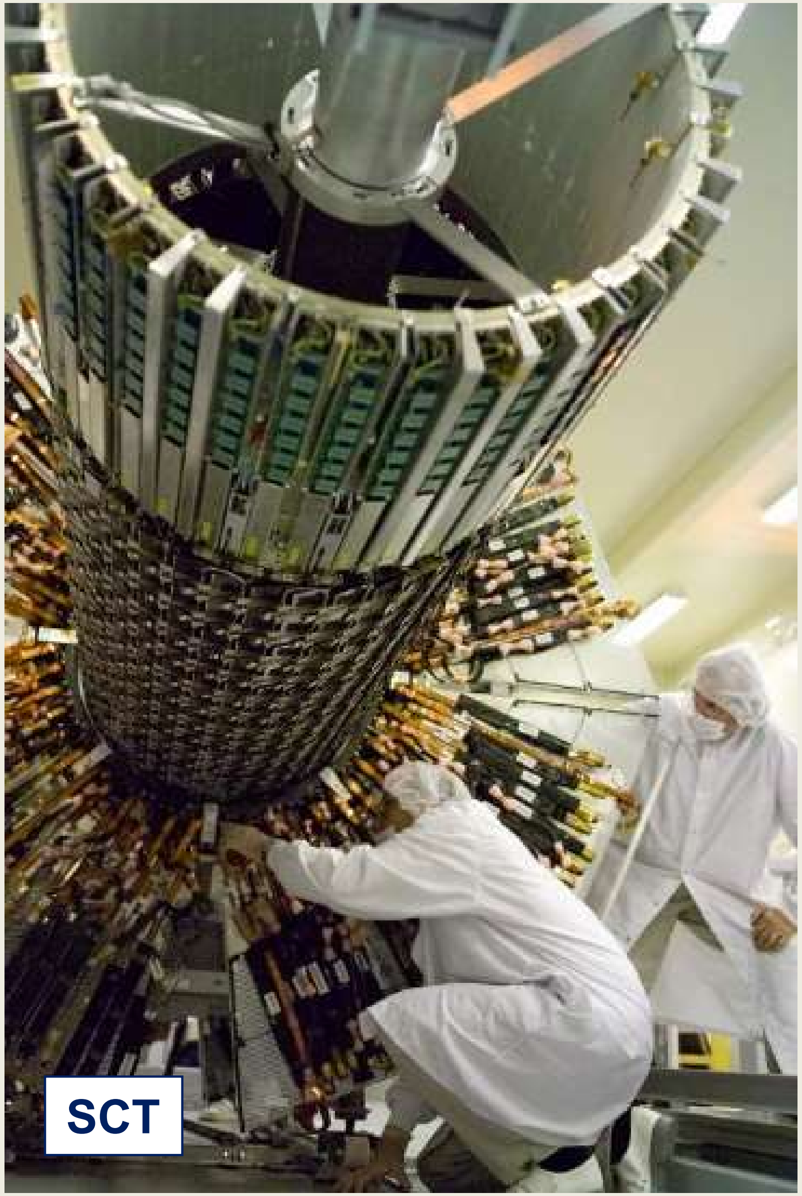

1st EC calorimeter transport 22nd Sep 2005

First barrel muon chamber installation (January 2005)

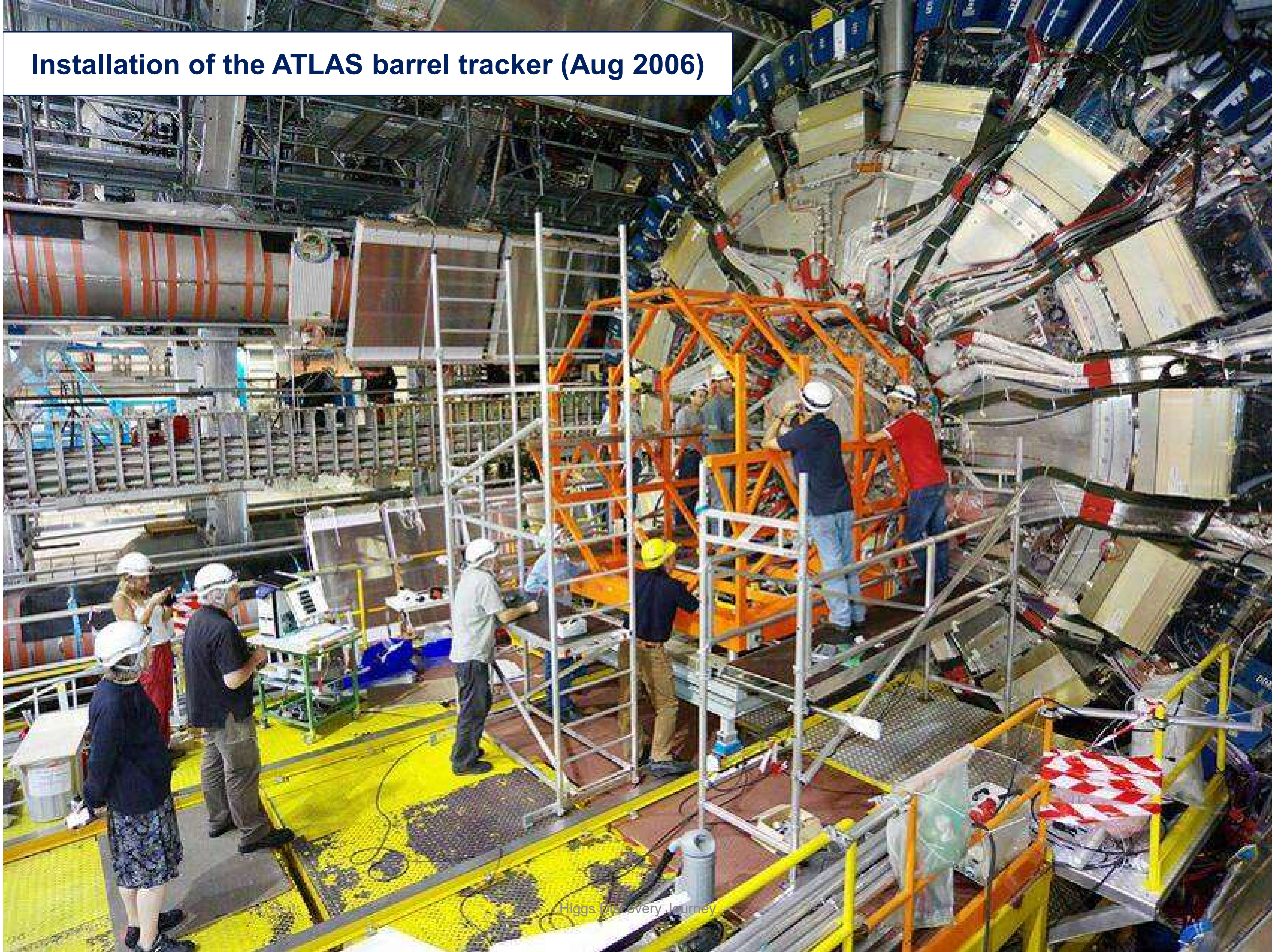
Israel-Japan-Pakistan: Teams working together in assembling TGC Big Wheel sectors (Hall 180, March 2006)

Snapshots from the Inner Detector construction years (2001 – 2007)

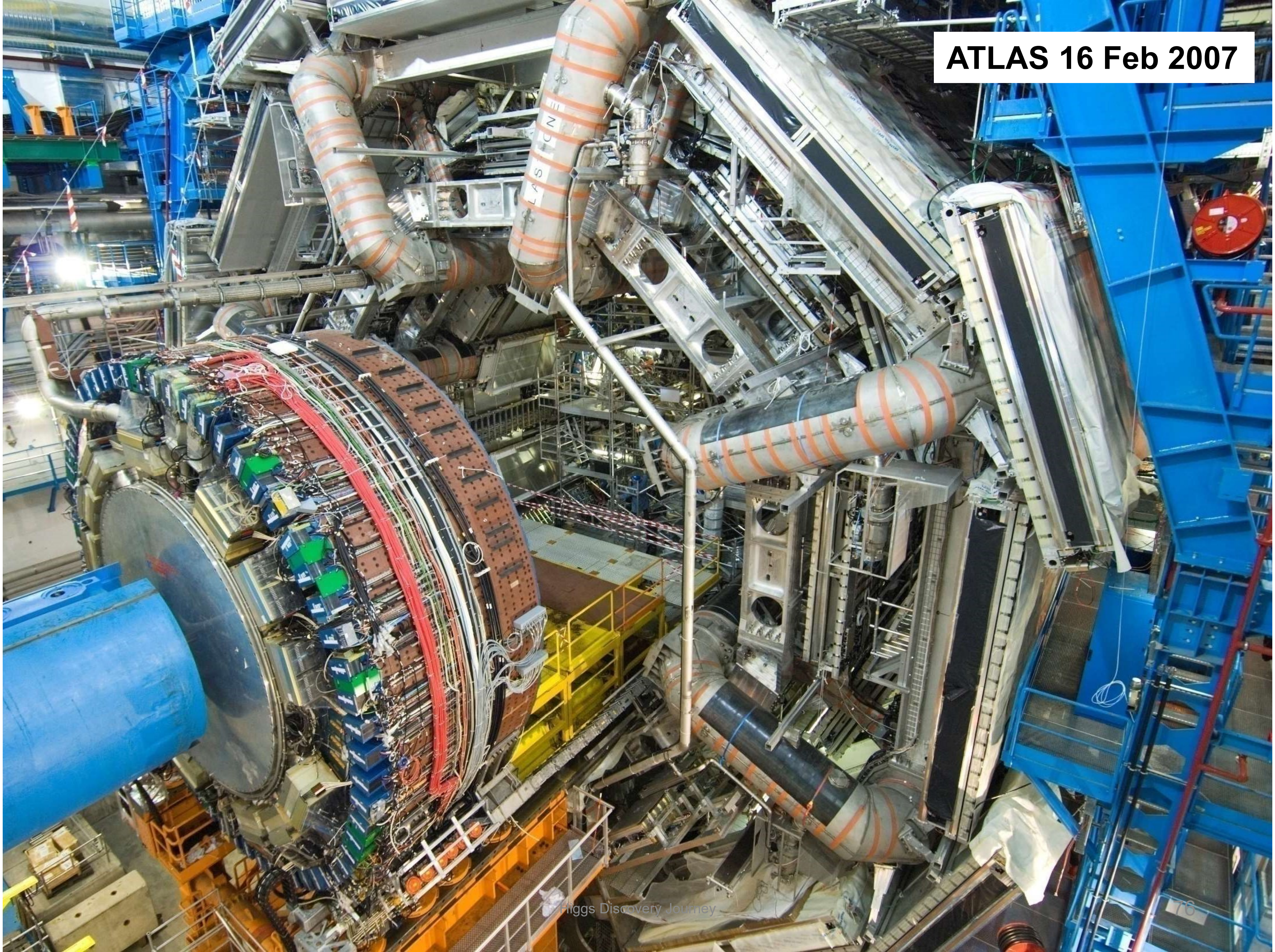




Installation of the ATLAS barrel tracker (Aug 2006)

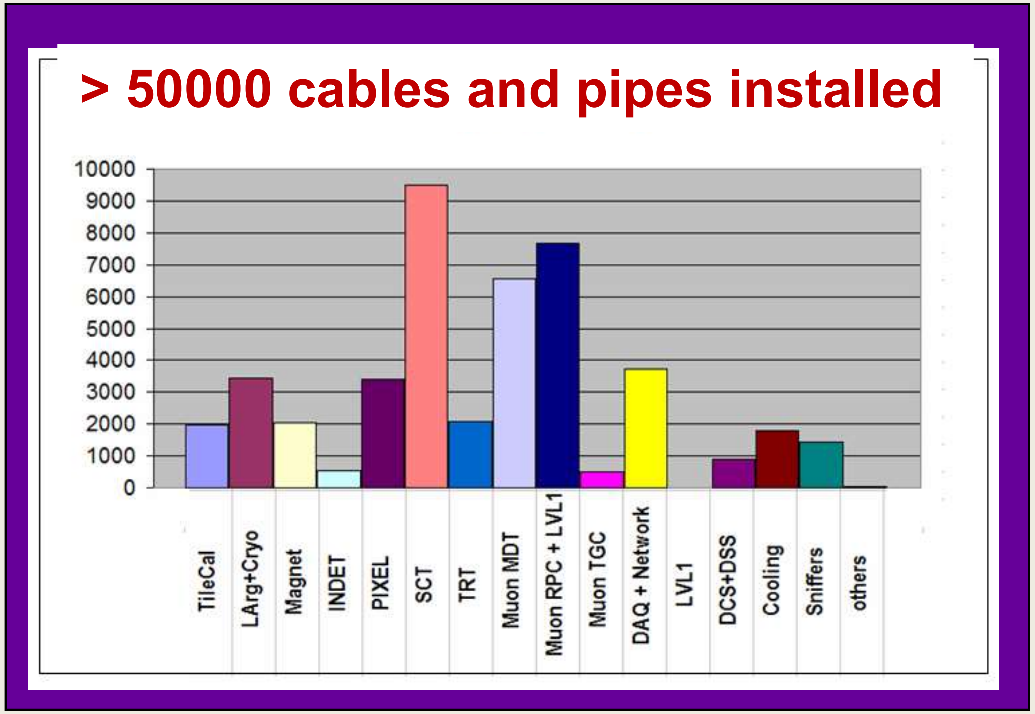


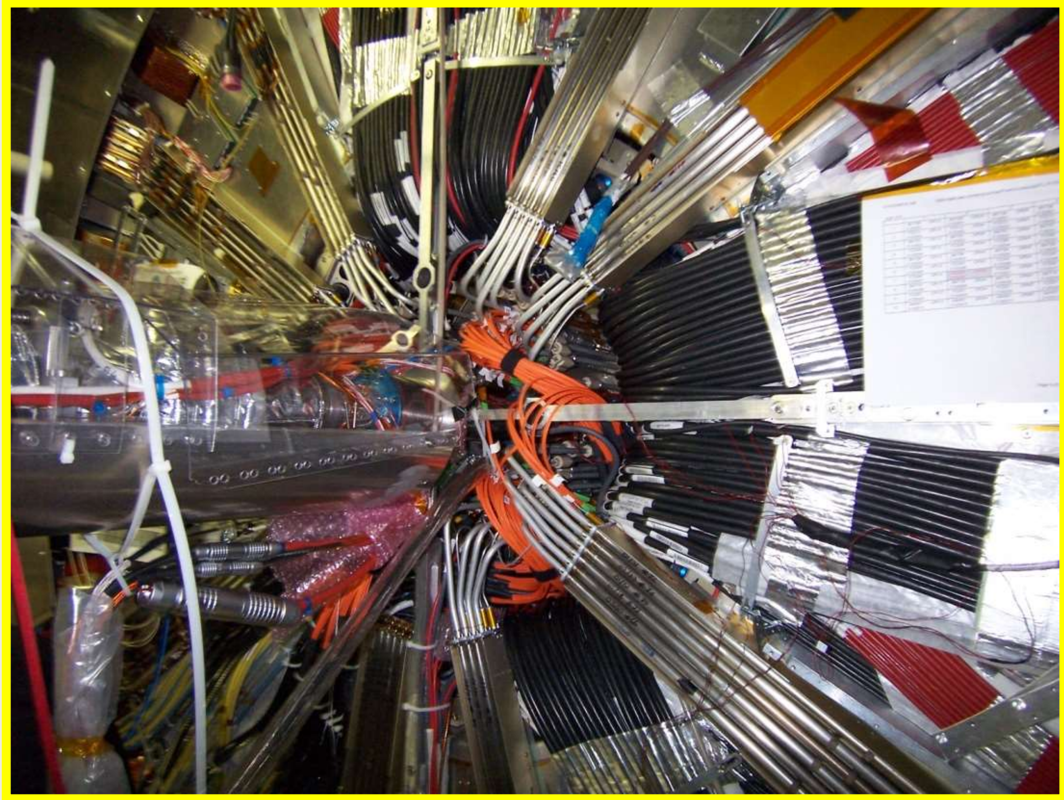
ATLAS 16 Feb 2007



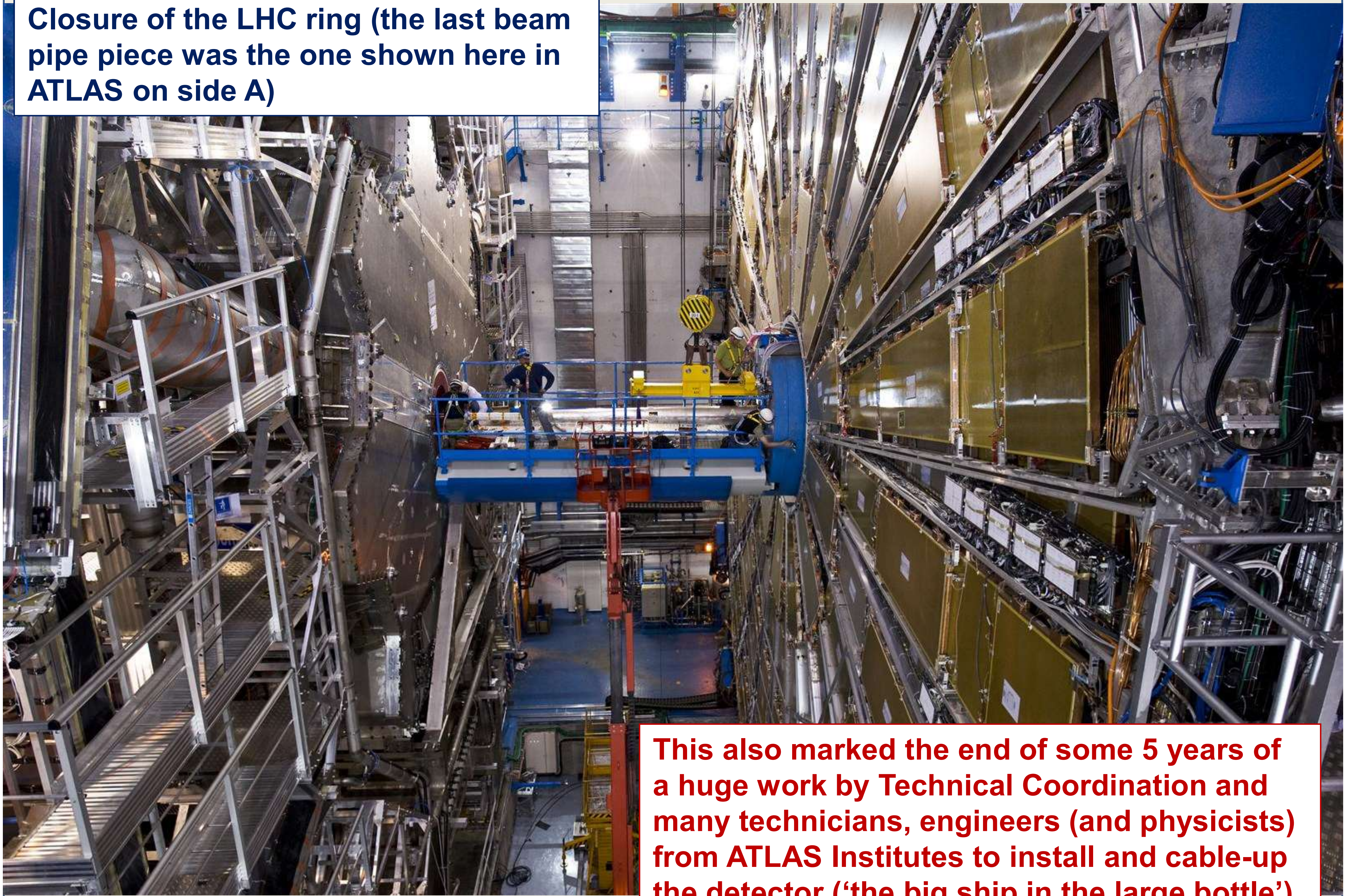
End-Cap Toroid A on its way to Point-1 (29 May 2007)

A lot of cables and pipes …





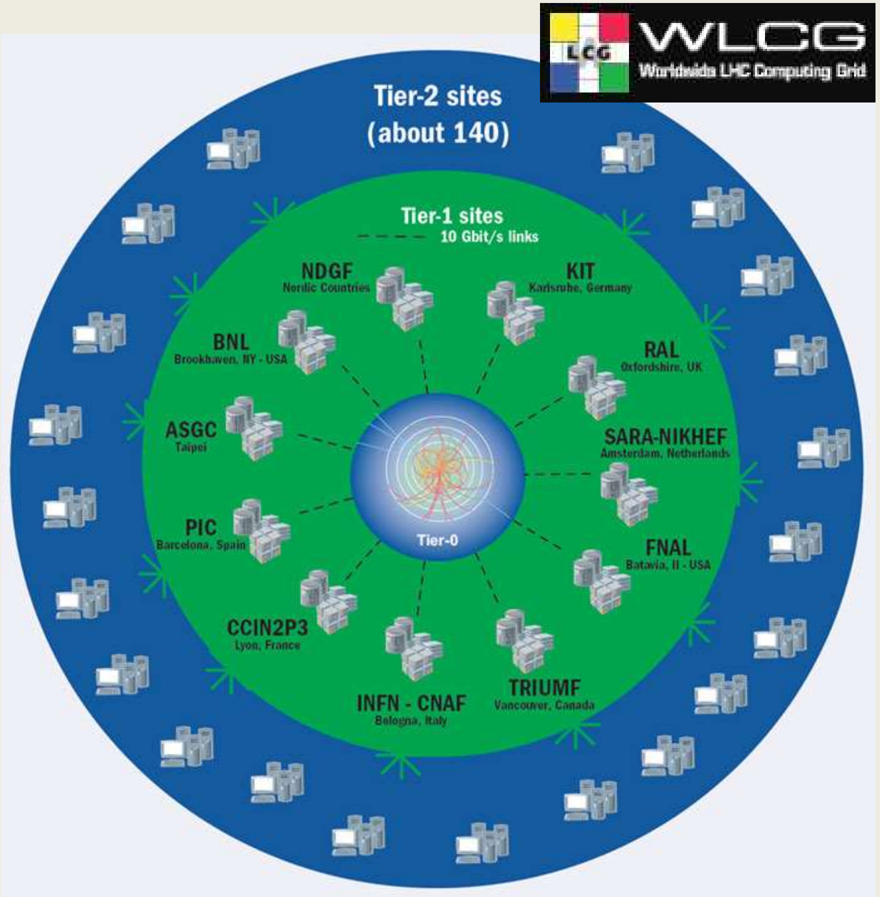
A historical moment on 16th June 2008: Closure of the LHC ring (the last beam pipe piece was the one shown here in ATLAS on side A)

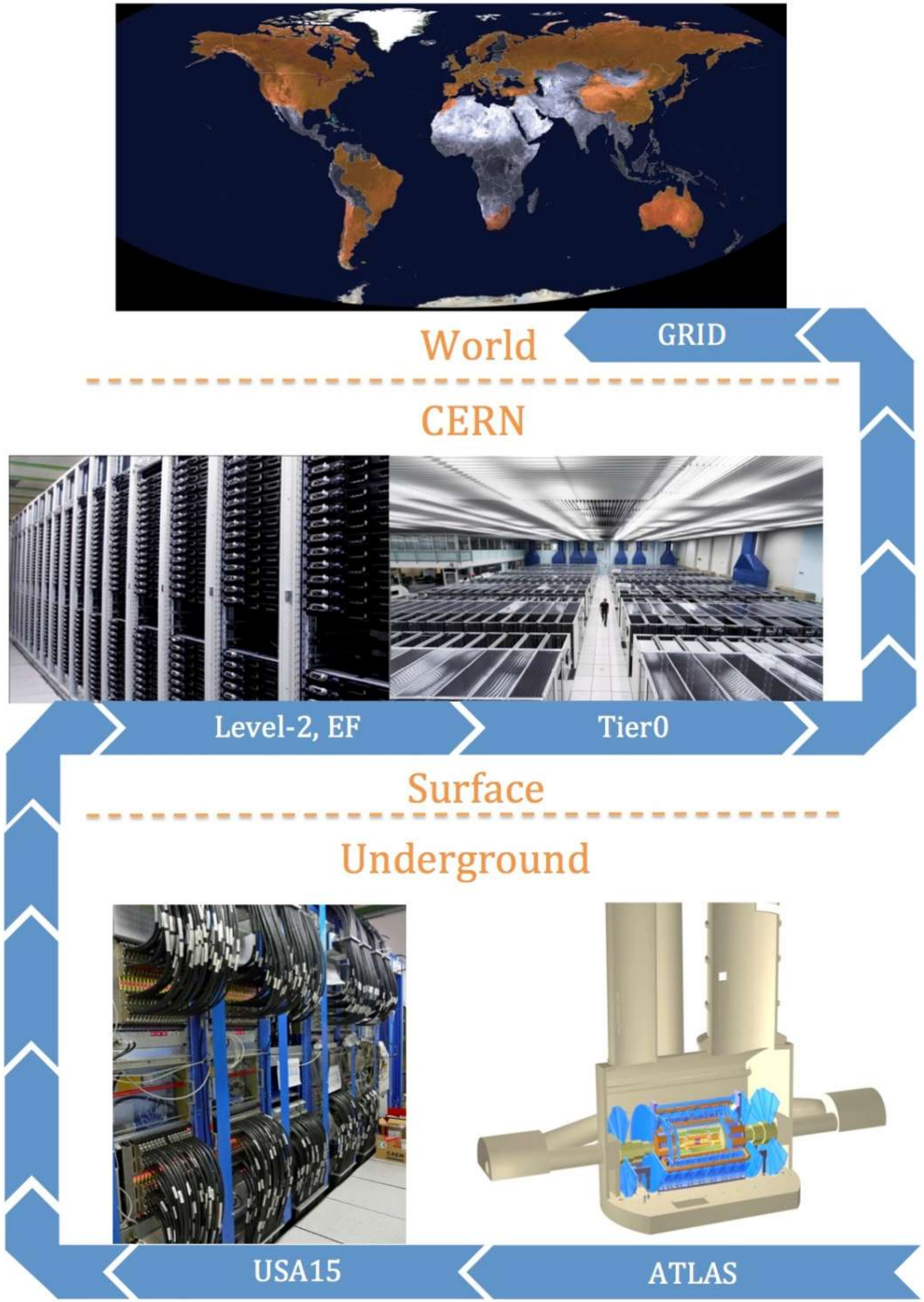


This also marked the end of some 5 years of a huge work by Technical Coordination and many technicians, engineers (and physicists) from ATLAS Institutes to install and cable-up the detector ('the big ship in the large bottle')

Trigger, DAQ, Software and Computing

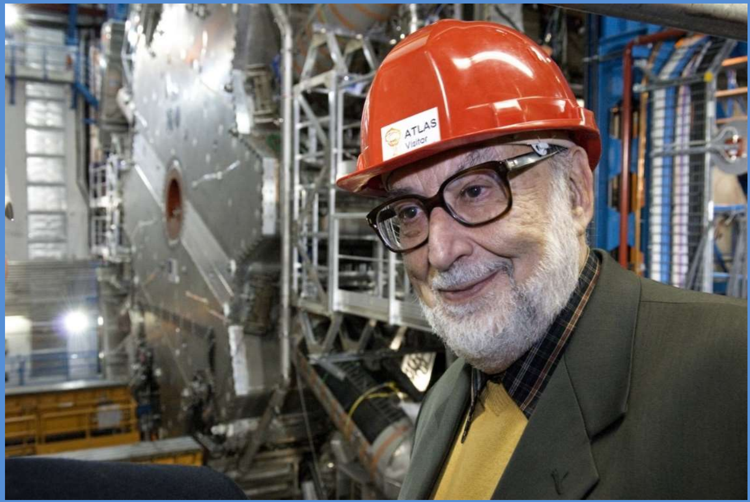
(An absolutely essential part of the success story, only left out for time…)



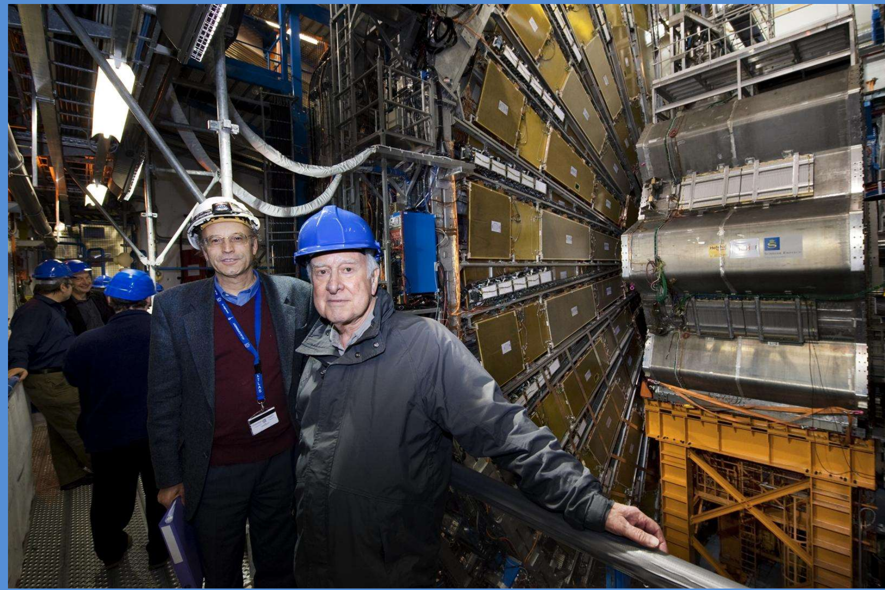


Data flow

Famous visitors in ATLAS and CMS



Francois Englert Dec 2007



Stephen Hawking Sep 2006

Steven Weinberg Jul 2009

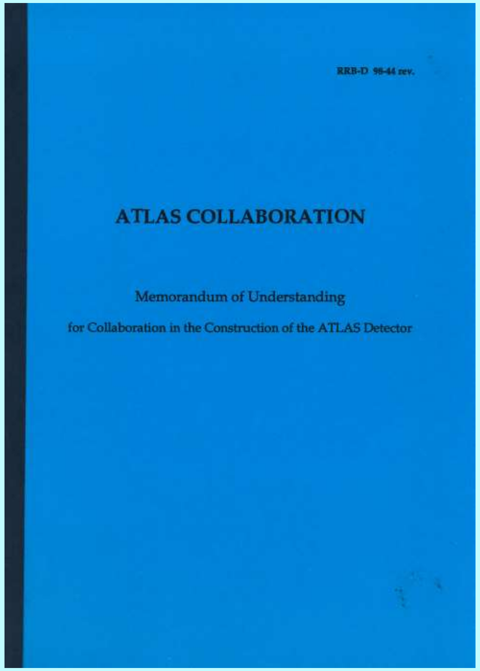
Peter Higgs Apr 2008

Since 1995 there are ATLAS and CMS Resources Review Board meetings twice a year

At the RRB the legal ('best effort') resources framework for ATLAS were/are agreed, in two stages for the initial construction, and later for the operation (M&O) and computing, and now for the upgrades …

20-Oct-1997

The Construction MoU was signed by all initial ATLAS Funding Agencies in 1998-1999



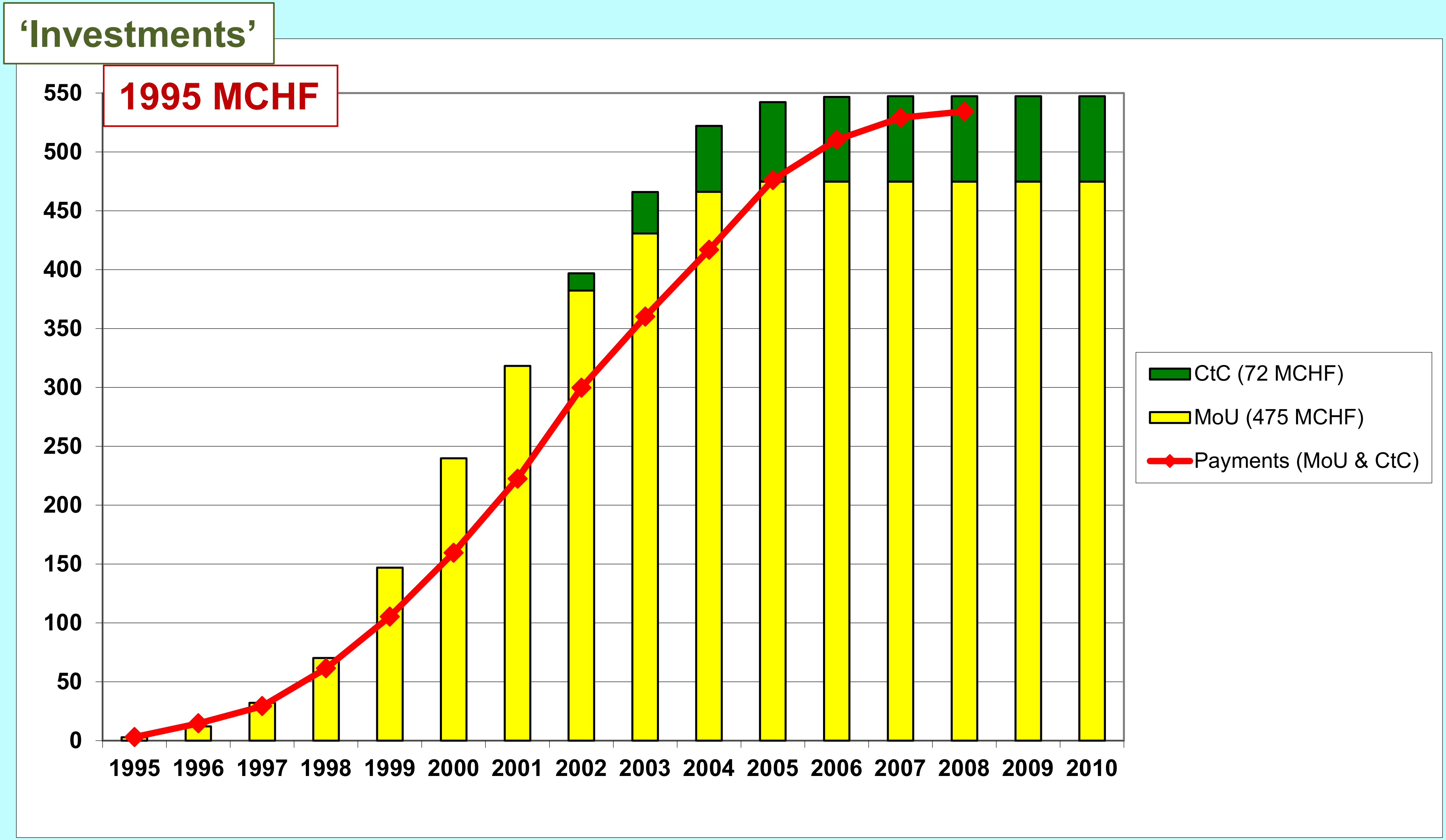
28th April 1998

	signed date	signed by
Armenia	10/7/98	R. Mkrtchyan
Australia	26/5/98	S. Tovey
Austria	18/6/98	R. Kneuker
Azerbaijan	30/6/98	N. Guliyev
Belarus	24/6/98	V.A. Gaisyonok
Brazil	6/9/99	E. Mirra de Paula e Silva
Canada	26/4/99	N. Lloyd
China	30/11/99	N. Wang
Czech Republic	26/5/98	F. Suransky, J. Niederle
Denmark	26/5/98	E. Larsen
Finland	26/5/98	E. Byckling
FRANCE CEA	6/1/99	C. Cesarsky
France IN2P3	8/6/98	C. Detraz
Georgia	22/11/99	A. Tavkhelidze
Germany BMBF	12/6/98	H. Schunck
Germany MPI	22/4/99	V. Soergel
Greece	15/6/98	E. Floratos
Israel	1/6/98	D. Horn
Italy	28/5/98	L. Maiani
Japan	23/6/98	H. Sugawara
JINR	10/6/98	A.N. Sissakian
Morocco	1/6/98	S. Belcadi
Netherlands	15/10/98	G. van Middelkoop
Norway	22/6/98	K. Kveseth
Poland	28/5/98	J. Frackowiak
Portugal	5/6/98	A. Trigo de Abreu
Romania	30/7/98	V. Lupei
Russia	10/10/98	N. Kirpichnikov
Slovak Republic	7/7/98	O. Nemcok
Slovenia	15/12/99	L. Marincek
Spain	30/4/98	F. Aldana
Sweden	29/4/99	G. Oequist
Switzerland	26/5/98	B. Fulpius, Ch. Schäublin
Turkey	2/6/98	D. Ulkü
United Kingdom	14/7/98	I.G. Halliday
US DoE + NSF	26/10/98	. O'Fallon, N. Lightbody, T. Kirk, W. Willis
CERN	26/6/98	V.G. Goggi

And new partners also signed Addenda to the MoU as they joined later

We should never forget to thank all Funding Agencies for their support

Overview of the integrated financial evolution of the 'CORE' costs of ATLAS (Constr. MoU deliverables and Common Fund, Cost-to-Completion, in 1995 MCHF)



LHC incident

Interconnections of two magnets

One (superconductor) joint failed on 19th September 2008, and it caused a catastrophic He-release that made serious collateral damage to sector 3-4 of the LHC machine (required a 15 months repair period)

LHC incident

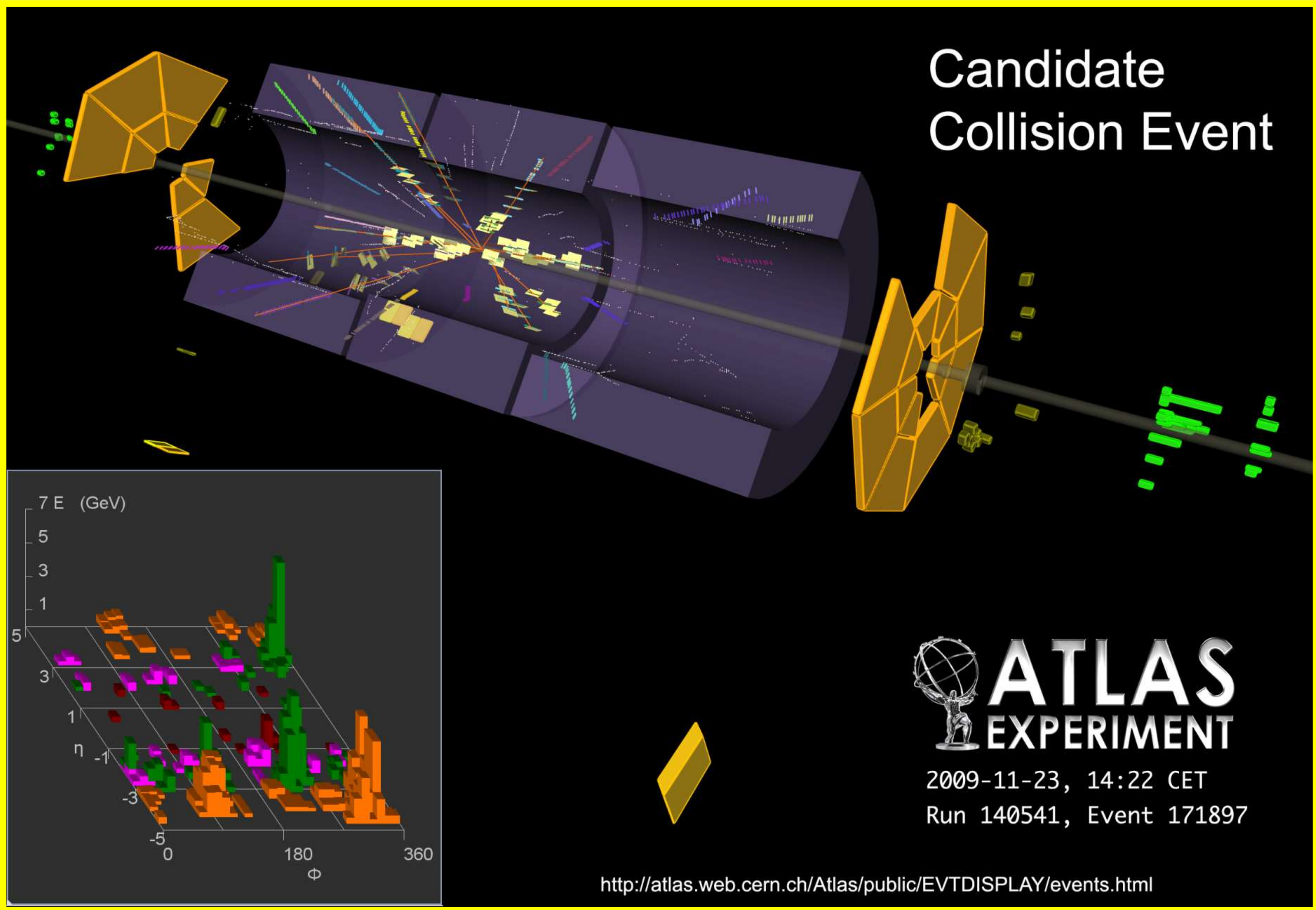
Interconnections of two magnets

One (superconductor) joint failed on 19th September 2008, and it caused a catastrophic He-release that made serious collateral damage to sector 3-4 of the LHC machine (required a 15 months repair period)

Expecting in the ATLAS Control Room the first LHC beam to collide on November 23rd, 2009....

The joy in the ATLAS Control Room when the first collisions were appearing on the display

First collisions in ATLAS 23rd November 2009 with LHC beams at the injection energy of 450 GeV

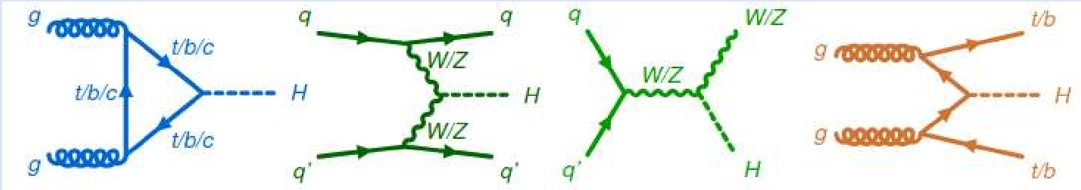


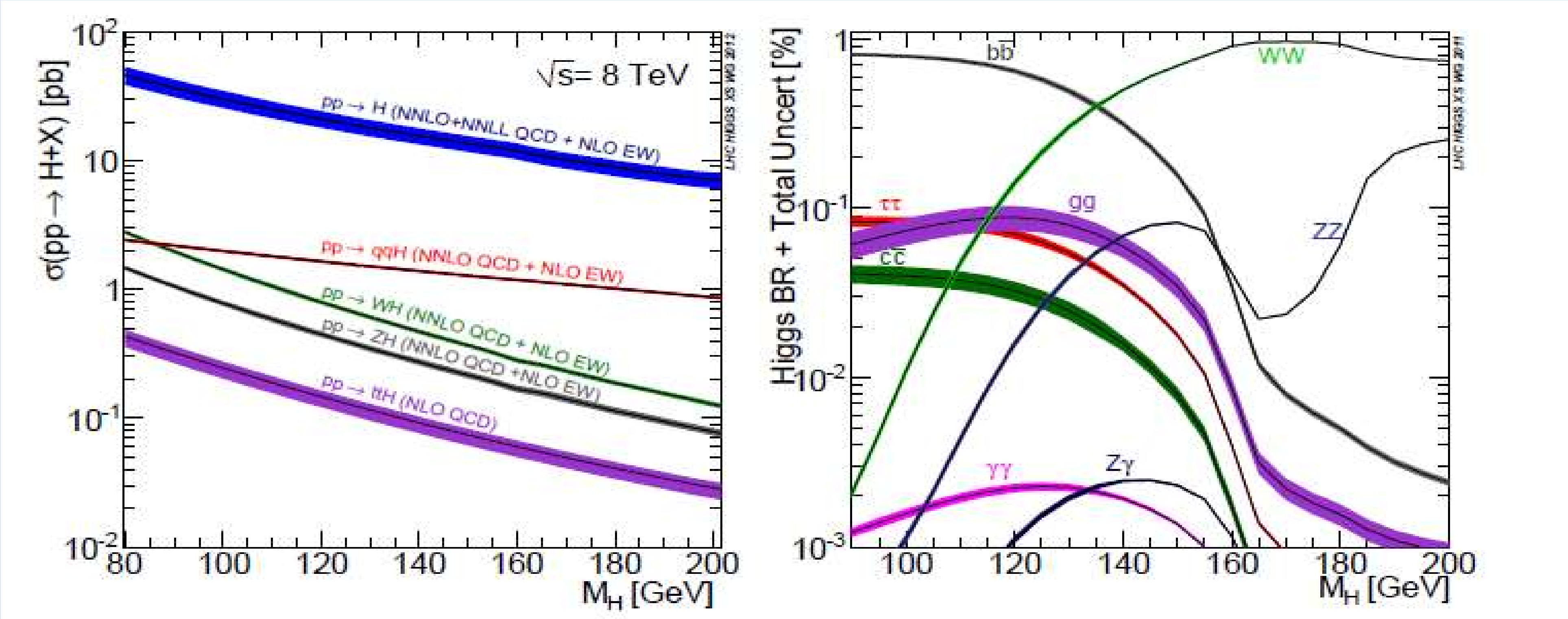
A well-deserved toast to all who have built such a marvelous machine, and to all who operate it so superbly

(first 7 TeV collisions on 30th March 2010)

Thanks to our theory friends we knew what to expect …

Higgs production cross-sections at 8 TeV, and branching fractions



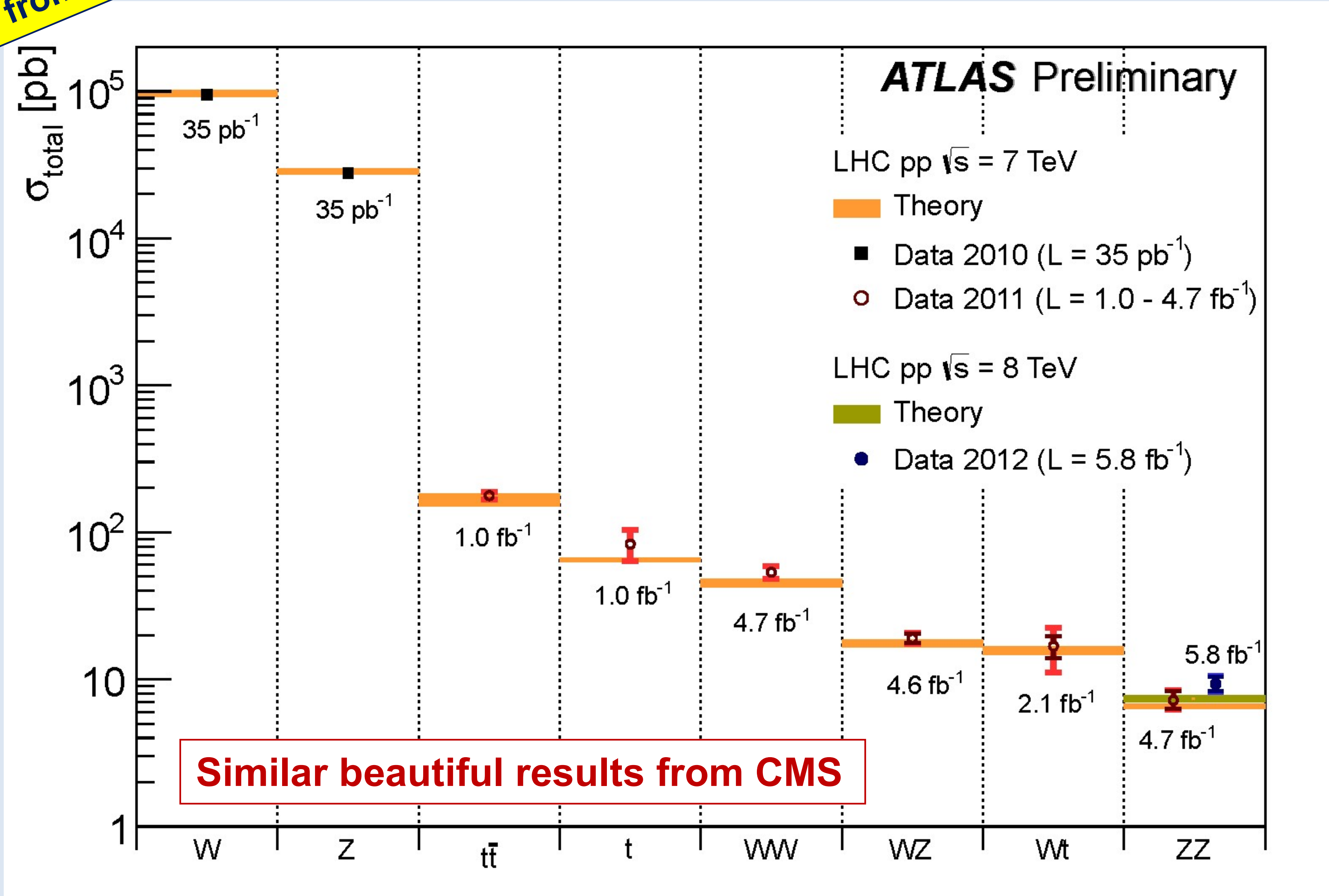


Handbook of LHC Higgs Cross Sections.

arXiv: 1101.0593 and 1201.3084; 2011/2012 (the theoretical uncertainties are indicated by the width of the curves)

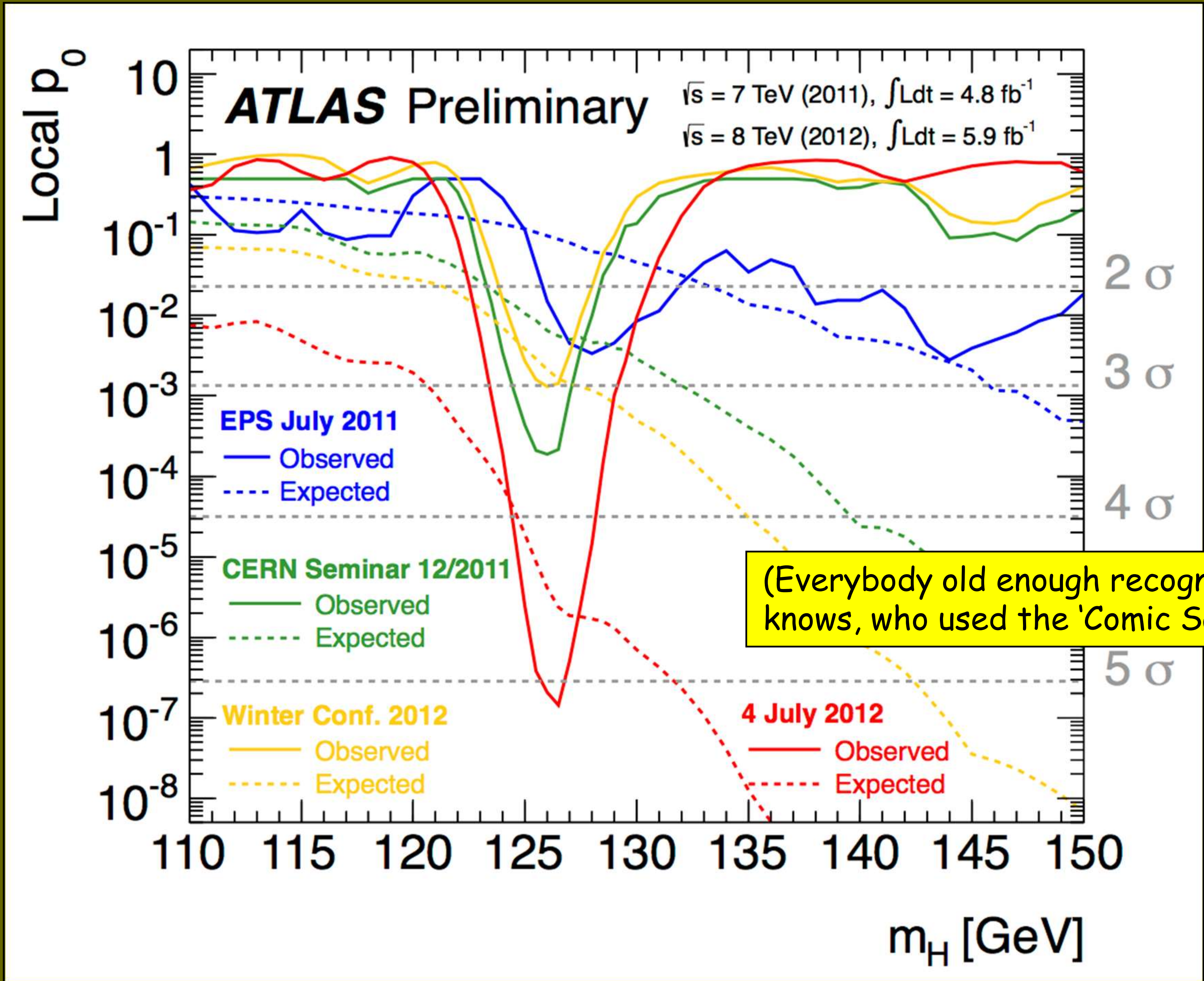
A summary of Standard Model measurements

A slide from 2012



The excellent performance in measuring Standard Model physics gives confidence for the readiness of the two experiments to search for New Physics

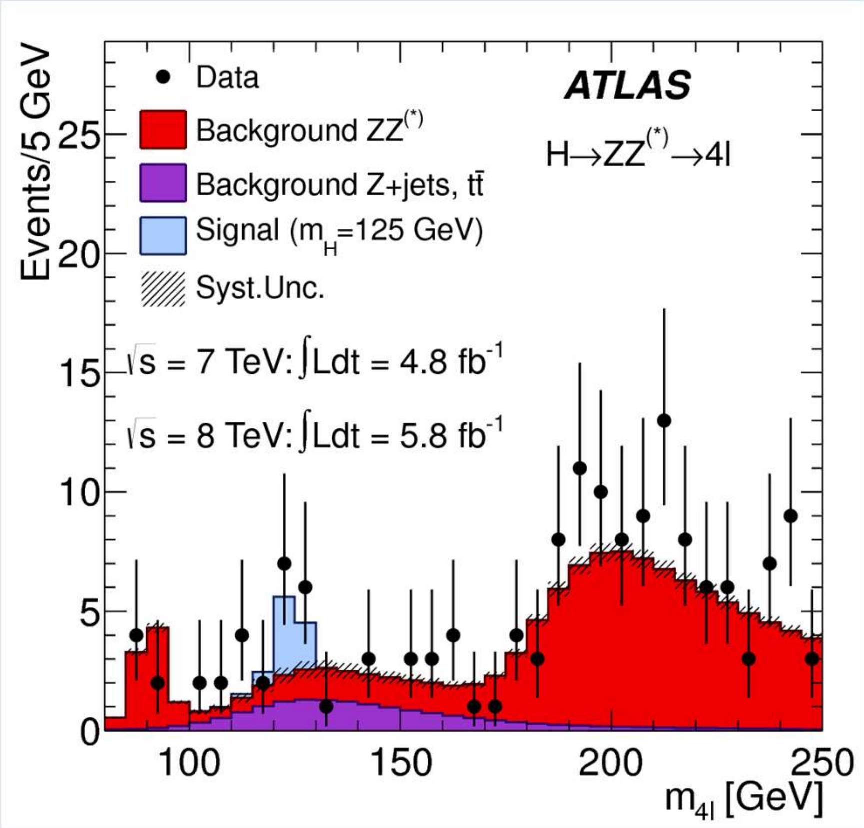
Evolution of the excess with time

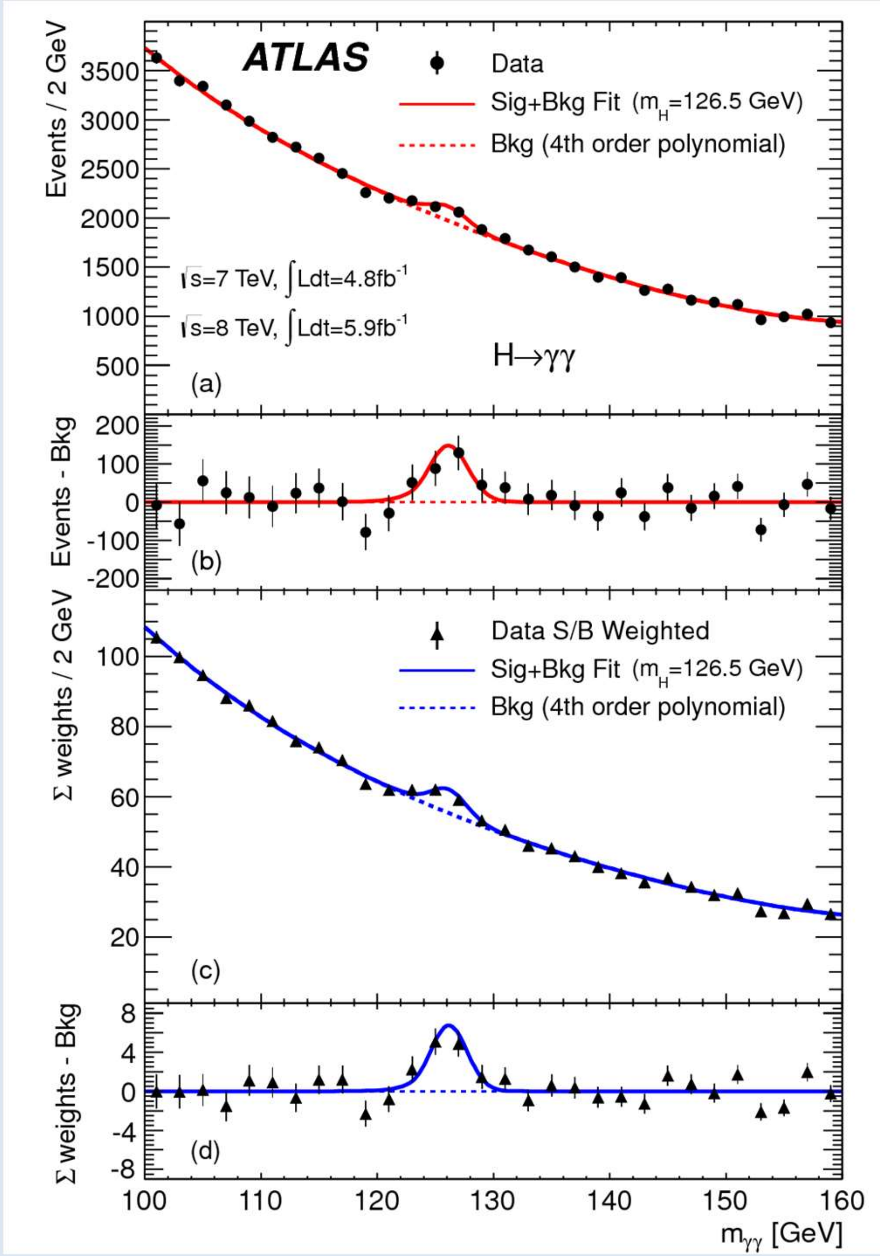


(Everybody old enough recognizes, and knows, who used the 'Comic Sans MS' font!)

Happy faces after the announcement of the Higgs boson discovery at CERN (and at ICHEP Melbourne) on 4th July 2012

ATLAS Higgs boson discovery signal peaks

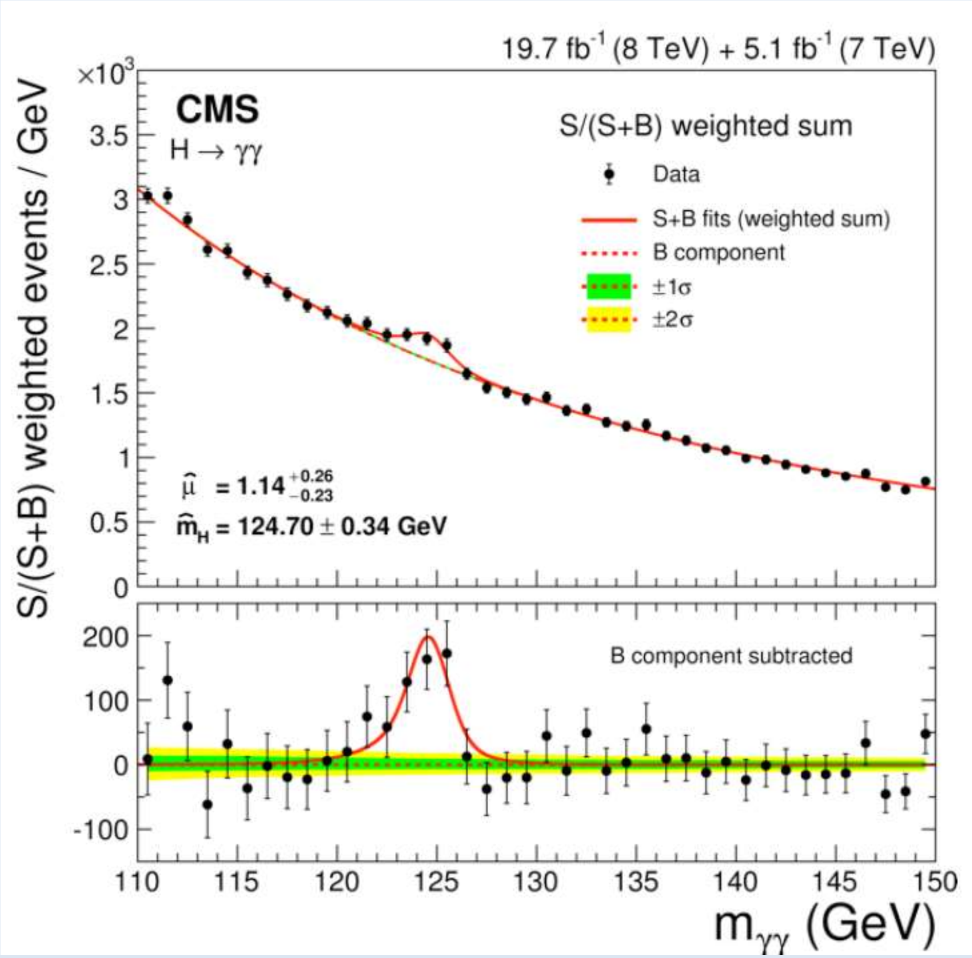




Phys. Lett. B716 (2012) 1-29, dated 31 July 2012, which includes also the H → WW channel

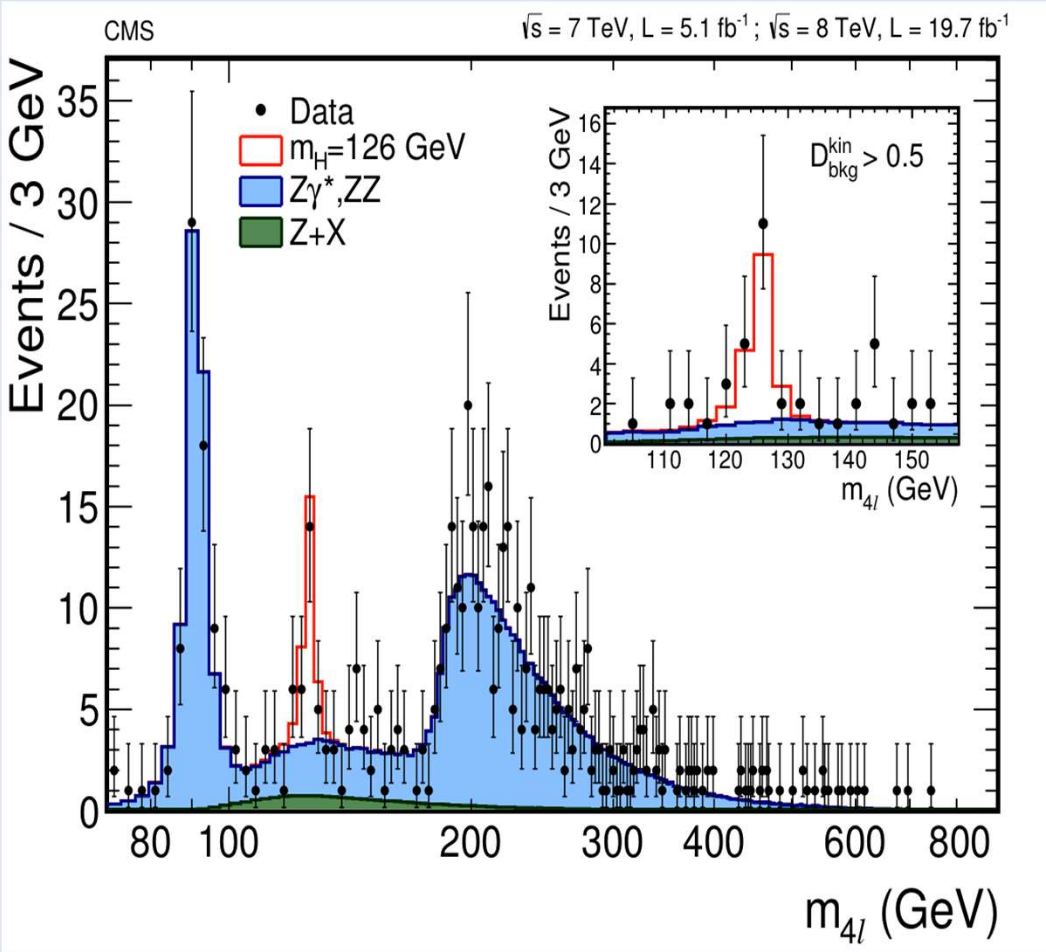
CMS Run-1 signal peaks ('Run-1 legacy')

H → γγ



Eur. Phys. J. C74 (2014) 3076

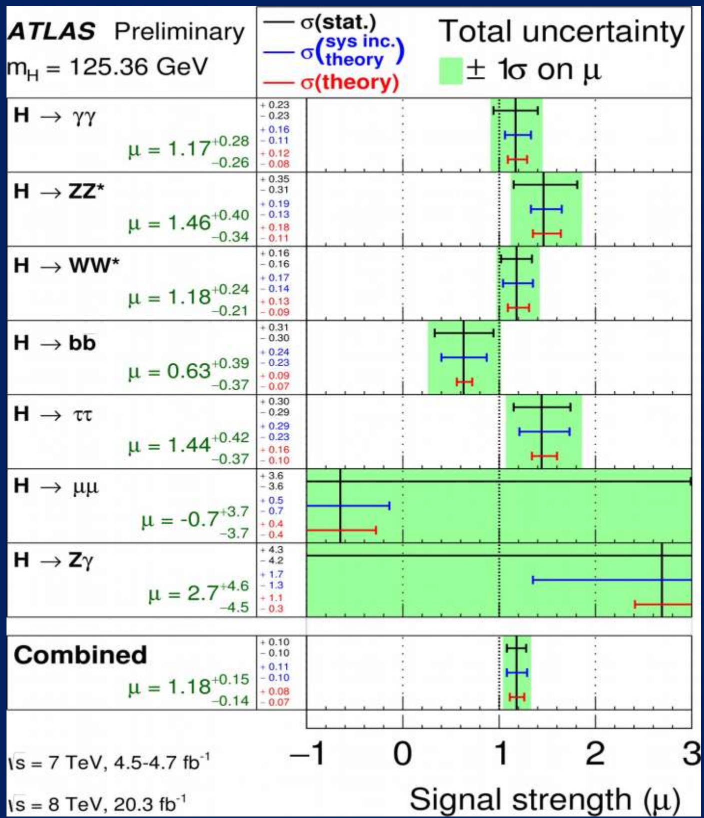
H → ZZ(*) → 4l (4e, 4μ, 2e2μ)

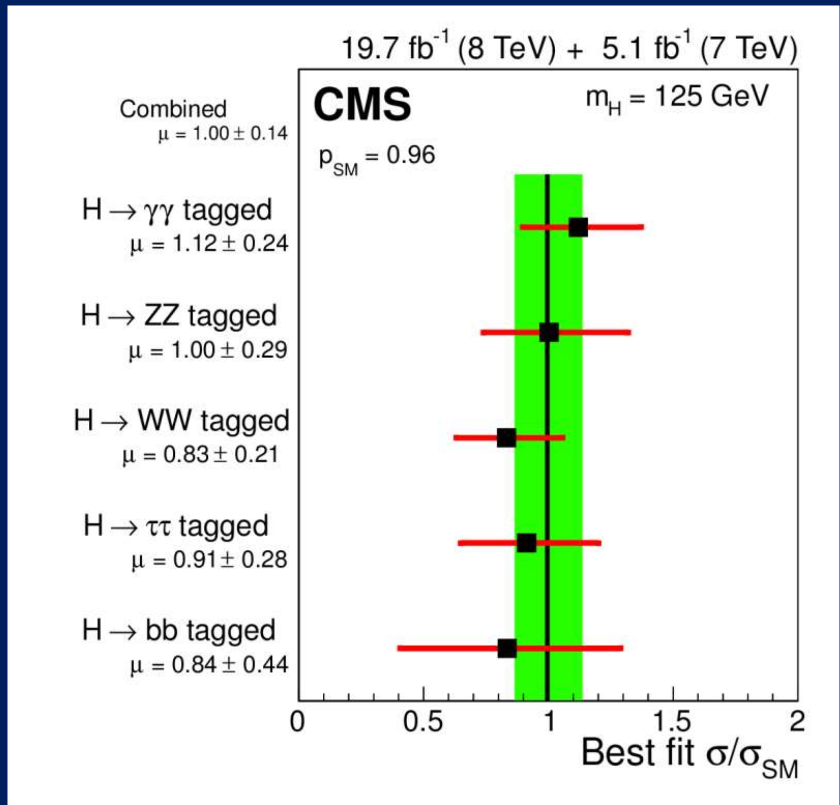


Phys. Rev. D 89 (2014) 092007

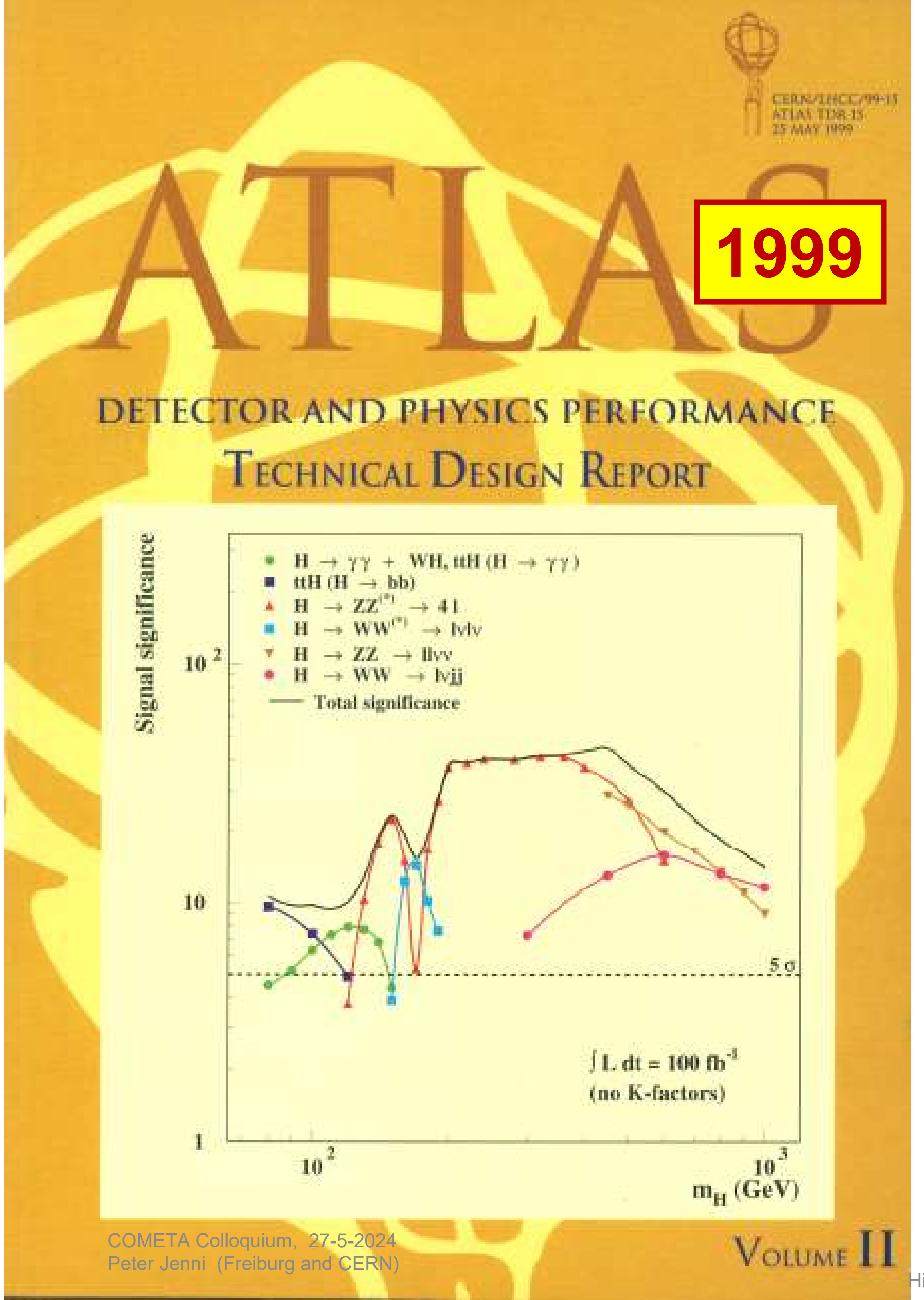
Complementary technologies provided comparable performances in term of significance of the signals (Run-1) !

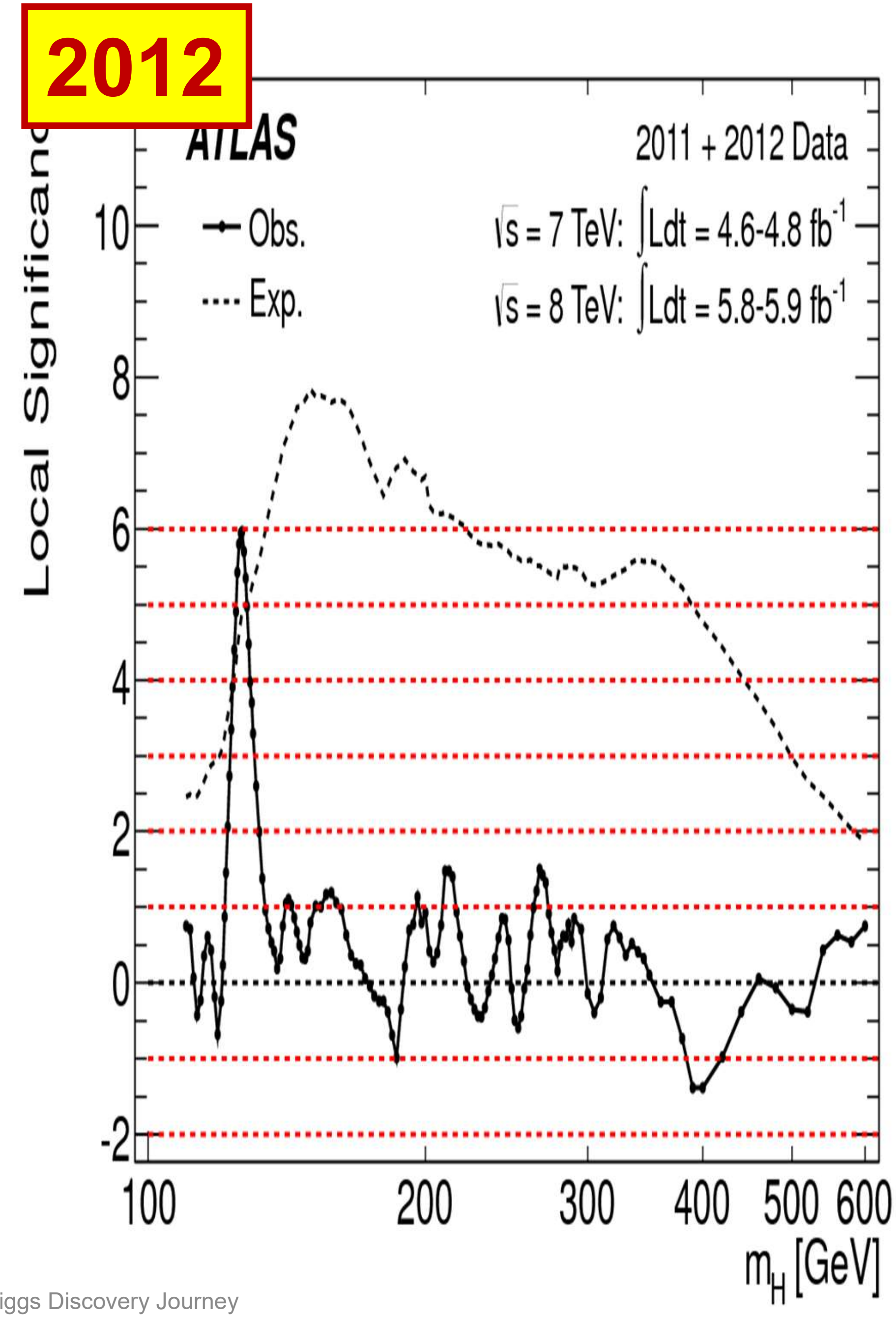
Experiment	ATLAS		CMS	
Decay mode/combination	Expected (σ)	Observed (σ)	Expected (σ)	Observed (σ)
γγ	4.6	5.2	5.3	5.6
ZZ	6.2	8.1	6.3	6.5
WW	5.8	6.1	5.4	4.7
bb	2.6	1.4	2.6	2.0
ττ	3.4	4.5	3.9	3.8

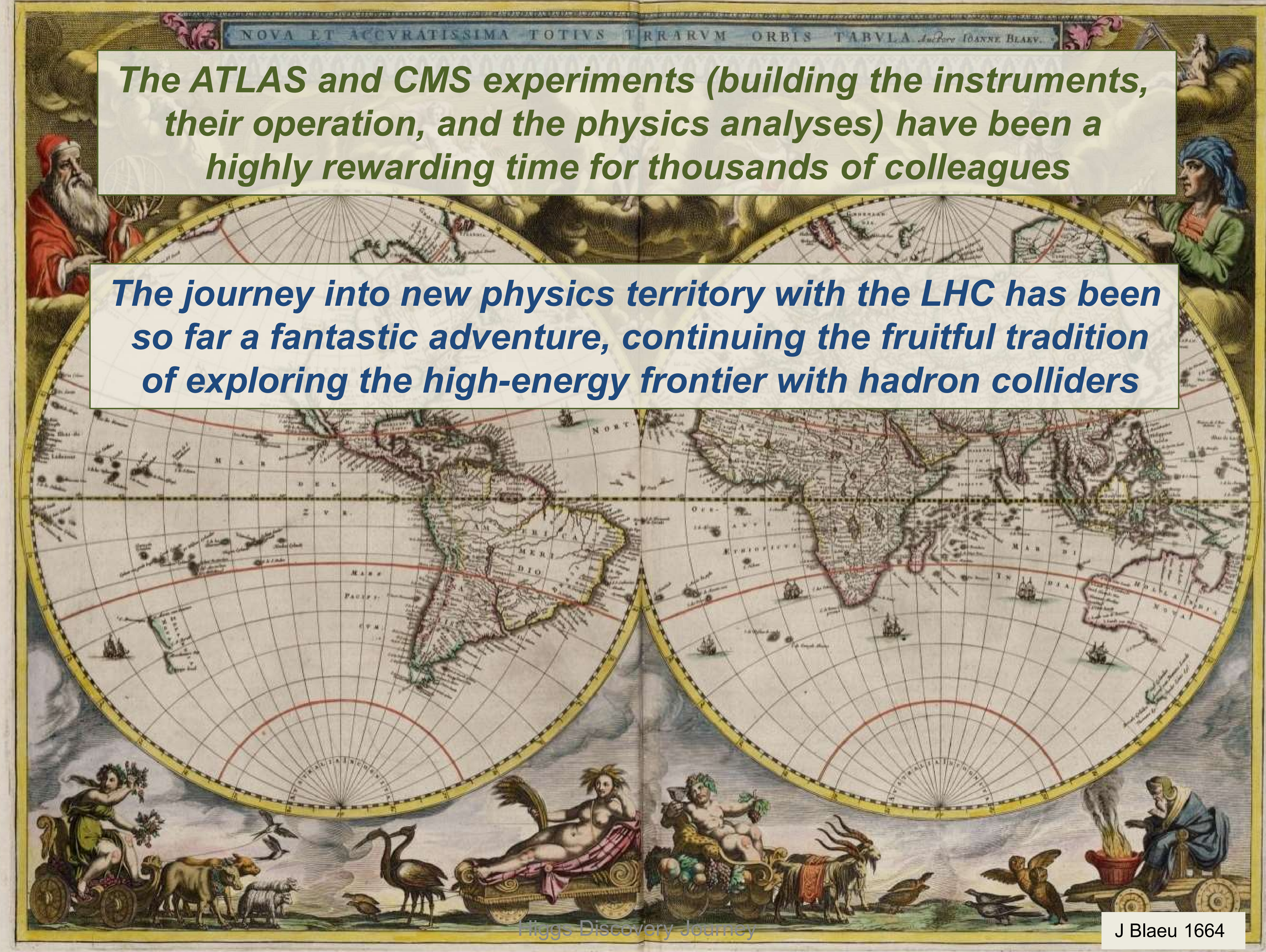




A dream became true much faster than anticipated long ago



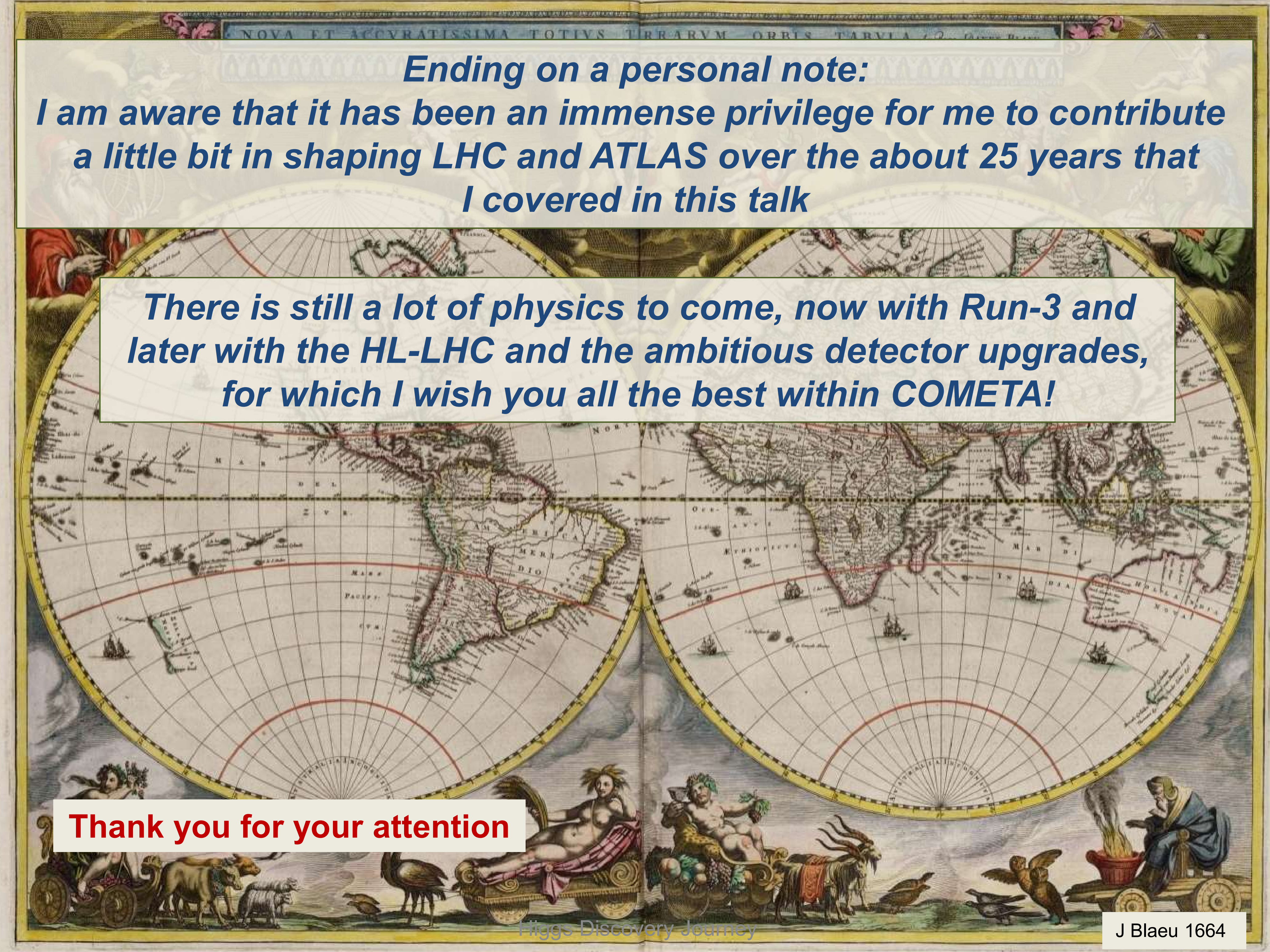




The ATLAS and CMS experiments (building the instruments, their operation, and the physics analyses) have been a highly rewarding time for thousands of colleagues

The journey into new physics territory with the LHC has been so far a fantastic adventure, continuing the fruitful tradition of exploring the high-energy frontier with hadron colliders

J Blaeu 1664



Ending on a personal note:
I am aware that it has been an immense privilege for me to contribute a little bit in shaping LHC and ATLAS over the about 25 years that I covered in this talk

There is still a lot of physics to come, now with Run-3 and later with the HL-LHC and the ambitious detector upgrades, for which I wish you all the best within COMETA!

Thank you for your attention

J Blaeu 1664

Spares

Some resources on the web available in open access:

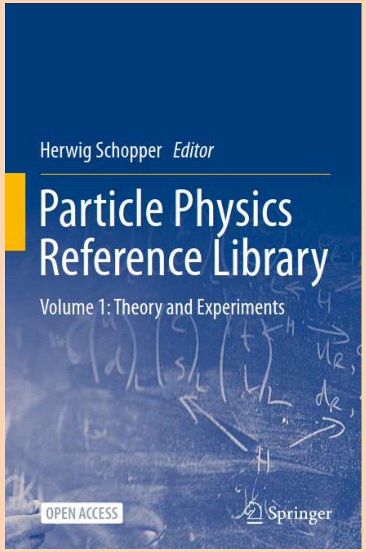
The evolution of hadron collider experiments
Paul Grannis and Peter Jenni, Physics Today 66, 6, 38 (2013)
http://dx.doi.org/10.1063/PT.3.2010

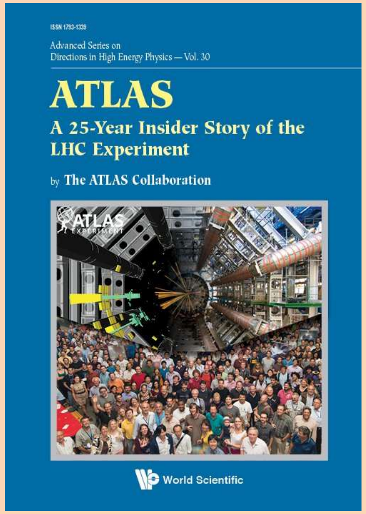
Journey in the Search for the Higgs Boson
The ATLAS and CMS experiments
M Della Negra, P Jenni, T S Virdee, Science 338, 1560 (2012)
http://www.sciencemag.org/content/338/6114/1560.full.html

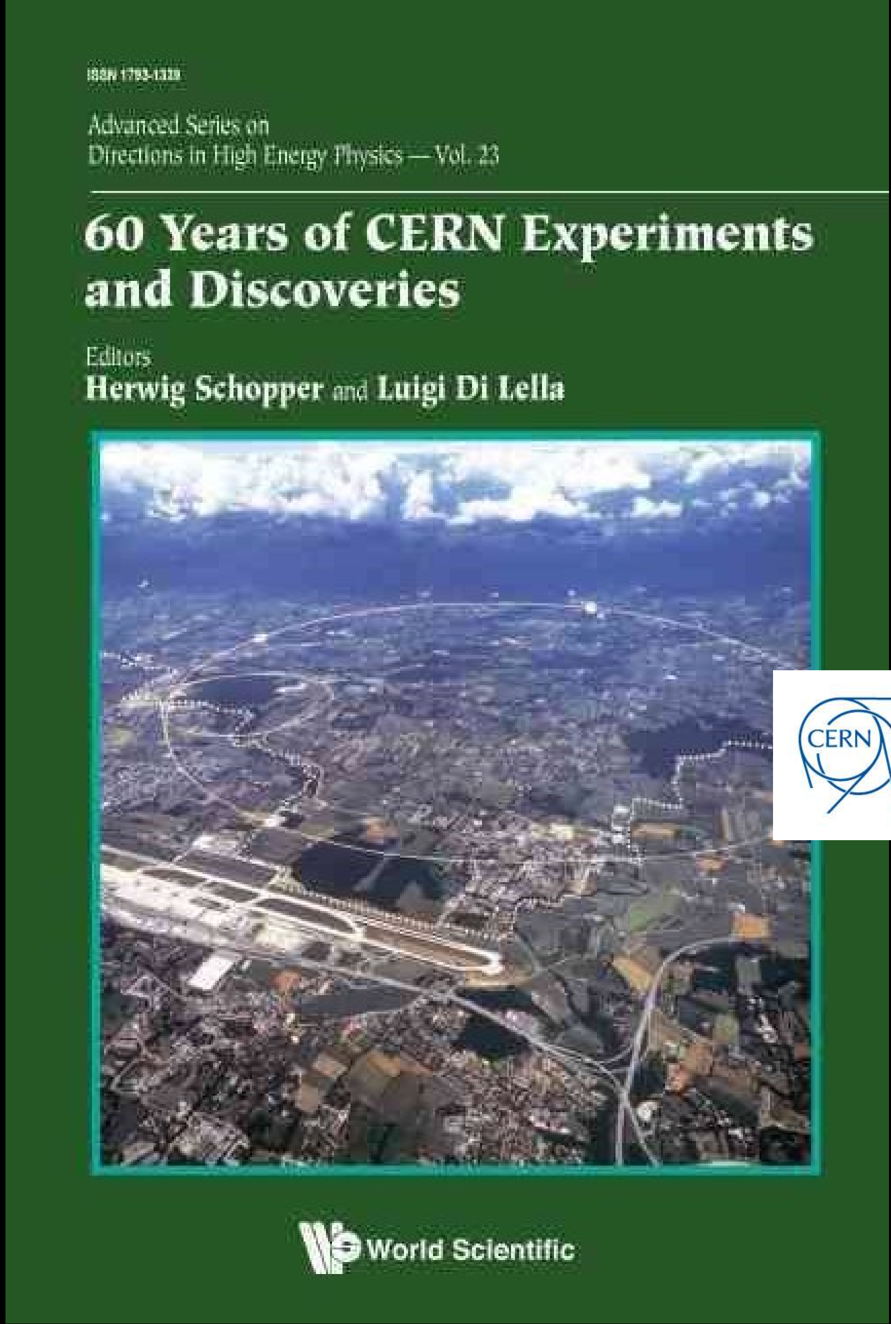
The Discovery of the Higgs Boson at the LHC
P Jenni and T S Virdee, Particle Physics Reference Library (former Landolt-Börnstein), Chapter 6, Springer 2020
https://cds.cern.ch/record/2743162/files/Jenni-Virdee2020_Chapter_TheDiscoveryOfTheHiggsBosonAtT.pdf

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 (open access book):
https://www.worldscientific.com/worldscibooks/10.1142/11030







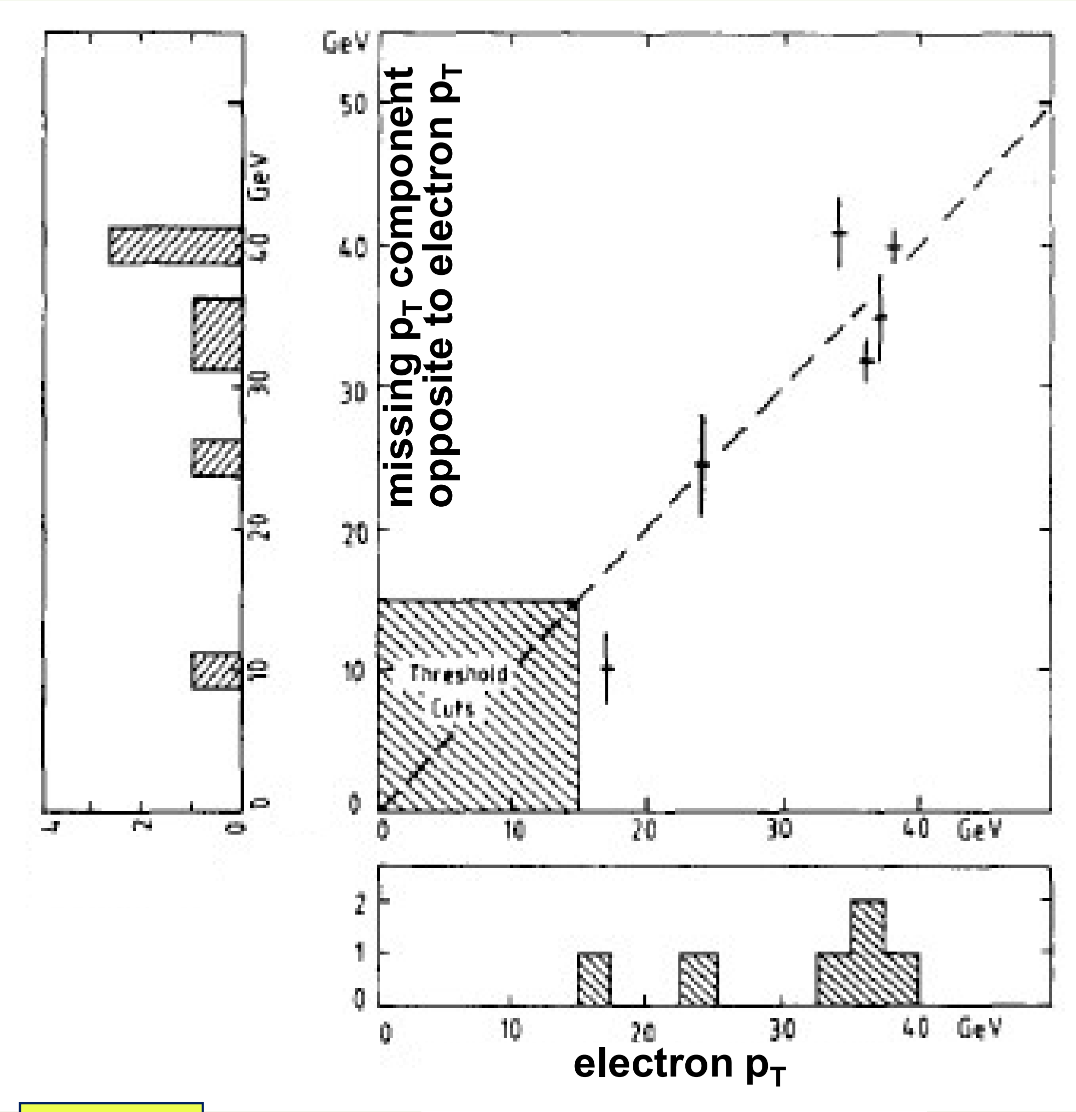
CERN | 60 YEARS/ANS CERN

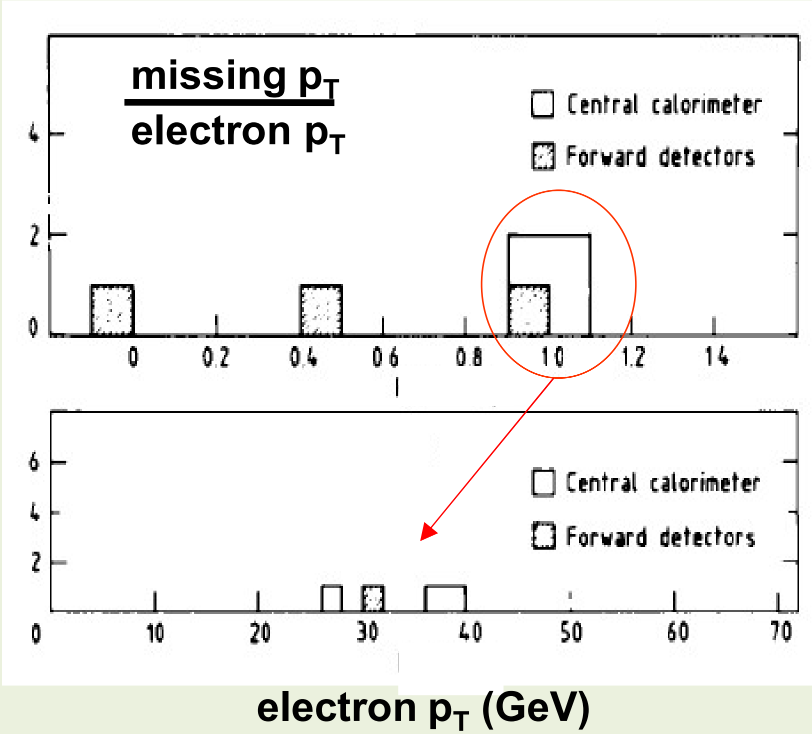
Chapter 1, p. 1-30, P.Jenni and T.S.Virdee:
The discovery of the Higgs Boson at the LHC

Chapter 8, p. 263-326, G.Brianti and P.Jenni:
The Large Hadron Collider: The Energy Frontier

OPEN ACCESS

UA1 *UA2*





The W → eν results presented on 20 and 21 January 1983 by both teams at CERN

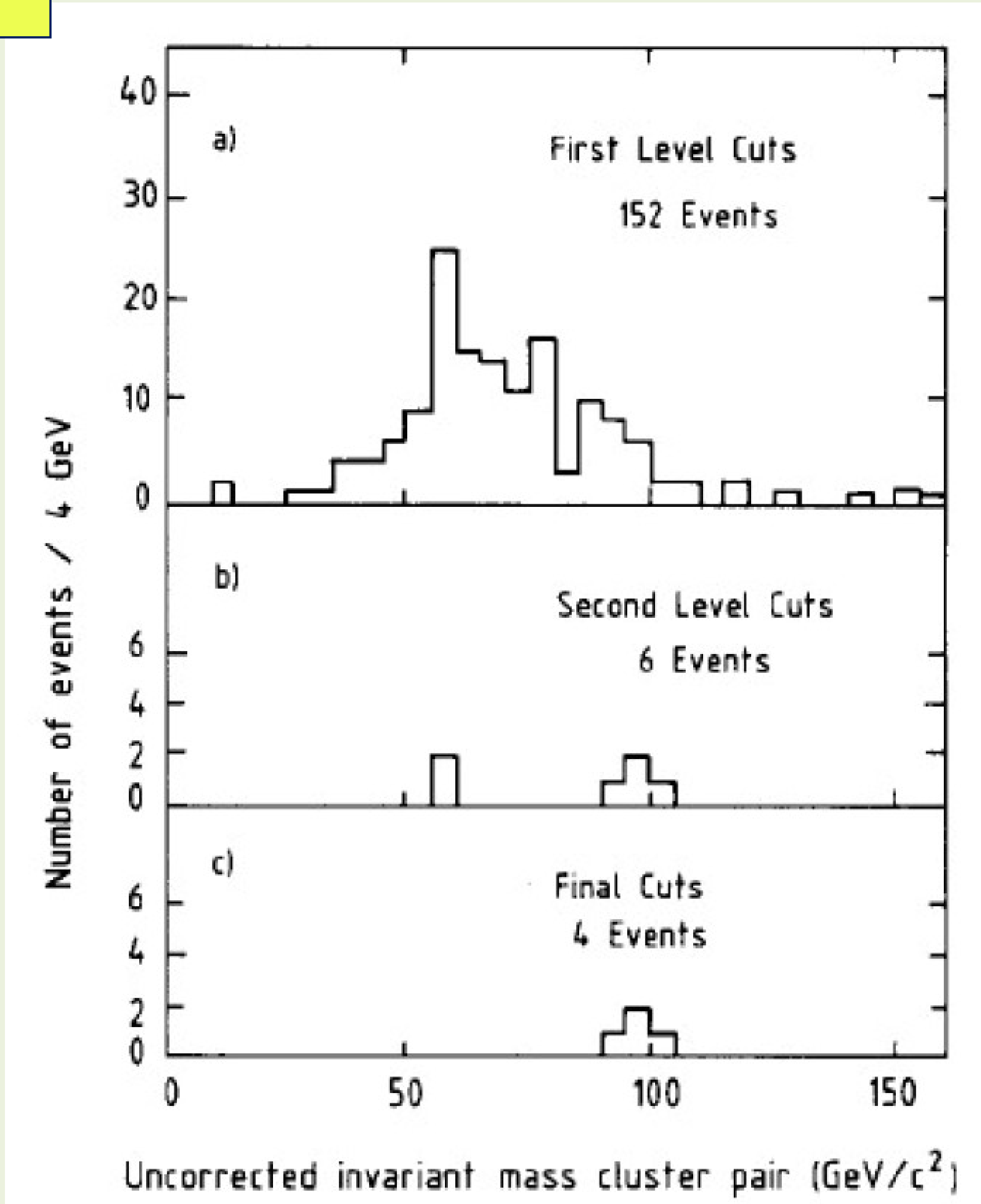
W±

UA1, Phys. Lett. B 122 (1983) 103

UA2, Phys. Lett. B 122 (1983) 476

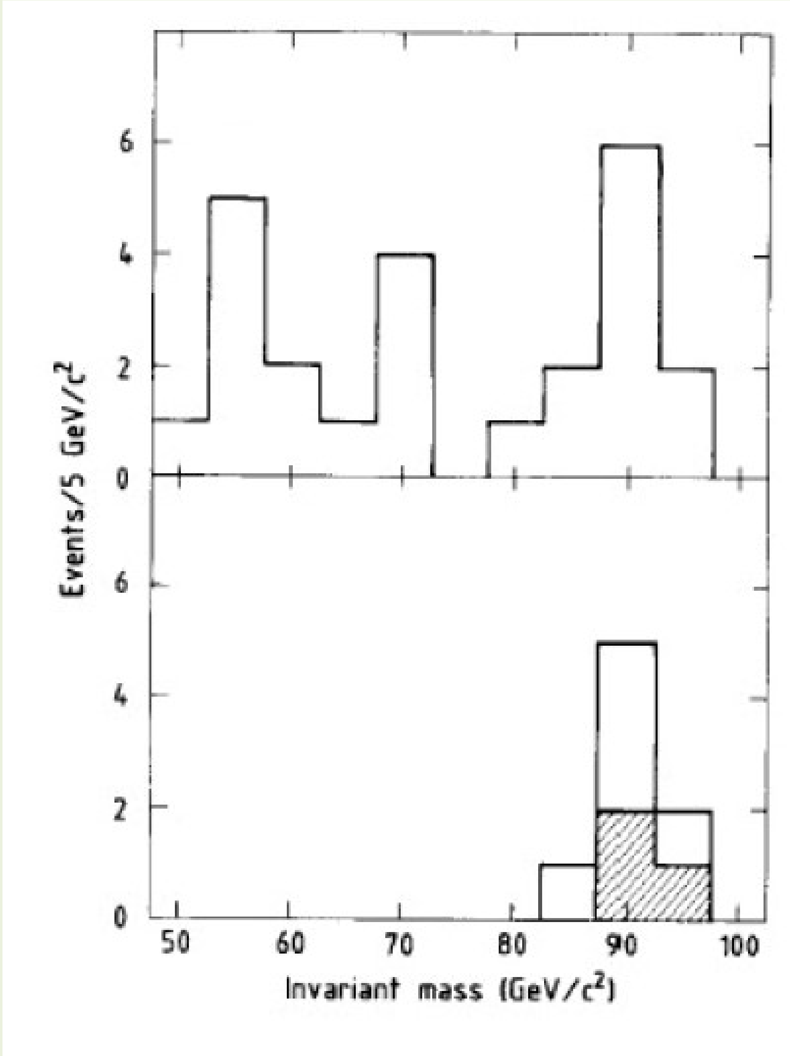
Z°

UA1



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

UA2

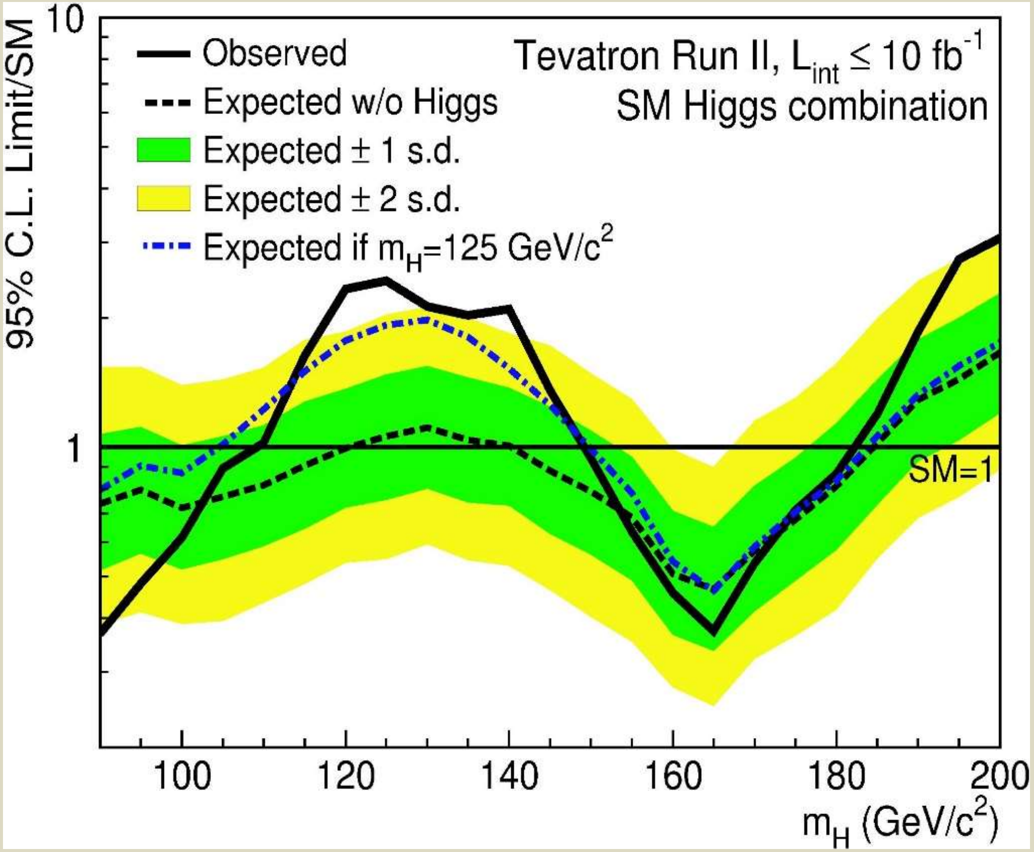


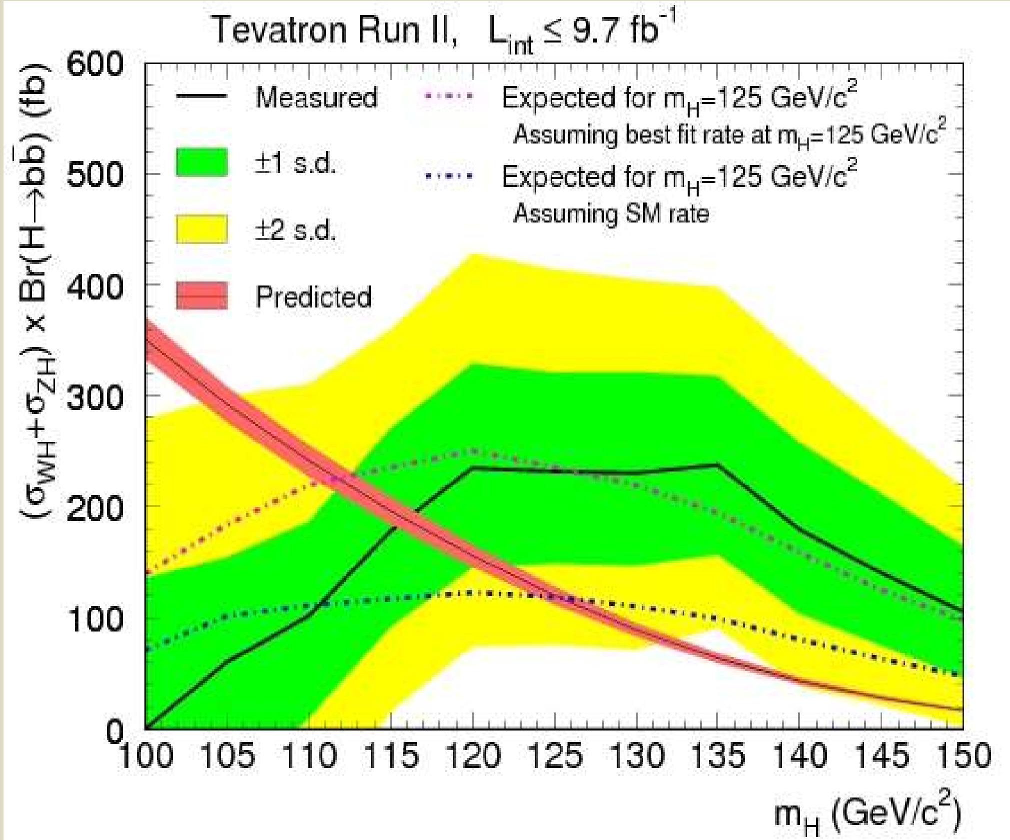
The Z → ee results presented in May and June 1983 at CERN

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

The hunt for the Higgs boson

CDF and D0 combined
Phys. Rev. Lett. 109 (2012) 071804





To quote Paul Grannis in his June 2018 Fermilab Users Meeting 'Tevatron Highlights' talk:

'The Higgs was discovered in 2012 at LHC in the $\gamma\gamma$ & ZZ decays. Simultaneously, CDF & DØ obtained the first 3σ evidence for H→bb using the combined W(lν)H, Z(ll)H and Z($\nu\nu$)H channels. This preceded the LHC evidence for fermionic Higgs decays by 4 years and was the first direct evidence for the Higgs Yukawa coupling.'

1989 ECFA Study Week in Barcelona for LHC instrumentation
(forming of first proto-Collaboration)

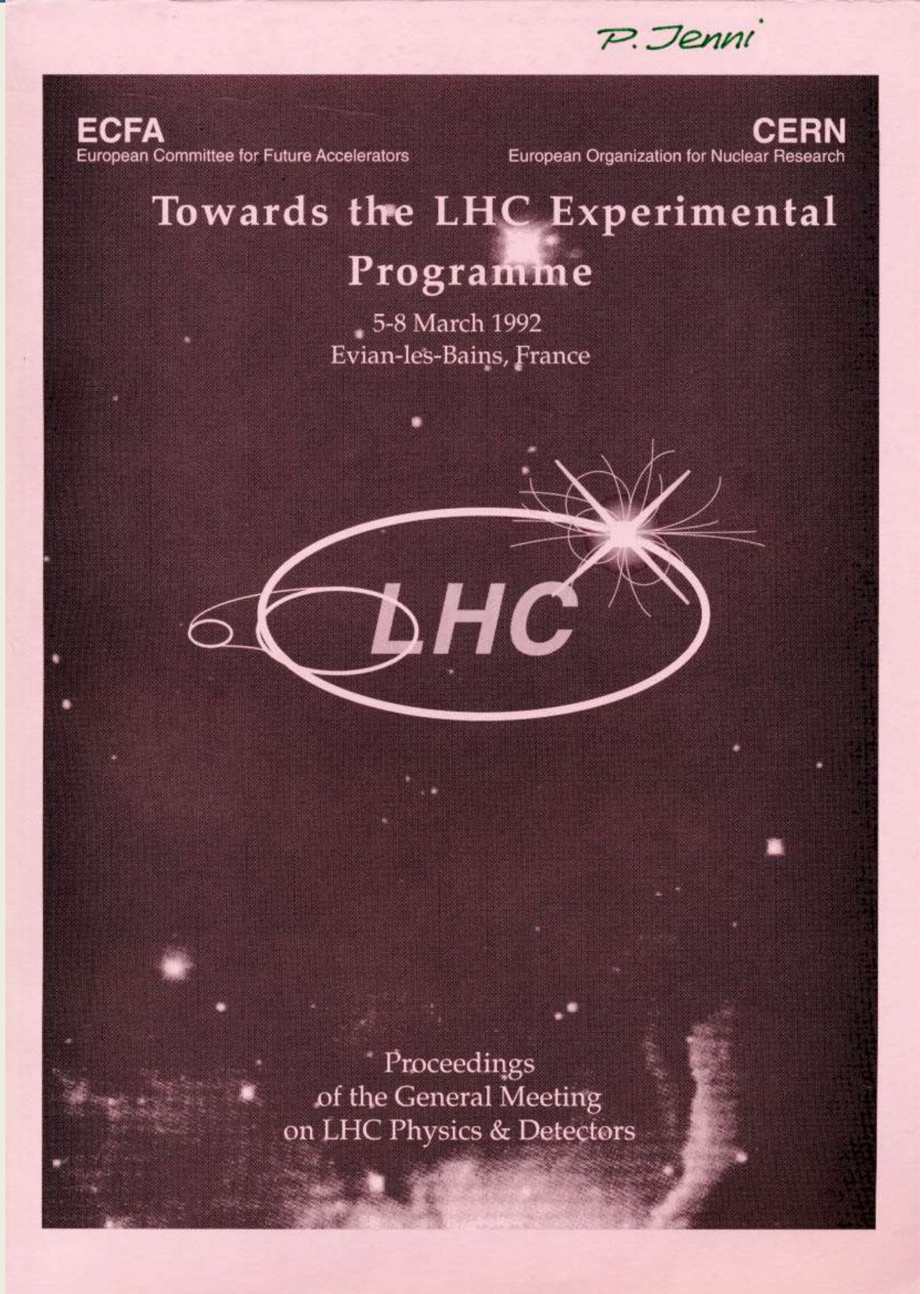
1990 Large Hadron Collider Workshop Aachen (CERN - ECFA)
(First serious R&D results and detailed realistic Monte Carlo studies, first ideas of detector concepts)

1992 CERN – ECFA meeting 'Towards the LHC Experimental Programme' in Evian

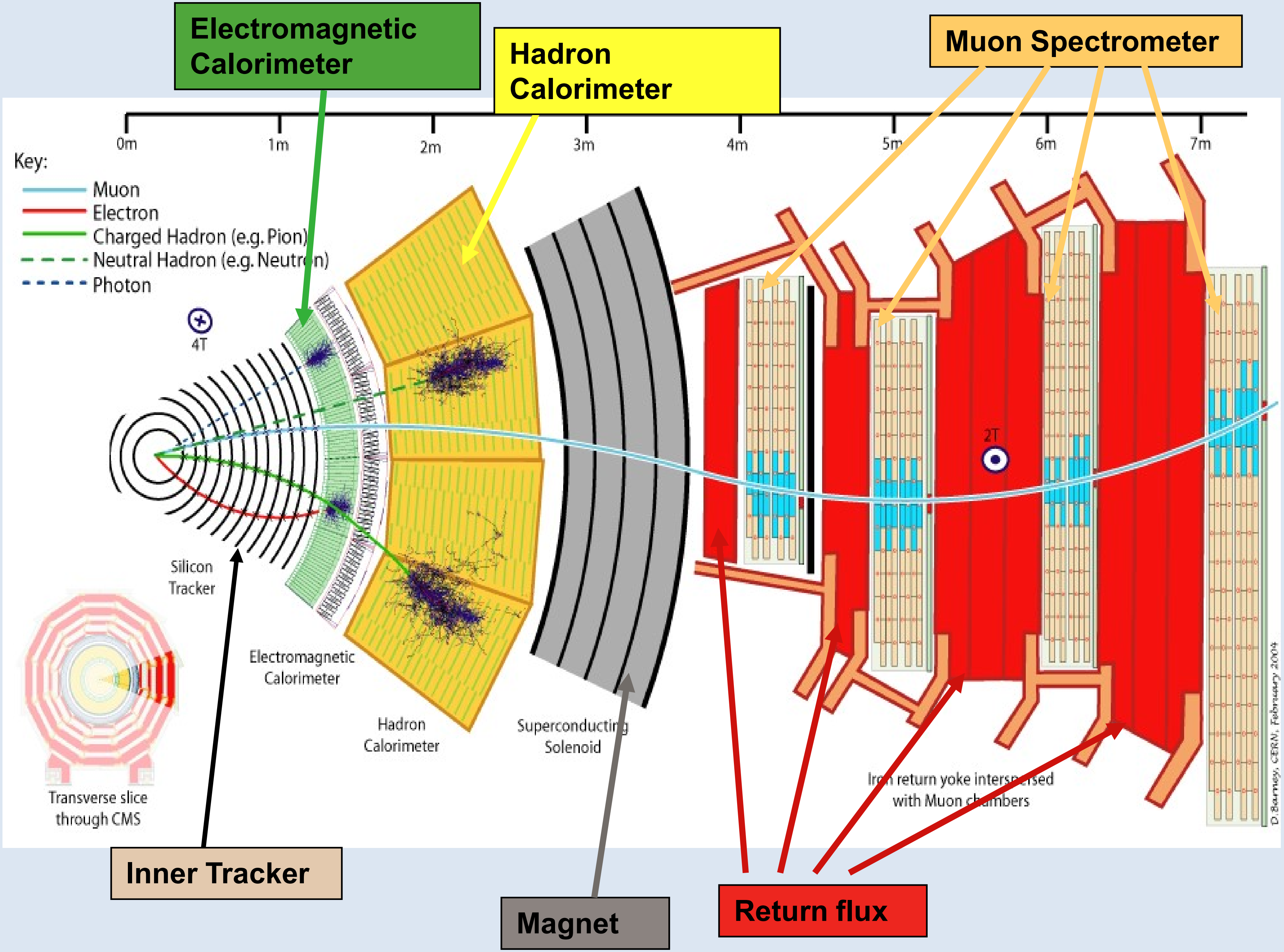
See more 'pre-history' accounts for the LHC at:

Symposium 25 Years of LHC Experimental Programme CERN, 15th December 2017

https://indico.cern.ch/event/653848/timetable/?print=1&view=standard

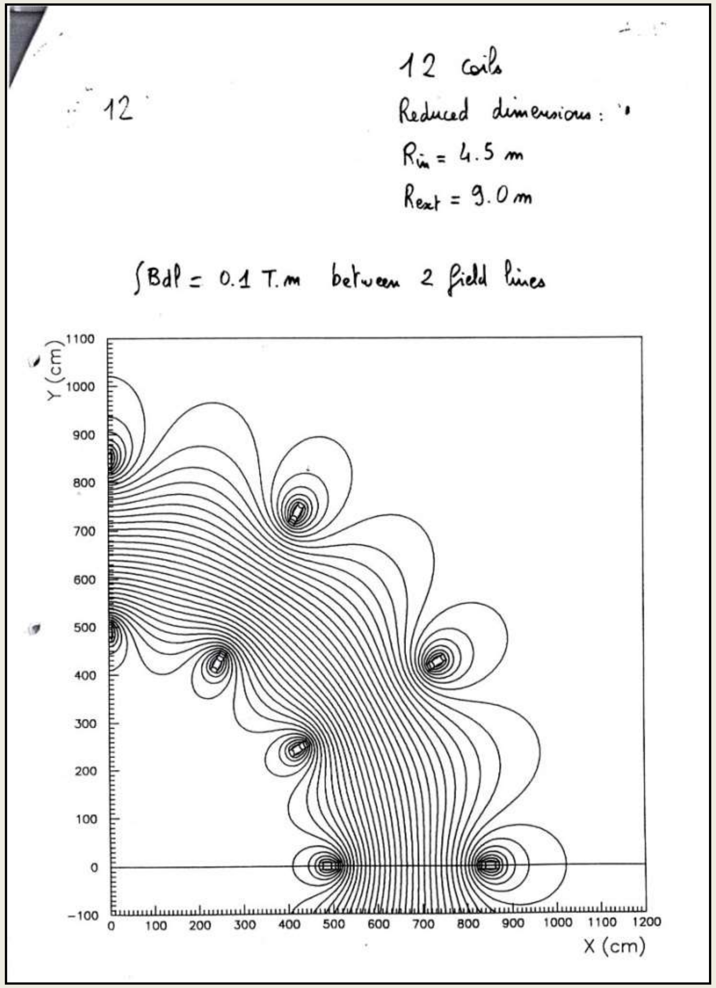


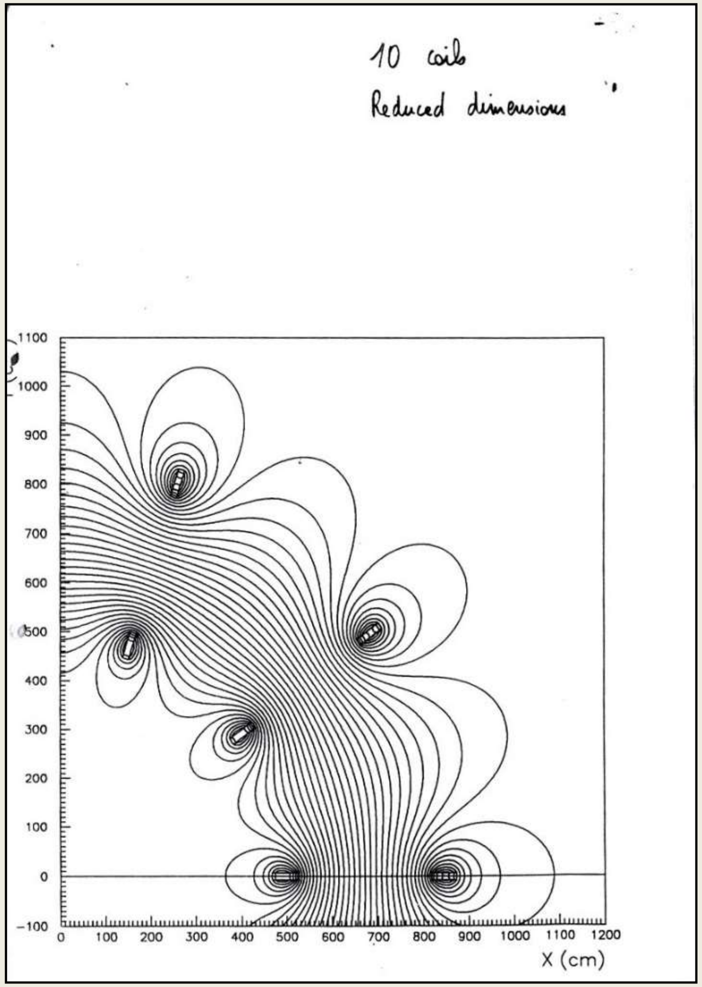
Main components of the CMS detector

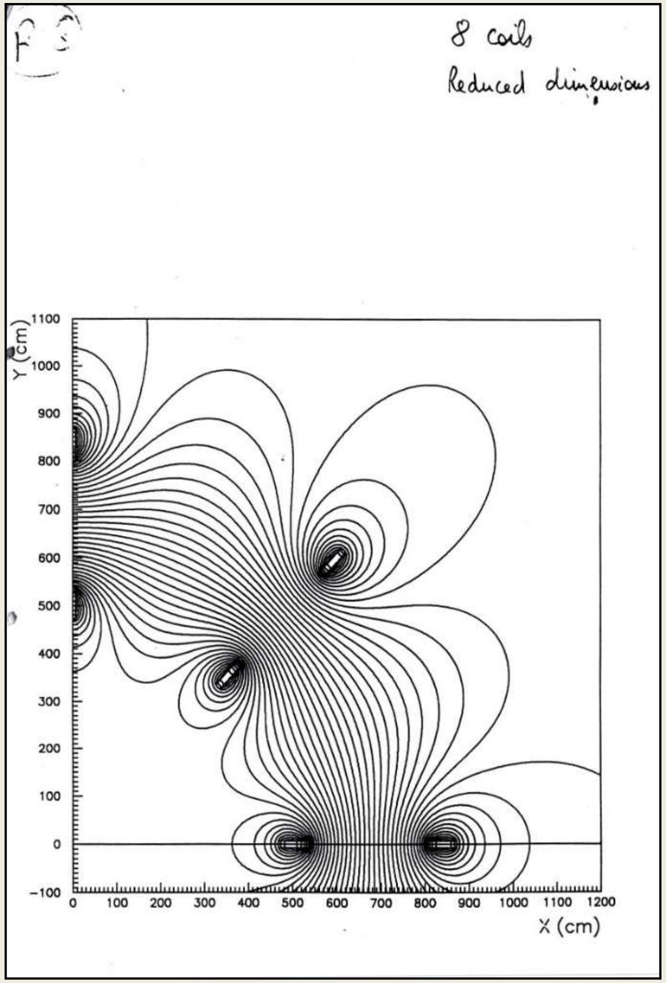


First reaction of the LHCC to the LoI in December 1992: It was well received, but a long saga started for ATLAS about costs and funding …

One of many ingredients… reduced number of coils from 12 to 8 in the toroid system







ATLAS

is a general-purpose pp detector designed to exploit the full discovery potential of LHC

The primary goal is to operate at high luminosity (10^{34} $cm^{-2}s^{-1}$) with as many signatures as possible (e, γ, μ, jet, E_T^{miss}, b-tagging, ...)

---> *robust and redundant physics measurements with the ability of internal cross-check*

Emphasis is also put on the performance necessary for the physics accessible during initial lower luminosity (10^{33} $cm^{-2}s^{-1}$) using in addition more complex signatures (τ and heavy-flavour tags from secondary vertices, ...)

The design goals are achieved using a magnet configuration combining

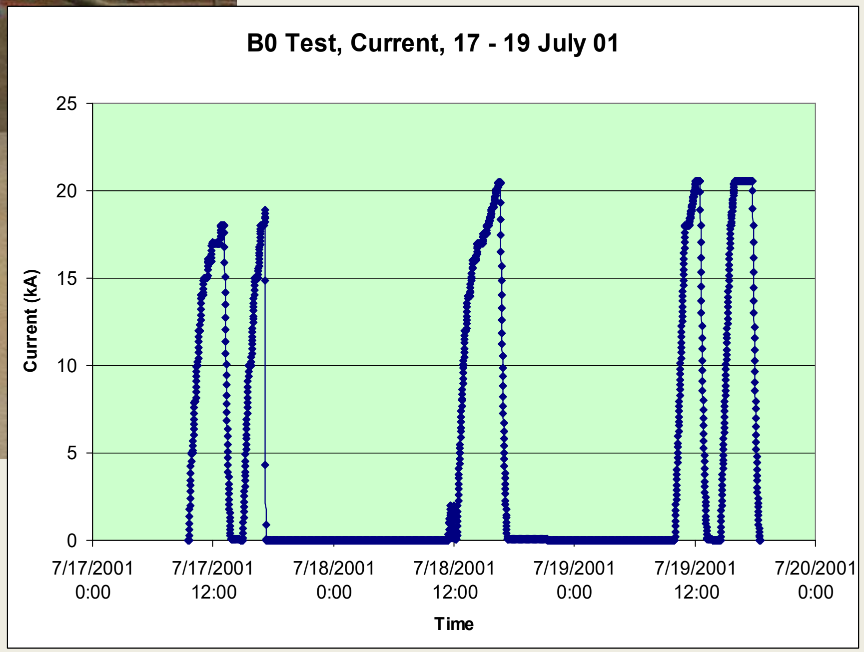
- inner superconducting solenoid around the inner detector cavity
- superconducting air-core toroids consisting of independent coils arranged in an eight-fold symmetry outside the calorimetry

This concept offers

- *almost no constraints on calorimetry and inner detector*
- *high-resolution, large-acceptance and robust stand-alone muon spectrometer*

From the TP presentation

The B0 model coil reaching full current of 20.5 kA (July 2001) at CERN



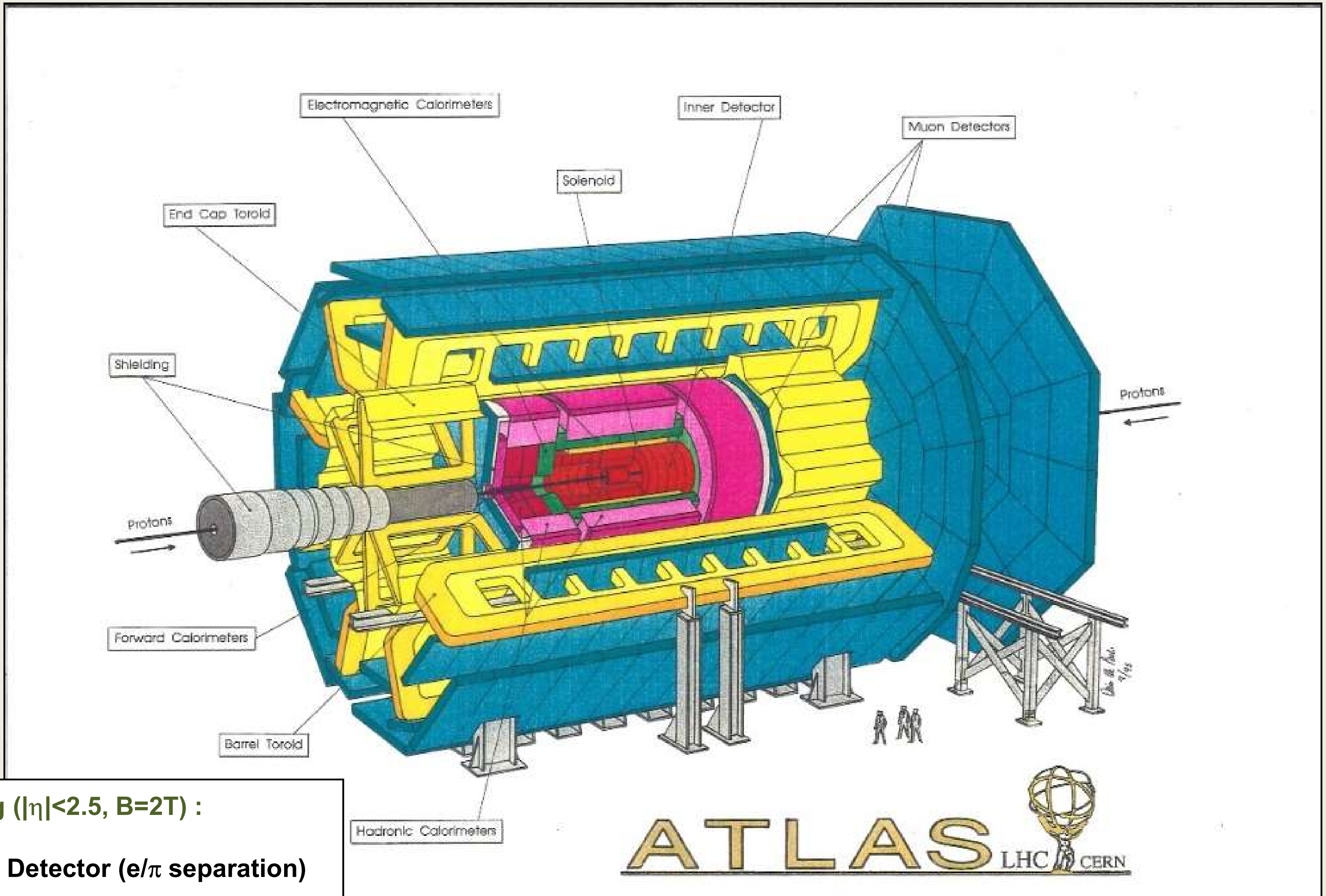
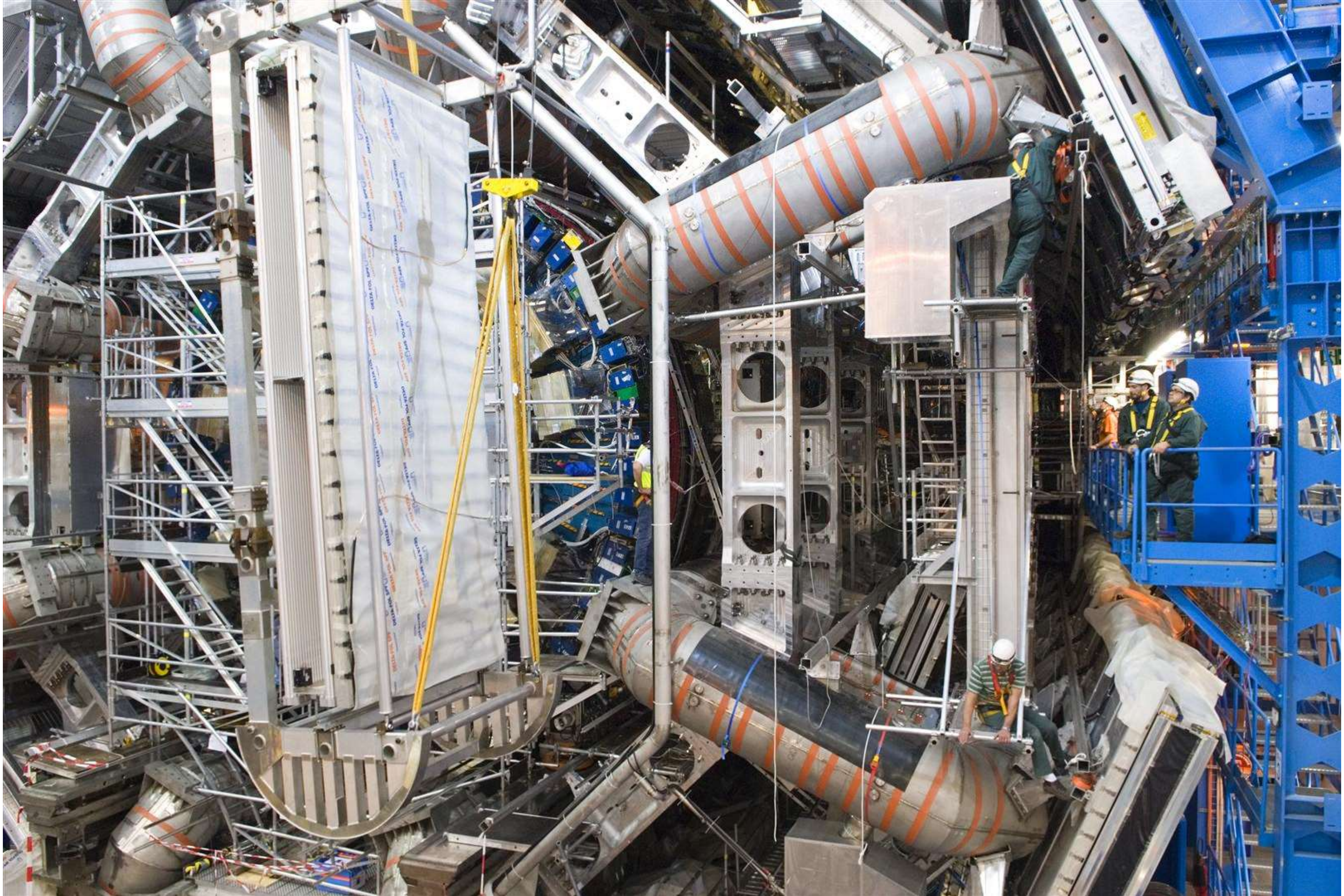


Figure from the TP presentation

- **Inner Detector Tracking (|η|<2.5, B=2T) :**
  - **-- Si pixels and strips**
  - **-- Transition Radiation Detector (e/π separation)**
- **Calorimetry (|η|<5) :**
  - **-- EM : Pb-LAr**
  - **-- HAD: Fe/scintillator (central), Cu/W-LAr (end-caps/fwd)**
- **Muon Spectrometer (|η|<2.7) :**
  - **-- air-core toroids with precision (MDT and CSC) and trigger (RPC and TGC) muon chambers**

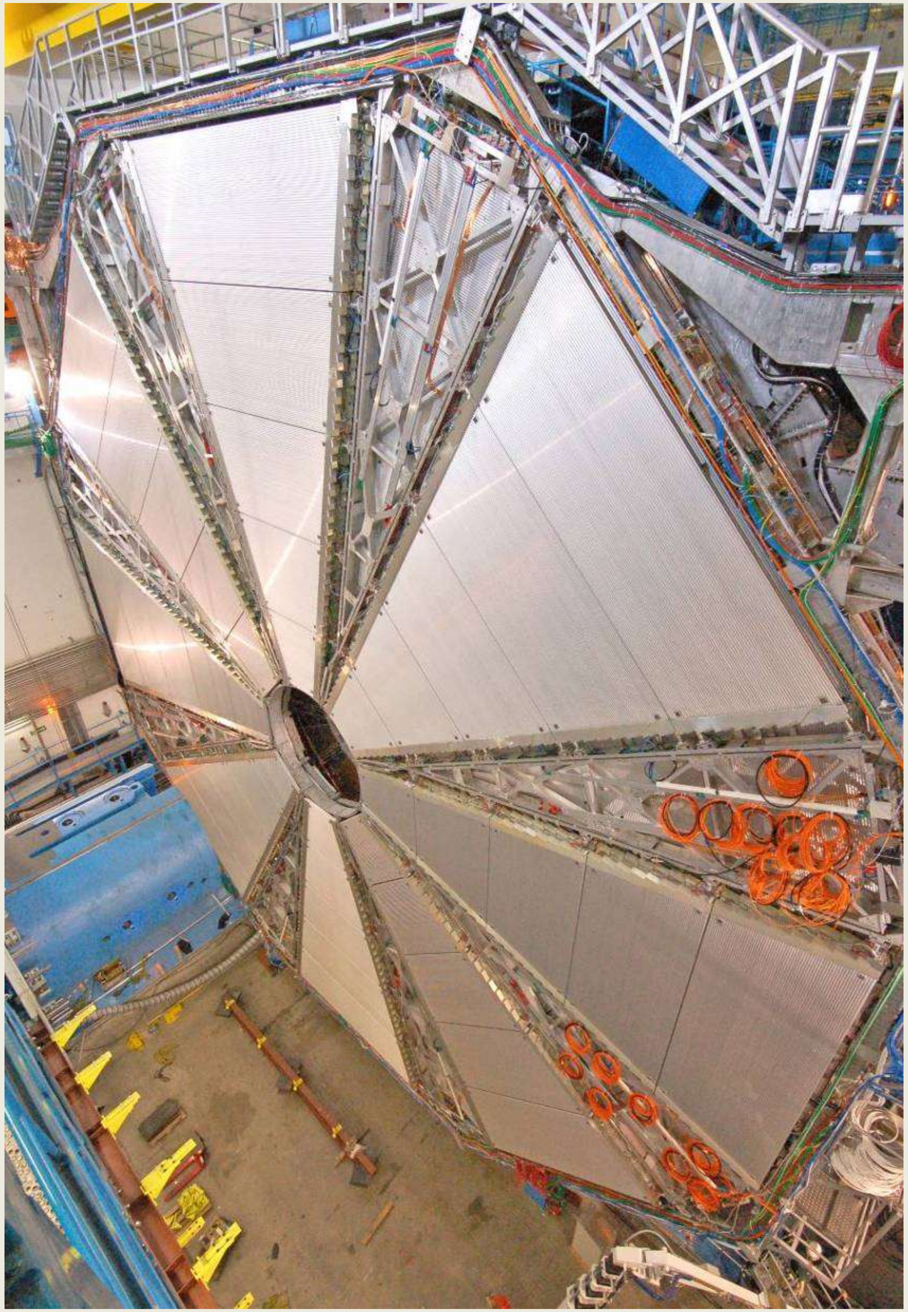
Tile calorimeter Module-0 at the JINR Dubna workshop, April 1996



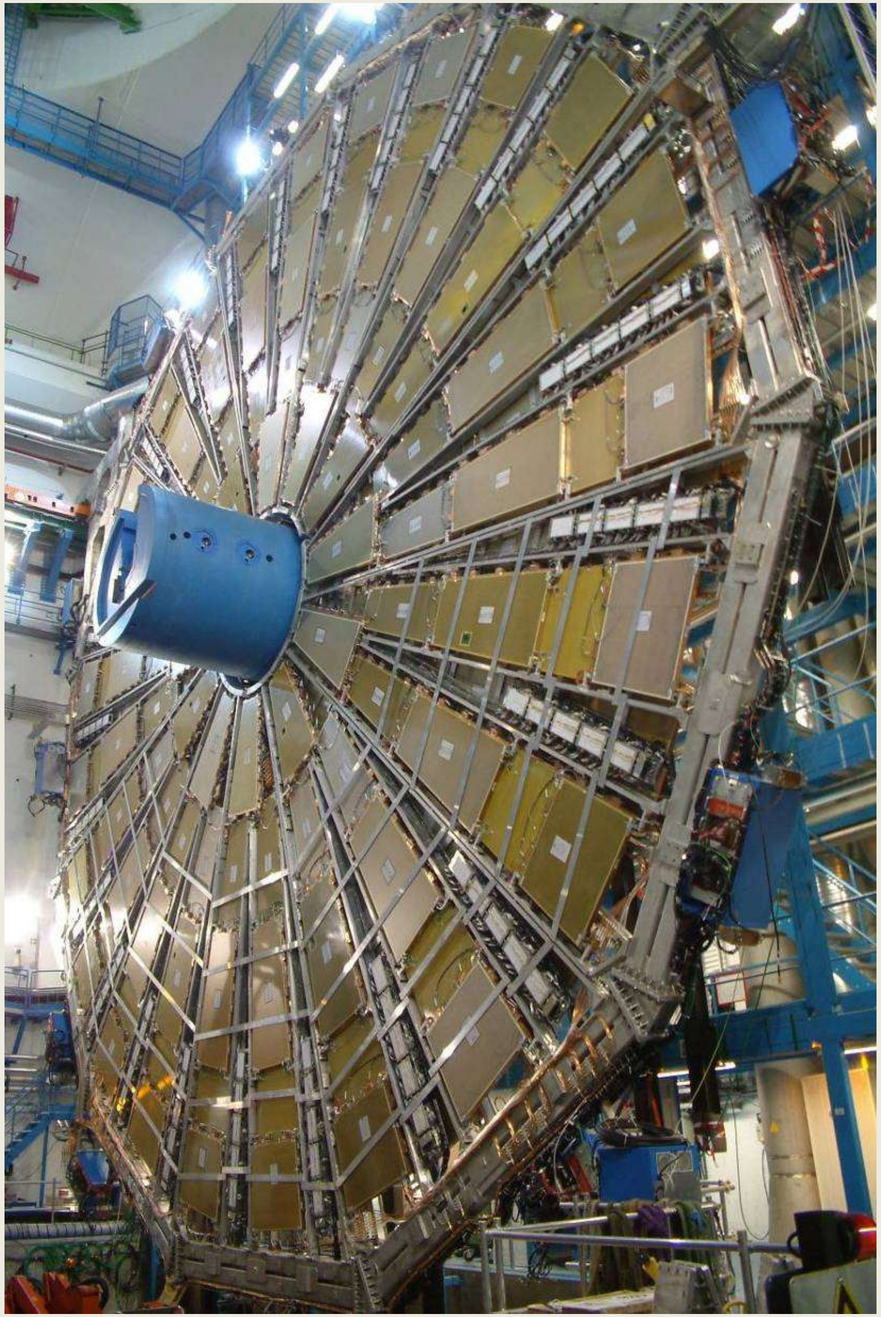
Example of a barrel chamber (BOL) installation – Oct 2006

Transport of a muon end-cap sector to LHC interaction Point-1 (Dec 2006)

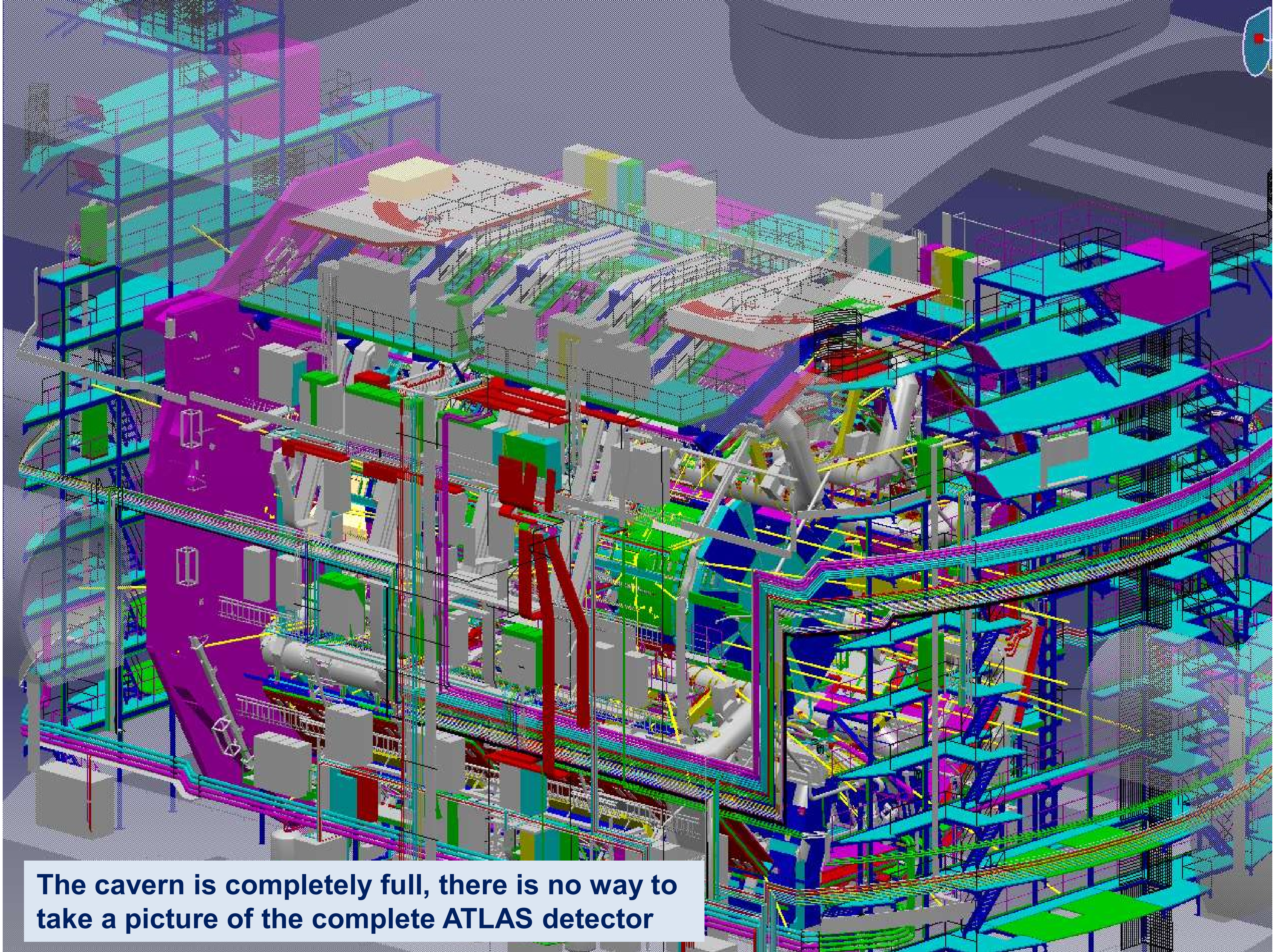
MDT Big Wheel
(one plane on both sides)



TGC Big Wheel
(three planes on both sides)



February 2006: the barrel SCT was inserted into the barrel TRT



The cavern is completely full, there is no way to take a picture of the complete ATLAS detector

The huge engineering effort that went into the ATLAS detector cannot be over-stressed

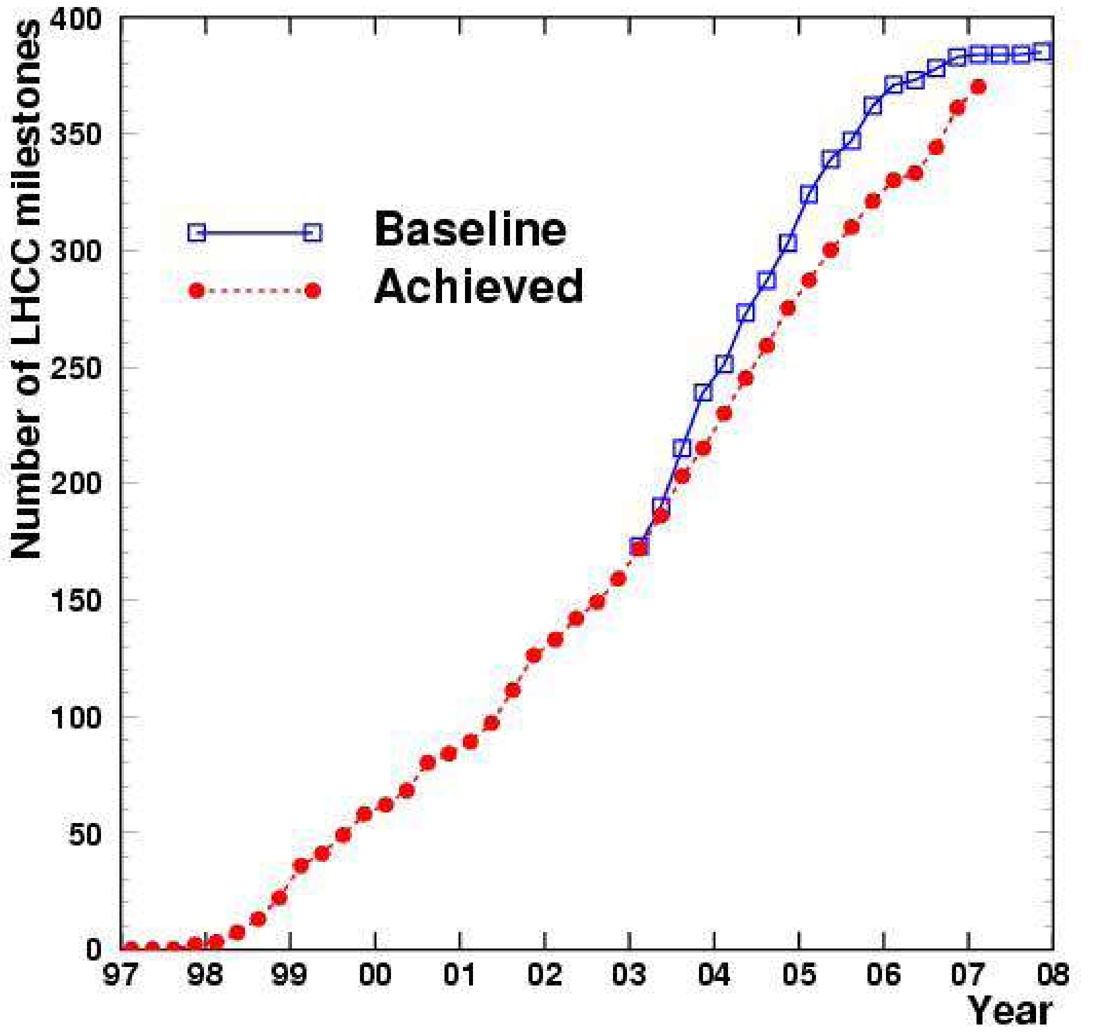
It is easy as physicist to sketch detector concepts, but to make it all fit together in reality, to be mechanically and electrically sound, safe, and maintainable is another story!

A most important lesson: involve experienced engineers early-on in the project, to avoid painful later changes when construction has already been launched of system components …

The cavern is completely full, there is no way to take a picture of the complete ATLAS detector from a 2007 slide:

Construction follow-up: LHCC milestones evolution

The technical and scientific progress of the project was frequently (6x per year…) reviewed by an external expert committee (‘LHCC’) that reports to the CERN Directors

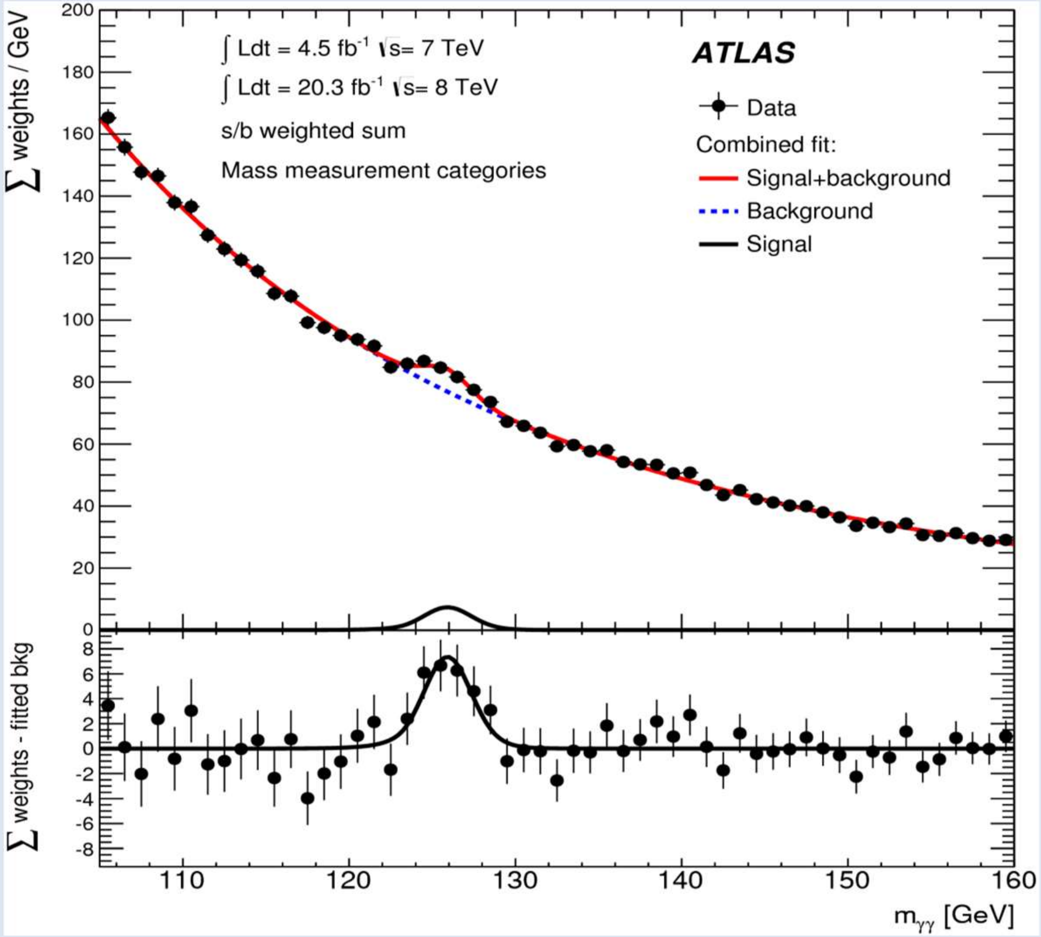


Construction issues and risks (‘Top-Watch List’)

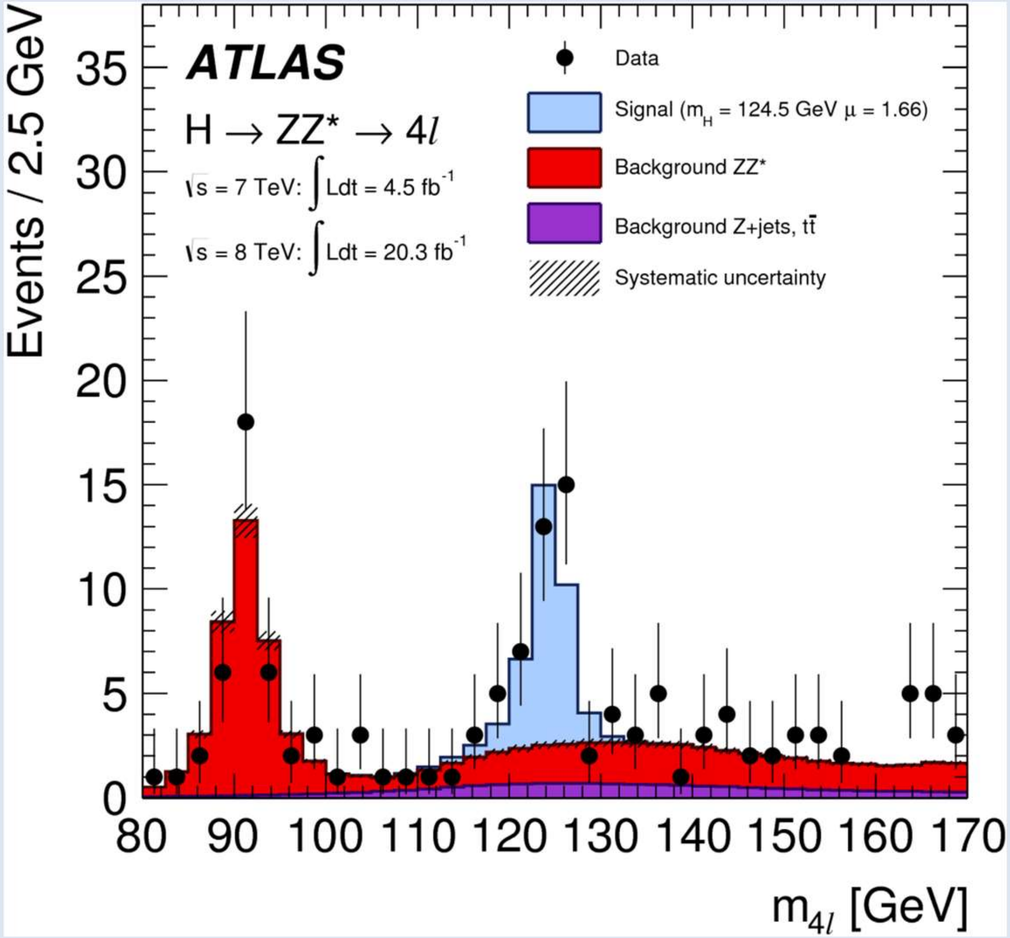
A list of these issues is monitored monthly by the TMB and EB, and it is publicly visible on the Web, including a description of the corrective actions undertaken

ATLAS Run-1 signal peaks (‘Run-1 legacy’)

H → γγ

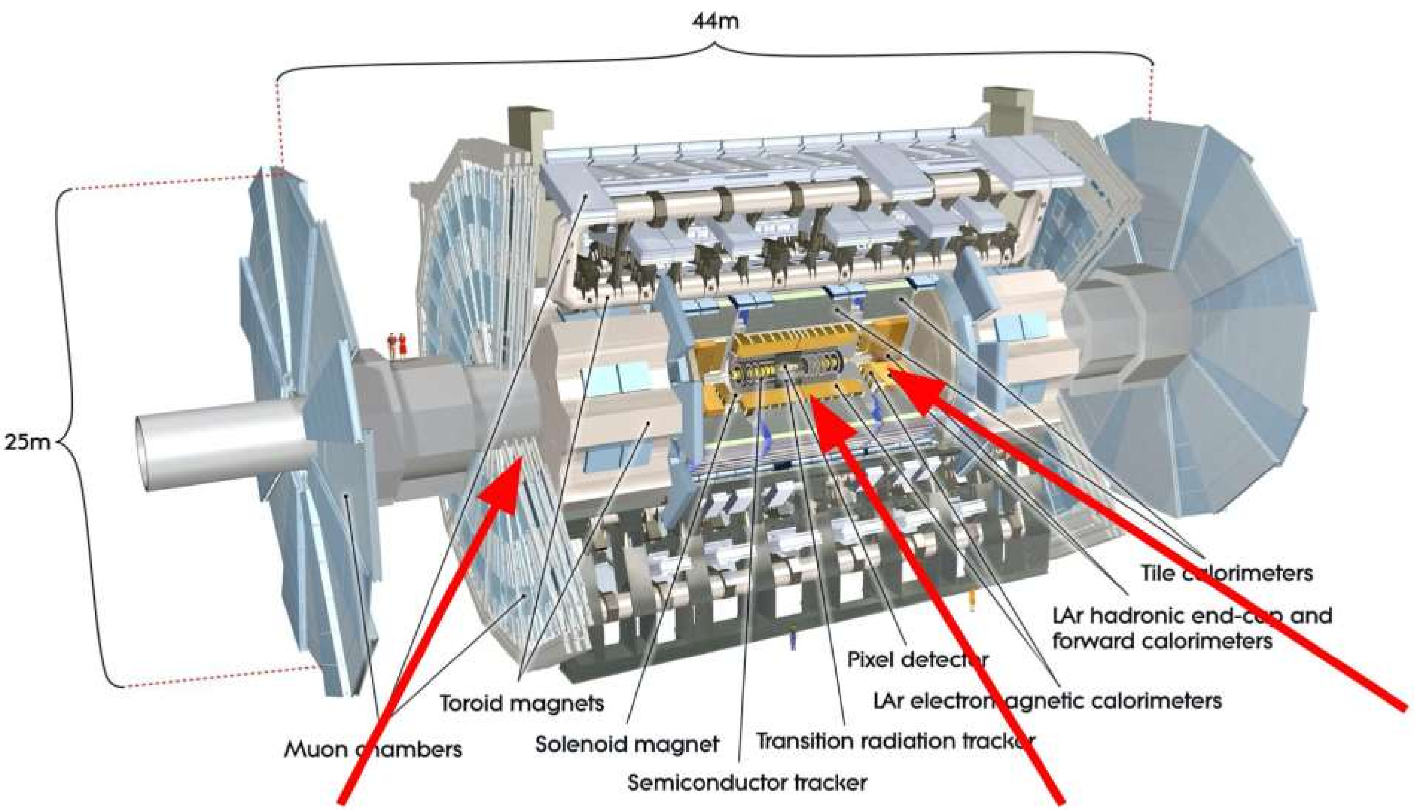


H → ZZ(*) → 4l (4e, 4μ, 2e2μ)



Phys. Rev. D 90 (2014) 052004

Overview of ATLAS Phase-II Upgrades



Upgraded Trigger and Data Acquisition system

- Level-0 Trigger at 1 MHz
- Improved High-Level Trigger
- (150 kHz full-scan tracking)

Electronics Upgrades

- On-detector and off-detector electronics upgrades of:
- LAr Calorimeter
- Tile Calorimeter
- Muon Detectors

High Granularity Timing Detector (HGTD)

- Forward region
- Precision time recon. (30 ps) with Low-Gain Avalanche Detectors (LGAD)

New Muon Chambers

- Inner barrel region with new Resistive Plate Chambers and new Monitored Drift Tubes (sMDT) detectors

New Inner Tracking Detector (ITk)

- All silicon (9 layers), up to $|\eta| = 4$

Additional small upgrades

- Luminosity detectors (1% precision)
- HL-ZDC (Heavy Ion physics)

34

Status: January 2024

A big 'thank you' to CERN, all the Funding Agencies, Universities, Laboratories, Computing Centres, and to all the other bodies which made this experiment possible

Argentina
Armenia
Australia
Austria
Azerbaijan
Belarus
Brazil
Canada
Chile
China
Colombia
Czech Republic
Denmark
France
Georgia
Germany
Greece
Israel
Italy
Japan
Mongolia
Morocco
Netherlands
Norway
Palestine
Philippines
Poland
Portugal
Romania
Russia
Serbia
Slovakia
Slovenia
South Africa
Spain
Sweden
Switzerland
Taiwan
Türkiye
UAE
UK
USA
CERN
JINR

ATLAS Collaboration

183 institutions (253 institutes) from 42 countries

Active members	**5900**
Scientific authors	**2894**
with PhD (share M&O)	**1956**
PhD students	**~1200**
Master/Diploma students	**~450**

ATLAS EXPERIMENT