Historical ATLAS Milestones: From Design to Discovery
The plan is to comment a bit on:
- History of the LHC experiment studies in general
- Some early milestones leading to ATLAS as it is now, namely:
  ‘A general purpose experiment with exploring the EW symmetry breaking as a major benchmark’
- Some milestones of the ATLAS construction (pictures…)
(The physics results will be covered by several colleagues, in particular by Kerstin Tackmann (ATLAS) and André David (CMS) this morning)
Arguing around the mid-1980s of being ambitious and design a general purpose detector …

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<th>detector</th>
<th>accessible</th>
<th>physics process</th>
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<td>$\mu^+$</td>
<td>$H \rightarrow ZZ \rightarrow 4 \mu^+$</td>
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<tr>
<td>$Z' \rightarrow \mu^+ \mu^-$</td>
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</table>

$\mu^+$, jets, $p_T$

add: $H \rightarrow ZZ \rightarrow \mu^+ \mu^- \nu \bar{\nu}$

$W' \rightarrow \mu^+ \nu$

compositeness

$\tilde{q}, \tilde{g}$ (direct decays)

jet spectroscopy

$e, \mu^+, jets, p_T$

(add: $4 \times$ rate $H \rightarrow ZZ \rightarrow 4e^+$

$2 \times$ rate $H \rightarrow ZZ \rightarrow e^+ e^-\nu\bar{\nu}$

$2 \times$ rate $Z', W'$

$\tilde{q}, \tilde{g}$ (also cascade decays)

mass resolution

$e, \mu$ heavy $Q, L$

$H \rightarrow \gamma \gamma$

$e, \mu^+, \tau^+, jets, p_T$

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

$\Rightarrow$ detection of $e$ and $\mu$

Muons are relatively easy to identify but hard to measure well.

(precise $\mu$ 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
After the 1979 LEP White Book (ECFA-LEP WG) which mentioned the possibility of a far future LHC, and the discoveries of the W and Z bosons by UA1 and UA2 in the early 1980s ...

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

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
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La Thuile 1987
1989 ECFA Study Week in Barcelona for LHC instrumentation (forming of first proto-Collaboration)

1990 Large Hadron Collider Workshop
Aachen (CERN - ECFA)

1992 CERN – ECFA meeting ‘Towards the LHC Experimental Programme’ in Evian
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1990 Large Hadron Collider Workshop Aachen (CERN - ECFA)

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
Sensitivity for all yet unexplored Higgs boson masses (in the late 1980s) called for a detector concept offering as many final state signatures as possible.

It was also clear for the lower mass range that the instrumental resolution would dominate the width of the reconstructed H mass peak, and thus determine the signal/background ratio.

Cross-section times branching ratios (left) and the natural width (right) from the Handbook of LHC Higgs cross-sections, Yellow Report CERN-2011-002 (for the LHC start-up energy)

Best channels at the LHC:
- < 130 GeV: $H \rightarrow \gamma\gamma$
- 125-180 GeV: $H \rightarrow WW(\tau\tau) \rightarrow l_vl_v$
- 125-300 GeV: $H \rightarrow ZZ(\tau\tau) \rightarrow llll$
- 300-600 GeV: $H \rightarrow ZZ \rightarrow llVV$
The ASCOT and EAGLE proto-collaborations both presented detector concepts with a toroid magnet configuration for the muon spectrometer at the Evian meeting

**ASCOT**

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

**EAGLE**

EAGLE with warm iron barrel and end cap toroids
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 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)
• **Inner Detector Tracking** ($|\eta|<2.5$, $B=2\,T$):
  -- Si pixels and strips
  -- Transition Radiation Detector ($e/\pi$ separation)

• **Calorimetry** ($|\eta|<5$):
  -- EM: Pb-LAr
  -- HAD: Fe/scintillator (central),
    Cu/W-LAr (end-caps/fwd)

• **Muon Spectrometer** ($|\eta|<2.7$):
  -- air-core toroids with precision (MDT and CSC)
  and trigger (RPC and TGC) muon chambers
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…
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\textbf{The formal construction approval was then given with the approval of the first TDRs (25 years ago)}
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

Very few examples of the many technical challenges.
The B0 model coil reaching full current of 20.5 kA (July 2001) at CERN
Barrel Toroid coil integration and testing in Hall 180

November 2003
Point-1 Civil Engineering 1998-2003
(underground cavern 56 x 32 x 35 m³)
Barrel toroid and barrel calorimeter (plus solenoid) installations 2004-2005
Tile calorimeter Module-0 at the JINR Dubna workshop, April 1996
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...

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
  - $<> \sim 2.2 \text{ mm}$
  - $\sigma \approx 9 \text{ μm}$

- 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)

- Test-beam measurements
  - 1 barrel module:
    - $\Delta \eta \times \Delta \varphi = 1.4 \times 0.4$  
    - $\approx 3000$ channels

- End-cap: 1536 plates
  - Overall uniformity: ~0.54%
Insertion of the solenoid into the LAr EM calorimeter barrel cryostat

February 2004
First barrel muon chamber installation
(January 2005)
Snapshots from the Inner Detector construction years (2001 – 2007)
Installation of the ATLAS barrel tracker (Aug 2006)
End-Cap Toroid A on its way to Point-1 (29 May 2007)
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’)
Francois Englert
6 Dec 2007

Peter Higgs
4 April 2008

Famous visitors in ATLAS
Trigger, DAQ, Software and Computing

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

10y Higgs discovery 4 July 2022
Peter Jenni (Freiburg and CERN)
Expecting in the ATLAS Control Room the first LHC beam to collide on November 23\textsuperscript{rd}, 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

Candidate Collision Event

ATLAS EXPERIMENT
2009-11-23, 14:22 CET
Run 140541, Event 171897

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)
The excellent performance in measuring Standard Model physics gives confidence for the readiness of the two experiments to search for New Physics.
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, 10 years ago

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

(Everybody recognizes, and knows, who used the 'Comic Sans MS' font ...!)
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.
Spares
A comprehensive insider story of all aspects of the ATLAS history and highlights of the first 25 years of the experiment
La Thuile 7 – 13 January 1987
(Carlo Rubbia’s Long Range Planning Committee)
From an early talk about the LHC, must have been around 1986/7 …
March 1992

Evian Meeting with EoI presentations

Four Expressions of Interest for general purpose experiments with the Higgs Boson as benchmark

ASCOT
CMS
EAGLE
L3+1

Other Expression of Interests

LHC Beauty Collider
B extracted beam
B gas jet
Neutrino at LHC
LHC HI
Delphi LHC HI
The ATLAS LoI was presented to the new 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


(88 Institutions with about 850 authors on LoI)

Spokespersons: F. Dydak and P. Jenni
**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 \(10^{34}\ \text{cm}^{-2}\text{s}^{-1}\) with as many signatures as possible (e, \(\gamma\), \(\mu\), jet, \(E_T^{\text{miss}}\), 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 \(10^{33}\ \text{cm}^{-2}\text{s}^{-1}\) using in addition more complex signatures (\(\tau\) and heavy-flavour tags from secondary vertices, ...)

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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

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This concept offers

- almost no constraints on calorimetry and inner detector
- high-resolution, large-acceptance and robust stand-alone muon spectrometer
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)
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
Formal inauguration of the point-1 cavern on 4<sup>th</sup> June 2003
LAr hadronic End-Cap Calorimeters (pictures show stacking 2000, wheel assembly 2003 and cryostat before closing 2005)

10y Higgs discovery 4 July 2022
Peter Jenni (Freiburg and CERN)
1st EC calorimeter transport 22nd Sep 2005
February 2006: the barrel SCT was inserted into the barrel TRT
Israel-Japan-Pakistan: Teams working together in assembling TGC Big Wheel sectors (Hall 180, March 2006)
Transport of a muon end-cap sector to LHC interaction Point-1 (Dec 2006)
MDT Big Wheel
(one plane on both sides, all installed)

TGC Big Wheel
(three planes on both sides, all installed)
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.
A snapshot of the many parallel installation and commissioning activities in the cavern in both end-cap regions A and C under the shafts, as well as in the barrel region: a huge, successful activity of the Technical Coordination.
A lot of cables and pipes

> 50,000 cables and pipes installed

10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0

TileCal
LAr+Lyo
Magnet
INDET
PIXEL
SCT
TRT
Muon MD
Muon RPC + LVL1
DAQ + Network
LVL1
DCS+SS
Cooling
Sniffers
others

Higgs discovery 4 July 2022
Peter Jenni (Freiburg and CERN)
Since 1995 there are ATLAS 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 …
The Construction MoU was signed by all initial ATLAS Funding Agencies in 1998-1999

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<th>Country</th>
<th>Date</th>
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Today is also a very appropriate occasion to thank all Funding Agencies for their support.

10y Higgs discovery  4 July 2022
Peter Jenni (Freiburg and CERN)
Overview of the integrated financial evolution of the ‘CORE’ costs of ATLAS (Constr. MoU deliverables and Common Fund, Cost-to-Completion, in 1995 MCHF)

‘Investments’

1995 MCHF

10y Higgs discovery   4 July 2022
Peter Jenni (Freiburg and CERN)
A dream became true much faster than anticipated long ago.

1999

2012

ATLAS history
ATLAS Run-1 Higgs boson signal peaks

\[ \int \text{Ldt} = 4.5 \text{ fb}^{-1} \, \text{Ls} = 7 \text{ TeV} \]
\[ \int \text{Ldt} = 20.3 \text{ fb}^{-1} \, \text{Ls} = 8 \text{ TeV} \]

s/b weighted sum
Mass measurement categories

ATLAS
- Data

Combined fit:
- Signal+background
- Background
- Signal

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

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<tr>
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<th>CMS</th>
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Complementary technologies provided comparable performances in term of significance of the signals (Run-1)!
MUON NEW SMALL WHEELS (NSW)
Installed new muon detectors with precision tracking and muon selection capabilities. Key preparation for the HL-LHC.

NEW READOUT SYSTEM FOR THE NSWs
The NSW system includes two million micromega readout channels and 350,000 small strip thin-gap chambers (STGC) electronic readout channels.

LIQUID ARGON CALORIMETER
New electronics boards installed, increasing the granularity of signals used in event selection and improving trigger performance at higher luminosity.

TRIGGER AND DATA ACQUISITION SYSTEM (TDAQ)
Upgraded hardware and software allowing the trigger to spot a wider range of collision events while maintaining the same acceptance rate.

NEW MUON CHAMBERS IN THE CENTRE OF ATLAS
Installed small monitored drift tube (sMDT) detectors alongside a new generation of resistive plate chamber (RPC) detectors, extending the trigger coverage in preparation for the HL-LHC.

ATLAS FORWARD PROTON (AFP)
Re-designed AFP time-of-flight detector, allowing insertion into the LHC beamline with a new “out-of-vacuum” solution.
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)

**Additional small upgrades**
- Luminosity detectors (1% precision)
- HL-ZDC (Heavy Ion physics)

**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 $|\eta| = 4$