The Large Hadron Collider project is a global scientific adventure, combining the accelerator, a worldwide computing grid and the experiments, initiated more than 25 years ago.

There is a fourth, essential element: the constant driving motivation from our theory colleagues, and Julius Wess and Bruno Zumino with SUSY have created such an essential one!

It is a great privilege and pleasure to present now first physics results.
pp physics at the LHC corresponds to conditions around here

HI physics at the LHC corresponds to conditions around here

ATLAS physics road map

Particle Data Group, LBNL, © 2000. Supported by DOE and NSF
A most basic question is why particles (and matter) have masses (and so different masses)

The mass mystery could be solved with the ‘EW symmetry breaking mechanism’ which predicts the existence of a new elementary particle, the ‘Higgs’ particle (theory 1964: R. Brout and F. Englert; P.W. Higgs; G.S. Guralnik, C.R. Hagen and T.W.B. Kibble)

The Higgs (H) particle has been searched for since decades at accelerators …

The LHC has sufficient energy to produce it for sure, if it exists
**Supersymmetry (SUSY)**

*(Julius Wess and Bruno Zumino, 1974)*

Establishes a symmetry between fermions (matter) and bosons (forces):

- Each particle \( p \) with spin \( s \) has a SUSY partner \( p' \) with spin \( s - \frac{1}{2} \)

- Examples
  
  \[
  \begin{align*}
  q \ (s=1/2) & \rightarrow \tilde{q} \ (s=0) \quad \text{squark} \\
  g \ (s=1) & \rightarrow \tilde{g} \ (s=1/2) \quad \text{gluino}
  \end{align*}
  \]

**Our known world...**

**Maybe a new world?**

**Motivation:**

- Unification (fermions-bosons, matter-forces)
- Solves some deep problems of the Standard Model
How the LHC came to be ...  
(see a nice article by Chris Llewellyn Smith in Nature 448, p281)

Some 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

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

This also triggered a famous quote from a 1983 New York Times editorial:

‘Europe: 3 - US Not Even Z-Zero’

A very early $Z \rightarrow ee$ online 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

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: a clear evolution started for detectors away from a 4 \( \mu \) iron-ball experiment towards multi-purpose detectors …)

1989 ECFA Study Week in Barcelona for LHC instrumentation

1990 Large Hadron Collider Workshop Aachen (ECFA)

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

ATLAS and CMS were born with Letters of Intent (LoI), submitted on 1\textsuperscript{st} October 1992, 20 years ago

Spokesperson Fabiola Gianotti, celebrating 20 years of ATLAS on 1\textsuperscript{st} October 2012
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

1994 June Council:

Construction was formally proposed by DG Chris Llewellyn Smith, but few countries could not yet agree, so the Council session vote was suspended until

16 December 1994 Council:

(Two-stage) construction of LHC was approved
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, 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 DG L Maiani and A Skrinsky in the centre.
For the experiments it was a long way convincing the LHCC, but finally, on 16\textsuperscript{th} November 1995, our referees were happy, and Hugh Montgomery, ATLAS main referee at that time, gave us the following ‘official leak’ from the committee…

The LHCC recommendations meant in particular that ATLAS and CMS could now proceed in developing their series of Technical Design Reports
General purpose detectors
Specialized detectors
It is a pleasure to collaborate with 425 colleagues, senior and junior, from 13 Universities, DESY and MPI Munich from Germany
Age distribution of the ATLAS population

<table>
<thead>
<tr>
<th>Age Group</th>
<th>Male</th>
<th>Female</th>
<th>(&lt; 35 y)</th>
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<tbody>
<tr>
<td>&lt; 25</td>
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<td>&gt; 69</td>
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<tr>
<td>All</td>
<td>81.8%</td>
<td>18.2%</td>
<td>47.2%</td>
</tr>
<tr>
<td>(&lt; 35 y)</td>
<td>44.0%</td>
<td>61.3%</td>
<td></td>
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</table>

(Status 1.1.2010)
The Underground Cavern at Point-1 for the ATLAS Detector

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

KIT Karlsruhe
1-2-2013, P Jenni (CERN)
Hector Berlioz, “Les Troyens”, opera in five acts
Valencia, Palau de les Arts Reina Sofia, 31 October -12 November 2009
The joy in the ATLAS Control Room when the first LHC beam collided on November 23rd, 2009....
First collisions at the LHC end of November 2009 with beams at the injection energy of 450 GeV
The experiment records typically 94% of the stably delivered luminosity, and uses up to 90% of the LHC luminosity in the final analyses!
The Worldwide LHC Computing Grid (wLCG)

Tier-0 (CERN):
• Data recording
• Initial data reconstruction
• Data distribution

Tier-1 (12 centres):
• Permanent storage
• Re-processing
• Analysis
• Simulation

Tier-2 (68 federations of >100 centres):
• Simulation
• End-user analysis
Physics Highlights:

General event properties

Heavy flavour physics

Standard Model physics including QCD jets

Higgs searches

Searches for SUSY

Examples of searches for ‘exotic’ new physics
Candidate $Z \rightarrow \mu^+\mu^-$

$W \rightarrow e\nu$ candidate

Today ATLAS has in the data more than:

100 M $W \rightarrow \mu\nu, e\nu$ events

10 M $Z \rightarrow \mu\mu, ee$ events

after all selection cuts
Z and W production

\[ m = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2} \]

Z peak (di-lepton pair mass distributions, can be extracted essentially background-free)
What a contrast to the Intermediate Vector Boson discovery distributions in 1982 and 1983 by UA1 and UA2 ...

(Here are shown the UA2 distributions)

30 years ago!
$W$ cross section measurement with $e$ and $\mu$

Jet physics

\[ m_{jj} = 4.7 \text{ TeV} \]
\[ p_T^j = 2.3 \text{ TeV} \]
\[ E_{T}^{\text{miss}} = 47 \text{ GeV} \]
Note also that the event displays have become more sophisticated since the first spectacular events, hand-drawn, at a hadron collider …

Highest mass event in the 1981 UA2 data, \( m_{jj} = 140 \text{ GeV} \)
Very detailed jet measurements are now available from LHC that can be compared with QCD calculations …

Example:
The inclusive di-jet cross sections as a function of the di-jet mass for various rapidity separations

The data are spanning jets over a large phase space:

- \( 20 \text{ GeV} < p_T < 2 \text{ TeV} \)
- \( |\eta| < 4.4 \)

\((y^* = 0.5 |\eta_1 \pm \eta_2|)\)
Top measurements

- Complete set of ingredients to investigate production of $t\bar{t}$bar, which is the next step in verifying the SM at the LHC:
  - $e$, $\mu$, $E_T^{\text{miss}}$, jets, b-tag

- Assume all tops decay to $Wb$: event topology then depends on the $W$ decays:
  - one lepton ($e$ or $\mu$), $E_T^{\text{miss}}$, jjbb (37.9%)
  - di-lepton ($ee$, $\mu\mu$ or $e\mu$), $E_T^{\text{miss}}$, bb (6.5%)

- Data-driven methods to control QCD and $W$+jets backgrounds
tt candidate event  

$e + \mu + 2 \text{ jets (b-tagged)} + \text{ETmiss}$
The excellent performance in measuring Standard Model physics gives confidence for the readiness of the two experiments to search for New Physics.
ATLAS and CMS have announced the discovery of a new boson together on 4th July 2012, published in a special issue of Physics Letter B.


KIT Karlsruhe
1-2-2013, P Jenni (CERN)

ATLAS physics road map
Selected diphoton sample

- Data 2011+2012
- Sig+Bkg Fit ($m_H = 126.5$ GeV)
- Bkg (4th order polynomial)

ATLAS Preliminary

Raw data

$\sqrt{s} = 7$ TeV, $\int L dt = 4.8$ fb$^{-1}$

$\sqrt{s} = 8$ TeV, $\int L dt = 13.0$ fb$^{-1}$

6.1 $\sigma$
ATLAS Preliminary

H→ZZ(*) →4l

s = 7 TeV: \( \int L dt = 4.6 \text{ fb}^{-1} \)

s = 8 TeV: \( \int L dt = 13.0 \text{ fb}^{-1} \)

- Data
- Background ZZ(*)
- Background Z+jets, t\(\bar{t}\)
- Signal (\(m_H = 125\) GeV)
- Syst.Unc.
(Just as an example of several subsamples)

**ATLAS** Preliminary
\( \sqrt{s} = 8 \text{ TeV}, \int L dt = 13.0 \text{ fb}^{-1} \)

\( H \rightarrow WW^* \rightarrow e\nu\nu \) (1 jet)

<table>
<thead>
<tr>
<th>Events / 10 GeV</th>
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<tbody>
<tr>
<td>45</td>
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<td>40</td>
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<th>( m_\ell ) [GeV]</th>
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</table>

\[ m_\ell = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - (P_T^{\ell\ell} + P_T^{miss})^2} \]

(All subsamples, background subtracted)

**ATLAS** Preliminary
\( \sqrt{s} = 8 \text{ TeV}, \int L dt = 13.0 \text{ fb}^{-1} \)

\( H \rightarrow WW^* \rightarrow \mu\nu\nu \) (0/1 jets)

<table>
<thead>
<tr>
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</table>

\[ m_\ell = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - (P_T^{\ell\ell} + P_T^{miss})^2} \]

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ATLAS physics road map

ATLAS-CONF-2012-158
Summary and combination

\( \mu = 0 \) background only hypothesis
\( \mu = 1 \) SM Higgs hypothesis

ATLAS Preliminary

- \( W, Z, H \rightarrow bb \)
  - \( \sqrt{s} = 7 \text{ TeV}; \int L dt = 4.7 \text{ fb}^{-1} \)
  - \( \sqrt{s} = 8 \text{ TeV}; \int L dt = 13 \text{ fb}^{-1} \)
- \( H \rightarrow \tau\tau \)
  - \( \sqrt{s} = 7 \text{ TeV}; \int L dt = 4.6 \text{ fb}^{-1} \)
  - \( \sqrt{s} = 8 \text{ TeV}; \int L dt = 13 \text{ fb}^{-1} \)
- \( H \rightarrow WW^{(*)} \rightarrow 4l \)
  - \( \sqrt{s} = 7 \text{ TeV}; \int L dt = 4.6 \text{ fb}^{-1} \)
  - \( \sqrt{s} = 8 \text{ TeV}; \int L dt = 13 \text{ fb}^{-1} \)

Combined

\( \mu = 1.35 \pm 0.24 \)

\( m = 125.2 \pm 0.3 \text{ (stat)} \pm 0.6 \text{ (syst)} \text{ GeV} \)

Observed data compared to the probability that the background fluctuates to fake the observed excess of events, and what is expected from a SM Higgs

\( \text{(Local } p_0\) \)

(First analyses and fits for the Higgs couplings and spin have been made as well which are still very much limited by statistics, albeit well compatible with the Standard Model)
Searches Beyond the Standard Model
(only very few examples out of many…)

KIT Karlsruhe
1-2-2013, P Jenni (CERN)
Dark Matter in the Universe

Astronomers found that most of the matter in the Universe must be invisible Dark Matter.

Supersymmetric particles?
In practice SUSY searches at LHC are rather complicated

- Complex (and model-dependent) squark/gluino cascades

- Focus on signatures covering large classes of models while strongly rejecting SM background
  - Large missing $E_T$
  - High transverse momentum jets
  - Leptons
    - Perform separate analyses with and without lepton veto (0-lepton / 1-lepton / 2-leptons)
    - B-jets: to enhance sensitivity to third-generation squarks
    - Photons: typically for models with the gravitino as LSP

\[ M_{\text{eff}} = E_{\text{miss}} + \sum pT(\text{jets}) \]
Analyses re-optimized and updated with full 2011 Luminosity

- 0-lepton + 2–6 jets + high MET (based on Et-miss+jet triggers)
- 0-lepton + 6–9 (multi-)jets + MET (based on multi-jet triggers)
- 1-lepton + 3,4 jets + high MET (based on lepton triggers)

Example: O-leptons + 2-6 Jets analysis

A signal region

A control region where no signal is expected

ATLAS-CONF-2012-033, 037, and 041
Interpretation of the results
Consider phenomenological MSSM models containing only squarks of 1st and 2nd generation, gluino and light neutralinos

\[ \int L \, dt = 5.8 \, fb^{-1}, \, \sqrt{s} = 8 \, TeV \]

0-lepton combined
- Observed limit \((\pm 1 \, \sigma_{\text{theory}})\)
- Expected limit \((\pm 1 \, \sigma_{\text{exp}})\)
- Observed limit \(4.7 \, fb^{-1}, 7 \, TeV\)
SUSY limits

**ATLAS SUSY Searches** - 95% CL Lower Limits (Status: HCP 2012)

- **Inclusive searches**
  - MSUGRA/CMSSM: $0$ lep + $j$'s + $E_t^{miss}$
  - GMSB (I NLSP): $2$ lep (OS) + $j$'s + $E_t^{miss}$
  - GMSB (R NLSP): $1 - 2 + 0 - 1$ lep + $j$'s + $E_t^{miss}$
  - GGM (higgsino NLSP): $γ$ + $j$'s + $E_t^{miss}$
  - GGM (higgsino NLSP): $Z$ + jets + $E_t^{miss}$

- **3rd gen. squark direct production**
  - $b\bar{b}$, $b\bar{b}$ + $E_t^{miss}$
  - $t\bar{t}$ (very light), $t\bar{b}$ + $E_t^{miss}$

- **EW direct**
  - Stable $\tilde{g}$ R-hadrons: low $β, β'$ (full detector)
  - Stable $t$ R-hadrons: low $β, β'$ (full detector)
  - GMSB: stable $\tilde{t}$

- **RPV**
  - $\tilde{χ}_0 \rightarrow q\bar{q}$ (RPV): $μ +$ heavy displaced vertex
  - Bilinear RPV CMSSM: $1$ lep + $7$'s + $E_t^{miss}$

- **Scalar gluon**
  - 2-jet resonance pair

- **WIMP interaction** (D5, Dirac $\tilde{χ}_i$): $\text{monojet} + E_t^{miss}$

![Diagram of SUSY limits with ATLAS SUSY Searches](image)

- **8 TeV results**
  - $\tilde{g} = 7, 8$ TeV

- **7 TeV results**

- **Mass scale [TeV]**

- **SUSY limits**
  - $\tilde{q}$ mass ($m(\tilde{q}) < 200$ GeV, $m(\tilde{q}) > 120$ (GeV) + $m(\tilde{g})$
  - $\tilde{g}$ mass ($t\tilde{g}$, $b\tilde{g}$)
  - $\tilde{q}$ mass ($m(\tilde{q}) > 200$ GeV)
  - $\tilde{q}$ mass ($m(\tilde{q}) > 300$ GeV)
  - $\tilde{g}$ mass ($m(\tilde{g}) > 50$ GeV)

*Only a selection of the available mass limits on new states or phenomena shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.*
Searches for heavy $W$ and $Z$ like particles

These searches are quite straight-forward, following basically the same analyses as for the familiar $W$ and $Z$ bosons.

$Z$ square Di-lepton pairs

$W$ square Lepton + ETmiss

ATLAS physics road map

KIT Karlsruhe
1-2-2013, P Jenni (CERN)
Randall-Sundrum Graviton
Search for direct Dark Matter (DM) particles in pair-production

A single photon (150 GeV) or jet plus ETmiss

ATLAS-CONF-2012-085
arXiv:1210.4491v1[hep-ex]
On a personal note:

The search for SUSY has been a motivation for me for 30 years, and in spite of exclusion limits only so far I have not given up yet!

I am therefore particularly happy and grateful to be honoured with the Julius Wess Award
The journey with LHC into new physics territory has only just begun, and for sure, further exciting times are ahead of us!

Thank you for your attention
Further reading:

http://www.sciencemag.org/content/338/6114/1560.full.html