The plan:

- A bit about the history of the LHC
- A bit about the history of ATLAS
- Examples of technical challenges
- Testing/Commissioning the detector
- Comments on computing
- The physics landscape
- Some physics highlights results
  - Standard Model
  - Higgs (combination with CMS)
  - Beyond the SM searches
- Outlook

International School of Subnuclear Physics, 55th Course
Erice, 14 – 23 June 2017

Peter Jenni, Freiburg and CERN

The Long Journey to the Higgs Boson and Beyond at the LHC
(with highlights from ATLAS)
The Large Hadron Collider project is a global scientific adventure, which was initiated more than 30 years ago, combining the accelerator, the experiments, a worldwide computing grid, and with lots of motivation from our theory colleagues.
How the LHC came to be …

Some very early key dates

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

1979 LEP White Book:

ECFA-LEP Working Group 1979 chaired by A Zichichi

‘Tunnel with 27 km circumference and a diameter of 5 m, with a view to the replacement of LEP at the end of its activities by a proton-proton Collider using cryogenic magnets’
1981 LEP was approved with a large and long (27 km) ring tunnel

1983 The early 1980s were crucial

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

A very early $Z \to ee$ 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

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
Some history: 30 years ago ...
La Thuile 7 – 13 January 1987
(Carlo Rubbia’s Long Range Planning Committee)
From a very early talk about the LHC, must have been around 1987 ...

Possible LHC Schedule

<table>
<thead>
<tr>
<th>Year</th>
<th>LEP</th>
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</tbody>
</table>

- Magnet Intensive R&D
- Study of LEP
- Detector Intensive R&D
- Machine Installation
- Exp. Hall Construction
- Assembling of Detectors
- Final Inst.

[Diagram showing possible LHC schedule with specific timelines and milestones.]
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

ATLAS provided comparisons between 10 and 14 TeV... \( \rightarrow \) worthwhile to start with

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

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

\[ p(\text{TeV}) = 0.3 \, B(T) \, R(\text{km}) \]
The LHC beams are accelerated by superconducting Radio-Frequency (RF) cavities

Note: The acceleration is not such a big issue in pp colliders (unlike in ring e⁺e⁻ colliders), because of the $\sim 1/m^4$ dependance of the synchrotron radiation energy losses [$\sim E_{\text{beam}}^4/Rm^4$]
Special quadrupole magnets (‘Inner Triplets’) are focusing the particle beams to reach highest densities (‘luminosity’) at their interaction point in the centre of the experiments.
CERN’s particle accelerator chain
Collisions at the LHC

Event rate:

\[ N = L \times \sigma (pp) \approx 10^9 \text{ interactions/s} \]

Mostly soft (low \( p_T \)) events

Interesting hard (high-\( p_T \)) events are rare

New physics rate \( \approx 0.00001 \text{ Hz} \)

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

\( \Rightarrow \) Interesting events are very, very rare

\( \Rightarrow \) One needs highly sophisticated instruments to find them
Arguing after the mid-1980s of being ambitious and design a general purpose detector ...

A very simplified summary:

<table>
<thead>
<tr>
<th>detector signature</th>
<th>accessible physics process</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu^\pm )</td>
<td>( H \rightarrow ZZ \rightarrow 4 \mu^\pm )</td>
</tr>
<tr>
<td>( Z' \rightarrow \mu^+ \mu^- ) (( \sigma_m )?)</td>
<td></td>
</tr>
<tr>
<td>( \mu^\pm, \text{jets, } p_T )</td>
<td>add: ( H \rightarrow ZZ \rightarrow \mu^+ \mu^- \nu \nu )</td>
</tr>
<tr>
<td>( W' \rightarrow \mu^+ \nu )</td>
<td></td>
</tr>
<tr>
<td>compositeness ( \tilde{q}, \tilde{g} ) (direct decays)</td>
<td></td>
</tr>
<tr>
<td>jet spectroscopy</td>
<td></td>
</tr>
<tr>
<td>( e, \mu^\pm, \text{jets, } p_T )</td>
<td>add: ( 4 \times \text{rate } H \rightarrow ZZ \rightarrow 4e^\pm )</td>
</tr>
<tr>
<td>(non-magnetic) central part (reduced tracking)</td>
<td></td>
</tr>
<tr>
<td>( 2 \times \text{rate } H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \nu )</td>
<td></td>
</tr>
<tr>
<td>( 2 \times \text{rate } Z' \rightarrow \ell^+ \ell^- )</td>
<td></td>
</tr>
<tr>
<td>( \tilde{q}, \tilde{g} ) (also cascade decays)</td>
<td></td>
</tr>
<tr>
<td>mass resolution ( e \mu ) heavy Q, L</td>
<td></td>
</tr>
<tr>
<td>( H \rightarrow gg )</td>
<td></td>
</tr>
<tr>
<td>( \ell^\pm, \tau^\pm, \text{jets, } p_T )</td>
<td>add: more redundancy and cross-checks on above, ( H^+, \text{SUSY-H, heavy flavour tags} )</td>
</tr>
</tbody>
</table>

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

\[ \Rightarrow \text{detection of } e \text{ and } \mu \]

Muons are relatively easy to identify but hard to measure well

\( \text{(precise } \mu \text{ measurements may mean hundreds of mCHF) } \)

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

\( \text{(radiation-hard inner detector) } \)

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

1989 ECFA Study Week in Barcelona for LHC instrumentation.

1990 Large Hadron Collider Workshop
Aachen (CERN - ECFA).

1992 CERN – ECFA meeting ‘Towards the LHC Experimental Programme’ in Evian.
The birth of ATLAS

March 1992 – Summer 1992

Merging of EAGLE and ASCOT

September 1992: Decision on the name

October 1992:

ATLAS LoI submitted to the LHCC (as well as the CMS LoI)
For the experiments it was a long way convincing the LHCC, but finally, on 16th November 1995, our referees were happy, and Hugh Montgomery, ATLAS main referee at that time, gave us the following ‘official leak’ from the committee…

The LHCC recommendations meant in particular that ATLAS and CMS could now proceed in developing their series of Technical Design Reports
ATLAS Collaboration
(Status January 2017)

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

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

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

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

- **Tracking** ($|\eta|<2.5, B=2T$):
  - Si pixels and strips
  - Transition Radiation Detector ($e/\pi$ separation)

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

- **Muon Spectrometer** ($|\eta|<2.7$):
  - air-core toroids with muon chambers
**ATLAS Toroid Magnet System**

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

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

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

BT test area

BT5 excitation tests to 22 kA current

EMFISC, Erice, June 2017
First Barrel Toroid coil on its way to Point-1 (21-10-2004)
The Pixel tracker is a particularly high-tech device close around the LHC beam pipe.

Another example

Insertion in June 2007
**Strategy toward physics**

**Before data taking starts:**
- Strict quality controls of detector construction to meet physics requirements
- Test beams (a 15-year activity culminating with a **combined test beam in 2004**) to understand and calibrate (part of) detector and validate/tune software tools (e.g. Geant4 simulation)
- Detailed simulations of realistic detector “as built and as installed” (including misalignments, material non-uniformities, dead channels, etc.) → test and validate calibration/alignment strategies
- Experiment commissioning with cosmics in the underground cavern

**With the first data:**
- Commission/calibrate detector/trigger in situ with physics (min.bias, Z→ll, ...)
- “Rediscover” Standard Model, measure it at $\sqrt{s} = 7$ TeV (minimum bias, W, Z, tt, QCD jets, ...)
- Validate and tune tools (e.g. MC generators)
- Measure main backgrounds to New Physics (W/Z+jets, tt+jets, QCD-jets, ...)

---

A slide from 2008, at the time of anticipating first collisions

---

Prepare the road to discoveries ...
Construction example: ATLAS LAr em Accordion Calorimeter

Construction quality

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

End-cap: 1536 plates

< > ~ 2.2 mm
σ ≈ 9 μm

Absorber thickness (mm)

1 barrel module:
Δη x Δφ = 1.4 x 0.4
≈ 3000 channels

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)

Overall uniformity: ~0.54%

End-cap: 1536 plates

EMFCSC, Erice, June 2017
P Jenni (Freiburg and CERN)
LHC, Higgs and Beyond (ATLAS)
Commissioning with cosmics in the underground caverns
(the first real data in situ ...)

Started when the first components were installed. Very useful to:

- Run an increasingly more complete detector with final trigger, data acquisition and monitoring systems. Data analyzed with final software.
- Shake-down and debug the experiment in its final position \(\rightarrow\) fix problems.
- Perform first calibration and alignment studies.
- Gain global operation experience in situ before collisions start.

Rate of cosmics in ATLAS: 0.5-100 Hz (depending on sub-detector size and location)
Correlation between measurements in the ATLAS Inner Detector and the Muon Spectrometer

Difference between the muon momentum measured in the ID and in the MS for tracks in the bottom part of the detector (~3 GeV energy loss in the calorimeter)
Interconnections of two magnets

One (superconductor) joint failed on 19\textsuperscript{th} 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 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

Candidate Collision Event

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

The LHC and experiments performances were simply fantastic over the three years of Run-1.

The experiments record typically 94% of the stably delivered luminosity, and use up to 90% of the LHC luminosity in the final analyses!
The LHC and ATLAS performances for Run-2 (2015-2018) at 13 TeV

The machine worked outstandingly well and delivered in 2016 about 40 fb⁻¹ data.

The LHC and ATLAS performances for Run-2 (2015-2018) at 13 TeV

The machine worked outstandingly well and delivered in 2016 about 40 fb⁻¹ data.

ATLAS Online Luminosity

- 2011 pp \( \sqrt{s} = 7 \) TeV
- 2012 pp \( \sqrt{s} = 8 \) TeV
- 2015 pp \( \sqrt{s} = 13 \) TeV
- 2016 pp \( \sqrt{s} = 13 \) TeV

ATLAS pp 25ns run: April-October 2016

<table>
<thead>
<tr>
<th>Inner Tracker</th>
<th>Calorimeters</th>
<th>Muon Spectrometer</th>
<th>Magnets</th>
<th>Trigger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel, SCT, TRT</td>
<td>LAr, Tile</td>
<td>MDT, RPC, CSC, TGC</td>
<td>Solenoid, Toroid</td>
<td>L1</td>
</tr>
<tr>
<td>98.9, 99.9, 99.7</td>
<td>99.3, 98.9</td>
<td>99.8, 99.8, 99.9, 99.9</td>
<td>99.1, 97.2</td>
<td>98.3</td>
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</table>

Good for physics: 93-95% (33.3-33.9 fb⁻¹)

Luminosity weighted relative detector uptime and good data quality efficiencies (in %) during stable beam in pp collisions with 25ns bunch spacing at \( \sqrt{s} = 13 \) TeV between April-October 2016, corresponding to an integrated luminosity of 35.9 fb⁻¹. The toroid magnet was off for some runs, leading to a loss of 0.7 fb⁻¹. Analyses that don’t require the toroid magnet can use that data.
Excellent LHC performance is a (nice) challenge for the experiment:

- Trigger
- Pile-up
- Maintain accuracy of the measurements in this environment

Inner Detector for a $Z \rightarrow \mu \mu$ event with 25 primary vertices
The Worldwide LHC Computing Grid

GRID computing was developed to solve problem of data storage and analysis (tens of Petabytes)
Physics Highlights

General event properties

Heavy flavour physics

Standard Model physics including QCD jets

Higgs searches

Searches for SUSY

Searches for ‘exotic’ new physics
A commissioning example from the Run-2 start-up 2015 with a new 4\textsuperscript{th} Pixel layer in ATLAS (called ‘IBL’, standing for insertable B-layer’)

Conversions
Radial vertex position for photon conversion candidates.

Hadron interactions ("radiography")
Vertex position for had. int. candidates in xy-plane, reconstructed from multiple tracks.
Di-jet events

Highest mass central di-jet event 2015
\( p_{T1} = p_{T2} = 3.2 \text{ TeV} \quad m_{JJ} = 6.9 \text{ TeV} \quad \text{ET}_{\text{miss}} = 46 \text{ GeV} \)
A recent example of a QCD analysis: Inclusive jet cross-section at 13 TeV

Jet energy scale (JES) and jet energy resolution (JER) uncertainties

ATLAS Preliminary
- $|y| < 0.5 \times 10^6$
- $0.5 \leq |y| < 1.0 \times 10^3$
- $1.0 \leq |y| < 1.5 \times 10^6$
- $1.5 \leq |y| < 2.0 \times 10^6$
- $2.0 \leq |y| < 2.5 \times 10^9$
- $2.5 \leq |y| < 3.0 \times 10^{15}$

Relative uncertainty of 2.1% on the integrated luminosity not included
An example of physics that was certainly not anticipated at the time of the conception of ATLAS:

Evidence of light-by-light scattering in heavy ion collisions

‘Standard Candles’ for the LHC physics: W and Z bosons

$W \rightarrow e\nu$ candidate

Candidate $Z \rightarrow \mu^+\mu^-$
What a contrast to the Intermediate Vector Boson discovery distributions in 1982 and 1983 by UA1 and UA2 with just a few events …

Some 35 years ago!

The UA1 $W \rightarrow e\nu$ events

The UA2 distributions
Fermilab celebration 50 years, with the CERN DG Fabiola Gianotti recalling the pioneering collider pp experiments ...
W cross section measurements in pp collisions

ATLAS Preliminary
Data 2015 (\sqrt{s} = 13 TeV)

MSTW2008 NNLO

ATLAS-CONF-2015-039
Testing in detail the predictions of the Standard Model

Lepton Universality

Cross-section predictions for different parton distributions

arXiv:1612.03016[hep-exp], submitted to EPJC
Detailed performance studies for electrons and muons (mass scales, efficiencies, dependence on pile-up ...) are most important for precision measurements.
Precision measurement of the W mass recently released by ATLAS

\[ m_W = 80.370 \pm 0.019 \text{ GeV} \]

arXiv:1701.07240[hep-exp], submitted to EPJC
Standard Model consistency

(SM prediction for $m_w$ is assuming:
$m_H = 125.09 \pm 0.24 \text{ GeV}$
$m_t = 172.84 \pm 0.70 \text{ GeV}$)
Some recent results on EW boson pair productions

ZW at 13 TeV

→ NNLO calculations are required to describe the data

ZZ and ZW are very important processes to probe the EW boson self-couplings, they could reveal physics beyond the Standard Model
A great triumph of the Standard Model

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

ATLAS Preliminary
Run 1,2 $\sqrt{s} = 7, 8, 13$ TeV

Similar impressive results from CMS
Happy faces after the announcement of the discovery on 4th July 2012 at CERN and at ICHEP Melbourne
Happy faces after the announcement of the discovery on 4th July 2012 at CERN and at ICHEP Melbourne
Announced on 8th October and celebrated on 10th December 2013:

2013 NOBEL PRIZE IN PHYSICS
François Englert
Peter W. Higgs

“for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN’s Large Hadron Collider”
Candidate for a $H \rightarrow \gamma \gamma$ event

Candidate for a $H \rightarrow ZZ^* \rightarrow \mu \mu \mu \mu$ event

Higgs event candidates
LHC Run-1 Higgs peaks

A dream becoming true much faster than anticipated long ago.
Complementary technologies provided comparable performances in term of significance of the signals (Run-1)!

<table>
<thead>
<tr>
<th>Experiment</th>
<th>ATLAS</th>
<th>CMS</th>
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<tbody>
<tr>
<td>Decay mode/combination</td>
<td>Expected $(\sigma)$</td>
<td>Observed $(\sigma)$</td>
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<td>$\gamma\gamma$</td>
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<td>5.2</td>
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<td>ZZ</td>
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<td>8.1</td>
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<tr>
<td>bb</td>
<td>2.6</td>
<td>1.4</td>
</tr>
<tr>
<td>$\tau\tau$</td>
<td>3.4</td>
<td>4.5</td>
</tr>
</tbody>
</table>

ATLAS Preliminary
$m_H = 125.36$ GeV

| $H \rightarrow \gamma\gamma$ | $\mu = 1.17_{-0.28}^{+0.28}$ |
| $H \rightarrow ZZ^*$ | $\mu = 1.46_{-0.40}^{+0.40}$ |
| $H \rightarrow WW^*$ | $\mu = 1.18_{-0.34}^{+0.34}$ |
| $H \rightarrow bb$ | $\mu = 1.16_{-0.24}^{+0.24}$ |
| $H \rightarrow \tau\tau$ | $\mu = 0.63_{-0.39}^{+0.39}$ |
| $H \rightarrow \mu\mu$ | $\mu = 0.62_{-0.37}^{+0.37}$ |
| $H \rightarrow Z\gamma$ | $\mu = 0.73_{-0.37}^{+0.37}$ |
| Combined | $\mu = 1.12_{-0.24}^{+0.24}$ |

CMS
$m_H = 125$ GeV

| $P_{SM} = 0.96$ |
| $H \rightarrow \gamma\gamma$ tagged | $\mu = 1.12_{-0.24}^{+0.24}$ |
| $H \rightarrow ZZ$ tagged | $\mu = 1.00_{-0.29}^{+0.29}$ |
| $H \rightarrow WW$ tagged | $\mu = 0.83_{-0.21}^{+0.21}$ |
| $H \rightarrow \tau\tau$ tagged | $\mu = 0.91_{-0.28}^{+0.28}$ |
| $H \rightarrow bb$ tagged | $\mu = 0.84_{-0.44}^{+0.44}$ |
$m_H = 125.09 \pm 0.24$ (±0.21 stat ± 0.11 syst) GeV

ATLAS and CMS combined mass measurements

ATLAS $H \rightarrow \gamma \gamma$

CMS $H \rightarrow \gamma \gamma$

ATLAS $H \rightarrow ZZ \rightarrow 4l$

CMS $H \rightarrow ZZ \rightarrow 4l$

ATLAS+CMS $\gamma \gamma$

ATLAS+CMS $4l$

ATLAS+CMS $\gamma \gamma + 4l$

Accuracy already ~ 0.2%
Fingerprints for a Standard Model Higgs Boson: ATLAS and CMS combined coupling strengths

Within the current rather limited precision the Higgs couplings scale with the particle masses as predicted by the SM.

ATLAS+CMS JHEP 08 (2016) 045
Selection of SM cross-sections including from Run-2 (2015 and first part of 2016)
Searches Beyond the Standard Model
(only very few examples out of many...)

N C Flammarion 1888
(colours added later)

EMFCSC, Erice, June 2017
P Jenni (Freiburg and CERN)

LHC, Higgs and Beyond (ATLAS)
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

\[ \text{Meff} = \text{Etmiss} + \sum \text{pT(jets)} \]
As an example of the virtue of the higher energy now in Run-2:

Strongly produced gluinos and squarks with $E_{T\text{miss}}$ and multiple jets, with 0, 1, 2 leptons

ATLAS CONF-2016-078
squark-gluino-neutralino model, $m(\tilde{\chi}_1^0) = 0$ GeV

ATLAS

0 leptons, 2–6 jets
$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
all limits at 95% CL.

$\tilde{q}_L + \tilde{q}_R (\tilde{u}, \tilde{d}, \tilde{s}, \tilde{c})$

$M_{\text{eff}}$ or RJR (best expected)
Another topical example: direct stop-pair production

Illustrative diagrams for stop decay modes
### SUSY limits

#### ATLAS SUSY Searches - 95% CL Lower Limits

**Status:** March 2017

<table>
<thead>
<tr>
<th>Model</th>
<th>$\ell$, $\mu$, $\tau$, $\gamma$</th>
<th>Jets</th>
<th>$E_{\text{miss}}$</th>
<th>$\mathcal{L} d[\text{fb}^{-1}]$</th>
<th>Mass limit</th>
<th>$\sqrt{s} = 7, 8$ TeV</th>
<th>$\sqrt{s} = 13$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSUGRA/CMSSM</td>
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| $\tilde{b}_{1}, \tilde{b}_{2}, \til Similar limits come from CMS
Searches for heavy W and Z like particles

Highest mass Di-electron event
\[ m_{ee} = 2.4 \text{ TeV} \]
\[ E_{Te1} = 889 \text{ GeV} \]
\[ E_{Te2} = 868 \text{ GeV} \]
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': Di-lepton pairs

W': Lepton + ETmiss

ATLAS-CONF-2016-045

ATLAS-CONF-2017-016
Lower mass limits, at 95% CL, for di-lepton final states

\[
\sigma(p p \to W') \times BR(W' \to l\nu) \text{ [pb]}
\]

\[
\sqrt{s} = 13 \text{ TeV, 36.1 fb}^{-1}
\]

\[
W' \to l\nu
\]

95% CL

---

ATLAS Preliminary

---

Expected limit

- Expected ± 1σ
- Expected ± 2σ

- Observed limit

\[
W'_{\text{SSM}}
\]
Highest mass dijet event at the LHC so far

\[ m_{jj} = 8.2 \text{ TeV} \]
Searching for deviations from QCD (Black Holes, Compositeness…)

At 95% CL:
\[ m(q^*) > 6.0 \text{ TeV} \]
\[ \Lambda > 13 / 21 \text{ TeV} \]

\[ \chi = \exp \left( |y_1 - y_2| \right) = \frac{1 + \cos \vartheta^*}{1 - \cos \vartheta^*} \]

Similar limits come from CMS
LHC / HL-LHC Plan

ATLAS Phase-0
New inner pixel layer Detector consolidation
2015: FTK deployment

ATLAS Phase-1
Improve L1 Trigger, NSW and LAr electronics to cope with higher rates

ATLAS Phase-2
Prepare for 140-200 pile-up events
Replace Inner Tracker
New L0/L1 trigger scheme
Upgrade muon/calorimeter electronics
Upgrade of DAQ detector readout

EMFCSC, Erice, June 2017
P Jenni (Freiburg and CERN)

LHC, Higgs and Beyond (ATLAS)
The journey into new physics territory has just only begun, and for sure, exciting times are ahead of us!
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
Further reading (2):

High-energy accelerator beams colliding head-on have now completed the discovery of all the fundamental particles required by particle theory’s standard model. The search is on for new ones.

The evolution of hadron-collider experiments
Paul Grannis and Peter Jenni

Citation: Phys. Today 66(6), 38 (2013); doi: 10.1063/PT.3.2010
View online: http://dx.doi.org/10.1063/PT.3.2010
View Table of Contents: http://www.physicstoday.org/resource/1/PHTOAD/v66/i6
Published by the American Institute of Physics.

Spares
The Large Hadron Collider is a 27 km long collider ring housed in a tunnel about 100 m underground near Geneva.
**Standard Model of Elementary Particles**

The elementary particles arranged according to their properties

Three families of quarks and leptons

---

**Fermionen**

- **Up quark** (u) with mass ≈2.3 MeV/c²
- **Charmed quark** (c) with mass ≈1.275 GeV/c²
- **Top quark** (t) with mass ≈173.07 GeV/c²
- **Down quark** (d) with mass ≈4.8 MeV/c²
- **Strange quark** (s) with mass ≈95 MeV/c²
- **Bottom quark** (b) with mass ≈4.18 GeV/c²
- **Electron** (e) with mass ≈0.511 MeV/c²
- **Muon** (μ) with mass ≈105.7 MeV/c²
- **Tau** (τ) with mass ≈1.777 GeV/c²
- **Electron neutrino** (νₑ) with mass < 2.2 eV/c²
- **Muon neutrino** (νₘ) with mass < 0.17 MeV/c²
- **Tau neutrino** (νₜ) with mass < 15.5 MeV/c²

**Bosonen**

- **Gluon** (g) with mass ≈126 GeV/c²
- **Higgs boson** (H)
- **Photon** (γ)
- **Z boson** (Z) with mass ≈91.2 GeV/c²
- **W boson** (W) with mass ≈80.4 GeV/c²

---

EMFCSC, Erice, June 2017
P Jenni (Freiburg and CERN)
Age distribution of the ATLAS population

All 2690  (< 35 y 47.2%)
Male 81.8%  (< 35 y 44.0%)
Female 18.2%  (< 35 y 61.3%)
(Status 1.1.2010)
1st March 2004
Arrival of the bottom barrel Tile Calorimeter modules
Extrapolation to the surface of cosmic muon tracks reconstructed by RPC trigger chambers

RPC track impact point on surface

Access shafts

Elevators
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
Very basic measurement: the total cross-section

First inelastic cross-section measurement at 13 TeV LHC

Very basic measurement: the total cross-section

First inelastic cross-section measurement at 13 TeV LHC

\[ \sigma [\text{mb}] \]

\[ \sigma_{\text{tot}} \]

\[ \sigma_{\text{el}} \]

\[ 13.1 - 1.88 \ln(s) + 0.14 \ln^2(s) \]

\[ \text{Nucl. Phys. B889 (2014) 486-548} \]

\[ \text{ATLAS, Erice, June 2017} \]

P Jenni (Freiburg and CERN)
Measurement strategy

- Event representation

- Main signature: final state lepton (electron or muon): $\vec{p}_T^l$
- Recoil: sum of "everything else" reconstructed in the calorimeters; a measure of $p_T^{W,Z}$

$$\vec{u}_T = \sum_i \vec{E}_{T,i} + \text{useful projections (see later). No explicit jet reconstruction!}$$

- Derived quantities: $\vec{p}_T^{\text{miss}} = - (\vec{p}_T^l + \vec{u}_T)$. $m_T = \sqrt{2p_T^l p_T^{\text{miss}} (1 - \cos \Delta \phi)}$
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<td>80371.3</td>
<td>29.2</td>
<td>12.4</td>
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$p_T$-Fit

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<td>5.8</td>
<td>8.1</td>
<td>6.0</td>
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<tr>
<td>$W^- \to \mu\nu, 0.8 &lt;</td>
<td>\eta</td>
<td>&lt; 1.4$</td>
<td>80395.6</td>
<td>27.9</td>
<td>18.3</td>
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<td>5.6</td>
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<td>80380.6</td>
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<td>\eta</td>
<td>&lt; 1.2$</td>
<td>80345.8</td>
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<td>6.7</td>
<td>8.9</td>
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<tr>
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<td>7.2</td>
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<td>5.3</td>
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<tr>
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<td>\eta</td>
<td>&lt; 1.2$</td>
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<td>&lt; 2.4$</td>
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<td>2.7</td>
<td>11.5</td>
<td>8.3</td>
<td>5.3</td>
</tr>
</tbody>
</table>
Search for the boson (H) of the EW symmetry breaking

SM H boson production cross sections times observable decay branching ratios at 8 TeV

LHC, Higgs and Beyond (ATLAS)

EMFCSC, Erice, June 2017
P Jenni (Freiburg and CERN)
Higgs production cross-sections at 8 TeV, and branching fractions

LHC Higgs cross-section working group, arXiv: 1101.0593 and 1201.3084 (the theoretical uncertainties are indicated by the width of the curves)
How significant is the signal?

Observed data compared to the probability that the background fluctuates to fake the observed excess of events.

From ATLAS alone $< 10^{-23}$

and then there is the same independent result from CMS.

Beyond any doubt the discovery of a new particle.
Fingerprints for a Standard Model Higgs Boson:
1) Signal strength $\mu = \sigma / \sigma_{sm}$

As expected from the SM within ~ 10%
Fingerprints for a Standard Model Higgs Boson: 2) Leading production processes at the LHC

As expected from the SM within the still large errors.

ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002

$\mu_{V}/\mu_{f} = 1.06 \pm 0.35$ -0.27
Fingerprints for a Standard Model Higgs Boson:

4) Spin-parity tests (scalar particle with $J^P = 0^+$)

Testing decay angular distributions against alternative $J^P$ hypothesis (example)

Alternative $J^P$ assignments are disfavoured at more than 99.9%
Higgs boson signals from Run-2
(2015 and first part of 2016)
Astronomers found that most of the matter in the Universe must be invisible Dark Matter.
Expected production cross-sections at LHC

\[ \sigma_{\text{tot}}[\text{pb}]: \text{pp} \rightarrow \text{SUSY} \]

\[ \sqrt{S} = 8 \text{ TeV} \]

Prospino2, T. Plehn et al.
The search for high-mass objects is exciting with the much higher cross sections now in LHC Run-2.
Examples of SUSY and Z’ mass reaches at HL-LHC

\[ \int L \, dt = 3000 \text{fb}^{-1} \]

**ATLAS Preliminary (Simulation)**

LHC, Higgs and Beyond (ATLAS)
Outlook for HL-LHC on the Higgs physics

**ATLAS Simulation**

\[ s = 14 \text{ TeV}: \int L dt = 300 \text{ fb}^{-1}; \int L dt = 3000 \text{ fb}^{-1} \]

\[ \int L dt = 300 \text{ fb}^{-1} \text{ extrapolated from 7\&8 TeV} \]

\[ \frac{\Delta(G_t/G_Z)}{G_t/G_Z} \sim 2 \frac{\Delta(k_t/k_Z)}{k_t/k_Z} \]

\[ h \to \gamma\gamma, h \to ZZ^* \to 4l, h \to WW^* \to 4l \nu \nu \]

\[ h \to \tau\tau, h \to bb, h \to \mu\mu, h \to Z\gamma \]

\[ [\kappa_Z, \kappa_W, \kappa_t, \kappa_b, \kappa_{\tau}, \kappa_{\mu}] \]

\[ BR_{t\to\mu}=0 \]

\[ g_{VJ} = \sqrt{\frac{g_{VJ}}{G_V}} = \sqrt{\frac{m_{VJ}}{v}} \]

\[ g_{FJ} = \frac{g_{FJ}}{\sqrt{2}} = \frac{m_{FJ}}{v} \]

\[ s = 14 \text{ TeV} \]

**ATLAS Simulation Preliminary**

\[ \int L dt = 300 \text{ fb}^{-1} \]

\[ \int L dt = 3000 \text{ fb}^{-1} \]

**Ratio to SM**


EMFCSC, Erice, June 2017

P Jenni (Freiburg and CERN)

LHC, Higgs and Beyond (ATLAS)
## Time line of the LHC project

<table>
<thead>
<tr>
<th>Year</th>
<th>Event and Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1984</td>
<td>Workshop on a Large Hadron Collider in the LEP tunnel, Lausanne.</td>
</tr>
</tbody>
</table>
| 1987 | Workshop on Physics at Future Accelerators, La Thuile, Italy.  
The Rubbia “Long-Range Planning Committee” recommends the Large Hadron Collider as the right choice for CERN’s future. |
| 1990 | European Committee for Future Accelerators (ECFA) LHC Workshop, Aachen (discussion of physics, technologies and designs for LHC experiments) |
| 1992 | General Meeting on LHC Physics and Detectors, Evian les Bains (4 general-purpose experiment designs presented along with their physics performance) |
| 1993 | Three Letters of Intent submitted to the CERN peer review committee LHCC. ATLAS and CMS selected to proceed to a detailed technical proposal. |
| 1994 | The LHC accelerator approved for construction |
| 1996 | ATLAS and CMS Technical Proposals approved. |
| 1997 | Formal approval for ATLAS and CMS to move to construction (materials cost ceiling of 475 MCHF) |
| 1997 | Construction commences (after approval of detailed engineering design of subdetectors (magnets, inner tracker, calorimeters, muon system, trigger and data acquisition)) |
| 2000 | Assembly of experiments commences, LEP accelerator is closed down to make way for the LHC. |
| 2009 | LHC restarts operation, pp collisions recorded by LHC detectors |
| 2010 | LHC collides protons at high energy (centre of mass energy of 7 TeV) |
| 2012 | LHC operates at 8 TeV: discovery of a Higgs-like boson. |

*It took a long time, and we already had a tunnel…*
Future Circular Colliders (FCC)

International conceptual design study of a ~100 km ring:

- **pp collider (FCC-hh):** ultimate goal → defines infrastructure requirements
  \[ \sqrt{s} \sim 100 \text{ TeV}, \ L \sim 2 \times 10^{35}; \ 4\ IP, \sim 20\ ab^{-1}/\text{expt} \]

- **e^+e^- collider (FCC-ee):** possible first step
  \[ \sqrt{s} = 90-350 \text{ GeV}, \ L \sim 200-2 \times 10^{34}; \ 2\ IP \]

- **pe collider (FCC-he):** option
  \[ \sqrt{s} \sim 3.5 \text{ TeV}, \ L \sim 10^{34} \]

Also part of the study: HE-LHC: FCC-hh dipole technology (~16 T) in LHC tunnel → \( \sqrt{s} \sim 30 \text{ TeV} \)

**GOAL:** CDR in time for next ES

Machine studies are site-neutral. However, FCC at CERN would greatly benefit from existing laboratory infrastructure and injector complex.
Cross sections vs $\sqrt{s}$

**Process** | $\sigma$ (100 TeV)/$\sigma$ (14 TeV)
---|---
Total pp | 1.25
W | $\sim$ 7
Z | $\sim$ 7
WW | $\sim$ 10
ZZ | $\sim$ 10
tt | 30
H | $\sim$ 15 (ttH $\sim$ 60)
HH | $\sim$ 40
stop (m=1 TeV) | $\sim$ $10^3$

**Snowmass report:** arXiv:1310.5189

**EMFCSC, Erice, June 2017**
P Jenni (Freiburg and CERN)

**LHC, Higgs and Beyond (ATLAS)**

*Hadron colliders: direct exploration of the “energy frontier”*
FCC

FCC-hh: a ~100 TeV pp collider is expected to:
- explore directly the 10-50 TeV E-scale
- conclusive exploration of EWSB
- say the final word about heavy WIMP dark matter

FCC-ee: 90-350 GeV
- measure many Higgs couplings to few permill
- indirect sensitivity to E-scale up to O(100 TeV) by improving by ~20-200 times the precision of EW parameters measurements, $\Delta M_W < 1$ MeV, $\Delta m_{\text{top}} \sim 10$ MeV

Many huge technological, design and operational challenges: e.g. ~16 T Nb$_3$Sn magnets

The two machines are complementary and synergetic

(Demonstrator (16 T, 50 mm gap) ~ 1m, end 2018,

[Timeline with years 1980 to 2035 and stages: Design, Proto, Construction, Physics, LHC, HL-LHC]
## Hadron collider parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FCC-hh</th>
<th>SPPC</th>
<th>LHC</th>
<th>HL LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>collision energy cms [TeV]</td>
<td>100</td>
<td>71.2</td>
<td>14</td>
<td>8.3</td>
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<tr>
<td>dipole field [T]</td>
<td>16</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td># IP</td>
<td>2 main &amp; 2</td>
<td>2</td>
<td>2 main &amp; 2</td>
<td></td>
</tr>
<tr>
<td>bunch intensity $[10^{11}]$</td>
<td>1</td>
<td>1 (0.2)</td>
<td>2</td>
<td>1.1</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>25</td>
<td>25 (5)</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>luminosity/IP $[10^{34} \text{ cm}^{-2}\text{s}^{-1}]$</td>
<td>5</td>
<td>~25</td>
<td>12</td>
<td>1</td>
</tr>
<tr>
<td>events/bunch crossing</td>
<td>170</td>
<td>~850 (170)</td>
<td>400</td>
<td>27</td>
</tr>
<tr>
<td>stored energy/beam [GJ]</td>
<td>8.4</td>
<td>6.6</td>
<td>0.36</td>
<td>0.7</td>
</tr>
<tr>
<td>synchrotron radiation [W/m/aperture]</td>
<td>30</td>
<td>58</td>
<td>0.2</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Full parameter list: FCC-ACC-SPC-0001

M Benedikt, F Zimmermann et al., FCC studies

EMFCSC, Erice, June 2017  
P Jenni (Freiburg and CERN)  
LHC, Higgs and Beyond (ATLAS)
100 km layout for FCC-hh

- two high-luminosity experiments (A and G)
- two other experiments (F and H) grouped with main experiment in G
- two collimation lines
- two injection and two extraction lines

orthogonal functions for insertion sections

M Benedikt, F Zimmermann et al., FCC studies
CepC/SppC study (CAS-IHEP) 54 km (baseline)  
e$^+e^-$ collisions ~2028; \( pp \) collisions ~2042  

Qinhuangdao (秦皇岛)  
easy access  
300 km east  
from Beijing  
3 h by car  
1 h by train  

Yifang Wang

“Chinese Toscana”
Compact Linear Collider (CLIC)

Linear $e^+e^-$ collider with $\sqrt{s}$ up to 3 TeV

100 MV/m accelerating gradient needed for compact (~50 km) machine → based on normal-conducting accelerating structures and a two-beam acceleration scheme

Conceptual Design Report completed end 2012
International Collaboration: ~80 Institutions

Challenges:
- Minimise RF breakdown rate in cavities
- Efficient RF power transfer from drive beam to main beam
- Reduction of power consumption (600 MW at 3 TeV)
- Nm size beams, final focus
- Huge beamstrahlung in detectors
Most recent operating scenario: start at $\sqrt{s}=380$ GeV for H and top physics

- Direct discovery potential and precise measurements of new particles (couplings to $Z/\gamma^*$) up to $m \sim 1.5$ TeV
- Indirect sensitivity to $E$ scales $\Lambda \sim O(100)$ TeV
- Measurements of “heavy” Higgs couplings: $t\bar{t}H$ to $\sim 4\%$, $HH \sim 10\%$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>380 GeV</th>
<th>3 TeV</th>
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</thead>
<tbody>
<tr>
<td>Centre-of-mass energy</td>
<td>TeV</td>
<td>0.38</td>
<td>3</td>
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<tr>
<td>Total luminosity</td>
<td>$10^{34}$cm$^{-2}$s$^{-1}$</td>
<td>1.5</td>
<td>5.9</td>
</tr>
<tr>
<td>Luminosity above 99% of $\sqrt{s}$</td>
<td>$10^{34}$cm$^{-2}$s$^{-1}$</td>
<td>0.9</td>
<td>2.0</td>
</tr>
<tr>
<td>Repetition frequency</td>
<td>Hz</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Number of bunches per train</td>
<td></td>
<td>352</td>
<td>312</td>
</tr>
<tr>
<td>Bunch separation</td>
<td>ns</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Acceleration gradient</td>
<td>MV/m</td>
<td>72</td>
<td>100</td>
</tr>
</tbody>
</table>

CTF3 facility:
- testing two-beam acceleration concept: efficient power transfer from high-intensity low-$E$ “drive” beam to the accelerating structure of the main (“probe”) beam.
- to be completed in 2016

CLIC construction could technically start ~2025, duration ~6 years for $\sqrt{s} \sim 380$ GeV (11 km Linac)
- physics could start by ~2035
It was a very long road from first dreams to the fantastic scientific instrument we have now with the LHC and its experiments, and many visionaries deserve credit for it…

Herwig Schopper, CERN DG 1981 - 1988

Carlo Rubbia, CERN DG 1989 - 1993
Giorgio Brianti, first LHC Project Leader, until 1993

Sir Chris Llewellyn Smith, CERN DG 1994 - 1998
Lorenzo Foa († 2014), Research Director 1994 - 1998
Lyn Evans, LHC Project Leader 1994 - 2008
Luciano Maiani, CERN DG 1999 - 2003
Roger Cashmore, Research Director 1999 – 2003

Robert Aymar, CERN DG 2004 - 2008
Jos Engelen, Research Director 2004 - 2008

Rolf Dieter Heuer, CERN DG 2009 - 2015
Sergio Bertolucci, Research Director 2009 - 2015
Steve Myers, Director of Accelerators and Technology 2009 – 2013
(here shown together with the ATLAS and CMS Spokespersons Fabiola Gianotti and Joe Incandela, on the famous 4th July 2012)
Further reading:

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