The plan:

Short history of the LHC
The experiments
Comments on performance of the LHC
Comments on computing
The physics landscape
Some physics results
  Standard Model
  Higgs
  Beyond the SM searches
Outlook

(Note that I will use often examples from ATLAS, but the same applies for CMS!)

Drawing by Sergio Cittolin

Roadmap at the LHC
to the Higgs Boson and Beyond

Ettore Majorana International School of Subnuclear Physics
EMFCSC, Erice, 25/26 June 2013

Peter Jenni, Freiburg and CERN
The Large Hadron Collider project is a global scientific adventure, combining the accelerator, a worldwide computing grid and the experiments, initiated almost 30 years ago.

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

LHC roadmap to the Higgs

Particle Data Group, LBNL © 2000. Supported by DOE and NSF
The SM is not a complete theory

Some of the outstanding questions in fundamental physics addressed, at least in part, with the LHC are:

- What is the origin of the elementary particle masses?
- What is the nature of the Universe dark matter?
- Why is only matter observed in the Universe as primary constituents and not anti-matter?
- What are the features of the primordial plasma present \( \sim 10 \mu s \) after the Big Bang?
- What happened in the first moments of the Universe \( \sim 10^{-11} \) s after the Big Bang?
- Are there other forces in addition to the known four?
- Are there additional (microscopic) space dimensions?
- Are there other forces in addition to the known four?

New Physics beyond the Standard Model is needed to answer these and other questions. The huge amount of precise experimental data collected so far indicate that this New Physics could manifest itself at the \( \sim \) TeV energy scale being explored by the LHC.
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

A very early $Z \rightarrow ee$ online display from one of the detectors (UA2)
ATLAS and CMS were born with Letters of Intent (LoI), submitted on 1st October 1992, more than 20 years ago.

Spokesperson Fabiola Gianotti, celebrating 20 years of ATLAS on 1st 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:

Staged construction was proposed by DG Chris Llewellyn Smith, 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, 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)

1997

*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 Large Hadron Collider is a 27 km long collider ring housed in a tunnel about 100 m underground near Geneva.
The first cyclotron, and the famous 184” one of Berkeley

The first circular accelerator (Berkeley 1930)
The most challenging components were the 1232 high-tech superconducting dipole magnets

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic field</td>
<td>8.4 T</td>
</tr>
<tr>
<td>Operation temperature</td>
<td>1.9 K</td>
</tr>
<tr>
<td>(120 tons of superfluid Helium)</td>
<td></td>
</tr>
<tr>
<td>Dipole current</td>
<td>11700 A</td>
</tr>
<tr>
<td>Stored energy</td>
<td>7 MJ</td>
</tr>
<tr>
<td>Dipole weight</td>
<td>34 tons</td>
</tr>
<tr>
<td>7600 km of Nb-Ti superconducting cable</td>
<td></td>
</tr>
</tbody>
</table>

\[ p(\text{TeV}) = 0.3 \frac{B(T)}{R(\text{km})} \]
LHC Accelerator Challenge: Dipole Magnets

Coldest Ring in the Universe?
1.9 K (CMBR is about 2.7 K)
LHC magnets are cooled with pressurized superfluid helium

Magnetic Field for Dipoles
\[ p \, (\text{TeV}) = 0.3 \, B(\text{T}) \, R(\text{km}) \]

For \( p = 7 \, \text{TeV} \) and \( R = 4.3 \, \text{km} \)
\[ \Rightarrow B = 8.4 \, \text{T} \]
\[ \Rightarrow \text{Current} \ 12 \, \text{kA} \]
Dipole magnetic flux plot

EMFCSC, Erice, 25/26.6.13
P Jenni (Freiburg/CERN)
Descent of the last dipole magnet, 26 April 2007

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

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P Jenni (Freiburg/CERN)

LHC roadmap to the Higgs
The LHC is the largest cryogenic system on earth, cooler than outer space

Magnets cooled down in a bath of ~120 tons of superfluid Helium (excellent thermal conductor)

One sector: 3.3 km, 154 dipoles

- 105 years ago, on 10 July 1908: Heike K Onnes first liquefied Helium (60 ml in 1 hour) in Leiden
- LHC today: 32000 He liters liquefied per hour by eight big cryogenic plants (the largest refrigerator in the world)
The particle beams are accelerated by superconducting Radio-Frequency (RF) cavities

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

<table>
<thead>
<tr>
<th></th>
<th>LHC at 7 TeV</th>
<th>LEP at 100 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synchrotron radiation loss</td>
<td>6.7 keV/turn</td>
<td>3 GeV/turn</td>
</tr>
<tr>
<td>Peak accelerating voltage</td>
<td>16 MV/beam</td>
<td>3600 MV/beam</td>
</tr>
</tbody>
</table>
Special quadrupole magnets (‘Inner Triplets’) are focussing the particle beams to reach highest densities (‘luminosity’) at their interaction point in the centre of the experiments.
CERN’s particle accelerator chain

LHC roadmap to the Higgs
Collisions at LHC

Event rate:

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

Mostly soft (low \( p_T \)) events

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

\[ \text{Proton-Proton} \]
\[ \text{Protons/bunch} \quad 10^{11} \]
\[ \text{Beam energy} \quad 7 \text{ TeV (7x10^{12} eV)} \]
\[ \text{Luminosity} \quad 10^{34} \text{ cm}^2 \text{ s}^{-1} \]

Selection of 1 in 10,000,000,000,000

⇒ very powerful detectors needed

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The SM is not a complete theory

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What happened in the first moments of the Universe \( \approx 10^{-11} \, s \) after the Big Bang?

Are there other forces in addition to the known four? Are there additional (microscopic) space dimensions? ....
General purpose detectors
Specialized detectors
The LHC World of CERN

Plus smaller local earldoms
LHCf (point-1)
TOTEM (point-5)
Moedal (point-8)

CMS
3000 Physicists
184 Institutions
38 countries
550 MCHF

ALICE
1300 Physicists
130 Institutions
35 countries
160 MCHF

LHCb
730 Physicists
54 Institutions
15 (countries
75 MCHF

ATLAS
3000 Physicists
176 Institutions
38 countries
550 MCHF

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P Jenni (Freiburg/CERN)
The LHCb detector installed at Point-8
ALICE (January 2008)
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P Jenni (Freiburg/CERN)
Exploded View of CMS

Total weight: 12500 t
Overall diameter: 15 m
Overall length: 21.6 m
Magnetic field: 4 Tesla

http://cms.cern.ch

LHC roadmap to the Higgs
An Example of an Engineering Challenge: CMS Solenoid

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

Tested at full current in Summer 2006
The central, heaviest slice (2000 tons) including the solenoid magnet lowered in the underground cavern in Feb. 2007
CMS before closure 2008
ATLAS Collaboration

38 Countries
176 Institutions
3000 Scientific participants total
(1000 Students)

Age distribution of the ATLAS population

### Age Distribution

- **All**: 2690
  - (< 35 y: 47.2%)
- **Male**: 81.8%
  - (< 35 y: 44.0%)
- **Female**: 18.2%
  - (< 35 y: 61.3%)

*(Status 1.1.2010)*
**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

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LHC roadmap to the Higgs
**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

- 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%

1 barrel module:
\[ \Delta\eta \times \Delta\phi = 1.4 \times 0.4 \approx 3000 \text{ channels} \]

**Absorber thickness (mm)**

![Graph showing absorber thickness distribution with peak at 2.2 mm and σ ≈ 9 μm](image)

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**P Jenni (Freiburg/CERN)**

**LHC roadmap to the Higgs**
The Underground Cavern at Point-1 for the ATLAS Detector

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

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LHC roadmap to the Higgs
Hector Berlioz, “Les Troyens”, opera in five acts
Valencia, Palau de les Arts Reina Sofia, 31 October -12 November 2009
A historical moment: Closure of the LHC beam pipe ring on 16th June 2008
## Complementary Approaches in ATLAS and CMS

<table>
<thead>
<tr>
<th></th>
<th>ATLAS ≡ A Toroidal LHC ApparatuS</th>
<th>CMS ≡ Compact Muon Solenoid</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MAGNET (S)</strong></td>
<td>Air-core toroids + solenoid in inner cavity (4 magnets) Calorimeters in field-free region</td>
<td>Solenoid Only 1 magnet Calorimeters inside field</td>
</tr>
<tr>
<td><strong>TRACKER</strong></td>
<td>Si pixels+ strips TRT → particle identification B=2T $\sigma/p_T \sim 3.8 \times 10^{-4} p_T \oplus 0.015$</td>
<td>Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5 \times 10^{-4} p_T \oplus 0.005$</td>
</tr>
<tr>
<td><strong>EM CALO</strong></td>
<td>Pb-liquid argon $\sigma/E \sim 10%/\sqrt{E}$ uniform longitudinal segmentation</td>
<td>PbWO$_4$ crystals $\sigma/E \sim 2-5%/\sqrt{E}$ no longitudinal segm.</td>
</tr>
<tr>
<td><strong>HAD CALO</strong></td>
<td>Fe-scint. + Cu-liquid argon (10 l) $\sigma/E \sim 50%/\sqrt{E} \oplus 0.03$</td>
<td>Cu-scint. (&gt; 5.8 l +catcher) $\sigma/E \sim 100%/\sqrt{E} \oplus 0.05$</td>
</tr>
<tr>
<td><strong>MUON</strong></td>
<td>Air $\rightarrow \sigma/p_T \sim 10%$ at 1 TeV standalone ($\sim 7%$ combined with tracker)</td>
<td>Fe $\rightarrow \sigma/p_T \sim 15-30%$ at 1 TeV standalone (5% with tracker)</td>
</tr>
</tbody>
</table>
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.
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 → 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

The figure shows a scatter plot of the muon \( \phi \) coordinate measured in the Inner Detector (ID) against the muon \( \phi \) coordinate measured in the Muon Spectrometer (MS). The plot includes data from 2008 cosmic runs.

The 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) is shown in the graph. The graph also compares the data with the Monte Carlo (MC) predictions.

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P Jenni (Freiburg/CERN)
The joy in the ATLAS Control Room when the first LHC beam collided on November 23\textsuperscript{rd}, 2009....
First collisions at the LHC end of November 2009 with beams at the injection energy of 450 GeV
The LHC and experiments performances were simply fantastic over the last three years.

\[ N_{\text{events}} = \sigma \int L \, dt \]

The experiment records typically 94% of the stably delivered luminosity, and uses up to 90% of the LHC luminosity in the final analyses!
Current LHC Operation:

1380 bunches per beam
50 ns bunch spacing
1.5 x 10^{11} protons / bunch
Excellent LHC performance is a (nice) challenge for the experiment:

- Trigger
- Pile-up
- Maintain accuracy of the measurements in this environment
The prize to pay for the high luminosity: pile-up (number of simultaneous pp interactions per bunch crossing)

Experiment’s design value (expected to be reached at $L=10^{34}$!)

ATLAS Online Luminosity

**2010:** ~ 2 evts/x-ing

**2011:** ~ 10 evts/x-ing

**2012:** ~ 20 evts/x-ing

LHC roadmap to the Higgs
Example for the typical trigger rates

- L1: ~ 65 kHz
- L2: ~ 5 kHz
- EF: ~ 600 Hz

Level-1 underground with purpose-made electronics and processors.
Level-2 and Event Filter in a large computer farm located at the surface of Point-1.
(Noted in the plot are the output rates)

- Typical recorded rates for main streams e/γ, Jets/τ/E_{T}^{miss}, Muons: ~ 100 Hz each
- Delayed stream (future Tier0 reconstruction): B-physics (~65 Hz) and Hadronic (~80 Hz)
- Note: currently 564 items in the trigger menu

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P Jenni (Freiburg/CERN) LHC roadmap to the Higgs
LHC (and ALICE, ATLAS and CMS) has also been operated very successfully as Pb-Pb and as p-Pb colliders.
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
wLCG Grid Operation

The high quality of the WLCG computing system allows LHC experiments to show results from data taken just few weeks before.
Computing Grid Delivers Physics

Data preparation:
First-pass reconstruction at Tier-0 within ~2 days
Calibration good for physics analysis on Grid within ~1 week

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P Jenni (Freiburg/CERN)

LHC roadmap to the Higgs
<table>
<thead>
<tr>
<th>Subdetector</th>
<th>Number of Channels</th>
<th>Approximate Operational Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixels</td>
<td>80 M</td>
<td>95%</td>
</tr>
<tr>
<td>SCT Silicon Strip</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRT Transition</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LAr EM Calorimeter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tile calorimeter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hadronic endcap</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forward LAr calor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LVL1 Calo trigger</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LVL1 Muon RP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LVL1 Muon TG</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MDT Muon Drift tube</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CSC Cathode strip</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RPC Barrel Muon</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TGC Endcap Muon</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**CMS Operational Status**

* As of April 15th 2012

- Pixels: 97.1%
- Strips: 97.75%
- Presh. 97.1%
- ECAL Bar. 99.2%
- ECAL Endcaps: 98.54%
- HCAL bar. 99.9%
- HCAL Endcaps: 99.96%
- HCAL Forw: 99.9%
- HCAL Outer: 96.9%
- m DT: 99.1%
- Muon CSC: 97.7%
- Muon RPC: 98.2%
Physics Highlights

ATLAS and CMS have already published together more than 500 papers in scientific journals (and many more as public conference notes…)

The other experiments, ALICE, LHCb, LHCf, and TOTEM total another 200 journal publications together

It is clearly not possible to cover all these results…

No attempt is made to show in a democratic way, for example, CMS and ATLAS results, but examples are given that are meant to represent the others as well where applicable...

Note that all public results are available from the experiments Web pages, and from the CERN Document Server

Physics Highlights:

General event properties

Heavy flavour physics

Standard Model physics including QCD jets

Higgs searches

Searches for SUSY

Searches for ‘exotic’ new physics
Total cross-section measurement by TOTEM

Example: Roman Pots at 147 m from interaction point
Total cross-section measurement by TOTEM

Presented at HCP2012

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Feedback to modeling of Ultra High Energy Cosmic Rays (UHERCs)

LHCf 7 TeV $\pi^0$ signal

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P Jenni (Freiburg/CERN)
Charged hadron multiplicities at the three different $\sqrt{s}$

Average charged particle density for the central $\eta$ region (pp and pp)

**Charged hadron multiplicities at the three different $\sqrt{s}$**

**Average charged particle density for the central $\eta$ region (pp and pp)**

---

**EMFCSC, Erice, 25/26.6.13**

P Jenni (Freiburg/CERN) LHC roadmap to the Higgs
The tracking detector simulations are in a mature state, charged track measurements are well understood.

Example shows the ATLAS description of minimum bias tracks (silicon and pixel hits, transverse impact parameter)

Charged-particle multiplicities as a function of pseudorapidity $\eta$ and transverse momentum $p_T$ for minimum bias events selected as specified, and compared to various Monte Carlo models.

\[ n_{\text{ch}} \geq 2, \ p_T > 100 \text{ MeV}, \ |\eta| < 2.5 \]

ATLAS $\sqrt{s} = 7 \text{ TeV}$


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LHC roadmap to the Higgs
Strange particle production spectra

Example $\Xi^- \rightarrow \Lambda\pi^-$
2010 Data corresponding to ~40 pb⁻¹ collected → re-discovery of the Standard Model

The di-muon spectrum recalls a long period of particle physics: Well known quark-antiquark resonances (bound states) appear “online”
2010 Data corresponding to ~40 pb⁻¹ collected

The di-muon spectrum recalls a long period of particle physics: Well known quark-antiquark resonances (bound states) appear “online”
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 …
A considerable effort went into understanding the Jet Energy Scale (JES), the dominant source of uncertainties for most jet measurements.

Very detailed jet measurements are now available from LHC that can be compared with QCD calculations ...

Example: The inclusive jet cross sections as a function of the jet $p_T$ in rapidity bins
Very detailed jet measurements are now available from LHC that can be compared with QCD calculations …

Example: The inclusive jet cross sections as a function of the jet $p_T$ in rapidity bins.
Cross-section ratios of multi-jets allow one to determine $\alpha_s$

\[ R_{3/2}(p_T^{lead}) = \frac{d\sigma_{N_{jet} \geq 3}/dp_T^{lead}}{d\sigma_{N_{jet} \geq 2}/dp_T^{lead}} \]

$p_T > 40$ GeV and $|y| < 2.8$.

$\alpha_s(M_Z) = 0.111 \pm 0.006\text{(exp.)}^{+0.016}_{-0.003}\text{(theory)}$. 

\[ \alpha_s(Q) \]

ATLAS Preliminary

\[ \text{ATLAS 2010 } N_{3/2} \]

DØ inclusive jet

DØ $R_A^R$

H1 inclusive jet

ZEUS inclusive jet

PDG 2012 world average

$\alpha_s(M_Z) = 0.1184 \pm 0.0007$
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  - Standard Model
  - Higgs
  - Beyond the SM searches
- Outlook

(Note that I will use often examples from ATLAS, but the ~same applies for CMS!)

Drawing by Sergio Cittolin

Ettore Majorana International School of Subnuclear Physics
EMFCSC, Erice, 25/26 June 2013

Peter Jenni, Freiburg and CERN
Standard Model Physics

Candidate $Z \to \mu^+\mu^-$

$W \to e\nu$ candidate

Today each ATLAS and CMS have in their data more than:

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

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

after all selection cuts
Z and W production

**CMS preliminary**

36 pb\(^{-1}\) at \(\sqrt{s} = 7\) TeV

\[
\int L \, dt = 33\ \text{pb}^{-1}
\]

**ATLAS**

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

**Z peak (di-lepton pair mass distributions, can be extracted essentially background-free)**

Meeting of neutrino physicists

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P Jenni (Freiburg/CERN)
**W transverse mass**

$\mu$ with $p_T > 20$ GeV, $E_T^{miss} > 25$ GeV

*Missing transverse energy from the $W \rightarrow \mu + \nu$ decays*

$\int \mathcal{L} \, dt = 35 \, \text{pb}^{-1}$

**ATLAS-CONF-2011-041**

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LHC roadmap to the Higgs
What a contrast to the Intermediate Vector Boson discovery distributions in 1982 and 1983 by UA1 and UA2 …

30 years ago!

(first events 1982/3)

(here are shown the UA2 distributions)
**W cross section measurement with e and μ**

\[ \sigma_W \times Br(W \rightarrow l\nu) \ [nb] \]

ATLAS / CMS \( W \rightarrow l\nu \)
- \( W (p\bar{p}) \)
- \( W^+ (p\bar{p}) \)
- \( W^- (p\bar{p}) \)

CDF \( W \rightarrow (l/e)\nu \)

D0 \( W \rightarrow (e/\mu)\nu \)

UA1 \( W \rightarrow l\nu \)

UA2 \( W \rightarrow e\nu \)

Phenix \( W^z \rightarrow (e^+/e^-)\nu \)

MSTW2008 NNLO

68% CL PDF uncertainty

Data 2010 (\( \sqrt{s} = 7 \) TeV)

\( \sqrt{s} [\text{TeV}] \)


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P Jenni (Freiburg/CERN)

LHC roadmap to the Higgs
Cross section measurements

Theory: NNLO, FEWZ and MSTW08 PDFs

CMS-PAS-SMP-12-011

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P Jenni (Freiburg/CERN)
Two examples of confronting the 2010 data with SM theory
**W + jet(s) production**

Both an interesting QCD measurement as well as a dominant background to many searches.

---

**Graphs: W → lν + jets**

- Data 2010, √s = 7 TeV
- ALPGEN
- SHERPA
- BLACKHAT-SHERPA

**ATLAS**

- $W + \geq 1 \text{ jets}$
- $W + \geq 2 \text{ jets}$, $\times 10^{-1}$
- $W + \geq 3 \text{ jets}$, $\times 10^{-2}$
- $W + \geq 4 \text{ jets}$, $\times 10^{-3}$

**Theory/Data**

- $p_T^{\text{jet}} > 30 \text{ GeV, } |y| < 4.4$

**First Jet $p_T \text{ [GeV]}$**

---


EMFCSC, Erice, 25/26.6.13

P Jenni (Freiburg/CERN)
$W + b$-jet(s) production
Example: W and Z as a ‘tool’ to assure the performance of the detector

- vs time over the full 2011 run
- vs pile-up in 2012

Stability of EM calorimeter E-scale: better than 0.1%
$p_T(\mu) = 18 \text{ GeV}$

$p_{\text{vis}}(\tau_h) = 26 \text{ GeV}$

$m_{\text{vis}}(\mu, \tau_h) = 47 \text{ GeV}$

$m_T(\mu, E_T^{\text{miss}}) = 8 \text{ GeV}$

$E_T^{\text{miss}} = 7 \text{ GeV}$

$Z \rightarrow \tau\tau$

Candidate in 7 TeV Collisions
$W \to \tau \nu$ signal
Top measurements

• Complete set of ingredients to investigate production of ttbar, which is the next step in verifying the SM at the LHC:
  • e, μ, $E_T^{miss}$, jets, b-tag

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

• Data-driven methods to control QCD and W+jets backgrounds

P Jenni (Freiburg/CERN) LHC roadmap to the Higgs
\textbf{tt candidate event} \hspace{1cm} e + \mu + 2 \text{ jets (b-tagged)} + \text{ETmiss}
Example of top signals in the case of di-lepton channels

\[
\int L \, dt = 0.70 \text{ fb}^{-1}
\]

ATLAS b-tag

All channels

- Data
- $t\bar{t}$
- $Z/\gamma^* + \text{jets}$
- Fake leptons
- Other EW
- Uncertainty

number of b-tagged jets

entries

CMS 2.3 fb$^{-1}$ at $\sqrt{s} = 7$ TeV

ee, $\mu\mu, e\mu$

- Data
- DY
- $tW$
- $VV$
- non-prompt lepton
- $t\bar{t}$ signal

JHEP 1205 (2012) 059

EMFCSC, Erice, 25/26.6.13
P Jenni (Freiburg/CERN)
Example of top signals in the case of lepton-jet channels
tt pair production cross-sections

**ATLAS Preliminary**

- NLO QCD (pp)
- Approx. NNLO (µµ)
- Approx. NNLO (p̅p)
- CDF
- D0

- Single Lepton (8 TeV) 241 ± 32 pb
- Single Lepton (7 TeV) 179 ± 12 pb
- Dilepton 173 ± 14 pb
- All-hadronic 167 ± 81 pb
- Combined 177 ± 11 pb

CMS Preliminary

- CMS combined 7 TeV (1.1 fb⁻¹)
- CMS combined 8 TeV (2.8 fb⁻¹)

LHC roadmap to the Higgs

ATLAS-CONF-2012-149
CMS-PAS-TOP-12-006, 007
Example of top mass measurement: templates in the lepton-jet final state channel

Mass is determined from a likelihood fit taking into account all measured kinematical variables.
EMFCSC, Erice, 25/26.6.13
P Jenni (Freiburg/CERN)

WZ → eνμμ Candidate
LHC roadmap to the Higgs
# Electroweak di-boson production

<table>
<thead>
<tr>
<th>Process</th>
<th>Final state</th>
<th>Measured total cross-section</th>
<th>Theory (NLO SM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW</td>
<td>$l_\nu l_\nu$</td>
<td>$\sigma_{WW}^{tot} = 53.4 \pm 2.1 \text{(stat)} \pm 4.5 \text{(syst)} \pm 2.1 \text{(lumi)} \text{ pb}$</td>
<td>$45.1 \pm 2.8 \text{ pb}$</td>
</tr>
<tr>
<td>ZZ</td>
<td>4l</td>
<td>$\sigma_{ZZ} = 7.2^{+1.1}_{-0.9} \text{ (stat)} \pm 0.4 \text{ (syst)} \pm 0.3 \text{ (lumi)} \text{ pb}$</td>
<td>$6.5^{+0.3}_{-0.2} \text{ pb}$</td>
</tr>
<tr>
<td>ZZ</td>
<td>$l_l l_l$</td>
<td>$\sigma_{ZZ}^{tot} = 5.4^{+1.3}<em>{-1.2} \text{ (stat.)}^{+1.4}</em>{-1.0} \text{ (syst.)} \pm 0.2 \text{ (lumi.) \text{ pb}}$</td>
<td>$6.5^{+0.3}_{-0.2} \text{ pb}$</td>
</tr>
</tbody>
</table>

**Backgrounds to Higgs searches**

- Give access to triple gauge couplings
- And New Physics

ATLAS-CONF-2012-025, 26, and 27

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EMFCSC, Erice, 25/26.6.13
P Jenni (Freiburg/CERN)

LHC roadmap to the Higgs
A summary of Standard Model measurements

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

LHC roadmap to the Higgs

P Jenni (Freiburg/CERN)
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 cosmonics 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,...)

Prepare the road to discoveries ...
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
Search for the boson (H) of the EW symmetry breaking

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

EMFCSC, Erice, 25/26.6.13
P Jenni (Freiburg/CERN)

LHC roadmap to the Higgs
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)
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.
Very happy faces after the announcement of the discovery on 4\textsuperscript{th} July 2012
- Small cross-section: $\sigma \sim 40$ fb
- Expected S/B $\sim 0.02$
- Simple final state: two high-$p_T$ isolated photons
- Main background: $\gamma\gamma$ continuum (irreducible) and fake $\gamma$ from $\gamma j$ and $jj$ events (reducible)
Rare process, small cross section: $\sigma \sim 2-5$ fb

However: pure: $S/B \sim 1$

4 leptons:

Main background: ZZ(*) (irreducible)
In addition: Zbb, Z+jets, tt with two leptons from b-quarks or jets

ATLAS Preliminary

$H \rightarrow ZZ^{(*)} \rightarrow 4l$

CMS preliminary

$H \rightarrow ZZ^{(*)} \rightarrow 4l$

$\sqrt{s} = 7$ TeV: $\int L dt = 4.6$ fb$^{-1}$

$\sqrt{s} = 8$ TeV: $\int L dt = 20.7$ fb$^{-1}$

ATLAS-CONF-2013-013

CMS-PAS-HIG-13-002

EMFCSC, Erice, 25/26.6.13
P Jenni (Freiburg/CERN)

LHC roadmap to the Higgs

107
\( H \rightarrow WW(\ast) \rightarrow l\nu\bar{l}\nu (e\nu\nu, \mu\nu\nu, e\mu\nu) \)

- Very sensitive channel over \( \sim 125\text{--}180\text{ GeV} \) (\( \sigma \sim 200\text{ fb} \))
- Challenging: \( 2\nu \rightarrow \) no mass reconstruction/peak \( \rightarrow \) “counting channel”
- 2 isolated opposite-sign leptons, use \( e\mu\nu \) only for 2012 data, large \( E_T^{\text{miss}} \)
- Main backgrounds: WW, top, Z+jets, W+jets
- Topological cuts against “irreducible” WW background

(Just an example distributions from several categories used in both experiments)

\( \bar{s} = 8\text{ TeV}, \int Ldt = 20.7\text{ fb}^{-1} \)
\( H\rightarrow WW \rightarrow e\nu\mu\nu/\mu e\nu + 0/1 \) jets

To get a feeling for the number of events, this is for all categories the summed, background-subtracted distributions

\[ m_T = \sqrt{(E_T^{\text{eff}} + E_T^{\text{miss}})^2 - (P_T^{\text{eff}} + P_T^{\text{miss}})^2} \]

EMFCSC, Erice, 25/26.6.13
P Jenni (Freiburg/CERN)

LHC roadmap to the Higgs
How significant is the signal for the new particle?

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

Mass = 125.5 ± 0.2 (stat) ± 0.6 (syst) GeV [ATLAS]
125.7 ± 0.3 (stat) ± 0.3 (syst) GeV [CMS]

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

\[ \mu = 1.30 \pm 0.20 \] [ATLAS]
\[ \mu = 0.80 \pm 0.14 \] [CMS]
How significant is the signal for the new particle?

Mass measurements in the two high-resolution channels from CMS:

- **ATLAS**
  \[ m = 125.5 \pm 0.2 \text{ (stat)} \pm 0.6 \text{ (syst)} \text{ GeV} \]

- **CMS**
  \[ m = 125.7 \pm 0.3 \text{ (stat)} \pm 0.3 \text{ (syst)} \text{ GeV} \]

**Signal strength**

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

\[ \mu = 1.30 \pm 0.20 \text{ [ATLAS]} \]
\[ \mu = 0.80 \pm 0.14 \text{ [CMS]} \]

EMFCSC, Erice, 25/26.6.13
P Jenni (Freiburg/CERN)
Detailed studies of the production and decay properties have started in order to characterize the new particle.

It will be important to understand with great precision if it is the only scalar boson of the Standard Model ‘Brout-Englert-Higgs’ mechanism to break the electroweak symmetry, or if it is only part of a broader physics picture going Beyond the Standard Model.

These studies will be among the most central ones in the decades to come both at the LHC and at possible other future colliders.

For the experts:

Couplings
Production modes
Spin-parity

all support at the 2-3 $\sigma$ level the SM Higgs with present limited statistics.

ATLAS-CONF-2013-034

LHC roadmap to the Higgs

CMS-PAS-HIG-13-005
New particles in the $gg \rightarrow H$ and $H \rightarrow \gamma\gamma$ loops?

$\rightarrow$ New particle couples to other particles with strength proportional to their masses (to accomplish its job $\rightarrow$ Higgs mechanism) $\rightarrow$ 1st “fingerprint” of the Higgs boson
$\rightarrow$ No significant New Physics contributions to its couplings (within present uncertainty)
Outlook for HL-LHC on the Higgs physics (I)

ATLAS NOTE
ATL-PHYS-PUB-2012-004

October 15, 2012
EMFCSC, Erice, 25/26.6.13
P Jenni (Freiburg/CERN)

LHC roadmap to the Higgs
Outlook for HL-LHC on the Higgs physics (II)

**ATLAS NOTE**

**ATL-PHYS-PUB-2012-004**

October 15, 2012

EMFCSC, Erice, 25/26.6.13

P Jenni (Freiburg/CERN)

LHC roadmap to the Higgs
Birth and evolution of a signal: $H \rightarrow 4l$

$\sqrt{s} = 7$ TeV $\int L dt = 0.05$ fb$^{-1}$  Apr 24, 2011

**ATLAS** Preliminary

H$\rightarrow$ZZ$^{(*)} \rightarrow 4l$ channel

- **Signal** ($m_H = 125$ GeV)
- **Background** ZZ$^{(*)}$
- **Background** Z+jets, t$\bar{t}$
- **Data**

EMFCSC, Erice, 26/26.6.13
P Jenni (Freiburg/CERN)
Searches Beyond the Standard Model
(only very few examples out of many…)

EMFCSC, Erice, 25/26.6.13
P Jenni (Freiburg/CERN)

LHC roadmap to the Higgs

N C Flammarion 1888
(colours added later)
Dark Matter in the Universe

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

Vera Rubin ~ 1970

'Supersymmetric' particles?

M. F. Sc, Erice, 25/26.6.13

Jenni (Freiburg/CERN) LHC roadmap to the Higgs

F. Zwicky 1898-1974

<table>
<thead>
<tr>
<th>Atoms</th>
<th>4.6%</th>
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<tbody>
<tr>
<td>Dark Energy</td>
<td>72%</td>
</tr>
<tr>
<td>Dark Matter</td>
<td>23%</td>
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</table>
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 $\tilde{p}$ with spin $s - 1/2$

- Examples $q$ (s=1/2) $\rightarrow$ $\tilde{q}$ (s=0) squark
  $g$ (s=1) $\rightarrow$ $\tilde{g}$ (s=1/2) gluino

**Motivation:**

- Unification (fermions-bosons, matter-forces)
- Solves some deep problems of the Standard Model
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

\[ Meff = E_{\text{miss}} + \Sigma pT(\text{jets}) \]
An example from the 2011 data, to show the principle, final results will be quoted for updated analyses including 2012 data

- 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: 0-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 1\textsuperscript{st} and 2\textsuperscript{nd} generation, gluino and light neutralinos.

\[ \int L \, dt = 20.3 \text{ fb}^{-1}, \, \sqrt{s}=8 \text{ TeV} \]

0-lepton combined

\textbf{ATLAS Preliminary}

- \( m(\tilde{\chi}_1^0) = 0 \text{ GeV Observed limit} \) (\( \pm 1 \sigma_{\text{SUSY theory}} \))
- \( m(\tilde{\chi}_1^0) = 0 \text{ GeV Expected limit} \) (\( \pm 1 \sigma_{\text{exp}} \))
- \( m(\tilde{\chi}_1^0) = 395 \text{ GeV Observed limit} \)
- \( m(\tilde{\chi}_1^0) = 395 \text{ GeV Expected limit} \)
- \( m(\tilde{\chi}_1^0) = 695 \text{ GeV Observed limit} \)
- \( m(\tilde{\chi}_1^0) = 695 \text{ GeV Expected limit} \)

7 TeV (4.7 fb\(^{-1}\)) \( m(\tilde{\chi}_1^0) = 0 \text{ GeV Observed} \)

ATLAS-CONF-2013-047
Expected production cross-sections at LHC

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

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

EW production

Strong production

3rd generation

Prospino2, T. Plehn et al.
**ATLAS SUSY Searches** - 95% CL Lower Limits

**Status:** LHCP 2013

**ATLAS** Preliminary

---

**SUSY limits**

\[
\int L_{\text{eff}} = (4.4 - 20.7) \text{fb}^{-1}, \quad \sqrt{s} = 7, 8 \text{ TeV}
\]

**Model**

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<tr>
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**Inclusive searches**

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**3rd gen. G. med.**

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**EV direct**

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**Long-lived parables**

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**RPP**

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**Charged Higgs**

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**Other**

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<th>Emiss T</th>
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**Mass scale [TeV]**

<table>
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<th>Model</th>
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<th>L_{\text{tot}}</th>
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<td>0</td>
<td>ATLAS-CONF-2013-073</td>
<td></td>
</tr>
</tbody>
</table>

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*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.*

---

**Very similar limits come from CMS**
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**
The highest mass di-lepton events from ATLAS

\[ m (e^+e^-) = 1.54 \text{ TeV} \]

\[ m (\mu^+\mu^-) = 1.84 \text{ TeV} \]
Lower mass limits, at 95% CL, for spin-2 Randall-Sundrum Gravitons

\[ \sigma B [pb] \]

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

\[ G^* \rightarrow II \]

---

ATLAS Preliminary

- Expected limit
- Expected ± 1σ
- Expected ± 2σ
- Observed limit

- \( k/M_{Pl} = 0.1 \)
- \( k/M_{Pl} = 0.05 \)
- \( k/M_{Pl} = 0.03 \)
- \( k/M_{Pl} = 0.01 \)

---

ee, \( \mu \mu \): \( \int L dt = 20 \text{ fb}^{-1} \)

ATLAS-CONF-2013-017

R Sundrum
L Randall
F Gianotti

EMFCSC, Erice, 25/26.6.13
P Jenni (Freiburg/CERN)
New particles decaying into two photons

Example for a search of extra dimension signals (Kaluza-Klein Graviton in the Randall-Sundrum and Arkani-Hamed, Dimopoulos and Dvali models)

ATLAS

![Graph](image)

Example of searches for New Physics as deviations from QCD behaviour of hadronic jet distributions

Search for resonances in the di-jet mass spectrum
Example of searches for New Physics as deviations from QCD behaviour of hadronic jet distributions

Search for resonances in the di-jet mass spectrum

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

CMS Preliminary
\[ \sqrt{s} = 8 \, \text{TeV}, \, L = 19.6 \, \text{fb}^{-1} \]
\[ |\eta| < 2.5, \, |\Delta \eta| < 1.3 \]

ATLAS-CONF-2012-148

CMS-EXO-12-059

EMFCSC, Erice, 25/26.6.13
P Jenni (Freiburg/CERN)

LHC roadmap to the Higgs

129
If theories with Extra-dimensions are true, microscopic black holes could be abundantly produced and observed at the LHC.

Simulation of a black hole event with $M_{BH} \sim 8$ TeV in ATLAS.

They decay immediately through Stephen Hawking radiation.
If theories with Extra-dimensions are true, microscopic black holes could be abundantly produced and observed at the LHC.

A real ‘candidate’ event of a ‘black hole’ in CMS with 9 jets and ST = 2.6 TeV.

They decay immediately through Stephen Hawking radiation.
Search for Microscopic Black Hole production in models with large extra dimensions (Arkani-Hamed, Dimopoulos, Dvali)

Decay into many objects (jets, leptons, photons)

\[ \sum P_T : \text{scalar sum of the } E_T \text{ of the } N \text{ objects in the event} \]

**Examples:** (ATLAS) at least one electron or muon and two or more jets, (CMS) any three objects

No deviation is seen for events with at least 3 objects with > 50 GeV pT

Submitted to JHEP
arXiv:1303.5338v1[hep-ex]
Similar results exist from ATLAS

LHC roadmap to the Higgs

(TeV)

(TeV)
Similar beautiful results from ATLAS

Nov 2012

Production Cross Section, $\sigma_{\text{tot}}$ [pb]

Nov 2012

LHC roadmap to the Higgs

EMFCSC, Erice, 25/26.6.13
P Jenni (Freiburg/CERN)

©Ralph A. Clevenger/CORBIS

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LHC Schedule Assumptions

- **2009:** LHC start-up, $\sqrt{s} = 900$ GeV
- **2010:** $\sqrt{s} = 7$ TeV rising to 8 TeV, $\mathcal{L} = 6 \times 10^{33}$ cm$^{-2}$s$^{-1}$, bunch spacing 50 ns
- **2011:** Go to design energy and nominal luminosity
- **2012:** $\sqrt{s} = 13$-14 TeV, $\mathcal{L} = 1 \times 10^{34}$ cm$^{-2}$s$^{-1}$, bunch spacing 25 ns
- **2013:** Injector and LHC Phase-I upgrade to full design luminosity
- **2014:** $\sqrt{s} = 14$ TeV, $\mathcal{L} = 2-3 \times 10^{34}$ cm$^{-2}$s$^{-1}$, bunch spacing 25 ns
- **2015:** HL-LHC Phase-II upgrade, crab cavities, new IR, ...
- **2016:** $\sqrt{s} = 14$ TeV, $\mathcal{L} = 5 \times 10^{34}$ cm$^{-2}$s$^{-1}$ (luminosity levelling) 25 ns

- **2017:**
- **2018:**
- **2019:**
- **2020:**
- **2021:**
- **2022:**
- **2023:**
- **2024:**
- **2025:**
- **2026:**
- **2027:**
- **2028:**
- **2029:**
- **2030:**

- **2017-2020:**
- **2021-2024:**
- **2025-2028:**
- **2029-2030:**

- **2017:**
- **2018:**
- **2019:**
- **2020:**
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- **2022:**
- **2023:**
- **2024:**
- **2025:**
- **2026:**
- **2027:**
- **2028:**
- **2029:**
- **2030:**

- **2017:**
- **2018:**
- **2019:**
- **2020:**
- **2021:**
- **2022:**
- **2023:**
- **2024:**
- **2025:**
- **2026:**
- **2027:**
- **2028:**
- **2029:**
- **2030:**

- **2017:**
- **2018:**
- **2019:**
- **2020:**
- **2021:**
- **2022:**
- **2023:**
- **2024:**
- **2025:**
- **2026:**
- **2027:**
- **2028:**
- **2029:**
- **2030:**
LS1 - Accelerator complex

2013 | 2014 | 2015

2013: LHC, SPS, PS
2014: LHC, SPS, PS, PS Booster
2015: LHC, SPS, PS, PS Booster

- Physics
- Beam commissioning
- Shutdown
- Powering tests

LHC roadmap to the Higgs
Hadron colliders are the only realistic option to access very high-mass objects directly, and increasing the collision energy extends the mass reach most strongly.
Collider options for the high energy frontier

**pp colliders**

<table>
<thead>
<tr>
<th>Years</th>
<th>$E_{\text{cm}}$ (TeV)</th>
<th>Luminosity ($10^{34}$cm$^{-2}$s$^{-1}$)</th>
<th>Int. Luminosity (fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design LHC</td>
<td>2014-21</td>
<td>14</td>
<td>1-2</td>
</tr>
<tr>
<td>HL-LHC</td>
<td>2024-30</td>
<td>14</td>
<td>5</td>
</tr>
<tr>
<td>HE-LHC</td>
<td>&gt;2035</td>
<td>26-33*</td>
<td>2</td>
</tr>
<tr>
<td>V-LHC**</td>
<td>&gt;2035</td>
<td>42-100</td>
<td></td>
</tr>
</tbody>
</table>

Other options: $\mu^+\mu^-$ and $\gamma\gamma$ colliders with similar physics as $e^+e^-$ colliders

LHeC for ep collisions

See European Strategy Briefing Book for references
Lake-side option kept for further studies

Pre-Feasibility Study for an 80-km tunnel at CERN
- John Osborne and Caroline Waaijer

For a Very High Energy Hadron Collider ranging from 42 TeV (8.3T LHC magnets) to 100 TeV (20T very high field magnets with HTS), and could house first an $e^+e^-$ collider TLEP up to 350 GeV
Indicating the Scale for Liner Colliders

(Taken from C. Biscari, ‘High Energy Accelerators’, Krakow ES Symposium)
The journey into new physics territory has just only begun, and for sure, exciting times are ahead of us!

And don’t forget UEEC from Professor Zichichi’s talk!

Thank you for your attention
Further reading:

The Higgs Boson

ARTICLE

Journey in the Search for the Higgs Boson: The ATLAS and CMS Experiments at the Large Hadron Collider

M. Della Negra,1 P. Jenni,2 T. S. Virdée1*

The search for the standard model Higgs boson at the Large Hadron Collider (LHC) started more than two decades ago. Much innovation was required and diverse challenges had to be overcome during the conception and construction of the LHC and its experiments. The ATLAS and CMS Collaboration experiments at the LHC have discovered a heavy boson that could complete the standard model of particle physics.

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

Journey in the Search for the Higgs Boson: The ATLAS and CMS Experiments at the Large Hadron Collider
M. Della Negra et al.
Science 338, 1560 (2012);
DOI: 10.1126/science.1230827
Spares
The Standard Model of Particle Physics

(i) Constituents of matter: quarks and leptons

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

(iii) The Higgs field (problem of mass)
Physics Highlights:

General event properties

Heavy flavour physics

Standard Model physics including QCD jets

Higgs searches

Searches for SUSY

Searches for ‘exotic’ new physics

LHC roadmap to the Higgs
The first new particles ‘discovered’ at LHC, December 2011

\[ x_b(3P) \rightarrow Y(1s,2s) \gamma \]

\[ m[x_b(3P)] = 10.530 \pm 0.005 \text{ (stat)} \pm 0.009 \text{ (syst)} \text{ GeV} \]
Lepton charge asymmetry from $W$ decays in pp collisions at 7 TeV

$$A(\eta) = \frac{d\sigma/d\eta(W^+ \rightarrow \ell^+\nu) - d\sigma/d\eta(W^- \rightarrow \ell^-\bar{\nu})}{d\sigma/d\eta(W^+ \rightarrow \ell^+\nu) + d\sigma/d\eta(W^- \rightarrow \ell^-\bar{\nu})}.$$

ATLAS+CMS+LHCb

Preliminary

ATLAS (extrapolated data, $W \rightarrow l\nu$) 35 pb$^{-1}$
CMS ($W \rightarrow \mu\nu$) 36 pb$^{-1}$
LHCb ($W \rightarrow \mu\nu$) 36 pb$^{-1}$

MSTW08 prediction (MC@NLO, 90% C.L.)
CTEQ66 prediction (MC@NLO, 90% C.L.)
HERA1.0 prediction (MC@NLO, 90% C.L.)
Birth and evolution of a signal: $H \rightarrow \gamma \gamma$

- $\sqrt{s} = 7$ TeV
- $Ldt = 0.02$ fb$^{-1}$
- Apr 18, 2011

ATLAS Preliminary

H$\rightarrow\gamma\gamma$ channel
Two of the by now historical plots from the July 2012 discovery announcement

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
A dream becoming true much faster than anticipated long ago.

EMFCSC, Erice, 25/26.6.13
P Jenni (Freiburg/CERN)

LHC roadmap to the Higgs
**Signal strength**

μ = signal strength normalized to SM Higgs expectation at \( m_H = 125.5 \text{ GeV} \)

Best-fit value for \( m_H=125.5 \text{ GeV} \):

\[ \mu = 1.3 \pm 0.13 \text{ (stat)} \pm 0.14 \text{ (syst)} \]

→ in agreement with SM expectation

**Mass measurement**

Estimated mass from high-resolution \( H \rightarrow \gamma\gamma \) and \( H \rightarrow 4l \) channels:

- \( m_H \text{ (combined)} = 125.5 \text{ GeV} \pm 0.2 \text{ (stat)} \pm 0.5 \text{ (syst)} \text{ GeV} \)
- \( m_H \text{ (}\gamma\gamma\text{)} = 126.8 \text{ GeV} \pm 0.2 \text{ (stat)} \pm 0.7 \text{ (syst)} \text{ GeV} \)
- \( m_H \text{ (}\text{4l}\text{)} = 124.3 \text{ GeV} \pm 0.6 \text{ (stat)} \pm 0.5 \text{ (syst)} \text{ GeV} \)

Probability from same particle: 1.5-8%
First measurements of couplings (examples ..)

Measuring individual production modes (ggF, VBF, …)

New particles in the gg → H and H→ γγ loops?

Combined ratio VBF+VH/ggF+ttH over 4 channels → 3.3σ significance of VBF+VH from zero
### ATLAS Preliminary

<table>
<thead>
<tr>
<th>Parameter Value</th>
<th>$\pm 1\sigma$</th>
<th>$\pm 2\sigma$</th>
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<tbody>
<tr>
<td>$m_H = 125.5$ GeV</td>
<td>yellow</td>
<td>green</td>
</tr>
</tbody>
</table>

- $\sqrt{s} = 7$ TeV, $L_{ttt} = 4.6 \pm 4.8$ fb$^{-1}$
- $\sqrt{s} = 8$ TeV, $L_{ttt} = 13 - 20.7$ fb$^{-1}$

### Equations

- $k_\gamma = \frac{\Gamma_i}{\Gamma_{\Delta M}}$
Is this new particle the first elementary scalar? → Spin studies

Spin information from distribution of polar angle $\theta^*$ of the di-photon system in the Higgs rest frame

Compare $\theta^*$ distribution in the region of the peak for:
- spin-0 hypothesis: flat before cuts
- spin-2 hypothesis: $\sim 1 + 6\cos^2 \theta^* + \cos^4 \theta^*$ for Graviton-like (minimal models)

Fit to data disfavours $2^+$ hypothesis at 99.3% CL. (66% CL) for pure $gg \to G$ (mixture of $gg/qq \to G$) production (separation $0^+/2^+$ decreases with increasing qq contribution)
Spin-parity information from distribution of 5 production and decay angles combined in BDT or Matrix Element (MELA) discriminants

0+ vs 0- hypothesis

G-like spin-2 gg production

0- excluded at 99.6% C.L. when compared to 0+
Lower mass limits, at 95% CL, for various Z’ and W’ like objects
Search for direct Dark Matter (DM) particles in pair-production

A single photon (150 GeV) or jet plus ETmiss

ATLAS Preliminary

ATLAS CONF-2012-085
arXiv:1210.4491v1[hep-ex]

arXiv:1204.0821v1[hep-ex]
arXiv:1206.5663[hep-ex]

LHC roadmap to the Higgs

EMFCSC, Erice, 25/26.6.13
P Jenni (Freiburg/CERN)
$\tilde{g}-\tilde{g}$ production, $\tilde{g} \rightarrow t\tilde{t}\chi_1^0$, $\sqrt{s} = 8$ TeV

95% CL limits. $\sigma_{\text{SUSY}}^{\text{theory}}$ not included.

- 0-lepton, $7 \geq 10$ jets
  - ATLAS-CONF-2013-054
  - $[L_{\text{int}} = 20.3$ fb$^{-1}]$

- 0-lepton, $\geq 3$ b-jets
  - ATLAS-CONF-2012-145
  - $[L_{\text{int}} = 12.8$ fb$^{-1}]$

- 3-leptons, $\geq 4$ jets
  - ATLAS-CONF-2012-151
  - $[L_{\text{int}} = 12.8$ fb$^{-1}]$

- 2-SS-leptons, $0 \geq 3$ b-jets
  - ATLAS-CONF-2013-007
  - $[L_{\text{int}} = 20.7$ fb$^{-1}]$

---

**ATLAS** Preliminary

---

EMFCSC, Erice, 25/26.6.13
P Jenni (Freiburg/CERN)
Summary of dedicated searches for top squark pair production for some theoretically preferred models with relatively light 3rd generation squarks

**ATLAS** Preliminary

- Observed limits
- Observed limits \((-\kappa_{\text{thre}})\)
- Expected limits

**Status:** March 26, 2013

- \(L_{\text{tot}} = 13-21 \text{ fb}^{-1} \)
- \(L_{\text{tot}} = 4.7 \text{ fb}^{-1}\)

EMFCSC, Erice, 25/26.6.13
P Jenni (Freiburg/CERN)
LHC roadmap to the Higgs
Indirect indications for physics BSM, like SUSY, could come from rare decays showing rates deviating from the SM expectations
The search for $B_s (d) \rightarrow \mu \mu$

Very rare decay sensitive to New Physics (in particular to models with high $\tan \beta$)

Precise predictions in SM:
$\text{BR}(B_s \rightarrow \mu \mu) = 3.5 \pm 0.2 \times 10^{-9}$
$\text{BR}(B_d \rightarrow \mu \mu) = 1.1 \pm 0.2 \times 10^{-10}$

Very clean experimental signature

With 2011+2012 data (2.1/fb)
first evidence of $B_s \rightarrow \mu \mu$ decay at $\sim 3.5 \sigma$

$\hat{B}(B^0_s \rightarrow \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$

in agreement with SM.
Potential impact on models
Also best limit on $B_d \rightarrow \mu \mu$

$\hat{B}(B^0 \rightarrow \mu^+\mu^-) < 9.4 \times 10^{-10}$ at 95% CL
Search for Lepto-Quarks (LQ)

$pp \rightarrow LQ \ LQ \rightarrow lljj \ or \ l\nu jj \ (l = e \ or \ \mu)$

**ATLAS**

LQ\LQ \rightarrow eejj

\[ Ldt = 1.03 \text{ fb}^{-1} \]

Events / 20 GeV

Significance

Events / 20 GeV

Average LQ Mass [GeV]

Data ($\sqrt{s}=7$ TeV)

V+Jets

Top

QCD

Diboson

LQ (m=600GeV)
95% CL exclusion limits for Lepto-Quarks

1\textsuperscript{st} generation LQ (electron-quark)


2\textsuperscript{nd} generation LQ (muon-quark)

LHC roadmap to the Higgs
Search for New Heavy Quarks

Example: pair-production of a heavy up-type quark ($t'$) decaying into $W + b$
ATLAS 95% CL limits

Extra dimensions

- Large ED (ADD): monojet + $E_{\text{T,miss}}$
- Large ED (ADD): monophoton + $E_{\text{T,miss}}$
- Large $\mathbb{Z}$ (ADD): diphoton & dilepton, $m_{\gamma\gamma}$
- UED: diphoton + $E_{\text{T,miss}}$
- $S^2\mathbb{Z}$: dilepton, $m_{\mathbb{Z}}$
- RS1: WW resonance, $m_{t,t'}$
- Bulk RS: ZZ resonance, $m_{t,t'}$
- ADD BH ($m_{H}$, $m_{A}$): SS dimuon, $N_{\text{ch,part}}$
- ADD BH ($m_{H}$, $m_{A}$): leptons + jets, $\Sigma_{\ell}$
- Quantum black hole: dijet, $F_{m_{\ell}}$

qqqg contact interaction: $\chi$

Cl

- qqlt Cl.: SS dilepton + jets + $E_{\text{T,miss}}$
- $Z'_{(SSM)}$: $m_{\mu\nu}$
- $Z'$ (leptophobic topcolor): $tt\rightarrow j+j$, $j=j$,

W

Scalar LQ pair ($f=1$): kin. vars. in eejj, eujj
Scalar LQ pair ($f=2$): kin. vars. in eujj, uujj
Scalar LQ pair ($f=1$): kin. vars. in eujj, uujj

4th generation: $t'=WbWb$

4th generation: $b'b'\rightarrow SS$ dilepton + jets + $E_{\text{T,miss}}$

New quarks

- Vector-like quark: $TT\rightarrow H+X$
- Vector-like quark: $CC, m_{q'}$

Excited fermions

- Excited b quark: $WW$ resonance, $m_{b'}$
- Excited b quark: dijet resonance, $m_{b'}$
- Excited b quark: dilepton + jets, $m_{b'}$
- Techni-hadrons (LSTC): $WZ$ resonance ($W_{L}$), $m_{W_{L}}$
- Major neutr. (LRSM, no mixing): 2-lep + jets

Other

- Heavy lepton $N'$ (type III seesaw): $Z$-I resonance, $m_{N'}$
- $H^+$ (DY prod., BR($H^+$--1) = 1): SS ee ($\mu\mu$), $m_{H^+}$
- Multi-charged particles (DY prod.): highly ionizing tracks
- Magnetic monopoles (UY prod.): highly ionizing tracks

ATLAS Exotics Searches* - 95% CL Lower Limits (Status: May 2013)

*Only a selection of the available mass limits on new states or phenomena shown
CDF and D0 Collaborations