Hunting the Higgs (and Other Animals) at the CERN LHC

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Outline

- Status of the LHC and the ATLAS experiment
- Search for the Standard Model Higgs boson
- Search for Beyond the Standard Model particles decaying into top quark pairs
LHC (Large Hadron Collider)

- CERN is located outside Geneva, Switzerland
- The ring circumference is 27 km
- The energy of the LHC is now $7 \text{ TeV} = 3.5 \text{ TeV} + 3.5 \text{ TeV}$
LHC (Large Hadron Collider)

The experiments (detectors) are located 100m underground.
ATLAS CSC (Electronics) by UA
First Beam in the LHC

- September 10, 2008 in the ATLAS control room
First Malfunction at the LHC

September 19, 2008 in the LHC tunnel
LHC Dipole Magnets

- Bending is provided by 1232 15-m dipoles @ 8.33 T
LHC Dipole Magnets

- Busbar interconnections are used to carry the current between magnets
LHC Dipole Busbars

- The copper busbar must take the current during the current decay after a quench
September 2008 Incident

➢ The electrical arc destroyed the busbars
September 2008 Incident

- The large pressure forces from He entering the cryo vacuum resulted in magnet displacements.
September 2008 Incident

- Beam vacuum contamination

Beam Screen (BS): The red color is characteristic of a clean copper surface.

BS with some contamination by super-isolation (MLI multi layer insulation).

BS with soot contamination. The grey color varies depending on the thickness of the soot, from grey to dark.
LHC Repairs

The LHC repairs in detail

1. 14 quadrupole magnets replaced
2. 39 dipole magnets replaced
3. 54 electrical interconnections fully repaired. 150 more needing only partial repairs
4. Over 4 km of vacuum beam tube cleaned
5. A new longitudinal restraining system is being fitted to 50 quadrupole magnets
6. Nearly 900 new helium pressure release ports are being installed around the machine
7. 6500 new detectors are being added to the magnet protection system, requiring 250 km of cables to be laid
In the LHC there are

- 3372 RB interconnect splices
- 6744 RQ interconnect splices

Sample 1 (61 μΩ)
Sample 3A left (26 μΩ)
Sample 2A left (32 μΩ)
Sample 3A right (43 μΩ)
Sample 2A right (43 μΩ)
Sample 3B (21 μΩ)

Pictures by J.-M. Dalin
LHC Operating Energy

Of the 10000 such splices in the LHC, some less than perfect splices remain:
- Cannot run at 14 TeV without replacing all splices by new clamped, shunted ones
  - Ditto even for 8 TeV; it’s just too risky
- Present plan is to run through 2012 at 7 TeV
- Then take the LHC down for one-two years in 2013 to install shunts, repair bad joints, and do accelerator upgrade work such as commission linac4 injector to PS
7 TeV versus 14 TeV

- Must run longer with more limited mass reach to exclude or discover new particles

Fig. 40: The total SM Higgs production cross section at $\sqrt{s} = 7$ and 14 TeV.
LHC and ATLAS 2011 Running

- Fantastic! x5 what we hoped for in 2011

**Graph:**
- **ATLAS Online Luminosity**
- **$\sqrt{s} = 7$ TeV**
- **LHC Delivered**
- **ATLAS Recorded**
- Total Delivered: 5.45 fb$^{-1}$
- Total Recorded: 5.09 fb$^{-1}$

**Graph:**
- **ATLAS Online Luminosity**
- **$\sqrt{s} = 7$ TeV**
- **LHC Stable Beams**
- Peak Lumi: $3.59 \times 10^{33}$ cm$^2$ s$^{-1}$

**Dates:**
- 01/03 to 14/11

Pileup Problems?

- Running with 50 ns bunch spacing gives an average of 6 pp interactions per crossing.
Fundamental Forces

Gravity Force

Electromagnetic force

Strong force

Weak force

- Graviton?
- Solar systems
- Galaxies

- Gravity Force

- Oxygen atom
- Protons and Neutrons
- Electron
- Hydrogen atom
- Water molecule
- Oxygen atom
- Photon
- Atoms
- Light
- Chemistry
- Electronics

- Gluons (8)
- Quarks
- Mesons
- Baryons
- Nuclei

- u d u d up quark
- down quark
- proton
- neutron

- u u d down quark
- up quark
- anti-neutrino
- electron
- W force
carrier particle
- u d d d neutron
- proton

- Bosons (W,Z)

- Neutron decay
- Beta decay
- Neutrino interactions
- Burning of the sun
Fundamental Particles

**ELECTRONIC PARTICLES**

- **Quarks**
  - u, c, t (up, charm, top)
  - d, s, b (down, strange, bottom)
- **Leptons**
  - e, μ, τ (electron, muon, tau)
  - ν_e, ν_μ, ν_τ (electron neutrino, muon neutrino, tau neutrino)

**Force Carriers**

- Photon (γ)
- Gluon (g)
- Z boson ( Zw )
- W boson ( W^+ , W^- )

**Three Generations of Matter**

- I: Electron, ν_e, e^-
- II: Muon, ν_μ, μ^-
- III: Tau, ν_τ, τ^-
Fundamental Particles

➢ Or another pattern to unravel?

Standard Model of Elementary Particles

3 Generations of Fermions

<table>
<thead>
<tr>
<th>Quarks</th>
<th>Leptons</th>
</tr>
</thead>
<tbody>
<tr>
<td>u, c, t</td>
<td>ν₁, ν₂, ν₃, e, μ, τ</td>
</tr>
</tbody>
</table>

Masses are in MeV

Charge mass MeV

Force Carriers

Strong Interactions

Electromagnetism

Weak Interactions

Periodic Table of the Elements

Lanthanide Series

Actinide Series
Standard Model

- **Summary**

- SSB and Higgs Mechanism
- Massive Higgs Boson
- Local Gauge Invariance
- Massive Gauge Bosons
Standard Model

**Standard Model Lagrangian**

\[
\mathcal{L}_{GWS} = \sum_f (\bar{\Psi}_f (i \gamma^\mu \partial_\mu - m_f) \Psi_f - e Q_f \bar{\Psi}_f \gamma^\mu \Psi_f A_\mu) + \\
\frac{g}{\sqrt{2}} \sum_i (\bar{a}_L^i \gamma^\mu b^i_L W^{+}_\mu + \bar{b}_L^i \gamma^\mu a^i_L W^-_\mu) + \frac{g}{2 c_w} \sum_f \bar{\Psi}_f \gamma^\mu (I^3_f - 2 s_w^2 Q_f - I^3_f \gamma_5) \Psi_f Z_\mu + \\
-\frac{1}{4} |\partial_\mu A_\nu - \partial_\nu A_\mu - ie(W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 - \frac{1}{2} |\partial_\mu W^+_\nu - \partial_\nu W^+_\mu + \\
-ie(W^+_\mu A_\nu - W^+_\nu A_\mu) + ig' c_w (W^+_\mu Z_\nu - W^+_\nu Z_\mu)^2 + \\
-\frac{1}{4} |\partial_\mu Z_\nu - \partial_\nu Z_\mu + ig' c_w (W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 + \\
-\frac{1}{2} M_{\eta}^2 \eta^2 - \frac{g M_{\eta}^2}{8 M_W} \eta^3 - \frac{g'^2 M_{\eta}^2}{32 M_W} \eta^4 + |M_W W^+_\mu + \frac{g}{2} \eta W^+_\mu|^2 + \\
+\frac{1}{2} |\partial_\mu \eta + i M_Z Z_\mu + \frac{ig}{2 c_w} \eta Z_\mu|^2 - \sum_f \frac{g}{2 M_W} \bar{\Psi}_f \Psi_f \eta
\]
The Standard Model is mathematically complete.

There are no significant experimental discrepancies with Standard Model predictions.

But no Higgs boson has been observed either.
Where to Search for the Higgs

A direct search for the Higgs was carried out by the four LEP experiments from 1995-2000

- Center-of-mass energy of 205-208 GeV
- The production and decay were primarily by

\[
\begin{array}{c}
e^- \\
e^+ \\
Z^* \\
H \\
q \\
\bar{q} \\
\bar{b} \\
b
\end{array}
\]
Where to Search for the Higgs

- Indirect constraints on the Higgs mass can be found by considering electroweak radiative corrections like
Where to Search for the Higgs

- Electroweak observables depend quadratically on the top quark mass and logarithmically on the Higgs boson mass

- A global fit yields

  \[ m_H < 161 \text{ GeV} @ 95\% \text{ CL} \]
  \[ m_H < 185 \text{ GeV} @ 95\% \text{ CL w LEP direct} \]
Where to Search for the Higgs

- The DZero and CDF experiments at the Fermilab Tevatron continue to search for the Higgs
  - Many different channels
Higgs Production at the LHC

- **Gluon Fusion (GGF)**
  - Dominant process

- **Vector Boson Fusion (VBF)**
  - Second largest cross section
  - Distinctive topology useful for small \( m_H \)

- **Associated W/Z (AW)**
- **Associated Top (AT)**
  - Interesting topologies but smaller cross section
Higgs Production at the LHC

Fig. 41: The SM Higgs production cross section at $\sqrt{s} = 7$ TeV.
VBF (Vector Boson Fusion)

- Higgs production with a distinctive topology
  - Forward jets
  - No central jet activity because no color flow

\[ \begin{align*}
q_1 & \quad q_2 \\
W/Z & \quad H^0 \\
q_3 & \quad q_4
\end{align*} \]
Higgs Decay Modes

- The Standard Model rules say the Higgs decays into the heaviest pair of particles that is kinematically allowed.
Higgs Production x Decay

- ATLAS searches for the Higgs using many different decay modes

\[ \sqrt{s} = 7 \text{ TeV} \]

\[
\begin{align*}
\sigma \times \text{BR} [\text{pb}] & \\
\text{MW} & \\
\text{ZZ} & \\
\text{WW} & \\
\text{ZZ} & \\
\text{WW} & \\
\end{align*}
\]

Number of expected events for 1 fb^{-1}

<table>
<thead>
<tr>
<th>m_H [GeV]</th>
<th>WW→l_l'lv'</th>
<th>ZZ→4l</th>
<th>γγ</th>
</tr>
</thead>
<tbody>
<tr>
<td>120 GeV</td>
<td>127</td>
<td>1.5</td>
<td>43</td>
</tr>
<tr>
<td>150 GeV</td>
<td>390</td>
<td>4.6</td>
<td>16</td>
</tr>
<tr>
<td>300 GeV</td>
<td>89</td>
<td>3.8</td>
<td>0.04</td>
</tr>
</tbody>
</table>
Generalities

- Effective for $120 < m_H < 240$ GeV
- All production processes are considered (GGF, VBF, and associated W/Z)
  - Separate search is carried out for $H+0$ jet and $H+1$ jet events ($P_T > 25$ GeV)
- Common selection
  - 2 oppositely charged, high $P_T (>25, 20$ GeV) leptons
  - $M_{ll} > 15$ GeV and $|M_{ll} - M_Z| > 15$ GeV
  - Missing $E_T > 40$ GeV (ee and $\mu\mu$)
- Major backgrounds (determined mostly by data-driven methods)
  - WW, W+jets, top
Additional selection criteria

- Leptons are used to infer the W spin direction
- $\Delta \phi_{ll} < 1.3$ radians ($m_H < 170$ GeV)
Results

- Additional selection criteria and the background estimates are done separately for H+0 and H+1 jets.

\[ H \rightarrow WW^* \rightarrow l\nu l\nu \]

\[ m_T = \sqrt{\left( E_T^{ll} + E_T^{miss} \right)^2 - \left( \rightarrow ll + \rightarrow miss \right)^2} \]
Limit Plots Explained

- 95% CL Limit on $\sigma/\sigma_{SM}$
- Excess
- Deficit

Higgs production cross section we exclude, divided by the expected Higgs cross section in the Standard Model.

- "Observed" (example data)
- Higgs excluded at 95% CL below this line
- Expected without Higgs
- Expected region at 68% Confidence Level
- Expected region at 95% Confidence Level

mass of Higgs [GeV]
$H \rightarrow WW^{*} \rightarrow l\nu l\nu$

- **Observed and expected limits**

- At 95% CL, the following $m_H$ is excluded
  - 142-186 GeV
Generalities

- Effective for $110 < m_H < 140$ GeV
- BR $\sim 0.002$ but possesses a distinctive signature

Backgrounds
- Irreducible background: $\gamma\gamma$
- Reducible background: $\gamma$+jet, jet+jet

Selection
- Two isolated photons $> 40$ and $25$ GeV
- Photon energies are measured by the calorimeter
- Photon directions are measured using shower position in the first and second layers of the calorimeter
Photon identification and reconstruction

- High granularity of the first calorimeter layer can be used to reject photon pairs from neutral meson decays
- Photon direction (used in the mass reconstruction) is estimated from the shower position in the first and second calorimeter layers
Data driven methods are used to estimate the background.

\[ H \rightarrow \gamma\gamma \]
The resulting diphoton invariant mass

- No excess is observed

Currently this channel can only set observed 95% CL limits at ~4 times the SM cross section
Combined observed and expected limits

At 95% CL, can only exclude $\sim 4 \times$ SM production cross section $\times$ BR
Limit Plots Explained

Higgs production cross section we exclude, divided by the expected Higgs cross section in the Standard Model.

- "Observed" (example data)
- Higgs excluded at 95% CL below this line
- Expected without Higgs
- Expected region at 68% Confidence Level
- Expected region at 95% Confidence Level

95% CL Limit on $\sigma/\sigma_{SM}$

Mass of Higgs [GeV]

Excess

Deficit
Higgs Mass Exclusion Limits

- Combined observed and expected limits

- At 95% CL, the following is excluded
  - 146-242 GeV, 256-282 GeV, 296-466 GeV

\[ \int L dt = 1.0 - 2.3 \text{ fb}^{-1} \]
\[ \sqrt{s} = 7 \text{ TeV} \]
Higgs Mass Exclusion Limits

- Combined observed and expected limits

- At 95% CL, the following $m_H$ is excluded
  - 146-242 GeV, 256-282 GeV, 296-466 GeV

- $\int Ldt = 1.0-2.3 \text{ fb}^{-1}$
- $\sqrt{s} = 7 \text{ TeV}$
Higgs Mass Exclusion Limits

- Combined observed and expected limits for individual channels

![Graph showing Higgs mass exclusion limits with ATLAS Preliminary results.](Image)
ATLAS and CMS Limits

- Combination of both experiments is in progress

ATLAS Preliminary

\[
\int \mathcal{L} = 1.0-2.3 \text{ fb}^{-1}
\]
\(\sqrt{s} = 7 \text{ TeV}\)

CLs Limits

95% CL Limit on \(\sigma/\sigma_{\text{SM}}\)

- Observed
- Expected

\(\pm 1 \sigma\)
\(\pm 2 \sigma\)

Higgs boson mass (GeV/c^2)

CMS Preliminary, \(\sqrt{s} = 7 \text{ TeV}\)
Combined, \(L_{\text{int}} = 1.1-1.7 \text{ fb}^{-1}\)
Higgs Search Prospects at 7 TeV

- Exclusion and discovery at 7 TeV
  - Nearly the entire range of Higgs boson masses can be excluded at 95% CL with 5 fb$^{-1}$
  - Discovery of a SM Higgs boson will require more data - masses between 130 and 450 GeV could be discovered with 10 fb$^{-1}$
What If We Don’t Find the Higgs?

- The Higgs is needed for perturbative unitarity in $W_L W_L \rightarrow W_L W_L$ scattering

- At $\sim 1$ TeV
  - Strong WW scattering (resonances?, …)
  - If no strong WW scattering, go back and search some more for a light Higgs
Beyond the Standard Model (BSM)

- Supersymmetry, string theory, extra dimensions, dark matter, ...
SM Top Quark Pair Production

- SM top quark production and decay are measured and understood.
SM Top Quark Pair Production

- Cross section at 7 TeV
Search for Top Quark Pair Resonances

New particles that decay into pairs of top quarks are predicted in a number of models including:

- New $Z'$ boson (associated with Sequential SM models)
- Topcolor $Z'$ (found in models of dynamical electroweak symmetry breaking)
- Kaluza-Klein gluons (found in models with warped extra dimensions)
- Randall-Sundrum graviton (also found in models with warped extra dimensions)
- Randall-Meade quantum black holes (resulting from two colliding partons with impact parameter less than the Schwarzschild radius)
Search for Top Quark Pair Resonances

**Strategy**

- Identify top quark pairs as in a cross section measurement
  - Optionally remove jets that are too far from other jets or leptons in the event
- Plot the invariant mass of the top quark pairs
- Search for excess pairs above SM predictions
  - Proceed to set upper limits in the absence of any signal
- Complications begin to arise for top quark pair resonances > 1 TeV because boosted top quarks may be reconstructed as a single fat jet rather than the usual three distinct jets
Search for Top Quark Pair Resonances

- The $t\bar{t}$ invariant mass spectrum after all selection criteria
Search for Top Quark Pair Resonances

- Systematic errors to consider

<table>
<thead>
<tr>
<th>Source</th>
<th>$\tau\tau$</th>
<th>$W+\text{jets}$</th>
<th>All MC</th>
<th>$Z'$, $m_{Z'} = 1000,\text{GeV}$</th>
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<td>+18.7%</td>
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<td></td>
<td>-11.5%</td>
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<td>$\pm 9%$</td>
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<td>$&lt; 1%$</td>
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<tr>
<td>$b$-tagging efficiency</td>
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<tr>
<td>(incl. mistag rate)</td>
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<td>Muon efficiency</td>
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<tr>
<td>Electron energy resolution</td>
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<td>$&lt; 1%$</td>
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</tr>
<tr>
<td>Electron ID efficiency</td>
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<td>$\pm 1.1%$</td>
<td>$\pm 1.1%$</td>
<td>$\pm 1.2%$</td>
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<td>$&lt; 1%$</td>
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<tr>
<td>$m_\ell$ shape</td>
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<td>-</td>
<td>-</td>
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<td>$&lt; 1%$</td>
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<tr>
<td>Pile-Up</td>
<td>$&lt; 1%$</td>
<td>$&lt; 1%$</td>
<td>$&lt; 1%$</td>
<td>$&lt; 1%$</td>
</tr>
</tbody>
</table>
Limits for Topcolor $Z'$ and KK Gluon Resonances

- 95% CL upper limits including stat. and sys. errors

- $Z'$ with $m < 9xx$ GeV is excluded at 95% CL
- KKg with $m < 1xxx$ GeV is excluded at 95% CL
ATLAS BSM Searches

Many other searches to talk about another day
Conclusions

- The LHC and ATLAS experiment performed exceedingly well in 2011, with > 5 fb$^{-1}$ of data recorded.
- A wide range of Higgs masses have been excluded using ~half of the 2011 data.
- Increased integrated luminosity may allow us to discover the new animals that await beyond the SM landscape.
LHC Interconnect Busbars

For safe running at 14 TeV, all 10k interconnect splices must be repaired.
LHC Dipole Busbars

- Carrying up to 13 kA
LHC Dipole Busbars

- Unfortunately conceptual mistakes plus design errors plus execution errors =

Gamma rays QBBI.B25R3-M3 before disconnection (QRL connection & QRL lyra sides)

Courtesy: Christian Scheuerlein
Where to Search for the Higgs

An upper limit can be found by considering the scattering amplitudes for

- Partial wave unitarity yields

\[ m_H \leq 1 \, TeV \]
One of the goals in physics is to understand complex phenomena in terms of a few simple principles.

The Standard Model joins the strong, weak and electromagnetic interactions in the sense that they all arise from a common symmetry principle.

- The symmetry is called local gauge invariance.
- It is the breaking of this symmetry (electroweak symmetry breaking) that provides us with an opening to formulate a general mechanism for mass generation.
Requiring the electromagnetic and weak interaction Lagrangians to be locally gauge invariant necessitates the introduction of 1 + 3 gauge fields.

- These we’d like to identify as the photon, $W^+$, $W^-$, and $Z$

Unfortunately any mass term associated with these gauge fields would spoil the local gauge symmetry.

- Thus in this theory the photon, $W^+$, $W^-$, and $Z$ are massless.
Local gauge invariance

- One can easily imagine that quantum field theories are invariant under global gauge (phase) transformations

\[ \psi(x) \rightarrow \psi'(x) = e^{i\alpha} \psi(x) \]

- One could ask whether they are also invariant under local gauge transformations

\[ \psi(x) \rightarrow \psi'(x) = e^{i\alpha(x)} \psi(x) \]

- The answer turns out to be yes if we introduce a gauge covariant derivative that includes a gauge boson field – the photon
Standard Model

- Spontaneous Symmetry Breaking (SSB) occurs when a Lagrangian is invariant under some symmetry but the ground state (vacuum) is not.
  - Pencil falling
  - Heisenberg ferromagnet

- 2008 Nobel Prize to Nambu for discovering SSB
Standard Model

Higgs mechanism

- We have SSB when a Lagrangian is invariant under some symmetry but the ground state (vacuum) is not.
- If the broken symmetry is a continuous symmetry, then there necessarily exists one or more massless spin 0 particles (Goldstone bosons).
- If the broken symmetry is a local gauge symmetry, then the Goldstone bosons get absorbed (eaten) by the massless gauge bosons thereby acquiring mass.
Where to Search for the Higgs

- The combined result was
  \[ m_H > 114.4 \text{ GeV} \at 95\% \text{ CL} \]
- Of course there were interesting events
The ATLAS detector

Muon Spectrometer: $|\eta|<2.7$
Air-core toroids and gas-based muon chambers $\sigma/p_T = 2\% @ 50$
GeV to $10\% @ 1\mathrm{TeV}$ (ID+MS)

EM Calorimeter: $|\eta|<3.2$
Pb-LAr Accordion $\sigma/E=10\% \sqrt{E} @ 0.7\%$

Inner Detector: $|\eta|<2.5,$
$B=2T,$ Si pixels/strips and Trans. Rad. Det.; $\sigma/p_T = 0.05\% p_T (\mathrm{GeV}) \oplus 1\%$

Hadronic calorimeter: $|\eta|<1.7$
Fe/scintillator $1.3<|\eta|<4.9$ Cu/
W-LAr; $\sigma/Ejet= 50\% /\sqrt{E} \oplus 3\%$
<table>
<thead>
<tr>
<th>Inner Tracking Detectors</th>
<th>Calorimeters</th>
<th>Muon Detectors</th>
<th>Magnets</th>
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<tbody>
<tr>
<td></td>
<td>LAr EM</td>
<td>LAr HAD</td>
<td>LAr FWD</td>
</tr>
<tr>
<td>Pixel</td>
<td>SCT</td>
<td>TRT</td>
<td>99.8</td>
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</table>

Luminosity weighted relative detector uptime and good quality data delivery during 2011 stable beams in pp collisions at $\sqrt{s}=7$ TeV between March 13th and June 6th (in %). The inefficiencies in the LAr calorimeter will partially be recovered in the future. The magnets were not operational for a 3-day period at the start of the data taking.
Particle Identification in ATLAS
First Beam in the LHC

- No black hole or stranglet production

The CERN black hole
Beam Re-estabilished in the LHC

November 20, 2009 - 14 months later in the ATLAS control room