LHC Begins...

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Outline

- Brief look at the Large Hadron Collider (LHC)
  - Design features
  - Machine commissioning and early beams
- Detectors
  - ATLAS and CMS mostly
- Expectations for first physics
  - Commissioning for physics
  - Early Standard Model measurements
  - Early discoveries?
- Outlook
The Large Hadron Collider (LHC)

Machine
- Occupies old LEP tunnel at CERN, Geneva, Switzerland & France
- About 27 km long
- 50-100m underground
- 1232 bending magnets
- 392 focusing magnets
- All superconducting
  - ~96 tons of He for ~1600 magnets

Beams (design)
- **pp collider**
  - 7 TeV on 7 TeV (14 TeV collision energy)
  - Luminosity $10^{34}$ cm$^{-2}$s$^{-1}$
  - 2808 x 2808 bunches
  - Bunch crossing time 25 ns (40 MHz)
  - ~20 pp collisions/bunch crossing

- **Heavy ion collider (Pb)**
  - Collision energy 1150 TeV (2.76 TeV/nucleon)

Proton acceleration chain:
LINAC $\rightarrow$ Proton Synchrotron Booster (PSB) $\rightarrow$ Proton Synchrotron (PS) $\rightarrow$ Super Proton Synchrotron (SPS) $\rightarrow$ LHC

Pb ion acceleration chain:
LINAC $\rightarrow$ Low Energy Ion Injector Ring (LEIR) $\rightarrow$ Proton Synchrotron (PS) $\rightarrow$ Super Proton Synchrotron (SPS) $\rightarrow$ LHC
**Initial LHC Running Conditions**

<table>
<thead>
<tr>
<th>Stage A (5 TeV/beam):</th>
<th># bunches</th>
<th>$\beta^*$ [μ]</th>
<th>Intensity $\times 10^{10}$</th>
<th>Lumi [cm$^{-2}$s$^{-1}$]</th>
<th>Coll. rate</th>
<th>X-ing</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC commissioning</td>
<td>1×1</td>
<td>11</td>
<td>1</td>
<td>$1.6 \times 10^{27}$</td>
<td>~0</td>
<td>70 ms</td>
</tr>
<tr>
<td>Single beam</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pilot physics running</td>
<td>43×43</td>
<td>2</td>
<td>4</td>
<td>$6.1 \times 10^{29}$</td>
<td>0.76</td>
<td>1.6 ms</td>
</tr>
<tr>
<td>First collisions</td>
<td>156×156</td>
<td>2</td>
<td>9</td>
<td>$1.1 \times 10^{32}$</td>
<td>3.9</td>
<td>450 ns</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stage B (5 TeV/beam):</th>
<th># bunches</th>
<th>$\beta^*$ [μ]</th>
<th>Intensity $\times 10^{10}$</th>
<th>Lumi [cm$^{-2}$s$^{-1}$]</th>
<th>Coll. rate</th>
<th>X-ing</th>
</tr>
</thead>
<tbody>
<tr>
<td>75 ns commissioning</td>
<td>936×936</td>
<td>10</td>
<td>4</td>
<td>$2.3 \times 10^{31}$</td>
<td>0.13</td>
<td>75 ns</td>
</tr>
<tr>
<td>12-23% of nominal</td>
<td>936×936</td>
<td>1</td>
<td>6</td>
<td>$5 \times 10^{32}$</td>
<td>2.8</td>
<td>75 ns</td>
</tr>
<tr>
<td>current</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>End of 2008 run year?</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stage C (7 TeV/beam):</th>
<th># bunches</th>
<th>$\beta^*$ [μ]</th>
<th>Intensity $\times 10^{10}$</th>
<th>Lumi [cm$^{-2}$s$^{-1}$]</th>
<th>Coll. rate</th>
<th>X-ing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Move to 25 ns bunch</td>
<td>2808×2808</td>
<td>4</td>
<td>4</td>
<td>$1.7 \times 10^{32}$</td>
<td>0.32</td>
<td>25 ns</td>
</tr>
<tr>
<td>spacing</td>
<td>2808×2808</td>
<td>0.55</td>
<td>6</td>
<td>$2.8 \times 10^{32}$</td>
<td>5.2</td>
<td>25 ns</td>
</tr>
<tr>
<td>35-52% of nominal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>current</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Early 2009?</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stage D (7 TeV/beam):</th>
<th># bunches</th>
<th>$\beta^*$ [μ]</th>
<th>Intensity $\times 10^{10}$</th>
<th>Lumi [cm$^{-2}$s$^{-1}$]</th>
<th>Coll. rate</th>
<th>X-ing</th>
</tr>
</thead>
<tbody>
<tr>
<td>70-100% of nominal</td>
<td>2808×2808</td>
<td>0.55</td>
<td>11</td>
<td>$1.0 \times 10^{34}$</td>
<td>19.3</td>
<td>25 ns</td>
</tr>
<tr>
<td>current</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Requires phase 2 collimators to be installed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Very preliminary! See [http://lhc-commissioning.web.cern.ch](http://lhc-commissioning.web.cern.ch) for current status!
LHC Status

All segments are cold!
ATLAS: A General Purpose Detector For LHC

- Muon Detectors
- Tile Calorimeter
- Liquid Argon Calorimeter
- Toroid Magnets
- Solenoid Magnet
- SCT Tracker
- Pixel Detector
- TRT Tracker

Total weight: 7000 t
Overall length: 46 m
Overall diameter: 23 m
Magnetic field: 2T solenoid + toroid
CMS: A General Purpose Detector For LHC

Total weight: 12500 t
Overall length: 22 m
Overall diameter: 15 m
Magnetic field: 4T solenoid
Typical Detector Features

- **Hermetic coverage over a wide angular range**
  - Efficient missing transverse energy reconstruction due to large coverage in pseudo-rapidity
    \[ |\eta| = \frac{1}{2} \ln \left( \frac{p + p_z}{p - p_z} \right) = \ln \left( \frac{\tan \frac{\theta}{2}}{2} \right) \leq 5 \]
  - Very forward detection of particles and jets produced in pp collisions

- **High particle reconstruction efficiency**
  - Important for final state reconstruction and classification

- **Relative energy resolution for electrons, photons and muons is 2–4%**

<table>
<thead>
<tr>
<th>Particles</th>
<th>Efficiency</th>
<th>Jet Rejection</th>
</tr>
</thead>
<tbody>
<tr>
<td>muon</td>
<td>~90%</td>
<td>10^5</td>
</tr>
<tr>
<td>e^±</td>
<td>~80%</td>
<td>10^5</td>
</tr>
<tr>
<td>photon</td>
<td>~80%</td>
<td>10^3</td>
</tr>
<tr>
<td>b-jet</td>
<td>~60%</td>
<td>100</td>
</tr>
<tr>
<td>tau</td>
<td>~50%</td>
<td>100</td>
</tr>
</tbody>
</table>
Both ATLAS and CMS are or will be sufficiently complete for physics:

- Detector integration and commissioning ongoing since several months
- So far calibration (pulses), noise studies ("empty" readings) and cosmic data

Some repairs and completion needed:

- Scheduled for first break winter 2008/2009
Challenges To Physics Reconstruction

Underlying event in proton-proton collisions

- Collisions of other partons (quarks and gluons) in the same two protons generating the (high transverse momentum) interaction of interest
  - Cannot easily be suppressed
  - Has been extensively studied at Tevatron
- Large phase space at LHC
  - Activity is correlated with hard scattering


LHC prediction: x2.5 the activity measured at Tevatron!

A. Moraes, HERA-LHC Workshop, DESY, March 2007
**Pile-Up Events**

- Multiple collisions of other protons in bunch crossings
  - Effect of high luminosity at LHC
  - Independent of (triggered) hard scattering process
  - Generates additional particles and particle jets

- Generates additional noise in detectors
  - High bunch crossing rate creates signal history from pile-up in detectors
    - Sensitivity up to 25 bunch crossings for “slow” detectors (calorimeters)
  - Average contribution cancels due to chosen signal shaping

- Pile-up noise is not gaussian
  - Coherent effects due to physics source

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- $E_t \sim 58 \text{ GeV}$
- $E_t \sim 81 \text{ GeV}$

- No pile-up added
- LHC design luminosity pile-up added

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- $\text{RMS}(E_t)$ in jet
  - $\text{RMS}(E_t)$ vs jet size
  - $R = 0.5$

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P. Savard et al., ATLAS-CAL-NO 084/1996

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SLAC Summer Institute 2008

Peter Loch
August 5, 2008
Reconstruction Challenges

Complex but common signal objects final states in LHC collisions: particle jets

- Longitudinal energy leakage
- Detector signal inefficiencies (dead channels, HV...)
- Pile-up noise from (off- and in-time) bunch crossings
- Electronic noise
- Calo signal definition (clustering, noise suppression, ...)
- Dead material losses (front, cracks, transitions...)
- Detector response characteristics ($e/h \neq 1$)
- Jet reconstruction algorithm efficiency
- Jet reconstruction algorithm efficiency
- Added tracks from in-time (same trigger) pile-up event
- Added tracks from underlying event
- Lost soft tracks due to magnetic field

Physics reaction of interest (interaction or parton level)
Tasks For First Collisions

Calorimeter calibration
- Validate simulation and test beam based hadronic calibration functions
- In-situ calibration with collision physics
  - $Z \rightarrow ee$ for electromagnetic signals
  - Prompt photons, $Z+\text{jets}$, $W \rightarrow jj$ for hadrons

Response to low transverse momentum physics
- Particle flow in “minimum” bias physics
  - Understand modeling for LHC!
- Needed to correct for underlying event and pile-up

Measure Standard Model Physics
- Inclusive jet cross-section
  - Hard to believe discoveries if standard physics is not seen!
- Particle density functions of the proton
  - Needed for all cross-section analysis

Transverse momentum balance in direct photon production

$W \rightarrow jj$

<table>
<thead>
<tr>
<th>mjj</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bins &amp; 18770</td>
</tr>
<tr>
<td>Mean &amp; 121.6</td>
</tr>
<tr>
<td>RMS &amp; 52.26</td>
</tr>
<tr>
<td>$\chi^2$/ndf &amp; 89.52 / 73</td>
</tr>
<tr>
<td>Prob &amp; 0.09174</td>
</tr>
<tr>
<td>Height &amp; $193.3 \pm 7.5$</td>
</tr>
<tr>
<td>Mean_value &amp; 83.27 $\pm$ 0.30</td>
</tr>
<tr>
<td>Sigma &amp; $8.376 \pm 0.289$</td>
</tr>
<tr>
<td>p0 &amp; $-105.4 \pm 21.4$</td>
</tr>
<tr>
<td>p1 &amp; $4.431 \pm 0.762$</td>
</tr>
<tr>
<td>p2 &amp; $-0.6299 \pm 0.00632$</td>
</tr>
<tr>
<td>p3 &amp; $5.811e-05 \pm 1.296e-05$</td>
</tr>
</tbody>
</table>
pp Collisions @ LHC

Increased reach on various final states
- 100 times more top-anti-top pairs than Tevatron
- Higgs cross-section several orders of magnitude larger
  - Discovery potential!
- Enormous increase of inclusive jet cross-section

Potentially small signal-to-background ratios for discoveries
- Background is Standard Model
  - E.g. top pairs for Higgs!
  - Needs to be well understood
- Large statistics may afford hard cuts on event topologies to increase signal significance
Jet physics

High transverse momentum jets quickly accessible!

100,000 jets with $p_T > 1$ TeV at 1 fb$^{-1}$

First attempt at cross-section as early as 2009?
Main goal of LHC: find the Higgs particle!

- Search will start day 1
- Expected mass range 115-160 GeV/c²
- But significant statistics needed for full discovery
  - Few 100 pb⁻¹: some final state exclusions
  - ~1 fb⁻¹: discovery if 160-180 GeV/c²
  - ~10 fb⁻¹: full mass range covered

Unlikely in the first two years

Collected from T.Vickey’s talk at Moriond 2008!
New Physics: SUSY

Focus on (minimal) Super Symmetry

- Some signatures can be quickly detected
- Typical "busy" final state from long decay chains with several leptons, jets, and significant missing transverse momentum

![Diagram of SUSY decay chains](image)
SUSY Searches

- **Inclusive effective mass spectrum**
  \[ M_{\text{eff}} = \sum |p_{T,i}| + E_{T,\text{miss}} \]

- **Exclusive search**
  - Ask for same flavour, opposite charged leptons in decay chain
  - Look at lepton invariant mass
  - Characteristic kinematic endpoint
  - Small background
    - Early discovery possible?

Note top-anti-top pair production is (large) background!
Outlook

The LHC experiments are getting ready for data

- Important early data to understand backgrounds from multiple interactions and underlying event
  - Analysis strategies for soft physics triggers lined up, but extraction of input for models challenging due to detector acceptance and resolution limitations
- Initial physics analysis is prepared and tested for Standard Model physics
  - Electroweak and QCD
  - Recent and ongoing important tests of worldwide computing infrastructure due to large amount of data

Early discoveries possible

- Higgs discovery faces large background
  - Unlikely very fast
- Some new physics indications early on
  - SUSY candidates
  - But good understanding of detector required

We all hope for first collisions this year!

- At least useful data for commissioning of the detectors for physics