PHENO 2009 Symposium
University of Wisconsin (Madison), 13/05/2009

LHC Alive!

Mónica L. Vázquez Acosta (Imperial College London)
On behalf of the CMS and ATLAS Collaborations
The Large Hadron Collider is a 27 km long collider ring housed in a tunnel about 100 m underground near Geneva.
**Large Hadron Collider**

- **pp:** $\sqrt{s} = 10\text{-}14\text{ TeV}, L_{\text{design}} = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ (after 2012-2013)
  - $L_{\text{initial}} < \text{few} \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
  - $\sqrt{s}(\text{LHC}) \sim 7 \sqrt{s} (\text{Tevatron}), L_{\text{design}} (\text{LHC}) \sim 100 L_{\text{design}} (\text{Tevatron})$
- **Heavy ions:** (e.g. Pb-Pb at $\sqrt{s} \sim 1000 \text{ TeV}$)

**First collisions:** expected in November 2009

**ATLAS and CMS**
- **pp, general purpose**

**LHC 27 km ring** (previously used for the LEP $e^+e^-$ collider)

**ALICE**
- ion-ion
- p-ion

**LHCb**
- pp, B-physics, CP-violation

**Plus two experiments with very forward detectors at**
- **Point-1:** LHCf
- **Point-5:** Totem
LHC: dipole magnets

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
- Nb-Ti superconducting cable: 7600 km
Special quadrupole magnets (‘Inner Triplets’) to focus beams to reach highest luminosity at their interaction in the centre of the experiments.
ATLAS Detector

ATLAS superimposed to the 5 floors of building 40

45 m

24 m

7000 Tons

Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker
ATLAS: toroid magnets
ATLAS: Closure of LHC beampipe ring
16th June 2008
CMS Detector

Pixels
Tracker
ECAL
HCAL
MUON Dets.
Superconducting Solenoid

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

http://cms.cern.ch
CMS yoke was ready in 2003
The central, heaviest slice (2000 tons) including the solenoid magnet lowered in the underground cavern in Feb. 2007.

In total 15 slices were installed in this way.
CMS closed ready for beam!
After almost 20 years of design and construction the experiments started taking data with LHC beams

- Sunday/Monday 7-8 September
  Single shots of Beam 1 (clockwise via ALICE) onto collimator 150 m upstream of CMS, ~ 1 hour

- Tuesday 9-September 2008
  20 shots of Beam 1 onto collimator 150m upstream of CMS

- Wednesday 10 September 2008
  Nice splash events observed when beam onto collimators 100-1000 TeV observed in the CMS/ATLAS calorimeters
  Halo muons observed once beam started passing experiments

Beam splash events onto all four detectors
First Events: beam going through CMS

Halo Muons in CSCs and HB

Beam Pickup (ch1) CMS Beam Condition Monitors (ch 3, 4)

Point 5 Control Room

CMS Centre Meyrin
The very first beam-splash event from the LHC in ATLAS at 10:19, 10\textsuperscript{th} September 2008

Online display

Offline display
CMS: first events with collimators closed
beam-splash events

$\sim 2.10^9$ protons on collimator $\sim 150$ m upstream of CMS

Longitudinal views

HCAL energy

ECAL energy

Transverse views

DT muon chamber hits
A busy beam-halo event with tracks bent in the Toroids
CMS: beam-halo events

Beam Halo: Muons outside of beam-pipe, arising from decays of pions created when off-axis protons scrape collimators or other beamline elements

CSC Hit Distribution from Beam Halo Events

ME–1  ME–2  ME–3  ME–4
LHC Tunnel Profile
Incident 19th September 2008

• During commissioning of the last main bend circuit to 5 TeV and incident occurred resulting in the trigger of quench heaters of about 100 magnets and a large Helium discharge into the tunnel
• The 7 other octants of the LHC had been commissioned to 5 TeV (and well above) without problems

At 8.7 kA (corresponding to ~ 5.1 TeV), a resistive zone appeared in the superconducting busbar between quadrupole Q24 and the neighboring dipole (probably due to a bad welding ‘splice’).
Interconnection of two LHC magnets
ATLAS: Cosmic Runs after LHC incident

# of cosmic triggers

### Cosmic events recorded and processed by ATLAS since Sep 13, 2008

<table>
<thead>
<tr>
<th>Trigger Type</th>
<th>Events (in million)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum of RPC, TGC, MBTS L1 Triggers</td>
<td>216 million</td>
</tr>
<tr>
<td>RPC Triggers (L1)</td>
<td></td>
</tr>
<tr>
<td>Bottom 'Downward' RPC Triggers (L1)</td>
<td></td>
</tr>
<tr>
<td>TGC Triggers (L1)</td>
<td></td>
</tr>
<tr>
<td>Min. Bias Scint. Triggers (L1)</td>
<td></td>
</tr>
<tr>
<td>Calorimeter Triggers (L1)</td>
<td></td>
</tr>
<tr>
<td>Inner Detector Track Trigger (L2)</td>
<td></td>
</tr>
<tr>
<td>EM Calorimeter Triggers (L1)</td>
<td></td>
</tr>
</tbody>
</table>

Several hundred million cosmic events taken in various detector configurations before the first LHC beams.


Vertical areas indicate magnetic field status:
- ORANGE: solenoid on
- GREEN: toroid on
- BLUE: Both fields on

# of tracks w. pixel hits

Approximate Number of Tracks with Pixel Hits

- All Tracks
- B-field on
- B-field off

Run number

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ATLAS Commissioning with cosmics: tracker alignment/hit efficiency

Pixels/Silicon alignment with cosmics

Achieved precision $\sim 25 \, \mu m$

Residuals: distance between fitted track & hits in individual layers

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Goal:

- Run CMS for 4 weeks continuously to further gain operational experience
- Study effects of B field on detector components
- Collect 300M cosmic events w. tracking detectors

Facts:

- Ran 4 weeks continuously from 13-Oct to 11-Nov 2008: 19 days with B=3.8T
- 370M cosmic events collected in total
- 290M with B=3.8T and with strip tracker and DT in readout: 194M with all components in
CMS Commissioning with cosmics: tracker alignment

Barrel

Pixel

RMS

26 μm

47 μm

Mean of the residual distribution per sensor: sensitive to module displacements

Using 4M tracks for alignment & 1M for validation

- Unaligned: nominal geometry
- CRUZET: geometry obtained from B=0T runs using Hits and Impact Point method and survey constraints
- CRAFTHIP: geometry obtained from Hits and Impact Point algorithm on CRAFT data, including survey constraints
- CRAFTMP: geometry obtained from Millepede algorithm on CRAFT data
• Conclusion 5 TeV/beam for Physics for 2009/2010 run

• Machine Protection will be tested with beam (at 0.5 TeV energy levels)

• 4 TeV “on the way” to 5 TeV

• Estimated integrated luminosity
  • during first 100 days of operation.. $\approx 100\text{pb}^{-1}$
    • Peak L of $5.10^{31}\eta$ (overall) = 10% gives $0.5\text{pb}^{-1}/\text{day}$
    • Peak L of $2.10^{32}\eta$ (overall) = 10% gives $2.0\text{pb}^{-1}/\text{day}$
  • During next 100 days of operation.. $\approx 200\text{pb}^{-1}$?

• Then towards end of year ions (to be planned in detail soon)
Gains 20 weeks of LHC physics (independent of “slip”)

Gain 20 weeks of physics in 2010 by running during winter months

HIGH price Electricity

4 to 5 TeV

> 6 TeV

44 weeks physics possible

24 weeks physics possible
Parton Luminosities at 10 and 14 TeV

Ratios of cross-sections at 10/14 TeV for processes induced by gg and qq

At 10 TeV

More difficult to produce high mass objects

< 300 GeV the suppression is <50% (process-dependent)

eg. tt cross section is a factor 2 lower

Above ~1 TeV effects more marked
Standard Model Candles

- tracker momentum scale, trigger performance, detector efficiency, sanity checks, ...
- Muon Spectrometer alignment, ECAL uniformity, energy/momentum scale of full detector, lepton trigger and reconstruction efficiency
Standard Model Candle: Z boson

- 25k $Z \rightarrow e^+e^-$ with 50 pb$^{-1}$ at 14 TeV
- Precision $\sigma (Z \rightarrow e^+e^-) \sim 4$-5%
- $Z \rightarrow \mu^+\mu^-$ with 100 pb$^{-1}$ at 14 TeV
- Precision $\sigma (Z \rightarrow \mu^+\mu^-) < 2\%$ (exp), $\sim 10\%$ (lumi)

CMS Sizeable sample of $Z \rightarrow \mu^+\mu^-$ events expected in early 10 TeV data: useful in detector understanding & calibration

<table>
<thead>
<tr>
<th>CMS</th>
<th># of Events 10 pb$^{-1}$ @ 14 TeV</th>
<th># of Events 10 pb$^{-1}$ @ 10 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \mu^+\mu^-$</td>
<td>5197</td>
<td>4390</td>
</tr>
<tr>
<td>$W \rightarrow \mu\nu$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>ttbar</td>
<td>17</td>
<td>7</td>
</tr>
<tr>
<td>QCD</td>
<td>6</td>
<td>3</td>
</tr>
</tbody>
</table>

$\frac{\sigma(Z) @ 14 \text{ TeV}}{\sigma(Z) @ 10 \text{ TeV}} = 1.4$
Top physics: semileptonic channel

**CMS Preliminary @ 10pb⁻¹**

**CMS**

- # of Events: 10 pb⁻¹
- # of Events: 10 pb⁻¹

**muon semileptonic channel**

<table>
<thead>
<tr>
<th>Event Type</th>
<th>CMS @ 14 TeV</th>
<th>CMS @ 10 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>ttbar</td>
<td>153</td>
<td>45</td>
</tr>
<tr>
<td>W</td>
<td>67</td>
<td>32</td>
</tr>
</tbody>
</table>

\[
\frac{\sigma(t\bar{t})_{14 TeV}}{\sigma(t\bar{t})_{10 TeV}} = 2.3
\]

\[
\frac{\sigma(W)_{14 TeV}}{\sigma(W)_{10 TeV}} = 1.4
\]

**PYTHIA**

- ATLAS Preliminary @ 100 pb⁻¹
- ATLAS Preliminary @ 10 TeV

**M_{jj}^{inv} [GeV/c²]**

- tt → Wb Wb → ℓνb qqb

- Clear W peak!

**after b-tag and W-mass selection**

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Search for New Resonances: $Z'$

$Z’ \rightarrow \mu\mu$

CMS Preliminary

$Z_{\psi}$ & $Z_{SSM}$: two extremes in “reach”

<table>
<thead>
<tr>
<th>$Z’$ mass (TeV)</th>
<th>$\sigma(14 \text{ TeV}) / \sigma(10\text{ TeV})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

With 100 pb$^{-1}$ @ 10 TeV

$Z’$ discovery up to $\sim$1.5 TeV

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Search for new resonances: $W'$

$W' \rightarrow e\nu$ cross section

CMS Preliminary

$M(W')$

1 TeV

CMS Preliminary

$M(W')$

3 TeV

CMS Preliminary

With 100 pb$^{-1}$ @ 10 TeV

$W'$ discovery up to ~1.5 TeV

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SUSY: sparticle production at the LHC

- Squarks and gluinos produced via strong processes → large cross-section

\[ q \xrightarrow{\alpha_s} \tilde{q} \quad g \xrightarrow{\alpha_s} \tilde{g} \quad \tilde{q} \xrightarrow{\alpha_s} q \quad \tilde{g} \xrightarrow{\alpha_s} g \]

For \( m(\tilde{q}, \tilde{g}) \sim 1 \text{ TeV} \) \( \sim 100 \) events produced with 100 pb\(^{-1}\)

- Charginos, neutralinos, sleptons direct production occurs via EW processes → much smaller rate (produced more abundantly in squark and gluino decays)

\[ \tilde{q} \tilde{q}, \tilde{q} \tilde{g}, \tilde{g} \tilde{g} \]

production are the dominant SUSY process @ LHC if accessible

\[ \tilde{q}, \tilde{g} \] heavy (present Tevatron limits: \( m > 300-400 \text{ GeV} \))

→ cascade decays favored

Lightest neutralino is stable, neutral & weakly interacting
→ missing energy in final state

spectacular signatures (many jets, MET, leptons)

<table>
<thead>
<tr>
<th>M (GeV)</th>
<th>( \sigma ) (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>100</td>
</tr>
<tr>
<td>1000</td>
<td>1</td>
</tr>
<tr>
<td>2000</td>
<td>0.01</td>
</tr>
</tbody>
</table>

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Reach for equal Squark- Gluino masses:

- 0.1 fb\(^{-1}\) \(\Rightarrow\) \(M \sim 750\) GeV
- 1 fb\(^{-1}\) \(\Rightarrow\) \(M \sim 1350\) GeV
- 10 fb\(^{-1}\) \(\Rightarrow\) \(M \sim 1800\) GeV

Deviations from Standard Model due to SUSY at TeV scale can be observed fast!

\[ M_{\text{eff}} = p_t + \sum p_{t\text{jet}} \]

Average \(M_{\text{eff}}\) correlated with mass of strong interacting SUSY particles.
Standard Model Higgs Boson Search

\[ \sigma(pp \rightarrow H+X) \] [pb]

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

\[ M_t = 178 \text{ GeV} \]

CTEQ6M

Djouadi, Kalinowski, Spira

hep-ex/0507091
Simulation of a 130 GeV mass Higgs→μμee event in ATLAS
Standard Model Higgs in CMS

\[ H \rightarrow \gamma \gamma \]

\[ H \rightarrow ZZ^* \rightarrow 4l \]

\[ H \rightarrow WW^* \rightarrow 2l2\nu \]

CMS full simulation, \( L = 10 fb^{-1} \)

\[ H \rightarrow WW \rightarrow 2l, m_H = 165 GeV \]

All selection cuts

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Similar performance/sensitivity expected in both experiments

In the low mass region the CMS Higgs → γγ optimized analysis better performance
With 10 fb\(^{-1}\) per experiment discover SM Higgs boson in large mass range.
CMS Higgs→ZZ* /WW* sensitivity with 1 fb⁻¹ @ 14 TeV

CMS, 1 fb⁻¹ @ 14 TeV
Higgs → ZZ*

CMS, 1 fb⁻¹ @ 14 TeV
Higgs → WW*
Higgs search @ 10 TeV

14 TeV → 10 TeV:
loss of a factor of 1.5 in sensitivity
or factor of 2 in luminosity

Combination of 0j and 2j, H to WW to ll

m_H = 130 GeV ●
m_H = 150 GeV ▲
m_H = 160 GeV ▼
m_H = 170 GeV *
m_H = 180 GeV ■

1 fb^{-1}

With roughly ~200 pb^{-1} reach
sensitivity for SM Higgs with
m_H \sim 160-170 GeV
(comparable to the current Tevatron sensitivity)
• After almost 20 years of design and construction the experiments started successfully taking data with LHC beams on the 10th of September 2008

• Operation interrupted shortly after by an incident due to a faulty electrical connection between two magnets. Repairs progressing well and the revised schedule foresees first collisions at 10 TeV at the end of 2009

• Commissioning of the experiments in the underground caverns with cosmics has demonstrated excellent detector quality and has allowed first alignment, calibration and timing studies to be made with the final detectors → experiments ready to do good physics with first collision data
Summary

With the first 100-200 pb\(^{-1}\) collision data at 10 TeV

• Re-Establish the Standard Model
  - Measure particle multiplicity in minimum bias
  - Measure QCD jet cross sections
  - Measure W/Z jet cross section with \(~10\%\) precision and improve knowledge on proton PDFs
  - Observe first top signals with 50 pb\(^{-1}\) and measure ttbar cross sections with 100-200pb\(^{-1}\)
  - First tuning of MC (minbias, underlying event, tt, W/Z+jets, QCD jets, ...)

• Searches
  - Discover SUSY up to gluino masses of \(~1\) TeV
  - Discover Z’ up to masses of \(~1\) TeV
  - With 200pb\(^{-1}\) reach sensitivity for SM Higgs with \(m_H\approx160-170\) GeV
  - Other surprises ...
BACKUP
First QCD measurements

Charged Particle Multiplicity

Integrated luminosity required to reach a 0.5% precision ($p_T$ balance fit mean) for various $p_T$ ranges in the region $0.7<\eta<0.8$ with different selection cuts

QCD Dijets $p_t$ balance

$dN_{ch}/d\eta$ in different bins of multiplicity in the first pixel layer

Underlying Event studies

Densities $dN/d\eta d\phi$ for tracks $p_t>0.9$ GeV as a function of the leading charged jet $p_t$ in the transverse plane for 100 pb$^{-1}$ @14TeV
• W and Z cross sections predicted exactly for LHC
• Rapidity for lepton decays sensitive to PDFs
• Simulate events (HERWIG6.505+CTEQ6.1) with addition of a random 4% “systematic error” scatter on these pseudo-data. Redo the PDF fit including them.
• Error on parameter $\lambda (xg(x) \sim x-\lambda)$ reduced by 35%

ZEUS-PDF before inclusion of W pseudo-data

ZEUS-PDF after inclusion of W pseudo-data
The LHC will confirm the outcome soon! ☺

Higgs boson in the mass range 160-170 GeV excluded
- Expected limits of 1.1 (1.4) x sSM at 160 (170) GeV

S. Pagan Griso
Moriond QCD 2009