First LHC Results

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Content

LHC performance
CMS and ATLAS detectors
SM measurements
SUSY discovery potential
Status of first SUSY analyses
Geneva

Tunnel circumference: 27 km, ~ 100m under ground.
1232 main +7000 smaller magnets,
\[ B = 8 \text{ Tesla (at 14TeV)} \]
Operating temperature: 1.9K

4 Experiments: ATLAS, CMS, ALICE, LHCb.
ATLAS

Support structure and magnet coils
2006

Beam pipe installation

Magnetic end-cap

Muon wheel
2008
Past
Data taking at 7TeV since 03/2010.

Current program
Alternating periods of machine LHC commissioning and physics data taking
• Initial collisions with $2 \times 10^{10}$ p/bunch
• Squeeze, increase # bunches to 13/beam
• Commission nominal bunch of $10^{11}$ p with 3, 6, … 25 bunches per beam
• August 2010 → 100s bunches (nominal LHC 2880/beam)

Future aims
L = $10^{32}$ cm$^{-2}$s$^{-1}$ by end 2010
I L = 1 fb$^{-1}$ by end 2011.

Delivered luminosity increasing exponentially!
Current peak luminosity: 1.6 $10^{30}$ cm$^{-2}$s$^{-1}$

Luminosity uncertainty: 11%!

Recent fill example:

<table>
<thead>
<tr>
<th>Inner Tracking Detectors</th>
<th>Calorimeters</th>
<th>Muon Detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel</td>
<td>SCT</td>
<td>TRT</td>
</tr>
<tr>
<td>97.1</td>
<td>98.2</td>
<td>100</td>
</tr>
</tbody>
</table>

Luminosity weighted relative detector uptime and good quality data delivery during 2010 stable beams at $\sqrt{s}=7$ TeV between March 30th and July 15th (in %)

Total collected:

ATLAS uptimes at 7 TeV
Claus Horn: First LHC Results

**ATLAS Detector**

Coverage in pseudorapidity
- Tracking $|\eta| < 2.5$
- Calorimeter $|\eta| < 4.9$
- Muon spectrometer $|\eta| < 2.7$

Size: 44m x 25m
Weight: 7000 tons
Readout channels: $10^8$

**Trigger system**
- Input: 40 MHz
- L2: 75 kHz
- Output: 200 Hz
Calorimeter contained inside solenoid

Muon chambers embedded in iron return yoke.

Weight: 12500 t
Length: 12.6m
Diameter: 15m
Magnetic Field: 4 T
Detector Performance
CMS observation of $D^0 \rightarrow K \pi$

$p_T(K) > 1.25 \text{ GeV}, \ p_T(\pi) > 1 \text{ GeV}$

good sec vertices

$\angle(p_{D0}^\ast, PV : SV) < 0.1$

ATLAS observation of $D^* \rightarrow D^0 \pi$

$|m(K\pi) - 1.865 \text{ GeV}| < 20 \text{ MeV}$

$p_T$ of $D^*$ > 4.5 GeV

$m_{D^*} - m_{D^0} = 145.56 \pm 0.12 \text{ MeV}$

(PDG: $145.436 \pm 0.016 \text{ MeV}$)

Other observed particles:

$\Lambda, K_s, K^*(890), \phi(1020), \Xi(1320), \Omega(1670)$
Measurement of high $p_T$ jets

Jet distributions for jet $p_T > 30$ GeV

Good agreement in jet $p_T$ spectrum over many orders of magnitude.

Dijet properties well described.
Observation of $J/\psi$

Using combined muon+ID tracks.
Good agreement observed.
Di-muon invariant mass: $3.095 \pm 0.001$ GeV
(PDG: $3.09 \pm 0.00001$ GeV)

Observation of Y excited states

Selecting events with $|\eta(Y)| < 1.0$

- Signal events $Y(1S)$: $218 \pm 17$
- Signal events $Y(2S)$: $43 \pm 9$
- Signal events $Y(3S)$: $22 \pm 8$
- Background events: $385 \pm 24$
Fundamental questions of particle physics:

- Origin of matter: Higgs
- Hierarchy problem: SUSY
- Extra dimensions, black holes
- Origin of dark matter: WIMPs,
- Many other scenarios: 4\textsuperscript{th} generation, LFV, etc.

Dark matter candidates at LHC:
- Lightest SUSY particle (LSP)

Signatures
- Missing energy
- High pT jets and leptons
- Kinematic edges
Rediscovering the SM: $W^\pm$

**$W \rightarrow e\nu$ by ATLAS**

- Data events: 815
- MC normalized to number of observed data events.

**$W \rightarrow \mu\nu$ by CMS**

- Data events: 940
- Expected in MC:
  - 1019 signal
  - 50 background
CMS W→μν candidate

CMS Experiment at LHC, CERN
Run 133875, Event 1228182
Lumi section: 16
Sat Apr 24 2010, 09:08:46 CEST

Muon $p_T = 38.7$ GeV/c
ME$_T = 37.9$ GeV
M$_T = 75.3$ GeV/c$^2$
Z-$\rightarrow$$\mu\mu$ peak observation

Data events: 93

Expected in MC:
100.0 signal
0.4 background

Cross section measurement from Z-$\rightarrow$ee + Z-$\rightarrow$$\mu\mu$

Requiring $66 < m_{ll} < 116$
125 candidate events in 225 nb$^{-1}$

Deduced cross-section:
$0.83 \pm 0.07$ (stat) $\pm 0.06$ (syst) $\pm 0.09$ (lumi) nb
(theoretical prediction: $0.964 \pm 0.039$)
MET in MinBias data: modeling of fake MET.

$E_T^{\text{miss}}$ well behaved, excellent detector performance.

Even tail is well described -> we are ready to look for new physics!

Four different algorithm give similar results.
Typical example, but untypical SUSY event:

Production of two strongly interacting sparticles: squark/gluino has highest x-sect.

Possible LSPs: χ, \tilde{\nu}, \tilde{\chi} (model specific)

Possible decay chains (dependent on spectrum and neutralino/chargino composition):

(Gauginos χ are the superpartners of the SM bosons (γ, Z₀, W±, Higgs)).
Missing transverse energy (MET)
Calculated from calorimeter cells.
Actually we only measure $p_T$-miss
Scalar jet $p_T$ sum (MHT):
If jet $p_T$ are high

MPT
Calculated from tracks:
$M_{\text{eff}}$
$M_{\text{PT}} \equiv | - \sum_i p_T^2(\text{track}_i) |
If jet and lepton $p_T$ are high

Transverse mass $M_T$:
$M_T = \sqrt{2(p_T^\text{lep}E_T^\text{miss}(1 - \cos(\Delta \Phi(\text{lep},E_T^\text{miss}))))}$

• Depends on mass difference, not $m_{\text{LSP}}$.
• Can be small.
MC Studies of mSUGRA Reach (@ 7TeV)
ATLAS expected Reach

Inclusive channels: 0 lepton, 1 lepton ($e, \mu$), 2 leptons (same-sign, opposite-sign)
Calculating 5 $\sigma$ discovery reach in $m_0$-$m_{1/2}$ plane, $\tan\beta=10$, $A_0=0$, $\mu>0$:
Assuming conservative uncertainties (20% electroweak, 50% QCD).

Gluino/squark masses up to 600 GeV.  
Gluino/squark masses up to 800 GeV.
0 Lepton Analysis

- Quite inclusive selection
- Based on $H_T$ and $p_T^{miss}$
- Vetoing leptons
- SM Backgrounds estimated from the data.

Same-Sign Dilepton Analysis

- Less inclusive, but small backgrounds.
- Three channels analyzed: $\mu\mu$, $ee$, $\mu e$
- Main background from $t\bar{t}$: <1 evt/100 pb$^{-1}$

Extension of LEP & Tevatron limits with $\leq 100$ pb$^{-1}$. 
First SUSY Studies with 7 TeV Data

Complete list of 7TeV results:

https://atlas.web.cern.ch/Atlas/GROUPS PHYSICS/CONFNOTES/
Generally good data/MC agreement observed in all cases.

Fraction of background events decreases exponentially with increasing $H_T$.

SUSY analysis typically require $H_T>300$ GeV
Using QCD to predict fake MET in γ+jets events

MET measured for QCD multi-jet events in bins of #jets and H_T.

selecting γ pT > 15GeV, ≥ 3 jets with pT>40 GeV.

Calculate predicted MET by looking up MET in #jets, HT bin for each γ+jets event.

Distinguishing real and fake MET

Simulating real MET by randomly removing one jet (‘EmulatedMHT’).

MPT and MHT are aligned for real MET, uncorrelated for QCD.

Data shows no sign of real MET.

Kinematic region will be extended with more luminosity.
Estimation of lepton backg

Muon background prediction with isolation fits

Determination of background from non-prompt muons to prompt muon signal.

Extrapolation from the non-isolated to the isolated muon region.

Estimating QCD backgrounds in lepton channels

Very small QCD backg expected, may be estimated by assuming factorization of selection efficiencies:

\[ \epsilon_{ABC} = \epsilon_A \epsilon_B \epsilon_C \]

Application to same-sign di-muon search:
- Cut A \( \equiv \) Relative isolation of \( \mu_1 \) below some value
- Cut B \( \equiv \) Relative isolation of \( \mu_2 \) below the same value as A
- Cut C \( \equiv \) Presence of a 3rd jet and large MET

Confirmation observed in data: \( \epsilon_{AB} = (\epsilon_A)^2 \)
Final state: jet + MET [ATLAS-CONF-2010-065]

Same inclusive channels as in MC studies (+Monojet).

Selection criteria for different channels

<table>
<thead>
<tr>
<th>Number of jets</th>
<th>Monojets</th>
<th>$\geq 2$ jets</th>
<th>$\geq 3$ jets</th>
<th>$\geq 4$ jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leading jet $p_T$ (GeV)</td>
<td>$&gt; 70$</td>
<td>$&gt; 70$</td>
<td>$&gt; 70$</td>
<td>$&gt; 70$</td>
</tr>
<tr>
<td>Subsequent jets $p_T$ (GeV)</td>
<td>veto if $&gt; 30$</td>
<td>$&gt; 30$</td>
<td>$&gt; 30$ (Jets 2 and 3)</td>
<td>$&gt; 30$ (Jets 2 to 4)</td>
</tr>
<tr>
<td>$E_T^{miss}$</td>
<td>$&gt; 40$ GeV</td>
<td>$&gt; 40$ GeV</td>
<td>$&gt; 40$ GeV</td>
<td>$&gt; 40$ GeV</td>
</tr>
<tr>
<td>$\Delta\phi(jet, E_T^{miss})$</td>
<td>no cut</td>
<td>$[0.2, &gt; 0.2]$</td>
<td>$[0.2, &gt; 0.2, &gt; 0.2]$</td>
<td>$[0.2, &gt; 0.2, &gt; 0.2, &gt; 0]$</td>
</tr>
<tr>
<td>$E_T^{miss} &gt; f \times M_{cut}$</td>
<td>no cut</td>
<td>$f = 0.3$</td>
<td>$f = 0.25$</td>
<td>$f = 0.2$</td>
</tr>
</tbody>
</table>

Loose selection for comparison with SM.
70 nb$^{-1}$ analyzed so far.

More luminosity needed for SUSY to become visible.

All results agree with SM expectations.

QCD normalized to data in low MET control region.
1 lepton Analysis

Electron Channel:
- lepton $p_T > 20$ GeV
- 2 jets with $p_T > 30$ GeV
- $|\eta| < 2.5$

Muon Channel:
- lepton $p_T > 20$ GeV
- 2 jets with $p_T > 30$ GeV
- $|\eta| < 2.5$

For all lepton channels: QCD normalized to data in low MET control region.

Data: 1
MC: 2.8±1.2

Data: 2
MC: 3.6±1.6
At least 2 leptons, one with $p_T > 20 \text{GeV}$, others with $p_T > 10 \text{ GeV}$

Dilepton invariant mass $> 5 \text{ GeV}$

No jet requirements.

**Opposite-sign channel**
Leptons from $Z^0, H^0$ or $\tilde{\ell}^+ \tilde{\ell}^-$ chain

**Same-sign channel**
Leptons from different decay chains

General result: SM backgrounds to SUSY searches are under good control!
Interesting Event

\[ \text{MET} = 118 \text{ GeV}; \mu \text{on } p_T = 25 \text{ GeV} \]

\[ M_{\text{eff}} = 915 \text{ GeV (using two highest } p_T \text{ jets)} \]
Outlook

Standard approach looks at convolution of all decays at specific SUSY point.

Future: Decay mode specific analyzes

- SUSY model-independent interpretation of results
- Increased coverage of SUSY scenarios (mass constraints in special SUSY models)
- Increased sensitivity (less inclusive)
- Favors determination of sparticle properties

[arXiv:0905.4497v2]
LHC is producing proton-proton collisions at world-record energies of 7TeV.

ATLAS and CMS are showing excellent performance.

Large amount of measurements let us rediscover the SM at 7 TeV.

Searches for new physics phenomena have started!

Large number of SUSY and dark matter searches!

Sensitivity advantage over Tevatron, great potential for the near future.
Bonus Material
The ATLAS Collaboration

~2900 authors
(1000 students)
38 countries
174 institutes
Sensitivity LHC/Tevatron

Unitary limit for scattering in the J = 0 (S-wave) partial wave:

\[ \delta_{j=0}^{\text{max}} = \frac{4\pi}{k^2} \]

(k: wave number)

Expected events:

\[ \delta N = \left( \int \mathcal{L} \, dt \right) \times \left( \int x_1 f(x_1) x_2 f(x_2) \frac{2}{\sqrt{s}} \frac{16\pi}{\hat{s}} \, dy \right) \times (\delta \sqrt{s}) \]

Reduced by \( \alpha_s^2 \) for strong sparticle pair-production.

Already now (with factor \( 10^5 \) less luminosity)
LHC has higher sensitivity for \( \sqrt{s} > 1.1 \) TeV

[plot by A. Barr]
Using tracks from charged particles for track reconstruction

Association of tracks to PVs allows for robust results under pileup
Good data/MC agreement for jets with $p_T > 10$ GeV
Good agreement between track jets and calorimeter jets.