Early Physics Measurements at the LHC with ATLAS

Karsten Köneke
DESY
for the ATLAS Collaboration
**Outline**

**Introduction:**
- Why was the LHC built?
- What is the mission of ATLAS?

**Standard Model measurements**
- First, try to measure known processes to understand the detector!

**Possible early discoveries:**
- If we are lucky, we will see something unexpected…
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Introduction:
• Why was the LHC built?
• What is the mission of ATLAS?

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Possible early discoveries:
• If we are lucky, we will see something unexpected…

“Prediction is very difficult, especially if it is about the future.”
Niels Bohr
The 4 Forces in Nature

Gravity

Graviton?
Solar systems
Galaxies

Gravity Force
The 4 Forces in Nature

Gravity
- Graviton?
- Solar systems
- Galaxies

Gravity Force

Electromagnetic force
- Hydrogen atom
- Water molecule
- Oxygen atom
- Protons and Neutrons
- Electron
- Oxygen atom
- Atoms
- Light
- Chemistry
- Electronics
The 4 Forces in Nature

Gravity

Strong

Electromagnetic
The 4 Forces in Nature

Gravity

Strong

Electromagnetic

Weak
The 4 Forces in Nature

Gravity

Electromagnetic

Strong

Weak

Standard Model
**Probably the best tested theory:**

- Describes 3 out of 4 known forces in nature.
- Tested in numerous experiments and sometimes incredible precision!
What is the LHC and ATLAS build for?

*Standard Model is very successful,…*
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…but incomplete! Some of the open questions are:
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• What is the origin of particle masses?
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• What is the nature of the dark matter in the Universe?
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• What is the origin of matter – antimatter asymmetry?
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• What are the constituents of the primordial plasma in the early Universe?
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• What happened in the first moments of the Universe after the Big-Bang?
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• What happened in the first moments of the Universe after the Big-Bang?
Finding new physics at the energy frontier!

\[ E = mc^2, \text{ or better (as it was in Einstein’s original paper): } m = E/c^2 \]
Finding new physics at the energy frontier!

\[ E = mc^2, \text{ or better (as it was in Einstein’s original paper)}: m = \frac{E}{c^2} \]

But in order to find new physics:

New physics = measurement – known backgrounds
What is the LHC and ATLAS build for?

Finding new physics at the energy frontier!

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But in order to find new physics:

New physics = measurement – known backgrounds

Or in other words:

Yesterday’s signal is today’s control sample and tomorrow’s background
What does the proton look like?

The proton is composed of three quarks: two up quarks (u) and one down quark (d).
What does the proton look like?

Partons =
- Quarks
- and Gluons
Figure 1: MSTW 2008 NLO PDFs at $Q^2 = 10 \text{ GeV}^2$ and $Q^2 = 10^4 \text{ GeV}^2$. 
How do pp collisions actually look like?

M. Wobisch
Louisiana Tech University

proton

two high-energetic hadrons

proton
How do pp collisions actually look like?

$m = E/c^2$

two high-energetic hadrons

M. Wobisch
Louisiana Tech University
How do pp collisions actually look like?

partons inside the hadrons:
parton density functions (PDFs)

Universal = process independent

two high-energetic hadrons

M. Wobisch
Louisiana Tech University
How do pp collisions actually look like?

Standard Model or New Physics??

proton

high $p_T$

hard interaction

outgoing parton(s) (quark, gluon, $\gamma$, $Z^0$, $W^\pm$)

proton

outgoing parton(s)

inclusive jets ($p_T$, $y$)
dijets ($M_{jj}$, $y'$)
$\gamma$, di-$\gamma$, $\gamma +$ jet
($Z^0$, $W^\pm$) + jet
top + anti-top

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hadron-hadron physics

proton

outgoing parton(s)

hard process (2 or more partons)
ISR/FSR
hadronization / fragmentation
underlying event
How do pp collisions actually look like?

It is really a big mess!!
LHC schedule for 2009/2010

First beam:
- Mid/end of November 2009

First collisions:
- At injection energy, i.e., 900 GeV center-of-mass energy
- For a short time (few days?)

First high-energy collisions:
- 7 TeV center-of-mass energy, i.e., 3.5 TeV per beam
- For a few months, to take a good amount of data for

First high-energy collisions:
- 10 TeV center-of-mass energy, i.e., 5 TeV per beam
- For another few months.
- Total integrated luminosity is planned to be around 200 pb⁻¹

1 Month of heavy ion running towards the end of the running period (November 2010)
Examples of cross section suppression in going from 14 TeV to 7 TeV:

- $W, Z \sim 45\%$
- $H (120 \text{ GeV}) \sim 30\%$
- $Z' (1 \text{ TeV}) \sim 18\%$
What we will do with the first collisions

Understanding the detector and reconstruction algorithms:
- Beyond the current understanding based on simulations, test beam, and cosmics data

Rediscovery of the Standard Model
- Establish how pp collisions at the LHC really look like
- Later on: precision measurements

Search for new physics:
- And determine what new model can actually describe the data

few pb\(^{-1}\) → ~10 pb\(^{-1}\) → ~100 pb\(^{-1}\)
Expected data samples

<table>
<thead>
<tr>
<th>Channel (example)</th>
<th>Expected event in ATLAS after cuts ($\sqrt{s} = 10$ TeV, 100 pb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi \rightarrow \mu\mu$</td>
<td>$\sim 10^6$</td>
</tr>
<tr>
<td>$Y \rightarrow \mu\mu$</td>
<td>$\sim 5 \times 10^4$</td>
</tr>
<tr>
<td>$W \rightarrow \mu\nu$</td>
<td>$\sim 3 \times 10^5$</td>
</tr>
<tr>
<td>$Z \rightarrow \mu\mu$</td>
<td>$\sim 3 \times 10^4$</td>
</tr>
<tr>
<td>$tt \rightarrow Wb\ Wb \rightarrow \mu\nu + X$</td>
<td>$\sim 350$</td>
</tr>
<tr>
<td>QCD jets $p_T &gt; 1$ TeV</td>
<td>$\sim 500$</td>
</tr>
<tr>
<td>Gluino, squark $m \sim 1$ TeV</td>
<td>$\sim 5$</td>
</tr>
</tbody>
</table>

Commission and calibrate detector

- $J/\psi, Z \rightarrow ee, \mu\mu; \ tt \rightarrow blv \ bjj$

Rediscover Standard Model

Early discoveries?

- $Z',$ SUSY,$\ldots$ or???
Jet measurements

What is actually a jet?

- Different jet algorithms give somewhat different results

Challenge:

- Jet energy scale determination and resolution.

Jet measurements

\[ \frac{d^2\sigma}{d p_T d y} \]

QCD-LO, $\mu = E_T/2$

- CTEQ4M
- CTEQ4HJ
- MRST

LHC

10 events with 100 pb$^{-1}$

$\sqrt{s} = 1.8$ TeV

Tevatron

$\sqrt{s} = 14$ TeV
Estimated number of events after cuts per pb$^{-1}$:

- At 10 TeV:
  - $\sim 10000 \ J/\psi \rightarrow \mu\mu$
  - $\sim 500 \ Upsilon \rightarrow \mu\mu$
  - $\sim 2000 \ J/\psi \rightarrow \text{ee}$
  - $\sim 400 \ Upsilon \rightarrow \text{ee}$

- At 7 TeV:
  - $\sim 7000 \ J/\psi \rightarrow \mu\mu$

Besides the cross-section measurement, this is useful for:

- Muon spectrometer and inner detector alignment, ECAL calibration, energy/momentum scale of full detector, lepton trigger and reconstruction efficiencies,…
Z boson measurement

Selection:
• 2 electrons with $E_T > 15$ GeV
• Loose identification criteria

Accuracy on inclusive cross section (no lumi):
• 2-4% (stat.) and 2-4% (syst.)

Measure e and $\mu$ efficiencies:
• In data: Tag&Probe with Z events
Measure differential $pp \rightarrow Z$ cross-section:

- As a function of $Z$ rapidity and of $Z\ p_T$
- More data needed. $\sim 200\ \text{pb}^{-1}$
- Interesting for constraining the parton density functions

$Z \rightarrow \text{ee}, 200\ \text{pb}^{-1}, 14\ \text{TeV}$
W boson measurements

Measure missing $E_T$ efficiency:

- Not easy to determine, lots of event cleaning needed (e.g. cosmic muons, hot cells in calorimeters,…)
- Use $Z$ events and replace one lepton to measure missing $E_T$ with data
**Selections:**
- Single isolated lepton with $|\eta| < 2.5$ and $p_T > 25$ GeV
- Missing $E_T > 25$ GeV
- Transverse mass $m_T^W = \sqrt{2p_T^l p_T^\nu (1 - \cos \Delta \phi)} > 40$ GeV

**W → ev, 50 pb$^{-1}$, 14 TeV**

**W → μν, 50 pb$^{-1}$, 14 TeV**

<table>
<thead>
<tr>
<th>Process</th>
<th>$N \times 10^4$</th>
<th>$B \times 10^4$</th>
<th>$A \times \epsilon$</th>
<th>$\delta A/A$</th>
<th>$\delta \epsilon/\epsilon$</th>
<th>$\sigma$ (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \rightarrow e\nu$</td>
<td>$22.67 \pm 0.04$</td>
<td>$0.61 \pm 0.92$</td>
<td>$0.215$</td>
<td>$0.023$</td>
<td>$0.02$</td>
<td>$20520 \pm 40 \pm 1060$</td>
</tr>
<tr>
<td>$W \rightarrow \mu\nu$</td>
<td>$30.04 \pm 0.05$</td>
<td>$2.01 \pm 0.12$</td>
<td>$0.273$</td>
<td>$0.023$</td>
<td>$0.02$</td>
<td>$20530 \pm 40 \pm 630$</td>
</tr>
<tr>
<td>$Z \rightarrow ee$</td>
<td>$2.71 \pm 0.02$</td>
<td>$0.23 \pm 0.04$</td>
<td>$0.246$</td>
<td>$0.023$</td>
<td>$0.03$</td>
<td>$2016 \pm 16 \pm 83$</td>
</tr>
<tr>
<td>$Z \rightarrow \mu\mu$</td>
<td>$2.57 \pm 0.02$</td>
<td>$0.010 \pm 0.002$</td>
<td>$0.254$</td>
<td>$0.023$</td>
<td>$0.03$</td>
<td>$2016 \pm 16 \pm 76$</td>
</tr>
</tbody>
</table>
**W boson measurement** – mass

**Two methods:**

1. Lepton $p_T$ measurement
   - $M_W \pm 120$ (stat.) $\pm 117$ (syst.)
   - Energy scale dominates

2. Transverse mass measurement
   - $M_W \pm 57$ (stat.) $\pm 231$ (syst.)
   - Recoil modeling dominates

<table>
<thead>
<tr>
<th>Method</th>
<th>$p_T(e)$ [MeV]</th>
<th>$p_T(\mu)$ [MeV]</th>
<th>$M_T(e)$ [MeV]</th>
<th>$M_T(\mu)$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta m_W$ (stat)</td>
<td>120</td>
<td>106</td>
<td>61</td>
<td>57</td>
</tr>
<tr>
<td>$\delta m_W$ ($\alpha_E$)</td>
<td>110</td>
<td>110</td>
<td>110</td>
<td>110</td>
</tr>
<tr>
<td>$\delta m_W$ ($\sigma_E$)</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>$\delta m_W$ (tails)</td>
<td>28</td>
<td>&lt; 28</td>
<td>28</td>
<td>&lt; 28</td>
</tr>
<tr>
<td>$\delta m_W$ ($\varepsilon$)</td>
<td>14</td>
<td>–</td>
<td>14</td>
<td>–</td>
</tr>
<tr>
<td>$\delta m_W$ (recoil)</td>
<td>–</td>
<td>–</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>$\delta m_W$ (bkg)</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>$\delta m_W$ (exp)</td>
<td>114</td>
<td>114</td>
<td>230</td>
<td>230</td>
</tr>
<tr>
<td>$\delta m_W$ (PDF)</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Total</td>
<td>167</td>
<td>158</td>
<td>239</td>
<td>238</td>
</tr>
</tbody>
</table>

**With 15 pb$^{-1}$:**
- Use of template fits
- Shown is a W mass change of 2%
W/Z + jets

**Z → µµ + jets**

- Background for many processes:
  - Top measurements, SUSY searches, …

**W → eν + jets**

- Diagrams showing Feynman diagrams for W→eν and Z→µµ + jets
- Graphs showing event distribution for Z→µµ + jets and W→eν + jets
- Cross section ratio uncertainty for Z→ee + jets

Karsten Köneke
August 24th 2009

HEP-MAD 2009 - Antananarivo
Top pair events

**Top Pair Branching Fractions**

- "alljets" 46%
- τ+jets 15%
- μ+jets 15%
- e+jets 15%
- "dileptons"
- "lepton+jets"

**After cuts in μ-channel:**
- 10 TeV: ~1600 events
- 7 TeV: ~600 events
- Uncertainty on cross section < 20% (+lumi)

**Contains most physics objects:**
- Leptons, jets, b-jets, missing $E_T$
- Background to almost all searches
- **When top is measured, experiment is ready for discovery physics!**

**tt → bW bW → blν bjj**

- 3 jets $p_T$ > 40 GeV
- 1 jet $p_T$ > 20 GeV
- $E_T^{miss}$ > 20 GeV
**First top quarks in Europe**

**Cross section:**
- Semi-leptonic channel
- No b-tagging!
- Precision expected on $\Delta \sigma/\sigma$:
  \[3(\text{stat.}) \oplus 15(\text{syst.}) \oplus 22(\text{lumi})\]

**Top mass:**
- Semi-leptonic channel
- With b-tagging!
- Precision: $1 - 3.5$ GeV
  for absolute scale knowledge $1 - 5\%$

**tt → bW bW → bev bjj**

**tt → bW bW → blv bjj**

*ATLAS Preliminary Simulation*

- $10$ TeV
- $200$ pb$^{-1}$

*ATLAS*

- $14$ TeV
- $1$ fb$^{-1}$
Ready for discovery…

BSM theory landscape (Murayama)
Searches

To find a deviation is easy…

• To prove that it comes from new physics is much harder!
• Simple-minded recipe:
  • Find variable(s) discriminating between signal and background
  • Cut away most background (maximize signal significance)
  • Estimate remaining background events and look at event yield in data

Need to worry and care about:

• Is the detector behavior really understood?
  • Efficiencies, fake rates, energy and momentum scales, non-gaussian resolutions,…
  • Try to obtain as much information as possible from data
• Is the Standard Model prediction really understood?
  • Cross sections, kinematic distributions, underlying event,…
  • Must know sources of uncertainties on these!
Possible early on: Z’ with mass ~1 TeV

- **Z’ → ee, 14 TeV, 1 fb⁻¹**

**New forces or new dimensions of space?**

- From angular distribution of leptons can disentangle Z’ (spin=1) from Graviton (spin=2)
- Requires more data…

- **Signal is (narrow) mass peak above small and smooth SM background**
- **Does not require ultimate EM calorimeter performance**
- **Sensitivity beyond Tevatron limits with 200 pb⁻¹ at 7 TeV (100 pb⁻¹ at 10 TeV)**
- **Perhaps sometime in 2010, if we are lucky??**
If it is at TeV scale, it could be found “quickly”… due to:

- Huge production cross section for $\tilde{q}\tilde{q}, \tilde{g}\tilde{q}, \tilde{g}\tilde{g}$
- If $m(\tilde{q}, \tilde{g}) \sim 1$ TeV:
  expect 1 event every 5 days at $L = 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$
- Spectacular final states (many jets, leptons, missing transverse energy)
Supersymmetry

5σ discovery reach, 10 TeV, 200 pb\(^{-1}\)

- Jets + \(E_T^{\text{miss}}\) channel: highest reach
- 1-lepton channel: more robust

\[ m(\tilde{q}, \tilde{g}) \sim 410 \text{ GeV} \]

- With 200 pb\(^{-1}\) at 7 TeV reach beyond Tevatron (~400 GeV)
- Tricky: understanding the background, i.e., missing \(E_T\)
- Ultimate LHC reach: ~ 3 TeV
Summary – Early physics potential at ATLAS

\[ \int \mathcal{L} dt \ (\text{pb}^{-1}) \]

- PDF constraint (150 \(\text{pb}^{-1}\))
- \(e^+e^-\) resonance @ 1 TeV (70 \(\text{pb}^{-1}\))
- \(\Delta \sigma/\sigma(W \rightarrow e\nu) \pm 0.05(\text{exp}) \pm 0.1(\text{lumi}) \ (50 \text{ pb}^{-1})\)
- First top in Europe (\(~20 \text{ pb}^{-1}\))
- \(\delta m_{\text{top}} < 10 \text{ GeV}, \delta \sigma_t \sim 20\% \ (100 \text{ pb}^{-1})\)
- \(Z\) peak (10 \(\text{pb}^{-1}\))
- \(J/\psi, \Upsilon\) peaks (1 \(\text{pb}^{-1}\))
Outlook – long term potential

Integrated Luminosity (fb⁻¹)

- 10⁴
- 10³
- 10²
- 10
- 1
- 10⁻¹
- 10⁻²
- 10⁻³
- 10⁻⁴


- H, m_H = 115 GeV
- H → 4l, m_H = 180 GeV
- m = 1 TeV SUSY (g, q)
- Z' → e⁺e⁻, m~1 TeV
- Leptoquarks, m~1.5 TeV
- Compositeness, Λ~30 TeV
- Extra-dimensions G → e⁺e⁻, m~1 TeV
- m = 2.5 TeV SUSY (g, q)
- TeV-scale resonances from WW scattering
- m = 3 TeV SUSY
- Z', m = 6.5 TeV
- Compositeness, Λ = 60 TeV

L = 10³⁵

SLHC

shutdown

Karsten Köneke
August 24th 2009
Outlook – long term potential

- Extra-dimensions $G \rightarrow e^+e^-$, $m \approx 1$ TeV
- $H, m_H = 115$ GeV
- $H \rightarrow 4l, m_H = 180$ GeV
- $m \approx 1$ TeV SUSY ($\tilde{g}, \tilde{q}$)
- $Z' \rightarrow e^+e^-$, $m \approx 1$ TeV
- Leptoquarks, $m \approx 1.5$ TeV
- Compositeness, $\Lambda \approx 30$ TeV
- $m = 2.5$ TeV SUSY ($\tilde{g}, \tilde{q}$)
- TeV-scale resonances from WW scattering
- $m = 3$ TeV SUSY
- $Z', m \approx 6.5$ TeV
- Compositeness, $\Lambda \approx 60$ TeV

$L = 10^{35}$
backup
The ATLAS Detector

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

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HEP-MAD 2009 - Antananarivo
Interaction of different particles in ATLAS
First ATLAS “beam splash event” recorded

September 10th, 10:19 am:
~ 100 TeV in the detector!

Beam bunches (2x10^9 protons at 450 GeV) stopped by (closed) collimators upstream of experiment “splash” events in the detector (debris are mainly muons)
First top quarks in Europe

\[ \text{tt} \rightarrow bW \ bW \rightarrow blv \ bjj \]

**Tri-jet mass**
- 10 TeV, 200 pb\(^{-1}\), \(\mu\)-channel
- No b-tagging!

**1 lepton** \(p_T > 20\) GeV

- 3 jets \(p_T > 40\) GeV
- 1 jet \(p_T > 20\) GeV

**\(E_T\text{miss} > 20\) GeV**

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