The latest results of the ATLAS experiment
Valeria Perez Reale (Columbia University)
• Large Hadron Collider (LHC) at CERN has entered a new energy regime: pp collisions at \( \sqrt{s} = 7 \) TeV
• New physics era for ATLAS experiment

- ATLAS Detector status and operation
- B-physics
- Rediscovery of SM processes:
  - Soft QCD
  - Hard QCD: Jets
  - Photons
  - W/Z bosons and top quark
- Physics searches beyond the SM at TeV scale

Many more results can be found at: https://twiki.cern.ch/twiki/bin/view/Atlas/AtlasResults
Atlas status and operation
Muons Spectrometer ($|\eta|<2.7$): air-core toroids with gas-based muon chambers. Muon trigger and measurement with momentum resolution $< 10\%$ up to $E_\mu \sim 1$ TeV.

3-level trigger reducing the rate from 40 MHz to $\sim 200$ Hz

Length: $\sim 46$ m
Radius: $\sim 12$ m
Weight: $\sim 7000$ T
$\sim 10^8$ electronic channels

EM calorimeter: Pb-LAr Accordion e/\gamma trigger, identification and measurement E-resolution: $\sigma/E \sim 10\%/\sqrt{E/GeV} \oplus 0.7\%$

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing $E_T$
E-resolution: $\sigma/E \sim 50\%/\sqrt{E/GeV} \oplus 0.03$ $|\eta|<3.2$

Inner detector ($|\eta|<2.5$): Si strips/pixels; TRT straws Vertexing, tracking, e/\tau separation
Resolution: $\sigma/pT \approx 3.8$ pT (GeV) x$10^{-4}$ $\oplus 0.015$

## Atlas Status

<table>
<thead>
<tr>
<th>Subdetector</th>
<th>Number of Channels</th>
<th>Approximate Operational Fraction</th>
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</thead>
<tbody>
<tr>
<td>Pixels</td>
<td>80 M</td>
<td>97.4%</td>
</tr>
<tr>
<td>SCT Silicon Strips</td>
<td>6.3 M</td>
<td>99.2%</td>
</tr>
<tr>
<td>TRT Transition Radiation Tracker</td>
<td>350 k</td>
<td>98.0%</td>
</tr>
<tr>
<td>LAr EM Calorimeter</td>
<td>170 k</td>
<td>98.5%</td>
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<tr>
<td>Tile calorimeter</td>
<td>9800</td>
<td>97.3%</td>
</tr>
<tr>
<td>Hadronic endcap LAr calorimeter</td>
<td>5600</td>
<td>99.9%</td>
</tr>
<tr>
<td>Forward LAr calorimeter</td>
<td>3500</td>
<td>100%</td>
</tr>
<tr>
<td>LVL1 Calo trigger</td>
<td>7160</td>
<td>99.9%</td>
</tr>
<tr>
<td>LVL1 Muon RPC trigger</td>
<td>370 k</td>
<td>99.5%</td>
</tr>
<tr>
<td>LVL1 Muon TGC trigger</td>
<td>320 k</td>
<td>100%</td>
</tr>
<tr>
<td>MDT Muon Drift Tubes</td>
<td>350 k</td>
<td>99.7%</td>
</tr>
<tr>
<td>CSC Cathode Strip Chambers</td>
<td>31 k</td>
<td>98.5%</td>
</tr>
<tr>
<td>RPC Barrel Muon Chambers</td>
<td>370 k</td>
<td>97.0%</td>
</tr>
</tbody>
</table>

### Total fraction of good quality data

<table>
<thead>
<tr>
<th>Inner Tracking Detectors</th>
<th>Calorimeters</th>
<th>Muon Detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel</td>
<td>SCT TRT</td>
<td>LAr EM LAr HAD LAr FWD Tile MDT RPC TGC CSC</td>
</tr>
<tr>
<td>96.7</td>
<td>97.5 100</td>
<td>93.8 98.8 99.0 99.7</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 30\textsuperscript{th} and August 30\textsuperscript{th} (in %)

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Van-der-Meer beam-separation method for calibration of luminosity detectors

The systematic uncertainty of the luminosity measurement is estimated to be 11%.

Overall data taking efficiency (with full detector on): 94%

To date collected: 14.43 pb^{-1}
Expected end of October 2010: ~ 50 pb^{-1}
Expected end of 2011: ~ 1 fb^{-1}
Challenging environment

- New peak record luminosity in ATLAS last Friday is $L \sim 8.8 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$
- LHC bunch trains: 248

“pile-up” (~40% of the events have > 1 pp interaction per crossing is $L \sim 2 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$)
- average number of pp interactions per bunch-crossing: up to 1.3

Event with 4 pp interactions in the same bunch-crossing

~ 10-45 tracks with $p_T > 150$ MeV per vertex
Vertex z-positions: −3.2, −2.3, 0.5, 1.9 cm
(vertex resolution better than ~200 µm)
• Three-level trigger architecture, exploiting the “region-of-interest” (RoI)
• Level1 (hardware FPGAs) and software based L2 and EventFilter (HLT)
• L < few $10^{27}$ cm$^{-2}$ s$^{-1}$: minimum-bias
  LVL1 trigger: hits in scintillator counters (MBTS) located at 
  $Z=\pm 3.5$ m from collision centre
  HLT running in transparent mode
• L > $10^{27}$ cm$^{-2}$ s$^{-1}$ : MBTS prescaled
  (only fraction of events recorded)
  Others items (EM2, J5, TAU5, MU0, ...): un-prescaled
• L ~ $10^{29}$ cm$^{-2}$ s$^{-1}$: start to activate HLT
  chains to cope with increasing rate
  while running with low LVL1 thresholds.

Figure gives examples for L up $7 \times 10^{29}$

All three trigger levels are now actively selecting events
HLT Tracking efficiency for electrons ET>5 GeV

LVL1 trigger efficiency from tag and probe for lowest threshold MU0

LVL1 trigger efficiency for lowest jet threshold J5

• Very important performance for physics measurements:
  • di-muon resonances
  • jet cross section
  • J/ψ to electron decays
Early resonances

- J/psi resonances and production
**J/ψ → e⁺e⁻**

Requirements:
- 2 EM clusters matched to tracks
- \(p_T(e\pm \text{tracks}) > 4, 2 \text{ GeV}\)
- track quality, calo shower shapes
- key handle: large transition radiation in TRT
- invariant mass from track parameters after Brem recovery (GSF)

Signal : 222 ±11 events
Background : 28 ±2 events
Mass peak : 3.09±0.01 GeV
Mass resolution : 0.07 ±0.01 GeV
J/ψ reconstruction uses the muon spectrometer to identify ID tracks that are muons from which we form combinations.

From J/ψ mass peak and resolution reconstructed in the ID: absolute momentum scale known to ~0.2% and momentum resolution to ~2% in the few GeV region
Di-muon resonances

Simple analysis:
- LVL1 muon trigger with $p_T \sim 6$ GeV threshold
- 2 opposite-sign primary muons reconstructed by combining tracker and muon spectrometer

J/Ψ production:
- measured over $|y (J/ψ)| < 2.25$, down to $p_T (J/ψ) \sim 1$ GeV in forward region
- pythia (Color Octet Model): good agreement in shape
- uncertainty dominated by (unknown) spin-alignment
Re-discovery of SM processes

- soft QCD
- hard QCD physics: Jets
- W and Z boson decays, W/Z+jets
- Top quark candidates
Particle multiplicities in minimum bias

- Measured over a well-defined kinematic region: 
  \( \geq 2 \) charged particle with \( p_T > 100 \) MeV, \( |\eta| < 2.5 \)
- No subtraction for single/double diffractive components
- Distributions corrected back to hadron level
  - High-precision *minimally* model-dependent measurements
  - Provide strong constraints on MC models

Experimental error: < 3 %

New results
- lower \( p_T \)
- larger diffractive component
  - poorer description by models
Jets: anti-kt algorithm

1. Start with a list of preclusters.

2. For each precluster i, define
   \[ d_i = p_{T,i}^2 \]
   For each pair of preclusters,
   \[ d_{ij} = \min(p_{T,i}^{-2}, p_{T,j}^{-2}) \frac{\Delta R_{ij}^2}{D^2} \]

3. Find the minimum of all \( d_i \) and \( d_{ij} \).

4. If \( d_{\text{min}} \) is a \( d_{ij} \), merge preclusters i and j into a new precluster.

5. If \( d_{\text{min}} \) is a \( d_i \), precluster i is a jet.

6. Repeat until no preclusters remain.

In practice:

- Like kT, anti-kT clusters nearby particles, but soft particles are combined with hard particles before combining with each other
- Collinear particles are still recombined first, but now with more circular jets
- No split/merge step necessary
- Infrared and collinear safe!
Missing energy: sensitive to calorimeter performance (noise, coherent noise, dead cells, mis-calibrations, cracks, etc.) and cosmics/beam- backgrounds

Jet momenta corrected (for calorimeter non-compensation, material, etc.) using $\eta/p_T$ dependent calibration factors derived from MC

JES systematic uncertainty: 7% for $p_T > 100$ GeV for $|\eta|<2.8$
• Understanding of jet constituents and properties very important for high pT physics

• Use anti-kT algorithm with distance parameter R=0.4 or 0.6
Key test of perturbative QCD in high $Q^2$, low-$x$ proton-proton collisions

- Measured jets corrected to particle-level using parton-shower MC (Pythia, Herwig)
- Experimental uncertainty: ~30-40% dominated by Jet E-scale
- Results compared to NLO QCD (with corrections for hadronization and underlying event)
- Theoretical uncertainty: ~20% from PDFs and scale normalizations

NLO pQCD in good agreement with data over 5 orders of magnitude
Testing ground for pQCD at high energies (higher-order corrections) and background to exotic searches

\[
p_T^j > 30 \text{ GeV}, \text{ one jet } p_T^j > 60 \text{ GeV } |y| < 2.8
\]

\[
H_T = \Sigma p_T
\]

- Expectations based on LO QCD agree with data within uncertainties
- The cross section ratios of n-1 to n jets is better described by ALPGEN

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• In principle, prompt photons are an excellent probe of the gluon density.

• Today, the major global fits avoid them:
  – A very large (2-3 GeV) intrinsic $k_T$ is needed to fit the data.
• LHC dominantly produced via Compton scattering

Data analysis towards prompt photon cross section measurement has started
ATLAS has collected $\sim 10^4$ W’s and $\sim 10^3$ Z’s per channel.

Fundamental milestones in the “rediscovery” of the Standard Model at $\sqrt{s} = 7$ TeV

- Powerful tools to constrain q,g distributions inside proton (PDF)
- $Z \rightarrow ll$ is gold-plated process to calibrate the detector to the ultimate precision
- Among dominant backgrounds to searches for New Physics
W bosons

Electrons $W \rightarrow e\nu$:
- $E_T(e) > 20$ GeV, $|\eta|<2.47$
  - excluding $1.37<|\eta|<1.52$
- tight electron identification
- $E_T^{miss} > 25$ GeV
- transverse mass $m_T > 40$ GeV

Muons $W \rightarrow \mu\nu$:
- $p_T(\mu) > 20$ GeV, $|\eta|<2.4$
- $|\Delta p_T$ (ID-MS)$| < 15$ GeV
- isolated; $|Z_\mu - Z_{\nu vtx}|<1$ cm
- $E_T^{miss} > 25$ GeV
- transverse mass $m_T > 40$ GeV

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- Main background QCD. Estimation: data-driven method based on control-samples in background-enhanced regions
- Main uncertainties from low-statistics of data control samples and MC model
Z bosons

\[ Z \rightarrow ee \]
- 2 opposite-sign electrons
- \( E_T > 20 \text{ GeV}, |\eta| < 2.47 \)
- medium electron identification criteria
- \( 66 < M (e^+e^-) < 116 \text{ GeV} \)

\[ Z \rightarrow \mu\mu \]
- 2 opposite-sign muons
- \( p_T > 20 \text{ GeV}, |\eta| < 2.4 \)
- \( |\Delta p_T (ID-MS)| < 15 \text{ GeV} \)
- isolated; \( |Z_\mu - Z_{vtx}| < 1 \text{ cm} \)
- \( 66 < M (\mu^+\mu^-) < 116 \text{ GeV} \)

Acceptance x efficiency: ~ 40%
Main background: \( tt, Z \rightarrow \tau\tau \)

- Still some work to do on alignment of ID and forward muon chambers, and on calorimeter inter-calibration, to achieve expected resolution

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W & Z CROSS SECTIONS

- Dominant experimental uncertainties: electron identification efficiency $\mu$: trigger and reconstruction efficiency
- Cross sections compatible with SM expectations

$$\sigma (W \rightarrow l\nu) = 9.3 \pm 0.9 \text{ (stat)} \pm 0.6 \text{ (syst)} \pm 1.0 \text{ (lumi) nb}$$

$$\sigma (Z \rightarrow ll) = 0.83 \pm 0.07 \text{ (stat)} \pm 0.06 \text{ (syst)} \pm 0.09 \text{ (lumi) nb}$$

$$\sigma (W \rightarrow \ell^+\nu) - \sigma (W \rightarrow \ell^-\nu) \neq 0$$

$$\sigma (W \rightarrow ll) = 0.83 \pm 0.07 \text{ (stat)} \pm 0.06 \text{ (syst)} \pm 0.09 \text{ (lumi) nb}$$

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W assymetry measurements:

A ($W \rightarrow e\nu$) = 0.21 $\pm 0.18$ (stat) $\pm 0.01$ (syst)

A ($W \rightarrow \mu\nu$) = 0.33 $\pm 0.12$ (stat) $\pm 0.01$ (syst)

NNLO theory prediction: A=0.2
• Jets produced in association with $W \rightarrow l\nu$, where $l$ is an electron or muon.
• The jet algorithm used is Anti-kT with $R=0.4$ The MC is normalized to the inclusive data sample.

Jets $|\eta|<2.8$ and $p_T>20$ GeV

• Next steps is cross-section and jet-ratio measurements for $W/Z+jets$
Z \rightarrow \mu^- \mu^+ + 3 \text{ jets}

Z \ m_T = 144 \text{ GeV} \quad m_Z (\mu\mu) = 79 \text{ GeV}
\ p_T(\mu_1) = 96 \text{ GeV} \quad p_T(\mu_2) = 68 \text{ GeV}
\ p_T(\text{jet}_1, \text{jet}_2, \text{jet}_3) = 168, 105, 45 \text{ GeV}
“Rediscovery” of top quark requires good understanding of full detector performance:
lepton identification, b-tagging and missing energy
Studies to understand backgrounds from data underway

Candidate Selection for lepton+jet:
- one isolated lepton $p_T(\ell)>20$ GeV, $|\eta|<2.5$
- $\geq4$ jets $p_T$(jet)$>20$ GeV, $|\eta|<2.5$
- $\geq1$ b-tagged jet $\sim50\%$ b-jet efficiency
- $E_T>20$ GeV

7 events in 290 nb$^{-1}$: consistent with MC expectations
top pair e-mu dilepton candidate with two b-tagged jets
Present goals:
- understand backgrounds by comparing MC to data for key search-sensitive distributions
- be prepared to set competitive limits on (or discover) New Physics when enough data available
High mass dijets

- Search for bump in smooth dijet mass spectrum
- Selection: $p_T(\text{jet}1) > 150$ GeV, $p_T(\text{jet}2) > 30$ GeV, $|\eta| < 2.5$, $|\Delta\eta| < 1.3$, $M_{jj} > 350$ GeV
- Systematics: Jet energy scale, background fit, luminosity

New world limit: $m(q^*) > 1.53$ TeV at 95% CL for excited composite quark $q^*$
Dijet angular distributions

• Angular distributions are sensitive to s-channel vs. t-channel (QCD) production of dijets (almost flat for QCD)
• Search for quark contact interactions leading to modifications dijet angular distribution
• Selection: $p_T(j1) > 80\text{--}150\text{ GeV}$, $p_T(j2) > 30\text{ GeV}$, $|\eta| < 2.5$, $|y1+y2| < 1.5$, $|y1-y2| < 4.9$

No significant deviation from QCD is observed: contact interaction $\Lambda$ scale 3.5 TeV (95%CL)
Extensions of the Standard Model predict the existence of additional heavy gauge bosons: spin-1 W’

- Selection electron loose $p_T > 20$ GeV, missing energy $E_T > 25$ GeV

**Exclusion limit for electron channel** $m_{W'} > 465$ GeV @ 95C.L.

- Expect to be competitive with Tevatron ($m_W > 1$ TeV) with 5pb$^{-1}$ of data for both electron and muon channel combined
• Since 30th of March 2010 the ATLAS detector has been collecting LHC data at √s = 7 TeV: more than ~13 pb⁻¹.
  • Congratulate and thank the LHC team for the great performance!
• The ATLAS experiment is in excellent shape: very high data taking efficiency and very high data quality have been achieved. Analysis of 7 TeV collisions, shows better detector performance than expected at this stage of the experiment.
• Broad range of SM measurements from low p_T to high p_T: resonances, high transverse momentum jets (exploring new territory), W and Z bosons, top event candidates
• Search for new physics beyond the SM: unexplored territory at TeV scale
  • improved limit on exited quark production and dijet angular distributions
• After 20 years of efforts building all aspects of the experiment: ATLAS is now exploring physics at new energy regime …many more results to come in the next months!
ATLAS experiment public results:
https://twiki.cern.ch/twiki/bin/view/Atlas/AtlasResults

Physics Publications:
• Search for New Particles in Two-Jet Final States in 7 TeV Proton-Proton Collisions with the ATLAS Detector at the LHC (PRL arXiv:1008.2461)
• Search for Quark Contact Interactions in Dijet Angular Distributions in 7 TeV Proton-Proton Collisions with the ATLAS Detector at the LHC (PLB arXiv:1009.5069)
• Measurement of inclusive jet and dijet cross sections in proton-proton collisions at 7 TeV centre-of-mass energy with the ATLAS detector (EPJC arXiv:1009.5908)

ATLAS Conference notes:
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/
BACK-UP SLIDES
Inner Detector

Early $K_{S}^{0} \rightarrow \pi^{+}\pi^{-}$ observed few days after collisions

Minimum Bias Stream, Data 2009 ($\sqrt{s}=900$ GeV)

ATLAS Preliminary

$K_{S}^{0}$ Invariant Mass

- Data
- Simulation
- Gauss (+poly) fit
  
  $\mu = 497.5 \pm 0.1$ (stat) MeV
  $\sigma = 2.2 \pm 0.1$ (stat) MeV
  
  PDG (2009) $\mu_{K_{S}^{0}} = 497.614 \pm 0.004$ MeV

$\sqrt{s}=900$ GeV

Momentum scale known to per mil in this range. Resolution as expected (dominated by multiple scattering)

Reconstructed conversion point in the radial direction of $\gamma \rightarrow e^{+}e^{-}$ from minimum bias events (sensitive to $X_{0}$)

Present understanding of material~ 10%
Transverse region particle densities
• There is a factor of ~2 increase in activity going from $\sqrt{s} = 900$ GeV to 7 TeV; all tunes predict a comparable relative increase
• In the plateau region the measured density corresponds to ~2.5 particles per unit $\eta$ at $\sqrt{s} = 900$ GeV and 5 particles per unit $\eta$ at $\sqrt{s} = 7$ TeV

All tunes underestimate particle density by ~10-15% in the plateau region
Susy searches

- Mainly trying to understand backgrounds, levels consistent with MC predictions
- Many SUSY models predict production of 3rd generation squarks
- Adding b-tagging requirement can enhance sensitivity

Jet+ MissingET
2 jets pT>(70,30 GeV)+1 btag jet + MetSig>2GeV^{1/2}
**Expected atlas reach**

| **Z' (SSM): Tevatron limit ~ 1 TeV (95% C.L.)** |
|------------------|------------------|
| 50 pb⁻¹          | exclusion ~ 1 TeV (95% C.L.) |
| 100 pb⁻¹         | discovery ~ 1 TeV |
| 300 pb⁻¹         | exclusion ~ 1.5 TeV |
| 1 fb⁻¹           | discovery ~ 1.5 TeV |

| **W' (SSM): Tevatron limit ~ 1 TeV (95% C.L.)** |
|------------------|------------------|
| 10 pb⁻¹          | exclusion ~ 1 TeV |
| 20 pb⁻¹          | discovery ~ 1 TeV |
| 50 pb⁻¹          | exclusion ~ 1.5 TeV |
| 100 pb⁻¹         | discovery ~ 1.5 TeV |
| 1 fb⁻¹           | discovery ~ 2 TeV |

| **SUSY (q̄, ḡ): Tevatron limit ~ 400 GeV (95% C.L.)** |
|------------------|------------------|
| 200 pb⁻¹         | discovery up to ~ 480 GeV |
| 1 fb⁻¹           | discovery up to ~ 700 GeV |

LHC has started to compete with the Tevatron in 2010, and should take over in 2011 in most cases.
Higgs sensitivity

• Higgs at 7 TeV, H to WW, mH ~ 160 GeV (157-175 GeV Tevatron Exclusion)
  • 300 pb-1 per experiment: ~3σ sensitivity combining ATLAS and CMS
  • 1 fb-1 per experiment: Could exclude 130 < mH < 190 GeV ~4.5σ sensitivity combining ATLAS and CMS

• Higgs at 14 TeV:
  • Exclusion of the full mass range down to mH~115 GeV requires ~1.5 fb-1 per experiment at 14 TeV
  • Discovery for mH ~ 115 GeV requires ~ 10 fb-1 per experiment at 14 TeV

Main channels at LHC: H \rightarrow gg, qqH \rightarrow \tau \tau
Boosted H\rightarrow bb at the LHC: ~30 fb-1 @ 14 TeV ATLAS+CMS: ~ 5σ

Winter 2012: LHC sensitivity with 1 fb-1 likely very similar to Tevatron sensitivity with 10 fb-1.