ATLAS Results from Run-2

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Summary of Run-1 Data Taking

- Run-1 data taking completed in Feb. 2013
  - Outstanding performance of LHC machine and ATLAS detector

- 453 papers submitted to date
  - Higgs boson observation
  - 199 measurements
  - 228 (null) search results
  - 26 papers documenting performance of detector, reconstruction and simulation

One plot each from 32 most recent Run-1 papers

Run-1 dataset unique & still being analysed actively
What’s new in Run-2?

• **Improved LHC**
  – Higher $\sqrt{s}$
    • Large increase in cross sections
  – Reduced bunch spacing: 25 ns
  – Higher integrated luminosity
    • More than 100 fb$^{-1}$ by end of 2018

• **Improved ATLAS experiment**
  – Upgrades to detector and trigger
  – Improved online, offline reconstruction and analysis software
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- **Improved discovery potential**
  - SUSY, $Z'$, black holes,…

- **Observation and study of rare processes**
  - $ttH$, 4-top, VBS, 3-boson,…

- **Higher precision measurements**
  - Higgs, top, $W/Z$, $B$, …
The ATLAS detector
Upgrades to ATLAS during LS1

• Infrastructure:
  – New beampipe, improvements to magnet & cryogenic system

• Detector consolidation
  – Muon chambers completion ($|\eta| = 1.1-1.3$) and repairs, improved readout of various systems (L1 rate 100 kHz), repair of pixel modules and calorimeter electronics, new pixel services, new luminosity detectors, new MBTS detector

• 4th silicon pixel detector layer (IBL)
  – Innermost Pixel detector layer at $R = 3.3$ cm from beam

• Trigger improvements
  – New Topological L1 trigger, new central trigger processor, coincidence between Tile and muons, restructuring of high-level trigger, new Fast TracK Trigger (FTK), improved L1 calorimeter trigger

• Software
  – Many improvements to simulation, reconstruction, grid and analysis software

=> See talk this week by M. Backes
More than 97% of channels working in each system
- Significant improvements w.r.t. run-1 in Pixels, Tile cal., CSC and TGC
- Work on RPC chambers ongoing

### ATLAS Detector Status

**Status:** April 2015

<table>
<thead>
<tr>
<th>Subdetector</th>
<th>Number of Channels</th>
<th>Approximate Operational Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixels</td>
<td>92 M</td>
<td>99.0%</td>
</tr>
<tr>
<td>SCT Silicon Strips</td>
<td>6.3 M</td>
<td>98.9%</td>
</tr>
<tr>
<td>TRT Transition Radiation Tracker</td>
<td>350 k</td>
<td>97.3%</td>
</tr>
<tr>
<td>LAr EM Calorimeter</td>
<td>170 k</td>
<td>100%</td>
</tr>
<tr>
<td>Tile calorimeter</td>
<td>4900</td>
<td>99.2%</td>
</tr>
<tr>
<td>Hadronic endcap LAr calorimeter</td>
<td>5600</td>
<td>99.6%</td>
</tr>
<tr>
<td>Forward LAr calorimeter</td>
<td>3500</td>
<td>99.8%</td>
</tr>
<tr>
<td>LVL1 Calo trigger</td>
<td>7160</td>
<td>100%</td>
</tr>
<tr>
<td>LVL1 Muon RPC trigger</td>
<td>370 k</td>
<td>98.7%</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>357 k</td>
<td>99.8%</td>
</tr>
<tr>
<td>CSC Cathode Strip Chambers</td>
<td>31 k</td>
<td>98.4%</td>
</tr>
<tr>
<td>RPC Barrel Muon Chambers</td>
<td>370 k</td>
<td>97.1%</td>
</tr>
<tr>
<td>TGC Endcap Muon Chambers</td>
<td>320 k</td>
<td>99.8%</td>
</tr>
</tbody>
</table>
• Integrated luminosity recorded: **133 pb⁻¹**
  - Data taking efficiency: 86%
    - Some data taken in non-standard conditions for calibration purposes
    - Up to 85 pb⁻¹ used for physics analyses shown today (50ns data)
    - 25 ns data taking just started last week

• Average Pileup: **µ~20**
  - Special runs taken with low pileup (µ<<1) => soft QCD studies at new energy

• Mini-scan for luminosity calibration taken in June
  - Current uncertainty: \( \delta L/L \pm 9\% \)
    - More extensive calibration scan planned for next week
A HUGE THANKS from the ATLAS collaboration to the CERN accelerator team for getting LHC ready for delivering 13 TeV pp collisions!
Run-2 Detector Performance
New Pixel Detector Layer: IBL

- IBL fully operational
  - Material mapped using photon conversions and hadronic interactions
- Significant improvement in impact parameter resolution
  - Reduced multiple scattering
  - Reduced size of pixels in longitudinal direction (400µm => 250 µm)
- Improved b-tagging
  - Expect ~4x better rejection of light flavor jets for b-tagging algorithms

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/InDetTrackingPerformanceApprovedPlots#Run_2
Jets and $E_T^{\text{miss}}$

- **Jets**
  - Energy scale calibration and uncertainty estimated with 2012 data
    - Uncertainty: ~1-6%
      - Depending on $p_T$ and $\eta$
    - Verified with early run-2 data
      - Will improve with in-situ calibrations

- $E_T^{\text{miss}}$
  - Resolution measured in minimum bias and Z candidate events
    - Good agreement between data and MC
• **Z’s and J/psi’s used to evaluate electron energy scale**
  – Mean and resolution already well understood
• **Electron identification**
  – Based on many variables combined in likelihood
  – Efficiencies between 75% and 95%
    • Differences between data and MC corrected by *in-situ* calibration
    • Uncertainty ~2%
Muons

- High reconstruction efficiency
  - Well modeled by simulation
  - Uncertainty <1% for $p_T>$20 GeV

- Muon momentum measurement
  - Combines Inner Detector and Muon Spectrometer information
  - At low $p_T$ dominated by Inner Detector

- Momentum scale already understood with precision of 0.2%
  - Resolution also understood to within 5% in this $p$ range
First Physics Results at $\sqrt{s}=13$ TeV
First Stable Beams

proton-proton collisions at 13 TeV
Inelastic pp Cross Section

- Basic quantity of QCD
- Important for understanding of cosmic rays
  - Probes energy range near the knee
- Important for understanding of pileup at LHC
Inelastic pp Cross Section

- **LHC measurements use two techniques:**
  - Elastic events in roman pot detectors (TOTEM, ATLAS ALFA)
    - Use optical theorem to extract total & elastic $\sigma$
    - ALFA: $\sigma_{\text{inel}}(7 \text{ TeV})=71.34\pm0.90 \text{ mb} [\text{arXiv: 1408.5778}]
    - Requires special running periods with different optics
  - Inelastic event counting (all LHC exp.)
    - Define fiducial region of event for which detector has high efficiency
    - Uses data taken at low pileup
      - Took such data in June 2015

- **New MBTS scintillators installed during shutdown**
  - 2 cm thick discs at $z=\pm3.6$ m
  - Efficiency high and uniform within $\pm1\%$
  - Pseudorapidity range: $2.07<|\eta|<3.86$
    - defines acceptance of fiducial measurement ($M_X>13$ GeV, $\xi>10^{-6}$)
Inelastic pp Cross Section

- Require at least two MBTS counter hits
  - Reduces beam backgrounds
- Constrain fraction of diffractive event in situ using events with hits on just one side
  - Reduces model dependence of measurement

Fiducial cross section

$65.2 \pm 0.8 \text{ (exp.)} \pm 5.9 \text{ (lum.) mb}$
Charged particles in Minimum Bias Events

- **Event selection:**
  - Triggered by MBTS trigger (ε>99%)
  - ≥1 track with $p_T>0.5$ GeV and $|\eta|<2.5$
  - Vertex (≥2 tracks with $p_T>0.1$ GeV)

- **Systematic uncertainties:**
  - On track reconstruction efficiency: 1.1-6.5%
    - Affected by material causing hadronic interactions
  - On vertex and trigger: <0.2%
  - On unfolding and mismeasurements: up to 5%
Charged particles in Minimum Bias Events

- Measurement compared to variety of MC models and tunes
  - Important to tune MC well as these are used to model pileup pp interactions

- Difficult to describe all distributions well
  - Pythia tunes and EPOS provide adequate description of data
    - A2 is currently used in ATLAS for pileup modeling
Charged particle multiplicity for $p_T > 0.5$ GeV at $\eta = 0$ versus $\sqrt{s}$

$N(13\text{ TeV})/N(8\text{ TeV}) \approx 1.2$
- Dramatic increase in number of high-multiplicity events
Long-range Correlations: "Ridge"

- High multiplicity events show long-range correlation at $\Delta \Phi \approx 0$: "near-side ridge"
  - Phenomenon first seen in Heavy Ion collisions
  - Observed in 7 TeV pp data by CMS (2010)

$C(\Delta \eta, \Delta \phi) = \frac{S(\Delta \phi, \Delta \eta)}{B(\Delta \phi, \Delta \eta)}$

$\Delta \eta = \eta^a - \eta^b$

$\Delta \phi = \phi^a - \phi^b$

S = same event
B = mixed events (= proxy for no correlations)
13 TeV pp ridge analysis

- **Event and track selection**
  - Dedicated high multiplicity trigger: MBTS (L1) and $>$60 tracks (HLT)
    - Complemented by MBTS-only trigger at low multiplicities
  - Use good tracks with $p_T>$0.4 GeV and $|\eta|<$2.5
13 TeV pp ridge analysis

- Event and track selection
  - Dedicated high multiplicity trigger: MBTS (L1) and >60 tracks (HLT)
    - Complemented by MBTS-only trigger at low multiplicities
  - Use good tracks with $p_T > 0.4$ GeV and $|\eta| < 2.5$

Study integrated yield for $2 < |\Delta\eta| < 5$

$$Y(\Delta\phi) = \left( \frac{\int B(\Delta\phi) d\Delta\phi}{N_a \int d\Delta\phi} \right) C(\Delta\phi)$$

with

$$C(\Delta\phi) = \frac{\frac{1}{2} \int d|\Delta\eta| S(\Delta\phi, |\Delta\eta|)}{\frac{1}{2} \int d|\Delta\eta| B(\Delta\phi, |\Delta\eta|)} = \frac{S(\Delta\phi)}{B(\Delta\phi)}$$
Ridge in 13 TeV pp collisions

- **Strength of near-side ridge consistent with 7 TeV CMS data**
  - Depends on both track multiplicity and $p_T$

- **New 13 TeV pp data much more precise**
  - Detailed studies possible!
J/psi candidates selected in dimuon decay channel: sources
- Prompt
- Non-prompt (from b-hadron decay)

Measure fraction of non-prompt J/psi’s

Fraction varies between 30 and 65%
- Very similar to 7 TeV data
Jet Production

- Jets reconstructed with anti-\(k_T\) algorithm, \(R=0.4\)
  - Central jets: \(|y|<0.5\)
- Cross section measured using 78 pb\(^{-1}\)
  - Largest uncertainty: luminosity (±9%)
  - Data agree well with NLO QCD calculation for various PDF sets
W and Z bosons

13 TeV collisions

Run: 265573
Event: 970468
2015-05-21 11:10:20 CEST
W and Z boson signals

- **Isolated electron or muon**
  - $p_T > 25$ GeV

- **W bosons**
  - $E_T^{\text{miss}} > 25$ GeV, $m_T > 50$ GeV

- **Z bosons**
  - Require two opposite-charge leptons
  - $66$ GeV$< m(\ell\ell) < 116$ GeV

<table>
<thead>
<tr>
<th>Number of events</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \rightarrow ev$</td>
<td>463,063</td>
</tr>
<tr>
<td>$W \rightarrow \mu\nu$</td>
<td>487,090</td>
</tr>
<tr>
<td>$Z \rightarrow ee$</td>
<td>34,955</td>
</tr>
<tr>
<td>$Z \rightarrow \mu\mu$</td>
<td>44,899</td>
</tr>
</tbody>
</table>
W and Z cross section measurement

• Fiducial and total cross section determined

\[ \sigma_{W}^{\text{fid}} \cdot BR(W \rightarrow \ell \nu) = \sigma_{W}^{\text{tot}} \cdot BR(W \rightarrow \ell \nu) \cdot A_{W} = \frac{N_{W}^{\text{sig}}}{C_{W} \cdot \mathcal{L}} \]

• Correction factor $C_{W}$:
  – Correct for efficiencies of trigger, lepton selection, resolution etc.

• Acceptance $A_{W}$:
  – Correct for fraction of events outside detector acceptance

• Main systematic uncertainties on cross section:
  – Background uncertainty: $\sim$3% (W’s)
  – Lepton reconstruction + trigger: 2-4%
  – Jet energy scale: 1.5-2.0% (W’s only)
  – Luminosity: 9%
Electron vs Muon Decay Channel

- **Excellent agreement between electron and muon channels**
  - Gives confidence in detector and trigger performance
  - Measurements combined to improve precision
Combined measurements agree with predictions

- Precision limited by luminosity uncertainty of ±9%
- Other uncertainties: ±2.3% (Z’s) and ±3.9% (W’s)

- Similar to precision of theoretical calculations due to PDFs and higher order corrections
Dependence of $\sigma(W)$ and $\sigma(Z)$ on $\sqrt{s}$

Cross sections increase by factor ~2 for both W’s and Z’s compared to 7 TeV
Ratio of W to Z cross section

- Many uncertainties cancel in ratio of cross sections
  - E.g. luminosity, lepton and trigger efficiency (partially), ..
- Measurement of $\sigma(W) \times BR(W \rightarrow l\nu)/\sigma(Z) \times BR(Z \rightarrow l\nu)$:
  - 13 TeV: $10.30 \pm 0.04$ (stat.) $\pm 0.33$ (syst.)
  - 7 TeV: $10.89 \pm 0.08$ (stat.) $\pm 0.16$ (syst) [with 2010 data, 40 pb^{-1}]

- Agrees with expectation within uncertainties
Ratio of $W^+ \text{ vs } W^-$ production

- $W^+/W^-$ asymmetry at pp collider production due to asymmetry in valence quarks
  - Well described by PDF sets for run-1 data
Ratio of $W^+ \text{ vs } W^-$ production

- $W^+/W^-$ asymmetry at pp collider production due to asymmetry in valence quarks
  - Well described by PDF sets for run-1 data

- At higher $\sqrt{s}$ probing lower $x$ values
  - Less valence quarks at lower $x$
  - Expect reduced asymmetry

- Data agree with various PDFs
  - Exp. uncertainty $\sim$3%
Top Quark Production

Run: 267638
Event: 193690558
2015-06-13 23:52:26 CEST
Top Quark production

- Event selection for leptons +jets channel:
  - Isolated e or \( \mu \) with \( p_T > 25 \) GeV
  - \( \geq 4 \) jets with \( p_T > 25 \) GeV
  - 2 b-tagged jets

- 259 data events in 6 pb\(^{-1}\)
  - Very small background
  - Kinematic properties agree with SM expectation (PowHeg)
Top cross section: dilepton channel

• Event selection
  – Isolated e and μ with $p_T > 25$ GeV
  – One or two b-jets
    • $N_1$: 1 b-jet
    • $N_2$: 2 bjets
• Solve equations for cross section and fraction of b-jets found ($\varepsilon_b$)

$$N_1 = L\sigma_{t\bar{t}}\varepsilon_{e\mu}2\varepsilon_b(1 - C_b\varepsilon_b) + N_1^{bkg}$$
$$N_2 = L\sigma_{t\bar{t}}\varepsilon_{e\mu}C_b\varepsilon_b^2 + N_2^{bkg}$$

• Largest uncertainties:
  – Luminosity (10%)
  – Theor. Modeling (5%)

$$\sigma_{t\bar{t}} = 825 \pm 49 \text{ (stat)} \pm 60 \text{ (syst)} \pm 83 \text{ (lumi) pb}$$

<table>
<thead>
<tr>
<th>Event counts</th>
<th>$N_1$</th>
<th>$N_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>319</td>
<td>167</td>
</tr>
<tr>
<td>$Wt$ single top</td>
<td>$29.0 \pm 3.8$</td>
<td>$5.6 \pm 2.0$</td>
</tr>
<tr>
<td>Dibosons</td>
<td>$1.1 \pm 0.2$</td>
<td>$0.0 \pm 0.0$</td>
</tr>
<tr>
<td>$Z(\rightarrow \tau\tau \rightarrow e\mu) +$ jets</td>
<td>$1.3 \pm 0.7$</td>
<td>$0.1 \pm 0.1$</td>
</tr>
<tr>
<td>Misidentified leptons</td>
<td>$6.0 \pm 3.9$</td>
<td>$2.8 \pm 2.9$</td>
</tr>
<tr>
<td>Total background</td>
<td>$37.3 \pm 5.5$</td>
<td>$8.5 \pm 3.5$</td>
</tr>
</tbody>
</table>

Data: $\varepsilon_b = 52.7 \pm 2.6$ (stat.) $\pm 0.6$ (syst.)%
MC: $\varepsilon_b = 54.3\%$
Top pair cross section versus $\sqrt{s}$

- Large increase of cross section:
  - $\sigma(13 \text{ TeV})/\sigma(8 \text{ TeV}) \approx 3.4$

$\sqrt{s}$ [TeV]
Towards New Physics Searches...

**Dilepton mass spectrum**

**ATLAS** Preliminary
\( \sqrt{s} = 13\) TeV, 78 pb\(^{-1}\)
Dilepton Search Selection

- Data
- \(Z/\gamma^*\)
- Top Quarks
- Diboson
- Multi-Jet & W+Jets
  Not Included

**Control-region for mono-jet search**

- \(p_T^{miss} > 80\) GeV
- \(E_T^{miss} > 100\) GeV
- one muon (\(p_T > 30\) GeV, \(|\eta|<2.5\))

**Diphoton mass spectrum**

\(G^+ \to \gamma \gamma\) selection
\(\sqrt{s} = 13\) TeV, 78 pb\(^{-1}\)

- Data
- Total background (normalised to event yield in data)
- Contribution from reducible background

**Control-region for SUSY search**

**ATLAS** Preliminary
\(L = 78\) pb\(^{-1}\)

- Data
- SM Total
- W+jets
- Top
- Z+jets
- Diboson

Conclusions and Outlook

- **ATLAS is working as well or better than in Run-1**
  - Significant improvements to detector and trigger
    - Performance already excellent, even for new components
  - Simulation describes the data well
    - Physics modeling by MC generators already better than Run-1

- **Many measurements made with up to 85 pb\(^{-1}\)**
  - Energy dependence of many SM processes studied over wide mass range
    - Measurements already constrain models of soft interactions and PDFs
  - Many measurements limited by luminosity uncertainty
    - Luminosity calibration scan next week
  - All Run-2 results:

- **ATLAS is ready and excited to fully explore physics at 13 TeV!**
  - Higher \(\sqrt{s}\) => new mass range for new physics
  - Higher luminosity => access to rare SM processes & extend precision programme
Extras
Commissioning for Run-2

- Cosmic Runs every few weeks with full detector since September 2014
  - Integrate all systems into new DAQ, exercise system etc.
  - Initial alignment studies for IBL
- Beam splashes: April 5\(^{th}\) and 7\(^{th}\) 2015
  - Timing of calorimeters
- 900 GeV collisions: May 5\(^{th}\) and 6\(^{th}\) 2015
  - Pixel and IBL turned on during “quiet beam”
  - 7M collision events
- 13 TeV test collisions: May 20\(^{th}\) and 21\(^{st}\) 2015
  - Pixel and IBL turned on during “quiet beam”
  - 21M collision events

13 TeV collision event in “quiet beam” mode, with tracks from two interaction points (“pile-up”)
Track hits in new IBL (Insertable B-Layer)
Underlying Event with Tracks

- Data described by Pythia
  - Difficulties for Herwig and EPOS at low and high $p_T$, respectively
• Inclusive photon spectra measured
  – Background determined using isolation distribution
  – Good agreement with MC expectation
Searches for new particles

- Could find evidence (3σ) up to ~1.5 TeV with 5 fb⁻¹