Hints from Run 1 and Prospects from Run 2 at ATLAS

Catrin Bernius
New York University

on behalf of the ATLAS Collaboration

PPC 2015
Deadwood, SD, 2. July 2015
Outline

• LHC and Run 1 data-taking
• Physics results
  • Standard Model & Top physics
  • Search that became a measurement: the Higgs Boson
  • SUSY & Exotics
• Prospects from Run 2
  • Detector upgrades & Commissioning
  • SUSY prospects

Not possible to present everything in this talk:
• B-physics
• Heavy Ions results
• And many interesting results and details...

Deliberately not covering Dark Matter results from ATLAS (dedicated talk by Sascha Mehlhase this morning)
Overall view of the LHC experiments.

CERN Accelerators
(not to scale)

LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LiNear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso

LINAC → PSB → PS → SPS → LHC

Start the protons out here

0.3c by here

0.87c by here

0.999999c by here
The ATLAS Experiment

ATLAS Collaboration:
38 countries, 177 institutes
3000 scientific authors
Hints from Run 1

- The LHC Run 1 & the ATLAS Experiment
- Summary of Standard Model, Top, Higgs, SUSY and exotic analyses
The LHC Run 1

Successful LHC Run 1 collecting pp data with the ATLAS experiment under challenging conditions:

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<thead>
<tr>
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<th>2010</th>
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<td>$\sqrt{s}$ [TeV]</td>
<td>7</td>
<td>7</td>
<td>8</td>
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<td>Peak luminosity [cm$^{-2}$s$^{-1}$]</td>
<td>$2.1 \times 10^{32}$</td>
<td>$3.7 \times 10^{33}$</td>
<td>$7.7 \times 10^{33}$</td>
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- Trigger challenge: how to select 400 out of 20M events per second while keeping the interesting physics, including the unknown inclusive unprescaled trigger thresholds within 5 GeV throughout the large luminosity increase
- Computing challenge: Reconstruct, store and distribute 400 complex events per second (reached 120 PB of data and simulation)
  → Data taking efficiency for 2012 (2011) was ~93.1% (93 %), data quality selection ~95.8% (90 %)

→ Very successful and efficient Run 1 for ATLAS
The ATLAS trigger system is a 3-tiered system:

- The ATLAS trigger system is based on two main levels: L1 and High Level Trigger (HLT), which is subdivided in L2 and Event Filter
- L1 is hardware-based, designed to reduce the rate from 40 MHz to 75kHz
- HLT is software-based, the event rate is further reduced to on average ~ 400Hz

- The trigger menu is designed for a given target luminosity, prescales sets corresponding to various luminosity steps adjust the rates at which the various triggers accept events throughout the run when the luminosity decreases
Summary of several SM total production cross section measurements:

- Good agreement with SM expectations within uncertainties
- Experimental uncertainties are in some cases at the level of the theoretical predictions, in some even better; in fact, sensitive to QCD in a few processes effects beyond NLO.
- Preliminary measurements of the cross-sections down to few pb (~ tens of fb in some cases if BR is included)

First evidence of electroweak $W^\pm W^\pm jj$ production:

- $W^\pm W^\pm jj$ and electroweak-only $W^\pm W^\pm jj$ production observed with a significance of 4.5 and 3.6 standard deviations respectively
- Measured production cross sections are in agreement with Standard Model predictions
- Limits at 95% confidence level are set on anomalous quartic gauge couplings

Top Production & Mass Measurement

Top-pair production cross-section at 8 TeV:
- compared to exact NNLO QCD calculation complemented with NNLL resumption
- theory band represents uncertainties due to renormalisation and factorisation scale, parton density functions and strong couplings

Precision mass measurement using 3D fit to reduce effect of Jet Energy Scale (JES) and bJES on the final measurement;
Combination of lepton + jets and dilepton channels gives a measured $m_t = 172.99\pm0.48\text{(stat)}\pm0.78\text{(syst)}$ GeV with a total uncertainty of 0.91 GeV
Since the discovery of the Higgs boson, an entire new field has emerged.

The Higgs boson observed is to a good precision compatible with the SM Higgs boson:
- direct evidence of coupling to W and Z
- direct evidence of coupling to taus (and therefore to fermions)
- direct evidence for non-universal couplings
- evidence for VBF production
- indirect evidence of coupling to top quarks
- evidence of the scalar nature

Establishing the properties of the Higgs boson has been possible and will continue to be through collaboration with the theory community.

Two key SM Higgs measurements submitted since Nov 14:
- $H \rightarrow WW^*\rightarrow 4l$: $6.1\sigma$ observed (5.8 exp) (arXiv:1412.2641)
- $H \rightarrow \tau\tau$: $4.5\sigma$ observed (3.4 exp) (arXiv:1501.04943)

The best fit of the signal strength is compatible with the SM:
- $\mu = 0 \rightarrow$ no Higgs
- $\mu = 1 \rightarrow$ SM Higgs
Invariant mass distribution of
- four-leptons for the selected candidates, compared to the background expectation in the 80-250 GeV mass range for the combination of $\sqrt{s} = 7$ and 8 TeV data
- di-photon candidates after all section for the combined 7 and 8 TeV data sample
  - (a/c) inclusive sample & weighted version
  - (b/d) residuals of the data/weighted data wrt respective fitted background component

Dominant SUSY particle production modes at the LHC
- squark-gluino, squark-squark, gluino-gluino
- Decay in cascades to Lightest SUSY Particles (LSP)

Assume R-Parity conservation
- The LSP is stable and escapes the detector unseen

Final states:
- Final states with jets and missing transverse momentum ($E_T^{\text{miss}}$)
- Additional objects, e.g. electrons, muons, taus, photons depending on decay chains

Also quite a few motivations to study BSM at the EW scale:
- Dark matter is WIMPs?
- Gauge group unification?
- Hierarchy problem?
  - Assuming new physics at some high scale, fine tuning can be greatly reduced by BSM near the EW scale

Search strategies developed by ATLAS target all these SUSY production modes

ATLAS excludes squarks < 850GeV for eight degenerate squarks, $m(\text{LSP}) = 0$
- gluinos up to 1330GeV excluded ($m(\text{LSP})=0$)

arXiv:1405.7875
SUSY Searches in Z+jets+MET

Two searches presented with SUSY particles in final states with same-flavour opposite-sign lepton pair, jets and large missing transverse momentum at \( \sqrt{s} = 8 \text{ TeV} \) and integrated luminosity of 20.3 fb\(^{-1} \) considering:

- decays of squarks and gluinos with Z bosons in the final state (\( Z \rightarrow \ell\ell \)) resulting in a peak in the di-lepton invariant mass distribution (m\(_{\ell\ell} \)) around the Z-boson
- decays of heavy neutralinos leads to a rising distribution in m\(_{\ell\ell} \) that terminates at a kinematic endpoint (events with larger m\(_{\ell\ell} \) values would violate energy conservation in the decay of a neutralino)

**Analysis:**
- Look at events with a \( Z \rightarrow \ell\ell \) candidate
- \( E_T^{\text{miss}} > 225\text{GeV} \) and \( H_T > 600 \text{ GeV} \) (applied to SR and CR)
  - \( H_T \) is the sum of the \( p_T \) of the jets and leptons
- VR regions at lower \( E_T^{\text{miss}} \) and \( H_T \) to cross-check SM background estimation methods
- Main background (ttbar) estimated from data using e\(\mu\) events with the same cuts as the SR, cross checked using Z side-bands
Results:

- squark/gluino case: excess of events above the expected SM background with a significance of 3σ (1.7σ) in the ee (μμ) channel
- neutralino case: data is well-described by expected SM background
Summary of ATLAS searches for electroweak production of charginos and neutralinos based on 20fb$^{-1}$ at $\sqrt{s} = 8$ TeV:

- Exclusion limits at 95% CL are shown in the $m_{\text{chargino}}$-$m_{\text{neutralino}}$ plane
- Four decay modes of the charginos and neutralinos are considered separately with 100% branching fraction, decays via sleptons and sneutrinos occur with 50% probability each

→ Stringent limits for EW production and production of third generation particles placed!

Summary of dedicated ALTAS searches for top squark (stop) pair production based on 20fb at $\sqrt{s} = 8$ TeV and 4.7fb at $\sqrt{s} = 7$ TeV:

- Exclusion limits at 95% CL are shown in the stop1-neutralino1 mass plane
- Three decay modes are considered separately with 100% BR

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/
Summary of ATLAS SUSY Searches

Mass reach of ATLAS searches for Supersymmetry:
- only a representative selection of available results is shown
- blue (green) bands indicate 7 TeV (8 TeV) data results

Inclusive Searches

<table>
<thead>
<tr>
<th>Model</th>
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<th>Mass limit</th>
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<td>mono-jet</td>
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3rd gen. squarks + gluinos

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Other

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*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/

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Hints from New Physics Searches

• High mass di-boson resonance searches with boson-tagged jets at $\sqrt{s} = 8$ TeV (arXiv:1506.00962)
  • Di-boson resonances are predicted in several extensions to the SM, such as
    • technicolor
    • warped extra dimensions
    • Grand Unified Theories
  • Production of W, Z bosons from decay of the massive resonance together with large transverse momentum relative to their mass:
    • each boson is reconstructed in a single large-radius jet
    • looking for resonance structure on a smoothly falling dijet invariant mass spectrum

• Results:
  • Most significant discrepancy with the background-only model occurs around 2 TeV in WZ channel with local significance of 3.4$\sigma$
  • Global significance with entire mass range in all three channels (WZ, WW, ZZ) of 2.5$\sigma$
• B-jet(s) with same-sign leptons and $E_T^{\text{miss}}$ (arXiv: 1504.04605)
  • SM processes rarely produce these final states but several BSM models predict them; considered:
    • vector-like quarks, chiral b’-quark pair production, two positively charged top quarks, $4$-top production
  • 2.5 $\sigma$ excess with 2/3 b-jets and large MET and $H_T$
    • Main background is tt+X (taken from simulation)
    • tt+X cross-checked with several generators, scaled to NLO
• Di-jet angular analysis (arXiv:1504.00357)
  • LHC di-jet production dominated by t-channel gluon exchange
  • Sensitive to new contact interactions, quark compositeness
  • QCD prediction reweighted to NLO with EW corrections
  • Amazing agreement with theory, small $\sim 2\sigma$ possible hint (?) at large mass…
• hh resonances in the bb $\gamma\gamma$ channel (arXiv:1406.5053):
  • Searches for non-SM physics with events consistent with either resonant ($X \rightarrow hh$) or non-resonant pair production of Higgs bosons
  • Look in the clean bb+$\gamma\gamma$ final-state
  • Small excess ($2.1 \sigma$ at $m_X \sim 300$ GeV)
B-jet(s) with same-sign leptons and $E_T^{\text{miss}}$ (arXiv: 1504.04605)
- SM processes rarely produce these final states but several BSM models predict them; considered:
  - vector-like quarks, chiral $b'$-quark pair production, two positively charged top quarks, 4-top production
- 2.5 $\sigma$ excess with 2/3 b-jets and large MET and $H_T$
  - Main background is $tt+X$ (taken from simulation)
  - $tt+X$ cross-checked with several generators, scaled NLO

Di-jet angular analysis (arXiv:1504.00357)
- LHC di-jet production dominated by t-channel gluon exchange
- Sensitive to new contact interactions, compositeness
- QCD prediction reweighted to NLO with EW corrections
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hh resonances in the $bb\gamma\gamma$ channel (arXiv:1406.5053):
- Searches for non-SM physics with events consistent with either resonant ($X \rightarrow hh$) or non-resonant pair production of Higgs bosons
- Look in the clean $bb+\gamma\gamma$ final-state
- Small excess ($2.1 \sigma$ at $m_X \sim 300$ GeV)

More Hints from New Physics Searches

FOLLOW UP IN RUN 2!!
New Physics Summary

Mass reach of ATLAS searches for new phenomena other than Supersymmetry:
- only a representative selection of available results is shown
- blue (green) bands indicate 7 TeV (8 TeV) data results

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/

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### ATLAS Exotics Searches* - 95% CL Exclusion

**Status:** March 2015

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<th>( E^{\text{min}}_T )</th>
<th>( \mathcal{L} dt ) [fb(^{-1})]</th>
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Catrin Bernius, NYU
Prospects from Run 2

- Detector upgrades & Commissioning
- Glimpse of Run 2 performance
- Higgs & SUSY prospects
ATLAS Upgrades for Run 2

Detector upgrades:
- Additional silicon layer (IBL) → improved tracking performance (e.g. ATL-INDET-PROC-2014-008)
- Diamond Beam Monitor (Background and Luminosity at $3.2 < |\eta| < 3.5$)
- Upgrade of Beam Condition Monitors
- New LUCID detectors
- New beam pipe
- Complete muon coverage
- Various repairs (TRT, LAr, Tile)

Software:
- Improved reconstruction software
- New analysis framework with new data format

Trigger/DAQ:
- Central Trigger Processor allowing for topological trigger
- Fast tracker (FTK): Real-time tracking for the HLT
- Increase L1 bandwidth from 75kHz → 100 kHz
- Higher HLT output rate (limited by storage capacity of ~1-1.5kHz)
- Merge of L2+EF farms, network upgrade → Flexible resource allocation in conjunction with combined network
Commissioning of the ATLAS Detector

First 13 TeV Stable Beam Collisions on June 3rd! Commissioning of the detector & software with the first data!
Prospects for SUSY in Run 2

• Expected sensitivity studies for gluino and squark searches using the early LHC 13 TeV studied for three cases:
  • gluino pair production in final states with large missing transverse momentum and
    • no leptons or
    • exactly one isolated lepton
  • bottom squark pair production
  • E.g. for gluino pair production with only a gluino and the lightest neutralino, a gluino with mass of 1.5 TeV could be seen with 3σ significance with 5 fb⁻¹
Conclusion

ATLAS and the LHC achieved important results
• Higgs boson discovery
• Strong constraints on new physics phenomena

Still many unanswered questions:
• Dark Matter candidate
• Naturalness of the Higgs Boson
• and many more!

Upgraded LHC & ATLAS detector
• Tremendous achievement of consolidation of the machine
• Smooth start-up
• On-going commissioning of the ATLAS detector so far very successful

Exciting times ahead: Run 2 will offer the opportunity to continue to explore the standard model and beyond with the upgraded ATLAS detector!!