Review on the LHC Run2 results

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Outline of this talk

• Introduction to LHC and the ATLAS Run2 experiment
• Review of physics results
  – Standard Model measurements
  – Higgs physics
  – Searches for New Physics phenomena; Exotics, SUSY
• Summary
Large Hadron Collider

• LHC is an energy-frontier collider at CERN, delivering proton-proton collision events
  – to two multi-purpose detectors; ATLAS and CMS
  – to dedicated detectors; LHCb for B-physics studies and ALICE for heavy-ion studies

• Recent history and future
  – LHC Run1 (2009-2012) with p-p collisions at $\sqrt{s} = 7-8$ TeV
  – Currently in a high-energy phase at $\sqrt{s} = 13-14$ TeV, Run2 (2015-2018), followed by a bit higher luminosity phase Run3 (2021-2023)
    • I review recent physics highlights in this talk
  – For future, high-luminosity LHC (2026-) and FCC (far beyond) is planned
    • B. Petersen will present the future physics program
    • M. Tomoto will present muon trigger upgrade (KMI’s contribution)
The ATLAS experiment

- The ATLAS detector is a multi-purpose detector that can directly explore energy scale from $O(10)$ GeV to $O(10)$ TeV
- The ATLAS experiment has around 2900 collaborators from 180 institutions across 38 countries
- KMI has been contributing to ATLAS
  - with primary focuses on “Muon Detector and Trigger system”, as well as on “Top physics and New Physics searches”
Physics highlights with the Run1 dataset

• Higgs discovery
  – Higgs-like particle discovery was announced on July 4th 2012 - Phys. Lett. B 716 (2012) 1-29
  – March 2013: key papers on particle properties. New particle declared as “a Higgs boson”
  – Citation for the 2013 Nobel Prize in Physics

• Deep and broad range of experimental results, all beautifully fitting in the Standard Model framework of elementary particle physics
√s = 13 TeV: parton luminosity increase

ratios of LHC parton luminosities: 13 TeV / 8 TeV

- gg
- ∑qq
- qg

> 10 x at High Mass

2 x at Low Mass
ATLAS in Run2

• Primary physics focuses
  – on New Physics searches using early datasets and
  – on measurements of Higgs properties using higher-statistics datasets

• New detectors installed
  – Innermost pixel layer (IBL); 3.4cm from the interaction point
  – Forward proton detectors (AFP); 210m from IP

• In addition, various consolidations provide improved running at high luminosities and rates
ATLAS data taking in 2016

- The 2016 pp data taking lasted until 26th October
  - Set a record in peak luminosity: $1.4 \times 10^{34}$
  - Total dataset recorded $\sim 36 \text{ fb}^{-1}$ with excellent data quality; >90% of data collected usable for analyses

Operations in the ATLAS control room

- 2016 was an extremely productive year, comparing with previous years

Delivered luminosities to ATLAS (per year)
Trigger challenge in high luminosities

- Critical contribution from KMI, including menu-coordination role

- Designed and operated a complex list of trigger selections to meet varied physics, monitoring and performance requirements
  - Typically ~2000 active trigger selections, driven by the priorities in the ATLAS physics program
  - Stable primary triggers
  - Peak output rate at Level-1; 90kHz
  - Ave. output rate at High Level to storage; 1.0kHz
  → meeting detector operation and DAQ requirements

<table>
<thead>
<tr>
<th>Main primary trigger</th>
<th>Trigger thresholds at HLT [GeV]</th>
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<tbody>
<tr>
<td>single leptons</td>
<td>Isolated $\mu$, $p_T &gt; 26$</td>
</tr>
<tr>
<td></td>
<td>Isolated $e$, $E_T &gt; 26$</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>$&gt; 110$ (in MHT, jet-based)</td>
</tr>
<tr>
<td>single jet</td>
<td>$p_T &gt; 380$</td>
</tr>
<tr>
<td>single photon</td>
<td>$E_T &gt; 140$</td>
</tr>
<tr>
<td>di-muon for B-phys</td>
<td>$p_T(\mu_1, \mu_2) &gt; 6, 6 + \text{topological/mass cuts}$</td>
</tr>
<tr>
<td>di-tau</td>
<td>$p_T(\tau_1, \tau_2) &gt; 35, 25 + \text{jet requirement at L1}$</td>
</tr>
<tr>
<td>di-photon</td>
<td>$p_T(\gamma_1, \gamma_2) &gt; 35, 25$</td>
</tr>
</tbody>
</table>

- Trigger menu for the rest of Run2 is being prepared for $2e34$
Physics Results

• ATLAS has submitted 605 papers in total
  – including 51 papers using Run2 dataset
  – the full list here: [https://twiki.cern.ch/twiki/bin/view/AtlasPublic](https://twiki.cern.ch/twiki/bin/view/AtlasPublic)

• Following slides review a few selected highlights, mostly using 13 fb\(^{-1}\) dataset, collected up to 2016 summer
  – Disclaimer; Topics here are driven by the priorities in the Run2 ATLAS physics program, by my tastes, as well as by the KMI’s contributions
  – Apologies if your favorite topics are not covered

From varied physics areas
• Measurements
Inclusive cross-section measurements: broad range

**ATLAS Preliminary**

**pp → X**
- Pythia8 (LO)

**pp → W**
- NNLO

**pp → Z / γ**
- NNLO

**pp → t̅t**
- 7 TeV, 4.6 fb⁻¹, Eur. Phys. J. C76 (2016) 6
- 13 TeV, 13.3 fb⁻¹, ATLAS-CONF-2016-081

**pp → t̅q**
- 7 TeV, 4.6 fb⁻¹, PRD 87, 112001 (2013)
- 8 TeV, 20.3 fb⁻¹, arXiv:1606.04017

**pp → H**
- 7 TeV, 4.6 fb⁻¹, Eur. Phys. J. C76 (2016) 6
- 13 TeV, 13.3 fb⁻¹, ATLAS-CONF-2016-081

**pp → WW**
- 7 TeV, 4.6 fb⁻¹, PRD 87, 112001 (2013)
- 8 TeV, 20.3 fb⁻¹, arXiv:1606.03086
- 13 TeV, 3.2 fb⁻¹, ATLAS-CONF-2016-090

**pp → WZ**
- 7 TeV, 4.6 fb⁻¹, JHEP 03, 128 (2013)
- 8 TeV, 20.3 fb⁻¹, ATLAS-CONF-2013-020
- 13 TeV, 3.2 fb⁻¹, PRL 116, 101801 (2016)
Inclusive cross-section measurements: broad range

These many measurements from Run1 and Run2 are important steps forward in physics modeling in the last years:

• NLO event generators – now standard
• (N)NNLO calculations increasingly available - These help to face the challenge of the precision of the LHC data

Measuring complex topologies bench-test Monte Carlo models of backgrounds to New Physics searches
ttbar cross-section measurements

• Nagoya’s contributions since early Run1

• Precise measurements of inclusive ttbar cross-sections
  – Precisions $\pm (3.9-4.4)\%$ (7-13 TeV) is better than theory NNLO+NNLL predictions (~5%)

• High statistics allow detailed studies of production properties
  – e.g. differential cross-section measurements (Check poster by K. Kawade, the Nagoya ex-member)
W-boson mass measurement

- Precise measurement is motivated for a consistency test of the SM and a probe of BSM physics – yet with slow progress
- After long/huge efforts, the first ATLAS result using the 7 TeV dataset was released in Dec 2016
  - $m(W) = 80.370 \pm 0.019$ GeV, a competitive measurement, dominated by physics modeling uncertainties as expected
  - Consistency tests of the SM

**SM prediction for $m(W)$ vs $m(t)$, assuming $m(H) = 125.09 \pm 0.24$ GeV**

**SM prediction for $m(W)$, assuming $m(H) = 125.09 \pm 0.24$ GeV**

$m(t) = 172.84 \pm 0.70$ GeV
• Understanding the 125 GeV Higgs
Physics of the 125 GeV Higgs

• Higgs discovery opened the door on the scalar sector
• In Run1 we measured:
  – Its spin-parity, and its mass precisely (±0.2%)
  – Production via gluon-fusion, vector-boson fusion, and with a W or Z
  – The decays to $\gamma\gamma$, WW, ZZ, and the fermionic decay to $\tau\tau$

→ These proved true the BEH mechanism to break gauge symmetry
→ However, apart from the mass, none of these measurements are yet very precise and leave room for significant deviations. Also, important modes are still unseen ($bb$, $ttH$, $\mu\mu$, $Z\gamma$, $HH$)

• Run2 priorities:
  – Establish and measure at 13 TeV
  – Search for $ttH$ production to probe $ttH$ coupling directly
  – Search for $H \rightarrow bb$ decays
  – Search for rare decays
  – Refine measurements of couplings, mass, etc
  – Expand use of H as a tool to find New Physics
Clear Higgs observation at 13 TeV in bosonic channels

Combining $\gamma\gamma + 4\ell$ channels

$\sigma(pp \to H + X, \text{13 TeV}) = 59.0^{+9.7}_{-9.2} \text{ (stat.)} +4.4_{-3.5} \text{ (syst.) pb}$

SM prediction

Overall significance at 13 TeV $\sim 10\sigma$
First search for $ttH$ production at 13 TeV by CMS

- Direct measurement of Higgs-top coupling
- CMS showed preliminary results for $ttH$ in all major Higgs decay channels: $\gamma\gamma$, multi-lep, $bb$
- Highly complex analyses, huge effort to get these done so quickly after data taking (already by Moriond 2016)
First search for $ttH$ production at 13 TeV by ATLAS

- Direct measurement of Higgs-top coupling
- ATLAS showed preliminary results for $ttH$ in all major channels and their combination at ICHEP 2016

Individual channels and combination

- $ttH(H\rightarrow\gamma\gamma)\ (13\ \text{TeV}\ 13.3\ \text{fb}^{-1})$
- $ttH(H\rightarrow WW/\tau\tau/ZZ)\ (13\ \text{TeV}\ 13.2\ \text{fb}^{-1})$
- $ttH(H\rightarrow bb)\ (13\ \text{TeV}\ 13.2\ \text{fb}^{-1})$
- $ttH$ combination (13 TeV)
- $ttH$ combination (7-8 TeV, 4.5-20.3 fb$^{-1}$)

$\rightarrow$ Observed significance $2.8\sigma$
(expect $1.8\sigma$, improved sensitivity over Run1)
Searches for rare Higgs decays e.g. $H \rightarrow \mu \mu$

- Beyond SM reach at present, but could have New Physics contributions?
  - Strongly resolution dependent, improve sensitivity by categorising events (low/high $p_T$, central/forward, VBF)
  - Obs limit: 4.4 times SM. Needs ~300 fb$^{-1}$ data to reach SM (Run3)

- Can already exclude universal Higgs coupling to fermions
  - Would have observed $H \rightarrow \mu \mu$, if same BR as $H \rightarrow \tau \tau$
Beyond the Standard Model Higgs physics

- Higgs sector may be non-minimal and/or Higgs boson may couple to New Physics
- Diverse search program is in place;

No deviations from SM found in any of these searches

- Light or heavy neutral Higgs bosons
- Charged Higgs boson
- Lepton flavour violating Higgs decays
- Di-Higgs production (resonant or not)
- No sensitivity yet for SM di-Higgs production (Primary target for High-luminisity LHC)
- Higgs as portal to hidden sector
- Exotic Higgs decays
- Higgs in BSM decay chains

BSM constraint from coupling measurements
• New Physics searches

ratios of LHC parton luminosities: 13 TeV / 8 TeV

- > 10 x at High Mass
- 2 x at Low Mass
New Physics searches in Run2

• Broad search program
  – from inclusive surveys of basic event topologies
  – to dedicated searches ruling out corners of phase space
• Major extension of reach compared to Run1
• All results shown here include 2016 data
• They probe well into the TeV, even multi-TeV, mass scale range
Exploring Exotics

- **Guiding physics models**
  - Technicolor
  - Warped Extra Dimensions
  - Grand Unified Theories
  - Heavy Vector Triplet
  - Quantum Black Holes
  - Hidden valley
  - Contact Interactions
  - Compositeness
  - Exited Fermions
  - Leptoquarks
  - ...

- **Signatures**
  - Di-lepton / di-jet / di-b-jet resonances (Z', W', ...)
  - Di-boson resonances
    - WZ, ZZ, Wγ, Zγ
  - Multi-jet resonances
    - tb, Ht, Zt, Zb (Z', W', T, B, ...)
  - Excesses in high tails (non-resonances)
  - Long lived particles
  - Large missing energy
  - ...

→ Search as broad and general as possible (signatures, masses, rates) covering physics without guiding models

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Review of the LHC Run2 results
Di-photon searches

2015 ATLAS data: localised excess seen
• 2.1σ global (3.9σ local) significance at 750 GeV (spin-0 search), width ~50 GeV

2016 data: no clustering around 730-750 GeV, and 3.8x more data
• 2016 data consistent with 2015 at 2.7σ
• Appears that the 2015 excess was a statistical fluctuation

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Review of the LHC Run2 results
Finally with 2015+2016 data

- Small excess at 710 GeV (Γ/m~10%)
- Local significance 1.4σ, global <1σ
Massive di-boson searches

- Search for resonant di-boson production
  - Boosted (“fat jet”) selections vital at high-$p_T$
  - Explored many channels with 2016 data

- Overlaying limits from all WZ searches – no persistent excesses, in contrary to the Run1 excesses
Di-jet searches

- Search for New Physics in di-jet mass spectrum; bump hunter
  - Di-jet: $qq, qg, gg$ (high mass $> \sim 1$ TeV). High priority in early Run2
  - Sensitivity based on signal shapes including large low mass tails

For low-mass search, a dedicated trigger technique "data scouting at trigger level" allowed lower threshold by keeping partial info. and online calibration.
Di-jet searches: Dark Matter Interpretation

• Complementary to mono-(jet, γ, W, Z, b, t, H, ...) searches
  – Tag DM pair (E_T^{miss}) via Initial state radiation
  – Mediator (Z’) mixing with Z, H

• Mediator (Z’)
  – Couples to quarks (g_q) and DM (g_{DM})
  – Dijet searches cover a broad mediator mass range
  – DM interpretation of Z’ searches
Di-jet searches: Dark Matter Interpretation

$g_q = 0.25, g_{DM} = 1$

- Complementary to mono-X searches; cover a broad mediator mass range – Results highly depend on choice of coupling parameters ($L = g_q \gamma^\mu q Z'_\mu$)
SUSY searches

- The case for SUSY is well known
  - Natural Dark Matter candidate in *neutralino*¹
  - Can solve the fine-tuning problem – if *t~* and *g~* are light

In Run1 we identified:
- \( m(g~) > 1.4 \text{TeV} \) for low-mass *neutralino*¹
- \( m(t~) > 700 \text{GeV} \) if \( m(*neutralino*¹) < 100 \text{GeV} \)

Run2 priorities:
- Extend mass reach according to \( \sqrt{s} \) increase
- Fill “kinematic holes” where particles are soft
- “Leave no stone unturned” e.g. displaced decays from long-lived particles

¹ Neutralino is a type of supersymmetric particle, often considered a candidate for dark matter.
### ATLAS SUSY Searches - 95% CL Lower Limits

**Model** | $E_{T}^{miss}$ (GeV) | $M_{T}$ (GeV) | Mass limit $\sqrt{s} = 7, 8, 13$ TeV | Reference
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**Areas of Search**

- **Run1 data**
- **Run2 data**

**LO+NNLO Approximations**

- **1st Gen. squarks**
- **2nd Gen. squarks**
- **3rd Gen. squarks**
- **FV direct**
- **Log-boosted**

**ächter**

- **LSP**
- **R-parity violating (RPV)**

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*Only a selection of the available mass limits on new states is shown.*

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Review of the LHC Run2 results  
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In brief, huge number of signature-based searches for various production and decay processes within SUSY, in many final states, providing stringent limits under various assumptions;
- Many of these limits reach ~1 TeV in “easy” inclusive signatures using the Run2 data
- More searches will come for smaller-cross section processes (EW) or for difficult signatures (Long-lived particles)
Example: g~/q~ search with jets+$E_T^{\text{miss}}$

- Event selection: require 2-6 jets and veto isolated leptons
  - Sensitive to g~ and q~ production
  - High priority in early Run2
- Total of 30 signal regions to cover various mass spectra
  - No significant excesses in any signal region overall
  - For small $m(\text{neutralino1})$ exclusion reach extended
    $m(g~) < 1.4$ TeV (Run1) $ightarrow < 1.86$ TeV (2015+16)
  - Check details in poster by Y. Sano (a Nagoya PhD student)
t~ search summary

• Search for top squark pair productions
  – Explored many channels with 2016 data
  – Developing dedicated searches for such compressed spectra
    → Check details in poster by K. Onogi (a Nagoya PhD student)

For m(neutralino1) < 200 GeV, m(t~) < 800 GeV excluded except in rather small regions
Conclusion

• The LHC is performing extremely well
• A broad range of LHC Run2 results using early 2016 dataset
  – Starting precise measurements of H(125) at 13 TeV
    • Concluding on the Standard Model ttH sensitivity
  – 13 TeV in Run2 brings significant increase in sensitivity, shaping the
    search program in 2015 and early 2016
    • The limits set significantly extend the Run1 results, thus further
      constraining various models. No significant excesses, though some
      ~3σ effects as expected. More data will tell which, if any, will remain
  • The search program is moving toward more challenging signatures
    and scenarios
• Expecting exciting future
  – New results with ~40 fb^{-1} in early spring of 2017
  – Data analysed so far: a small fraction of total Run2 (100 fb^{-1})
• Backup slides
pMSSM scans

- LHC: simplified model $\rightarrow$ BR=1 (even for cascade decays)
- setting limits on various pMSSM using all ATLAS search results in Run1
  - Good coverage of pMSSM, dependence on LSP nature (via signatures)
  - Similar scan will be repeated with results using the Run2 full dataset