ATLAS Status Report
Operations, Physics & Upgrade Planning

P. Krieger, University of Toronto
(on behalf of the ATLAS Canada Collaboration)
ATLAS Canada Collaboration

Founded in 1992: M. Lefebvre, UVic
R. McPherson, IPP/UVic 2007-2015

Current Management

Spokesperson, PI (2015 –): P. Krieger, U of T
Deputy: A. Warburton, McGill
Physics Coord: A. Lister, UBC
Computing Coord: D. Gingrich, Alberta

39 University/Lab faculty (35.5 FTE) [details in backup slides]
28 Postdocs, 77 GS (Fall 2016), ≈ 25 UG students/year
Plus engineers and technicians (some MRS funded)
Group includes 5 IPP Research Scientists (4 FTE)
**Canadian Leadership in ATLAS**

- **Canadians present in all levels of ATLAS management and coordination:**
  - Some prominent examples below,
  - Also many roles in detector operations, data quality, upgrade and physics and performance sub-group coordination (not shown here):
    - Including both ATLAS and sub-system run coordinators

**Major (recent and present) ATLAS management / coordination roles**

<table>
<thead>
<tr>
<th>ATLAS Management</th>
<th>Publications Committee Chair</th>
</tr>
</thead>
<tbody>
<tr>
<td>McPherson (deputy spokesperson 2015-2017)</td>
<td>Vetterli</td>
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<table>
<thead>
<tr>
<th>Executive Board</th>
<th>Speakers Committee</th>
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</thead>
<tbody>
<tr>
<td>Vetterli (pubcom chair), McPherson (at-large)</td>
<td>Lefebvre (Chair), Warburton</td>
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<table>
<thead>
<tr>
<th>Physics coordination</th>
<th>Authorship Committee Chair</th>
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<tbody>
<tr>
<td>Lister (top), Savard (Higgs), Canepa (Upgrade physics), Gingrich (MC)</td>
<td>Trigger</td>
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<thead>
<tr>
<th>Speakers Committee Advisory Board</th>
<th>Publications Committee members</th>
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<tbody>
<tr>
<td>Krieger, Vachon, Taylor</td>
<td>Krieger, Trigger</td>
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</tbody>
</table>

| Computing resources management Chair | Vetterli |
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Updates from ATLAS Week Feb 2017

**Pierre Savard** elected as Deputy Physics Coordinator:
- Becomes Physics Coordinator for 2018-19

**Pekka Sinervo** appointed to Publication / Authorship Committees:
- Will chair Authorship Committee in Year 3

**Manuella Vincter** appointed to ATLAS Executive Board

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**ATLAS Management**

- McPherson (deputy spokesperson 2015-2017)
- Exec Board: Veferli (pubcom chair), McPherson (at-large)
- Physics coordination: Lister (top), Savard (Higgs), Canepa (Upgrade physics), Gingrich (MC)

**Speakers Committee Advisory Board**

- Krieger, Vachon, Taylor

**Publications Commitee members**

- Chair: Veferli
- Trigger

**Authorship Commitee Chair**

- Lefebvre
- Warburton

**Computing resources management Chair**

- Vetterli

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P.Krieger, U of T  
Institute of Particle Physics, AGM, May 27, 2017  Kingston, ON
ATLAS Canada committed to excellence in HQP training:
- Current graduate student and postdoc numbers shown on previous slide
- 70 PhDs awarded (Fall 2016), 45 with collisions (distribution below)
- About 100 postdocs have been trained on ATLAS Canada
- Of completed degrees / training in last 5 years*:
  - ~70% of MSc students continued to a PhD (usually in the same field)
  - ~40% PhD remained in research, ~30% went to industry, 20% became teachers
  - ~70% of postdocs remained in research, ~20% to industry

ATLAS PhD Degrees Awarded at Canadian Institutions

Post PhD careers (2010-2015)
- Research 40%
- Industry 30%
- Education 20%
- Other 10%
- * Career numbers based on incomplete information

ATLAS Collaboration management starting a new effort to track career paths of ATLAS HQP
ATLAS Canada HQP Training

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ATLAS RAs recognized with 3 of the 20 ATLAS Outstanding Achievement Awards awarded in 2016

ATLAS PhD Degrees Awarded at Canadian Institutions

ATLAS Collaboration management starting a new effort to track career paths of ATLAS HQP

P.Krieger, U of T
Institute of Particle Physics, AGM, May 27, 2017  Kingston, ON
The Large Hadron Collider at CERN

• The world’s highest-energy particle collider
  – Likely to remain at the energy-frontier for at least another two decades
• ATLAS: over 600 peer-reviewed publications
• Higgs Boson discovery in 2012 led to 2013 Nobel Prize to Higgs and Englert (with ATLAS and CMS mentioned in the citation)
  – Investigations of Higgs properties still important and on-going
  – This will remain true to the end of the LHC/HL-LHC experimental program
• Increased energy, decreased bunch spacing for Run-2 (2015-2018):
  – Bunch spacing of 25 ns (instead of 50 ns) for reduced pileup
  – 13 TeV up from 8 TeV in Run-1: new window for searches for BSM physics
  – LHC magnet training to 14 TeV investigated during 2016-17 EYETS
  – Energy will remain at 13 TeV for all of Run-2
• Maximum LHC energy is 14 TeV. After that, planned improvements associated with an increase of the collision rate (luminosity):
  – The is the goal of both the Phase-I and Phase-II LHC / ATLAS Upgrades
LHC/HL-LHC Schedule / ATLAS upgrade planning

LHC / HL-LHC Plan

- **New Pixel insertable b-layer (IBL): DBM**
- **Consolidation of LAr calorimeter LVPS**
- **LUCID upgrade**
- **Forward protons (AFP)**

Completed

**Phase-1 Upgrades**
- EYETS
- 13-14 TeV
- 2017-2018

**Phase-2 Upgrades**
- LS3
- HL-LHC installation
- 14 TeV
- 2024-2026

7 TeV
8 TeV

P.Krieger, U of T
Institute of Particle Physics, AGM, May 27, 2017  Kingston, ON
Canadian Hardware Contributions to ATLAS

Main contributions to the original detector

- Hadronic Endcap calorimeter
  - Two of four wheels
- Hadronic Forward calorimeter
  - All four modules
- Liquid argon front-end electronics
  - Switched capacitor array controller chips
- Liquid argon calorimeter endcap signal feedthroughs

Other contributions to the existing detector

- Diamond Beam Conditions Monitor (also used for luminosity)
- High-level trigger (HLT) processors
- MediPix / TimePix for cavern background monitoring, luminosity
- Inner Detector readout
- ATLAS Forward Protons (AFP) – installation completed in 2016/17 shutdown
First year of Run-2 (2015) dedicated to establishing machine performance at 13 TeV and 25 ns bunch spacing:

- Low integrated luminosity in 2015 but many important lessons learned
- These lessons laid the foundation for 2016 and the remainder of Run-2 (illustrated above by the 2016 luminosity ramp).
LHC/ATLAS 2016 Operations

LHC design luminosity exceeded in June

ATLAS Run-2 Detector Status (from Sept. 2016)

<table>
<thead>
<tr>
<th>Subdetector</th>
<th>Number of Channels</th>
<th>Approximate Operational Fraction</th>
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<tbody>
<tr>
<td>Pixels</td>
<td>92 M</td>
<td>98.0%</td>
</tr>
<tr>
<td>SCT Silicon Strips</td>
<td>6.3 M</td>
<td>98.8%</td>
</tr>
<tr>
<td>TRT Transition Radiation Tracker</td>
<td>350 k</td>
<td>97.2%</td>
</tr>
<tr>
<td>LAr EM Calorimeter</td>
<td>170 k</td>
<td>100%</td>
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<tr>
<td>Tile calorimeter</td>
<td>5200</td>
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<tr>
<td>Hadronic endcap LAr calorimeter</td>
<td>5600</td>
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</tr>
<tr>
<td>Forward LAr calorimeter</td>
<td>3500</td>
<td>99.7%</td>
</tr>
<tr>
<td>LVL1 Calo trigger</td>
<td>7160</td>
<td>99.9%</td>
</tr>
<tr>
<td>LVL1 Muon RPC trigger</td>
<td>383 k</td>
<td>99.8%</td>
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<tr>
<td>LVL1 Muon TGC trigger</td>
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<tr>
<td>MDT Muon Drift Tubes</td>
<td>357 k</td>
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<tr>
<td>CSC Cathode Strip Chambers</td>
<td>31 k</td>
<td>97.7%</td>
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<tr>
<td>RPC Barrel Muon Chambers</td>
<td>383 k</td>
<td>96.6%</td>
</tr>
<tr>
<td>TGC Endcap Muon Chambers</td>
<td>320 k</td>
<td>99.6%</td>
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<tr>
<td>ALFA</td>
<td>10 k</td>
<td>99.9 %</td>
</tr>
<tr>
<td>AFP</td>
<td>188 k</td>
<td>98.8%</td>
</tr>
</tbody>
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Data Quality Efficiency (good for physics):
- Run-1 average was 94%.
- 2016: 93-95% with some improvements expected from reprocessing in 2017

Excellent performance in 2016 of both LHC machine and ATLAS detector
ATLAS Computing

- **Excellent LHC performance in 2016: availability for physics ≈ 50% !**
  - almost 50% larger data sample than anticipated
  - This performance expected to be maintain through Run-2
    - need additional computing resources, or *mitigation strategies*, or both
      - Increases to trigger thresholds
      - *Parking* of data (for later reconstruction / analysis)
      - Reduction of numbers of Monte Carlo simulated events
    - Mitigation strategies extensively investigated:
      - all deemed to have too negative an impact on the ATLAS physics program

- **Many software optimizations implemented prior to 2016 (LS1):**
  - Factor of 4 improvement in reconstruction speed
  - no more low-hanging fruit

- **Feb 2017 LHCC review:**

  *The LHCC notes that the margins to reduce the resource usage in the short term without impact on physics have been exhausted.*
ATLAS Computing

Significant use by ATLAS of both Beyond Pledge grid resources and opportunistic use of Cloud and HPC resources

Large effort put into data management: lifetime model for derived data files

HPC + Cloud ≈ 15%

Canadians leading the ATLAS cloud computing effort
ATLAS: 629
Run-1: 567
Run-2: 62

• Most papers based on analysis of Run-1 data (2011, 2012)
• A few Run-1 papers still in progress: SUSY and Exotics searches complete
• Well into the Run-2 (13 TeV) publications phase: 62 papers submitted:
  – Additionally, many preliminary results prepared for: ICHEP 2016 and 2017 winter, spring and summer conferences (e.g. LHCP) http://lhcp2017.physics.sjtu.edu.cn/
• Will include just a few brief examples here
Physics Highlights: W Boson Mass

- Based on 4.6 fb\(^{-1}\) of 7 TeV data from 2011
- Huge effort put into modeling: high quality results in \(e\nu\) and \(\mu\nu\) final state

\[
M_W = 80.370 \pm 0.019 \text{ GeV}
\]

\[
\pm 7 \text{ MeV (statistical)}
\]

\[
\pm 11 \text{ MeV (systematic)}
\]

\[
\pm 14 \text{ MeV (modeling)}
\]

Same precision as current best CDF measurement
Data from 2015 heavy-ion run: 5 TeV x 5 TeV Pb-Pb collisions (ultra-peripheral) [arXiv:1702.06125]

Two back-to-back $\gamma$ in ATLAS with no additional activity

Measured cross-section consistent with expectations
High-mass Resonance Searches

Dijet search: first publication on complete 2015+2016 dataset: 37 fb⁻¹

Searched for excited quarks, W’, microscopic black holes, contact interactions. 95% CL limits placed: e.g.

\[ M(q^*) > 6.0 \text{ TeV} \quad (5.8 \text{ TeV exp.}) \]

Dilepton resonance search also based on full 13 TeV dataset: 36.1 fb⁻¹

No significant deviations from SM expectations:

SSM Z’ mass limit increased to 4.5 TeV (95% CL)
SUSY Searches

New jets + missing transverse energy results for full Run-2 dataset: 36.1 fb\(^{-1}\)

Effective mass distribution well described by SM contributions

Gluino mass limits now extend past 2 TeV for low \(M_{\tilde{\chi}^0_1}\)

*Supersymmetry remains elusive*
Other SUSY mass limits also approaching 2 TeV using 13 TeV dataset
LHC / ATLAS Startup 2017

- Beam splashes late April / early May
- Pilot-bunch collisions May 9
- First collisions May 11 (no Stable Beams)
- First Stable Beam declared May 23
  - 3 x 3 bunches

- **ATLAS: ready for data-taking**
LHC/HL-LHC Schedule / ATLAS upgrade planning

LHC / HL-LHC Plan

- **Completed**
  - New Pixel insertable b-layer (IBL): DBM
  - Consolidation of LAr calorimeter LVPS
  - LUCID upgrade
  - Forward protons (AFP)

- **In progress**
  - sTGC for Muon New Small Wheel
  - Liquid Argon Calorimeter electronics

- **Proposed**
  - New ATLAS Inner Tracker (ITk)
  - Liquid Argon Calorimeter electronics

**Main ATLAS Canada shutdown / upgrade activities**
• NSW key component of ATLAS trigger strategy for Run-3 (fake rejection with pointing)
• sTGC construction / testing infrastructure in place at TRIUMF, Carleton and McGill.
• Module-0 sTGC completed by Canadian group in May 2016
• Production Readiness Review (PRR) passed in June 2016
• Production of sTGC quadruplets delayed by challenges with cathode board production:
  – Currently on the critical path
• Leading coordination roles in NSW project:
  – Overall project management, schedule, finances
  – Cathode board procurement (for all sTGCs)
    • Requires large PCBs that are beyond industry standard size
    • Recent improvements encouraging
    • Experience may be relevant to future large-area detector development projects
  – Wedge assembly at CERN
  – Software / simulation
  – Electronics / software for cosmic-ray test station
  – Production test pulser board for sTGCs

Phase-1 Upgrades: Muon New Small Wheel
Phase-1 Upgrades: LAr Calorimeter Electronics

- Another key component of ATLAS trigger strategy for Run-3
- Improve granularity of information supplied to the L1 trigger
  - Provide additional background suppression at trigger level

Amongst other things, implementation requires new Front-End Crate baseplanes
- For the HEC, these are being developed and produced by Victoria / TRIUMF
  - Design approved in 2015: pre-production board have been produced and tested
    - Environmental testing
    - Electrical testing: TDR test illustrated for one trace -- displays proper 50Ω impedance)
    - TRIUMF-designed multiplexors for production acceptance testing

PRR currently planned for Summer 2017
Phase-1 Upgrades: LAr Calorimeter Electronics

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Phase-1 trigger granularity

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**ATLAS at the High Luminosity LHC**

- **Proposed instantaneous luminosity of** $7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ($\mu\approx200$)
  - Needed for the desired ($\times10$) increase in integrated luminosity
  - Rate and accumulated dose causes problems for some detector subsystems
  - Need for pileup suppression becomes crucial issue for detector upgrades

- **Proposed L0/L1 trigger scheme with rates of** 1MHz/400KHz is incompatible with both tracker and calorimeter readout electronics:
  - Calorimeters modules can operate but:
    - Forward calorimeter response will be somewhat degraded at high $|\eta|$.
    - **Calorimeter front- and back-end electronics must be entirely replaced**
      - FE electronics also need replacing due to increased expected dose

- **Radiation dose and occupancy also an issue for the tracker**
  - This will be entirely replaced by a new all-silicon tracker, the ITk
    - Pixels at low radius, strips at higher radius.
      - Coverage out to $|\eta|=4.0$ (from 2.5 for current inner tracker)
    - 160 m$^2$ of silicon. Almost half the cost / effort of Phase-II upgrades

- **Anticipate some coverage improvements for Muon system**

- **ATLAS investigating dedicated (Si) timing detector in the forward region**
Phase-II Tracker Upgrade (ITk)

- **Excellent tracking needed for the HL-LHC physics program**
  - Need precision vertexing to identify the primary vertex to which hard-scatter products are associated (pileup suppression)

- **Canadian group proposing to contribute to construction of the Endcap Strips detector:**
  - about 18k Si strip modules needed (~7000 in endcap):
  - plan for 1500 in Canada (2 sites: Vancouver, Toronto)
  - Additional planned contributions:
    - Industrialize production of “hybrid boards”: Eastern site
    - Module placement on support structure for Endcap “petals”: Western site
    - Readout electronics ASIC wafer probing and dicing (Ottawa)
Canadian group well established in the ITk collaboration:

- Detector layout studies
- Management: electronics coordination
- Radiation testing of Strip ASICs
- Adhesive studies (modules to support structure)
- Module placement ("Module-on-core") work
- Module construction preparations:
  - Two sites: both have produced good quality prototypes
  - Moving into “site qualification” stage
  - Sensor just starting to arrive in at CERN and in Canada
- DAQ development (using prototype built in Canada):
  - Includes contributions to firmware development:
    - single / multiple module
  - Module test stands available at both sites
- Development of QA/QC procedures:
  - Si sensor testing
  - Hybrid board manufacture / testing
  - Modules: measurements of per channel noise, gain, signal-to-noise ratio

NSERC-funded R&D in progress
Construction funding requested from CFI
Phase-II LAr Calorimeter Upgrade Work

• **Proposed FCal replacement decided against in Sept. 2016**
  – Risk (damage to other endcap calorimeter subsystems) vs reward (improved performance) study concluded that the benefits are not work the risks

• **Canadian groups integrating into Phase-II electronics effort:**
  – Naturally follows our Phase-I work and historical contributions to ATLAS
  – Focus on front-end electronics for the HEC
    • HEC was built in part in Canada
    • Different from other LAr subsystems, due to cold preamplifiers in the cryostat
      – Exploit particular Canadian expertise in the HEC readout
  – Also contributing to development of back-end (BE) filtering algorithms for energy reconstruction (FPGA-based)

• **Canadians in LAr Phase-2 Upgrade management**

• **Canadians also involved with characterizing the response of the FCal at the HL-LHC (which will be degraded at high-|\eta| due to ion-buildup and other problems)**
ATLAS Canada Operations & Upgrade Funding

- **Operations:** currently in final year of three-year NSERC project grant
  - New proposal to be submitted in Fall 2017

- **Phase-1 Upgrades**
  - LAr, NSW projects currently under construction, funded by CFI, IF 2015 award
  - Significant initial R&D support from NSERC in 2013, 2014

- **Phase-2 Upgrades**
  - NSERC RTI awards in 2016 and 2017 for R&D phase
  - Construction funding requested from CFI in IF 2017 competition:
    - LAr Electronics, ITk, Upgrade Common Fund
    - Decision expected by June 20

- **Canadian contributions to LHC → HL-LHC upgrade still being pursued**
  - CERN has requested that we contribute to the HL-LHC accelerator upgrade
    - We made significant contributions to the original LHC construction
    - Will needs support of the community and involvement of TRIUMF
    - Discussions re-starting: this probably needs to converge in time for the 2018 Federal budget.
New or Developing Technologies: Upgrades

Detector and associated electronics upgrades pose challenges in terms of rate, radiation tolerance, and measurement precision: need development of improved pile-up suppression techniques. For example:

- **Phase-2 tracker upgrade (ITk)**
  - Rad hard silicon sensors, high-speed / reliability readout for huge # of channels
  - 3D silicon and CMOS possibilities for ITk Pixels
  - Challenges for radiation hardness of other components (e.g. glue)
  - CHESS: R&D for CMOS version of ITk Strips (may have useful future applications): Canadians working on readout as part of ITk Strips DAQ development

- **Phase-1 upgrades (NSW)**
  - Industrial production of large-area PCBs beyond industry standards
    - may have future applications

- **Phase-1/2 LAr Calorimeter upgrades**
  - Ultimately, faster, higher-granularity signals to L0-trigger
  - Digital pipeline instead of current analog pipeline
  - Use of modern FPGAs for back-end (BE) signal processing
  - Exploration of alternative BE digital filtering algorithms
New or Developing Technologies: Computing & Analysis

• **Computing**
  – Canada leading in ATLAS implementation of Cloud computing
    • Development of high-speed networks offers future computing model that differs from the current one
  – Development of data management tools to optimize use of resources
    • Data-lifetime model to optimize use of disk
  – Lots of work in ATLAS software framework (Athena) to make better use of modern multi-core cpus: AthenaMP (multi-process) exists; AthenaMT (multi-threaded) under development

• **Reconstruction & Analysis Tools (some examples)**
  – Tracking in Dense Environments (TIDE)
    • Will be important at HL-LHC with $<\mu> \approx 200$
  – Top-quark tagging:
    • ATLAS currently employs a “simple” top-tagger
    • Machine learning (ML) techniques provide superior performance
  – Use of ML tools in other areas (e.g. jet calibration)
Summary

- **LHC/ATLAS operations exceptional in 2016, just starting in 2017**

- **Canadian group successfully engaged in all aspects of ATLAS**
  - Important and visible roles in the Collaboration
  - Physics output (Analysis, Review, Physics Group / sub-group Convenors)
  - Detector construction
  - Detector operations (run coordinators for multiple subsystems)
  - Strong participation detector upgrade activities
    - Phase-1: LAr trigger electronics, sTGCs for NSW
    - Phase-2: LAr readout electronics, ITk
    - Canadian coordination roles in both Phase-1 and Phase-2 projects
    - Active preparations for Phase-II contributions
      - Decision on Phase-II construction funding expected June 20

- **Canadian group planning to extend our historical and present level of commitment to ATLAS into Run-3 and then the HL-LHC era**
7 ATLAS talks at 2017 CAP Congress

Invited

• Operation and performance of the ATLAS detector in LHC Run-II, E. Kuwertz
• Standard Model and Higgs boson studies with the ATLAS detector, A. Bellerive
• Searches for new physics with the ATLAS detector, O. Ducu
• Upgrades to the ATLAS detector at the LHC, I. Trigger

Contributed

• Search for a doubly charged Higgs boson through vector boson scattering in the Georgi-Machacek model with the ATLAS detector at the LHC, J. Claude.
• Search for Higgs production in association with a tt pair in the H->bb final state, D. Mori.
• Studies of cosmic ray events in ATLAS sTGC muon chamber prototypes, F. Leger
Backup
Phase-II Upgrade Project Schedule

• ITk Strips Technical Design Report (TDR) approved by LHCC:
  – Sent to CERN Research Board for approval at June meeting
  – This is the first Phase-II Upgrade TDR to be submitted

• LAr Phase-II Initial Design Report (IDR) submitted and reviewed in March 2017:
  – Approved as official ATLAS Phase-II Upgrade project
  – TDR to include section on proposed High-Granularity timing detector (sits in front of LAr endcap / forward calorimeters.

  Schedule exists for completion of TDR submission, LHCC review and approval process by April 2018
LHC Availability for Physics 2016

2016 Availability

[2015 - 25 ns Run]

Remarkable availability:
- **Increased** operational efficiency
- **Enhanced** system availability
- **New** pre-cycle strategy

Downtime of technical infrastructures

30% less downtime in 2016 than 2015

Non-availability of beams from the injector complex is the largest source of LHC downtime

TS1 - TS2: stable beams 58%
TS2 - TS3: stable beams 54%

P.Krieger, U of T
Institute of Particle Physics, AGM, May 27, 2017 Kingston, ON
## LHC Schedule 2017

<table>
<thead>
<tr>
<th>Week</th>
<th>April</th>
<th>May</th>
<th>June</th>
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**July**

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**October**

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<td>We</td>
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</tbody>
</table>

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Technical Stop  
Recommissioning with beam  
Machine development  
Special physics runs (indicative - schedule to be established)  
Scrubbing (indicative - dates to be established)

---

**Note:** No heavy-ion running in 2017
Phase-II Upgrades: Physics Motivations

- Primary goals: discovery of BSM and more detailed studies of the Higgs boson:
  - Higgs studies, in particular couplings:
    - Improvements over results with 300 fb\(^{-1}\)
    - Access to second-generation fermion couplings via \(H \rightarrow \mu\mu\)
    - Investigations of Higgs self coupling (via \(HH\) production)
    - Vector boson scattering: is this Higgs alone responsible for unitarizing \(\sigma(V_L V_L \rightarrow V_L V_L)\)
      - Sensitivity to VBF/VBS drives performance requirements in forward region
  - Searches: increased sensitivity to rare SM/BSM processes
    - Exploration of Run-3 hints observations or discoveries.
    - Or (better?) the unexpected

\[
\sigma_{bgg} = 30\%
\]

[ATLAS Simulation]

\[
\begin{align*}
\sigma(V_L V_L \rightarrow V_L V_L) & \\
VBF H & \rightarrow ZZ^{(*)} \rightarrow \ell\ell\ell\ell \\
VBF H & \rightarrow WW^{(*)} \rightarrow \ell\ell\ell\ell \\
SM VBS ssWW & \\
SUSY, \chi_1^0 \chi_2^0 & \rightarrow t\bar{b}b + X \\
BSM HH & \rightarrow b\bar{b}b
\end{align*}
\]

[SLHC-G-166: physics processes for Phase-II performance studies]
# ATLAS Exotics Searches - 95% CL Exclusion

**August 2016**

<table>
<thead>
<tr>
<th>Model</th>
<th>( \ell, \gamma )</th>
<th>Jets</th>
<th>E_{miss}</th>
<th>( \mathcal{L}dt) [fb^{-1}]</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADD GeV + g/a</td>
<td>( \geq 1 )</td>
<td>Yes</td>
<td>3.2</td>
<td>6.56 TeV</td>
<td></td>
</tr>
<tr>
<td>ADD Higgs ( g \to \gamma \gamma )</td>
<td>( 2, e, \mu )</td>
<td>-</td>
<td>2.03</td>
<td>4.7 TeV</td>
<td></td>
</tr>
<tr>
<td>ADD Higgs H ( g \to \gamma \gamma )</td>
<td>( 1, e, \mu )</td>
<td>1</td>
<td>20.3</td>
<td>5.2 TeV</td>
<td></td>
</tr>
<tr>
<td>ADD Higgs H ( g \to \gamma \gamma )</td>
<td>( \geq 2 )</td>
<td>Yes</td>
<td>3.6</td>
<td>6.2 TeV</td>
<td></td>
</tr>
<tr>
<td>RSL GeV ( \rightarrow \ell \ell )</td>
<td>( 2, e, \mu )</td>
<td>-</td>
<td>20.3</td>
<td>2.04 TeV</td>
<td></td>
</tr>
<tr>
<td>RSL GeV ( \rightarrow \gamma \gamma )</td>
<td>( 2, e, \mu )</td>
<td>1</td>
<td>13.3</td>
<td>1.24 TeV</td>
<td></td>
</tr>
<tr>
<td>Bulk RS GeV ( \rightarrow \gamma \gamma )</td>
<td>( 2, e, \mu )</td>
<td>-</td>
<td>3.2</td>
<td>3.2 TeV</td>
<td></td>
</tr>
<tr>
<td>Bulk RS GeV ( \rightarrow \ell \ell )</td>
<td>( 2, e, \mu )</td>
<td>1</td>
<td>Yes</td>
<td>1.46 TeV</td>
<td></td>
</tr>
</tbody>
</table>

| SM Z' \( \rightarrow \ell \ell \) | \( 2, e, \mu \) | - | 13.3 | 2.02 TeV |
| SM Z' \( \rightarrow \gamma \gamma \) | \( 2, e, \mu \) | - | 19.5 | 1.5 TeV |
| Left-handed SM Z' \( \rightarrow \ell \ell \) | \( 2, e, \mu \) | 2 | 3.2 | 4.74 TeV |
| SM W' \( \rightarrow \ell \ell \) | \( 2, e, \mu \) | - | 13.3 | 2.4 TeV |
| HVT W' \( \rightarrow \gamma \gamma \) | \( 0, e, \mu \) | 1 | Yes | 3.0 TeV |
| HVT W' \( \rightarrow \gamma \) | \( 0, e, \mu \) | 1 | Yes | 1.28 TeV |
| LUSM W' \( \rightarrow \gamma \) | \( 0, e, \mu \) | 1 | Yes | 1.76 TeV |
| CI \( \gamma \gamma \gamma \gamma \) | \( 0, e, \mu \) | 1 | 200 | 19.9 TeV |

| VLO \( \rightarrow H \) | \( 1, e, \mu \) | \( 2, b, \geq 3 \) | 20.3 | 805 GeV |
| VLO \( \rightarrow W \) | \( 1, e, \mu \) | \( 2, b, \geq 3 \) | 20.3 | 710 GeV |
| VLO \( \rightarrow Z \) | \( 1, e, \mu \) | \( 2, b, \geq 3 \) | 20.3 | 550 GeV |
| VLO \( \rightarrow H \) | \( 1, e, \mu \) | \( 2, b, \geq 3 \) | 20.3 | 640 GeV |

| Excited fermions \( \gamma \rightarrow \ell \gamma \) | \( 1, e, \mu \) | \( 1, 2, \geq 1 \) | 3.2 | 4.4 TeV |
| Excited fermions \( \gamma \rightarrow \ell \gamma \) | \( 1, e, \mu \) | \( 1, 2, \geq 1 \) | 3.2 | 5.6 TeV |
| Excited fermions \( \gamma \rightarrow \ell \gamma \) | \( 1, e, \mu \) | \( 1, 2, \geq 1 \) | 3.2 | 2.3 TeV |
| Excited fermions \( \gamma \rightarrow \ell \gamma \) | \( 1, e, \mu \) | \( 1, 2, \geq 1 \) | 3.2 | 1.5 TeV |
| Excited fermions \( \gamma \rightarrow \ell \gamma \) | \( 1, e, \mu \) | \( 1, 2, \geq 1 \) | 3.2 | 1.0 TeV |

| LSTC \( \gamma \rightarrow W \) | \( 1, e, \mu \) | \( 1, 2, \geq 1 \) | 3.2 | 660 GeV |
| LSTC \( \gamma \rightarrow W \) | \( 1, e, \mu \) | \( 1, 2, \geq 1 \) | 3.2 | 2.0 TeV |
| Higgs triplet H_1 \( \rightarrow \ell \ell \) | \( 3, e, \mu \) | \( 1, 2, \geq 1 \) | 3.2 | 570 GeV |
| Higgs triplet H_2 \( \rightarrow \ell \ell \) | \( 3, e, \mu \) | \( 1, 2, \geq 1 \) | 3.2 | 600 GeV |

| Other | \( 1, e, \mu \) | \( 1, 2, \geq 1 \) | 3.2 | 1.34 TeV |

| \( \sqrt{s} = 8 \) TeV | \( \sqrt{s} = 13 \) TeV |

\[ \mathcal{L} dt = (3.2 \text{ to } 20.3) \text{ fb}^{-1} \]

\( \sqrt{s} = 8, 13 \text{ TeV} \)

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*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

†Small-radius (large-radius) jets are denoted by the letter \( \ell \) (\( J \)).

P. Krieger, U of T
Institute of Particle Physics, AGM, May 27, 2017 Kingston, ON