Physics motivation and detector upgrades for the new era of the ATLAS experiment

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On behalf of the ATLAS Collaboration

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Luminosity and Energy Increases at LHC

- **Long Shutdown 2 (Phase-1 upgrade) preparing for Run 3**
  - Luminosity leveling at $2 \times 10^{34}/\text{cm}^2/\text{s}$, possible increase to $\sqrt{s}=13.5$ or 14 TeV
  - Expecting accumulation of 300 fb$^{-1}$ during Run 3 pp campaign

- **Long Shutdown 3 (Phase-2 upgrade) to prepare for HL-LHC**
  - The HL-LHC era with lumi of $7.5 \times 10^{34}/\text{cm}^2/\text{s}$ at $\sqrt{s}=14$ TeV
  - Large data samples and major experimental challenges
ATLAS Run-3 and HL-LHC Physics Program

- Very broad program covering all areas of hadron collider physics
- Many studies performed for TDRs and European Strategy input
  - Measurement of **Higgs** boson properties: couplings, mass, width
  - Precision **electroweak** measurements: vector boson scattering, W mass, weak mixing angle, triboson couplings, rare processes
  - Searches for **Beyond Standard Model** physics: SUSY, dark matter
  - **QCD** measurements: precision PDF sets, especially in forward regions
  - **Flavor physics** studies: rare b-decays, constraints on CKM
  - **High-density QCD** measurements with heavy-ion and pp collisions
  - **Forward physics** with tagging of exclusive production processes
- Studies in ATLAS benefit from full HL-LHC simulation
  - Updated detector performance and systematic uncertainties

Focus on an interesting subset of the ATLAS results in my limited time
Muon Detector Upgrades

- Limited $p_T$ resolution and high hit occupancy in current detector dictate higher L1 trigger thresholds for single muons
  - Impact on electroweak physics measurements with leptonic signatures
- Precision angle measurements in the small wheel region can sharpen the L1 trigger turn-on and restore the lower threshold
  - New Small Wheel needed with 1 mrad angular resolution measurement

![ATLAS Simulation](chart)

$\text{WH} \rightarrow \mu \nu b\bar{b}$

- Events
- $p_T \leq 20$ GeV (Eff = 93%)
- $p_T > 40$ GeV (Eff = 61%)

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• Small-strip Thin Gap Chambers provide fast readout for trigger, while MicroMegas detectors give precision tracking resolution
  – MM spatial resolution of 100 μm based on fine strip pitch
  – Redundant system with good offline precision from sTGCs, too
  – Large-scale precision chambers require careful quality control at distributed fabrication sites

• Commissioning is underway at CERN
LAr Calorimeter and L1Calo Trigger

• Improve trigger energy resolution and identification efficiency for e, γ, τ leptons, and jets by increasing readout granularity

• Coarse trigger towers replaced by super cells

Super Cells

• Increased information in trigger allows for shower shape measurements
  – Improved jet rejection gives a lower trigger rate and allows ATLAS to maintain lower EM trigger thresholds in Run 3
Run-3 Higgs Boson Measurements

- Estimates of Run-3 sensitivity are based on late Run-1 results
  - Expect these to be very conservative projections, nearly surpassed already
- Lepton, photon, and missing energy trigger improvements offer improved sensitivity to the most common event signatures

![Graph showing results](image-url)
Run-3 SUSY and Exotic Searches

**Monojet signature (WIMP recoil)**

Jet + missing energy signature with WIMPs produced through axial-vector mediator

**ATLAS** Simulation Preliminary

- $\sqrt{s} = 13\text{ TeV}, 300\text{ fb}^{-1}$
- $3\sigma$
- $5\sigma$
- Axial-Vector Mediator
- Dirac Fermion DM
- $g_q = 0.25$, $g_\chi = 1$
- Projection from Run-2 data

**Dark photon decays**

Higgs decay to dark photons, with subsequent decays to displaced collimated muon jets

**ATLAS** Simulation Preliminary

- $\sqrt{s} = 14\text{ TeV}, 300\text{ fb}^{-1}$
- BR($H \rightarrow 2\gamma_d + X = 10\%$
- FRVZ $2\gamma_d$ model
- $m_H = 125\text{ GeV}$, $m_{\gamma_d} = 400\text{ MeV}$
- expected limit
- expected $\pm 1\sigma$
- expected $\pm 2\sigma$
Run-3 Vector Boson Scattering

- Three channels: WW, WZ, ZZ leptonic signatures
  - All observable at HL-LHC luminosities, but extracting the longitudinal scattering component to test unitarity is much more challenging
  - New muon performance and jet-finding capabilities are key improvements
- WV and VV scattering accessible with Run 3 dataset
- WW scattering: <10% precision overall, <1σ sensitivity to $W_LW_L$
HL-LHC Physics Challenges

- HL-LHC is the culmination of the 27-km ring program at CERN
  - Increase of $\sqrt{s}$ to 14 TeV, integrated luminosity goal of 3-4 ab$^{-1}$
  - Era of precision Higgs and top physics, small BSM cross sections
  - See Simone Pagan Griso’s talk in Friday’s plenary session

- Inst. lumi 7.5E34/cm$^2$/s implies pileup up to $<\mu>$=200 per crossing
  - Higher hit occupancy in the detector, leading to higher rate of fake tracks
  - Stochastic accumulation into "pileup jets", especially in forward region
  - Additional energy in calorimeters degrades resolution
  - Increased radiation dose to sensitive detectors and electronics

- Many improvements needed to maintain or improve performance
  - Improved triggering using all detector information and improved resolution
  - Increased detector acceptance in forward regions
  - Better association of particles to primary vertex to reject pileup effects
  - Timing measurements for pileup rejection and particle flow

- Major ATLAS detector upgrades planned for Long Shutdown 2
Overview of HL-LHC Upgrades

- All-silicon Inner Tracker replacement
  - Improved pseudorapidity coverage to $|\eta| < 4$
- New calorimeter front-end electronics to digitize signal at 40 MHz
- Muon electronics upgrade with additional trigger layer
- Trigger upgrade to use full detector information for 1 MHz decision
- Improved triggers are key to physics in many different signatures

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ITk Silicon Tracker

- Nearly 13 m² of pixels and 165 m² of strips with improved coverage
  - Innermost layer of “3-d” pixel sensors with 25x100 μm² pixel size
  - Inclined sensors and ring structures ensure normal track incidence at high η
  - New readout electronics radiation hard to 1 GRad in inner pixels, with 5 GHz digital data bandwidth to optical readout transition

- Improves tracking and b-tagging performance compared to Run-2
• Goal of better $e, \gamma, \tau$, jet identification and measurement, at hardware and software trigger levels and in offline
  – Full granularity detector data into HW trigger at 1 MHz from calorimeters and muon system
  – Feed into L0 accept with 10 $\mu$s latency
  – Event Filter output increases to 10 kHz
High-Granularity Timing Detector

- Vertex association at high $\eta$ improved with picosecond timing
- Low-Gain Avalanche Detector stations located on cryostat wall
- Timing information enhances the ITk pileup jet rejection

![Graph and diagram showing performance metrics related to ATLAS simulation and timing.]
**Higgs Coupling Measurements**

- **Cross section measurements improve with high statistics**
  - Projections assume systematic and theory uncertainties will be halved
- **Measurements re-interpreted in coupling modifier $\kappa$ framework**
  - All of those couplings are constrained at the 2-7% level
  - Even $\mu\mu$ and $Z\gamma$ couplings can be constrained at HL-LHC

**ATLAS** Preliminary
Projection from Run 2 data
$\sqrt{s} = 14$ TeV, 3000 fb$^{-1}$

<table>
<thead>
<tr>
<th>Cross section norm. to SM value</th>
<th>Total</th>
<th>Stat.</th>
<th>Syst.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ggF$</td>
<td>± 0.024 (± 0.008 ± 0.022)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$VBF$</td>
<td>± 0.042 (± 0.020 ± 0.036)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$WH$</td>
<td>± 0.077 (± 0.041 ± 0.065)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$ZH$</td>
<td>± 0.049 (± 0.034 ± 0.035)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}H$</td>
<td>± 0.053 (± 0.019 ± 0.050)</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter value</th>
<th>Total</th>
<th>Stat.</th>
<th>Syst.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_W$</td>
<td>± 0.022 (± 0.008 ± 0.021)</td>
<td></td>
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<tr>
<td>$\kappa_Z$</td>
<td>± 0.018 (± 0.009 ± 0.015)</td>
<td></td>
<td></td>
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<tr>
<td>$\kappa_t$</td>
<td>± 0.041 (± 0.011 ± 0.040)</td>
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<td></td>
</tr>
<tr>
<td>$\kappa_b$</td>
<td>± 0.043 (± 0.016 ± 0.041)</td>
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</tr>
<tr>
<td>$\kappa_g$</td>
<td>± 0.031 (± 0.010 ± 0.029)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\kappa_\gamma$</td>
<td>± 0.024 (± 0.009 ± 0.022)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\kappa_{\mu}$</td>
<td>± 0.071 (± 0.064 ± 0.028)</td>
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<td></td>
</tr>
<tr>
<td>$\kappa_{Z\gamma}$</td>
<td>± 0.123 (± 0.102 ± 0.069)</td>
<td></td>
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</tr>
</tbody>
</table>
HH Production Measurements

- Current Run-2 ATLAS limit: 4 x SM
- Most sensitive channel: bb\(\tau\tau\) uses fit to BDT score by category
- Second channel: bb\(\gamma\gamma\) analysis w/ parameterized simulation: fit \(m_{HH}\)
- Third channel: bbb\(b\) result suffers large syst. uncertainties

**ATLAS** Preliminary

Projection from Run 2 data

\(\sqrt{s} = 14\ TeV,\ 3000\ fb^{-1}\)

\(\tau_{\text{had}}\) 2 b-tags

Events / Bin

**ATLAS** Simulation Preliminary

\(\sqrt{s} = 14\ TeV,\ 3000\ fb^{-1}\)

SM HH \(\rightarrow b\bar{b}\gamma\gamma\)

Single Higgs

Other

Uncertainty

Events / 2 GeV

**ATLAS/CMS** combination in arXiv:1902.00134: \(~4\sigma\) for SM HH
SUSY Searches

• High-statistics HL-LHC dataset: an opportunity to test the TeV mass scale for electroweak SUSY, even for lowest cross sections

• Projections with full b-tagging simulation & realistic uncertainties

• Largest gains in statistics-limited searches with tight selections
Summary and Conclusions

- ATLAS projects a broad and deep Run-3 and Run-4 physics program
  - Precision Higgs, electroweak, and top measurements with large datasets
  - Improved PDF measurements with high lumi at 14 TeV
  - Searches for BSM physics, especially in small cross-section processes
  - High-density QCD studies in heavy-ion and pp collisions
- Detailed studies prepared both with full detector simulation and with extrapolated systematic uncertainties
- Challenging experimental conditions require new detector upgrade designs and improved reconstruction algorithms.
- These studies and improvements depend on continued progress in theoretical calculations and computational tools.

Already looking forward to lots of 14 (or 13.5) TeV data!
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ATLAS Detector Upgrades and Upgrade Physics
More public ATLAS upgrade physics results available at
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies

Collections of HL-LHC studies

- High-Density QCD: arXiv:1812.06772
- Flavor Physics: arXiv:1812.07638
- BSM Physics: arXiv:1812.07831

Contributions to HL-LHC workshop

  (Vol. 2 of Yellow Report)

ATLAS HL-LHC TDRs

- ITk Silicon Strips: https://cds.cern.ch/record/2257755
- Muon Spectrometer: https://cds.cern.ch/record/2285580
- LAr Calorimeter: https://cds.cern.ch/record/2285582
- Tile Calorimeter: https://cds.cern.ch/record/2285583
- ITk Silicon Pixels: https://cds.cern.ch/record/2285585
- High-Granularity Timing Detector: https://cds.cern.ch/record/2719855

J. Nielsen (Santa Cruz) ATLAS Detector Upgrades and Upgrade Physics