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

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Luminosity and Energy Increases at LHC

- **Long Shutdown 2 (Phase-1 upgrade) preparing for Run 3**
  - Luminosity leveling at $2 \times 10^{34}$/cm$^2$/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 $7.5 \times 10^{34}$/cm$^2$/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
Muon New Small Wheel

Detector sandwich: TGC-MM-MM-TGC

- 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

- 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

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ATLAS Detector Upgrades and Upgrade Physics
Run-3 SUSY and Exotic Searches

**Monojet signature (WIMP recoil)**

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

**Dark photon decays**

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

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**ATL-PHYS-PUB-2018-043**

ATLAS Simulation Preliminary

- $\sqrt{s} = 13$ TeV, 300 fb$^{-1}$
- 3 $\sigma$
- 5 $\sigma$

Axial-Vector Mediator

- Dirac Fermion DM
- $g_q = 0.25$, $g_{\chi} = 1$

Projection from Run-2 data

**ATL-PHYS-PUB-2019-002**

ATLAS Simulation Preliminary

- $\sqrt{s} = 14$ TeV, 300 fb$^{-1}$
- BR($H\rightarrow 2\gamma + X$) = 10%
- BR($H\rightarrow 2\gamma + X$) = 1%

FRVZ $2\gamma_d$ model

- $m_H = 125$ GeV, $m_{\chi_d} = 400$ MeV
- expected limit
- expected ± 1 $\sigma$
- expected ± 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 $W_L W_L$
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 $\langle \mu \rangle = 200$ 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
**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

**Efficiency**

\[
\begin{align*}
\text{Run-2, } &\mu > 20 \\
\text{ITk Layout, } &\mu = 200
\end{align*}
\]
• Goal of better e, γ, τ, 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 μs 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
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$^{-1}$

| | Total | Stat. | Syst. |
|---|---|---|---|
| $ggF$ | $\pm 0.024$ ($\pm 0.008 \pm 0.022$) |
| $VBF$ | $\pm 0.042$ ($\pm 0.020 \pm 0.036$) |
| $WH$ | $\pm 0.077$ ($\pm 0.041 \pm 0.065$) |
| $ZH$ | $\pm 0.049$ ($\pm 0.034 \pm 0.035$) |
| $t\bar{t}H$ | $\pm 0.053$ ($\pm 0.019 \pm 0.050$) |

| Parameter value |
|---|
| $\kappa_W$ | $\pm 0.022$ ($\pm 0.008 \pm 0.021$) |
| $\kappa_Z$ | $\pm 0.018$ ($\pm 0.009 \pm 0.015$) |
| $\kappa_t$ | $\pm 0.041$ ($\pm 0.011 \pm 0.040$) |
| $\kappa_b$ | $\pm 0.043$ ($\pm 0.016 \pm 0.041$) |
| $\kappa_{g}$ | $\pm 0.031$ ($\pm 0.011 \pm 0.026$) |
| $\kappa_{\gamma}$ | $\pm 0.024$ ($\pm 0.009 \pm 0.029$) |
| $\kappa_{\mu}$ | $\pm 0.071$ ($\pm 0.064 \pm 0.028$) |
| $\kappa_{Z\gamma}$ | $\pm 0.123$ ($\pm 0.102 \pm 0.069$) |
HH Production Measurements

- Current Run-2 ATLAS limit: 4 x SM
- Most sensitive channel: bbττ uses fit to BDT score by category
- Second channel: bbγγ analysis w/ parameterized simulation: fit $m_{HH}$
- Third channel: bbbγ analysis suffers large syst. uncertainties

**ATLAS** Preliminary
Projection from Run 2 data

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

- ATLAS/CMS combination in arXiv:1902.00134: ~4σ for SM HH

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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
- Higgs Physics: arXiv:1902.00134
- SM Physics: arXiv:1902.04070

Contributions to HL-LHC workshop
- Joint ATLAS-CMS addendum with collection of notes: arXiv:1902.10229
  (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