Expected performance of the upgrade
ATLAS experiment for HL-LHC

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Outline

- Physics programs and challenges at HL-LHC
- The upgrades of ATLAS detector for HL-LHC
- Expected performance
  - Trigger and reconstruction of physics objects
  - Physics sensitivity
- Summary
The high-luminosity LHC (HL-LHC) is intended to provide 300 fb\(^{-1}\) of data each year during an operating period of roughly 10 years.

- An instantaneous luminosity of \(\mathcal{L} \sim 7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}\)
- An average of 200 inelastic proton-proton interactions per bunch crossing (pile-up, \(< \mu > = 200\))
Physics programs at HL-LHC

• Precision measurements of Higgs boson couplings
  – As many Higgs production and decay channels as possible
  – Providing constraints on potential non-Standard Model

• Exploration of Higgs potential by study of Higgs-boson pair production
  – Higgs trilinear self-coupling, $\lambda_{HHH}$, related to the form of the Higgs potential
  – A direct test of the spontaneous symmetry breaking in SM
  – Promising channels: $HH \rightarrow b\bar{b} + b\bar{b}$, $b\bar{b} + \gamma\gamma$, $b\bar{b} + \tau^+\tau^-$
    ➢ High efficiency $b$-tagging is critical

• Sensitivity to new particles or rare decays involving new physics
  – Taking the BSM predicted $Z'$ boson (mass $\sim$ TeV) in the TopColour mode which primarily decays to $t\bar{t}$ as an illustration
  – A $t\bar{t}$ resonance search is a benchmark to evaluate BSM physics prospects at HL-LHC
    ➢ Dense tracking environment inside the high $p_T$ jets
      • Highly boosted top quarks due to the high mass of $Z'$
HL-LHC environment

- **High pile-up density** at HL-LHC
  - Current detector could not stand such harsh radiation environment
- **Challenging for track-to-vertex association**
- Detector need to be upgraded
  - High-granularity robust against the high occupancy
  - Radiation-hard withstanding the high particle fluence
  - Extended coverage of tracking with improved performance
- **Essential to mitigate effects from pile-up**
  - Good objects reconstruction (leptons, jets, $E_T^{\text{miss}}$, b-tagging)
The Trigger and DAQ Upgrade

- High instantaneous luminosity means higher data rates

- New designed trigger/DAQ system
  - To cope with high rates while keeping low trigger thresholds
  - The baseline architecture: a single-level hardware trigger + event filter
  - 1 MHz trigger rate instead of 100 kHz
    - A big challenge for the detector readout
  - 10 kHz output data rate instead of 1 kHz

- New readout electronics for all systems
  - To cope with the increased occupancies and data rates
The Upgrades of ATLAS Detector for HL-LHC

- To maintain or improve ATLAS performance
- To cope with the increased occupancies and data rates

- All-silicon new Inner Tracker (ITk)
- New inner Muon barrel trigger chambers
- Calorimeters (only TDAQ)
- New readout electronics for all systems
- New High-Granularity Timing Detector
- Possible High-$\eta$ muon tagger
TDRs for the ATLAS phase-II upgrades

- **6 Technical Design Reports**
  
  - **Tracker Strip TDR**  
    - CERN-LHCC-2017-005  
  
  - **Muon TDR**  
    - CERN-LHCC-2017-017  
  
  - **Tracker Pixel TDR**
  
  - **LAr TDR**
  
  - **Tile TDR**
  
  - **TDAQ TDR**

- **1 Technical Proposal**

  - **HGTD TP**  
    - Under review

  TDR is planned for early 2019
ATLAS Inner Tracker (ITk)

- High-granularity
- Radiation-hard
- Extended coverage to $\eta$ of 4 ($|\eta| < 2.5$ for Run 2)

- **200m$^2$ of silicon** with 5G pixels and 80M strips

**The Pixel detector**: 5 layers with inclined sensors in barrel
- **Inclined sensors** reduce the amount of silicon needed due to the large angular coverage
- **End-cap rings** (replacing traditional disks) are individually placed to optimize the coverage

**The Strip detector**: 4 barrel layers and 6 end-cap disks on each side
- **Double modules with a small stereo angle** to provide 2D measurements
Phase-II Tracking Performance (1)

- **Tracking efficiency**
  - Fraction of high quality tracks matched to a truth primary particle

- **Fake or mis-reconstructed tracks**
  - Secondary tracks
  - Mis-measured low-$p_T$ tracks due to the limited $\sigma_{p_T}$ in the forward region

- Tracking efficiency and fake rates are stable over the full range of pile-up for all intervals of $\eta$
- Good performance even at high pile-up
Phase-II Tracking Performance (2)

- Better track parameter resolution
  - Smaller pixels

**Better momentum resolution** example
- Higher precision of strip tracker compared to TRT
- Reduced material

**Better momentum resolution** $\rightarrow$ **better mass resolution**

- Comparable resolution of transverse impact parameter with Run 2
- Better resolution of longitudinal impact parameter (smaller pixel pitch in beam direction)

- **Track parameter resolutions** directly determine the $b$-tagging capability and lepton or jet reconstruction
b-tagging Performance

• **Multivariate techniques** based on
  – Impact parameters of associated tracks
  – Properties of reconstructed secondary vertex

• **b-tagging algorithms have been fully re-optimized** for the new layout
  - Better rejection capability of ITk even at high pile-up levels
  - The extended coverage of ITk enables the **b**-tagging in the forward region.

• **b**-tagging is sensitive to the contamination of pile-up tracks
  – It considers **tracks with large impact parameters**
  – Essential to mitigate effects from pile-up
Muon Spectrometer

- **Phase-II** (2024 – 2026, mainly about trigger for Muon spectrometer)
  - New inner RPC stations
  - Monitored Drift Tubes information to be added at the hardware trigger
  - Investigating the addition of a high-\(\eta\) tagger

- **Phase-I** (2019 - 2020)
  - New Small Wheel
  - Upgrades to the inner barrel Resistive Plate Chambers
    - NSW required to maintain low-\(p_T\) lepton triggers at high rates
      - reject \(~90\%\) of fake triggers

See Benoit’s talk about Muon phase-I upgrade
High-Granularity Timing Detector

- Precise assignment of tracks to Hard-Scatter (HS) vertex → to mitigate the pileup effects
  - **Space separation** of vertices in the beam direction (z)
    - High pile-up density at HL-LHC
    - $\sigma_z$ is not good in the forward region
  - **Time separation of vertices**

**HGT D**

- Designed to distinguish between **collisions occurring very close in space but well separated in time**
- Located just outside of ITk covering the forward region $2.4 < |\eta| < 4.0$
- Consisting of 4 silicon layers
  - 10% occupancy in $1.3 \times 1.3$ mm$^2$ pixels
- Expected **timing resolution of 30 ps** will greatly improve the track-to-vertex association in the forward region
  - Compared to 180 ps RMS spread of collisions
Pile-up Jets Suppression

- **Pile-up jet tagging** with the discriminant
  \[ R_{p_T} = \frac{\sum_k p_T^{\text{trk}_k}(pV_0)}{p_T^{\text{jet}}} \]
  - Defined as the scalar sum of the \( p_T \) of all tracks within a jet associated with the HS vertex, divided by the jet \( p_T \)
  - Small value of \( R_{p_T} \) for pile-up jets

- Rejection vs efficiency as a scan over the \( R_{p_T} \) requirement

- Significant improvement of pile-up jet rejection in the forward region
  - Extended coverage of ITk
    - Track-based pile-up suppression
  - HGTD
    - Timing information
The Expected Sensitivity to $HH \rightarrow 4b$

- The effects of upgraded ATLAS detector are taken into account by
  - applying energy smearing, object efficiencies and fake rates to truth level quantities
  - following parameterizations based on detector performance studies with full simulation and HL-LHC conditions

- $HH \rightarrow 4b$ High sensitivity to $b$-jet trigger threshold → Trigger system upgrade is critical
  - Substantial degradation with increased minimum jet $p_T$ requirement
  - $100 \text{ GeV} \rightarrow 65 \text{ GeV}$ (w/o → w/ upgrade) $\sim \times 2$ sensitivity

- More channels combined to get enough statistics
  - $b\bar{b} + \gamma\gamma$
  - $b\bar{b} + \tau^+\tau^-$

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**ATLAS**

$6\tau = 14 \text{ TeV}, L = 3000 \text{ fb}^{-1}$

$HH \rightarrow 4b$
No sys. uncertainty

$95\% \text{ C.L. exclusion limit on } \sigma_{SM}$

Minimum offline jet $p_T$ [GeV]

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$\lambda_{\text{HH}}$

$6\tau = 14 \text{ TeV}, L = 3000 \text{ fb}^{-1}$

$HH \rightarrow 4b$
No sys. uncertainty

$68\% \text{ C.L. interval for } \lambda_{\text{HH}}$
$95\% \text{ C.L. interval for } \lambda_{\text{HH}}$

Minimum offline jet $p_T$ Threshold [GeV]
The Expected Sensitivity to $Z' \rightarrow t\bar{t}$

- Single lepton + jets channel ($t\bar{t} \rightarrow WbWb \rightarrow lνbqq'b$)

- **Stable tracking efficiency inside jets with increasing** $p_T$
  - Top quarks tend to produce $b$-jets with $p_T > 600$ GeV
  - Robust against the high-density tracking environment

- If no signals observed, expect to exclude this resonance for $m_{Z'} < 4$ TeV after HL-LHC (ATL-PHYS-PUB-2017-002)
  - Topcolour model of spin-1 $Z'$ assuming $\Gamma = 1.2\%$
  - $\text{LO} \times 1.3$ to account for NLO effects
  - The most recent ATLAS search using 36.1 fb$^{-1}$ of data taken at $\sqrt{s} = 13$ TeV excludes $m_{Z'} < 3.2$ TeV (Talk by Siyuan Sun)
Conclusions

• Challenging to maintain or improve the performance in very dense environment with pileup up to 200

• Significant upgrades planned for the ATLAS detector for HL-LHC
  – All-silicon ITk with extended coverage to improve the tracking performance
  – HGTD to mitigate pile-up effects
  – Trigger system upgrade to keep lower trigger threshold

• The performance of the physics objects reconstruction is expected to be better than the current detector.
Backup
Phase-II Tracking Performance

- **Track parameter resolutions** directly determine the $b$-tagging capability and lepton or jet reconstruction

- Better resolution of transverse momentum ($p_T$)
  - Higher precision of strip tracker compared to TRT
  - Reduced material

- Expected comparable resolution of transverse impact parameter ($d_0$)
  - Larger radius of ITk
  - Analog clustering would help

- Better resolution of longitudinal impact parameter ($z_0$)
  - Decreased pixel pitch in the z direction
Jet reconstruction

• Pileup is one of the main challenges for jets
  – Soft particles from nearby pileups are likely to contaminate the jets from HS.
  – This is especially true for boosted objects the products of which are very collimated.

• Typical boosted signature with jet radius $R = 1.0$ for $Z' \rightarrow t\bar{t}$
  – Grooming algorithms significantly reduce the sensitivity to pileup (reduced jet area)
    https://cds.cern.ch/record/1459530
  – After grooming and applying pileup corrections, the leading jet mass resolution is
    significantly improved and the pileup dependency is removed.
Missing Transverse Energy

• An important variable in searches for exotic signatures.
  – In SM, $E_T^{\text{miss}}$ arises from neutrinos.
  – There are also prospects for such particles in BSM theories.

• $E_T^{\text{miss}}$ is computed as the vector momentum sum of high $p_T$ physics objects, plus the soft-term from low $p_T$ particles associated to the HS vertex.

- Better $E_T^{\text{miss}}$ resolution in the high pile-up conditions
  ✓ Benefitting from the strong pile-up jet rejection of ITk in the forward region
  ✓ The gain in the soft term using tracks in the forward region is small
Performance of electron reconstruction

- **Similar performance with Run2 is expected**
  - Likelihood based electron identification, combing calorimeter and track variables
  - It improves about a factor of 2-5 in rejection of jets.
  - This would also be carried out for ITk.

- **Charge mis-identification** is caused predominantly by Bremsstrahlung.
  - The EM cluster corresponding to the initial matched to the wrong-charge from the conversion leptons
  - The electron track may fail the tracking recovery for Bremsstrahlung, leading to a poorly measured short track.
  - Reduced material of ITk significantly decreases the mis-identification probability.
Performance of photon reconstruction

- Photon conversion $\rightarrow$ affects the reconstruction efficiency and the energy calibration
  - Much-reduced material budget of the ITk significantly decreases the probability of photon conversion.
  - A conversion track-finding algorithm has been developed for the ITk based on the Run 1 and Run 2 experience
  - The conversion reconstruction efficiency is slightly lower in high pile-up condition

- The energy resolution of photons under $\langle \mu \rangle = 200$ is worse than $\langle \mu \rangle = 0$ (studied in very central region)
  - Pileup-only contribution $= \sqrt{\sigma_{\mu=200}^2 - \sigma_{\mu=0}^2}$
  - The pileup noise dominates the energy resolution for photons with energy up to 130 GeV, and has an increasing impact for lower $E_r$
Two-level hardware-based TDAQ Upgrade

- A two Level hardware-based trigger system
  - The L0 trigger accepts inputs from the Calorimeter and Muon trigger systems.
  - Hardware-based track reconstruction is implemented in the L1 trigger system
  - The track segments are matched with calorimeter and muon features in the Global Trigger, after which the Central Trigger Processor forms the L1 decision.

- The L1 trigger provides the necessary rejection using precision pattern recognition and by building topological triggers that match data across detector systems.
- The readout capacity is increased from 100kHz to 1 MHz and the output data are increased from 1 kHz to 10 kHz
Higgs Signal Strength at HL-LHC

• Assuming a SM Higgs boson
  – A mass of 125 GeV

• Not including improved analyses techniques
  – Run 1 analysis strategy with expected performance at $< \mu > = 140$
  – New estimations are going on.

• **Statistical uncertainty reduced** relative to 300 fb$^{-1}$ data which would be accumulated before Phase-II
  – 4-5% for main channels, 10-20% on rare modes
  – Theoretical uncertainty (hashed area) not negligible for several channels $\rightarrow$ expected to be improved
Material Budget of ITk

- A reduction of multiple scattering of all particles improves the tracking efficiency and resolution
- Reduced conversion probability of photons
- Less energy of particles lost before the calorimeters
The technology chosen for the HGTD sensors is Low Gain Avalanche Detectors (LGAD)
- n-on-p silicon detectors containing an extra highly-doped p-layer below the n-p junction to create a high field which causes internal gain
- an initial current is created from the drift of the electrons and holes in the silicon
- When the electrons reach the amplification region, new electron/hole pairs are created and the holes drift towards the p$^+$ region and generate a large current

An LGAD thickness of 50 microns has been adopted.
pileup