ATLAS Upgrades Towards the High Luminosity LHC
extending the discovery potential

on behalf of the ATLAS Collaboration
Motivation

- expectations and present status

- motivations for higher luminosity
  - perform measurements of Higgs properties
  - observe/measure rare (SM and BSM) processes that occur at rates below the current sensitivity
  - extend exploration of the energy frontier to increase the discovery reach

For illustration: physics reach as expected pre-2010
LHC is doing fantastically well

- **2012 operation**
  - peak event pileup routinely exceeding design values
- **event pileup and other induced effects (e.g. radiation damage)**
  - challenge for the detector, T/DAQ and offline
    - so far ATLAS is doing very well
  - aim of the ATLAS upgrade program:
    - preserve and improve physics performance to fully benefit from increasing luminosity
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### Graphs and Data

**ATLAS Online Luminosity**

- **2010**
- **2011**
- **2012**

**ATLAS design**

**Luminosity Leveling**

The peak luminosity is not fully exploited, but the collider is rather operated at a slightly lower peak luminosity, which will result in longer fills and a less demanding environment for the experiments.
Upgrade Schedule Assumptions

- LHC startup, $\sqrt{s} = 900$ GeV
- $\sqrt{s} = 7\sim 8$ TeV, $L = 6 \times 10^{33}$ cm$^{-2}$ s$^{-1}$, bunch spacing 50 ns
- Go to design energy, nominal luminosity (Phase-0)
- $\sqrt{s} = 13\sim 14$ TeV, $L = 1 \times 10^{34}$ cm$^{-2}$ s$^{-1}$, bunch spacing 25 ns
- Injector and LHC Phase-1 upgrade to full design luminosity
- $\sqrt{s} = 14$ TeV, $L = 2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$, bunch spacing 25 ns
- HL-LHC Phase-2 upgrade, IR, crab cavities?
- $\sqrt{s} = 14$ TeV, $L = 5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$, luminosity leveling

... as shown in Chamonix 2012
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... outline for the following as shown in Chamonix 2012

- $\sim 20-25$ fb$^{-1}$
- $\sim 75-100$ fb$^{-1}$
- $\sim 350$ fb$^{-1}$
- $\sim 3000$ fb$^{-1}$
Phase-0: 2013/14 Shutdown (LS1)

- **detector consolidation:**
  - new tracker evaporative cooling plant
  - new Calorimeters LV power
  - magnets cryogenics consolidation
  - muon spectrometer consolidation
  - infrastructure consolidation (electronics, ventilation, radiation protection, …)
  - maintenance and repairs everywhere

- **detector upgrade:**
  - Insertable B Layer (IBL): 4th pixel layer
    - install (?) new pixel services (nSQP), incl. new Diamond Beam Monitor
  - new small radius central Be pipe
  - new forward aluminum beam pipes
  - new chambers in the muon spectrometer to improve geometrical coverage

Complex access with only ~20 months available

ATLAS Pixel detector + IBL
Insertable B Layer (IBL)

- **4th pixel layer**
  - add low mass layer closer to beam, with smaller pixel size
  - improve tracking, vertexing, b-tagging and $\tau$-reconstruction
  - recovers from defects, especially in present b-layer
  - FE-I4b overcomes bandwidth limitations of present FE-I3

- **IBL key specifications:**
  - 14 staves, $<R> = 33.25 \text{ mm}$
  - CO2 cooling, $T < -15^\circ\text{C} @ 0.2 \text{ W/cm}^2$
  - $X/X0 < 1.5 \%$ (B-layer is 2.7 \%)
  - $50 \mu$m x $250 \mu$m pixels (planar and 3D sensors)
  - $1.8^\circ$ overlap in $\phi$, $< 2\%$ gaps in Z
  - 32/16 single/double FE-I4 modules per stave
  - radiation tolerance $5 \cdot 10^{15}$ neq/cm$^2$

- **mounted on new beam pipe**
  - installation options still to be decided
  - may extract present Pixel Detector to replace nSQPs (decision this year)
Phase-1: Installation in or before LS2

- pileup up to 80 at luminosities up to $3 \cdot 10^{34} \text{cm}^{-2}\text{s}^{-1}$
  - challenge: keep trigger threshold around 20-25 GeV
  - raising muon $p_T$ thresholds not effective in the forward
  - higher EM $E_T$ thresholds eat into physics acceptance

- trigger and related upgrades
  - new muon small wheels for forward trigger and tracking
  - high granularity calorimeter Level-1 trigger electronics
  - fast tracker trigger (FTK) using Pixel and SCT information
  - topological trigger processor for Level-1 (starts before LS2)
  - High Level Trigger farm upgrade, especially network
  - new Tiles crack-gap scintillators and trigger electronics

- ATLAS Forward Physics (AFP)
  - new forward detectors installed at 210 m, start before LS2
Granularity LVL1 Calorimeter Trigger

- explore LAr lateral show shapes to improve trigger rejection
  - super-cells formed in 2nd layer of EM calorimeter
  - goal: reduced Level-1 trigger rate and preserve un-prescaled threshold at ~25 GeV

- requires new front end digital chain
  - super-cells with higher granularity are formed in the front end shaper sum ASIC and individually digitized
  - Level-1 uses ratio of energies of different size clusters
New Muon Small Wheel

- Improve forward muon trigger
  - \( < 1 \text{ mrad} \) angular resolution on track segments at Level-1
  - Trigger studies demonstrate Level-1 rate reductions

- 2 multilayers per sector, each with
  - 4 layers sTGC (Thin Gap Chambers) for trigger
    - Reduced cathode resistivity, rates > 30 kHz/cm\(^2\)
  - 4 layers of MicroMegas for a total of 2 \( M \) channels
    - Both coordinates, direction information, \( \sim 70 \text{ um} \)

- TDR planned for 2013

trigger rate reduction, studied using data
\( \sim \) factor 6

1.2 \( < \eta < 2.4 \)
The Fast Tracker (FTK)

- current ATLAS trigger chain
  - Level-1: hardware based (~50 kHz)
  - Level-2: software based with RoI access to full granularity data (~5 kHz)
  - Event Filter: software trigger (~500 Hz)

- FTK: hardware based tracking
  - descendent of the CDF Silicon Vertex Trigger (SVT)
  - inputs from Pixel and SCT
    - data in parallel to normal read-out
  - two step reconstruction
    - associative memories for parallel pattern finding
    - linearized track fit implemented in FPGAs
  - provides track information to Level-2 in ~ 25 μs

- major Level-2 improvement for
  - b-tagging, τ-reconstruction
  - lepton isolation
  - primary and pileup vertex reconstruction
ATLAS Forward Physics (AFP)

- study tagged color singlet or photon exchange processes
  - p-p tagged high mass central system
  - anomalous WW couplings, diffractive jet production, new physics?

- system of timing and silicon detectors
  - installed in movable beam pipe to move detectors in while stable beams
  - at 210 m away from P1
  - 2x6 layer 3D pixel detector (IBL) to measure proton position ~15 μm
  - radiation few mm from beam
  - array of 4x8 quartz bars to measure proton timing ~10 psec to separate signal and pileup interactions
Phase-2: Installation 2022/23

• by end of Phase-1 LHC will have delivered 300-500 fb\(^{-1}\)
  ➪ LHC will be made ready for 5\(\times\)10\(^{34}\)cm\(^{-2}\)s\(^{-1}\) with luminosity leveling

• ATLAS Phase-2 upgrade program is taking shape
  ➪ main activity is construction of a new Inner Detector
  • already ongoing major R&D, prototyping and engineering effort
  • including feasibility studies for a Level-1 hardware track trigger (Level-0 seeded)
  ➪ Phase-2 conditions may require to replace FCAL (Forward Calorimeter) and change HEC (Hadronic EndCap) electronics
  ➪ muon spectrometer will be upgraded, in particular in the big wheel region
  ➪ existing electronics/computing/TDAQ will need to be upgraded and modernized to face additional 8-10 years of running in extreme conditions

• plan is to be ready for installation in 2021
  ➪ will need a 2 year shutdown to prepare ATLAS for its new phase

• Letter of Intent to be presented in December
Inner Tracker Upgrade

• to keep ATLAS running requires tracker replacement
  ➡ current tracker designed to survive up to 10 MRad in strip detectors (≤ 700 fb⁻¹)
  ➡ replace with an all silicon tracker to match the challenge of 140-200 pileup events

• main ITK design parameters
  ➡ **Inner Pixels:**
    • 2 replaceable layers close to enlarged Phase-2 beam pipe
    • smaller pixel pitch to improve b-tagging (FE-I5)
  ➡ **Outer Pixels:**
    • 2 barrel layers at increased radii to improve tracking in jets
    • pixel endcaps ensure full tracking coverage to η=2.5
    • some standalone tracking capability to η=2.7 (muons)
  ➡ **Strip Detector:**
    • maximize momentum resolution (B·dl)
    • double sided strips in 5 layer, 7 disk, plus stub
    • shorter strips close to PST to limit occupancy
  ➡ overall a 14 hit system down to η=2.5
    • robustness, avoid fakes at high pileup
    • overall much reduced material budget
Computing and Offline

- vital part of the upgrade program
  - support upgrade with detector simulation
  - upgrade of the computing and offline software infrastructure

- many challenges ahead
  - computing infrastructure is constantly evolving
    - GRID middleware, cloud computing, storage systems, networking...
  - increasing integrated luminosity, trigger rates and event sizes
    - ATLAS Production System and Data Management needs to scale
    - GRID luminosity for simulation is becoming rapidly a factor
  - reconstruction needs to cope with even higher levels of event pileup

- upgrade on the fly, while experiment is operating

- industry may move to new technologies
  - many-core architectures may replace present X86 boxes (a la Intel MIC)
  - need to be prepared to adapt or re-implement large parts of framework as well as offline (and high level trigger) software chain

- part of Phase-2 Letter of Intent
Summary of ALTAS Upgrade Program

• preserve excellent detector performance to take full benefit of increasing luminosity to fully explore the ATLAS physics potential
  ➡ adapt and upgrade detector, electronics, TDAQ and offline computing to match challenges ahead

• Phase-0: preparation advancing well
  ➡ IBL approaches construction phase

• Phase-1: Letter of Intent
  ➡ various upgrades to cope with luminosities up to $3 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
  ➡ next year(s) to prepare TDRs

• Phase-2: ensure ATLAS operation until the end of the next decade for a total of 3000 $fb^{-1}$
  ➡ Lol in preparation
BACKUPS...
# 10 year plan (not yet approved)

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**Technical stop or shutdown**

- **Proton physics**
- **Ion Physics**
- **Recommissioning**

Mike Lamont (CERN BE-OP) 21.5.2012 at CMS Upgrade week
Improve Muon Spectrometer Coverage

- **Endcap Extension (EE) Chambers**
  - improve coverage in $1.0 < |\eta| < 1.3$
  - will install missing 52 chambers (out of 62)
  - address low tracking efficiency in the region

- **new shielding at 7 m**
  - cover gap between forward calorimeter and shielding disk
  - reduce forward hit occupancy in Muon Small Wheel region

![EE Muon Chambers](image)

**FLUGG**

- hits with/out additional shielding

![ATLAS Simulation](image)
The thermosiphon is the baseline solution for the consolidation of the ATLAS ID evaporative cooling system.

The new cooling system will increase the present performances of the existing compressor system to 60 kW @ -30°C (gaining 10 K), to guarantee these performances we shall manage fluid blends C₃F₈-C₂F₆.

The present compressor system will remain as full power back up cooling source.

Procurement and installation are advancing as part of M&O A!
Active Sensor

Hybrid Pixel Chip Assembly:
- sensor and FE chip are produced separately
- connected via bump bonding

Planar Sensor
- “classic” sensor design
- oxygenated n-in-n
- 200µm thick
- Minimize inactive edge by shifting guard-ring underneath pixels (215 µm)
- Radiation hardness proven up to $2.4 \cdot 10^{16}$ p/cm$^2$
- Problem: HV might need to exceed 1000V

3D Silicon
- Both electrode types are processed inside the detector bulk
- Max. drift and depletion distance set by electrode spacing
- Reduced collection time and depletion voltage
- Low charge sharing

IBL baseline:
- 75 planar sensors
- 25 (3D sensors@large eta)
New Front End Chip FE-I4

Reasons for a new front-end chip

- Increased radiation hardness (> 250 MRad)
- Greater fraction of the footprint devoted to pixel array
  - Move the memory inside the array
- Lower power
  - Don't move the hits around unless triggered
- Able to take higher hit rate
  - Store the hits locally and distribute the trigger
- Still able to resolve the hits at higher rate
  - Smaller pixels and faster recovery time
- No need for extra control chip
  - Significant digital logic blocks on array periphery

=> 19 x 20 mm$^2$ 130 nm CMOS process, based on an array of 80 by 336 pixels (each 50 x 250 µm$^2$)

Improved version B was received and used for various tests
New Service Quarter Panel

- New service layout for all pixel service (nSQP)
- Redundant and safer location for fibers transmitters
- Doubling of the readout bandwidth in view of Phase 1 upgrade
- **Diamond Beam Monitor attached to nSQP**
  - Uses Diamond Si detectors produced for IBL trials
  - Will provide very fast monitoring of beam in high rate environment

Be ready to take the final decision if to extract and repair or not the pixel detector on the surface during 2012 (first half)
Phase 1: Trigger & DAQ Upgrades

- Incorporate Muon Small Wheels, L1Calo higher granularity, FTK
- L1 (including topological trigger) -> FTK -> L2 & EF
  - Greater integration of Level-2 and Event Filter selections + Event Builder
p-type (n-in-p) and n-in-n pixel and miniature strip planar silicon detectors irradiated to HL-LHC inner layer doses of $2 \times 10^{16} \text{n}_{\text{eq}} \text{cm}^{-2}$ \textit{(D. Muenstermann)}

\textbf{FE-I4 thresholds down to 1600e (even lower for diamond)}
Phase 2: Calorimeters

- EM LAr Barrel & Tile Calorimeter will work fine: no upgrade.
- Full upgrade of FE and BE electronics (radiation, lifetime, performance ...)
  - Both LAr and Tiles
- Hadronic EndCap electronics designed for 1000 fb^{-1} – possible replacement
- Forward Calorimeter @ HL-LHC instantaneous luminosity: overheating / ion build-up / HV drop / signal loss...

Option 1:
Complete replacement of the FCal
Smaller LAr gaps (to reduce ion build-up/HV drop) + better cooling (avoid overheating)

Option 2:
Installation of a small calorimeter in front of the current FCal: Mini-FCal =>
Reduce energy and ionization @ FCal
Radiation Background Simulation

At inner pixel radii - target survival to $2-3 \times 10^{16} \text{n}_{eq}/\text{cm}^2$

For strips $3000 \text{fb}^{-1} \times 2$ implies survival required up to $\sim 1.3 \times 10^{15} \text{n}_{eq}/\text{cm}^2$