ATLAS and CMS Upgrade programs and performance goals
RLIUP LHC workshop
Archamps, Oct. 29
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- Physics goals and detector longevity in presentations of Fabiola & Beniamino
- In this talk
  - ATLAS and CMS upgrades through LHC luminosity rise
  - Focus on performance at high rate and pile-up
The challenge of high luminosity

- Sophisticated algorithms combine all information to reconstruct:
  - Physics objects
    - Identified and isolated particles
      - Jets - total and missing energy
    - Decay of fundamental particles
      - $W$, $Z$, $H$, $t$ ...

- Detector measures charge deposits:
  - Charged particles (tracker)
  - $e/\gamma$ (electromagnetic calorimeter)
  - Hadrons (hadronic calorimeter)
  - $\mu$ (gas chambers)
The challenge of high luminosity

- With multiple collisions per bunch crossing (Pile-Up) we mainly rely on the measurement of the charged track origin in the tracker to properly associate physics objects to the primary interaction of interest
  - The increasing PU affects
    - Mostly the Tracker and Calorimeters and the online Trigger event selection
    - And the data flow and the event complexity increase also requires higher readout bandwidth for all detectors and more computing capabilities

Experiments can reconstruct high piled-up event but are not designed to sustain it as a mean
ATLAS and CMS upgrade stages

**LS1:**
- Complete original detectors and consolidate operation for nominal LHC beam conditions 13-14 TeV, $1 \times 10^{34}$ Hz/cm$^2$, Ave. Pileup ($<PU>$) $\sim$ 25
- Prepare or start upgrades for higher $<PU>$

**LS1 through LS2:**
- Prepare detector to maintain physics performance for
  - $1.6 \times 10^{34}$ Hz/cm$^2$, $<PU>$ $\sim$ 40, $\leq$ 200 fb$^{-1}$ by LS2
  - $2.5 \times 10^{34}$ Hz/cm$^2$, $<PU>$ $\sim$ 70, $\leq$ 500 fb$^{-1}$ by LS3

**LS2 through LS3:**
- Prepare for $\geq 5 \times 10^{34}$ Hz/cm$^2$ (with leveling), $<PU>$ 140 total of $\sim$ 3000 fb$^{-1}$ in $\sim$10 years operation - consider higher PU operation
  - Replace subsystems that no longer function due to radiation damage or aging
  - Maintain physics performance at very high PU
ATLAS upgrades for Phase 1

**Trigger/DAQ**
- New backend electronic systems
- Fast Track Trigger (FTK) input at High Level Trigger - before LS2

**Liquid Argon calorimeter (barrel - endcap)**
- Front-end for finer granularity in Trigger - during LS2

**Forward proton spectrometer (AFP)**

**Muon systems**
- Complete muon spectrometer - during LS1
- New Small Wheel forward muon chambers (micromegas) - during LS2

**Pixel detector**
- Insertable Barrel Layer - during LS1

CMS upgrades for Phase 1

Trigger/DAQ
→ New backend electronic systems
  - Commission in parallel in 2015

Muon systems
→ Complete muon coverage of CSCs and RPCs
→ CSC higher read-out granularity
  - during LS1

Forward proton spectrometer (PPS)
- staged from LS1 to LS2

Hadron calorimeters HF/HE/HB
→ Replace photo-detectors and read-out
  - staged from LS1 to LS2

Pixel detector
→ Full replacement
  - extended YETS in 2016

ATLAS upgrades for Phase 2

Trigger/DAQ
→ L1 rate at least 500 kHz
→ Tracks at L2 - 20 μs latency at least 200 kHz
→ Possible HLT output up to 10 kHz

Muon systems
→ New Front-End Electronics

Forward calorimeter
→ Replace FCAL?
→ Replace HEC cold electronics?

Calorimeters: Liquid Argon - Tile calorimeter
→ New front-end and back-end electronics
  (full digital information at L1 trigger)

New Tracker
→ Longevity - occupancy - readout bandwidth
→ Implement Track Trigger in L2
→ Extend η coverage?

LoI in 2013 https://cds.cern.ch/record/1502664/
CMS upgrades for Phase 2

**Trigger/DAQ**
- L1 rate up to 1 MHz with tracks
- Latency $\geq 10\mu$s
- Possible HLT output up to 10 kHz

**Muon systems**
- Complete CSC coverage with new technology GEM/RPCs
- Replace DT readout
- Muons tagging up to $\eta \sim 4$?

**Upgrade/Replace HE/EE**
- Longevity
- Extend coverage up to $\eta \sim 4$?
- Precise timing measurement (also in barrel)?

**Replace Tracking**
- Longevity - occupancy - readout bandwidth
- Implement Track Trigger in L1
- Extend coverage up to $\eta \sim 4$?

Technical Proposal in 2014
ATLAS and CMS Tracker upgrades
From Phase 1 to Phase 2
Upgrade of ATLAS and CMS pixel detectors in Phase 1

- **Common features**
  - 4 space points and smaller inner radius (3 cm)
  - Acceptance up to $\eta = 2.5$
  - Lighter detector

- **ATLAS Insertable Barrel Layer**
  - Use planar (75% at smaller eta) and 3D (25% at higher eta) technologies
  - Installation during LS1

- **CMS new detector**
  - Similar technology as present
  - New readout chip for high rate
  - Installation in Year End
  - Technical Stop 2016-17
Performance of pixel detectors in Phase 1

- Improved track reconstruction efficiency and resolution
- Improved association of tracks at primary vertex and improved b-tagging (close secondary vertex)

→ Illustration below, gain in efficiency squares for multiple objects

- B-tagging efficiency
- Track efficiency and IP precision

~ 65% gain with upgrade

• Pixel detector upgrade is needed for Phase 1
• Can handle up to ~ 70 PU with present detector performance
Trackers for Phase 2

- At 140 PU Phase 1 track reconstruction performance degrades significantly
  - Despite significant improvements in offline algorithms and tuning (efficiency versus rate of fake tracks)

- Tracker requisites for Phase 2:
  - Higher granularity for efficient track reconstruction at 140 to 200 PU
  - And also increased readout bandwidth and improved computing and algorithms capabilities
  - Low beam pipe radius (as now) for precision
  - Integration in hardware Trigger level
ATLAS and CMS Phase 2 Tracker designs

- **Common features**
  - Granularity
    - Strip pitch ~ 80-90 μm & length ~ 2.5/5 cm in inner/outer layers (& macro-pixel sensors in CMS 1.5 mm long)
    - Pixel pitch ~ 25-30 μm and ~ 100 μm length
  - Sensor Technology
    - n-in-p planar technology for increased radiation hardness
    - n-in-n, 3D, diamond or other technologies for innermost layers
  - Trigger implementation
    - Custom ASIC Associative Memory chips (as developed for FTK) for pattern recognition followed by a track fit in FPGA

- **Specific configurations**
  - CMS trigger read-out at 40 MHz - Pt-module concept select “stubs” for tracks with Pt ≥ 2 GeV
  - ATLAS read-out region of interest at ≥ 500 kHz

- **Proposal to extend coverage of Pixel detectors up to |η| ~ 4**
  - Associate jets to primary vertex through track matching
Performance of Phase 2 Trackers

- **Light weight** → improved momentum precision and lower rate of photon conversion
- **Lower pixel size** → improved tagging efficiency - good performance up to 200 PU
- **η extension** → lower rate of fake jets in region of VBF processes

This will have major benefit for key physics channels at HL-LHC
ATLAS and CMS Trigger upgrades

From Phase 1 to Phase2

(includes upgrades of calorimeter and muon detectors)
Upgrade of ATLAS and CMS L1-Trigger systems in Phase 1

- In Phase 1 ATLAS and CMS L1-Trigger bandwidth is limited to 100 kHz
- Hardware event selection is based on calorimeter and muon information

Aside, threshold raise to remain within 100 kHz at $2 \times 10^{34}$ Hz/cm$^2$ without upgrades
- Multi-object trigger rates are highly non-linear with increasing PU
- Physics acceptance will be significantly affected (example in plot below)

<table>
<thead>
<tr>
<th>CMS simplified menu</th>
<th>8 TeV 7E33 ~25 PU</th>
<th>14 TeV 2E34 50 PU</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Thresh (GeV)</td>
<td>Rate (kHz)</td>
</tr>
<tr>
<td>Single EG</td>
<td>22</td>
<td>10</td>
</tr>
<tr>
<td>Single IsoEG</td>
<td>18</td>
<td>9</td>
</tr>
<tr>
<td>DoubleEG</td>
<td>13, 7</td>
<td>9</td>
</tr>
<tr>
<td>Single Muon</td>
<td>16</td>
<td>9</td>
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<td>Dble Muon</td>
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<td>5</td>
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<td>EG+Mu</td>
<td>12, 3.5</td>
<td>3</td>
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<tr>
<td>Mu+EG</td>
<td>12, 7</td>
<td>2</td>
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<tr>
<td>SingleJet</td>
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<tr>
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<tr>
<td>MET</td>
<td>36</td>
<td>7</td>
</tr>
<tr>
<td>HTT</td>
<td>150</td>
<td>2</td>
</tr>
</tbody>
</table>

L1-Trigger upgrades are needed to operate at 50 pile-up
Upgrade of ATLAS and CMS L1-Trigger systems in Phase 1

- **Common features**
  - Higher bandwidth and processing power with modern FPGAs and xTCA back-plan
    - Improved calorimeter granularity
    - Improved muon trigger with new chambers and readout
    - More objects and topological triggers

- **ATLAS**
  - Fats Track Trigger input at HLT
    → Installation through LS1 to LS2

- **CMS**
  - New architecture (Time Multiplexed Trigger) with full event in 1 Processor
    → Slice after LS1 to grow to commissioning of new trigger in parallel for 2016 run
Upgrade of ATLAS and CMS Muon chambers in Phase 1

Similar issues and benefit in trigger for upgrades in ATLAS and CMS

Rates in endcaps
Upgrade of ATLAS and CMS Calorimeter Trigger systems in Phase 1

- Different implementations in ATLAS and CMS but similar benefits
  - $e$ and $\gamma$ isolation with PU subtraction
  - Jet finding and $E_t$ missing with PU subtraction
  - Improved $\tau$ identification
  - $\mu$ isolation

- Global trigger with topological capabilities
  - Mass selection, angular correlations...

$e/\gamma$ isolation W/O upgrades $1 \times 10^{34}$ Hz/cm$^2$ cm$^{-2}$s$^{-1}$
Trigger/DAQ systems for Phase 2

○ ATLAS
  • Increase Level 1 bandwidth to 500 kHz in 5 µs latency
    – Readout of tracker information in Region of Interest
  • Level 2 in 20 µs latency with tracks and 200 kHz HLT input
  • Possible HLT output up to 10 kHz
  → Requires
    – Upgrade of front-end and back-end electronics of Calorimeter and Muon detectors

○ CMS
  • Readout Tracker “stubs” at 40 MHz
  • Readout crystal granularity in ECAL
  • Increase latency to 10 µs and level 1 rate up to 1 MHz
  • Possible HLT output up to 10 kHZ (present HLT rejection)
  → Requires
    – New ECAL Barrel front-end electronics
    – Upgrade of back-end electronics
    – Increased computing power - HLT can benefit from L1-track reconstruction (as for ATLAS phase 1 FTK)
**Performance of Trigger/DAQ systems for Phase 2**

- **Track trigger provides**
  - High momentum resolution for improved momentum selection of leptons
  - Surrounding tracks for isolation of $e/\gamma/\mu/\tau$
  - Association of trigger objects to a primary or secondary vertex to reduce combinatorial effect of PU in multiple object triggers (especially Jet triggers)

- **Increase of L1 bandwidth provides**
  - Flexibility to allocate higher trigger bandwidth (lower trigger thresholds) for objects where track-trigger is less efficient
  - Further margin to operate at PU beyond 140

Studies confirm significant rate reductions as expected - with factor $\sim 10$ for lepton triggers, with good efficiency - this allows to maintain low trigger thresholds
Another means of pile-up mitigation: collision density

- Preliminary studies with CMS Phase 1 detector
  - Tracking acceptance covers flat luminous region
  - No significant tracking efficiency difference at 140 PU
  - Vertex finding efficiency decrease & number of merged vertices increase for Gaussian density

- Track association to primary and secondary vertices will be more efficient with flat density
  - Improved corrections to calorimeter energies
  - Improved b-tagging efficiency. Ex. a 10% gain as shown in right bottom plot will increase 2b-tagging efficiency by ~ 40%

Scenarios of interaction density / crossing S. Fartouk presentation at ECFA workshop
Another means of pile-up mitigation: precise timing

- Tracking does not allow to mitigate PU effect due to neutral particles
  - Limiting performance for photon and Jet ID and energy resolution at high PU
  - Precise timing measurement in front or within calorimeters with ~ 30 ps could allow to significantly reduce number of fakes and background
  - This would depend both on $z$ and timing distributions of the collisions in the bunch crossings
  - More studies to estimate benefit and R&Ds are on-going to develop technical solutions

S. Fartouk presentation at ECFA workshop
Concluding remarks

- Phase 1 upgrades are needed to maintain performance beyond $1 \times 10^{34}$ Hz/cm$^2$, PU ~ 25

- With these upgrades ATLAS and CMS will be able to operate with good performance up to PU of ~ 70 and integrated luminosity ~ 500 fb$^{-1}$

- For Phase 2 HL-LHC physics program ATLAS and CMS are preparing for operation up to 140-200 PU - but with luminosity leveling depending on performance at high PU
  - Present simulations assume $5 \times 10^{34}$ Hz/cm$^2$, 140 PU with a Gaussian luminous region

- A lot of work is ongoing to understand the limitations with Phase 1 detectors and benefits with Phase 2 upgrades
  - Important effort to develop and tune data reconstruction and physics analyses

- A flat density luminous region scenario as presented at the ECFA workshop could be effective to allow detectors to run at higher PU
  - But limitation might remain due to neutral particles - collision time dispersion & precision timing could be a mean to mitigate this PU effect

It is essential that Accelerator & Experiments investigate all opportunities to mitigate PU effects to fully profit from the LHC High Luminosity potential