Collecting and analysing data at high pile-up with ATLAS and CMS.

Detector designs, reconstruction performance, and analysis strategies

N. Styles, for the ATLAS and CMS Collaborations, Rencontres De Moriond, 18/03/15
High-Luminosity LHC (HL-LHC), planned to begin operation in 2025

- Comprehensive program of accelerator upgrades
- “Phase 2” LHC Upgrade
- Peak instantaneous luminosity $5 - 7 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$
- Integrated luminosity $250-300 \text{fb}^{-1}$ 14 TeV pp collisions per year, aiming at total dataset of $3 \text{ab}^{-1}$
- Implies events with pile-up 140-200

Will provide extremely rich physics potential

- To make best use of this, experiments will need to find ways to cope with challenging environment
- Upgrades to detectors, new reconstruction techniques, revised analysis strategies

See talk from Mike Lamont
ATLAS Detector Phase 1 upgrades

> ATLAS will already undergo a series of 'Phase 1' upgrades prior to HL-LHC operation – to be completed by 2020 – which will remain in place for Phase 2

**Muon “New Small Wheels”**
Improved tracking & trigger in forward region

**L1 Calorimeter Trigger**
Upgraded electronics
Allows finer granularity readout

**Fast Track Trigger (FTK)**
Hardware-based track finder
Based on hit pattern matching to pre-stored patterns
Runs after L1 Trigger
For Phase 2 upgrade, ATLAS plans full replacement of Inner Tracker

- All silicon tracker (pixels and microstrips)
- Significantly increase granularity
- Minimise material budget within tracking acceptance
- Sufficient hits on track to maintain high efficiency and combat combinatorics at high pile-up

ITK “Letter of Intent” layout has been developed

- Used as baseline for majority of performance studies
New Trigger Architecture

- 2-Level Hardware trigger design
  - Level 0: 1 MHz, 6μs latency, uses Calo + Muons
  - Level 1: 300-400 kHz, 24μs latency
  - L1Track: Use tracking information earlier in trigger processing – move part of HLT track reconstruction to L1
  - Region-of-Interest (RoI) based approach

Calorimeters

- Tile and Liquid Argon calorimeters require full electronics replacements
- Needed to cope with increased radiation levels and trigger rates
- Forward calorimeter may be fully replaced if significant degradation of current system, or higher granularity mandated by physics requirements
Potential for extending tracking coverage to $|\eta|<4$ under serious consideration

- Tracking performance under investigation – limitations from field strength in forward region
- Extension of pixel system proposed with “rings” in place of traditional endcap disks – offers more flexibility for placement of modules and services

Could be combined with modifications to other systems to maximise impact

- Additional muon chambers
- Increase granularity in forward calorimeter

See also talk from Alex Tuna
CMS Detector Phase 1 Upgrades

- CMS also plans Phase 1 Upgrades that will remain in place for Phase 2
  - Pixel system will be replaced for Phase 1, but not remain in place

### L1 Trigger
Upgrade to Architecture
Based on powerful FPGAs
And high bandwidth optics

### Pixel Upgrade
- Additional layer
- Smaller inner and larger outer radii

### HCAL Upgrade
- New backend & readout electronics
- HPDs replaced with SiPM as photon detectors
CMS Phase 2 Inner Tracker Upgrade

CMS baseline design for full tracker replacement in Phase 2

- As ATLAS, emphasis on minimising material and increasing granularity, with ample hit coverage over tracking acceptance
- CMS baseline includes tracking coverage up to $|\eta|<4$
- CMS Tracker replacement designed to allow self-seeded L1 Track Trigger – different approach to allowing tracking information at earlier stage of trigger
CMS Self-Seeded Track Trigger

- Use lever-arm between sensor sides to trigger on high-\(p_T\) tracks
  - Different granularities used in different regions as necessary

- 2 Hardware implementations under consideration
  - Associative memory & commercial FPGAs
  - L1 tracking performance under study
  - Requires \(\sim 10 \mu s\) latency

### CMS Preliminary Simulation, Phase-2

- Single muons
- Single pions
- Single electrons

L1 Tracker reconstruction, \(<PU>\sim 140\)

### Pixel + Strip sensors
- Strips: 2.5 cm \(\times\) 100 \(\mu\)m
  - \(P = 5.0\) W
  - \(\sim 44\) cm\(^2\) active area
  - For \(r > 20\) cm

### Strip sensors
- Strips: 5 cm \(\times\) 90 \(\mu\)m
  - \(P = 2.7\) W
  - \(\sim 92\) cm\(^2\) active area
  - For \(r > 40\) cm
CMS Upgrades to other systems

> Forward calorimetry will need replacement due to radiation-induced signal loss – 2 concepts under consideration
  
  - Compact Pb/LYSO Shashlik Forward EM Calorimeter with Scintillator-based HCAL
  - Silicon/lead/copper EM and silicon/brass HCAL, with scintillator/brass backing calorimeter

> Improvements to Muon system
  
  - Electronics upgrades to comply with Trigger upgrade
  - IRPCs and GEMs in forward (1.6<|\eta|<2.4) region – enhanced redundancy and cope with higher rates
  - Very-Forward extension to higher \( \eta \) with GEMs – baseline 2.0<|\eta|<3.0 (dependent on calorimetry)
Performance of Upgraded Detectors - Vertexing

- CMS studied vertexing performance of new detector together with algorithmic improvements
  - Shows improvements with respect to 'aged' Phase I detector
  - Improvement of vertex finding efficiency from 80% (aged detector, old algorithm) → 96% (new detector, new algorithm)

- ATLAS studied effect of different beam profiles
  - \( \sigma = 5\text{cm} \) gaussian, and 'long, flat' beamspot from -15cm to +15cm in z
  - Currently using “non-optimised” vertexing

'Long, flat' beamspot requires crab cavities
Performance of Upgraded Detectors - B-tagging

- Upgraded detectors allow b-tagging performance at phase 2 very similar to that at phase 1 despite significantly increased pile-up
  - Performance helped further if correct primary vertex identification can be improved
  - If correct primary vertex identified, performance independent of beam profile

ATLAS plots assuming correct PV identified
Mitigation of pile-up effects and rejection of pile-up objects will be crucial to achieving optimum physics reach

- Timing information has proved promising as a way to mitigate pile-up effects in reconstruction – dedicated timing layer could provide both charged particle and photon timing

- Applying cuts on variables related to charged fraction helps reduce number of pile-up jets, as does requiring track-jet matching criteria

Assuming new ECAL detector element with 50ps timing resolution
Higgs Measurement Potential at HL-LHC

HL-LHC will function as a “Higgs Factory”

- Will greatly increase precision of coupling and signal strength measurements – particularly if theory uncertainties also improve significantly
- New measurements will become possible

ATLAS Simulation Preliminary

\[ \sqrt{s} = 14 \text{ TeV}: \int L dt = 300 \text{ fb}^{-1} ; \int L dt = 3000 \text{ fb}^{-1} \]

Higgs boson couplings

\[ \Delta \mu / \mu \]

Hashed area represents theory uncertainties

Scenario 1:
- Systematics as Run1

Scenario 2:
- Theory uncertainties x 0.5
- Other uncertainties x \( \sqrt{\int L} \)

See also talks from Giacinto Piacquadio and Josh Bendavid
Measurement of Higgs Pair Production necessary for determining Higgs Self-Coupling

- Very small cross section means HL-LHC is great opportunity for this
- Destructive interference between diagrams with/without self-coupling contribution
- $HH \rightarrow bb\gamma\gamma$ one of the most promising channels
- Eventual measurement will utilise combination of results across channels and experiments – CMS and ATLAS discussing analyses to understand differences and explore potential improvements

ATLAS projects $S/\sqrt{B}$ 1.3 with 3 $ab^{-1}$

See also talk from Paolo Meridiani
HL-LHC BSM Potential

> HL-LHC & Detector Upgrades offer great potential for BSM searches

- Mass reach >doubled in EW $\chi_1^+\chi_2^0$ WH search
- “Mono-X” Dark Matter search - 5σ discovery up to suppression scale $M^*$ of 2.6 TeV (with optimistic systematics)

Results assume EFT is valid approach
Summary

- High Luminosity upgrade of the LHC offers huge potential to further explore the High Energy Physics landscape
  - 3 ab\(^{-1}\) dataset at 14 TeV allows large gains in precision, discovery potential, and makes a number of important, low cross-section measurements possible
  - CMS Upgrade Studies: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP
  - ATLAS Upgrade Studies: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies

- Challenges presented by high pile-up will necessitate extensive detector upgrades
  - Highly promising ATLAS & CMS baselines being further developed and improved

- Techniques under development for reconstruction and analysis of data from new detectors under new conditions
  - Performance & physics reach projections may improve further with future developments and optimisations
Back-up Slides
Beamspot Profiles

**ATLAS** Simulation Preliminary

**Beamspot Profiles**

- Red line: \( \sigma(z) = 50\text{mm} \)
- Blue line: long beamspot

**Arbitrary units**

**\( z_{PV} \text{ [mm]} \)**

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Higgs Systematics

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