Computing for High Energy Physics Experiments

Simon Connell - UJ

- The Standard Model and beyond?
- The LHC and ATLAS at CERN
- Data Processing

Credits
K Assamagan
CERN and ATLAS www-stes
Play accelerator animation (EPOG HEP Masterclasses)
Matter particles

A proton consists of three quarks (up, up, down)

A proton consists of three quarks (up, up, down)

A pion consists of two quarks (up, anti-up)
Families of Matter Particles
Previous experiments at LEP (fore-runner of the LHC) have shown there are three families of particles.

Rabi's famous comment on being given a telegram about the discovery of the muon (second family) while being served his dinner in a hotel.
In Quantum Field Theory, forces are represented by “force particles” which are exchanged between the “matter particles.”

<table>
<thead>
<tr>
<th>Force</th>
<th>Carried By</th>
<th>Acts on</th>
<th>Strong</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity</td>
<td>Graviton (not yet observed)</td>
<td>All</td>
<td>Gluon</td>
</tr>
<tr>
<td>Weak (Electroweak)</td>
<td>W⁺ W⁻ Z⁰</td>
<td>Quarks and Leptons and W⁺ W⁻</td>
<td>Photon</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strong</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Graviton**: Carries gravitational force.
- **W⁺ W⁻ Z⁰**: Carries weak force.
- **Photon**: Carries electromagnetic force.
- **Gluon**: Carries strong force.
The Z and W particles are carriers of the weak force (involved for example, in beta decay radioactivity)
A neutron decays to a proton via the change of a don quark to an up quark, emitting a $W^-$, which decays to an electron and a anti-neutrino.

The 8 quarks are carriers of the strong force (binding nucleons in a nucleus, or quarks in a hadron)
6 of the gluons are shown, each exhibiting a colour:anti-color combination
The SM proposes the existence of another particle, the Higgs Field. Particles acquire mass by interacting with this field. The particle associated with this field is the Higgs Particle.
Beyond the Standard Model

- The Standard Model has given a very successful description of:
  - The strong force, the electro-magnetic force and the weak force
  - The elementary particles and force carriers
  - Just like Maxwell united the Electric force and the magnetic in the Electro-magnetic force, the Electromagnetic force and the weak force have united into the Electroweak force

- However, there are still problems:
  - The Higgs boson has not been discovered - there may be more than one Higgs bosons. Higher order corrections to the Higgs mass diverge; you have to finely tweak parameters to cancel this divergence: the fine-tuning or naturalness problem
  - Gravity is not “a part“ of the SM
  - Why is gravity so week compared all the other forces (the hierarchy problem)
  - Are there super-particles? Are there extra dimensions (large)?
  - Why are there only 3 generations of leptons?
  - Neutrinos are not massless: neutrino oscillations
  - Grand Unified Theory (GUT)- to unify the strong force and the Electroweak force. The inclusion of Gravity would require String Theory ...
Grand Unified Theories

The theory which (we hope!) will unify the strong, weak, and electromagnetic interactions is called the "Grand Unified Theory." Physicists can write such theories today, but more data is needed to tell which of the many versions, if any, describes nature.

Still GUT must protect against rapid proton decay, Otherwise the world would exist today!
Data: Proton lifetime > $10^{32}$ years
Super Symmetry (SUSY)

Many physicists have developed theories of supersymmetry, particularly in the context of Grand Unified Theories. The supersymmetric theories postulate that every particle we observe has a massive "shadow" particle partner. For example, for every quark there may be a so-called "squark" tagging along.

No SUSY particles have been discovered. To be searched At the CERN Large Hadron Collider
Dark Matter

that the majority of the universe is not made of the same type of matter as the Earth. From gravitational effects, we can infer the existence of this "dark matter," a type of matter that we cannot see. There is extensive circumstantial evidence that much of this is not made up of protons, neutrons, and electrons, as we are.

What is dark matter? We don't know. Possibly dark matter is composed of neutrinos, or even more exotic forms of matter hypothesized by theorists.

The Neutralino particle from Supersymmetry could be a Dark Matter candidate (WIMP).
Gravity is due to Curvature of space-time. Need Quantum Gravity where the force carrier would be the Graviton. Not easy to quantize space-time. Maybe Super String Theories have the answer but must be verified by experiments (at the LHC)
Proton-Proton Collisions inside the LHC at CERN

Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.
<table>
<thead>
<tr>
<th>Inner Tracker</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Silicon pixels + strips</td>
<td>- Silicon pixels + strips</td>
<td>- No dedicated particle identification</td>
</tr>
<tr>
<td>- TRT with particle identification</td>
<td>- $B = 2T$</td>
<td>- $B = 4T$</td>
</tr>
<tr>
<td>- $\sigma(p_T) \sim 3.8%$ (at 100 GeV, $\eta = 0$)</td>
<td>- $\sigma(p_T) \sim 1.5%$ (at 100 GeV, $\eta = 0$)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Magnets</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Solenoid + Air-core muon toroids</td>
<td>- Solenoid</td>
<td>- Calorimeters inside field</td>
</tr>
<tr>
<td>- Calorimeters outside field</td>
<td>- 4 magnets</td>
<td>- 1 magnet</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>EM Calorimeter</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Pb / Liquid argon accordion</td>
<td>- PbWO$_4$ scintillation crystals</td>
<td>- $\sigma(E) \sim 3$–$5.5% / \sqrt{E} \oplus 0.5%$</td>
</tr>
<tr>
<td>- $\sigma(E) \sim 10$–$12% / \sqrt{E} \oplus 0.2$–$0.35%$</td>
<td>- No longitudinal segmentation</td>
<td>- Saturation at 1.7 TeV</td>
</tr>
<tr>
<td>- Uniform longitudinal segmentation</td>
<td>- Saturation at $\sim 3$ TeV</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Had Calorimeter</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Fe / Scint. &amp; Cu-liquid argon</td>
<td>- Brass / scint.</td>
<td>- $\sigma(E) \sim 100% / \sqrt{E} \oplus 8%$ (Barrel)</td>
</tr>
<tr>
<td>- $\sigma(E) \sim 45% / \sqrt{E} \oplus 1.3%$ (Barrel)</td>
<td>- $\sigma(E) \sim 100% / \sqrt{E} \oplus 8%$ (Barrel)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Muon</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Monitored drift tubes + CSC (fwd)</td>
<td>- Drift tubes + CSC (fwd)</td>
<td>- $\sigma(p_T) \sim 13 / 4.5%$ (1 TeV, $\eta = 0$) (standalone / combined with tracker)</td>
</tr>
<tr>
<td>- $\sigma(p_T) \sim 10.5 / 10.4%$ (1 TeV, $\eta = 0$) (standalone / combined with tracker)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Play CMS detector animation (EPOG HEP Masterclasses)
About 100 million channels of information

<table>
<thead>
<tr>
<th>Sub-detector</th>
<th>Number of Channels</th>
<th>% of non-working channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixels</td>
<td>$80.0 \times 10^6$</td>
<td>0.2</td>
</tr>
<tr>
<td>Silicon Strips (SCT)</td>
<td>$6.0 \times 10^6$</td>
<td>0.3</td>
</tr>
<tr>
<td>Transition Radiation Tracker</td>
<td>$3.5 \times 10^5$</td>
<td>1.0</td>
</tr>
<tr>
<td>Electromagnetic Calorimeter</td>
<td>$1.7 \times 10^5$</td>
<td>0.04</td>
</tr>
<tr>
<td>Scintillator Tile Calorimeter</td>
<td>9800</td>
<td>0.8</td>
</tr>
<tr>
<td>Liquid Argon Had. End-cap Calorimeter</td>
<td>5600</td>
<td>0.09</td>
</tr>
<tr>
<td>Liquid Argon Forward Calorimeter</td>
<td>3500</td>
<td>0.2</td>
</tr>
<tr>
<td>Barrel Muon Spectrometer</td>
<td>$7.0 \times 10^5$</td>
<td>0.5</td>
</tr>
<tr>
<td>End-cap Muon Spectrometer</td>
<td>$3.2 \times 10^5$</td>
<td>0.02</td>
</tr>
</tbody>
</table>
The LHC

$E_{cm} = 14 \text{ TeV}$

- Beam Energy: $7 \times 10^{12} \text{ eV}$
- Luminosity: $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- Bunches/Beam: 2835
- Protons/Bunch: $10^{11}$

$\int L dt \approx 100 \text{ fb}^{-1}$

Bunch Crossing: $4 \times 10^7 \text{ Hz}$

Proton Collisions: $10^9 \text{ Hz}$

Parton Collisions: $10^5 \text{ Hz}$

New Particle Production (Higgs, SUSY, ...)
ATLAS Data pipeline

Data rates
The bunch crossing rate is 40MHz
There are 25 interactions per crossing.
This gives an interaction rate of 1GHz.

Each interaction leads to an event of 1MB

The data rate must be reduced to 1kHz.

Trigger System
There are three Levels of Trigger, the first is hardware processing, and the next two are via Linux farms.

DAQ System
The Level three trigger is part of the DAQ which selects events for permanent storage.
Trigger System

Level 1 Trigger
The LVL1 trigger works on a subset of information from the calorimeter and muon detectors. It looks for clusters of tracks called Regions of Interest (RoI). It requires about 2 us to reach its decision. All of the information from the detector must be stored in pipeline memories until the LVL1 decision is available.

Level 2 Trigger
The data are transferred to readout buffers where they remain until the LVL2 decision is available. Many events are analysed concurrently by the LVL2 trigger system using processor farms. The selection of events is refined using full-granularity information from all detectors, including the inner tracker (not used at LVL1).

The final rate can be reduced to ~1kHz.
LVL1 Hardware Trigger

The LVL1 trigger works using Application Specific Integrated Circuits which operate in digital mode on each channel of digitised raw data directly from each granulated detector element.

It is a direct streaming pipeline mode, with no latency. Only LVL1 filtered data makes it through to the buffered transient storage.

1 GHZ in

2 us for decision

100 kHZ out
LVL1 Trigger
The LVL1 trigger searches specific event classes.
There is a high data rate.
Eg. in just the Calo 3000 GB/s
The LVL2 trigger uses full granularity of the detector, as well as the Inner Tracker, using the RoI concept to deal only with a small subset of the detector volume, accessing the data via the readout buffer of LVL1, spreading the events over the farm.

An interesting event, like

\[ H \rightarrow 4 \text{ leptons} \]

happens at a low rate, like 1 out of every \(10^{13}\) interactions

There needs to be a rather high event rejection rate.
The Data Acquisition System

Event filter
The read-out buffers from the LVL2 trigger are synthesised into a single Event Filter processor memory, using data switches.

About 1 billion instructions on a farm are needed in real-time in 1s.
LVL3/DAQ Prototype "-1"

- Essentially a vertical slice of full DAQ architecture including
  - 1- FrontEnd DAQ with
    - Intelligent I/O module
      - ReadOut Buffer, Lvl3 Link, ...
    - DAQ CPU (controller) with RT-OS
    - Trigger Interfaces
      - Link to Lvl1 and Lvl2
  - 2- Event Builder consisting of
    - Source/Destination Interface
    - Switching system
    - Data Flow Manager
  - 3- Lvl3 System with
    - Switch-Farm-Interfaces
    - A number of processor sub-farms
  - 4- BackEnd DAQ including
    - Run Control
    - DataBases
    - Software environment in general
Detector Control System (DCS) operational

Monitoring tools developed

Load tests with cosmics (200MB/s vs 1GB/s at LHC)

Full Dress Rehearsal (FDR): stress test of the full data processing and analysis chain

Average throughput (MB/s) from Tier-0 to Tiers-1
top-quark decays

Top quark decay modes

- $\text{BR}(t \rightarrow Wb) @ 100\%$
  - Both $W$'s decay via $W \rightarrow lv$
    - final state: $lv lv bb$ - DILEPTON
  - Both $W$'s decay via $W \rightarrow qq$
    - final state: $qq qq bb$ - ALL JETS

- One $W$ decays via $W \rightarrow lv$
  - final state: $lv qq bb$ - LEPTON+JETS

Legend:
- $e-e$ (1/81)
- $\mu-\mu$ (1/81)
- $\tau-\tau$ (1/81)
- $e-\mu$ (2/81)
- $e-\tau$ (2/81)
- $\mu-\tau$ (2/81)
- $e+$jets (12/81)
- $\mu+$jets (12/81)
- $\tau+$jets (12/81)
- jets (36/81)
The ATLAS DAQ Control room, nerve centre to interact with the experiment (farms for LVL2 Trigger, Event Builder, etc)
From physics to raw data

Simulation (Monte Carlo)

Basic physics

Fragmentation, Decay

Interaction with detector material
Multiple scattering, interactions

Detector response
Noise, pile-up, cross-talk, inefficiency, ambiguity, resolution, response function, alignment

Raw data
Read-out addresses, ADC, TDC values, Bit patterns
From raw data to physics

Raw data
Convert to physics quantities

Detector response
Apply calibration, alignment

Interaction with detector material
Pattern, recognition, Particle identification

Fragmentation
Decay
Physics analysis

Basic physics
Results

Reconstruction

Analysis

Simulation (Monte-Carlo)
Hardware

Requirements
The ATLAS data will be delivered at a rate of 100 events per second to the offline system. Each event will consist of about 1 Mbyte of raw data. The data produced in one second correspond to the information content of the phone-books of Switzerland.

The amount of data produced per year will amount to 1 Peta-Byte ($10^{15}$ Bytes) - filling 2 Million of today’s CD-ROMs.

In order to extract the physics out of these data, an enormous computing power of 250,000 SPECint95 will be needed. Today, this would require 50,000 of the most powerful PCs.

A large number of the 1600 physicists in ATLAS will participate in the physics analysis. As they all need to access the data, performing networks are essential elements in the ATLAS computing model.

Monte-Carlo production sites
Currently, simulated ATLAS events for detector optimisation and reconstruction studies are produced in many institutes of the collaboration, in particular: LBL Berkeley (USA), RAL Chilton (UK), Milano (Italy), Pavia (Italy), Lyon (France), Innsbruck (Austria) and CERN.
ATLAS Computing - Analysis

Must process $10^{15}$ bytes of raw data

ATLAS software comes in a kit. Is partially installed on the Wits-UJ cluster.

Analysis Object Data (AOD) has a summary of information, and is stripped of some physics, eg, a version with no jets.

Can be ROOT accessible.

Begin in SA by producing the AOD both locally and on the external GRID. Download a small event set. Develop analysis algorithms locally. Eventually run full physics analysis over the GRID with the full data set.
ATLAS Computing – QCD Phenomenology

Simulate effect in detector of possible new physics versus backgrounds

New Physics → Event Generator → Add known QCD / QED Fast MC of detector response

1000 kb/event → 100 kb/event → 10 kb/event

Requires a cluster with ATLAS software installed

Examples are shown below
**H → ZZ(*) → 4 leptons**

This decay channel into electrons and muons is the most promising one to observe the Standard Model Higgs boson in the mass-range $130 < m_H < 700$ GeV. This requires excellent charged-lepton momentum/energy resolution and very good electron and muon identification capabilities (rejection of QCD jets, impact-parameter measurements, etc).

For $m_H = 130$ GeV, reconstructed 4-electron mass-spectrum from a full simulation of the ATLAS electromagnetic calorimeter.

For three different Higgs-boson masses, expected signal from $H → ZZ^(*) → 4$ lepton decays above the residual background after three years of operation at low luminosity.

Discovery region of the MSSM parameter space covered by the search for $H → ZZ^(*) → 4$ lepton decays.
$h \rightarrow \gamma \gamma$ and $H \rightarrow \gamma \gamma$

This decay channel is the most promising one to observe the Standard Model Higgs boson in the mass-range $95 < m_H < 130$ GeV. This requires excellent energy and angular resolution in the electromagnetic calorimeter and a rejection against jets faking photons of about 500

For $m_H = 100$ GeV, $H \rightarrow \gamma \gamma$ mass spectrum reconstructed in the ATLAS EM calorimeter with full simulation at high luminosity.

Expected signal from $H \rightarrow \gamma \gamma$ decays with $m_H = 120$ GeV over the $\gamma \gamma$ continuum background after one year of operation at high luminosity.

Discovery region of the MSSM parameter space covered by the search for $h \rightarrow \gamma \gamma$ decays.
SA participation in ATLAS

UJ group joined ATLAS as an affiliate of Brookhaven (July 2008) working with K Assamagan
Strong

Gluons (8)
- Quarks
- Mesons
- Baryons
- Nuclei

Electromagnetic

Photon
- Atoms
- Light
- Chemistry
- Electronics

Gravitational

Graviton ?
- Solar system
- Galaxies
- Black holes

Weak

Bosons (W,Z)
- Neutron decay
- Beta radioactivity
- Neutrino interactions
- Burning of the sun