The ATLAS B-physics Trigger

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On behalf of the ATLAS T/DAQ group
LHC and ATLAS

- **LHC**
  - 14 TeV centre-of-mass p-p, bunch crossing @ 40 MHz
  - target peak luminosity $2 \times 10^{33}$ cm$^{-2}$s$^{-1}$ initially, rising to $1 \times 10^{34}$ cm$^{-2}$s$^{-1}$
  - 4.6 – 23 interactions per bunch crossing
  - discovery physics “needle in a haystack”

- **ATLAS**
  - decision every 25 ns
  - about $10^8$ channels
  - mass storage limits accept rate to $O(100\text{MB/s})$
Contents

• News headlines
• ATLAS challenge and physics programme
• T/DAQ system overview
• RoI strategy extended to B-physics
• Start up scenario
• Rates
• Trigger strategies
• Timing and resources
• Conclusion
News since last Beauty conference

• Technical Design Report
  – High Level Trigger, Data Acquisition and Control

• Further work on how to maintain B-physics programme within constraints
  – Higher target start-up luminosity
  – Incomplete detector at start up
  – Cost constraints for T/DAQ

• Software further advanced
  – new performance measurements
B-physics triggering – the challenge

• About 1% of collisions produce a $b\bar{b}$ pair
• Trigger must therefore be more selective
• At luminosity $\geq 2 \times 10^{33}$ cm$^{-2}$s$^{-1}$: di-muon trigger
• At lower luminosities: introduce additional semi-exclusive HLT Selection based on single muon and partial reconstruction of B-decays

• Channels of interest, e.g. CP violation
  – $B_d \rightarrow J/\psi K_S$ ($J/\psi \rightarrow e\bar{e}$ and $\mu\bar{\mu}$)
  – $B_d \rightarrow \pi^+\pi^-$ (or generally any $\pi/K$ combination)
• $B_s$ oscillations
  – $B_s \rightarrow D_s \pi/a_1$, $D_s \rightarrow \phi\pi$
• Final state analysis
  – $B_s \rightarrow J/\psi\phi$, $B_s \rightarrow J/\psi\eta$ (enhanced by new physics)
• Rare decays
  – $B_{d,s} \rightarrow \mu\bar{\mu}(X)$
• B-hadron production
  – $B_c$ properties, $\Lambda_b$ polarisation ($J/\psi \rightarrow \mu\bar{\mu}$)
  – precision measurements

• See Paula Eerola’s talk for physics programme.

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ATLAS T/DAQ system overview

- LVL1 decision based on coarse granularity calorimeter towers and muon trigger stations.
- LVL2 can get data at full granularity and combine info from all detectors. Emphasis on fast rejection.
  Region of interest from LVL1 used to reduce data requested to a few % of full event.
- EF refines selection according to LVL2 classification, performing fuller reconstruction. More detailed alignment and calibration data available.

Interaction rate: ~1 GHz
Bunch crossing rate: 40 MHz

- LVL1 TRIGGER: <75 (100) kHz
  Regions of Interest: <2.5 µs
  ~2 kHz out
  ~10 ms
  ~200 Hz out
  ~1 s

- LVL2 TRIGGER:
  ~2+4 GB/s

- EVENT FILTER:
  HLT
  ~2 kHz out
  ~10 ms

- Full-event buffers and processor sub-farms

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Region of interest mechanism

- LVL1 selection is mainly based on local signatures identified at coarse granularity in muon detectors and calorimeter.
- Further rejection can be achieved by examining full granularity muon, calo and inner detector data in the same localities.
- The **Region of Interest** is the geometrical location of a LVL1 signature.
- It is passed to LVL2 where it is quickly translated into a list of corresponding readout buffers.
- LVL2 requests RoI data sequentially, one detector at a time, only transfers as much data as needed to reject the event.
- The RoI mechanism is a powerful and important way to gain additional rejection before event building.
- Order of magnitude reduction in dataflow bandwidth, at small cost of more control traffic.
Two strategies for B-physics triggering

- At luminosity $\geq 2 \times 10^{33}$ cm$^{-2}$s$^{-1}$: di-muon trigger
- For low luminosity semi-inclusive B-physics selection ($\sim 1 \times 10^{33}$):

  1) RoI-guided
  - LVL1 single muon (e.g. $p_T > 8$ GeV)
    + jet or EM
  - LVL2 validate muon
  - LVL2 & EF reconstruct tracks in jet/EM RoI, select $J/\psi(ee) B_d(hh) D_s(\phi\pi)$
    - **Pro**: significantly reduces resources ($\sim 10\%$)
    - **Con**: could be too many RoIs or too low efficiency

  2) Full scan
  - LVL1 single muon (e.g. $p_T > 8$ GeV)
  - LVL2 validate muon
  - LVL2 reconstruct tracks in full acceptance of SCT + Pixels, select $B_d(hh) D_s(\phi\pi)$
  - $J/\psi(ee)$ requires further resources for TRT scan
  - EF full scan or use LVL2 tracks to form RoI
    - **Pro**: higher efficiency than option 1
    - **Con**: needs more resources (CPU and network)
B-Trigger for start up conditions

- At start up, expect
  - luminosity varying from fill to fill
  - variable beam-related background
  - incomplete detector
  - understanding and tuning of detector
  - limited T/DAQ processing capacity and bandwidth

- Take advantage of LHC luminosity drop
  - Fall by factor of ~2 from start of fill to end of coast
  - Initial T/DAQ system built to requirements of target peak luminosity ($2 \times 10^{33}$)
  - As luminosity drops, use spare capacity for B-physics triggers
  - “Checkpoint” feature of run control system planned to enable rapid update of configuration mid-run

- Robust algorithms
  - w.r.t. noise, alignment

- Flexible configuration
  - adapt thresholds, pre-scales and other parameters to cope with varying noise, luminosity, etc.
## Estimated Trigger Rates

<table>
<thead>
<tr>
<th>Trigger</th>
<th>LVL2 (2 × 10^{33} cm^{-2} s^{-1})</th>
<th>EF</th>
<th>LVL2 (1 × 10^{33} cm^{-2} s^{-1})</th>
<th>EF</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{c,d,s} \rightarrow \mu^+\mu^-(X)$</td>
<td>200 Hz</td>
<td>small</td>
<td>100 Hz</td>
<td>small</td>
</tr>
<tr>
<td>$J/\psi(\mu^+\mu^-)$</td>
<td>10 Hz</td>
<td></td>
<td>5 Hz</td>
<td></td>
</tr>
<tr>
<td>$D_s(\phi\pi)$</td>
<td>–</td>
<td>–</td>
<td>60 Hz</td>
<td>9 Hz</td>
</tr>
<tr>
<td>$B(\pi\pi)$</td>
<td>–</td>
<td>–</td>
<td>20 Hz</td>
<td>3 Hz</td>
</tr>
<tr>
<td>$J/\psi(ee)$</td>
<td>–</td>
<td>–</td>
<td>10 Hz</td>
<td>2 Hz</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>200 Hz</td>
<td>10 Hz</td>
<td>190 Hz</td>
<td>20 Hz</td>
</tr>
</tbody>
</table>
LVL1 Overview

- Identify basic signatures of interesting physics
  - muons
  - em/tau/jet calo clusters
  - missing/sum $E_T$

- Hardware trigger
  - programmable and custom electronics (FPGA + ASIC)
  - programmable thresholds

- Decision based on multiplicities and thresholds
LVL1 Muon trigger

Cross section, nb

Muon Trigger Chambers (RPC)
Muon Precision Chambers (MDT)
Muon Trigger Chambers (TGC)

Single-µ cross section
2-µ cross section

Inner Detector

RPC: Restive Plate Chambers
TGC: Thin Gap Chambers
MDT: Monitored Drift Tubes
LVL1 Jet & EM triggers

Jet RoI Multiplicity ($E_T > 5$ GeV)

EM RoI multiplicity vs. threshold

Jet RoI Multiplicity

Hadronic calorimeter

Electromagnetic calorimeter

Trigger towers ($\Delta \eta \times \Delta \phi = 0.1 \times 0.1$)

Vertical Sums

Horizontal Sums

De-cluster/RoI region: local maximum

Electromagnetic isolation < e.m. isolation threshold

Hadronic isolation < inner & outer isolation thresholds

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High Level Trigger

- Commodity electronics (PCs, switches)
  - few custom components e.g. readout buffers
- Software based
  - large and complex software engineering project
Common selection software for LVL2, EF, offline - differences hidden behind interfaces
Re-use of offline software in framework, basic services, data unpacking
LVL2 has specialised algorithms and constraints of multi-threading
EF re-uses offline reconstruction algorithms (toolkit approach)
Integration tool “AthenaMT” provides single-PC test environment for offline software
Test data has fully simulated detector, format expected from readout electronics
RoI mechanism and data access

Algorithm

1. send geometrical region
2. pre-load full ROB list
3. return detector identifiers
4. request data in detector elements

Region Selector

5. request data in ROBs
6. request data in ROBs

Event Data Store
create data on demand cache data

7. raw data from ROBs
8. return object data
9. return collection of data

Raw Data converter
unpack raw data and build C++ objects

Database converter
offline implementation unpack data and build C++ objects

Raw data provider implementations

LVL2
interface to data collection from ROBs over network fetch + cache data

EF
interface to data in shared memory

Offline emulator
interface to data in memory
LVL2 Muon algorithm

- LVL2 MuFast algorithm uses data from precision chambers
  - better $p_T$ measurements allows tighter threshold, rejects low-$p_T$ background
- output rates after LVL2 muon-spectrometer trigger still dominated by $\pi/K$ decays
- reject $\pi/K \rightarrow \mu$ by combining muon and inner detector tracks
  - $z$, $\phi$ and $p_T$ matching
  - $p_T$ resolution further improved
  - $\pi/K \rightarrow \mu$ rate reduction by factor 3
- Total rate (extrapolate from barrel to full detector)
  - $\sim 5$ kHz for a 6 GeV threshold and $1 \times 10^{33}$

<table>
<thead>
<tr>
<th>Physics process</th>
<th>Rate (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi/K$ decays</td>
<td>3.00</td>
</tr>
<tr>
<td>$b$ decays</td>
<td>0.90</td>
</tr>
<tr>
<td>$c$ decays</td>
<td>0.50</td>
</tr>
<tr>
<td>$W \rightarrow \mu \nu$</td>
<td>0.003</td>
</tr>
<tr>
<td>cavern background</td>
<td>negligible</td>
</tr>
<tr>
<td>Total</td>
<td>4.40</td>
</tr>
</tbody>
</table>

$1 \times 10^{33}$, $|\eta|<1$

Full simulation results for barrel only
Di-muon trigger

- LVL1 trigger efficient to low $p_T$
  - down to $p_T > 5$ GeV in barrel, 3 GeV in endcaps.
  - Actual thresholds determined by rate limitations
- LVL1 rate at $2 \times 10^{33}$ will be a small fraction of the total LVL1 rate, < 1 kHz for a reasonable threshold around 6 GeV
  - dominated by heavy flavour decays
  - Subject to uncertainties in low $p_T$ rate
- LVL2 can give e.g. ~200 Hz
  - sharpen $p_T$ threshold
  - Resolve double counting
- EF does near offline-quality track reconstruction, vertex fit and mass cuts
  - to select for example $J/\psi$ decays
  - ~10 Hz
- At all levels, cuts can be tuned to optimise rate vs. efficiency
  - Further studies
Hadronic final states

- Reconstruct tracks in jet RoI or full scan
- LVL1 muon $p_T > 6$ GeV + jet RoI, $E_T > 5$ GeV $\Rightarrow$ average $\sim 2$ RoIs per event
- Either way, use tracks to do semi-inclusive, partial decay reconstruction
  - $B_d \rightarrow hh$
  - $D_s \rightarrow \phi(KK)\pi$
- Kinematical and topological cuts
- EF makes tighter mass cuts and vertex fit
- Overall HLT efficiency $\sim 60\%$ ($D_s$, full scan) w.r.t. events selected by offline analysis

- Studies show this is very robust w.r.t.
  - missing middle pixel layer (initial layout)
  - anticipated levels of misalignment (LVL2)
Muon-electron final states

- To select channels such as
  - $B_d \rightarrow J/\psi(\text{ee})K_S$ with opposite side muon tag, or
  - $B_d \rightarrow J/\psi(\mu\mu)K_S$ with opposite side electron tag
- Two options:
  - Use LVL1 EM RoIs to find low-$E_T$ electrons
  - Full reconstruction of tracks in TRT (for electron identification)
- LVL1 EM cluster $E_{T}>2$ GeV gives average of 1 RoI/event
  - about 80% efficiency to find RoI for both daughters of $J/\psi \rightarrow \text{ee}$, when they both have $p_T>3$ GeV.
- LVL2 confirm cluster at full granularity in calorimeter, including presampler, then find matching track in SCT+pix (+TRT).
- Tracks reconstructed again in EF, plus vertex fit quality and decay length cuts.
- Conclusion
  - Using RoI guidance is much faster (typical size 0.2x0.2) than reconstructing the full volume of the inner detector
  - but the LVL1 lowest possible threshold is not efficient until a higher $p_T$ than the full scan permits.
Test bed results: LVL2 muon trigger

- Dual 2.2 GHz Xeon
- Confirmation of LVL1 muon trigger
- “Offline” framework and services re-used
- Prep time dominates
  - saves algo time
- Conservative result
  - high luminosity conditions, x2 cavern bg
- Already adequate
  - Continue to optimise
Resource estimates

• Estimates take into account
  – Reduced rates of later steps in sequential processing scheme
  – All aspects of processing time to the best knowledge we currently have
  – Extrapolated to 8 GHz CPUs

• Overall target
  – LVL2 target of 10 ms x 25 kHz LVL1 rate gives 250 CPUs
  – Scales to 750 CPUs for full system at 75 kHz LVL1 rate
  – From latest studies of high $p_T$ physics it looks like this is achievable.

• For lower luminosity fills, or as lumi drops during a fill
  – Spare capacity due to lower LVL1 rate
  – Allows general lowering of thresholds and pre-scale factors
  – Some room for additional B-physics based on muon & calo RoI

• Conclusion
  – Following detailed studies, current understanding is that the resources needed for the RoI-guided B-physics trigger can be found within the planned resources.
    • Based on di-muon trigger at higher luminosity ($2 \times 10^{33}$)
    • Introducing other triggers at lower luminosity ($\sim 1 \times 10^{33}$)
Conclusions

- The latest picture of ATLAS & LHC at start up does not look so favourable for B-physics, but ATLAS has responded with a variety of flexible trigger schemes to make the most of it.
- RoI-based strategy allows a full programme at modest resource cost, with slightly reduced trigger efficiency.
- Take advantage of beam-coast and lower-lumi fills to trigger on B-physics at lower luminosities.
- Algorithms are robust enough for initial detector and conditions.
- For muon spectrometer and calorimetry, now have simulation of realistic raw data and full chain of algorithms to retrieve, unpack and process it.
- Further studies of RoI strategy will be done and more of the software will be tested and optimised through test bed deployment.
- Now looking towards commissioning and first collisions in 2007 when we hope to record B-physics data from ATLAS.