Online Determination of the LHC Luminous Region with the ATLAS High Level Trigger

Machine Detector Interface & Beam Instrumentation

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(on behalf of the ATLAS Collaboration)
ATLAS as “Beam Instrumentation”

- The LHC is an extremely well instrumented machine
- It is amazing how much we know about its beams and how well we know it
- Nevertheless, close to the interaction region the experimental detectors are not only best positioned but overwhelmingly well equipped to characterize it
- Their sophisticated High Level Trigger systems allow to do that in real time

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Beam Position Monitor
~ 21.5 m from the IP
2 channels (analog)

ATLAS Inner Detector
~ 0.05 m from the IP
> 80 million channels
Overview

- The ATLAS High Level Trigger (HLT) provides a unique platform for measuring LHC luminous region parameters.
- Doing this in the online environment is particularly challenging in several ways:
  - Tightly constrained CPU and bandwidth budget of the trigger system.
  - Massively parallel execution of algorithms that need special infrastructure to be aggregated and fanned out again.
  - You get to see every event only once.
    - No iterations on conditions, resolution etc: everything is 'at the edge of time'.
- On the positive side, it offers unique advantages, too:
  - Unparalleled statistics, taking advantage of the many rejected events.
    - Practically the only place with enough rate to see per-bunch time-evolutions.
  - Very short latency to give quasi real-time feedback (minute scale).
- In addition, the Trigger itself needs to know very precisely - and adjust to - the position, size and orientation of the luminous region (e.g. $b$-tagging).
- This measurement is part of a bigger feedback loop around the HLT.
ATLAS Inner Detector

- Silicon Pixels
  - 3 barrel layers
  - 2 x 3 endcap discs
  - $\sigma_{r\phi} \approx 10 \mu m$
  - $\sigma_z \approx 115 \mu m$

- Silicon Strips (SCT)
  - 4 barrel layers
  - 2 x 9 endcap discs
  - $\sigma_{r\phi} \approx 17 \mu m$
  - $\sigma_z \approx 580 \mu m$

- Only the silicon detectors (Pixel+SCT) needed here for pattern recognition, track finding and fitting
- Vertex resolution is dominated by the Pixel detector
- Only a small fraction (~80 kB) of the total event size (~1.6 MB)
  - But all of the detector needed on every event (not just Region of Interest)
Primary Vertices

- At present luminosities, just above $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, there are on average 6 interactions per bunch crossing
  - Called “pile-up”
- In principle these allow us to make several measurements on each event
- However, they are computationally very expensive to reconstruct and resolve in real time
ATLAS High Level Trigger

- Runs after the Level 1 hardware trigger
- Massively parallel, farm of 1000+ nodes
- Two stages: Level 2 (L2) + Event Filter
- Current rates: 50 kHz L1 $\rightarrow$ 4.5 kHz L2 $\rightarrow$ 400 Hz Event Filter (logging to disk)
- L2 does partial reconstruction
  - First trigger with access to Si-tracker data
- Chose L2 Trigger to host beam spot algorithm
  - Highest available statistics, low latency
  - But: challenge to do full scan of silicon tracker detectors for data transfer and pattern recognition, track reconstruction
  - At the edge of available bandwidth + CPU
- Currently 10 racks of 30 nodes with 8 cores each (2400 processes)

For more on ATLAS Trigger/DAQ: c.f. earlier talks by Sergio Ballestreero and Srini Rajagopalan at this conference
Beam Spot Algorithm

- Dedicated algorithm that executes on the L2 processors (as part of a rich trigger menu of physics and calibration triggers)
- Invokes a “full-scan” track reconstruction using Pixel and SCT, and then employs a fast vertex fitter to reconstruct primary vertices
  - Clusters of tracks are formed along the beam line (z), around the highest transverse-momentum ($p_T$) seed track
  - In an iterative procedure, the clusters are fitted to a common vertex
- The coordinates (and other relevant properties) of each vertex are histogrammed online
- From the spatial distribution of primary vertices we extract through fits the position, size, and orientation of the luminous region
  - Parameters are the centroid $x,y,z$; widths $\sigma_x, \sigma_y, \sigma_z$; and title angles $\theta_{xz}, \theta_{yz}$
  - Together with their errors (significance)
- Challenge: An important ingredient to measuring the true luminous region widths is to correct for the intrinsic vertex resolution
  - Typical vertex resolution is on the same order as the transverse widths
- Special data needs to be acquired to accomplish this
Primary Vertex Distributions

- Projections of the three-dimensional distribution of reconstructed primary vertices are histogrammed and published once per minute.
- They are aggregated ("gathered") across the farm and re-published.
- The large amount of available statistics gives rise to very precise determinations of all parameters.
- In addition, the vertex count can serve as a measure of luminosity (although this gets increasingly difficult with pile-up).

- Transverse distribution of 100,000 vertices reconstructed by the HLT.
- One minute of data taking!
Primary Vertex Distributions (cont.)

- 1D-projections of the vertex distributions
- Means of gaussian fits measure centroid position to better than 1% of the width with one minute of data
- Transverse widths \((x,y)\) are not yet corrected for resolution
As an alternative to (and cross check of) the vertex method one can use the track transverse impact parameter $d_0$ versus azimuth angle $\phi$ distribution to extract the centroid position.

The results are in excellent agreement with the vertex method.

The method doesn't provide the widths and has less control over backgrounds or against pile-up (so vertex is the preferred method).

- Sinusoidal fit to track $d_0$ versus $\phi$
- $\rightarrow$ amplitude and phase translate to $x$ and $y$ position of point of closest approach
- (errors are too small to be visible)
Beam Line Tilt

- Horizontal and vertical angles of the luminous region in the ATLAS coordinate system can (and must) be measured very accurately.
- These are mostly a result of the residual global misalignment of the ATLAS pixel detector with respect to the LHC beam line.
- Transverse distributions are measured in bins along the beam (z)-axis, then a linear fit is performed to extract the slope.
- **Residual tilts are very small and stable in time.** We originally found a 500 μrad horizontal tilt, and decided to compensate for it by rotating the ATLAS global coordinate system.
Time-Variation of Beam Position

Three-dimensional centroid position is measured over the course of several LHC fills

- Significant variations of the transverse position (from orbit corrections and drifts) are visible within a fill and from fill to fill
- Similar significant longitudinal time variations are related to RF-phase changes
Effect on $b$-Tagging

- Algorithms that depend on track impact parameters or secondary vertex significance are sensitive to knowing the beam spot position and size.
- These triggers have to be configured with the current beam spot parameters.
- Currently the most sensitive trigger is the $b$-jet trigger.
  - Shifts on the order of a few $\sigma$ of the luminous size can kill the efficiency and increase the fake rate to make the trigger non-functional.
- The stored beam spot needs to be updated during the run to keep/get $b$-tagging working.

Probability that L2 jets originate from the luminous region:
- QCD jets will be flat.
- $b$-jets will peak near zero.
- An off-set beam spot will fake large impact parameters.

ATLAS Preliminary
$\sqrt{s} = 7$ TeV

LVL2 Jet probability to originate from PV

10^{-1}

10^{-2}

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
Measuring Resolution: Vertex Splitting

- The vertex resolution changes not only with detector conditions but also with the event mix from the (always evolving) trigger menu.
- The only way to account for this is to **measure it online**.
- We use the method of splitting each primary vertex into two, then fitting the two halves separately and measuring their displacement.
  - Represents $\sqrt{2}$ times the resolution of a vertex of half the multiplicity.
- A lot of care must be taken to avoid systematic effects (biases).

Tracks from one vertex are sorted in $\Phi$ and then split as: 1,2,1,2...

One original vertex...

... split into two half-vertices, fitted separately.

Two vertices from tracks coming from the same interaction.
Split-Vertex Resolution

- Vertex resolution is a strong function of track multiplicity
- The two transverse resolutions are the same; longitudinal resolution is about twice that amount; (less different than silicon hit resolutions)
- Split vertex distributions show two competing effects:
  - The resolution is highest for vertices with the highest number of tracks
  - Statistics is highest for the low-multiplicity vertices and falls precipitously
- To optimize precision, one has to include the lowest multiplicity that can still resolve the spot size to be measured
Online Resolution Correction

Method works down to track multiplicities for which the resolution is not more than twice the true spot size.

- The observed width and measured resolution are strong functions of the number of tracks in a vertex.
- The correction has to be applied in bins of track multiplicity.
- Corrected width stays approximately flat regardless of multiplicity.

It works up to track multiplicities for which there is still statistics from vertices with twice the number of tracks.
Vertex resolution along the beam axis (as expected) somewhat lower than in the transverse plane.

- Shows similar behavior as a function of number of tracks per vertex.
- Correction is entirely negligible on the scale of the longitudinal size (~55 mm).
Time-Evolution of Luminous Size

- Effect of transverse emittance blow-up during each fill is clearly visible
  - Approximately 15% horizontal, 10% vertical luminous width increase over a 10 hour fill
- Longitudinal emittance growth behaves similarly
- Fill-to-fill variations are comparatively small, but not negligible
LHC Feedback

Live histograms are published once a minute

Available in the control room as well as over the web

Give details of the track/vertex distributions and parameters

The luminous region parameters are extracted through fits also once a minute

Corrections are performed and values are sent over to the LHC
Beam Spot Parameter Redistribution

- Time variations make it necessary to update parameters used by the HLT during running (including a bootstrap at the beginning of a fill)
- Critical for algorithms sensitive to primary vertex such as $b$-tagging
- The first challenge is how to transmit the parameters back to the many thousands of HLT processes (on a sharp time boundary)
- ATLAS has a proxy-technology for database configurations that makes it possible to do such updates extremely fast also within a run

- CORAL Server & Proxy
  - Dedicated database technology developed for ATLAS HLT as example
  - Proxy hierarchy allows simultaneous access of 1000s of clients
  - Multiplexes and caches queries and responses

(Collaboration with CERN IT + U.Mainz)
High Level Trigger Feedback Loop

Conditions Database
- Beam spot parameters
- L2 Farm
- Oracle
- Coral Server
- Proxy
- Top Proxy

Online Monitoring
- Gatherer
- Vertex histograms
- DQMF
- BeamSpotTool
- Beam spot Information Services

Flow
- Event Data
- Monitoring
- Control
- Conditions
- Requests

Blocks
- Hardware
- Software

ATLAS
- Pixel Hits
- Fragments
- Read-Out System
- Central Trigger Processor
- Command Handler
- Data Fragment

Rainer Bartoldus
Online Luminous Region Determination in ATLAS, June 13, 2011
Trigger Auto-Updates

- Web interface to live L2 histograms
  - Cumulative or per minute

- Automatic updates of the farm are monitored online using “delta distributions” that compare observed values with the currently stored “nominal” values

- These are tuned to stay within a narrow range:
  - **Updates are triggered when** positions move by ±10% of the width, or widths change by ±10% from nominal (both with 2σ significance); or errors improve by more than 50%
Online-Offline Comparison

- A few hours after each fill, the more sophisticated offline beam spot determination runs on a fraction of the logged events
  - Complementary: > resolution, << statistics
  - Unbinned maximum likelihood fit with error scaling
- Automatic monitoring shows excellent agreement between these very different methods!
  - 1 μm difference in \( \sigma_y \) due to still uncorrected residual tilt
  - Slight difference in \( \sigma_z \) due to non-gaussian tails
Bunch-by-bunch Monitoring

- Luminous centroid positions for 1042 bunches colliding in ATLAS
- Distinct structures are visible across the bunches
  - Particularly in the vertical plane with variation of 5 μm
- Repeating patterns for bunch trains
- Data show entire fill: expect to be able to make a 5% measurement every ~20 min
Conclusions

- The ATLAS High Level Trigger is the first system able to see tracks and vertices, and to allow a reconstruction of the luminous region.
- High event rates make this both extremely challenging and precise.
- The ability to use (mostly) rejected events is unique to the HLT.
- A method to correct for resolution based on vertex splitting has been put in place that is working well down to current spot sizes.
- Timelines of luminous region parameters are produced online that provide interesting insights into IP-orbit and RF-phase variations as well as transverse and longitudinal emittance growth.
- Owing to the high rate of events, the system is able to do per-bunch measurements even at the current O(1000) colliding pairs.
- A feedback system has been developed that transmits live parameters to the LHC and also performs automatic updates of the HLT farm.
- In many respects, the ATLAS luminous region measurements can complement LHC beam instrumentation.
Outlook

- The online beam spot measurement in the ALTAS High Level Trigger continues to be a challenge
- Just when we managed to adapt to 25 μm spot sizes and 1042 bunches, the LHC keeps pushing the envelope
  - We may expect 1380 bunches in a couple of weeks (and will have to deal with 2808 bunches eventually)
- There is the possibility/hope to further squeeze the emittance while increasing the bunch charges for another factor of ~3 in luminosity
  - This would create on the order or 25 interactions per crossing, making it even harder to reconstruct the even smaller beam spot
- We have to work to turn the higher event rates into an advantage and refine and improve our methods (i.e. increase the resolution)
- Most of the instrumentation we added was not only not foreseen in the original design but seemed daring or impossible to do...
  - Yet the flexible architecture of the ATLAS online left room for new ideas
- We just have to rely on measurement capabilities to improve along the way and on new ideas to exploit them!
Backup Material
Primary Vertices