Challenges of vertexing in HL-LHC

Algorithm research using OpenDataDetector

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STAR Sensing and Sensibility Transcending Disciplines for a Responsible Future

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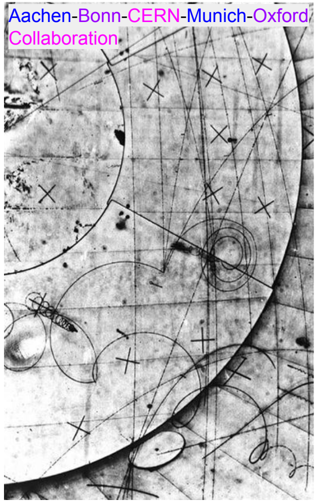
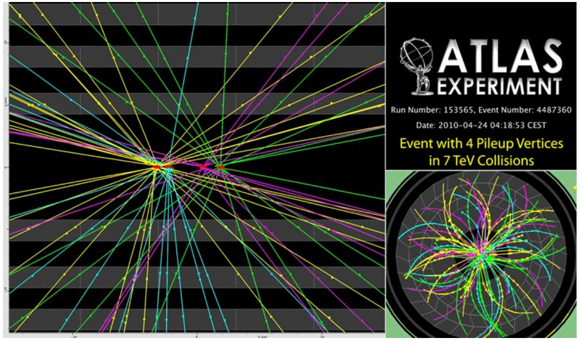
Vertexing and the HL-LHC

- Vertexing: Reconstructing particle interaction or decay points.
  - ➢ Crucial for identifying primary and secondary vertices.
  - ➢ Essential for flavor tagging (b/c quarks) and LLP searches.
- HL-LHC: Significant luminosity increase for precision studies.
  - ➢ Increased luminosity = increased challenges for vertexing.
  - ➢ Dramatic rise in pile-up (140-200 collisions/bunch crossing).

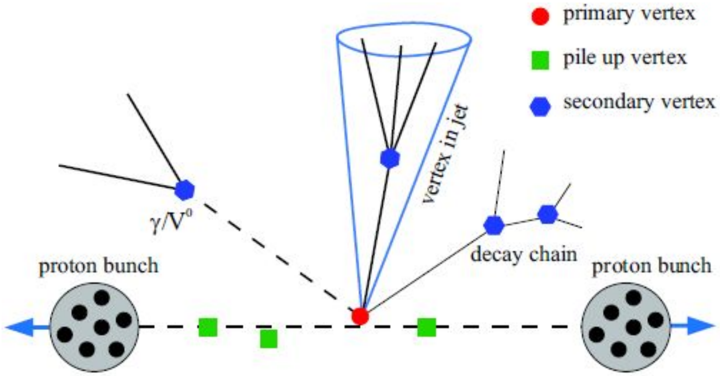
Parameter	**LHC (Typical Run)**	**HL-LHC (Expected)**
Peak Instantaneous Luminosity	~1.5 x 10^{34} $cm^{-2}s^{-1}$	5-7.5 x 10^{34} $cm^{-2}s^{-1}$
Integrated Luminosity/Year	~45 fb^{-1}	250-350 fb^{-1}
Total Integrated Luminosity Goal	~300 fb^{-1}	3000-4000 fb^{-1}
Average Pile-Up	20-70	~140-200

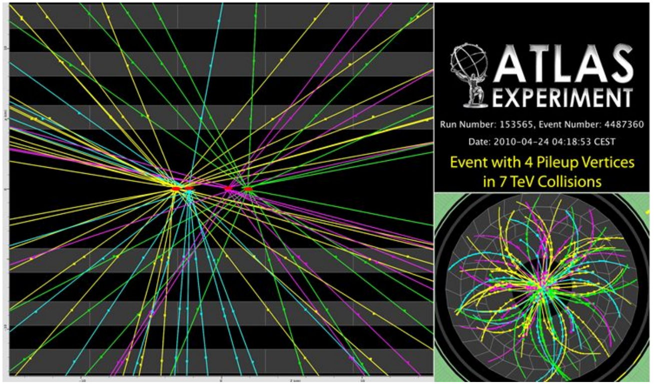




Primary vs. Secondary Vertex Reconstruction

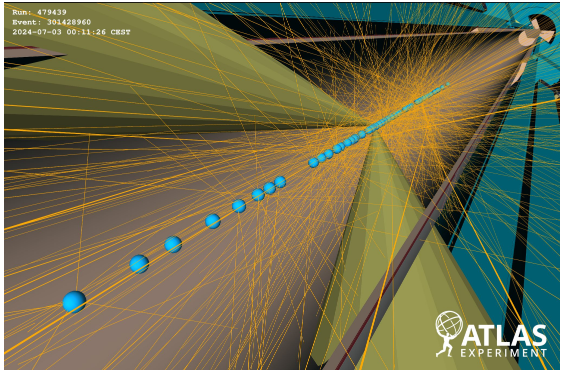
- Primary vertex: Initial proton-proton interaction.
- Secondary vertex: Decay of unstable particles (e.g. bottom/charm hadrons).
- Traditional two-stage process: vertex finding and vertex fitting.
- Importance of correct association of tracks to the correct vertex.

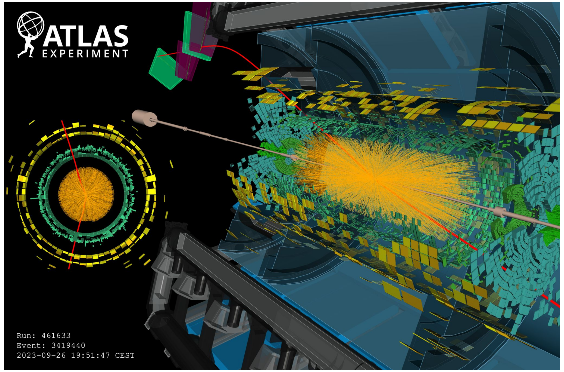




Vertexing in high luminosity environment

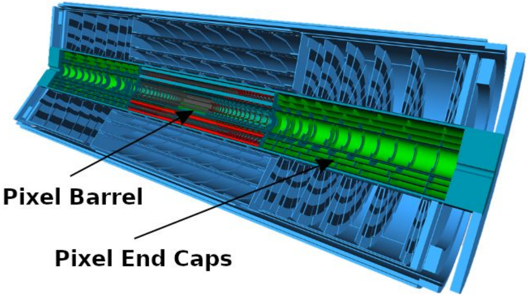
- The primary challenge: Pile-Up
  - ➢ Increased vertex density along the beamline.
  - ➢ Distinguishing hard scatter vertex from pile-up.
  - ➢ Track-vertex association becomes highly complex.
  - ➢ Merged and split vertex errors.
- Impact of Increased Track Density
  - ➢ Makes any kind of pattern recognition challenging.
  - ➢ Increased combinatorial complexity of vertex finding.
  - ➢ Potential for ghost tracks and fake vertices.



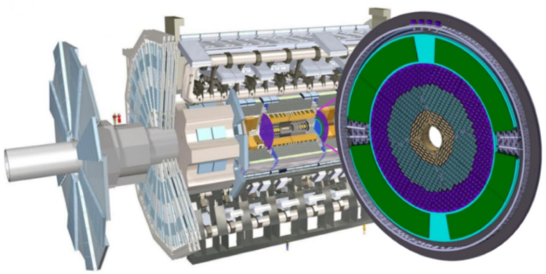


Maintaining and enhancing vertexing precision

- Importance of impact parameter and spatial resolution.
  - ATLAS Inner Tracker (ITk): increased granularity.
- Leveraging time information (4D-vertexing).
  - ATLAS HGTD and CMS MTD: precise timing information.



ATLAS ITk

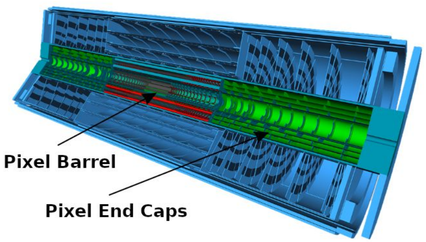


ATLAS HGTD

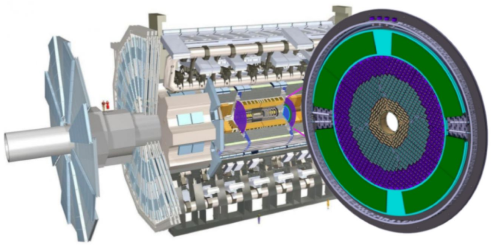
We will have a tour of ITk Pixel lab this afternoon.

Upgrading detectors for HL-LHC

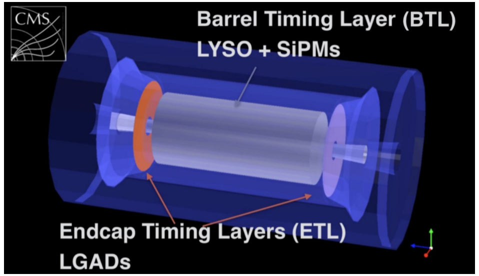
Detector Name	Experiment	Key Technology	Primary Benefit for Vertexing	Expected Performance
Inner Tracker (ITk)	ATLAS	All-Silicon (Strips/Pixels)	Increased granularity, improved spatial resolution	Spatial Resolution: ~10-15 µm
HGTD	ATLAS	Low Gain Avalanche Detectors (LGADs)	Precise timing for charged particles in forward region	Timing Resolution: 30-50 ps
MTD	CMS	Scintillators (Barrel), LGADs (Endcaps)	Precise timing for Minimum Ionizing Particles (MIPs)	Timing Resolution: ~30 ps
VELO Upgrade	LHCb	Hybrid Pixel Detector	Enhanced rate and timing capabilities for primary vertexing	Improved Efficiency & Precision



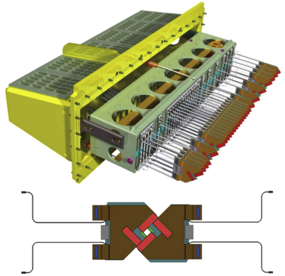
ATLAS ITk



ATLAS HGTD



CMS MTD



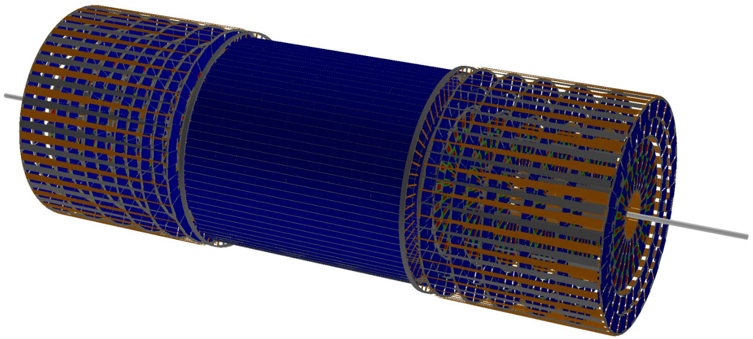
LHCb VELO

ACTS: *A Common Tracking Software*

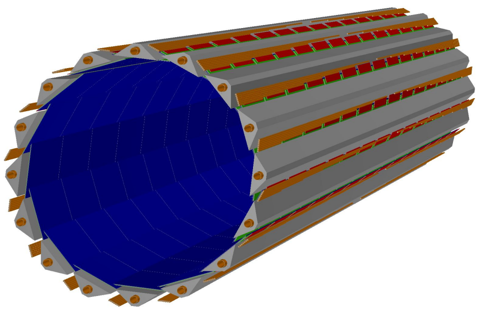
- Evolved from *ATLAS Common Tracking Software*
- Key Features:
  - ➢ Flexible tracking geometry description.
  - ➢ Simple and efficient event data model.
  - ➢ Algorithms for seed finding, track propagation, track fitting and vertexing.
- Designed in modern C++ (C++17/20): emphasis on parallel execution.
- Existing primary vertexing algorithms in ACTS:
  - ➢ Iterative Vertex Finder (IVF)
  - ➢ Adaptive Multi-Vertex Finder (AMVF)

ODD: Open Data Detector

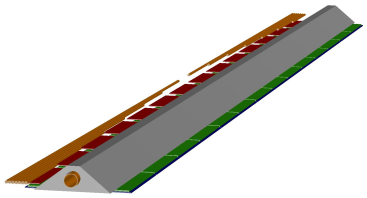
- Provides a template for an HL-LHC-style detector.
- Designed for algorithm research and development.
- Based on the detector used in the TrackML challenge.
- Inspired by the ATLAS Inner Tracker (ITk) upgrade.



The full Open Data Detector



Innermost layer (r = 36 mm)



A single stave

Synergy between ACTS and ODD

- ODD can be integrated as a third-party component within ACTS.
- Many ACTS example applications use ODD as the default geometry.
- ODD serves as a crucial platform for testing and benchmarking ACTS track and vertex reconstruction algorithms.
- ACTS provides a full reconstruction chain example utilizing the ODD.
- IRIS-HEP members actively contribute to ACTS development and often use ODD for testing.

Synthetic dataset for TrackOpt vertexing project

- We are using ODD to prepare our datasets for vertexing research.
  - ➢ Primary computational resource: OMNI cluster of Universität Siegen.
    - ■ Located in Adolf-Reichwein (AR) campus, operated by ZIMT.
    - ■ Total 439 HPC nodes, each with 64 cores and 256 GB of RAM.
      - Peak performance is ~1044 TFlops.
    - ■ Storage capacity ~500 TB.
  - ➢ Other possible resources:
    - ■ SiMPLE cluster at the HEP department can be a fallback solution.
      - Limited computational power, but also limited load (number of users).
    - ■ Cloud resources
      - Google Cloud Platform provides up to $5000 research credit for one year.

Preparation of synthetic dataset: the setup

- Inside the ACTS toolkit, the $pp \to t\bar{t}$ process is generated using Pythia 8.
- Full Geant4 simulation of the OpenDataDetector geometry.
- The value of pile-up is chosen to be 200.
- Built-in track and vertex reconstruction is performed after simulation.
- Each event takes around ~ 5 minutes, for gen+sim+reco.
    - ➢ Geant4 can utilize only one core at a time, memory consumption ~ 12 GB.

```
-rw-r--r-- 1 db466094 554M Mar 22 08:52 estimatedparams.root
-rw-r--r-- 1 db466094 825M Mar 22 08:52 measurements.root
-rw-r--r-- 1 db466094  54M Mar 22 08:57 my_full_chain_odd.log
-rw-r--r-- 1 db466094 106M Mar 22 08:52 particles.root
-rw-r--r-- 1 db466094  37K Mar 22 08:56 performance_finding_ambi.root
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-rw-r--r-- 1 db466094 232K Mar 22 08:56 performance_fitting_ambi.root
```

```
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-rw-r--r-- 1 db466094  57M Mar 22 08:52 tracksummary_ckf.root
-rw-r--r-- 1 db466094  12M Mar 22 08:52 vertices.root
```

Preparation of synthetic dataset: the challenges

- Each HPC node on OMNI cluster has 64 cores and 256 GB memory.
  - ➢ That's just 4 GB per core. So, we cannot use all the cores in a node simultaneously.
- CVMFS access is suboptimal as compared to CERN-managed lxplus.
  - ➢ Slow access and often crashes during too many concurrent accesses.
  - ➢ Working with ZIMT to mitigate this.
- OMNI cluster offers *unlimited* storage as “workspace”.
  - ➢ But it's time-limited (max 90 days), and non-sharable.
- Simulation of hadronic interaction is turned off by default in ODD.
  - ➢ Need to figure out how to enable it.

Summary and outlook

- Vertexing is one of the most challenging problems for the future experiments in particle Physics, and can be formulated as a clustering problem.
- ACTS/ODD provides a great means of generating synthetic dataset, useful for algorithm research and developments.
- Immediate next steps:
    - ➢ Generating a synthetic dataset of sufficient statistics (at least 100k events).
    - ➢ Building the preprocessing pipeline to stitch together separate ROOT files.
    - ➢ Deciding the interface to the TrackOpt software.

Backup

Performance Metric	Primary Vertices	Secondary Vertices
Spatial Resolution (x, y)	< 15 µm	< 20 µm
Spatial Resolution (z)	< 50 µm	< 75 µm
Reconstruction Efficiency	> 98%	> 90%
Pile-Up Rejection Rate	> 95%	N/A