Primary Vertex Reconstruction with the ATLAS Experiment

D. Casper (for the ATLAS Collaboration)

University of California, Irvine

July 12, 2017
Outline

• Motivations, Environment and Current Strategies
• Primary Vertex Performance in Run 1 and Run 2
• Pileup Effects
• Toward HL-LHC: New Strategies for Primary Vertexing
LHC Run 2 Conditions

• Rare searches and precision measurements put a premium on luminosity

• Increasing luminosity means more collisions per beam crossing
  • parameter $\mu \equiv$ number of pp interactions per crossing

$h \rightarrow \mu^+\mu^-e^+e^-$ (with pileup)
Factor $\sim 4$ improvement of signal:noise for $h \rightarrow \tau\tau$ from Vector-Boson Fusion at high pileup with vertex-based forward jet rejection (arXiv:1705.02211)


Vertex-based pileup suppression leads to robust $E_T^{\text{Miss}}$ resolution (ATLAS-CONF-2014-019)
Beam Spot Reconstruction

• Luminous region centroid, size and tilt reconstructed in five-minute intervals during “Express” stream data pre-processing
  • Typical transverse (x,y) size: 14 μm
  • Typical longitudinal (z) size: 45 mm
• Important constraint for final, “physics” reconstruction
  • Reduces vertex-finding to a one-dimensional problem
ATLAS Inner Detector

- **Pixel Detector**
  - 4 barrel layers
  - 3 end-cap layers on each side

- **Silicon Strip Detector (SCT)**
  - 4 double-sided barrel layers
  - 9 end-cap layers on each side

- **Transition Radiation Tracker (TRT)**
  - 73 barrel planes
  - 160 end-cap planes

- **Solenoid:**
  - 2 T axial field

- **Coverage extends over** $|\eta| < 2.5$
  - ~90% of solid-angle
Run 2 Tracking Performance

- Track transverse ($d_0$) and longitudinal ($z_0$) impact-parameter resolution is critical to vertex-reconstruction
  - $\sigma(d_0) \approx 30 - 100 \, \mu m$
    - Larger than luminous region
    - Beam-spot dominates ($x,y$) resolution
  - $\sigma(z_0) \approx 60 - 150 \, \mu m$
    - Significantly worse at high $|\eta|$ 
    - Much smaller than luminous region
    - Track measurement dominates $z$ resolution

(CTL-PHYS-PUB-2015-018)
Vertex Reconstruction: Overview

1. Track Pre-selection
2. Seed-Finding
3. Track Assignment
4. Vertex Fit
5. Finished

No seed? Iterate
No tracks?
Vertex Reconstruction: Seed-Finding

• Use reconstructed tracks to estimate the location of a $pp$ interaction
• One-dimensional (longitudinal) problem, since luminous region is known
• FSMW (“Fraction of sample mode weighted”) mode-finder
  • Create a weighted histogram of $z_0$ for tracks passing selection
    • Weight tracks by $\log p_T$ and $d_0$
    • Find the interval $[z_{min}, z_{max}]$, containing at least a fraction $f$ (default = 50%) of the tracks, which has the largest weight density ($\frac{\sum w}{z_{max} - z_{min}}$)
      • Recurse, using only entries in the interval just found
  • Seed $z$ position is weighted average of last 2 or 3 entries
  • Seed $(x, y)$ assumed to be center of luminous region
Vertex Reconstruction: Track Assignment

• Any track passing within $12\,\sigma$ of seed is added to list of tracks to fit
  • $\sigma$ includes track measurement errors only
  • Vertex fit is robust against outliers
  • May need tightening for poorly-measured large-|$\eta$| tracks as pileup increases

• If not at least two tracks passing $12\,\sigma$ cut, vertex-finding is finished
  • Typically occurs when only a few scattered tracks remain in seed-finding
  • Resulting seed is far from all of them
Vertex Reconstruction: Vertex Fit

- An “adaptive” vertex fit, based on the Kalman filter, is used
  - Luminous region centroid \((x, y)\) used as a constraint
- The Kalman filter itself is equivalent to a weighted least-squares fit
- Each track’s weight is determined by its consistency with the previous iteration of fitting
  - Outliers are gradually de-weighted according to an annealing schedule
  - After final iteration most tracks have weight close to 1 (inlier) or 0 (outlier)
  - Far outliers (weight < 0.01 and \(\chi^2 > 36\)) are removed from the vertex and available to future vertices

Measuring Vertex Resolution with Data

• The fit resolution can be measured with the data and compared to the calculated fit errors
  • Split each vertex in two vertices, each with half the tracks, and refit
  • The distance between refit split vertices is a measure of the resolution
• Determine a correction factor between computed and measured resolutions
• The beam constraint is not used, since it would dominate the resolution

Transverse (x)  Longitudinal (z)

- X Resolution (no beam spot): 25 – 70 μm
- Z Resolution: 50 – 100 μm

Scale factor: +20%
Scale factor: +10 – 30%
Vertex Reconstruction Efficiency (without Pileup)

- Using special data runs with low $\mu$ (i.e. little or no pileup), the intrinsic vertex-reconstruction efficiency can be measured
  - For isolated vertices with 4+ tracks, the efficiency is essentially 100%
Vertex Reconstruction With Pileup

• Pileup creates complications:
  • Must identify hard-scatter vertex
  • Pileup tracks may contaminate hard-scatter
  • Hard-scatter tracks may be split between multiple reconstructed vertices
  • Nearby pp interactions may be merged into a single reconstructed vertex

Clean: The hard scatter contributes at least 70% of the track weight to one reconstructed vertex, and does not contribute more than 50% of the weight of any other reconstructed vertex

Low pileup: The hard scatter contributes at least 50% of the weight to one merged vertex

High pileup: The hard scatter contributes 1-50% of the weight to one merged vertex

Hard Scatter Identification

• The “hard-scatter” vertex is identified as the one with largest $\sum p_T^2$
  • This discriminates against “minimum bias” – soft $pp$ – interactions


• Certain analyses (e.g. $H \rightarrow \gamma\gamma$) need to apply process-specific criteria
Pileup Vertex Efficiency

- The number of reconstructed vertices does not track the number of pp interactions ($\mu$) perfectly
  - Some vertices are lost because they have no associated charged particles within the ID acceptance
  - Additional vertices are lost due to track reconstruction inefficiencies or errors
  - Merging of vertices becomes a significant source of inefficiency for $\mu > 20$

Measuring the Merge Rate

- $\langle N_{vtx} \rangle = \epsilon \mu - F(\epsilon \mu, p_{merge})$
- Fit $f_{obs}(\Delta z)$ for $|\Delta z| \gg 0$ to get the expected Gaussian distribution $f_{exp}(\Delta z)$ in absence of merging
- Extract $p_{merge}(\Delta z)$ from observed $\Delta z$ distribution near $\Delta z = 0$:
  $$p_{merge}(\Delta z) = \frac{f_{exp}(\Delta z) - f_{obs}(\Delta z)}{f_{exp}(\Delta z)}$$
- Convolve $p_{merge}(\Delta z)$ with $f_{exp}(\Delta z)$ to get $p_{merge}$ (chance any random pair of vertices is merged)
- Use combinatorics to compute $F(\epsilon \mu, p_{merge}) = \epsilon \mu - \sum_{N} P(N, \epsilon \mu) Q(N, p_{merge})$
  - $Q(N, p_{merge})$ is the expected number of vertices reconstructed out of $N$ possible, in the presence of merging
- $\langle N_{vtx} \rangle$ vs. $\mu$ can then be predicted, and agrees extremely well (within 3%) with the data
The Challenges of High Luminosity

• (Relatively) near-term:
  • Run 3: $\langle \mu \rangle \sim 60 - 80$

• Long term:
  • High-Luminosity LHC: plans for $\langle \mu \rangle = 200$!
  • Peak interaction density $\rho$ up to 2.5/mm
  • New and improved tracking detector: ITK
**Expected ITK Performance**

- Extended coverage to $|\eta| < 4$
  - Vector Boson Scattering/Fusion
- Order of magnitude improvement in resolution

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**Expected ITK track $z_0$ resolution**

(ATL-PHYS-PUB-2016-025)
New Seeding Strategies

• Medical Imaging-inspired Seed-finder
  • 3-d FFT of track trajectories through space
  • Filter and invert transform
  • Problems:
    • Seed finding is a 1-d problem
    • No way to include track measurement errors correctly

• Gaussian Smoother
  • Conceptually and computationally simple
    • Unit normalized 2-d Gaussian centered at \( (d_0, z_0) \)
    • Sample along beamline \( (d_0 = 0) \) as function of \( z \)
  • Naturally incorporates track measurement errors
    • Leverage improved ITK resolution

\[
f(z) = \frac{1}{2\pi} \sum_{i} \left( \frac{d_i^2}{2\sigma_{d_i}^2} \right) e^{-\frac{(z-z_i)^2}{2\sigma_{z_i}^2}}
\]

For each point \( z \) along beamline
...sum over all tracks with \( z_0 \) within \( 3\sigma_z \)
...Gaussian shape of width \( \sigma_{d_0} \) centered at \( d_0 \)
...\( z \)-independent seeding quality factor...
Seeder Comparison

N.B. Plot approval pending

Will be updated or removed as appropriate
Conclusion

• ATLAS reconstructs primary vertices with high efficiency and excellent resolution
  • Essential input to mission-critical tools and relied on by many physics analyses
  • Performance validated by studies using real data
• Ever-increasing LHC luminosity means ever-increasing pileup
  • Merging of vertices due to pileup accurately described by data-driven model
• Continued refinement of reconstruction algorithms important
  • Detailed studies for HL-LHC and ITK already underway