Primary Vertex Reconstruction at the ATLAS Experiment

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on behalf of the Vertex Group and the ATLAS Collaboration
Vertex Reconstruction
• Finding, fitting, beam spot calculation

Current Performance
• Run 1 and Run 2 results

Challenges
• Influence of pileup on efficiency and accuracy

Toward the future
• Algorithm improvement, High pileup, and upgraded detectors
Primary Vertex Reconstruction relies on Charged Particle Tracks measured in 3 sub-detectors:

- **Pixel detector** – 4 barrel layers, including the new (IBL) layer, plus 3 end-cap layers from each side
  - **IBL**: Added in Run 2, $R_{\text{in}} = 31$ mm, $R_{\text{out}} = 40$ mm; 14 staves,
- **Silicon Strip tracker (SCT)** – 4 double sided barrel layers – 9 end-cap layers from each side
- **Transition radiation tracker (TRT)** – 73 barrel and 160 end-cap planes – Measure track position in the plane perpendicular to the beam ~30 hits per track

See talk by Louis-Guillaume Gagnon on Track Reconstruction
https://indico.cern.ch/event/505613/contributions/2230822/
• Reconstruction Overview
• **Tracks**: Tight selection of tracks

**TRACK REQUIREMENTS**

- $p_T > 400$ GeV, $|\eta| < 2.5$
- $\geq 1$ hit in the IBL+B-Layer
- $\geq 9$ hits in the pixel+SCT for $|\eta| < 1.65$
- $\geq 11$ hits in the pixel+SCT for $|\eta| > 1.65$
- Maximum of 1 shared module
- Pixel holes = 0
- SCT holes < 1
- $|d_0| < 4$ mm
- $\sigma(d_0) < 5$ mm
- $\sigma(z_0) < 10$ mm

Tighter selection than for standard tracking reduces fakes and secondary interactions
ATLAS Vertex Reconstruction Methods

• Reconstruction Overview
  • **Tracks**: Tight selection of tracks
  • **Seed** position for the first vertex is selected. Seed is placed at the (x,y) center of the beam spot and the estimated mode in Z, considering the track points of closest approach to the beam spot center

*Beam Spot Shapes*
• Reconstruction Overview
  • **Tracks**: Tight selection of tracks
  • **Seed** position for the first vertex is selected. Seed is placed at the (x,y) center of the beam spot and the estimated mode in Z, considering the track points of closest approach to the beam spot center
  • **Fit**: Use tracks and seed to estimate the best vertex position with a fit: annealing procedure → iterative procedure: in each iteration less compatible tracks are down-weighted and the vertex position is recomputed.
  • After vertex position is determined, tracks that are incompatible with the vertex are removed and allowed to be used in the determination of another vertex.
  • The procedure is repeated with the remaining tracks in the event.
ATLAS Beam Spot Reconstruction

- The luminous region, or beam spot, is determined during data taking (every ~10 min).
- Reconstructed as a 3D gaussian of the primary vertex positions.
- Offline the beam spot size is used to constrain primary vertices, removing outliers and improving the resolution.

In 2016 the beam spot is reduced further $\sigma_x \sim 0.008$ mm.

The size of the beam spot in 2012. Consistent size and shape.
Measurement of Vertex Resolution in Data

Vertex position resolution can be measured in data using the Split Vertex Method:
- The tracks used in a vertex fit are split into two groups.
- The vertex is recomputed for each of the two groups.
- The distance between the two calculated vertex positions is a measure of the resolution of the vertex.

Resolution computed with the Split Vertex Method (SVM) and using Monte Carlo Truth
Addition of the Beam Spot Constraint improves transverse resolution

Run 1

Run 2

IDTR-2016-007

Kathryn Grimm

CHEP, San Francisco – October 2016
Pile Up vertices are the result of multiple proton-proton interactions in the same bunch crossing. We differentiate between higher momentum Hard Scatter processes and the soft pile-up interactions. The number of $pp$ inelastic interactions per bunch crossing follows a Poisson distribution with mean value $\mu$.

How do pile-up tracks affect accurate reconstruction of Hard Scatter vertices?
Primary Vertex Performance in Pile Up

Pile Up vertices are the result of multiple proton-proton interactions in the same bunch crossing. We differentiate between higher momentum Hard Scatter processes and the soft pile-up interactions. The number of $pp$ inelastic interactions per bunch crossing follows a Poisson distribution with mean value $\mu$.

How do pile-up tracks affect accurate reconstruction of Hard Scatter vertices?

Pile-Up Classification

**Clean:** 1 Reconstructed vertex with more than 70% of the accumulated track weight from the hard-scatter (HS) interaction.

**Low pile-up contamination:** The hard-scatter interaction contributes more than 50% of the accumulated track weight to the vertex.

**High pile-up contamination:** The vertex has between 1 and 50% of the accumulated track weight from the hard-scatter interaction contributes.

Vertices become increasingly dominated by tracks from pile up, but the overall efficiency for Hard Scatter vertex reconstruction is near 100%.
Primary Vertex Performance in Pile Up

Pile Up vertices are the result of multiple proton-proton interactions in the same bunch crossing. We differentiate between higher momentum Hard Scatter processes and the soft pile-up interactions. The number of \( pp \) inelastic interactions per bunch crossing follows a Poisson distribution with mean value \( \mu \).

How do pile-up tracks affect accurate reconstruction of Hard Scatter vertices?

**Pile-Up Classification**

**Clean:** 1 Reconstructed vertex which is the hard-scatter (HS) interaction. The HS interaction does not contribute more than 50% of the accumulated track weight to any other vertex.

**Low pile-up contamination:** The hard-scatter interaction contributes more than 50% of the accumulated track weight to the vertex.

**High pile-up contamination:** The vertex has between 1 and 50% of the accumulated track weight from the hard-scatter interaction contributes

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<th>Clean</th>
<th>Low pile-up</th>
<th>High pile-up</th>
<th>Split</th>
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<td>(RMS 11 μm)</td>
<td>(RMS 12 μm)</td>
<td>(RMS 15 μm)</td>
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**Vertex position resolution for different levels of pile-up track contamination.** Degradation seen when vertices become dominated by pile-up tracks.
• The Hard Scatter vertex is often selected as the vertex with the highest track $\Sigma p_T^2$.
• Hard Scatter vertices with few tracks sometimes have lower $\Sigma p_T^2$ than pile-up vertices, causing a decrease in HS selection efficiency.
• Event selection requiring reconstructed tracks within the detector acceptance increases reconstruction+selection efficiency, and analysis-level cuts further remove pile-up events.
What is the efficiency of reconstructing pile-up vertices?

Reconstruction Classification:

**Matched vertex:** Tracks identified as coming from the same generated interaction contribute at least 70% of the total weight of tracks fitted to the reconstructed vertex.

**Merged vertex:** No single generated interaction contributes more than 70% of track weight to the reconstructed vertex. Two or more generated interactions contribute to the reconstructed vertex.

**Split vertex:** The generated interaction with the largest contribution to the reconstructed vertex is also the largest contributor to one or more other reconstructed vertices. In this case, the reconstructed vertex with the highest fraction of track $\Sigma pT^2$ is categorised as matched or merged and the vertex or vertices with lower $\Sigma pT^2$ are categorised as split.

Close-by vertices cannot be distinguished and are reconstructed as merged vertices. At high pile-up merging significantly degrades efficiency.

$\sim$30% vertices reconstructed without merging at high $\mu$. 

Entries / 0.1 mm

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Vertex Reconstruction behavior at high pileup

Reconstruction of Pile Up vertices: The number of reconstructed vertices does not equal the pile-up because of merging and other inefficiencies.

But these effects can be parameterized and we can accurately predict the number of vertices at a given pile up.

Reconstruction efficiency without merging

\[ \langle n_{\text{Vertices}} \rangle = p_0 + \epsilon \mu - F(\epsilon \mu, p_{\text{merge}}) \]

Number of vertices lost to merging

Accurate to 2% up to \( \mu = 70! \)

Beam Spot Shape has a large effect
Toward future improvements

What are the challenges moving forward?

Study pile-up simulation with $\mu = 200$:
- Increase in merged vertices
- Algorithm time increases with pile-up

In high pile up the fraction of time spent selecting tracks and reassigning tracks increases significantly.

Most time spent fitting
Toward future improvements

Future Changes:

Possible changes in luminous region shapes and sizes

Change in pile-up density

Effects on vertex resolution

Increase in merged vertices

One proposed ATLAS ID upgrade layout

Luminous region shape can give lower pile-up density for the same overall pile-up.
Toward future improvements

Run 2 improvements have brought increased efficiency

Studies ongoing in alternative seeding techniques

Seed finding method based on 3D medical imaging techniques: Initial improvements seen. Slow algorithm speed. Possible to overcome with tuning?

Algorithm improvements have given higher efficiency

Improved resolution = less merging

Initially time consuming
Summary

• Precise and well understood vertex reconstruction at ATLAS during Run 1 and Run 2

• One of the main challenge for the future is mediating the effects of pile up and pile-up density

• Controlling the effects on
  Vertex Reconstruction Efficiency
  Vertex Position Resolution and Precision
  Vertex Selection Efficiency

• Possible changes to the reconstruction algorithm, the beam spot shape and size, and in the future, the inner detector
Seed finding method based on medical imaging techniques

- Take all tracks simultaneously and fill a 3D spatial histogram centered around the beam axis
- Apply FFT & frequency filter. Reverse FFT.
- Collapse onto Z-axis, with bins weighted by distance from the axis
- Local maxima are taken as vertex seeds.
The ATLAS Primary Vertex reconstruction algorithm continues to deliver precise and well understood vertices with very high efficiency for hard scatter interactions.

One of the main challenges for the future is mitigating the effects of pile up on reconstruction efficiency for pile-up vertices, and the effect of pile-up tracks on Hard Scatter position resolution and precision.

Possible improvements to the reconstruction algorithm are being studied for $\mu$ up to 200 and for changes in beam spot shape.

Well modeled efficiency and resolution

Effect of algorithm changes on resolution