Tracking in Dense Environments for the HL-LHC ATLAS Detector

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Introduction
New ATLAS Inner Tracker

• HL-LHC upgrade to higher luminosity brings about a totally new Inner Detector for the ATLAS experiment, the ITk, seen in Noemi’s talk

• This allows for completely new possibilities for tracking in the dense environments the Energy Frontier brings

Improvements in ITk

• Higher average number of hits per track
• Small longitudinal pixel size (400/250 to 50 μm)
• Less material radiation lengths
• Precision Tracking layers at larger distance from interaction point (all silicon)
• Increasing Energy at the LHC has provided greater reach but numerous challenges
  • Charged particles in energetic decays or jets becoming more often collimated

• As momentum of initial particle increases, collimation of products nears pixel dimensions
  • This leads to tracks having ‘shared clusters’ with other tracks

• In Run-2, the current data-taking period, a **Neural Network** was devised to classify shared clusters into 1, 2 or 3-particle clusters and to estimate their positions
  • A 7x7 matrix of charges deposited in each pixel in a cluster is one of the input variables
  • Seen in talk by Louis-Guillaume Gagnon on NN training
Changing Charge Information in Dense Environment Neural Network
Each pixel stores the charge information as 8-bit Time-over-Threshold (ToT) in Run-2, except IBL(4-bit)

- This will be converted to n-bit ToT in ITk, with a probable maximum of n=4
- This may have an effect on dense environment NN in ITk
- Can use current IBL (4-bit ToT) to study effects of reducing information into NN

- The 8-bit ToT has high ToT overhead to measure highly ionizing particles, which is mostly unused by the high rate of singly charged particles

- A scheme was optimized to **convert 8-bit to 4-bit**, while keeping maximum information available
After re-training with emulated n-bit ToT, the performance of both the classification (number) and position Neural Network were evaluated and compared to networks with 8-bit ToT.

For the **number network**

- The Area under curve (AUC) of the Receiver-Operator curve (ROC) is used to gauge the relative performance.
- This is shown for all misclassification possibilities on the x-axis.
- The relative AUC of 2,3,4-bit versus 8-bit is shown.
- For 2,3-bit ToT there is significant degradation.
- For 4-bit this degradation is less than 10%, close to 0% with uncertainty.

### ATLAS Simulation Preliminary
PYTHIA8 dijet, $1.8 < p_T^{jet} < 2.5$ TeV
Barrel layer 1

<table>
<thead>
<tr>
<th>Number network classification</th>
<th>1vs2</th>
<th>2vs1</th>
<th>1vs3</th>
<th>3vs1</th>
<th>2vs3</th>
<th>3vs2</th>
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<td>2-bit charge</td>
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<td>4-bit charge</td>
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Relative performance drop [%]
After re-training with emulated n-bit ToT, the performance of both the classification (number) and position Neural Network were evaluated and compared to networks with 8-bit ToT.

For the position network:
- the residual of the position prediction - generator truth record position is shown.
- This is shown for possible number of particles in cluster on x-axis.
- The relative residual of 2,3,4-bit versus 8-bit is shown.
- Position 1 shows some degradation for 2,3-bit ToT.
- For positions 2,3, the degradation is below 2%.
• Higher particle density in events and smaller pixels lead to probable lowering of information from 8-bit

• The studies done with converting from 8-bit to 4-bit have shown that performance is very similar if information optimally transferred from 8-bit

• Any studies done into performance of ITk in dense environments should take into account the current algorithms developed for this challenging reconstruction
  • For this reason a number network is emulated using truth event record information
  • The same efficiencies for the neural network are used as Run-2, which is confirmed by the 4-bit study
ITk Dense Environment Performance
In order to gauge performance, have to look at truth record in Monte Carlo Simulation and compare with reconstructed tracks

To do this, only choose truth particles with the following properties

- \( p_T > 2 \text{ GeV} \)
- \( |\eta| < 4 \)
- Stable
- Charged

Calculating efficiencies

- Look at proportion of tracks, with truth match probability \( > 0.5 \), over all other selected truth particles

Truth match probability: a hit-based method matching charge deposits from a truth particle to reconstructed clusters belonging to a reconstructed track

- In this way, a probability of 1 means the track shares all clusters with a specific truth particle
• Look at single $\tau$ samples, decaying to 3 $\pi^\pm$
  • High momentum gives insight into **2/3 particles clusters**
  • 3-prong efficiency defined as proportion of times all 3 pions are reconstructed as tracks

• In this plot, switch which pixel layers in use Number Network
  • Gives insight on which layers benefit most from ToT info
  • Shows benefits from having 5 pixel layers with a number Neural Network
Performance in Jets

- For jets, use Anti-$k_T$ algorithm based on truth information to find jets
  - Count all truth particles meeting requirements within $\Delta R(\eta, \theta \text{ cone}) = 0.4$ of jet
  - Efficiency defined as proportion of tracks which match these truth particles in cone

- Compare efficiencies in different $\eta$ regions across the jet $p_T$ spectrum
  - As jet $p_T$ increases particles are increasingly collimated - dense environments are tested
  - Run-2 sees drop off at high momentum while ITk does not
Performance in Jets

• Can also look at performance as a function of the $\Delta R$ of the track from the jet
  - Jets are divided into b and light-jets using truth information

• $\Delta R$ here can be seen as local track density as low $\Delta R$ is in the core of the jet and corresponds to high track density
  - In Run-2 a degradation is seen in the core
  - In ITK this effect is not seen
• Tracks in dense environment can also be quantified in terms of **bad association** with clusters
  • Bad match rate looks at proportion of tracks with **0.5 to 0.8 truth matching probability**
• The bad match rate is shown to only be marginally affected by increasing pileup density
  • Thus it is dominated by the products of the jet and not pileup tracks not associated with the hadronisation

Performance in Jets
Performance in Jets

- The bad match rate as a function of $|\eta|$ is shown to be much smaller as well as constant for ITk compared to Run-2.
- The rate also shows some dependence on distance from the core of jet, when shown as function of $\Delta R$.
  - Compare to Run-2, dependence of bad match rate on $\Delta R$ is lessened.
  - Furthermore, the overall rate is also smaller across the whole jet cone.
Conclusion

• The new ATLAS Inner Tracker for the HL-LHC upgrade brings both improvements and challenges to reconstructing particles in dense environments
  • Better Pixel granularity, larger number of layers and larger lever arm all bring improvements
  • Smaller information in ToT could lessen effectiveness of current algorithms, but the anticipated change of 8bit (Run2) to 4bit (ITk) was shown to have small impact on performance

• Studies with $\tau$ leptons have shown the effectiveness of 5 pixel layers with a neural network on 2/3 particle clusters

• Studies of efficiency with jets show the robustness of tracker as compared to Run-2

• Studies of bad match rate with jets show that badly associated tracks have small dependence on pile-up, and much reduced rates with ITk detector
Backup
n-bit conversion

- Most ToT information is at lowest part of range
  - So choose a ToT saturation value when converting from 8-bit to n-bit
- At cluster level, sum up ToT of 7x7 = 49 pixels
  - Use a Mann-Whitney U test to determine degree of overlap between n-bit and 8-bit
  - Choose saturation ToT which better resembles original 8-bit