PHYSICS ASTRONOMY

Tracking in Dense Environments for the HL-LHC ATLAS Detector

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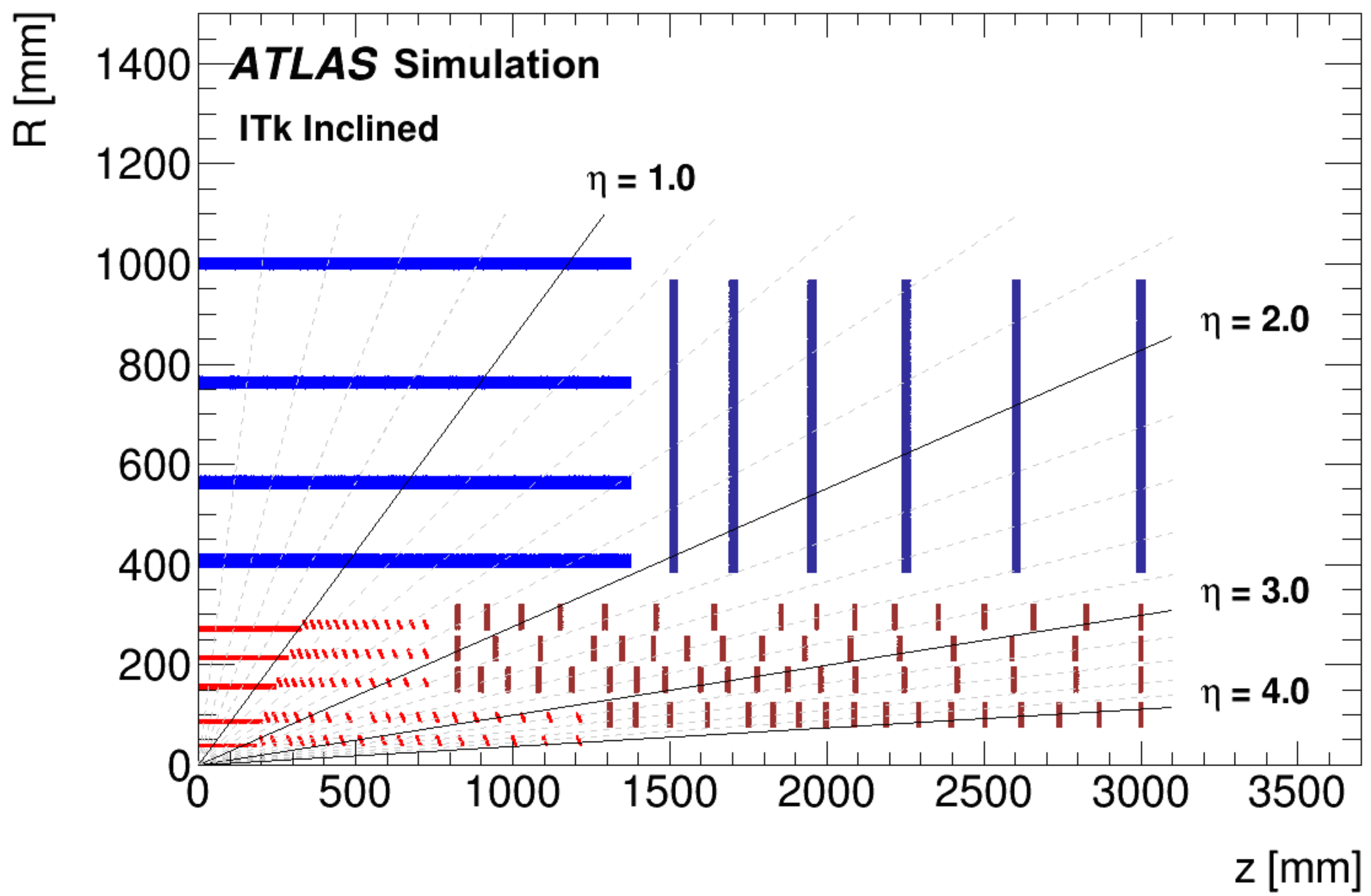
Introduction

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

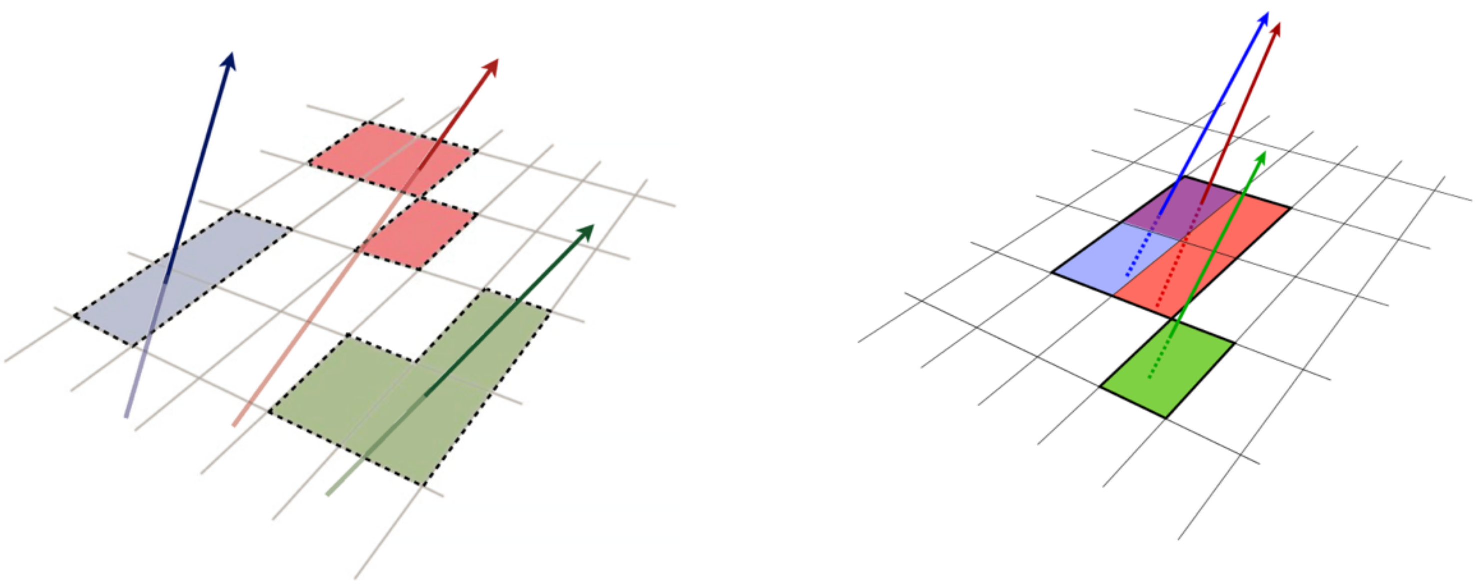
Improvements in ITk

- 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)

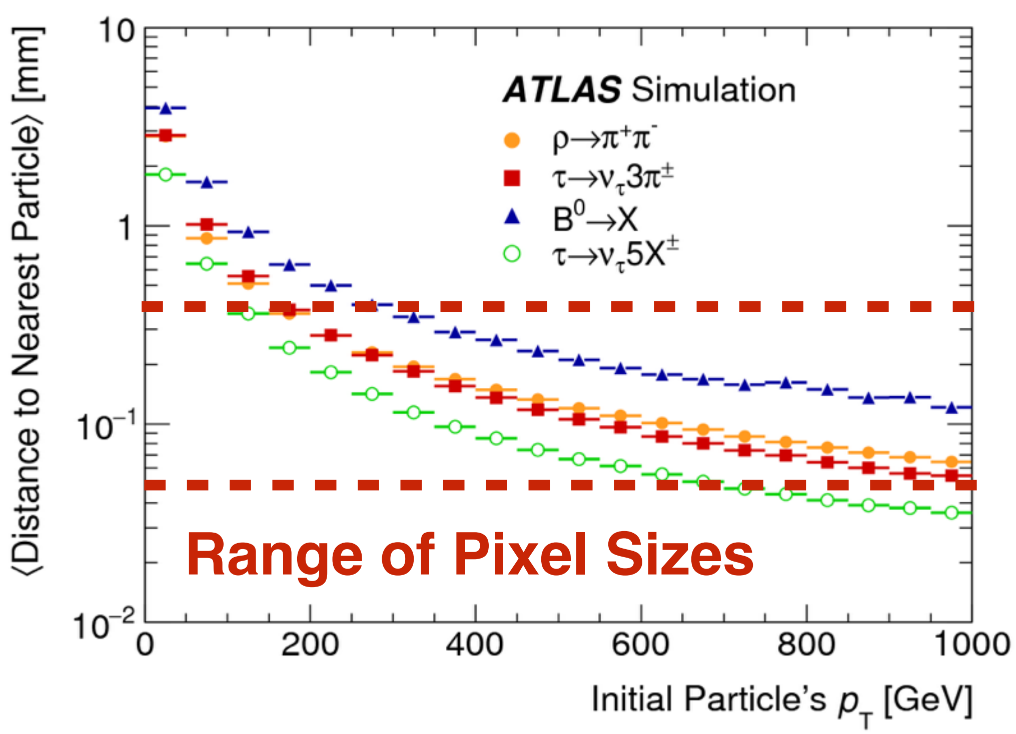


Clustering & Tracking in Dense Environments

- Increasing Energy at the LHC has provided greater reach but numerous challenges
  - Charged particles in energetic decays or jets becoming more often collimated



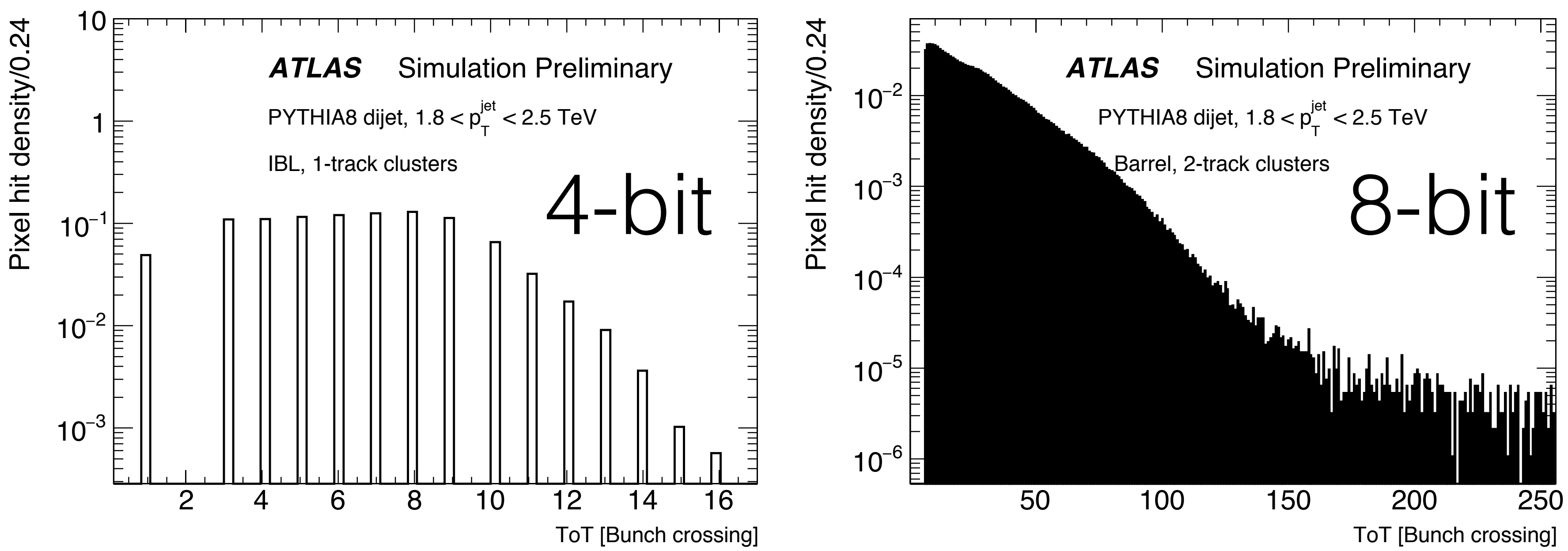
- As momentum of initial particle increases, collimation of products nears pixel dimensions
  - This leads to tracks having ‘shared clusters’ with other tracks
- In Run-2, the current data-taking period, a **Neural Network** was devised to **classify shared clusters into 1,2 or 3-particle clusters and 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

Going from 8-bit to n-bit

- 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

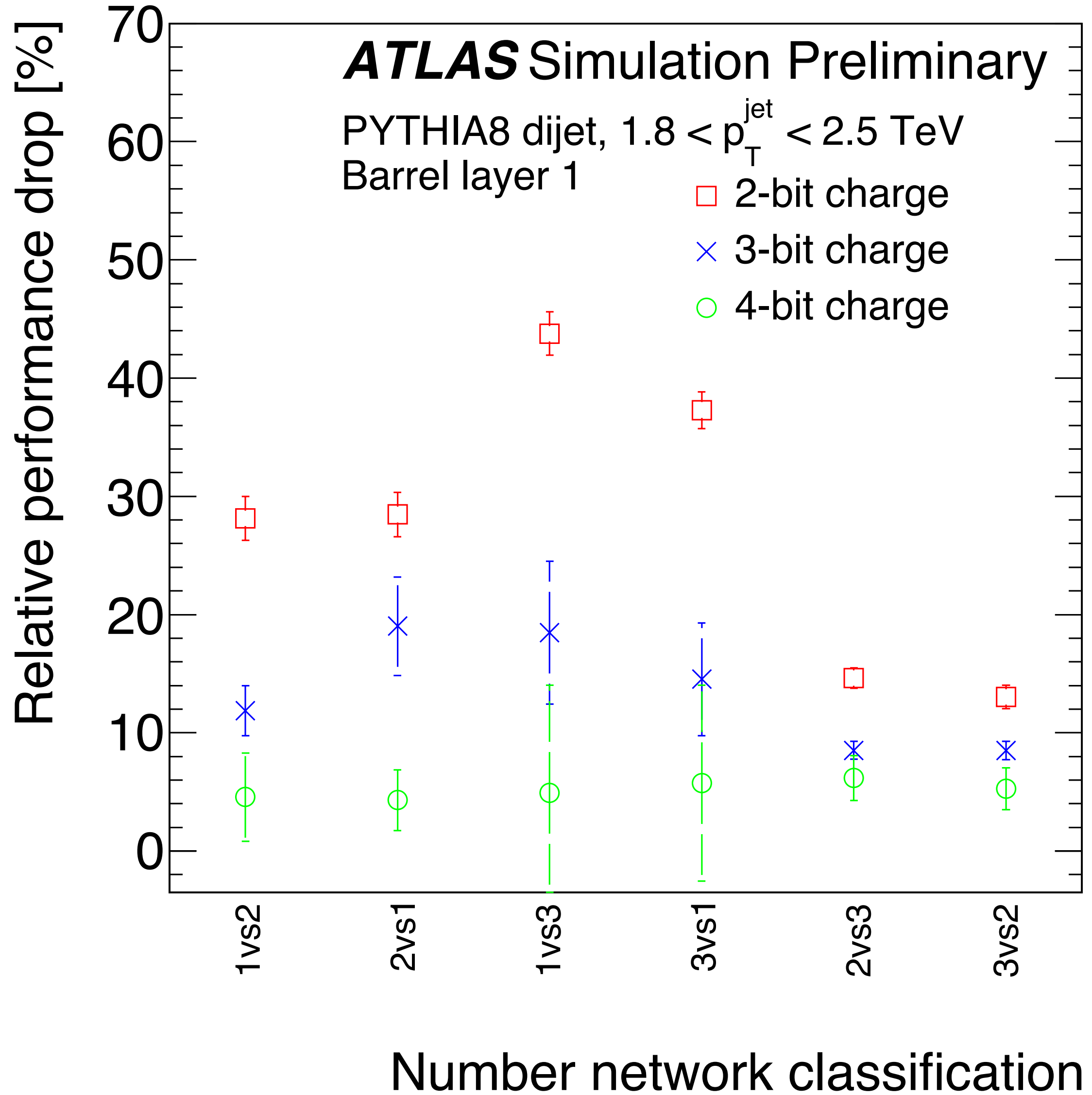


- The 8-bit ToT has high ToT overhead to measure highly ionizing particles, which is mostly unused by the high rate of singly charged particles
- A scheme was optimized to **convert 8-bit to 4-bit**, while keeping maximum information available

Number Network outlook in n-bit

- 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

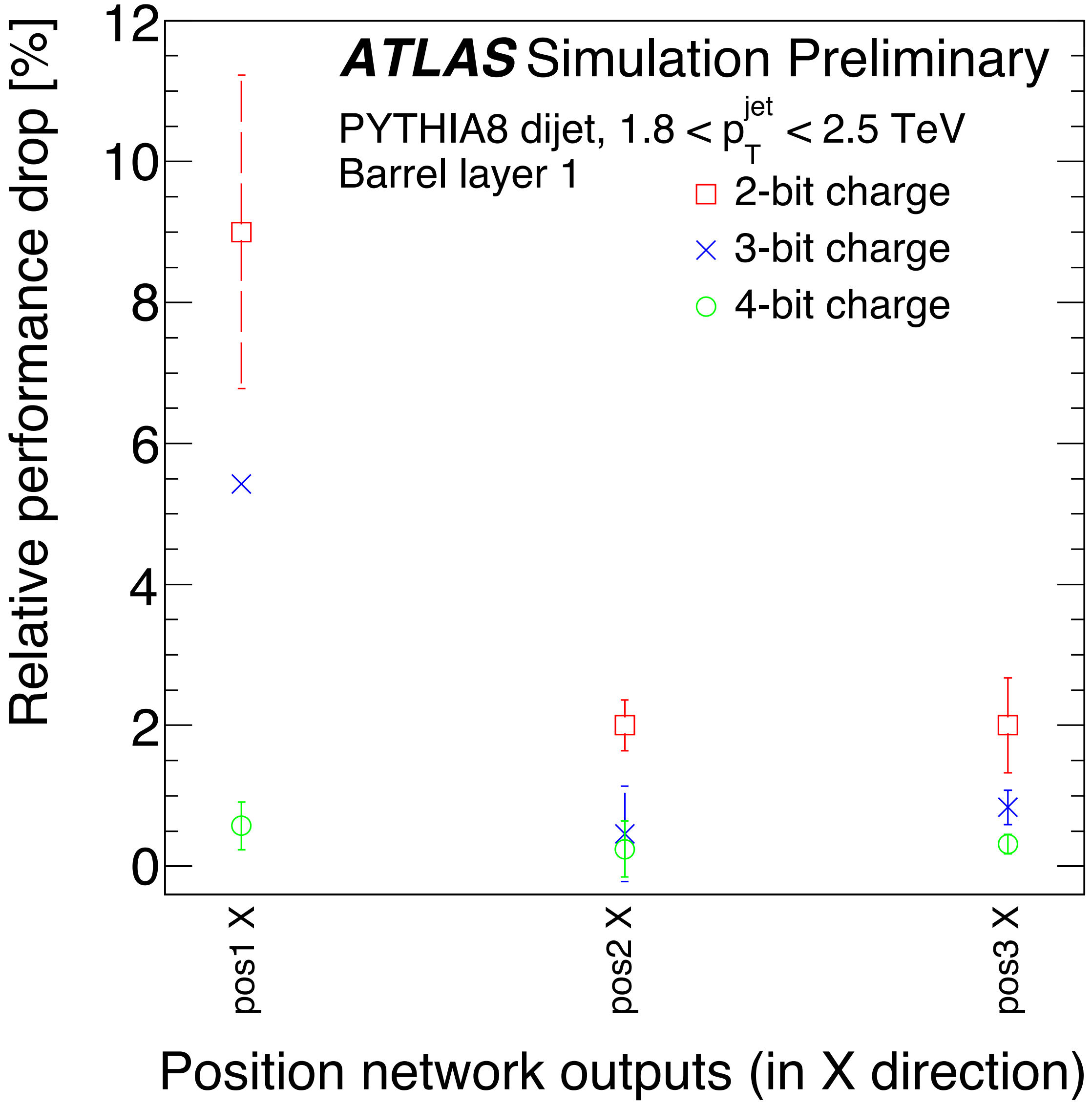
- For the **number network**
  - the Area under curve (AUC) of the Receiver-Operator curve (ROC) is used to gauge the relative performance
  - This is shown for all misclassification possibilities on the x-axis
  - The relative AUC of 2,3,4-bit versus 8-bit is shown
  - For 2,3-bit ToT there is significant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



Position Network outlook in n-bit

- 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%



Dense Environments in ITk

- 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

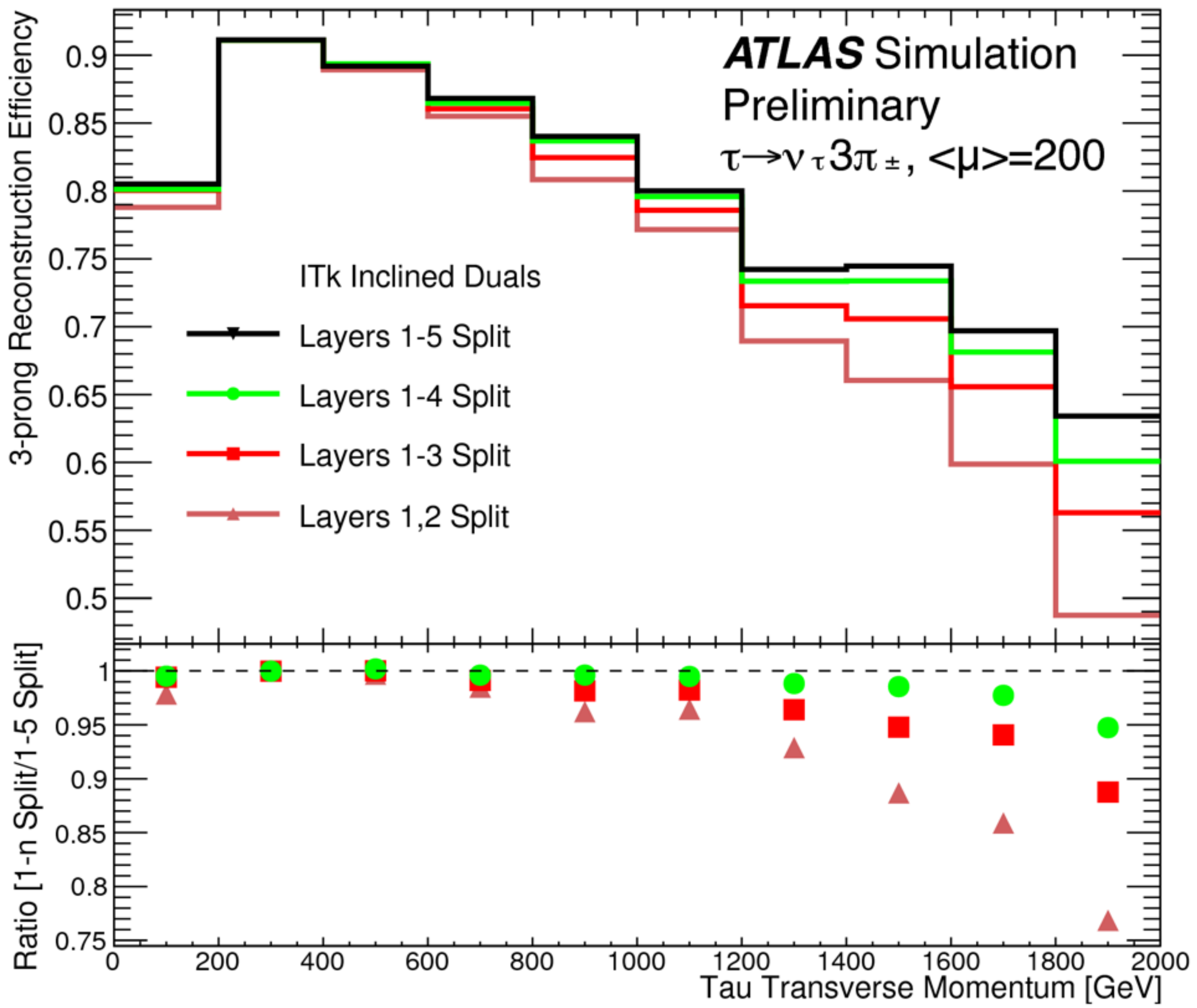
ITk Dense Environment Performance

Gauging ITk 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
  - $p_T > 2$ 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

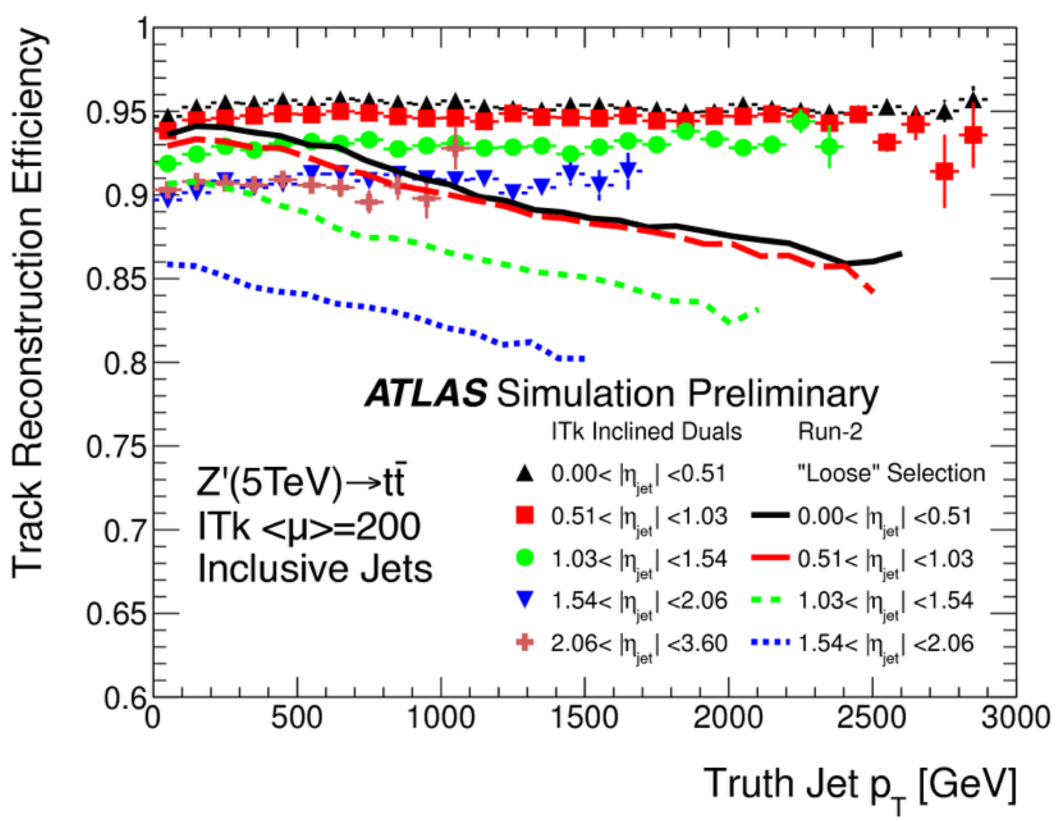
Performance with 2-3 particle clusters

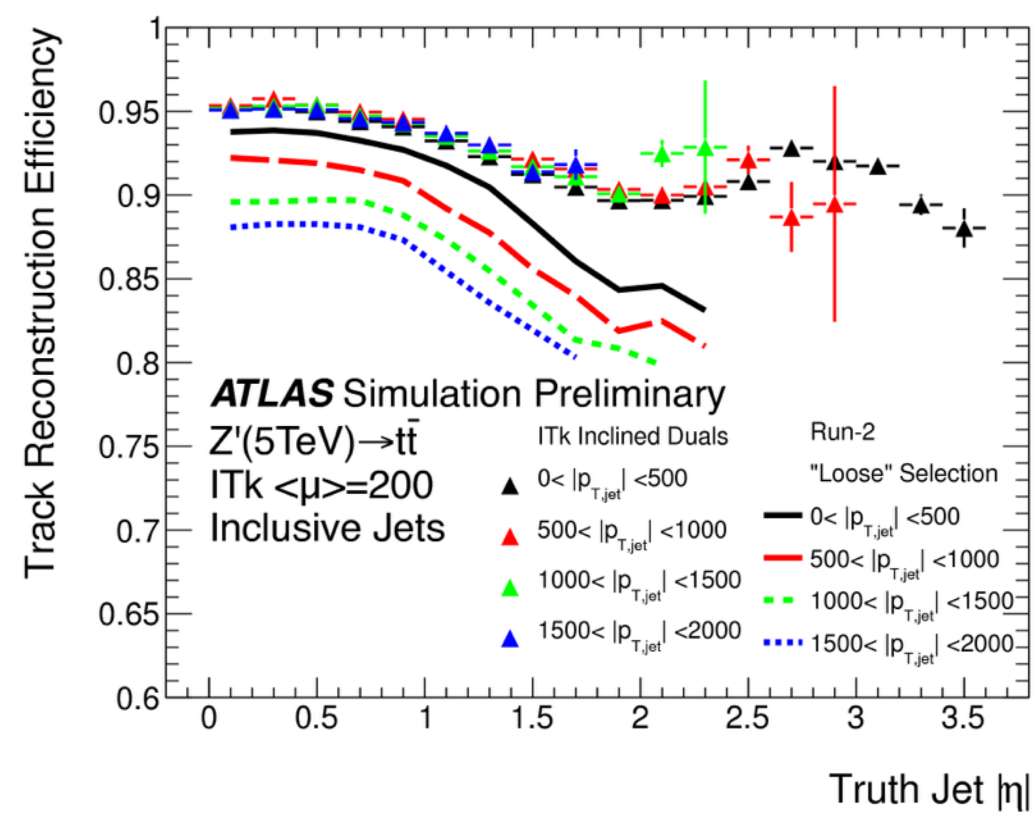
- Look at single τ samples, decaying to 3 $\pi^{\pm}$
    - High momentum gives insight into **2/3 particles clusters** CTIDE is meant to handle
    - 3-prong efficiency defined as proportion of times all 3 pions are reconstructed as tracks
- In this plot, switch which pixel layers in use Number Network
    - 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

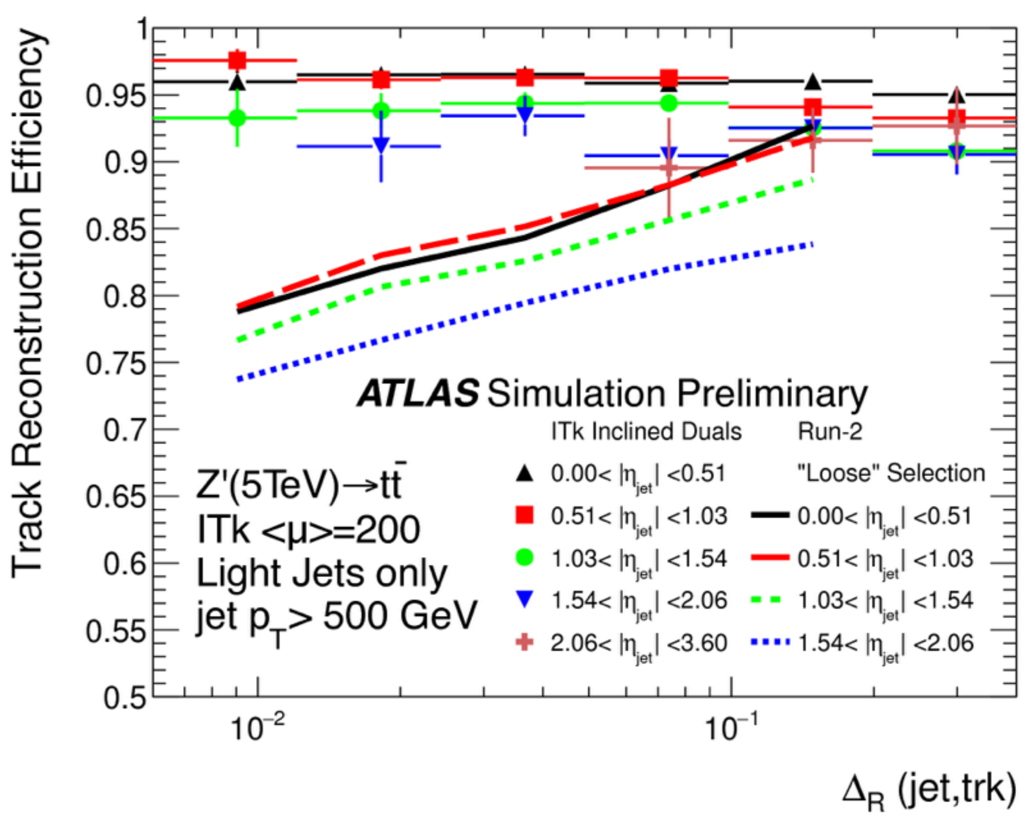
- For jets, use Anti-k_T algorithm based on truth information to find jets
  - Count all truth particles meeting requirements within ΔR(η,θ cone)=0.4 of jet
  - Efficiency defined as proportion of tracks which match these truth particles in cone
- Compare efficiencies in different η regions across the **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

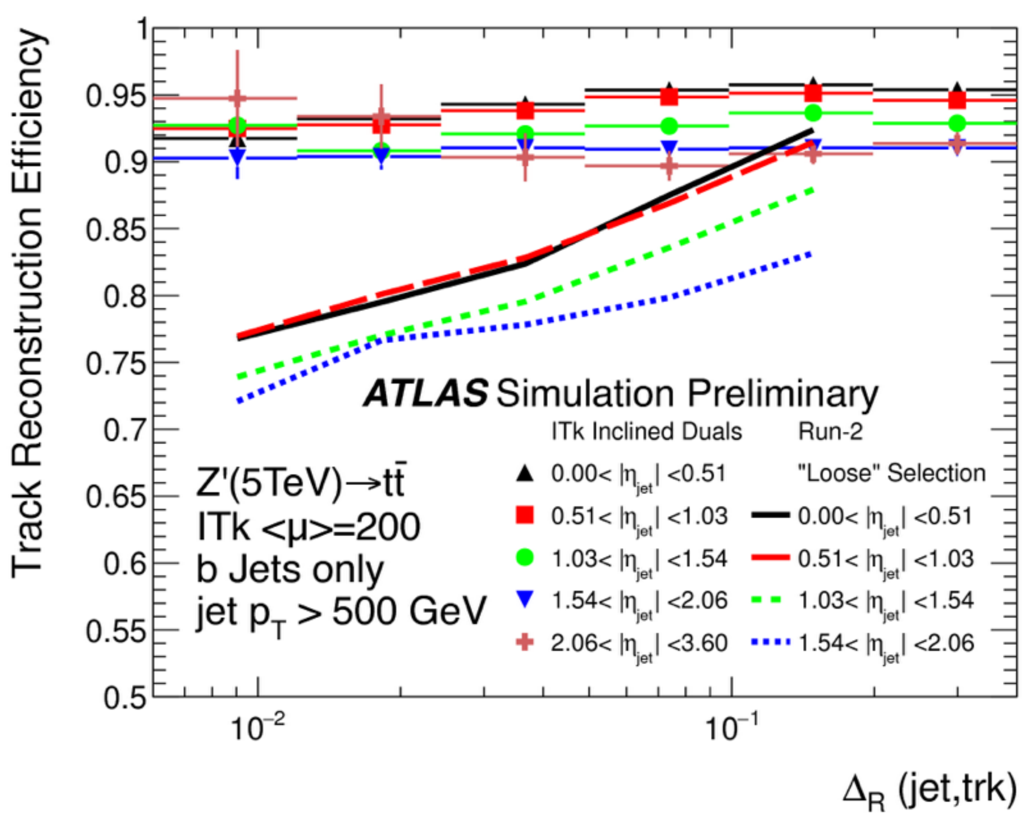




Performance in Jets

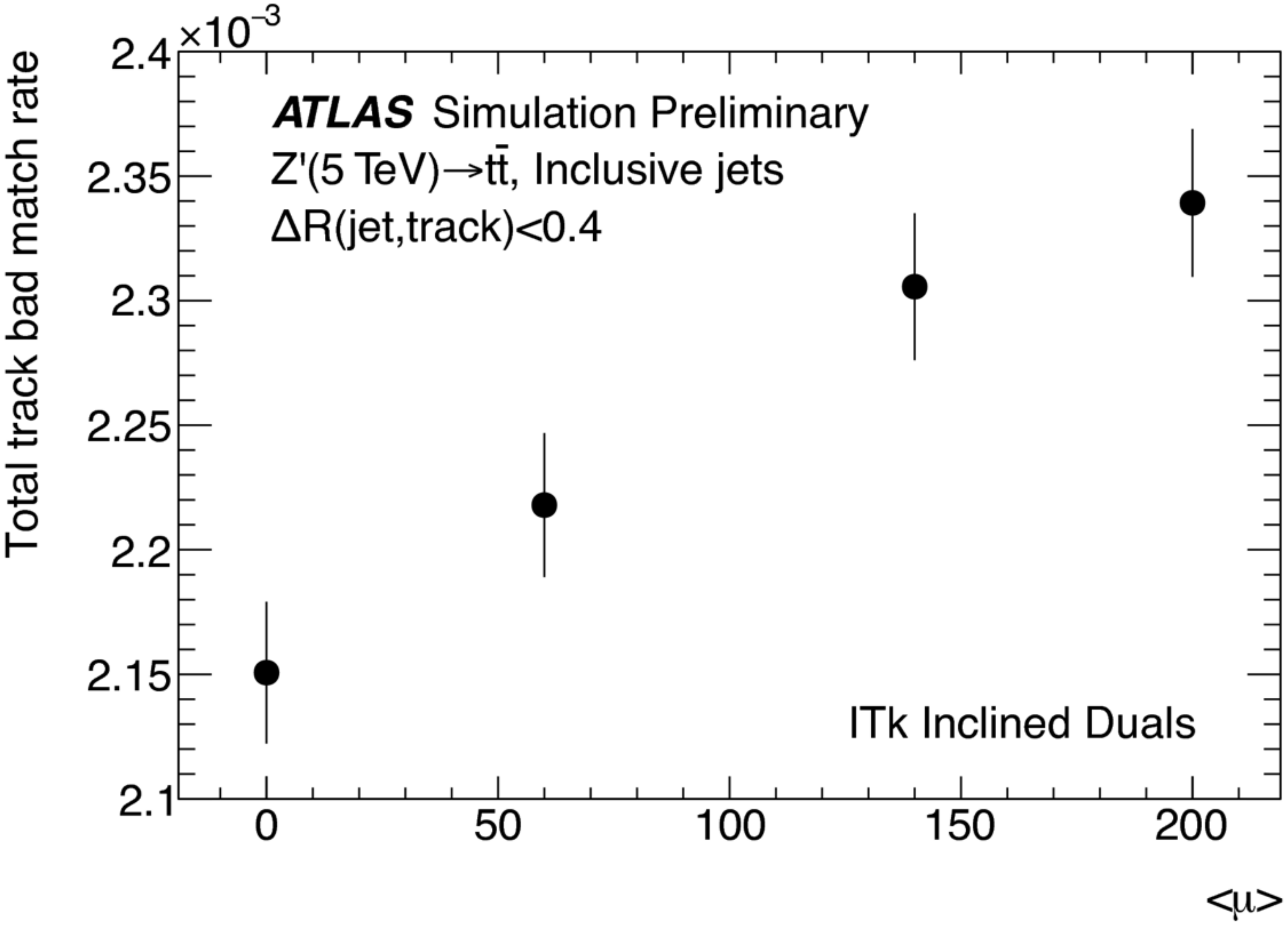
- Can also look at performance as a function of the **ΔR of the track from the jet**
  - Jets are divided into b and light-jets using truth information
- ΔR here can be seen as local track density as low ΔR is in the core of the jet and corresponds to high track density
  - In Run-2 a degradation is seen in the core
  - In ITK this effect is not seen





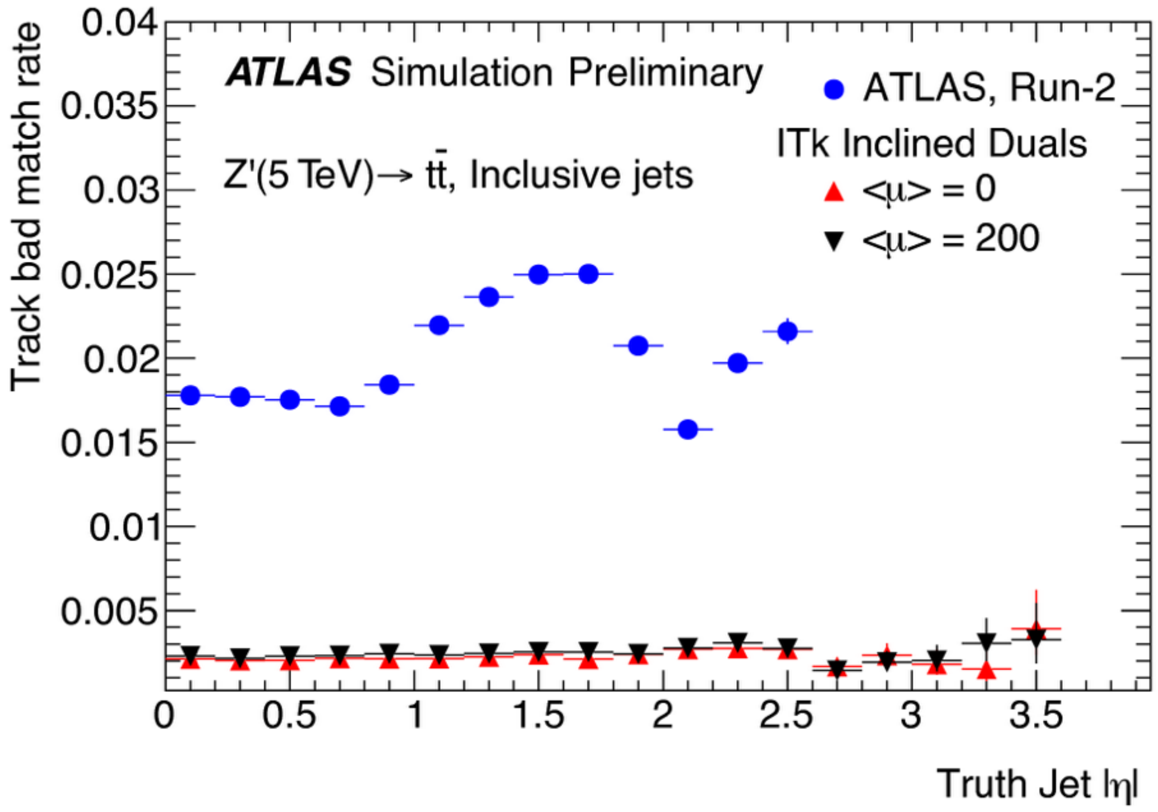
Performance in Jets

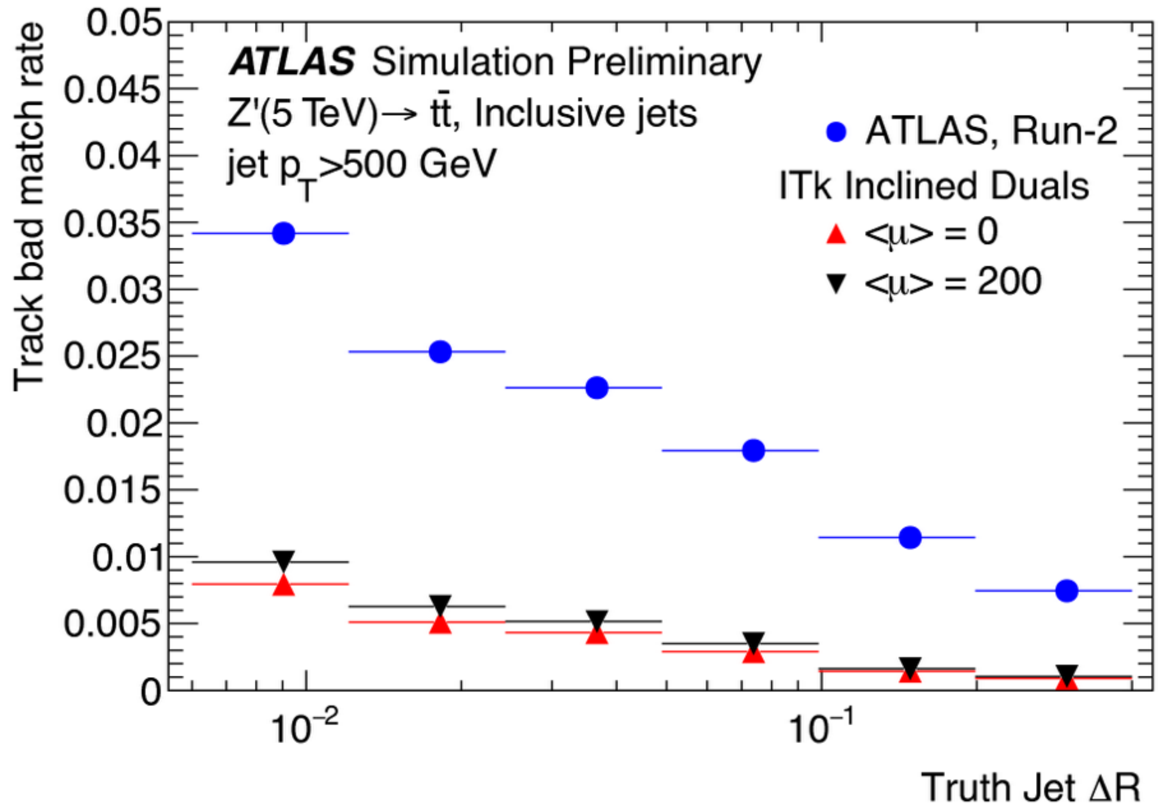
- Tracks in dense environment can also be quantified in terms of **bad association** with clusters
  - Bad match rate looks at proportion of tracks with **0.5 to 0.8 truth matching probability**
- The bad match rate is shown to only be marginally affected by increasing pileup density
  - Thus it is dominated by the products of the jet and not pileup tracks not associated with the hadronisation



Performance in Jets

- The bad match rate as a function of |η| 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 ΔR
  - Compare to Run-2, dependence of bad match rate on ΔR 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 τ 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