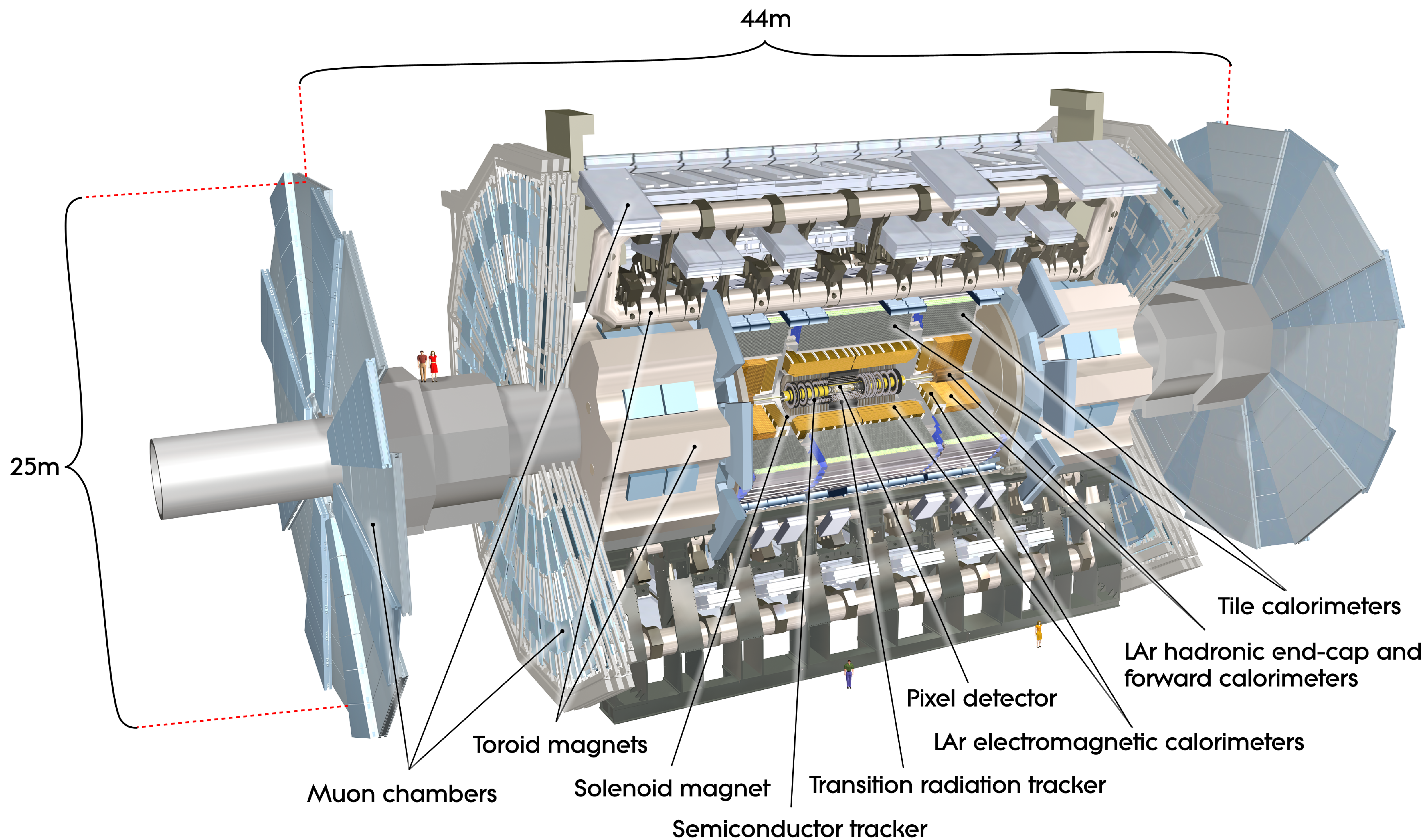
ATLAS Experiment: Novel Techniques for Track Reconstruction in Dense Environments

Gabriel Facini

Vertex 2015

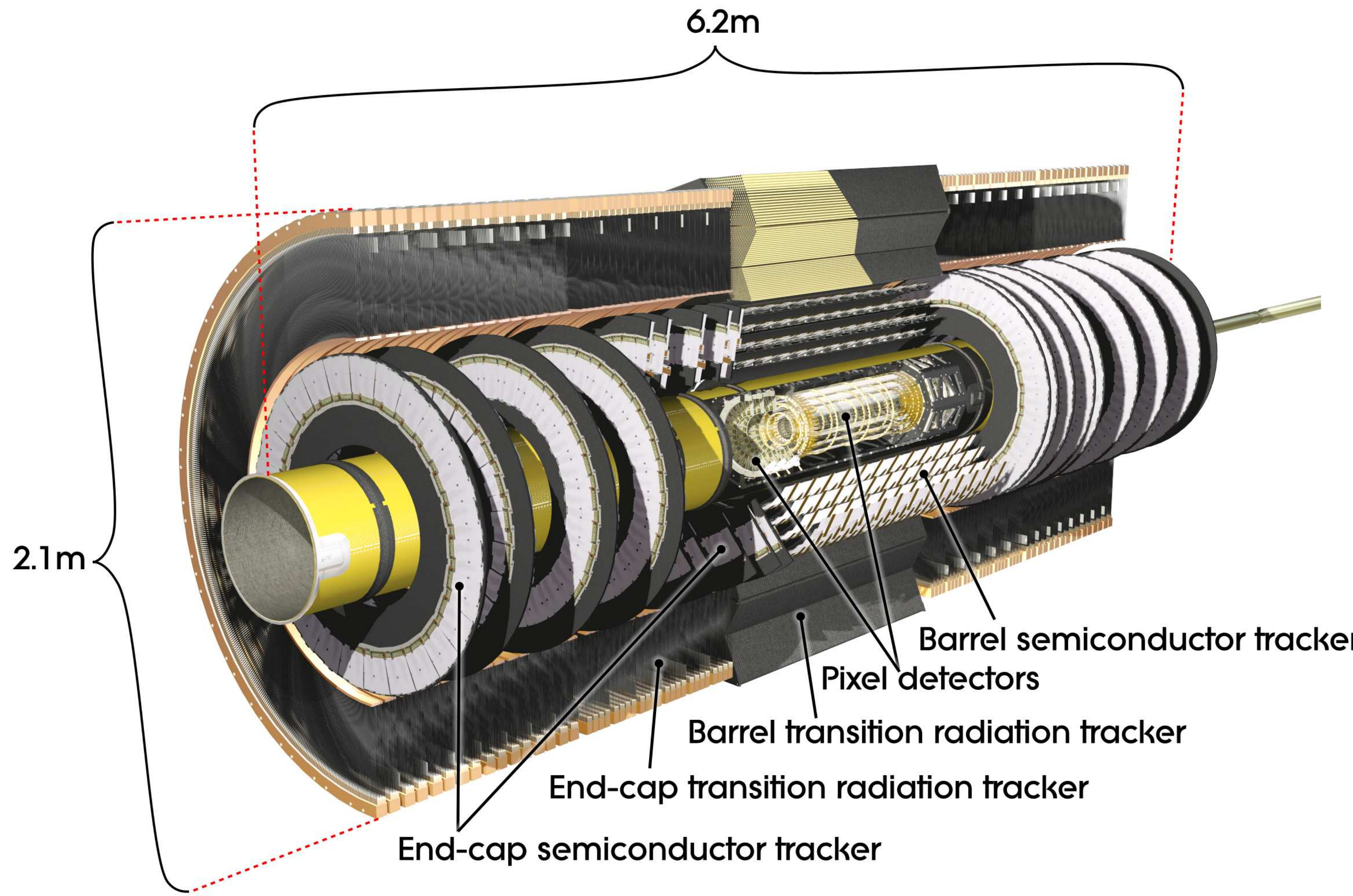
June 04, 2015

ATLAS & Track Reconstruction



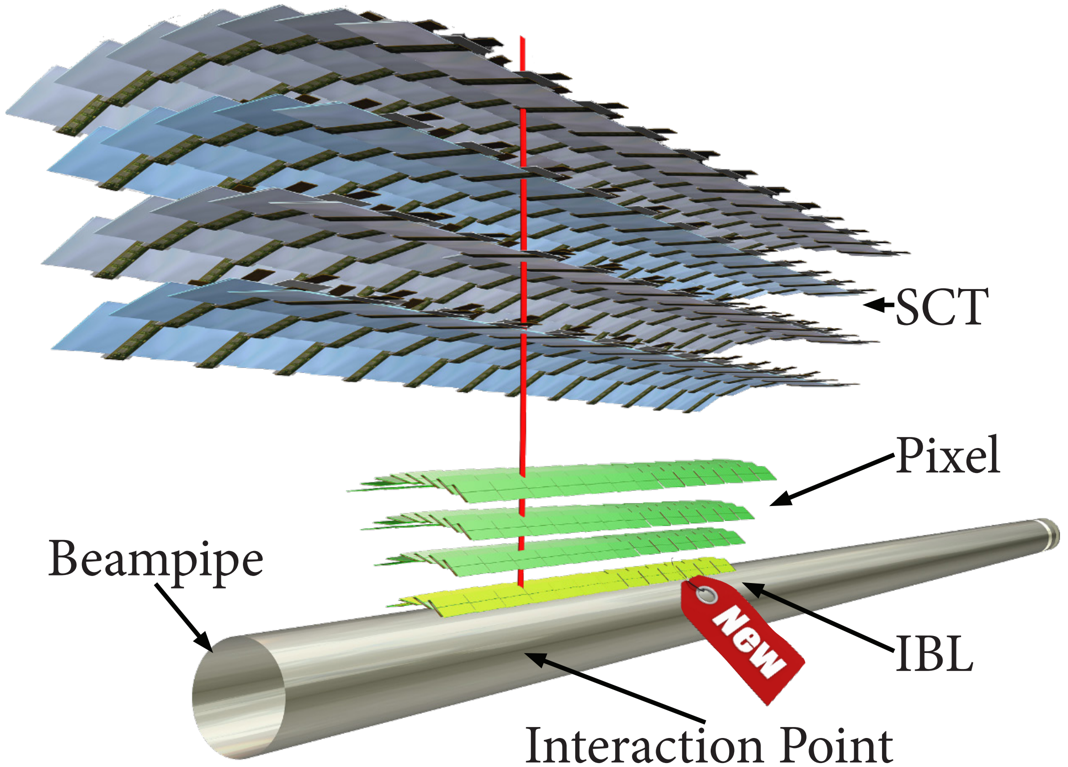
ATLAS Inner Detector

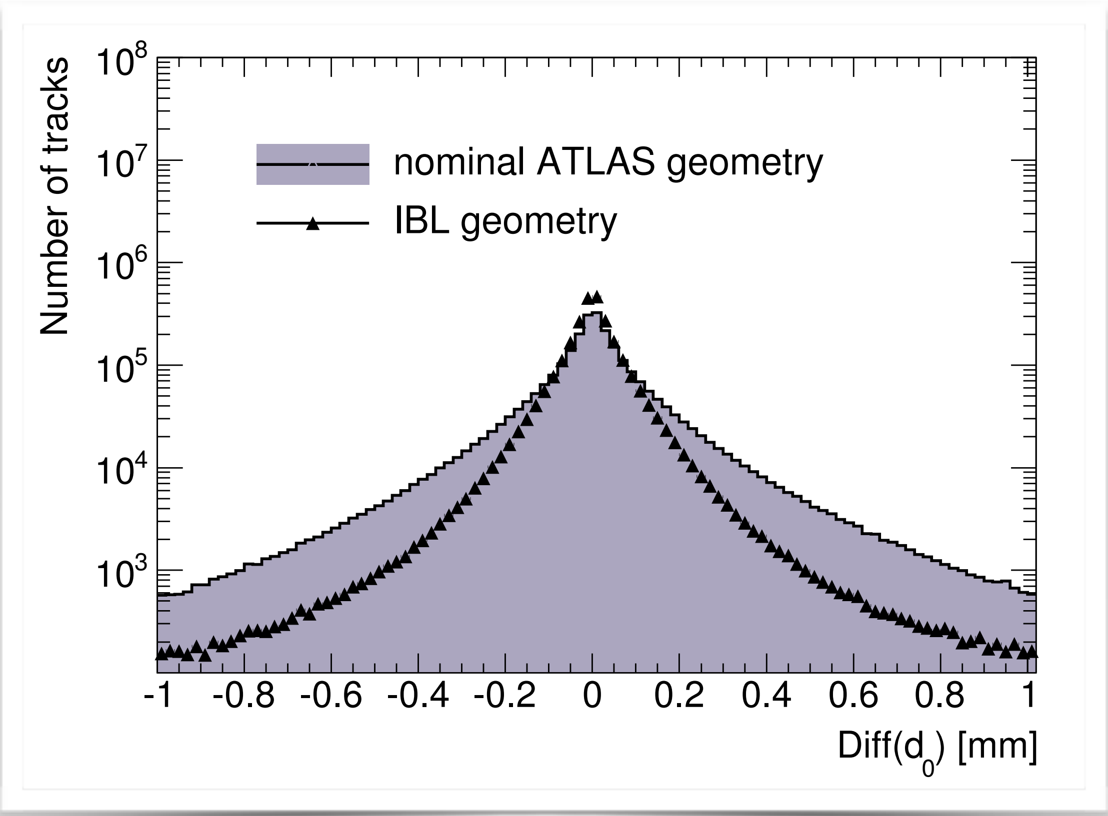
- Measures trajectories of charged particles originating from the interaction point
- Comprises **three** detector technologies:
  - **Silicon pixels**
  - **Silicon microstrips** (SCT)
  - **Drift tubes** (Transition Radiation Tracker – TRT)
- **Solenoid**: 2T B field

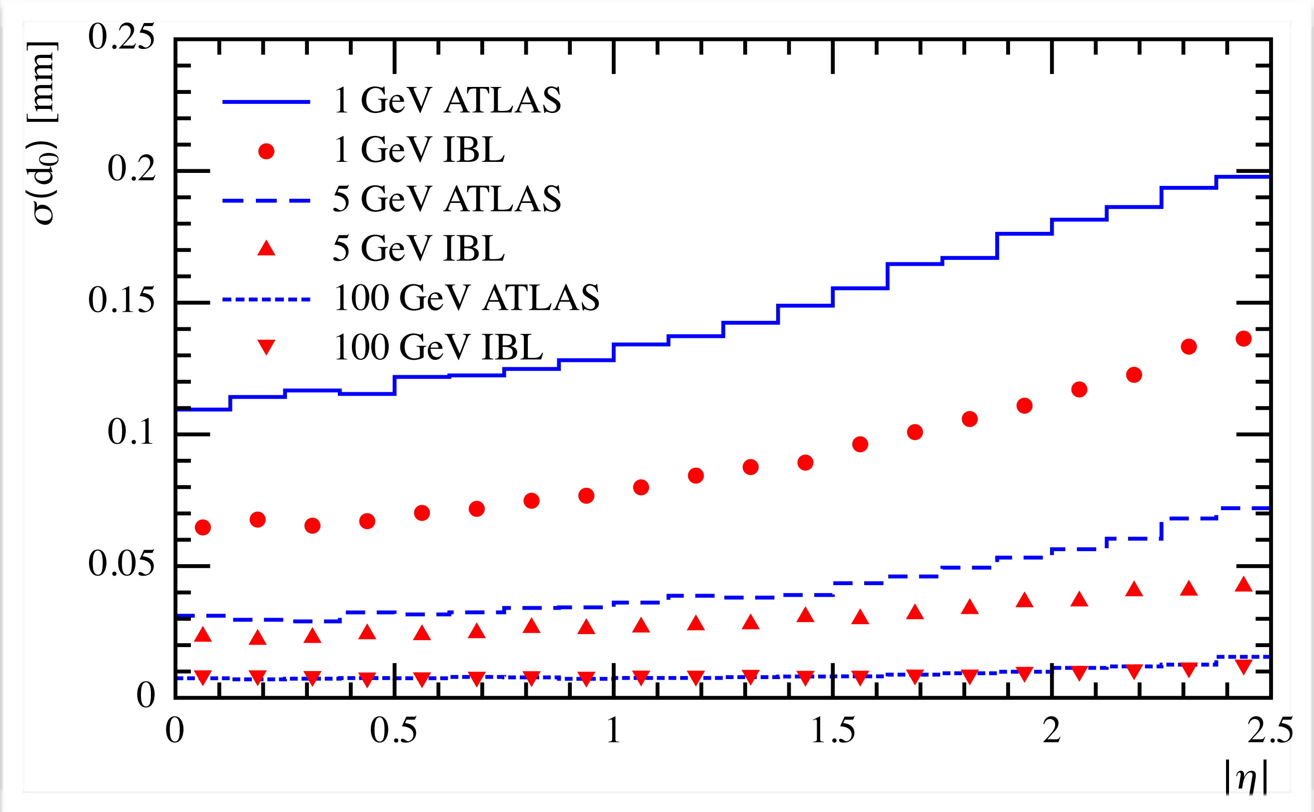


Pixel IBL

- A **new layer** has been added to ATLAS during LS1 (see Daniel's talk)
- Provide security against detector aging
- Improves IP resolution
- And provides an additional point on the track — more robust tracking

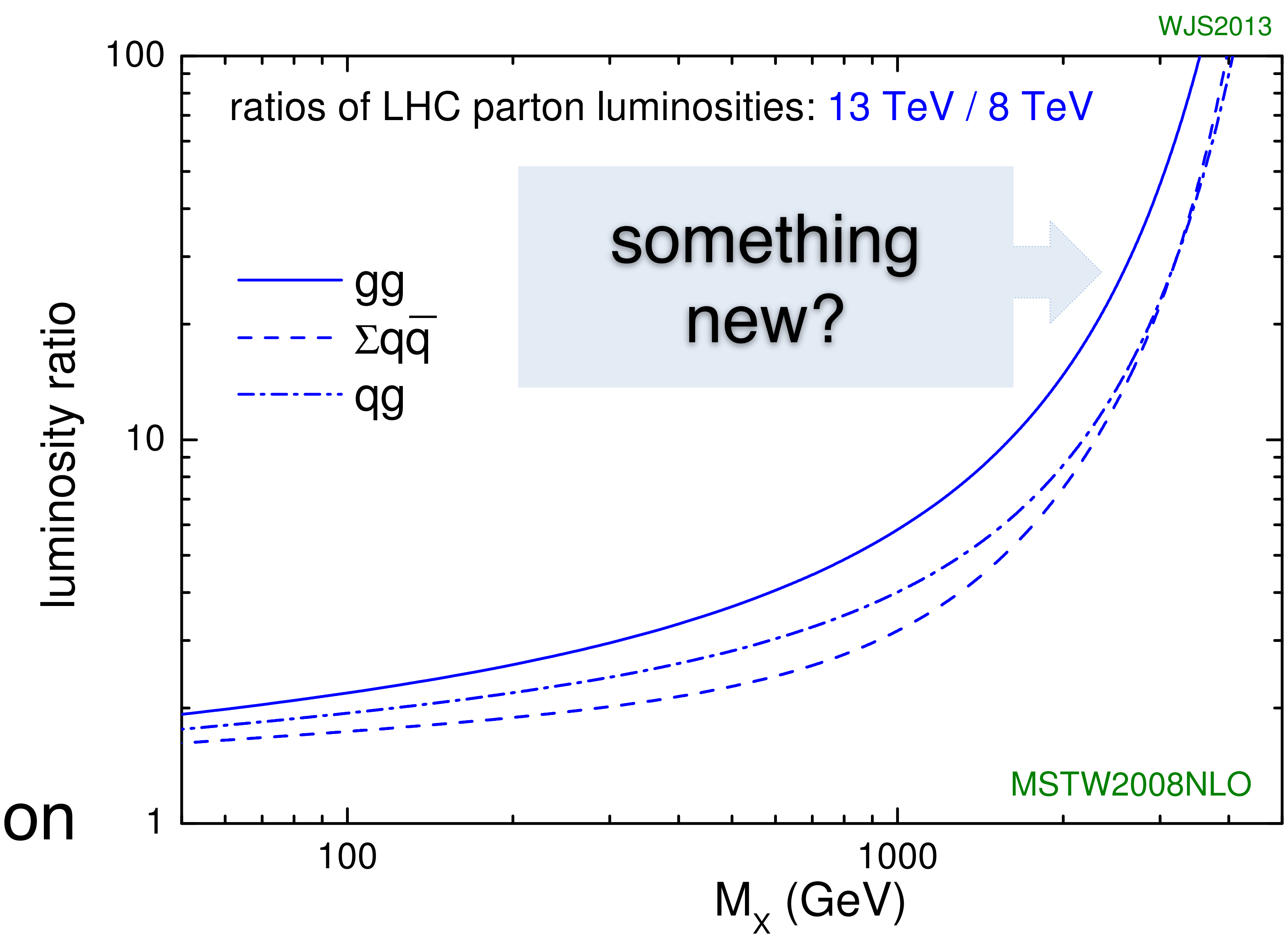






Run II

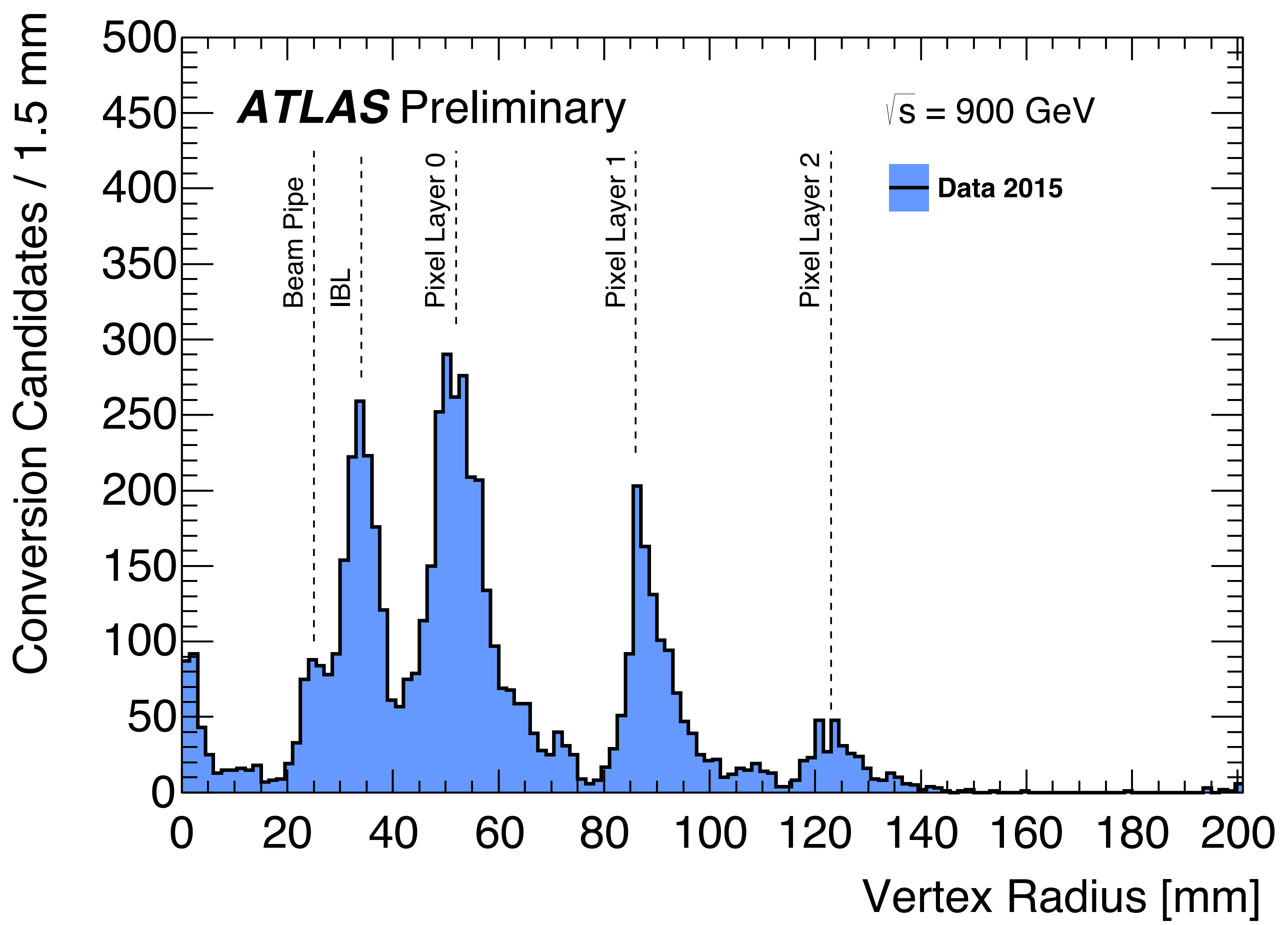
- Tremendous increase in reach for **new heavy particles**
  - hadronic decays will yield high pT jets
- Track usage:
  - jet calibration
  - b-jet identification
  - tau identification
- Numerous physics applications
  - studies of fragmentation



Run II Is Here!

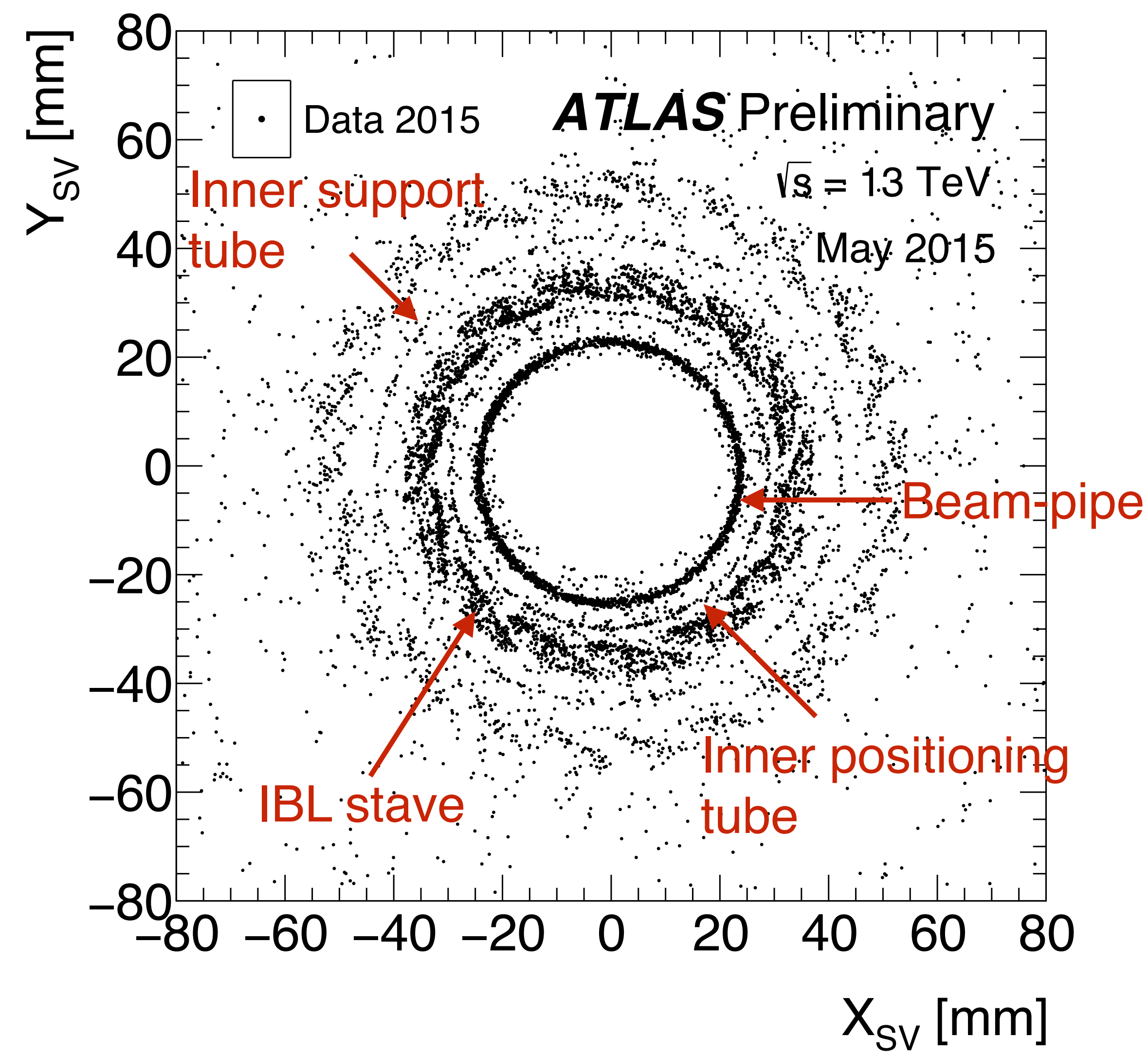
Conversions

Radial vertex position for photon conversion candidates.



Hadronic interactions ("radiography")

Vertex position for had. int. candidates in xy-plane, reconstructed from multiple tracks.



Started to look at conversions and hadronic interactions to validate detector material and geometry description.

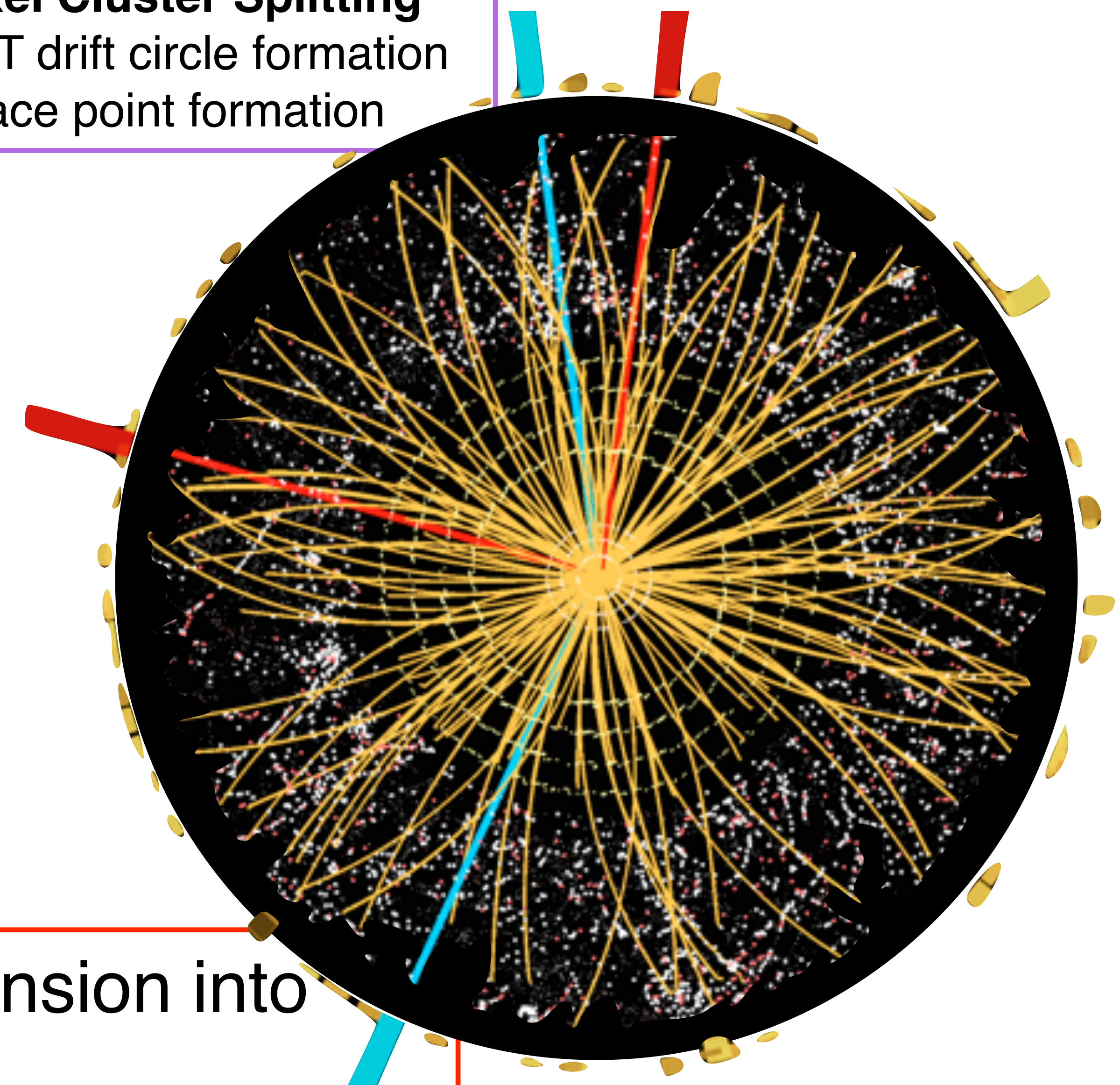
Track Reconstruction Chain

pre-processing
- ➡ Pixel+SCT clustering
- ➡ **Pixel Cluster Splitting**
- ➡ TRT drift circle formation
- ➡ space point formation

Combinatorial track finder
- ➡ iterative :
  1. SCT seeds
  2. Pixel seeds
  3. Pixel+SCT seeds
- ➡ restricted to roads
- ➡ removal of duplicate candidates

Ambiguity solution
- ➡ precise least square fit with full geometry
- ➡ select best silicon tracks using:
  1. hit content, holes
  2. number of shared hits
  3. fit quality…

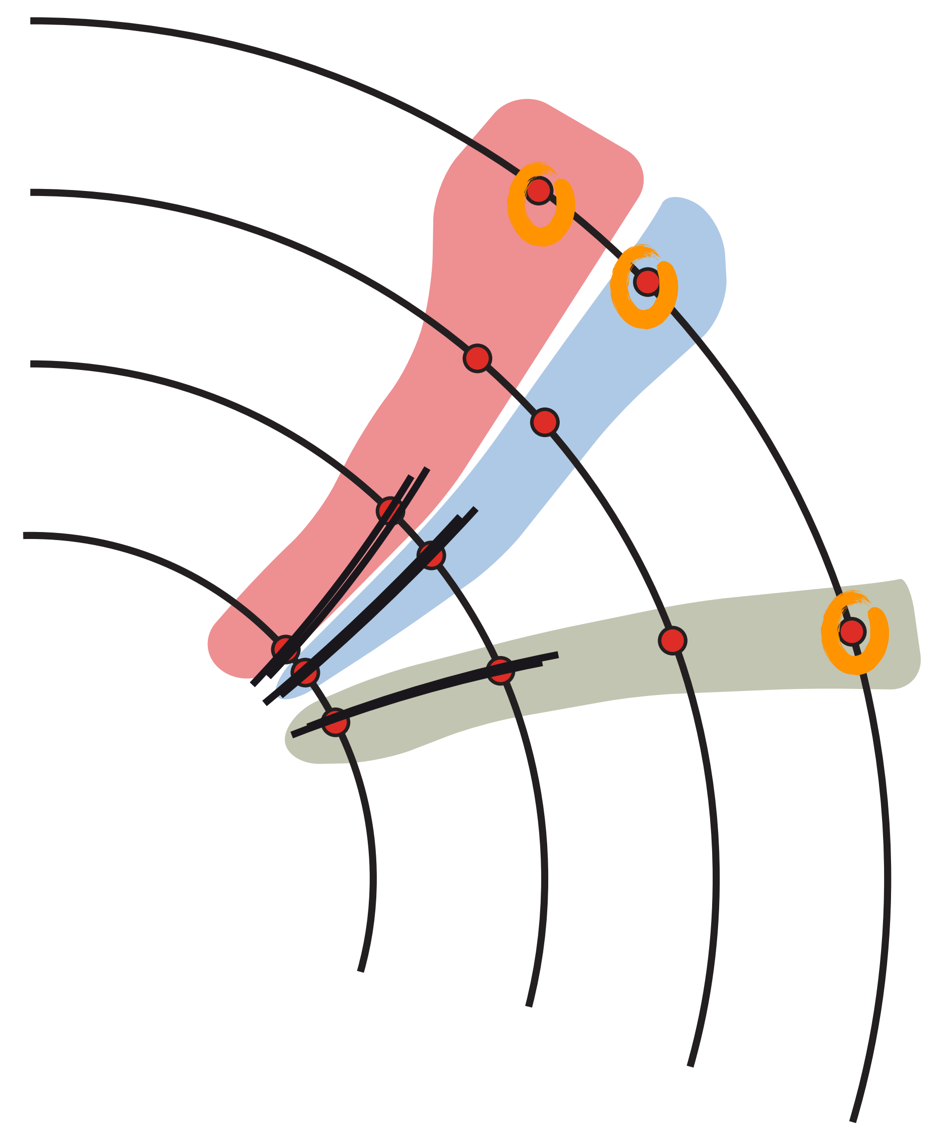
Extension into TRT
- ➡ progressive finder
- ➡ refit of track and selection



Excellent performance in Run I

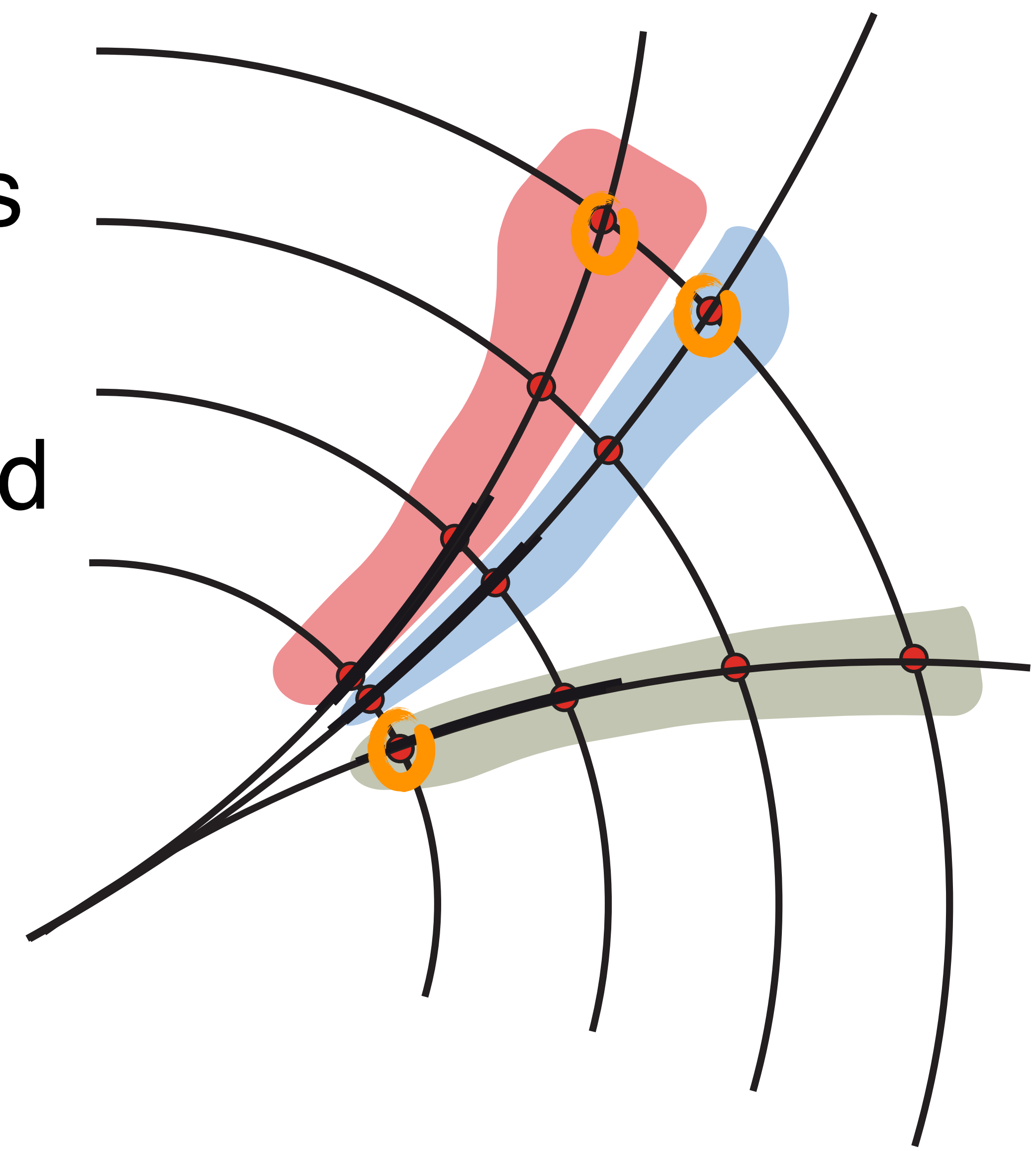
Seeding Strategy

- Seed built from 3 space-points (SP)
  - look for 1 additional compatible SP (added for Run II)
  - SP from good candidates removed
  - sequential seed finding to avoid combinatorial explosion
- ***Kalman Filter***
  - Exploration of all possible candidates
  - Basic material effects included
- Fakes are no longer random combinations but more from miss-assignment of clusters
  - Necessitates **Ambiguity Resolution**



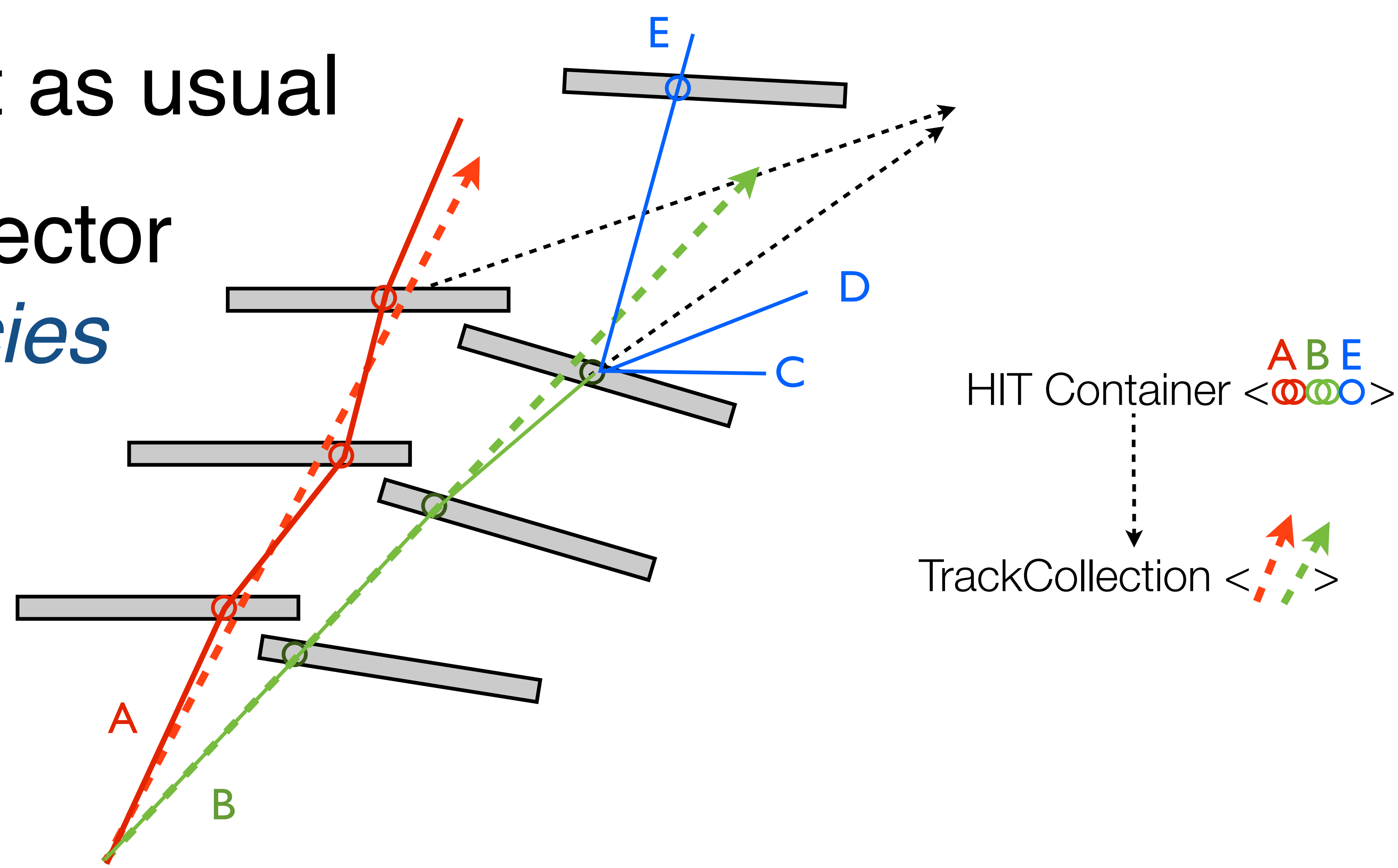
Ambiguity Resolution

- Candidates processed in descending **order of a track score**
- Score based on content (Clusters and Holes), log(pT), χ2
- Limit on ***cluster sharing*** enforced
  - candidate VS accepted tracks
  - Remove clusters from candidates if shared too often



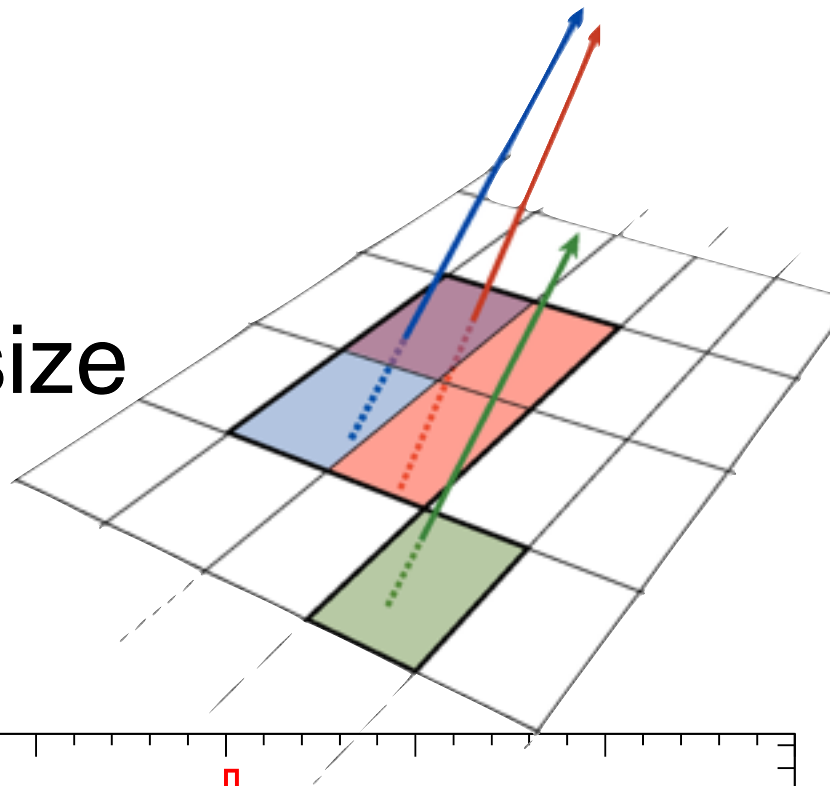
Truth Based Resolution

- use **truth** information to find perfect cluster collection
  - no need for pattern recognition or ambiguity resolution
- perform track fit as usual
- respects all detector *cluster efficiencies* and *resolutions*

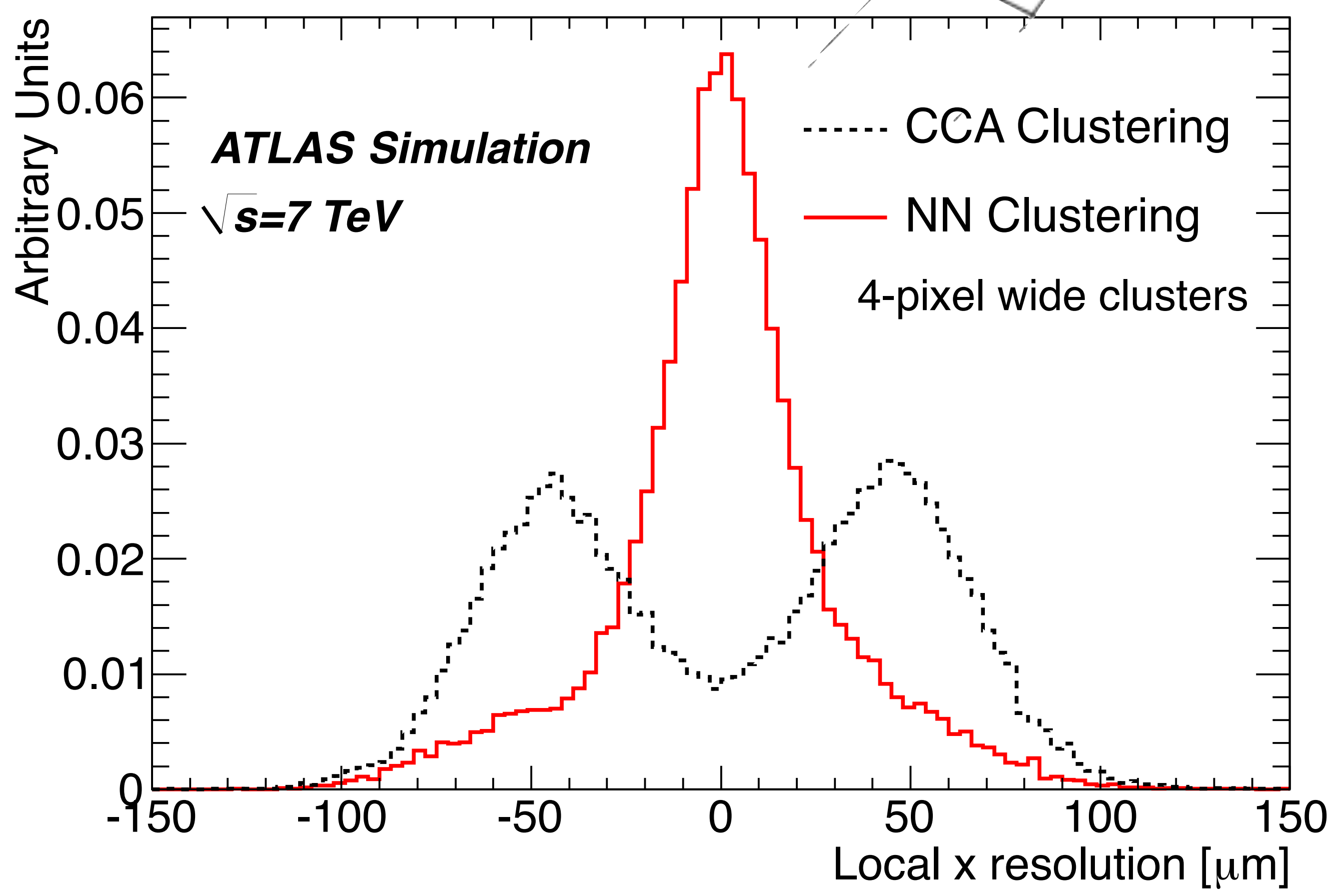


full documentation

Dense Environments



- Charge deposited on multiple pixels
- When separation of particles ~ cluster size reconstructed as a **merged cluster**
- Tracks compete for clusters
    - **shared clusters:** penalized to reduce fakes/duplicate
- Artificial neural network (**NN**) used to **identify merged clusters**
    - Run I: duplicate and assign new positions



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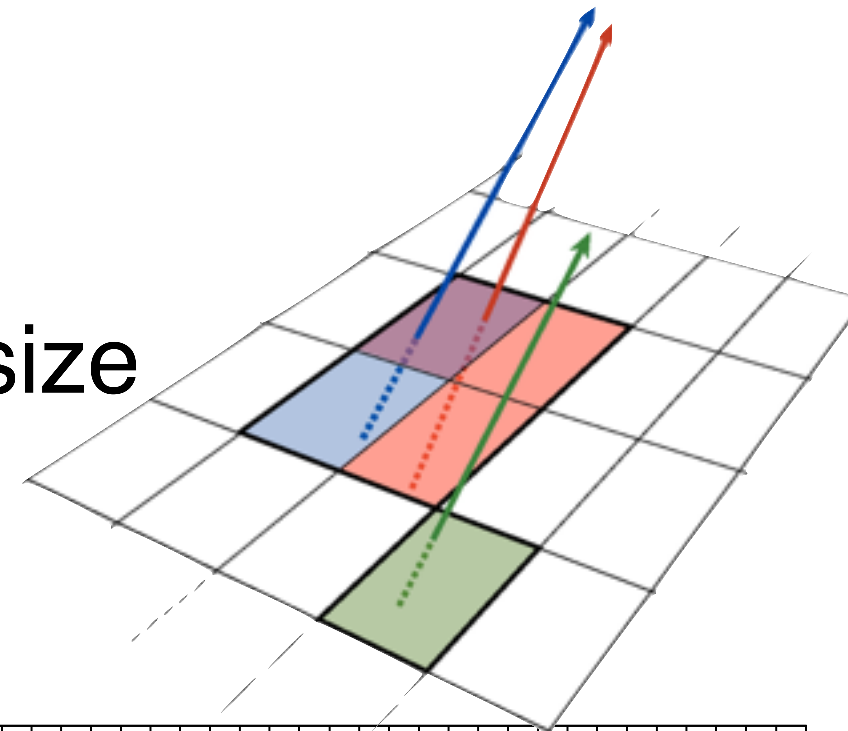
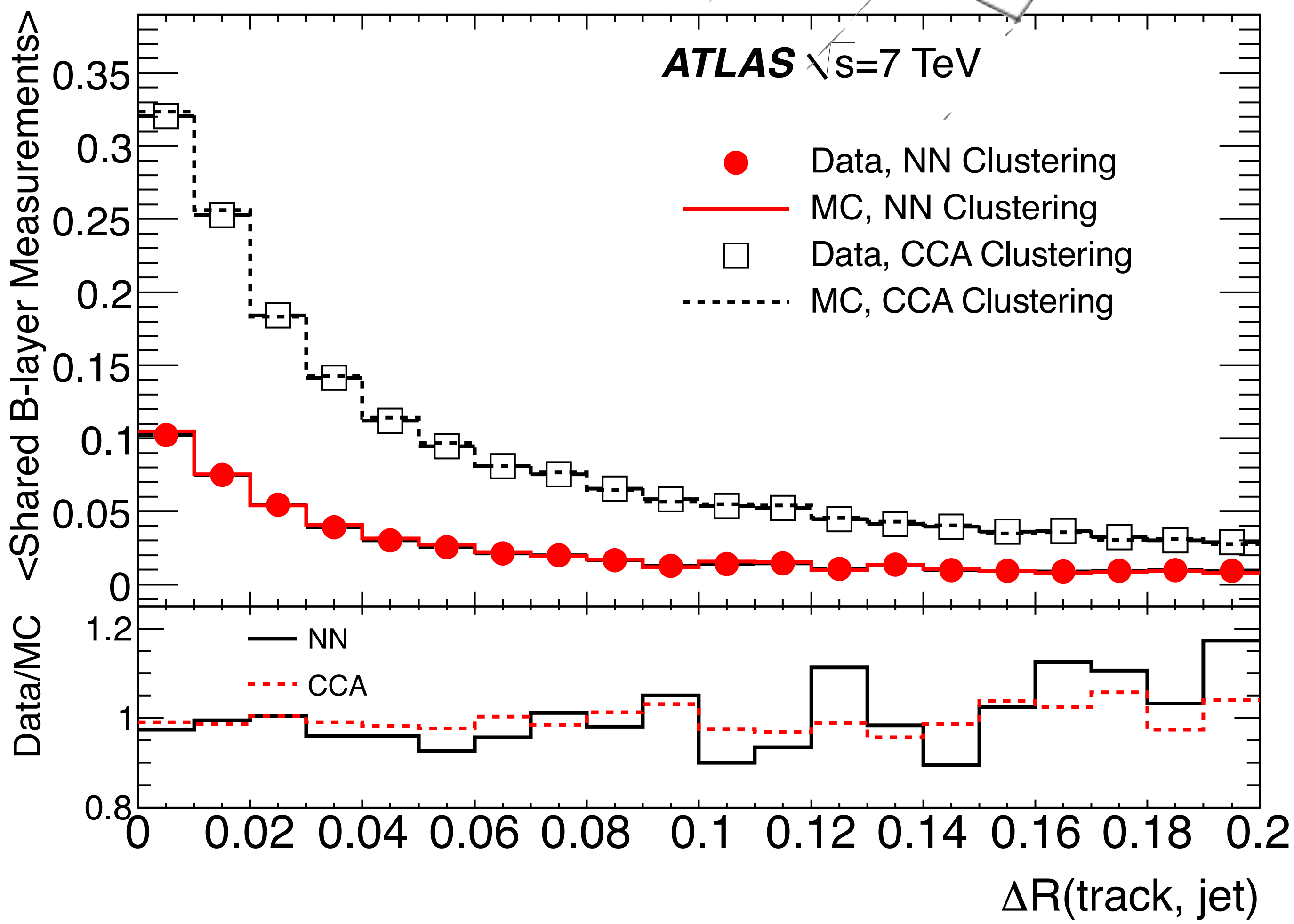
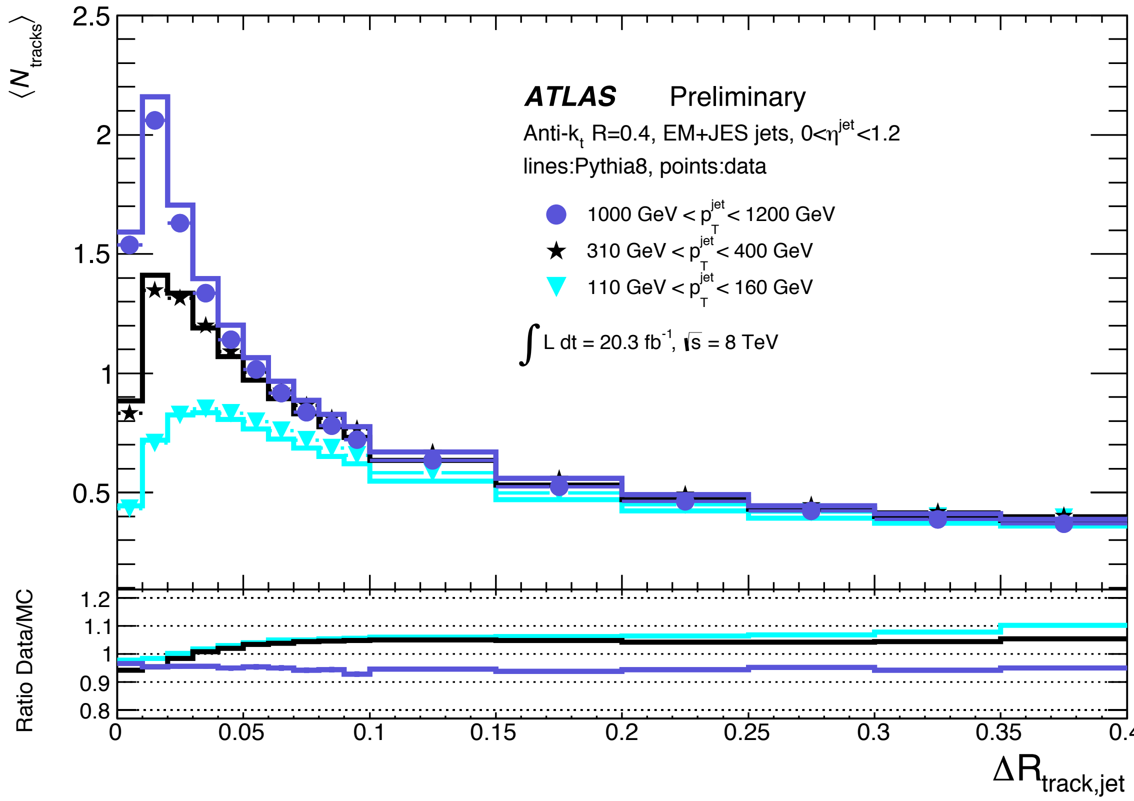
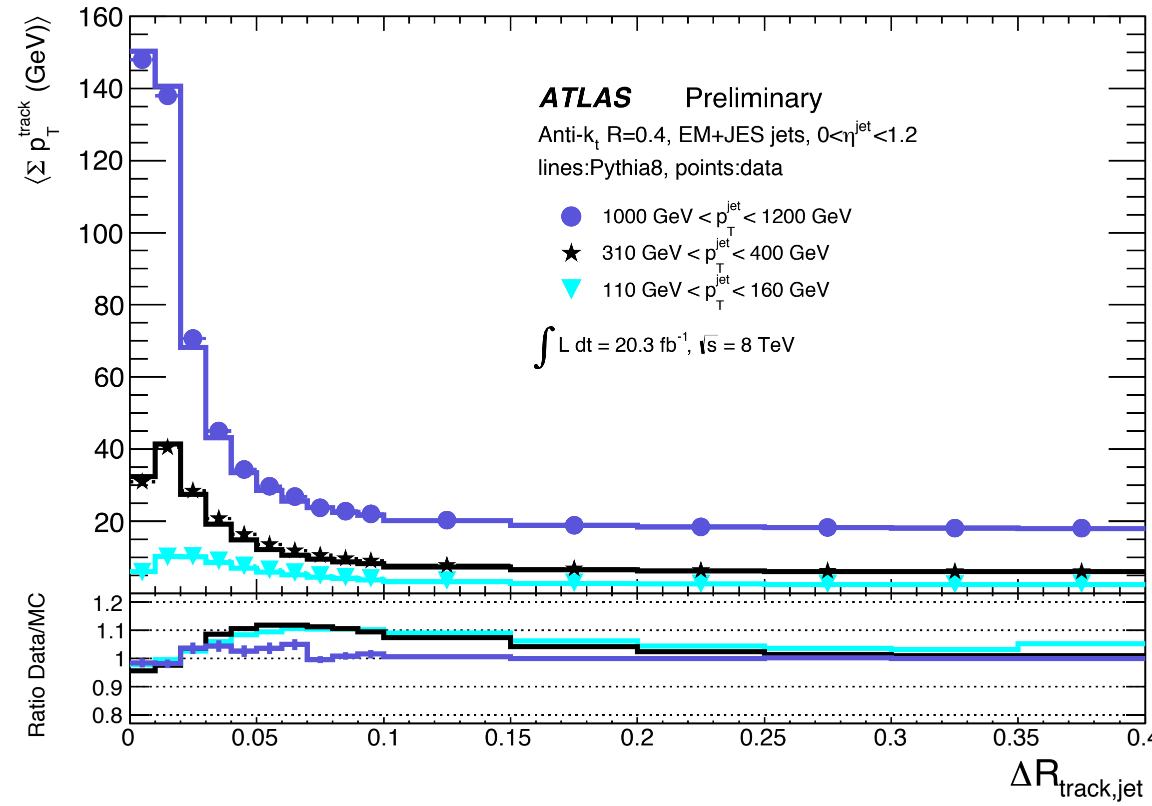


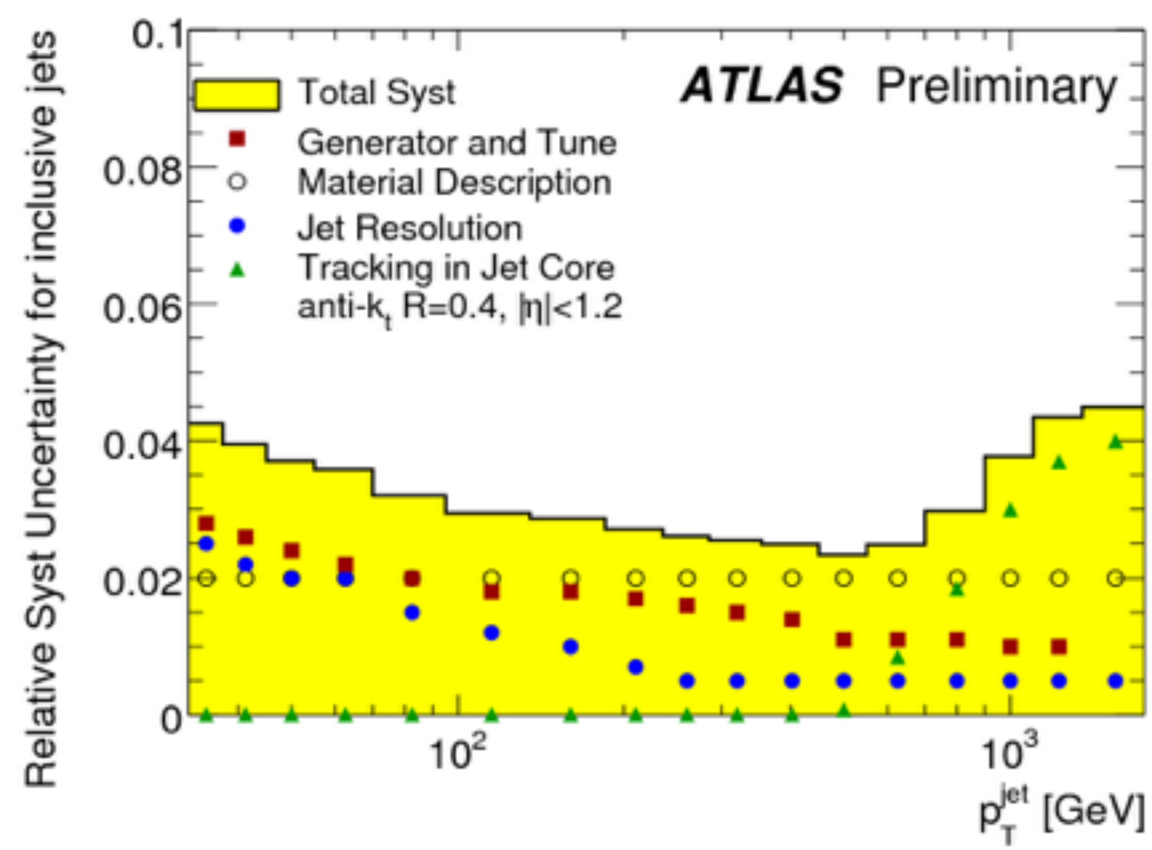


Run I Performance





- **Excellent agreement** seen in track based quantities
- Efficiency lose in high pT jets



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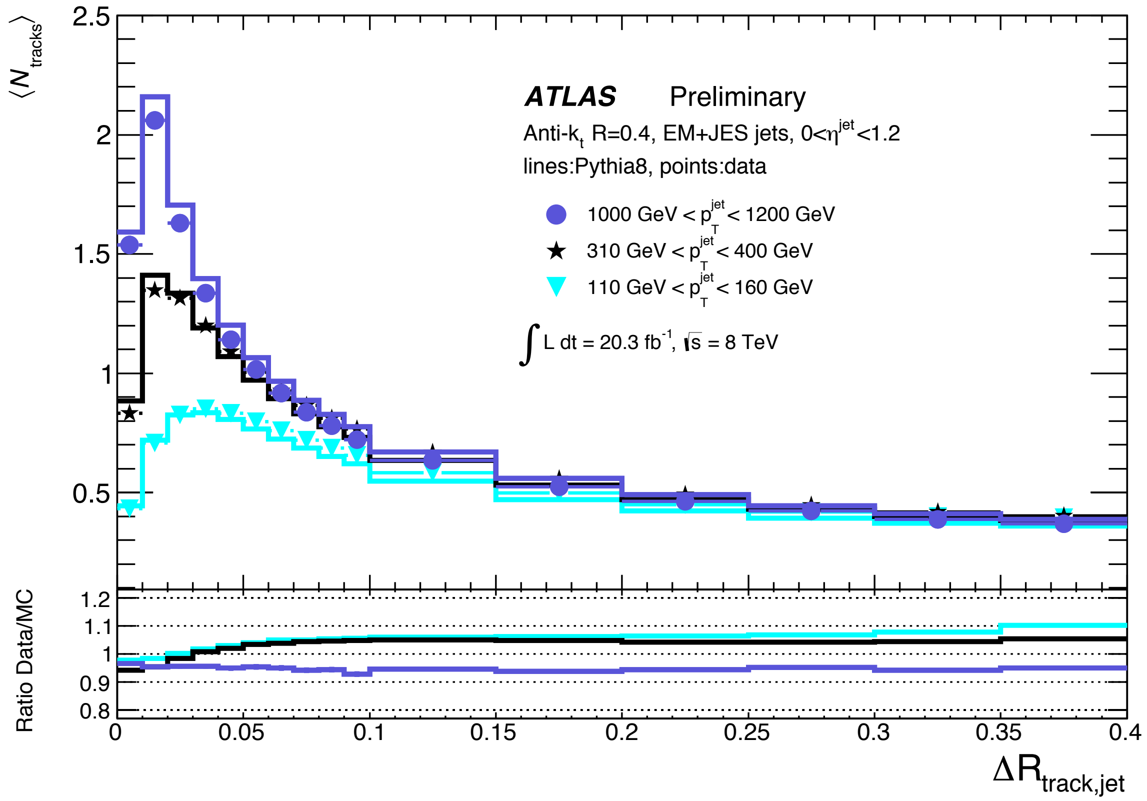

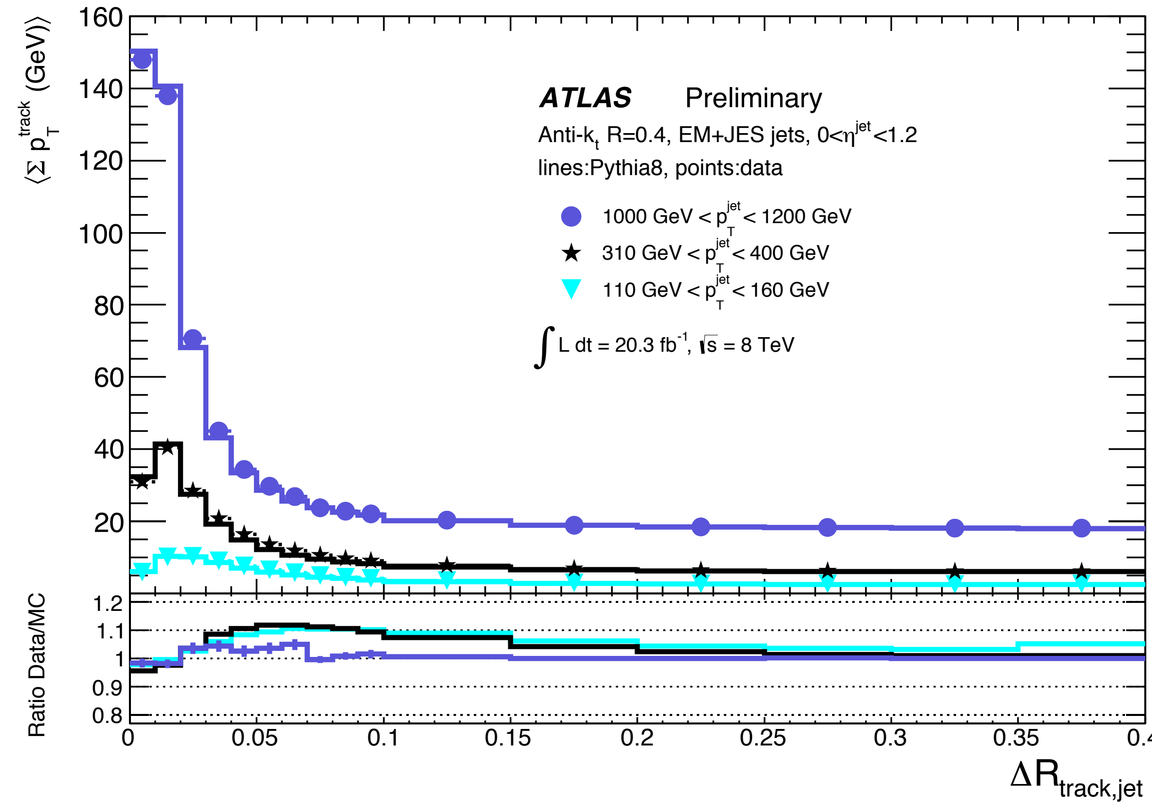

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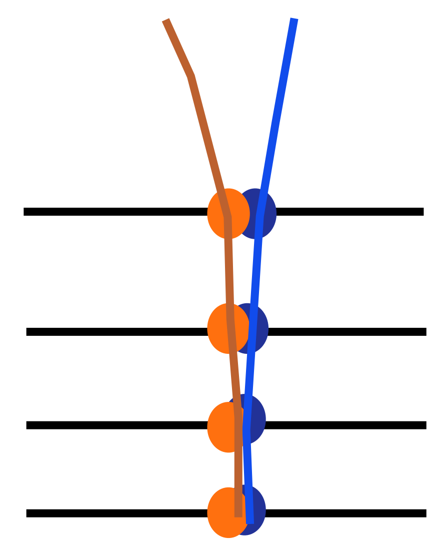
Double track resolution



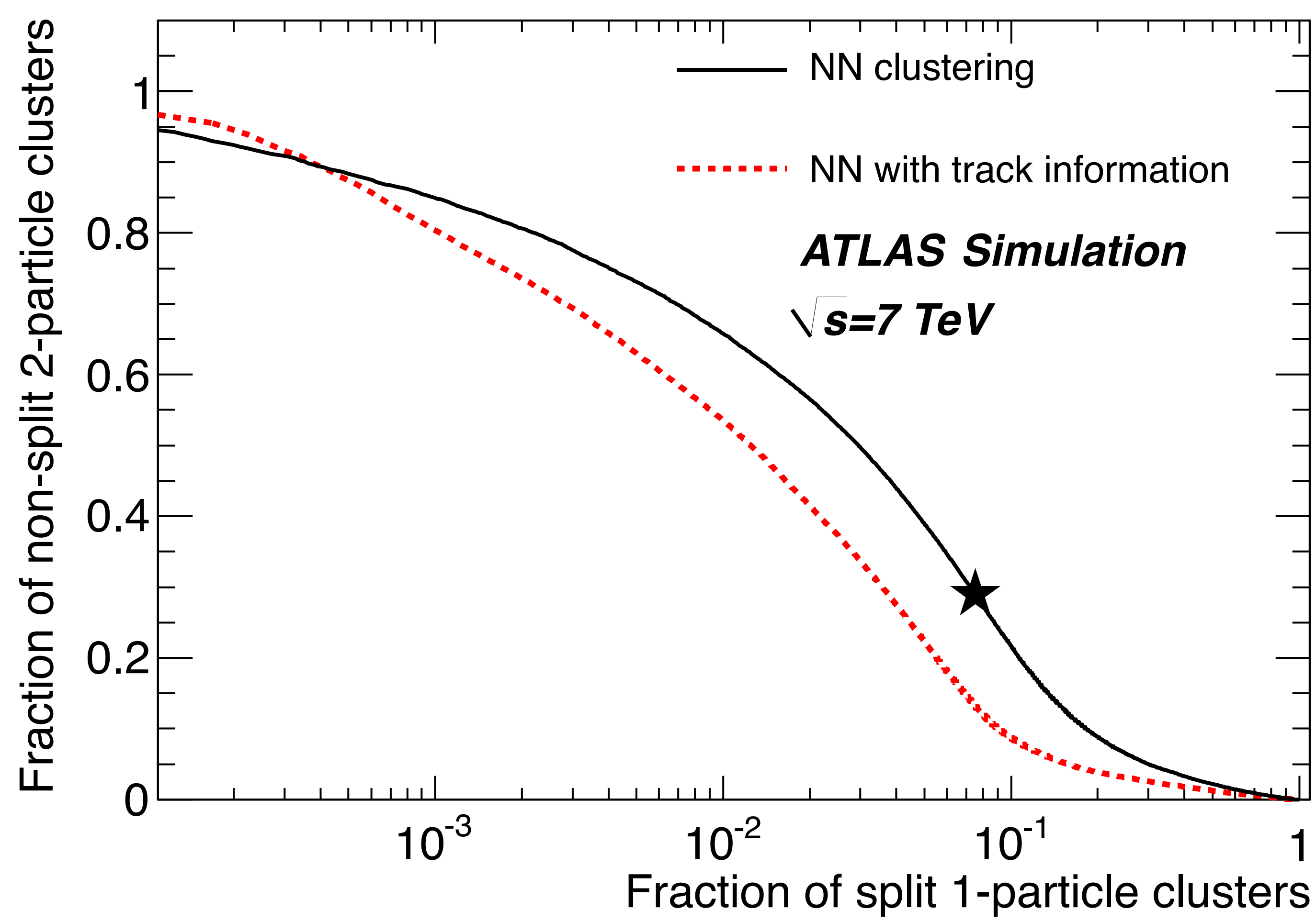
One track is reconstructed

Recovering the other can come **at the cost of fakes**

can we do better for Run II?

Neural Net Usage

- **NN can do better with a more precise track hypothesis**
- Move NN ***into*** Ambiguity Resolution stage
  - Clusters no longer “split”: idea of “shareable” introduced
- Only consider NN if cluster is used by *multiple track candidates*
- Reduces combinatorics of seed finding
  - 10% reduction in CPU time



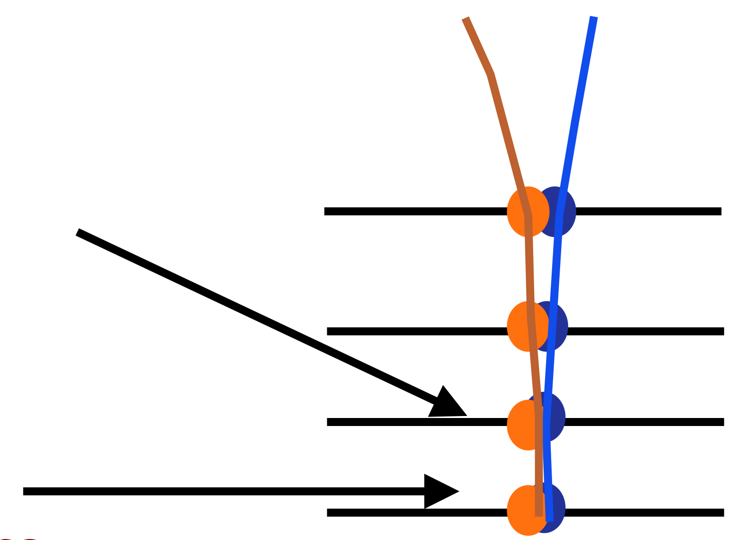
Shareable Clusters

- Cluster positions always taken from NN
- When *two tracks compete* for a cluster:
  - **NN > cut**: cluster is shareable consider additional position estimates
  - **NN < cut**: penalize both tracks for sharing a cluster
- *Implement physics knowledge*: correlate information on successive layers
  - only is clusters on both layers used on the same two tracks
  - recover NN inefficiencies

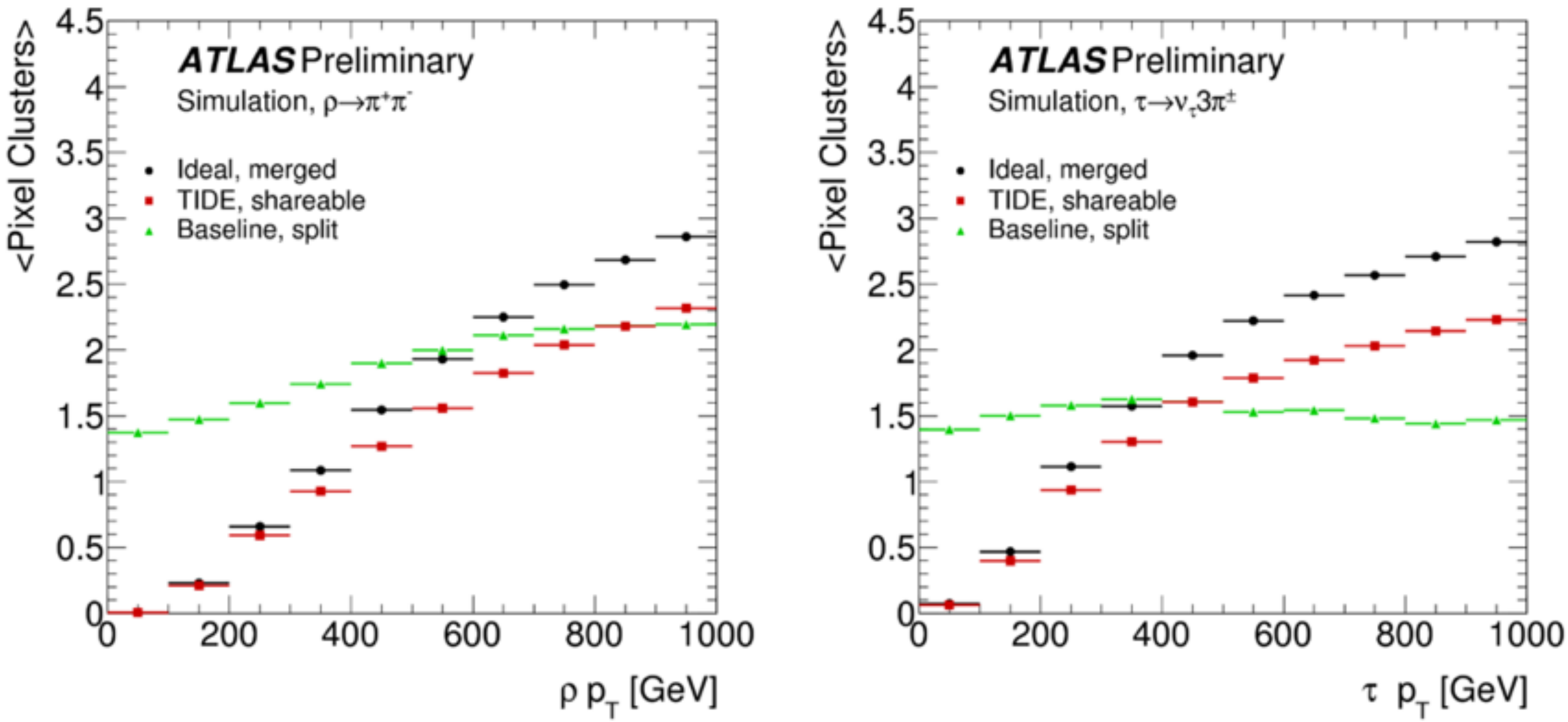
satisfies NN **shareable** condition

fails NN **shareable** condition

treat as sharable as *likely* NN inefficiency



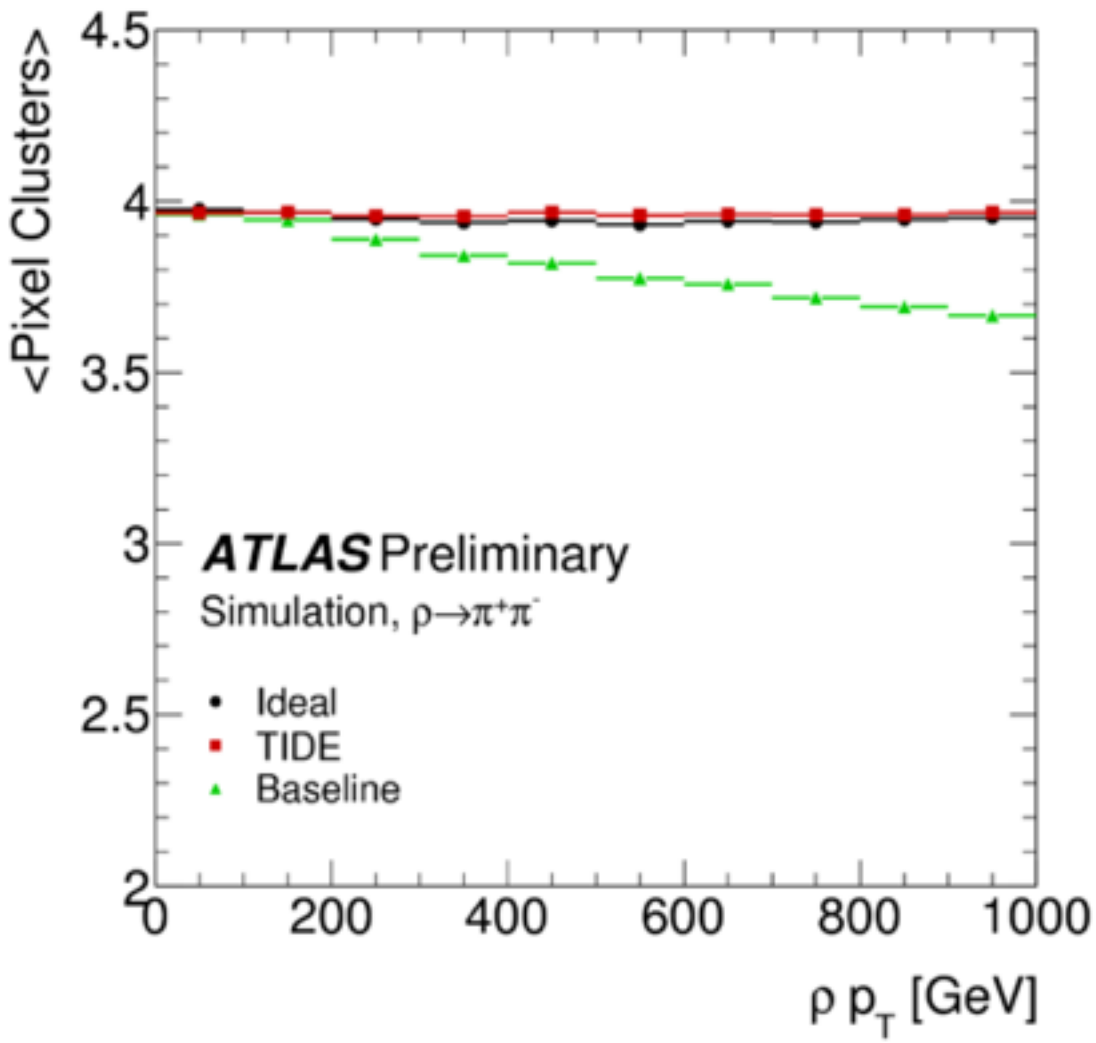
What is the Effect?



$\rho \to \pi^- \pi^+$ $\quad\quad$ $\tau \to \nu_\tau \pi^- \pi^- \pi^+$

Shareable hits follow trends of **merged** hits

What is the Effect?



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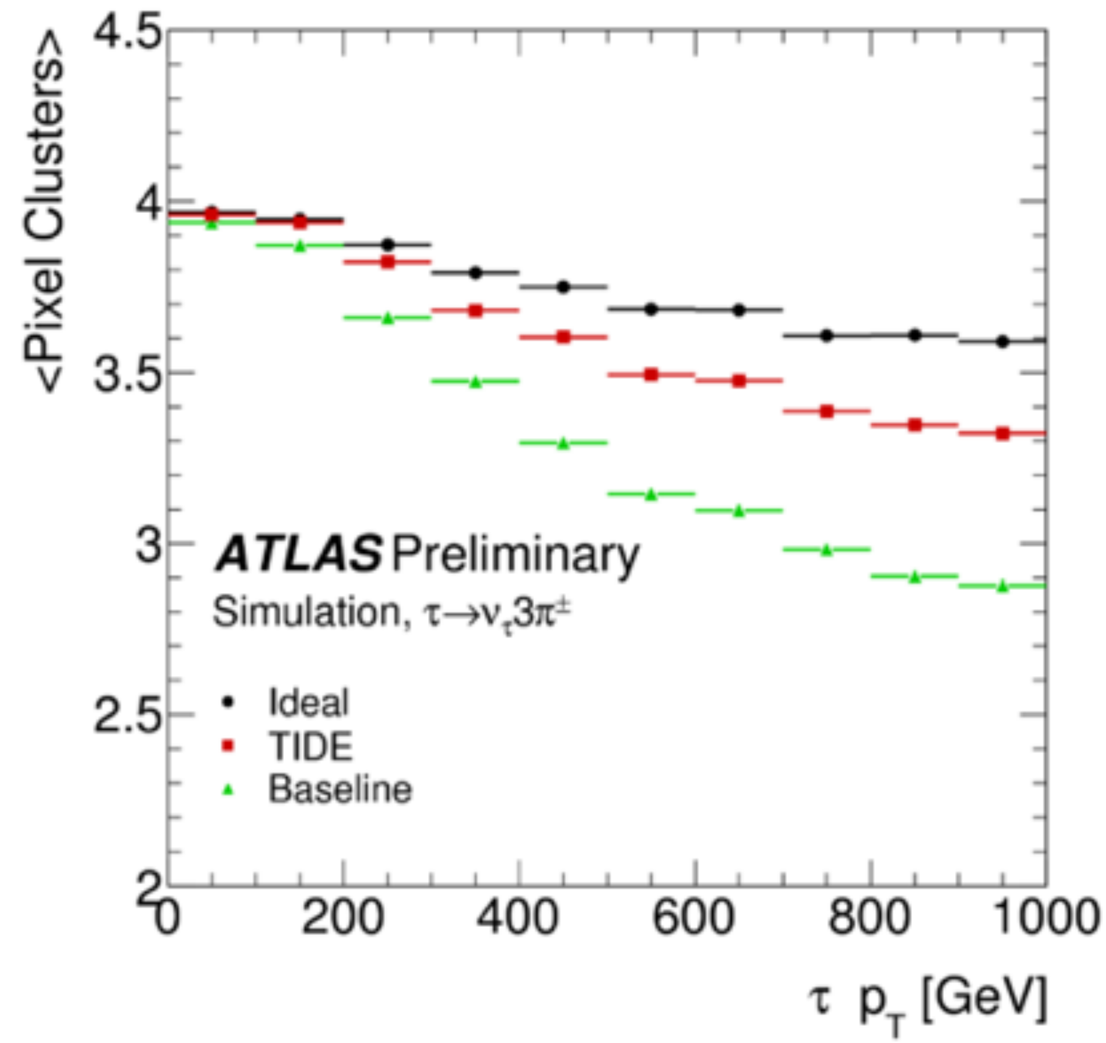

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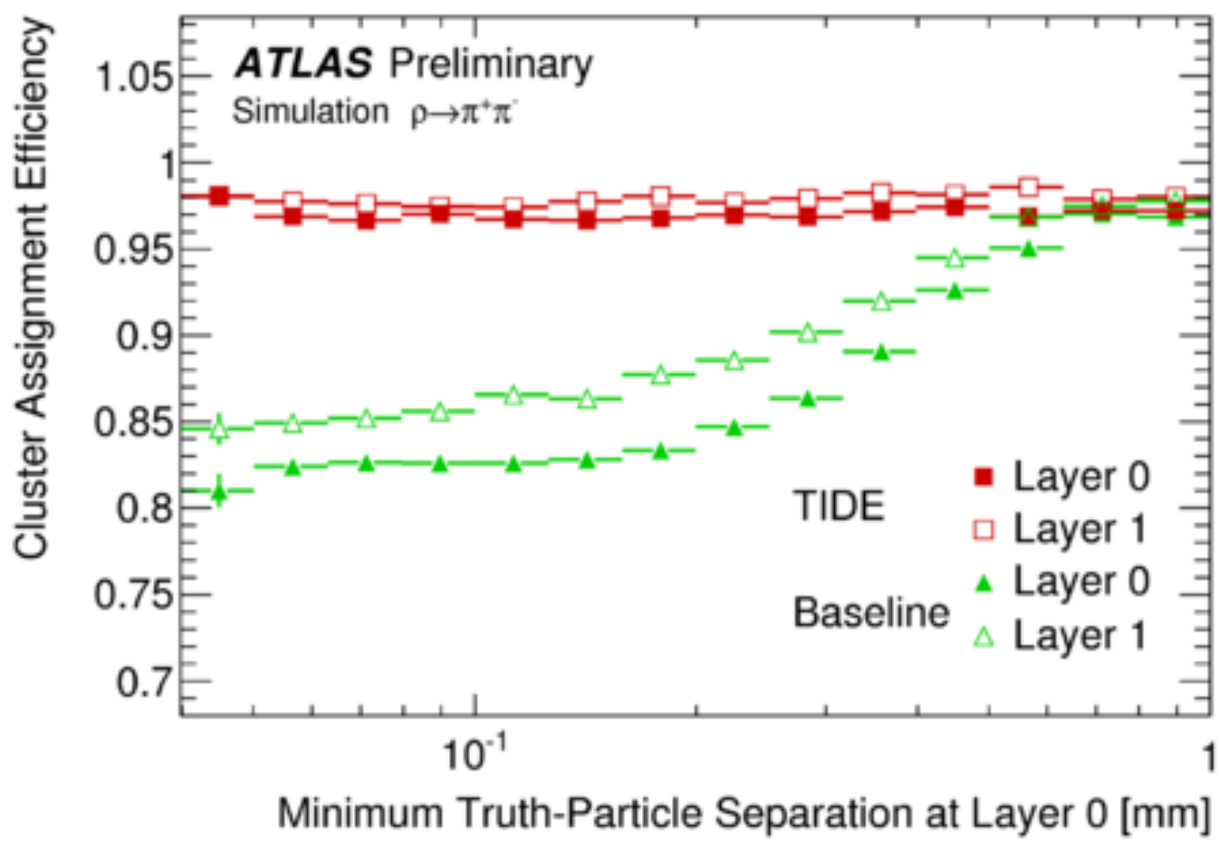
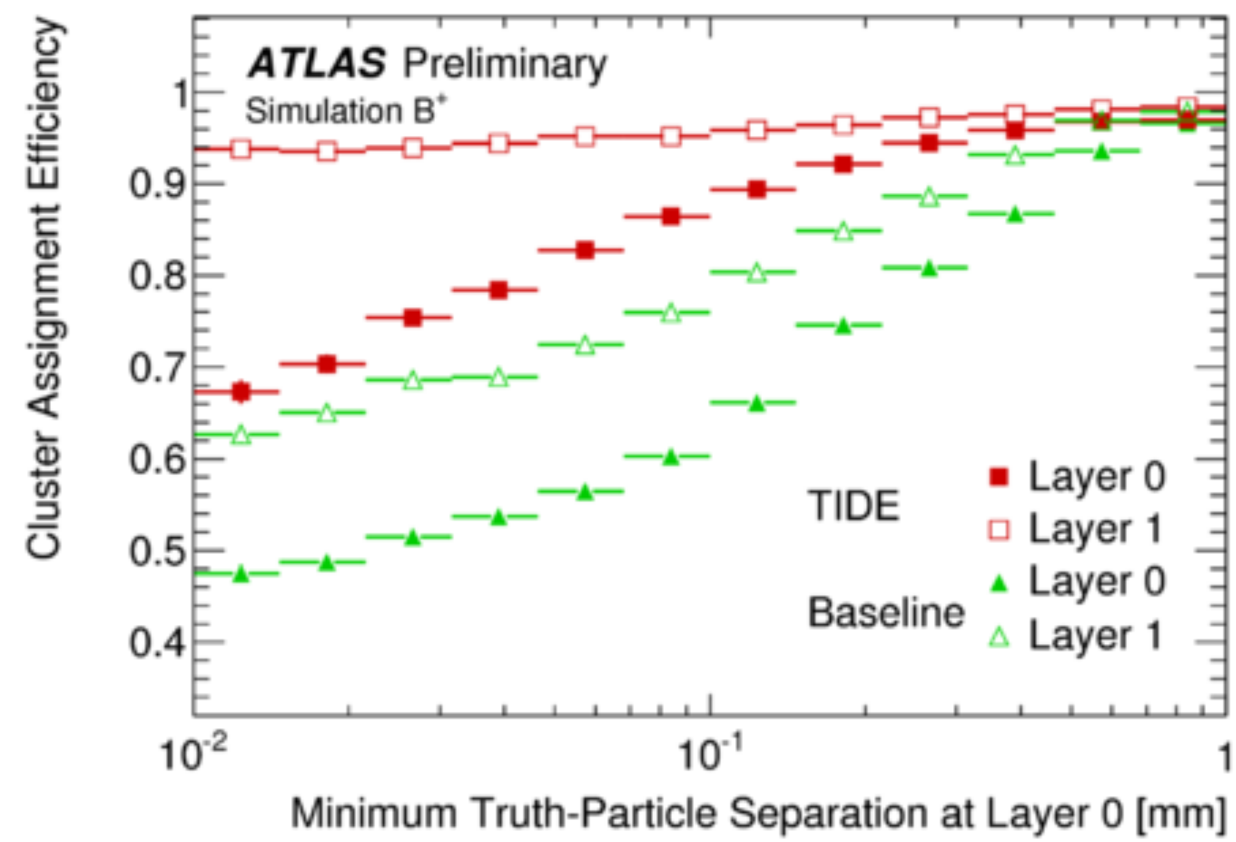
Better hit assignment efficiency

Remaining inefficiencies driven by 3 particle clusters

What is the Effect?





$\rho \rightarrow \pi^- \pi^+$

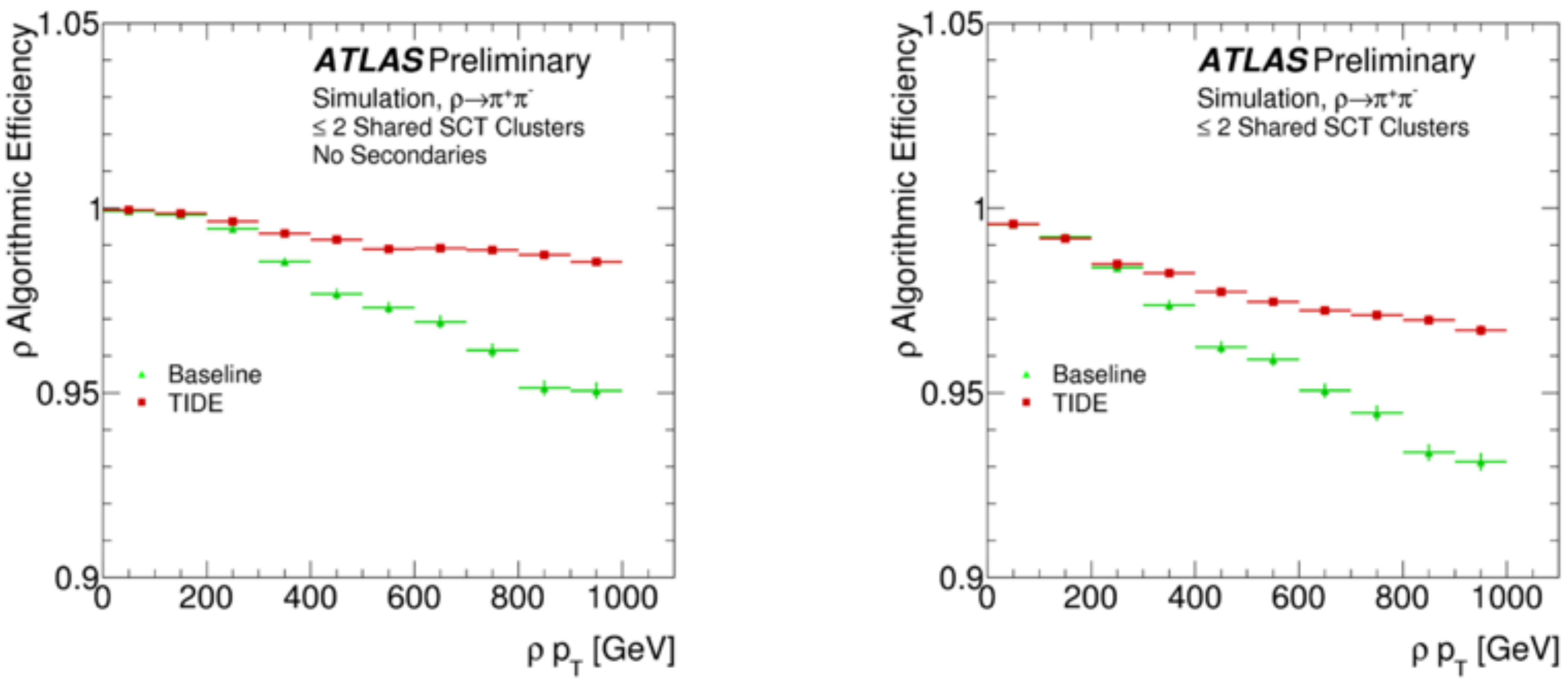
B+

Better hit assignment efficiency

At smallest separations ~40% more IBL hits on tracks in B^+ decays

Limits on Efficiency

- Large Efficiency improvement!
  - Limited by confusion in seed finding or wrong decision in ambiguity resolution
  - enhanced in **busy** environments i.e **hadronic interactions**
- Maximum number of **shared** clusters allowed on track: 2
  - **SCT** information is binary - no charge measurement available



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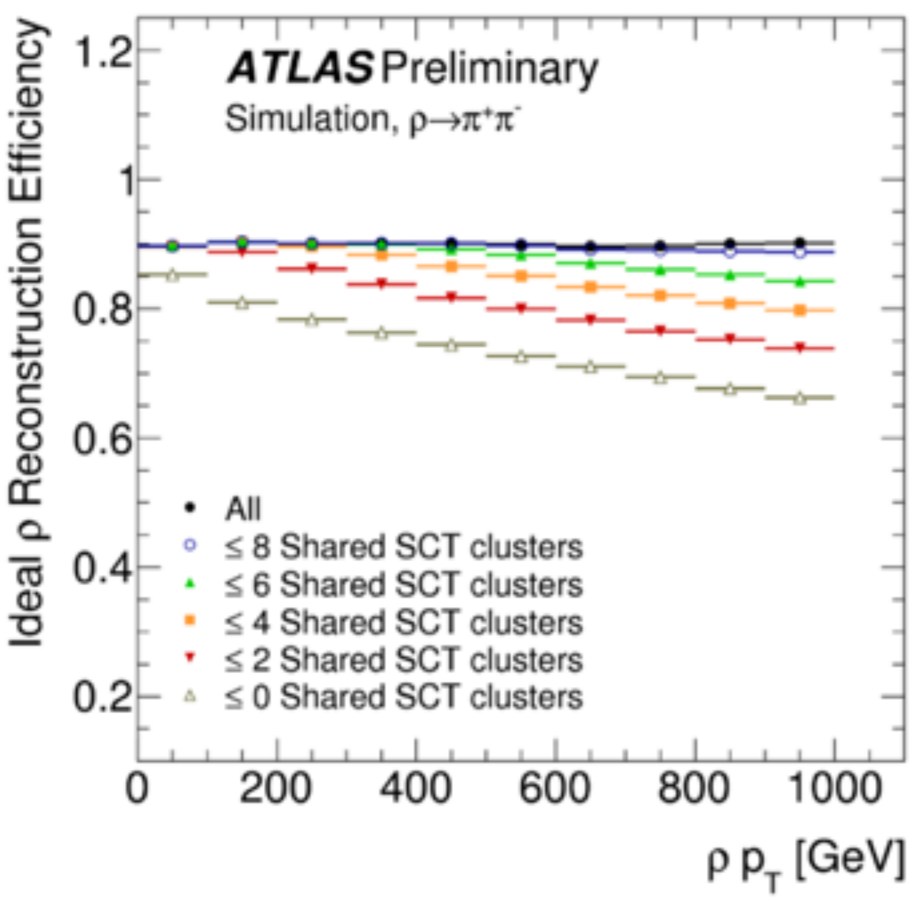

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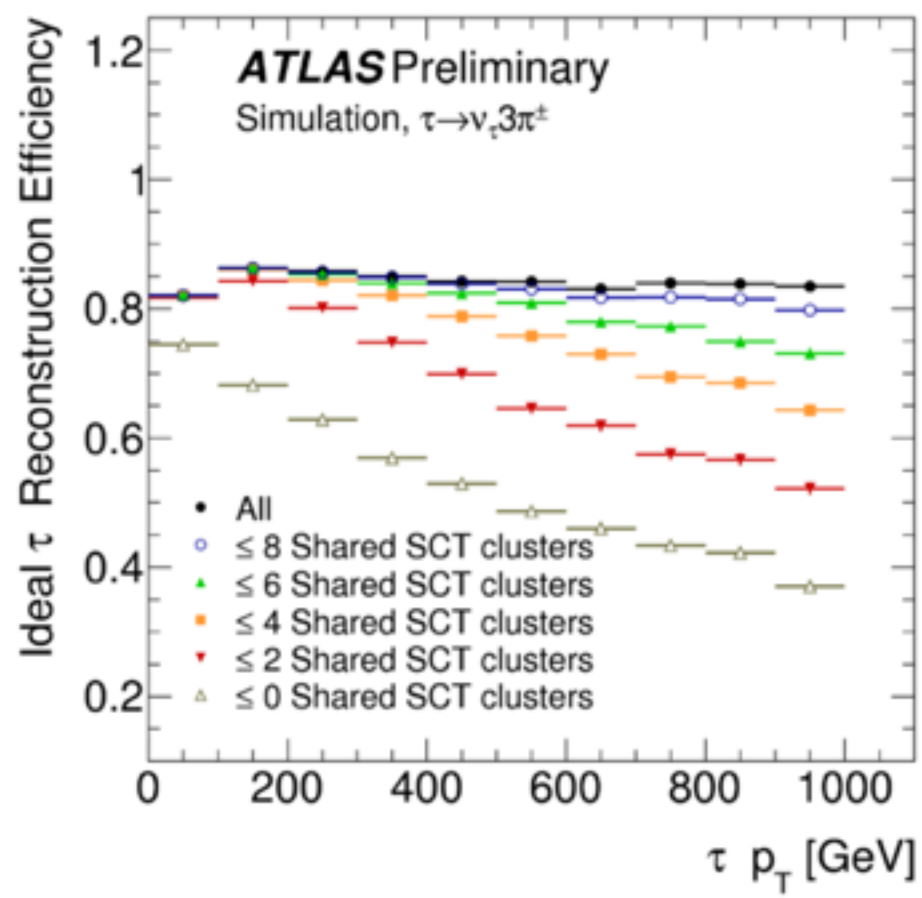
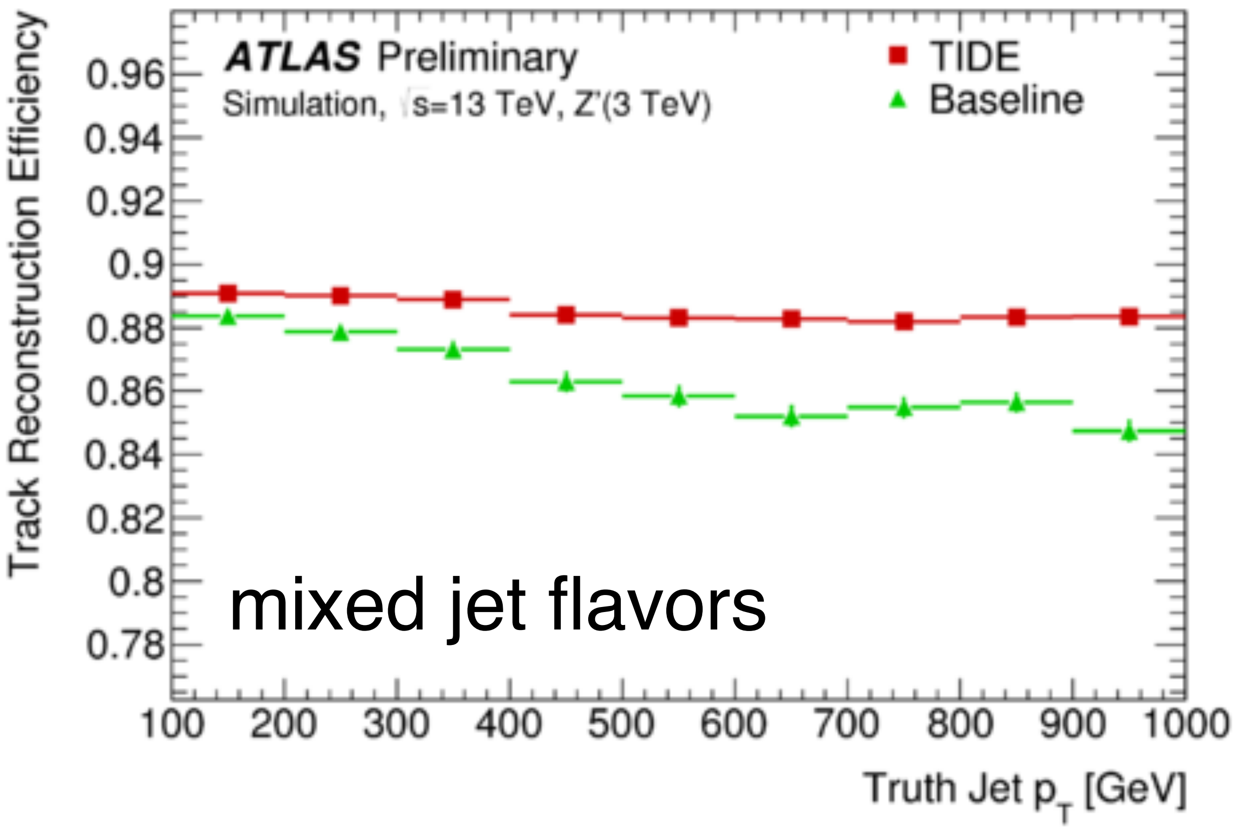
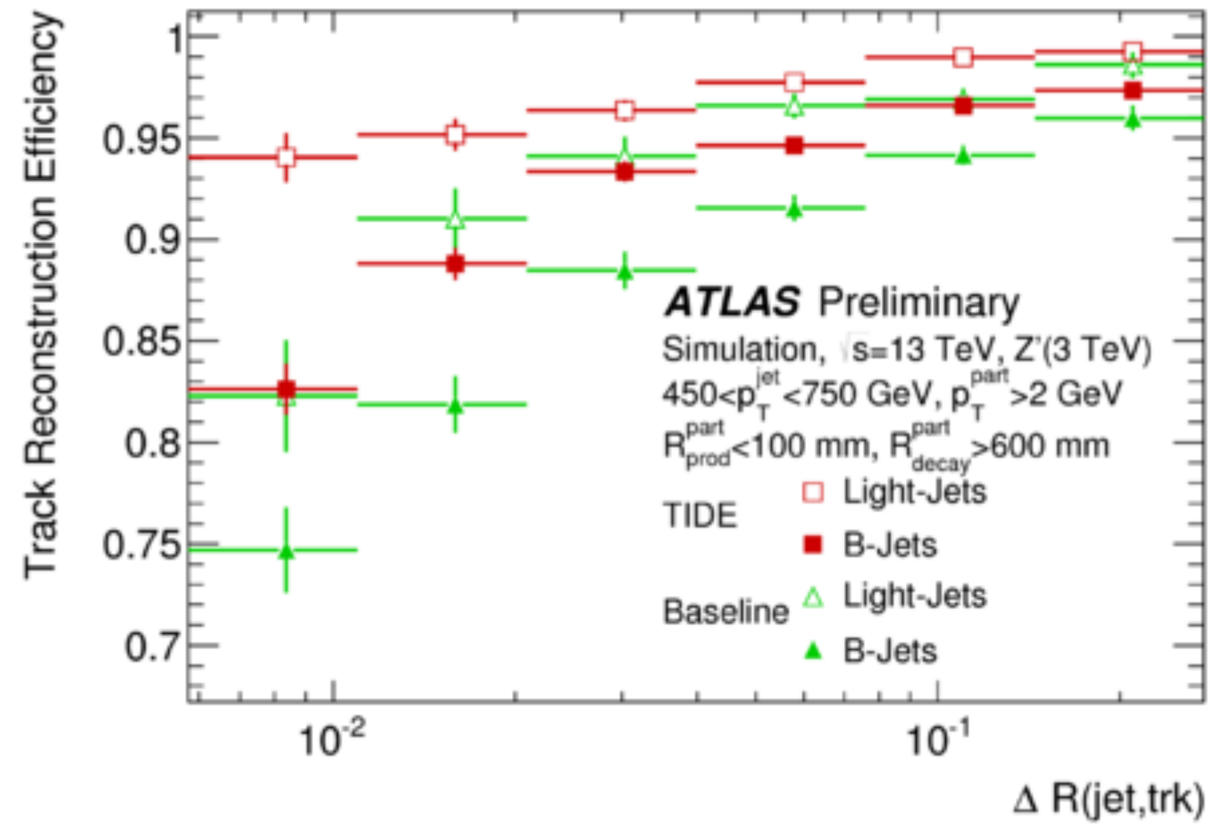


$\tau \rightarrow \nu_\tau \pi^- \pi^- \pi^+$

Jets!

- Improved tracking efficiency translates to **busy**, **dense jet environments**

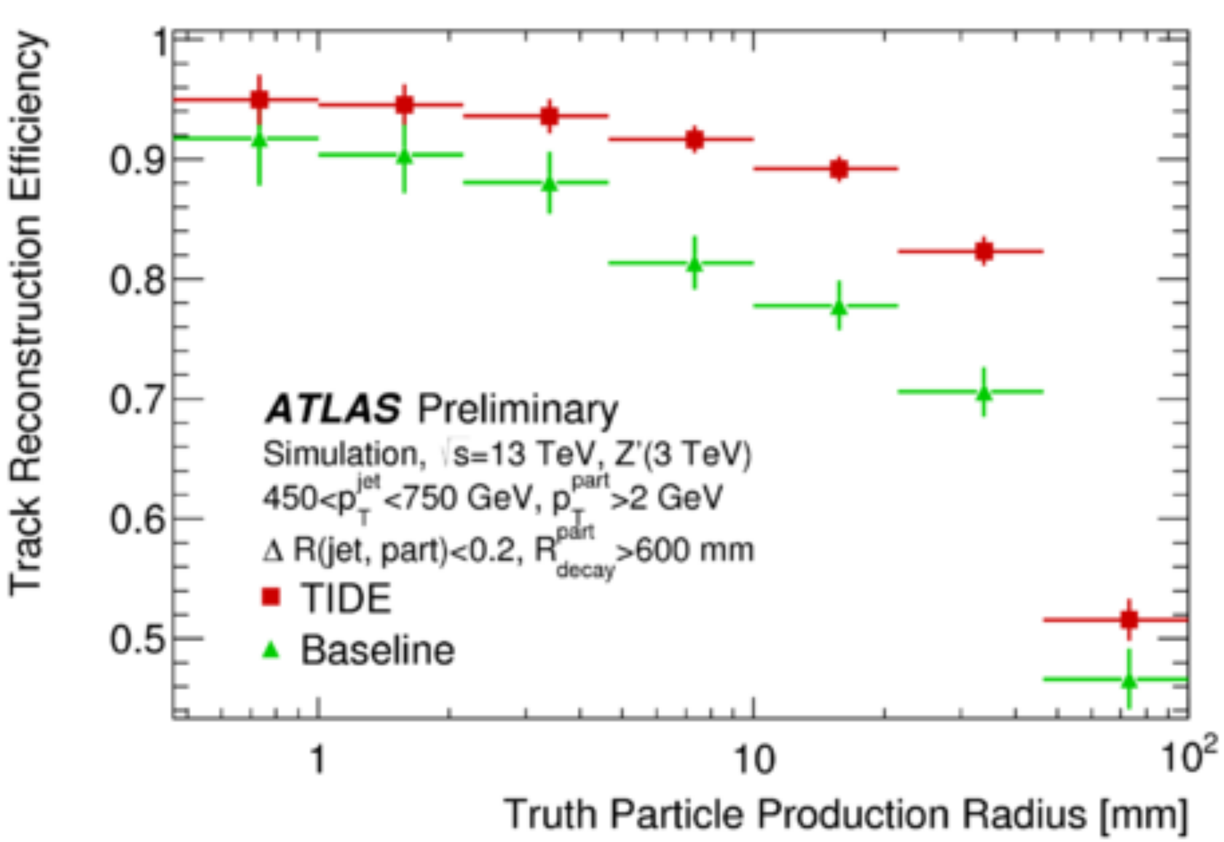


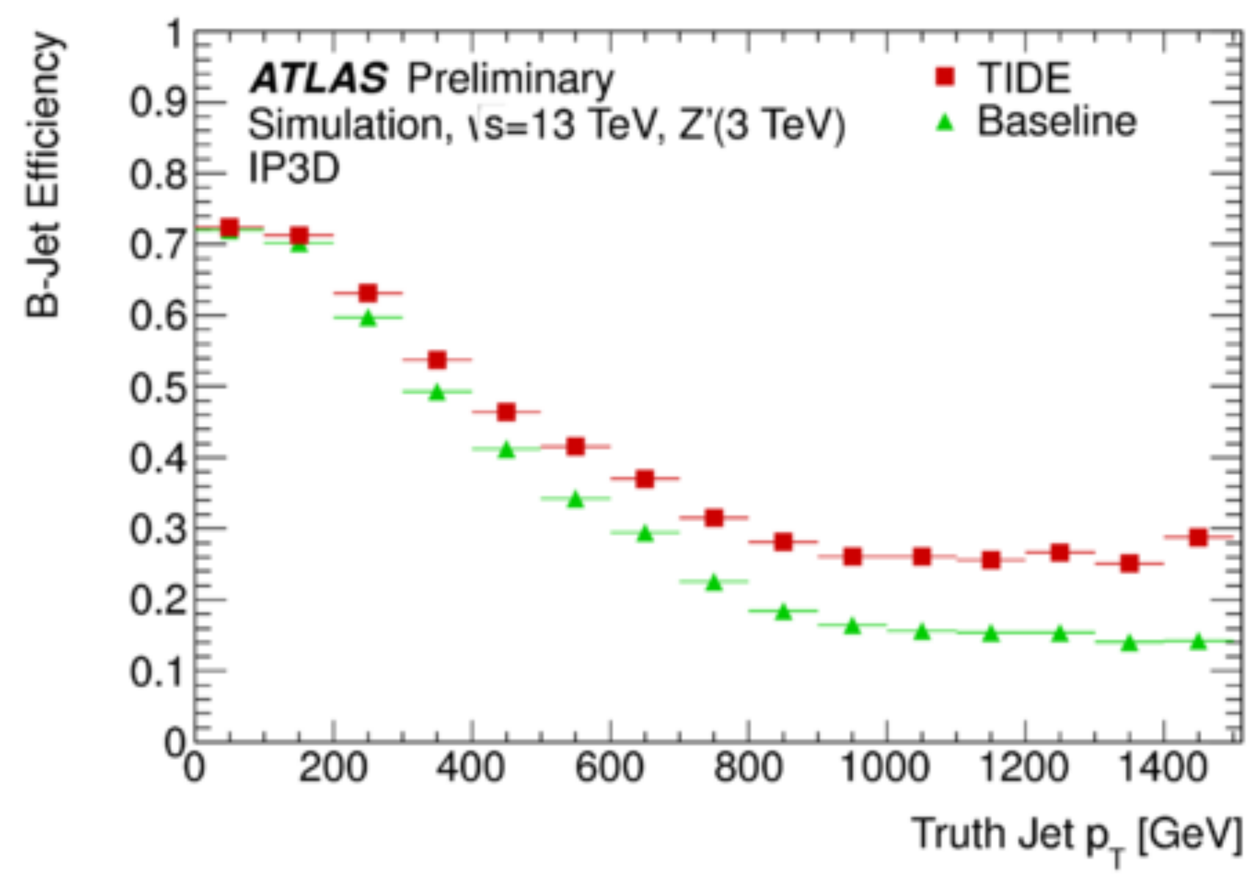


- Inefficiency in b-jets from:
  - displaced decays
  - higher multiplicity of particles contributing to a cluster

B-Jet Identification

- Main improvement in impact parameter tagger
  - Driven by improved efficiency for displaced tracks
- Factor of 2 at pT ~ 1 TeV for IP3D tagger
- Identification algorithms not optimized for the new tracking setup (in these plots)





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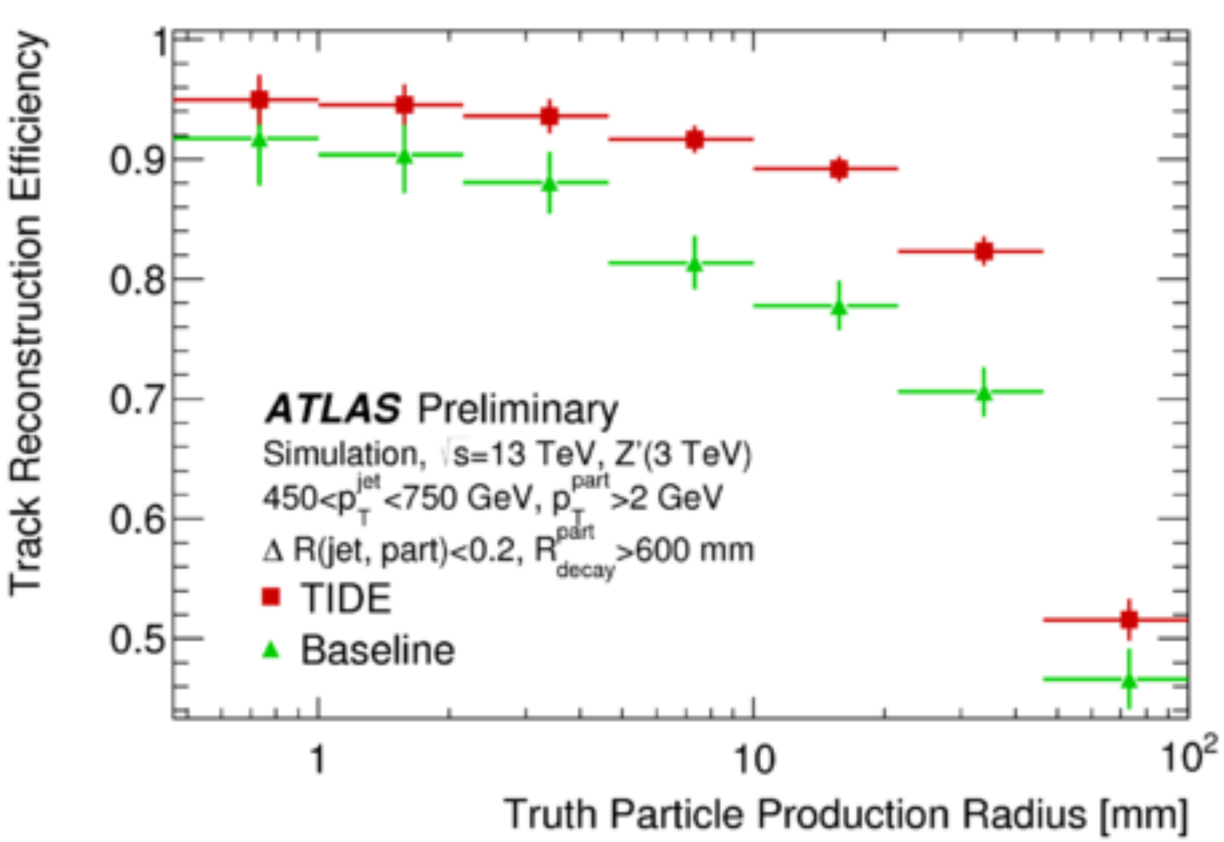
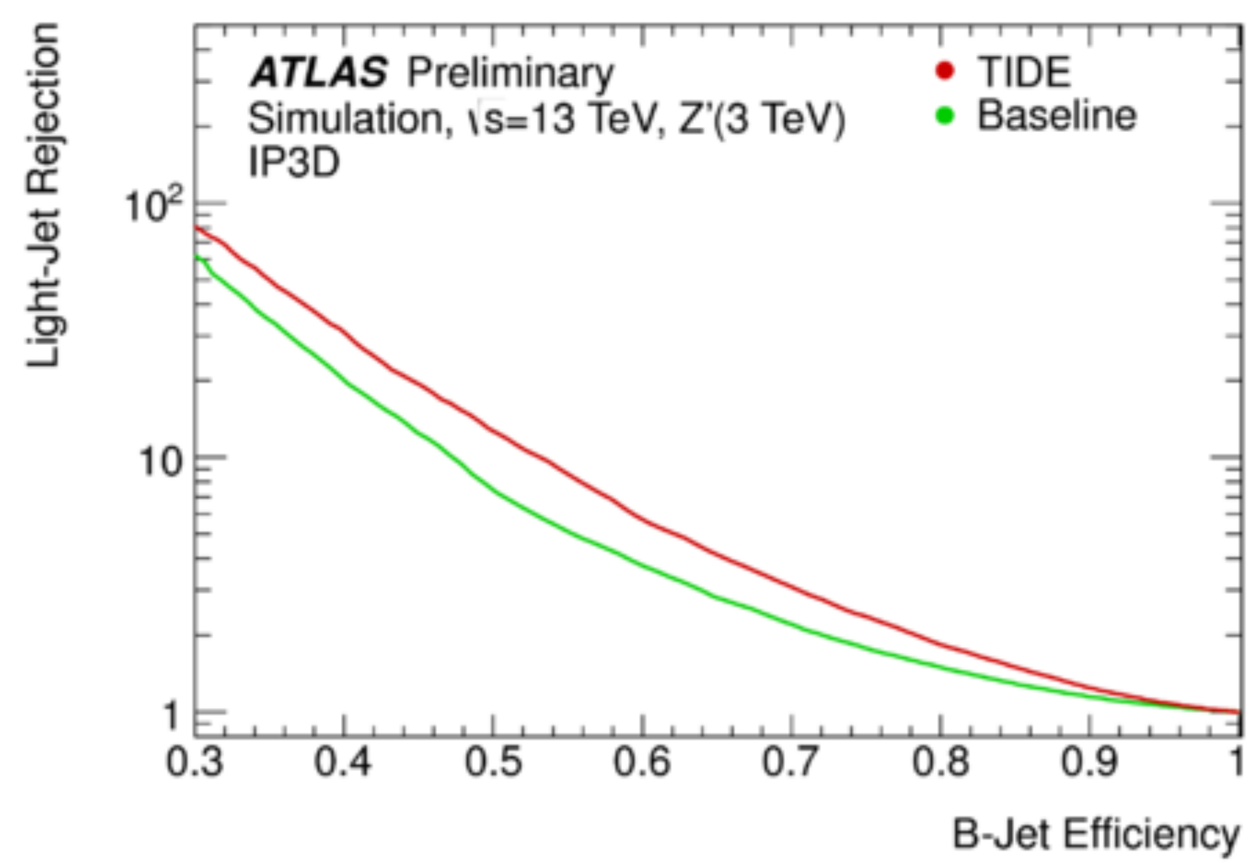




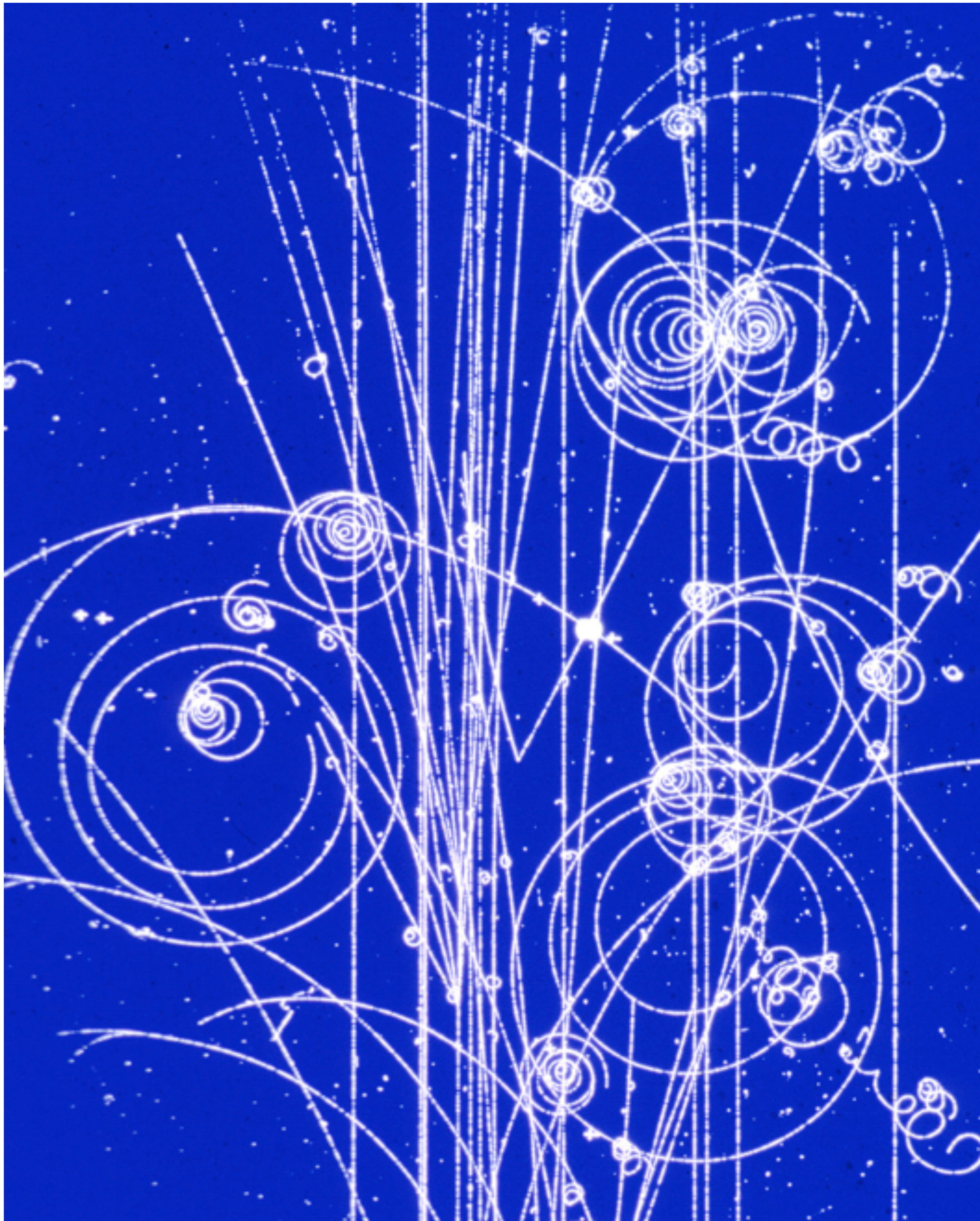
Conclusion

- Exciting prospects for new physics searches of heavy resonances
- Tracking in dense environments *has been improved* for Run II
- **Philosophy: Delay decision making to use all information**
  - Moved decision using NN information to ambiguity resolution stage
  - Correlate information on layers
  - Introduce notion of shareable clusters
- Remaining limitations:
  - Shared SCT hits - more information please!
  - Clusters with many contributing particles
- **Better hit efficiency, reconstruction efficiency, tau and b-tagging performance**

Bonus

Track reconstruction

- The ATLAS track reconstruction strategy is to reject bad candidates quickly to avoid combinatorial overhead
  - early rejection requires strategic candidate processing and hit removal
- Currently it is not a parallel approach, it is a sequential approach
- A new strategy would be required to maintain reproducibility and get good parallel performance
- The current strategy has decent scaling with pileup (factor 6-8 for 4 times pileup)



Gabriel Facini

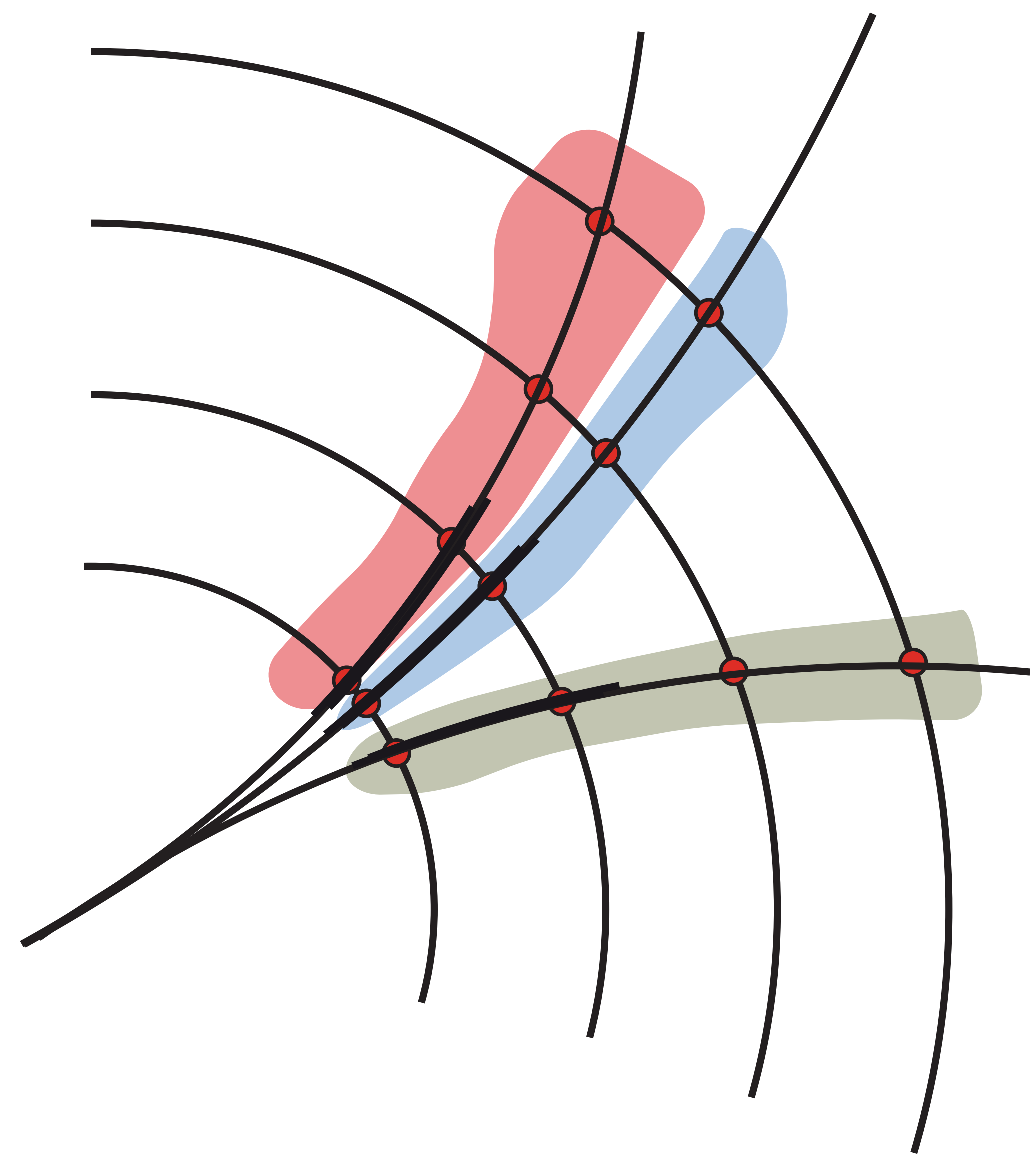
Aims for Run 2

- Unlike Run-1, our computing resources will be limited
- Track reconstruction is the single largest consumer of resource
- Target 1kHz throughput at Tier 0
  - requires a 3x speed up of the current software
- Strategy for the track reconstruction
  - Focus on improving what we have.
    - Fundamental changes to the track reconstruction strategy are not required at this stage
  - Making better use of current computing infrastructure/technology
  - Targeted reconstruction
- Focus here on preparation of tracking with 40 interactions per bunch crossing

Seeding Strategy Updates

- Build a seed from 3 hits
  - search using conformal transform
- Build a road along the likely trajectory to collect all modules in the path
- Run combinatorial Kalman Filter for a seed
  - Exploration of all possible candidates
  - update trajectory with hits at each layer
  - Basic material effects are taking in to account
- Iterative seeding approach (Run-1)
  - seeds are worked on in an ordered list
  - start with 3 Pixels, 2 Pixel+Strip, 3 Strips
- bookkeeping layer:
  - hits from good track candidates removed
  - build next seed ONLY from left over hits
  - sequential seed finding to avoid combinatorial explosion
- Tracks are found for one-after-the-other
  - The ordering matters !!!

Run 1 Strategy



Seeding Strategy Updates

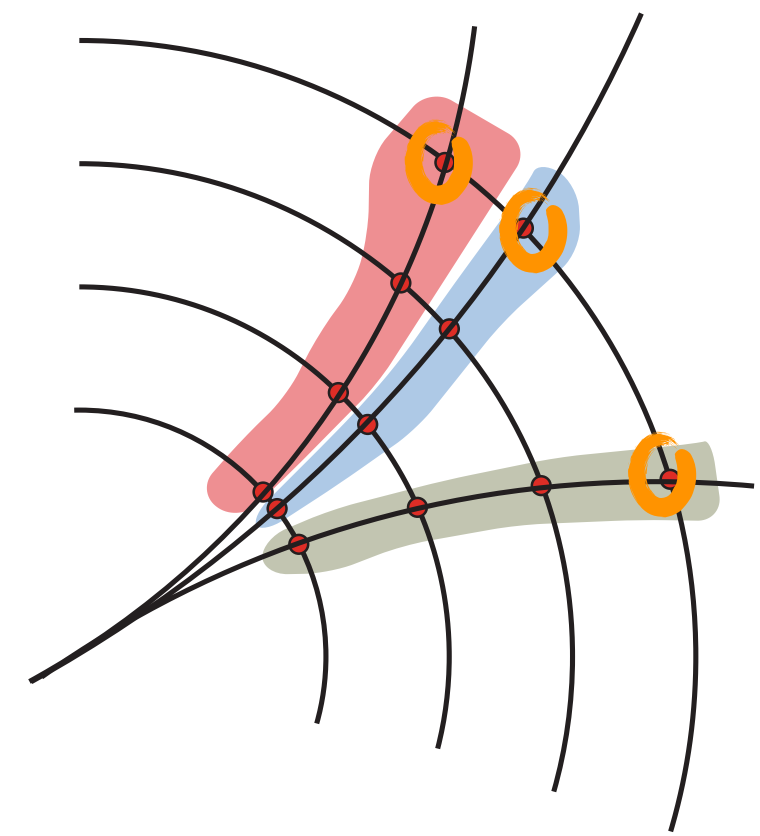
As the order of the seeds matter it is worth while looking at them in some detail

- efficiency of a seed to give a good track candidate:

pileup	PPP	PPS	PSS	SSS
0	57%	26%	29%	66%
40	17%	6%	5%	35%

  - further increase seed efficiency using 4th hit

pileup	PPP+1	PPS+1	PSS+1	SSS+1
0	79%	53%	52%	86%
40	39%	8%	16%	70%

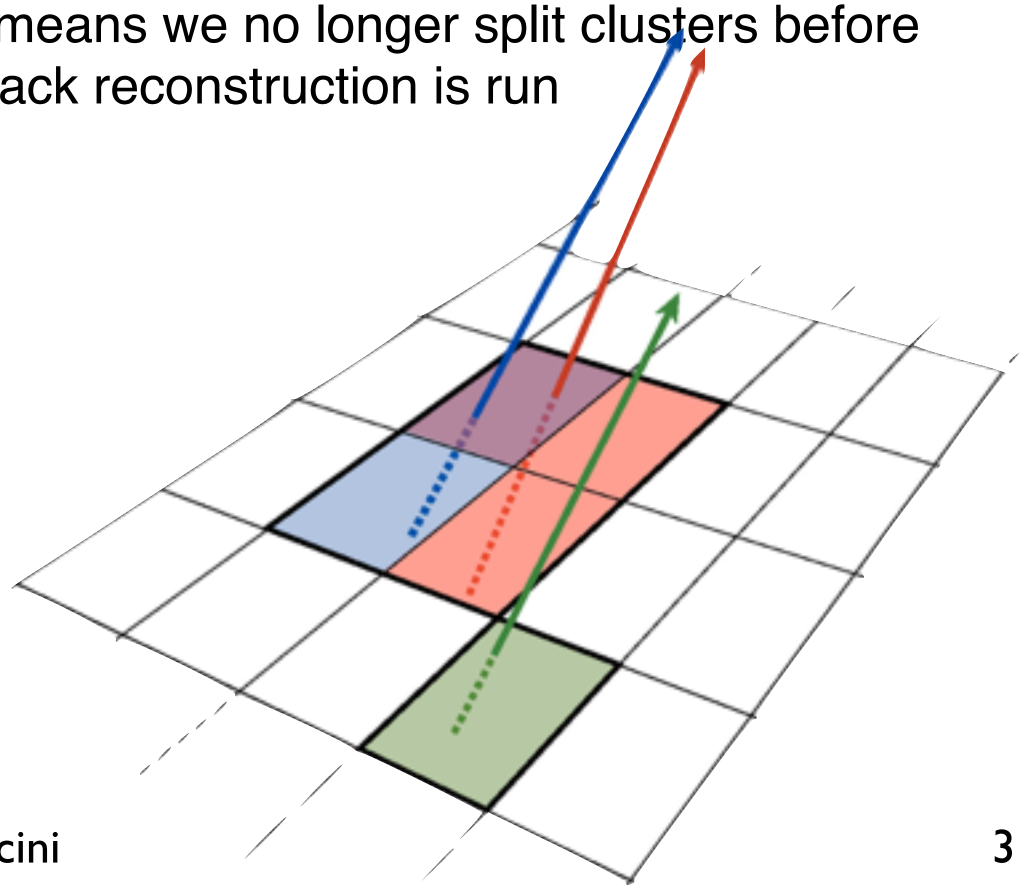


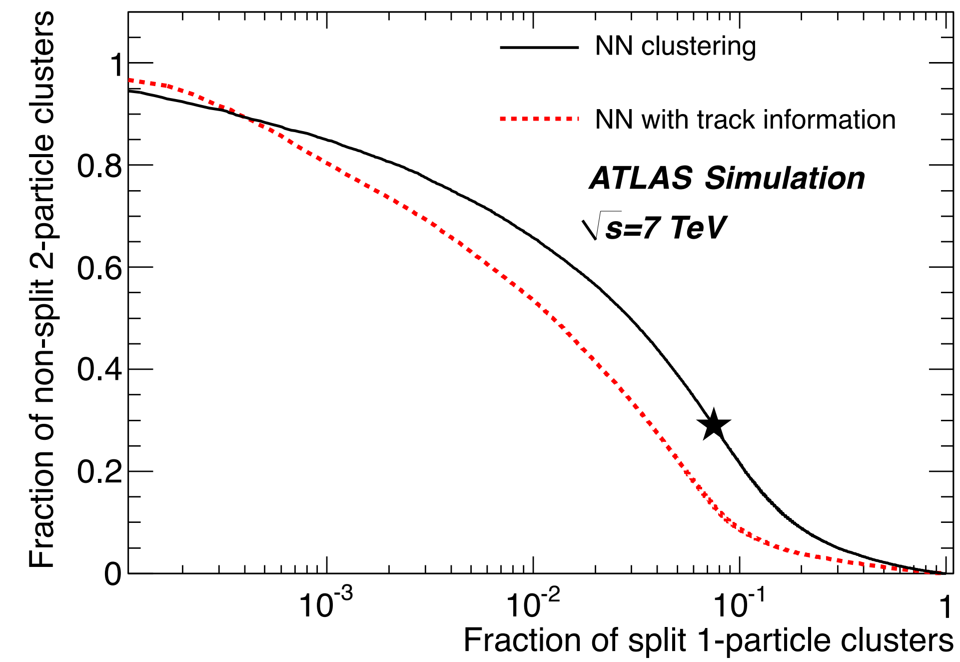
Make the most of the IBL

- final Run-2 seeding strategy
  - start with SSS+1
  - continue with PPP+1, PPS+1, PSS+1

Complex Environments: Jets

- The pattern recognition was found not to be the major limiting factor.
  - >80% losses are due to the ambiguity resolution
- Having knowledge of the tracks angle of incidence improves the NN's performance
  - Split later in the chain
- The new strategy is delays the decision if a cluster is to be shared or not until the ambiguity resolution.
  - This means we no longer split clusters before the track reconstruction is run





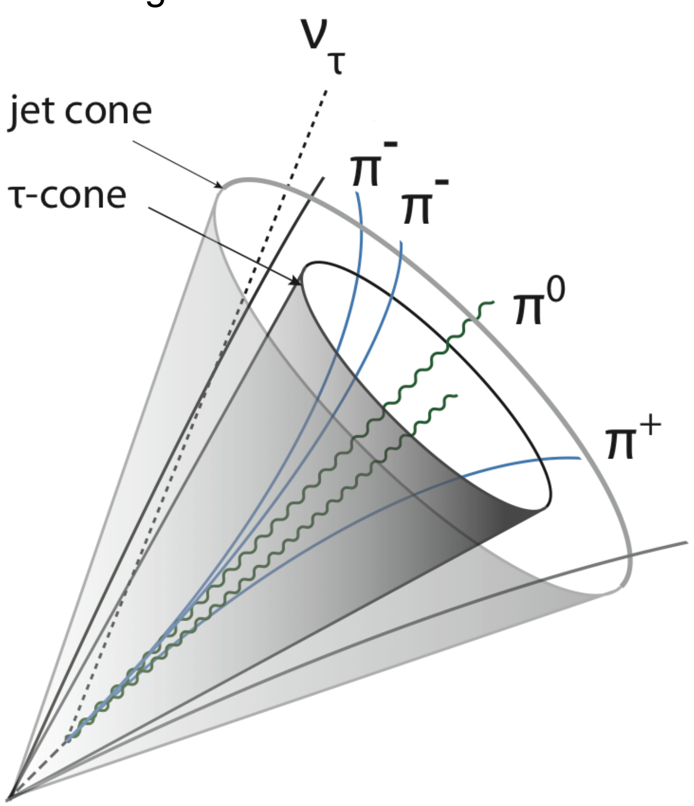
- Reduced combinatorics in the track finding stage
  - Less seeds
  - Less road searches
  - Less combinatorial Kalman filter calls
  - >10% reduction in CPU needed for this stage
- More information into the NN leads to better splitting performance
- This means we can spend a little more time in deciding what hit patterns we consider to be correct

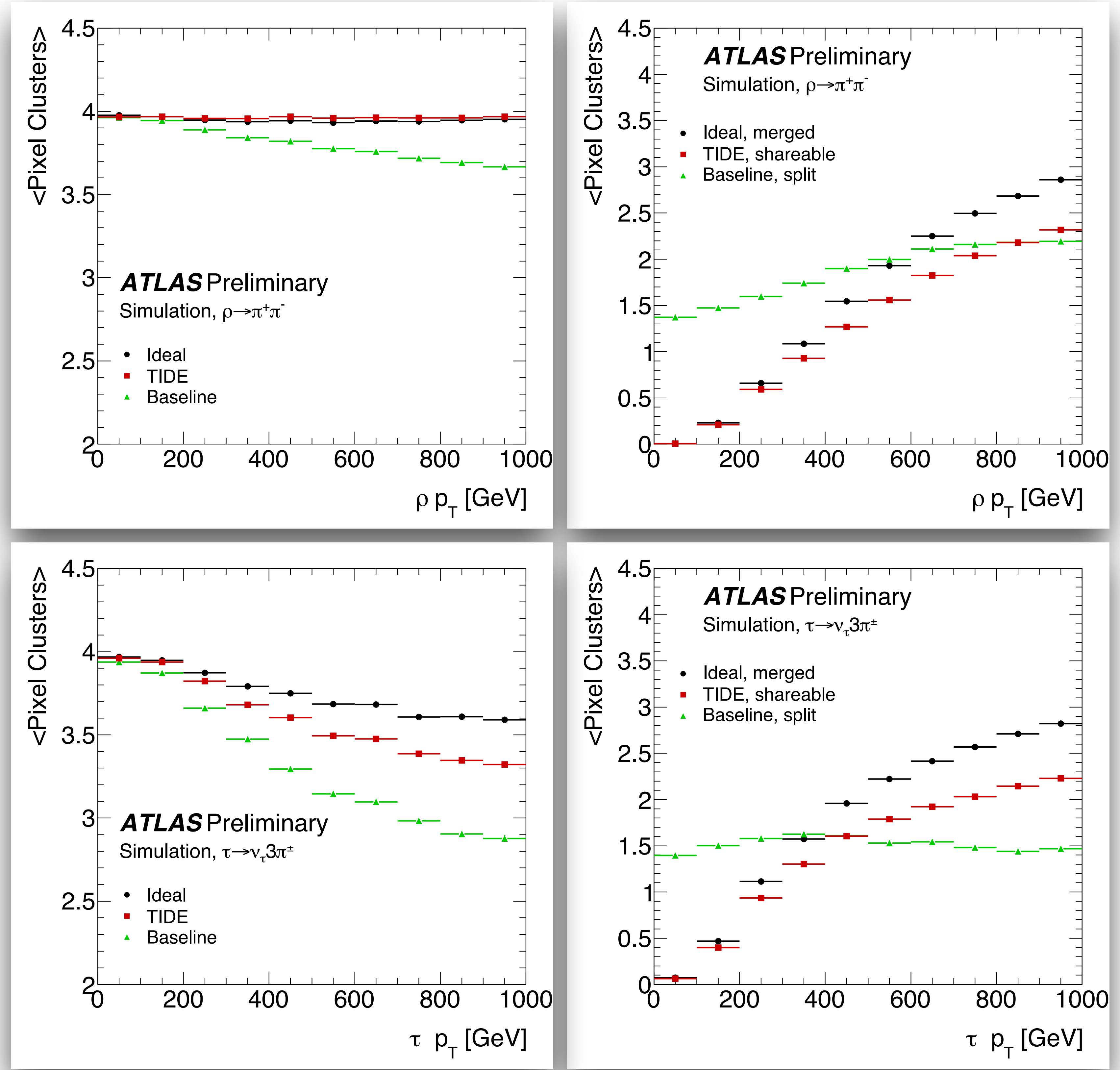
Ambiguity Updates: TIDE

- By splitting later we can control more what hits we share and what hits we do not.
- To illustrate the point look at some simplified situations

$$\rho \rightarrow \pi^- \pi^+$$
$$\tau \rightarrow \nu_\tau \pi^- \pi^- \pi^+$$

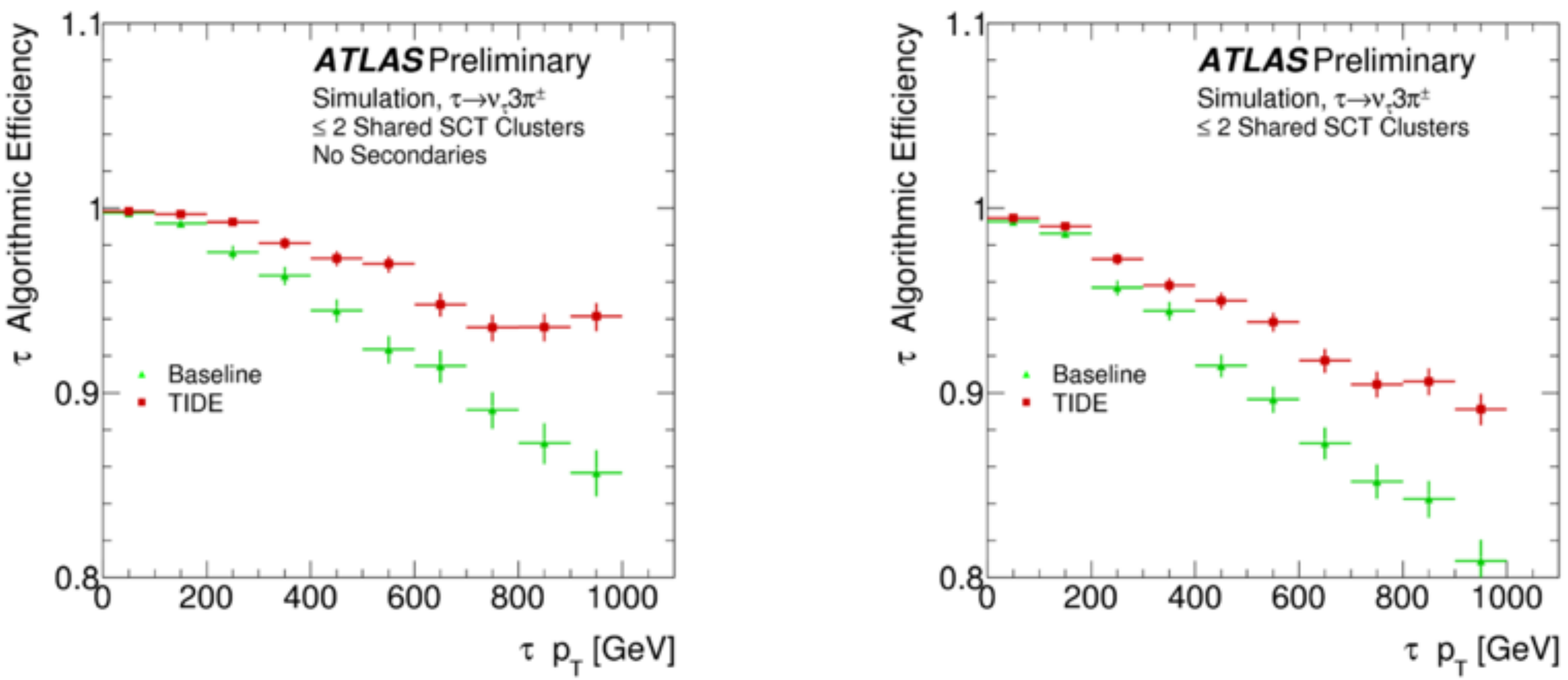
- The end results is:
  - an improved hit assignment efficiency
  - Split hits start to have some physical meaning.





Limits on Efficiency

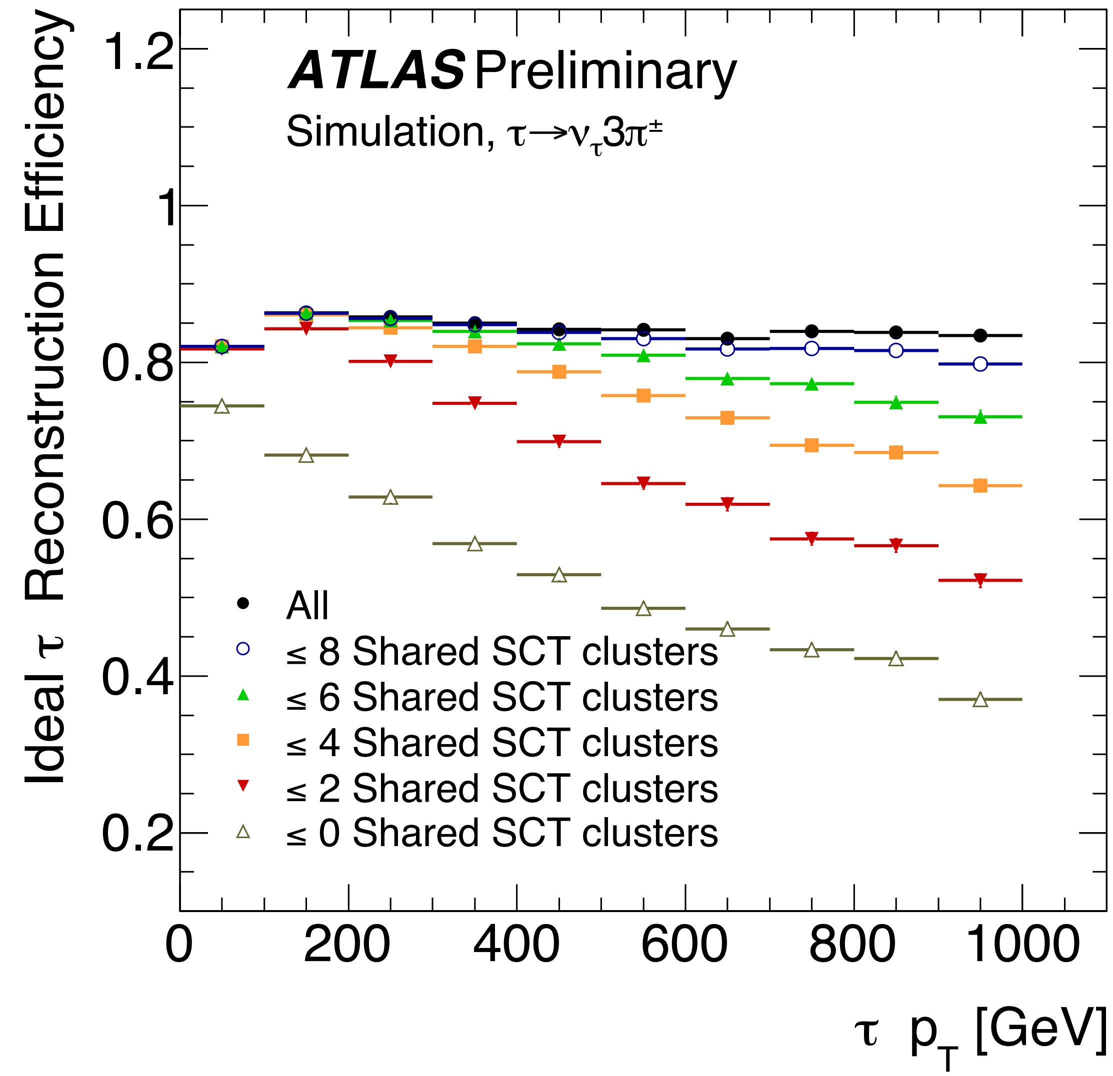
- Large Efficiency improvement!
  - Limited by confusion in seed finding or wrong decision in ambiguity resolution
  - enhanced in **busy** environments i.e **hadronic interactions**
- Maximum number of shared clusters allowed on track: 2
  - SCT information is binary - no charge measurement available

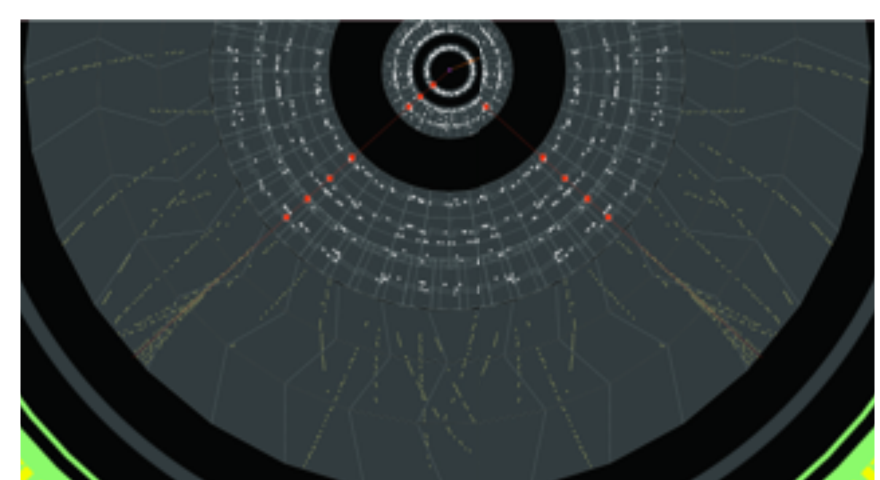


$\tau \to \nu_\tau \pi^- \pi^- \pi^+$

Limits to efficiency

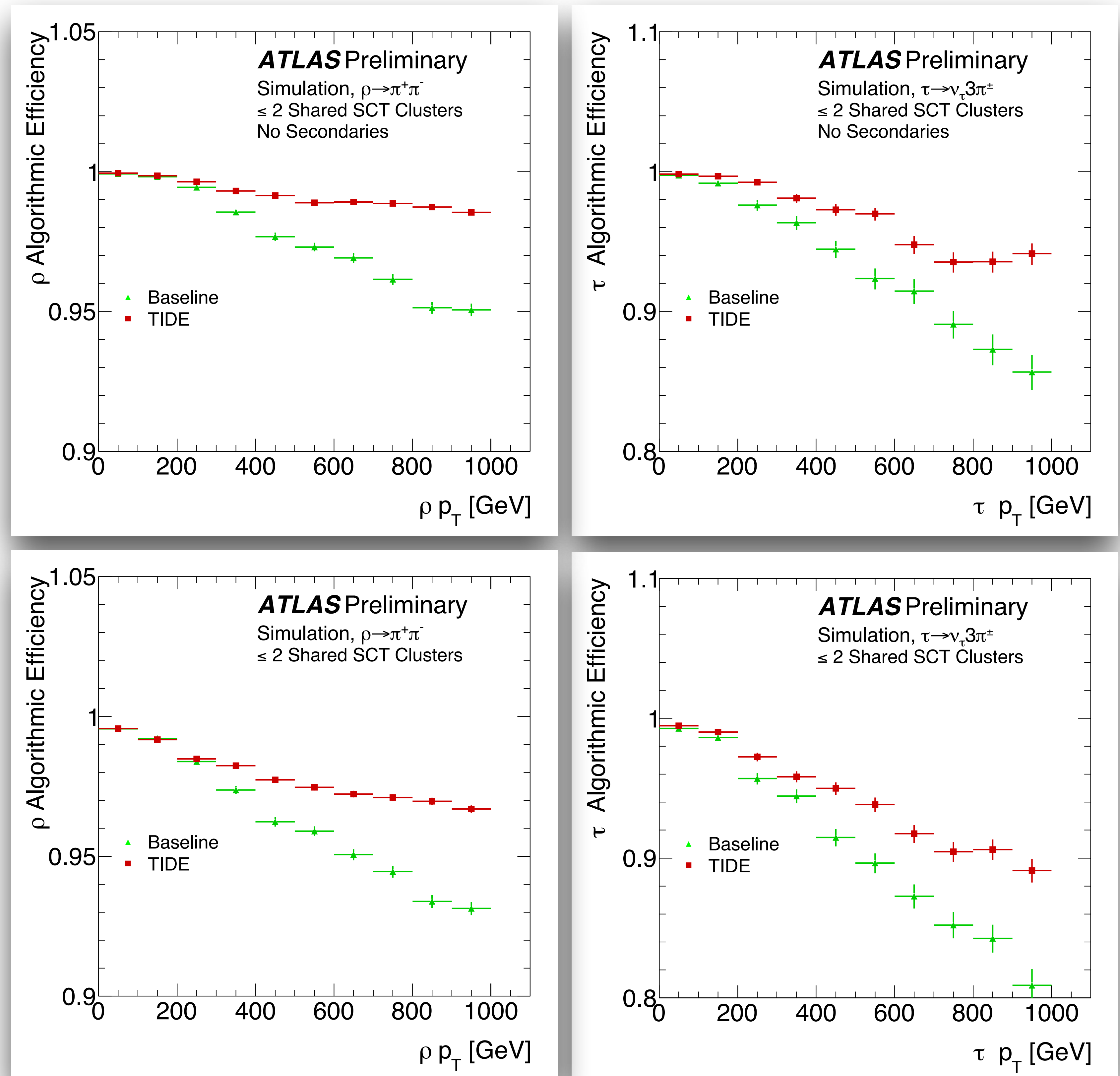
- Our reconstruction requires that there is a maximum of 2 shared hits on the track
- In truth the pixels are not the limiting factor
  - They can to provide a measurement of the charge and hence indicate if multiple particles passed through the cluster.
- SCT is treated as a purely binary output and we can not determine much about
  - Cluster size is the only useful measurement and that is only useful in 1D
- If we really want to improve the track reconstruction in these dense complicated environments we need more information



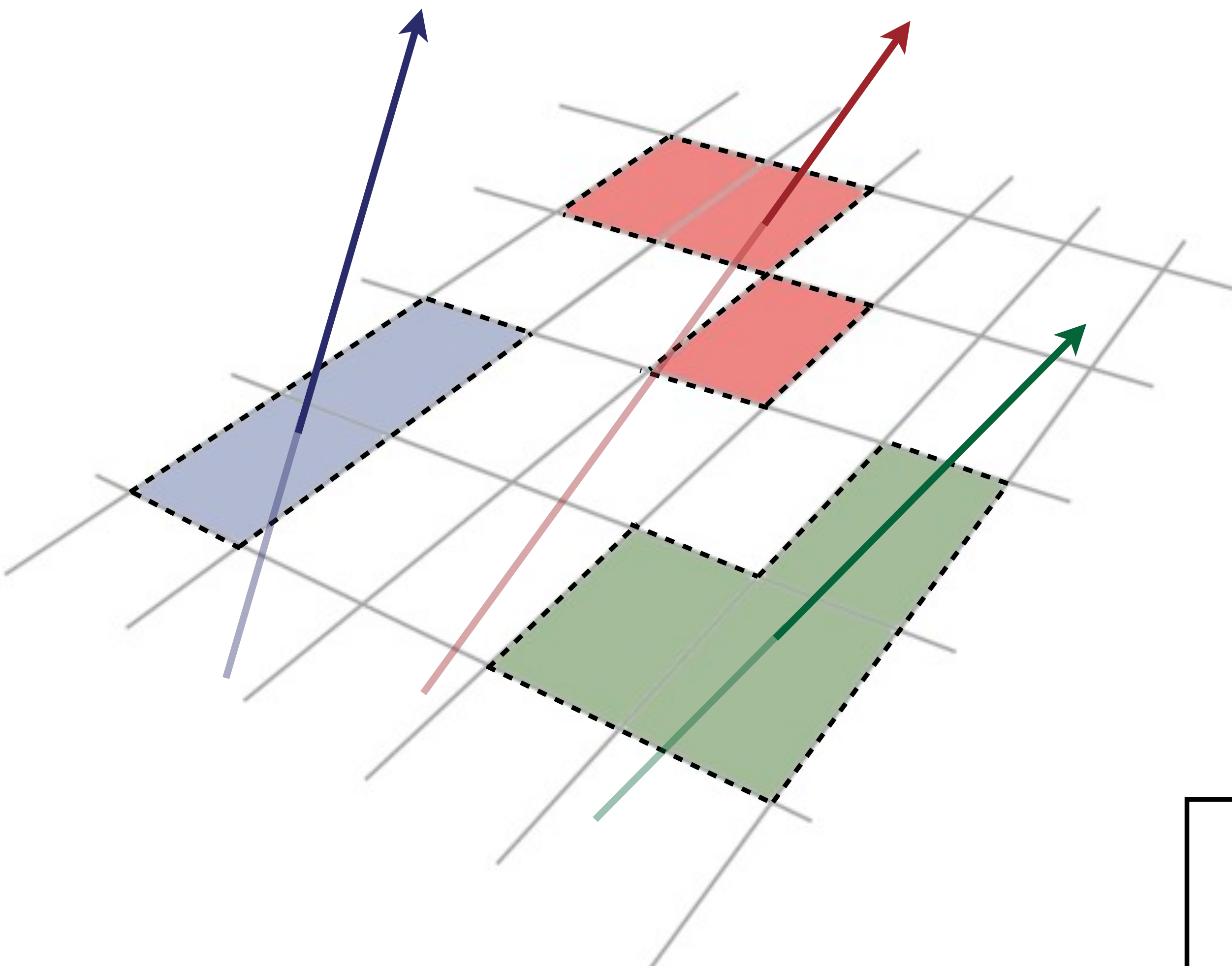


Ambiguity Updates: TIDE

- With the changes made there is a significant improvement
- Particle density still does play a role
  - The presence of additional particles either Primary or Secondary does degrade the efficiency
- Unsurprisingly minimising unnecessary dead material in the tracker does lead to significant gains the track reconstruction efficiency



Non-NN Cluster Positions



- Particle traversing detector typically deposits charge in more than one pixel.
- Charge deposited in a pixel measured using pulse-height time-over-threshold.
- Pixels with deposited charge are grouped into clusters if they have a common edge or a common corner.

- Position of crossing is computed from the signal heights inside the cluster of pixels:

$$x_{cs} = x_{\text{center}} + \Delta_x \cdot \left(\Omega_x - \frac{1}{2}\right)$$

$$y_{cs} = y_{\text{center}} + \Delta_y \cdot \left(\Omega_y - \frac{1}{2}\right)$$

$$\Omega_{x(y)} = \frac{q_{\text{last row(col)}}}{q_{\text{first row(col)}} + q_{\text{last row(col)}}}$$

Separation at b-layer

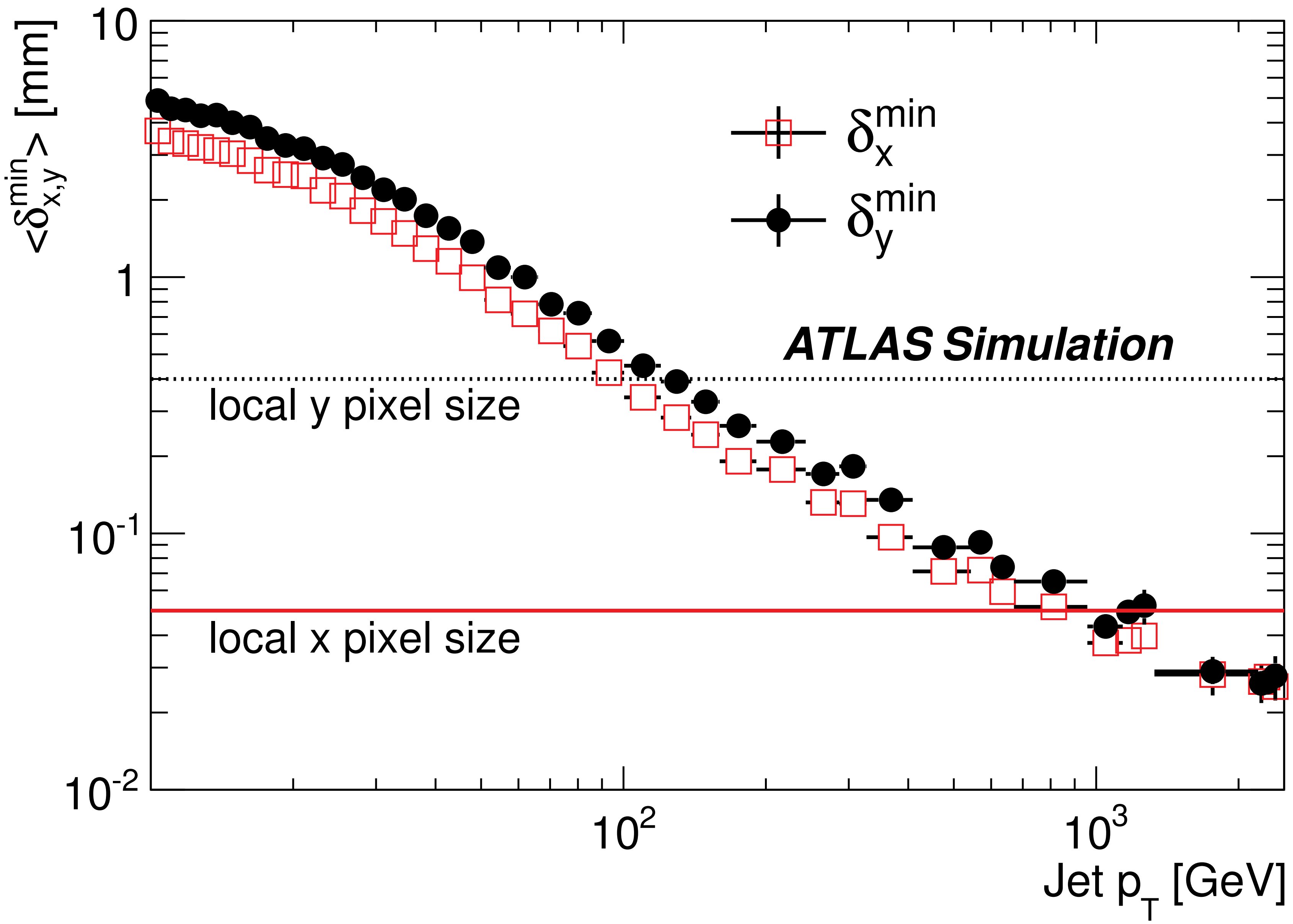


Figure 4. Average separation between the two closest charged particles in a jet in the transverse ($<\delta^{min}_{x}>$, open squares) and longitudinal ($<\delta^{min}_{y}>$, full circles) direction at the innermost layer of the pixel barrel. This is shown as a function of the transverse momentum of the jet. The pixel size in the transverse (50 μm) and longitudinal (400 μm) direction is indicated with the solid and dotted lines, respectively.

FTK