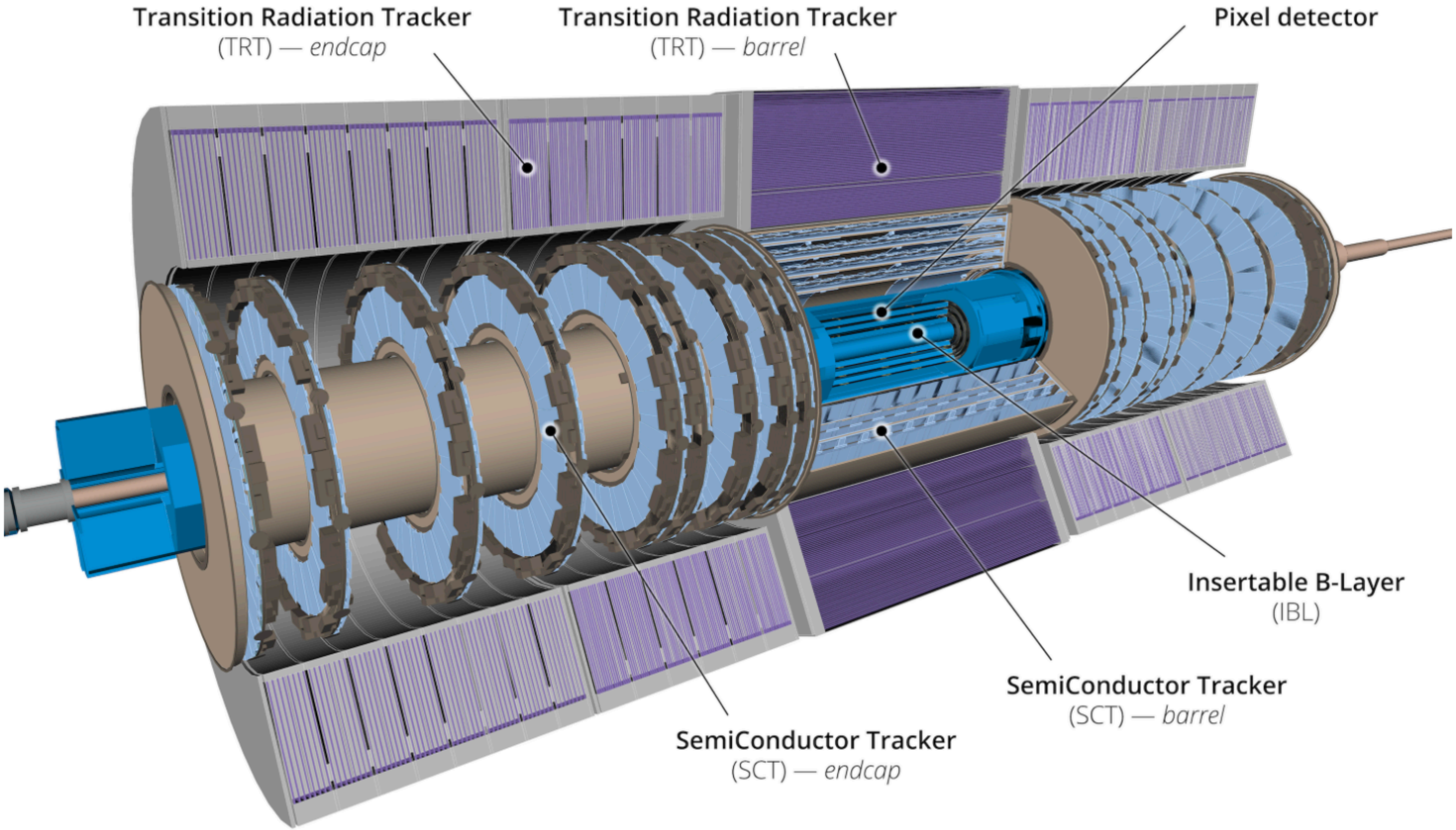
Track Reconstruction in ATLAS

17th May, 2024

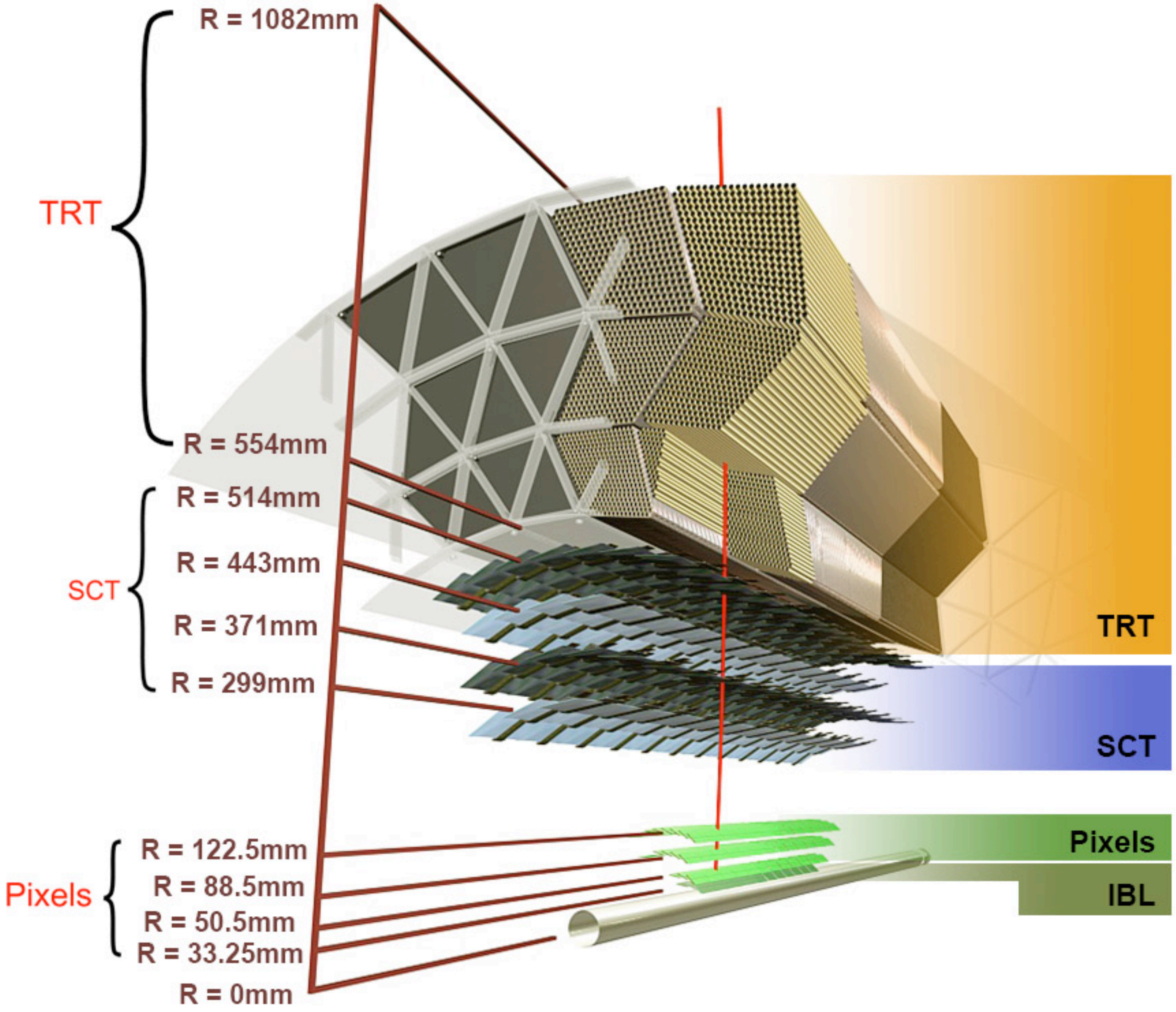
Christian Grefe

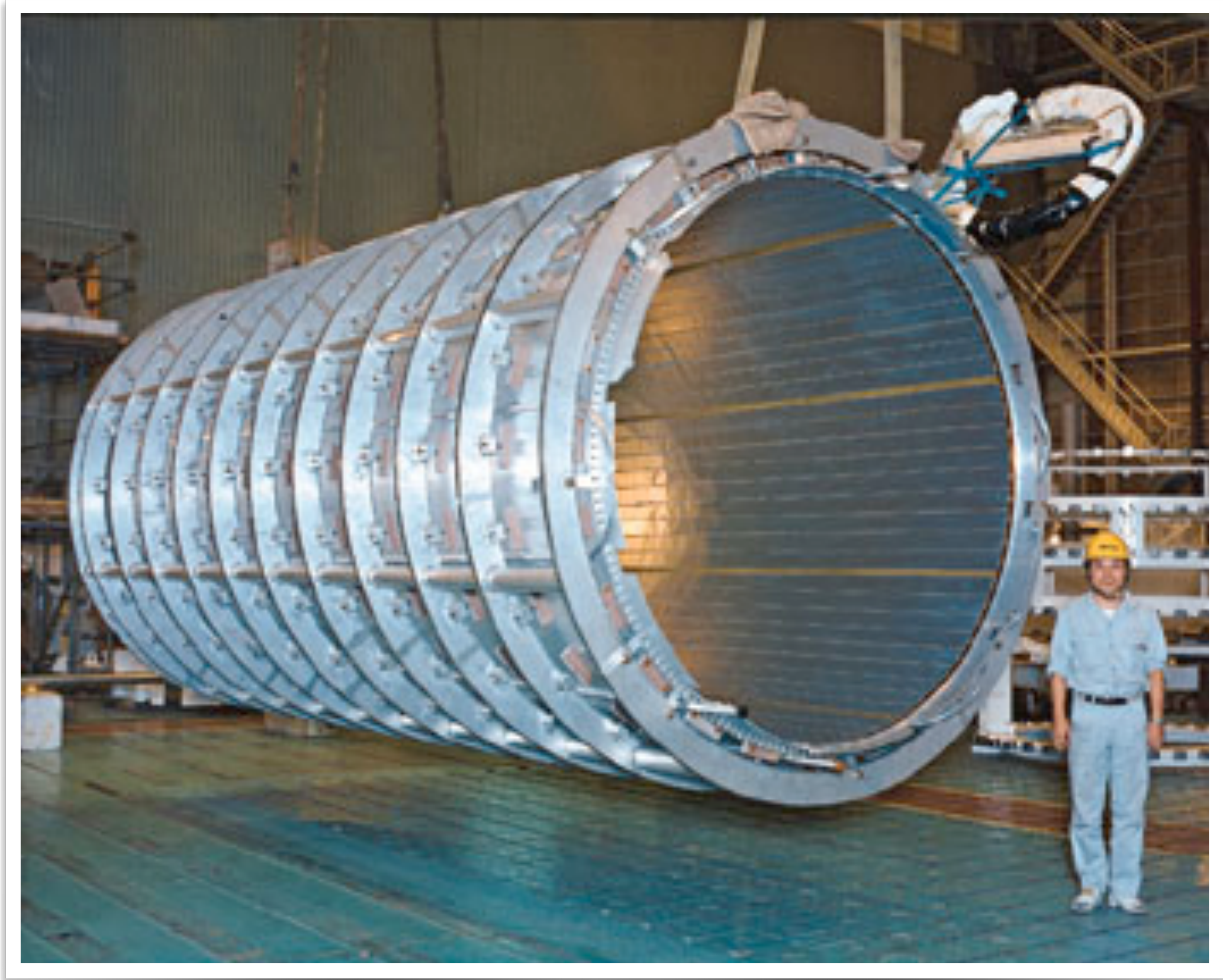
Pb-Pb collision event @ $\sqrt{s} = 5.36$ TeV

ATLAS Inner Detector



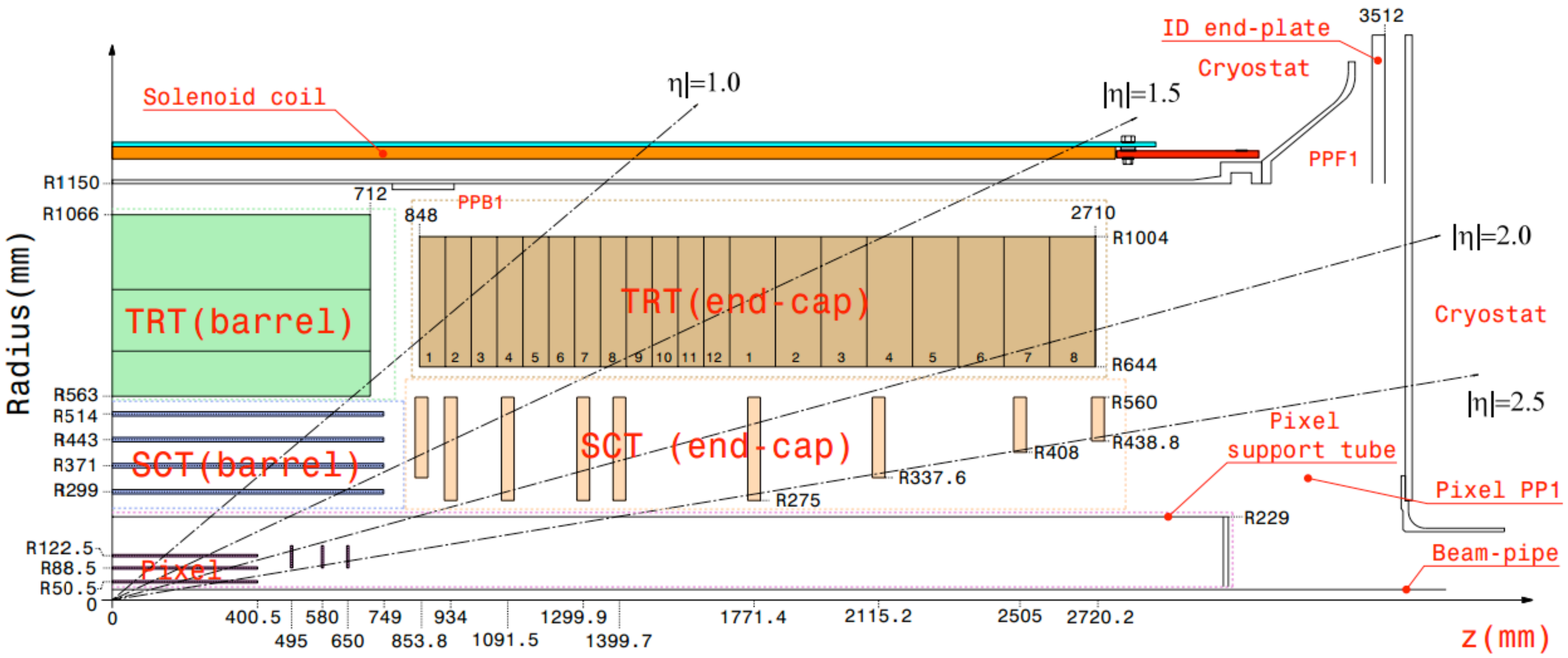
ATLAS Inner Detector





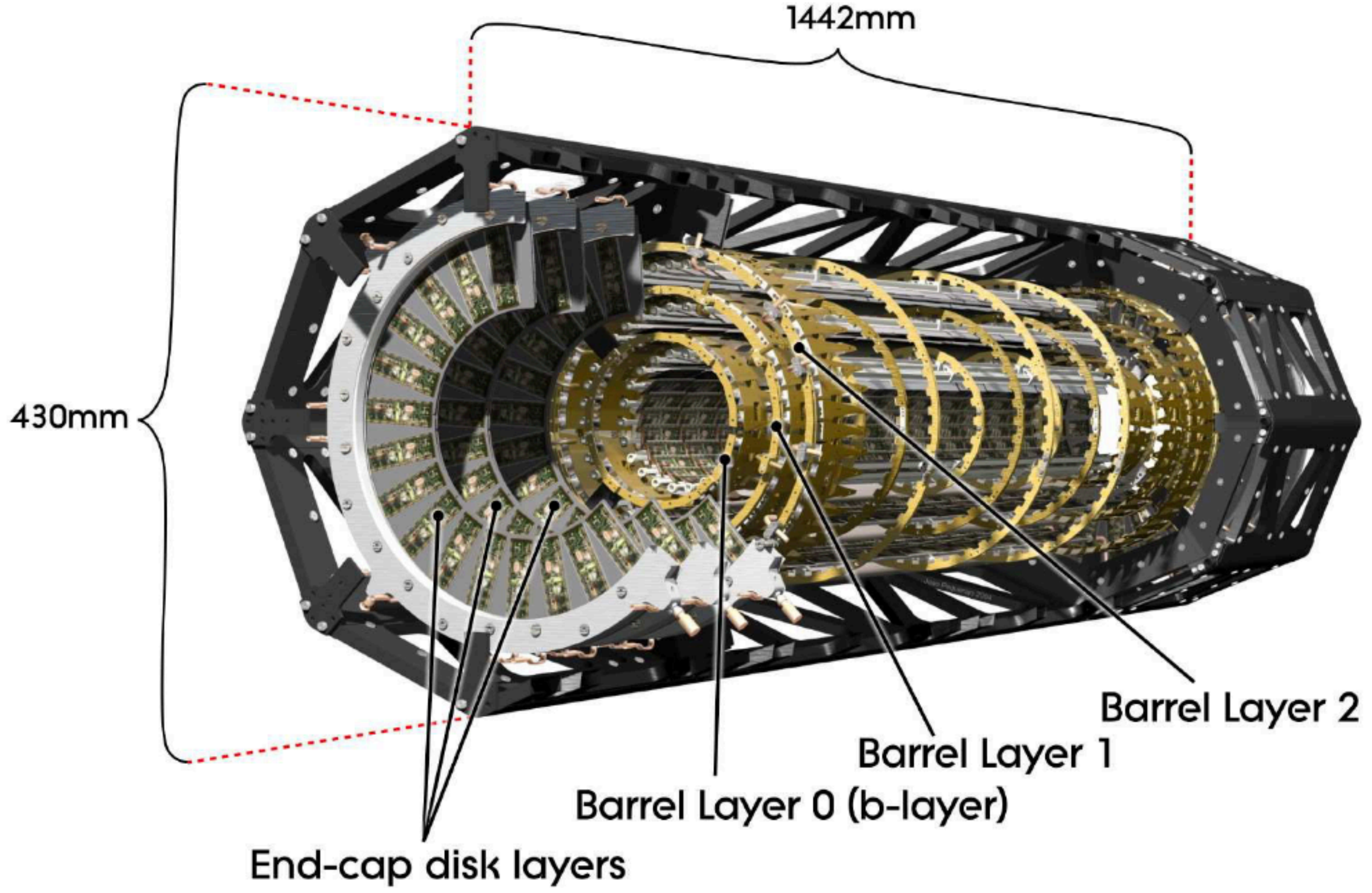
- Superconducting 2T solenoid

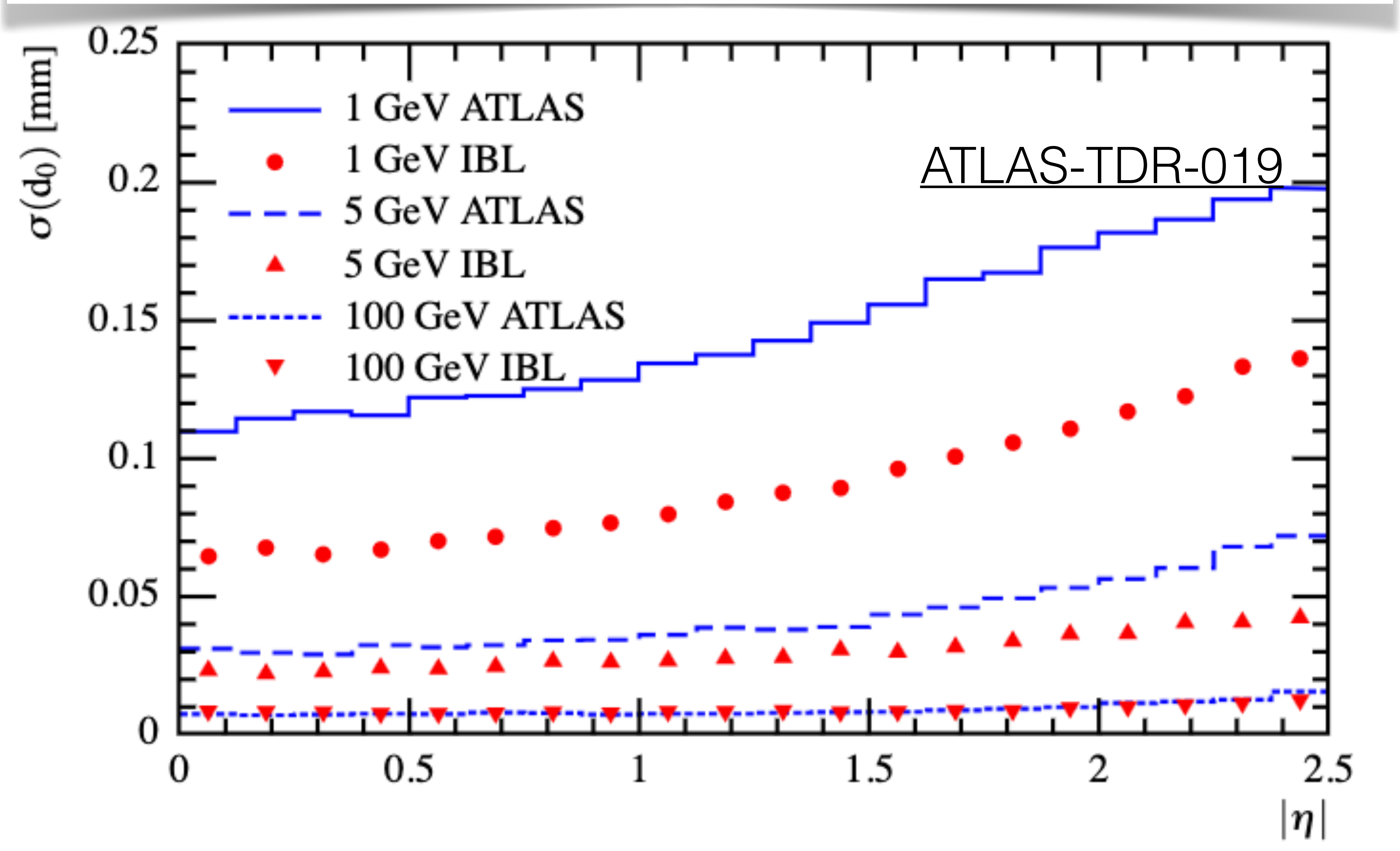
ATLAS Inner Detector



- Inner detector track reconstruction up to $|\eta| = 2.5$ ($\theta \approx 8°$)

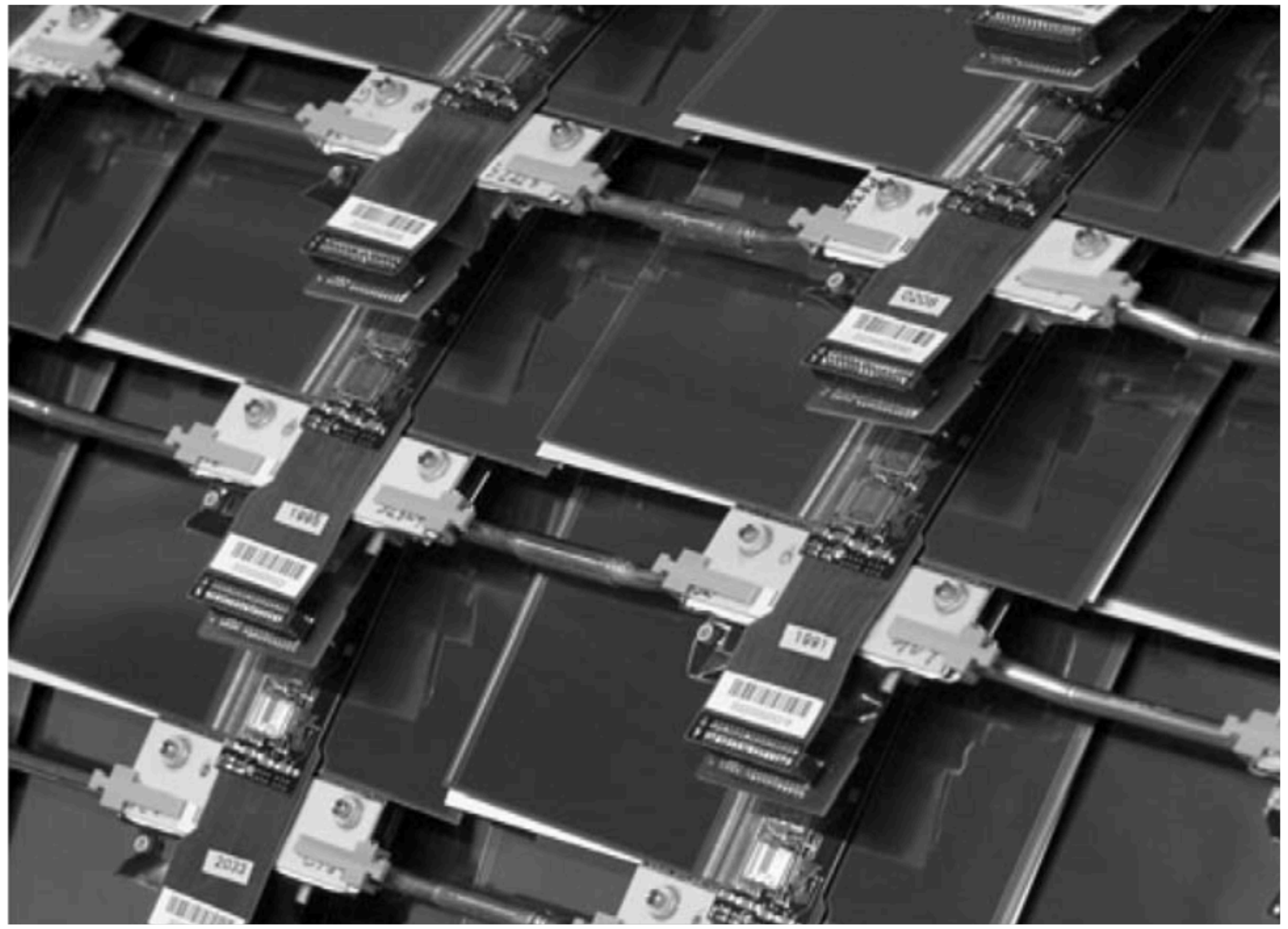
Pixel Detector

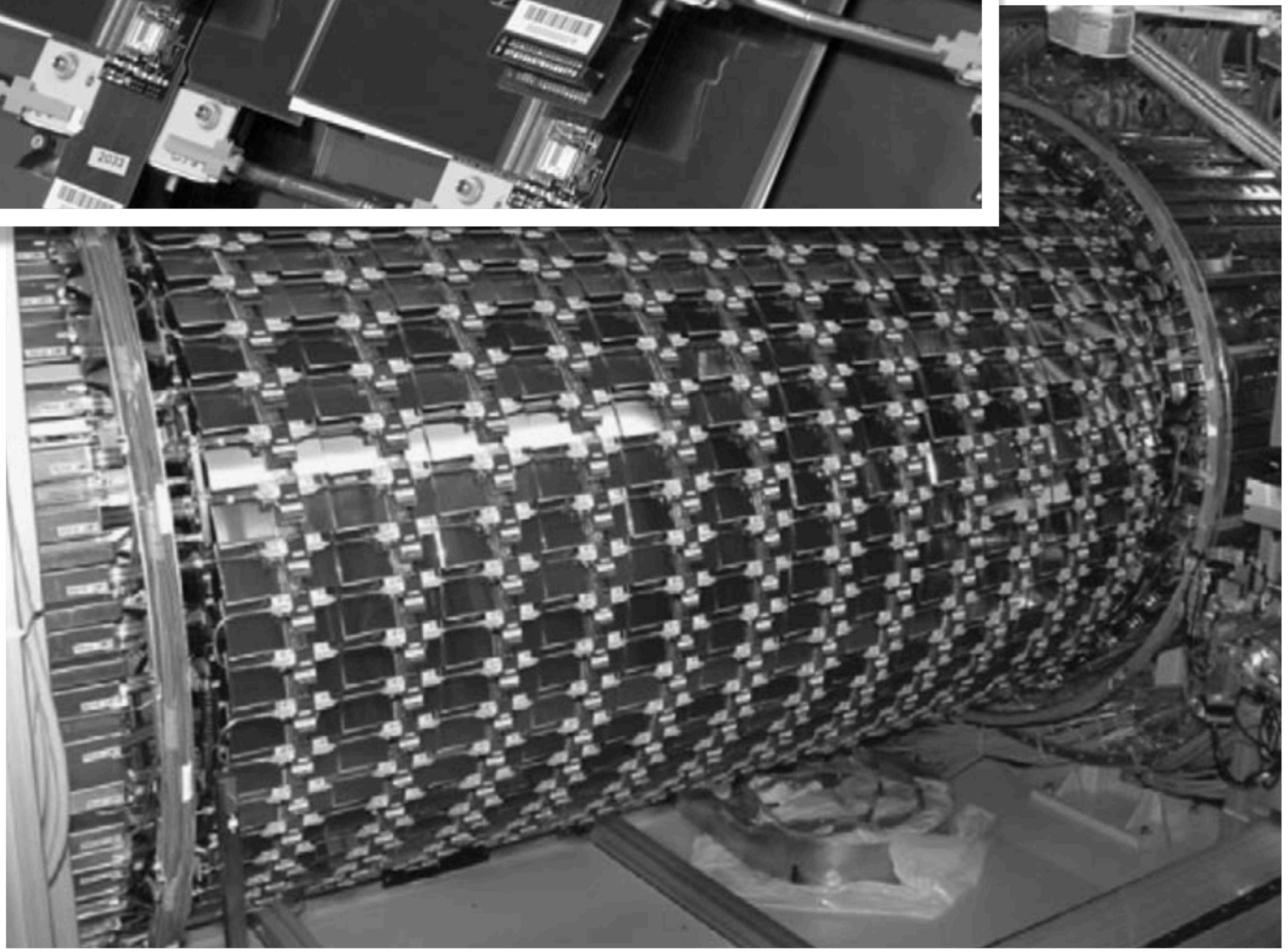




- Originally: 3 barrel + 3 endcap layers with planar Si-pixel sensors ($382 \times 30\,\mu$m^2)
- Since 2014: additional Insertable B-Layer (IBL) with planar and 3D Si-pixel sensors - significantly improved vertex reconstruction

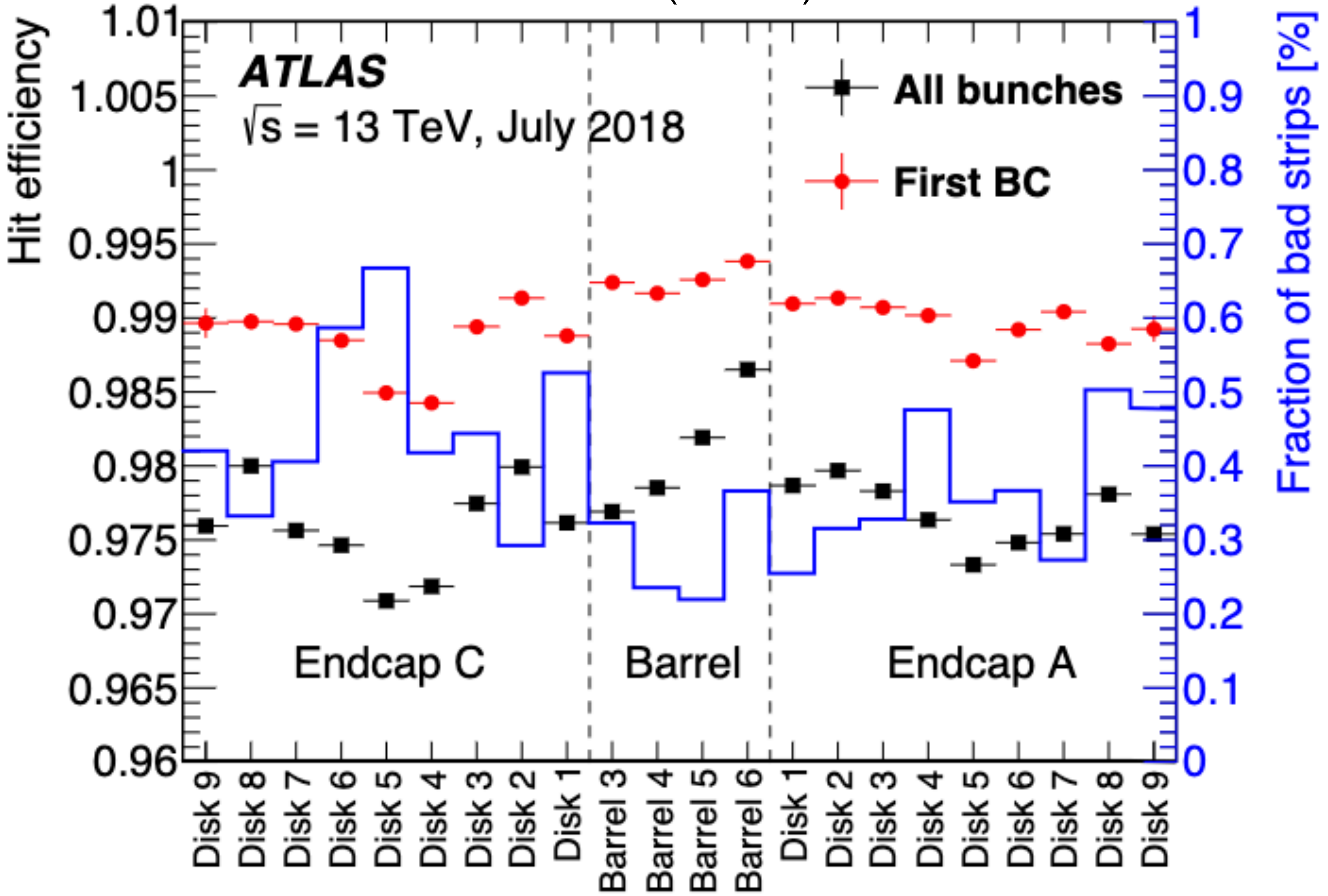
Silicon Strip Detector (SCT)





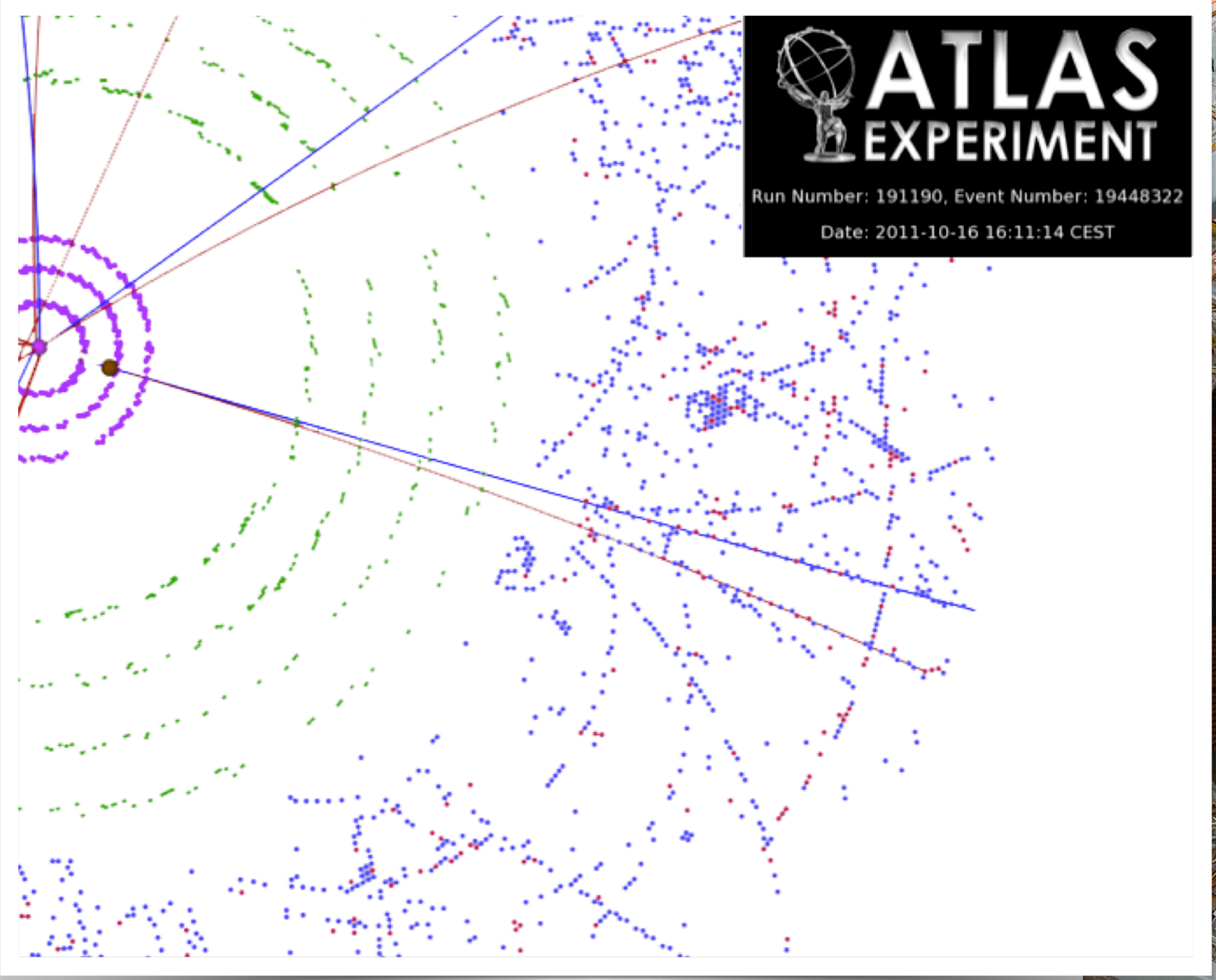
NIM.A 568 (2006)

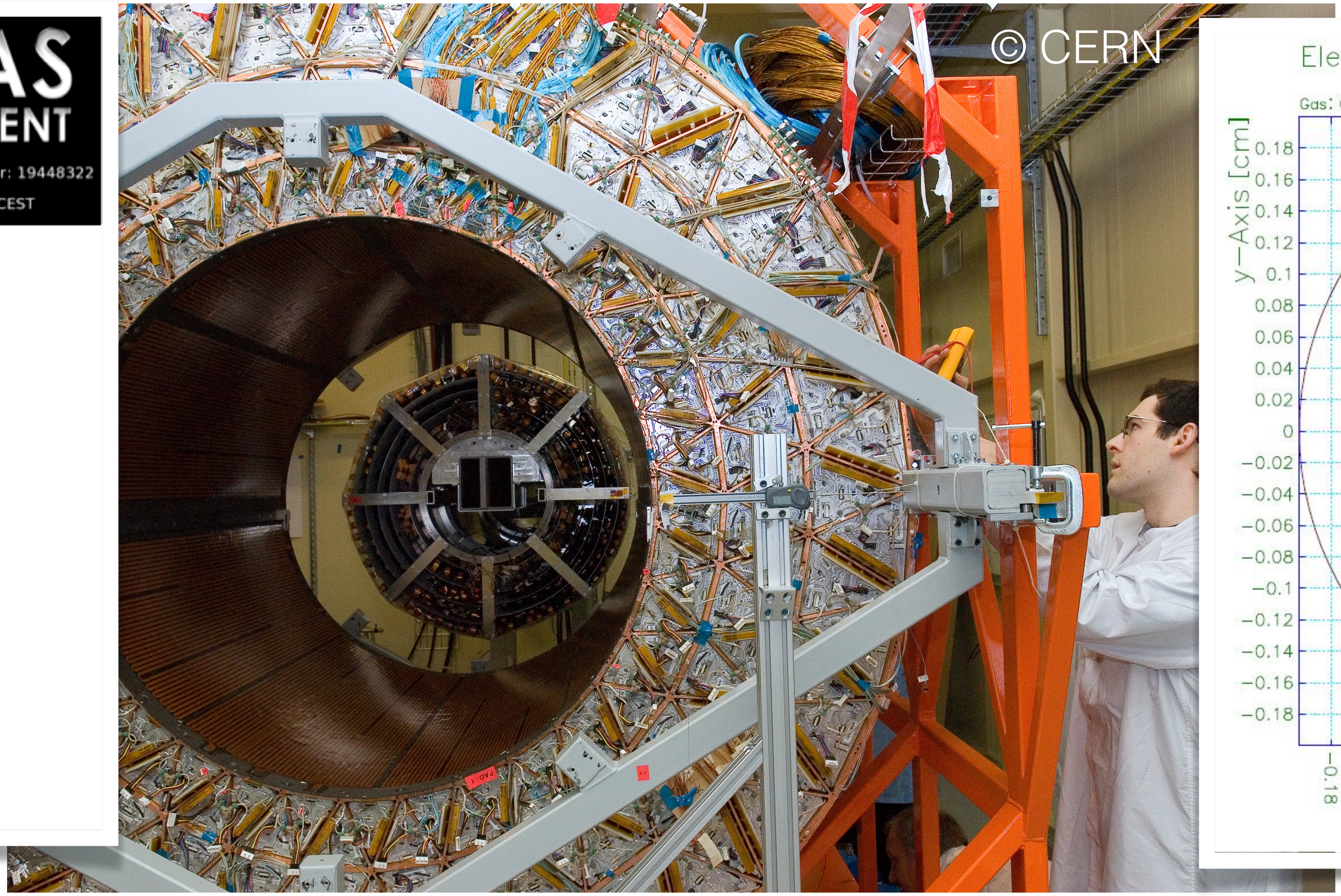
JINST 17 (2022) P01013

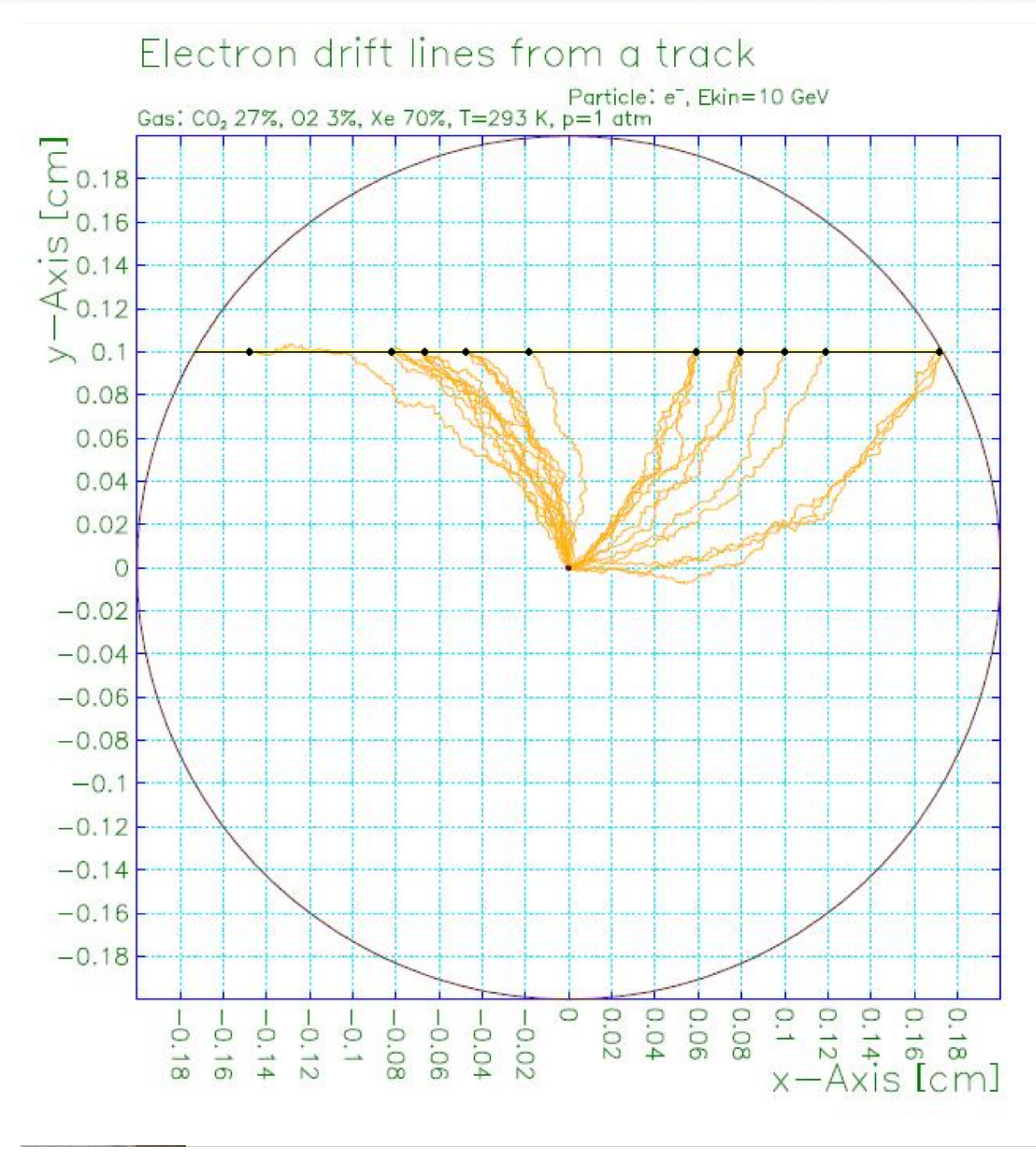


- 4 barrel and 9 endcap layers of silicon strip sensors ($80\,\mu$m pitch)
- Each module consists of 2 sensors that are mounted back-to-back with a stereo angle of 40mrad

Transition Radiation Tracker (TRT)

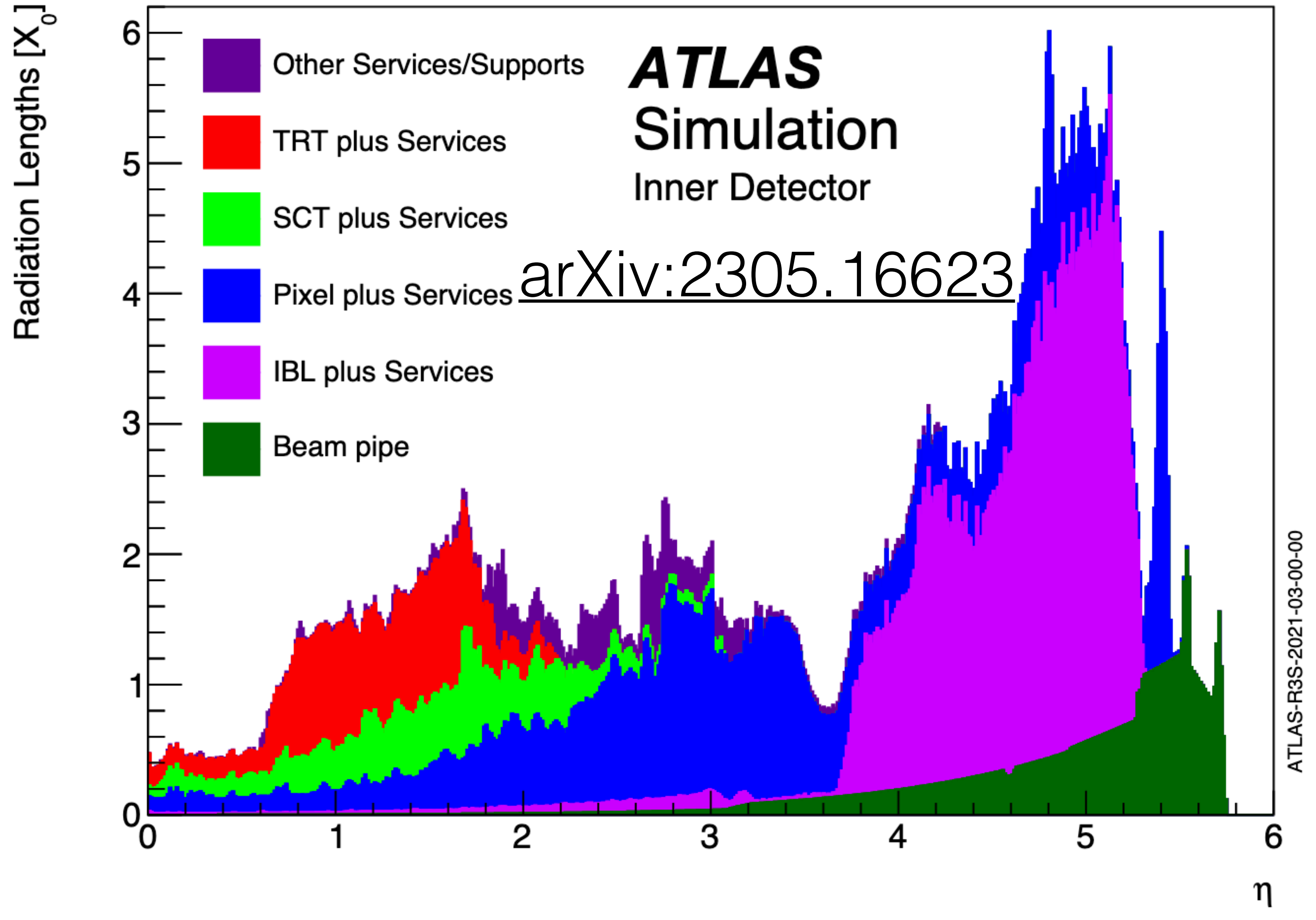


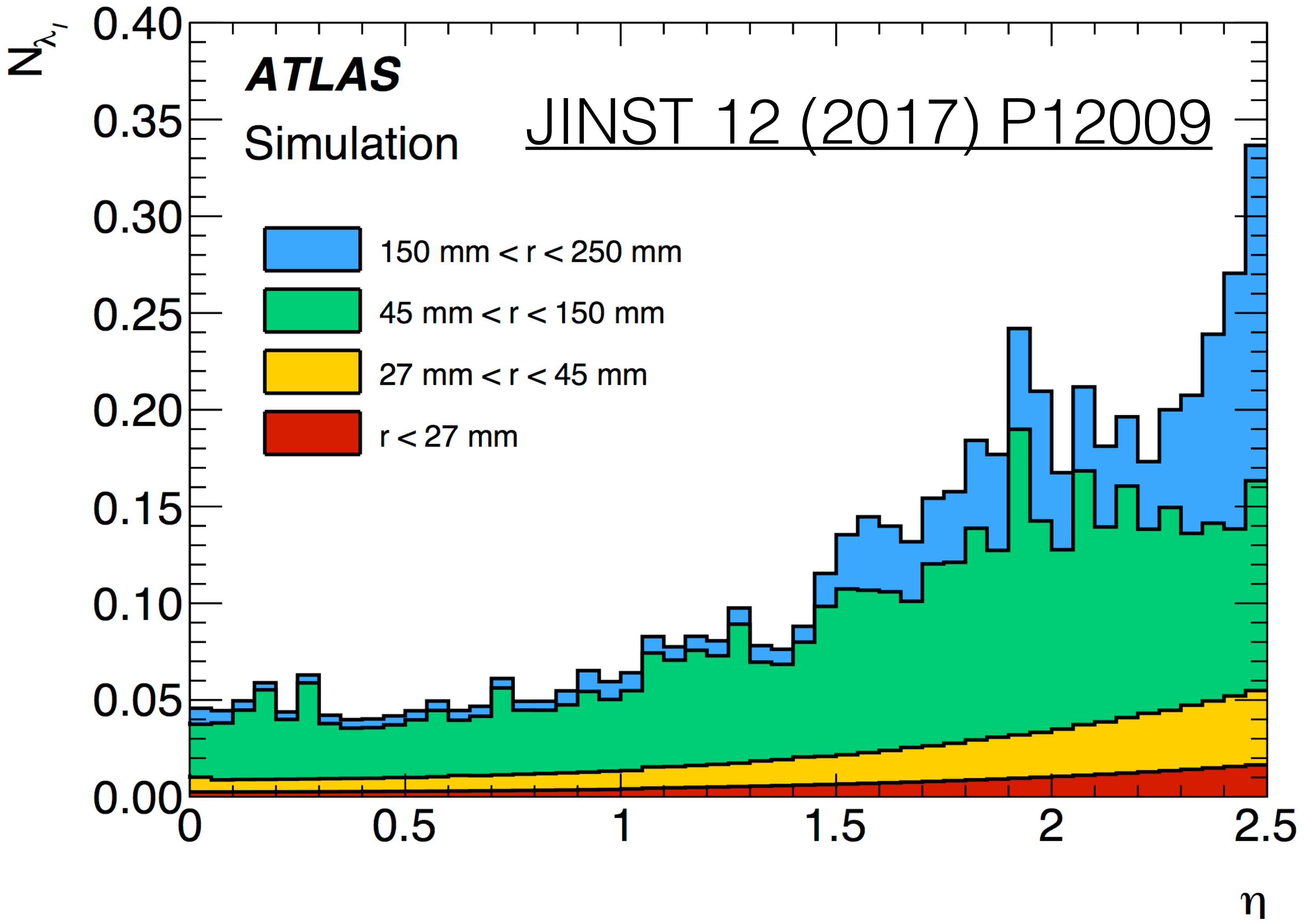




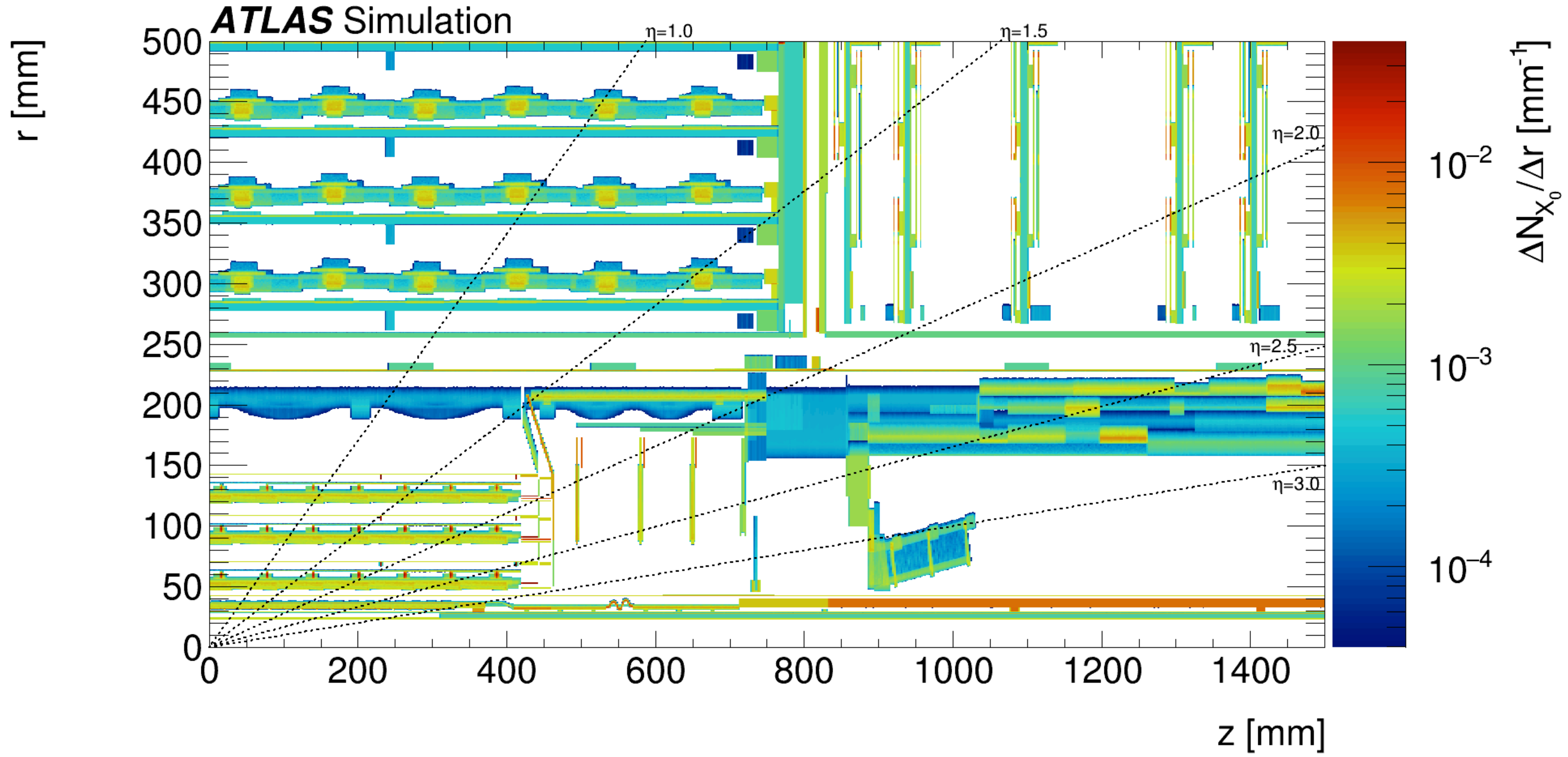
- 350k drift tubes filled with Xe- or Ar-based gas mixture
- Radiator material around each tube triggers transition radiation for highly relativistic particles - x-ray photons absorbed by active gas can be distinguished from ionisation signal (2 readout thresholds) - used for particle identification

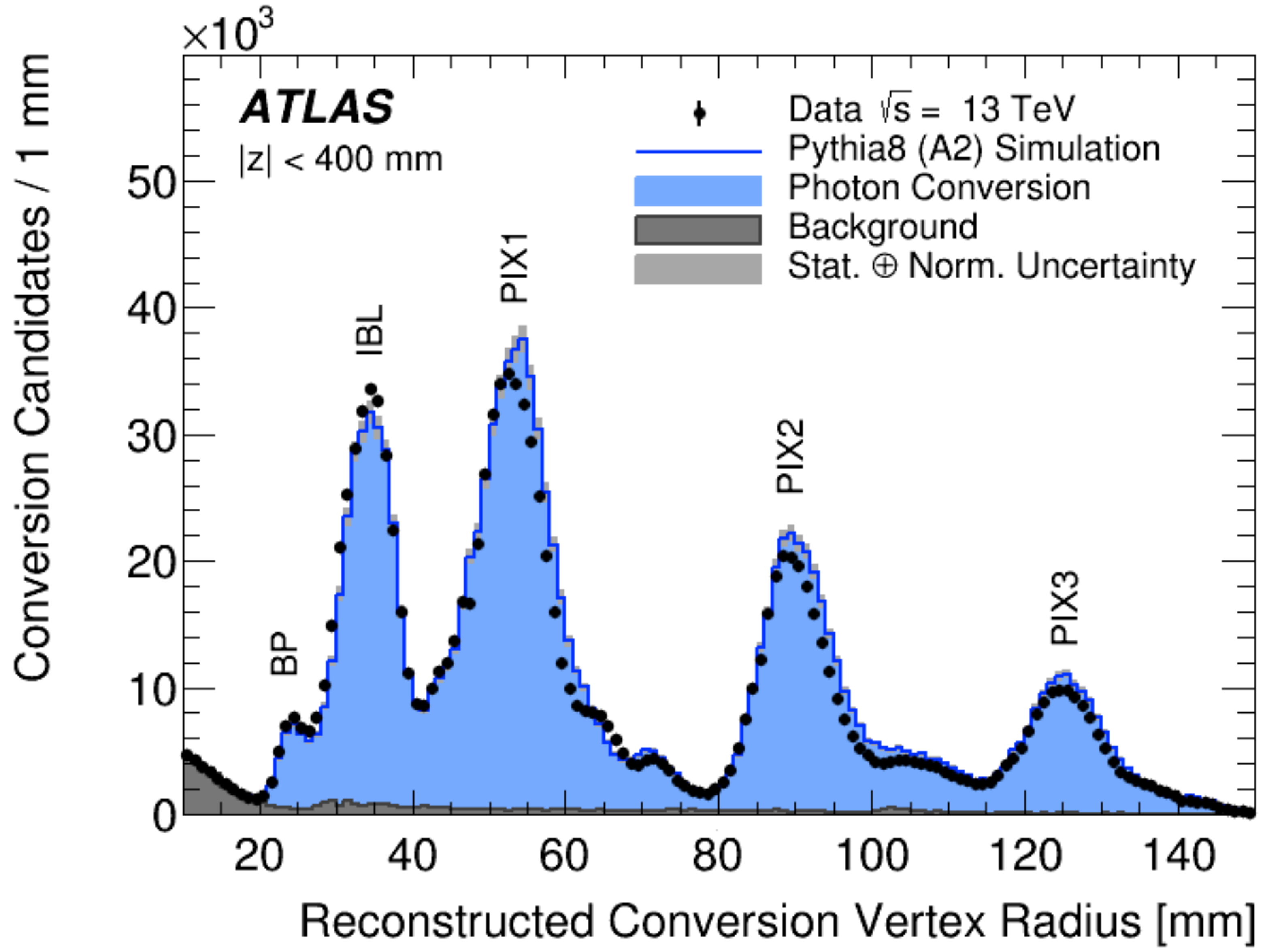
Material budget





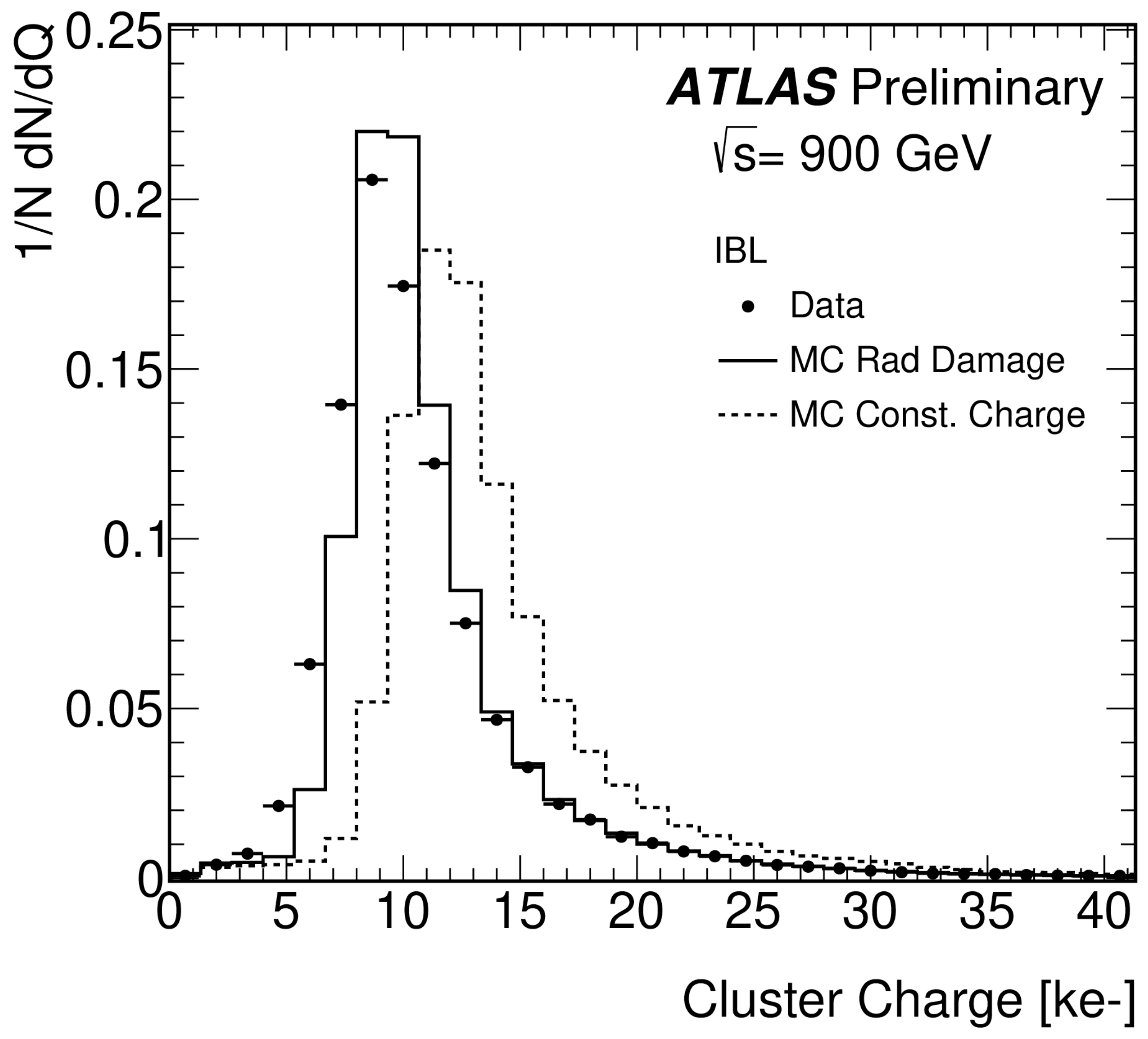
- Material budget can be validated through rate of secondary vertices from hadronic interactions and photon conversions in data

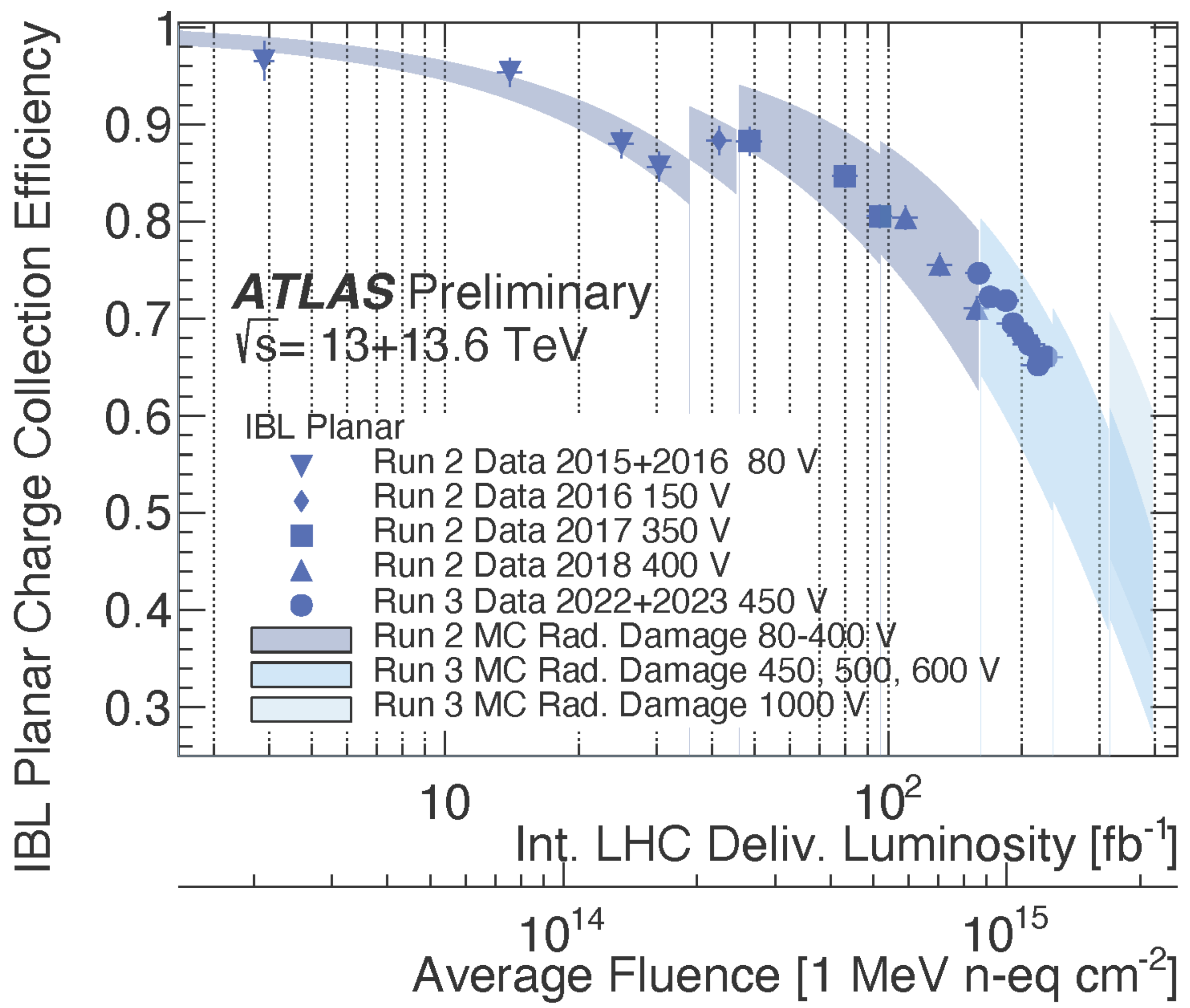


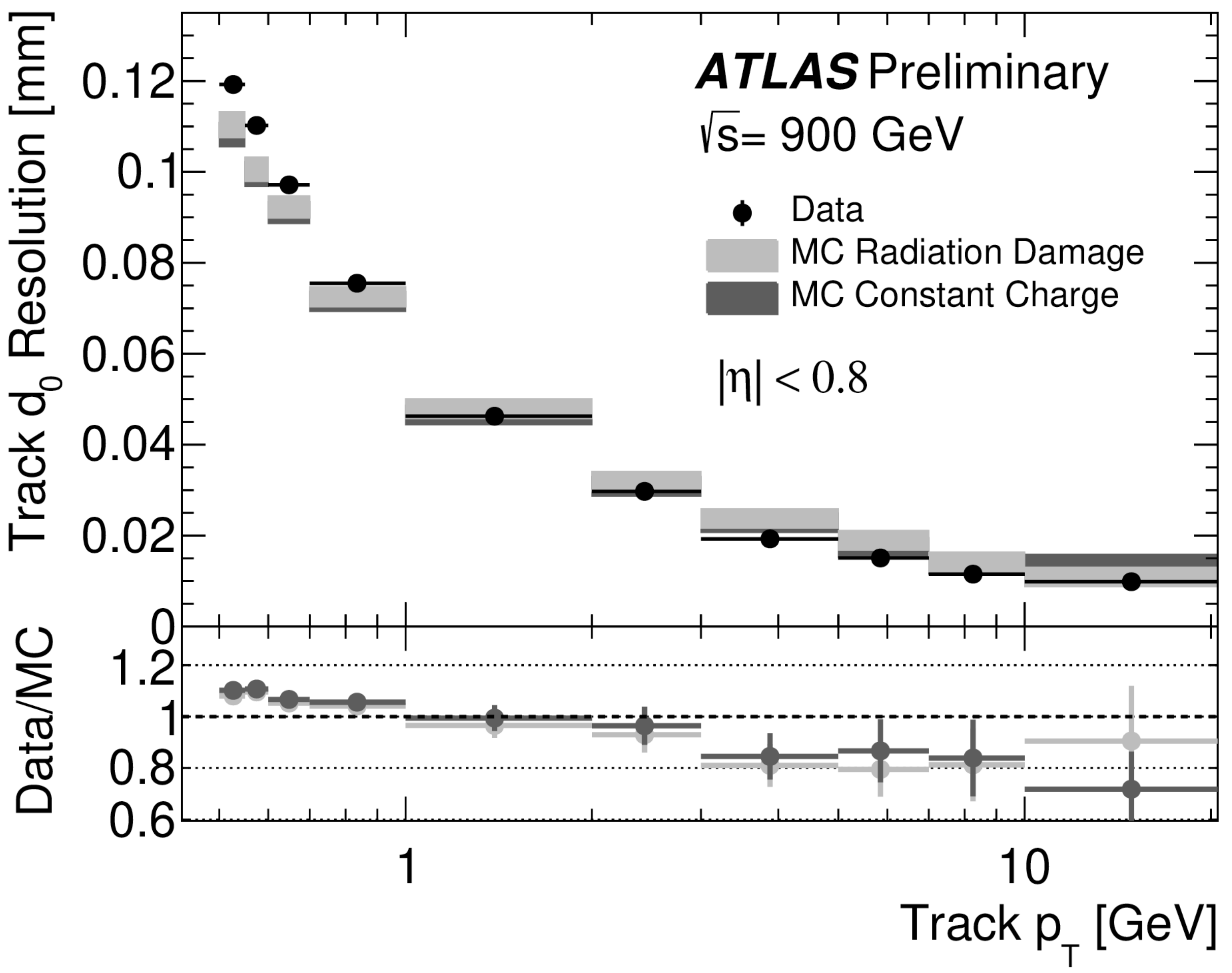


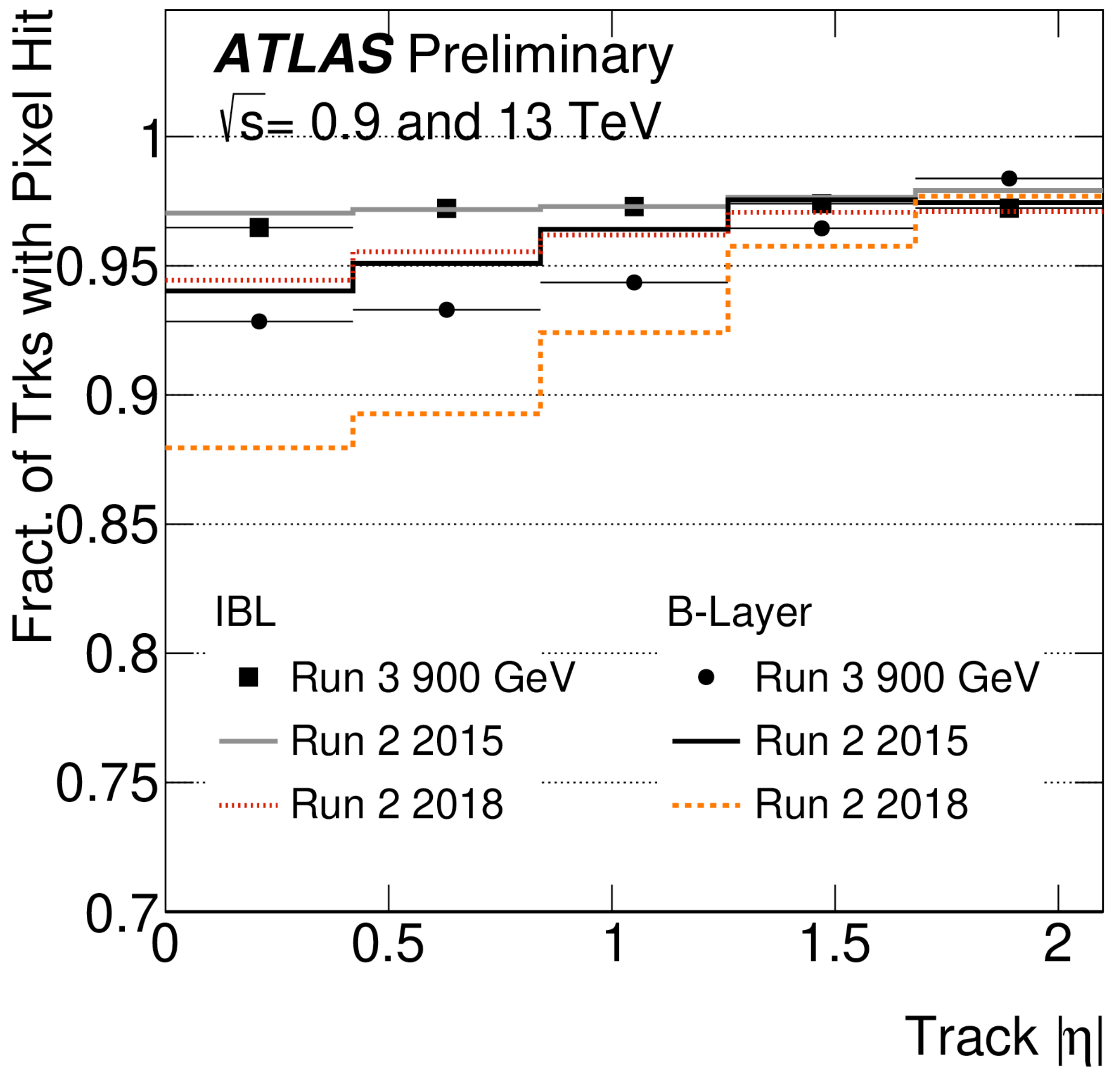
Radiation Damage

ATL-PHYS-PUB-2022-033





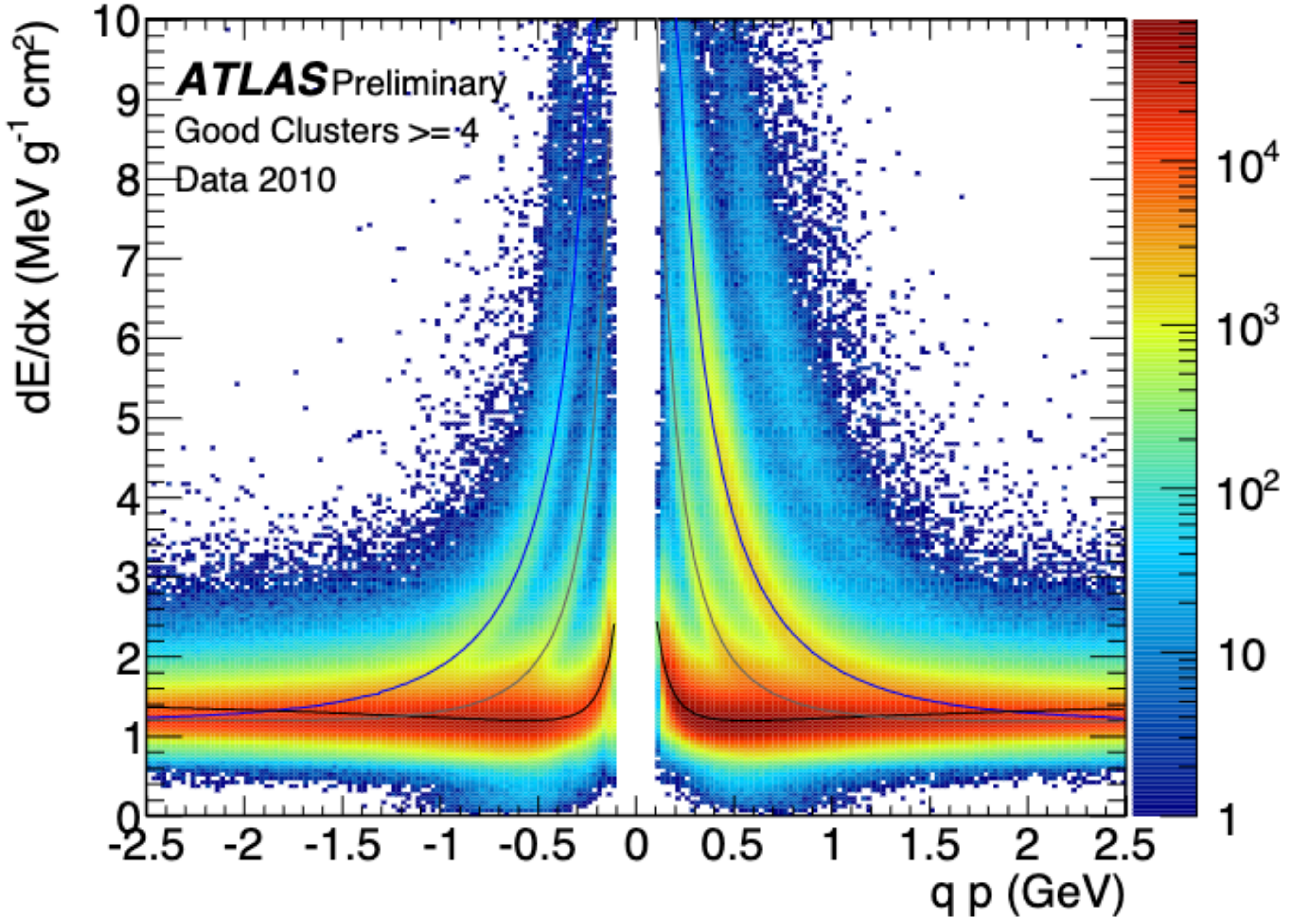




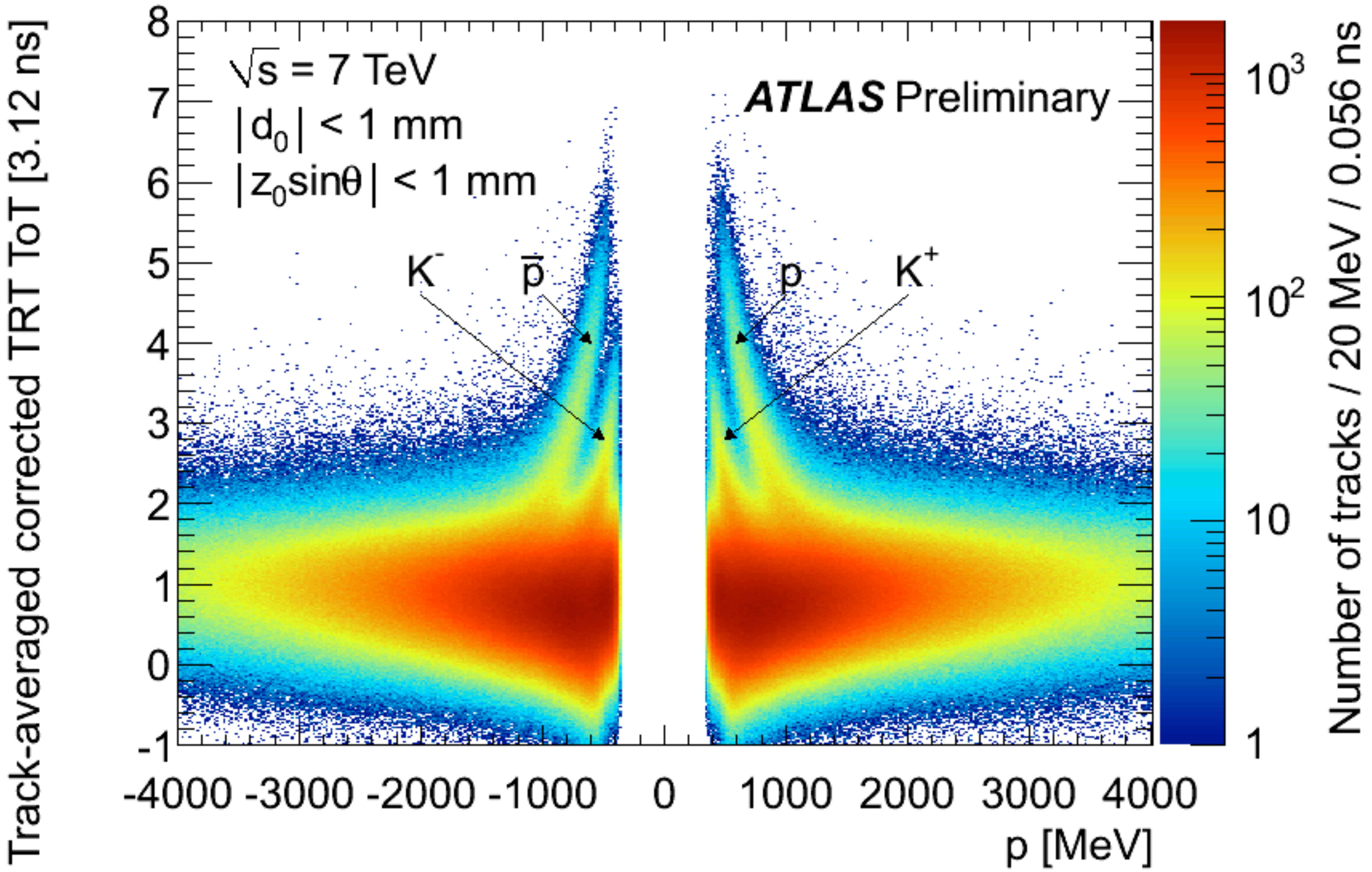
- Radiation damage induces significant reduction in charge collection efficiency
- Effect is well described in simulation - included since Run 3
- Thresholds need to be adapted over time: trade-off between noise and hit efficiency

Particle Identification with dE/dx

ATLAS-CONF-2011-016

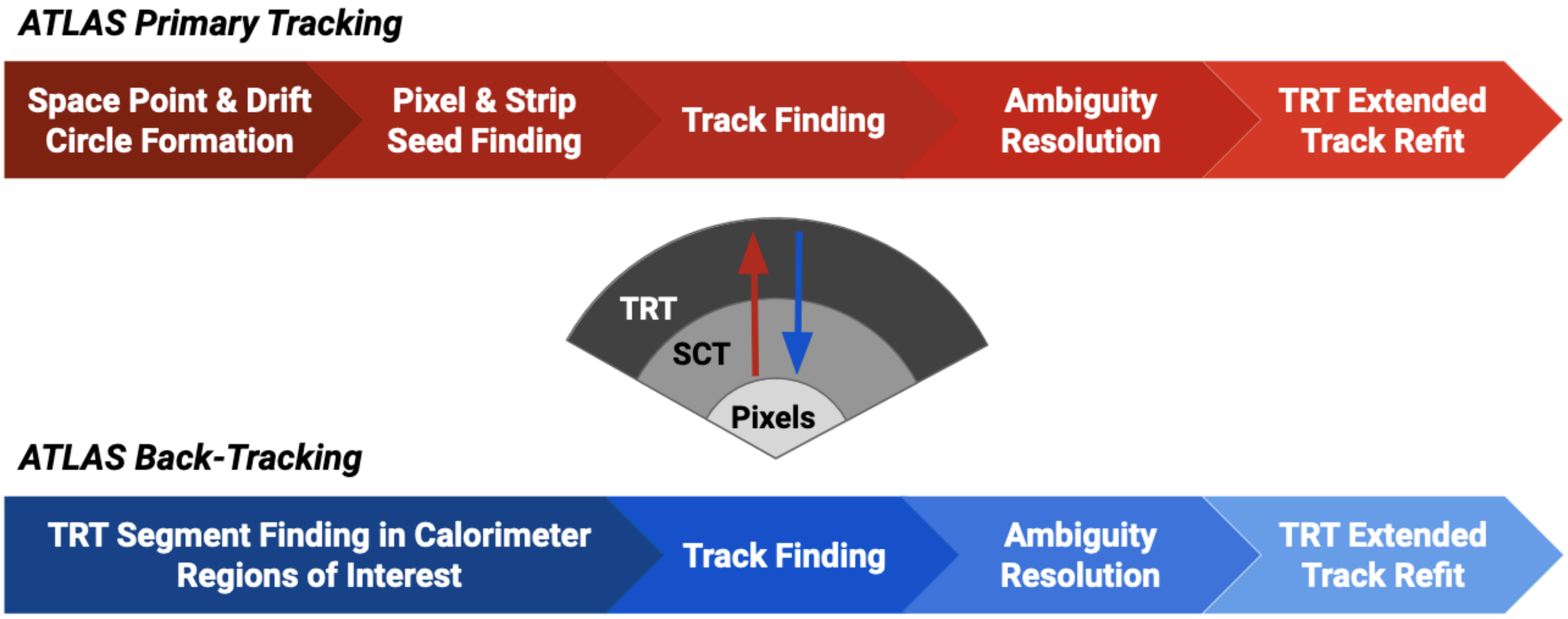


ATLAS-CONF-2011-128



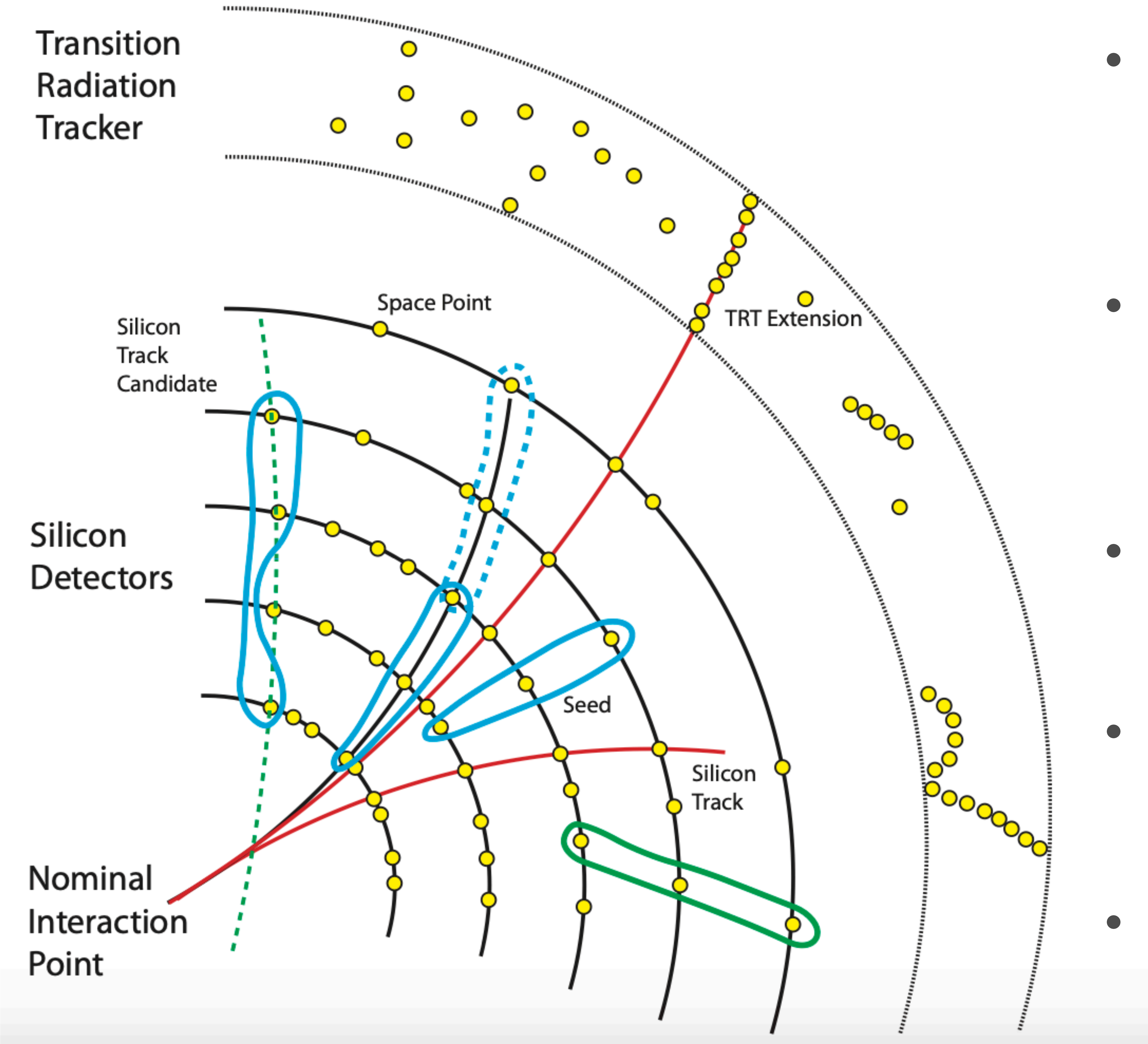
- Specific energy loss can be used for particle identification
  - Cluster charge in pixel detectors or time-over-threshold in TRT
- Mostly used for exotic particle searches (multi-charged, magnetic monopoles, …)
- In addition: particle identification from transition radiation signal in the TRT

Track Finding in ATLAS



- Run multiple track finding passes on the available hits using different strategies and constraints: primary tracking, back-tracking, large-radius tracking (+ dedicated setups for low-p_T, heavy ions, cosmics, etc. that are not run on all events by default)

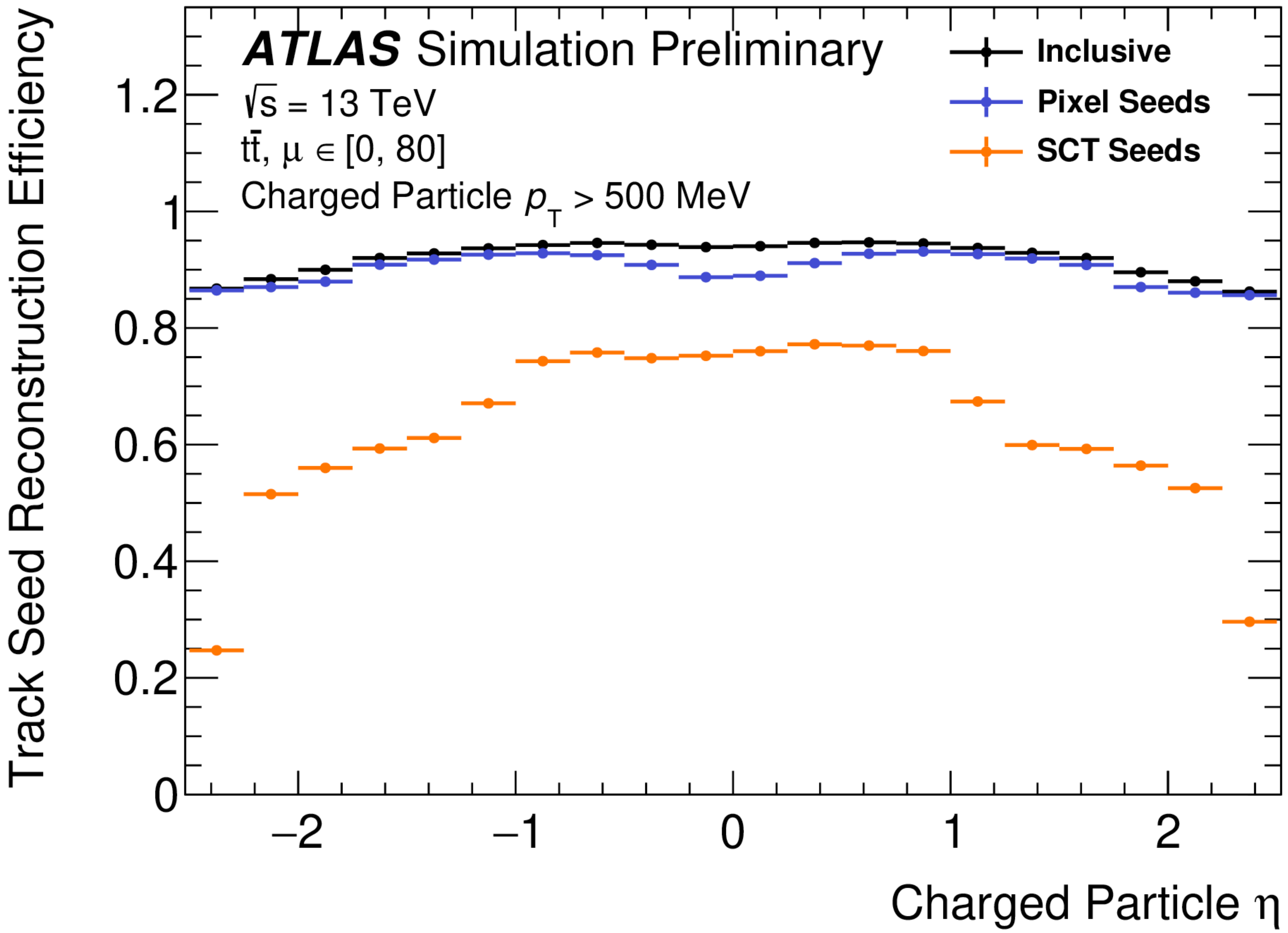
Inside-out Tracking

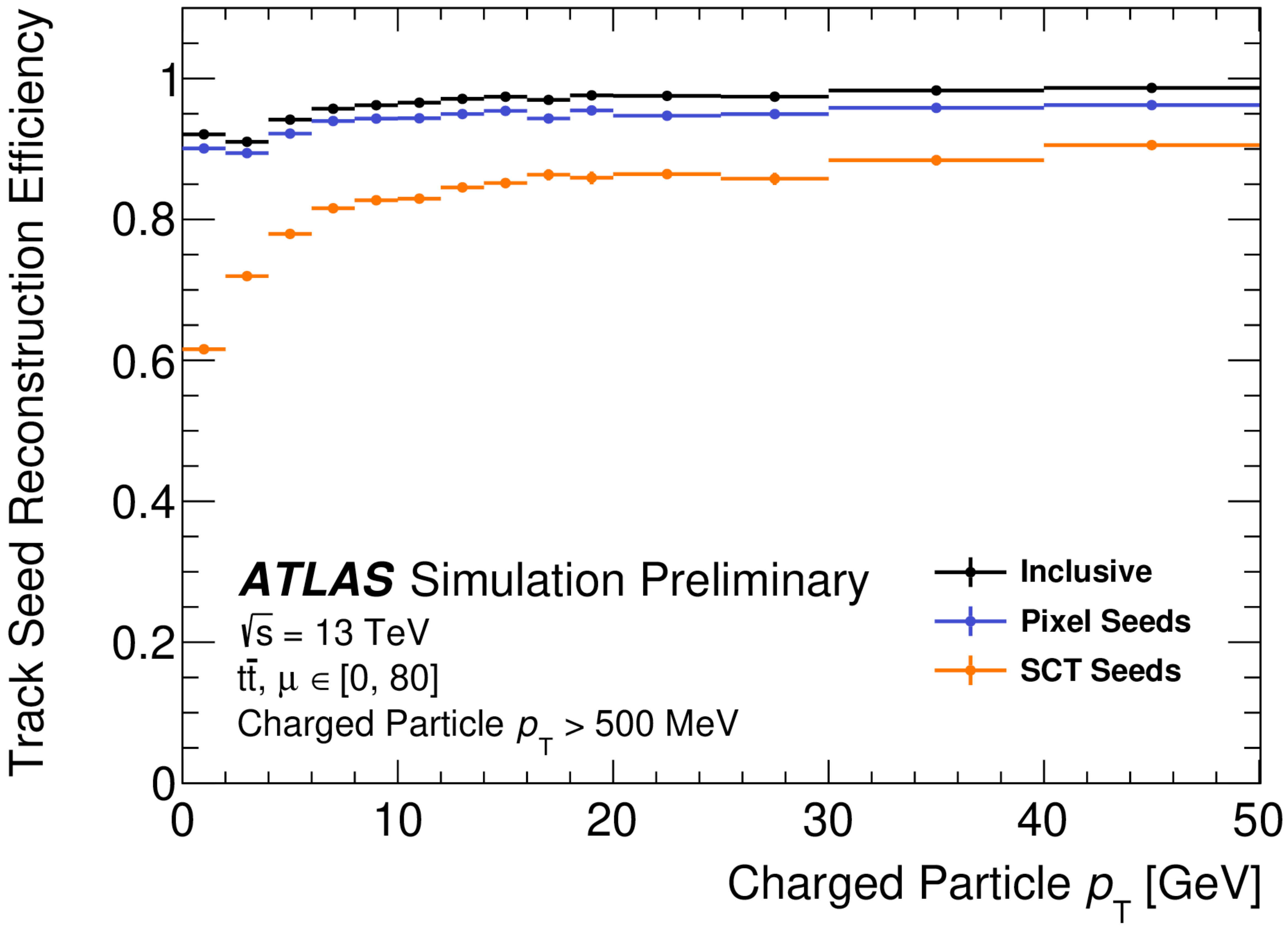


- Find all valid combinations of SCT and pixel hit triplets (no mixed seeds): $p_T > 500$ MeV, $d_0 < 5$ mm, $z_0 < 200$ mm
- Seeds are processed depending on their score: high-p_T, low-d_0 and a compatible hit in a 4th confirmation layer are preferred
- Combinatorial Kalman Filter is used to extend seeds inwards and outwards
- Confirmed Si-only tracks are extended into the TRT
- Global χ^2-fit is used to extract the final track parameters

Seeding Performance

ATL-PHYS-PUB-2023-034

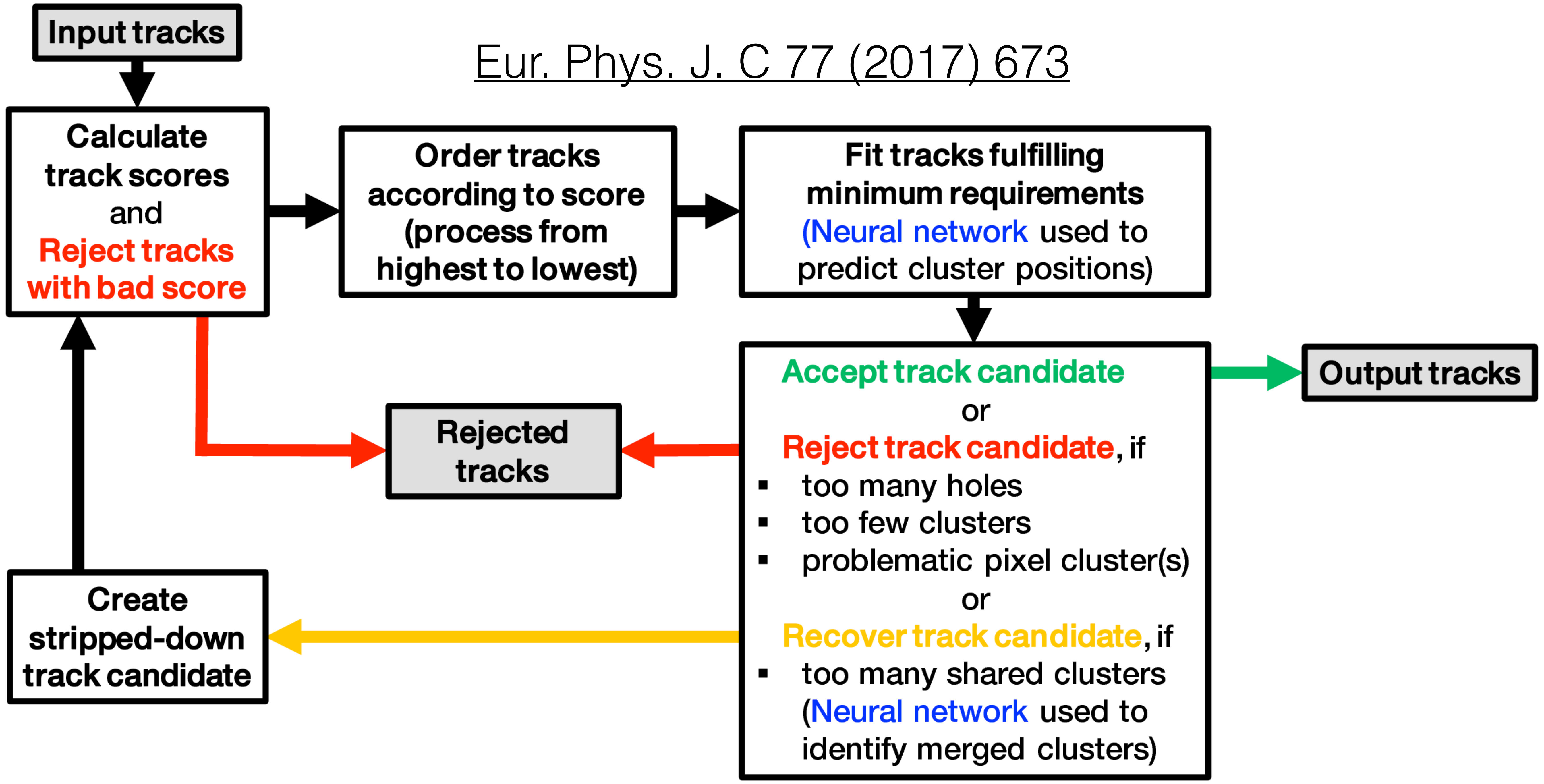


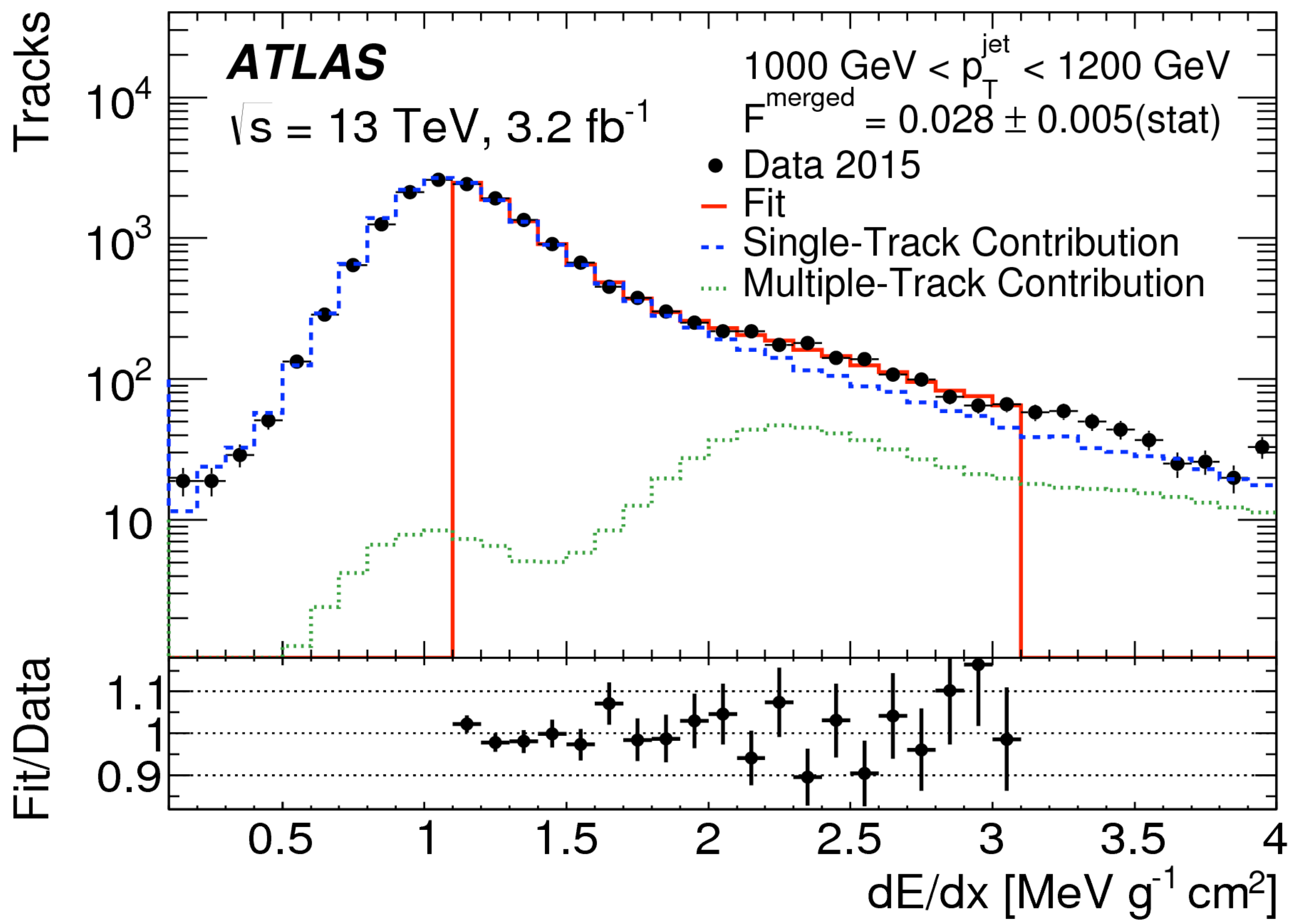


- SCT seeds are formed first. They allow to define the beam spot region, which can then be used to discard large z_0 seeds

Ambiguity Resolution

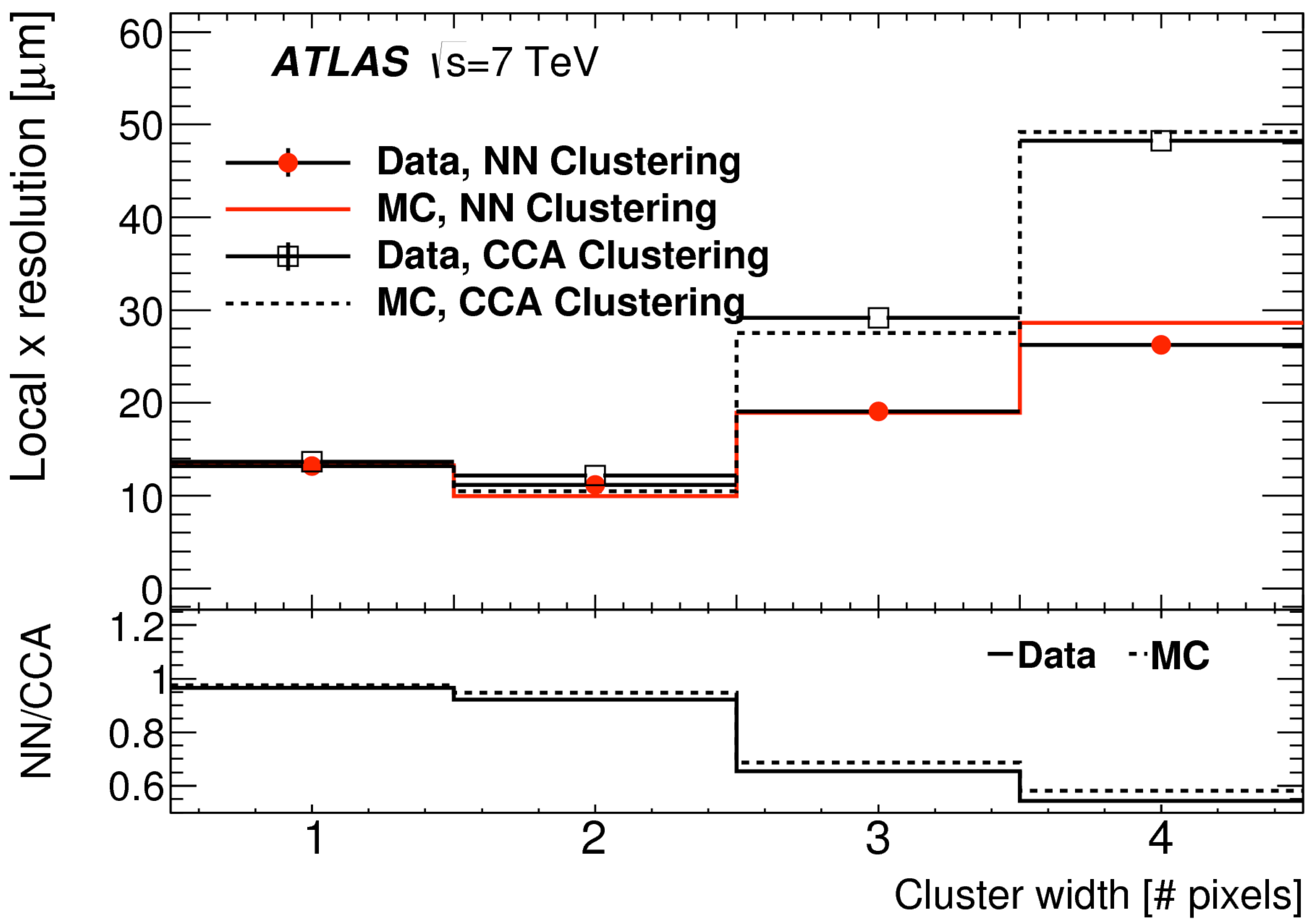
Eur. Phys. J. C 77 (2017) 673

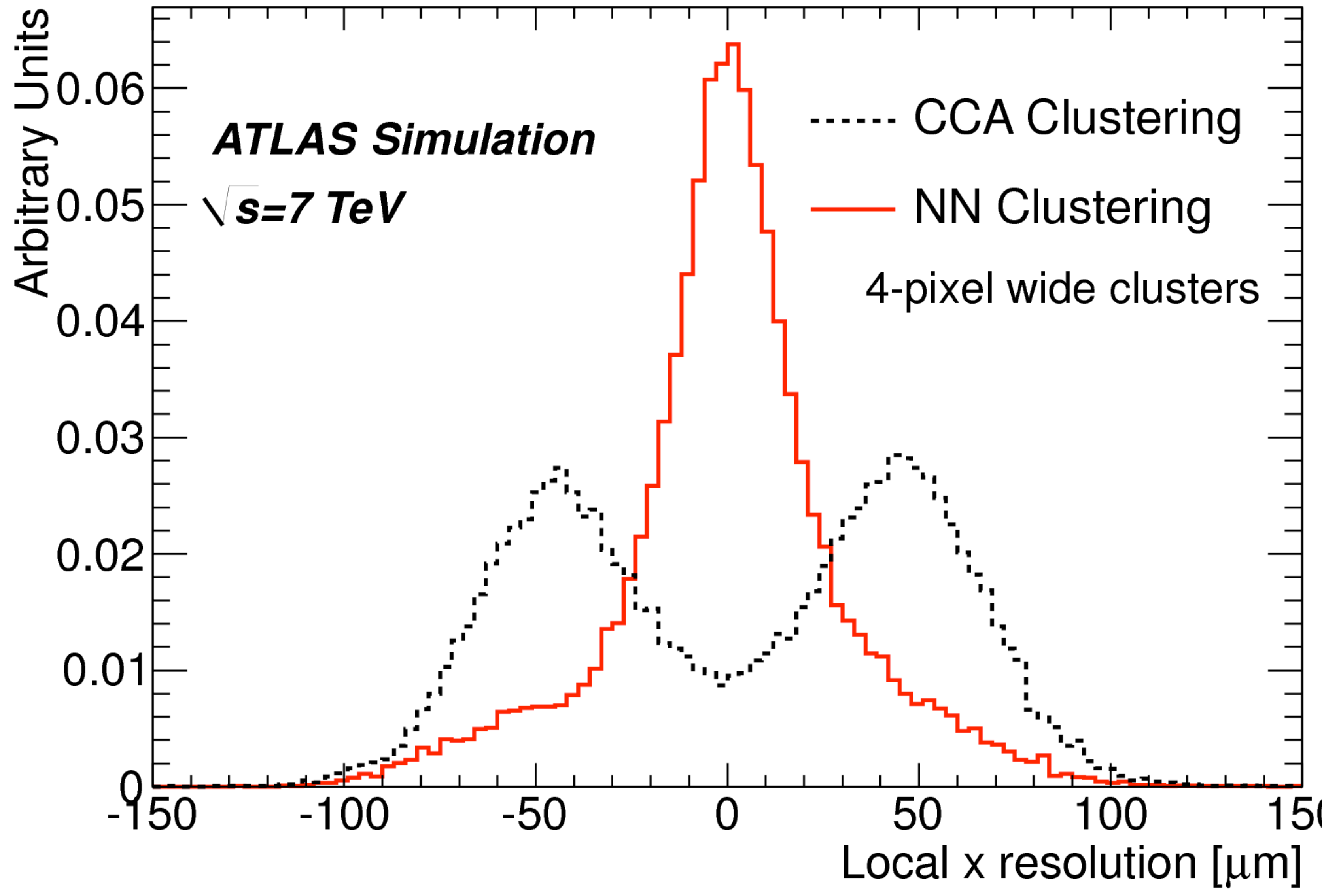




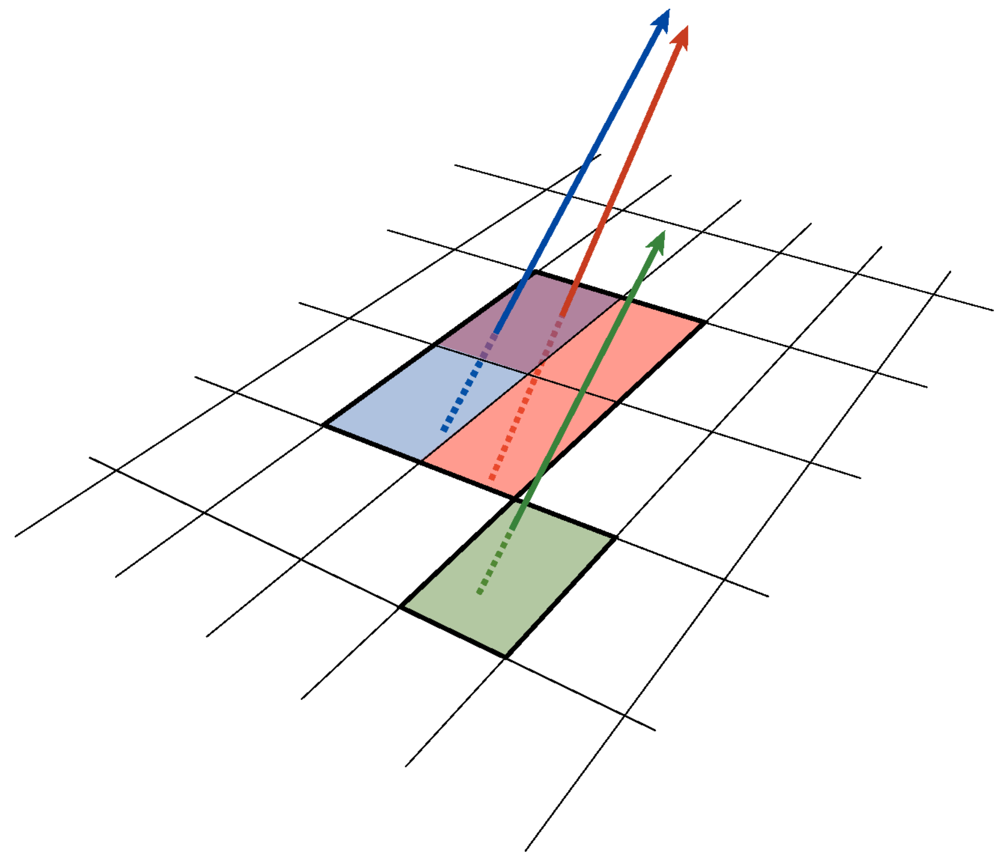
- An elaborate scoring is used to classify track candidates based on the number hits, number of holes, shared clusters, etc., before passing the tracks to the final track parameter fit
- For regions of interest within high-p_T jets shared hits are attempted to be split by a neural network. A second mixed-density network is used to assign position uncertainties to the split clusters
- The rate of merged clusters in jets can be measured in data using the dE/dx distribution extracted from the cluster charge

Pixel Cluster Splitting

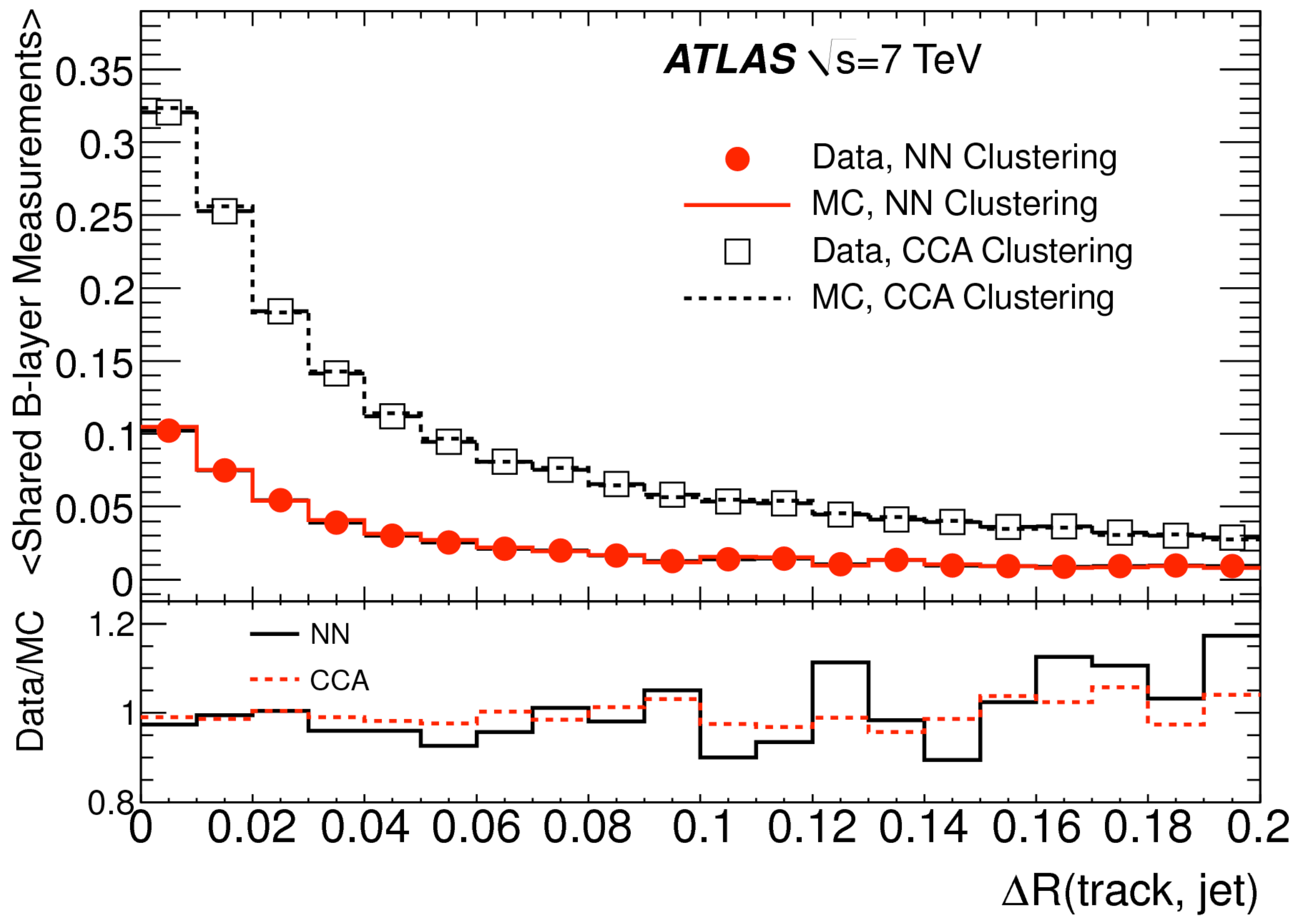




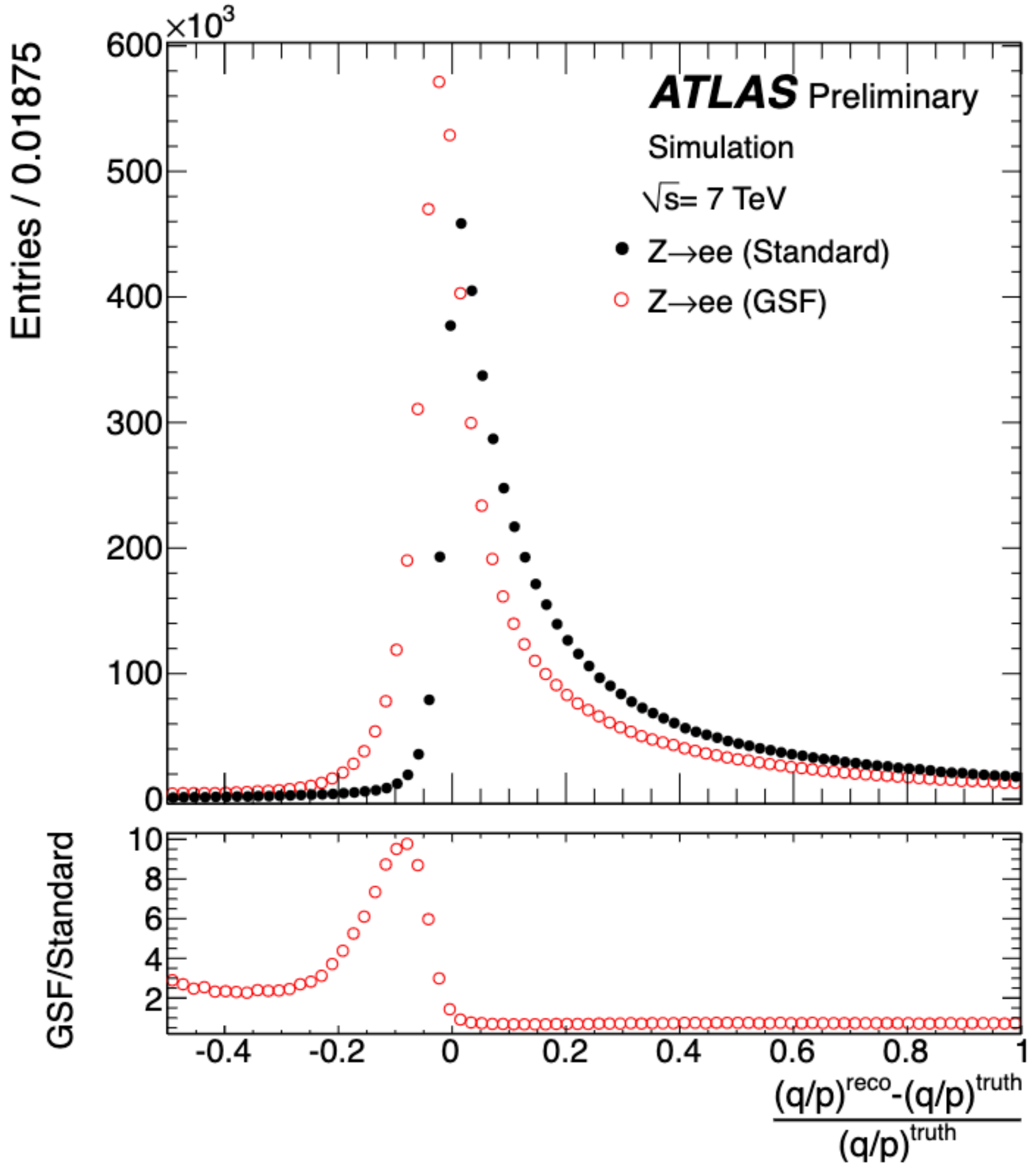
JINST 9 (2014) P09009

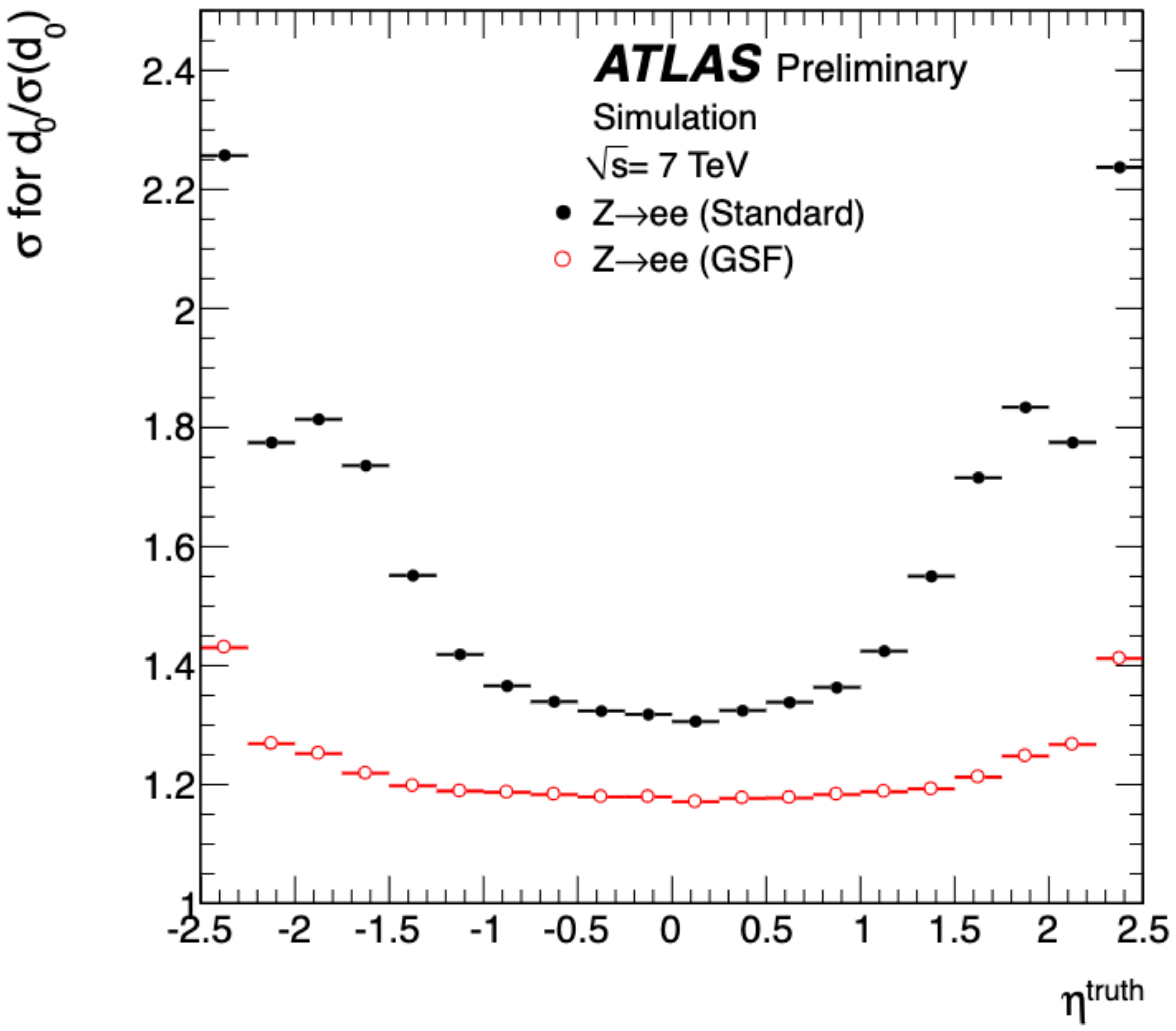


- In the core of jets, tracks can pass through the name or adjacent pixels, leading to shared clusters
- A simple center-of-gravity algorithm results in wrong hit position and larger uncertainties due to the cluster size
- Using the incident angles of the track candidates passing through a merged cluster candidate significantly improve the cluster splitting performance
- A NN is used to split the clusters if appropriate, leading to a significant reduction of shared clusters



Bremsstrahlung Recovery





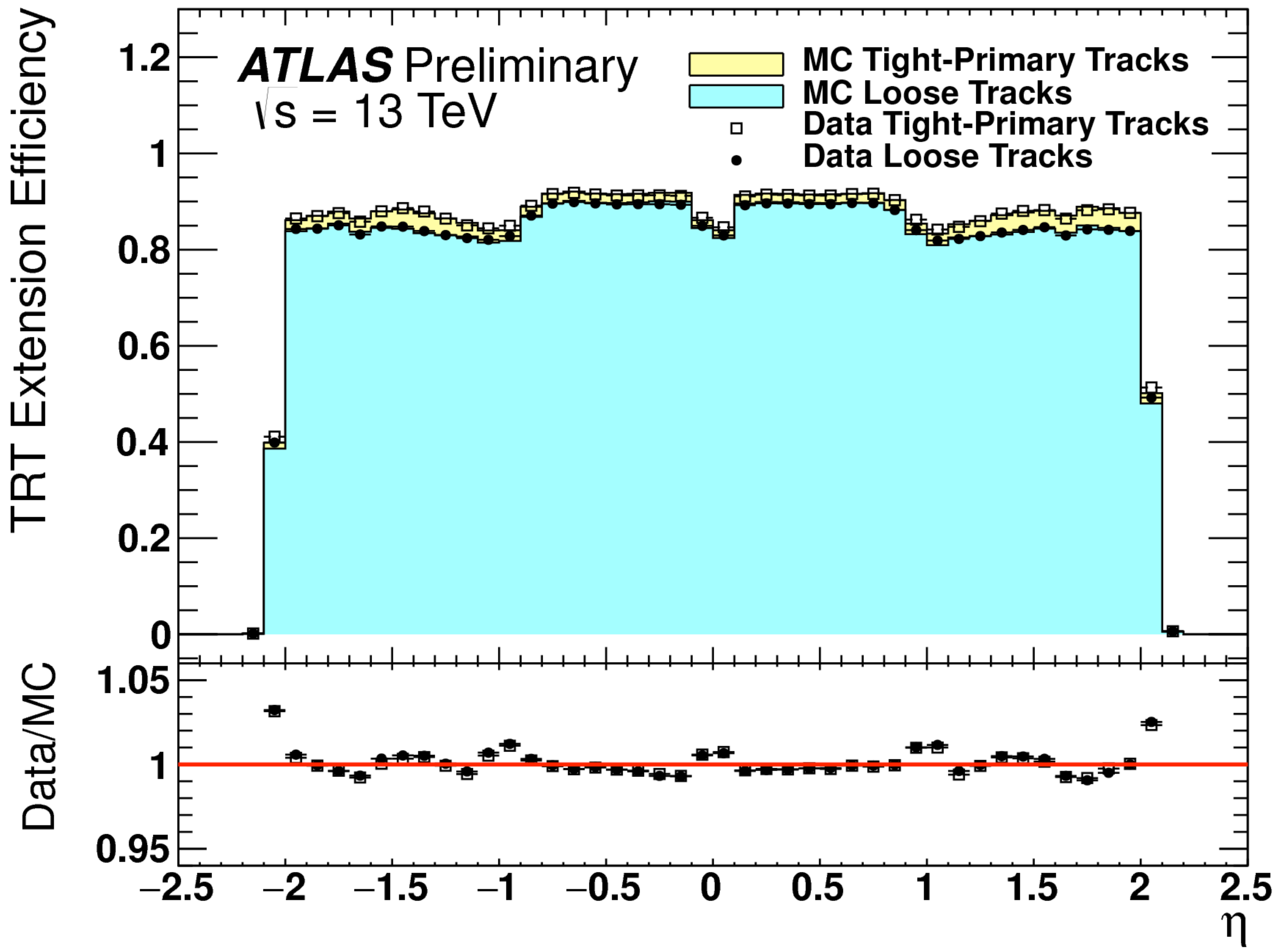
ATLAS-CONF-2012-047

- By default all trajectories assume pion tracks - electrons can have significantly larger energy loss from Bremsstrahlung which leads to larger scattering angles
- Allow additional scattering probabilities, modelled as a sum of Gaussian distributions (Gaussian Sum Filter)

TRT Track Extensions

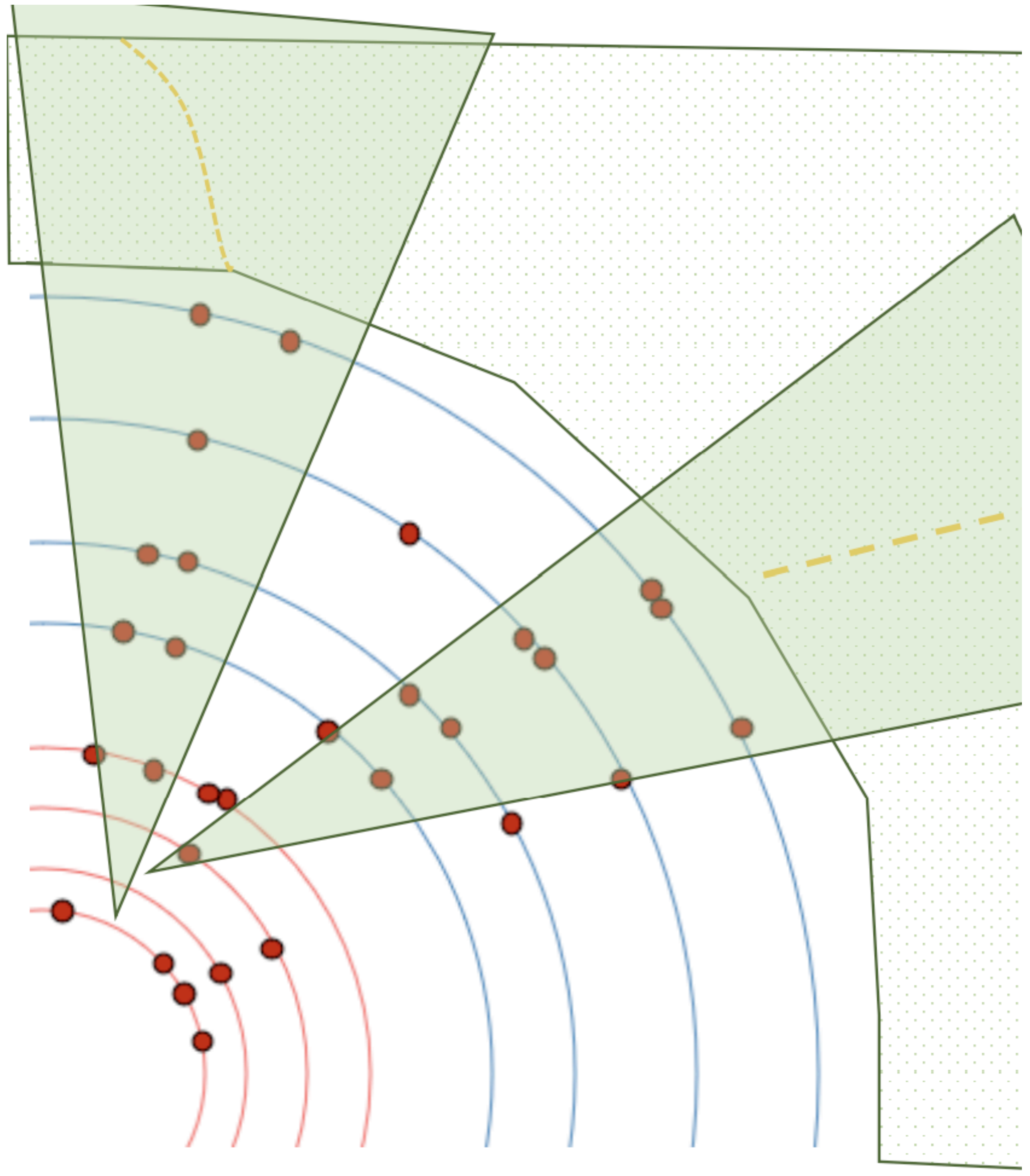
- Tracks from the Si-only tracking are attempted to be extended into the TRT
- All TRT straws consistent with the track road are considered and labelled as “precision hit” if the track passes within 1.75σ of the TRT drift-circle. Hits that are not precision hits get a penalty in the fit
- Several iterations of the global χ^2 fit are performed until it converges. Only candidates with more than 30% precision hits are accepted as TRT extensions to ensure improvement of the track parameter measurement

ATL-PHYS-PUB-2015-018



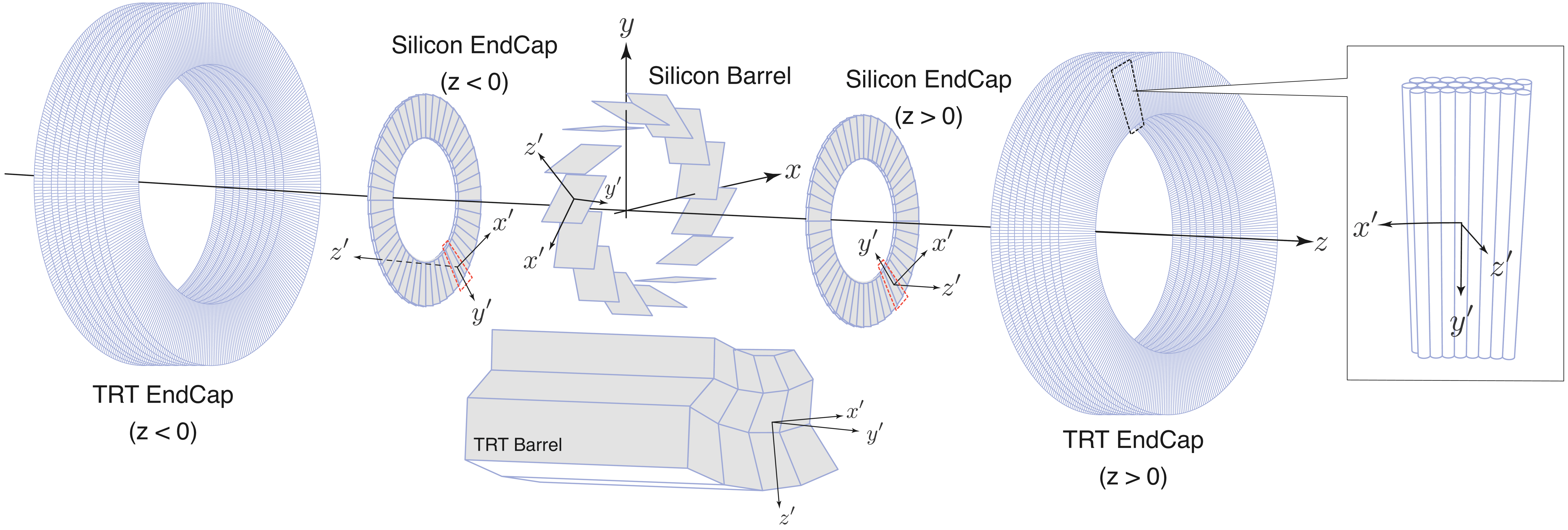
Back Tracking

- To recover photon conversion tracks and other late decays, a back-tracking pass is run after the inside-out tracking
- Start from EM cluster with $E_T > 6$ GeV to define a region of interest
- Use Hough-transformation of all TRT hits in this ϕ-region in a to form segments and define the initial track parameters
- Look for Si-hit pairs that confirm the TRT segment, and run the usual inside-out Kalman-Filter + TRT extension to finalise the tracks
- TRT segments that find only 1 or 0 Si-hits are not used as track candidates in general, but still used in photon conversion tagging



Inner Detector Alignment

Eur. Phys. J. C 80 (2020) 1194

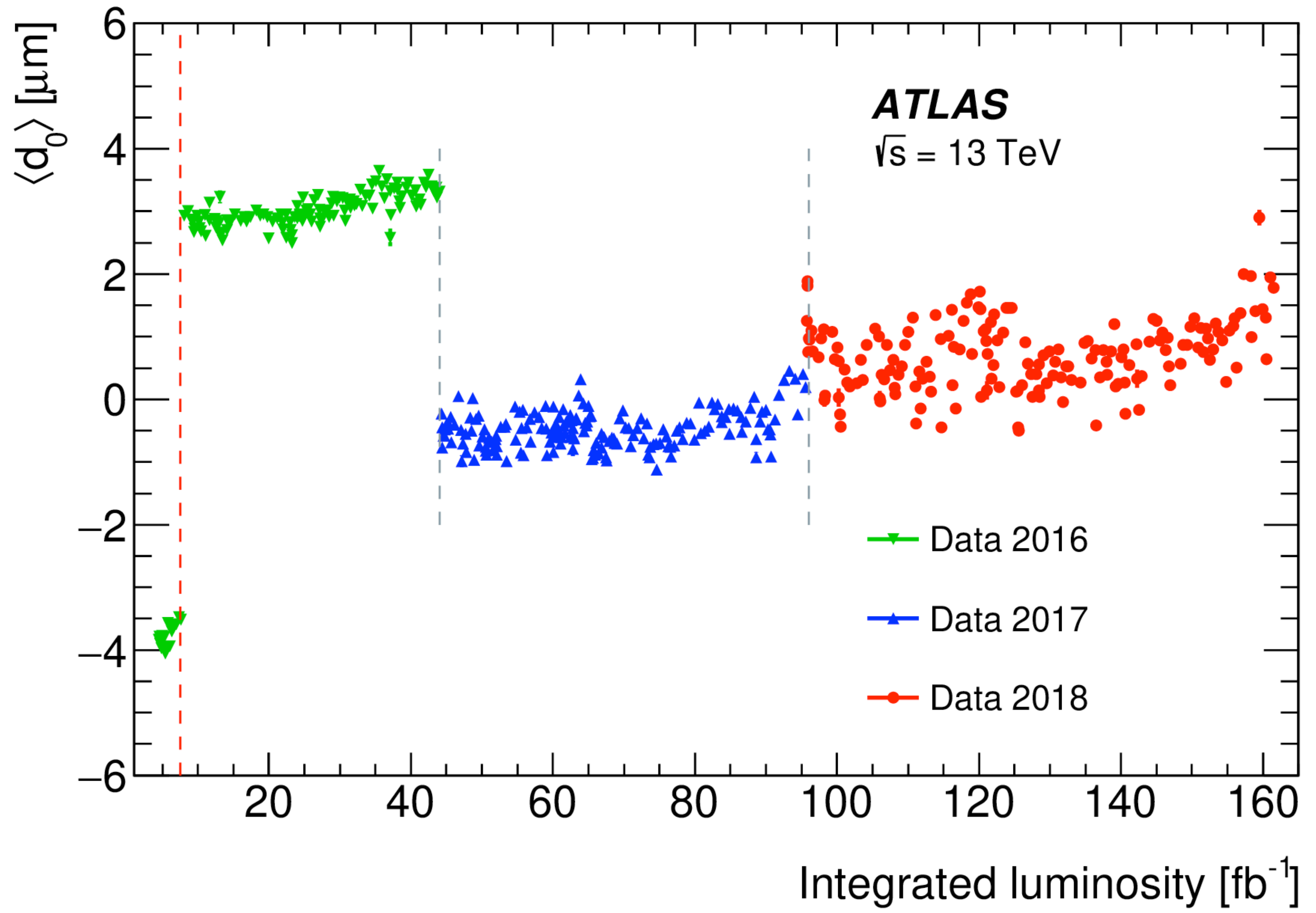


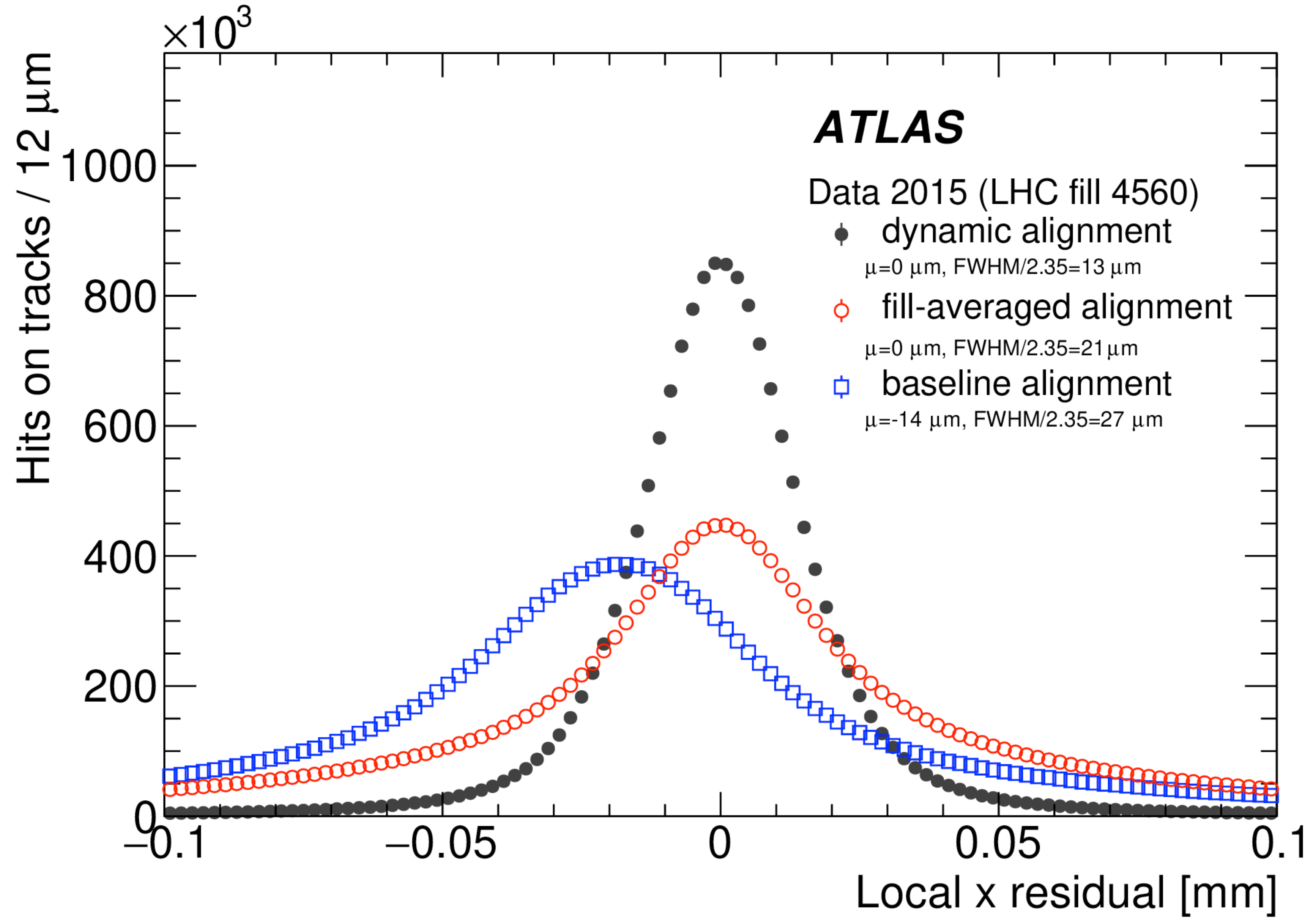
- The detector modules are not fixed in space: They move whenever the magnets are turned on, due to temperature effects, bending, etc.
- These effects need to be considered for ultimate precision
- Use muons from Z and J/ψ decays to determine all module positions and orientations by global χ^2 minimisation
- The alignment constants are updated for all runs, and even within runs (not all degrees of freedom)

Inner Detector Alignment

Eur. Phys. J. C 80 (2020) 1194

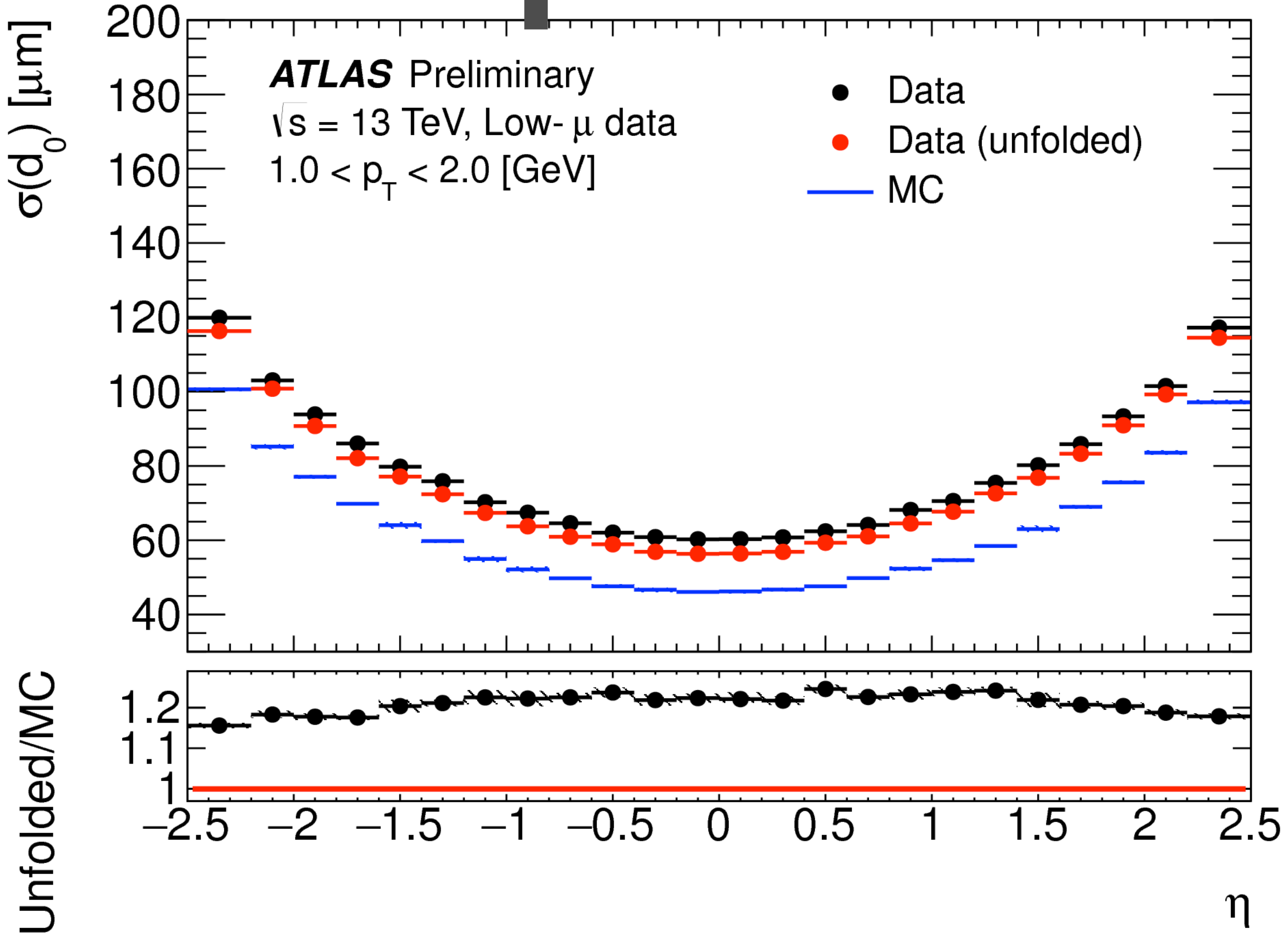
Level	Description	Structures	DoF	Additional constraints
1	IBL	1	All	
	Pixel detector	1	All	
	SCT endcaps (SCT barrel fixed)	2	All except T_z	
	TRT split into barrel and 2 endcaps	3	All except T_z	
Si 2	Pixel and IBL barrel split into layers	4	All	Beam spot,
	Pixel endcaps split into disks	6	All	momentum bias, and
	SCT barrel split into layers	4	All	impact parameter bias
	SCT endcaps split into disks	18	All	
Si 3	Pixel and IBL barrel modules	1736	All	Beam spot,
	Pixel endcaps modules	288	T_x, T_y, R_z	momentum bias,
	SCT barrel modules	2112	All	impact parameter bias, and
	SCT endcaps modules	1976	T_x, T_y, R_z	module placement accuracy
TRT 2	TRT barrel split into barrel modules	96	All except T_y	Momentum bias and
	TRT endcaps split into wheels	80	T_x, T_y, R_z	impact parameter bias
	Pixel and SCT detectors fixed			
TRT 3	TRT straws	351k	T_x, R_z	
	Pixel and SCT detectors fixed			

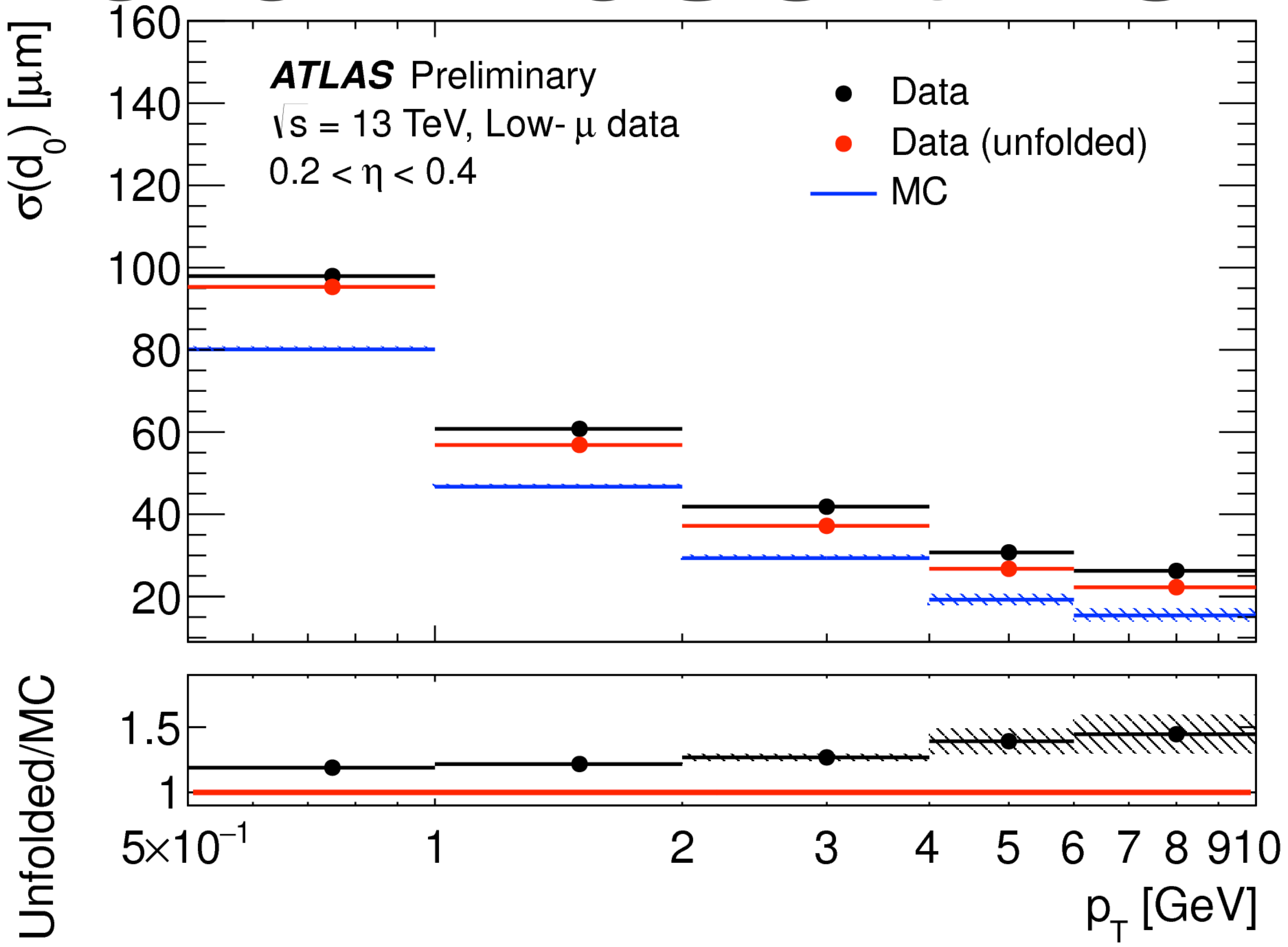


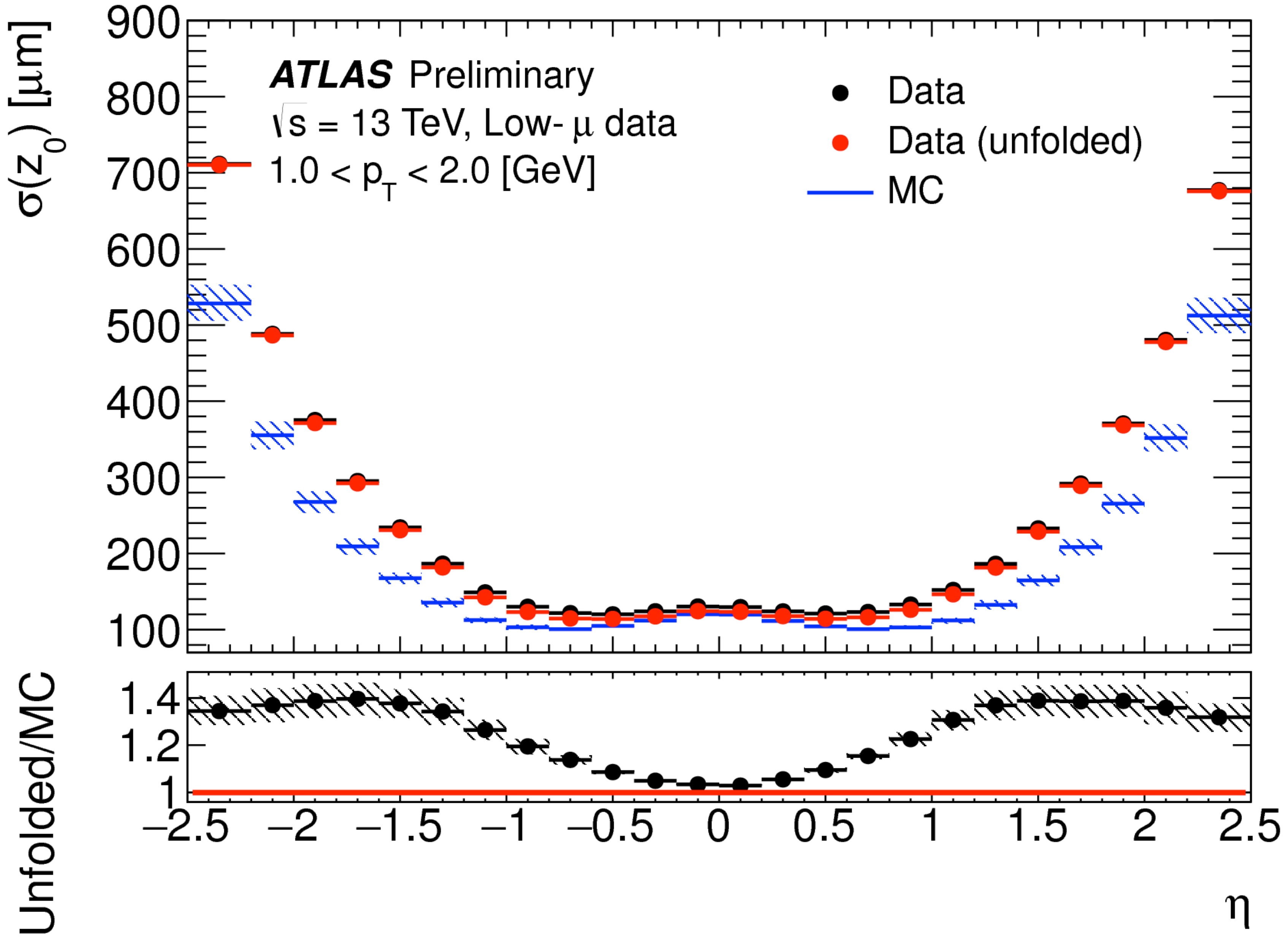


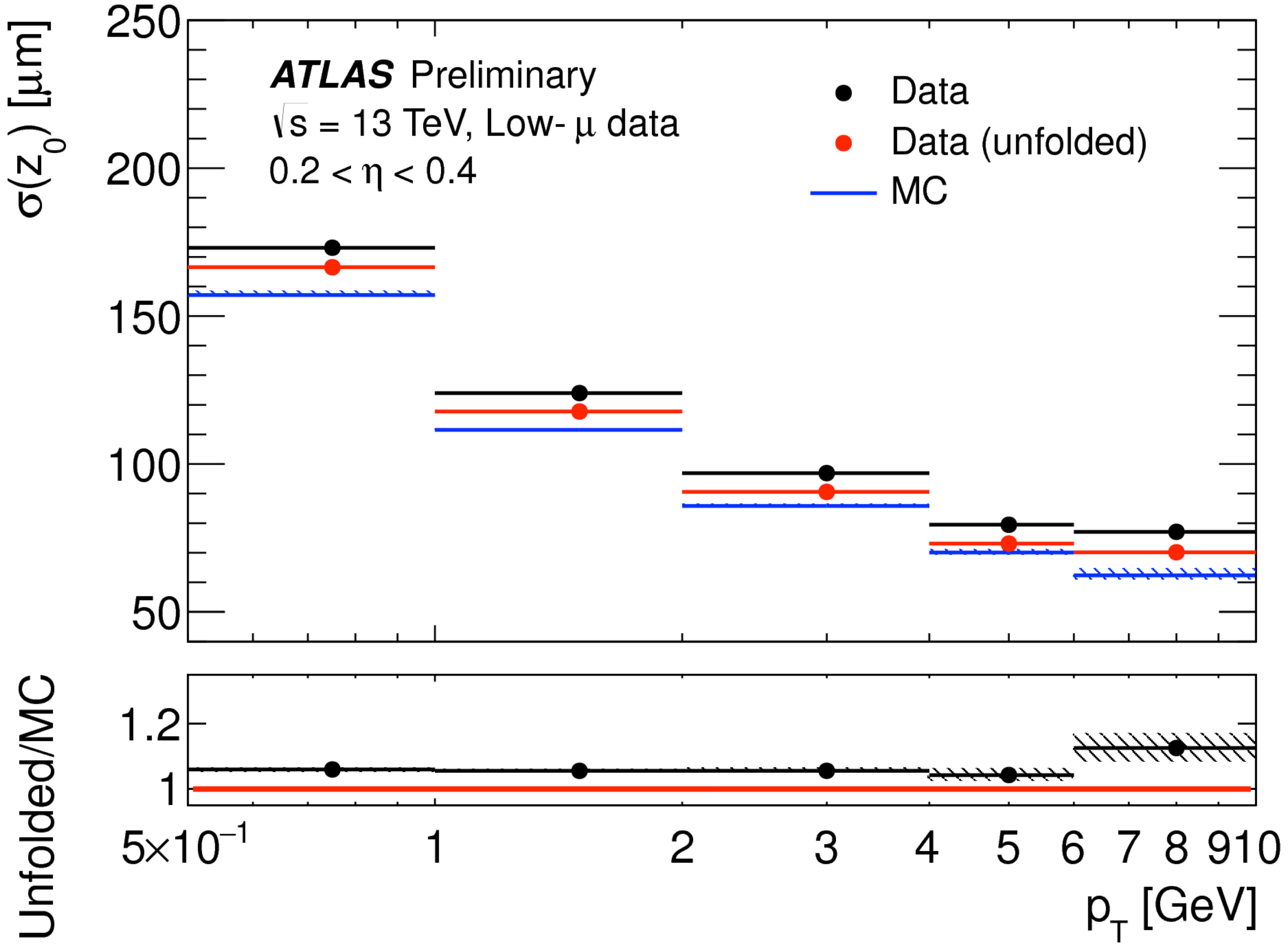
Impact Parameter Resolution

ATL-PHYS-PUB-2015-018



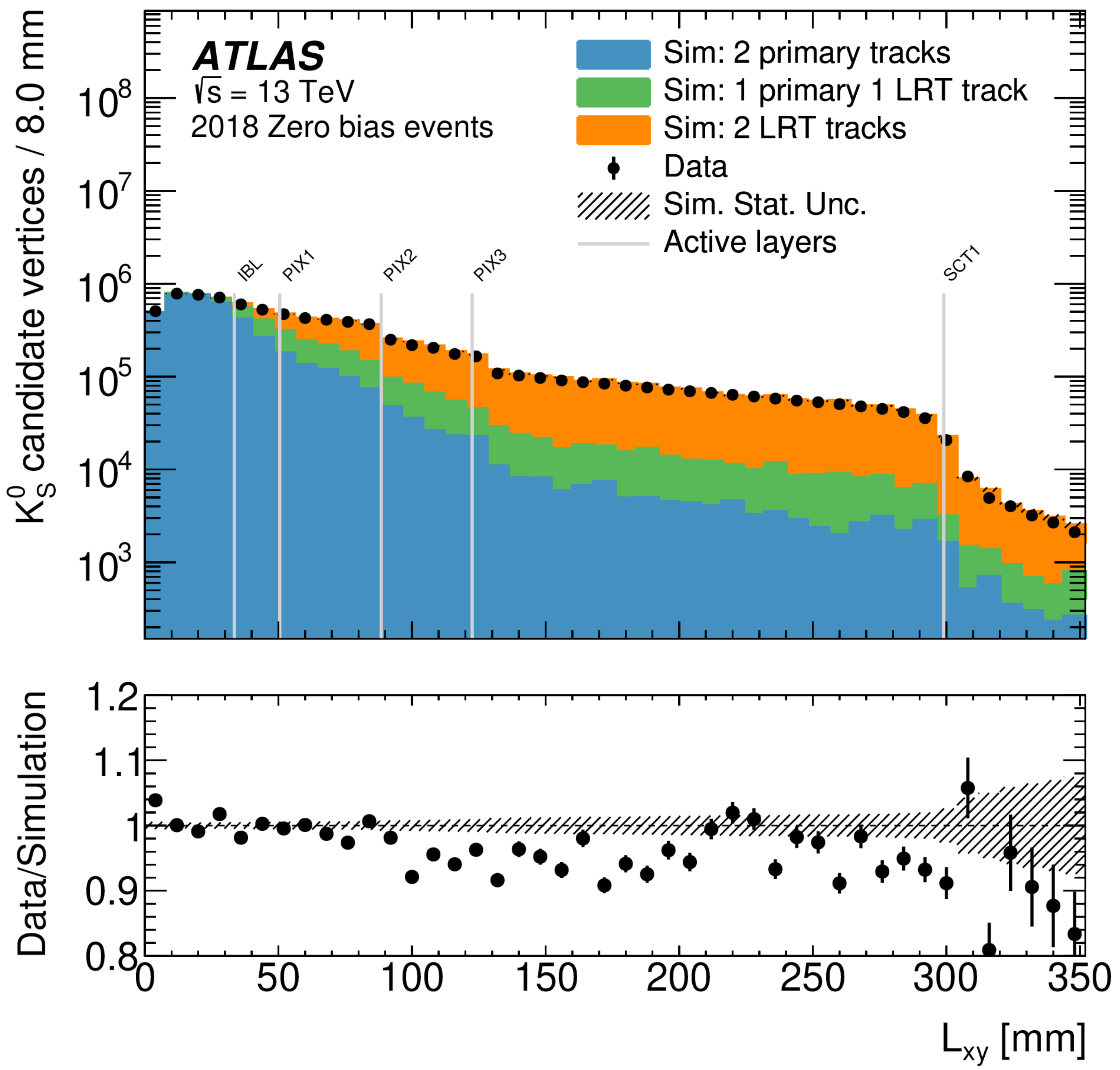


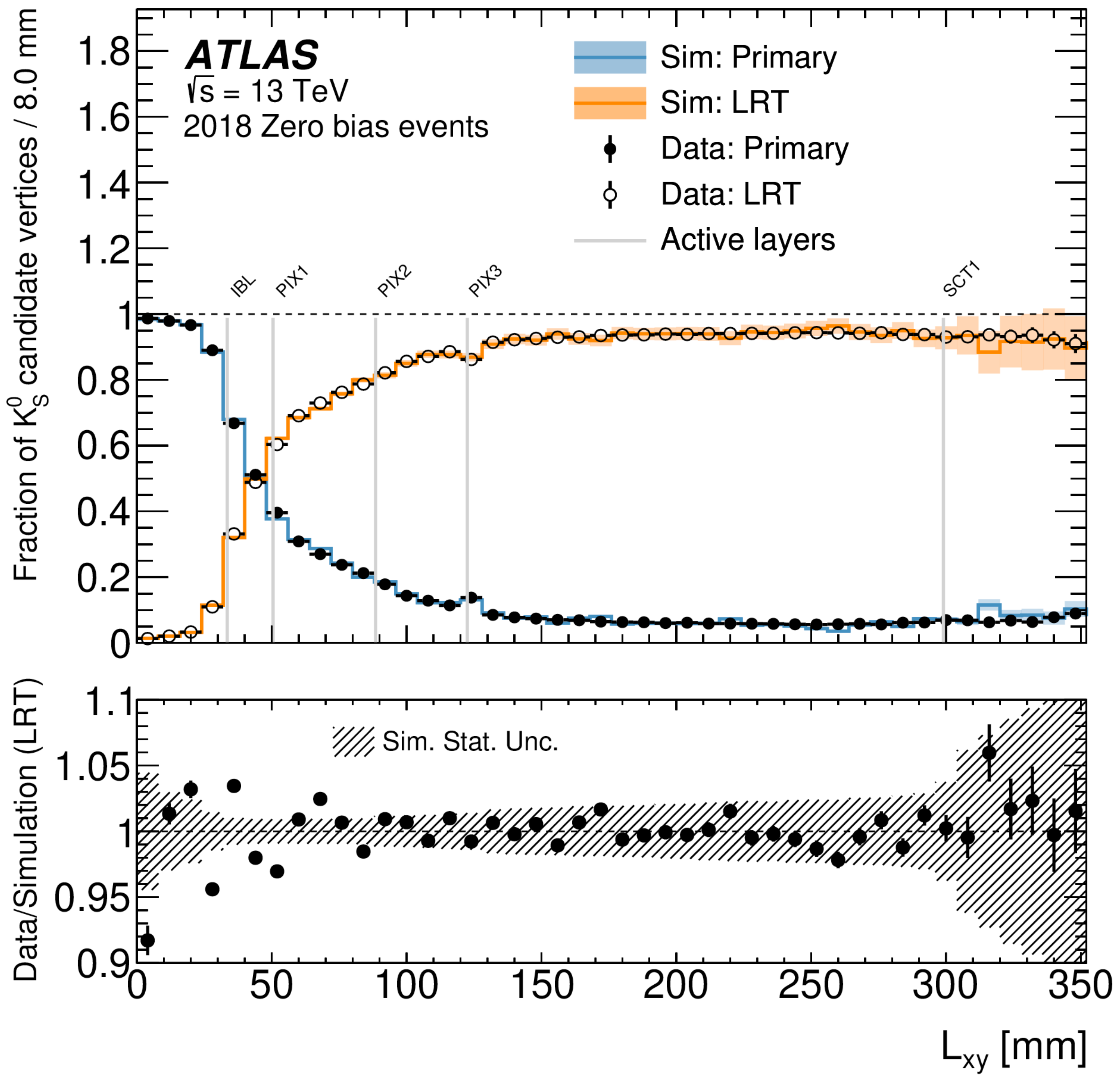




Long-Lived Particles

Eur. Phys. J. C 83 (2023) 1081

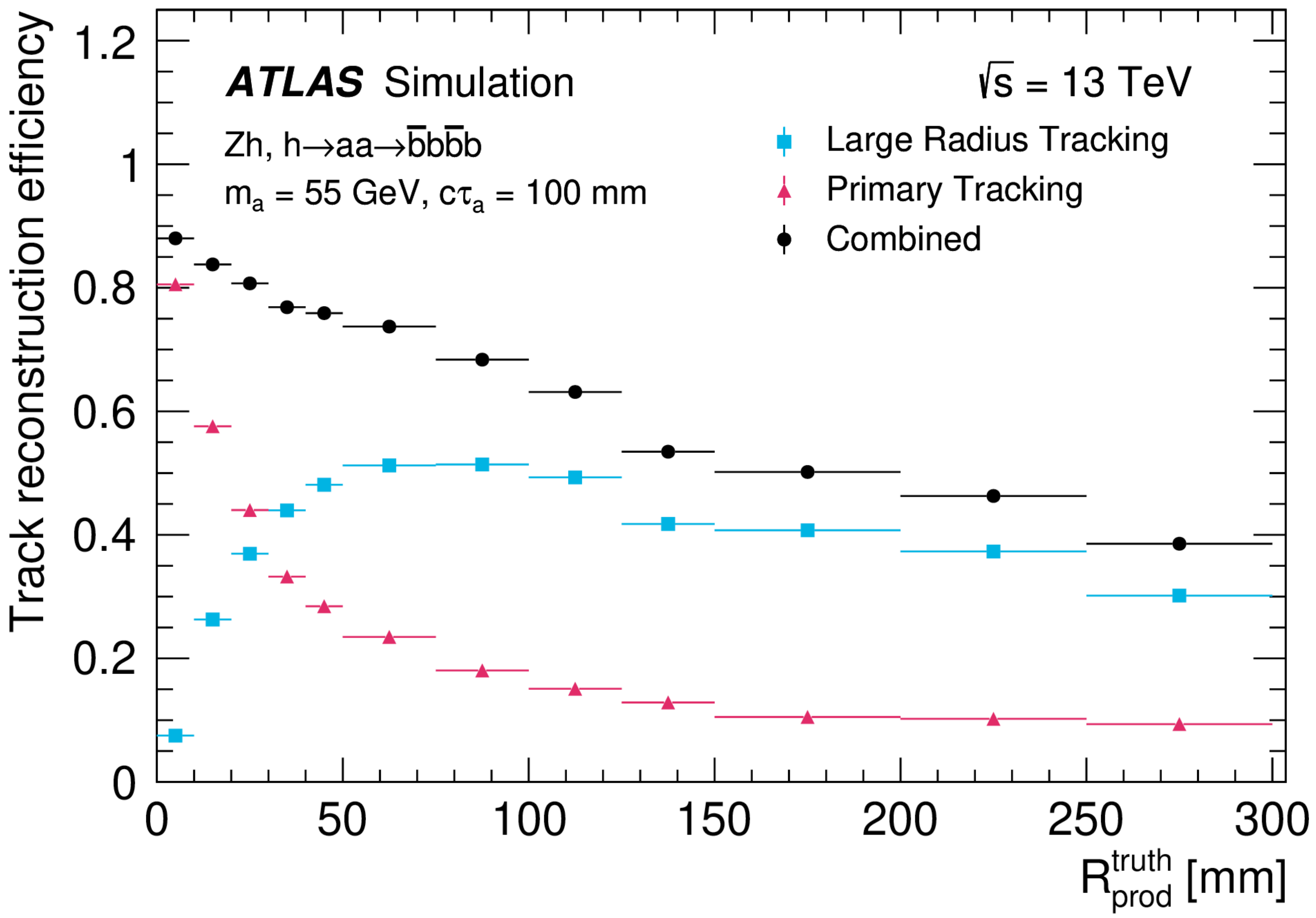


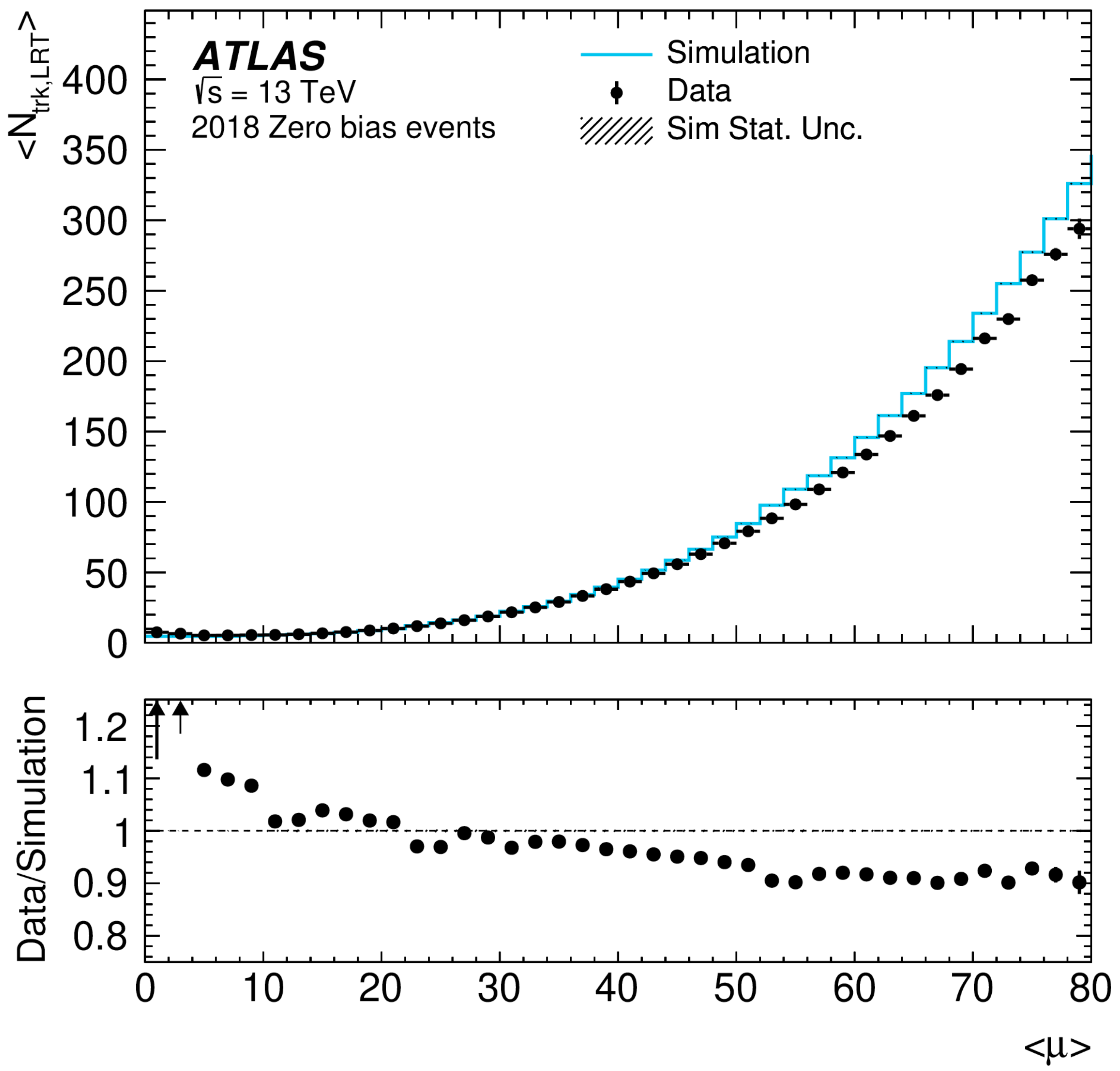


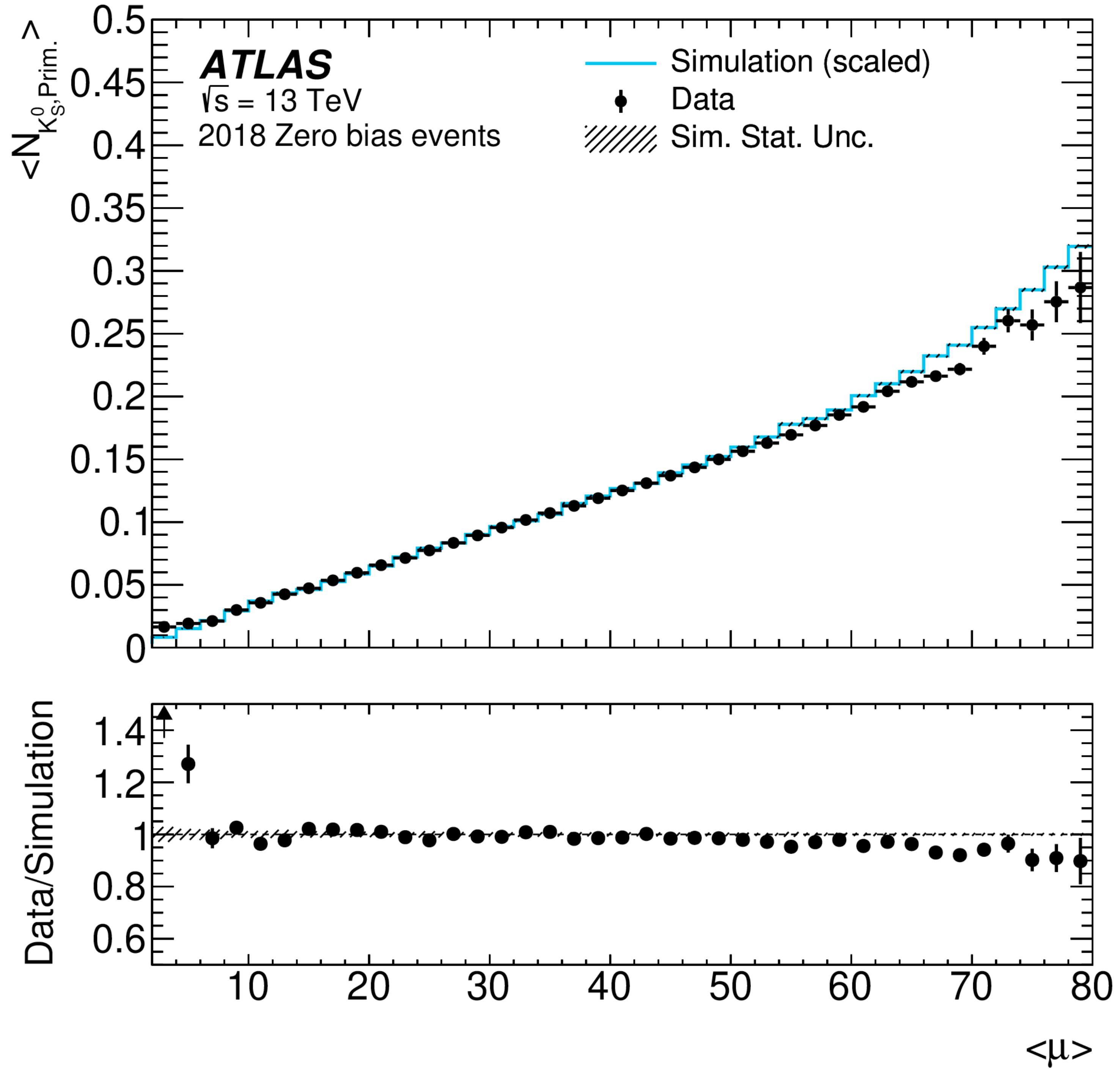
- Tracks originating from long-lived decays (K_s or BSM particles) often fail the default track parameter cuts
- Run dedicated pass on remaining hits with significantly relaxed requirements ($d_0 < 300$ mm, $z_0 < 500$ mm). Only consider SCT seeds since pixel hits are mostly missed.

Large Radius Tracking

Eur. Phys. J. C 83 (2023) 1081

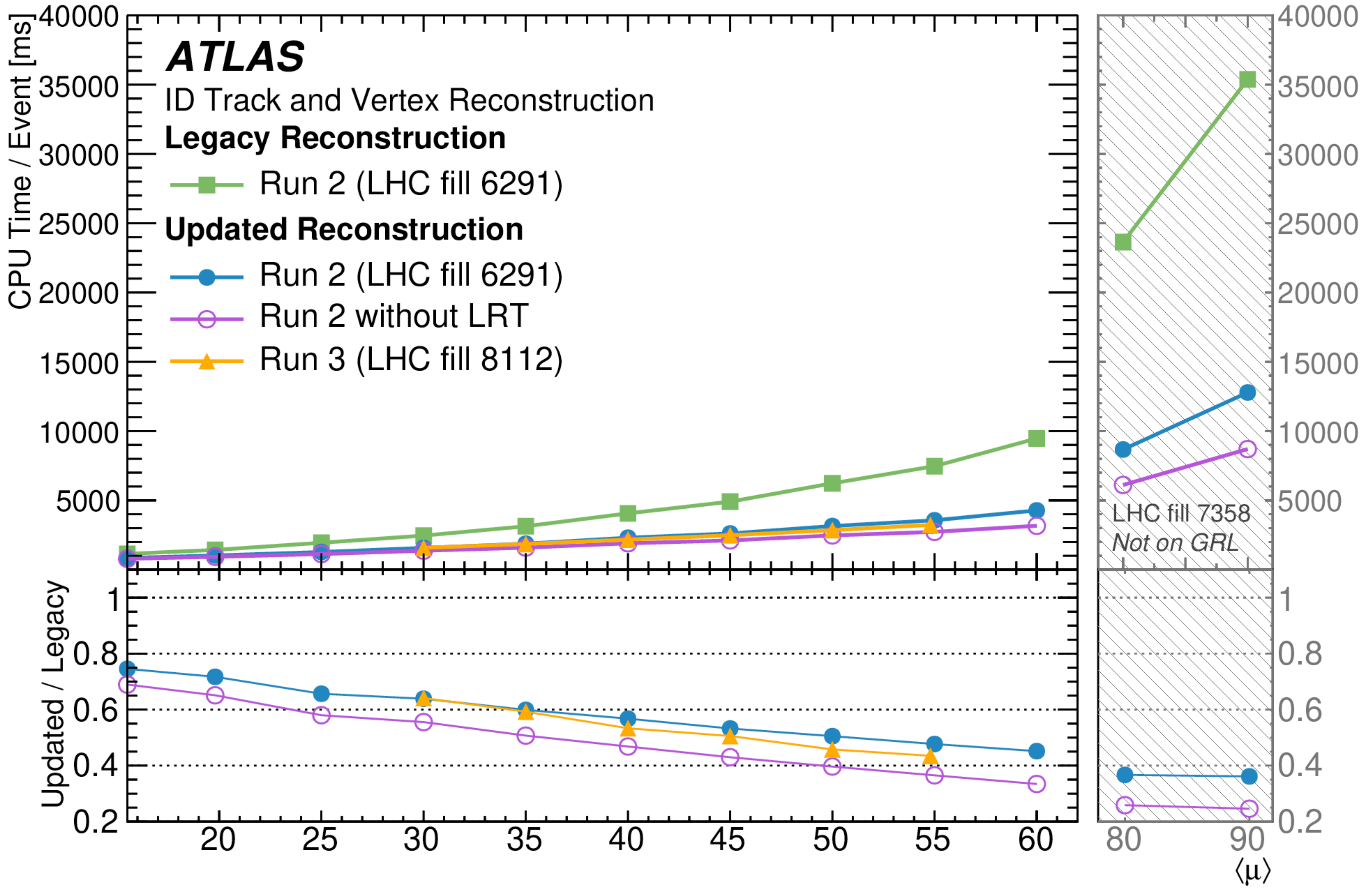


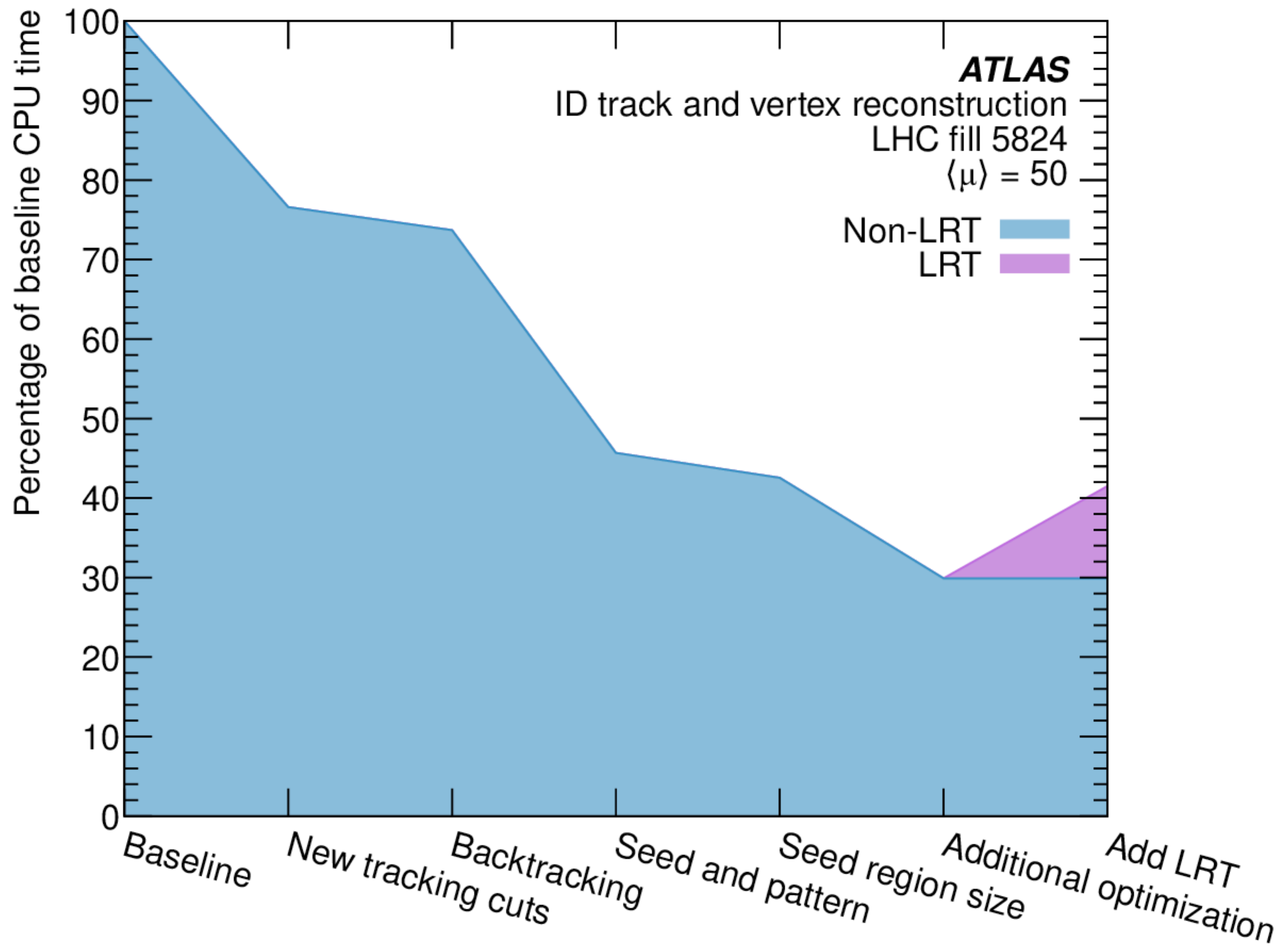




- The original version was only run on 10% of the data due to the large CPU time consumption.
- Significant reduction in run time by allowing at most 1 hole and narrowing the search road: losing about 5% track finding efficiency allows to run this algorithm by default on all data
- The large number of fake tracks at high pile-up gets reduced once physics requirements are applied (like secondary vertex fit)

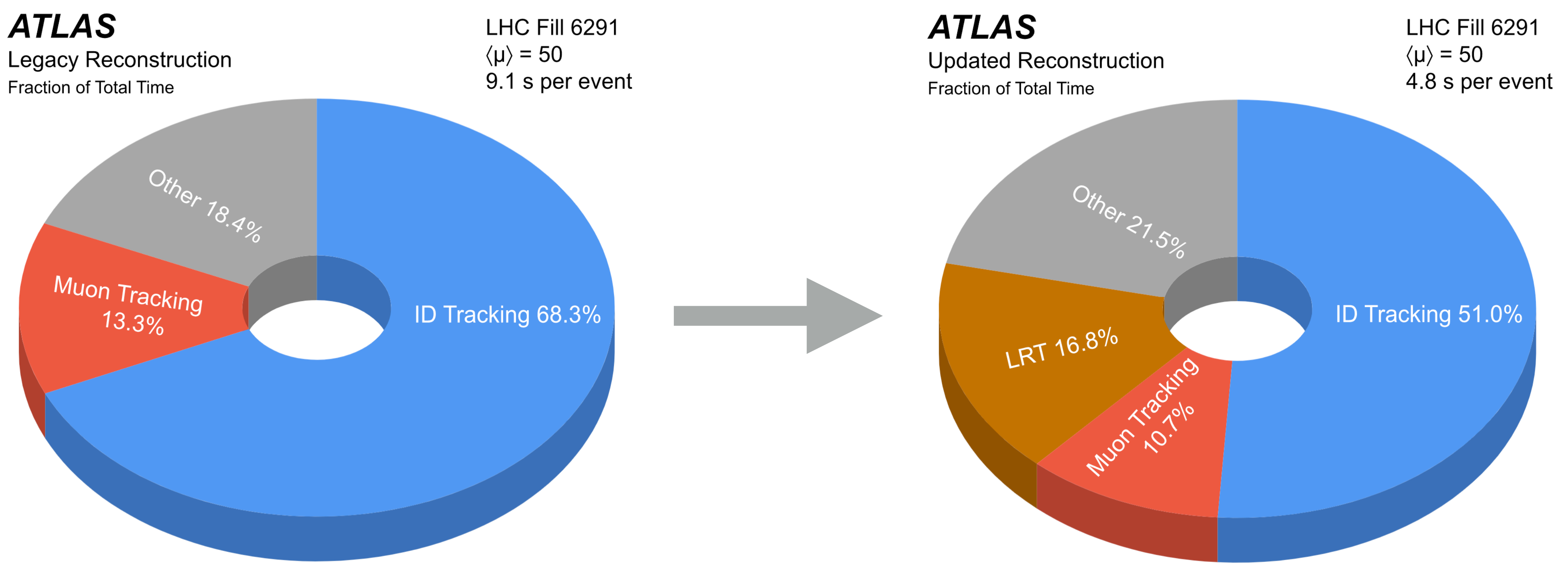
Optimising the Reconstruction Speed





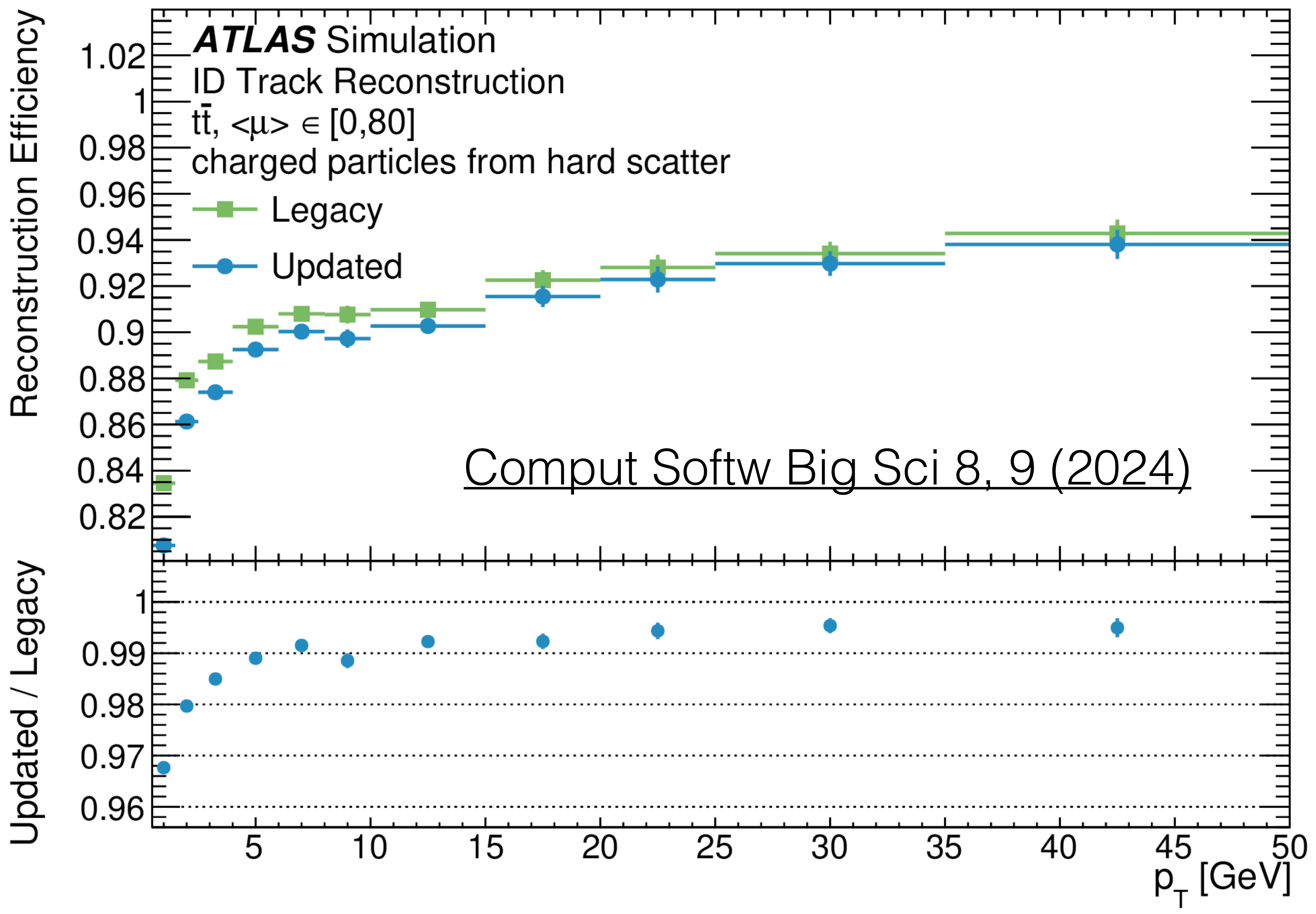
- Before the start of Run 3 the track finding logic was completely revisited to reduce the CPU time

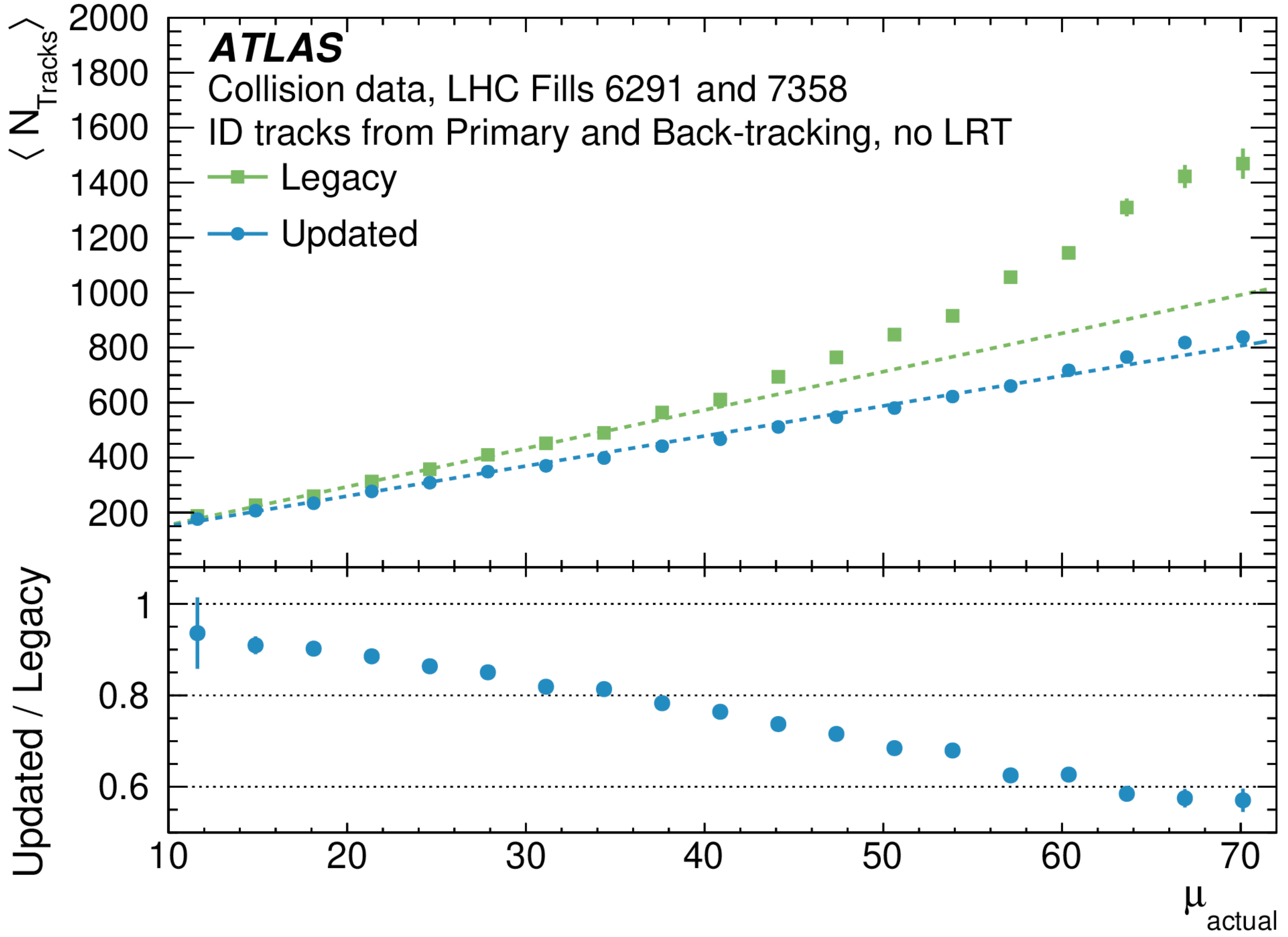
- Tighten impact parameter cuts in the seeding, no more shared pixel hits in seeds, narrower search road when extending seeds, require 8 instead of 7 silicon hits before TRT extension, higher cluster energy required to seed back-tracking, …



Comput Softw Big Sci 8, 9 (2024)

Performance after CPU Optimisation

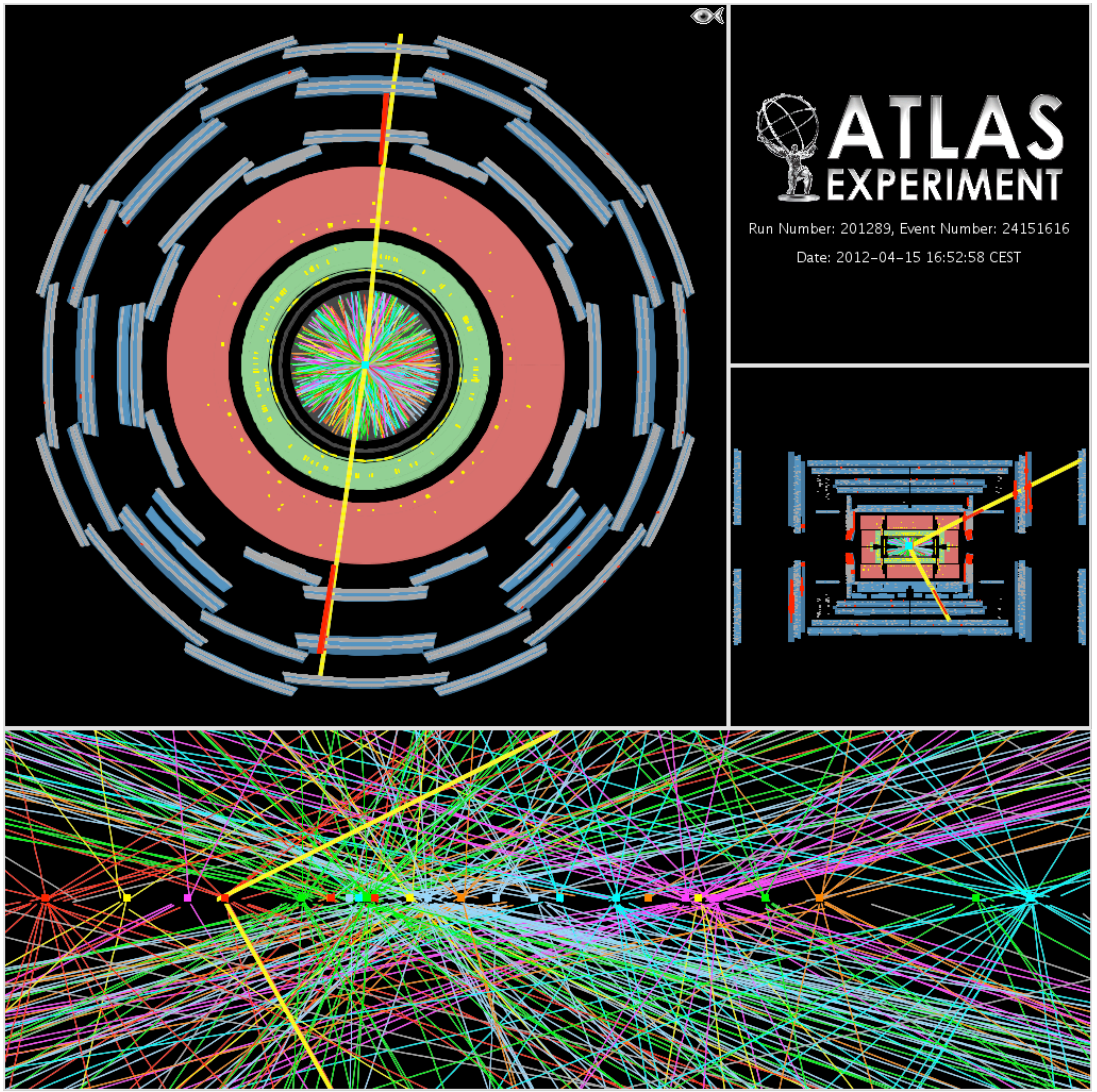


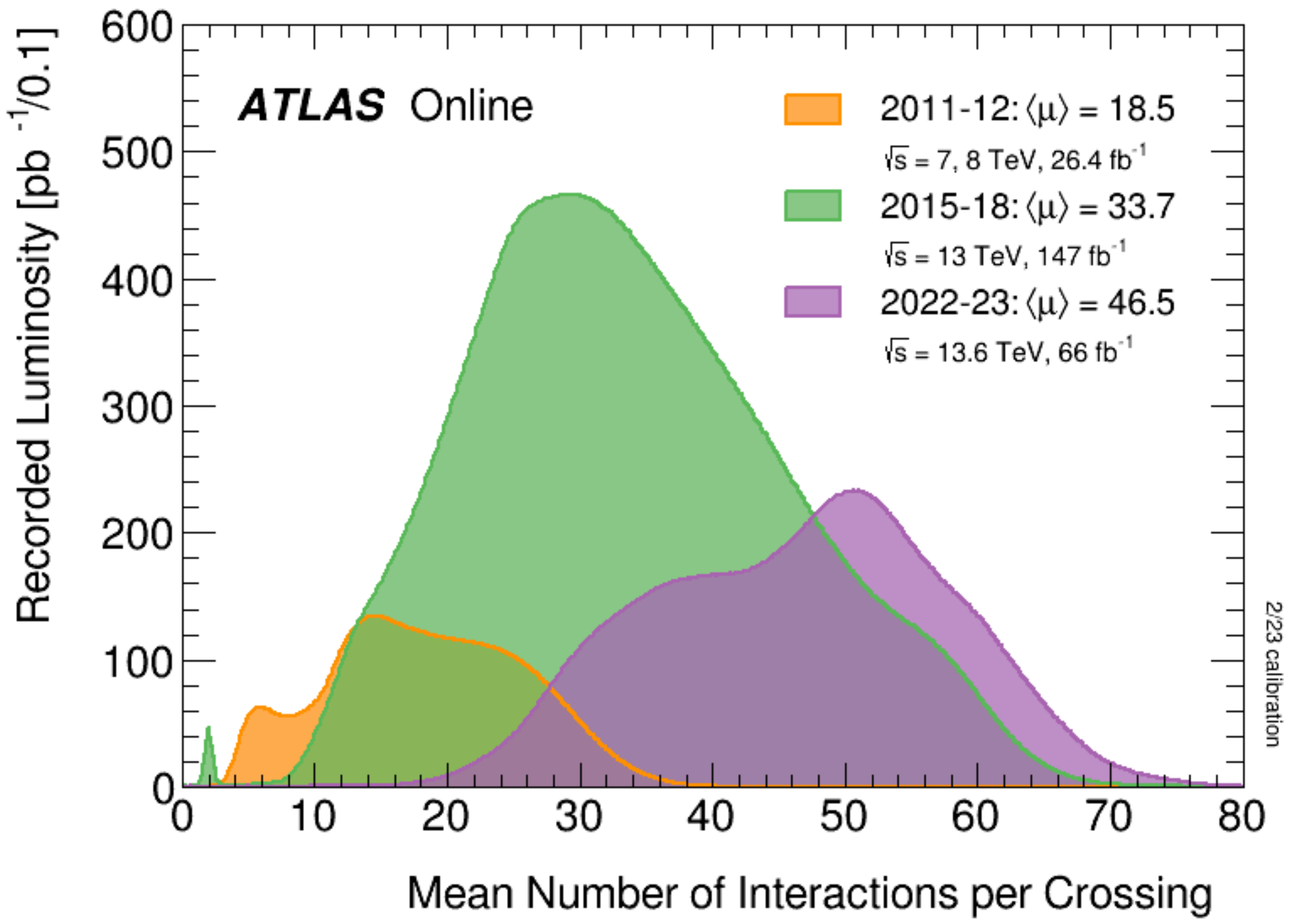


- The tightened selections results in 1-4% loss of track finding efficiency but reduces the number of fake tracks by more than one order of magnitude, especially at high pile-up

- Total speed up of up to factor 2, and and a reduction of event size by up to 40%, due to the reduced number of fake tracks

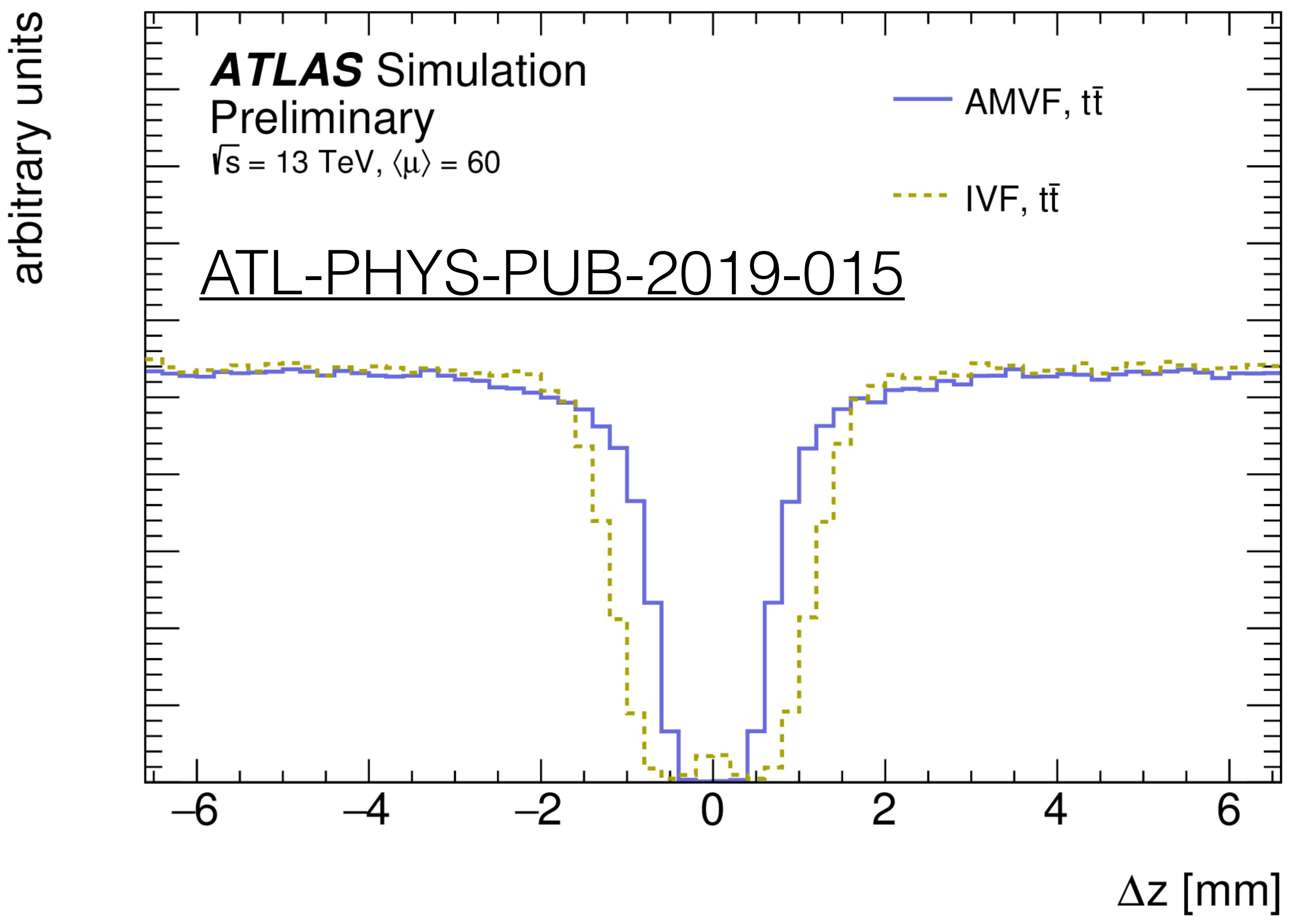
Finding and Fitting Vertices

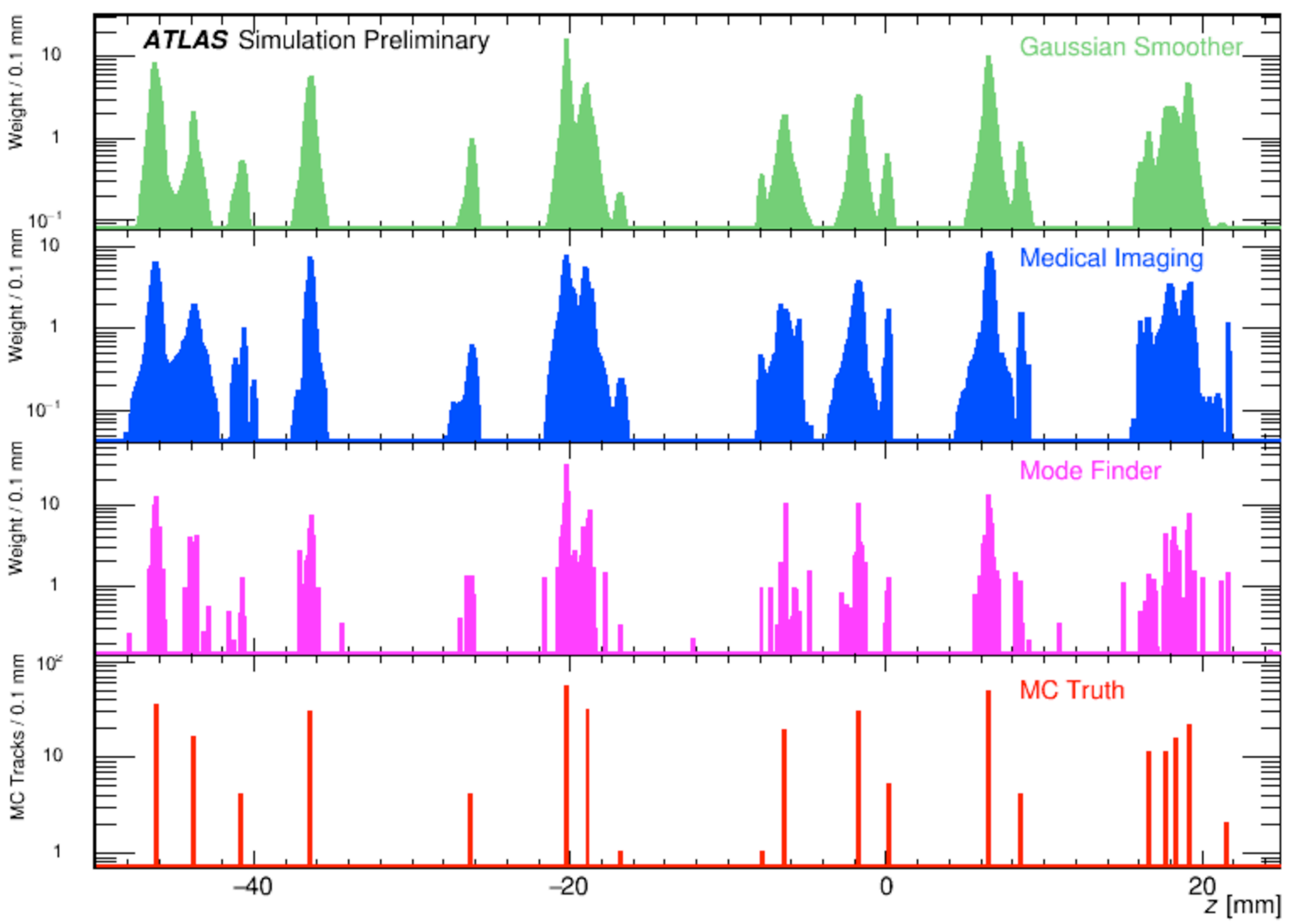


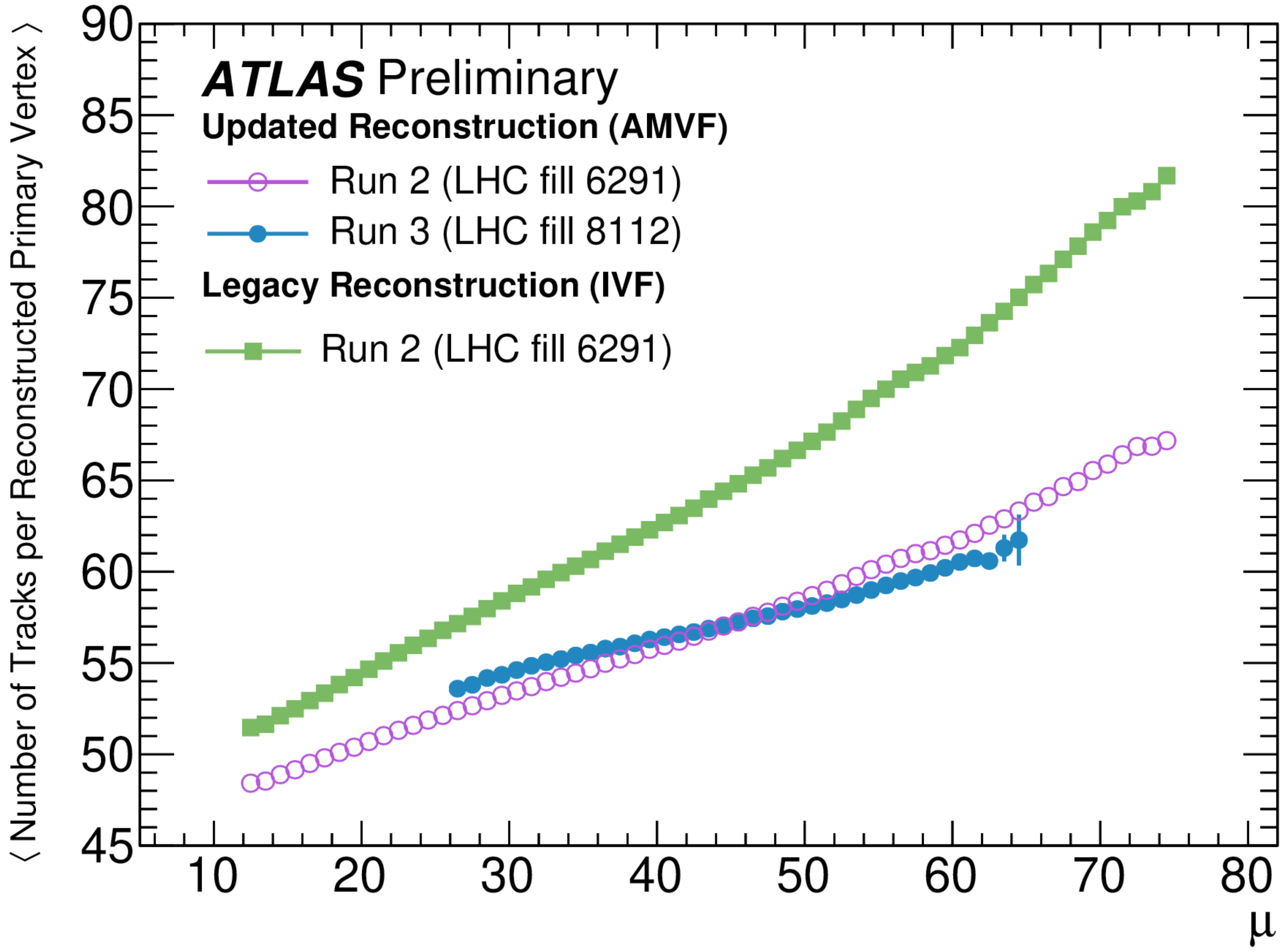


- Typically over 50-60 pile-up interactions per bunch-crossing in Run 3!

Primary Vertex Finding

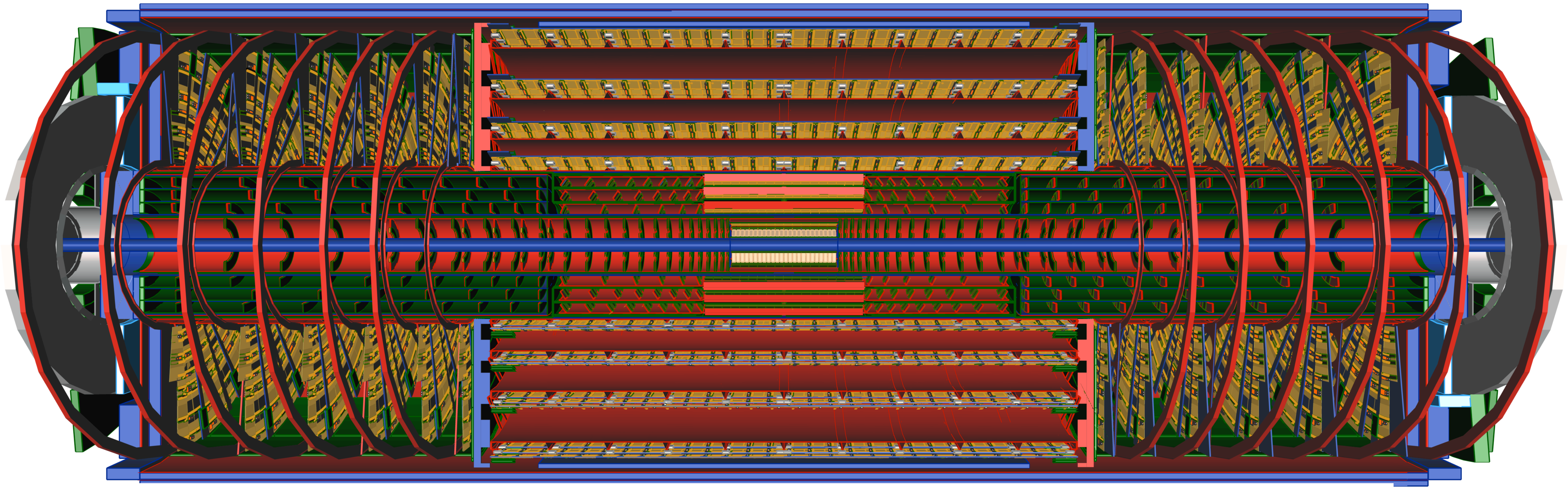




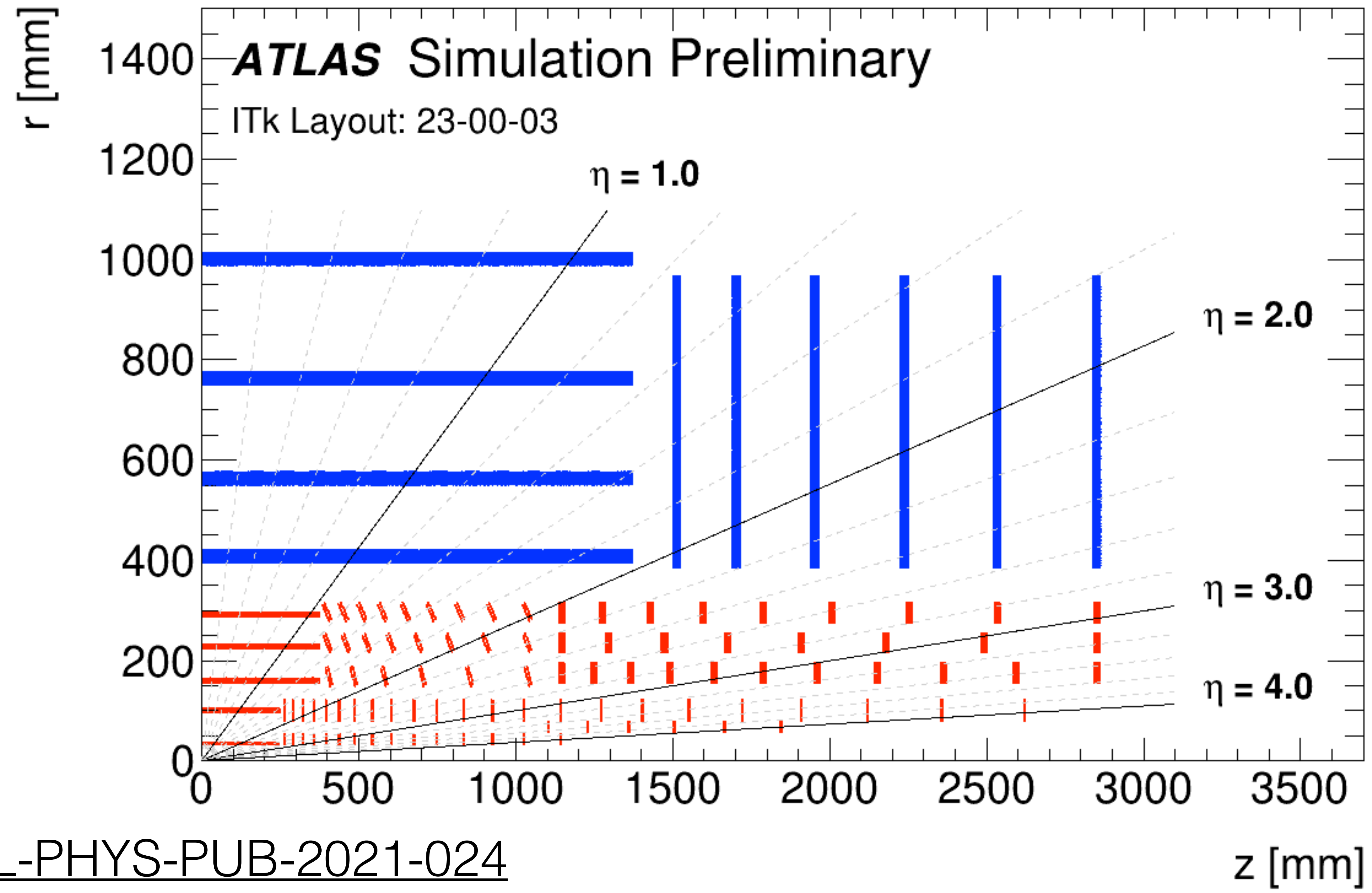


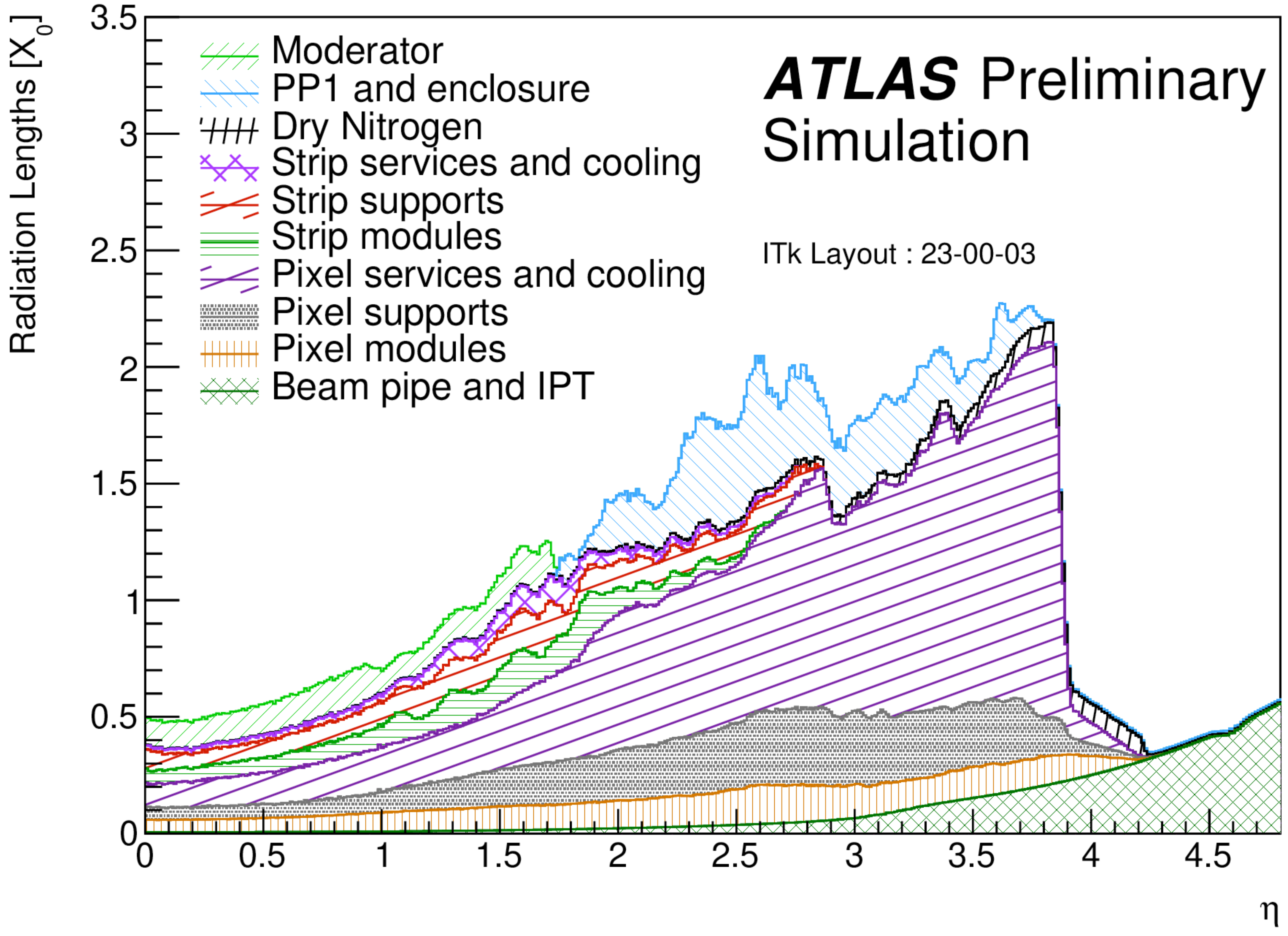
- Find maxima in track density along z, group tracks accordingly before using them for a primary vertex fit. Use the Gaussian smoother algorithm for the seed definition since Run 3 (before we used mode finder)
- Compatible tracks are combined in a weighted Kalman-Filter in the Adaptive Multi-Vertex Fitter
- Each track is assigned a weight for each vertex association. The track-to-vertex association is defined by cutting on these weights

Tracking at the HL LHC



- For Run 4 the ATLAS inner detector will be complete replaced by the all-silicon ITk

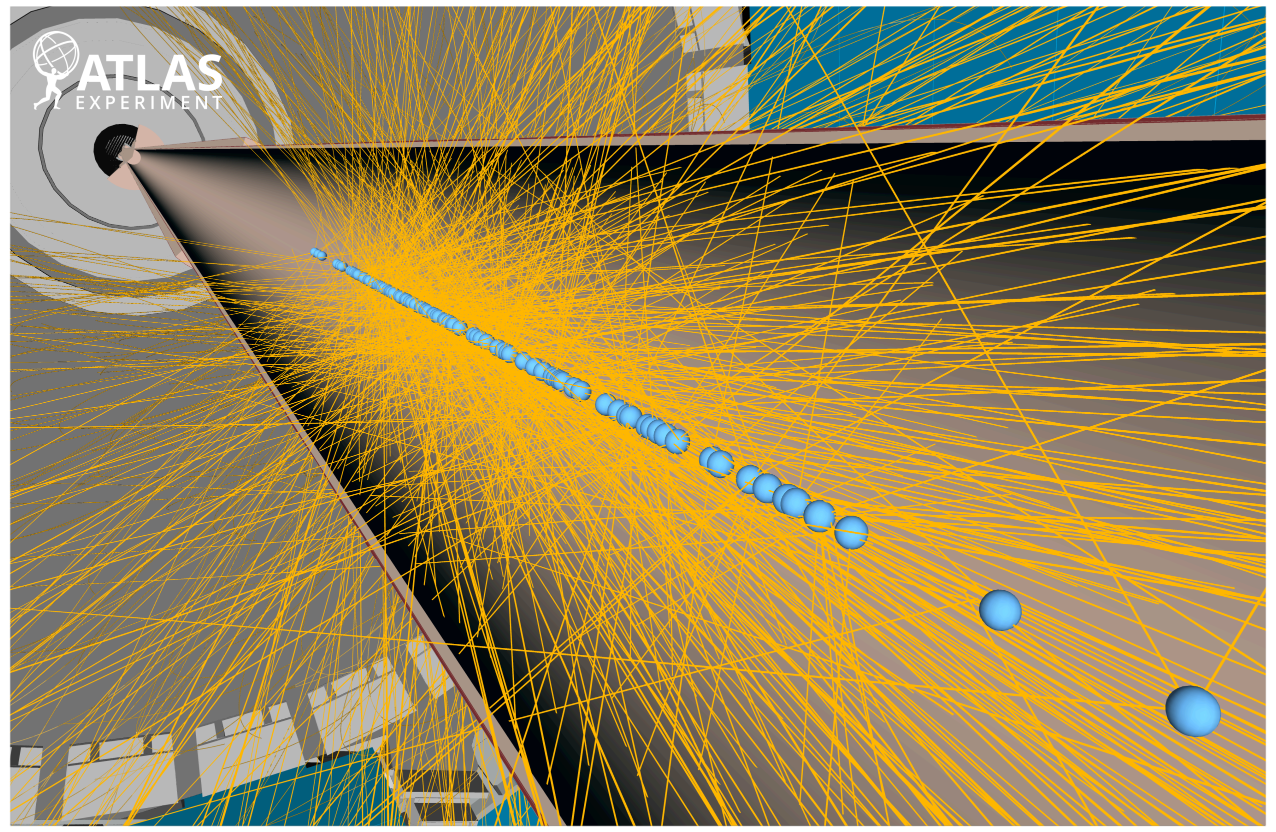


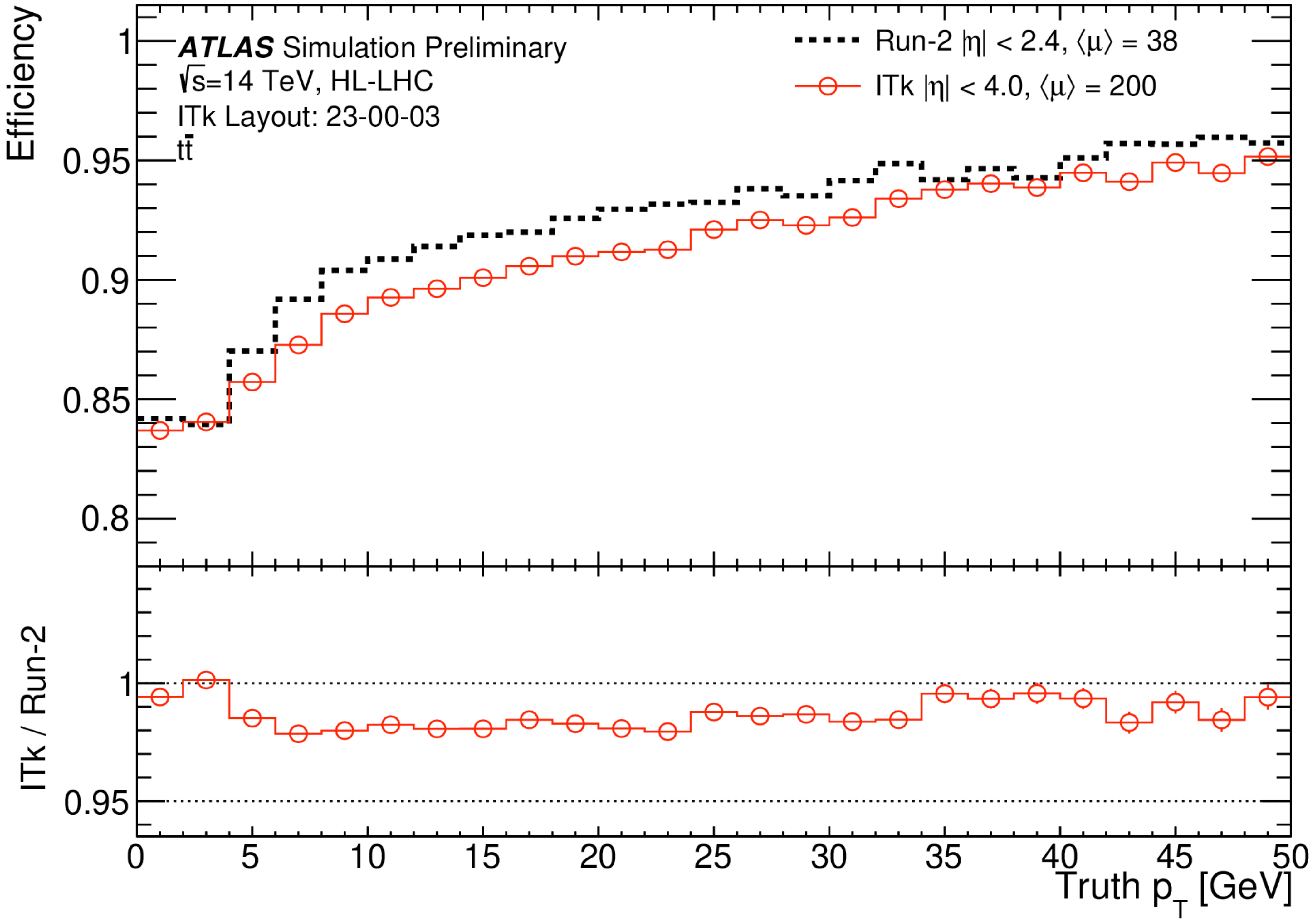


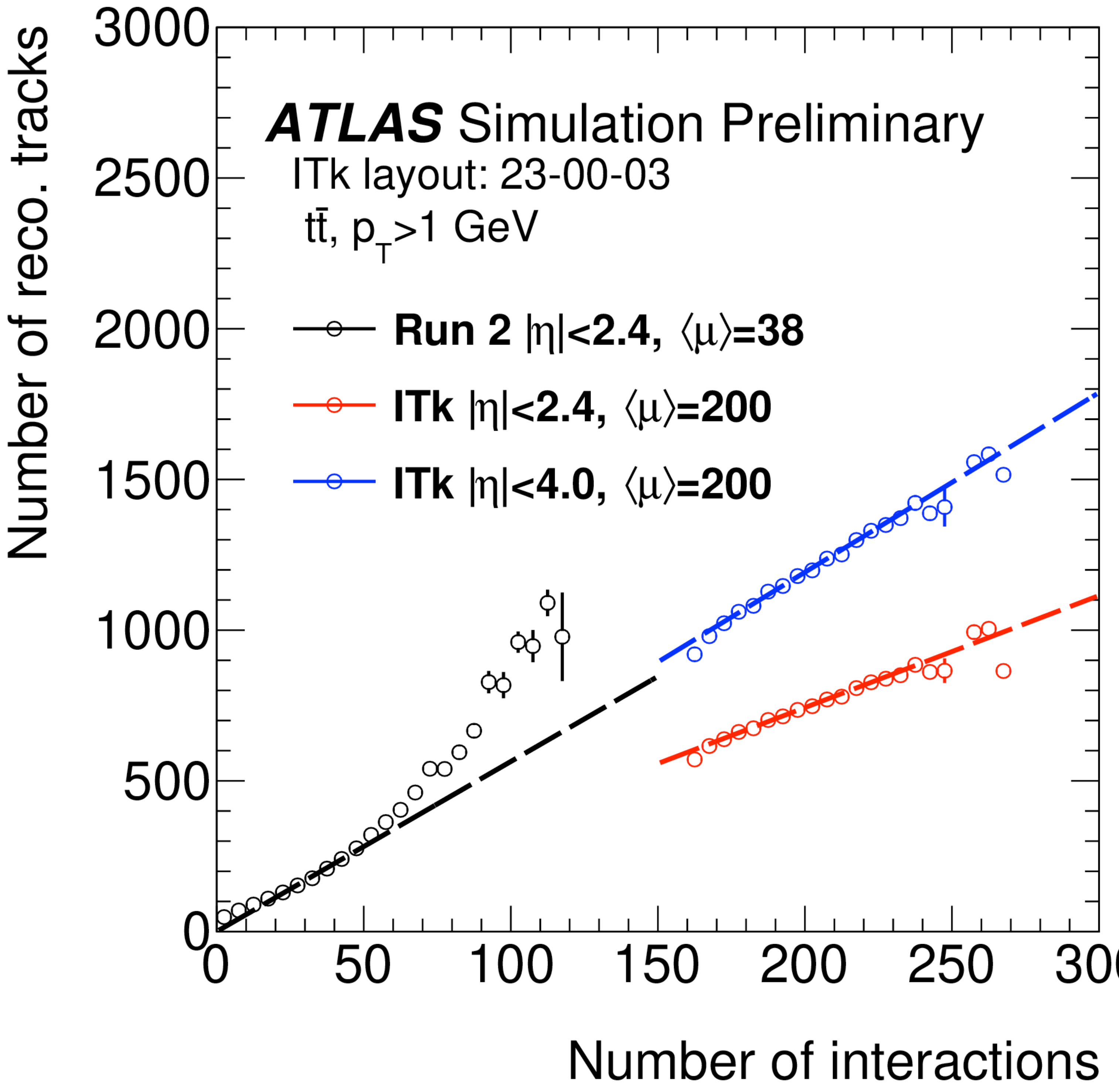
ATL-PHYS-PUB-2021-024

ITk Tracking Performance

ATL-PHYS-PUB-2021-024



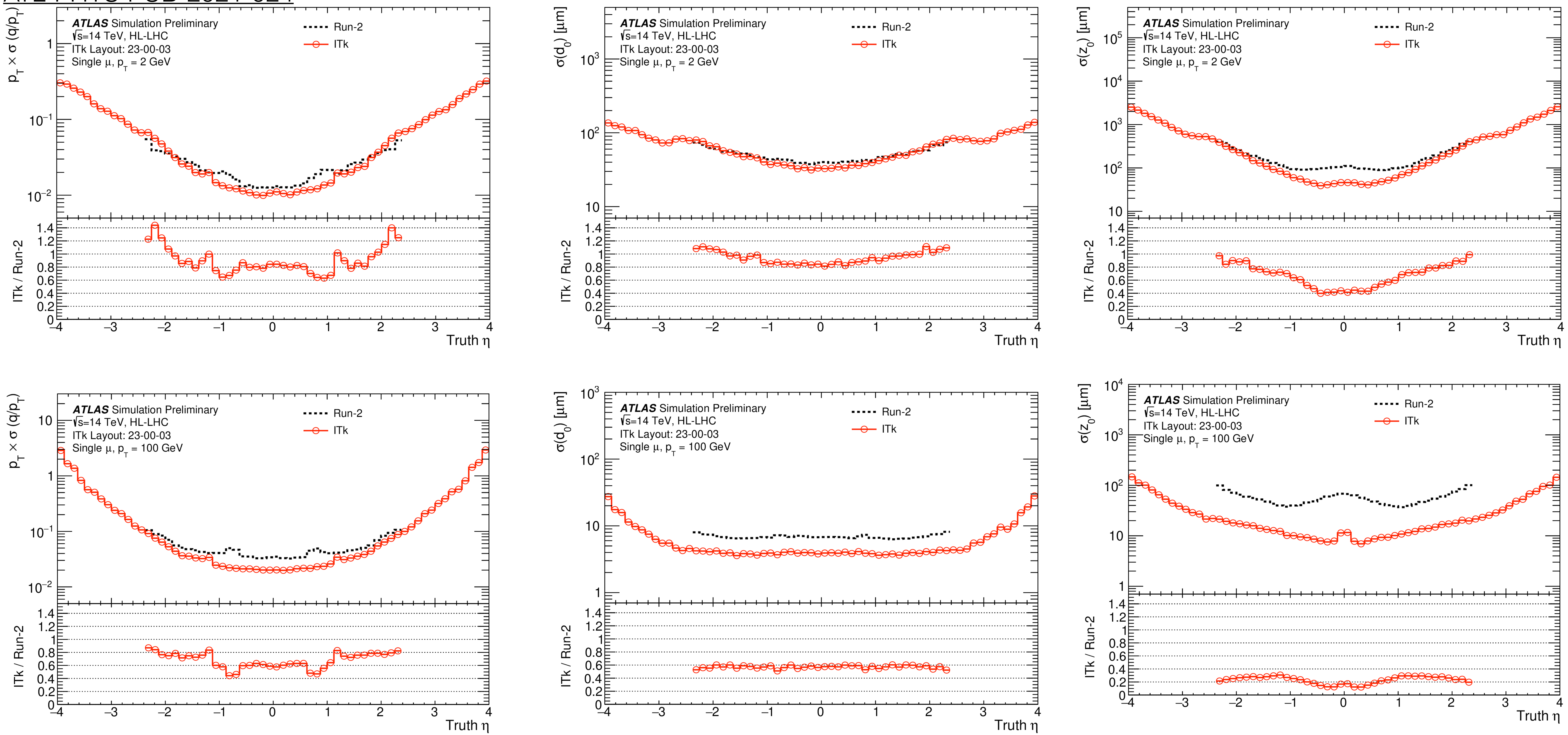




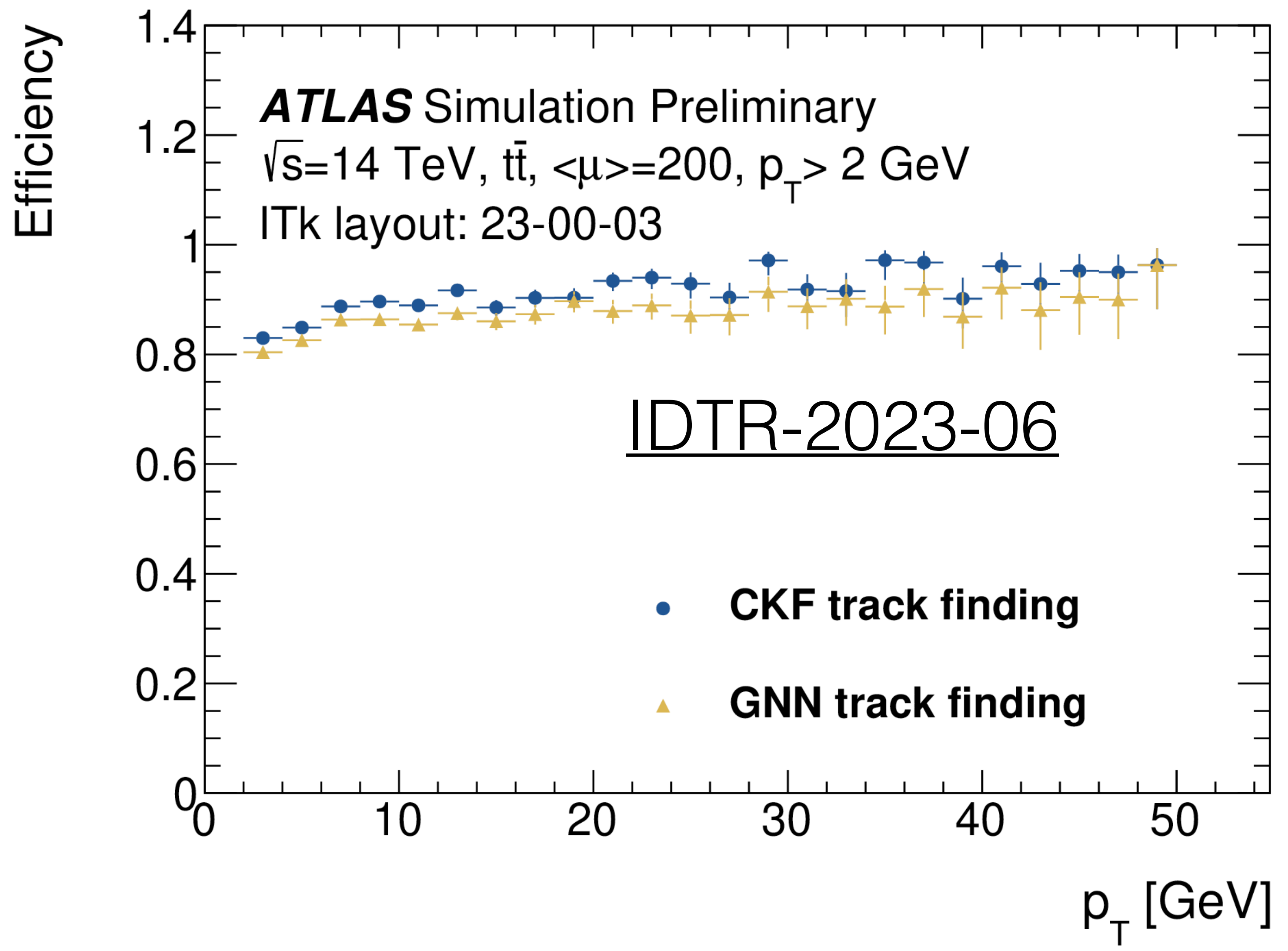
- Track finding follows the same principles as the current ATLAS tracking: find and confirm seed triplets in the pixel detector, extend using a combinatorial Kalman filter
- At the expected pile-up of 200, the ITk maintains a very similar track reconstruction efficiency and a significantly reduced number of fake tracks, allowing track finding up to $|\eta| = 4$
- The baseline inside-out tracking is implemented and stable - work on special cases and extra tracking passes

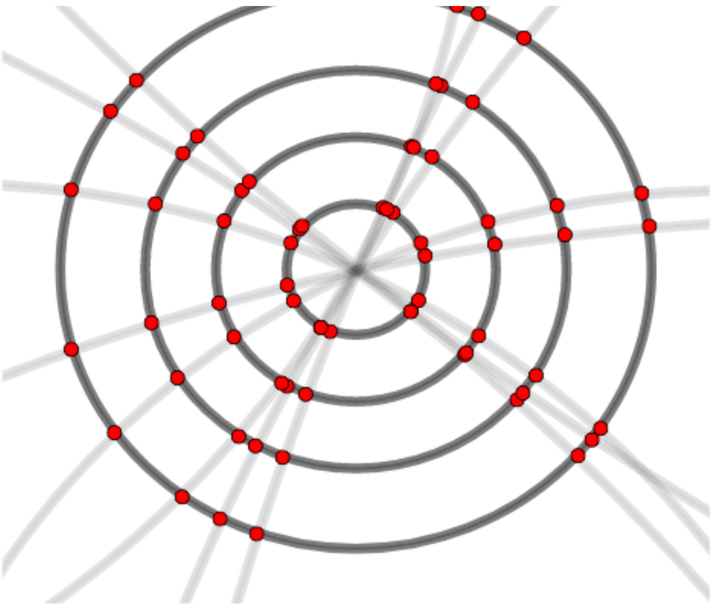
Expected p_T and IP Resolutions

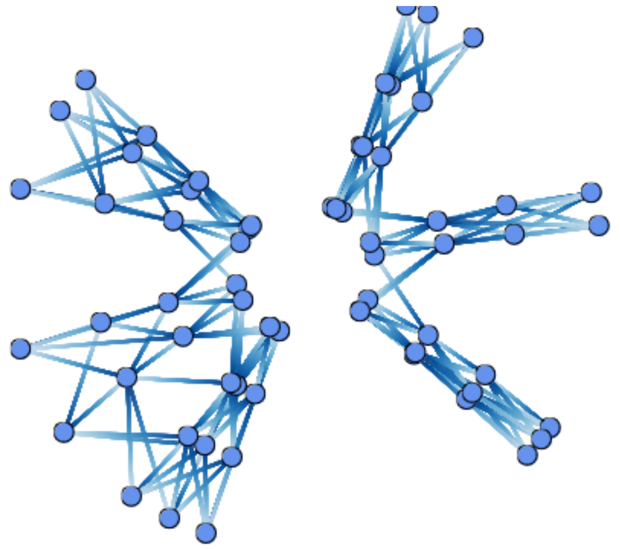
ATL-PHYS-PUB-2021-024



Outlook

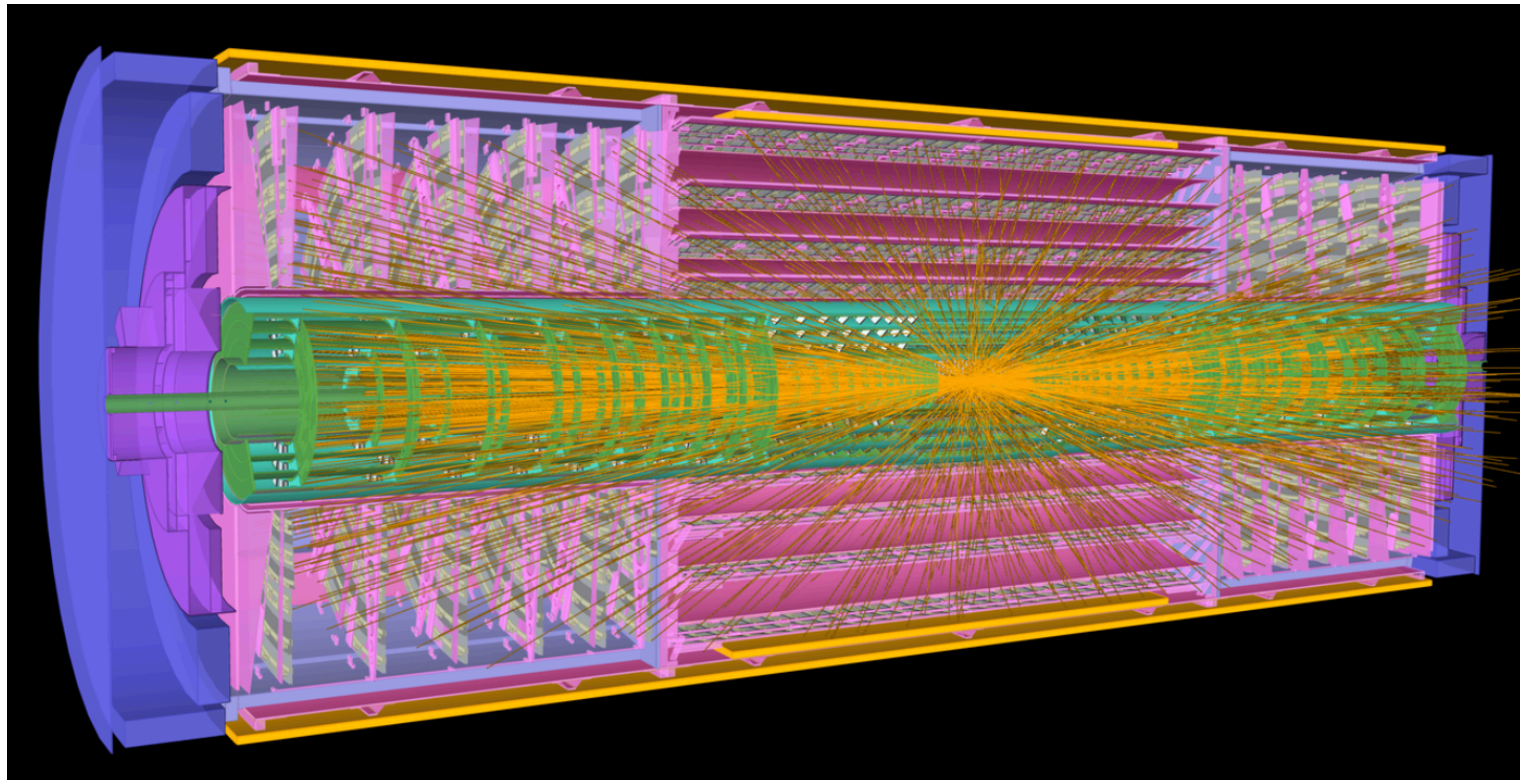






- The track finding is currently being re-implemented from scratch using ACTS - will be the default for Run 4 reconstruction

- Novel approaches are being investigated: track finding with GNNs; using GPUs (online or offline) or FPGAs (for HL LHC event filter tracking)



We still have 15+ years and most of the integrated luminosity ahead of us!