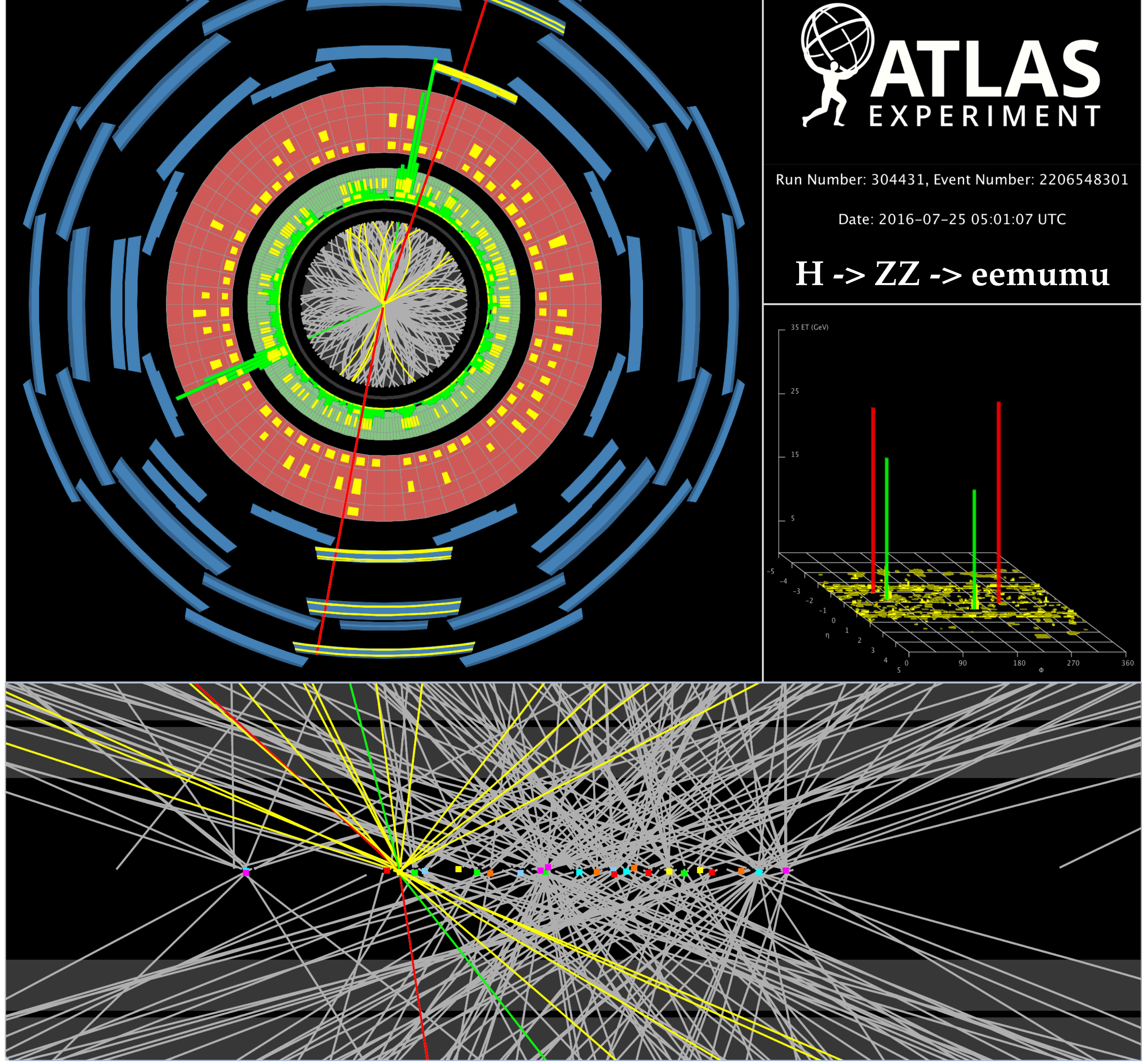


Performance of the ATLAS Tracking and Vertexing in the LHC Run-2 and Beyond

Alejandro Alonso (Niels Bohr Institute)
on behalf of the **ATLAS Collaboration**

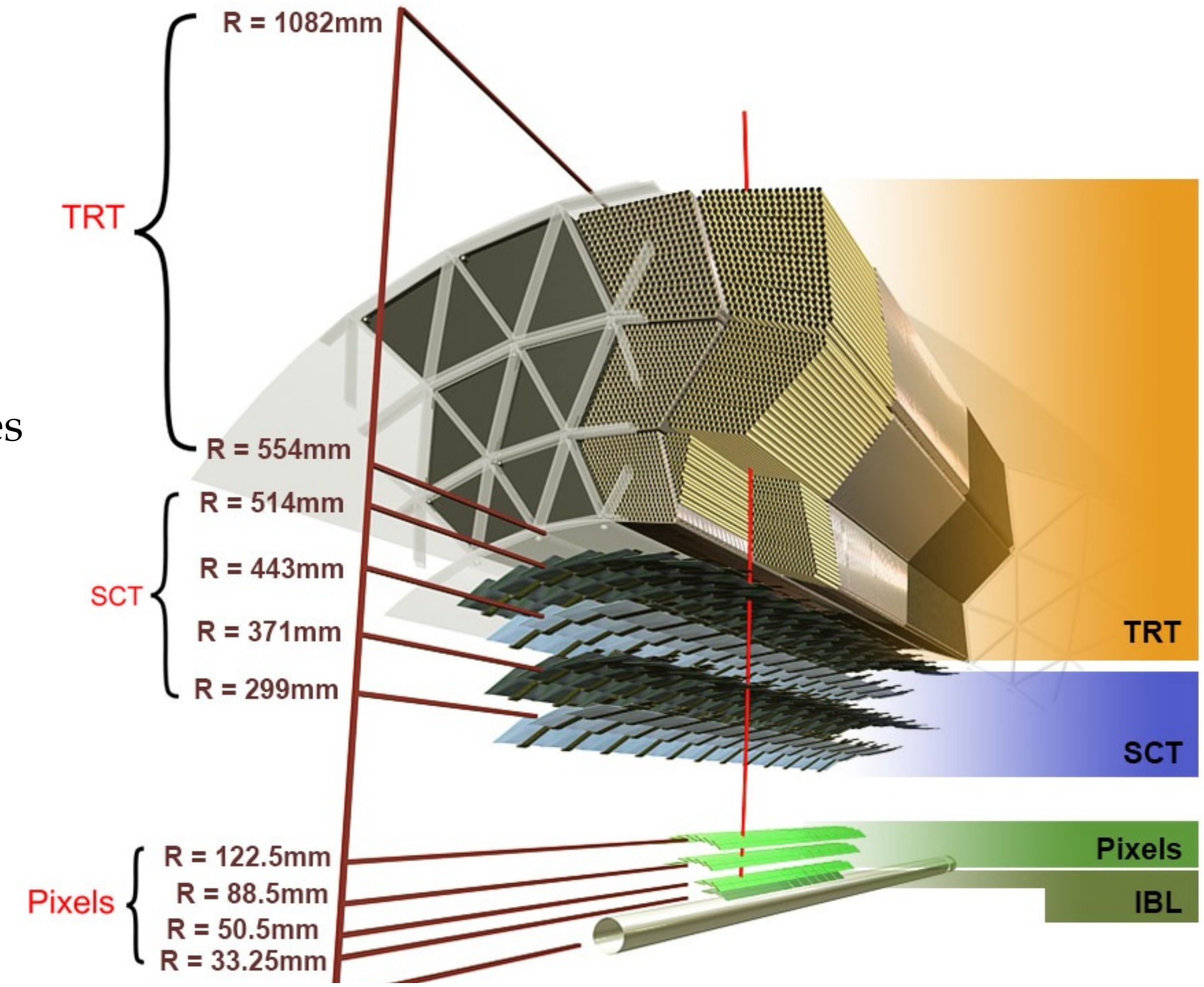
Ctdwit2017
8 March 2017

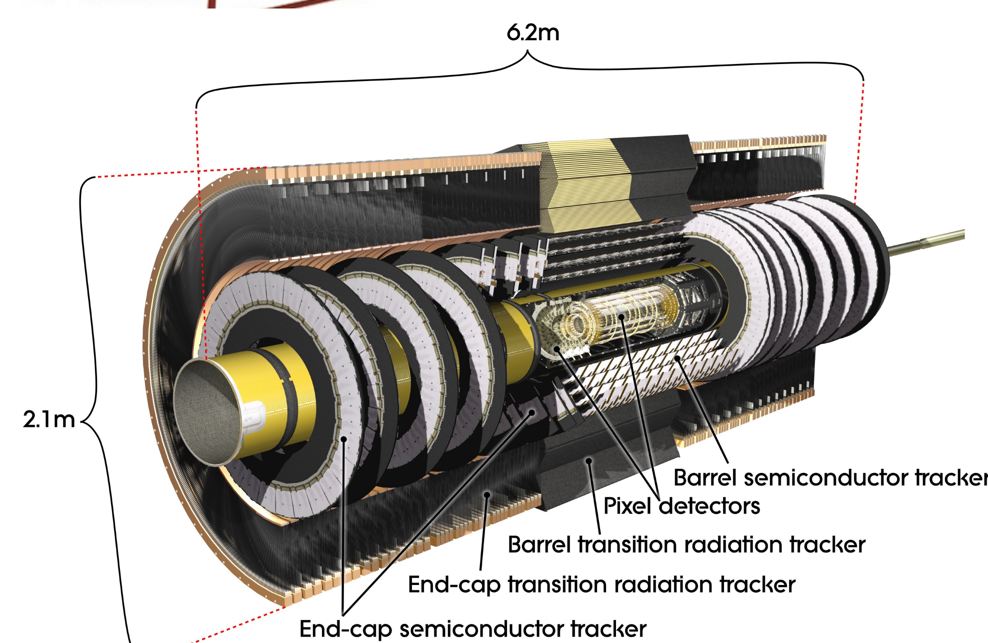
Introduction

- **In this talk:**
  - Hardware overview with details on Insertable b-layer and its impact for tracking
  - Software technicalities: The ATLAS approach, CPU reduction, plans for Run3
  - Material measurements
  - Time depending alignment
  - Tracking performance: standard, inside Jets, heavy ions and large radius tracking.
  - Vertex performance
- **ATLAS topics discussed in upcoming/passed talks:**
  - *Lossless data compression for the HL-LHC silicon pixel detector readout*
    by Stamatios Piulios (06/03/17, 18:15)
  - *The design and simulated performance of a fast Level 1 track trigger for the ATLAS High LuminosityUpgrade*
    by Mikael Martensson (07/03/2017, 09:00)
  - *Improved AM chip pattern recognition with optimized ternary bit usage*
    by Stefan Schmidt (07/03/2017, 11:30)
  - *Optimal use of charge information for HL-LHC pixel readout*
    by Ben Nachman
  - *Expected Performance of ATLAS Inner Tracking at the High-Luminosity LHC*
    by Nora Pettersson (08/03/17, 9:30)
  - *Identification of Jets Containing b-Hadrons with Recurrent Neural Networks at the ATLAS Experiment*
    by Zihao Jiang (09/03/2017, 10:30)

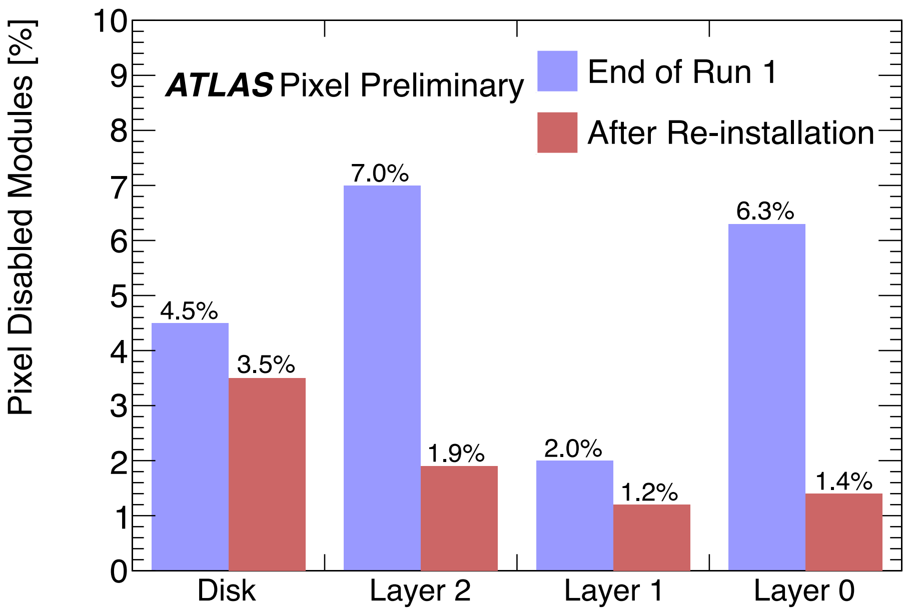
The Inner Detector (ID)

- **Reconstruction of charged particles with |η|<2.5:**
  - **input for many physics objects:**
    - Electrons and muons
    - Jet substructure and jets mass resolution
    - B-tagging
    - Mitigate pileup effects by separating Primary Vertexes
  - **New Insertable-B layer (IBL)**
    - 6.02 M channels
    - Resolution: 8x40 μm (pixel size 50x250 μm)
  - **Silicon Pixel detector (Pixel)**
    - ~80M channels
    - Resolution: 10x115 μm (pixel size 50x400 μm)
  - **Semiconductor tracker (SCT)**
    - Silicon microstrips
    - 6M channels
    - Resolution: 17x580 μm
  - **Transition Radiation Tracker (TRT)**
    - 2mm radius drift tubes + Transition radiation
    - ~350k channels
    - Resolution ~130 μm
  - **2T axial B-field**





ID Upgrades for Run 2



Done during Long Shutdown (2013-2015)

Pixel:

- New services, new optical links, 3% modules recovered.

TRT:

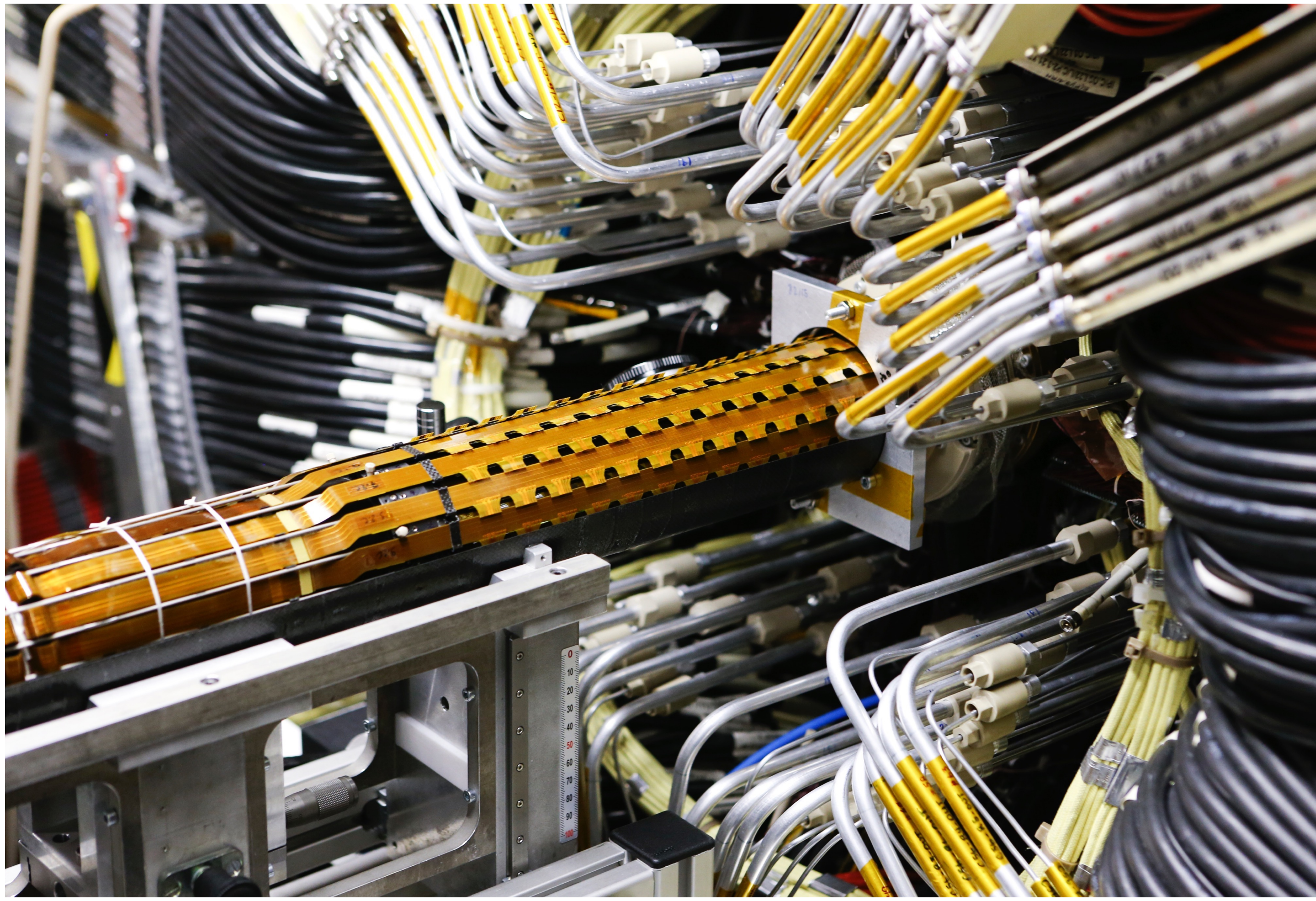
- Gas leaks for the end-caps repaired, new firmware to operate at

  100kHz, validity gate, PID optimised

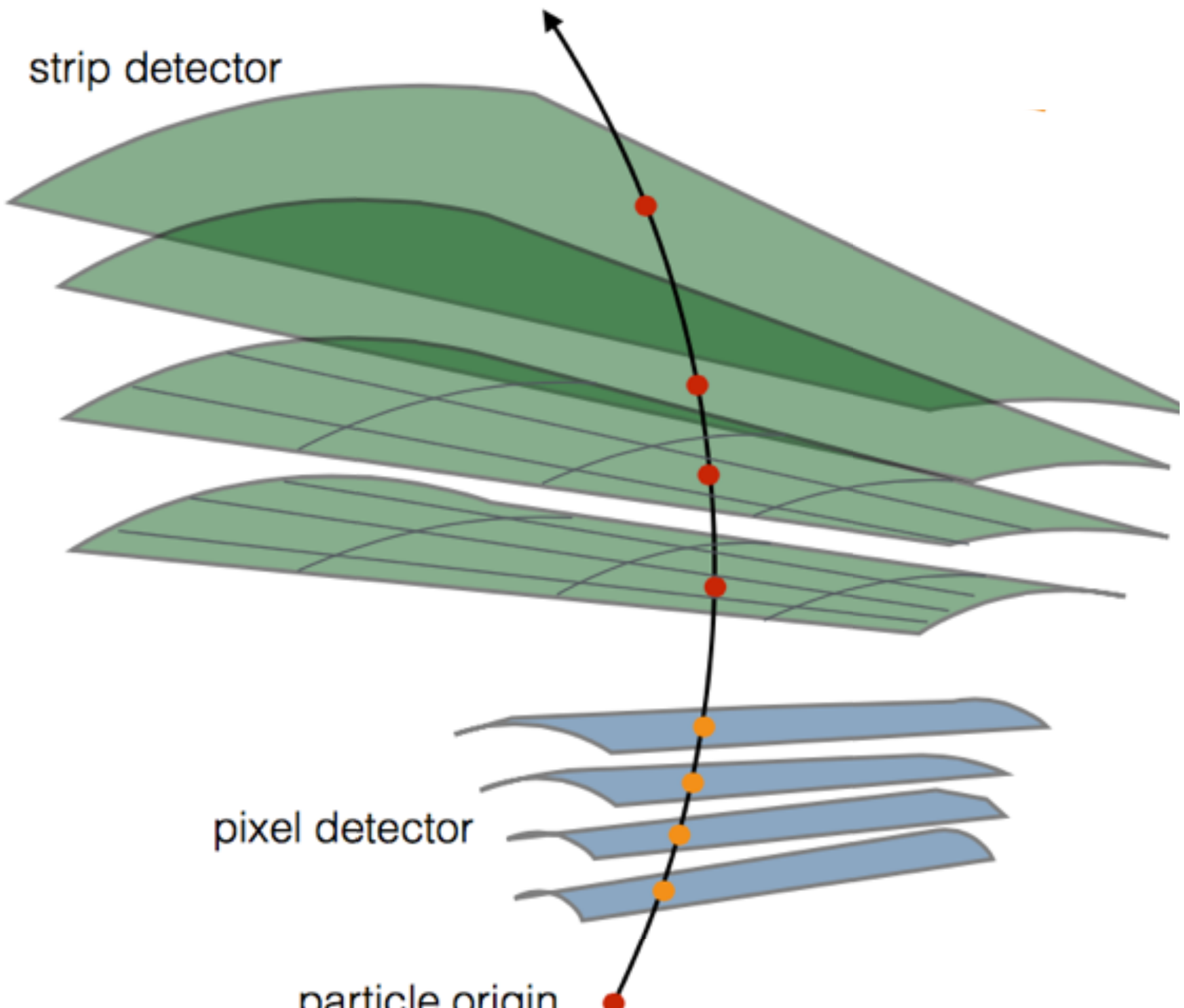
New Diamond Beam monitors (DBM) installed in the Pixel volume

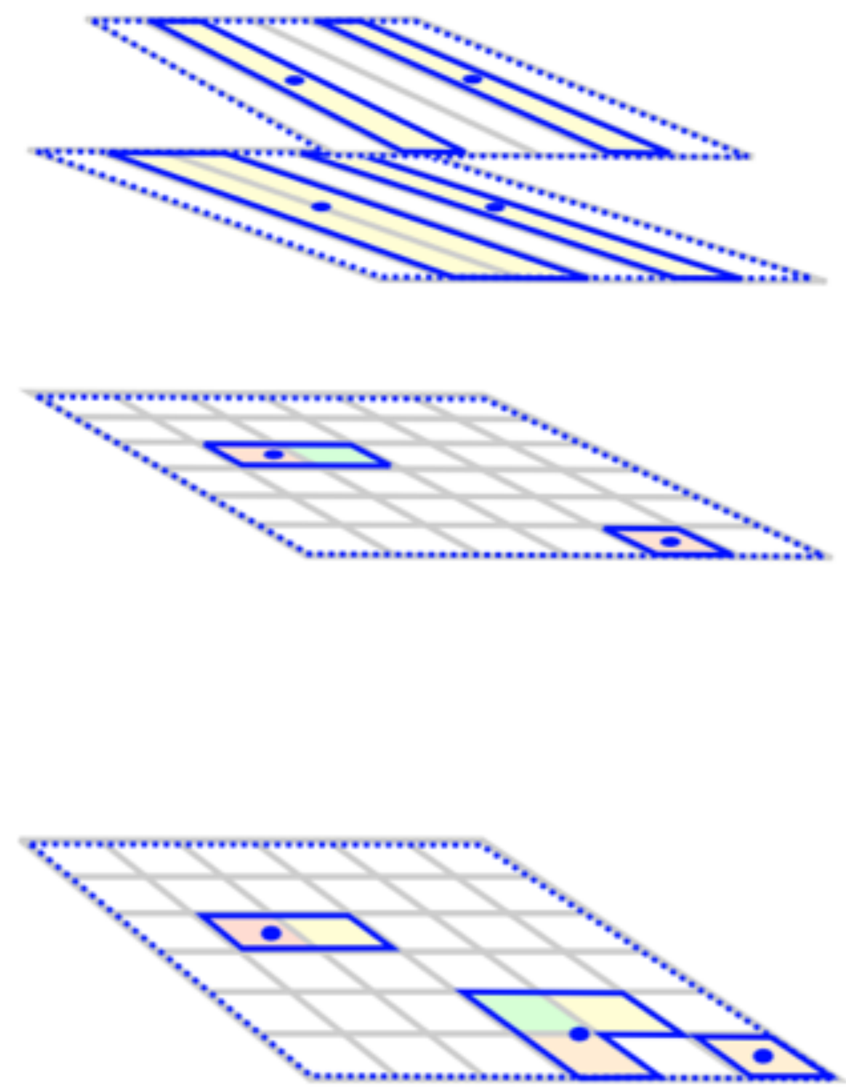
New insertable B-layer (IBL)

- Inner most additional pixel layer (4th) at radius 33 mm from the beam line
- New beampipe
- Preserve tracking with increased luminosity
- Improves vertexing, impact parameter resolution and b-tagging
- 14 staves overlapping in the r - ϕ plane of length 332 mm with 130nm CMOS modules with 2 technologies:
  - 12 planar and 2 x 4 3D modules

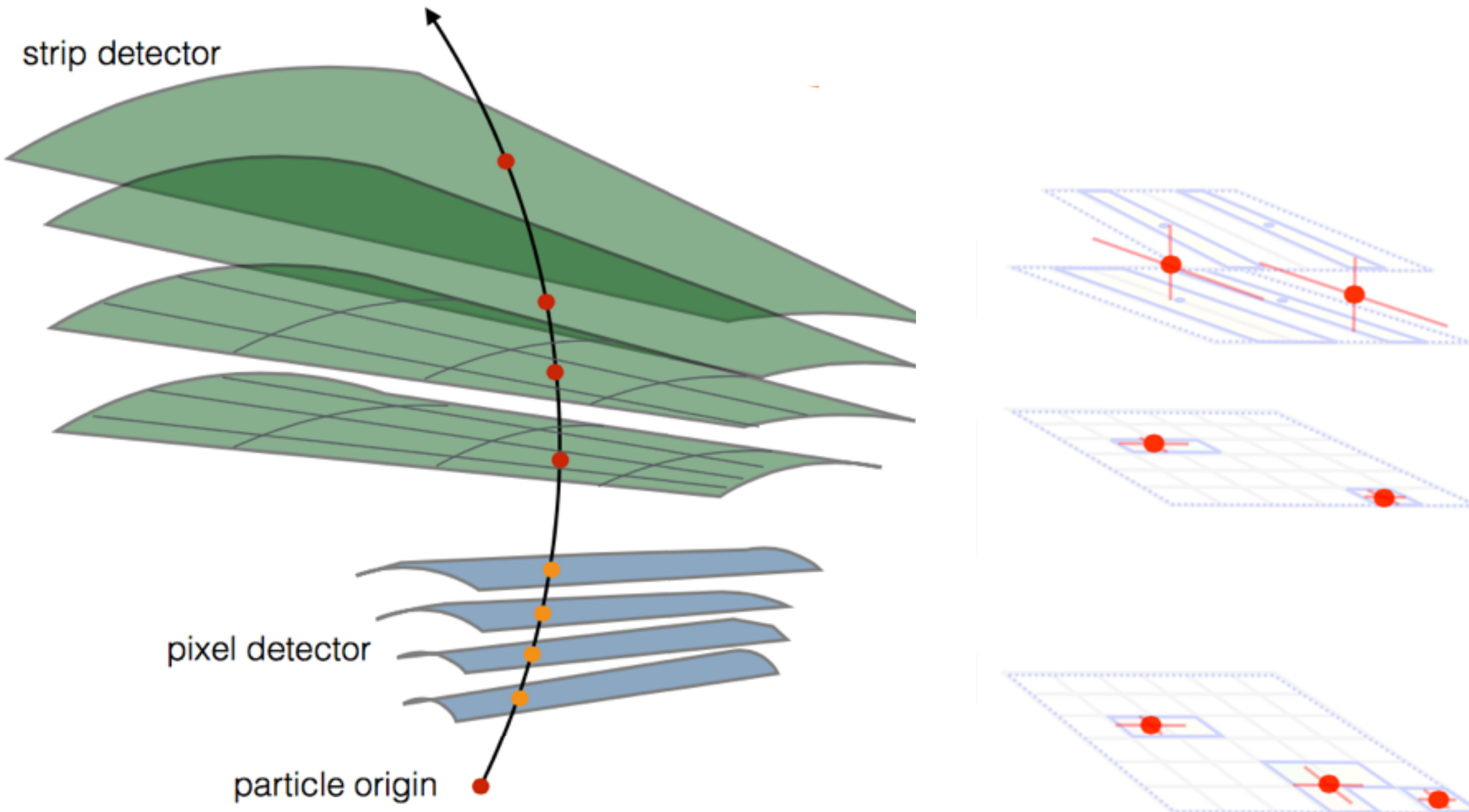


- **Hit preparation:**
  - **Pixel and SCT clustering:** finding connected cells (pixels/strips) on module via a connected component analysis
  - **TRT Drift Circle creation**



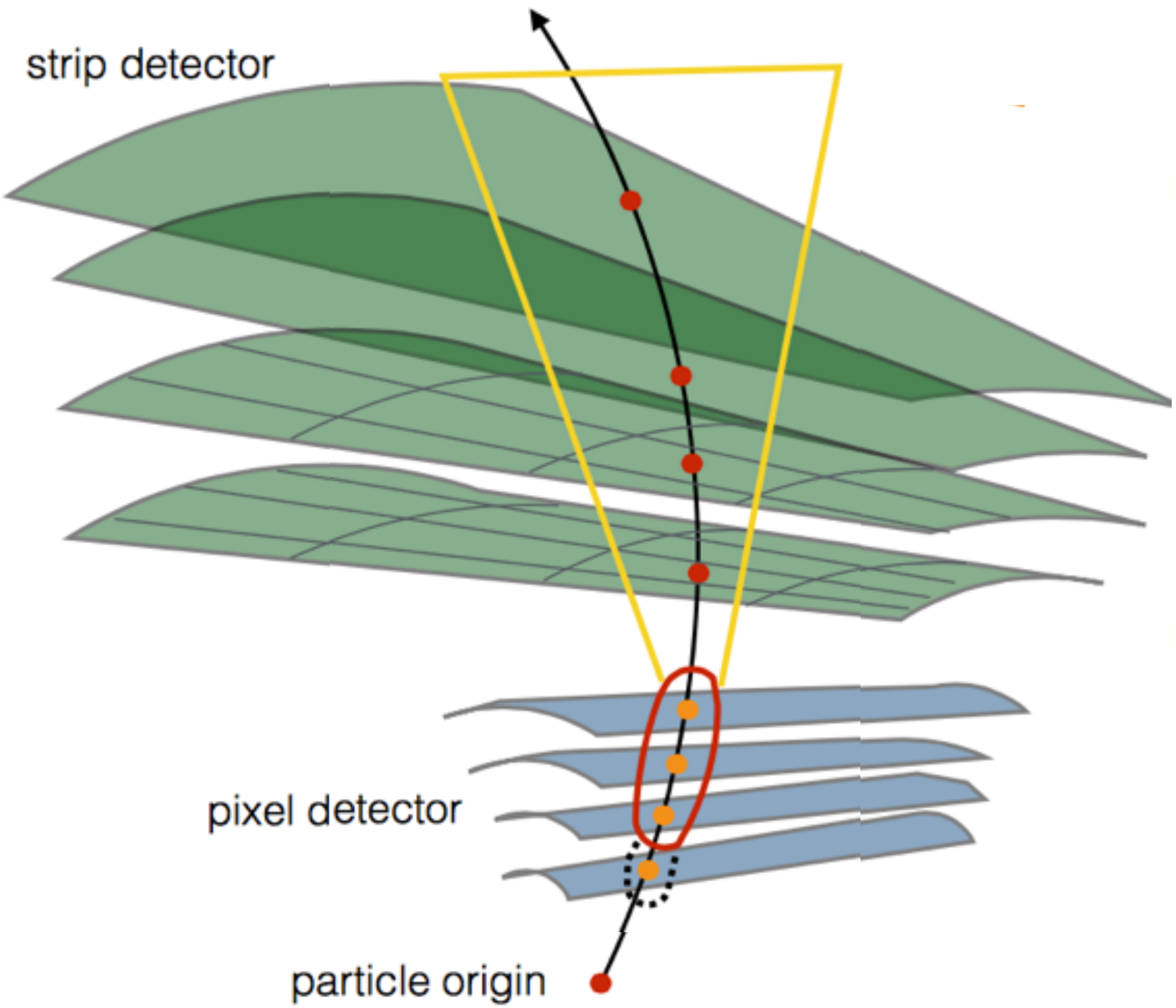


- **Space point formation:**
  - Using the local cluster positions and sensor surface form 3D/2D space points



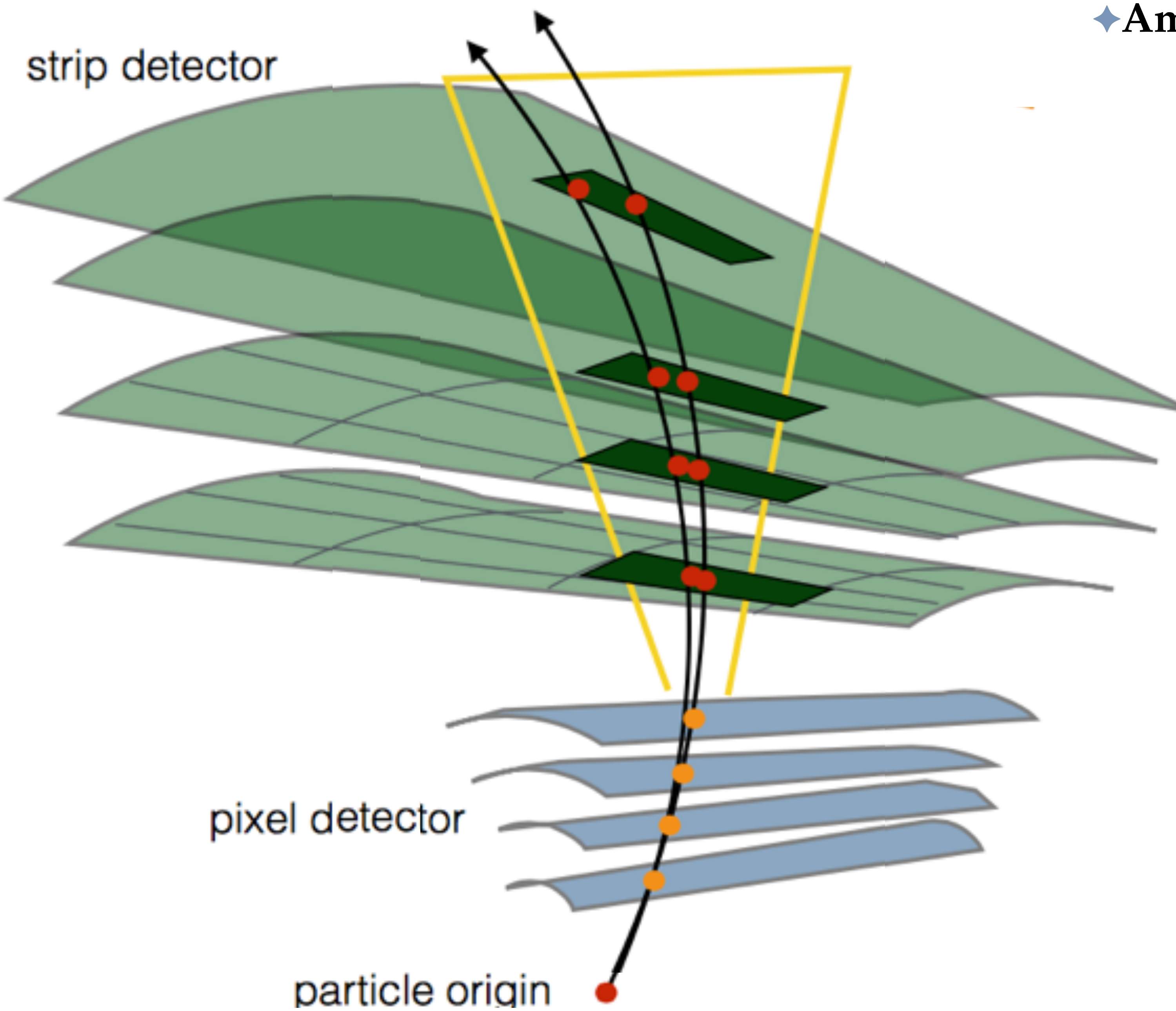
✦ **Space point seeding:**

- ✦ Build triplets of seeds and evaluate their compatibility (To 4th layer or to Beam Spot)
- ✦ Road building for combinatorial Kalman filter



Atlas Inner Detector Tracking

- **Track finding and ambiguity solving**
  - Resolve detector elements in a given road and start track candidate search based on space point seeds
  - Precise least square fit with full geometry of the track candidates
  - Tracks are ranked by an ambiguity solving

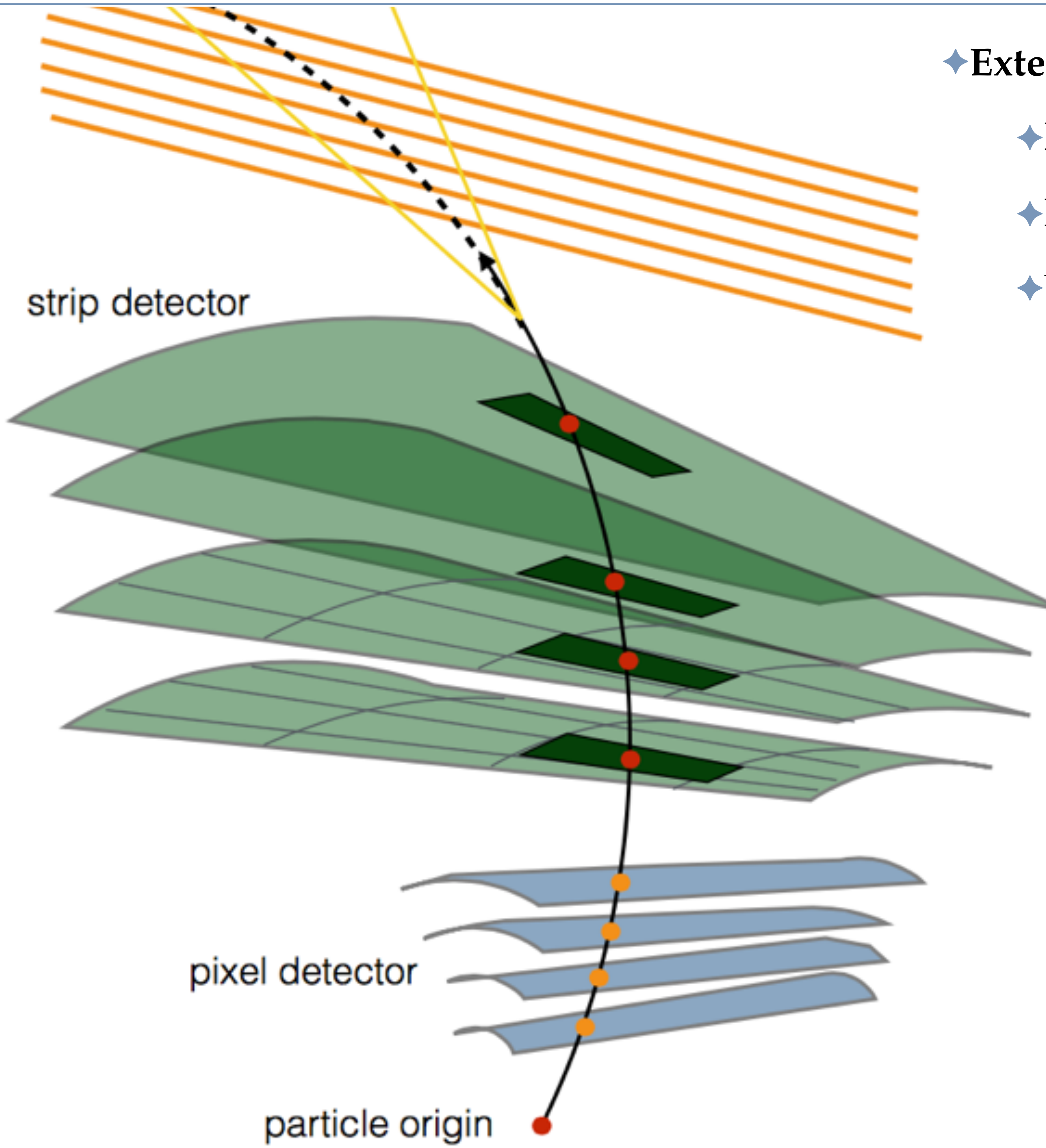


- **Ambiguity solving**
  - Favour tracks with good fit quality and large number of hits
  - Penalise tracks with holes or shared hits
  - Tracks with highest score survive

Track parameters:

$$t = (d_0, z_0, \eta, \phi, q/p)$$

Atlas Inner Detector Tracking



- **Extend to the TRT**
  - Progressive finder in a given road
  - Refit extended track
  - Use ambiguity to keep new or old track

- Up to here this is the **inside to outside tracking**
- ATLAS also performs **outside to inside tracking:**
  - Hough transform in the TRT for pattern recognition with remaining hits
  - Back-extrapolation to SCT and Pixel, only using unused hits
  - Full global Chi2 fit
  - This is only performed in regions of interest: **EM Calorimeter clusters (conversions)**

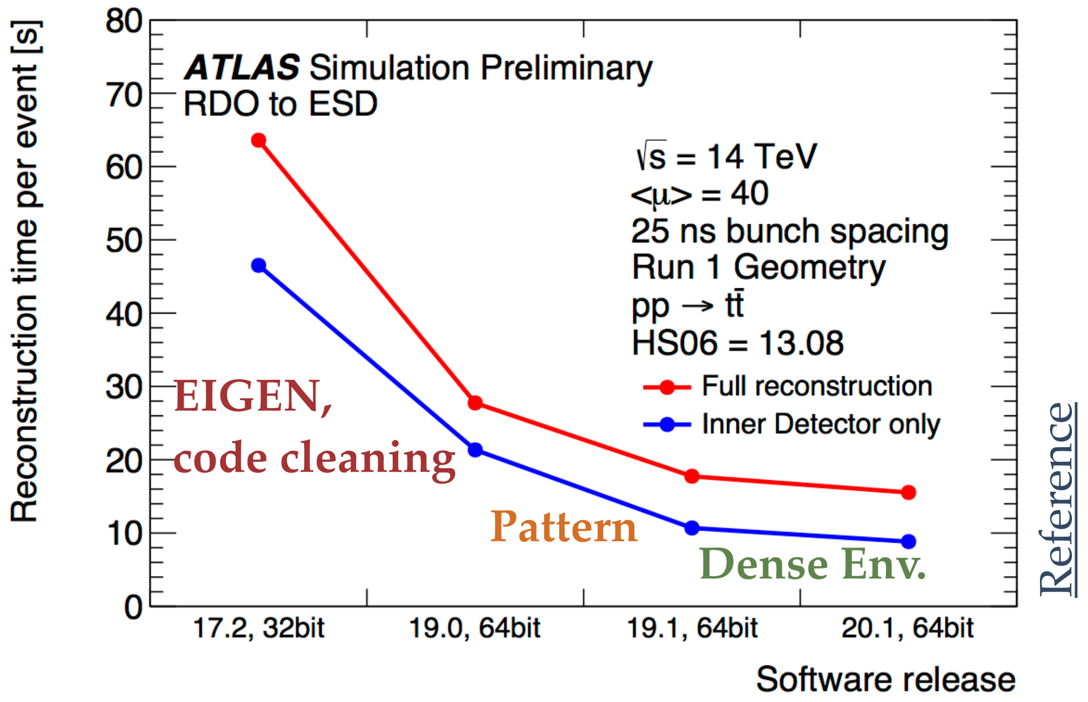
Some more details about SW

During Long Shut Down 1:

- Mayor campaign to clean and **SPEED UP** the code: *4x*
- Use of **EIGEN** + code optimisation
- Simplified data model
- Pattern recognition fine tuned
- Tracking in dense environments

Upcoming Challenge:

- ID tracking should be fully thread safe for LHC run 3



A-Common-Tracking-SW (ACTS):

- Ambitious plan to externalise tracking code from ATLAS, so can be used by other groups/experiments as FCC: **https://gitlab.cern.ch/acts/a-common-tracking-sw/**
- Tracking geometry description which can be constructed from TGeo, DD4Hep or gdml input
- Simple and efficient event data model
- Performant and highly flexible algorithms for track propagation and fitting
- Basic seed finding algorithms
- **Plenty of details in a dedicated talk: 09/03/17, 12:00**

Q1/2017:

Now release 0.4 coming, with:
- TrackingGeometry building for ID like detectors
- Material mapping from Geant4 for the TrackingGeometry
- Extrapolation, Geometry digitization, Fitting (Kalman filter)

Q2/2017:

- Try to release the first release 1.0-beta around summer with the full demonstrator without pattern recognition
- Thread-friendly

Q3/2017 - Q4/2017

- First wrapping with ATLAS:
 make a fork of ATLAS and exchange everything after pattern recognition with ACTS
- In parallel, port the pattern recognition, but that will not be there before the end of the year

Measuring the ID material

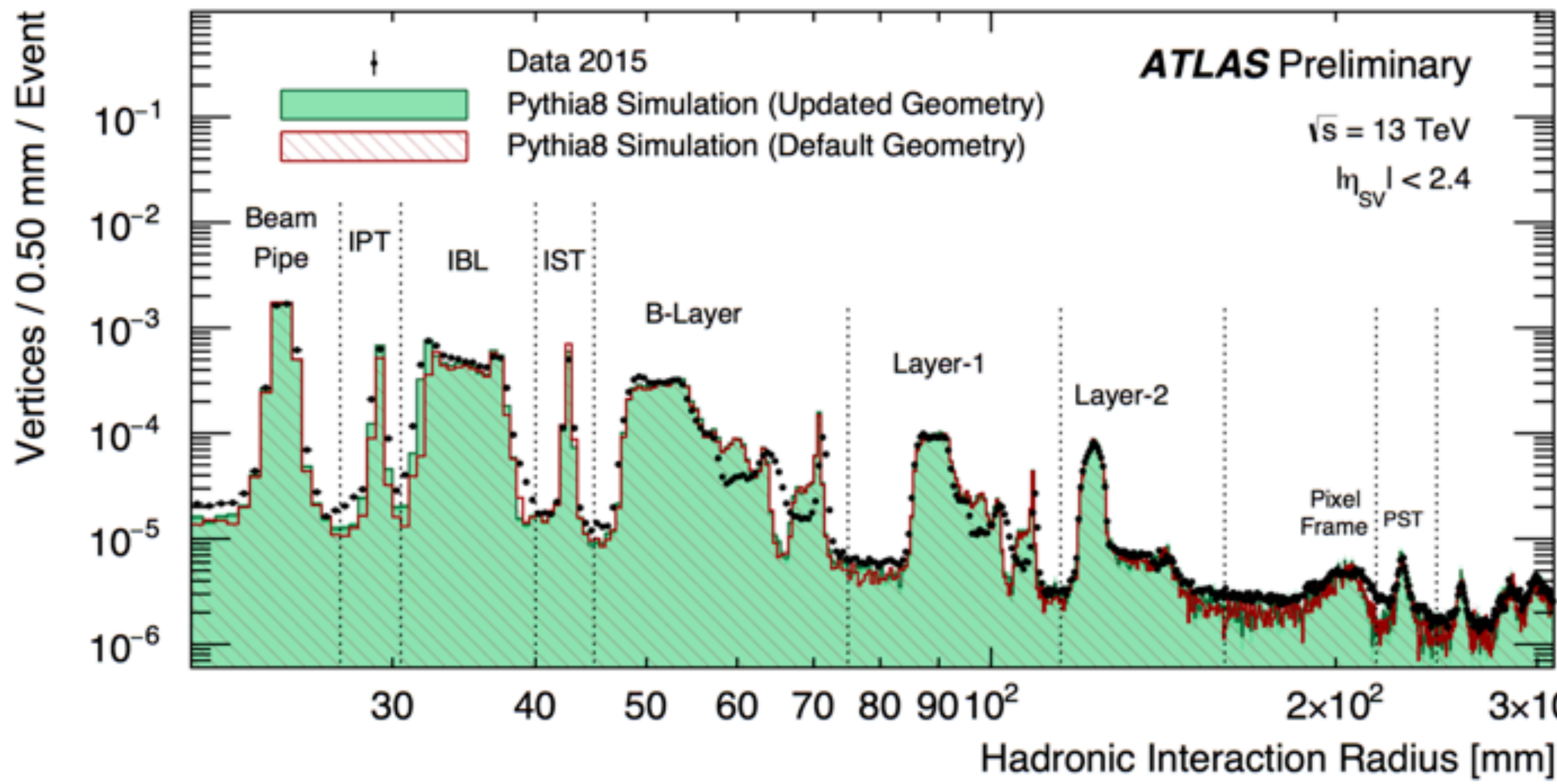
Beam pipe material known to 1% precision

- **SCT extension Efficiency:**
  - Material between SCT and Pixel
- **Photon conversions**
  - Sensitive to radiation lengths
- **Hadronic interactions**
  - Sensitive to interaction lengths
  - Very good position resolution

Updated Geometry for Run2:

- Initial underestimation of IBL material

Hadronic Interactions



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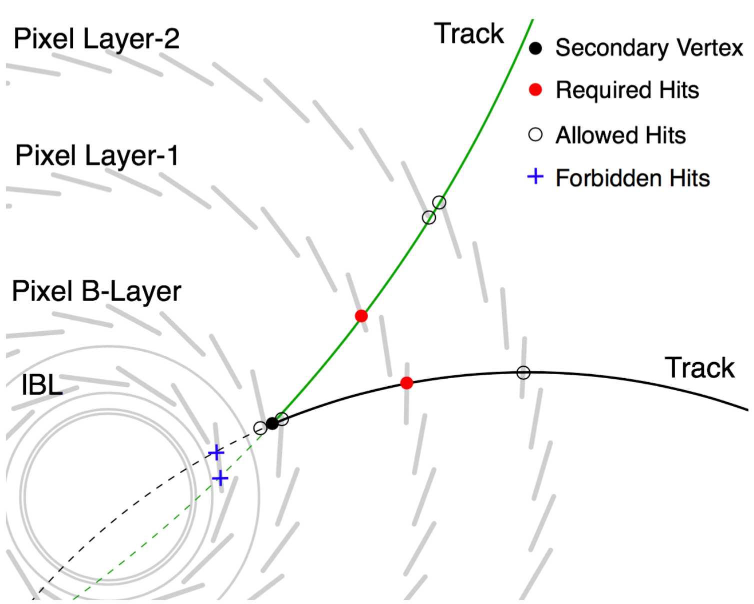
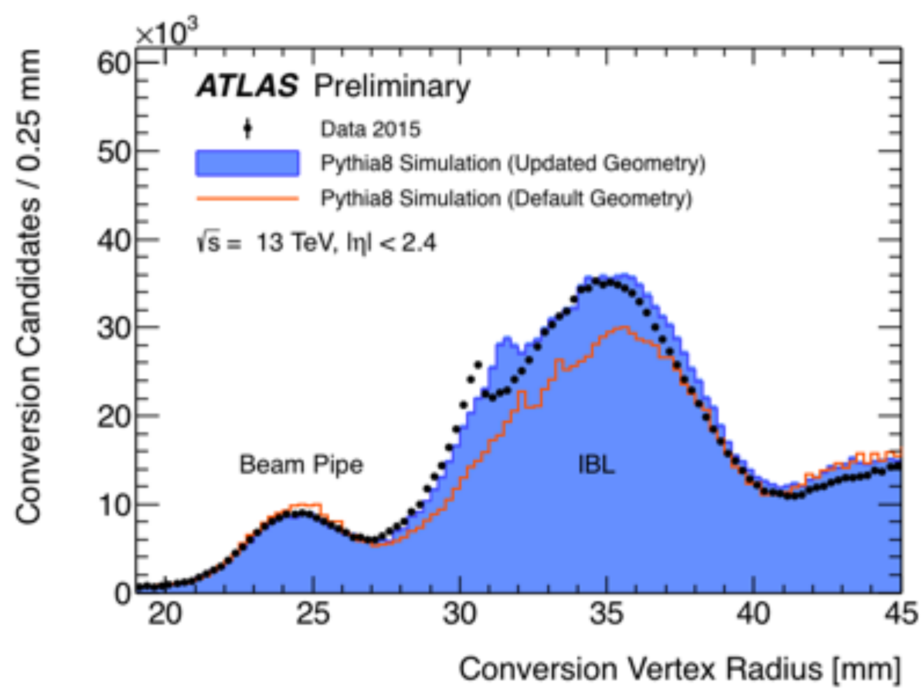


Photon Conversions



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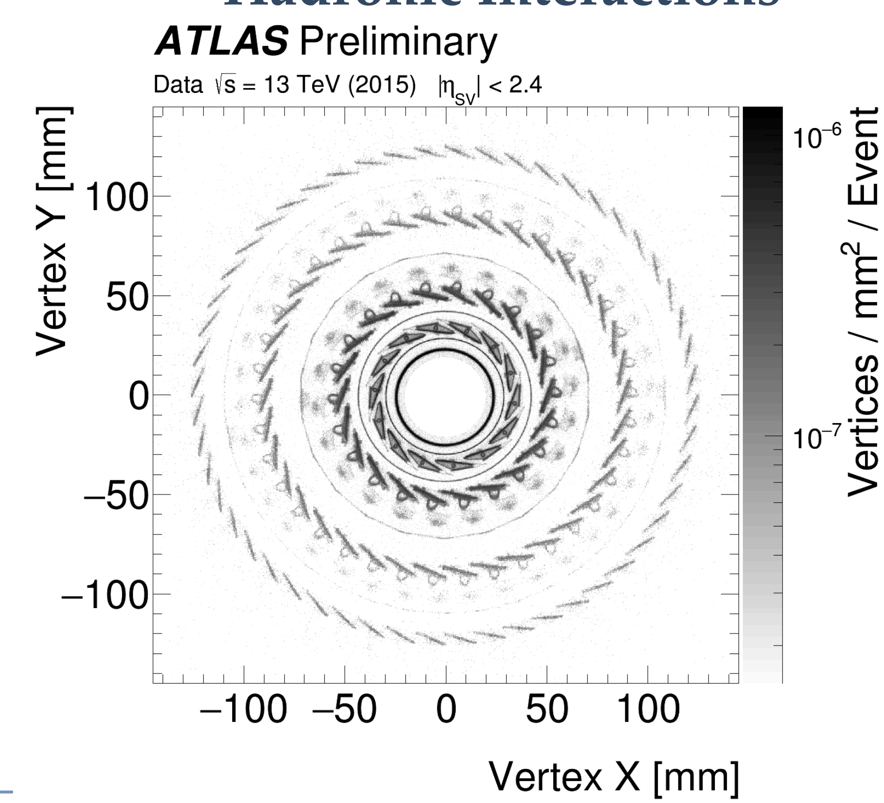
Hadronic Interactions



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Beam pipe ma
precision

- SCT extens
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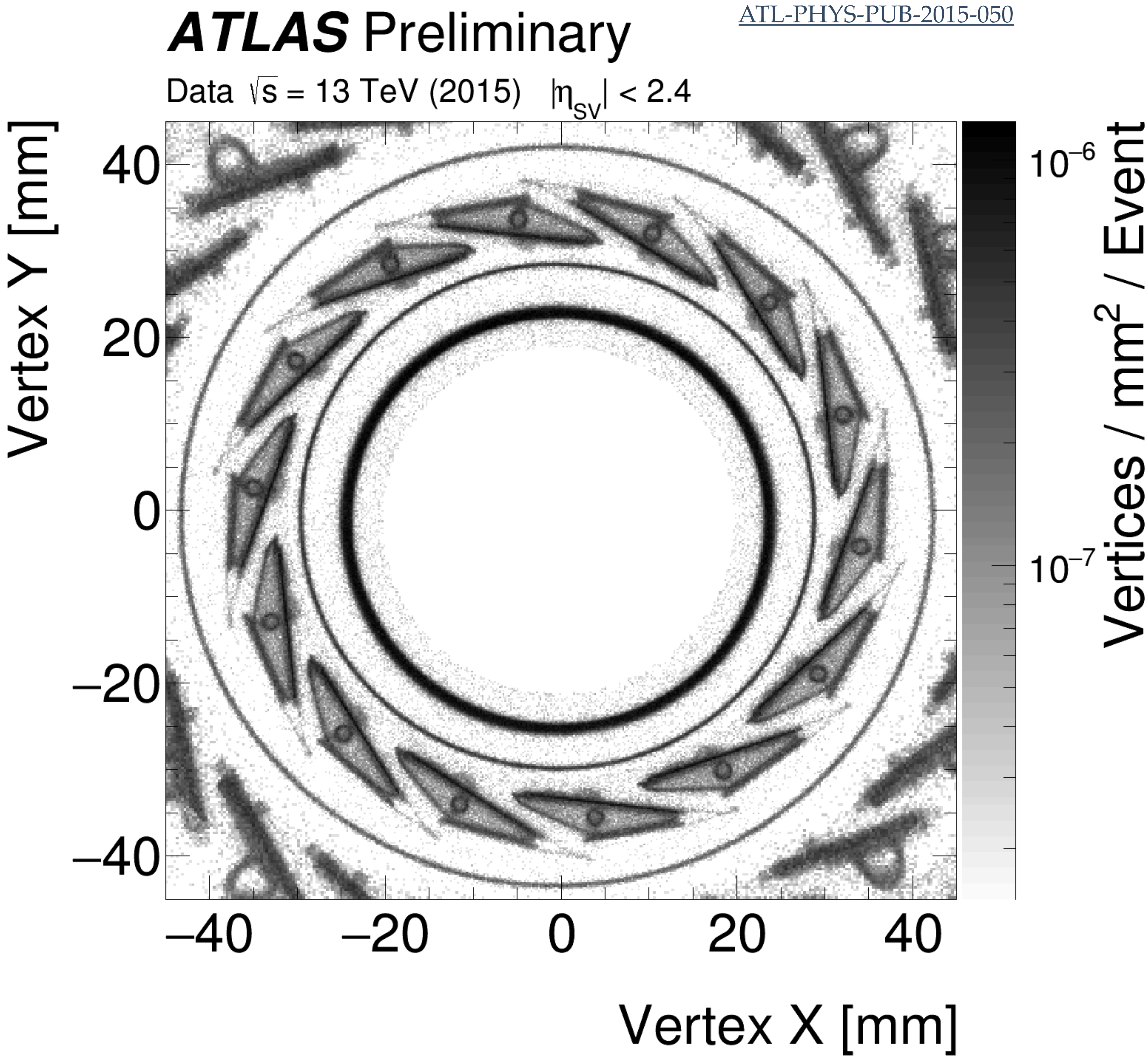
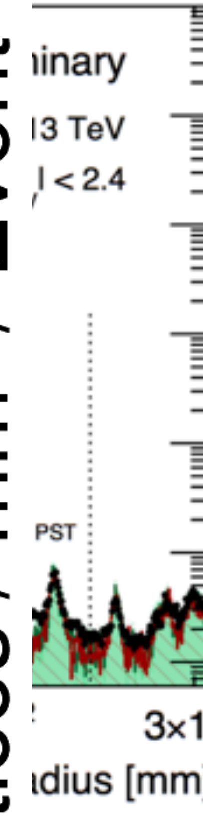
Updated Geo

- Initial unde





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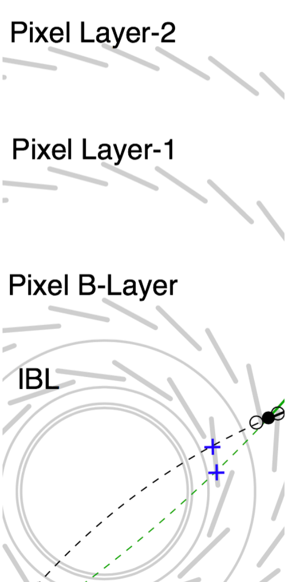
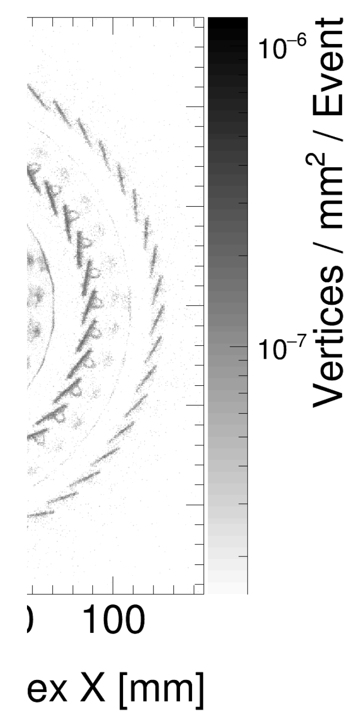




Track based algorithm

IDTR-2016-005

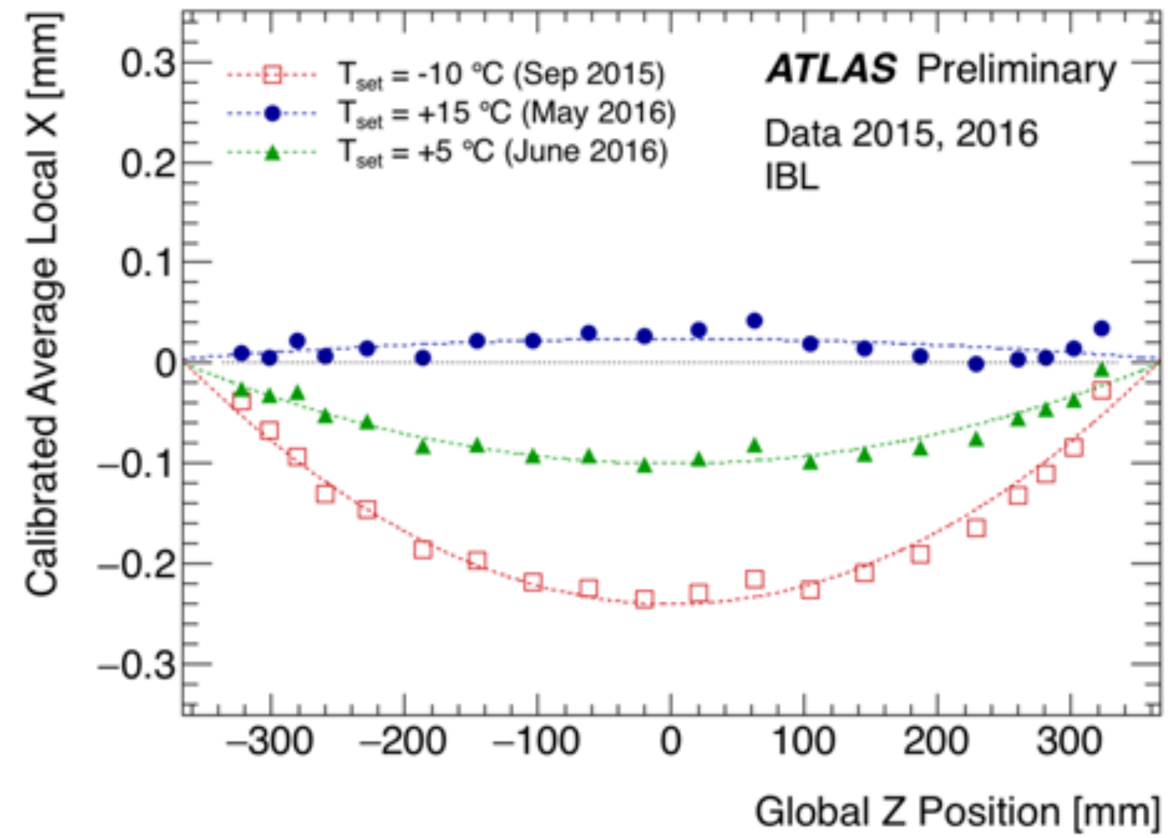
- Using track Chi2 to estimate alignment parameters (t) with r (residual) and covariance matrix (V):

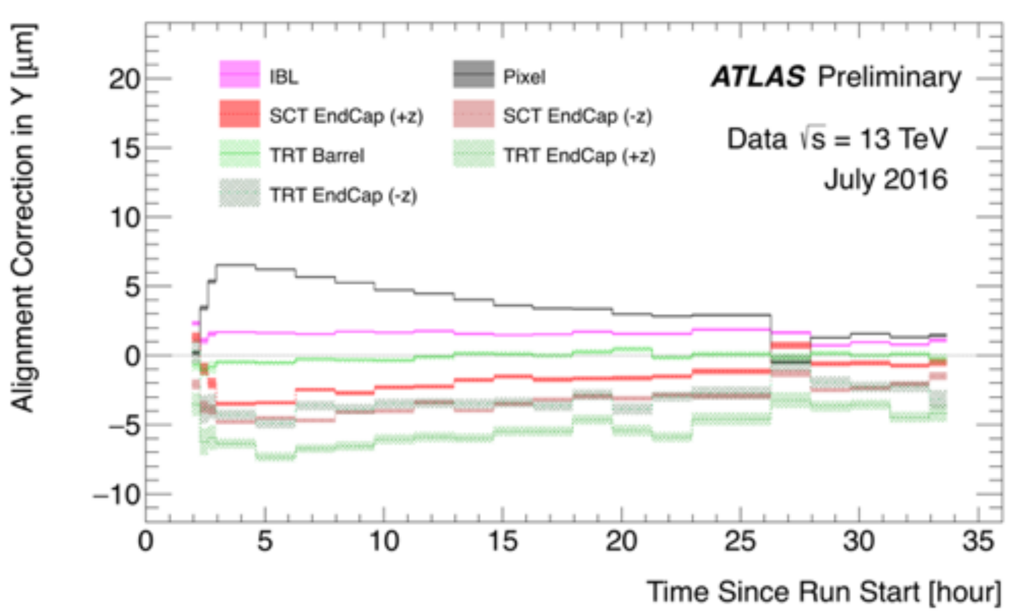
$$\chi^2 = \sum_{tracks} r^T(t,a)V^{-1}r(t,a)$$

Detector stable on long time scales
(no if power cut, magnet ramp, cooling issues..)

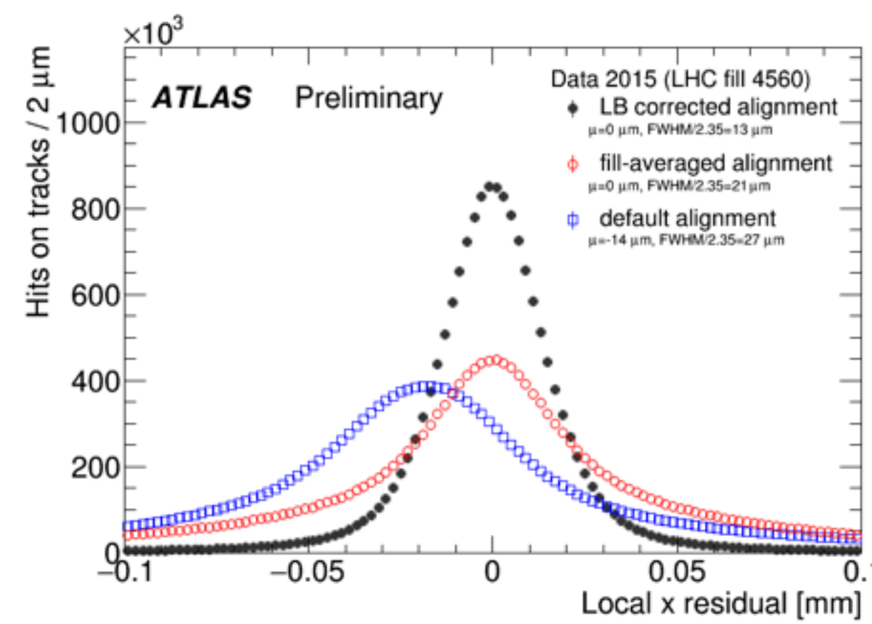
Run-by-run and with-in run alignment:

- IBL mechanical instability with temperature
- Vertical movement of pixel within fill
- Alignment determine movement of detector volumes / staves automatically:
  - Every 20 minutes during first hour of the fill
  - Every 100 minutes after
  - Alignment updated within 24h after the run is over





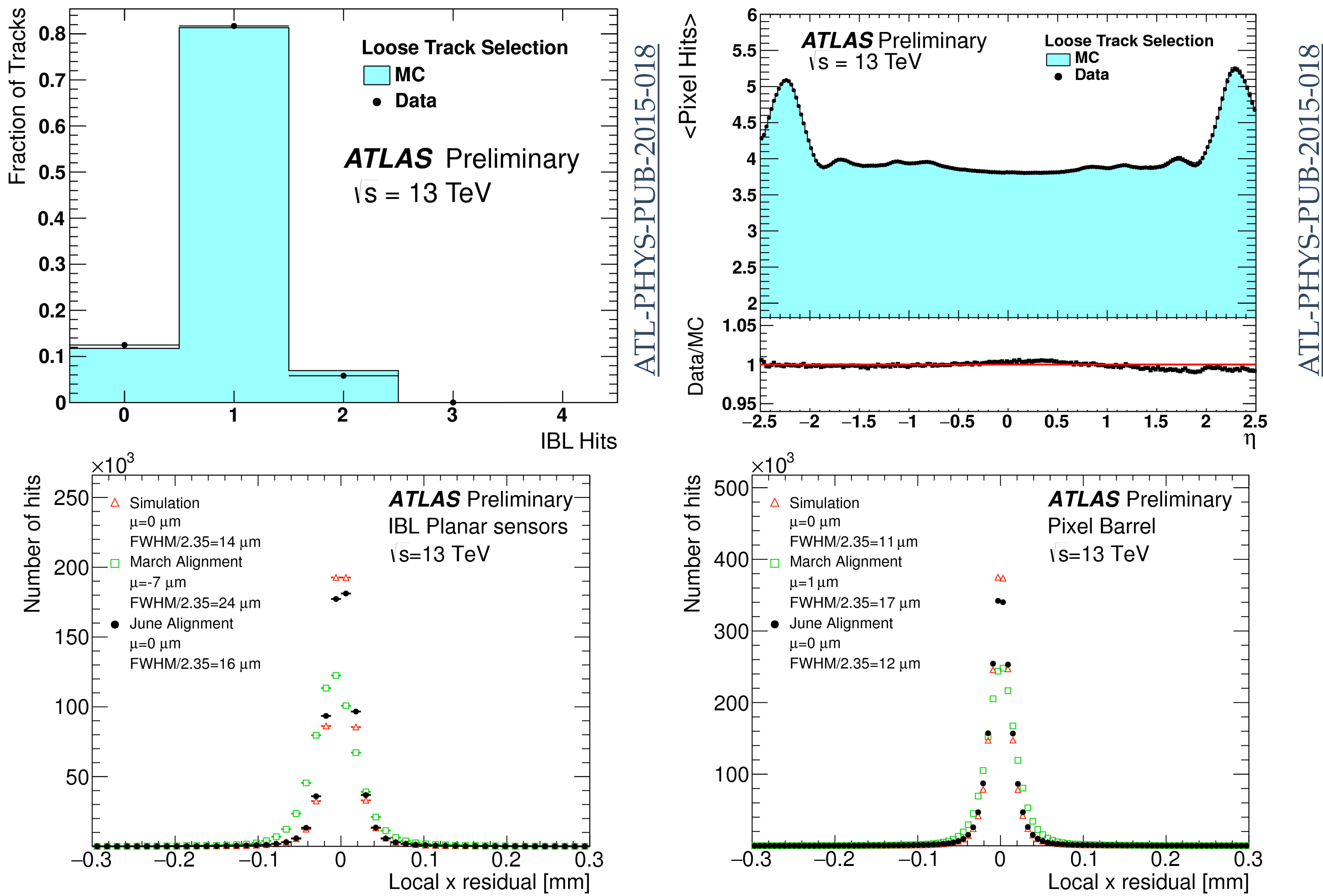
IDTR-2016-009



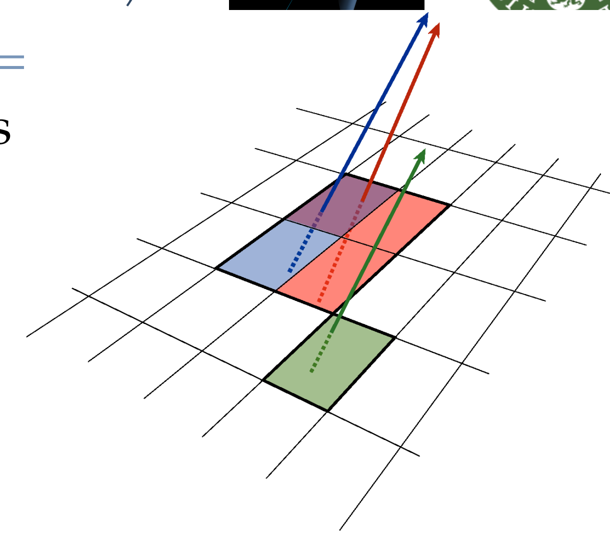
IDTR-2015-011

Inner detector in pp

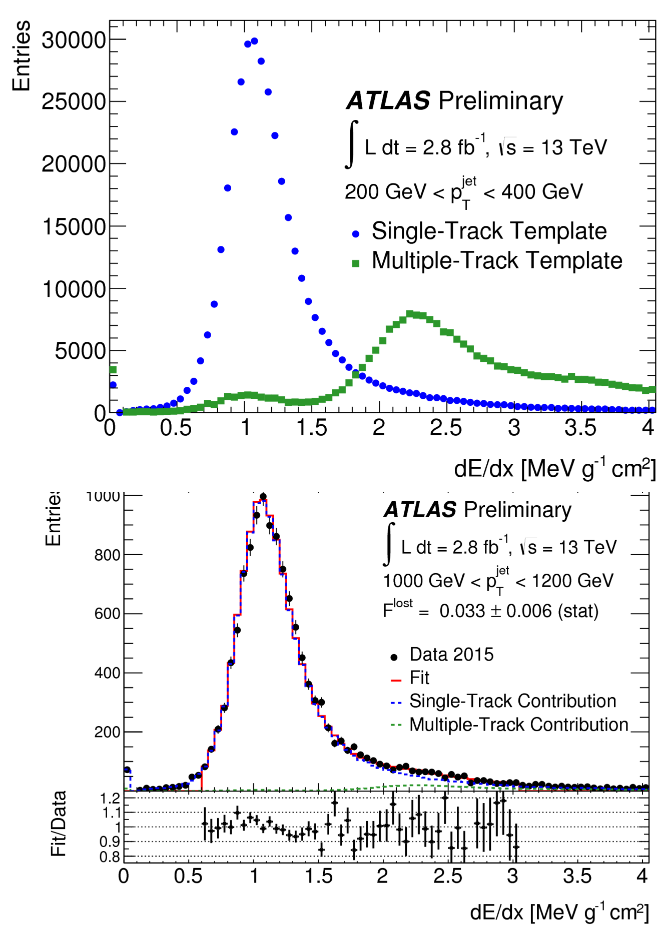
- MC and data for IBL, Pixel, SCT and TRT in great agreement
- After alignment, very good detector resolution, very close to MC expectations

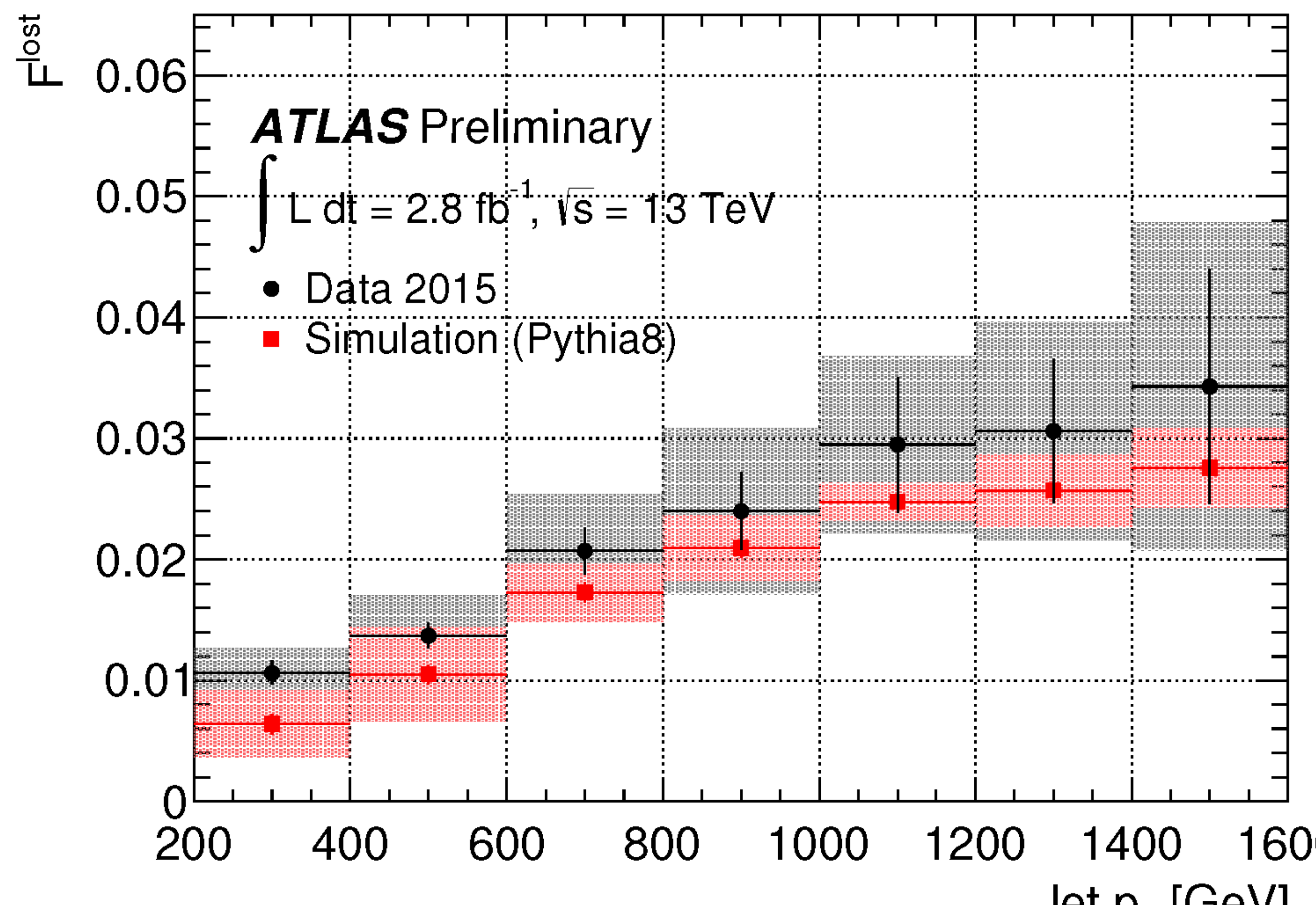


Tracking in Dense Environments (TIDE)



- In busy environment, large probability to have 2 or more very close charged particles
- **Neural network** to identify clusters *shared* by more than 1 particle, split them and estimate the position and error of each one:
  - Uses cluster charge, shape, correlation with previous layer and incidence angle
  - **Improves**: *b-tagging*, τ reconstruction, jet -mass reconstruction, etc..
- Performance validated in data by independent 2 methods:
  - Geometrical extrapolation and using the overlap region in phi ATL-PHYS-PUB-2015-044
  - Energy loss (dE/dx) in the pixel:





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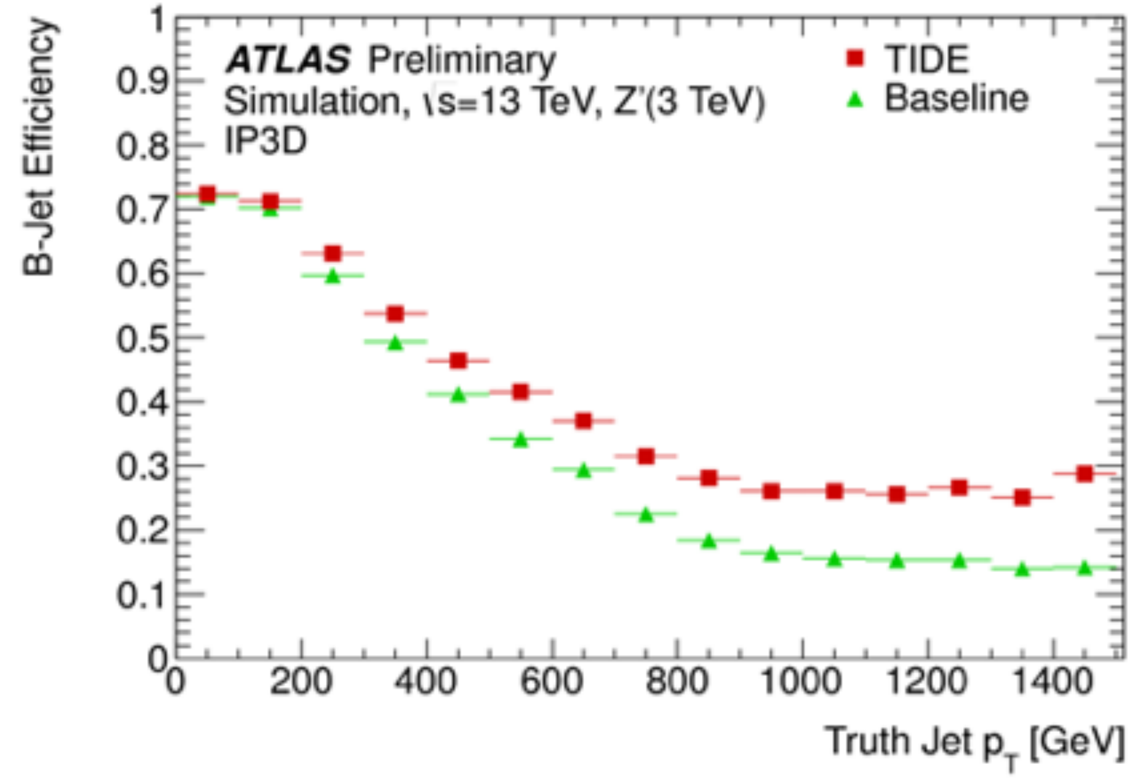
Tracking in Dense Environments (TIDE)

Tracking inside jets is fundamental for:

- *b-tagging*
- τ reconstruction
- High precision jet mass measurement (used for analysis as BSM searches)

Large efficiency increase with ATLAS tracking in dense environments (TIDE

TIDE is used as default for whole Run 2 and future:



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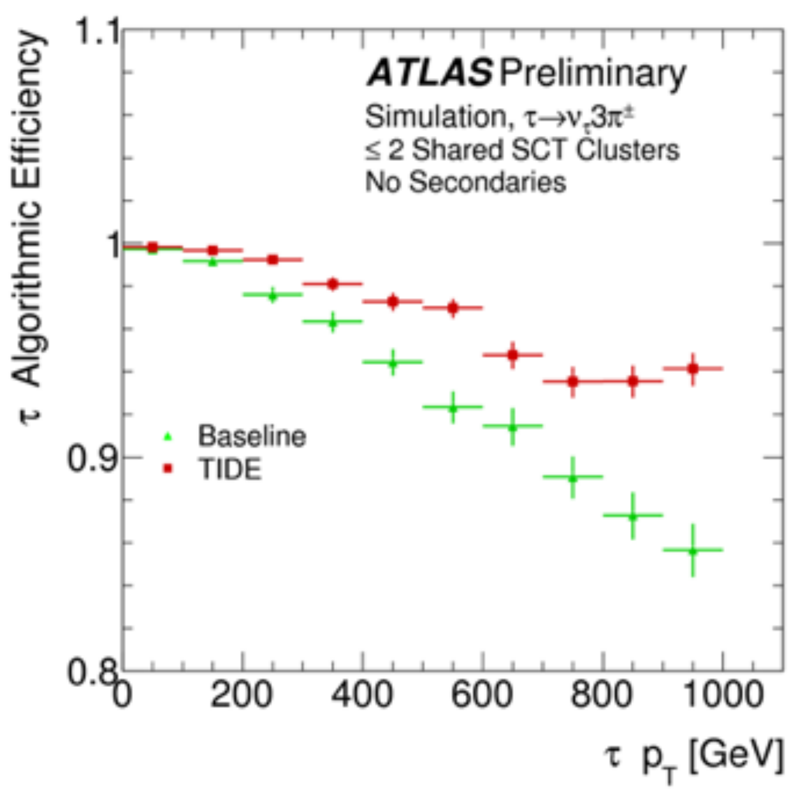
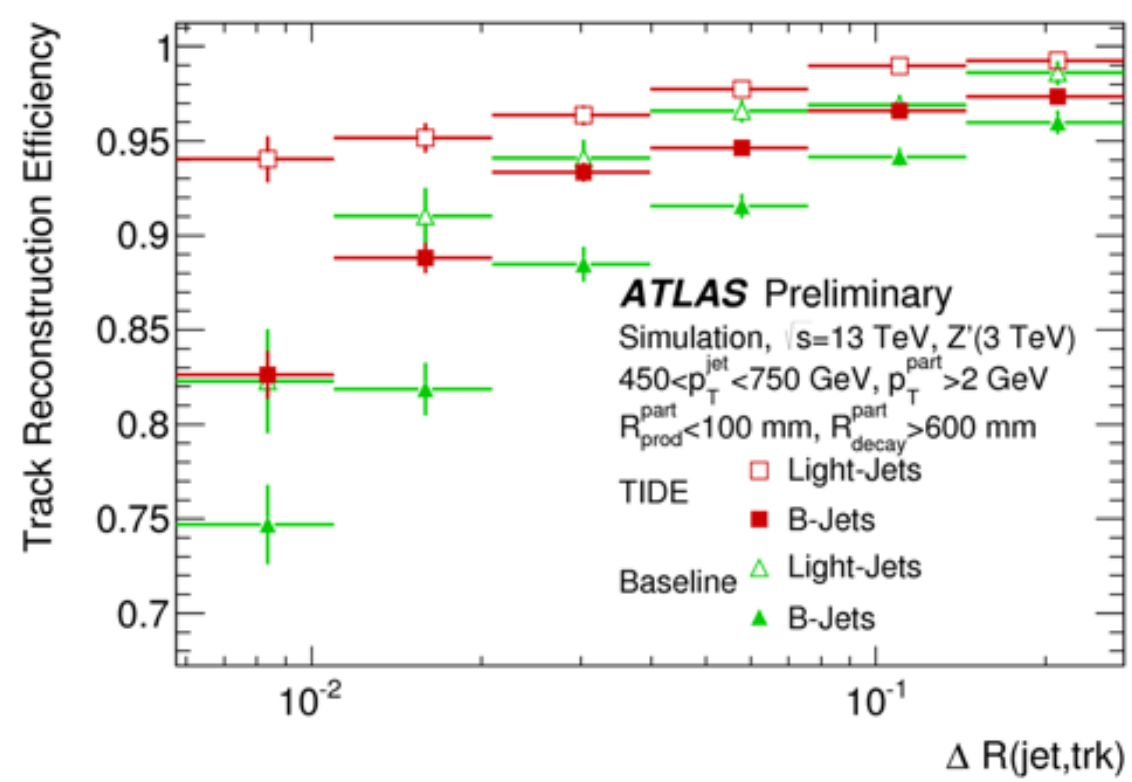




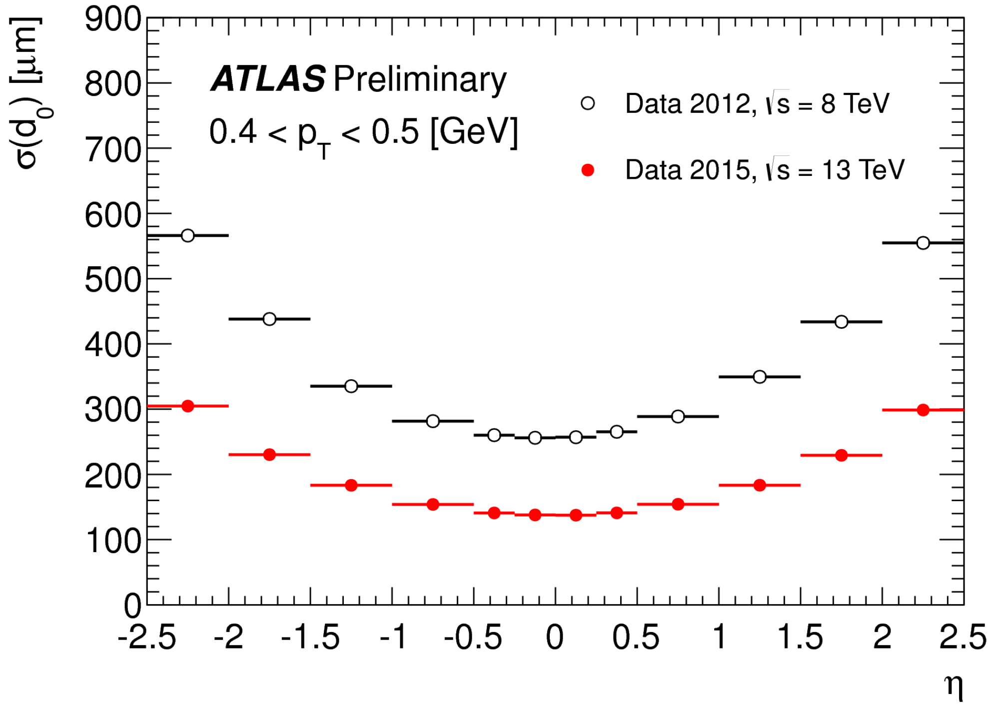
Impact parameter resolution

d_0 and z_0 resolution improved up to ~40%:

- New IBL
- Material reduction in the pixel boundaries

Impact parameter sensitive to material description at low pT

Improved discrimination between primary and secondaries: Important for MB analyses.



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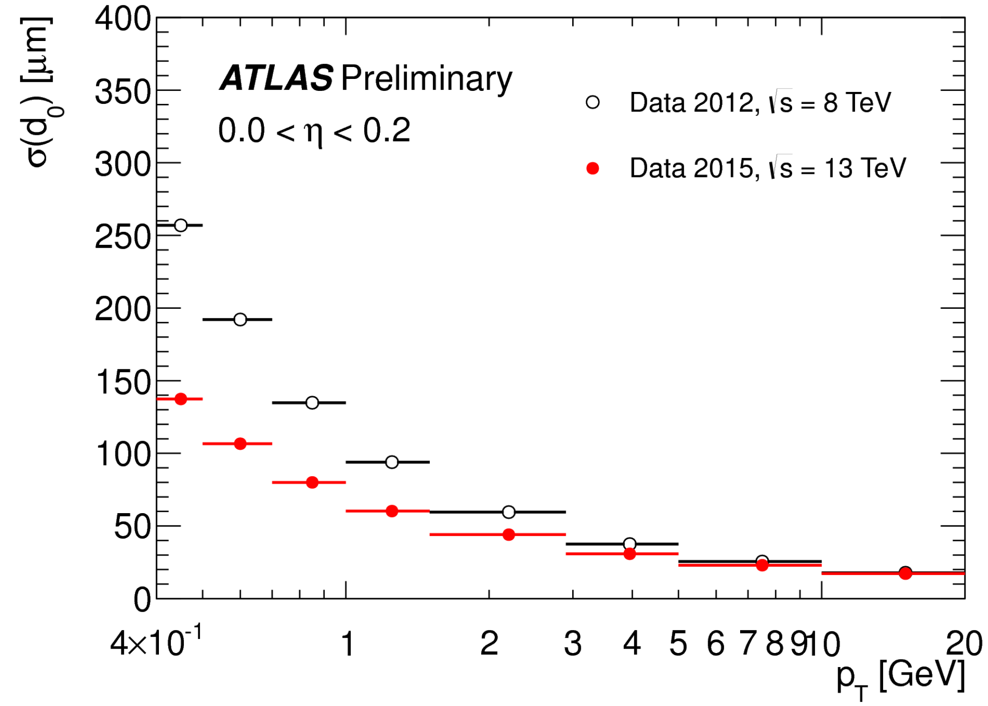

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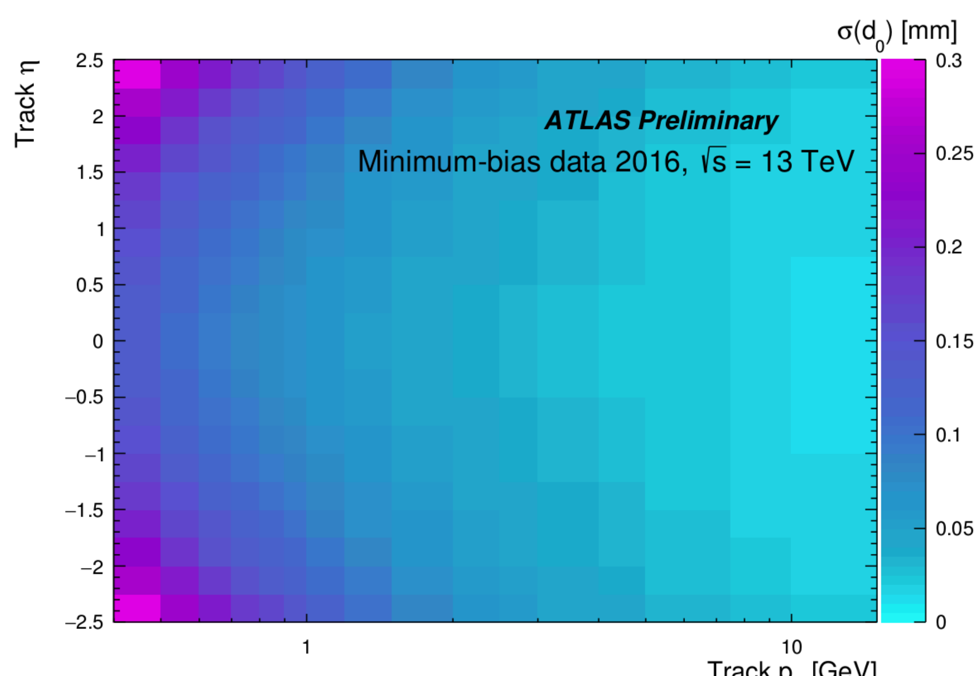

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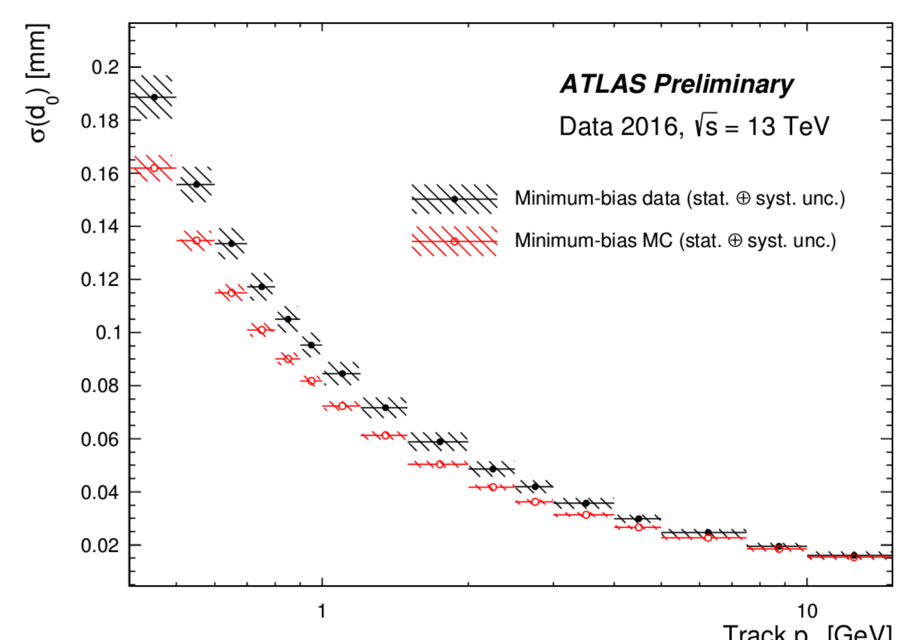


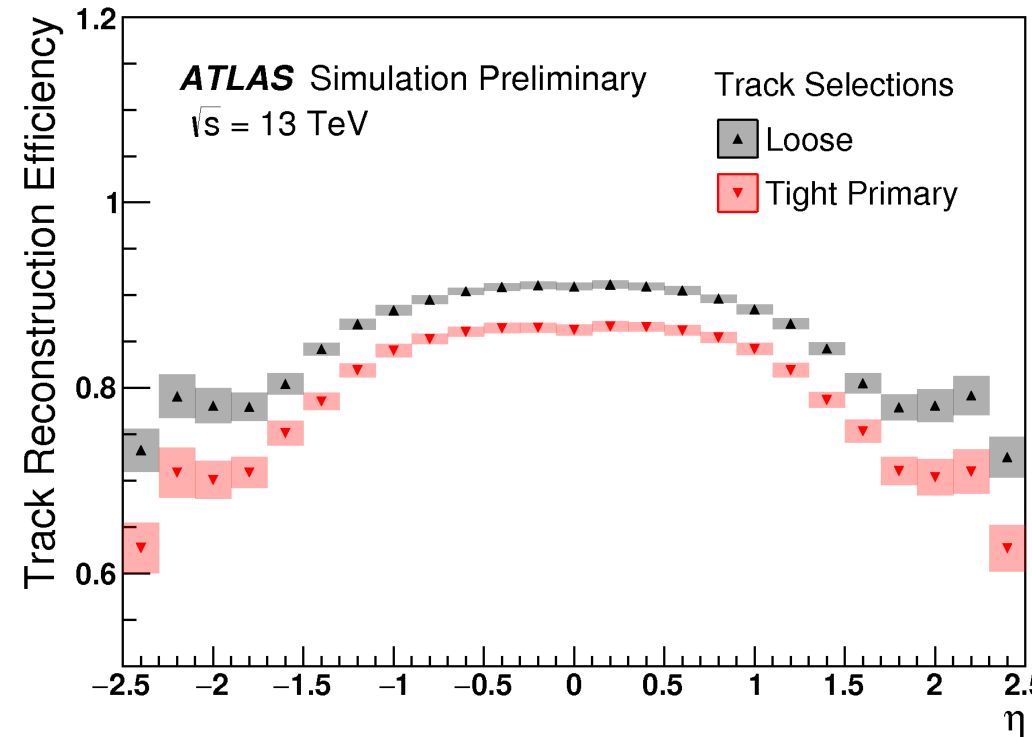
IDTR-2016-018

- **The impact parameter resolution has been unfolded to remove the contribution from the vertex resolution**

Tracking efficiency in pp

Very good tracking efficiency:

- at large instantaneous luminosity: increase of fakes mitigated by tighter track selection
- Track efficiency measure in MC and systematics applied to fit to data
- Large uncertainty is material budget



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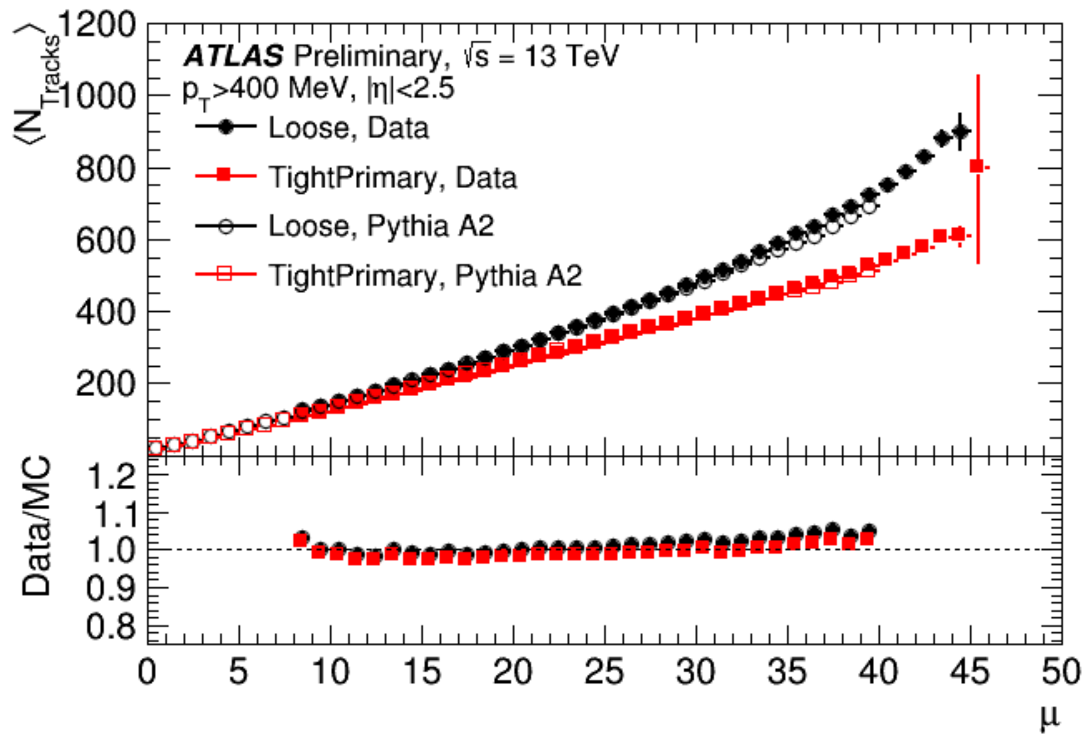

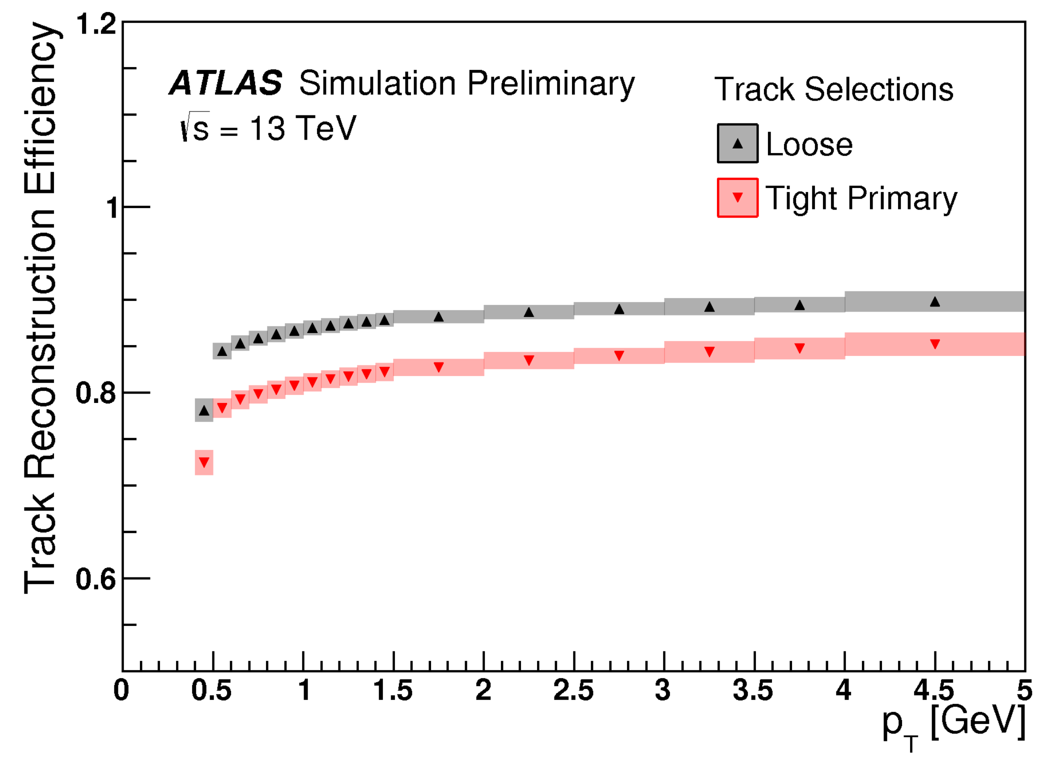

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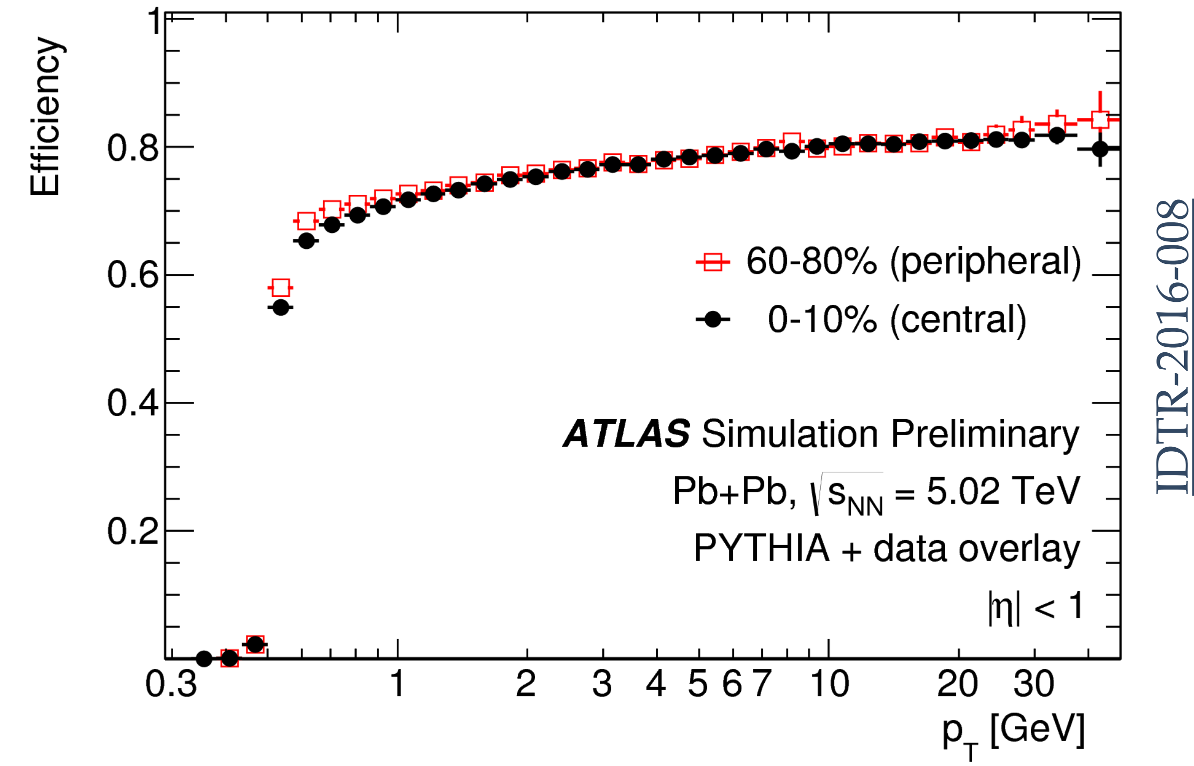
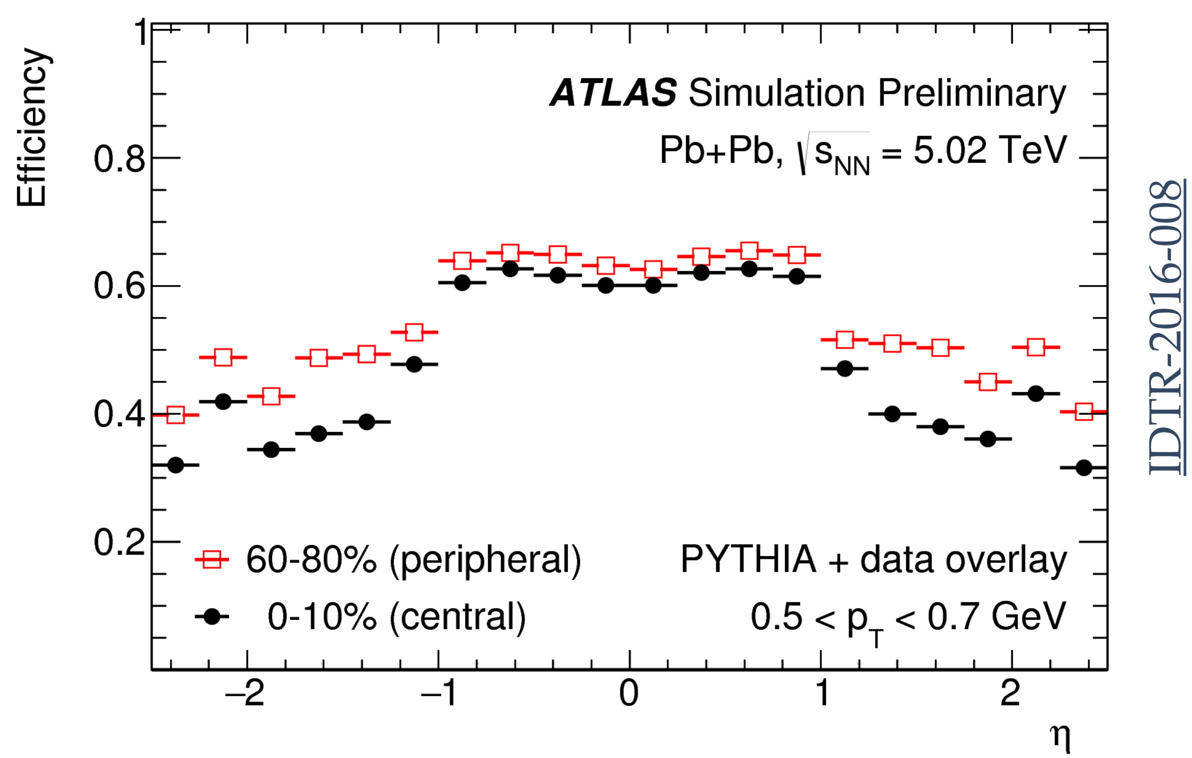
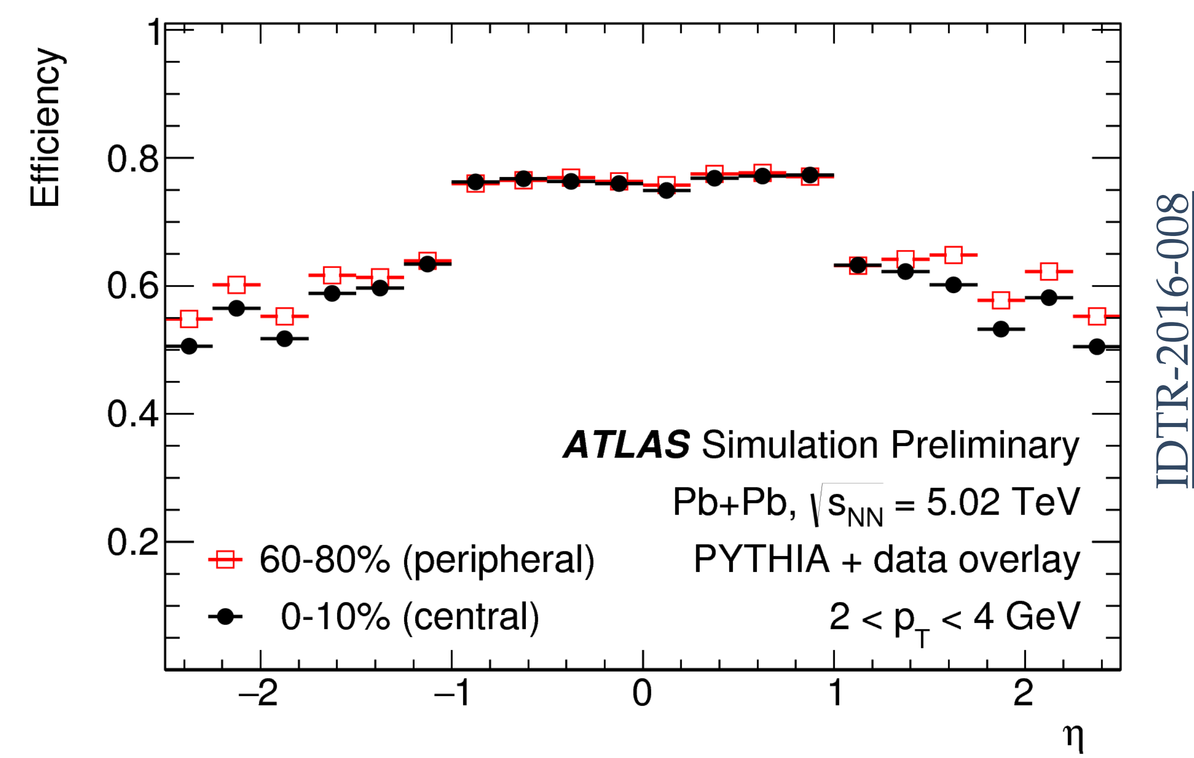
Tracking performance in Heavy Ions

- Insight of performance at very large occupancy
- Data overlay samples: simulated hard-scattering pp collisions embedded into real Pb+Pb events.
- Efficiency defined as a fraction of generated primary particles that are matched to reconstructed tracks with respect to all generated primary particles.

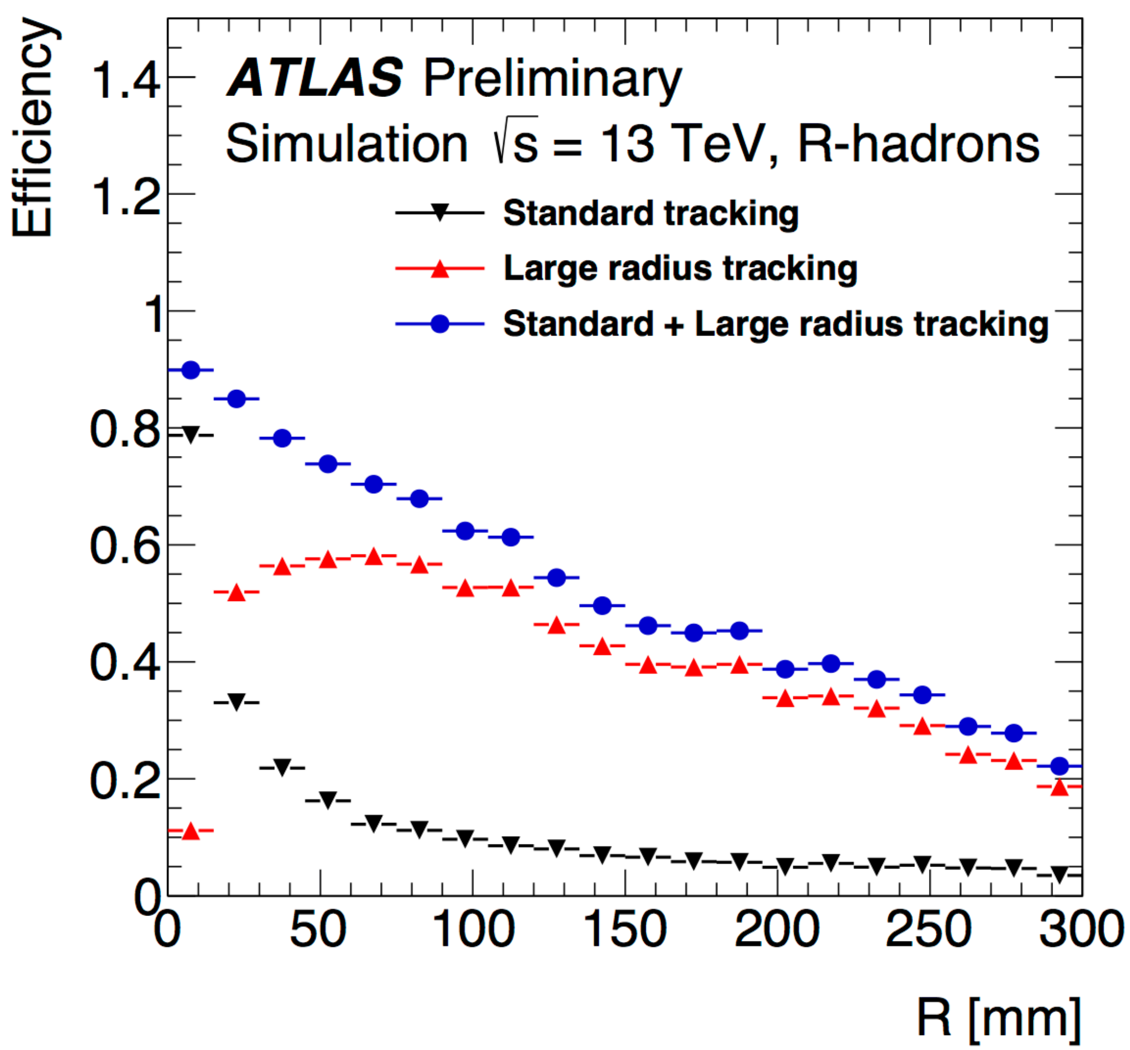


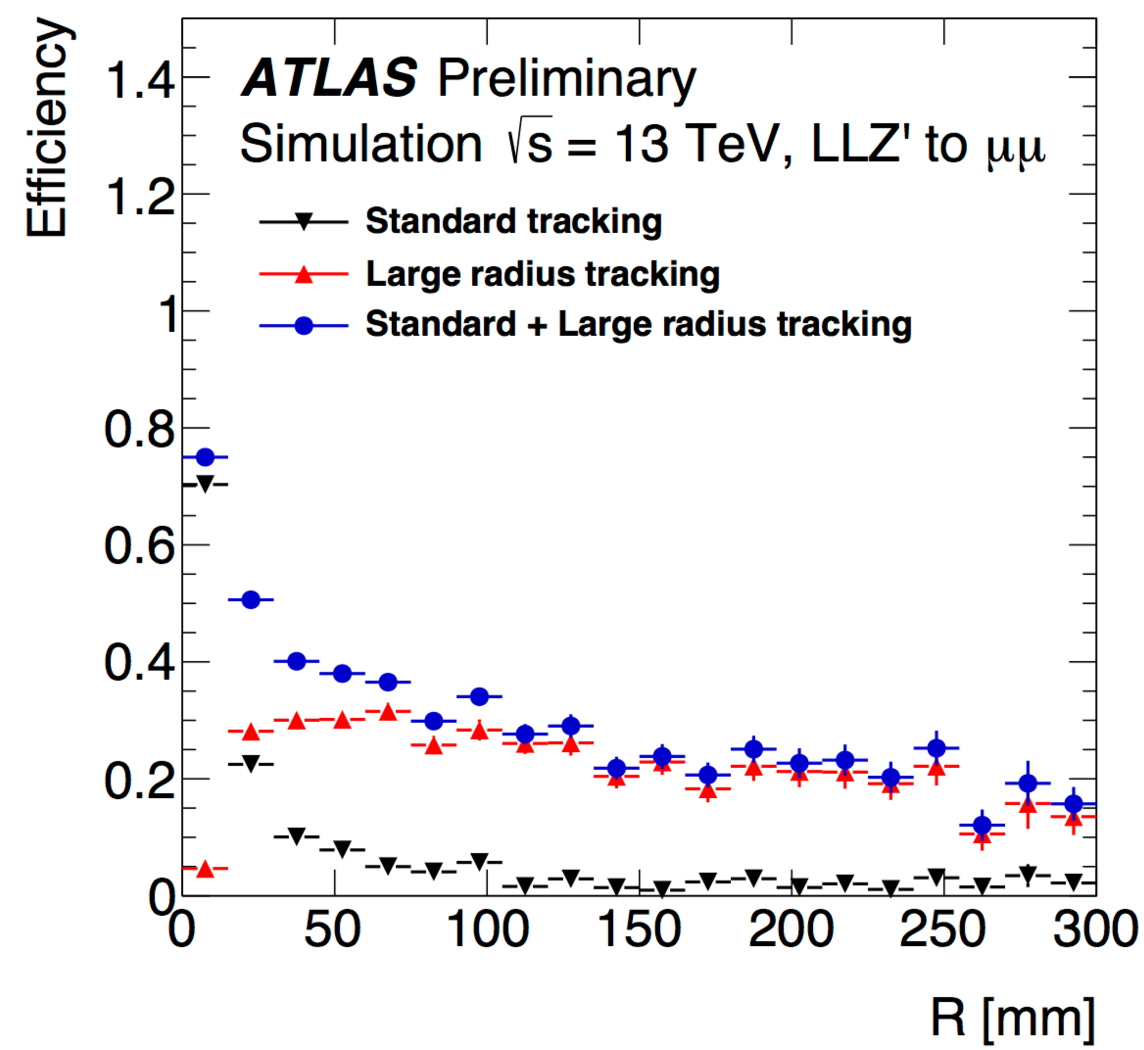




Large radius tracking

- The large radius tracking is performed as a second pass after the standard tracking using unused hits to improve the signal track reconstruction efficiency at large impact radii.
- The reconstructed tracks are required to fulfil the following quality criteria: pT > 1 GeV, |η| < 2.5, hit quality requirements, |d0| < 300 mm, |z0| < 1,500 mm. The efficiency is calculated for truth particles fulfilling the same η and pT requirements





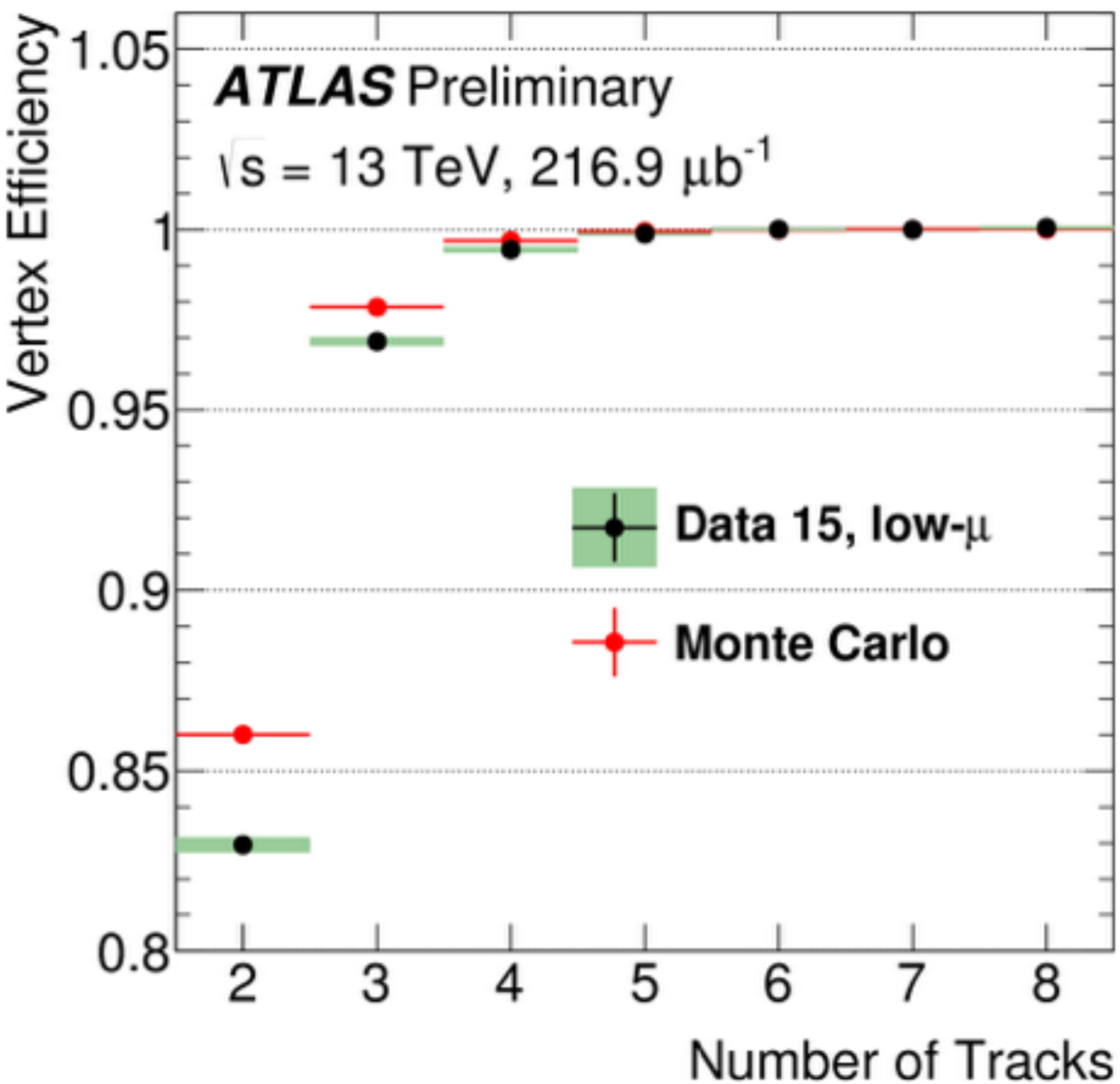
IDTR-2016-006

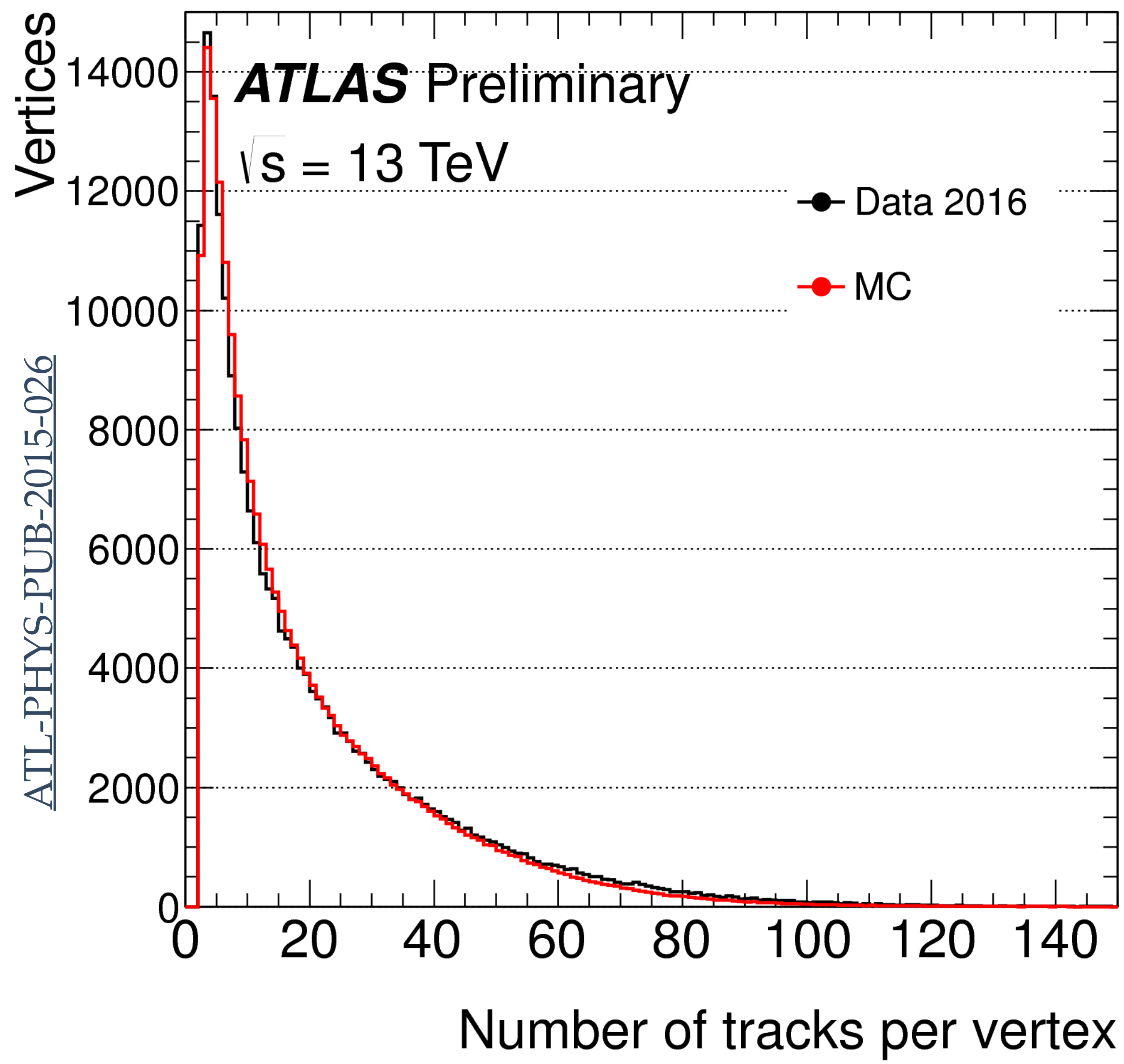
Vertex Performance

The standard vertex fitter used in ATLAS is a kalman filter with an iterative annealing procedure

- Due to the large number of tracks, it is very optimised to keep CPU time low

Up to 140 tracks per vertex:

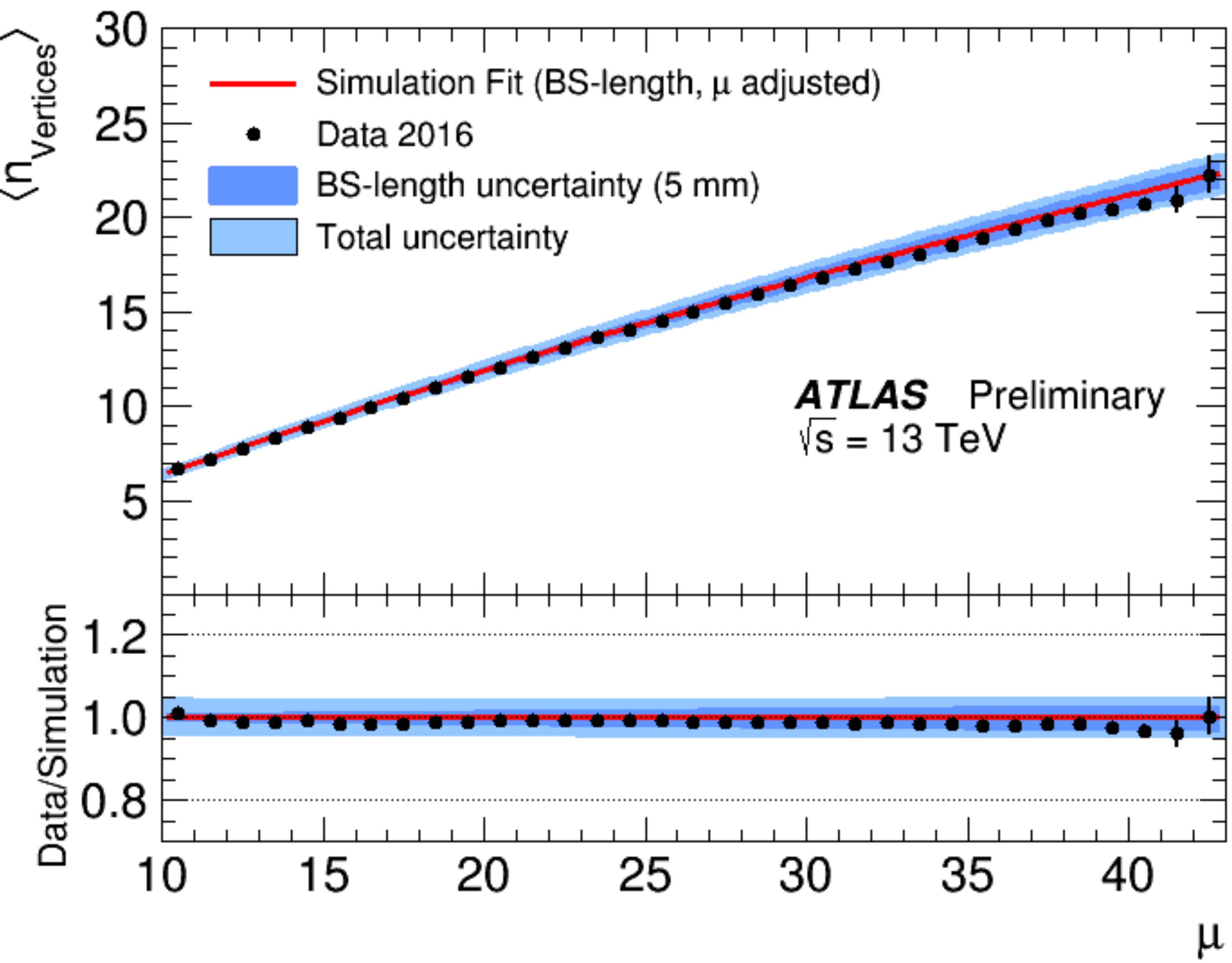


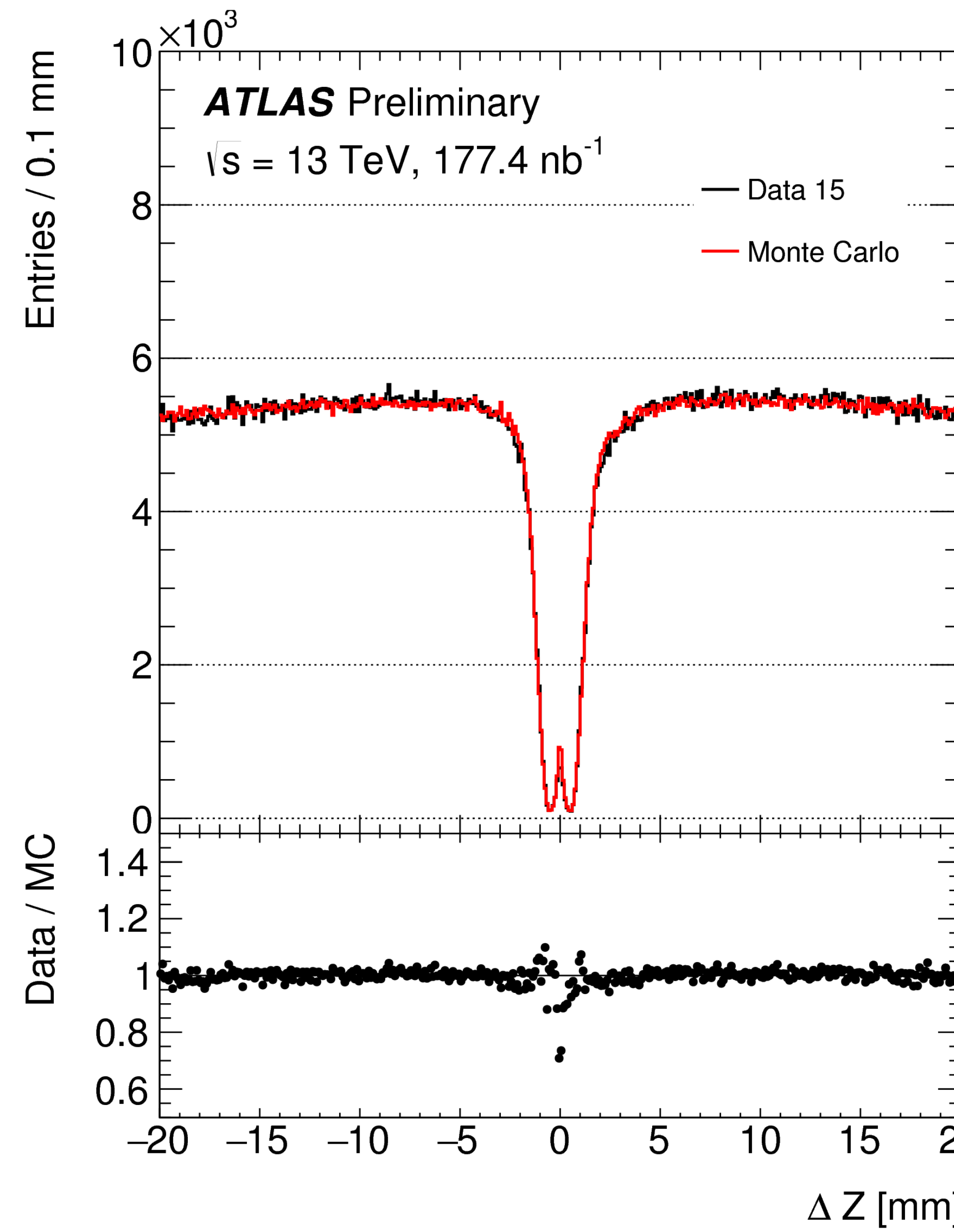


Vertex efficiency vs mu

Relationship between the number of reconstructed vertices and the average number of interactions per crossing

- Beam induced background extracted.
- Vertexes are merged when they are closer than vertex resolution causing a non-linearity in mu





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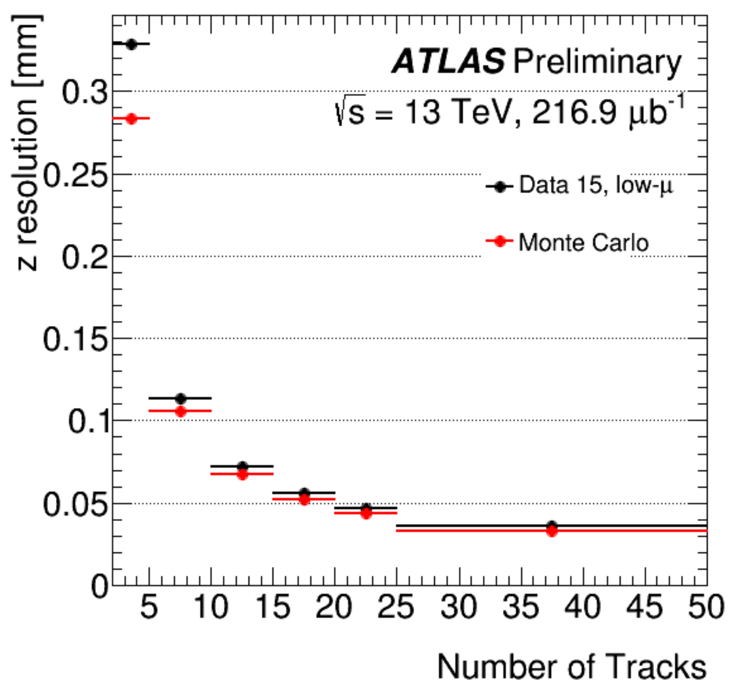
IDTR-2015-005

Vertex resolution

- **Estimated by Data/MC studies (minimum bias events), differences due to:**
  - Description of the sub-detector hit errors
  - Multiple scattering, ionization energy losses
  - Residual misalignment



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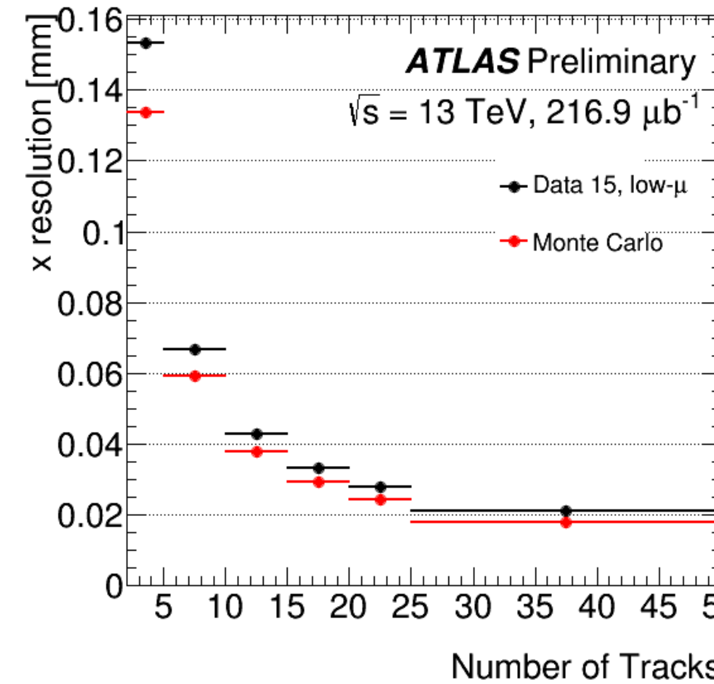

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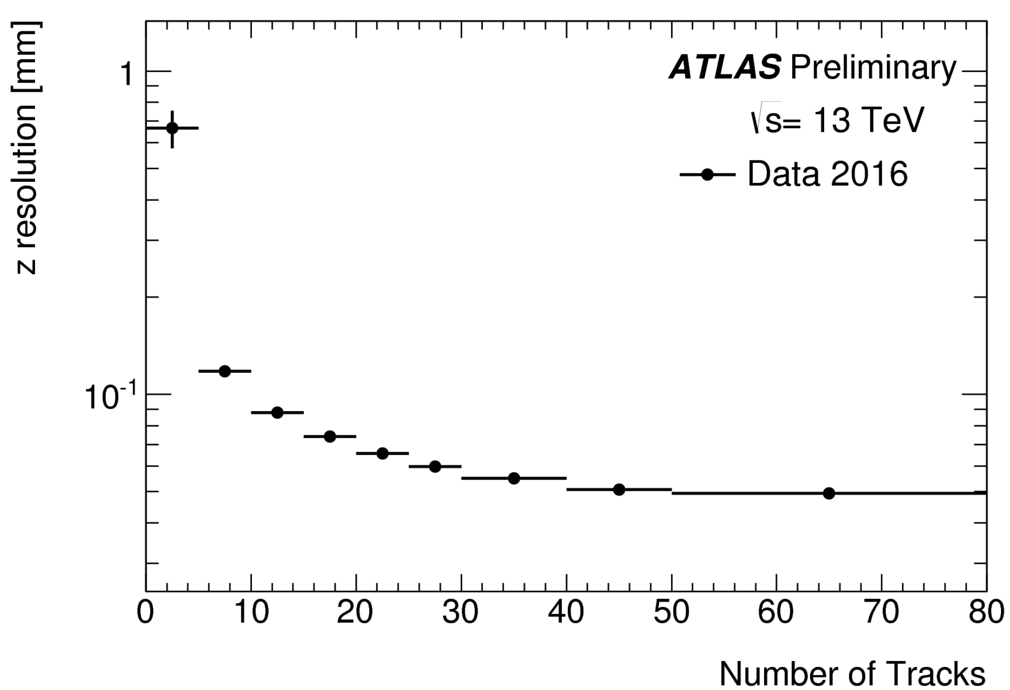
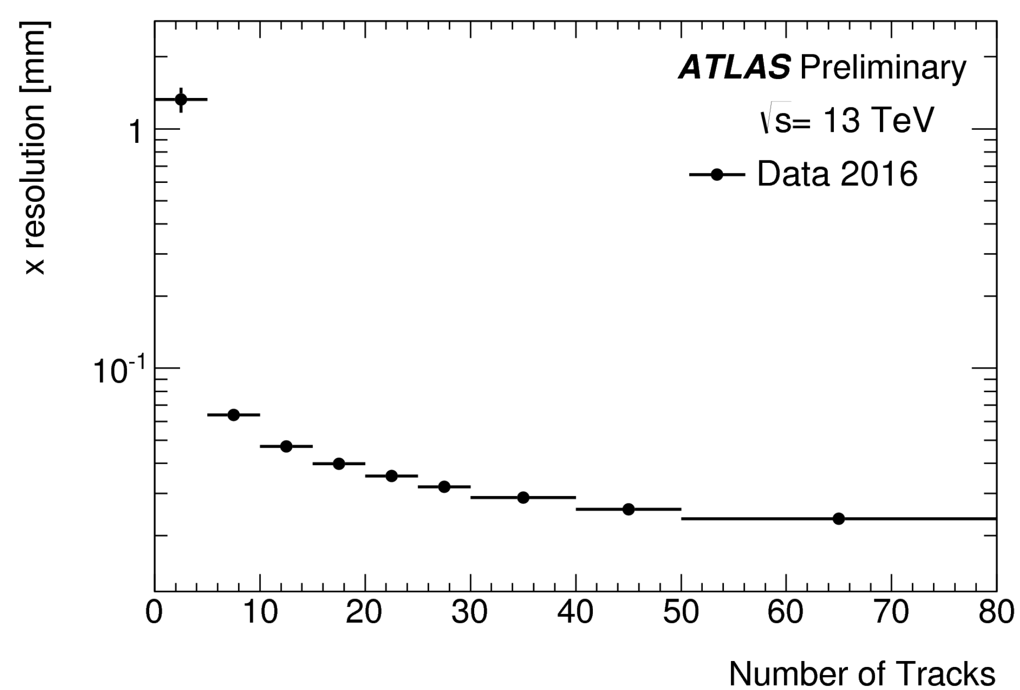


IDTR-2016-007



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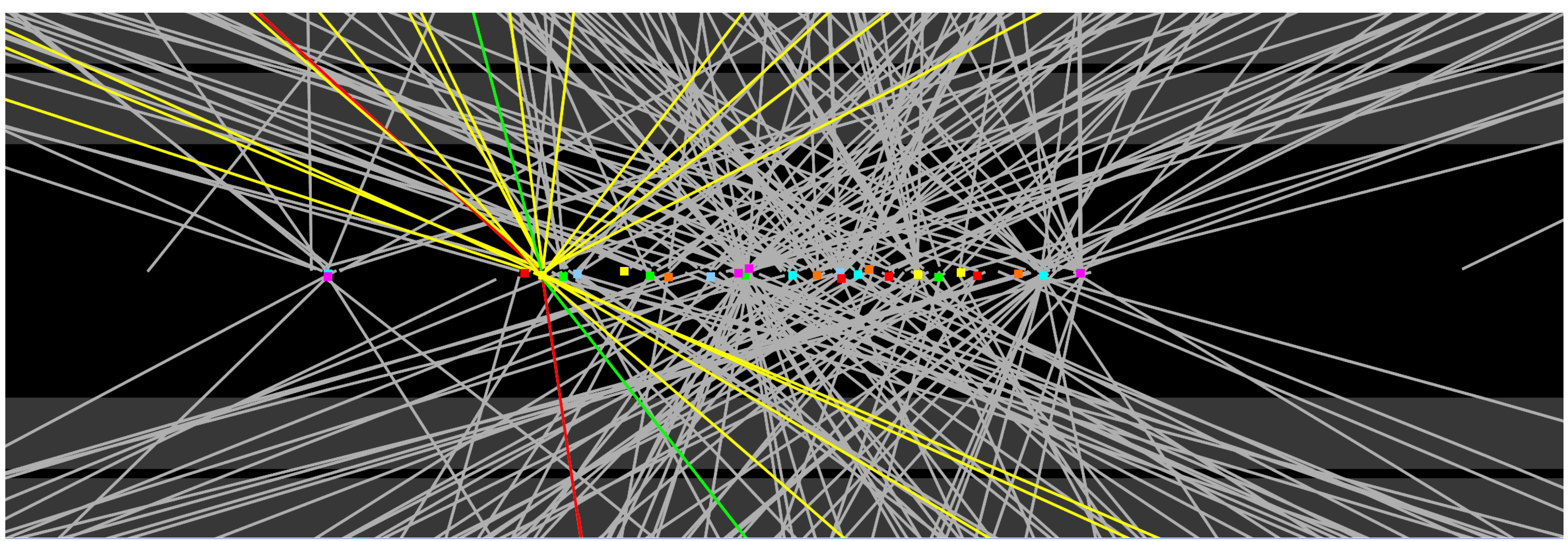
Summary

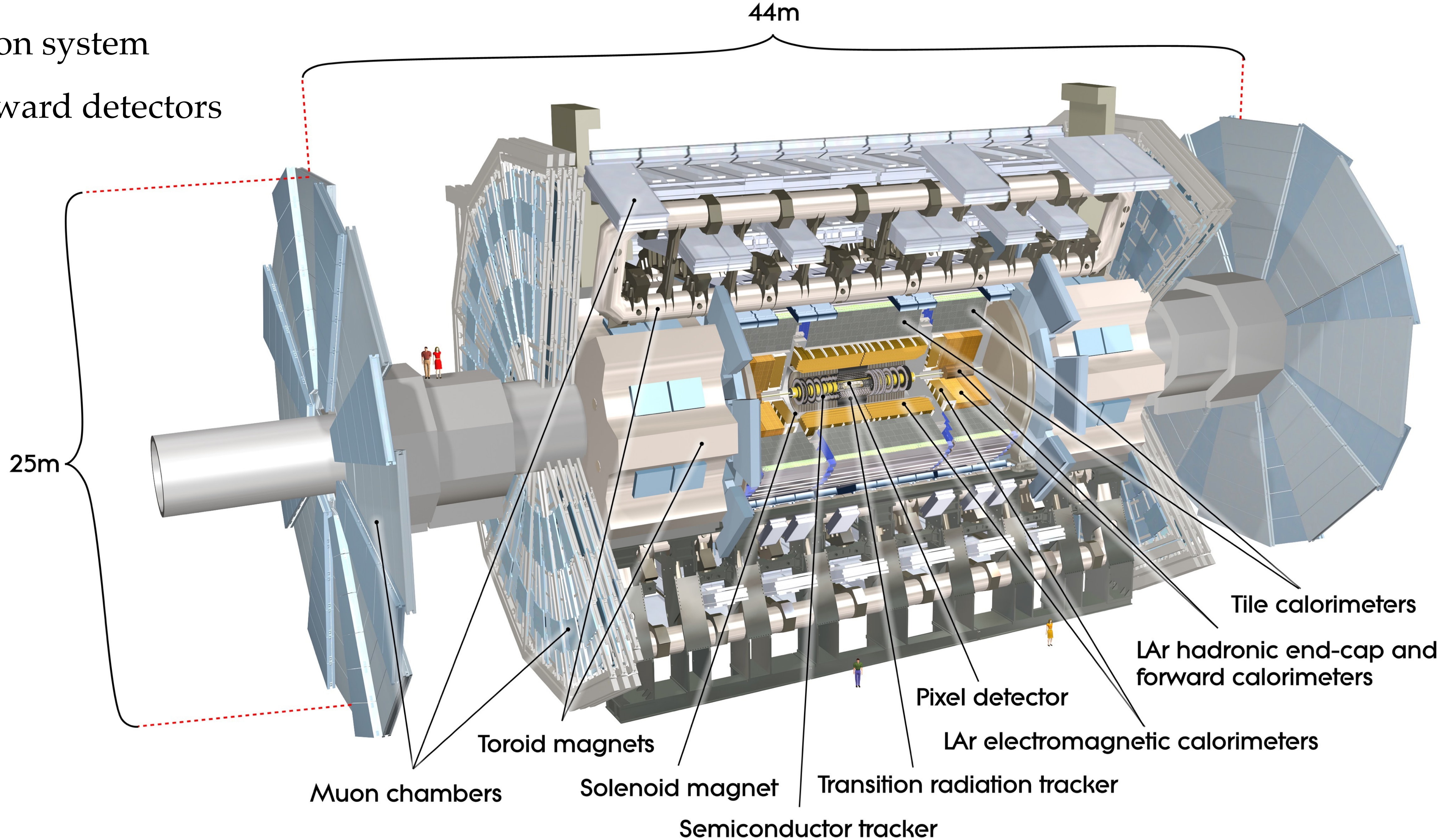
- ATLAS Inner Tracking has an outstanding performance even operating over its design specifications
    - ID detectors did a huge work to operate at very high rates
- IBL is operating smoothly, giving an improved performance with respect to Run 1
- Time dependent alignment allows to correct for detector changes within runs
- Tracking in dense environments improved the reconstruction at large mu and inside jets
- Ready to collect data for the remaining part of Run 2 and algorithms improvements expected for Run 3
- Preparing our tracking for Run 3: Multithread safe and new ideas **WELCOME**!



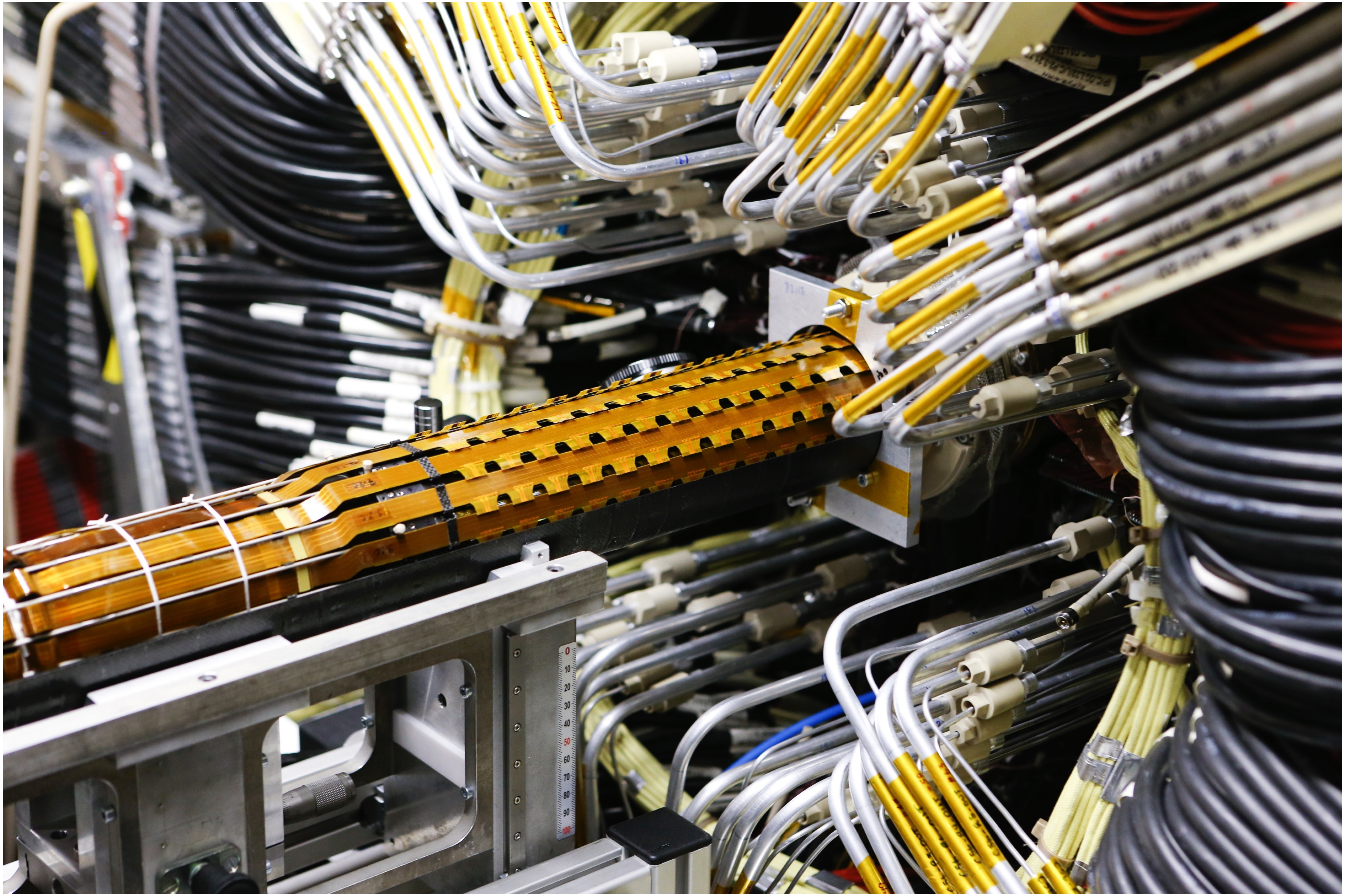
Backup

The ATLAS Experiment

- **LHC General purpose experiment:**
  - Inner tracking
  - Electromagnetic and hadronic calorimeter
  - Muon system
  - Forward detectors
- **Wide range of physics:**
  - Proton-proton collisions at 0.9, 7, 13 and hopefully 14 TeV
  - Lead-Lead and proton lead



The Insertable b-layer (IBL)



Imaging inspired vertexing

- **Alternative vertex finding algorithm inspired in medical imaging**
  - 3D binned histogram with linearised helical trajectories. Histogram content in each traversed bin is incremented by the path length of the track in that bin
  - The track image is transformed into frequency space using the FFTW3
  - A filter is multiplied with the frequency space histogram. The filtered frequency space image is then back transformed to position space,
  - The resulting image is then passed to a separate clustering
- Linear in CPU with luminosity. while combinatorial vertexing is quadratic.

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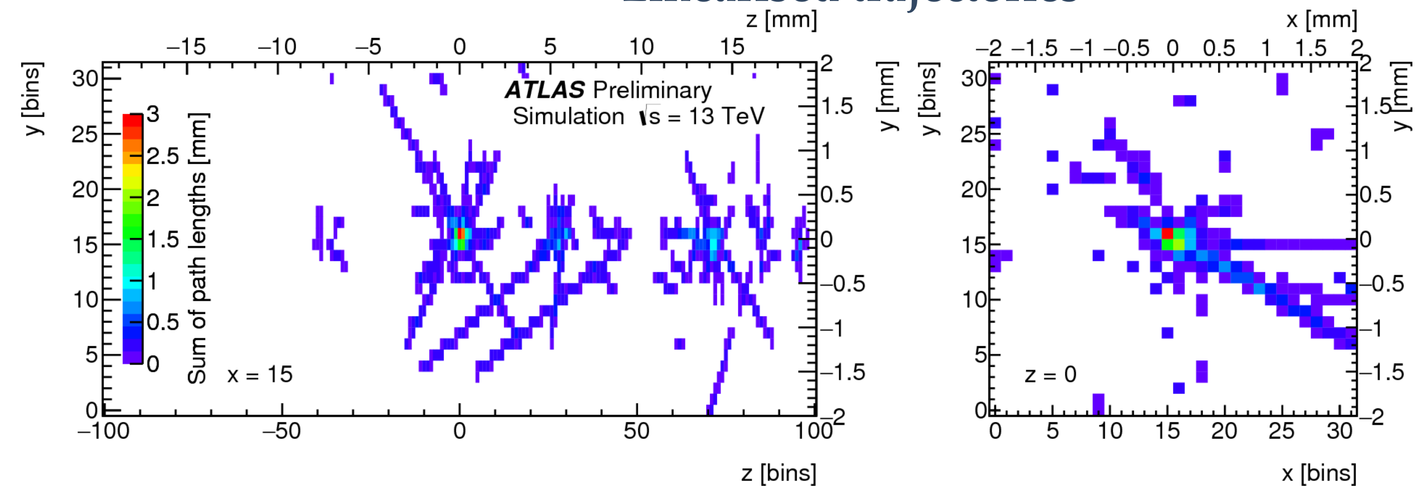
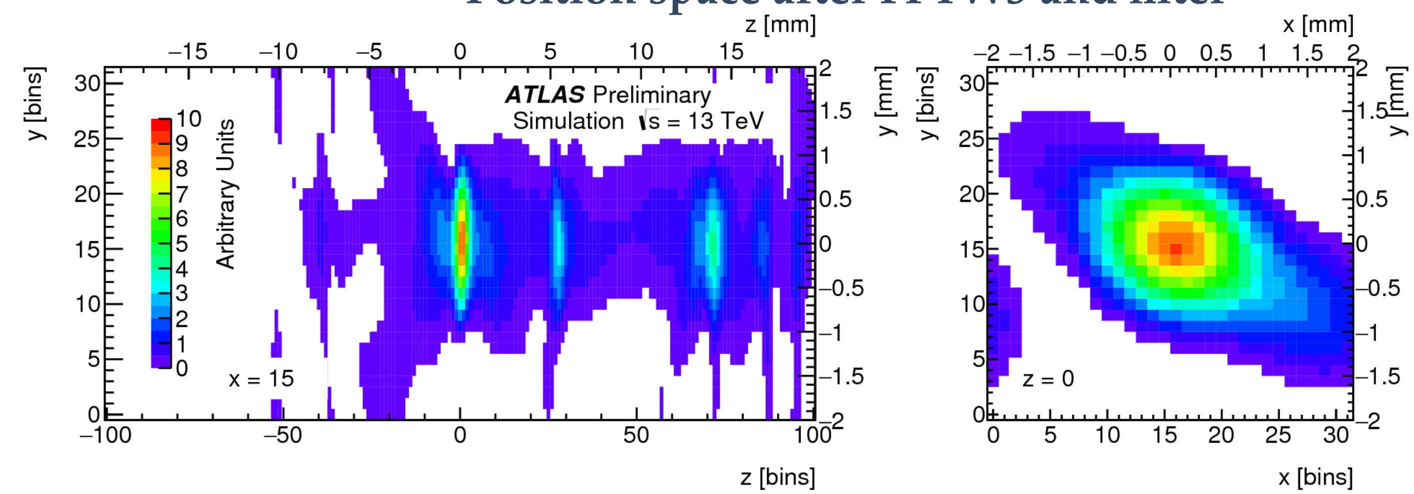
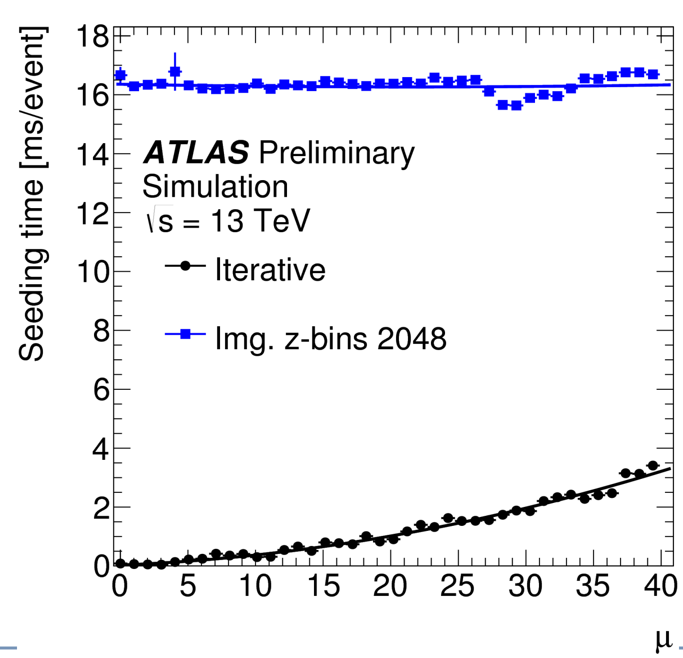
Linearised trajectories

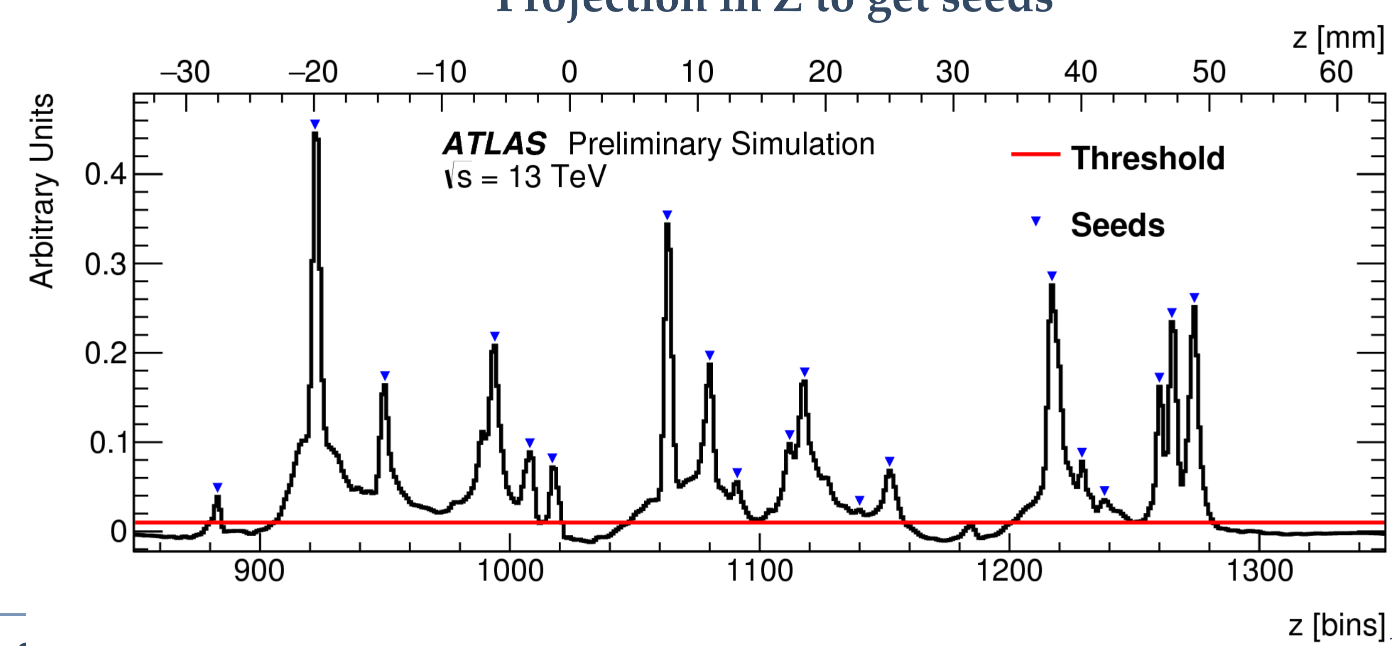


Position space after FFTW3 and filter





Projection in Z to get seeds



Vertex resolution vs mu

Overall vertex fitter is very insensitive to the presence of outlying tracks– this helps the performance of the hard-scatter primary vertex against infiltration from pile up tracks.

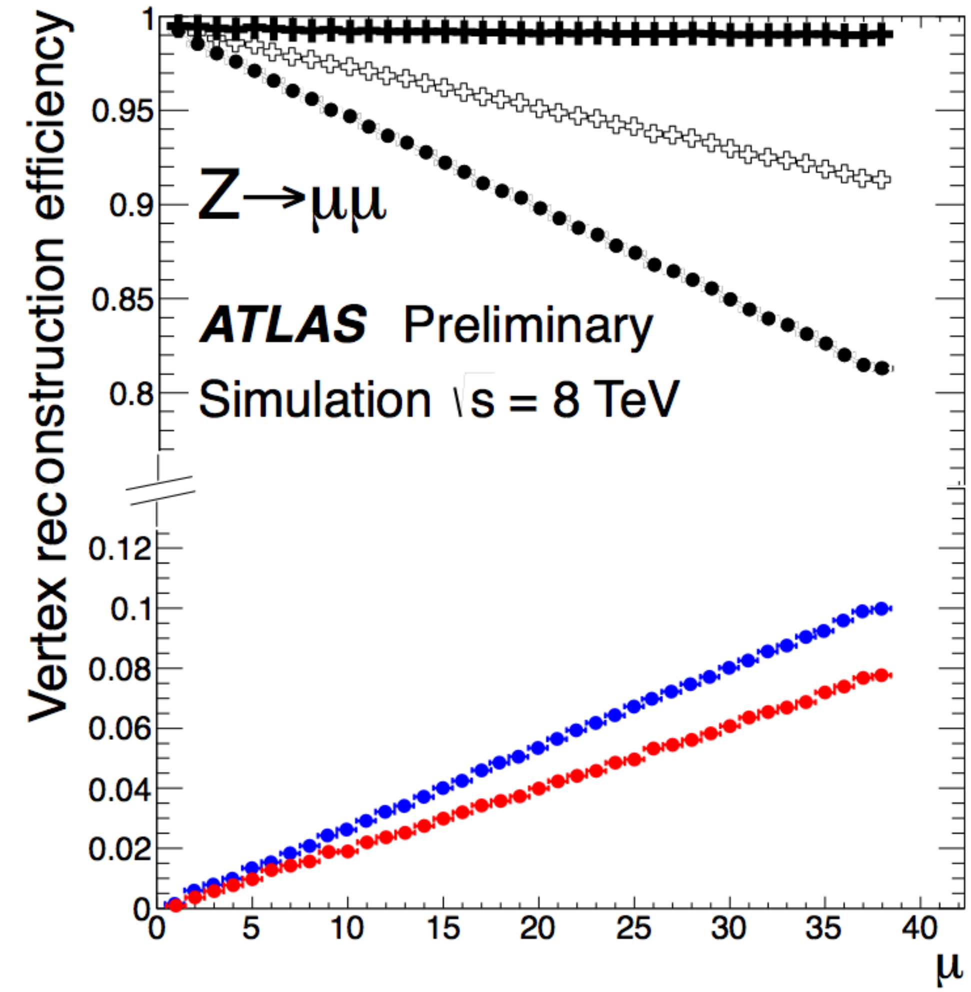
The efficiency for Hard Scatter vertex reconstruction is near 100% for all pile-up studied. At $\mu = 40$, 8% of Zmumu primary vertices have Highest level of pile-up contamination→ transverse resolution worsened by ~20%, longitudinal resolution worsened by factor of 5. (Transverse resolution is aided by beam spot constraint)

Contributions:

- A) Clean
- B) Low pile-up contamination
- C) High pile-up contamination
- (A)+(B)

Overall efficiency:

- (A)+(B)+(C)



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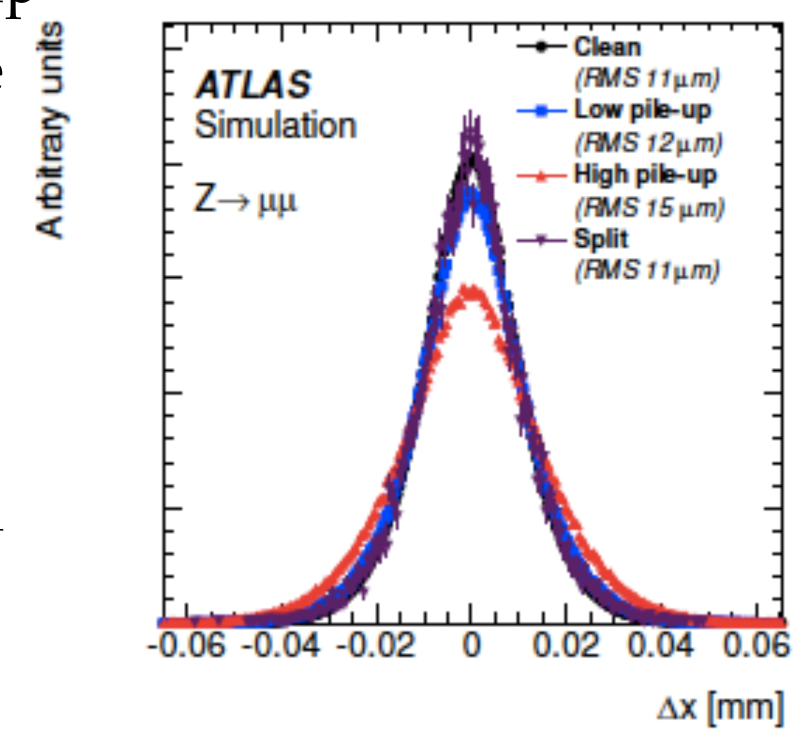

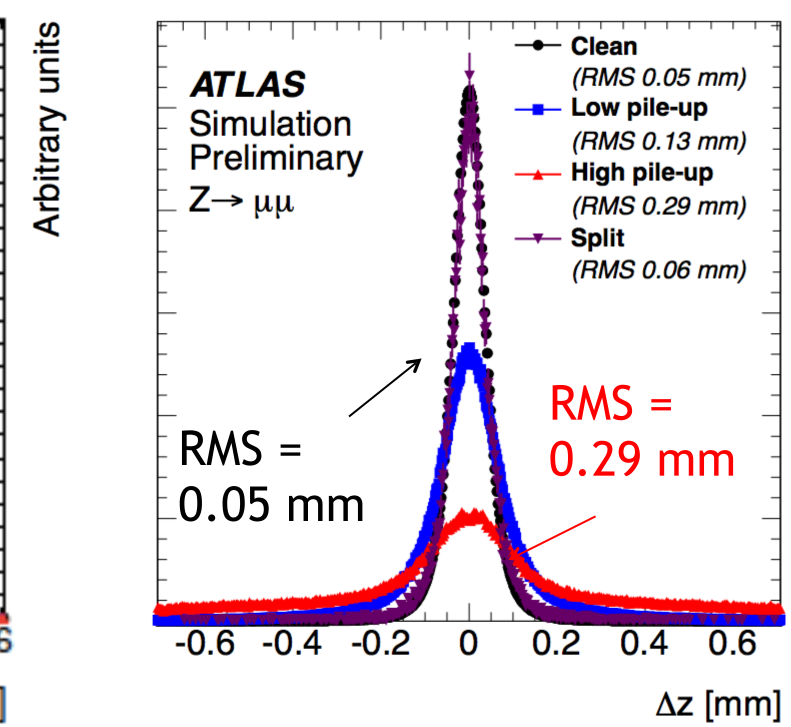

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