ATLAS New Small Wheel performance studies with LHC Run 3 data

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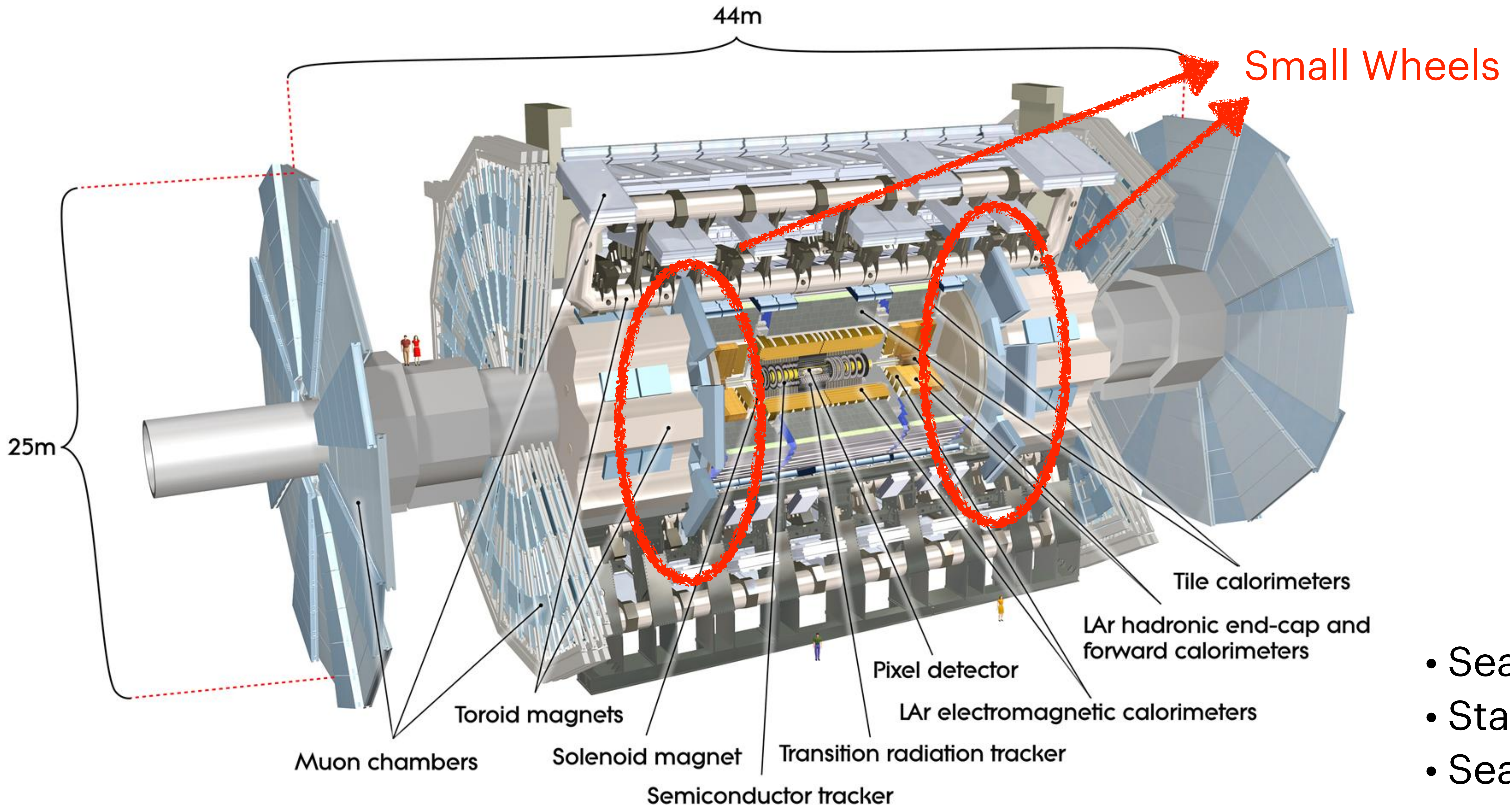
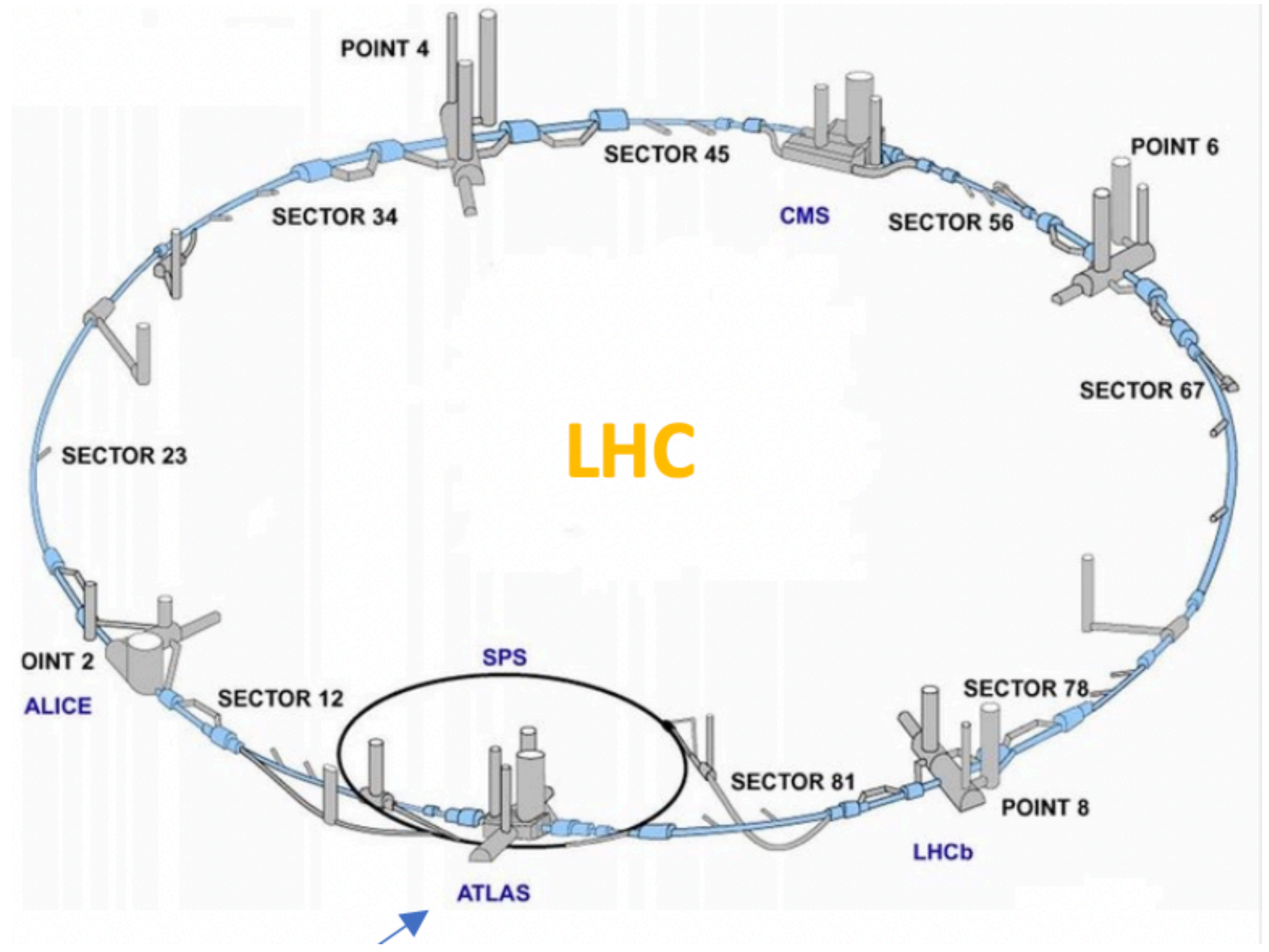
On behalf of the ATLAS Muon Spectrometer Community

ATLAS Detector





ATLAS is one of the 4 main experiments at the Large Hadron Collider

Multi-purpose detector dedicated to:

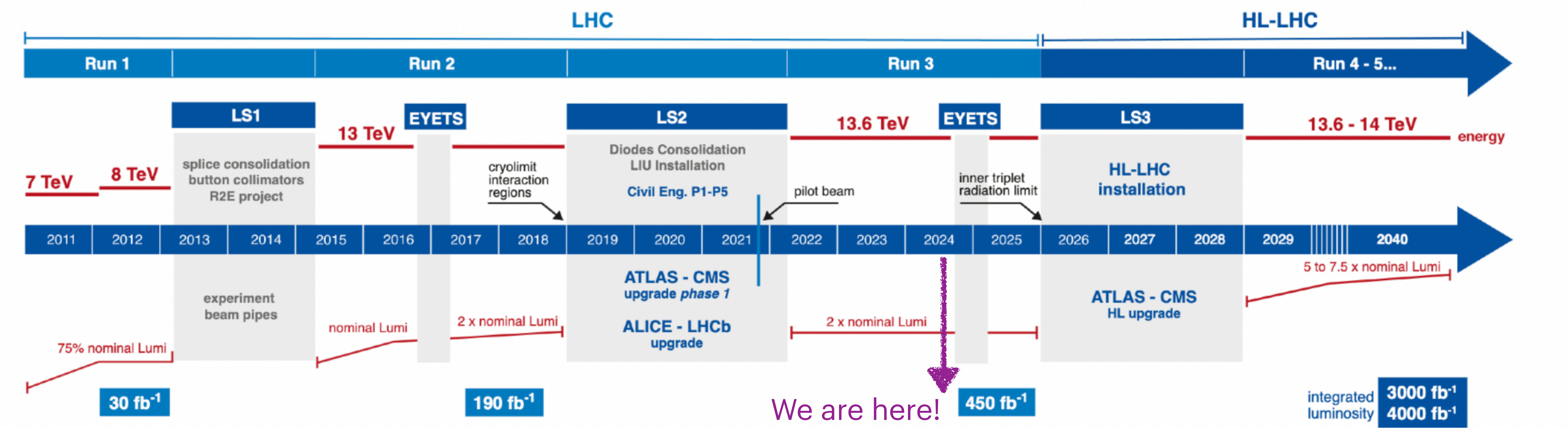
- Search and study of the Higgs Boson
- Standard Model precision measurements
- Search for new physics beyond the Standard Model

Detector with cylindrical shape around the p-p interaction point, divided longitudinally in barrel and 2 end-caps and organized in layers:

- Inner tracker for tracking and momentum measurement of charged particles
- Electromagnetic calorimeter for measurement of energies of electrons and photons
- Hadronic calorimeter for measurement of energy of hadrons
- Muon spectrometer for identification and momentum measurement of muons (Small Wheels: first stations in the end-caps)

LHC schedule

The LHC has a program of operation with different running periods and periods of shutdown for upgrades



- Long shutdown 2 (LS2) between 2019 and 2022 to upgrade the machine and the detectors (phase-1 upgrade)

- Run 3 started in 2022: instantaneous luminosity of about x1.5 the Run 2 value ($2 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$) and average pile-up that will reach about x2 the Run 2 value (60)

- Long shutdown 3 (LS3) between 2026 and 2028 to upgrade the machine and the detectors again (phase-2 upgrade)

- HL-LHC will start in 2029: very challenging operation environment with instantaneous luminosity of about x3 the Run 2 value ($5-7 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$) and average pile-up that will reach about x5 the Run 2 value (200)

Motivation for the New Small Wheel Upgrade

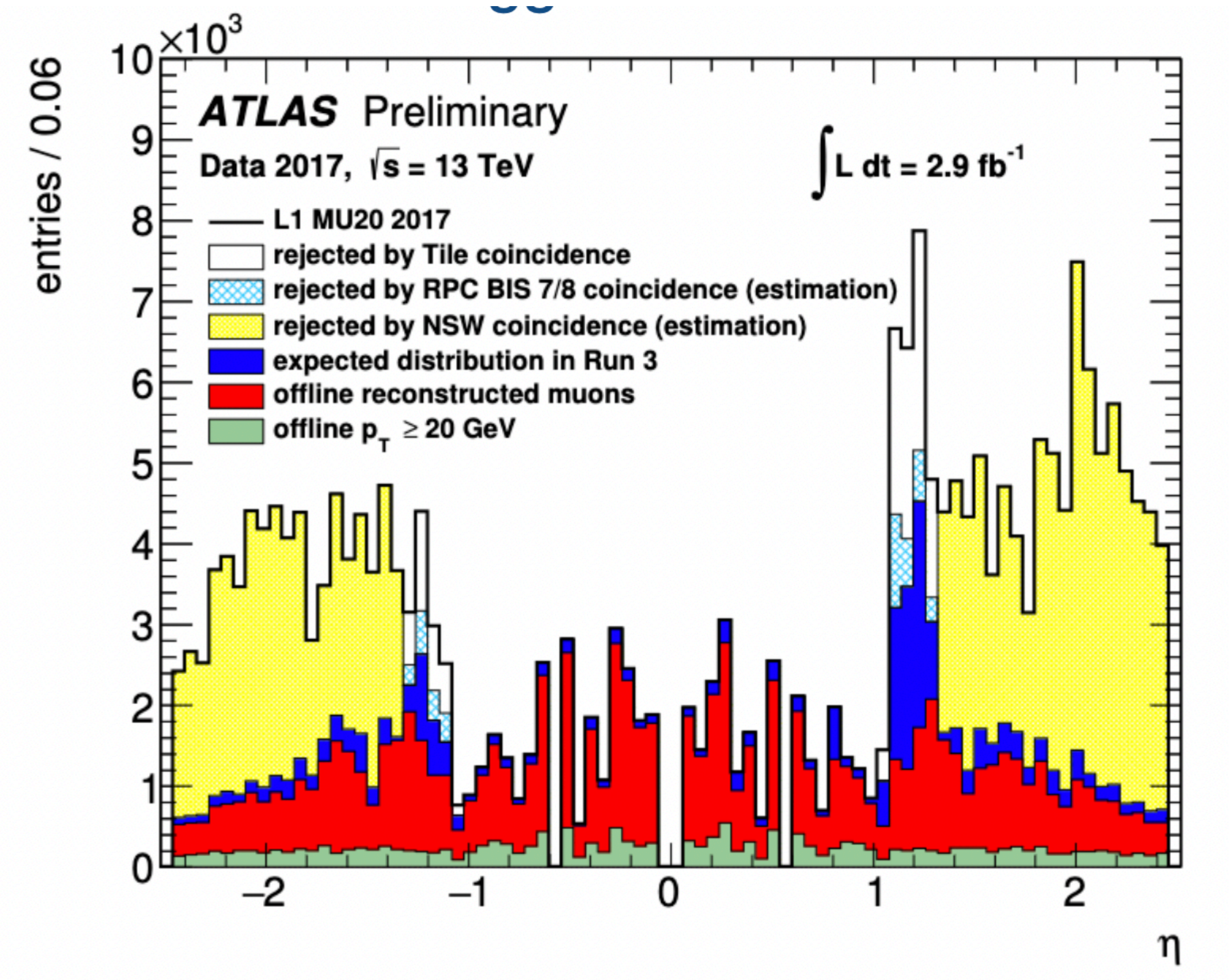
New Small Wheel installed during the LS2 ATLAS phase-I upgrade for commissioning and operation in LHC Run 3

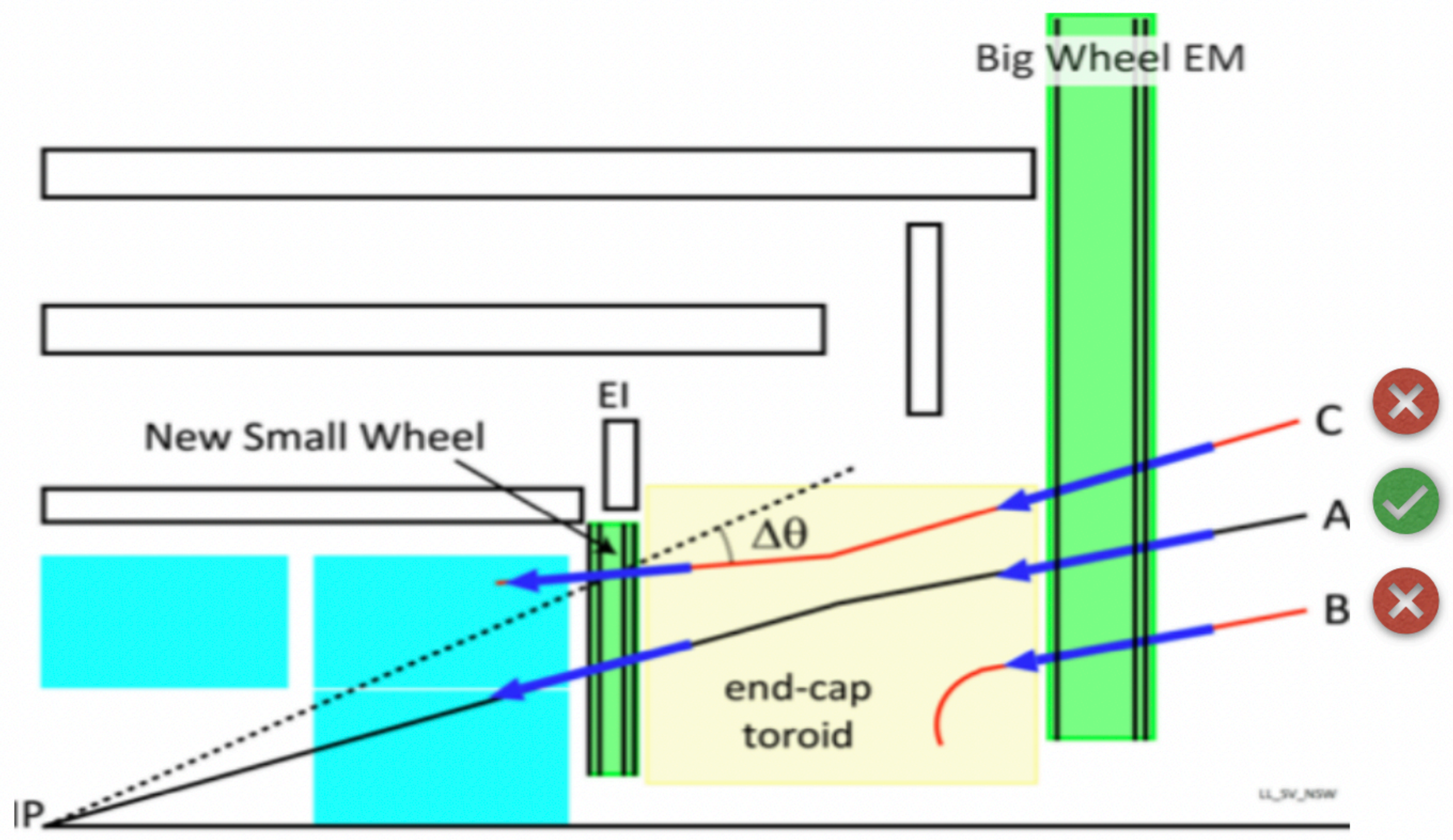
Motivations: during the LHC Run 3 instantaneous luminosity and the average pile-up increased compared to Run 2 values

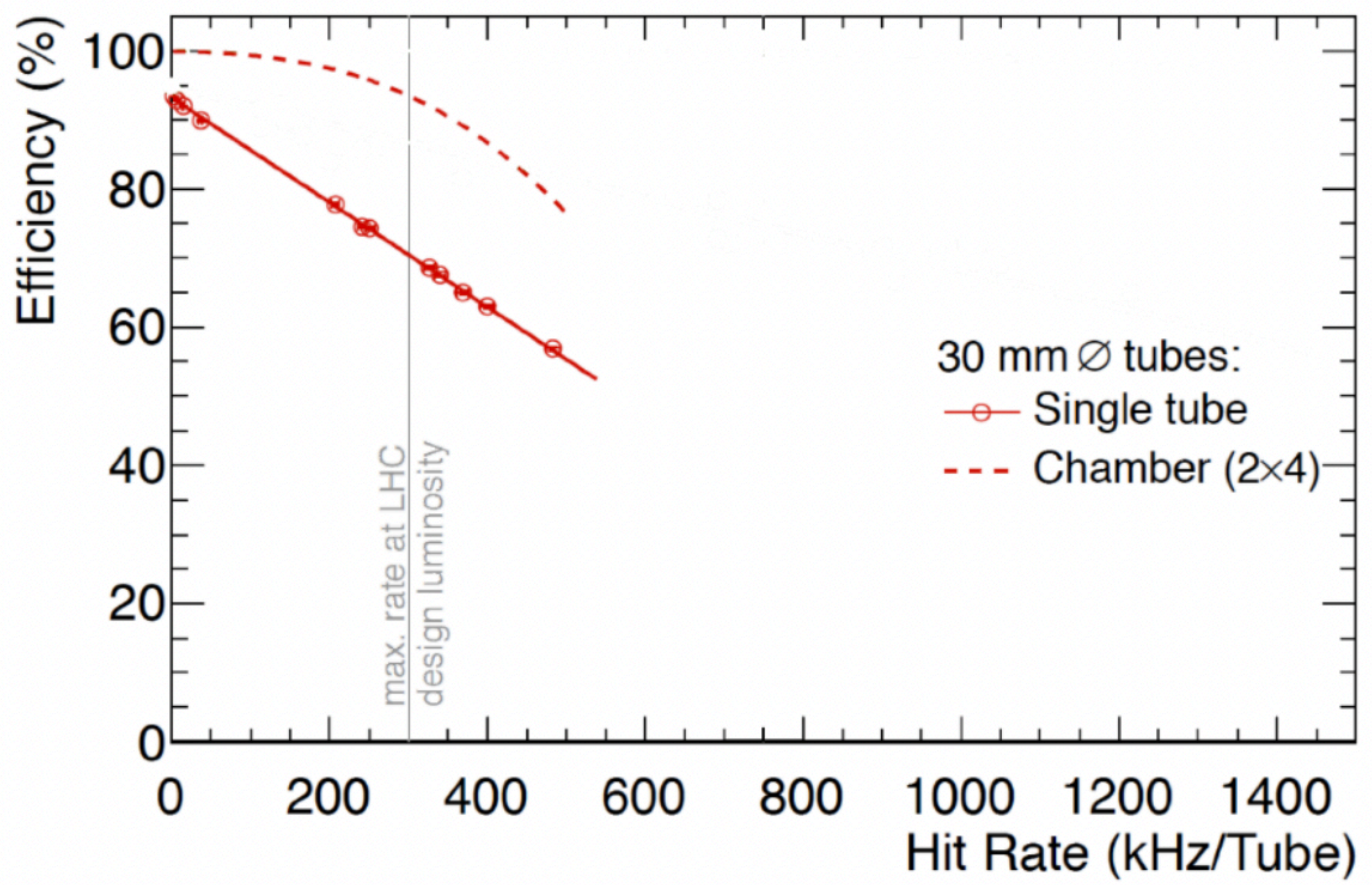
1) Expected increase of the muon trigger rates in the forward regions

- the sustainable ATLAS level-1 (L1) trigger rate will remain at $100\ \mathrm{kHz}$ ($20\ \mathrm{kHz}$ for muons)
- need to reduce the rate of fake-muon triggers to be able to keep the L1 threshold of muon $p_T > 20\ \mathrm{GeV}$ and the L1 rate at $20\ \mathrm{kHz}$

2) Expected MDT efficiency drop with the higher hit rates





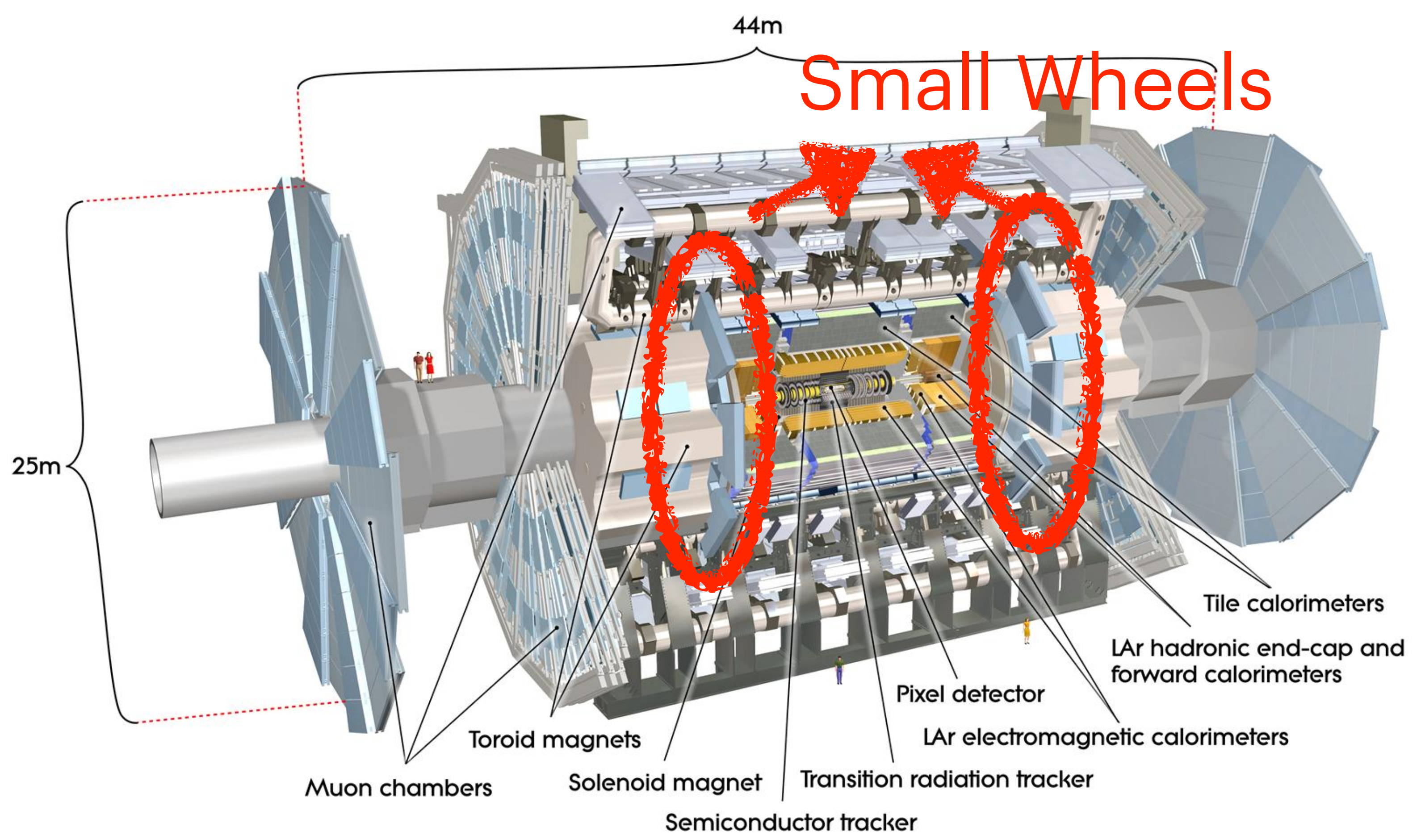


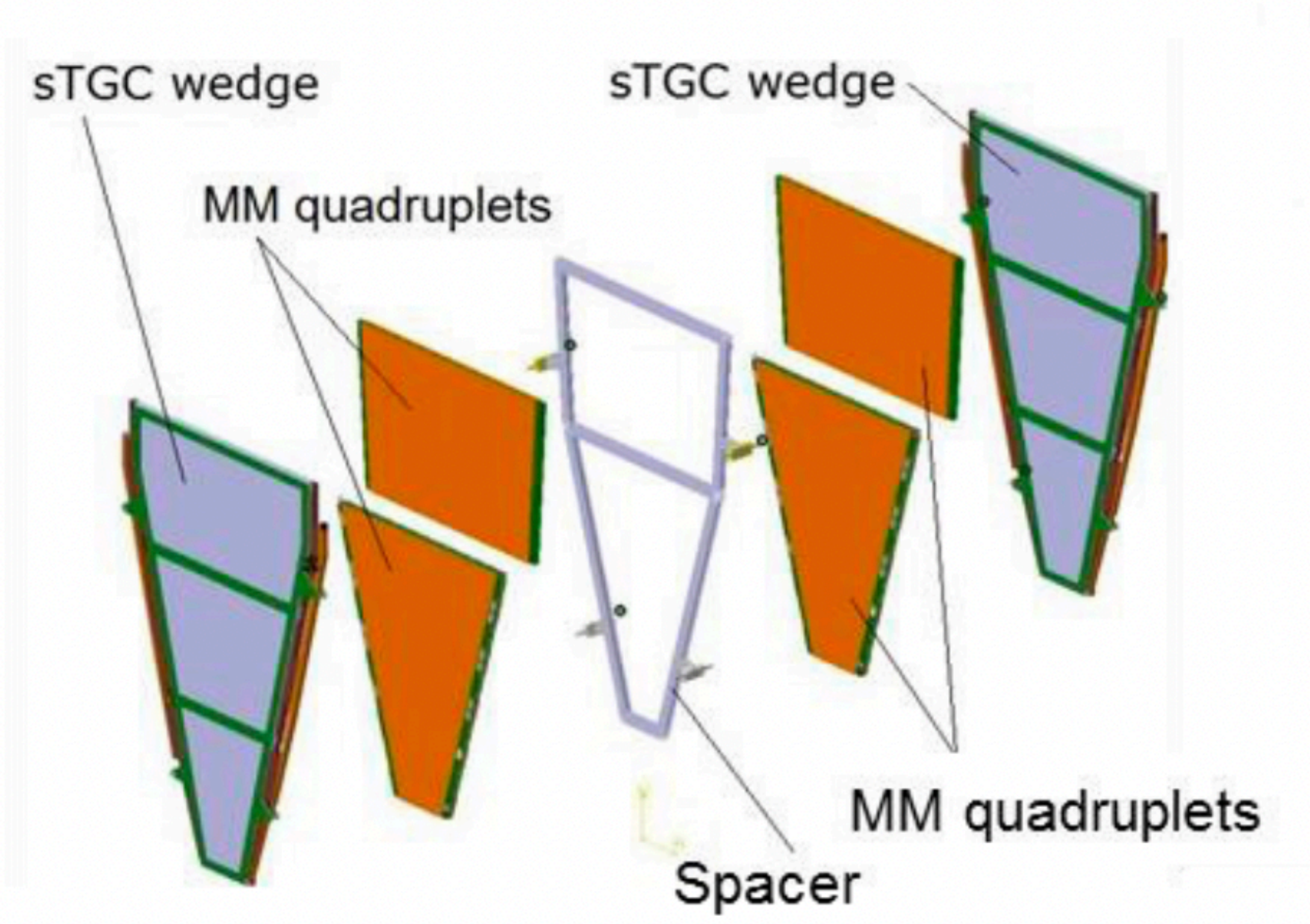
The New Small Wheel phase-1 upgrade aims at:

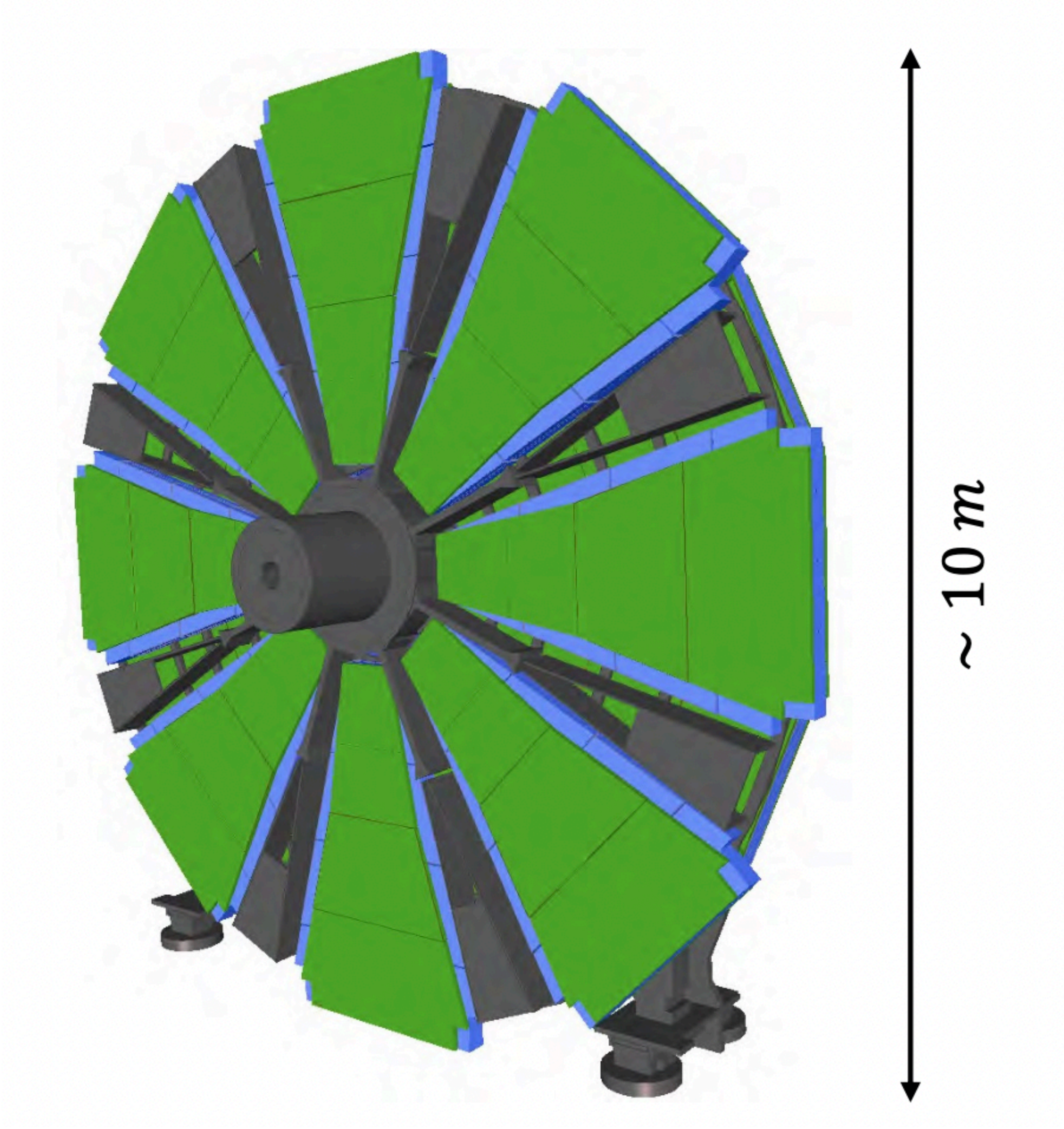
- Reducing fake-muon triggers with a new trigger station in the end-caps for coincidences with the trigger station in the big wheel
- Restoring high tracking efficiency, replacing the drift tubes with new detectors with high efficiency and high resolution

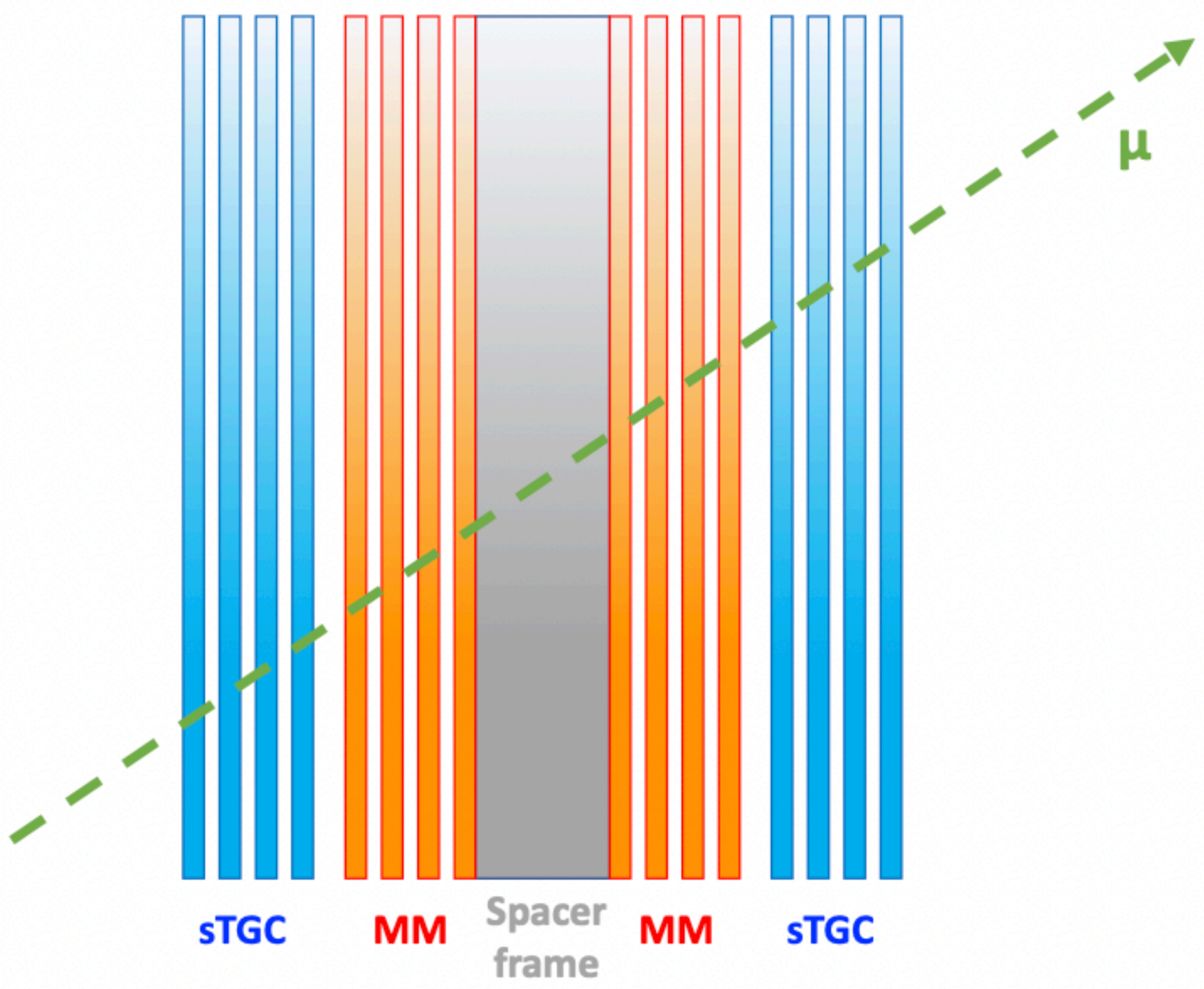
→ Will present here NSW rates, efficiencies and resolutions with Run 3 data, showing that they meet the design requirements

The New Small Wheel design







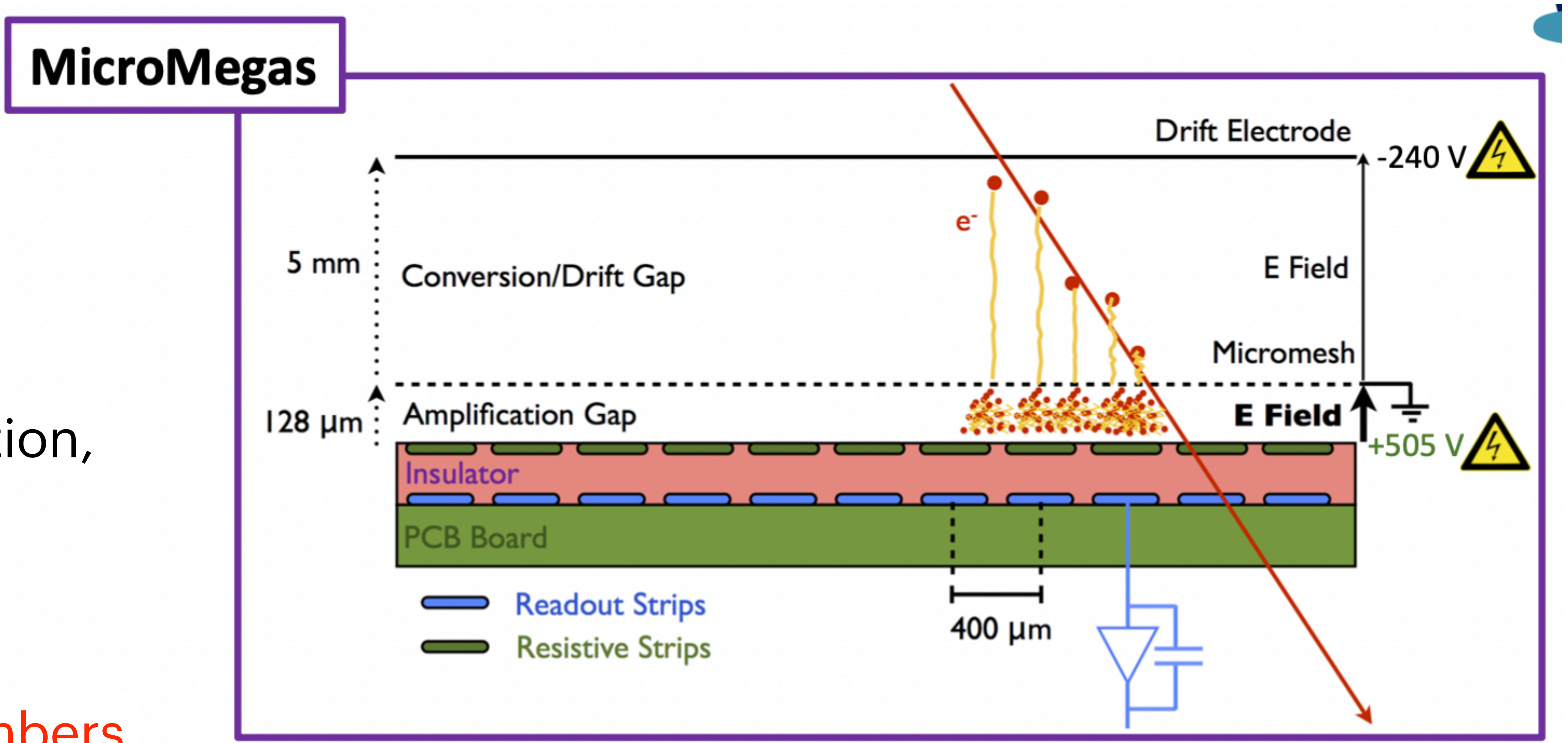


- 2 wheels (one in each detector end-cap, side A and side C of ATLAS)
- Each wheel with 16 sectors (8 small + 8 large)
- Equipped with 2 gas detector technologies:
  - Small Strip Thin Gap Chambers (sTGC)
  - MicroMegas chambers (MMG)
- 16 active detector layers (8+8) to have high redundancy for muon triggering and tracking

The New Small Wheel detector technologies

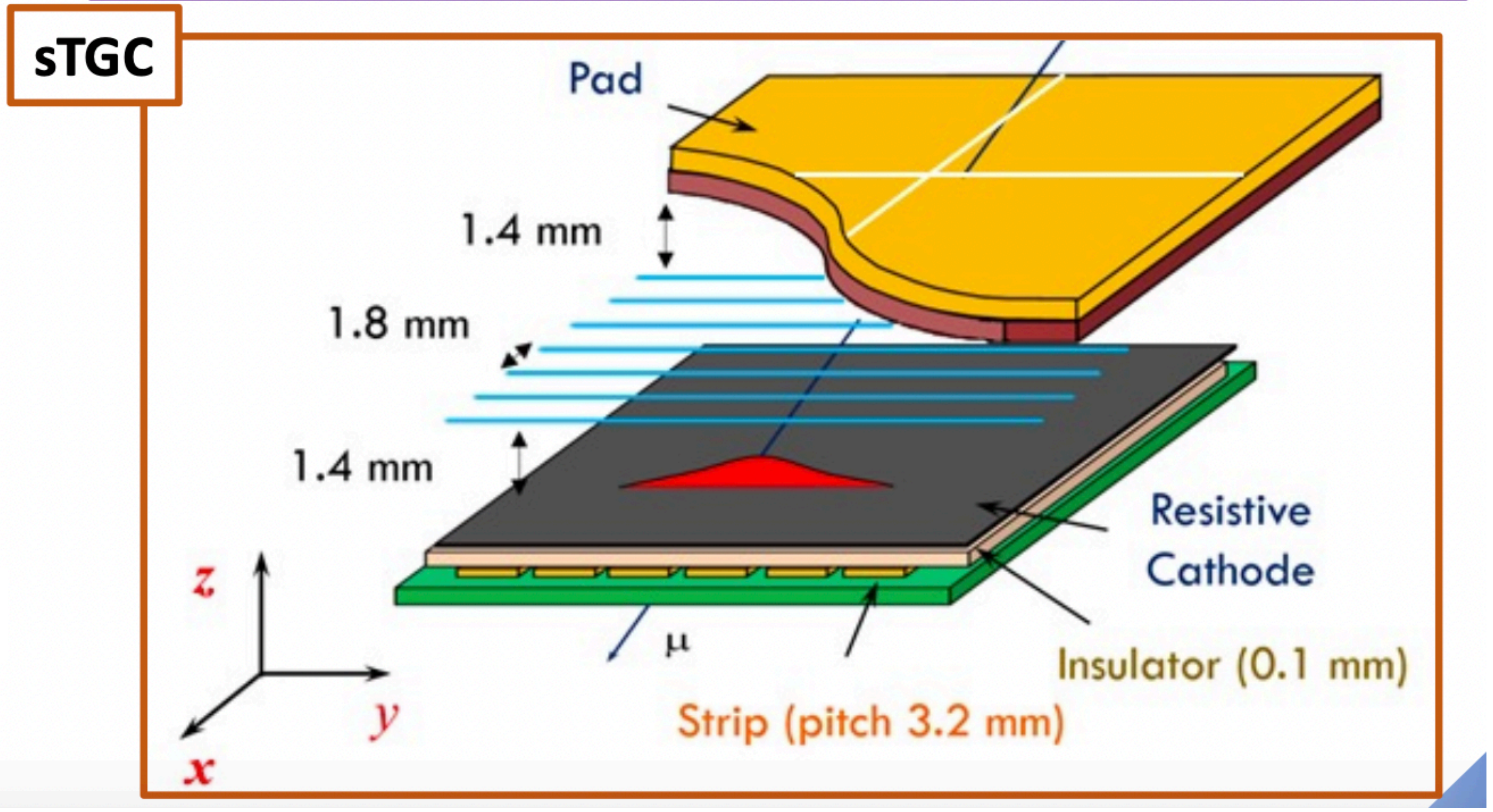
MicroMegas: Micro Mesh Gaseous Structure

- Gas mixture of Ar:CO2:iC4H10 93%:5%:2%
- 2 gas gaps separated by a metallic mesh
  - 5 mm drift gap and $120\ \mu$m amplification gap
- Readout strips, covered by resistive strips for spark protection, with pitch of $400\ \mu$m for precise spatial resolution



Small Strip Thin Gap Chambers: Multiwire proportional chambers with pads and strips segmented cathodes

- Gas mixture of CO2:n-pentane 55%:45%
- Pads for fast coarse trigger information
- Strips with pitch of 3.2 mm for good spatial resolution
- Wires for second coordinate in offline reconstruction

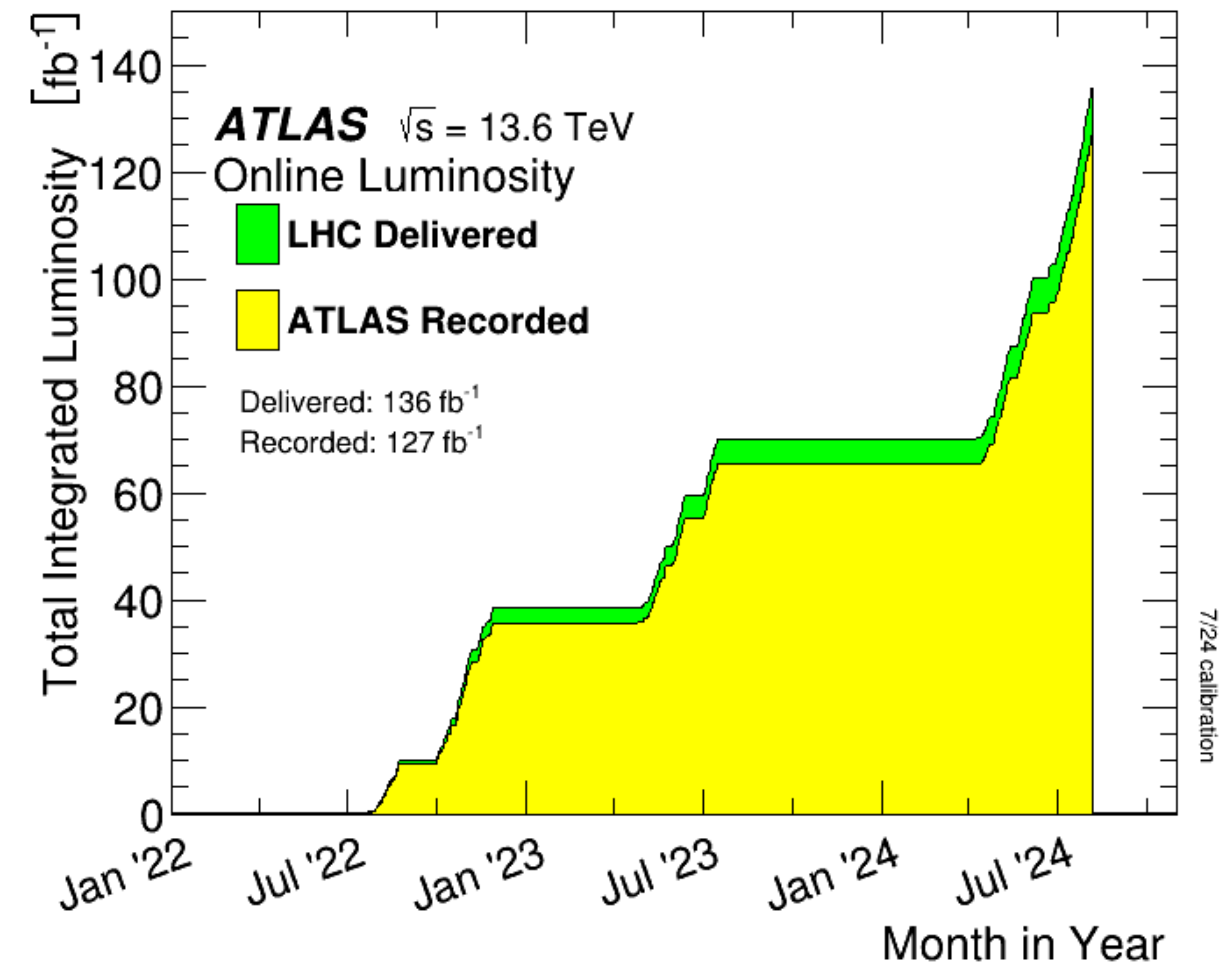


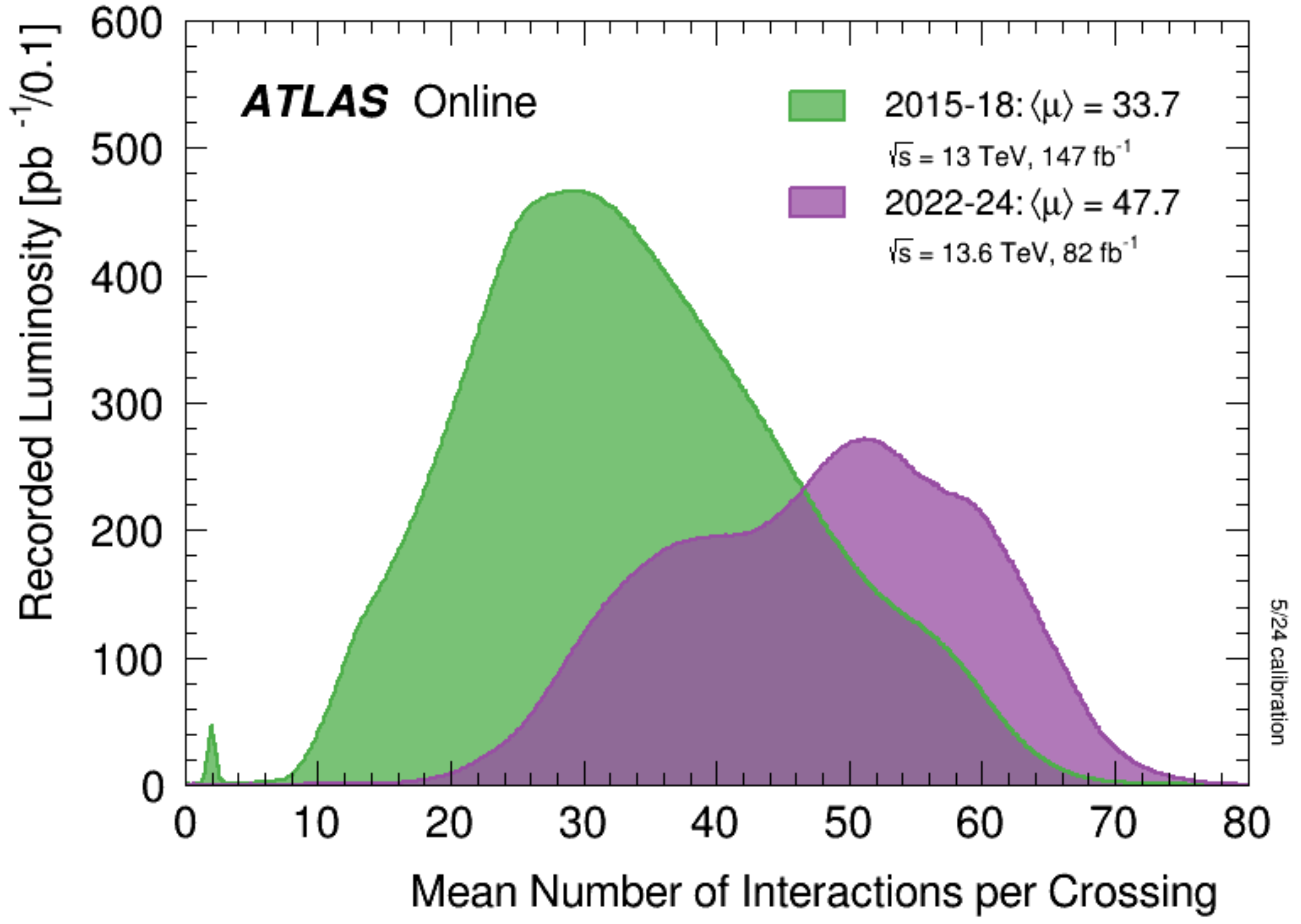
→ Providing time resolution of about $10-20$ ns, spatial resolution of the order $100\ \mu$m for the precision coordinate and of the order of a few mm for the second coordinate

New Small Wheel performance with ATLAS Run 3 data

NSW installed in ATLAS in 2021

NSW detectors included in the ATLAS combined DAQ system
since the start of Run 3 in 2022





The first year of Run 3, 2022, was planned to be a commissioning year for NSW,
It went very well and now the detector is fully integrated
with stable conditions for data-taking

Lots of ATLAS Run 3 data to analyze the NSW detector performance

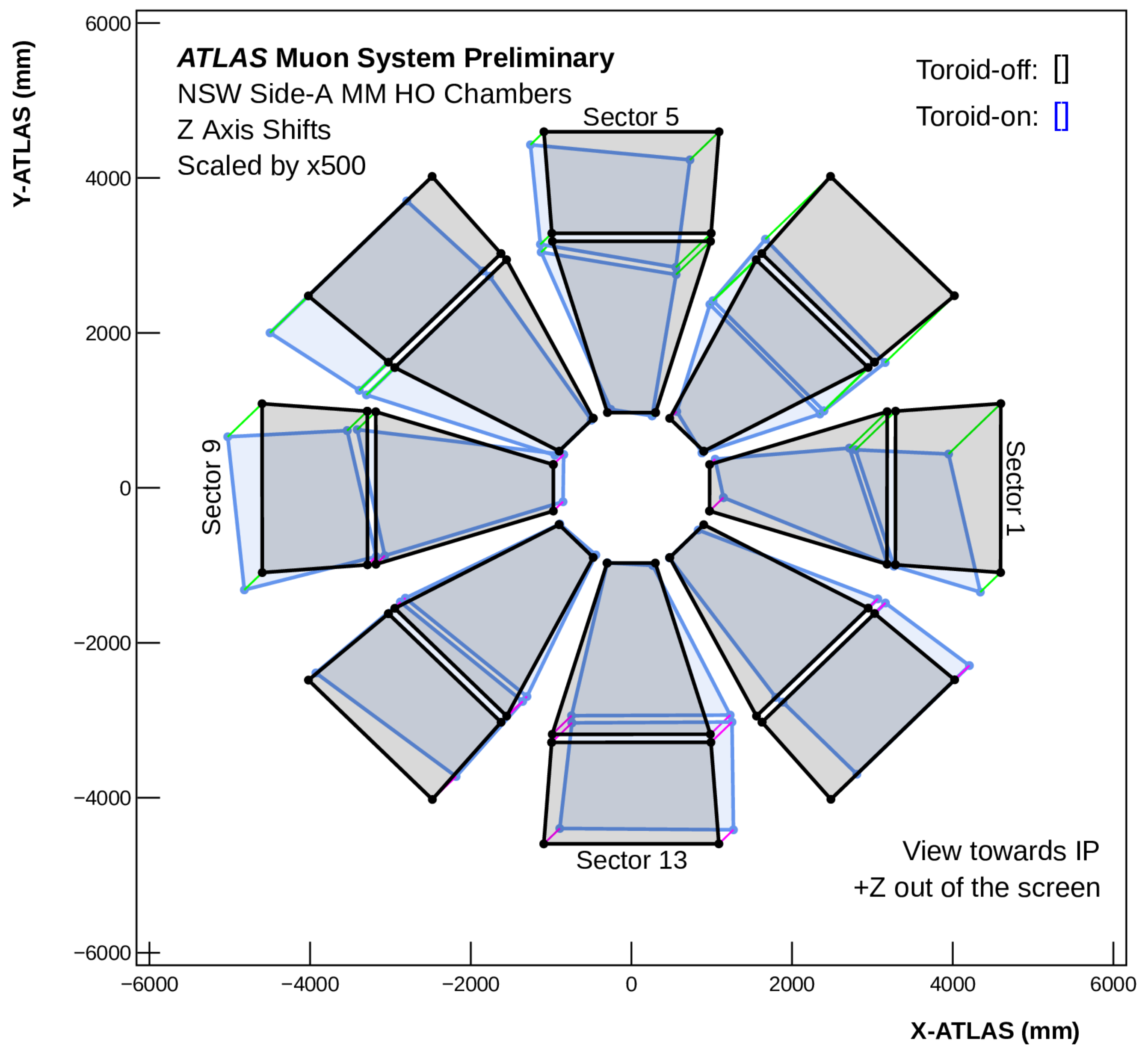
New Small Wheel alignment

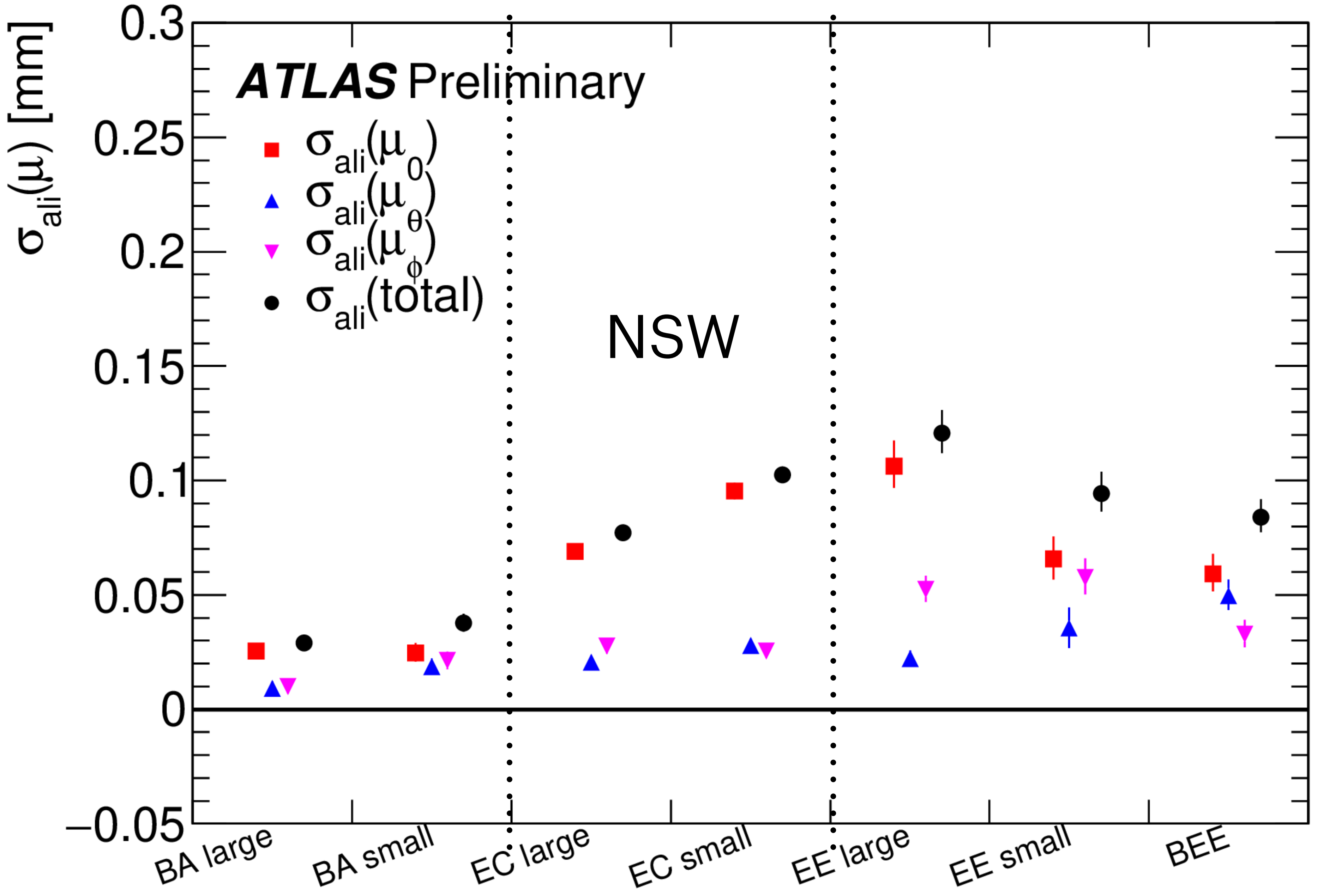
Optical alignment system used to monitor movements/deformations of ATLAS muon spectrometer

- When ATLAS toroid magnetic filed is turned ON the NSWs tilt up to 2.7 mm

- Optical alignment providing an independent set of global corrections for each MMG and sTGC quadruplet

→ For correcting translations, rotations and deformations



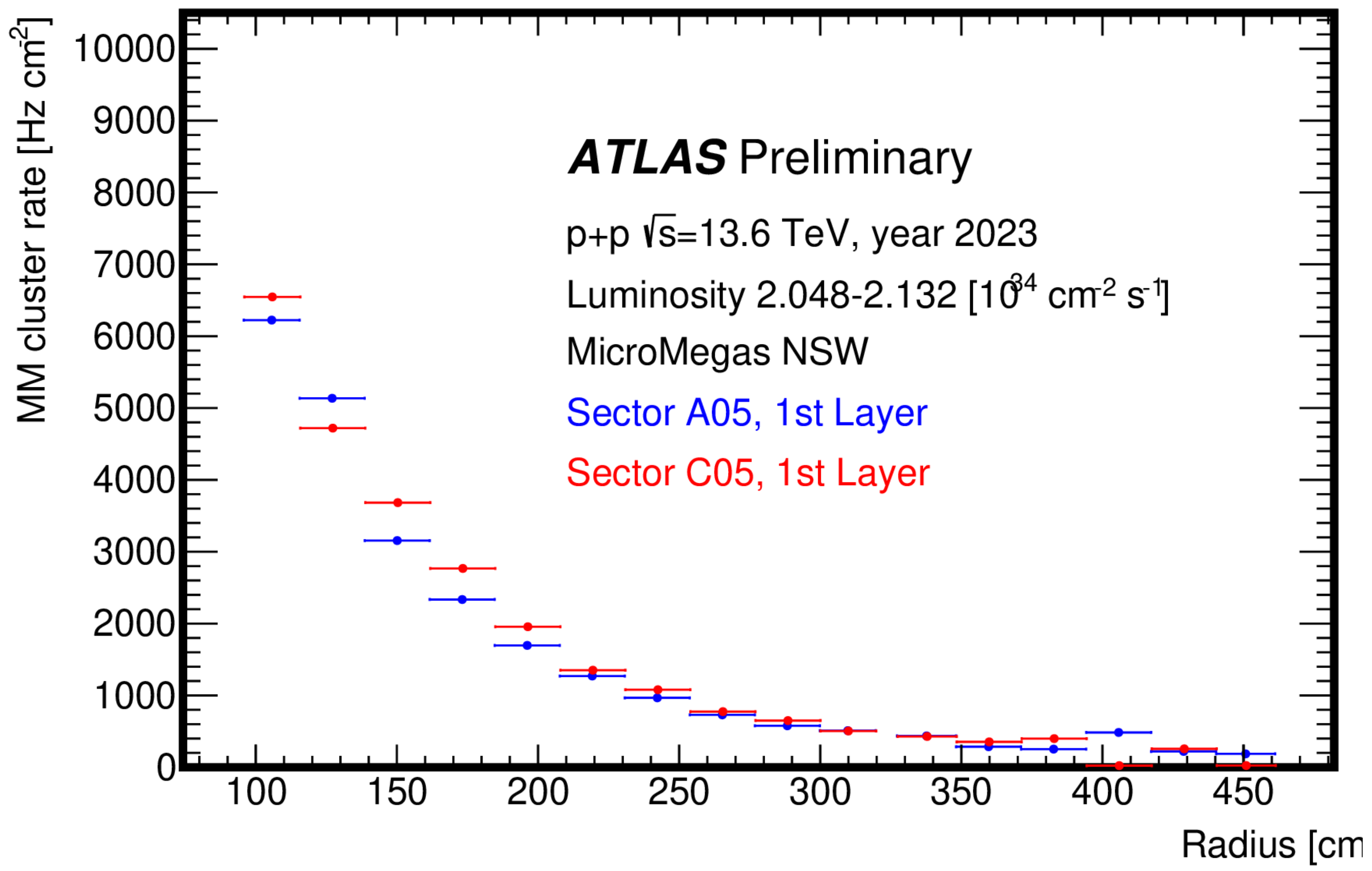


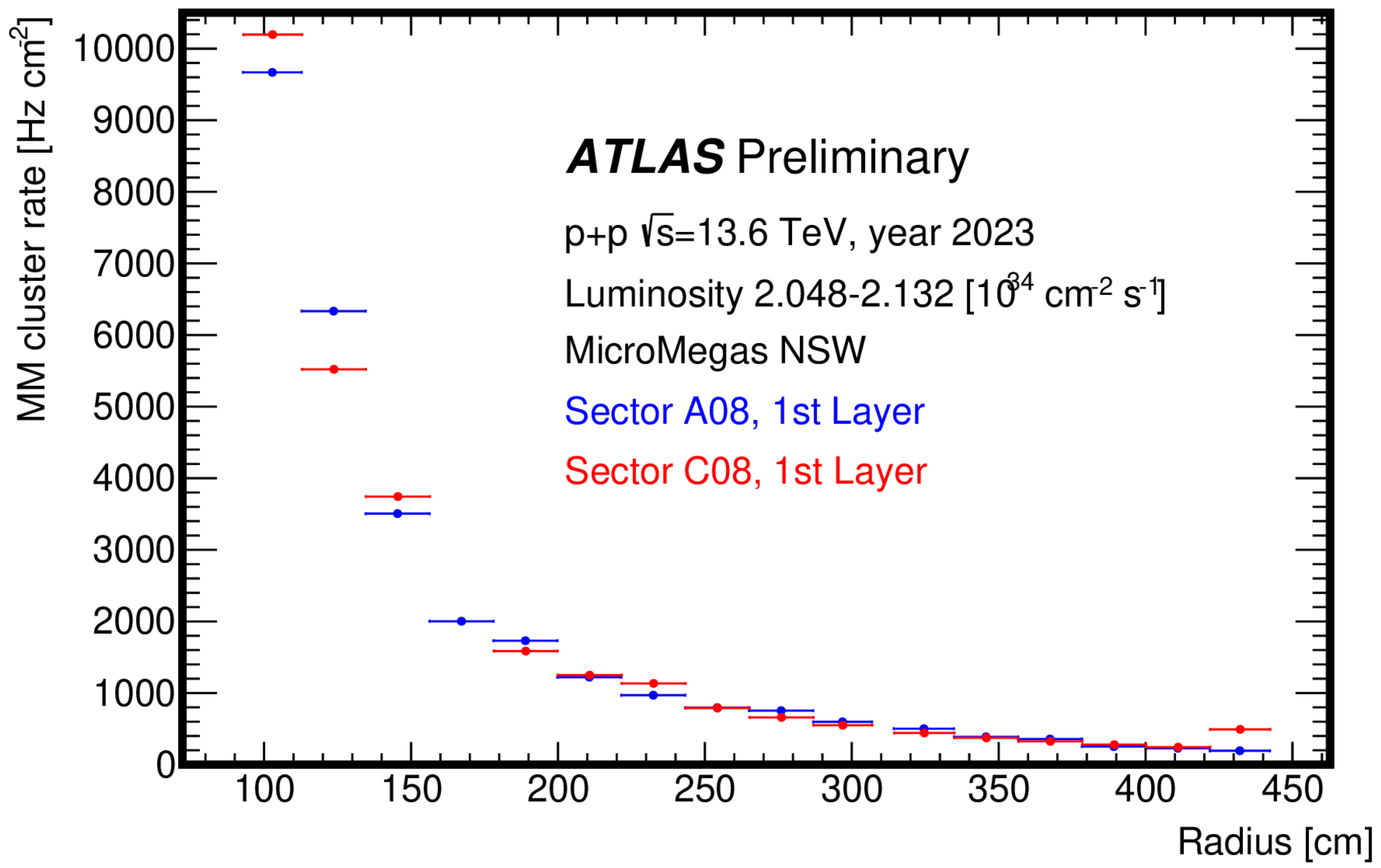
- Alignment uncertainty parametrized as an uncertainty on the global MS track sagitta, derived from analysis of runs with toroid magnetic field off

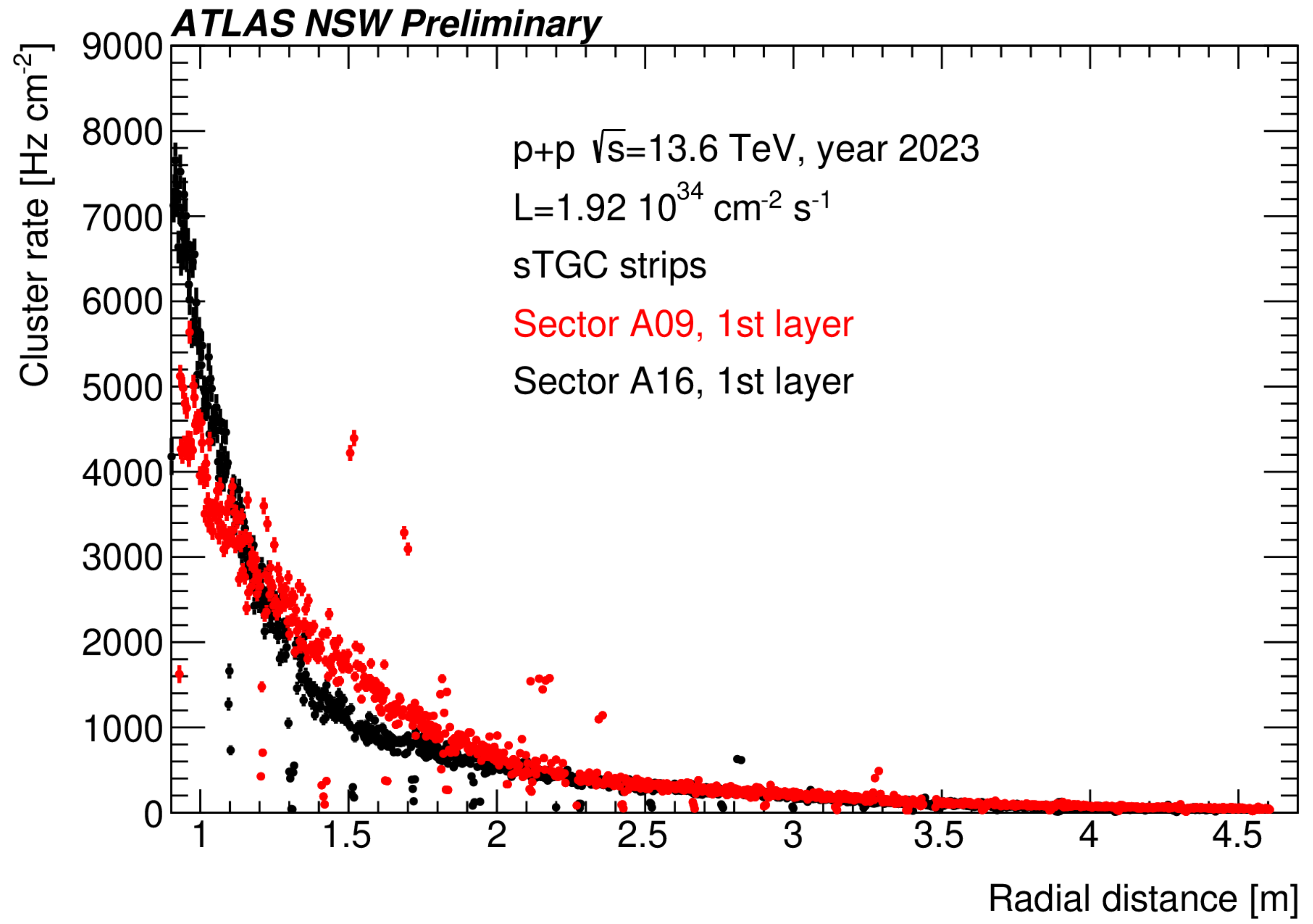
→ sagitta uncertainty from the alignment is at the moment about $80 - 100\ \mu m$ in the NSW region

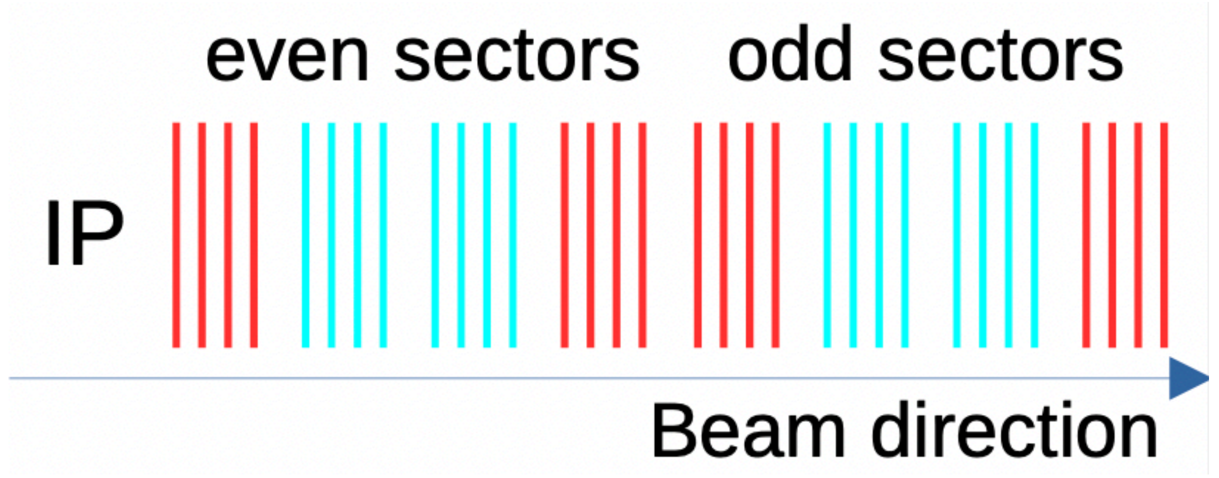
NSW hit rates

Hit rate measurements in a given detector layer of MMG or sTGC
as a function of the radial distance from the interaction point with 2023 data









Main contribution to the hit rates is coming from cavern background:

- Hit rates decreasing with R
- Hit rates increasing with luminosity
- For both MMG and sTGC higher rates in small sectors (even numbers) because they are closer to the interaction point
- MMG show higher rates than sTGC (more sensitive to photons and neutrons)

→ Rates in agreement with extrapolations from Run 2 and below maximum design rate of NSW ($20\ \mathrm{kHz/cm^2}$)

NSW Trigger

NSW included in the ATLAS L1 muon trigger since 2023
(Used to make coincidences with hits in the Big Wheel)

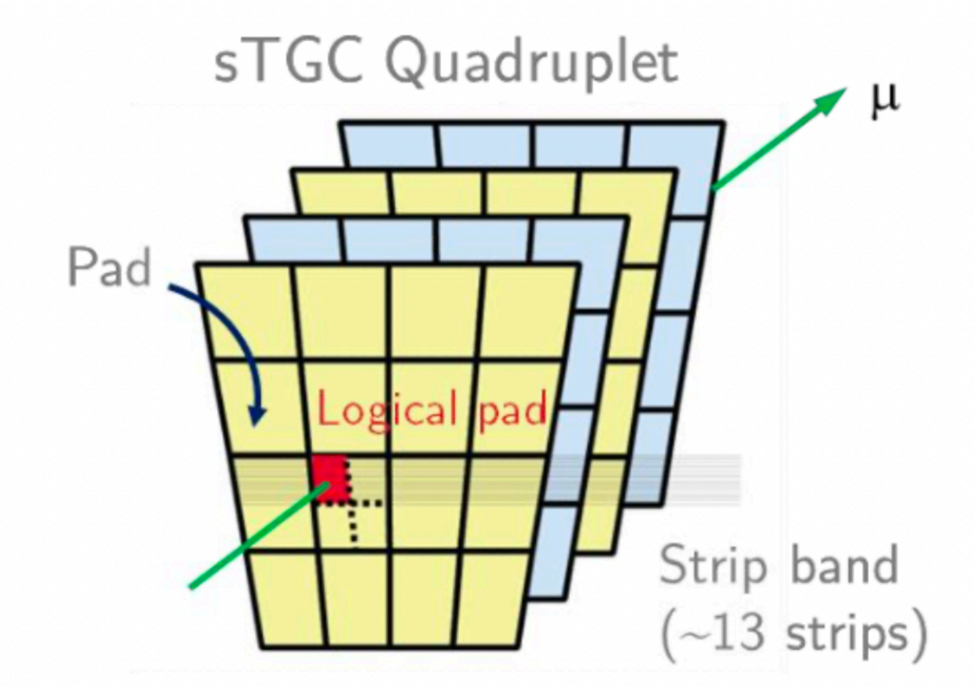
sTGC trigger (2 stages):

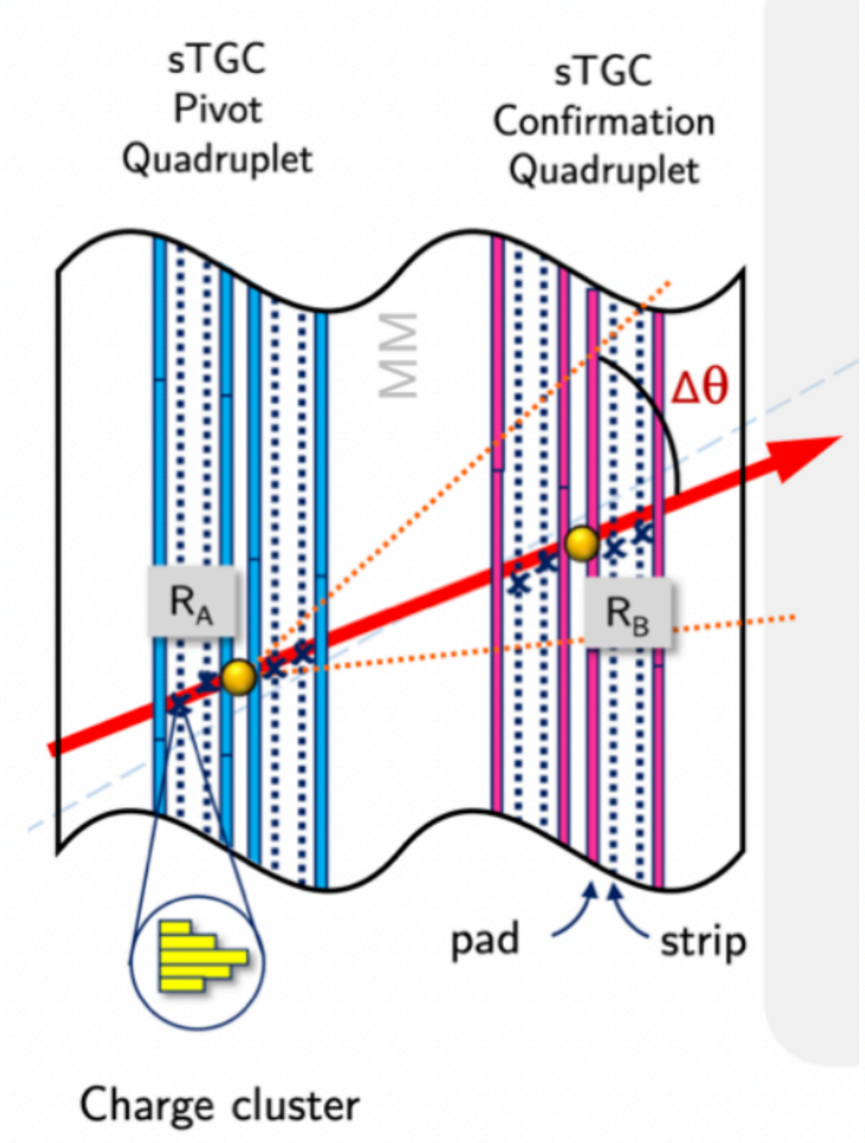
- sTGC Pad trigger coincidence: provides fast coarse information to feed the next stage

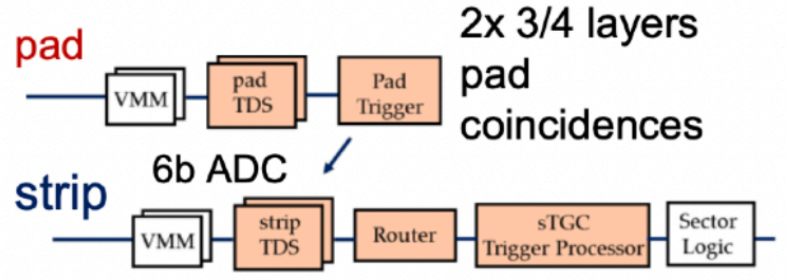
→ deployed during 2023 data-taking!

- sTGC strips trigger: reconstructs strip clusters in the region of interest given by the pads and uses them for precise measurement of the segment angle

→ under commissioning (will be used for HL-LHC)







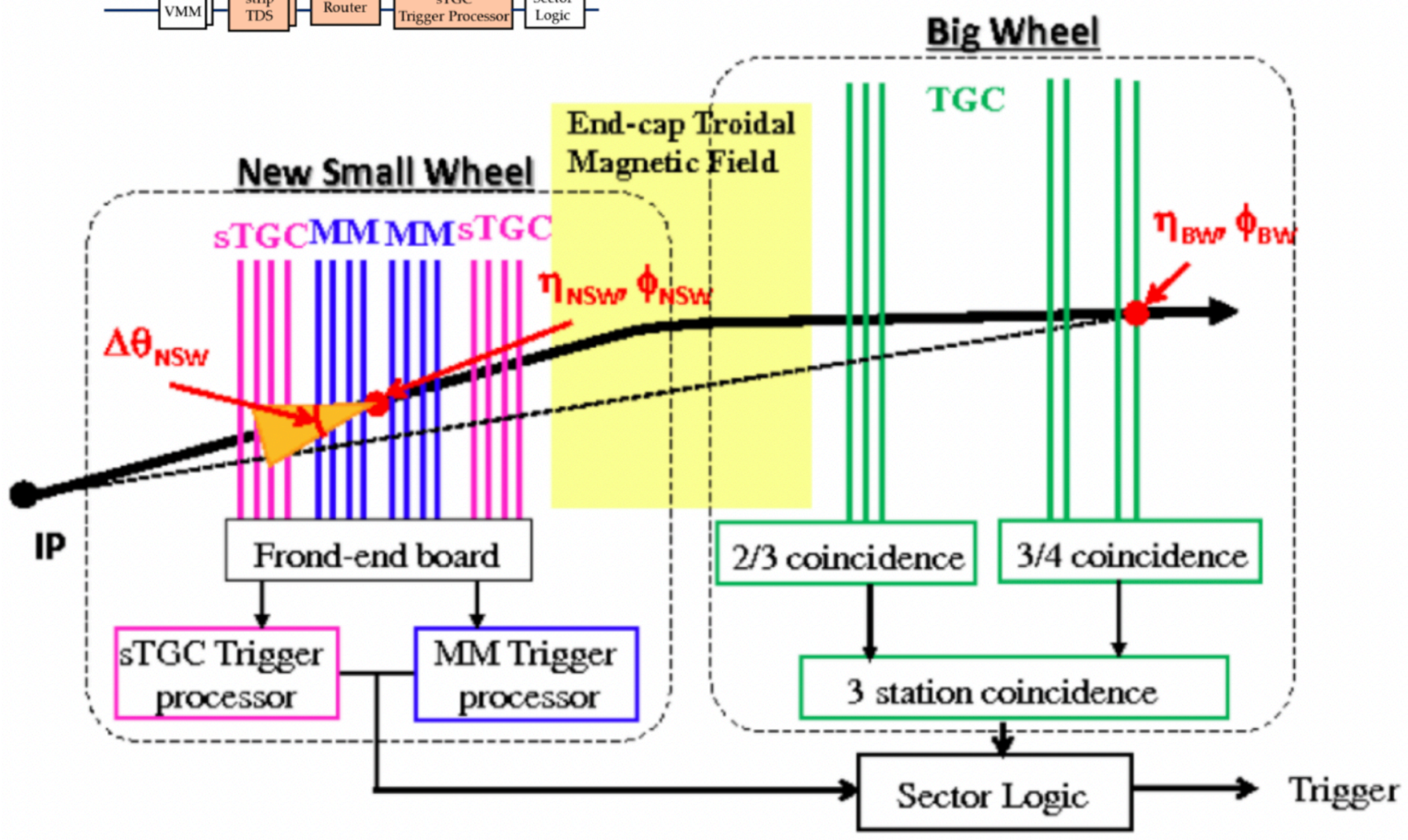
MM trigger:

- uses strip positions to reconstruct segments

(using address of the earliest strip in each VMM)

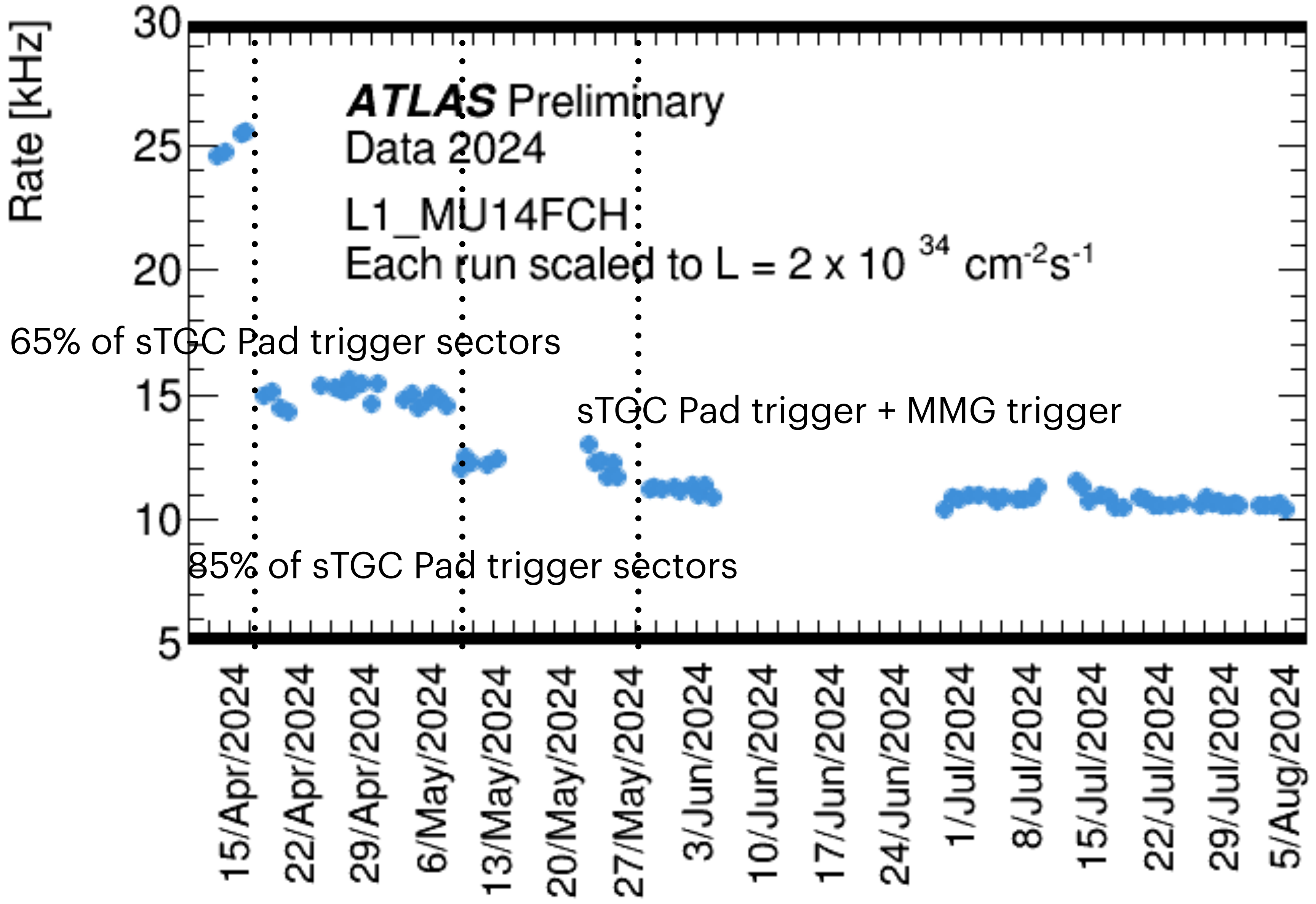
→ recently deployed in 2024!

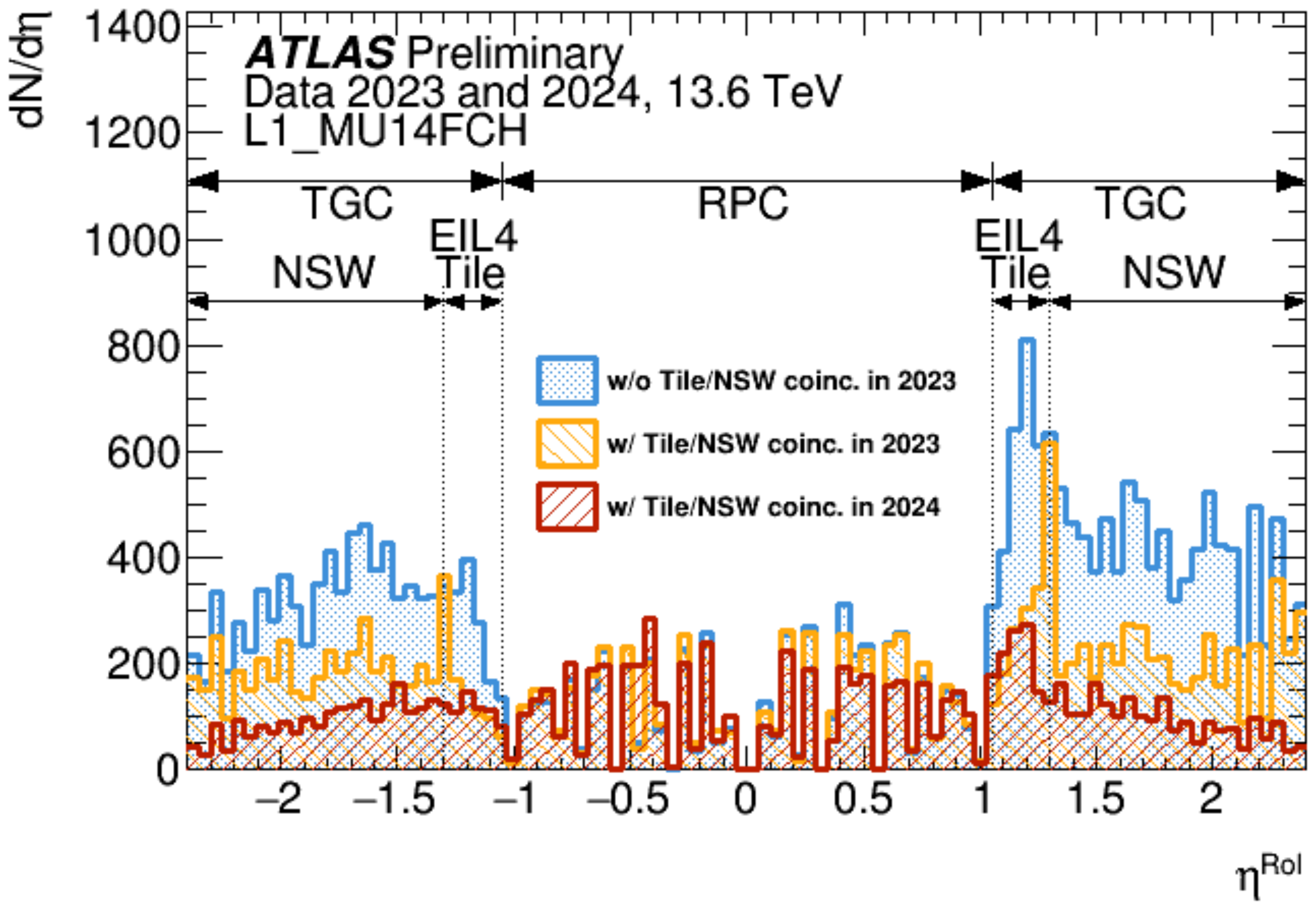
sTGC and MMG segments are sent to the trigger sector logic for checking coincidence with the big wheel



→ NSW trigger actively contributing to the background suppression in the forward region

NSW Trigger performance in 2024





Rate of L1 muon trigger vs time in 2024:

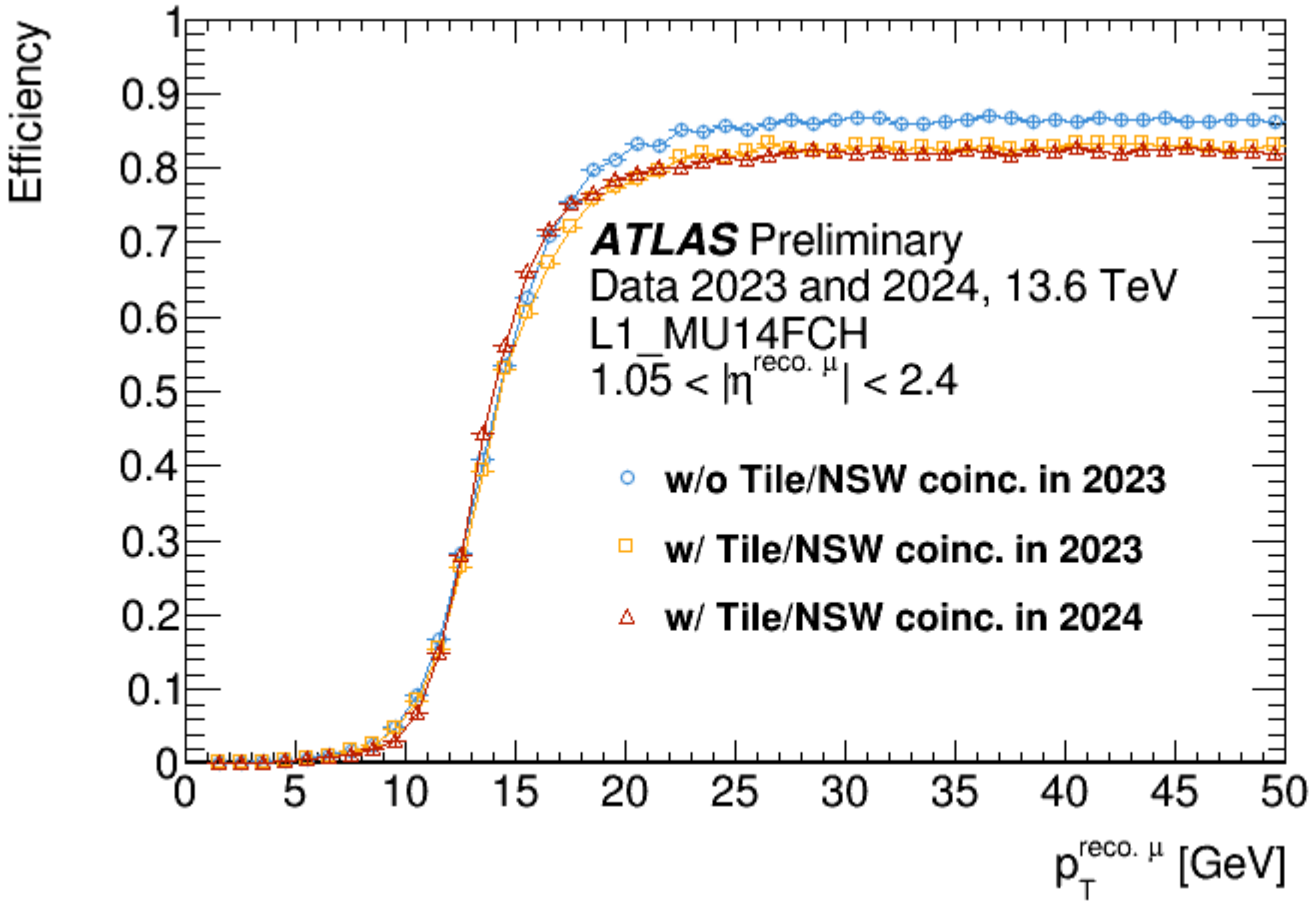
- In mid-April 65% of sTGC Pad trigger sectors included

→ rate decreased by 10 kHz

- In mid-May 85% of sTGC Pad trigger sectors included

→ rate decreased by additional 3 kHz

→ Rate reduction given by the reduction of fakes in the forward region as expected with the NSW detectors



- Towards end-May also MMG trigger included

→ stable rate and increased efficiency compared to sTGC Pad trigger alone

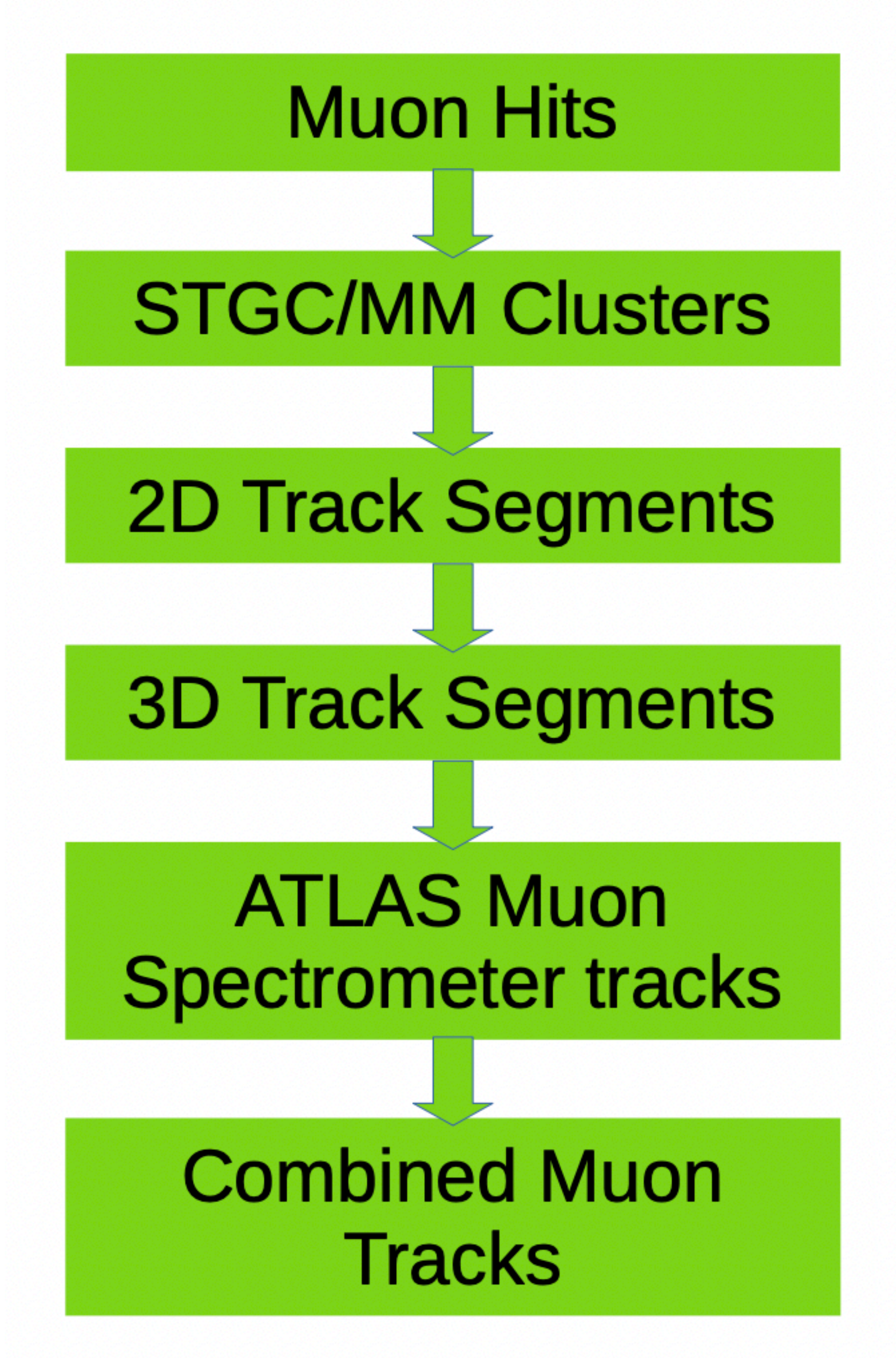
Efficiency of the L1 muon trigger as a function of the offline muon pT:
comparison of trigger efficiencies, before and after integrating coincidences between the Big Wheel and NSW
Before, efficiency of about 86.3%, after inclusion of NSW, with full integration (sTGC pad + MicroMegas), efficiency of about 82.2%

→ Inefficiency of approximately 4% in both 2023 and 2024 aligns with the design performance characteristics of the NSW detector

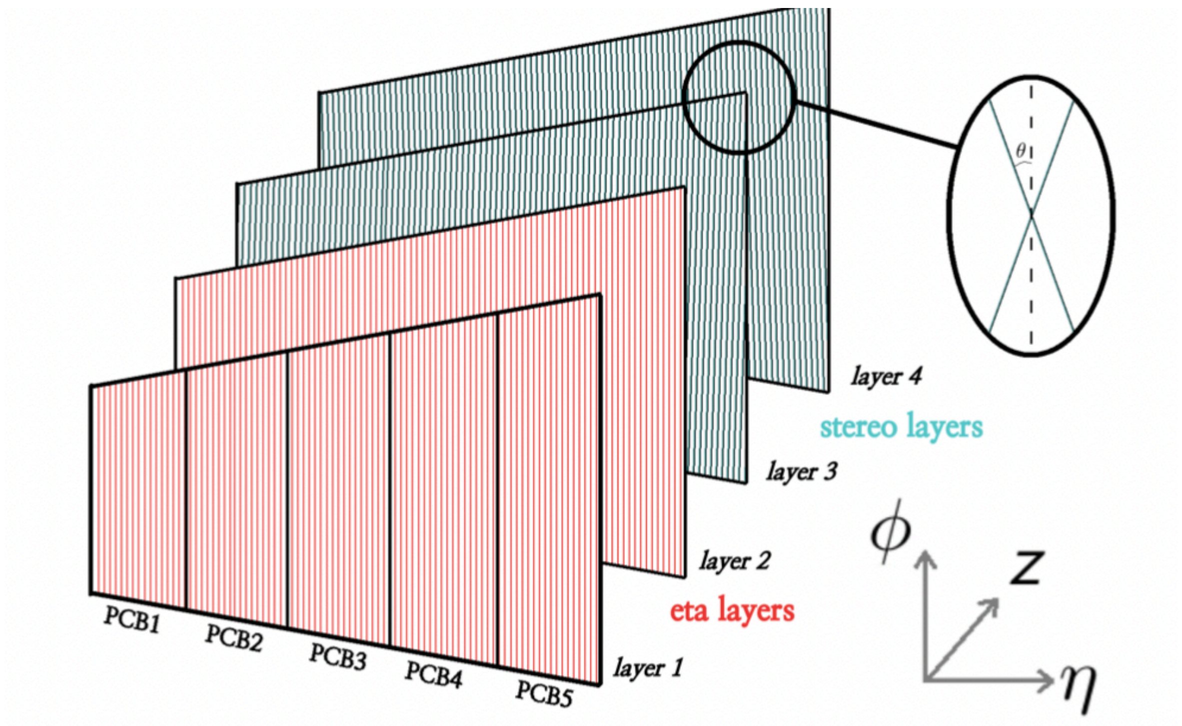
NSW hit position and muon track reconstruction

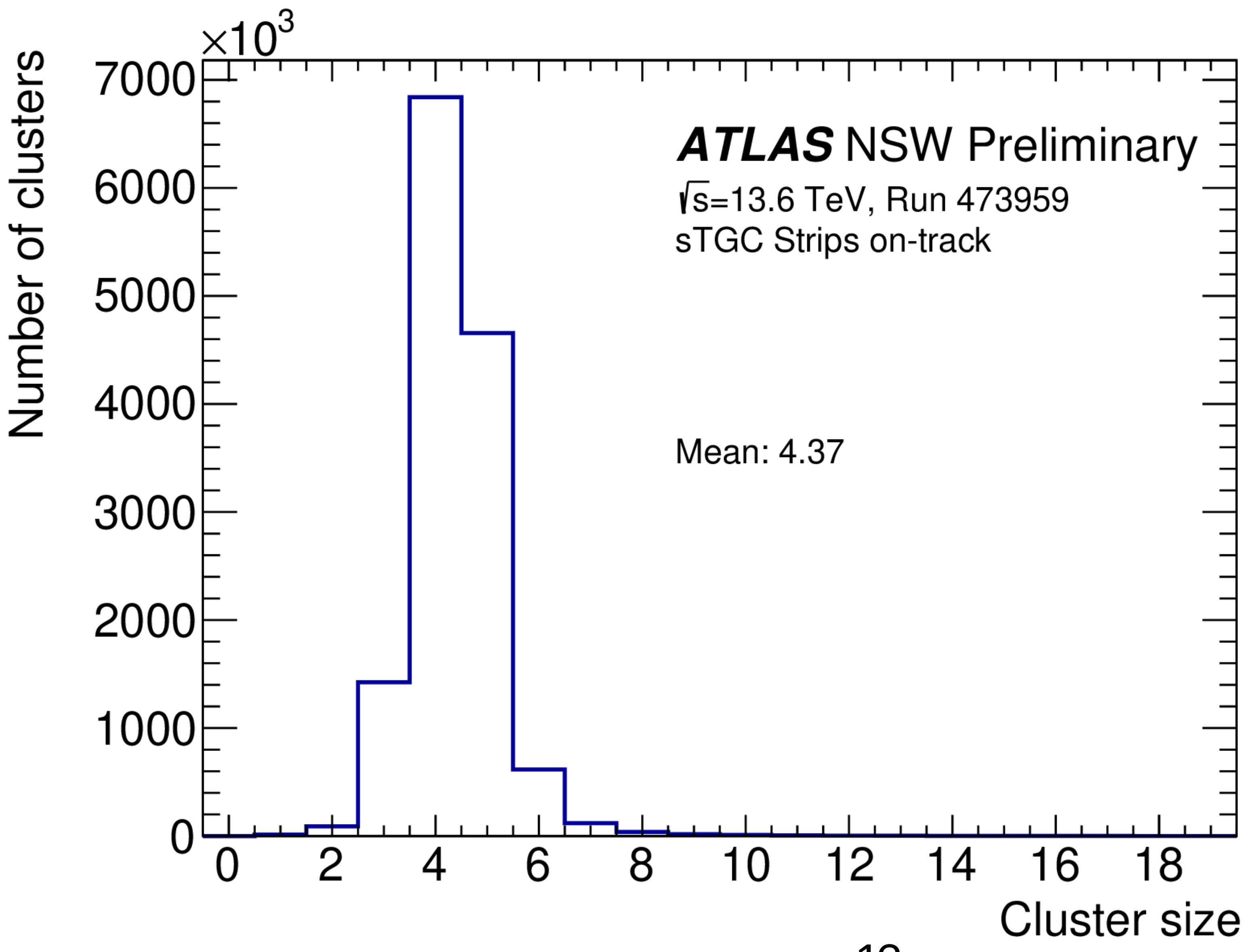
The NSW is fully integrated in the ATLAS muon reconstruction framework since the start of Run 3

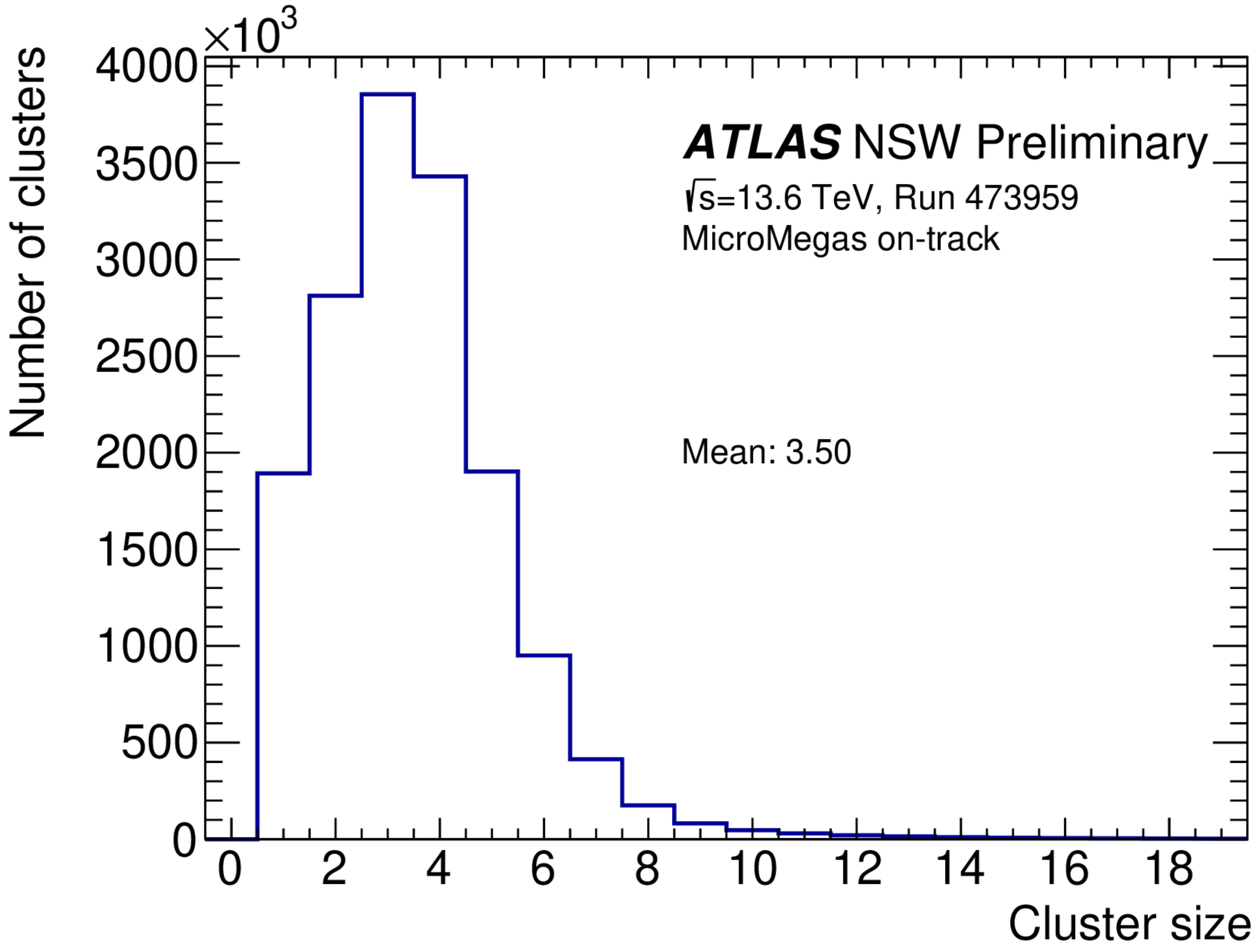
Contribution of NSW hits to muon track reconstruction:



- MM and STGC strip hits are clusterized
- Position of the clusters is computed
- Clusters on different layers are combined in track segments across the detector layers
- NSW segment positions are used to fit Muon Spectrometer (MS) and MS+ID muon tracks







NSW Efficiencies

NSW efficiencies evaluated with 2 different methods:

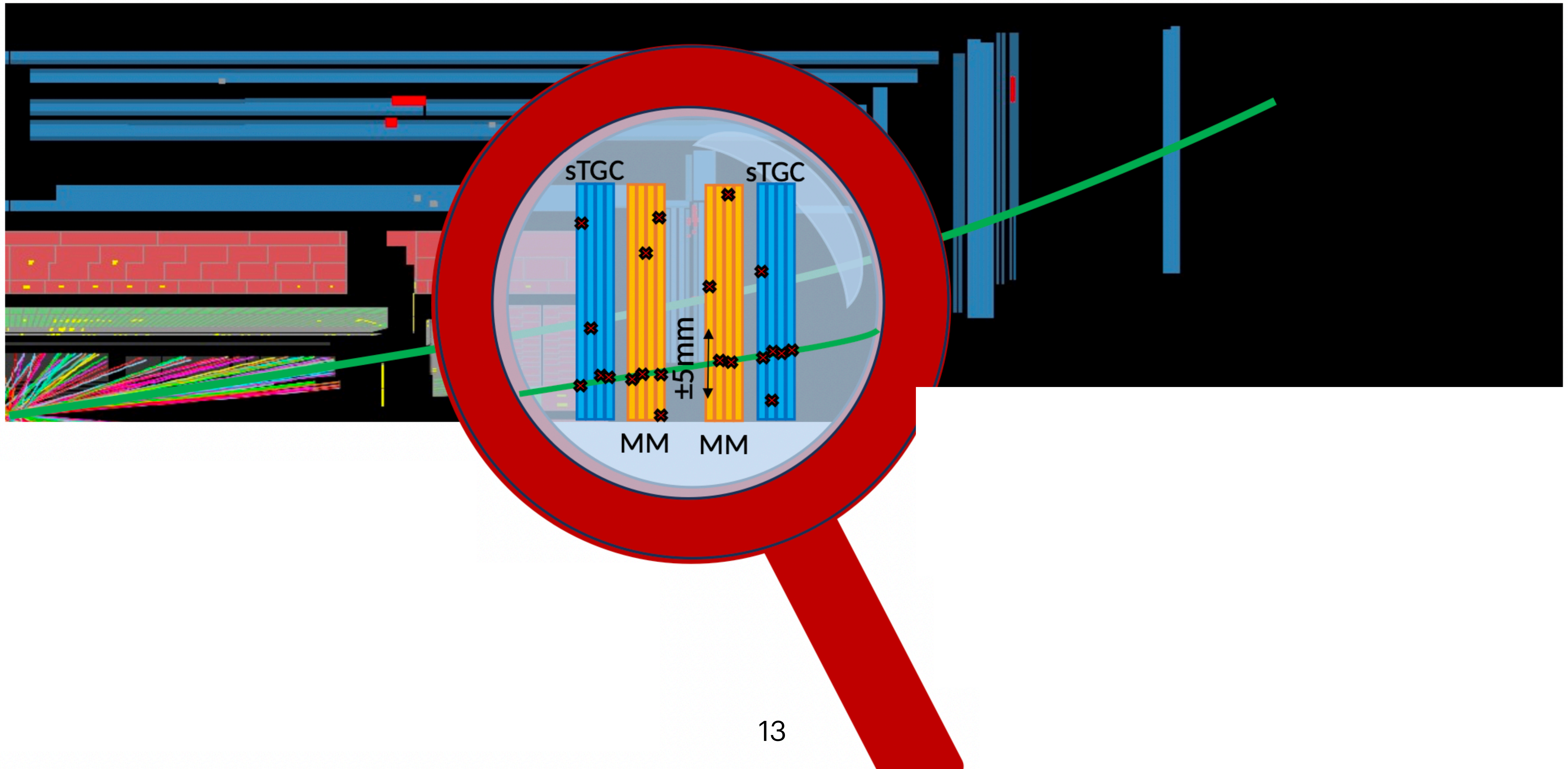
- Efficiency of having at least 1 NSW cluster within 5 mm to the track

(used mainly to evaluate, study and investigate detector efficiencies defects)

- Efficiency of having at least 4/8 NSW layers, of either detector type, with clusters on-track, used for the muon track fit

(used to evaluate final contribution of NSW to efficiency of muon reconstruction for physics analysis)

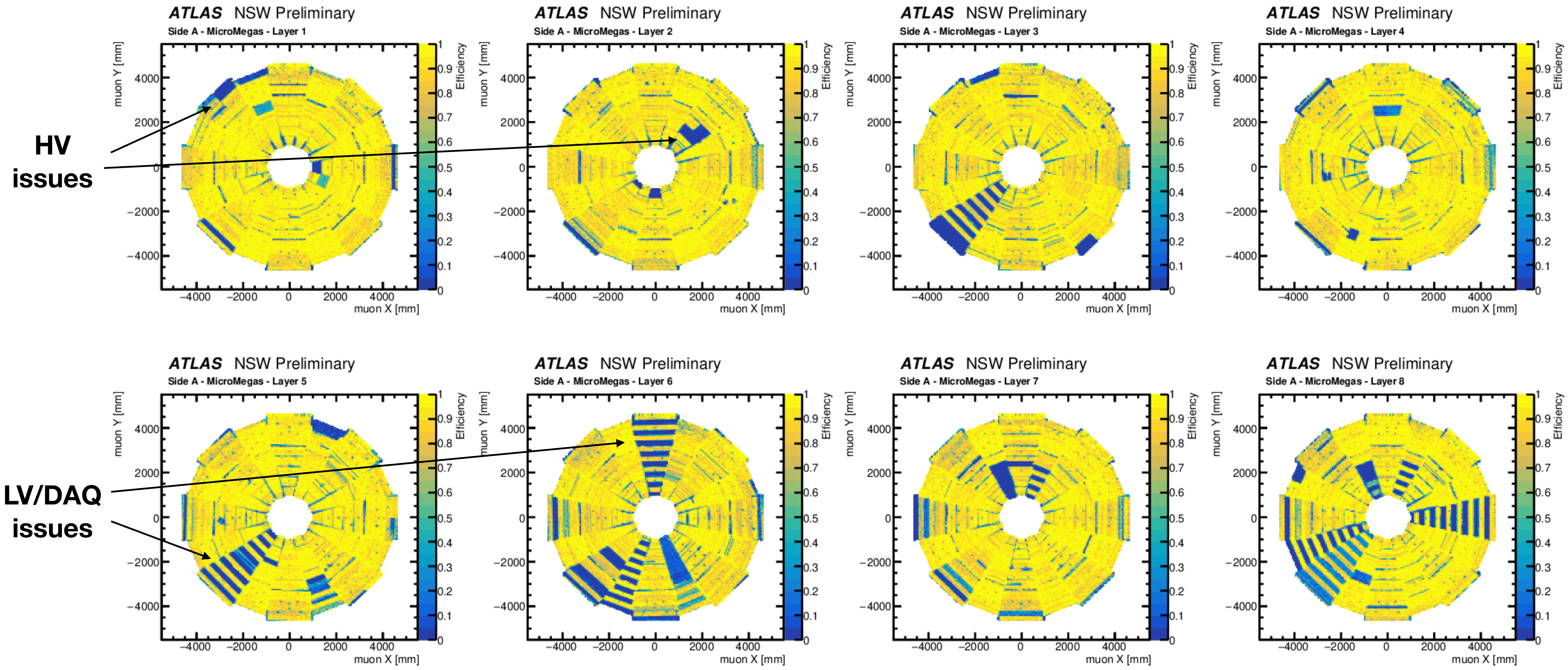
Both evaluated considering tracks from Combined ID+MS muons with $p_T > 15$ GeV



NSW Efficiencies: example MMG layer efficiencies

MMG detector layer efficiencies evaluated using the method of the presence of 1 cluster within 5 mm of the muon track:

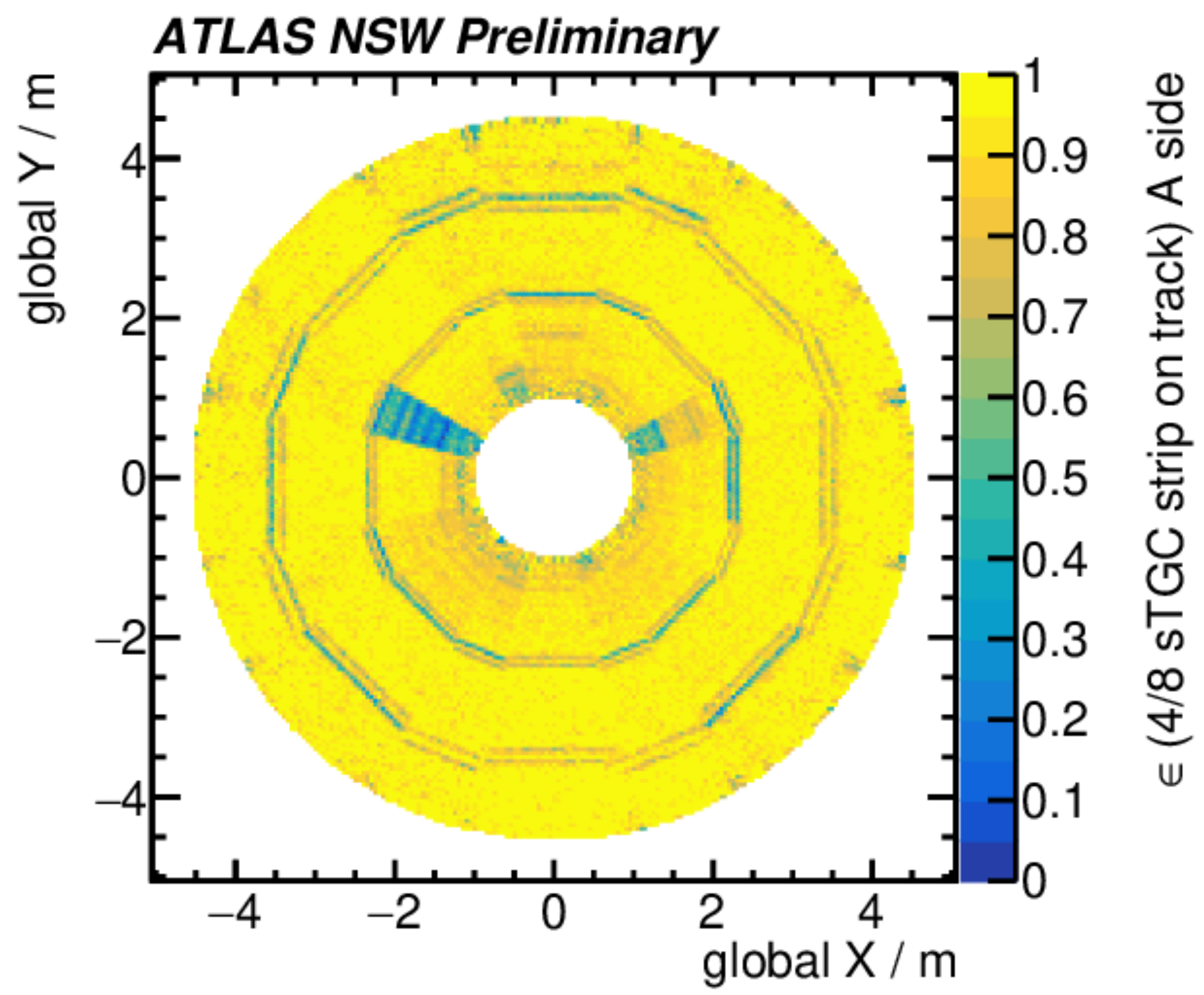
- Local regions of inefficiencies due to HV/LV/DAQ problems during the run (example run from 2024)
- Efficiencies above 90% for regions not affected by these problems

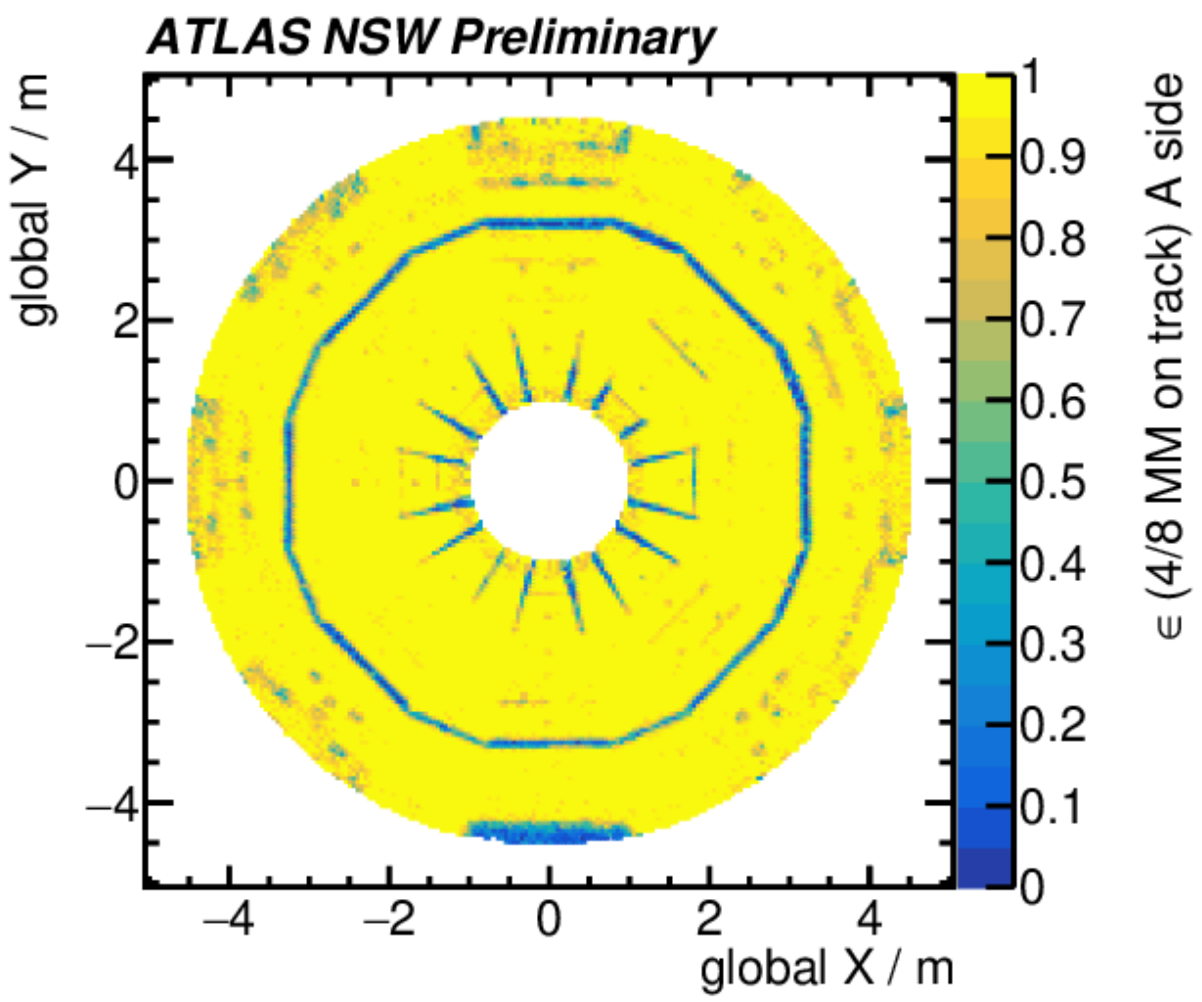


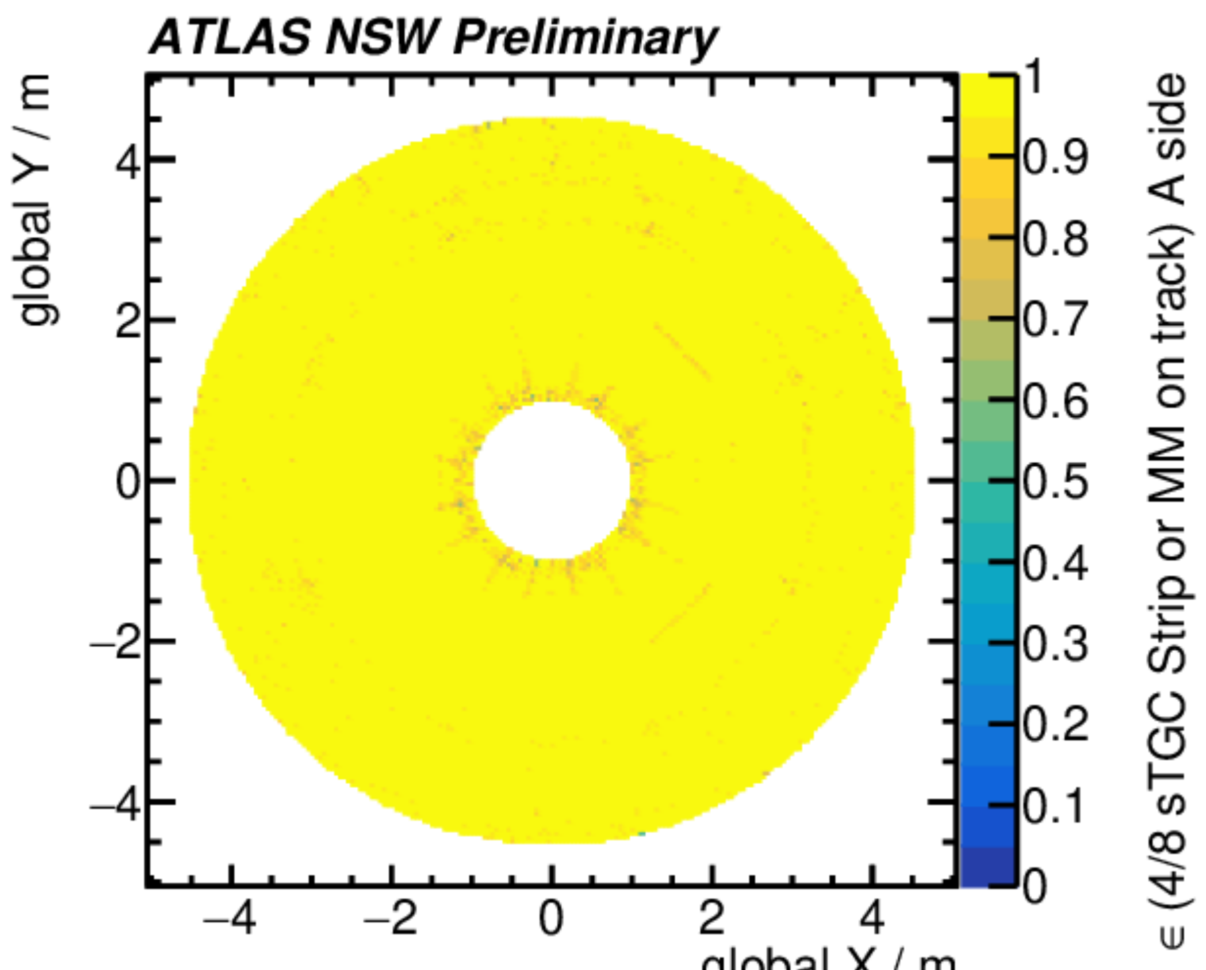
NSW Efficiencies: tracking efficiencies

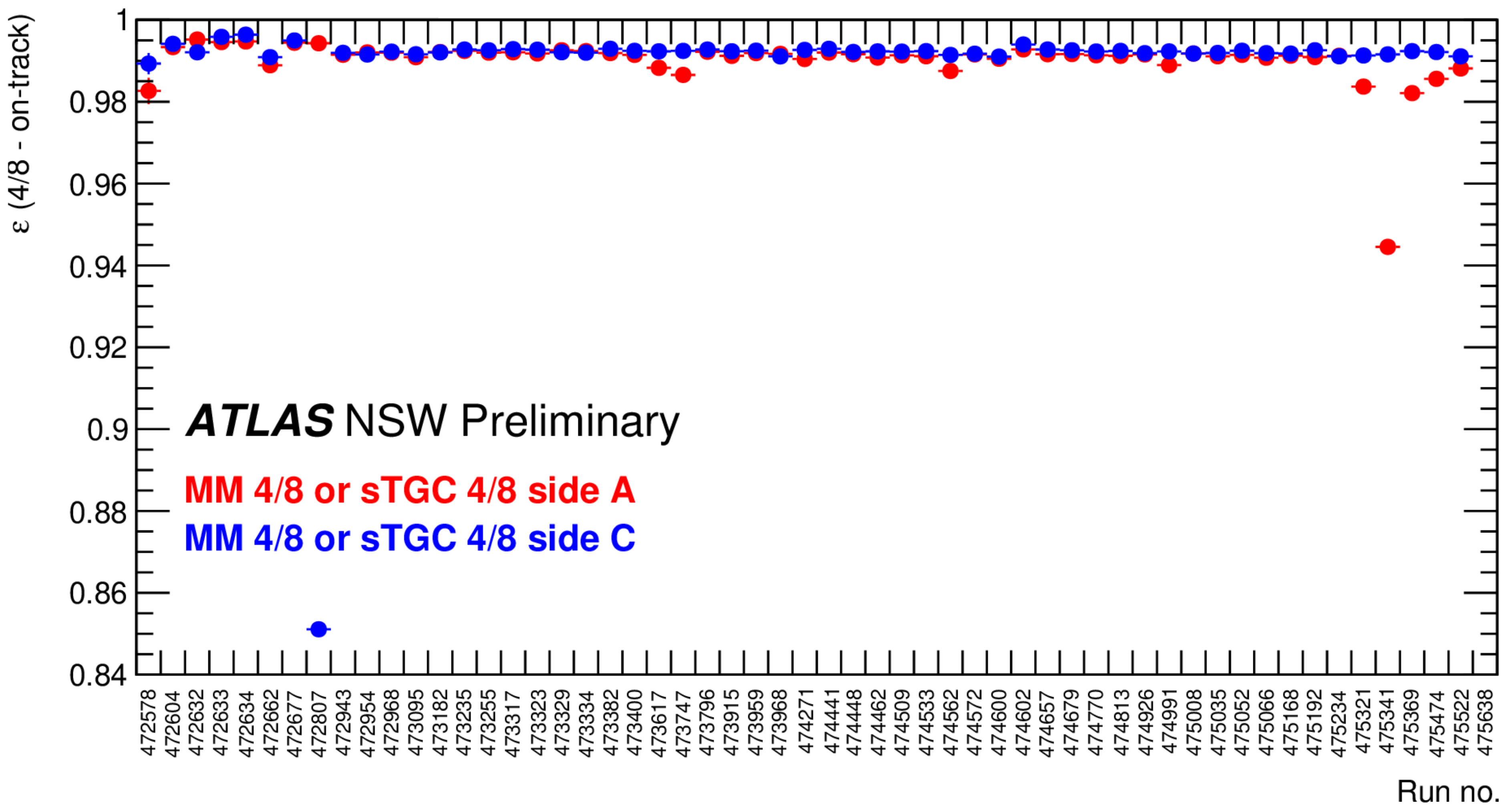
NSW "tracking" efficiencies evaluated using the method of the presence of clusters on-track:

- Requires 4/8 MMG or 4/8 sTGC layers with clusters on-track (used for muon track fit)
- Criterium that can be applied for muon reconstruction WP definition at high pt in order for the NSW to contribute to the tracking with good resolution









- Average 4/8 MMG or sTGC layers on-track efficiencies > 99%
- Very stable in different runs of 2024 data-taking

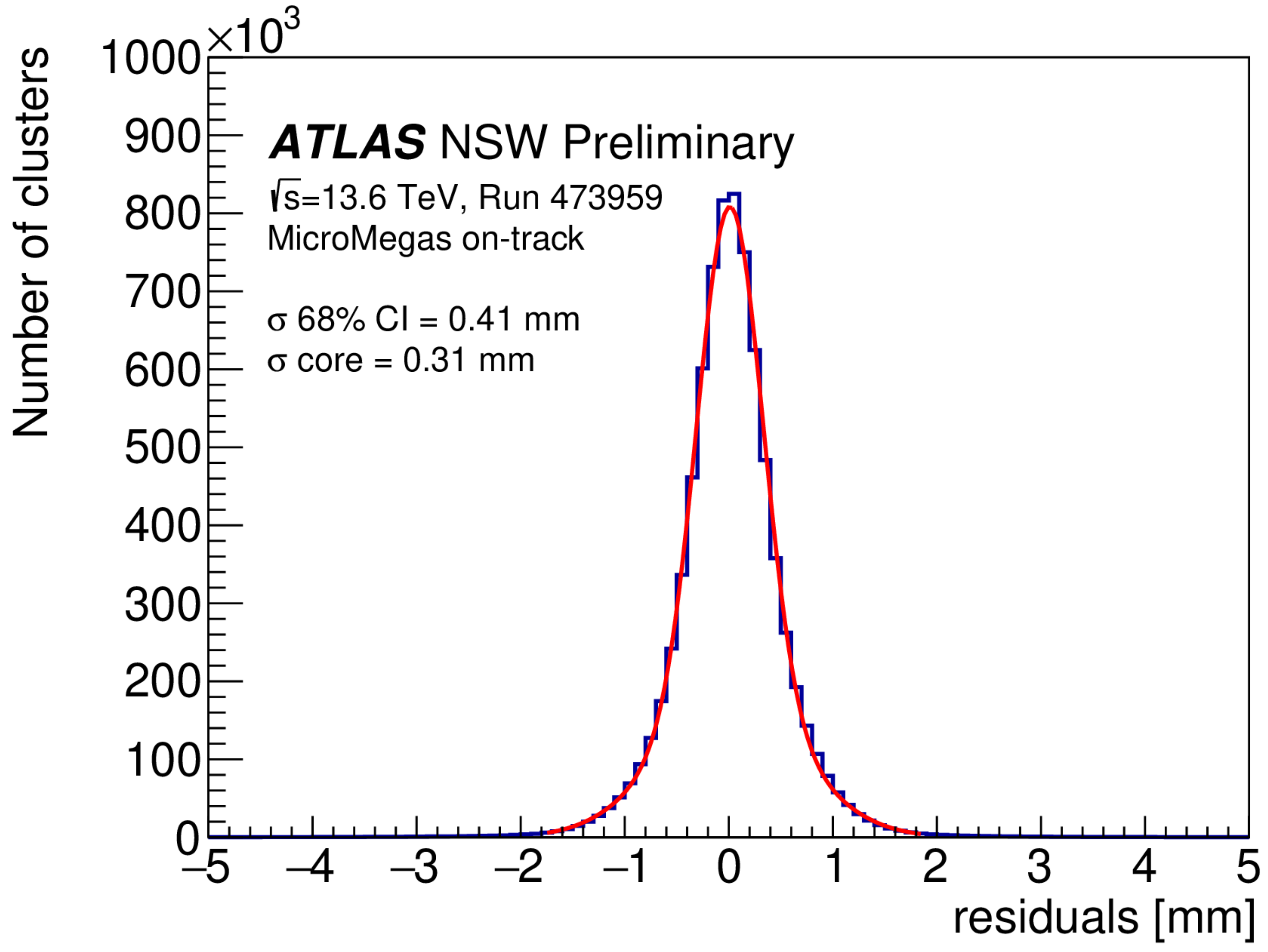
NSW Resolutions: MMG

MMG cluster positions reconstructed using the charge centroid method
(weighted average of strip positions with strip charge as weight)

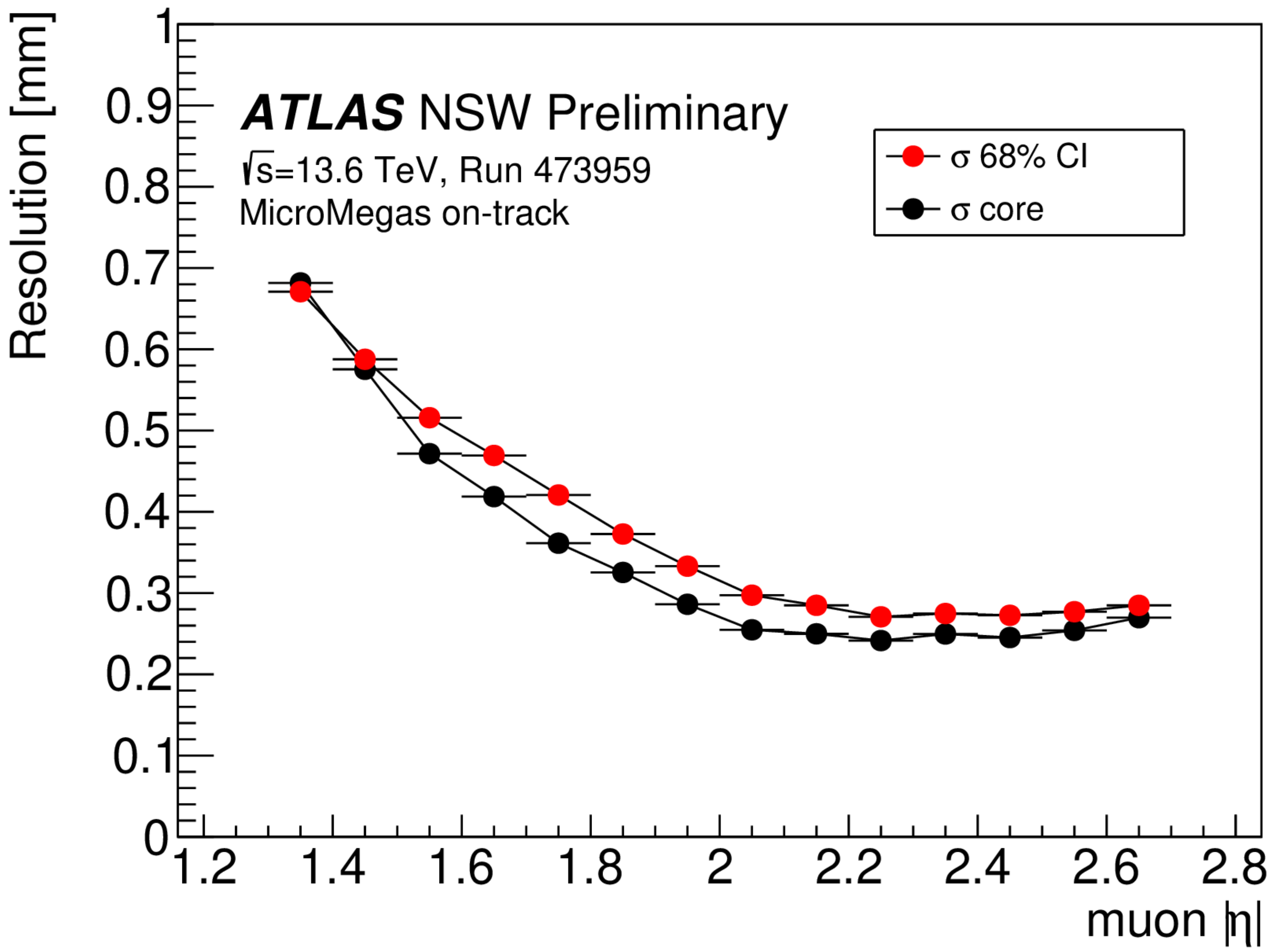
MMG resolutions evaluated from: Cluster-Track residuals and Layer-Layer residuals

→ in both cases distribution of residuals is fit with a double gaussian distribution and the resolution is extracted as the 68% confidence interval on the fit function

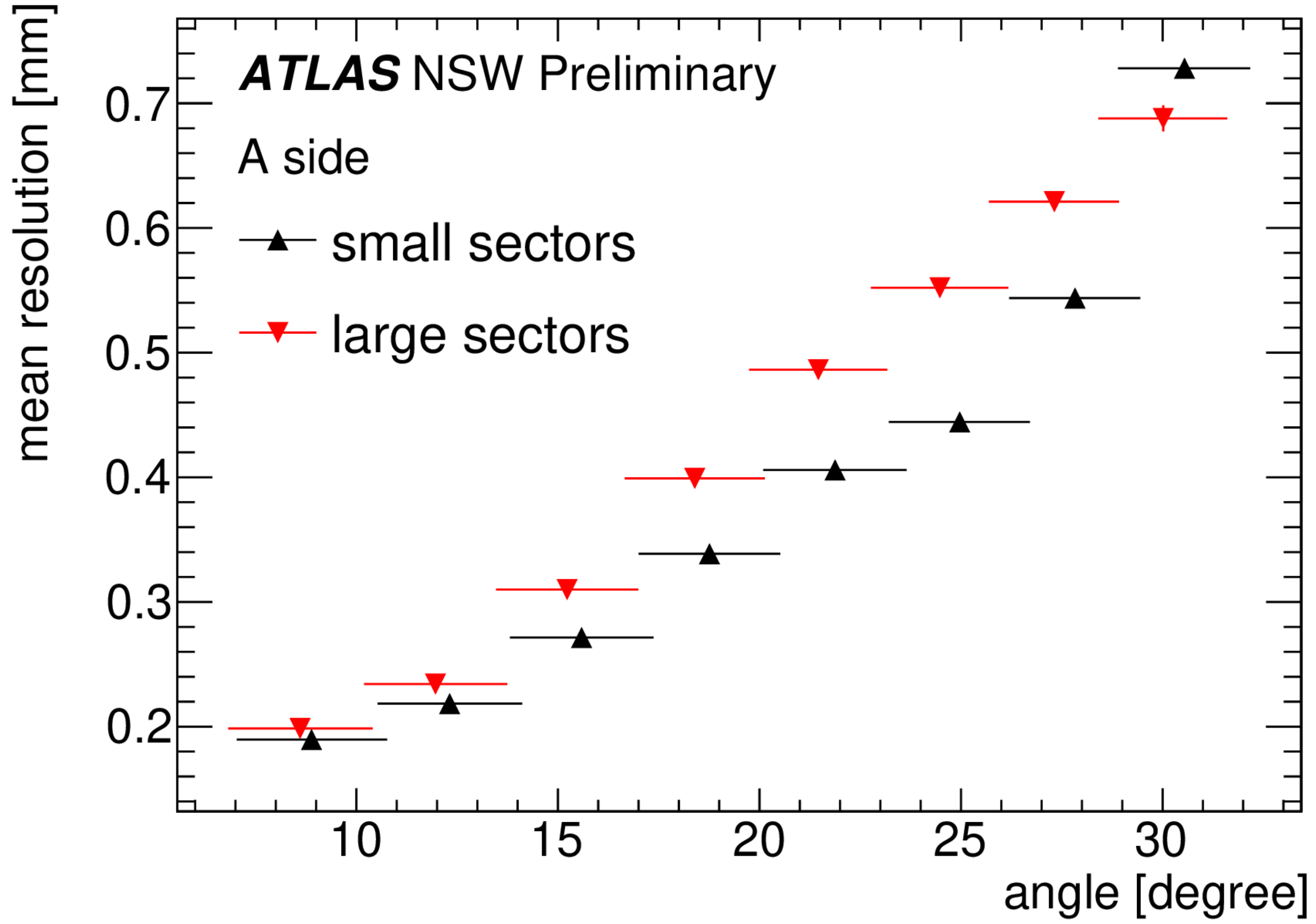
Average track resolution of $400\ \mu m$



Track resolutions of $300 - 700\ \mu m$ depending on η



Layer-layer resolutions of $200 - 700\ \mu m$ depending on η



Still using preliminary alignment that is under improvements (missing internal quadruplet misalignments) and also other position reconstruction methods using time information are under validation

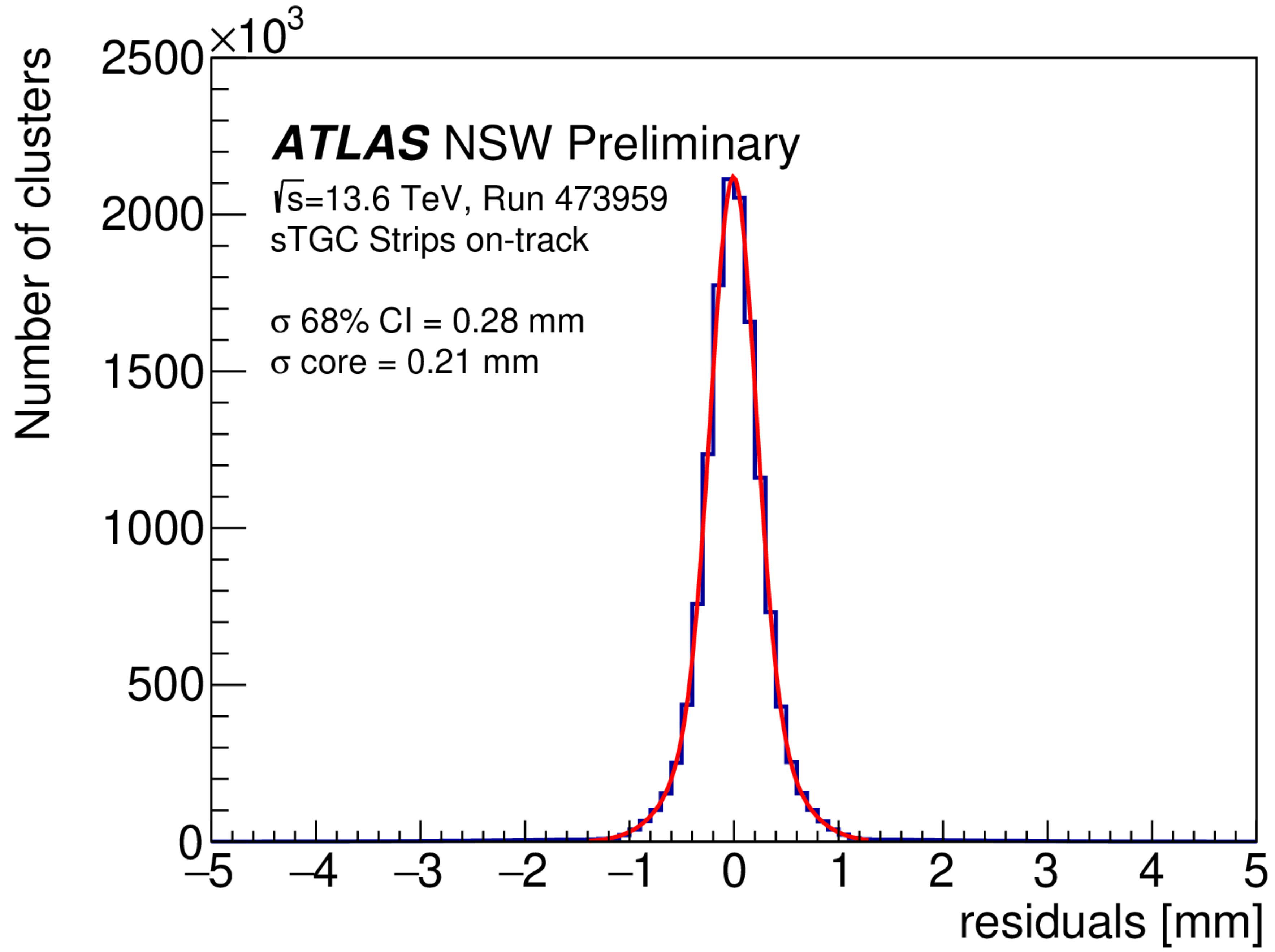
NSW Resolutions: sTGC strips

sTGC strips cluster positions reconstructed using the charge centroid method
(weighted average of strip positions with strip charge as weight)

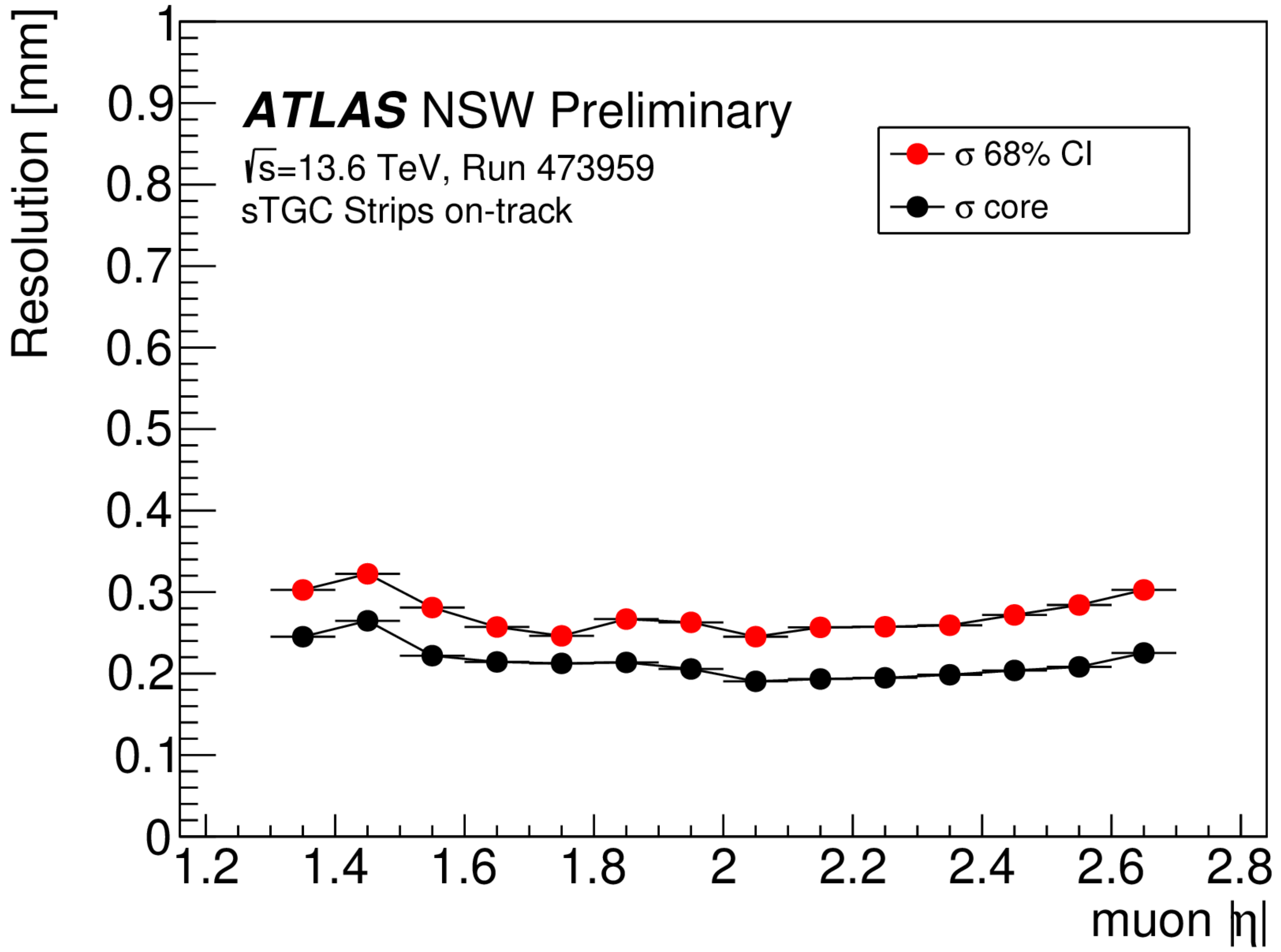
sTGC resolutions evaluated from: Cluster-Track residuals

→ distribution of residuals is fit with a double gaussian distribution and the resolution is extracted as the 68% confidence interval on the fit function

Average track resolution of $280\ \mu\mathrm{m}$



Track resolutions stable vs η



Still using preliminary alignment that is under improvements (missing internal quadruplet misalignments) and also other position reconstruction methods are under validation

Summary and outlook

- ATLAS New Small Wheels have been successfully built, installed and commissioned in ATLAS for Run 3 data-taking
- Both NSW detectors, sTGCs and MMGs, included in the ATLAS combined DAQ system since the start of Run 3 in 2022
- NSW included in the ATLAS L1 muon trigger since 2023
- NSW also fully integrated in the ATLAS muon reconstruction framework since the start of Run 3:
    - Tracking efficiencies > 99%
    - Resolutions $280 - 700\ \mu\mathrm{m}$, to be improved with improved alignment and improved position reconstruction methods
    - Full integration in the definition of muon reconstruction WP at high pt in progress
- Many optimizations towards performance improvement are still ongoing!

Thank you for your attention!

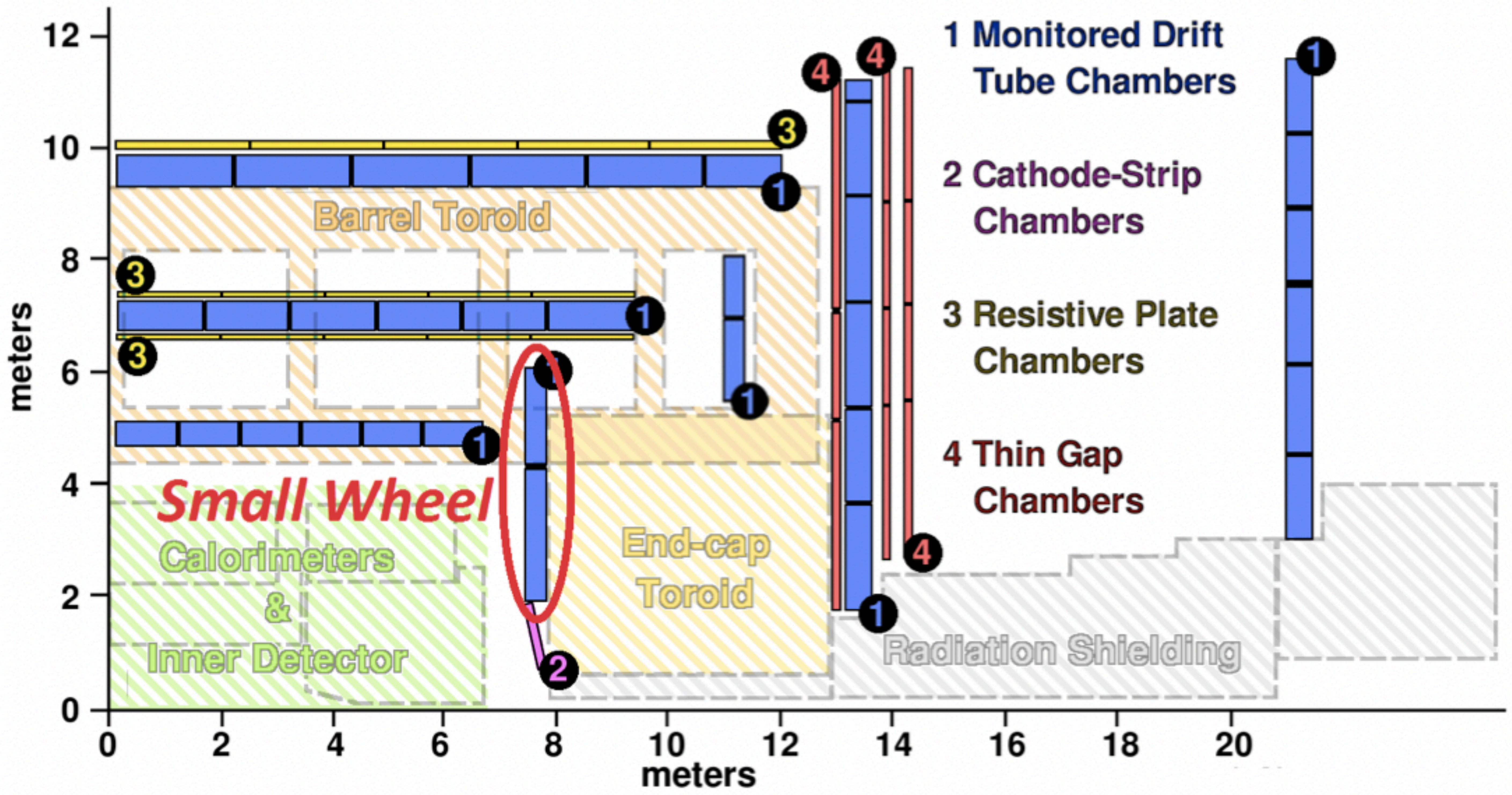
More details about sTGC rates in Sonia Kabana's talk on Tuesday September 3rd

Thank you for your attention!

Back-up slides

ATLAS Muon Spectrometer

ATLAS Muon Spectrometer

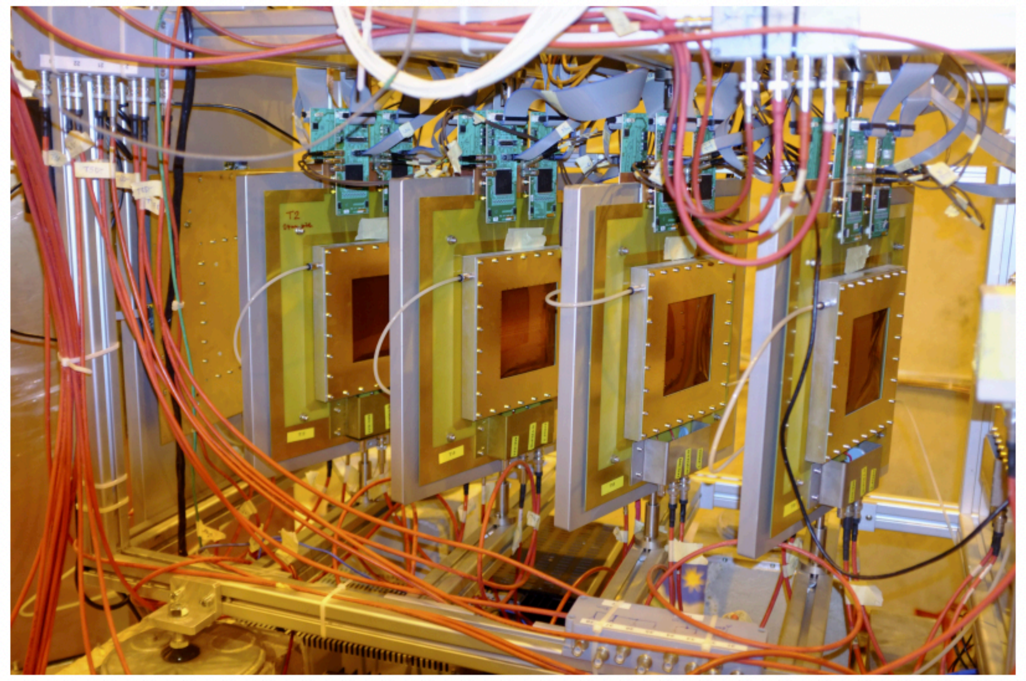


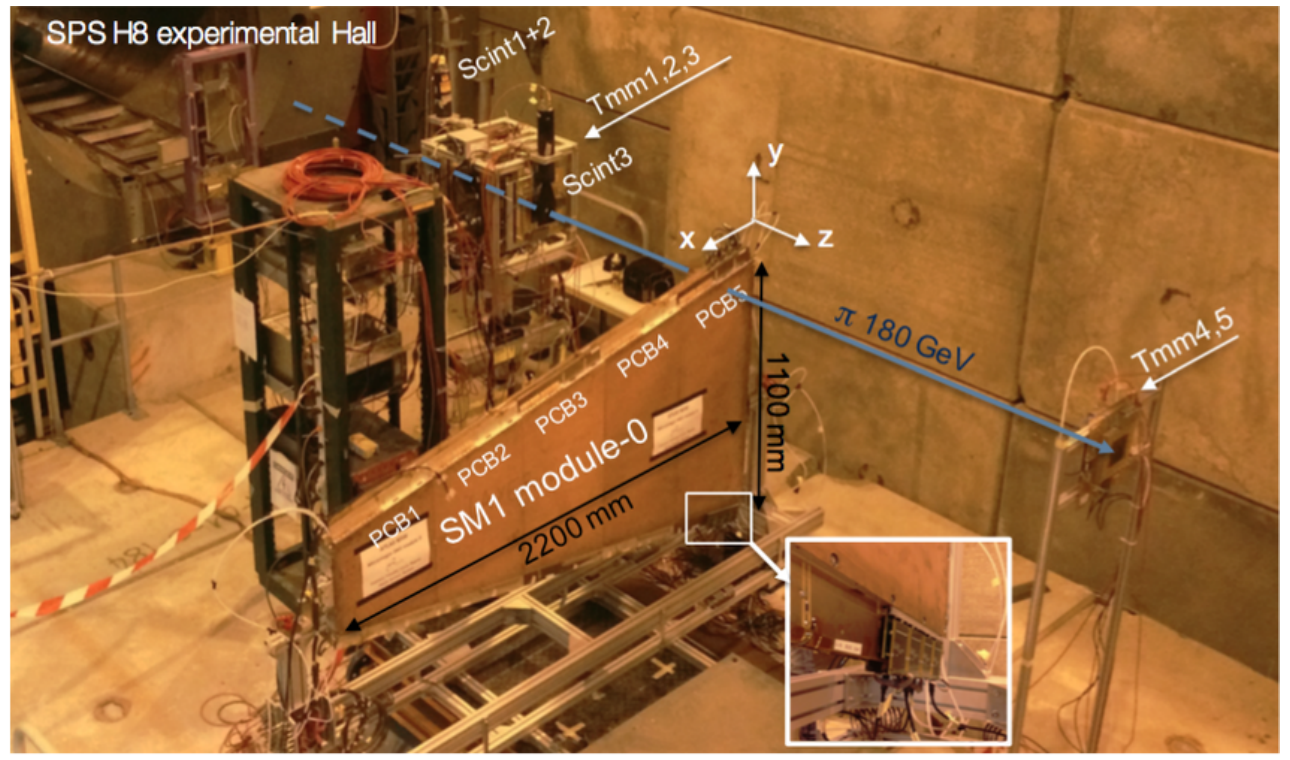
1. Monitored Drift Tubes (End-cap + Barrel) - tracking
2. Catode Strip Chambers (End-cap) - tracking
3. Resistive Plate Chambers (Barrel) - trigger
4. Thin Gap Chambers (End-cap) - trigger

The New Small Wheel upgrade timeline

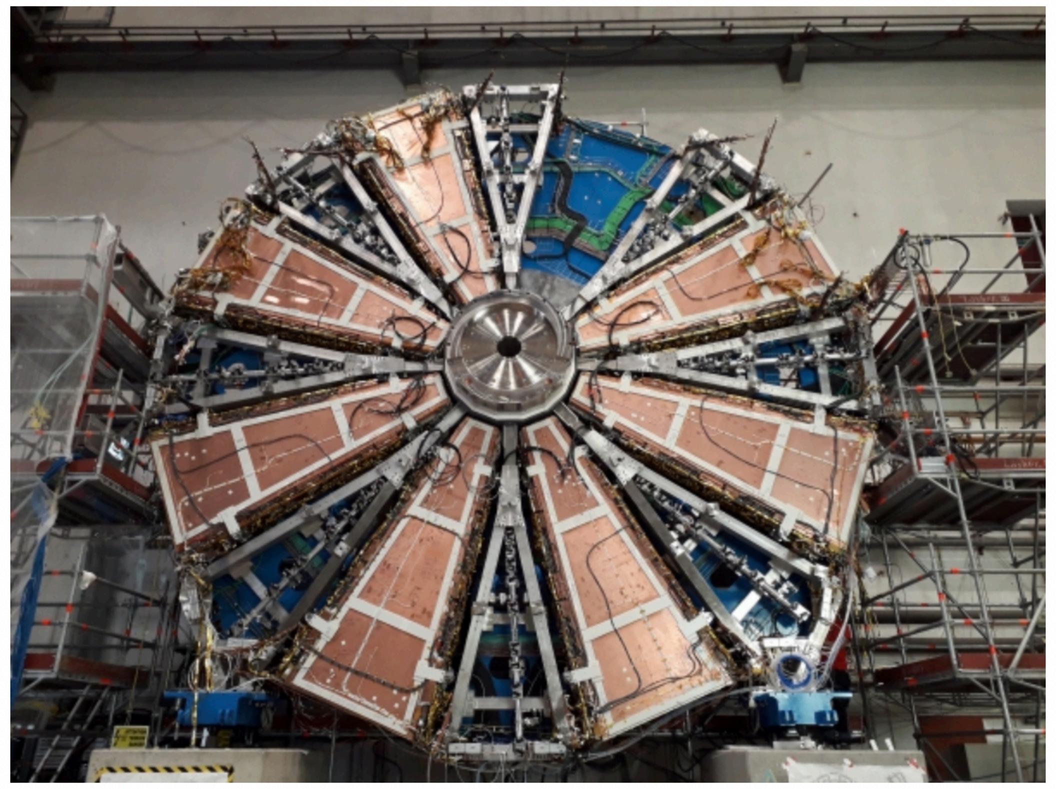
- 2013: ATLAS New Small Wheel TDR

- 2013-2017: R&D and detector performance studies with test beam data on prototypes

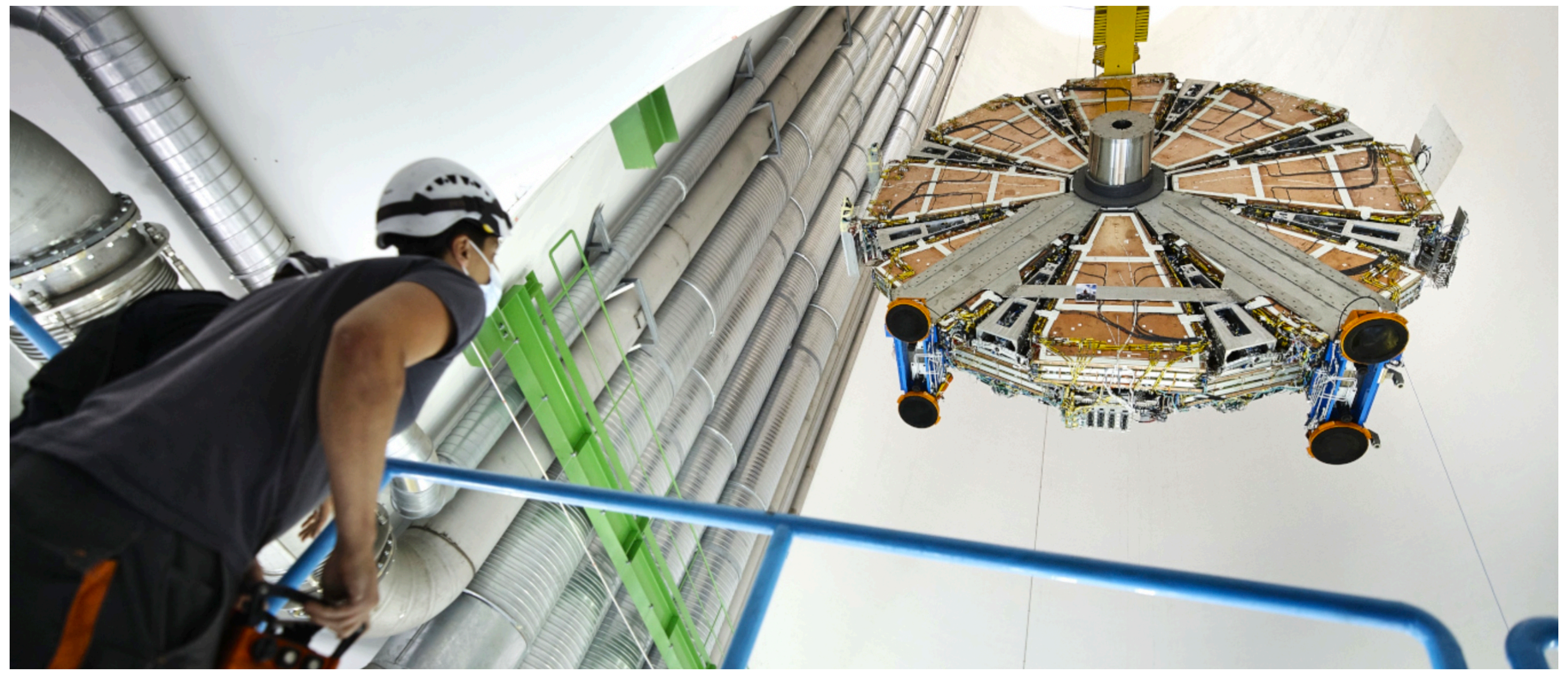


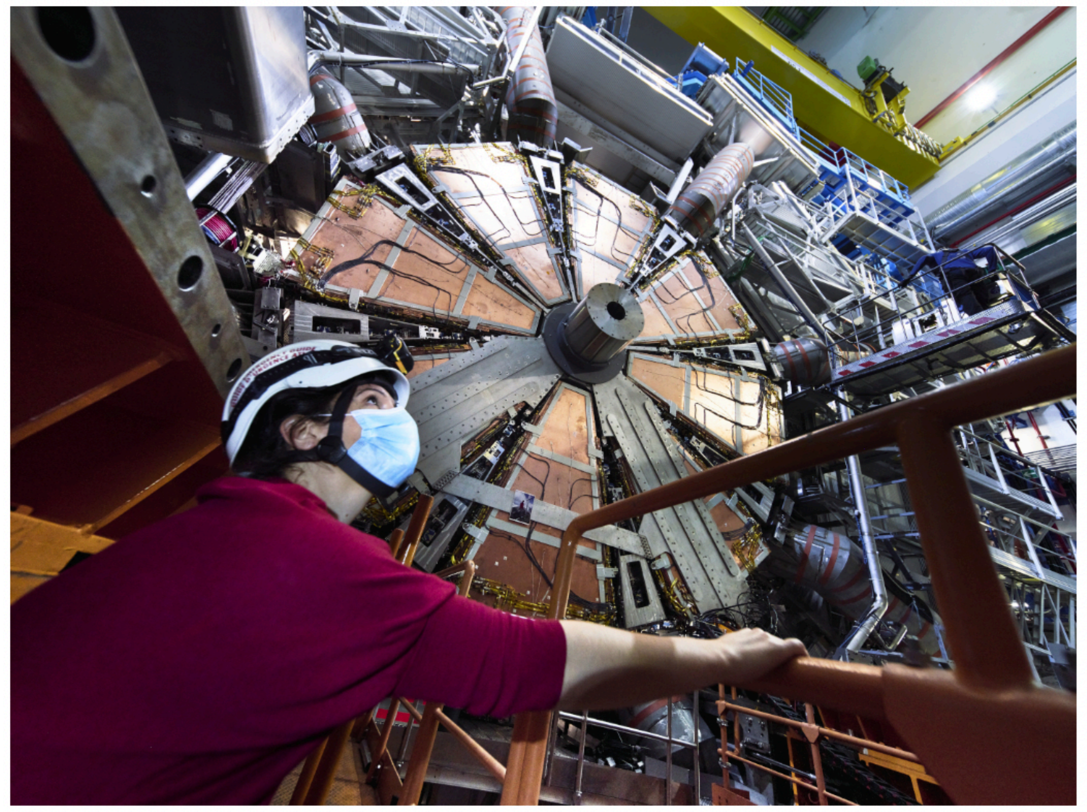


- 2017-2021: Chamber production, surface integration and commissioning at CERN



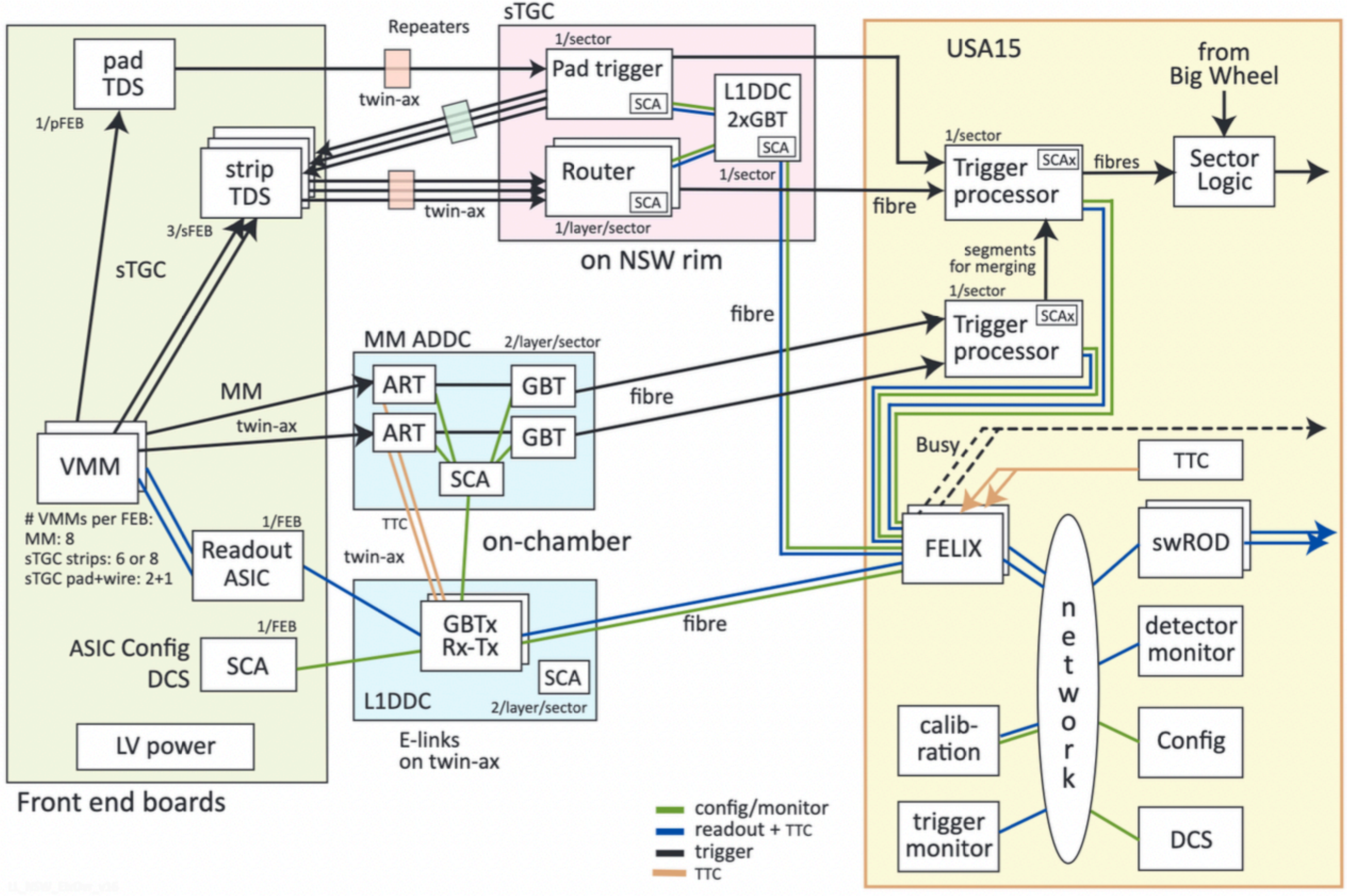
- August 2021: Completion of side-A wheel and installation in ATLAS
- October 2021: Completion of side-C wheel and installation in ATLAS





- July 2022: Start of the LHC Run 3 data-taking

The NSW electronics

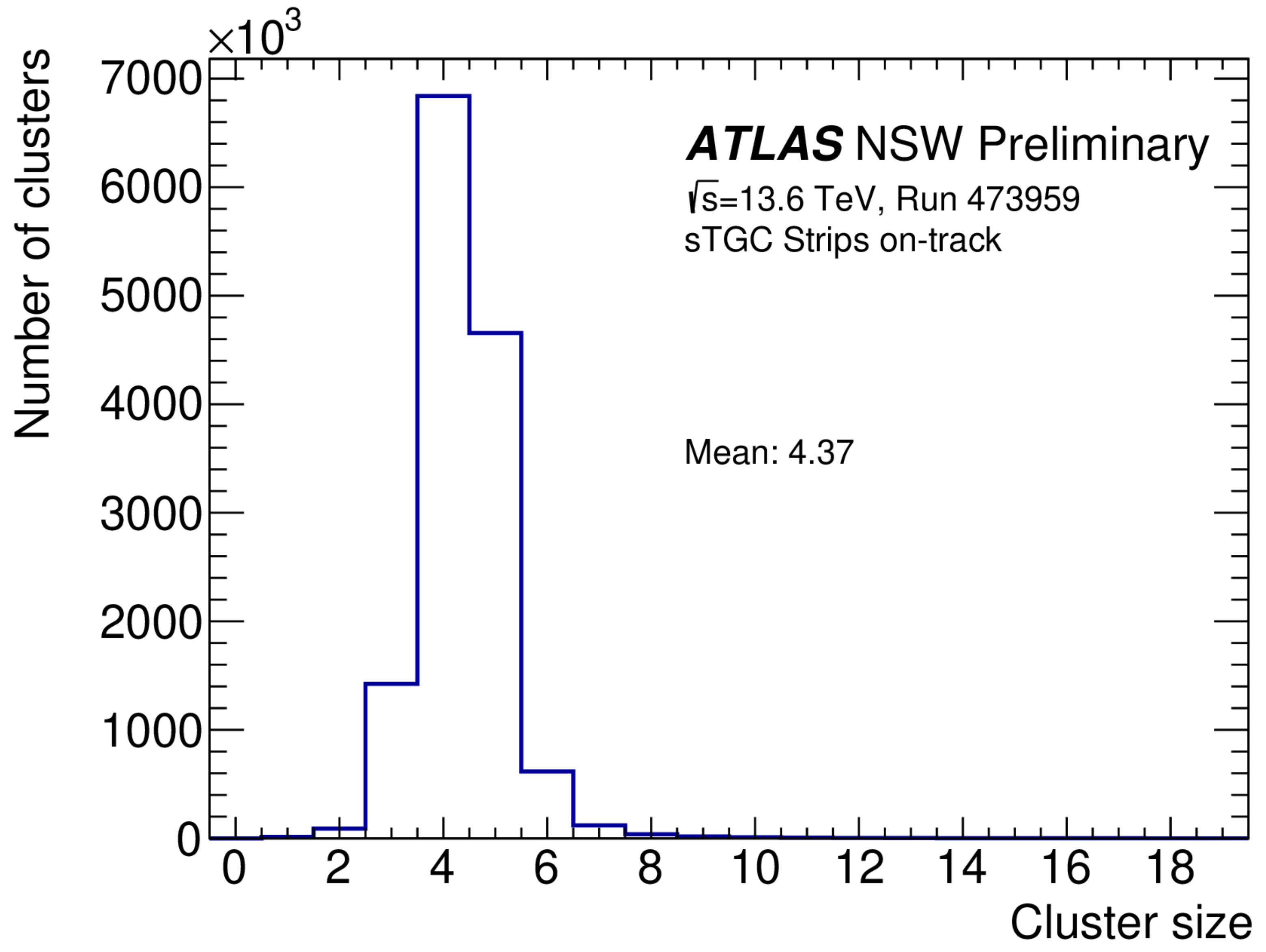


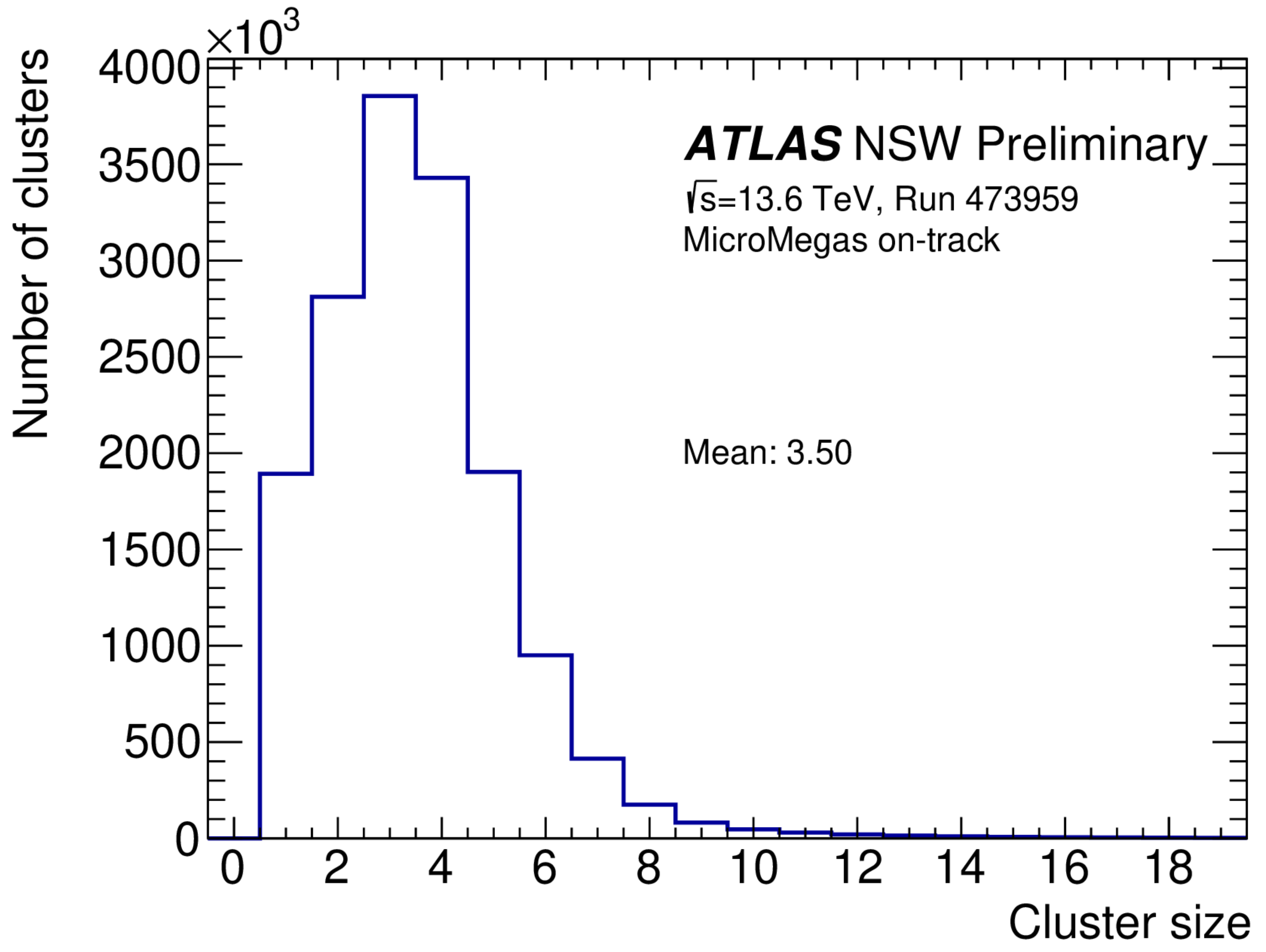
The NSW electronics

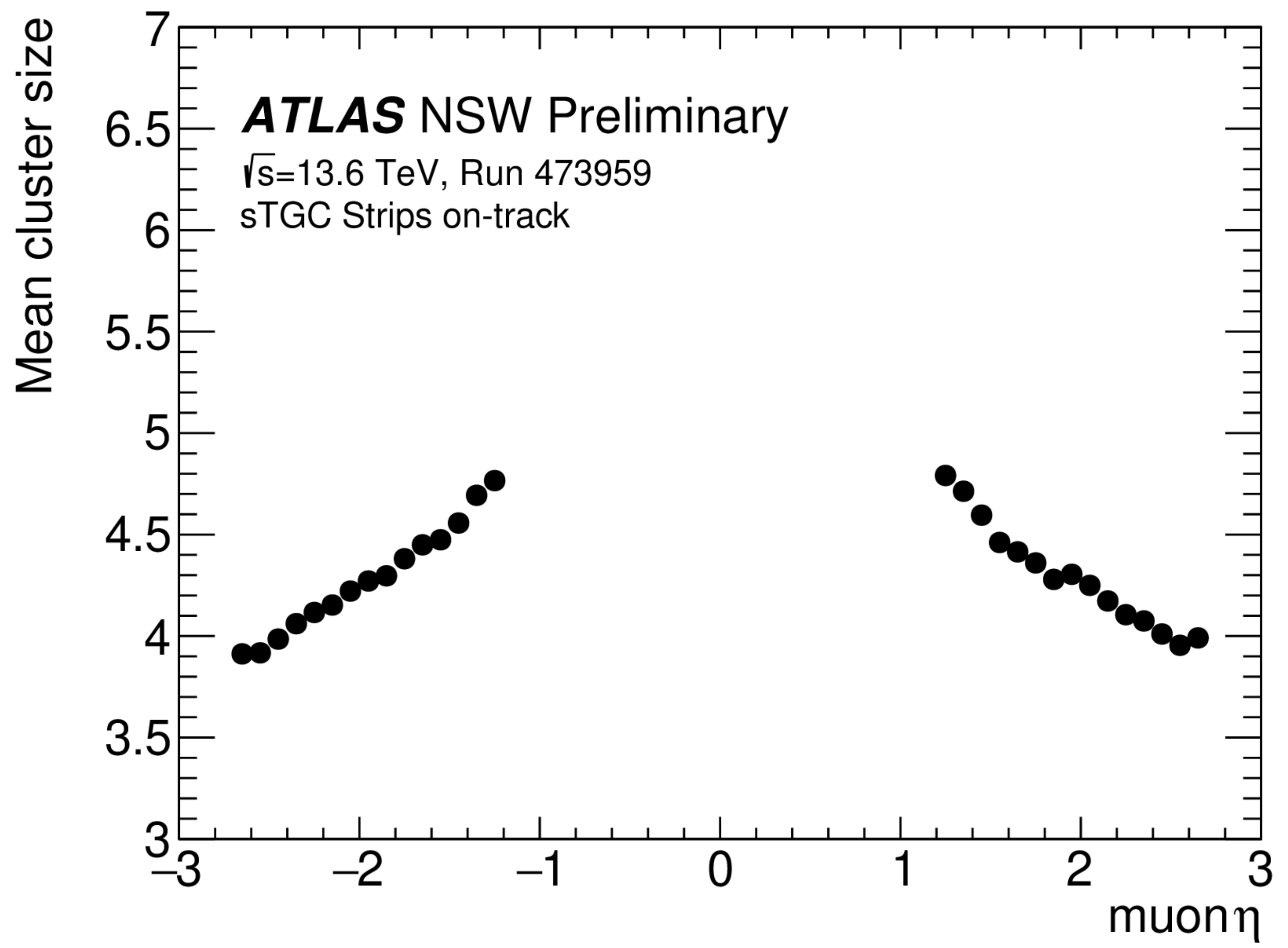
- NSW has more than 50K rad-tolerant front-end ASICs with >70M configuration registers

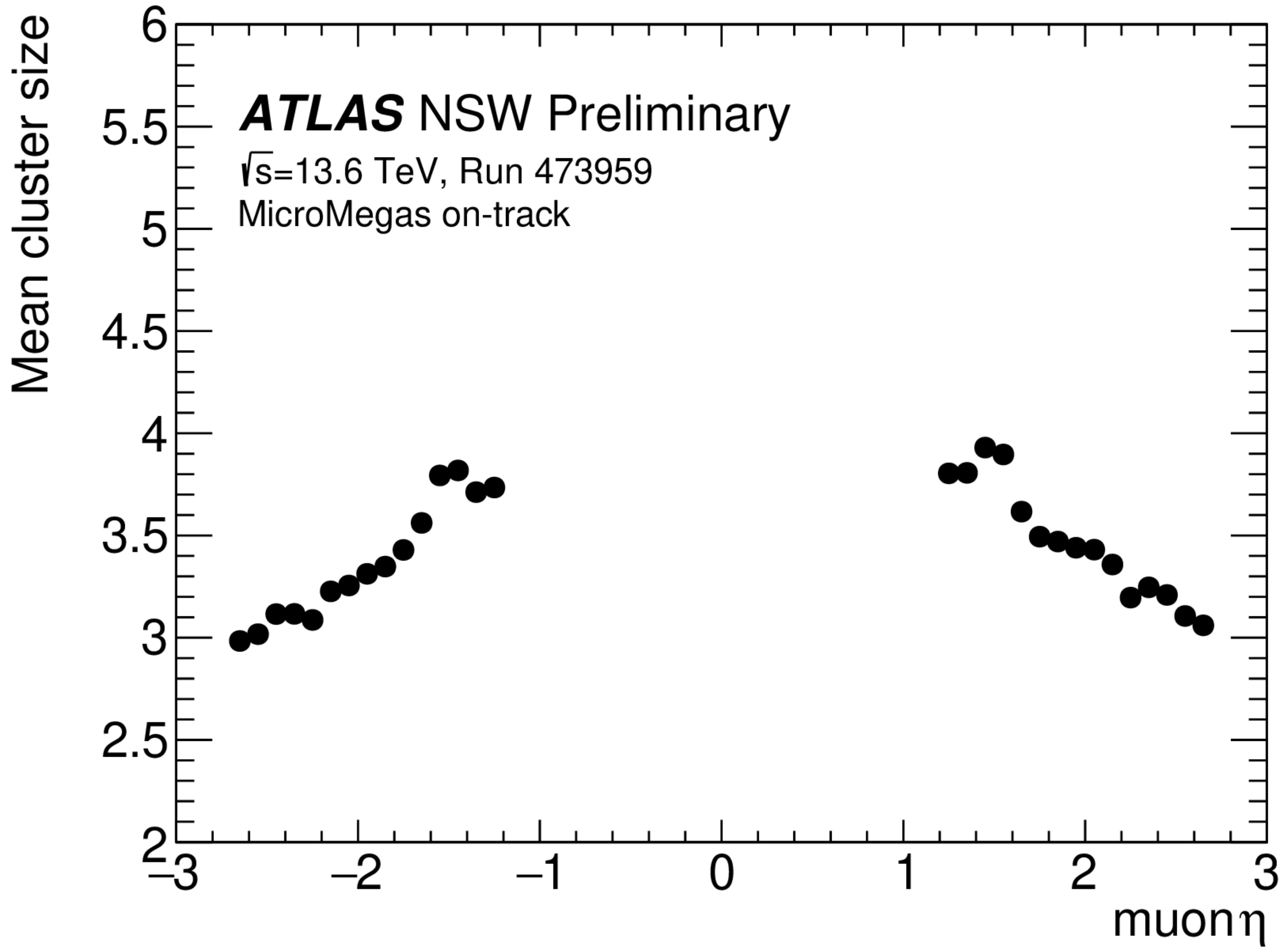
- VMM ASIC: baseline, threshold, pulser, charge and time
  - 64-channel ASIC with charge amplifiers and ADCs for charge, time measurements
  - Pulser for PDO (charge) and TDO (time) calibration
- ROC ASIC; TTC and VMM data decoding
  - Readout control ASIC: distribute TTC and get L0 data from 8 VMM per FEB
- TDS ASIC: strip charge, pad trigger
  - Trigger Data Serializer: prepares trigger data and performs pad-strip matching for STGC
- GBTx: elink data sampling phase
  - Gigabit transceiver for transmission of readout, TTC and slow-control data
- GBT-SCA: slow control data sampling phase
  - Slow control ASIC for the configuration of Front-end ASICs and Front-end monitoring

NSW cluster properties: cluster size









NSW cluster properties: cluster charge