Hadronic signals at the LHC: using calorimeter cell timing in ATLAS to face the challenges of higher luminosity

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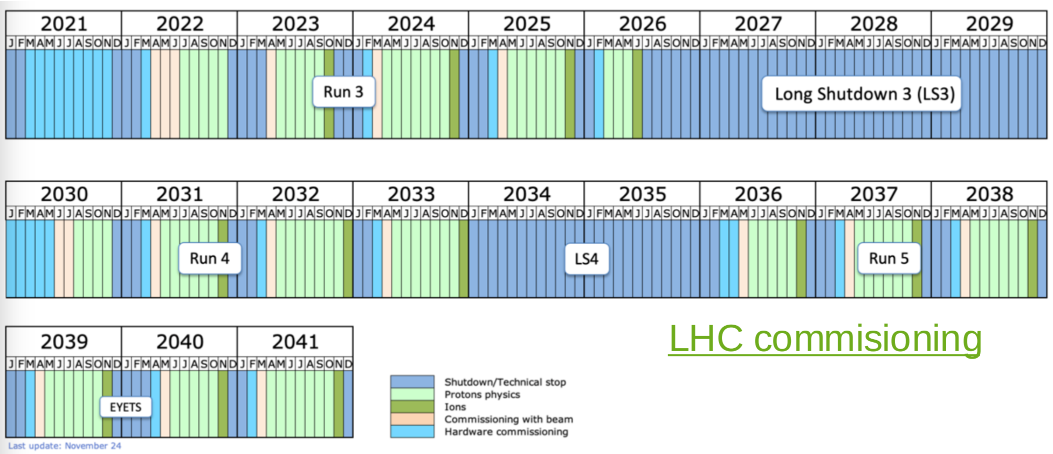
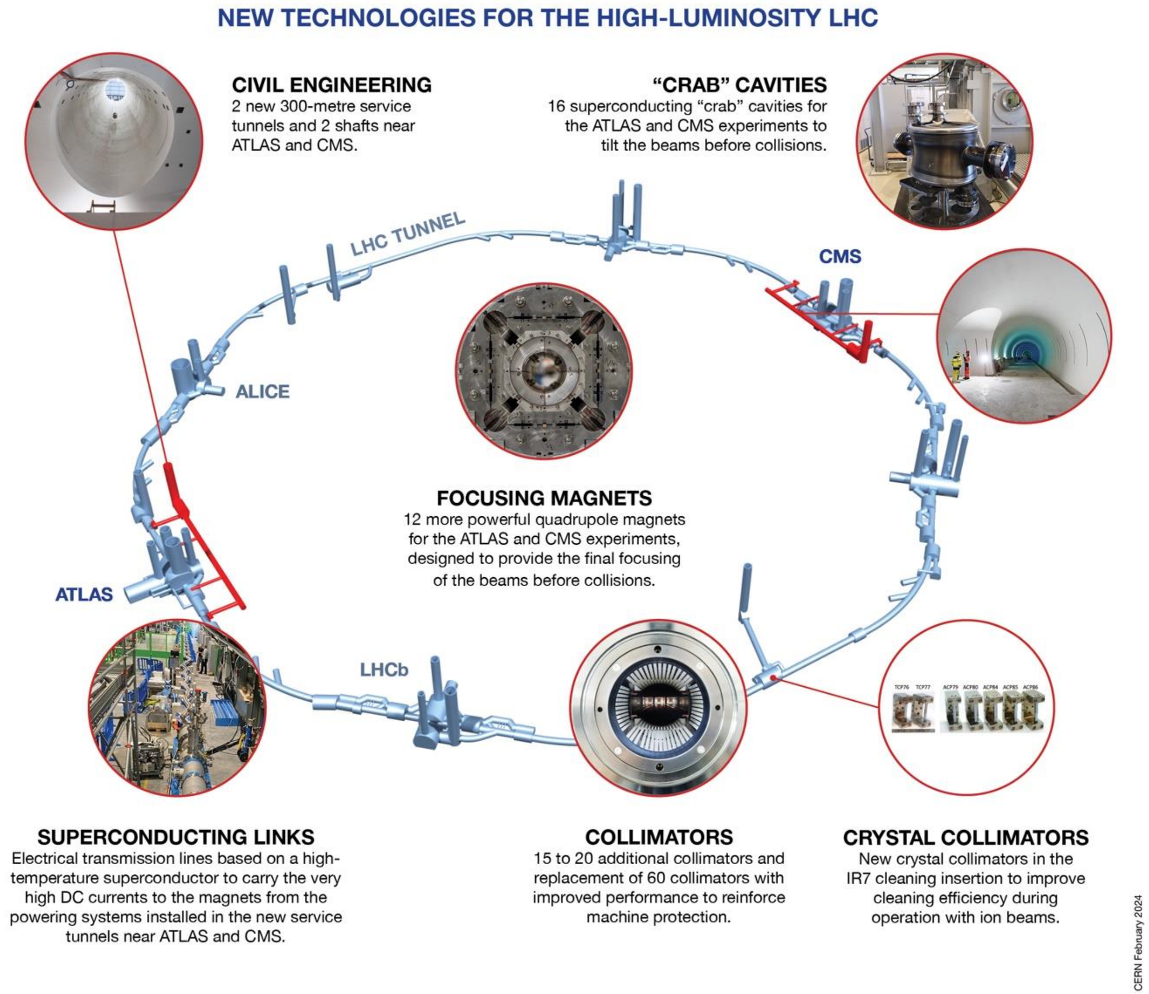
LHC Seminar – TUM
25/11/2024

Towards High Luminosity

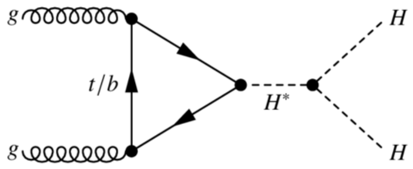


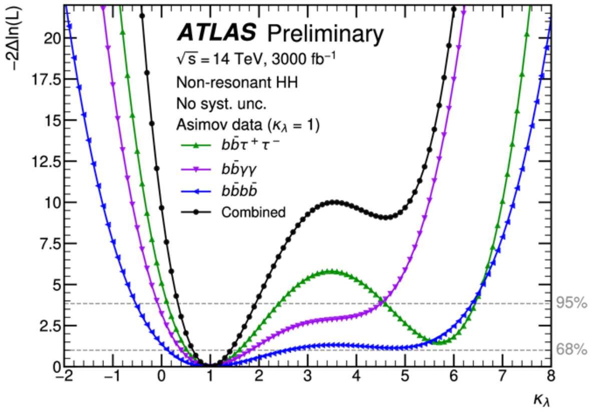
[LHC commisioning]

[New tech for HL-LHC]



High Luminosity LHC (HL_LHC) programme: increased luminosity for **improved precision** and access to **rare signals**





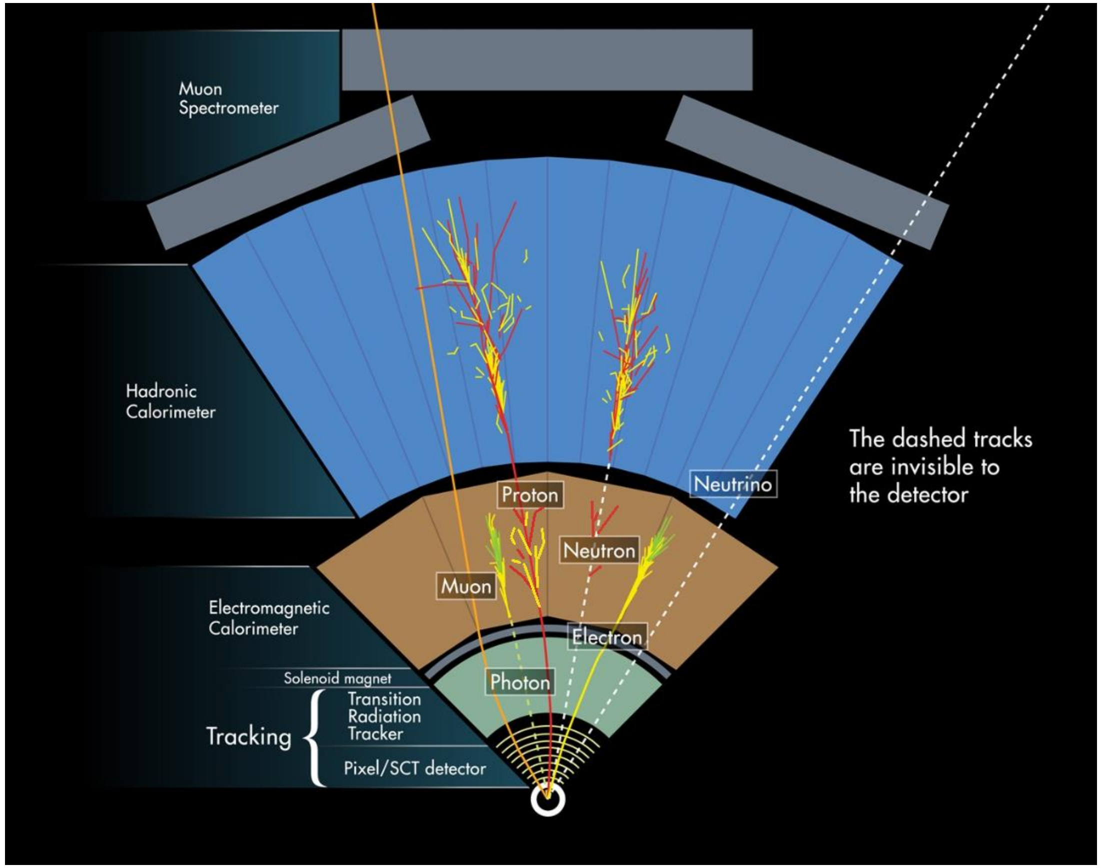
[ATL-PHYS-PUB-2022-053]

Signals in ATLAS

ATLAS-Outreach

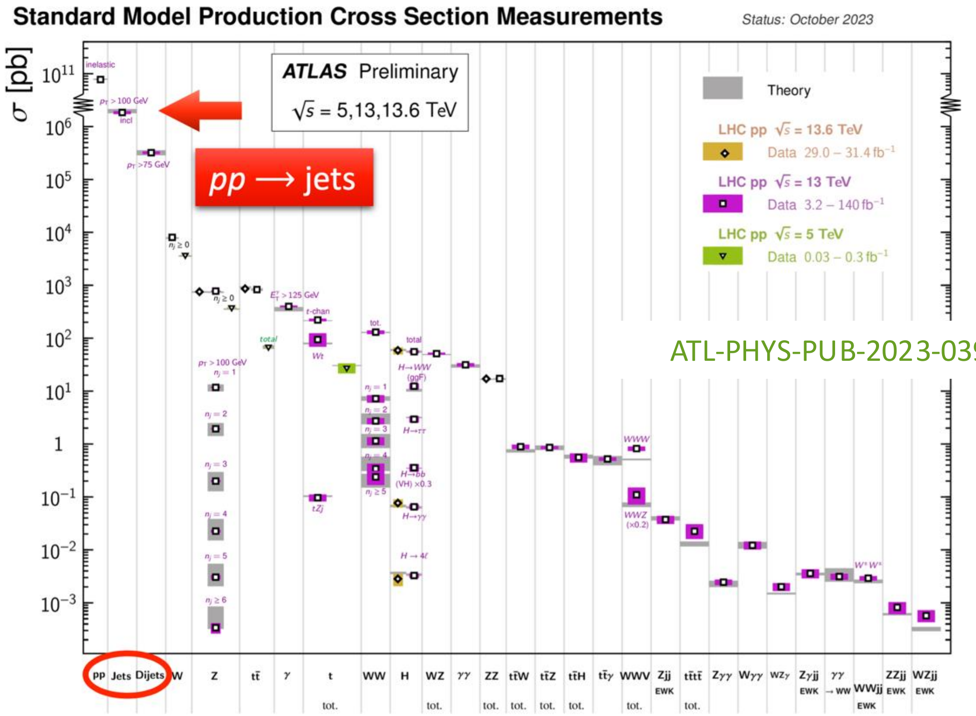
- **Tracks**: combine multiple detector hits to extract direction and momentum (curvature)
  - Fitting procedure to extract the reconstructed track
- **Calorimeter showers**:
  - energy deposited in multiple calorimeter cells, then combined into a cluster *(topo-cluster)* to extract the particle energy
  - Iterative algorithm to build the topo-cluster, based on signal to noise ratio

- Excellent performance during Run 1 and Run 2



Hadronic Signals

Hadronic signals are usually linked to **the biggest branching ratios**, but things are complicated by **large uncertainties** and a **massive background**



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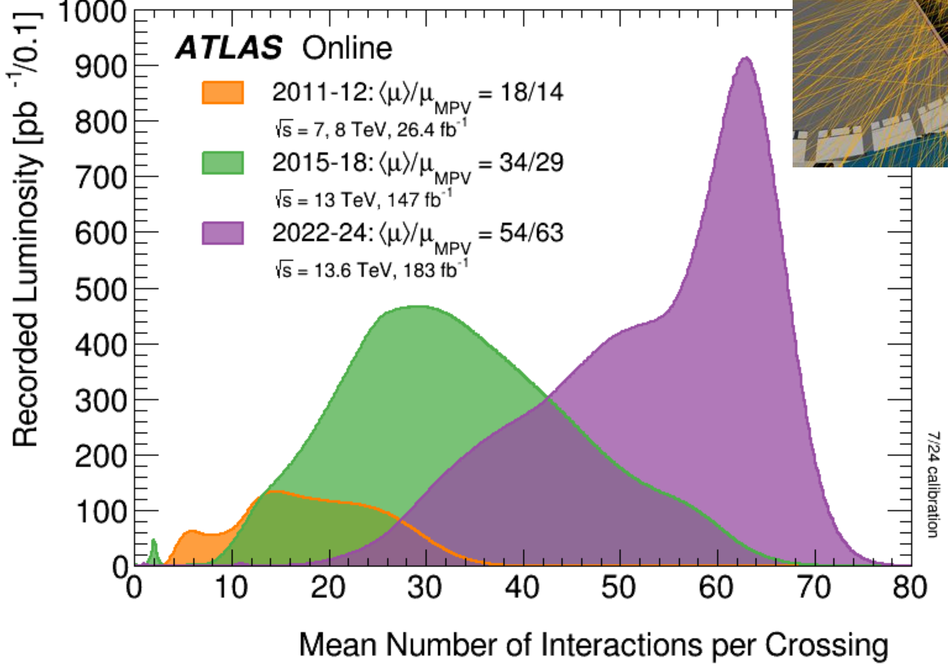
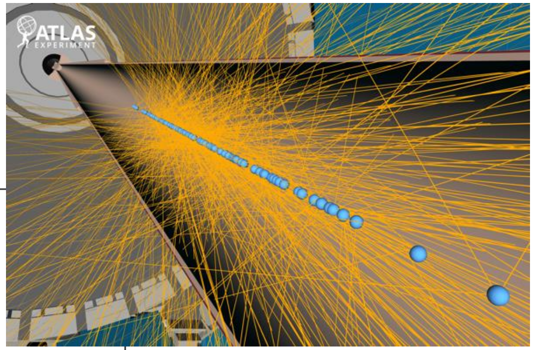
[Luminosity public results](#)



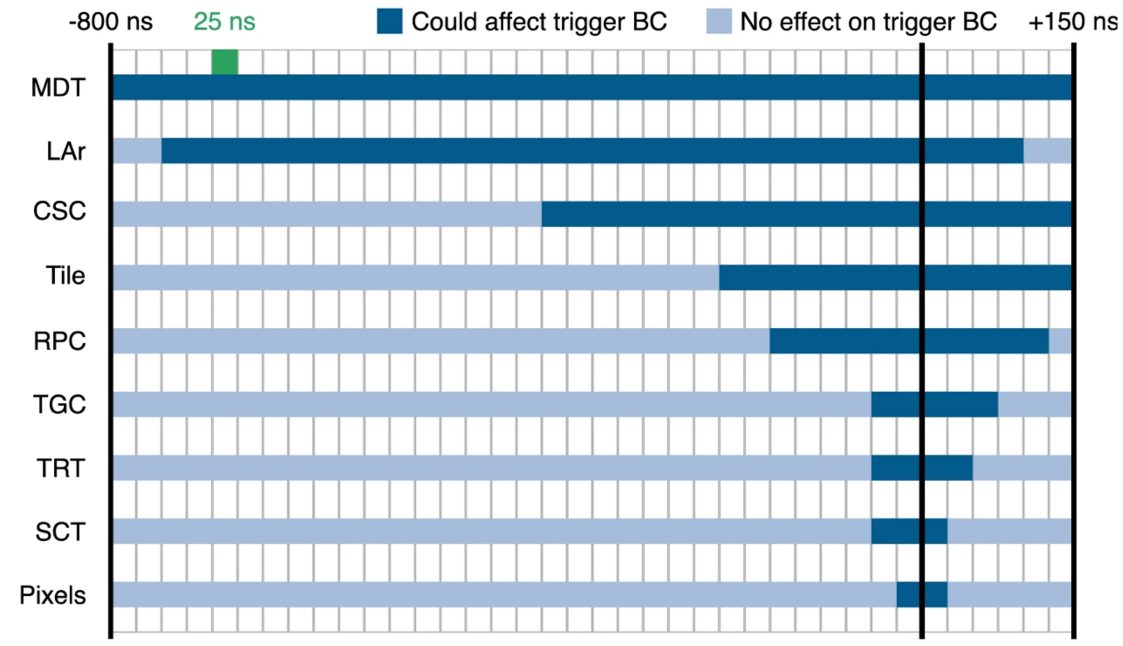


[HL-LHC-Simulation](#)

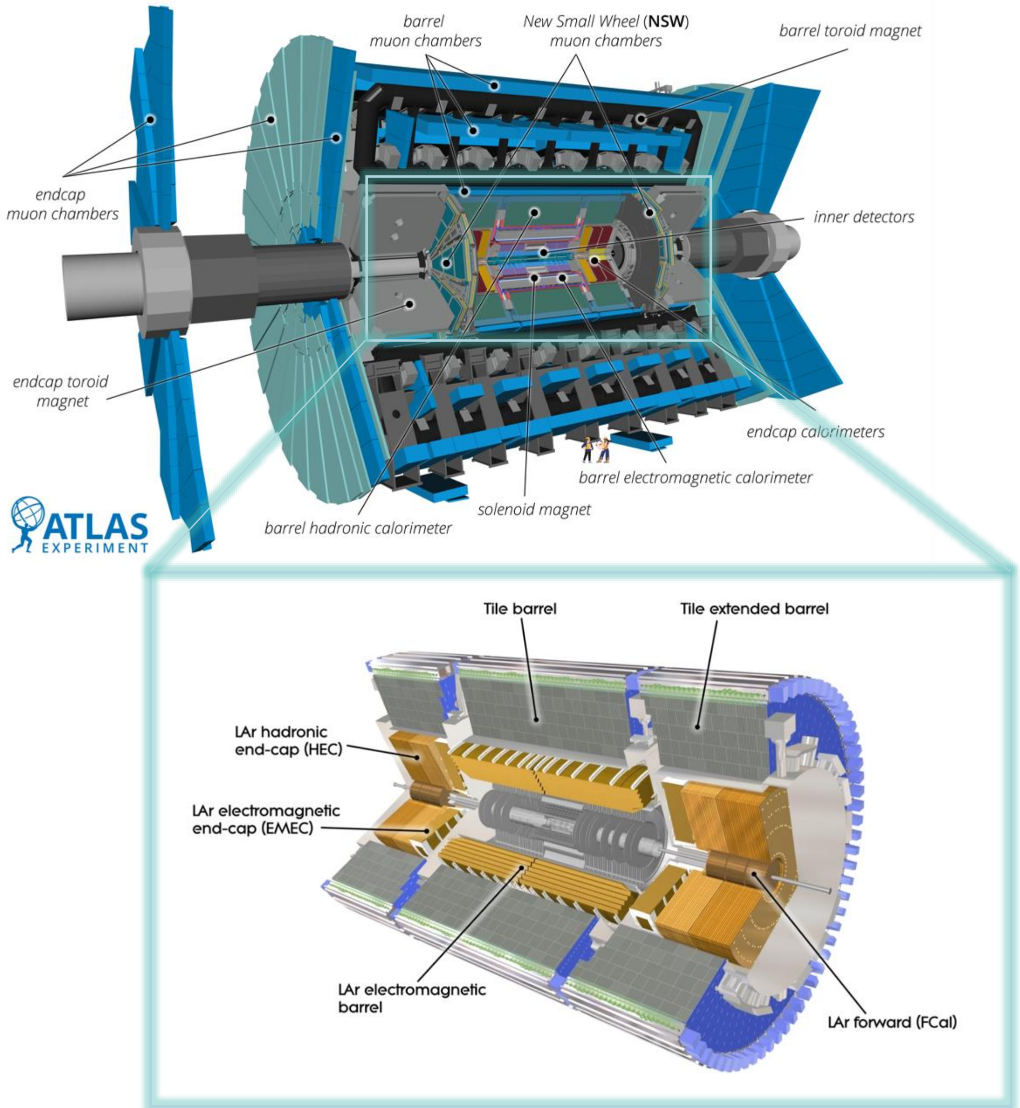
1. Multi-jet background events
   - Suppressed using e.g. taggers, advanced final state reconstruction
2. Contamination to signal events from additional interactions (***in-time pile-up***)
   - Multiple pp interactions per proton bunch crossing

More on pile-up: out-of-time signals

LHC filling scheme: one bunch crossing every 25 ns
o Integration time of ATLAS sub-detectors can exceeds 25 ns ➢ Often due to drift times
o Particles from different bunch crossings detected as part of the event: ***out-of-time pile-up***



Detector redout windows



Pile-up suppression

Developed at many levels of the reconstruction chain

Signals from calorimeter/tracker

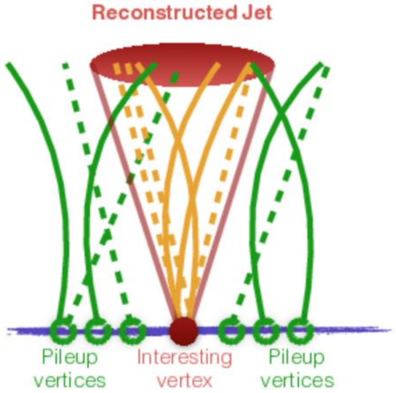
Particle-flow objects

More on PFlow

Jets

- Reject pile-up contribution to signal jets
  - Jet grooming
  - Reject (or correct for) pile-up signals when defining jet constituents (e.g. Constituent Subtraction, Soft Killer)

Jet Reco



- Reject pile-up originated jets: dedicated taggers

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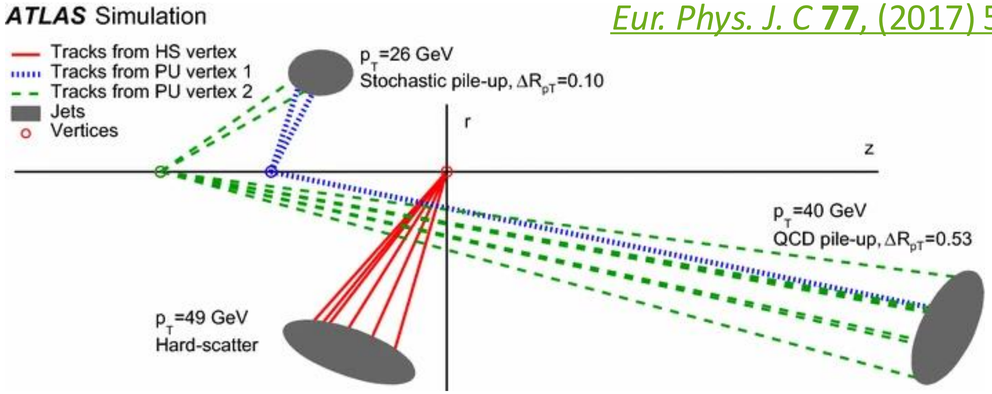

Can we improve further?

- Build a better detector

- Improve the way we combine the available information
  - Machine learning approaches for combining calorimeter cells / tracker hits

- Use additional information
  - **Timing:** detector returns information about when particle is detected
  - Variables used in Run 2 algorithms:
    - ➤ hit/cell location (detector granularity)
    - ➤ measured energy

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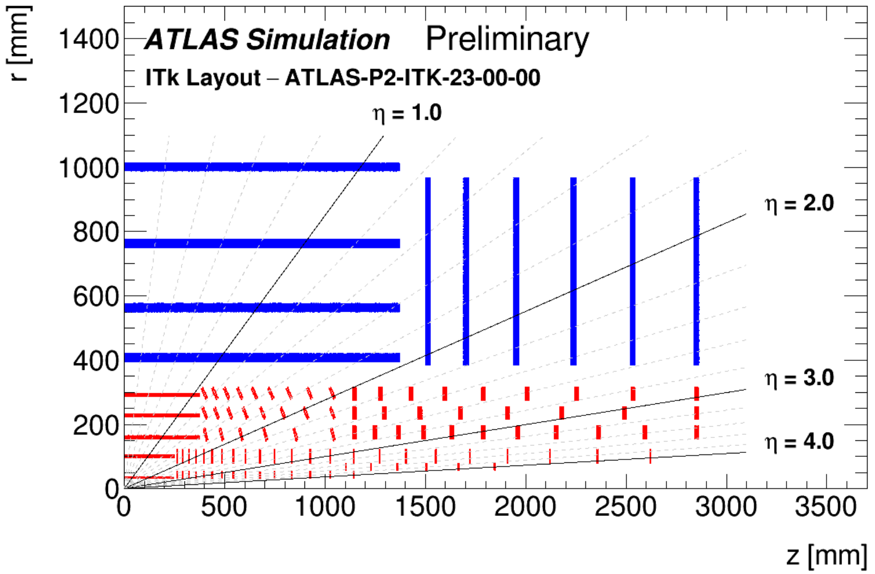

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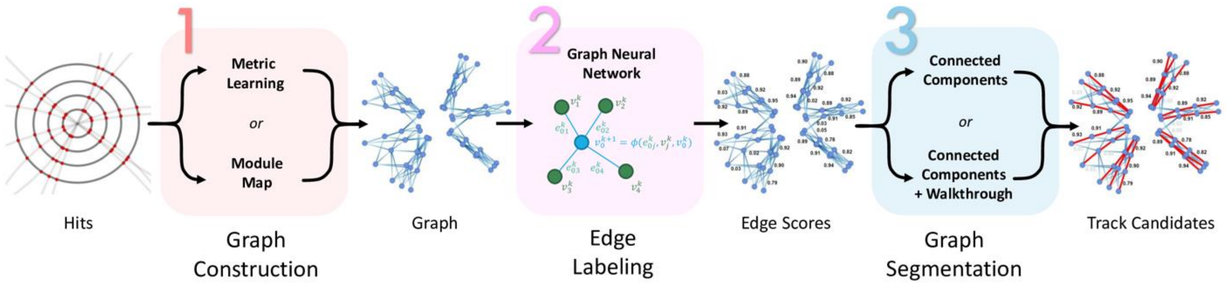


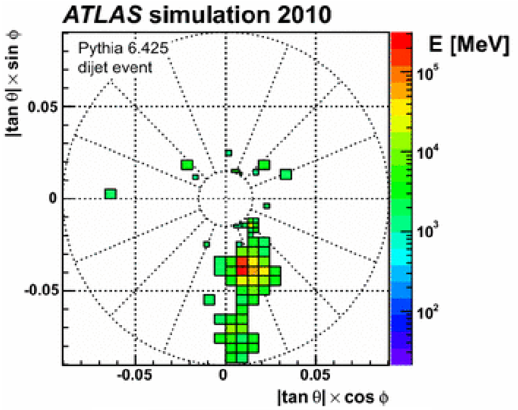
Topo-clustering in ATLAS

More on topo-clusters

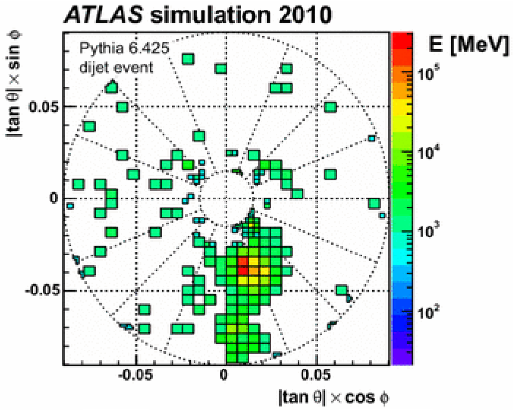
Hadronic signal reconstruction in the calorimeters is based on **a three-dimensional topological clustering** of individual calorimeter cell signals.

The cluster formation follows **cell signal-significance**

$$\sigma_{\text{noise}} = \sqrt{\left(\sigma_{\text{noise}}^{\text{electronic}}\right)^2 + \left(\sigma_{\text{noise}}^{\text{pile-up}}\right)^2}$$

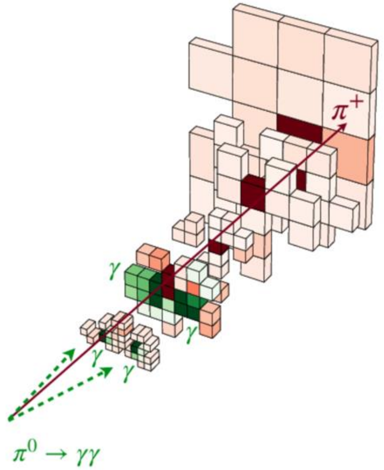


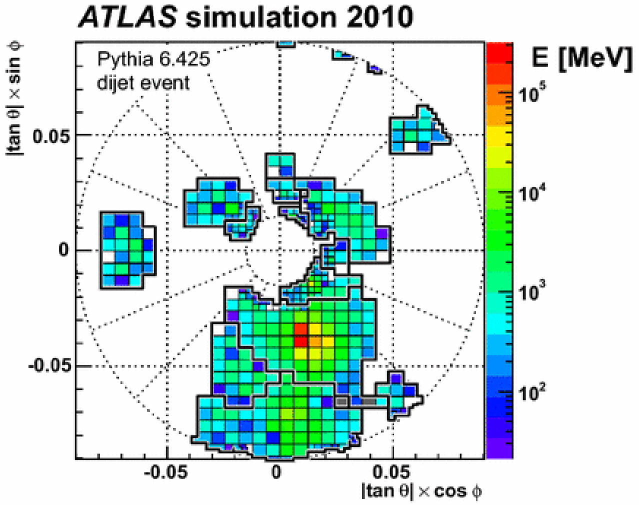
$|E|/\sigma_{\text{noise}} > 4$



$|E|/\sigma_{\text{noise}} > 2$

- Iterative algorithm based on $|E|/\sigma_{\text{noise}}$
  - Topo-cluster **seeds**: cells with $|E|/\sigma_{\text{noise}} > 4$
  - Topo-cluster **growth**: include all neighbouring cells if a neighbouring cell has $|E|/\sigma_{\text{noise}} > 2$, then also include its neighbours
- Additional step: cluster-splitting





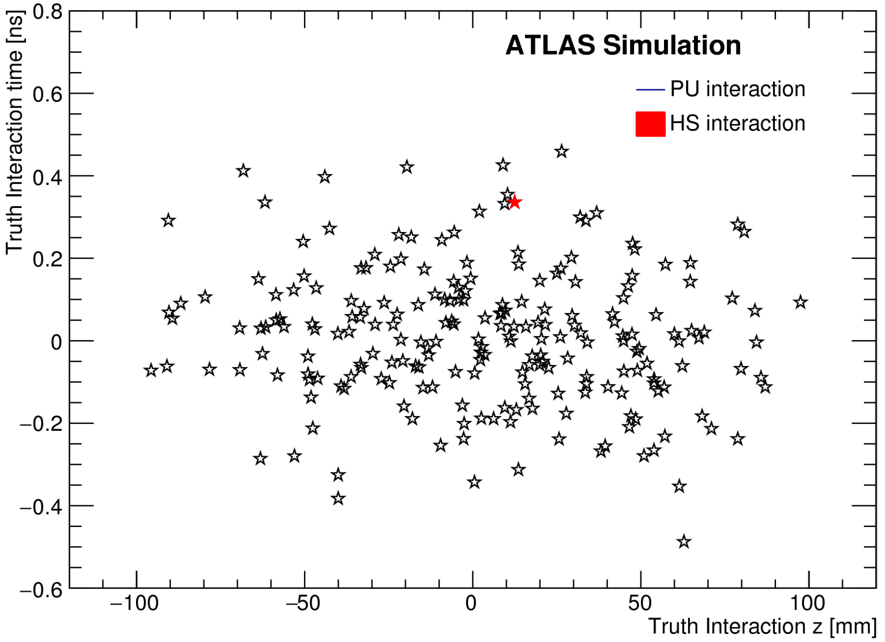
Final topo-cluster

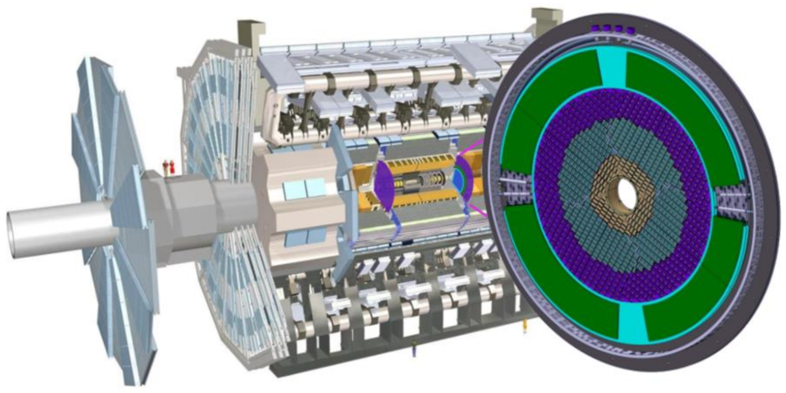
Particle timing and pile-up

CERN-LHCC-2020-007

- Signals from **out-of-time pile-up** expected to be inconsistent with the bunch crossing time
  - Resolution requirements: $\mathcal{O}$[ns]
    - Bunch spaced by 25 ns

- **In-time pile-up** also spread in time
  - Resolution required $\mathcal{O}$(10)- $\mathcal{O}$(100) ps
  - Dedicated detector planned for HL-LHC, to discriminate tracks from different vertices based on timing (High-Granularity Timing Detector)
  - In the current detector, timing is measured by the ATLAS calorimeters





Calorimeter time measurement

- Time measured by both the Liquid Argon (LAr) Calorimeter (EM and HAD end-cap) and Tile Calorimeter (HAD barrel)
- Calorimeter signal is shaped and sampled at 40 MHz
  - 4 (7) samples for LAr (Tile)
- Detected time and energy extracted optimal filtering algorithm

$$A = \sum_{i=1}^{n_{\text{samples}}} a_i S_i,$$

$$t = \frac{1}{A} \sum_{i=1}^{n_{\text{samples}}} b_i S_i$$

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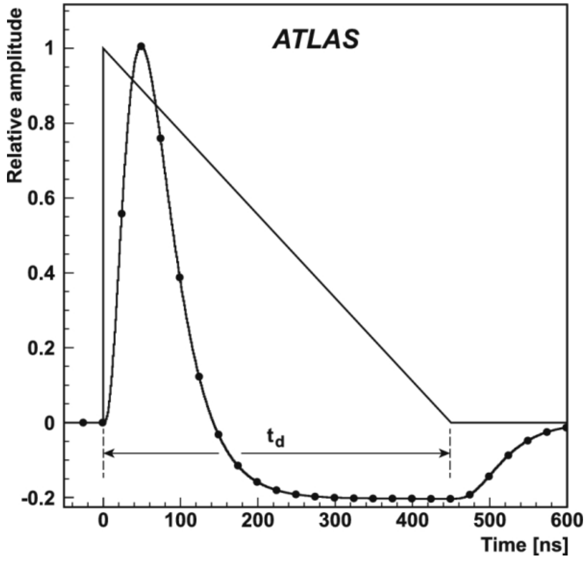
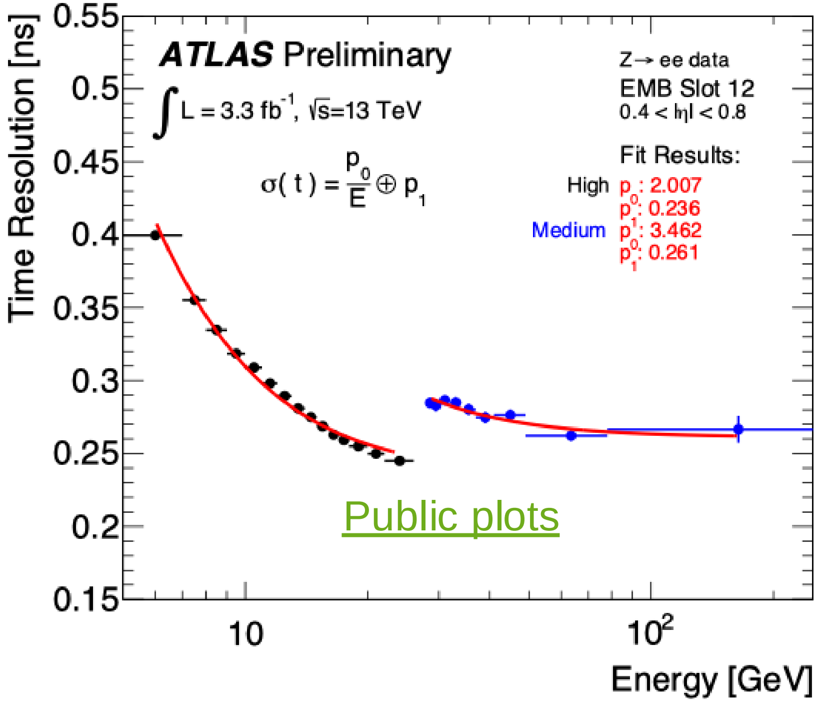
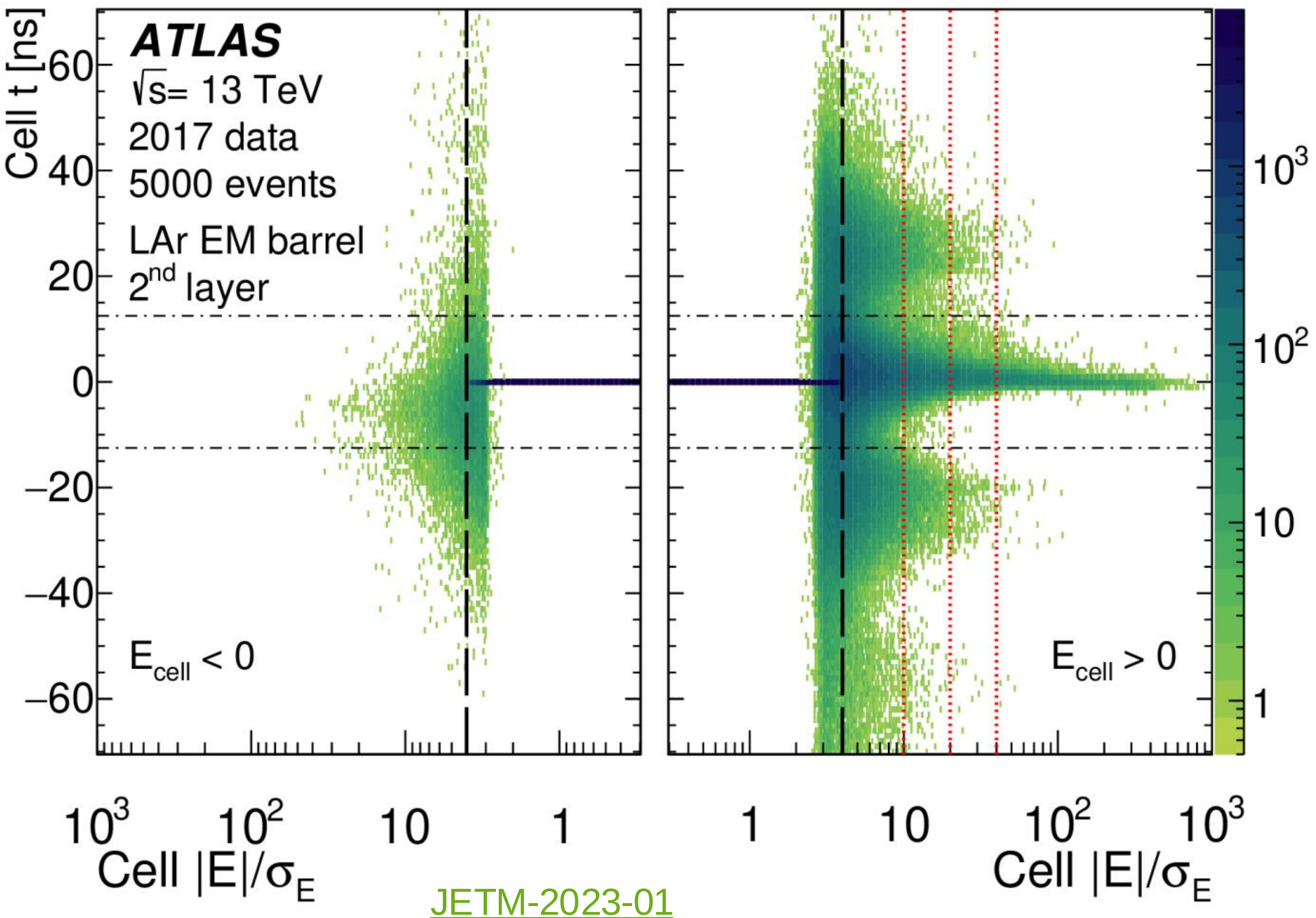




Public plots

The cell time is only measured if the detected energy is above a threshold ($3\sigma_{\text{noise}}$) otherwise, $t = 0$ is stored.

Calorimeter cell time in Run 2



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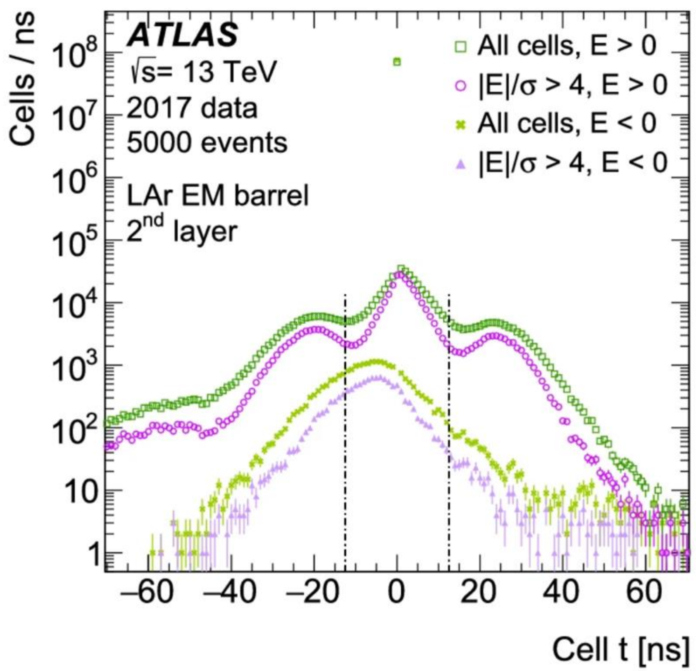
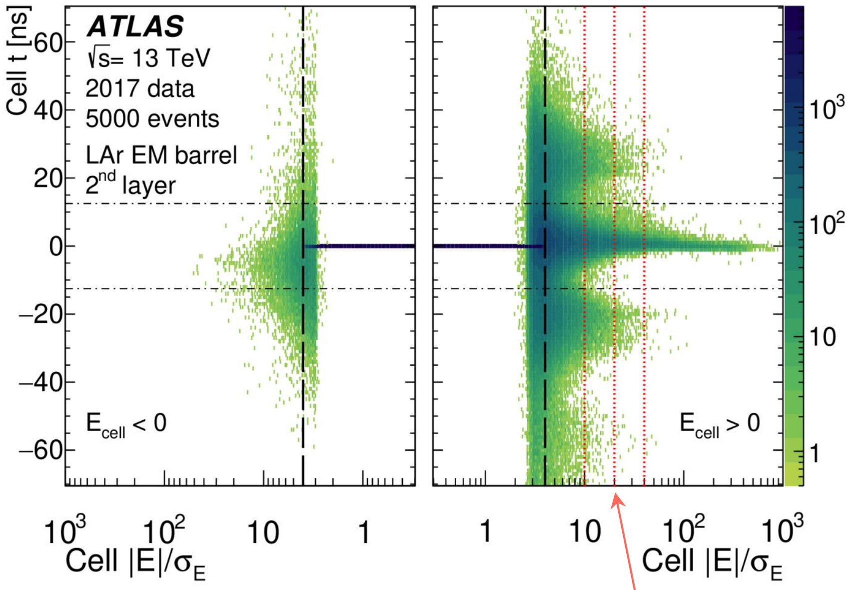


Time resolution depends on the cell signal-to-noise ratio

- Time is usable for energetic enough signals

Timing in topo-clustering: the *time cut*



$$\begin{cases} |E|/\sigma_E > 4 \\ |t_{\text{cell}}| \leq 12.5 \text{ ns} \end{cases} \quad \text{OR} \quad |E|/\sigma_E > X_{\text{UL}}$$

$$X_{\text{UL}} = 10,\ 20,\ 40$$

New topo-cluster seed requirement

- Time resolution too poor at lower $|E|/\sigma_{\text{noise}}$

$$|E|/\sigma_E > 4 \quad \Rightarrow \quad \begin{cases} |E|/\sigma_E > 4 \\ |t_{\text{cell}}| \leq 12.5 \text{ ns} \end{cases}$$

What if $|E|/\sigma_{\text{noise}} > 4$ but $|t|>12.5$ ns?

- Can be clustered as neighbour → Seed cut
- Vetoed from the cluster → Seed Extended cut

Avoid rejecting phase space sensitive to Beyond the Standard Model signals (*Long-Lived Particles*)

- Turn off the time cut if E/sigma is above a certain **Upper Limit** (xUL)

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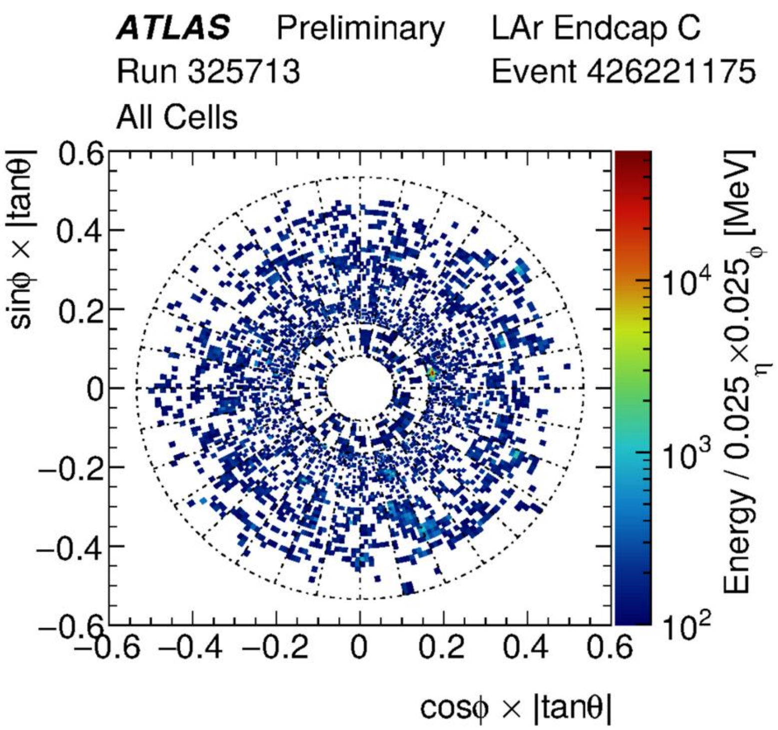
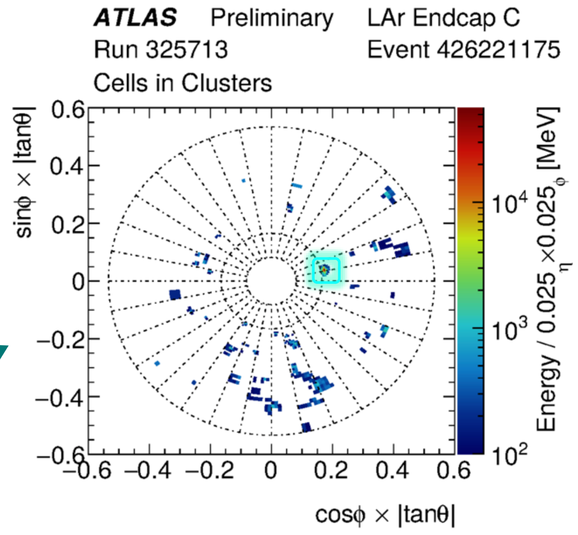
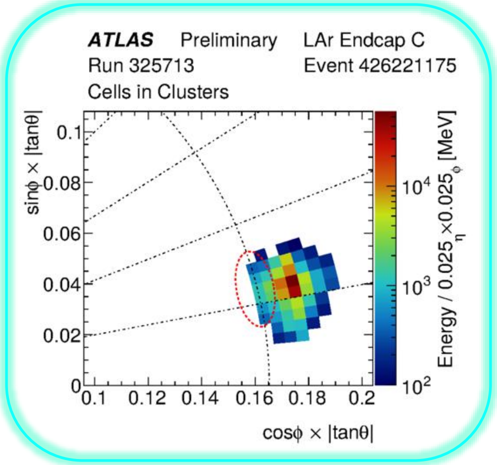
The *time cut*: an example

LaR public plots

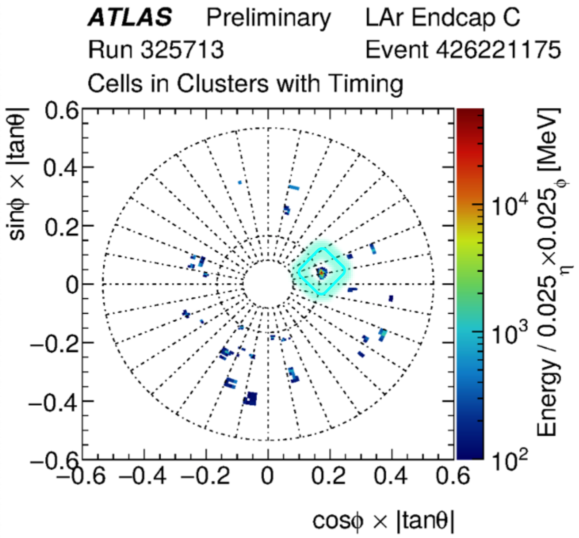


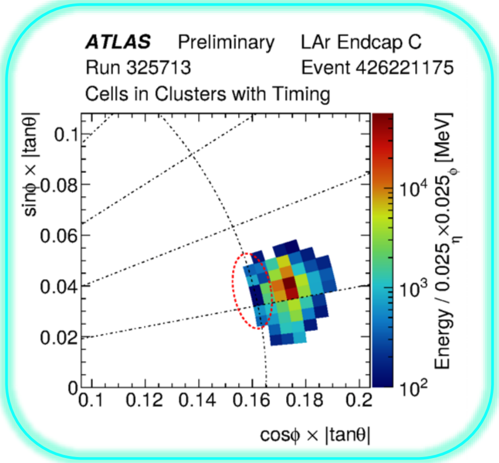
standard
topo-clustering





topo-clustering
with time cut
(Seed Extended
+ UL 20)





- Spurious contributions are removed
- Signal cluster becomes cleaner

Quantifying pile-up suppression

Reconstructed topo-cluster timing:

- weighted average of cell timing for cells belonging to the cluster
- shoulders showing out-of-time pileup very much reduced

Multiple options taken into consideration

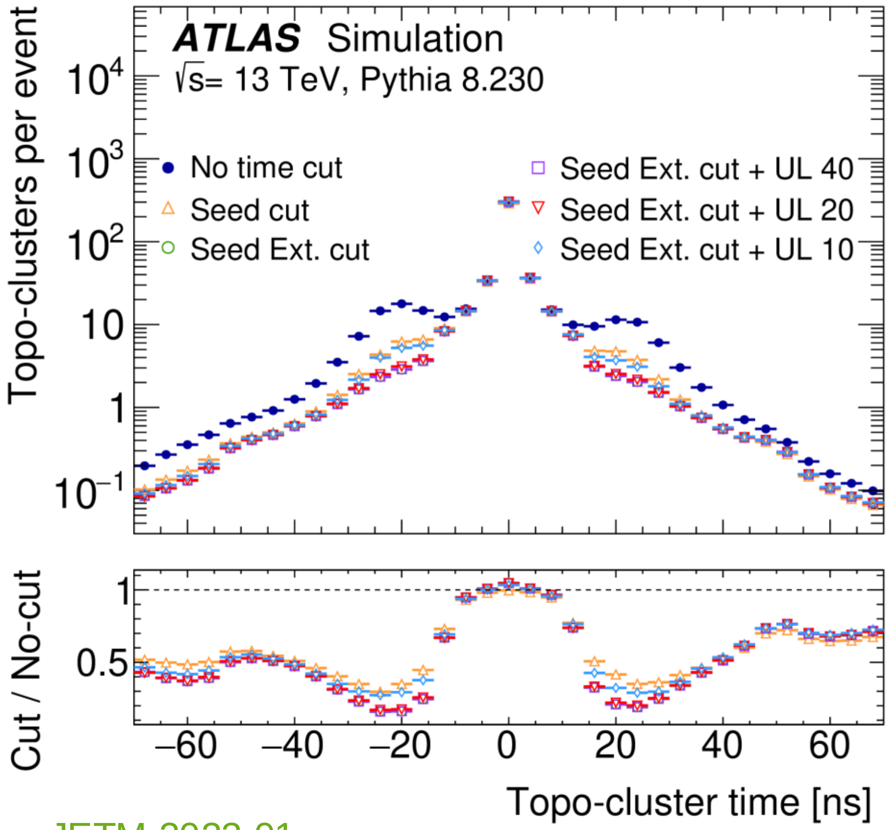
$$\begin{cases} |E|/\sigma_E > 4 \\ |t_{\text{cell}}| \leq 12.5 \text{ ns} \end{cases} \quad \text{OR} \quad |E|/\sigma_E > X_{\text{UL}}$$

$$X_{\text{UL}} = 10,\ 20,\ 40$$

What if $|E|/\sigma_{noise}$ > 4 but |t|>12.5 ns?

- Can be clustered as neighbour ➞ Seed cut
- Vetoed from the cluster ➞ Seed Extended cut

Di-jet simulated events, 2017 pile-up conditions



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Quantifying pile-up suppression: jets

Truth jets built clustering stable particles in Monte Carlo (MC) simulation

- Particles from simulated hard-scattering events ⇒ **HS-truth jets**
- Particles from overlay in-time pile-up events ⇒ **IT-truth jets**
- Particles from overlay out-of-time pile-up events ⇒ **OOT-truth jets**

Reconstructed jets built from calorimeter topo-clusters

- Matched to truth jets

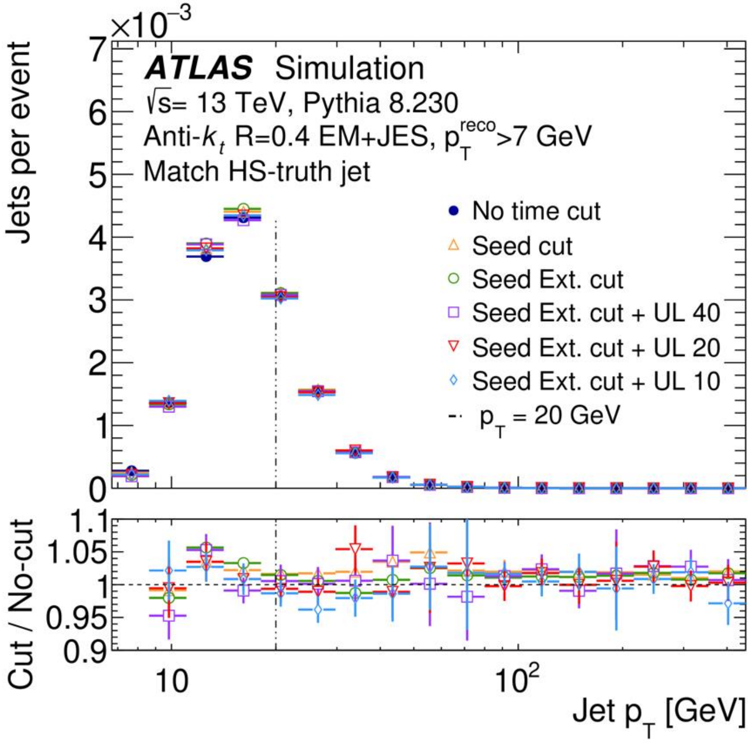
$$\Delta R(j_r, j_t) < 0.3$$

$$\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

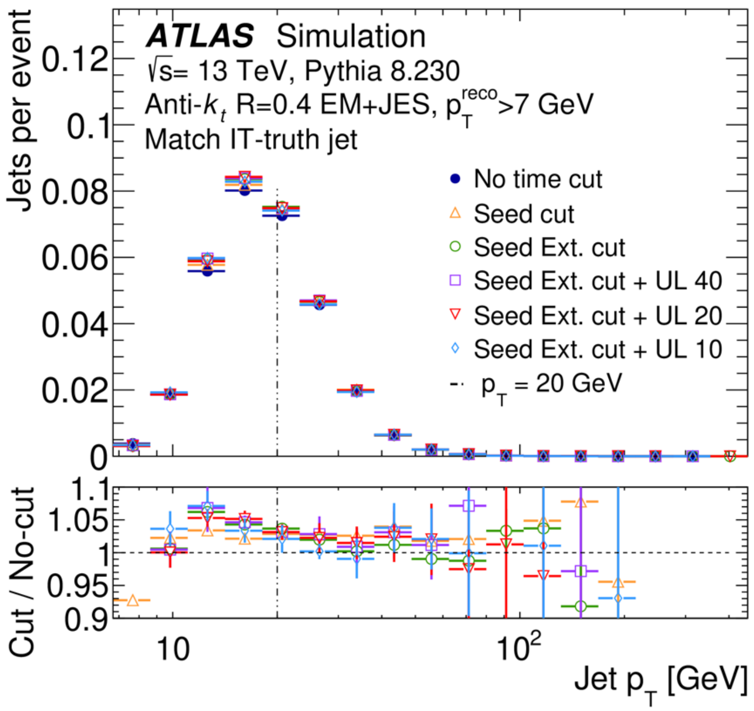
  - First check for matching against HS-truth jets
  - If none found, match IT-truth and OOT-truth

Quantifying pile-up suppression: reco jets

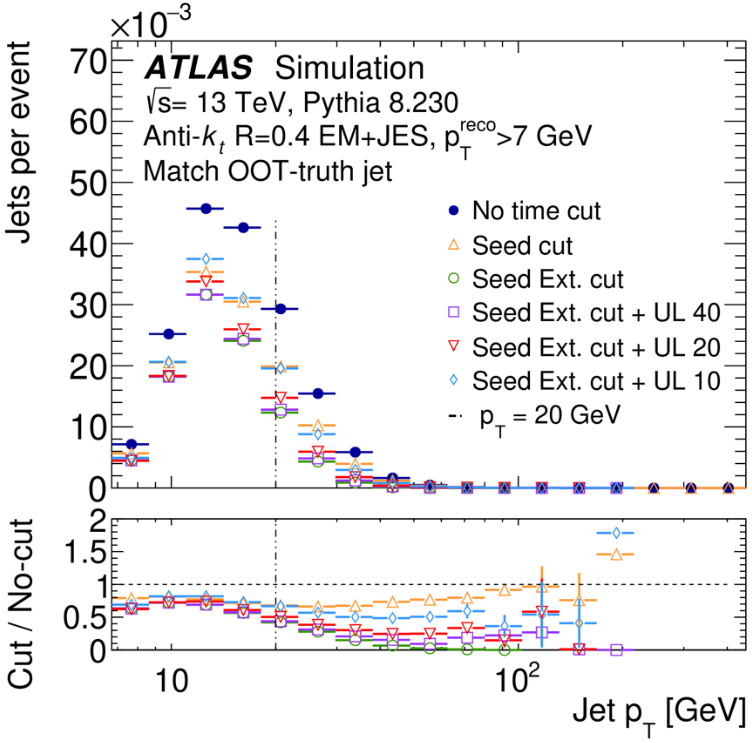
❖ Hard-scattering (signal) jets



❖ In-time pile-up jets



❖ Out-of-time pile-up jets



Very large reduction in jets matching OOT-truth jets

- ➢ Effect increases with pT
- ➢ Fairly stable across the detector

Seed cut and UL10 bring back too much pile-up

- ➢ Preferred option: Seed Extended + Upper Limit 20

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Global effects of pile-up suppression

- ATLAS topo-clusters are input to the reconstruction of electrons, photons and τ-leptons, in addition to jets
    - EM clusters also suffer from out-of-time pile-up

- Time cut improves overall ATLAS dataset size, thanks to topo-clusters wide usage

Size variation	Data	MC
ATLAS event	-6.1%	-7.1%
Topo-clusters	-17%	-17%
Particle-flow objects	-18%	-18%
τ-leptons	-8.2%	-6.8%
Electrons / Photons	-7.8%	-8.6%

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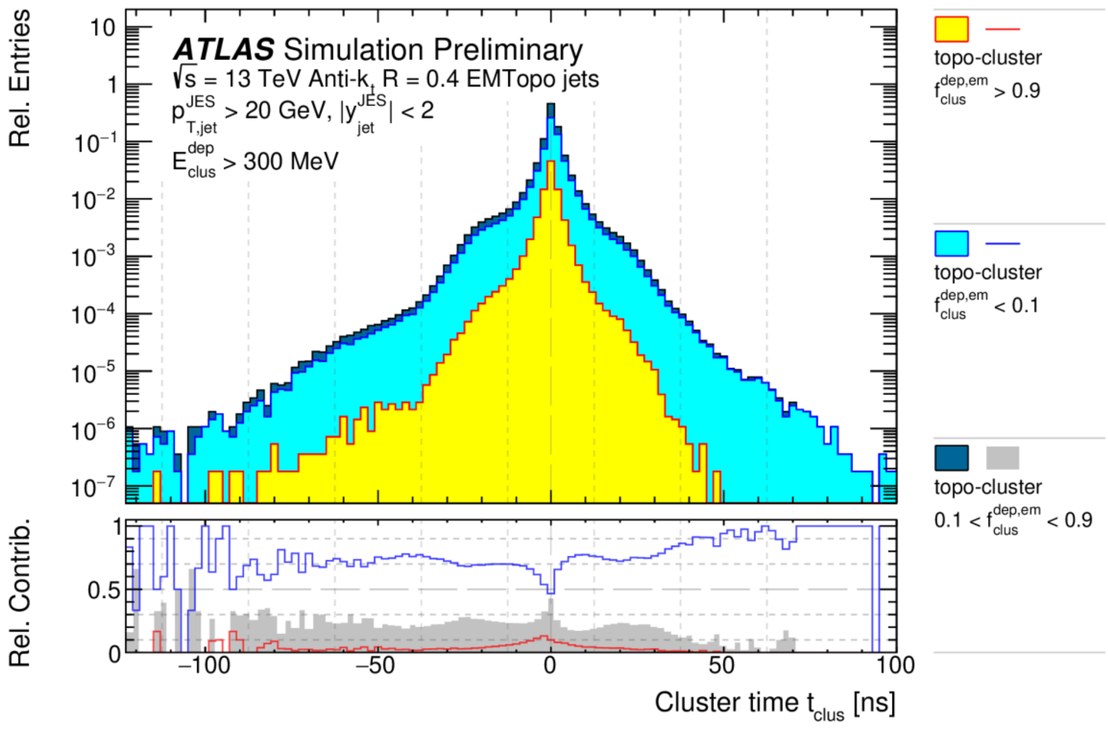


Conclusions

Applying a timing selection to ATLAS calorimeter signal reconstruction has proven a powerful pileup suppression tool

- The **Seed Extended + Upper Limit 20** cut has been set as ATLAS default for Run 3

What's next?

- Further studies are needed to adapt this concept to the HL-LHC upgraded detector and signal reconstruction

- Hadronic signals need to be calibrated
    - Topo-cluster response found to depend on timing
    - A Machine-Learning based topo-cluster calibration could handle the extra variable

Back up

ATLAS EXPERIMENT

MAX-PLANCK-INSTITUT FÜR PHYSIK

Calorimeters: a reminder

A **calorimeter** is a type of detector that measures the energy of particles.

- Particles enter the calorimeter and initiate a **particle shower** in which their energy is deposited in the calorimeter, collected, and measured.

Types of calorimeters

- **Electromagnetic calorimeter** (ECAL) ➝ designed to measure the energy of particles interacting primarily via EM interaction
  - Characterized by the **radiation length**
  - Tend to be 15–30 radiation lengths deep
- **Hadronic calorimeter** (HCAL) ➝ designed to measure particles that interact via the strong nuclear force
  - Characterized by the **nuclear interaction length**
  - Tend to be 5–8 nuclear interaction lengths deep

- **Sampling calorimeter** ➝ the material that produces the particle shower is distinct from the material that measures the deposited energy. Typically the two materials alternate.
- **Homogeneous calorimeter** ➝ the entire volume is sensitive and contributes a signal

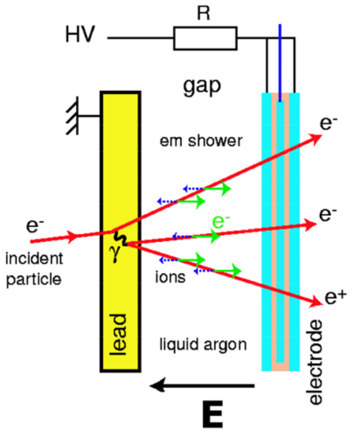
Calorimeters in ATLAS

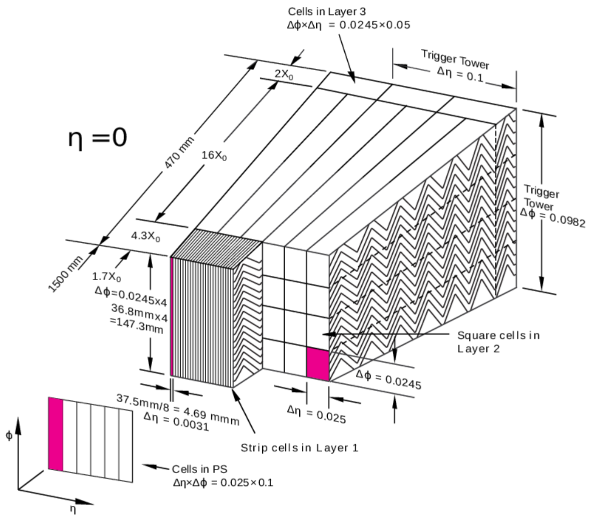
Electromagnetic - Lar

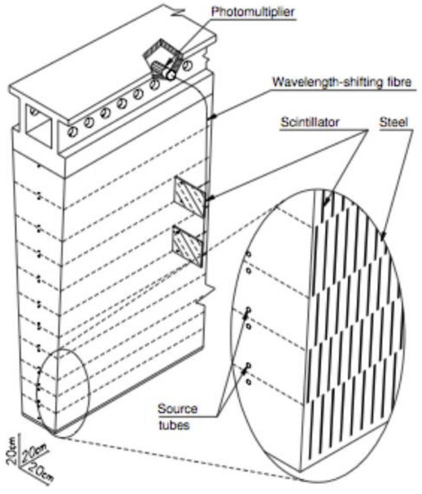
- Liquid argon as detection medium
- Lead as absorber
- Charged particles generate electromagnetic showers
- Electric field captures free electrons → signal pulse

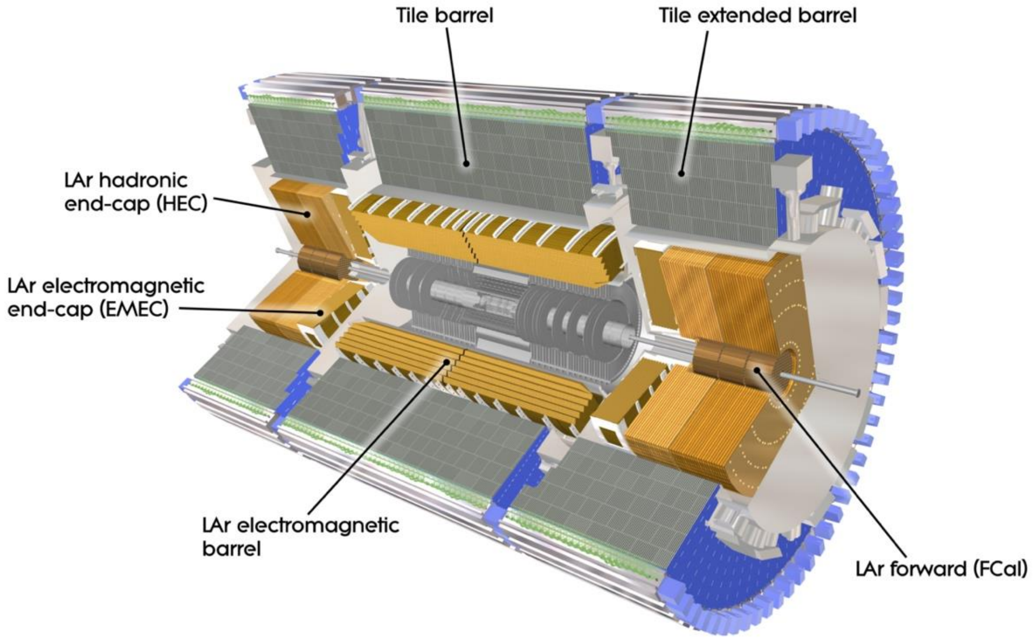
Hadronic – TileCal

- Scintillating tiles
- Iron to absorb the energy
- Energetic hadrons interact with the tiles light generation
- Photomultipliers transform the light in an electrical signal

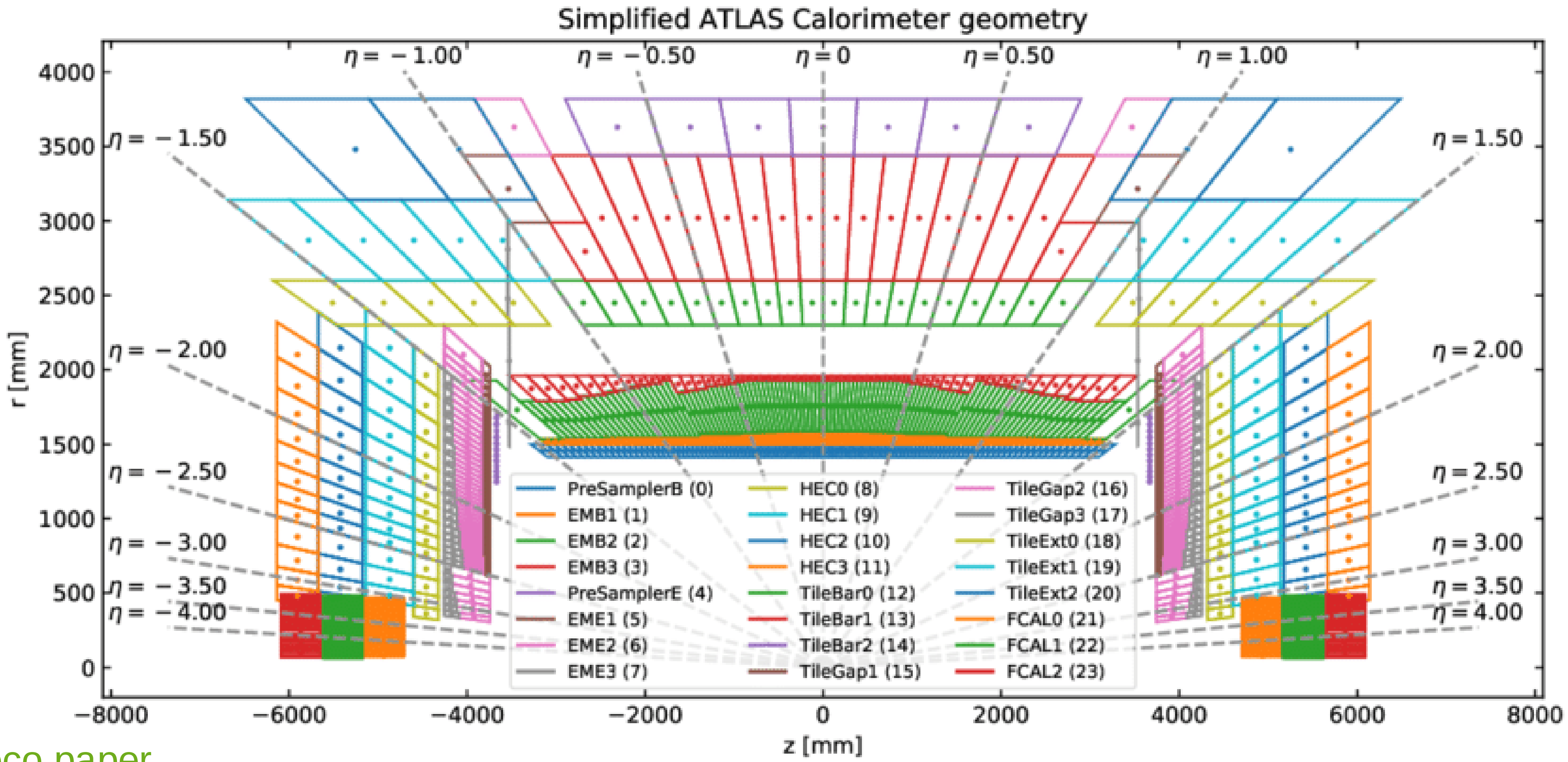








Simplified geometry of the ATLAS Calo system



[Track reco paper]

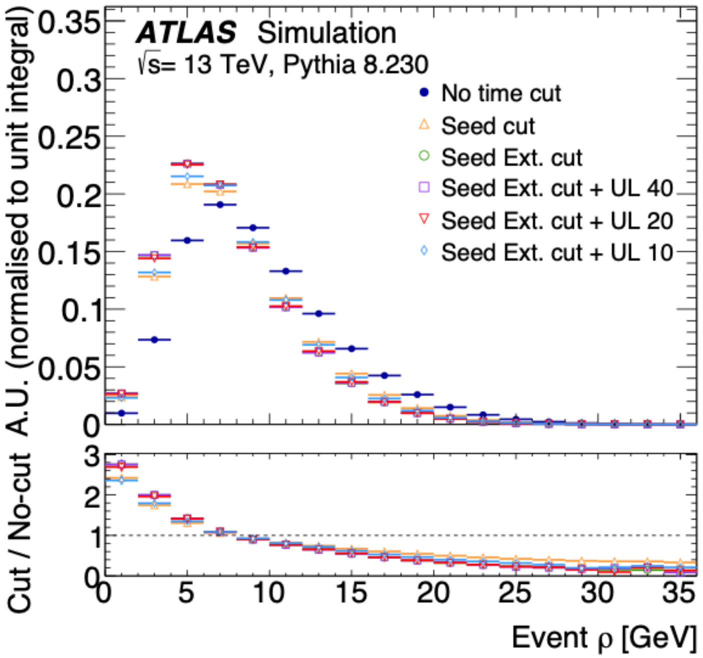
Quantifying pile-up suppression: event ρ

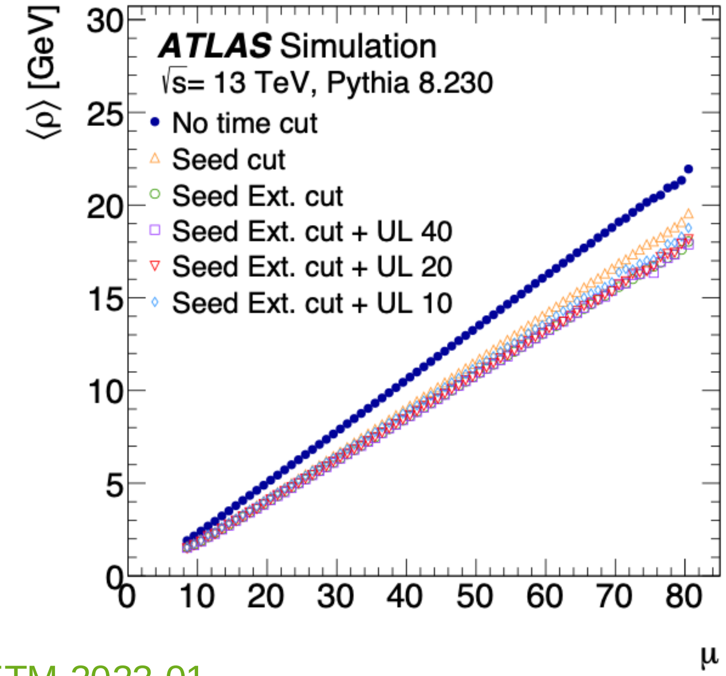
- “Event ρ” = Topo-cluster median pT density deposited by pile-up
  - Overall smaller and reduced dependence on the average number of interactions per bunch crossing (μ)

$$\rho \; = \; \text{median}\left[\left\{\frac{p_{Tj}}{A_j}\right\}\right]$$

p_{Tj}: jet p_T (k_t jets)

A_j: jet area from ghost-association





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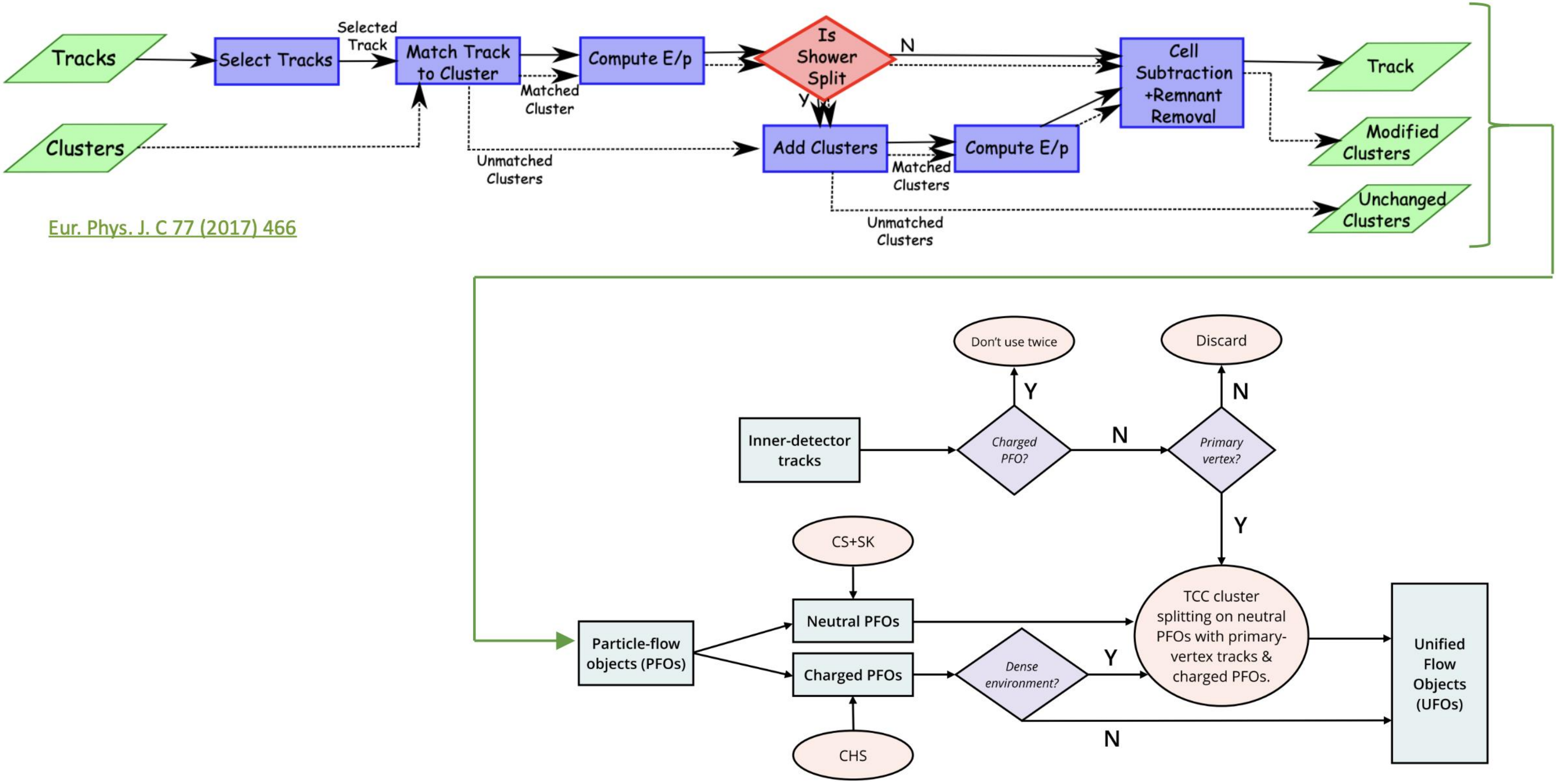

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