Improvements for reconstruction of physics objects with HL-LHC detector upgrades for ATLAS and CMS

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INTRODUCTION

- The development of Phase II reconstruction is a **work in progress** task for both ATLAS and CMS.

- It will need to:
  - cope with the **new HL - LHC conditions** (higher <PU> , higher luminosity);
  - exploit the **improved** (extended coverage, new layers, new materials) or **completely new** detectors;
  - fully explore **the HL-LHC physics potential**;

- The **minimal goal** is to maintain the same performance retained during Phase I.

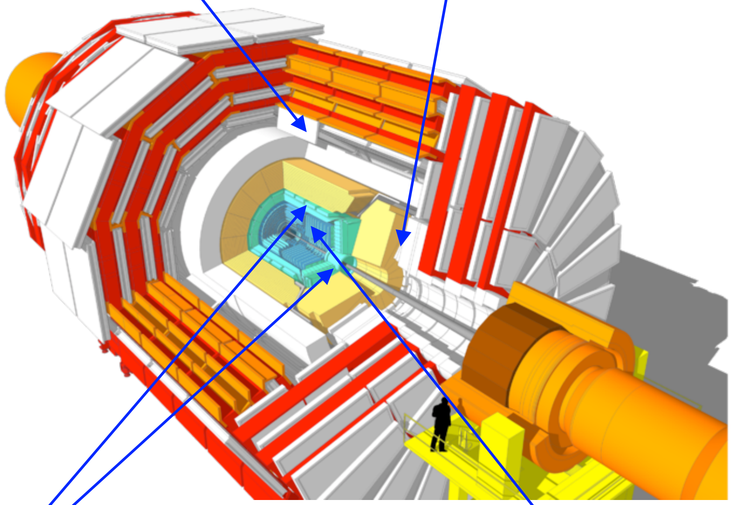
- In this talk the focus will be on the latest updates on reconstruction (trigger and offline) for both ATLAS & CMS.

- For further details on trigger performance @ Phase II for both ATLAS & CMS see Swagata's talk.

CMS & ATLAS – Phase II Upgrade

Improved muon system
new RPC coverage (1.5 < |η| < 2.4)
new electronics
GEM up to |η| = 2.8

New endcap calorimeters (HGCAL)
high granularity
4D showers



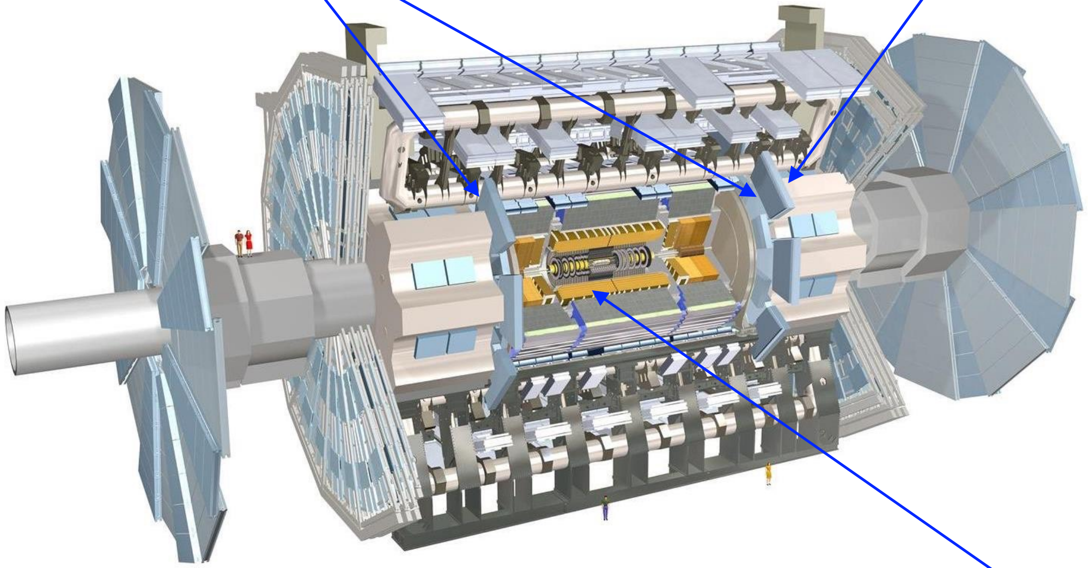
New precision timing detector
Timing resolution of 30-40 ps for MIPs
full coverage of |η| < 3.0

New inner tracker
all silicon tracker
track-trigger @ 40 MHz
coverage to |η| < 4

Upgrade to trigger and DAQ
L1 rate increased to 750 kHz High Level trigger rate to 7.5 kHz Track information at L1

Improved muon coverage and trigger
new RPCs in innermost layer
new MDT readout
new small wheels (already for Run 3)

New endcap high-granularity timing detector
30 ps/track in 2.4 < |eta| < 4.0
resolution of time dimension of beam spot



New inner tracker
all silicon tracker
coverage to |η| < 4

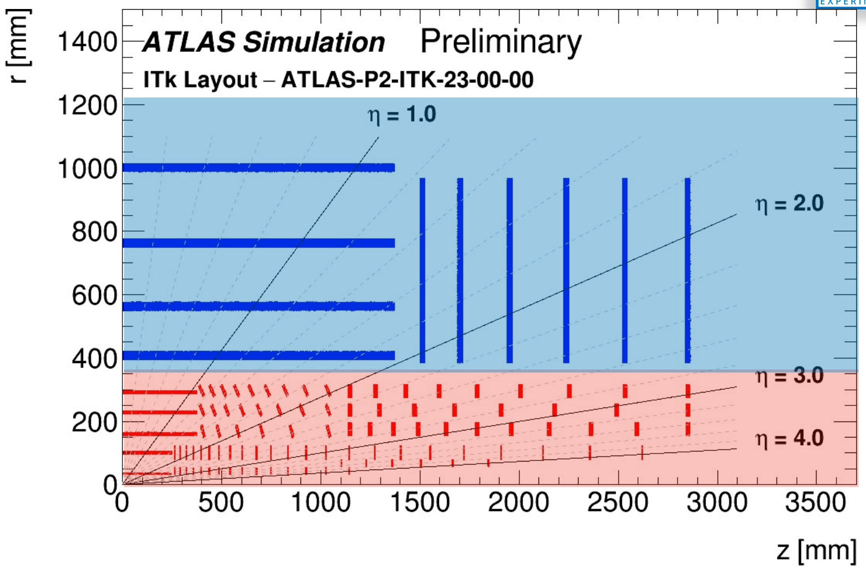
Upgrade to trigger and DAQ
L1 rate increased to 1 MHz
High Level trigger rate to 10 kHz

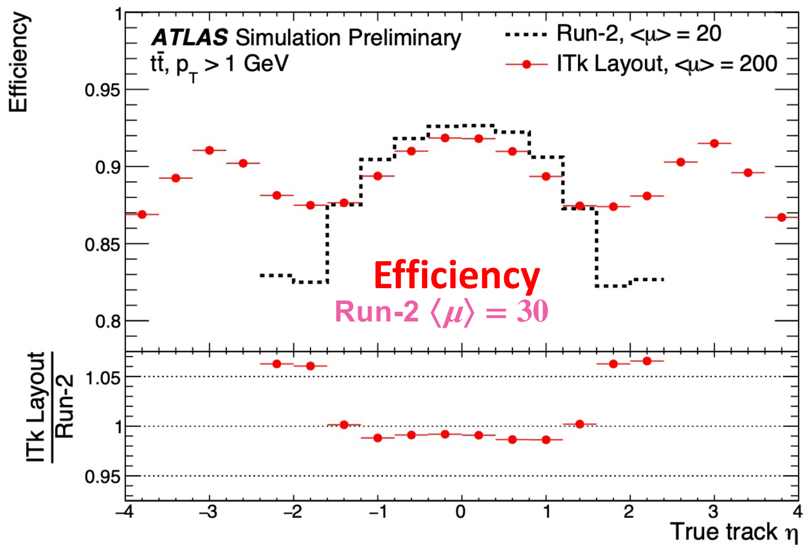
N.B. **not all** the planned upgrades to the detector are listed here

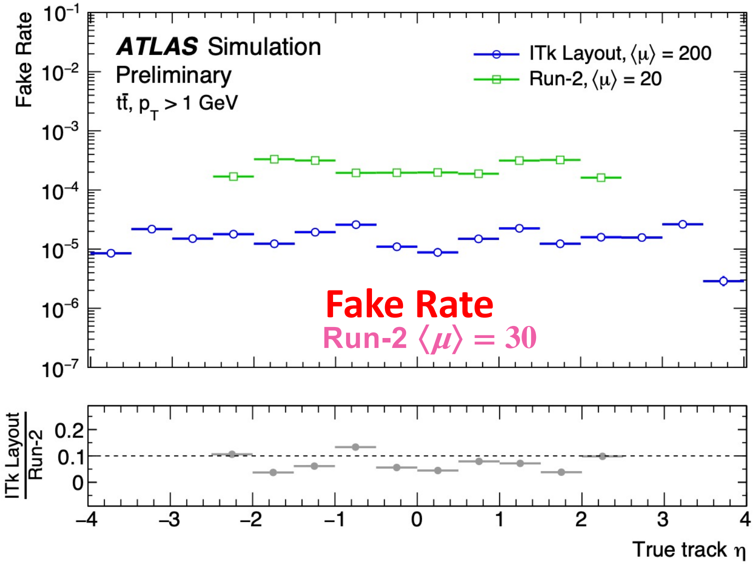
Complete replacement of current **ATLAS Inner Detector** for the **HL-LHC Finer granularity** and **improved radiation hardness** to cope with high fluences. Extended **forward pseudo-rapidity coverage** for increased tracking acceptance |η|<4.

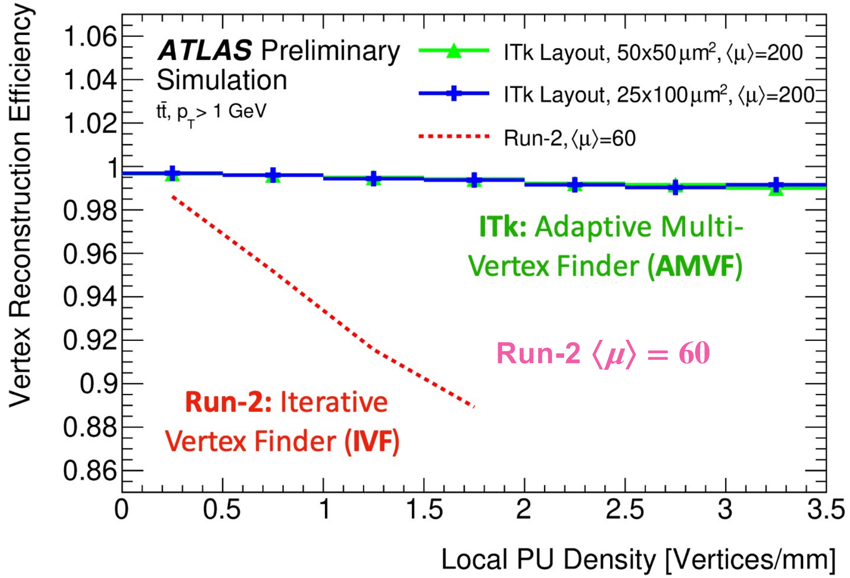
All-silicon design consisting of **inner pixel** and **outer strip sub-detectors.**

- **Tracking efficiency:** Comparable with Run-2 ID at <PU> = 20.
- **Tracking fake rate:** Excellent improvements over Run-2 ID, even with x10 <PU>.
- **Vertexing:** significant improvements over Run-2 ID especially under high pile-up conditions.









HL-LHC $\langle\mu\rangle = 200$

CMS DP-2021/013

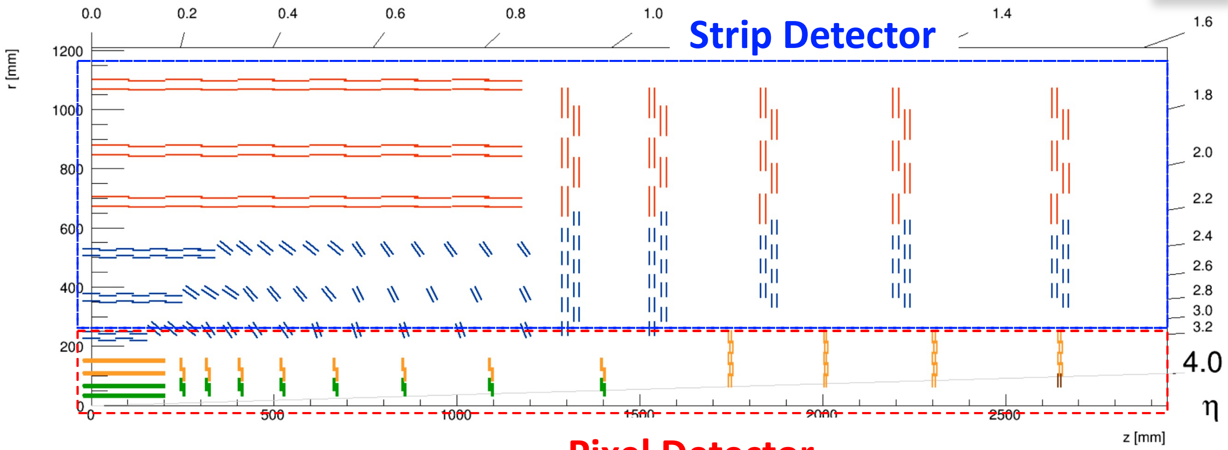
New CMS tracker with extended coverage (|η|<4) and increased number of layers.

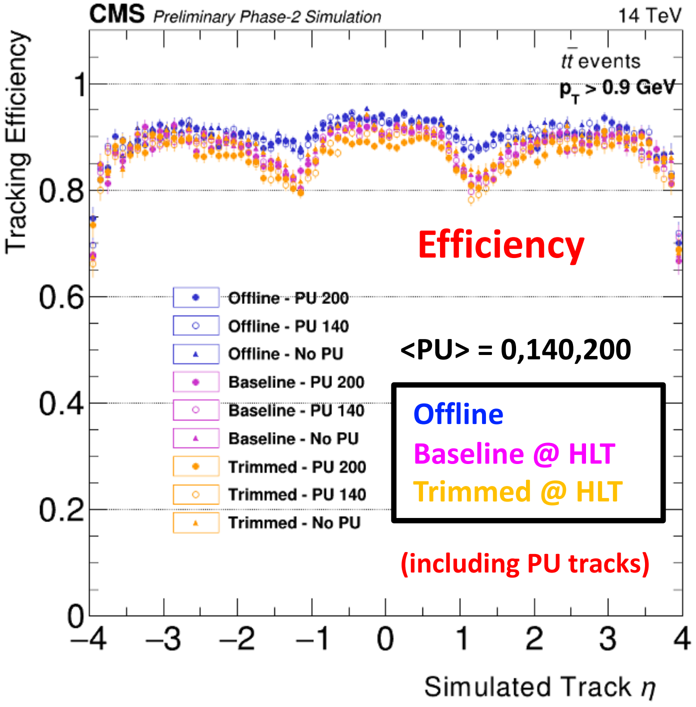
HLT and offline reconstruction are both based on an CKF iterative approach.

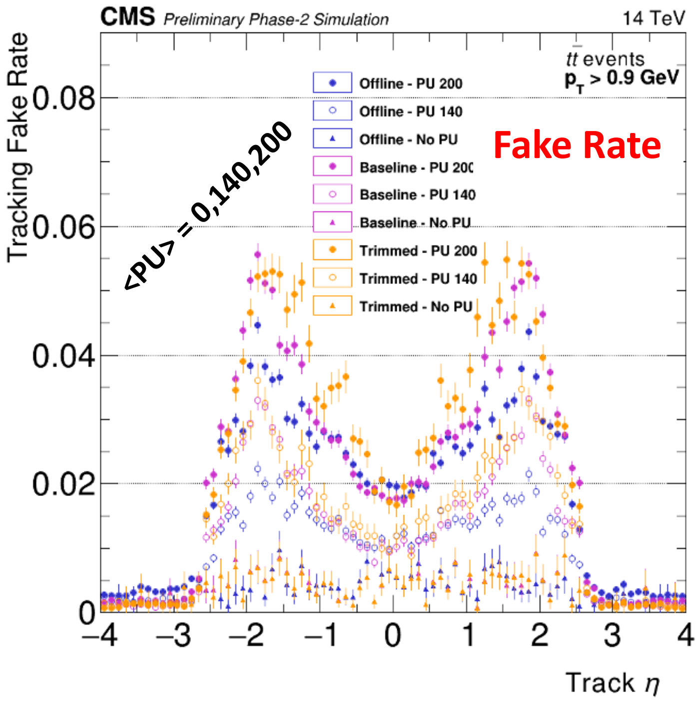
The HLT *baseline* reconstructions consists of **two iterations** with a factor 6 reduction of the execution time w.r.t. the offline.

Tracking efficiency & fake rate:

- Stable performance w.r.t. <PU>
- Compatible results for offline tracking and HLT tracking







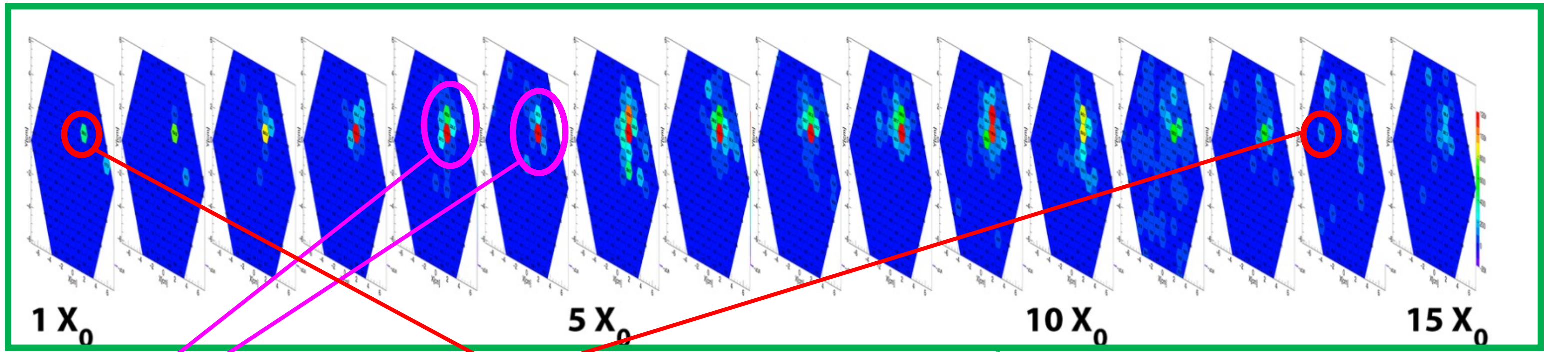
A *trimmed* configuration has been developed targeting a reduction in timing reconstruction reducing the tracking region around a collection of selected pixel vertices.

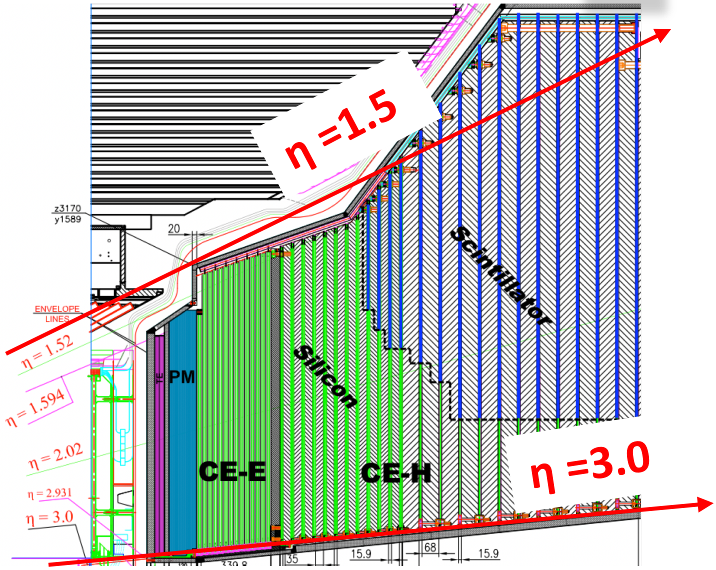
Performance w.r.t. *baseline* tracking are compatible while achieving a further 20-30 % reduction in timing.

NB. for all the studies following, if not stated differently, the *baseline* tracking configuration was used.

HGCAL: **a new imaging calorimeter (both hadronic & elettromagnetic)** with very fine lateral and longitudinal segmentation, and precision timing capabilities. **Completely new reconstruction needed.**

32 GeV electron



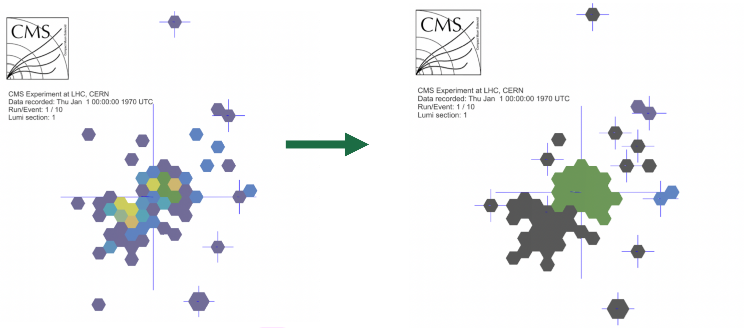


1.RecHits

Reconstructed hits: energy deposit in a sensor.

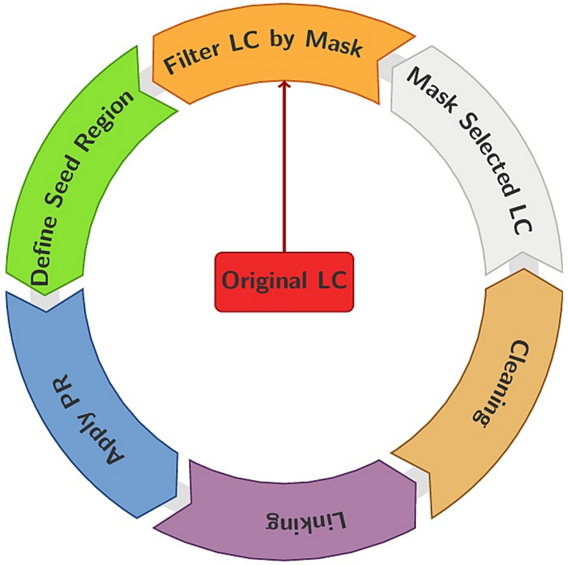
2. 2D Clusters

- 2D clusters (Layer Clusters): RecHits clustered on the same layer.
- **CLU**stering by **E**nergy (CLUE) algorithm. Fast. Using a concept of local energy density. Designed for high PUs. **GPU-friendly.**



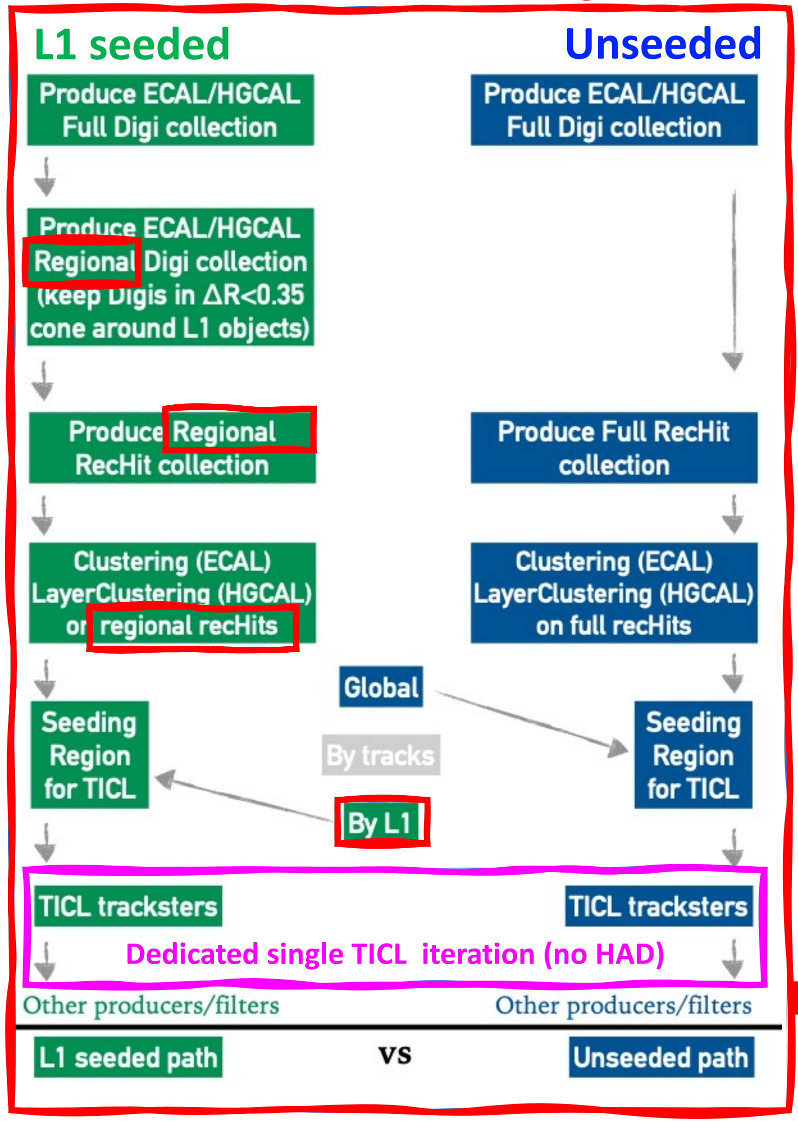
3.3D Clusters

- 3D clusters (tracksters): Layer Clusters from different layers linked.
- The **IT**erative **CL**ustering **framework (TICL)**
  - **Modular;**
  - **Flexible/efficient/versatile;**
  - **Iterative:**
    1. Track seeded EM
    2. Unseeded EM
    3. Track seeded HAD
    4. Unseeded HAD



Electrons and **photons** deposit almost all of their energy in the ECAL (barrel) or in the EM region of the HGCAL (endcap).

ECAL / HGCAL clustering



Two options for ECAL/HGCAL clustering

L1 seeded or unseeded (full detector)

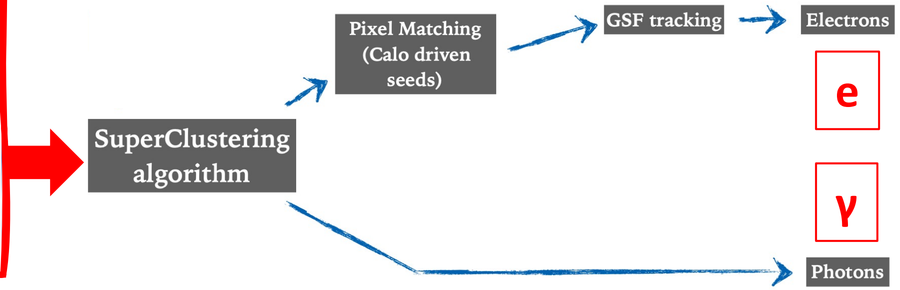
The seeded path allows a factor ~6 timing reduction:

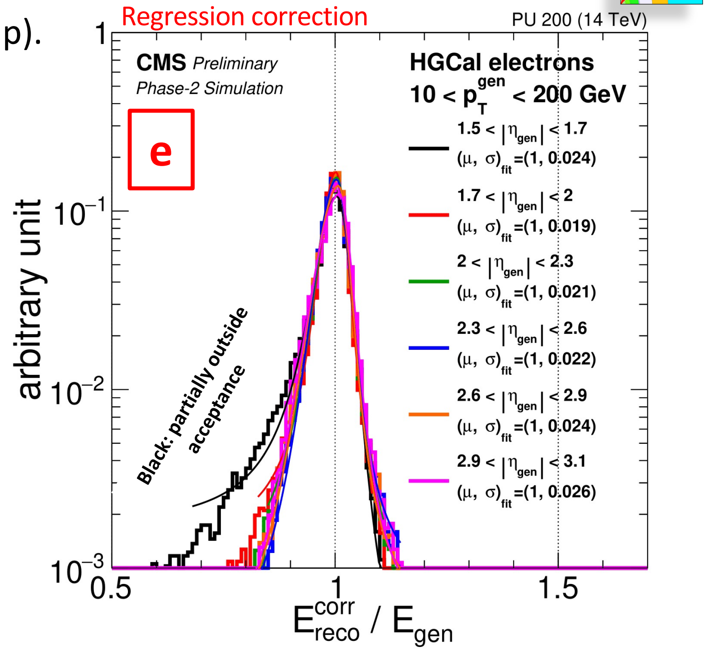
- Regional clusters/RecHits in both HGCAL & ECAL;
- TICL seeded by L1 objects.

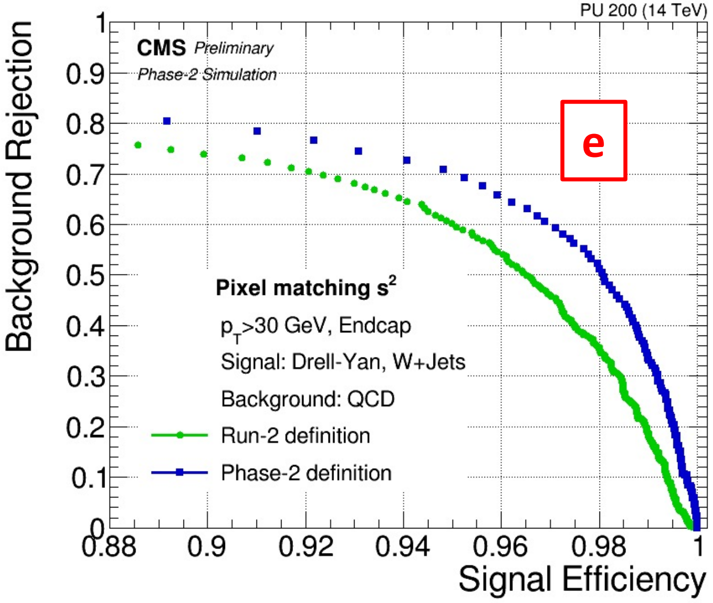
The same **SuperClustering (SC)** algorithm combines clusters in the ECAL and in HGCAL (flattened to 2D, 3D could be exploited in future).

After SC **photons** are ready. **Electrons** are further matched to pixel detector hits and fitted (GSF). Selected with a χ^2-like variable:

$$s^2 = \sqrt{\frac{(\Delta\phi_1)^2}{a^2_{\phi_1}} + \frac{(\Delta\phi_2)^2}{a^2_{\phi_2}} + \frac{(\Delta z/r_2)^2}{a^2_{z/r_2}}}$$



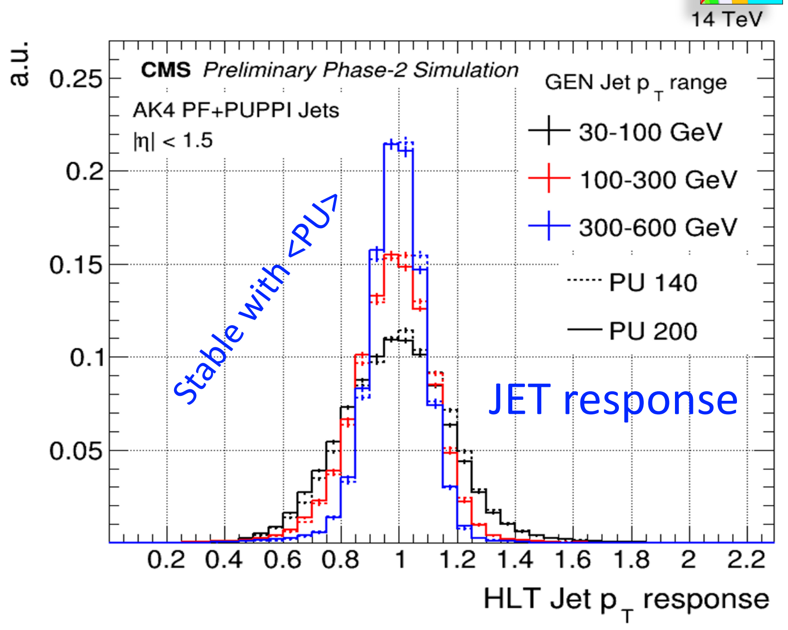


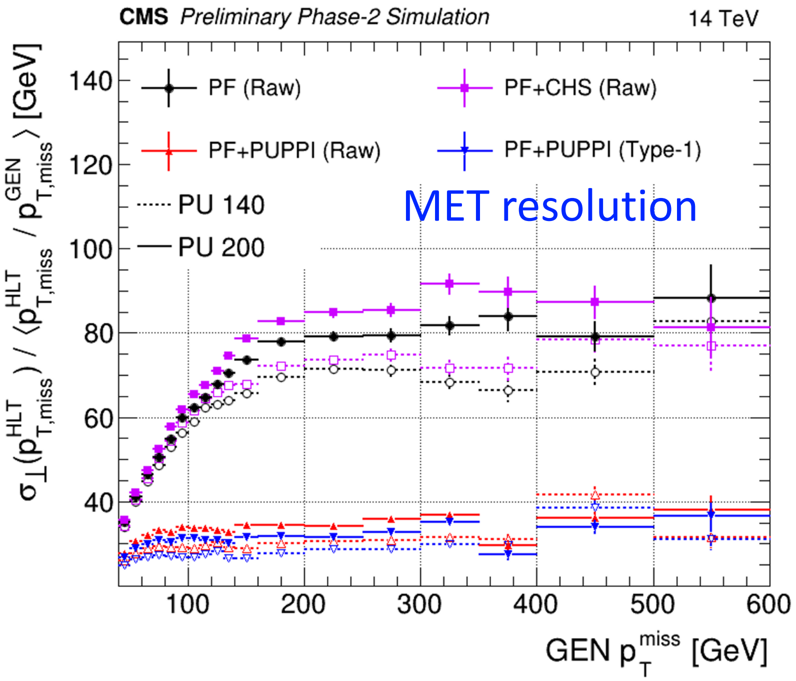


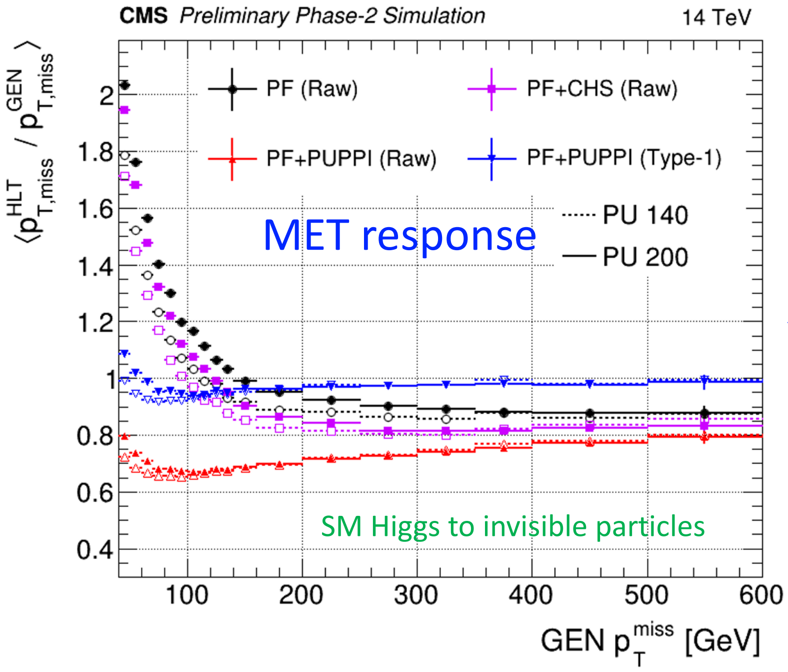
The reconstruction of **hadronic jets** and **global energy sums @CMS** is studied using the particle-flow (PF) paradigm: **full detector information** to define particle candidates.

For HL-LHC conditions to retain optimal performance achieved by complementing the PF with **PU-mitigation techniques:**

- **CHS**: removal of charged hadrons (CHs) coming from PU vertices
- **PUPPI**: CHS + p4-weighting of neutrals. **Particle level**: each particle has a weight /probability [0;1] for coming from the hard scattering.







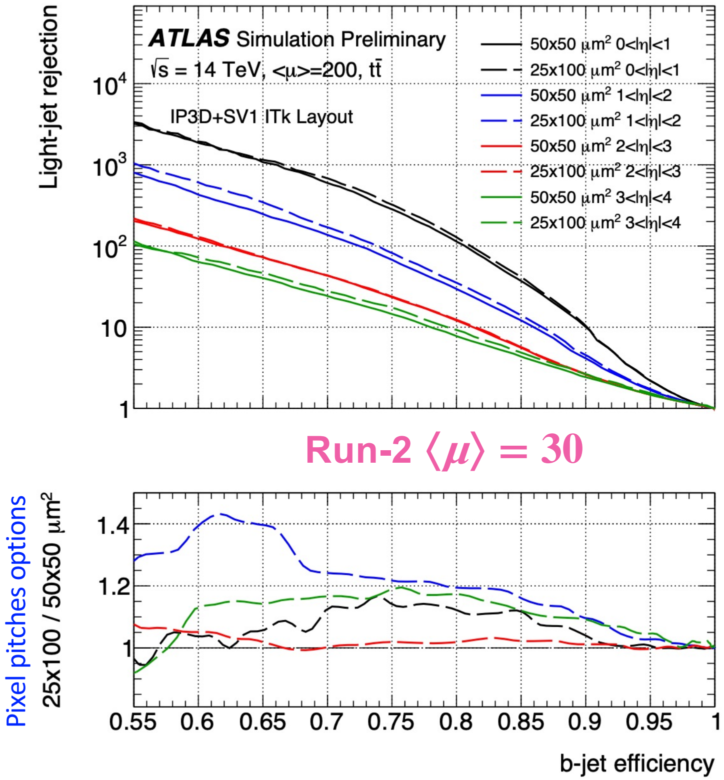
Missing Transverse Energy (MET)

- The PUPPI algorithm mitigates pile-up effectively (CHS not helping)
- Propagating the jet energy corrections to MET computations (*Type-1*)
  - MET response ⟶ 1
  - improvement in resolution

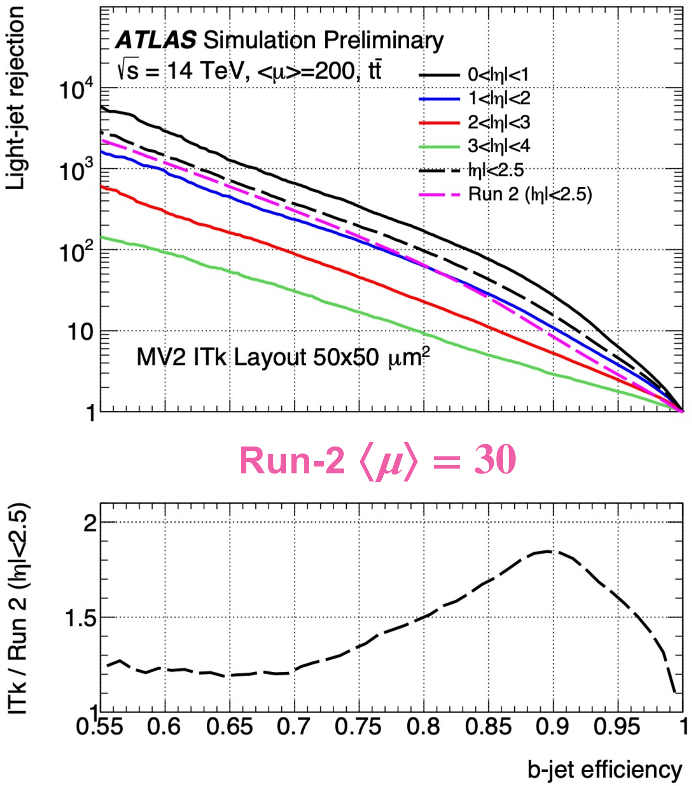
b quark jets identification (**b-tagging**) **@ ATLAS** is done with three taggers

- **IP3D :** (signed) impact parameter in 3D used as discriminant. Log-likelihood method per track.
- **SV1 :** based on Secondary Vertices reconstruction. Log-likelihood method. Uses the total invariant **mass**, the **energy** fraction, the **DeltaR** of PV-SV w.r.t the jet direction and the **number of tracks** as variables. It is used also associated to the IP3D tagger (IP3D+SV1) summing the weights.
- **MV2 :** multivariate algorithm based on a BDT combines inputs from SV1 and IP3D ⊕ jet properties (from JetFitter, not reoptimized, room for improvement)

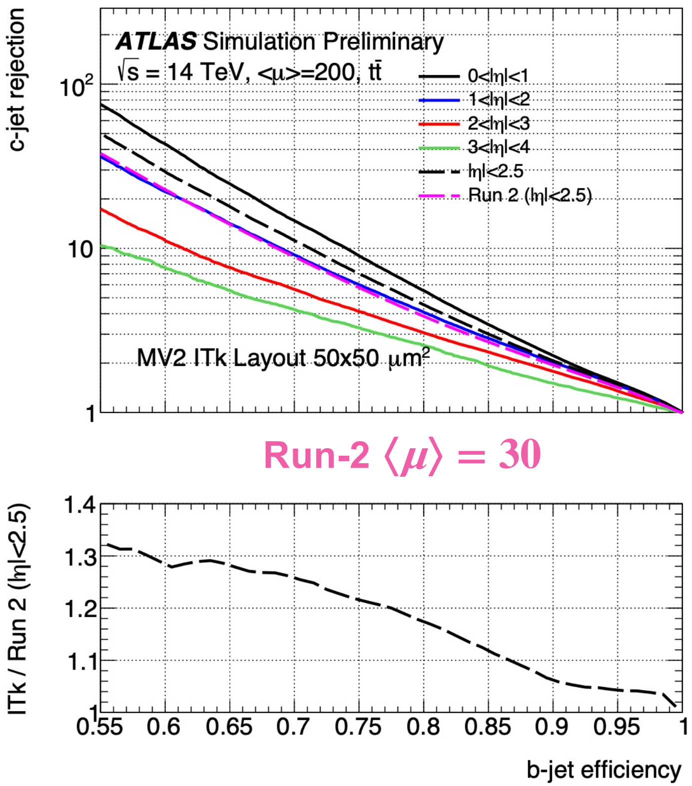
IP3D+SV1 (b vs light)



MV2(b vs light)



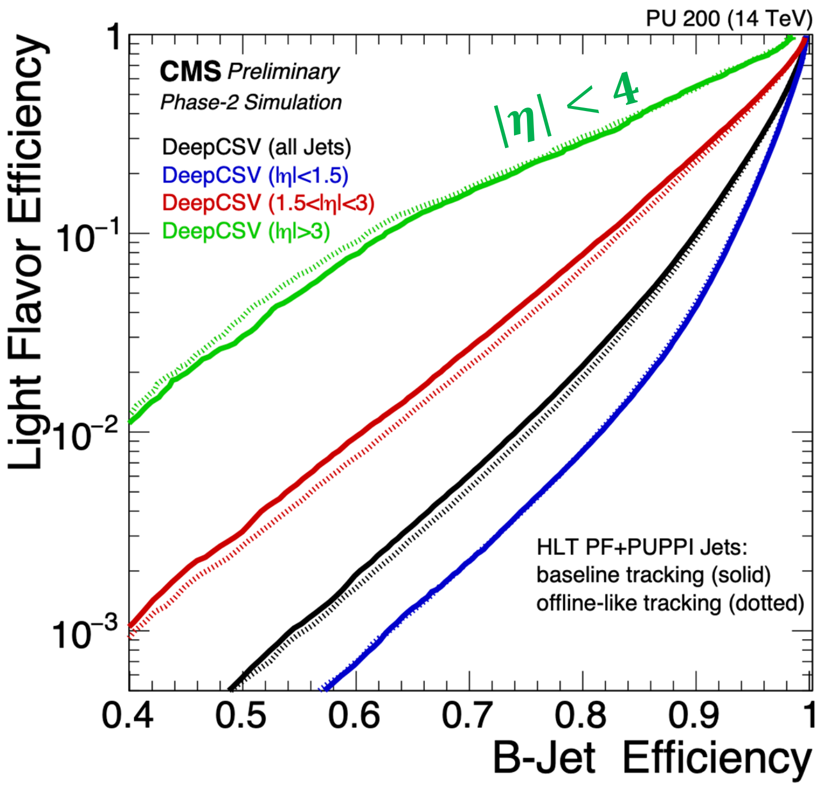
MV2(b vs c)

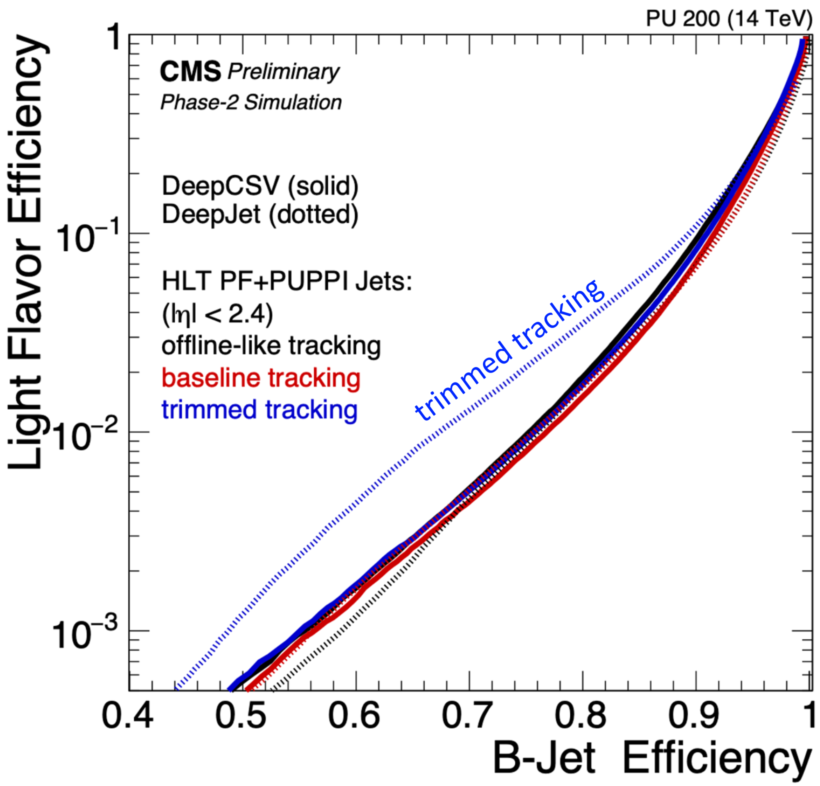


b-tagging@CMS is done with two taggers

- **DeepCSV:** NN architecture. **Inputs**: jets (*AK4* PF+PUPPI), tracks, and secondary vertex observables. **Outputs**: $p(b)$ & $p(c)$ & $p(\text{light})$. **HLT@Run2**.
- **DeepJet**. NN architecture: convolutional, recurrent, and fully connected layers. **DeepCSV Inputs ⊕ charged and neutral PF candidates**. Used offline. **First time tested at HLT**.

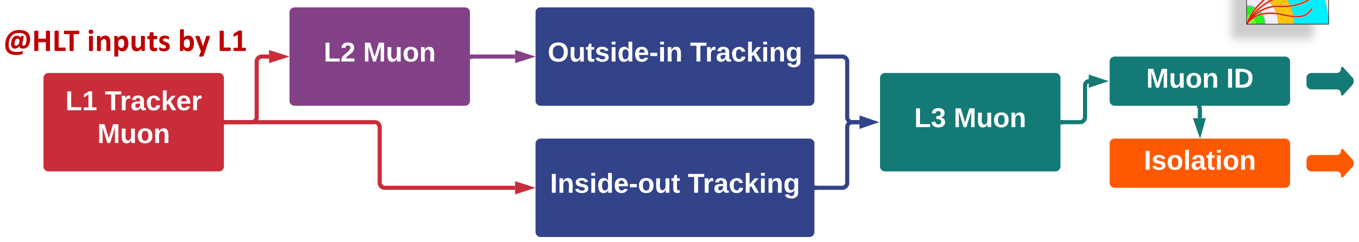
Extended coverage up to $|\boldsymbol{\eta}| < \mathbf{4}$ (includes HGCal)





N.B. DeepJet, while being the state of the art tagger, suffers from having its calibration derived from different reconstruction in the tracker and HGCAL. Room for improvement.

- At L1 trigger level in Phase II: L1 Muons + **new L1TkMuons** (muon system + tracker) used @ HLT.
- **L2 Muons** (*offline standalone muons*): muon system only muons ***@HLT***: compatible with a L1 Muon or L1TkMuon.
- **L3 Muons** reconstruct muons in the tracker and combine it with the muon system
  - ***Outside-in*** *(global muons)* L2 propagated onto the **outermost** tracker layer.
  - ***Inside-out*** *(tracker muons)* track extrapolated to muon system. ***@HLT:*** *L1TkMuons* used to select pixel ROIs.

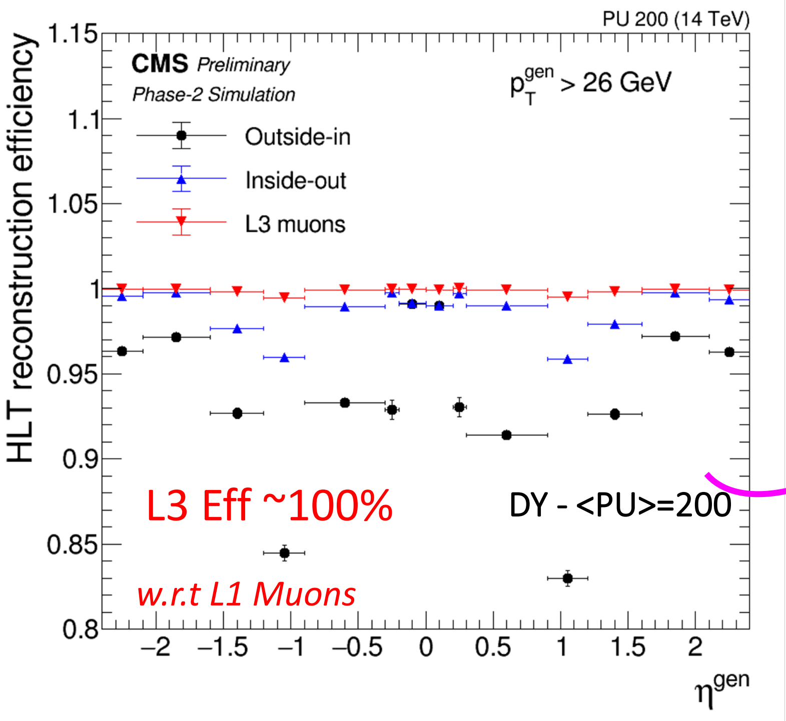


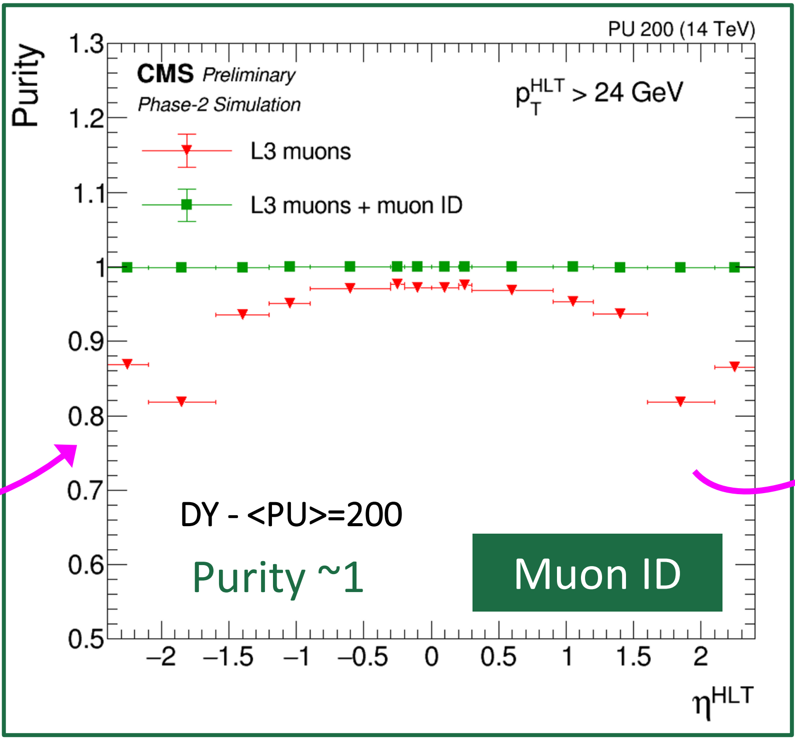
Muon ID

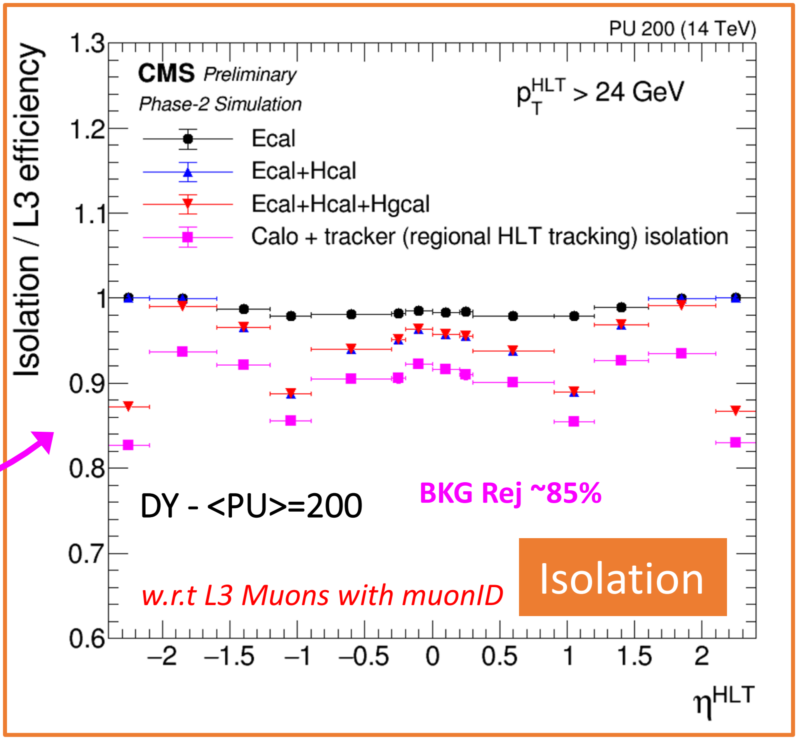
- Tracker muon.
- $\geq$ **6** OT layers $\oplus \geq$ **1** IT layer.
- If p_T>8 GeV, number of muon stations>1 (modulo detector geometry).

Isolation

- Suppress jet muons.
- **Barrel:** HCAL & ECAL clustering $\Delta R \leq 0.3$.
- **Edncap:** HGCAL, 2D clusters $\Delta R \leq 0.2$.
- **Tracker**: regional *baseline* tracking $0.005 \leq \Delta R \leq 0.3$.







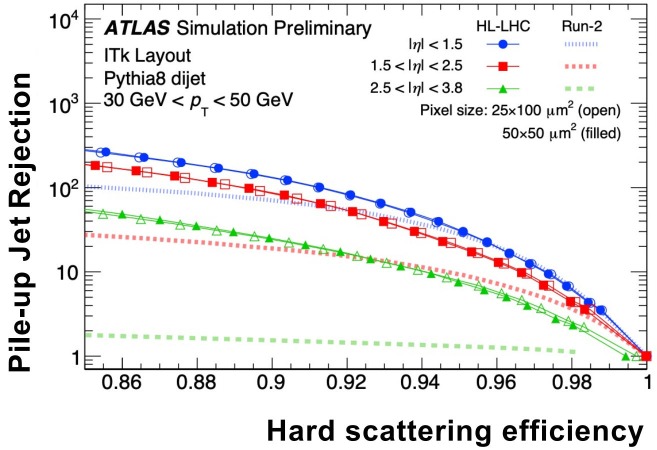
Pile-up jet rejection:

- $\mathbf{R_{pT}}$ discriminant:

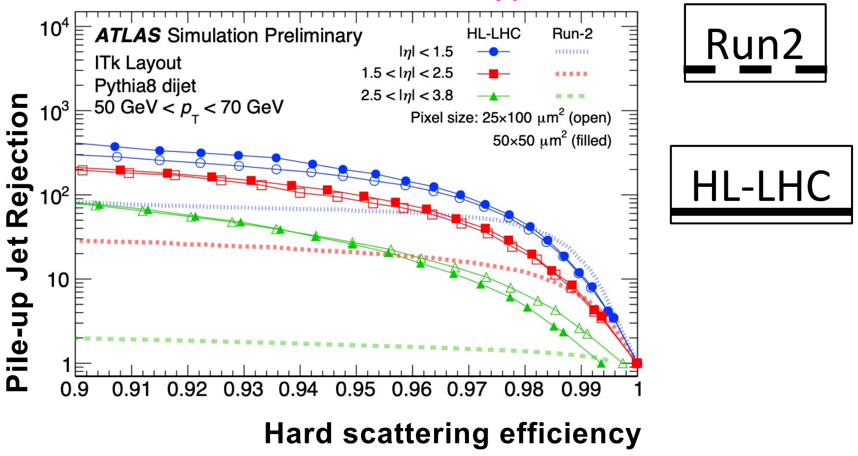
$$R_{pT} = \frac{\sum_{\text{Track } k}^{\text{Jet tracks from HS}} p_T^k}{p_T^{\text{Jet}}}$$

- **Significant improvements** in particularly in the forward region (Run-2 ID limited to $|\eta| < 2.5$).

30 GeV < p_T < 50 GeV



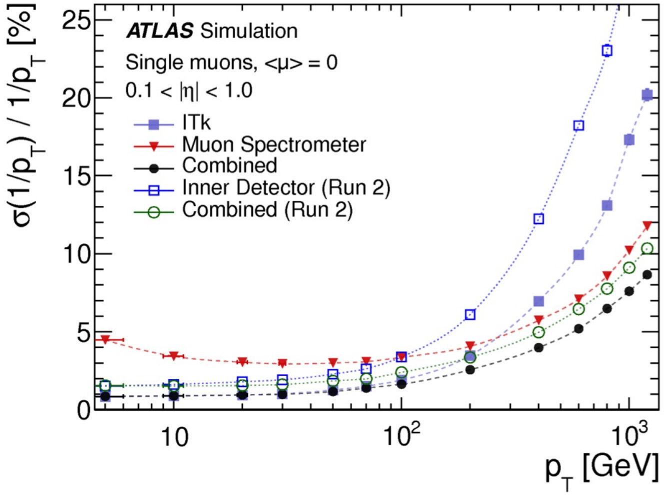
50 GeV < p_T < 70 GeV



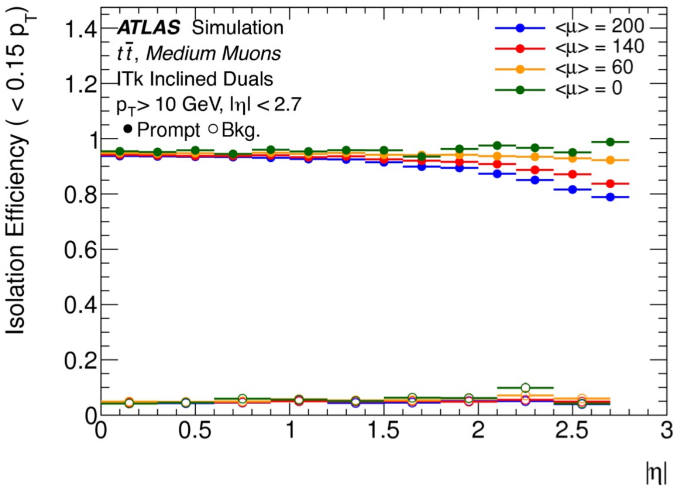
Muons reconstruction:

- Muon **momentum resolution** improved.
- Prompt **muon track isolation efficiency stable** against increasing **<PU>.**

p_T resolution



Muons isolation



Summary

- Performance **are compatible** with what we have seen in **Phase I**, still *room for improvement* and *enough time* to work.
- Some of the future capabilities of the **CMS** (e.g. *MTD detector*) and **ATLAS** (e.g. *HGTD detector*) **not yet exploited**.
- Phase II reconstruction is **already in place and working** for both **ATLAS** and **CMS**.

- CMS Phase II HLT Performance:
    - Electrons & photons: CMS DP-2021/009;
    - All the other objects: (link to the DP).

- ATLAS bTagging Performance for Phase II: ATL-PHYS-PUB-2020-005.

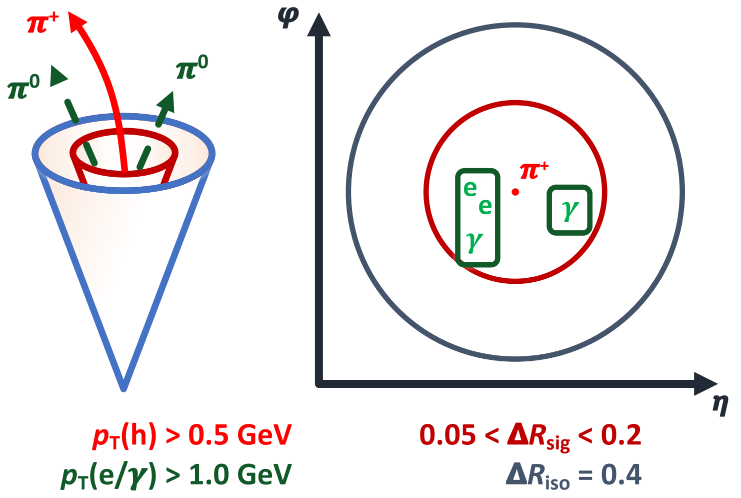
- ATLAS Tracking Performance for Phase II: ATL-PHYS-PUB-2019-014.

- ATLAS Detector Performance for Phase II: ATL-PHYS-PUB-2019-005.

Backup

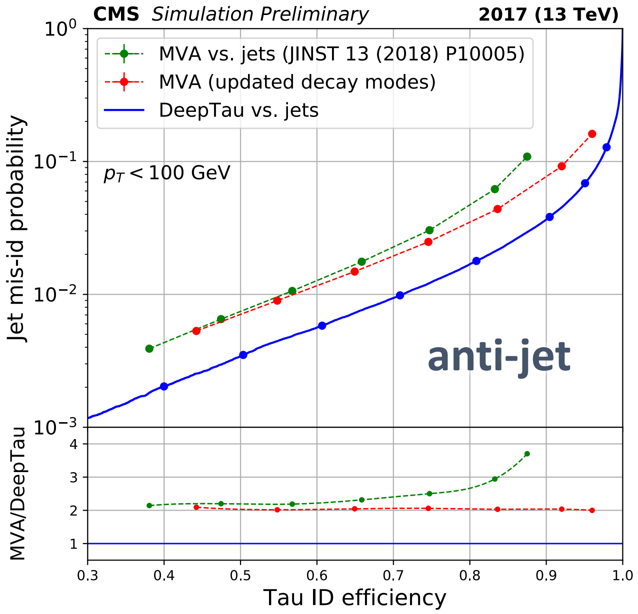
TAU reconstruction - Hadron-plus-strips (HPS) algorithm

- seed:
  - AK4 jet of particle flow (PF) hadrons, e/γ
  - L1 Seeds: L1T-NNPuppi & HPS@L1
- signal cone + isolation cone
- assign τ_h decay mode by counting
  - charged hadrons
  - ECAL/HGCAL clusters (e/γ merged into "strips")



TAU Identification:

- **Charged Isolation (at HLT)**
  - Computation of the τ isolation
- **DeepTau algorithm (now also at HLT)**
  - convolutional deep neural network (DNN)
    - high level: τ lifetime, isolation, e/γ kinematics, …
    - PF hadron/μ/e/γ information in small $\eta \times \varphi$ cells of τ_h
  - multiclassifier into τ_h, μ, e, or jet probabilities



For Phase II trigger developments (see Swagata's talk for trigger performance):

- significant improvement when using the DeepTau algorithm
- cuts re-optimized to improve PU robustness, and remove dependence on PV sorting

Impact parameter significance