Flavour tagging at HL-LHC

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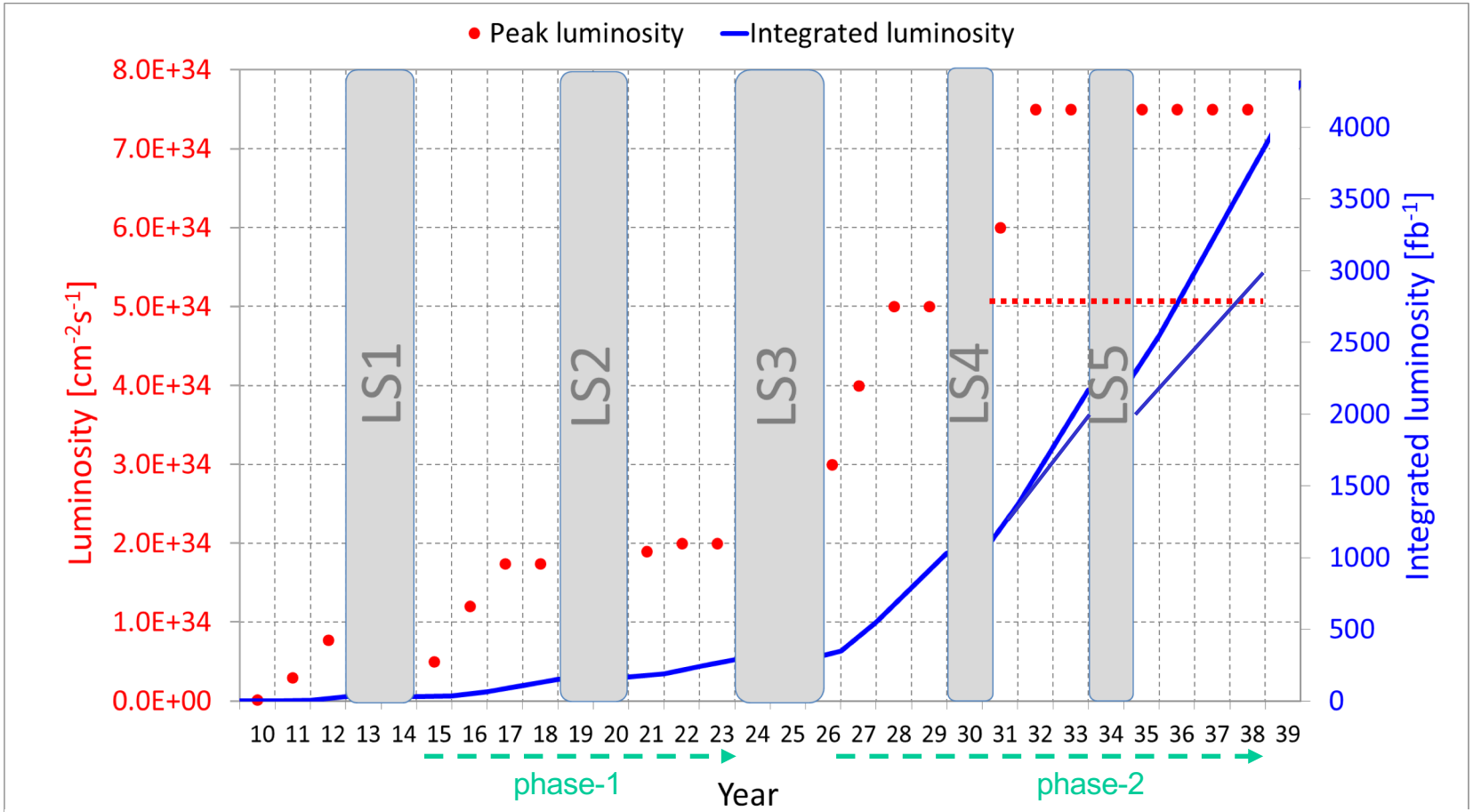
**Game of Flavours, CMS Heavy flavour tagging Workshop,
Dubrovnik, 30 April - 3 May 2019**

why the HL-LHC ?

- strong case to go on exploring the TeV scale:
  - Standard Model works very well but does not explain everything
    - low mass of Higgs boson and naturalness hypothesis advocate for the existence of new particles at the TeV scale
    - SM does not provide Dark Matter particle candidate
  - currently no evidence for new physics

- HL-LHC will deliver 3000 - 4000 fb^{-1}, allowing
  - detailed studies of the Higgs boson : standard model or BSM ?
  - precise measurements of standard model, rare processes: indirect evidence for new physics ?
  - search for new particles and processes at the TeV scale (dark matter candidate)
  - investigate any anomaly / signal found at Run 3

LHC / HL-LHC time-line



Phase-2 luminosity

instantaneous 5.0 to 7.5 x 10^{34} cm^{-2} s^{-1}

integrated 3000 to 4000 fb^{-1}

Challenges

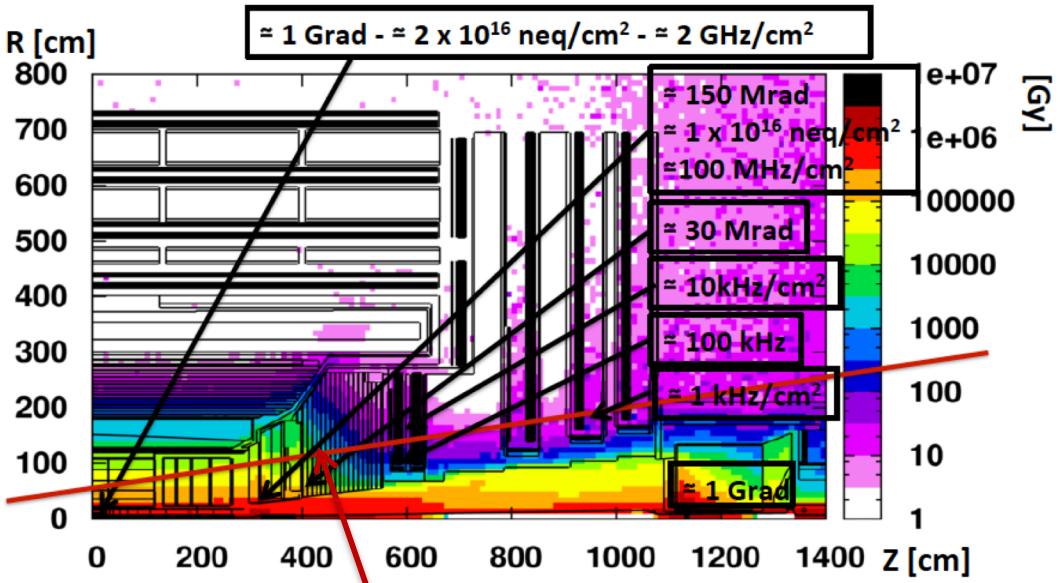
high pileup from 140 to 200

high irradiation

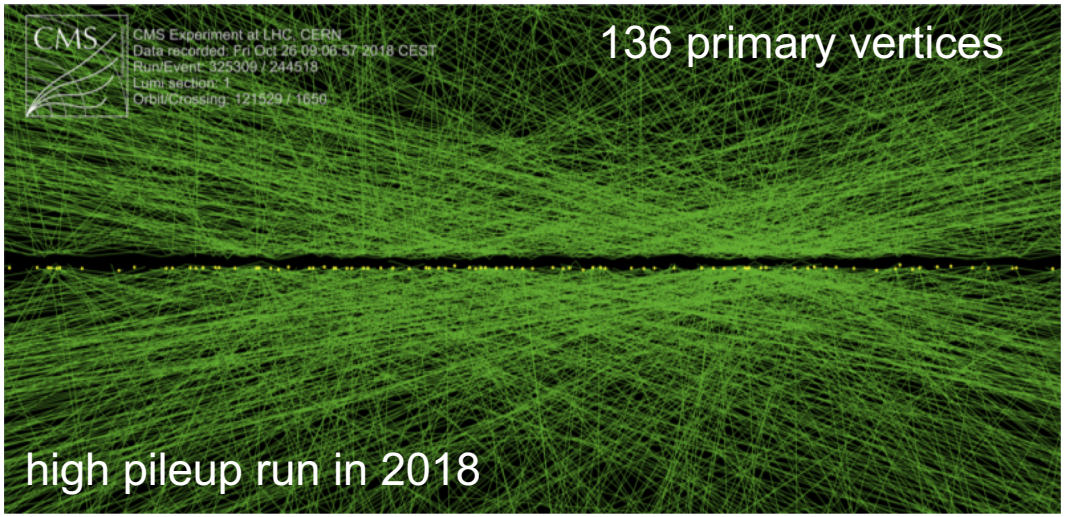
Phase-2 detectors requirements

- maintain and improve the current physics performance during the entire HL-LHC
- detectors must resist to the high radiation levels : many have to be replaced in LS3 !
- improve the detector granularity (trackers, forward calorimeters)
- install timing layers
- fast trigger and fast read-out
- higher band-width
  - up to 10 / 7.5 kHz in ATLAS/CMS with 5 times more tracks and >5 times more channels)

-> computing challenge !



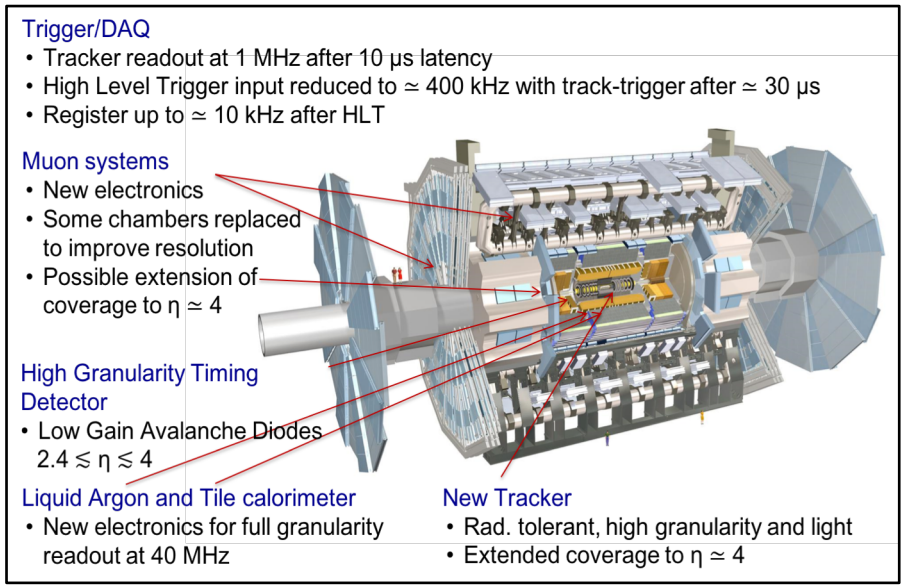
below the red line: beyond limit of currently used detector technologies in several systems



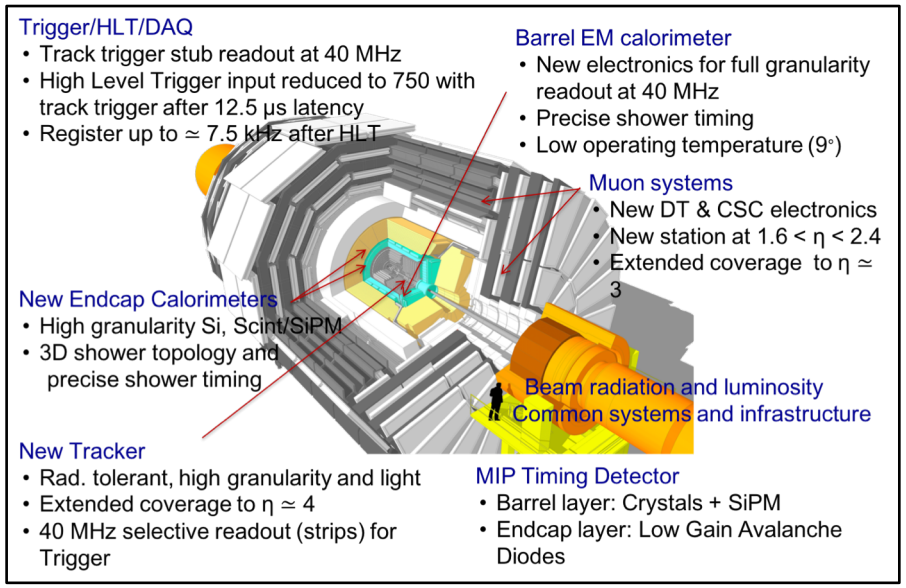
ATLAS and CMS upgrades

- tracker granularity increased by a factor ~5 (pixel and strips), reduced material by a factor 2, pixel extension up to $|\eta| < 4$
- precision timing detectors
- track reconstruction in hardware trigger:
  - ATLAS: 1 MHz (up to 4 MHz) with regional tracker readout (Fast TracKer)
  - CMS: 40 MHz with outer tracker (track p_T > 2-3 GeV) (track-pT at L1)
- new read-out electronics for calorimeters

  new high granularity calorimeter in endcap for CMS $(1.5 < |\eta| < 3.0)$
- extended muon detector coverage (up to $|\eta| < 2.8$)

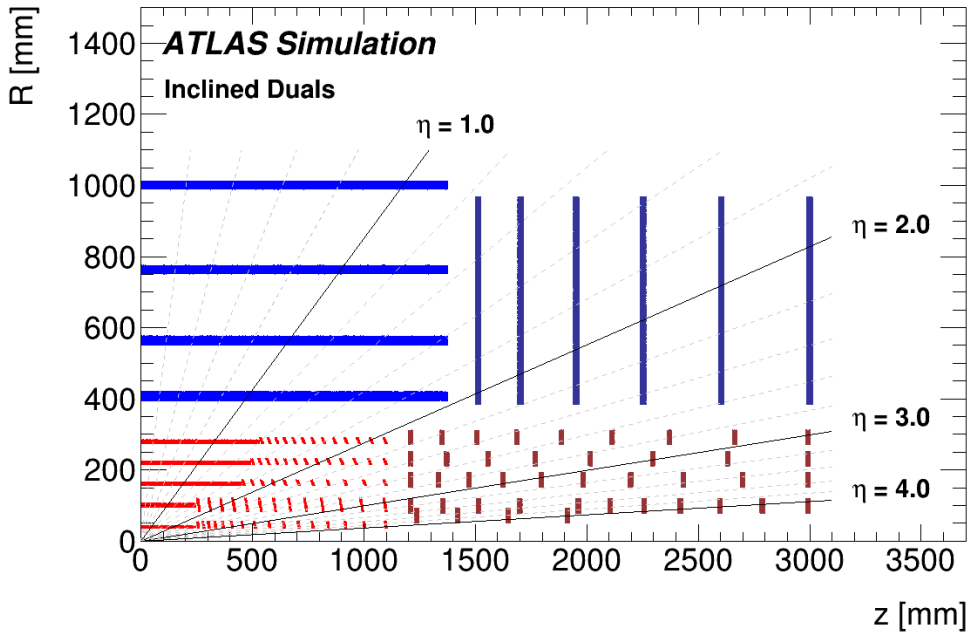


ATLAS



CMS

Phase-2 tracker: ATLAS



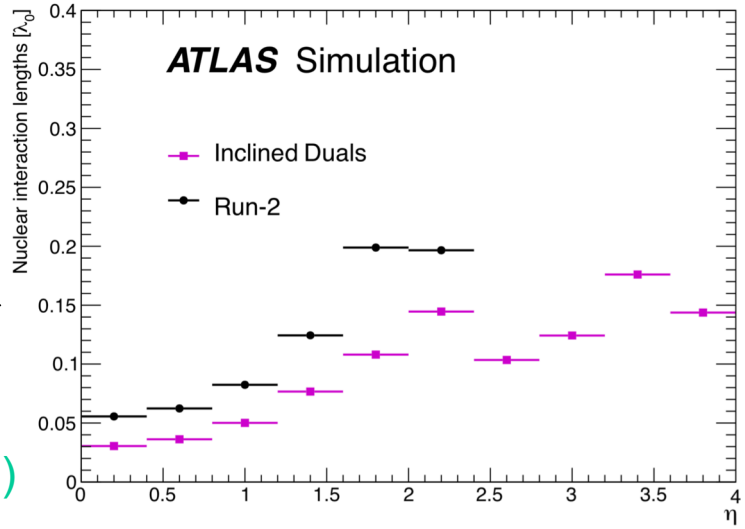
all silicon tracker

Strip detector:

- 4 barrel layers + 2x6 endcap disks
- acceptance up to $|\eta| < 2.6$
- modules with stereo angles (52 mrad barrel / 40 mrad endcap)
  -> 2 measurements / layer or disk

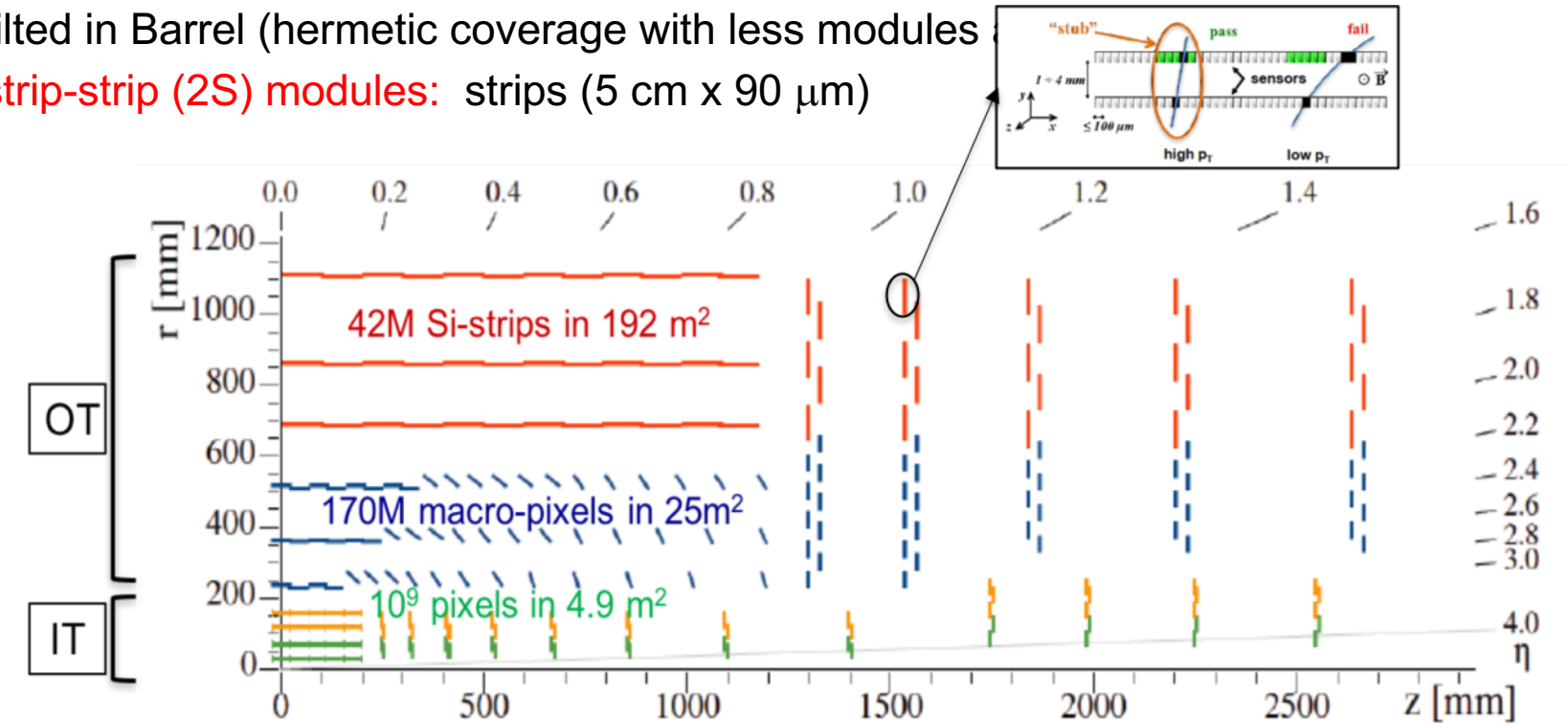
Pixel detector:

- 5 barrel layers (4 layers Phase 1) of inclined dual sensors for $|\eta| > 1$ -> reduces material (and cost) and improves tracking performance
- endcap rings allowing improved coverage (with reduced material) up to $|\eta| < 4.0$ ($|\eta| < 2.5$ Phase 1)
- pixel pitch 50 x 50 μm^2 (50 x 250 (400) μm^2 Phase 1)



Phase-2 tracker: CMS

- Outer Tracker: design driven to provide tracks (p_T > 2-3 GeV) at 40 MHz to the **L1 trigger** => each module consists of 2 closely spaced sensors (~mm)
  - pixel-strip (PS) modules: macro-pixel (1.5 mm x 100 μm), strip (2.4 cm x 100 μm) tilted in Barrel (hermetic coverage with less modules
  - strip-strip (2S) modules: strips (5 cm x 90 μm)

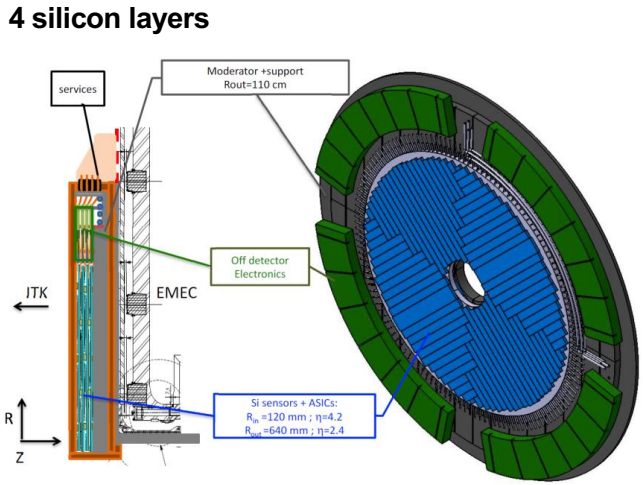


- Inner Tracker (Pixel):
  - extended coverage up to $|\eta| < 4.0$
  - 6x better granulariry than current Phase 1 pixel: 50x50 μm² or 25x100 μm² considered
  - improved material budget and radiation tolerance

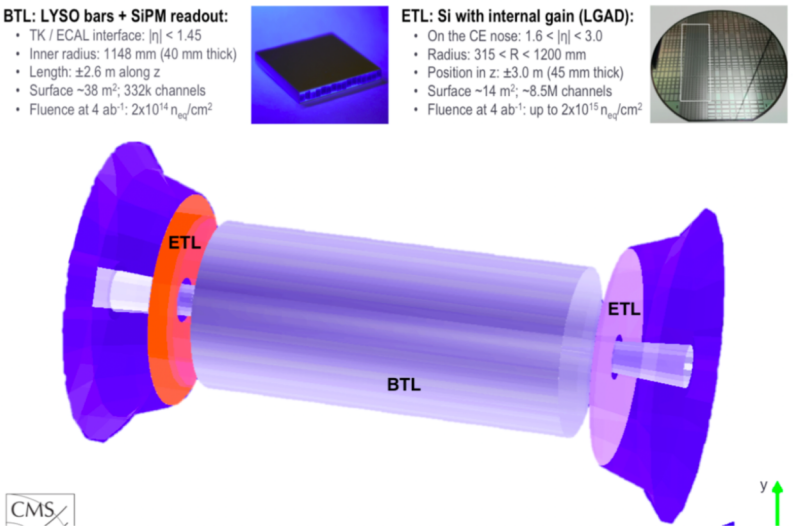
> 1 billion pixels and strips

track timing detectors

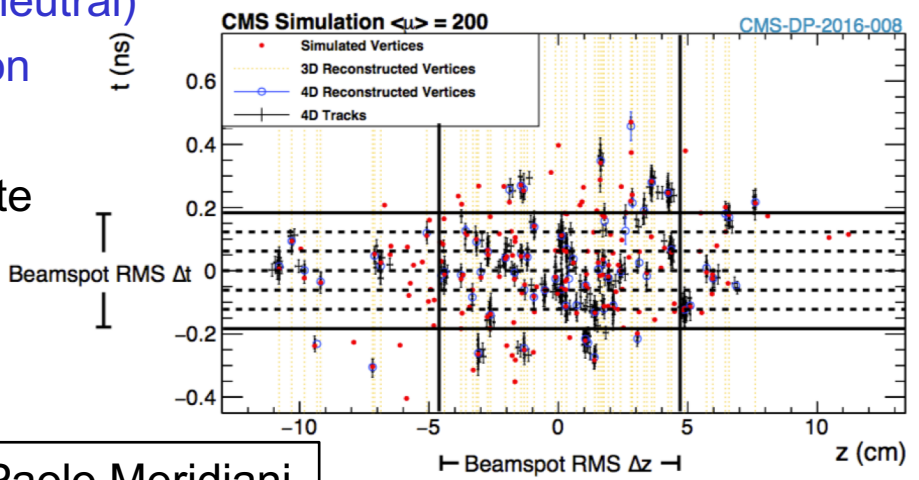
ATLAS: endcap disks 2.4 < |η| < 4.0



CMS: barrel layer + endcap disks |η| < 3.0



- pileup vertices spread along beam direction (σ_Z ~ 5 cm) and time (σ_t ~ 190 ps): precision timing (σ_t~35 ps) for charged (and neutral) particles allows to reduce pileup contamination
  - -> 4D (space+time) vertex reconstruction
  - -> factor 4-5 reduction of vertex merging rate and number of pileup tracks associated to the signal primary vertex (PV)

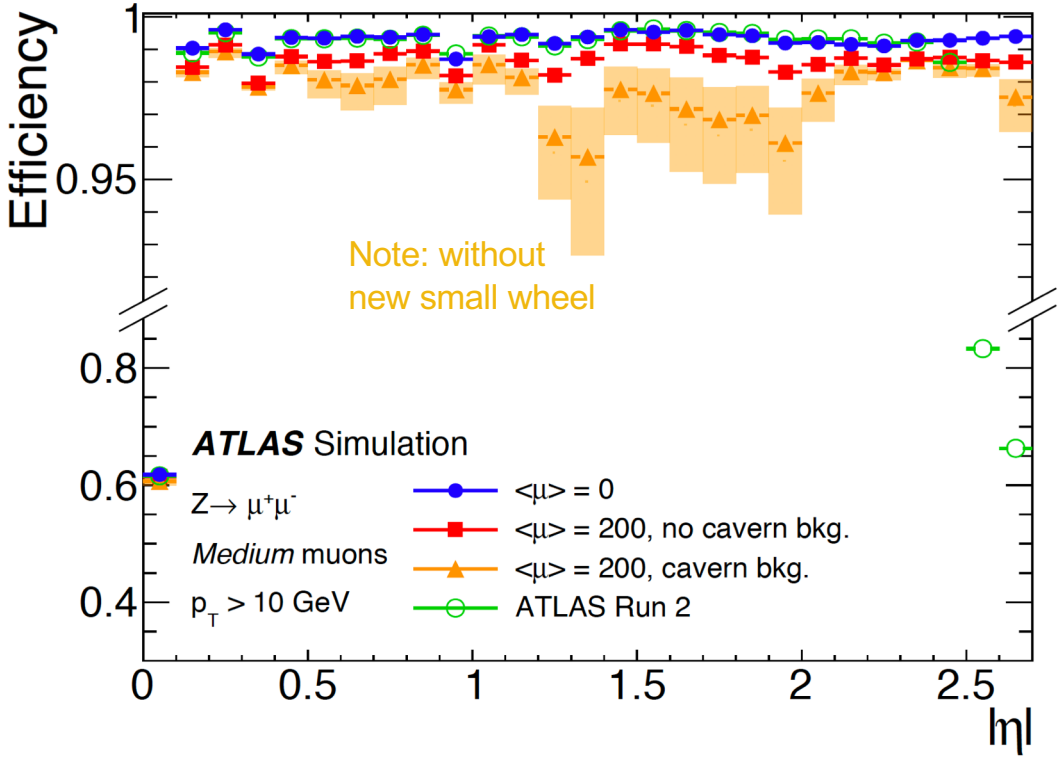


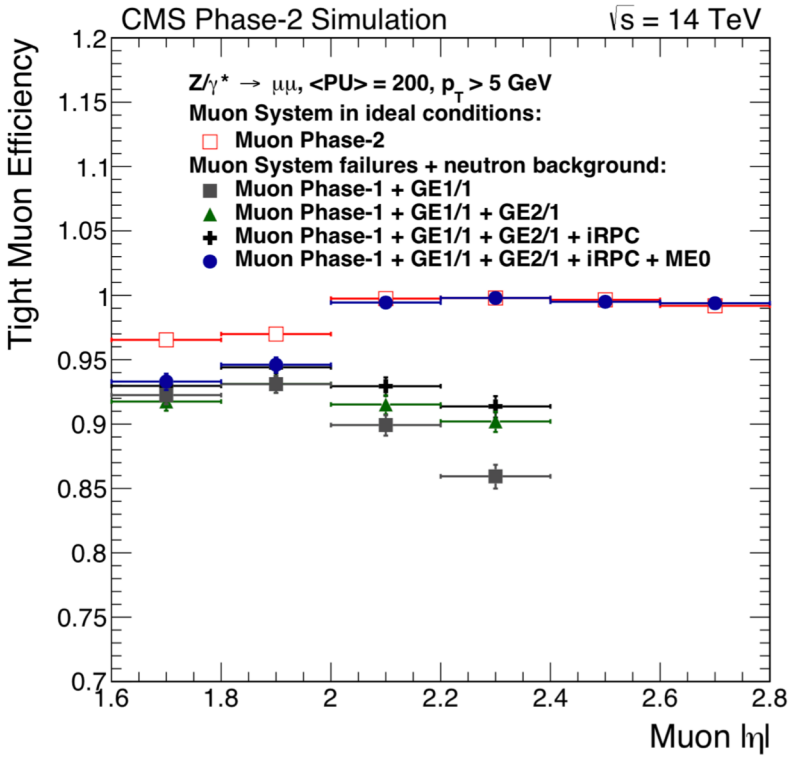
see talk from Paolo Meridiani

Muon reco+id efficiency

Muon detectors in Phase-2 :

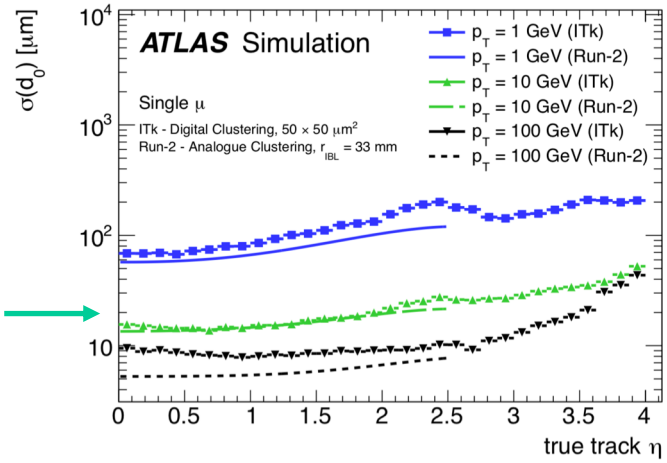
- will benefit from the improved tracking resolution and coverage
- muon id extended from $|\eta| < 2.5$ to 2.7 (ATLAS) and from $|\eta| < 2.4$ to 2.8 (CMS)
- important to be able to measure the b-tagging efficiency at HL-LHC with real data using muon-jets in multijet events or isolated muons (and electrons) in ttbar events



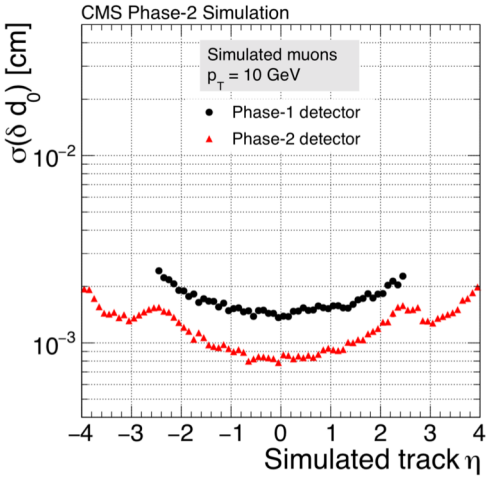


track resolution

- improved resolution and extended η range with Phase-2 pixels (here for muons)
  - transverse impact parameter resolution $\sigma(d_0)$ crucial for b-tagging



20 μm →



← 10 μm

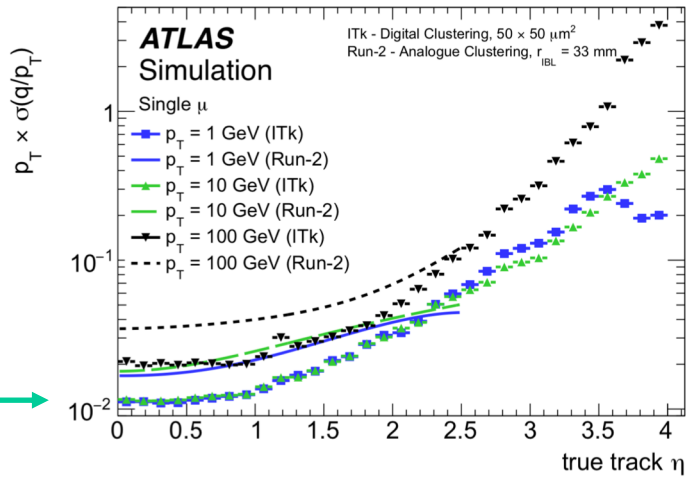
for CMS, see talk from Mia Tosi:
https://indico.cern.ch/event/795581/contributions/3381057/attachments/1836963/3010116/190502_HFT2019_miatosi.pdf

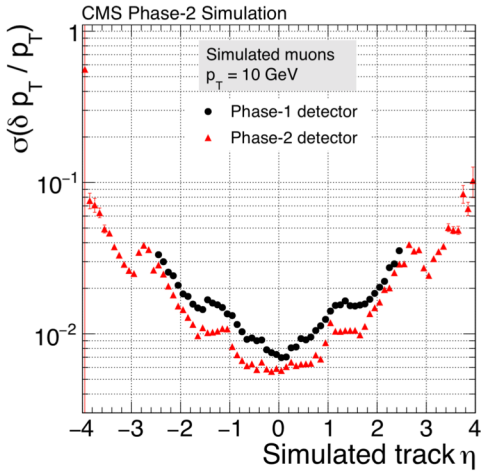
here and in the following simulated performances:

ATLAS: 50x50 μm² pixels
no timing used

CMS: 100x25 μm² pixels
timing in some b-tag plots

1% →

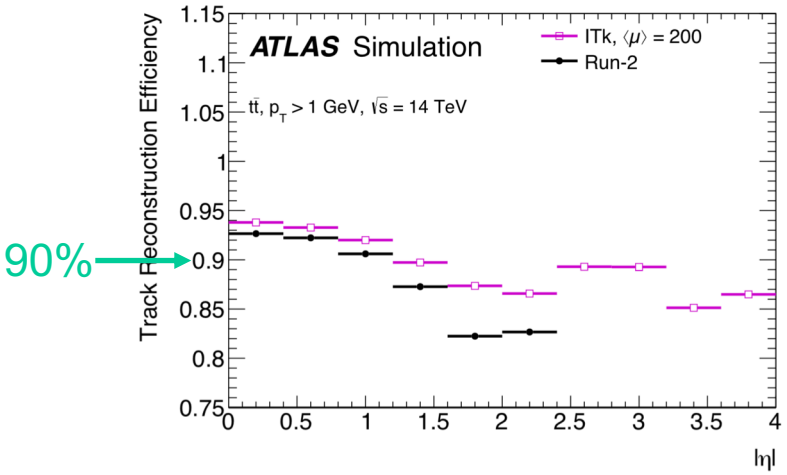


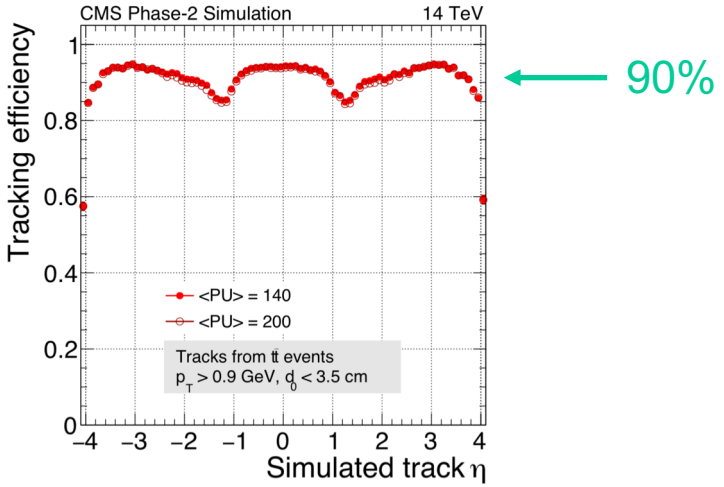


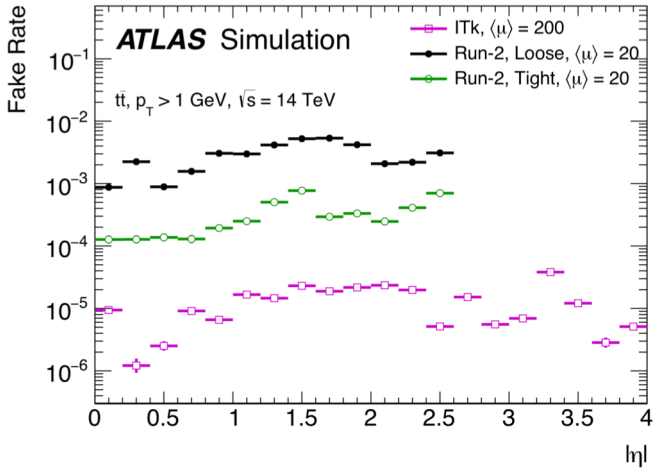
← 1%

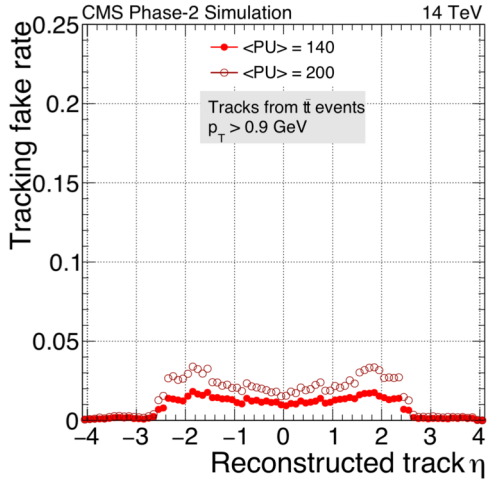
track efficiency and fake rate

- using tracks from PV, reconstruction efficiency > 85% for p_T > 1 GeV
  keeping low fake rates even at high pileup and high |η|
- benefit from the large number of sensitive layers and of the reduced material



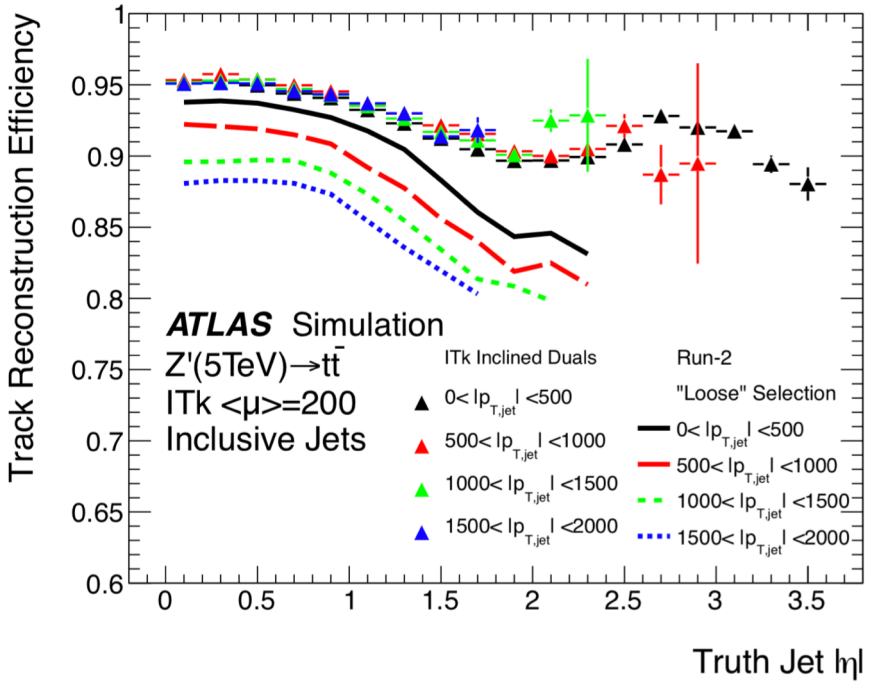


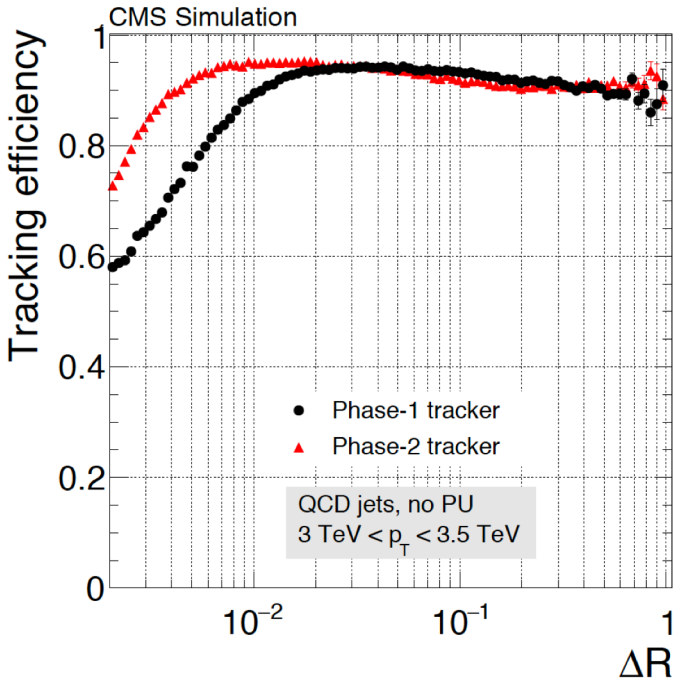




track efficiency in jet core

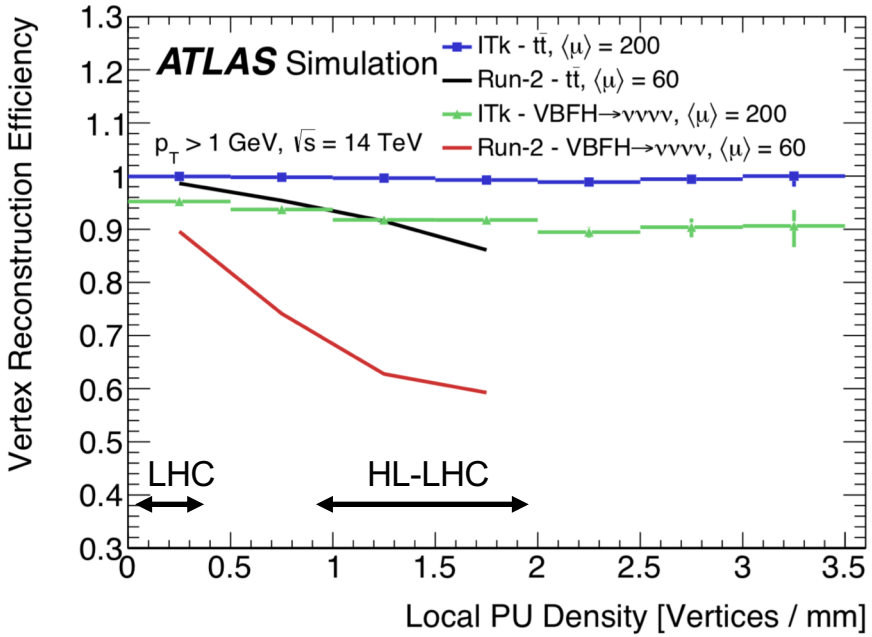
- improved tracking in jet core thanks to better tracker granularity
- important for high p_T jets and boosted objects measurements !

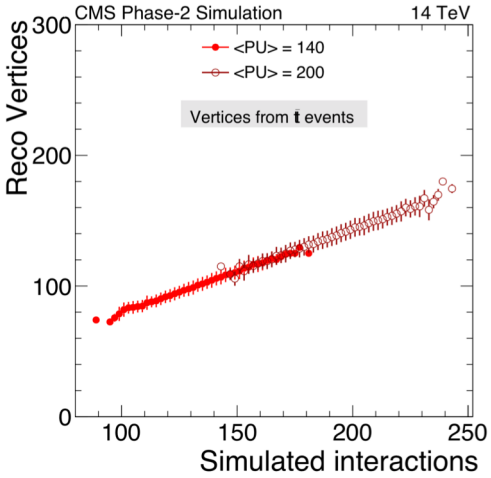


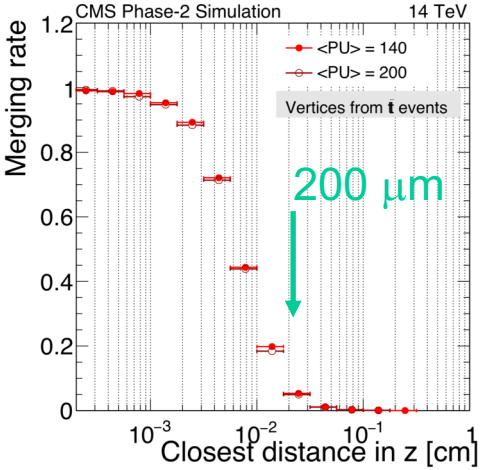


PV reconstruction efficiency

- good primary vertex reconstruction efficiency, even at high pileup
- timing will help to reduce merged PVs along z

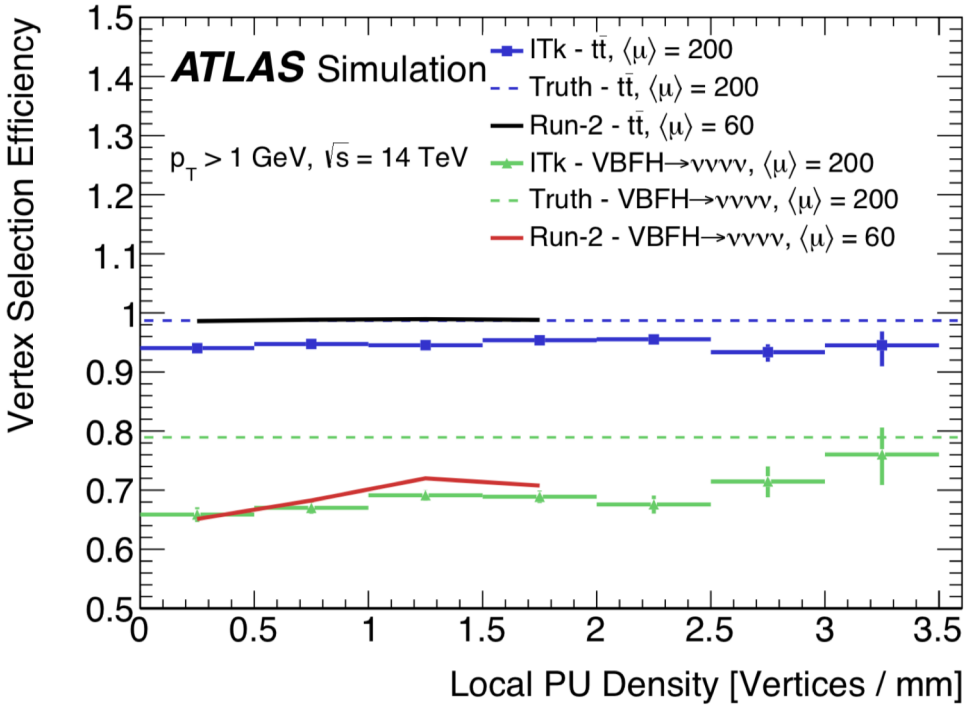


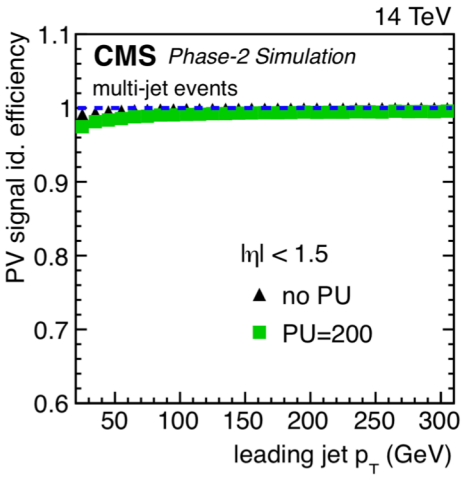


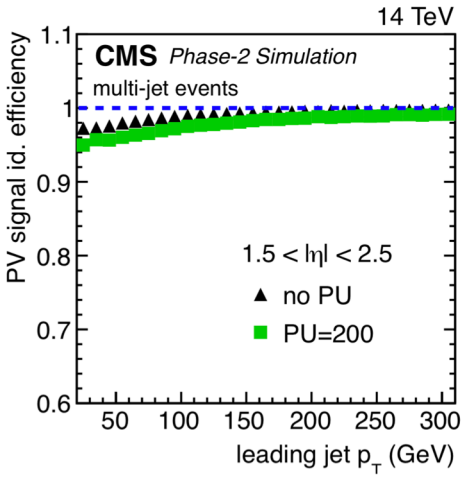


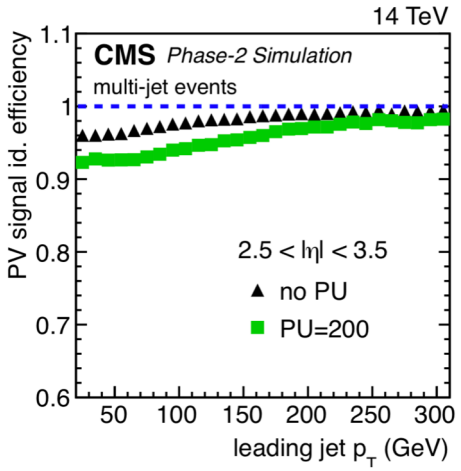
PV selection efficiency

- based on vertex with highest Σp_T^2 for tracks (ATLAS) or for track jets + MET (CMS)
- high efficiency but reduced for physics signals with fewer jets or charged particles





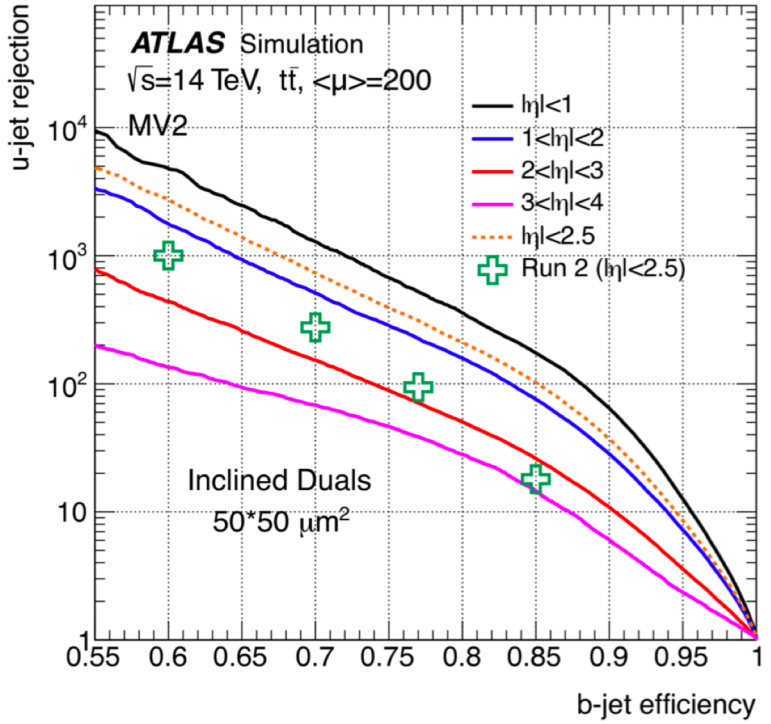


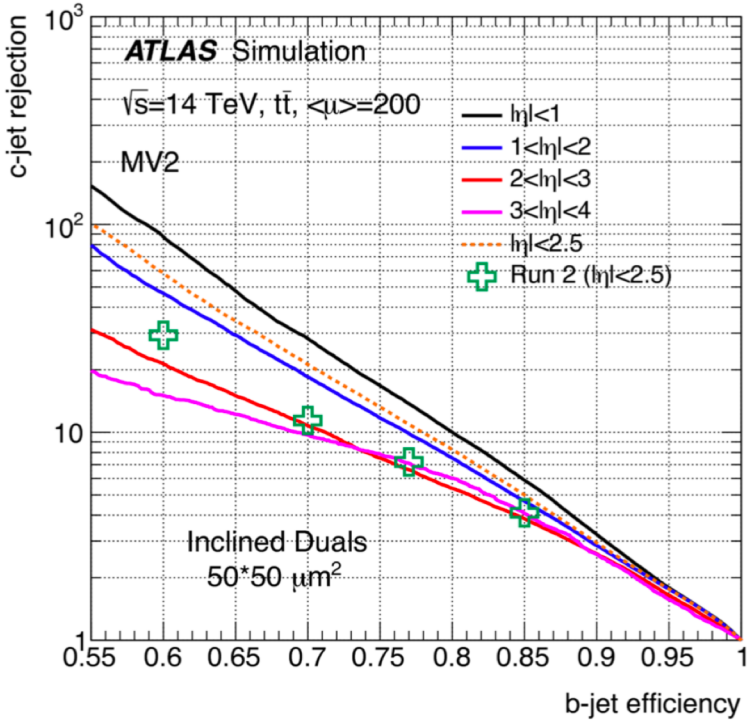


b-tagging performance

ATLAS: b-tagging capability up to $|\eta| < 4$

improved performance wrt Run 2, even at high pileup



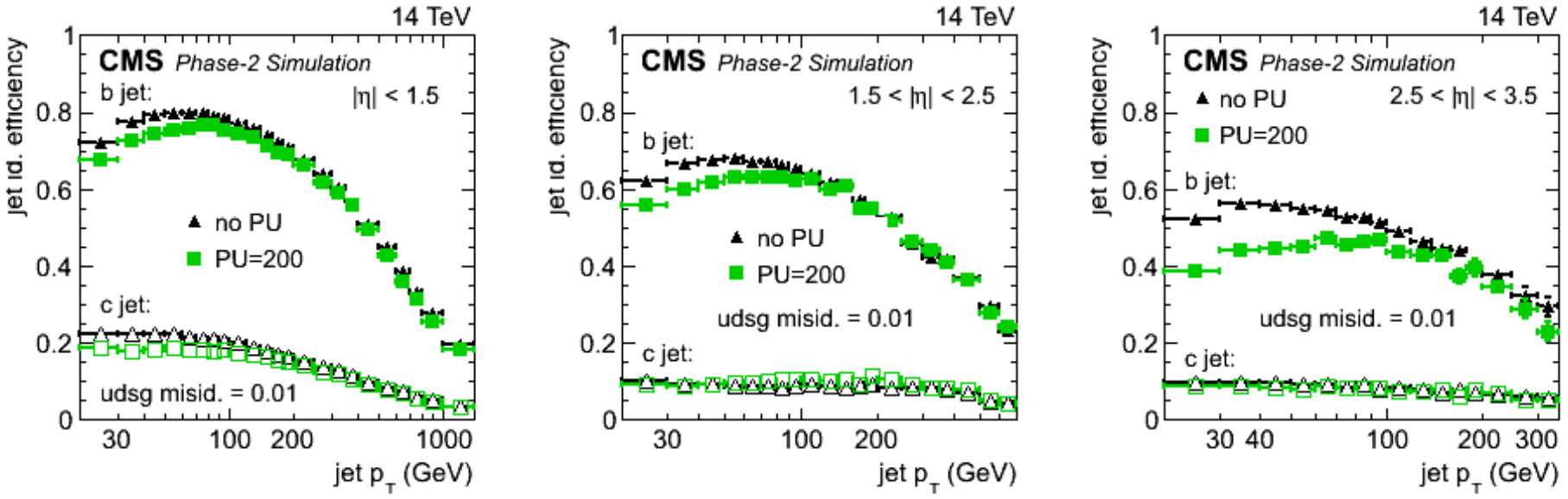


about MV2, see talk from Chris Pollard:
https://indico.cern.ch/event/795581/contributions/3335184/attachments/1837023/3010236/CMSFTag20190502.pdf

b-tagging performance (cont.)

CMS:

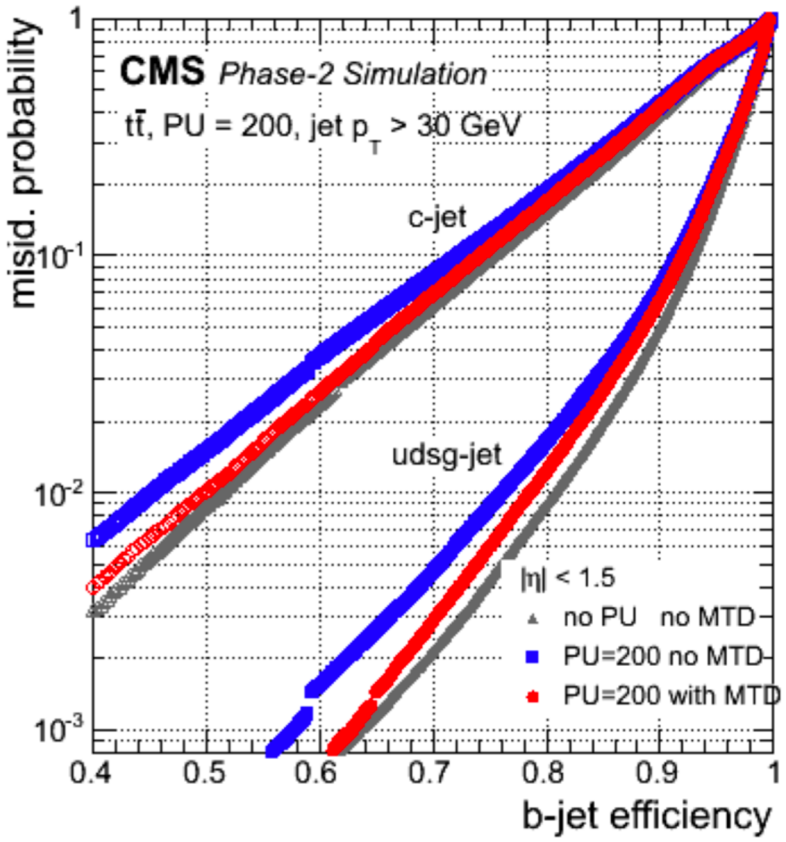
- b jet tagging efficiency and c and light jets mistagging parametrized as a function of jet p_T / η for Delphes studies
- performance preserved for high p_T jets in the full acceptance

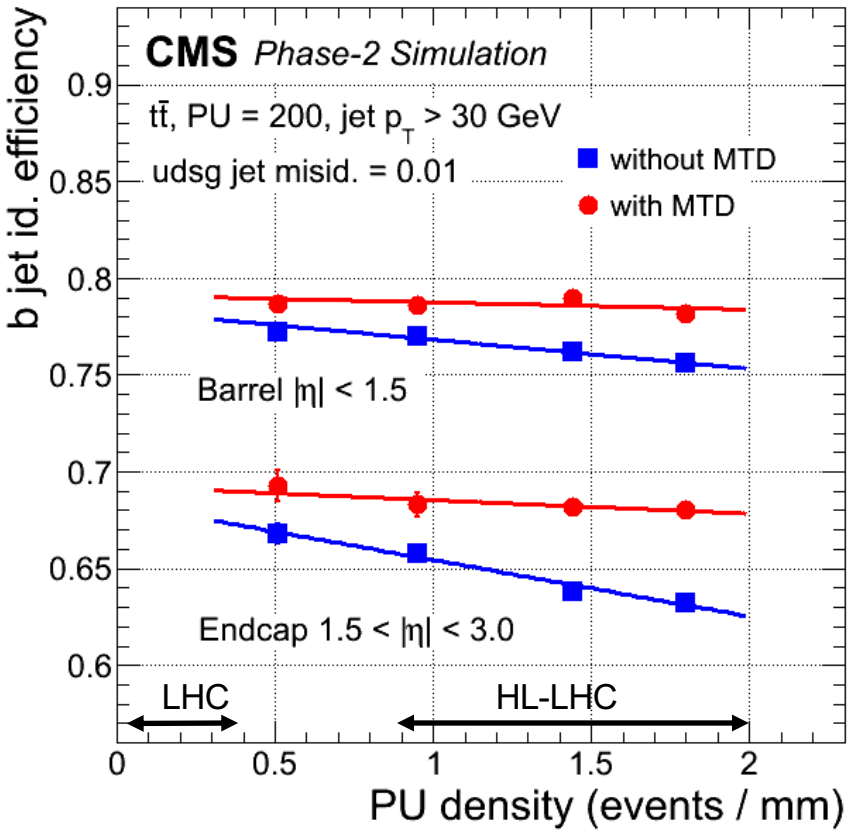


here for DeepCSV, see talk from Petra Van Mulders:
https://indico.cern.ch/event/795581/contributions/3335185/attachments/1837054/3010301/CMS_HF_tagging.pdf

b-tagging performance (cont.)

CMS: with timing information, b-tagging performance improves and is moderately sensitive to the high pileup conditions

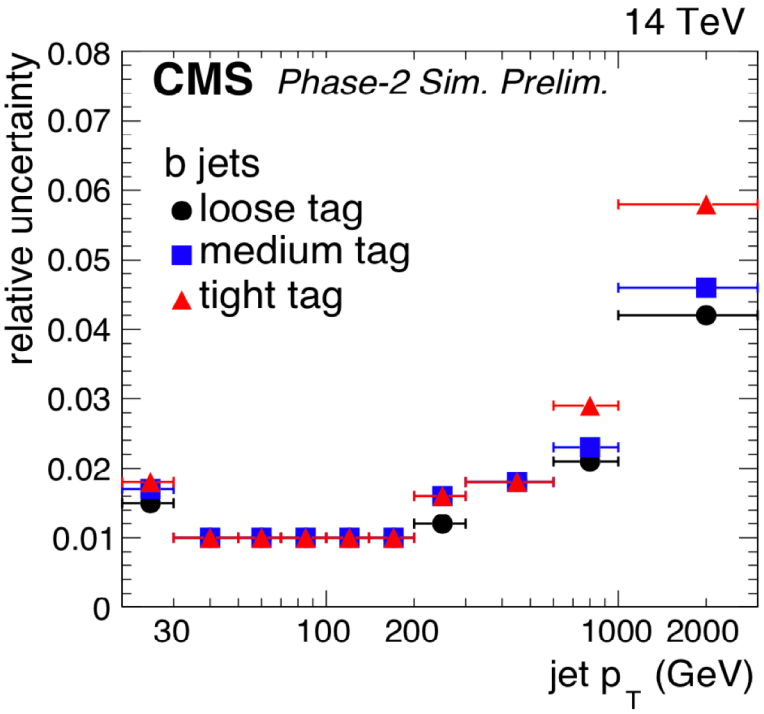


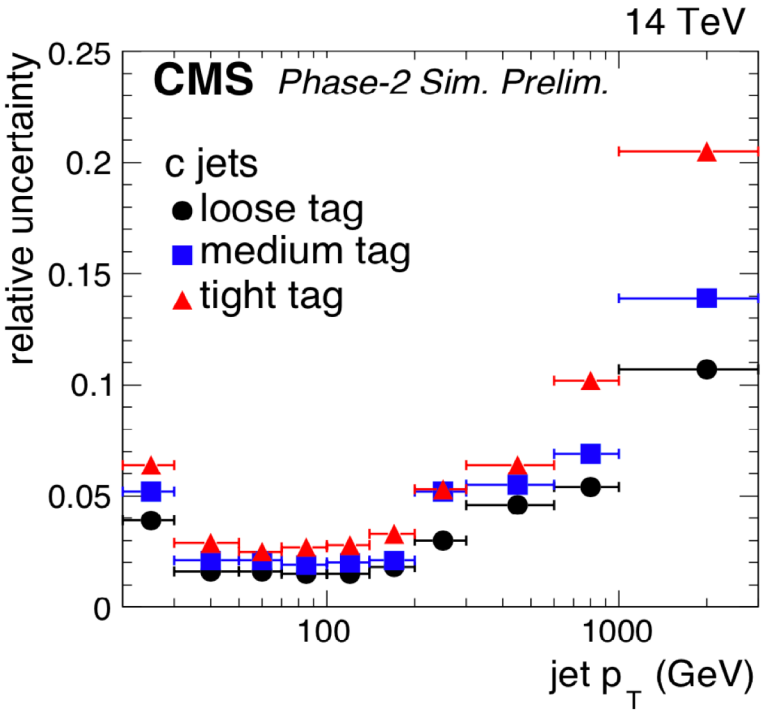


systematic uncertainties

ATLAS and CMS: expect that most of the systematics will be reduced by a factor up to 2 at HL-LHC (as compared to now)

- light jet mistag: 5% / 10% / 15 % uncertainty for 10^{-1} / 10^{-2} / 10^{-3} udsg efficiency)
- b jet tagging uncertainty (1% min.): c jet mistag rate uncertainty:





- applied to HL-LHC physics prospects (CERN Yellow reports 2019)

Conclusion

- the new detectors going to be built for the Phase 2 upgrades deserve to be exploited with the best precision and efficiency
- significant efforts have been deployed to evaluate their (promising) performance in realistic conditions
- but much has still to be done to improve the simulation, reconstruction and objects identification, especially to cope with the high pileup environment
- new developments have already started in order to define the future triggers and to innovate in using computing ressources.

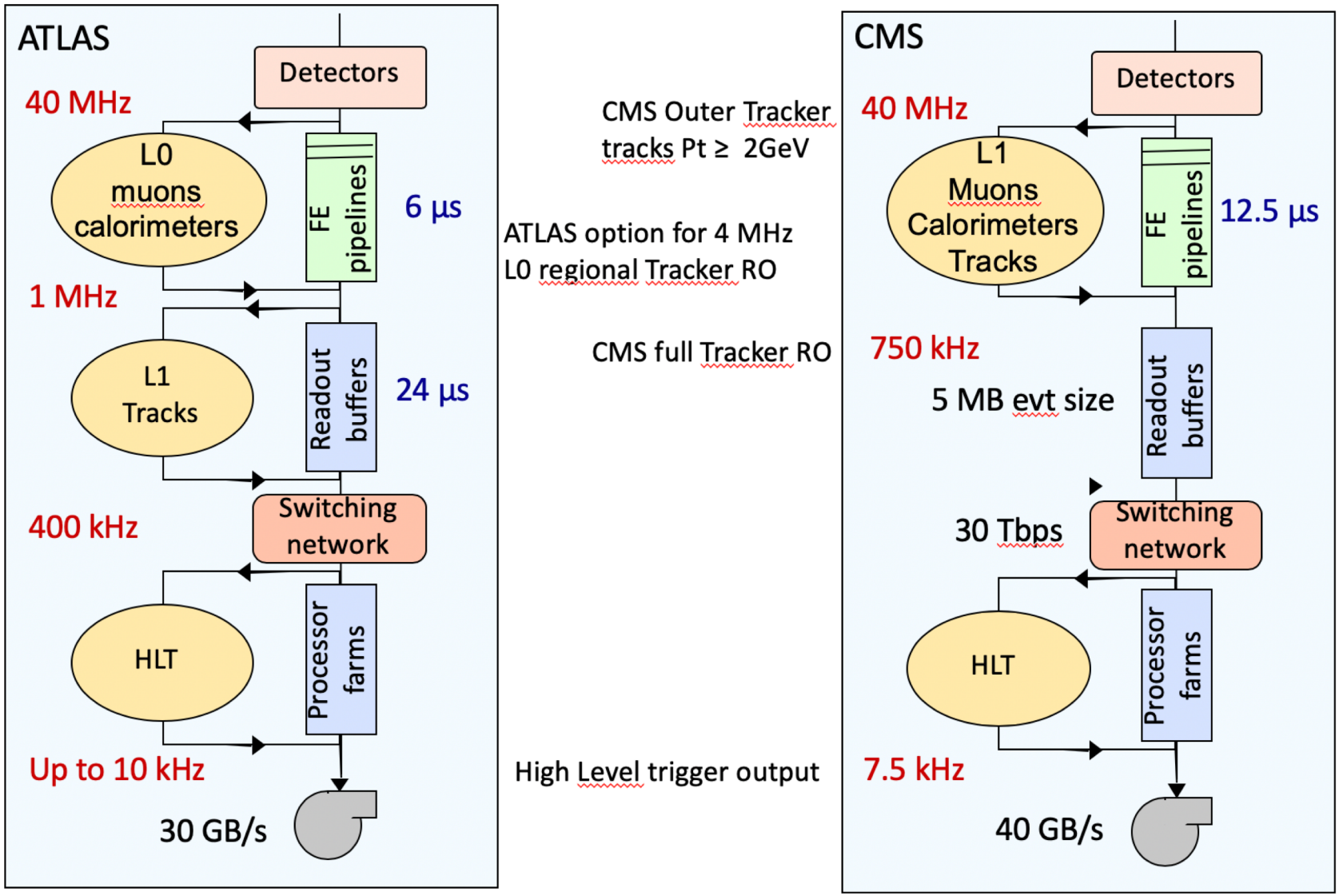
references

- ATL-PHYS-PUB-2019-005: https://cds.cern.ch/record/2655304
  - Expected performance of the ATLAS detector at the High-Luminosity LHC
- ATLAS-TDR-030, CERN-LHCC-2017-021: https://cds.cern.ch/record/2285585
  - Technical Design Report for the ATLAS Inner Tracker Pixel Detector
- ATLAS-TDR-026, CERN-LHCC-2017-017: https://cds.cern.ch/record/2285580
  - Technical Design Report for the Phase-II Upgrade of the ATLAS Muon Spectrometer

- CMS-NOTE-2018-006: http://cds.cern.ch/record/2650976
  - Expected performance of the physics objects with the upgraded CMS detector at the HL-LHC
- CERN-LHCC-2017-027: http://cds.cern.ch/record/2296612
  - Technical Proposal for a MIP Timing Detector in the CMS experiment Phase 2 upgrade
- CMS-TDR-019, CERN-LHCC-2017-023: http://cds.cern.ch/record/2293646
  - The Phase-2 Upgrade of the CMS Endcap Calorimeter
- CMS-TDR-014, CERN-LHCC-2017-009: https://cds.cern.ch/record/2272264
  - The Phase-2 Upgrade of the CMS Tracker

additional material

Trigger/DAQ upgrades



from D. Contardo, Split 2018