Design and object performance of the CMS High Granularity Calorimeter Level 1 trigger

Thomas Strebler

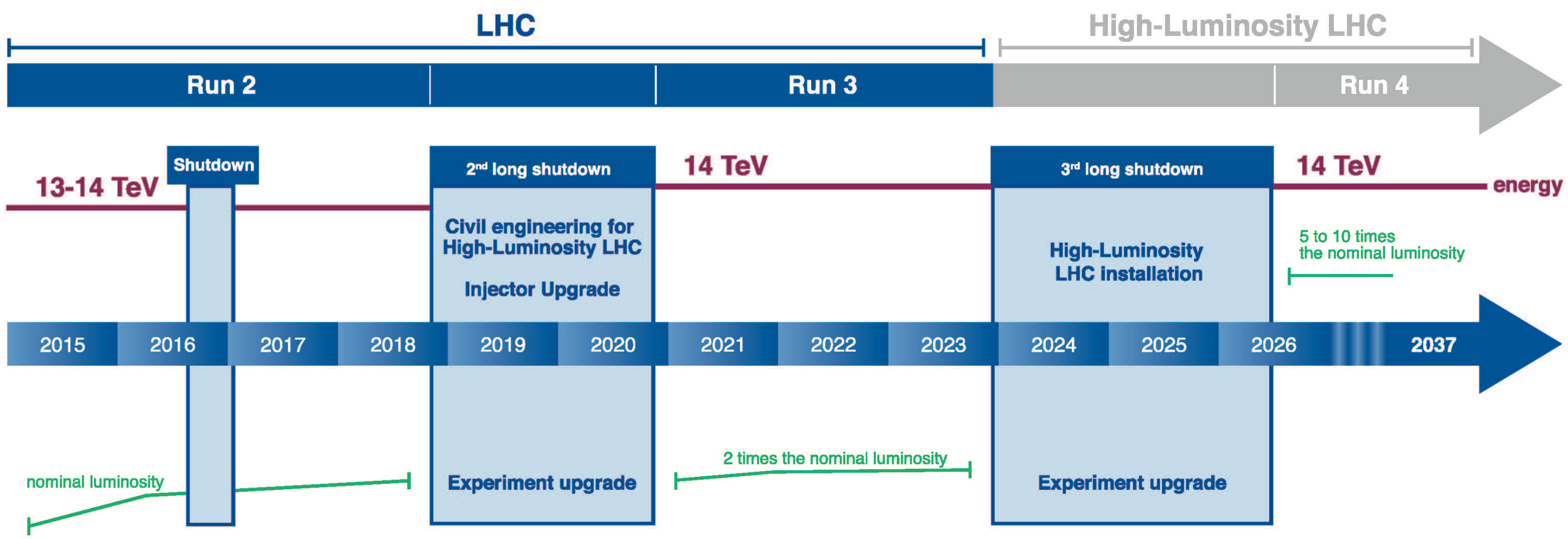
On behalf of the CMS collaboration

See N. Akchurin's talk
for an overview of the CMS HGCAL upgrade

CALOR 2018 conference
May 23rd, 2018

Imperial College London

Challenges of HL-LHC for L1 trigger



- **Significant changes in LHC conditions for Phase 2**:
  - increase in luminosity by up to a factor 4
  - interactions per bunch crossing (pile-up) up to 200

- **Very challenging conditions for L1 trigger**:
  - high occupancy in the detector
  - higher rates
  - higher radiation dose

- CMS physics programme for HL-LHC includes study of rare electroweak processes
  => Phase-1 trigger thresholds must be maintained

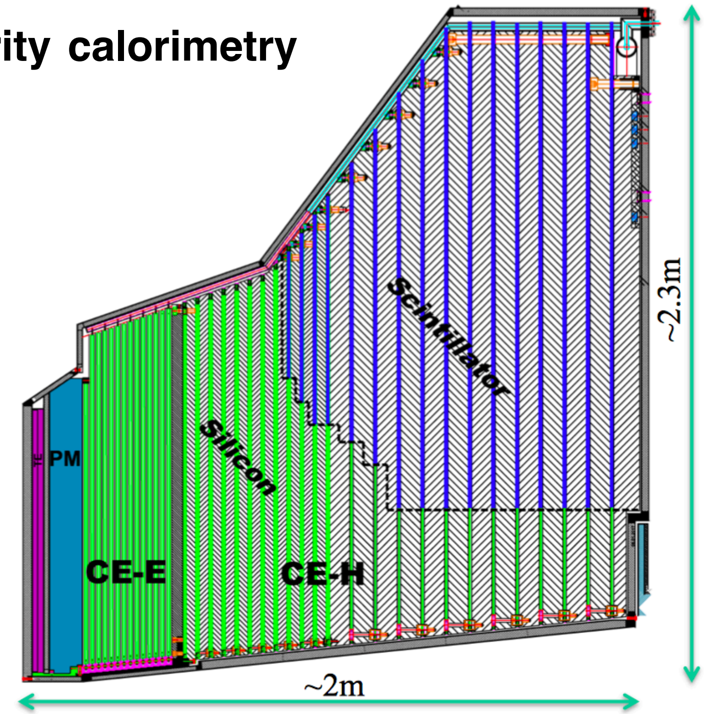
Changes in CMS L1 trigger and endcaps for HL-LHC

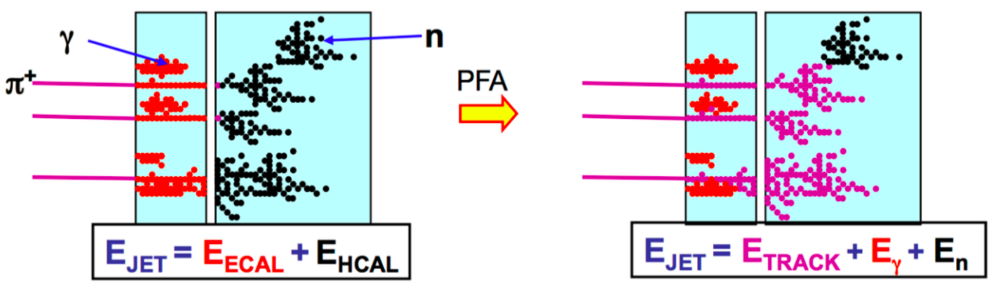
- **Brand new endcap detectors based on high-granularity calorimetry = HGCAL**
  - better radiation-hardness
  - better granularity
  - new longitudinal information to be exploited
  - 6M readout channels over 52 layers

  => huge data volume!

- **CMS L1 trigger upgrade phase 2**:
  - increased bandwidth (750 kHz)
  - increased latency (12.5 μs)

- New track trigger primitives **=> Particle-Flow algorithm at L1 trigger**





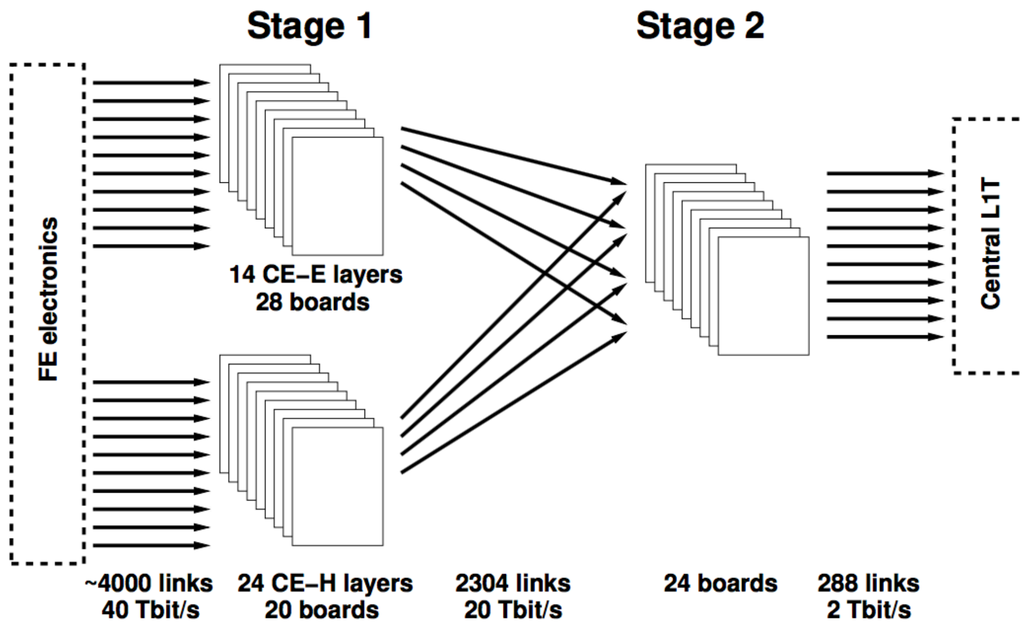
- **Good position resolution and shower separation** of the calorimeter trigger primitives needed **for track-cluster matching**

- L1 tracks only up to |η|=2.4, **standalone cluster needed for 2.4<|η|<3.0**

see A. Zabi's talk

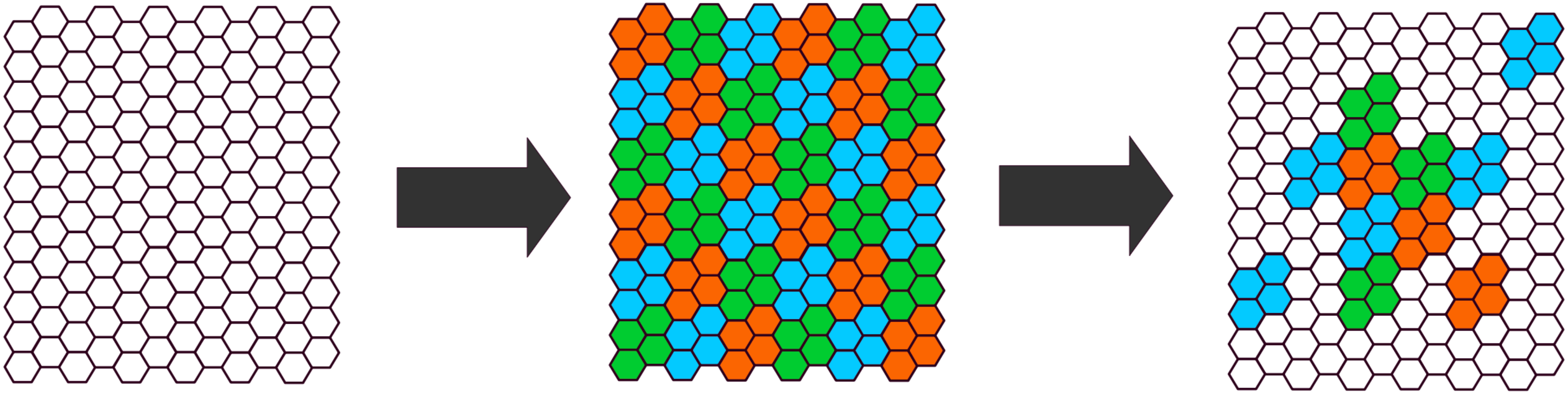
HGCAL trigger: on- and off-detector processing

- **Reduction of data-flow to send off-detector at 40 MHz in front-end ASICS**
- **Kept simple to:**
  - minimise power consumption
  - maximise flexibility



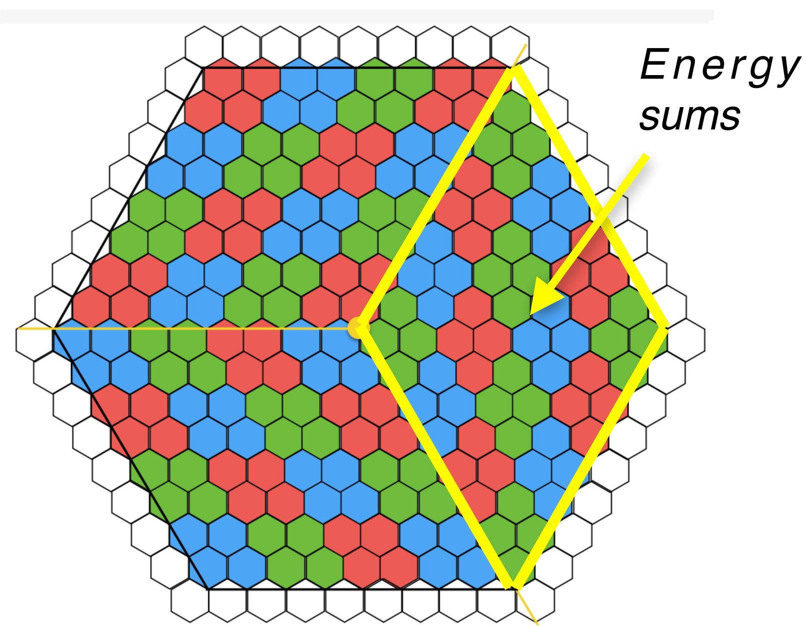
- **More involved processing to be done in off-detector FPGAs:**
  - Stage 1: 2D clustering layer by layer
  - Stage 2 (Time-Multiplexed Trigger architecture): 3D objects built combining 2D objects along longitudinal direction
- **Trigger primitives sent to central Level 1 trigger:**
  - 3D clusters, including position, energy and topological variables
  - projective energy map to evaluate unclustered energy

HGCAL front-end for data-flow reduction

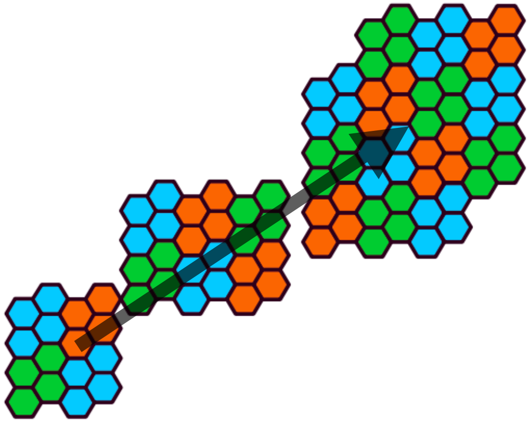


Sensor cells *Trigger cells* *Trigger cells over threshold*

- **Half of EM layers** used for triggering
- **Trigger cells** (TCs) built by summing energy from 2x2 or 3x3 neighbouring sensor cells (~4.5 cm^2)
- **Threshold** applied before sending TCs to back-end
- **Energy sums of all TCs covered by one read-out chip** (~36 cm^2) also sent



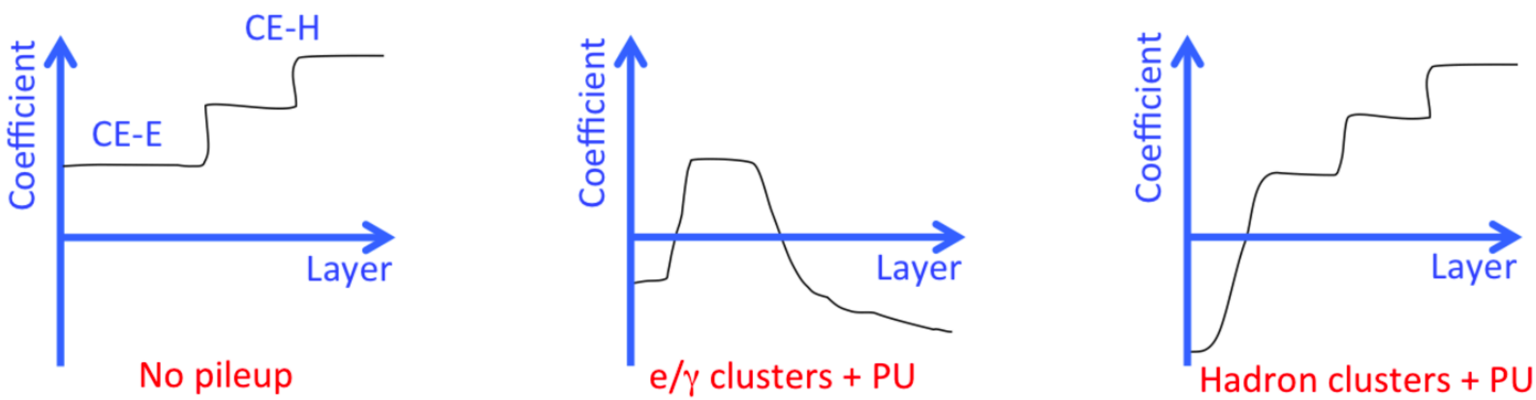
Clustering in the back-end: implementation



- **2D dynamic clustering performed layer by layer** (Stage 1):
  - inspired by good performance of Phase 1 L1 calorimeter trigger
  - nearest neighbour clustering around seed TCs
  - topological variables computed for background discrimination

- **3D clusters built by combining 2D clusters** (Stage 2):
  - new longitudinal dimension to be exploited
  - several approaches under study (cone-based, likelihood-based…)
  - additional discrimination variables computed
  - weighted energy sum to define 3D cluster energy

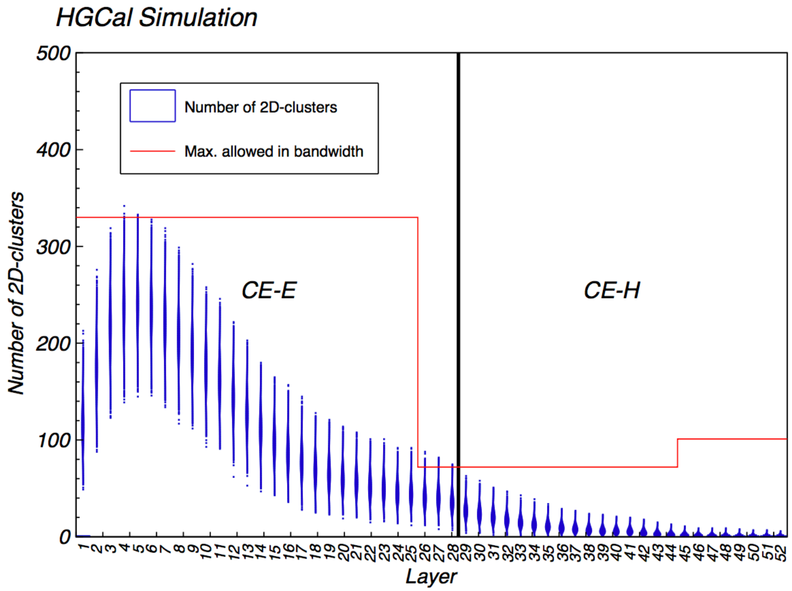
Calibration coefficients per layer

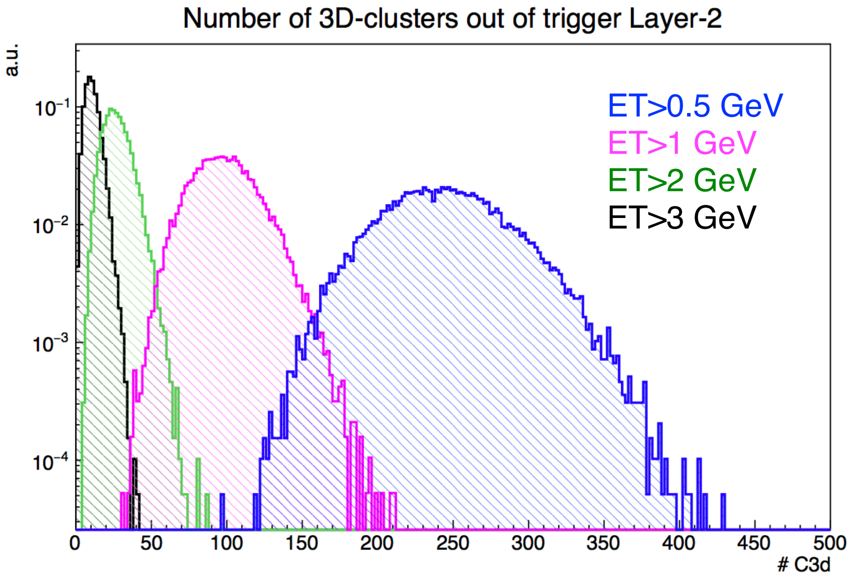


- **Different energy reconstruction strategies could be considered for different kinds of clusters**

Clustering in the back-end: impact of thresholds

- **Various thresholds used in the different clustering steps to:**
  - limit impact of electronic noise and pile-up
  - keep the number of objects produced within bandwidth constraints
- **Effect on response corrected with cluster calibration**
- **Impact on resolution of hadronic objects could be recovered by combining information from energy sums**





Object performance: e/γ ID

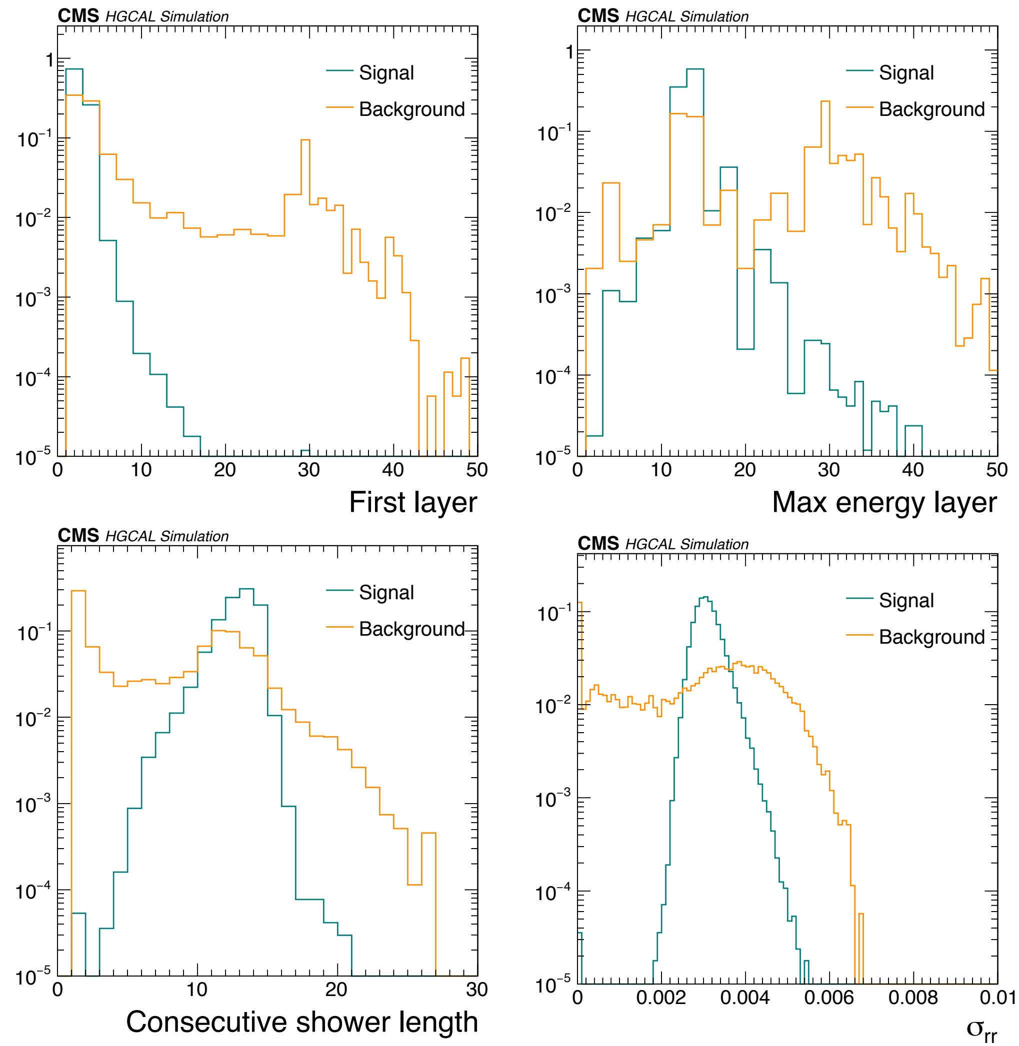
- **Calorimeter-only trigger object reconstruction developed to estimate impact of trigger primitive generation steps**
  => final trigger performance will also benefit from L1 track information in central L1 trigger

- **Electrons and photons = single 3D cluster**

- **ID variables used to reject background:**
  - First layer
  - Layer with max energy
  - Consecutive shower length
  - Transverse width in radial direction

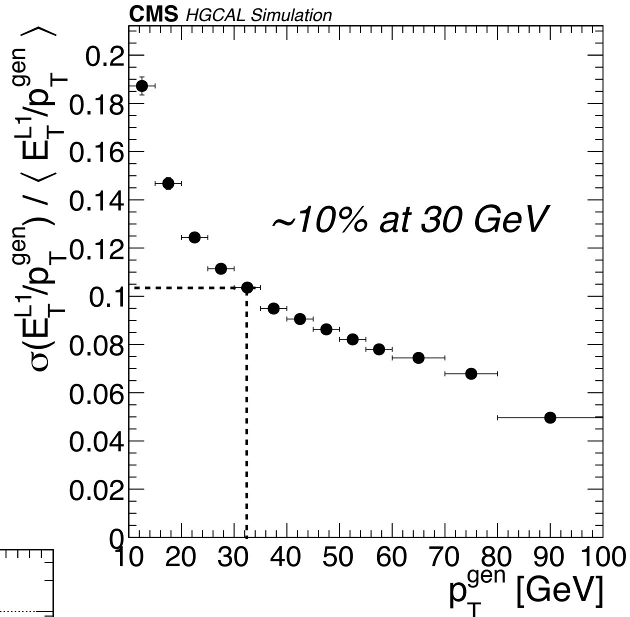
- **Combined in a BDT used to define ID working points**

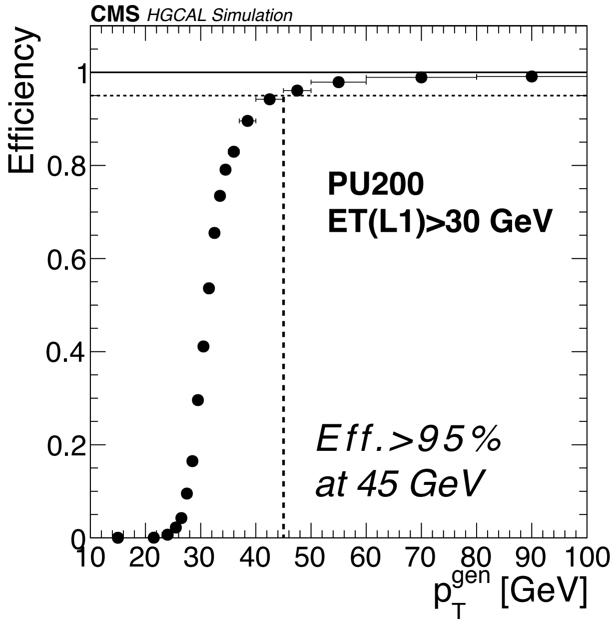
- Will be **complemented with tracking ID** variables in central L1 trigger where possible

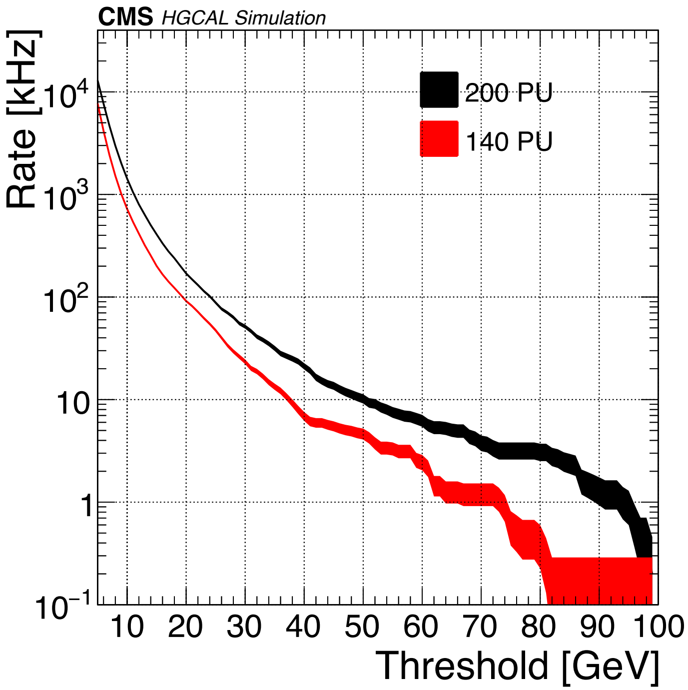


Object performance: e/γ resolution, efficiency and rate

- **Overall good performance for HGCAL trigger for electromagnetic objects:**
  - good resolution
  - high plateau efficiency





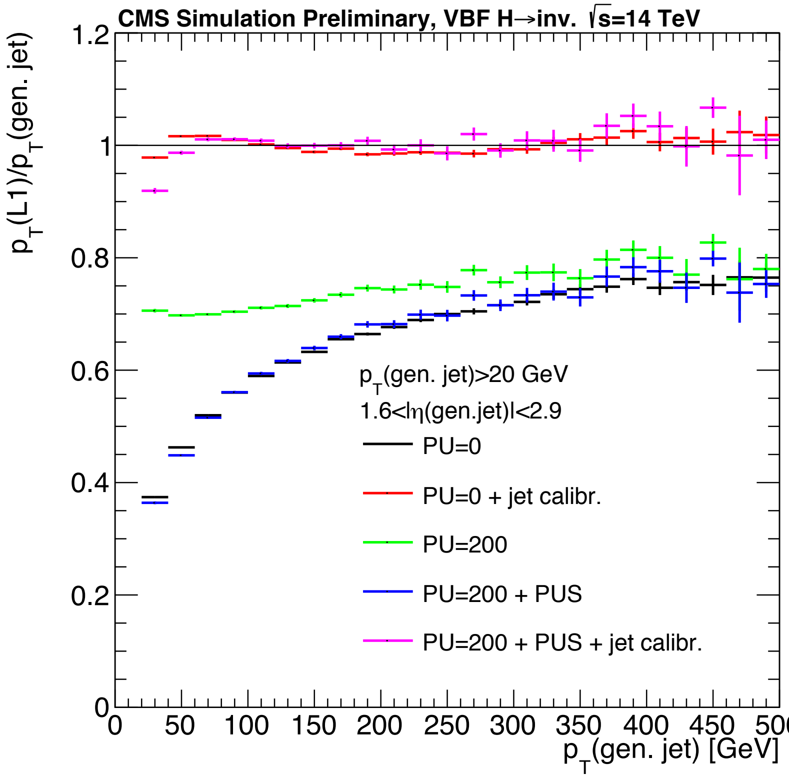


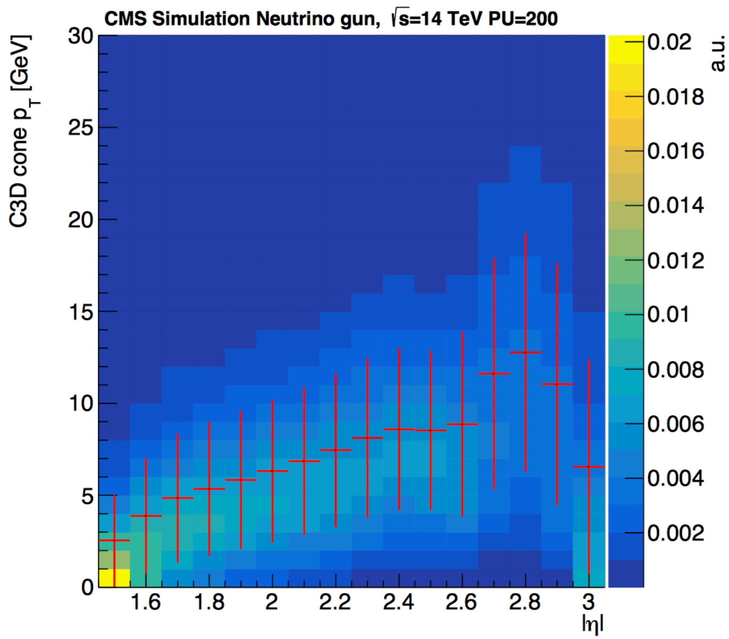
- **Sizeable rate reduction obtained thanks to electron ID criteria**
- **Rate increase from PU 140 to 200 kept under control by limiting the size of 2D clusters**

Object performance: jet pile-up subtraction and calibration

- **Jet reconstruction in the endcaps will be essential to study VBF/VBS processes during Phase 2**

- **Jets built from 3D clusters using anti-kT algorithm with ΔR=0.2:** small cone size to limit impact of PU



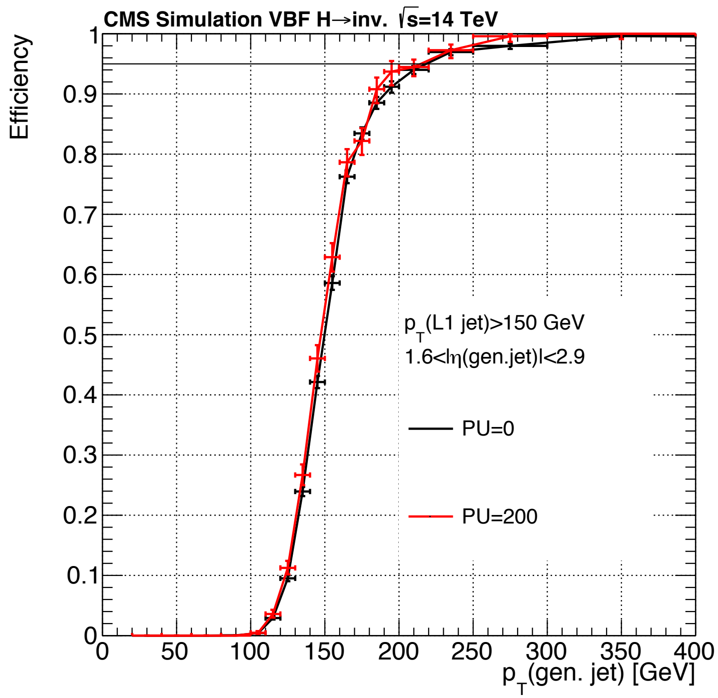


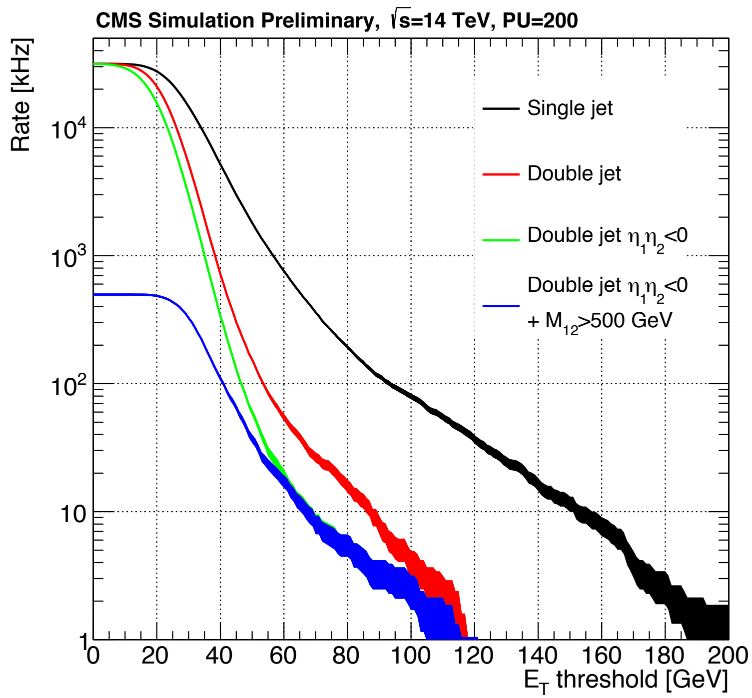
Estimated PU contamination in L1 jets

- **Energy corrections:**
  - η-dependent pile-up subtraction (=PUS)
  - pT-dependent calibration used to correct energy scale wrt anti-kT ΔR=0.4 jets

Object performance: jet efficiency and rate

- Overall good performance of single and double jet triggers: **limited impact of PU**
- **Longitudinal and transverse information** expected to further improve **PU rejection**
- Large improvement of jet trigger performance also expected to come from **Particle-Flow at Level 1 implementation**
- **Topological requirements** can be exploited to significantly reduce the rates





Conclusion

- **HL-LHC conditions will represent a major challenge for the CMS trigger system**

- New HGCAL detector presents **important challenges** in terms of **trigger data bandwidth and processing**
  => developing effective data reduction strategy with limited impact on physics

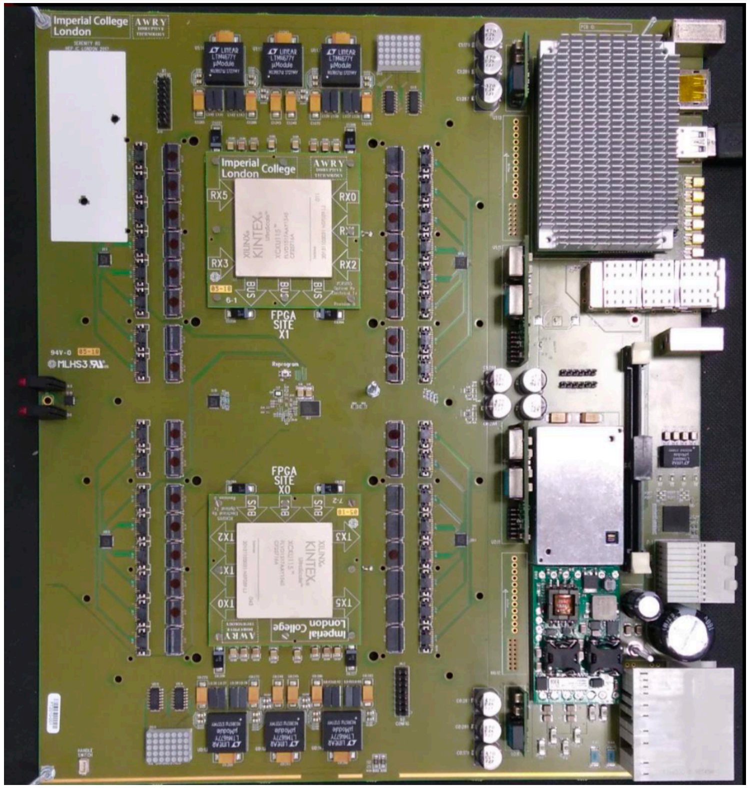
- **A lot of new opportunities to be exploited for trigger object reconstruction:**
  - new longitudinal information to be used for PU mitigation and rate reduction
  - fine granularity to be exploited for correlations with other subdetectors

- **HGCAL trigger object performance very promising:**
  very useful to assess impact of choices regarding the HGCAL trigger primitive generation

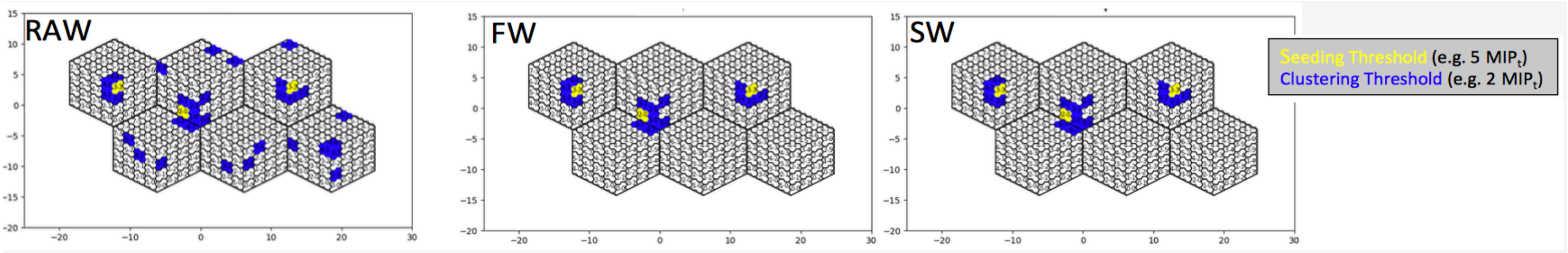
Back-up

Back-end TPG hardware

- **Trigger primitive generation requires boards with high I/O + significant processing power**
- **Generic boards developed for whole CMS trigger + DAQ systems:**
    - ATCA format
    - 96 I/O links up to 16 or 25 Gb/s
    - Ultrascale+ FPGA(s) for processing
- **Stage 1:** 0.5 to 2 boards per layer
- **Stage 1 to Stage 2 transmission x24 time multiplexed:** all data from one endcap to be processed by one single FPGA
- **Firmware implementation and software developments of trigger algorithm closely follow each other**



CMS Serenity board



Back-end data format

Table 8.1: Concept for the layer header data sent from Stage 1 to Stage 2.

Quantities	Bits	Total bits
Total transverse energy, BX number, number of 2D clusters	16, 8, 8	32
Energy map 15 (η) $\times$72 (ϕ)	12	12 960
Total		12 992

Table 8.2: Concept for data per 2D cluster sent from Stage 1 to Stage 2.

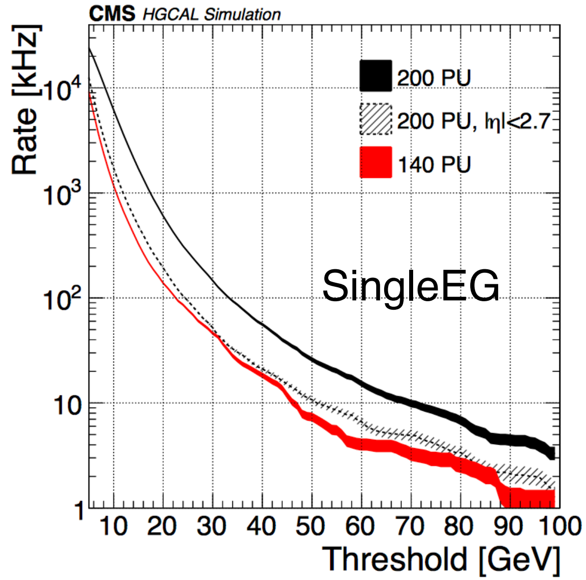
Quantities	Bits	Total bits
x, y, transverse E_T	12, 12, 8	32
Number of cells and local maxima, size in x and y, quality flags	8, 2, 8, 8, 6	32
Minimum total		64
Optional local maximum 0 Δx, Δy, normalised E_T	8, 8, 8	24
Optional local maximum 1 Δx, Δy, normalised E_T	8, 8, 8	24
Optional local maximum 2 Δx, Δy, normalised E_T	8, 8, 8	24
Optional local maximum 3 Δx, Δy, normalised E_T	8, 8, 8	24
Maximum total		160

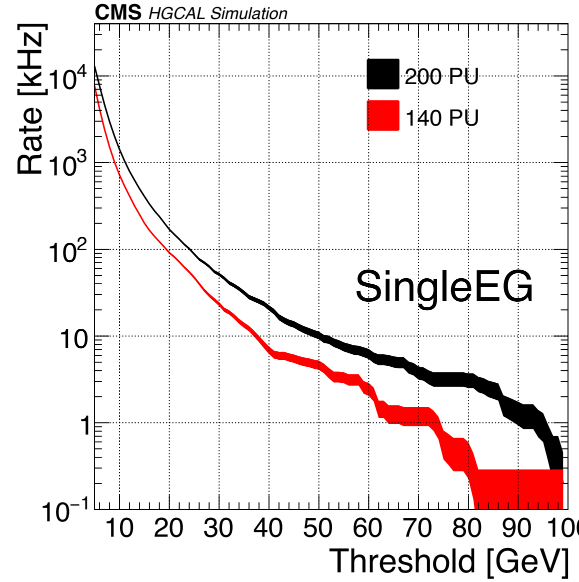
Table 8.3: Concept for the header data sent to the central L1T correlator per BX.

Quantities	Bits	Total bits
Total energy, BX number, number of clusters	16, 8, 8	32
Energy map 15 (η) $\times$72 (ϕ)	16	17 280
Total		17 312

Impact of cluster size restriction

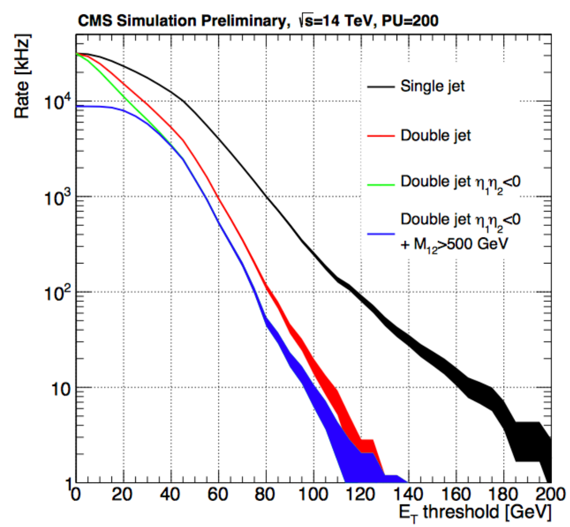
No cluster size restriction | *W/ cluster size restriction*

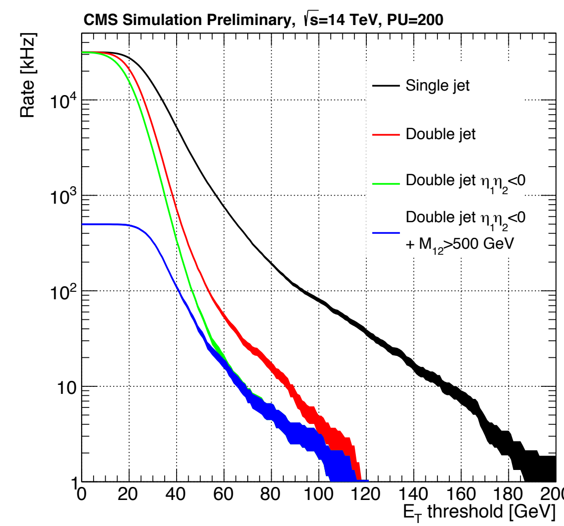




- **Early versions of the 2D clustering did not include size restriction of the clusters**
  => large rate of large high-energy clusters at high η due to high PU activity

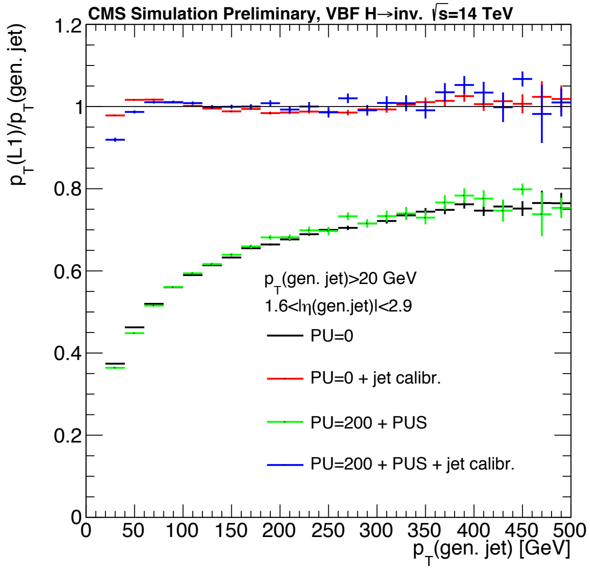
- **Improved in later versions**

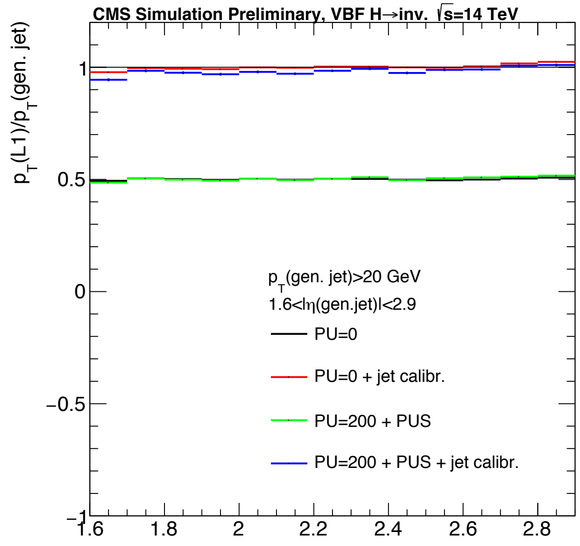




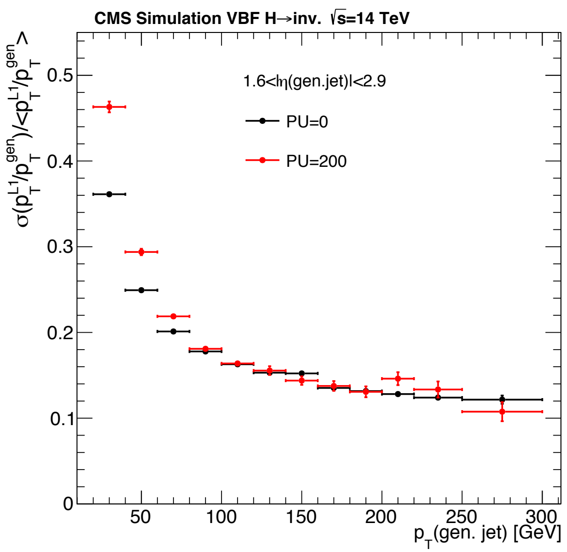
Object performance: jets

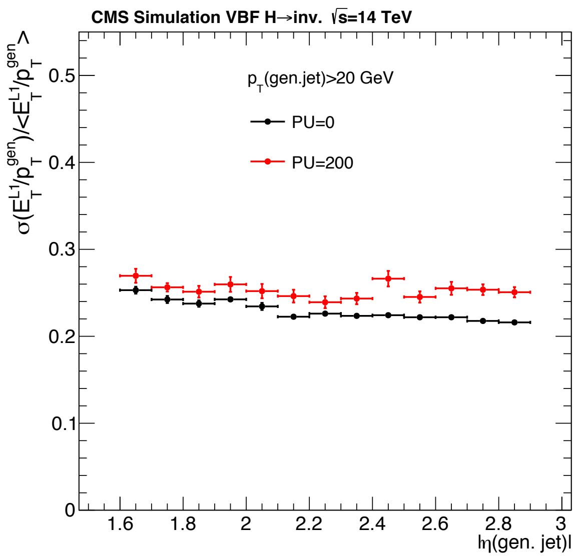
- **Response**





- **Resolution**

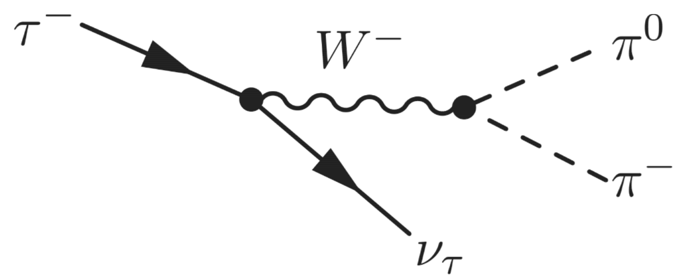




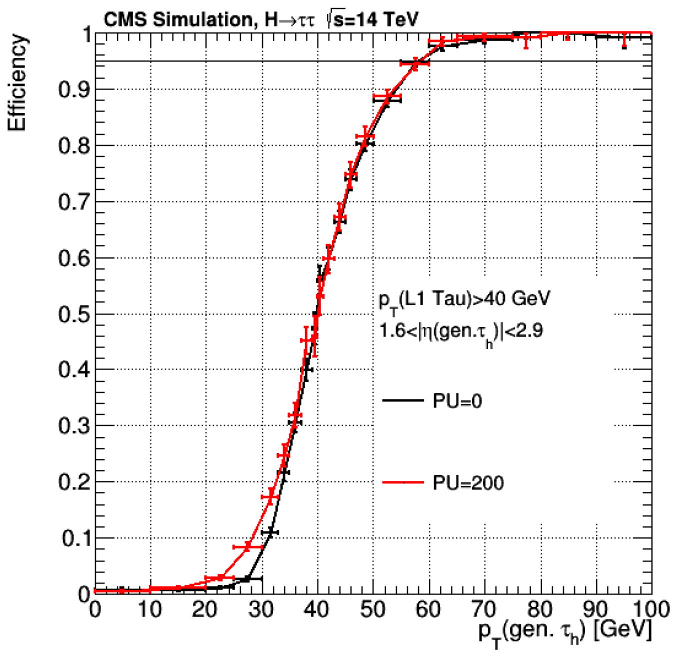
Object performance: hadronic taus

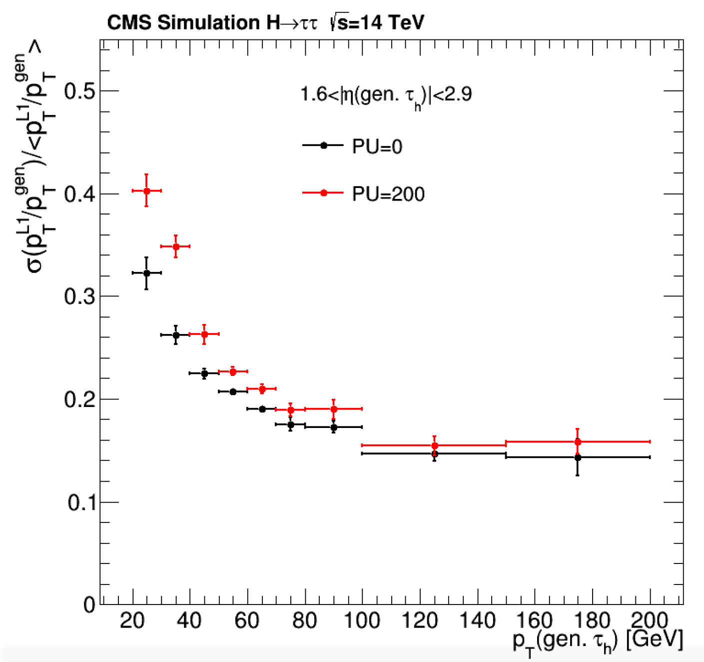
- **Hadronic tau decays important for Higgs physics in LHC Phase 2:** VBF production, double Higgs production…

- **Good trigger performance already achieved with simple adaptation of jet**



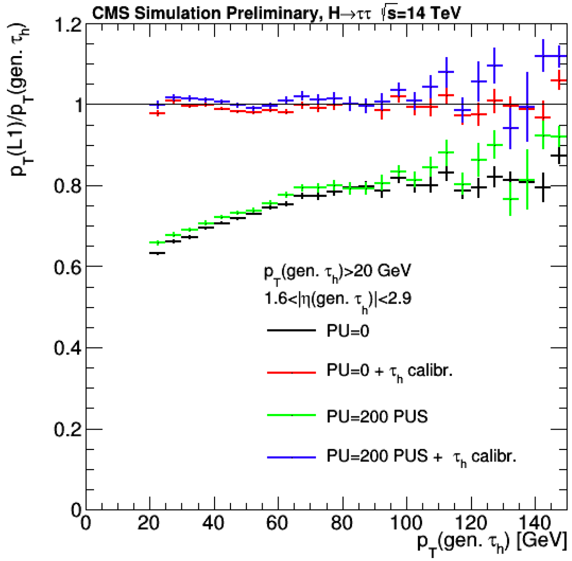
- **Reconstruction of individual calorimeter clusters combined with tracks to be exploited:**
  - in dedicated reconstruction of individual hadronic tau decay modes
  - in definition of PU resilient isolation criteria

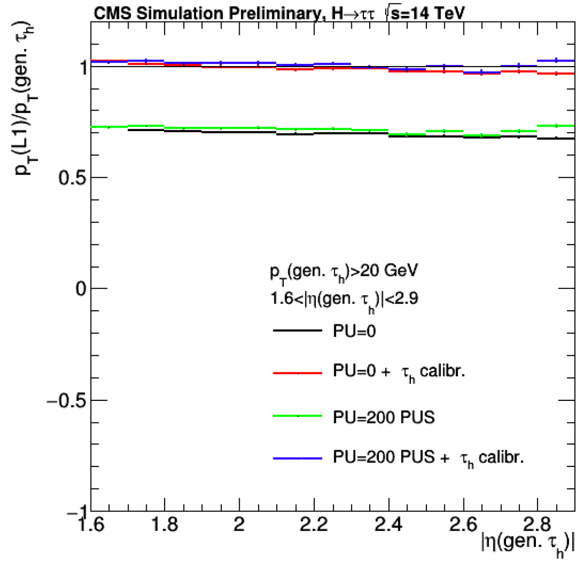




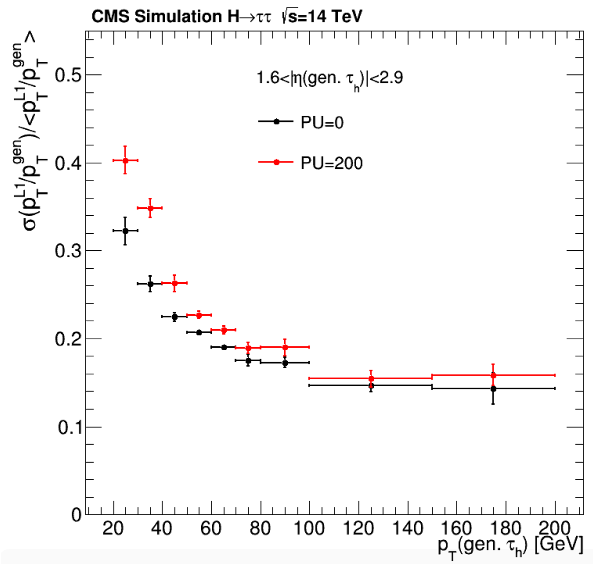
Object performance: hadronic taus

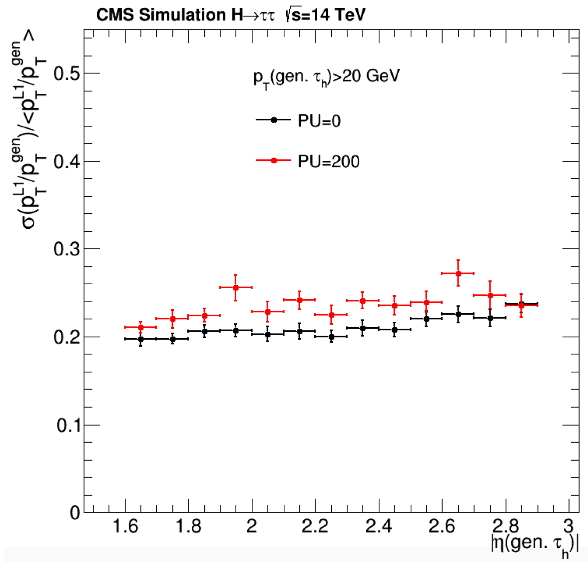
- **Response**



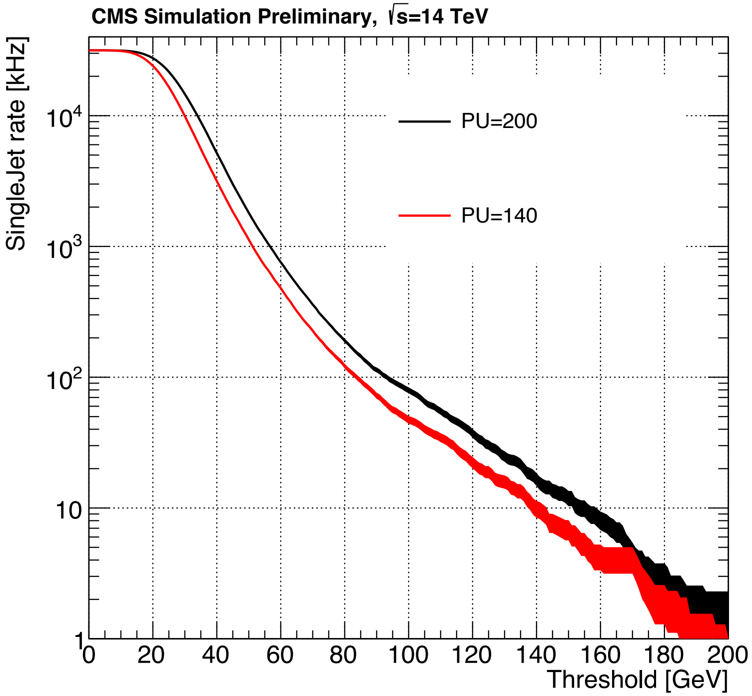


- **Resolution**

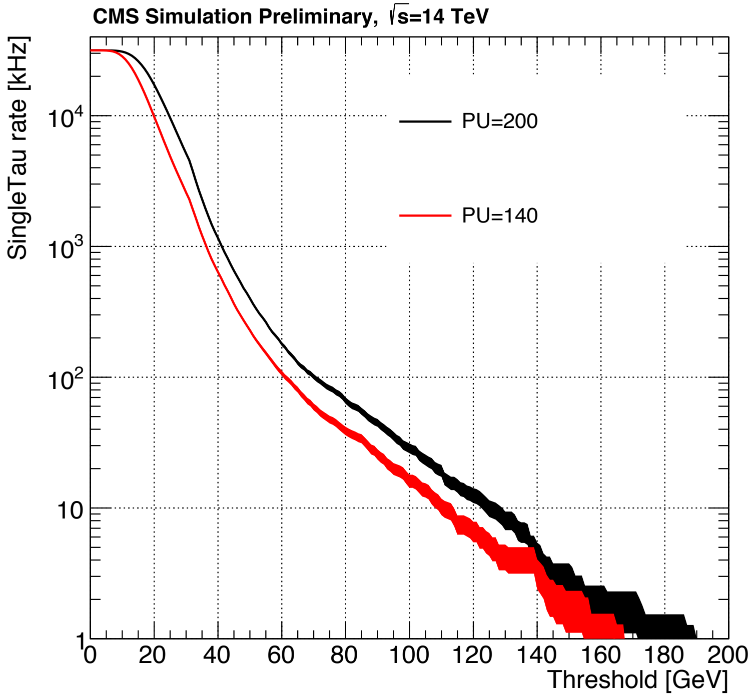




Object performance: hadronic taus



SingleJet



SingleTau