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CMS High Granularity Calorimeter Upgrade

University of Warwick Particle Physics seminar

Samuel Webb

samuel.webb@cern.ch

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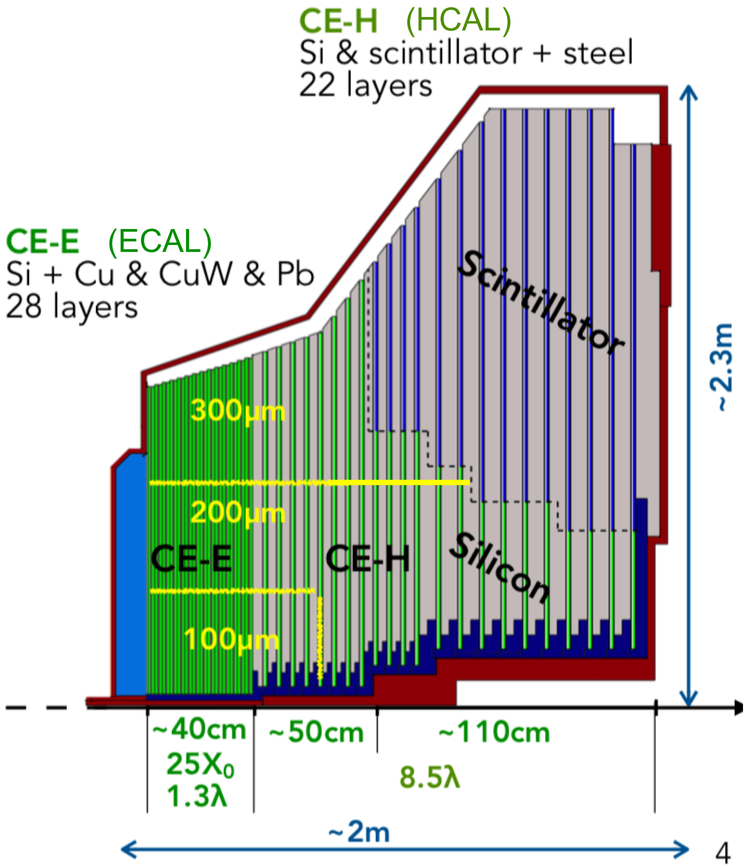
- CMS High Granularity End-cap Calorimeter
  - HGCal
  - Integrated ECAL + HCAL
- Part of the CMS upgrade for the High-Luminosity Large Hadron Collider (starting 2027)



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Why build the high-luminosity LHC?

Driven by a desire to better understand rare processes

- di-Higgs production
- vector boson scattering
- potential beyond-SM processes

Simply need many (factor 10) more events

Adverse consequences for CMS

- Greater number of interactions per bunch crossing (pileup)
  - Implications for detector occupancy and trigger
- Much higher radiation levels

Current end-cap calorimeter not suitable for these conditions → HGCal

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Physics motivation for HL-LHC

For more information see:

Report on the Physics at the HL-LHC,and Perspectives for the HE-LHC

CERN Yellow Reports: Monographs, 7/2019

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Motivation – Higgs physics

- Run 1: Discovery of Higgs boson, using decays to bosons
  - H → WW
  - H → Z Z
  - (H → γ γ)

  (H → WW, H → ZZ: Coupling proportional to square of mass; H → γγ: Loop coupling)
- Run 2: Establish couplings to 3rd generation fermions
  - H → τ τ
  - H → b $\bar{b}$

  (Coupling directly proportional to mass)
- **High-Lumi LHC**
  - Coupling to 2nd generation fermions, particularly H → μμ
  - **Higgs self-coupling**

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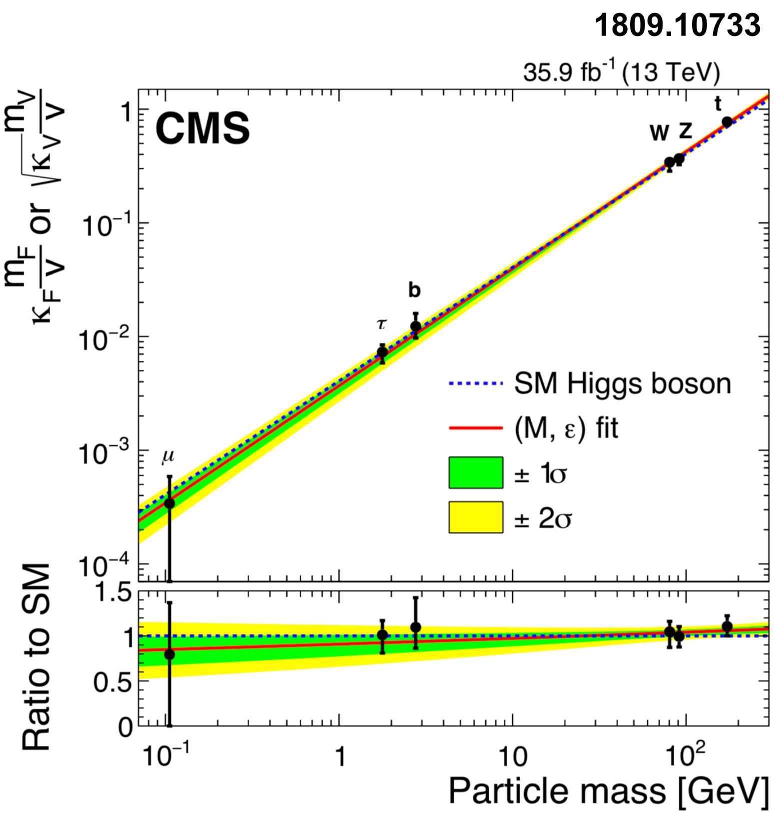

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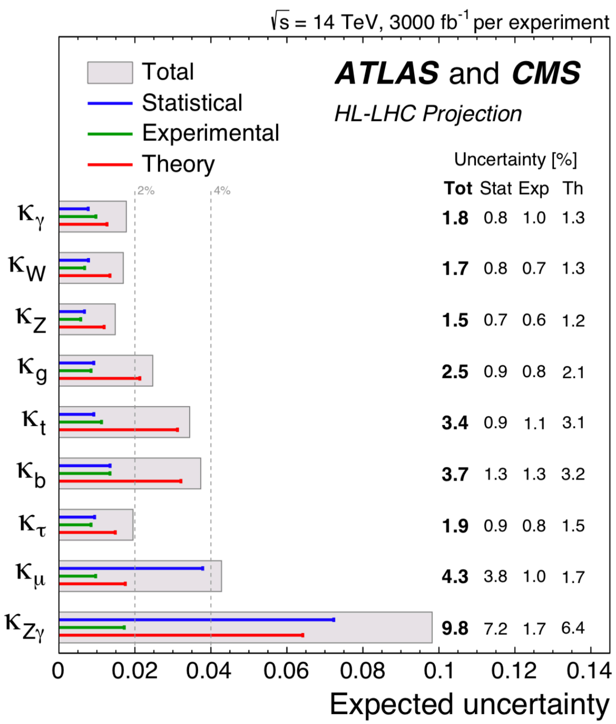
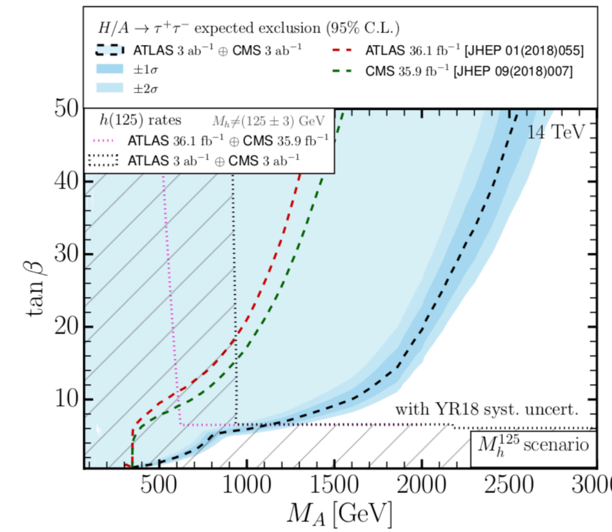
Motivation – Higgs physics



- Higgs SM couplings will be measured to the percent level
- Large statistics will particularly help with complex final states
- Assuming SM couplings 4σ evidence for HH (ATLAS+CMS)

- Large statistics will improve sensitivity to new Higgs bosons.
- One example decaying to $\tau^+\tau^-$ will have reach up to 2.5 TeV for tan β > 50.



https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHELHCWorkshop

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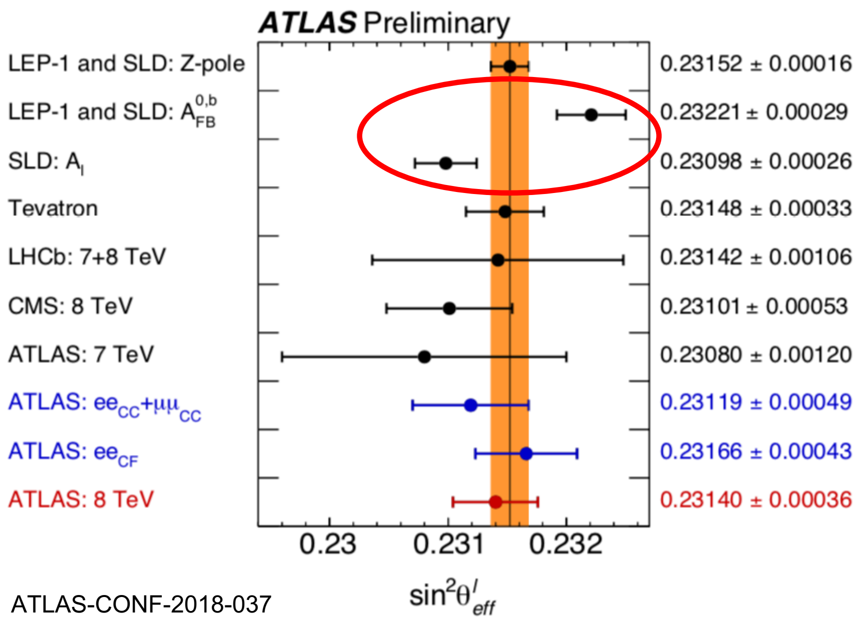
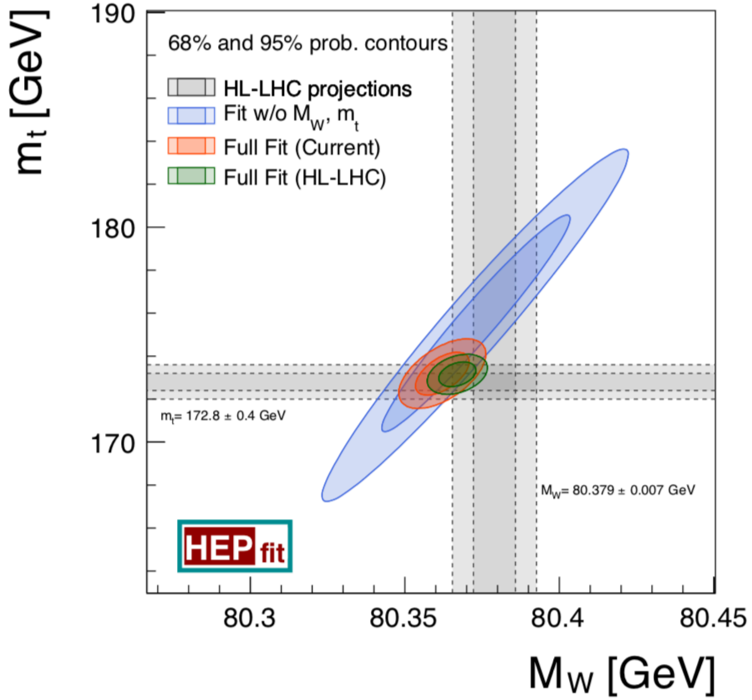
Motivation – SM physics



ATLAS-CONF-2018-037



- Precise measurement of weak mixing angle can help resolve discrepancy between complementary results from LEP and SLD
- Single measurement as good as current world average (PDF uncertainty still dominates)

- W boson mass uncertainty of 7 MeV (current world average 12 MeV)
- Higher statistics
- Increased constraint of PDFs (extended leptonic coverage)

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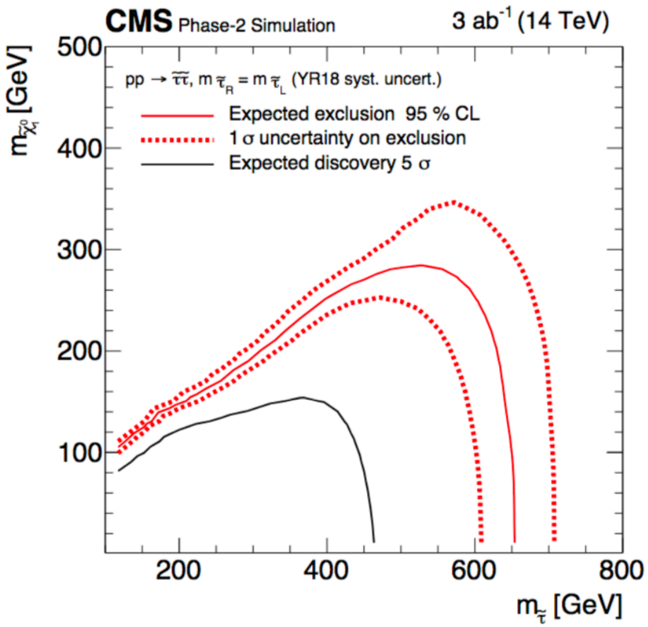
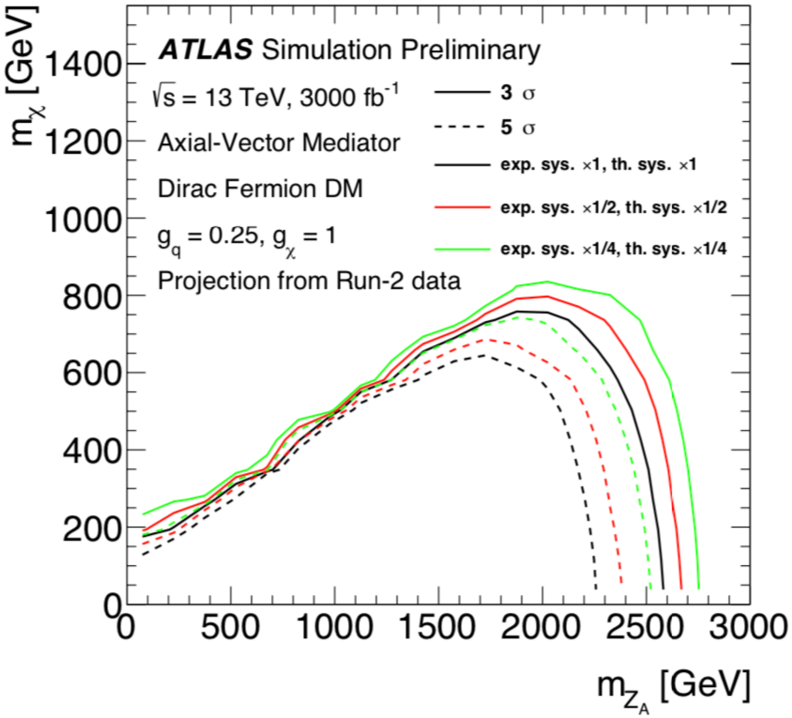
Motivation – Beyond the SM





- Large increase in sensitivity to Super-Symmetry signatures
- E.g. di-stau production
  - Only excluding ~100 GeV currently
  - Will be able to reach up to 500 GeV for discovery

- Searches for Dark Matter will have a much improved discovery reach - on the order of a TeV when using the monojet + missing energy signature

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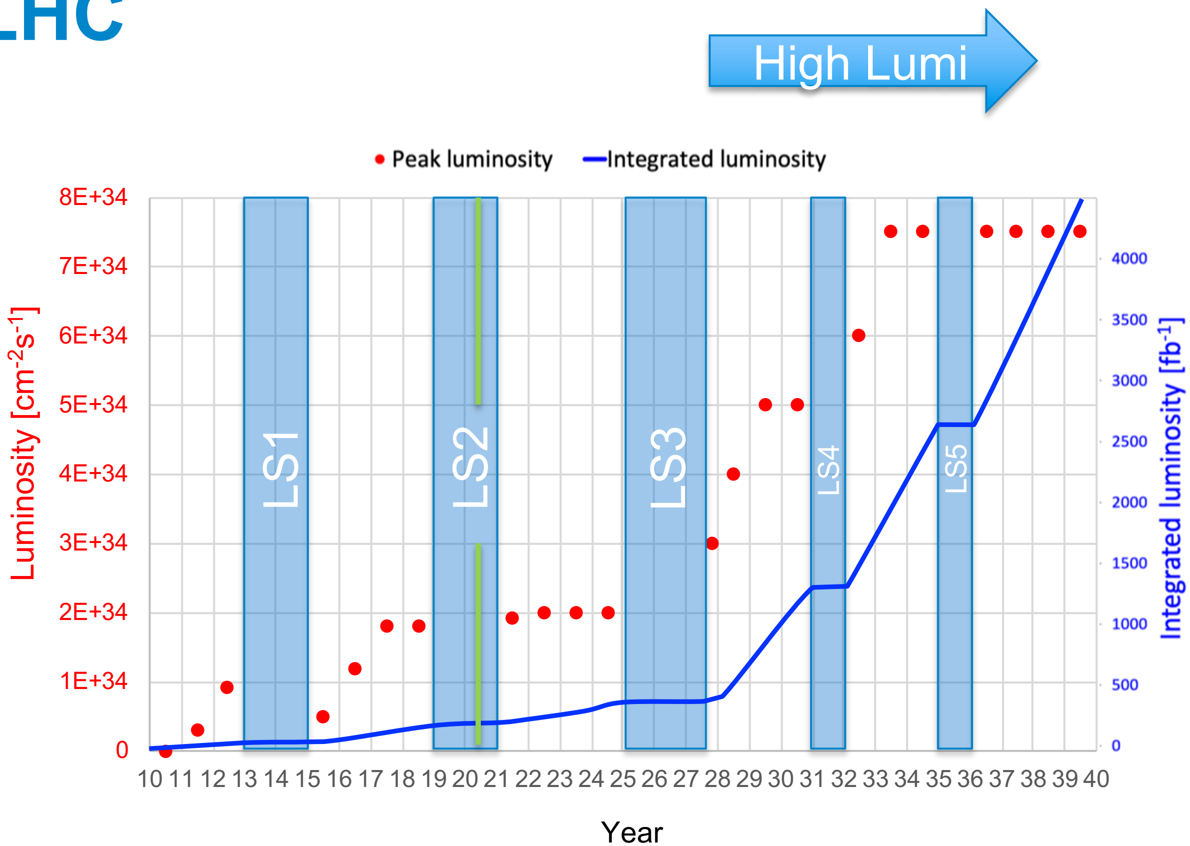
High-luminosity LHC

- Increased luminosity – typically 140-200 proton-proton interactions per bunch crossing
- Up to 250 fb^{-1} per year yielding ~3000 fb^{-1} by end of run
- Starting ~2027
  - Schedule recently pushed back by 1 year



Thanks to Sudan Paramesvaran for input to some of the following slides

System must be able to cope with higher radiation and more collisions per bunch crossing

CMS HL-LHC upgrades

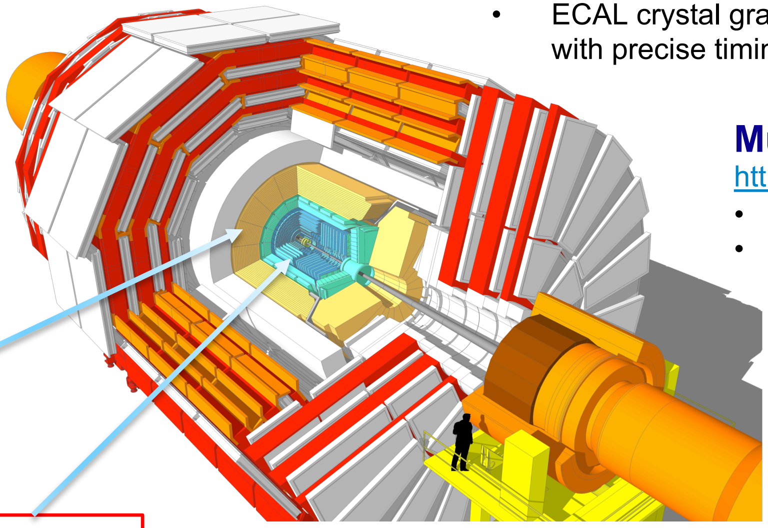
Technical proposal CERN-LHCC-2015-010 https://cds.cern.ch/record/2020886
Scope Document CERN-LHCC-2015-019 https://cds.cern.ch/record/2055167

L1-Trigger/HLT/DAQ
https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193

- Tracks in L1-Trigger at 40 MHz
- Particle-flow-like selection
  750 kHz output
- HLT output 7.5 kHz

Barrel Calorimeters
https://cds.cern.ch/record/2283187

- ECAL crystal granularity readout at 40 MHz with precise timing for e/ɣ at 30 GeV



Muon systems
https://cds.cern.ch/record/2283189

- New GEM/RPC 1.6 < η < 2.4
- Extended coverage to η ≃ 3

End-cap Calorimeter (HGCal)
https://cds.cern.ch/record/2293646

- 3D showers and precise timing
- Si, Scint+SiPM in Cu Pb/W-SS

Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure
https://cds.cern.ch/record/2020886

Tracker
https://cds.cern.ch/record/2272264

- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to η≃3.8

MIP Timing Detector
https://cds.cern.ch/record/2296612

- Precision timing with Crystals + SiPMs (Barrel layer) and Low Gain Avalance Diodes (Endcap layer)

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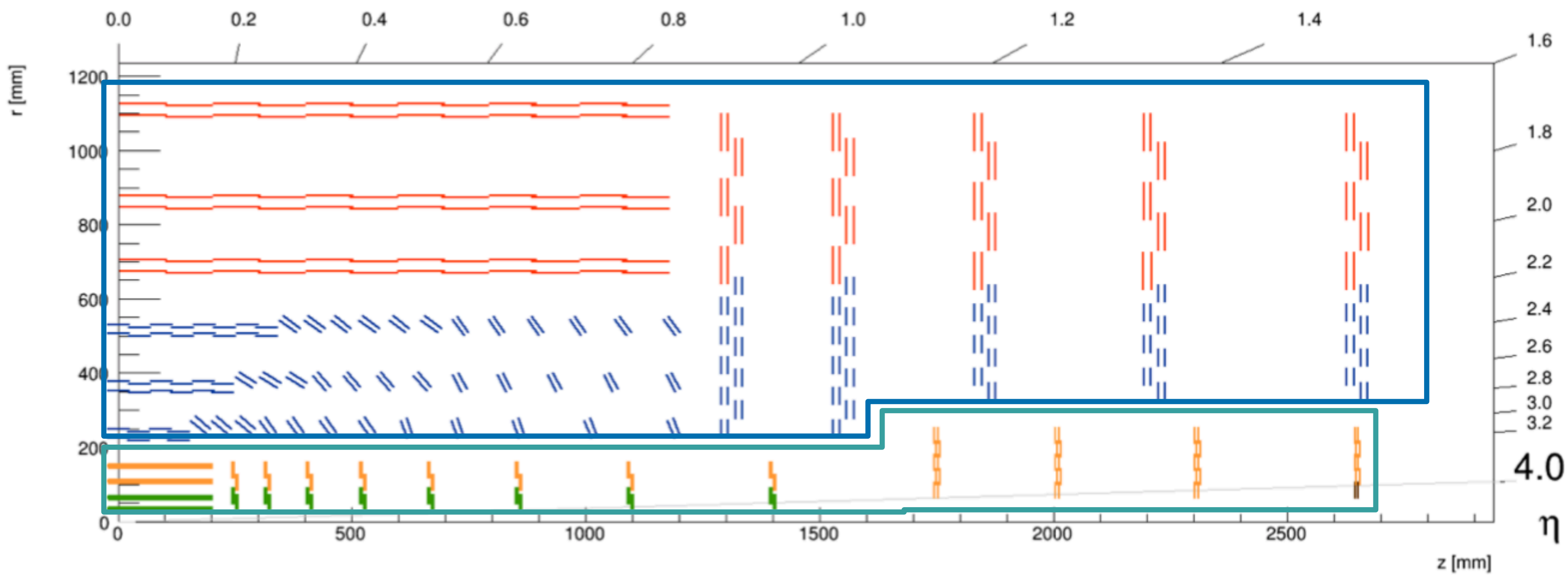
Tracker upgrade



Inner Tracker

- Tracking up to η=4
- 2×10^9 pixels
    - Thin, radiation hard

Outer Tracker

- 13200 "Pt modules" (providing L1 Trigger primitives):
    - Trigger coverage up to |η| ~ 2.4
- Occupancy < 1%

Tracking in the Level-1 trigger

- Better trigger selectivity needed to exploit high luminosity
  - In turn gives a better p_T resolution and e-γ discrimination
- Inclusion of data from the Outer Tracker at L1 (down to η=2.4)

C. Caillol, S. Paoletti

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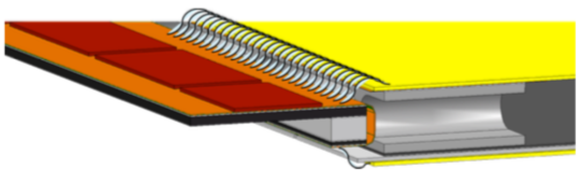

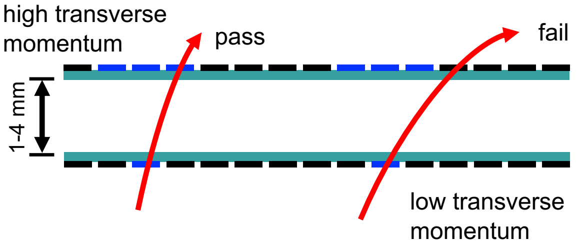

Forming track "Stubs"

- Two silicon sensors with small spacing in a module
- One ASIC correlates data from both sensors selecting tracker "stubs"

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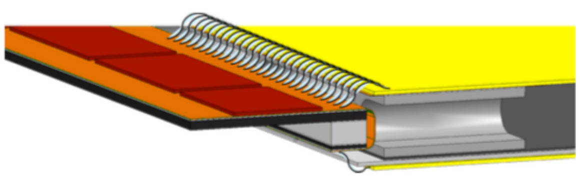
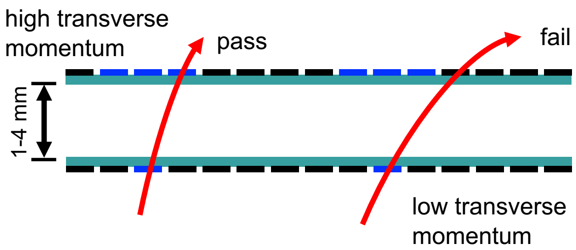
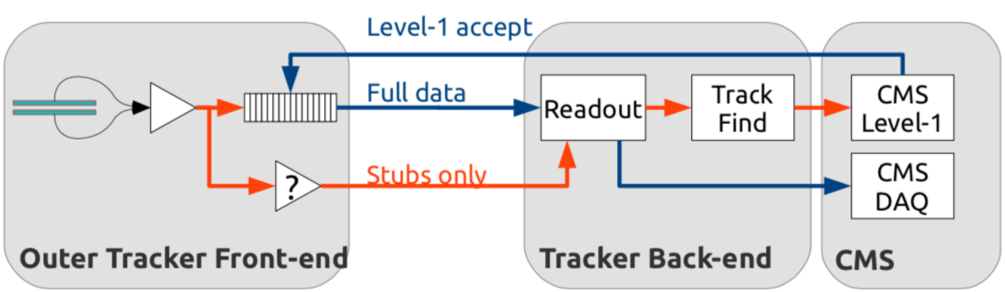




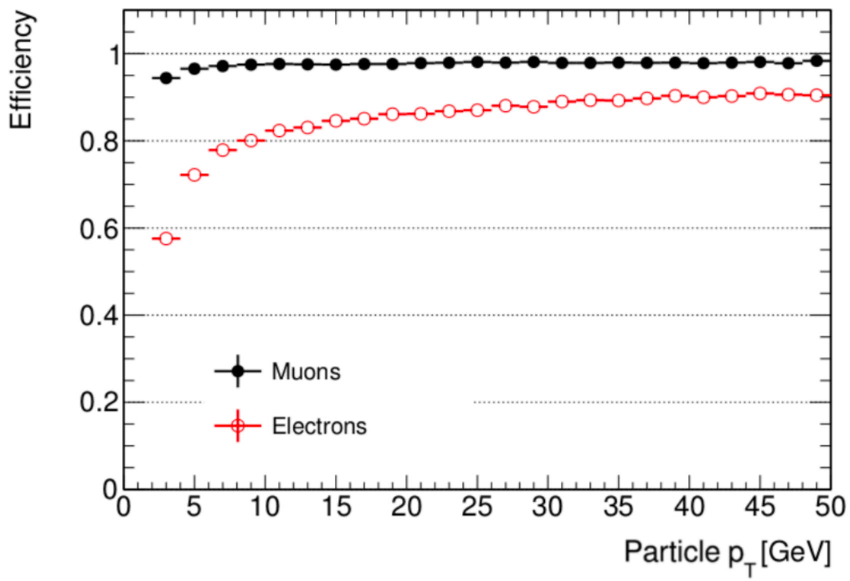
The "stubs" are sent to the FPGA-based track finder backend, and used to create L1 track primitives with p_T > 2 GeV @ 40MHz

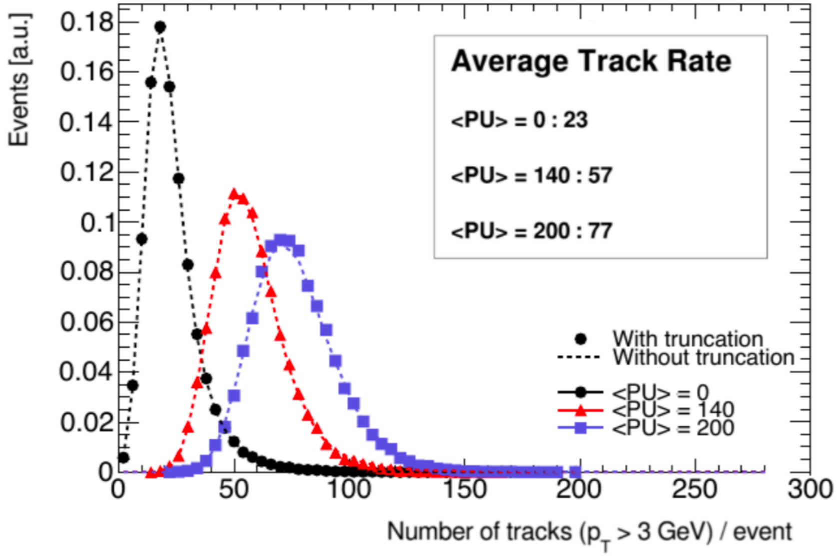
The vast majority of tracks have low p_T and can be discarded from L1



C. Caillol, S. Paoletti

Tracking in the Level-1 trigger





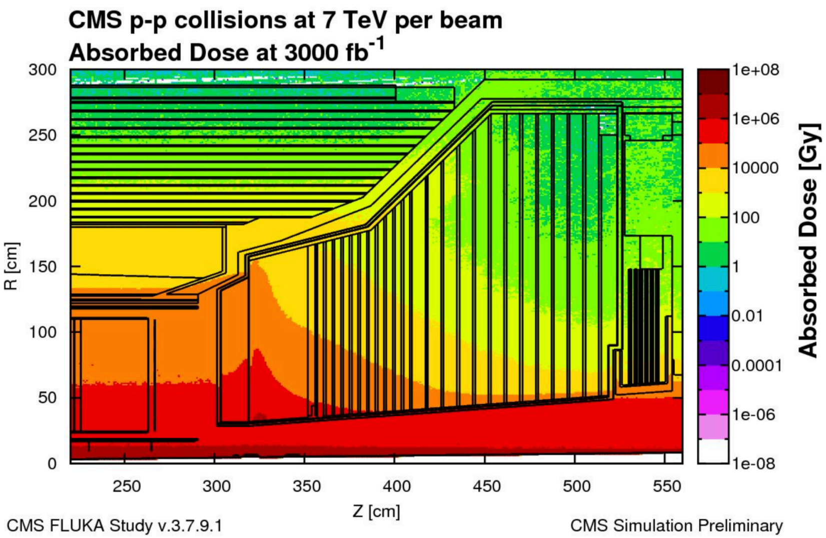
- L1 tracking efficiency vs p_T
- Muon turn-on around 3 GeV (stub threshold)

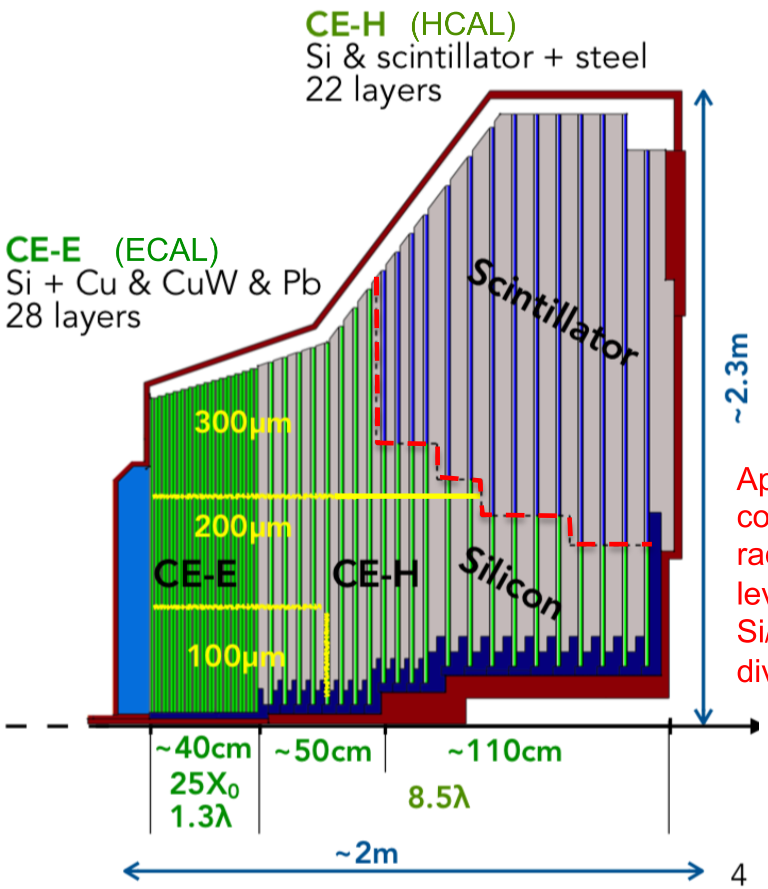
- Total L1 track rate for $t\bar{t}$ events
- The total rate for 200 pileup events is easily accommodated by the downstream L1 trigger processor

CMS-TDR-014

High-granularity end-cap calorimeter (HGCal)

Machine requirements
- Very high fluence and absorbed dose in forward region
  - Silicon sensors for the bulk of the calorimeter
  - Plastic scintillator tiles at the rear





Approx. constant radiation levels along Si/Scint division line

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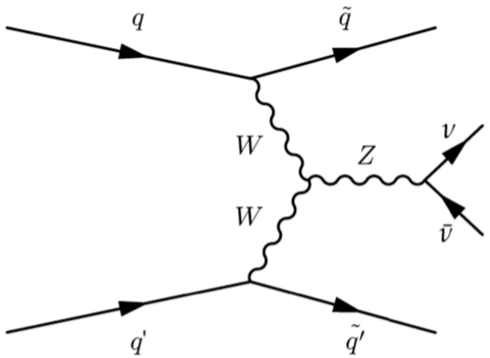
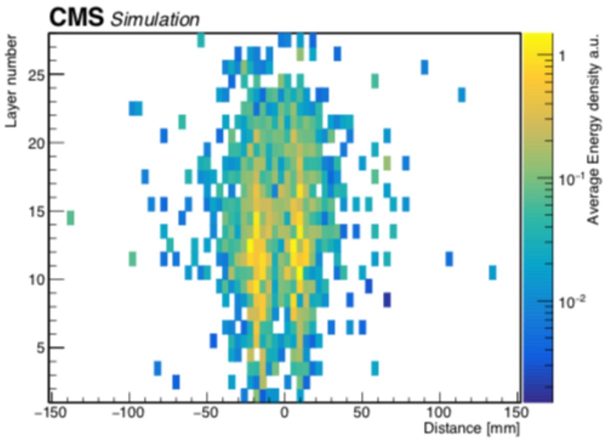
High-granularity end-cap calorimeter (HGCal)

Physics motivation

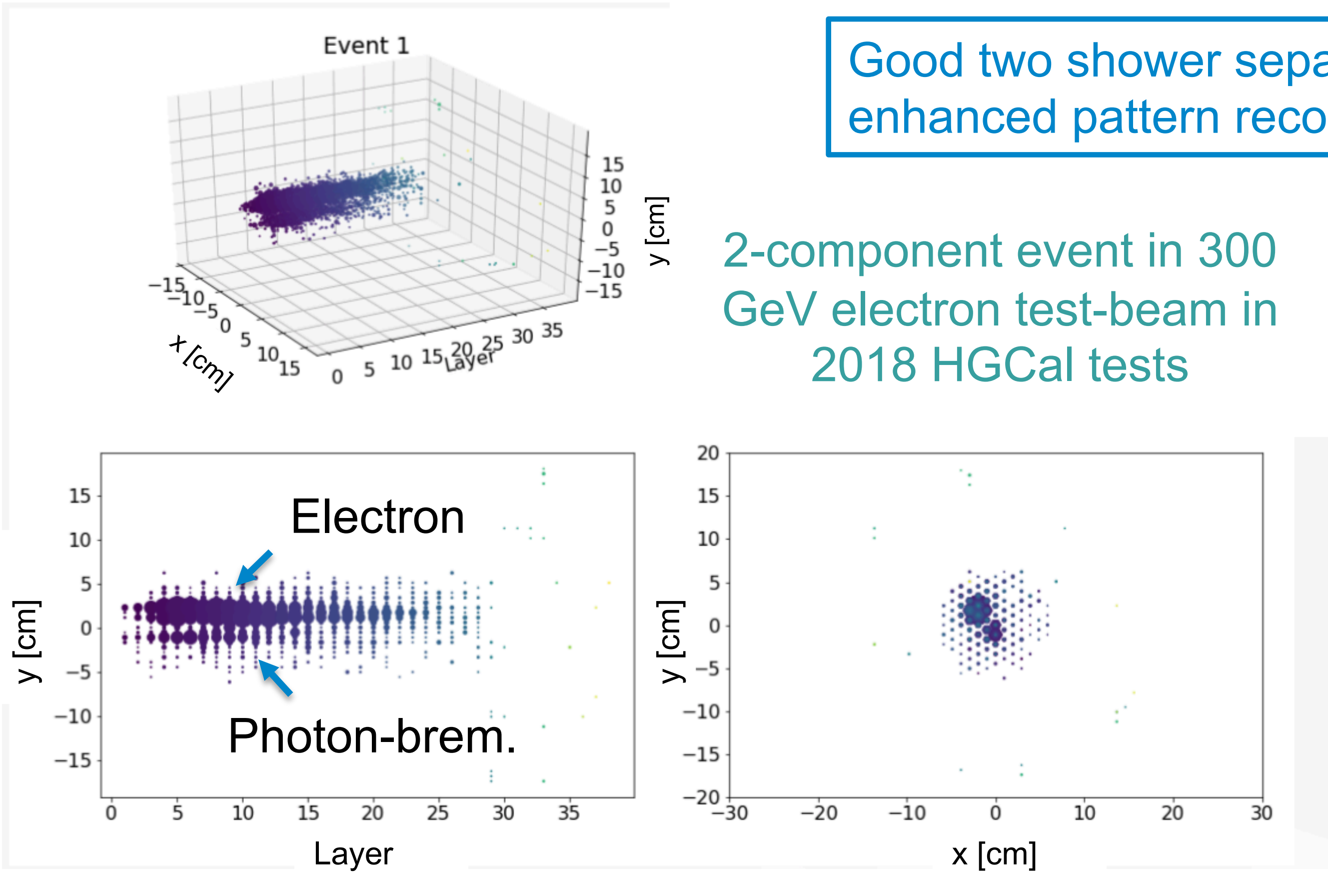
- Boosted topologies more relevant in end-cap
  - Need for high-granularity
  - Fine longitudinal readout segmentation
  - Good performance up to η=3.0 (complements tracker upgrade)
- Exploit VBF production
  - Narrow jets also benefit from high-granularity





14 GeV p_T photons at η=2.4 with 3 cm separation (single event simulated)

Advantages of high granularity – e / γ



Good two shower separation with enhanced pattern recognition

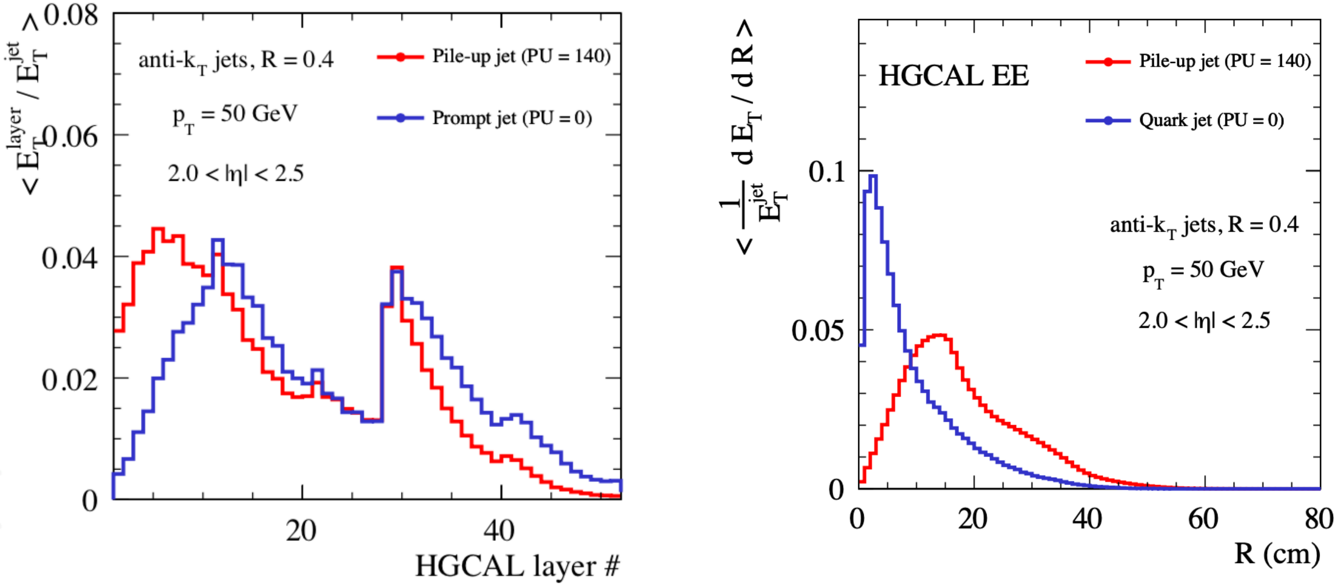
2-component event in 300 GeV electron test-beam in 2018 HGCal tests

A. Martelli, A. Lobanov

Advantages of high granularity – jets

Longitudinal and lateral energy profiles

Transverse energy deposited as a function of layer



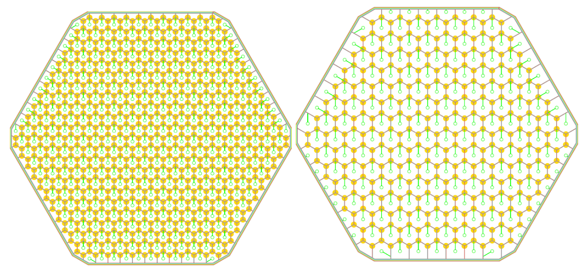
Radial profile of jets in the HGCAL ECAL

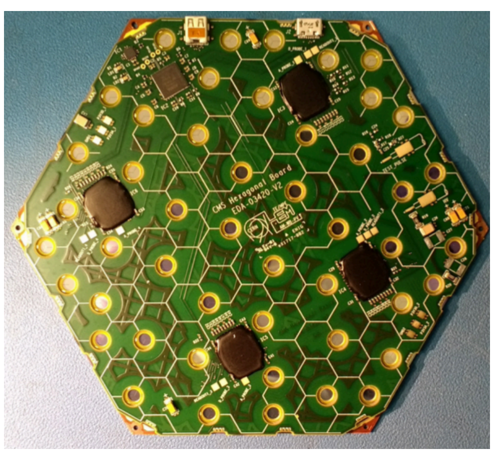
High granularity gives potential for separation of PU jets (mostly soft gluon jets) from interesting quark jets (e.g. from VBF)

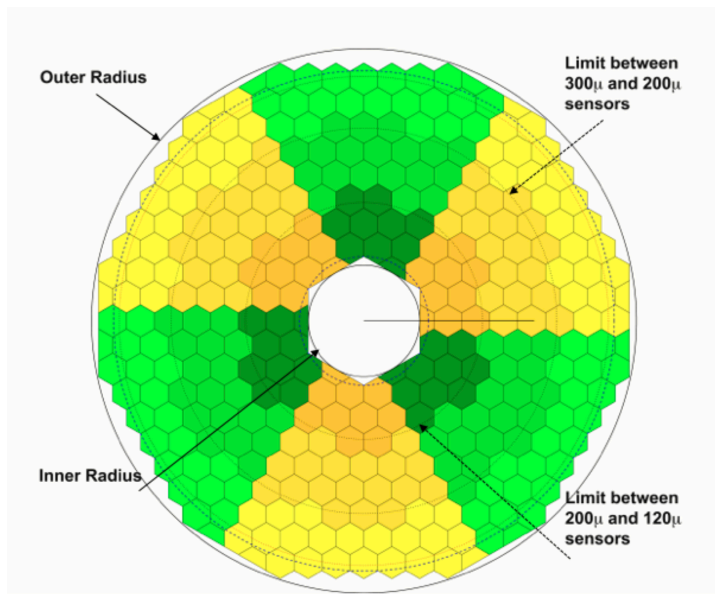
→ Useful for resolving boosted topologies, top-, VBF- and tau-tagging

Silicon Geometry

- Hexagonal silicon modules, "Hexaboards", to make most efficient use of circular 8 inch silicon wafers
- Hexagonal sensor cells within







High density silicon modules
- 432 sensor cells ($0.52\ cm^2$)
- Thickness 120 μm

Low density modules
- 192 sensor cells ($1.18\ cm^2$)
- Thickness 200 or 300 μm depending on radius (radiation levels)

3 (low density) or 6 (high density) readout ASICs per module, "HGCROCs"

A. Martelli, CMS-TDR-17-007

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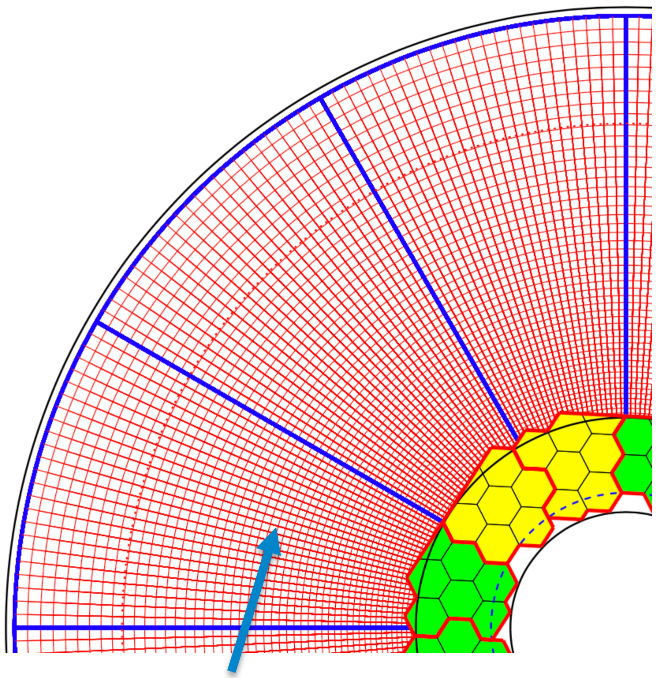
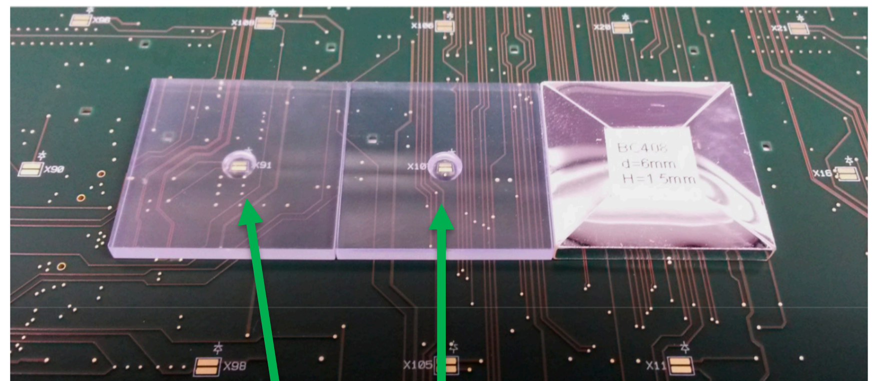
Scintillator Geometry (in mixed layers)





Plastic scintillator tiles (~3x3 cm) used in regions of lower radiation

Scintillation light read-out by SiPMs (silicon photo-multipliers) mounted on a PCB

Maral Alyari, CMS-TDR-17-007

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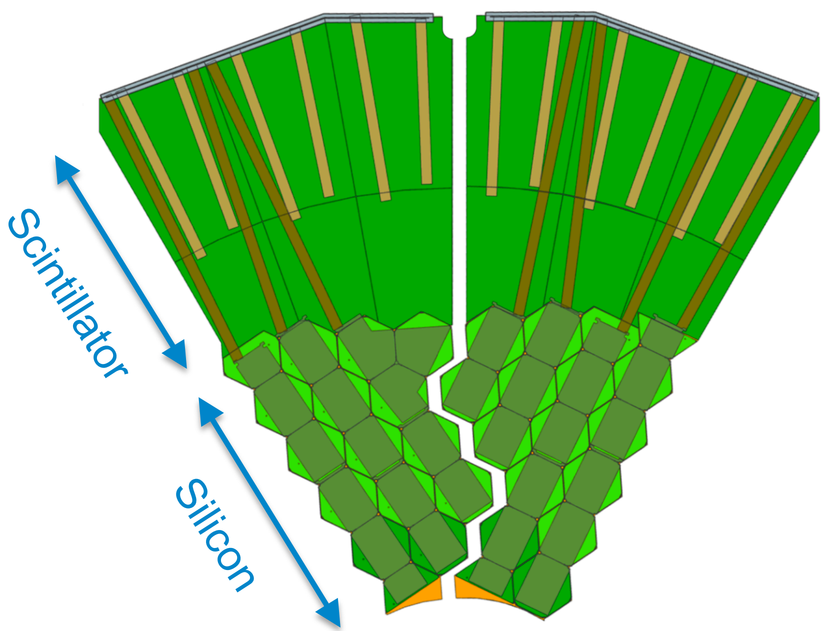
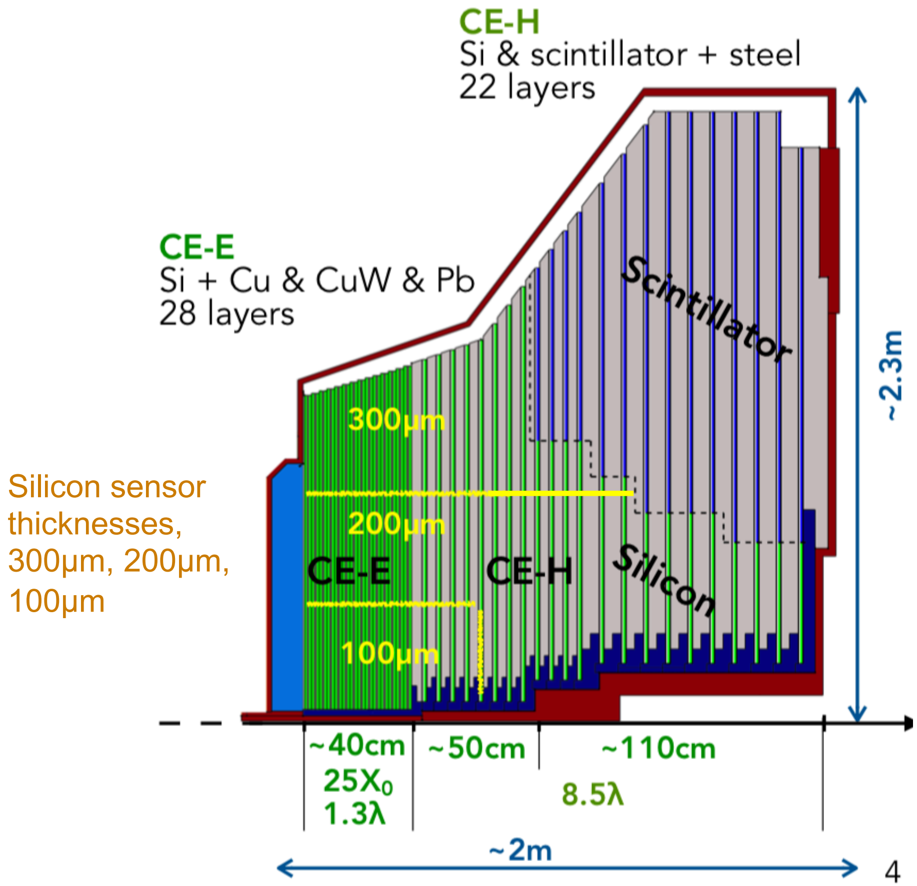
HGCal Geometry



Modules are assembled into 30° or 60° cassettes
Here: two mixed silicon/scintillator cassettes corresponding to CE-H layer 12.



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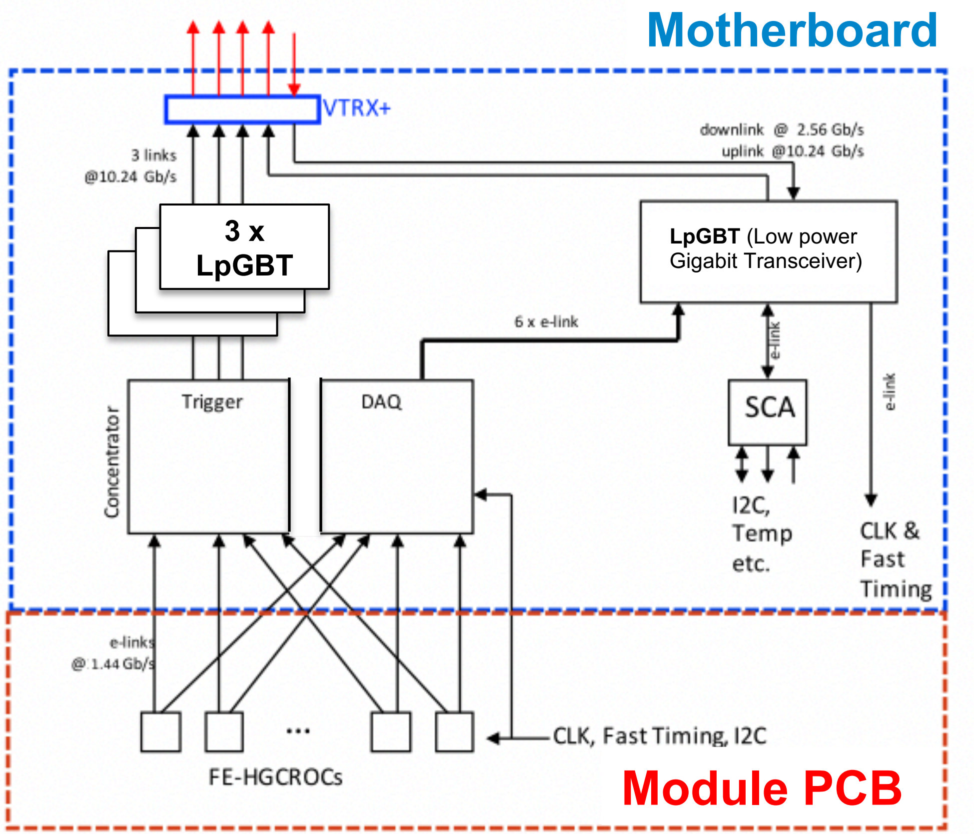
Front-end (on-detector) Electronics

Data sent out on optical fibres via the VTRX+ (versatile transceiver plus)

Charge sums sent to trigger concentrator (see later)

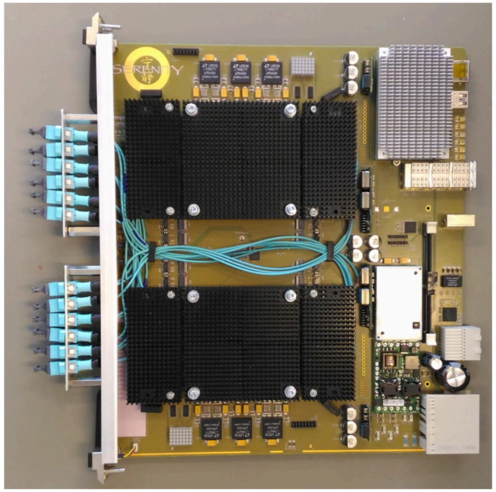
In parallel, after a Level-1 Trigger accept data is sent to concentrator ASIC and zero suppressed

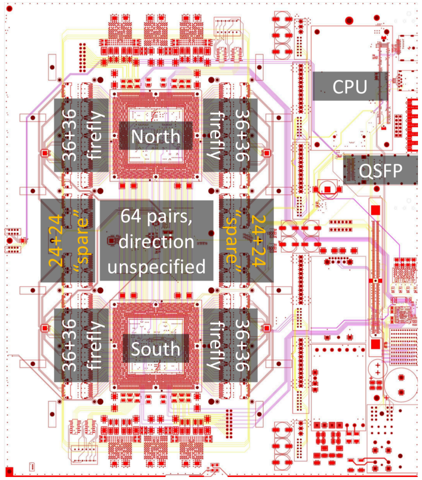
Silicon sensor pads connected to HGCROCs
- measures charge and time of arrival at 40MHz



Back-end (off-detector) Electronics

- Prototype ATCA card (Advanced Telecommunications Computing Architecture) to provide *back-end* electronic services for CMS: Serenity
  - Dual FPGA card board
  - Flexible, pluggable FPGA units
  - Generic, open processing platform



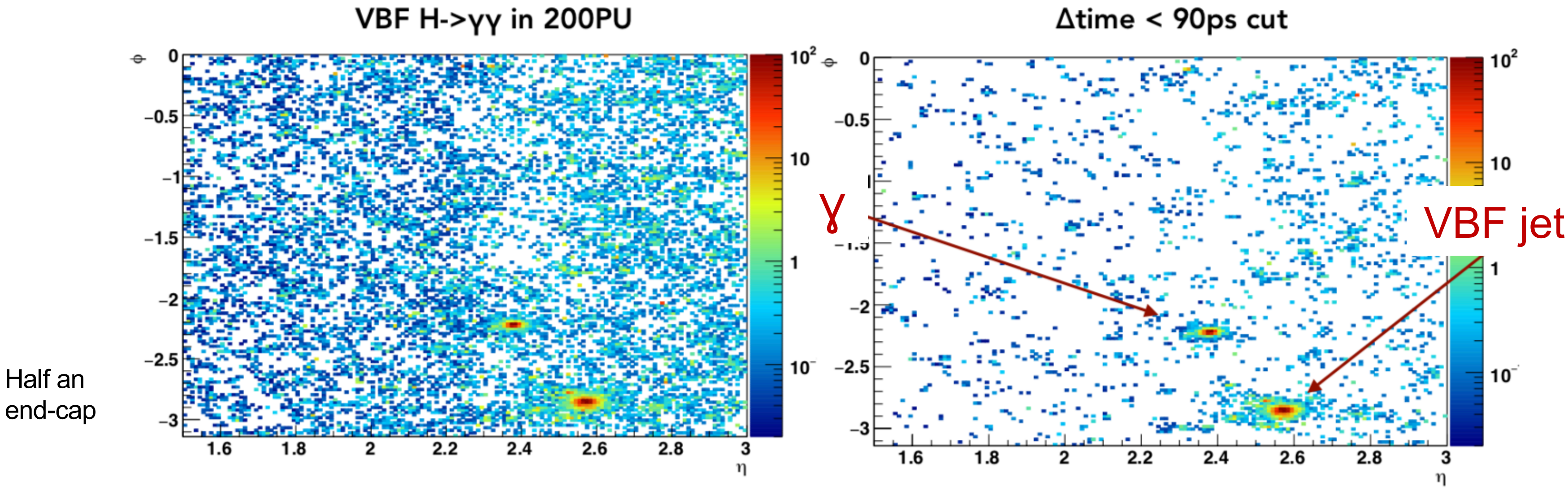


- Originated out of the UK CMS collaboration
- **Common** Back-end electronics for:
  - HGCal trigger and DAQ
  - Outer-tracker readout
  - L1 trigger

7Tb/s: 288 fibres @ 25Gb/s

Particle reconstruction overview

- Potential for 5D reconstruction (x,y,z, energy + time)



Powerful way to mitigate pileup
- allows a reduced PU effect on jet reconstruction and energy estimate

Improve track → vertex association, better b-tagging and lepton isolation

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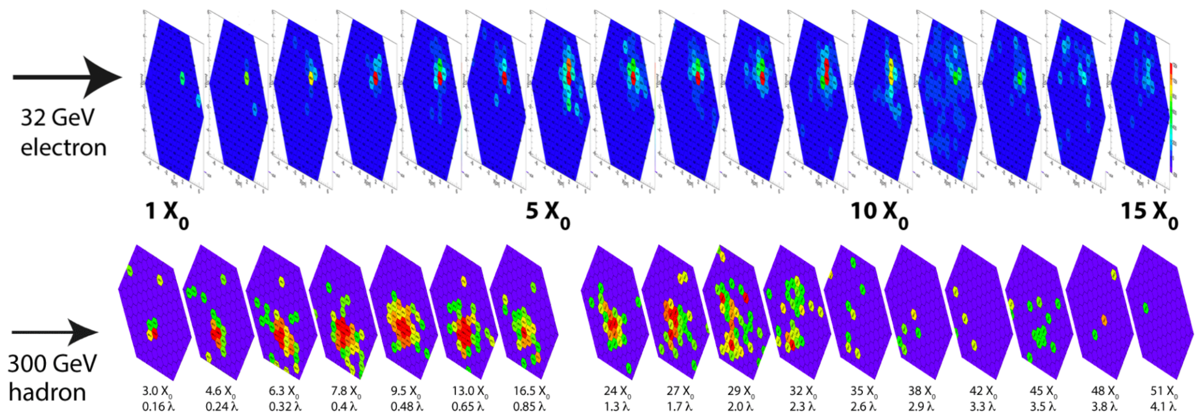
Particle reconstruction overview

1. Form ‘RecHits’ from the recorded digital signals (calibrated to correspond to energy lost in absorber layers)

Test beam event display (coloured points are RecHits)



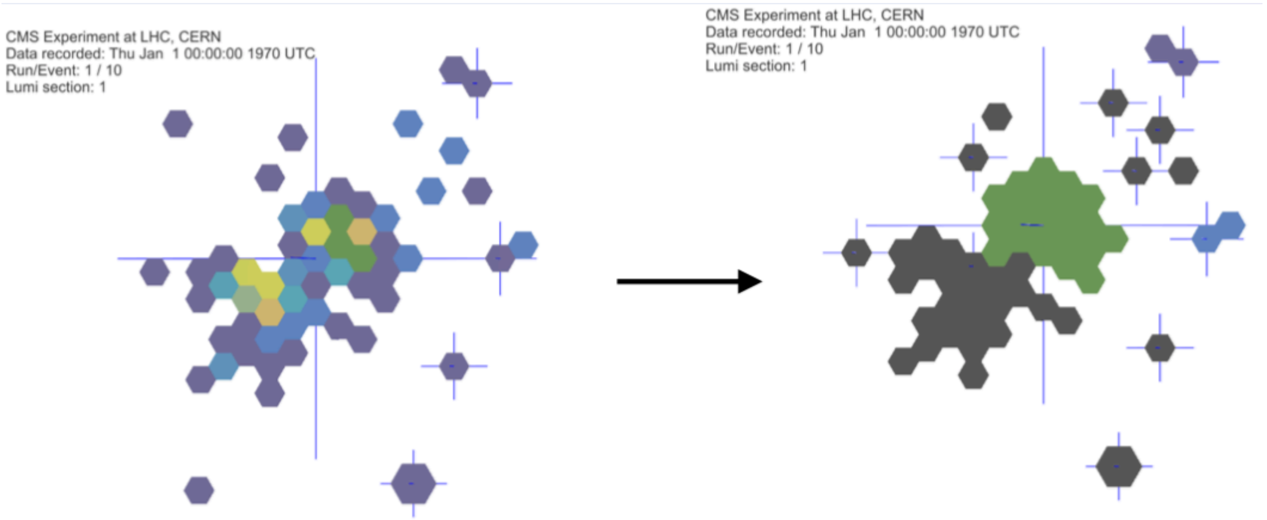
2. Cluster RecHits into 2D objects – “Layer Clusters”

3. Cluster Layer Clusters into track-like objects – “Tracksters”

Forming 2D Layer-Clusters

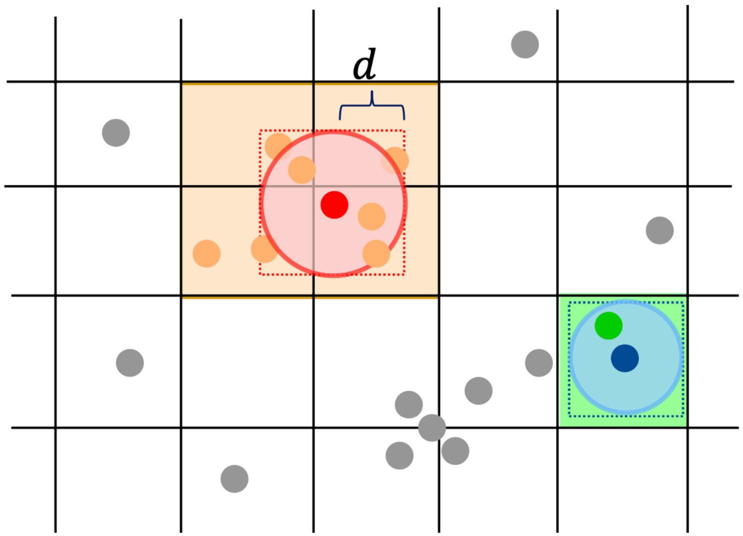
CLUE (clustering by energy) algorithm

- Go from ~10^5 RecHits to ~10^4 Layer-Clusters
- Small clusters, fast and good for processing on GPUs

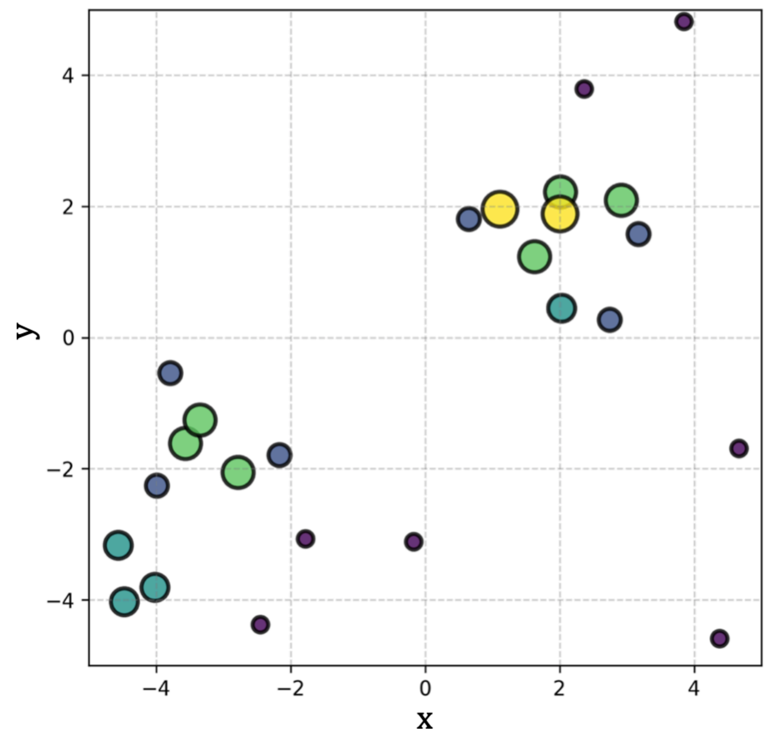


A Di Pilato, Z Chen

CLUE algorithm



1. Build “Grid Spatial Index”
   - Search box formed of tiles touched by a window of size ’d’ around RecHit



2. Calculate local density at each hit (using search box)
   - Fast query

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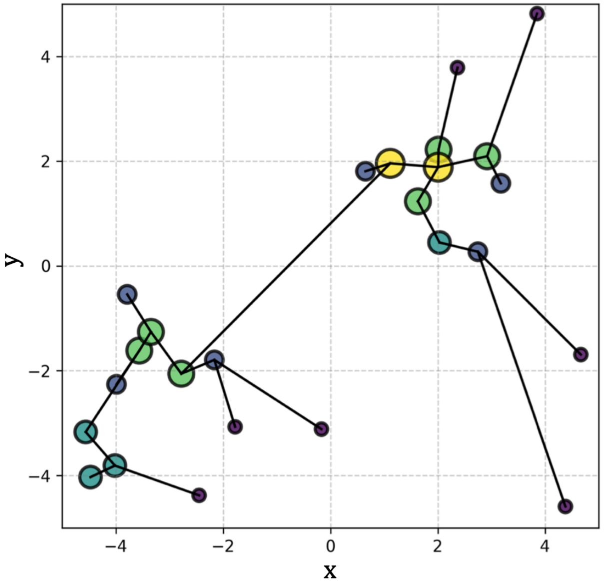
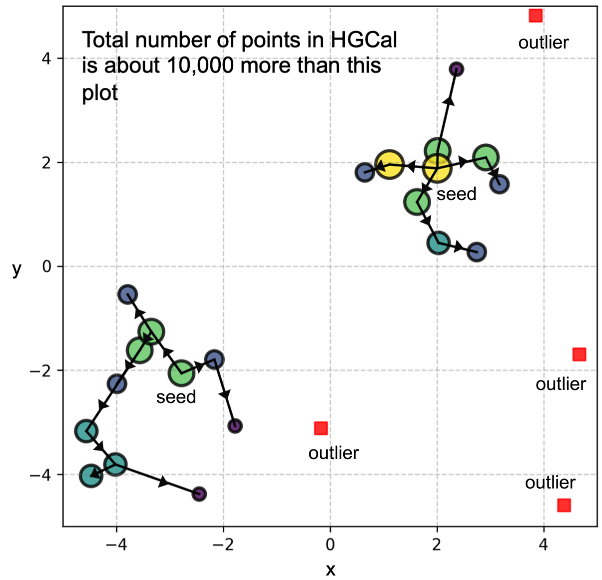




4) Seeding step

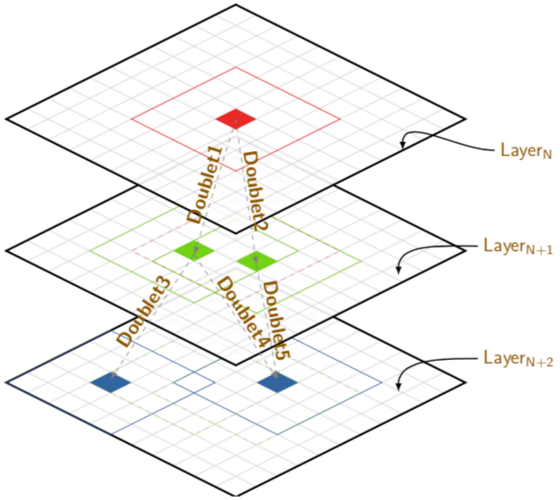
- If local density > ρ_c and distance > δ_s
  - Promote to seed
- If local density < ρ_c and distance > δ_0
  - Label outlier
- (ρ_c, δ_s, δ_0 are all parameters to be set)

3. Calculate "the nearest higher"
   - The nearest point with higher local density (joined with lines above)

5. Create clusters by assigning "followers" to seeds iteratively
   - Followers defined as nearby hits passing certain criteria

3D clustering

- **TICL** framework:
  - The **I**terative **Cl**ustering
  - Combining clustering and pattern recognition iteratively



1. Consider a Layer-Cluster
2. Project onto the next layer
3. Try to establish a "doublet"
   - Using certain geometry, energy or timing constraints
4. Repeat for all Layer-Clusters and all layers

↓

Forming "Tracksters" – do particle identification (see next slide)

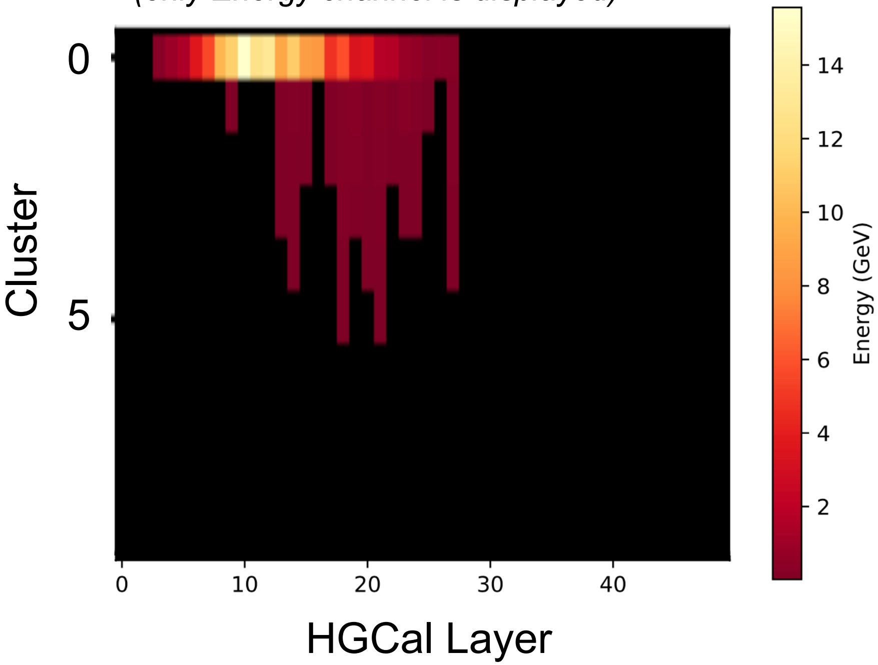
↓

Mask out Layer-Clusters associated to physics objects

Particle identification

Particle identification and energy obtained by using a convolutional neural network on "Trackster images"

Sample image for an electron/positron (only Energy channel is displayed)



- Each pixel represents a 2D layer-cluster
- Clusters sorted by decreasing energy in each layer
- Input features: layer-cluster energy, η, ϕ

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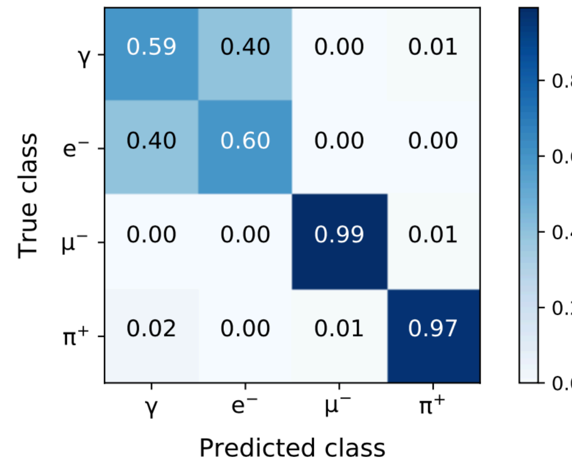
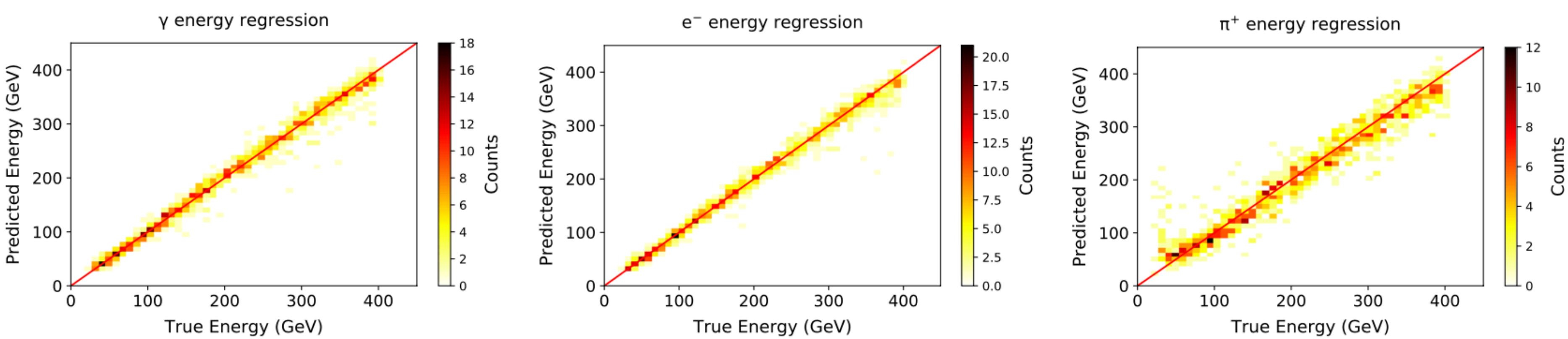
Particle identification – preliminary results

- Promising preliminary results in particle identification
    - Confusion between photons and electrons can be solved by adding information from the tracker
- Improvements are needed for charged hadrons (especially at higher energies)

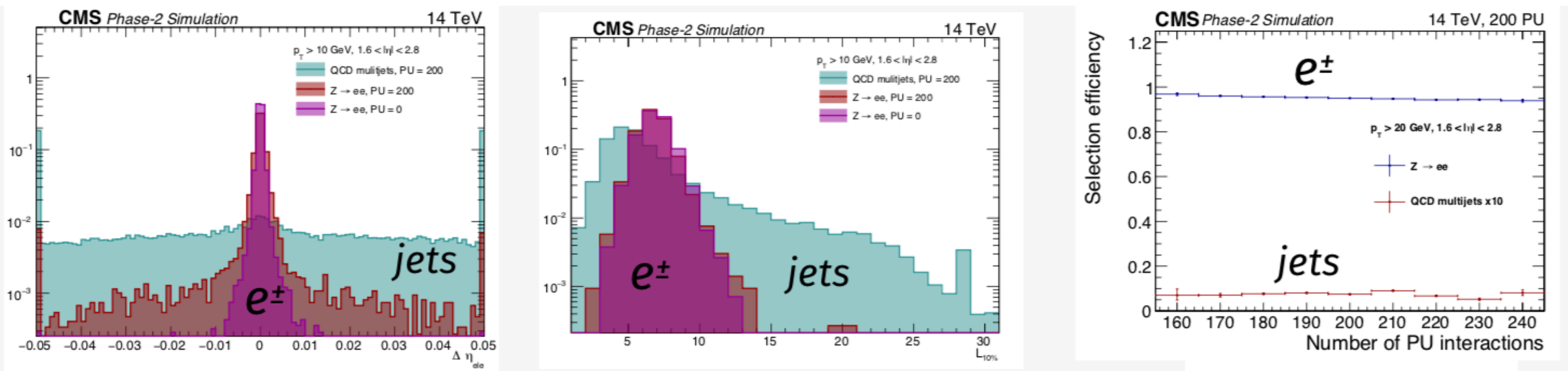




A. Di Pilato

Electron identification

- Electron are a standard candle for particle flow
  - Compact, of known shape and associated to a track
  - Axis pointing improves rejection of PU photons with respect to bremsstrahlung



Electron shower shapes shown to be independent of pileup

Efficiency vs number of PU interactions

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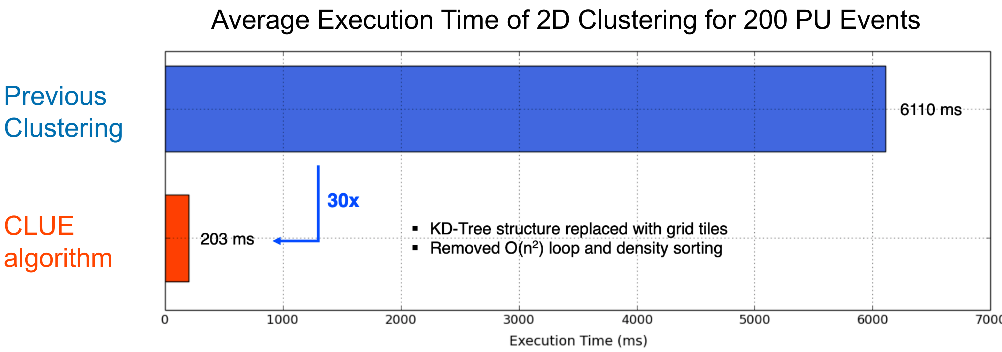
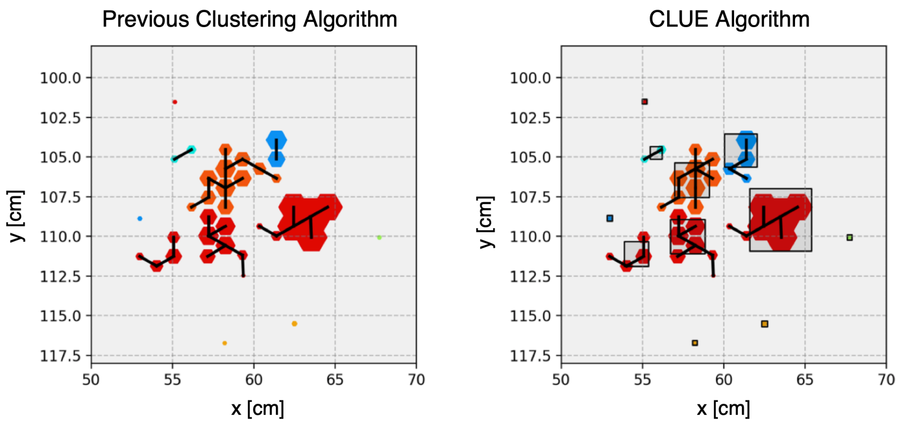
Reconstruction performance

- Around a factor 30 improvement in reconstruction speed with respect to current default
- Potentially a further factor 6 by using an optimised GPU implementation
  - Still preliminary





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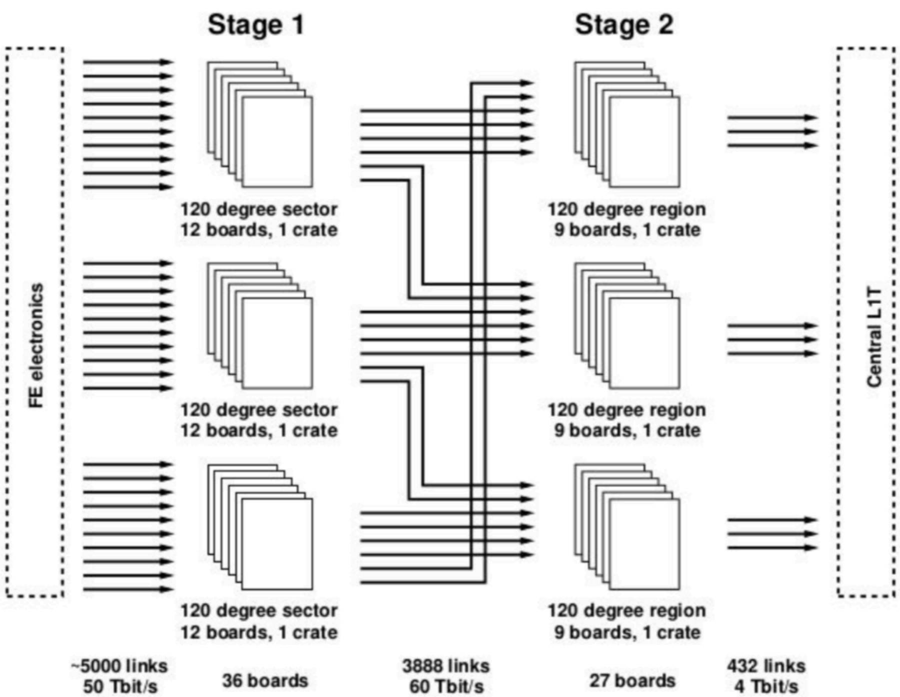
HGCal trigger system

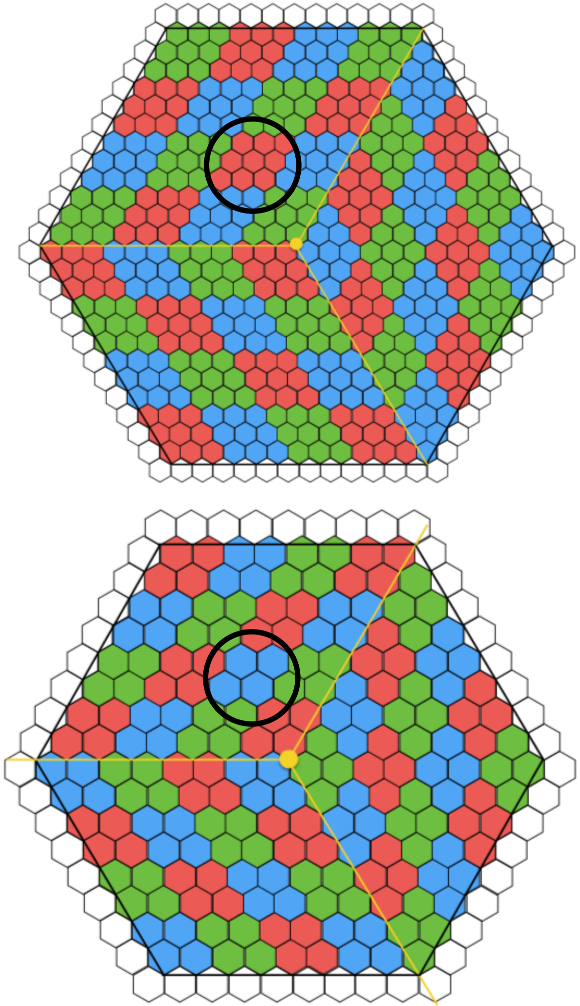
- Trigger capabilities in the forward region are key feature of the CMS upgrade
- HGCal will generate 'trigger primitives' (3D energy clusters) to pass to the L1 trigger
- Two-stage backend design
  - Stage 1: data reorganisation and event building
  - Stage 2: trigger primitive generation
- The firmware for the back-end stages 1 and 2 is currently being implemented



One end-cap

HGCal trigger system

- Reducing expensive bandwidth is a challenging element of the system
  - O(10000) links @10Gpbs from the front end to the trigger primitive generator
- Form basic "trigger cells" from the sensor cells in the front end
  - Combine either 4 or 9 depending if a high-density or low-density module
  - All trigger cells approximately the same size
- Cells are passed to the backend electronics after some selection in the trigger concentrator (on-detector)
  - Simplest: threshold cut on energy



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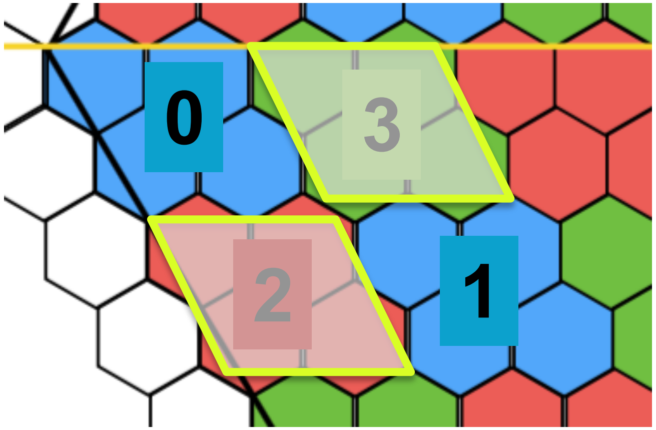
Front-end trigger cell selection

- Unaffordable to send every trigger cell for further processing off-detector
  - Some selection needed
  - Three main algorithms considered each with pros and cons



e.g. Threshold of 2: Energy lost

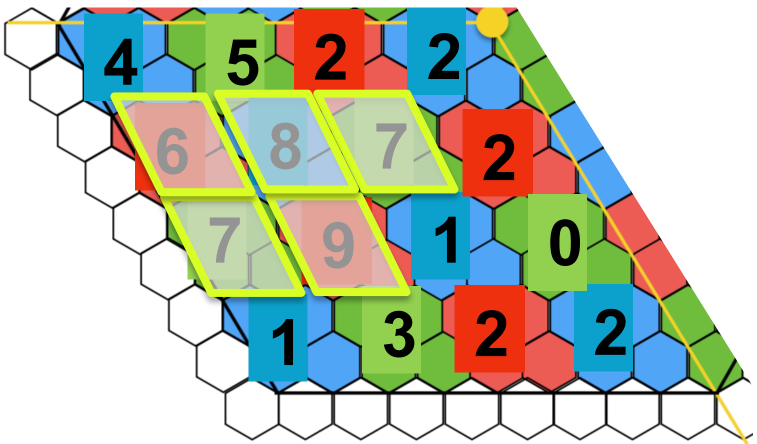
Threshold Selection

"Select all trigger cells above a certain energy threshold"

- Make good use of high granularity positional information
- Lose low energy trigger cells (these are most likely to be from pileup interactions)

- Variable amount of data selected per event (requires buffering in front-end); hard to handle in fixed latency L1 trigger system

Front-end trigger cell selection

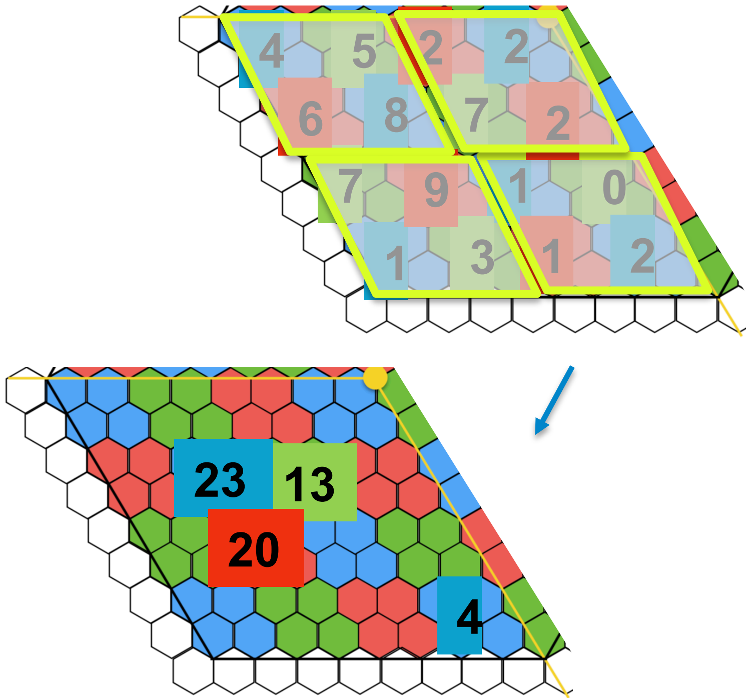


Best choice Selection (sorting)

"Select N highest energy trigger cells within certain region"
(here N = 5)

- Gives good energy resolution for small objects (e.g. electrons)
  - All energy and positional information is kept
- For larger objects (e.g. jets) a fraction of energy is lost
- Fixed amount of data per event

Front-end trigger cell selection

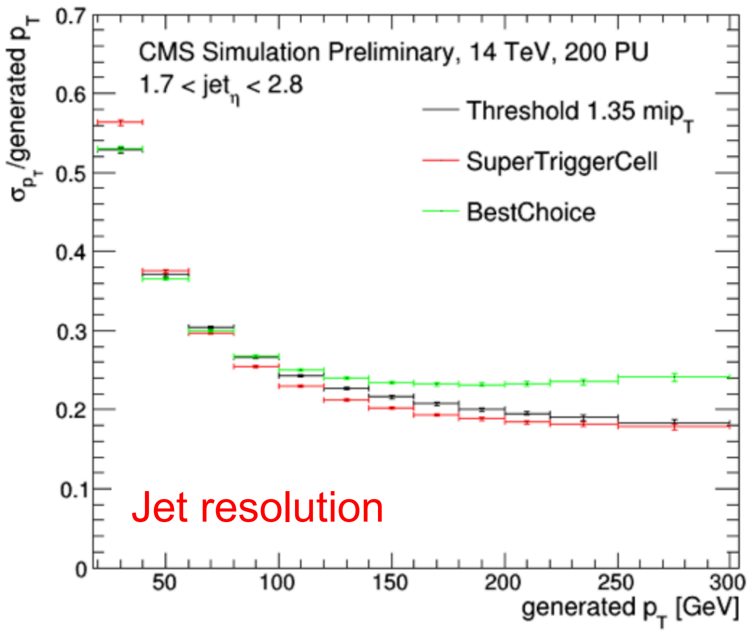


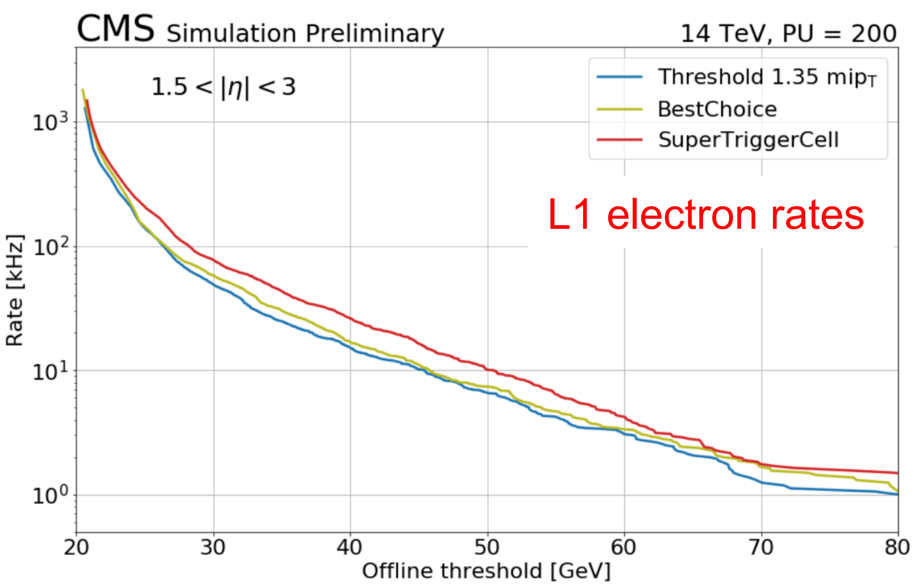
Super Trigger Cells

Combine nearby trigger cells into larger objects
Send sum and position of maximum

- Gives good energy resolution for large objects
  - Keep all energy, plus some positional information
- For smaller objects the loss of high granularity positional information affects identification
- Fixed amount of data per event

Front-end trigger cell selection

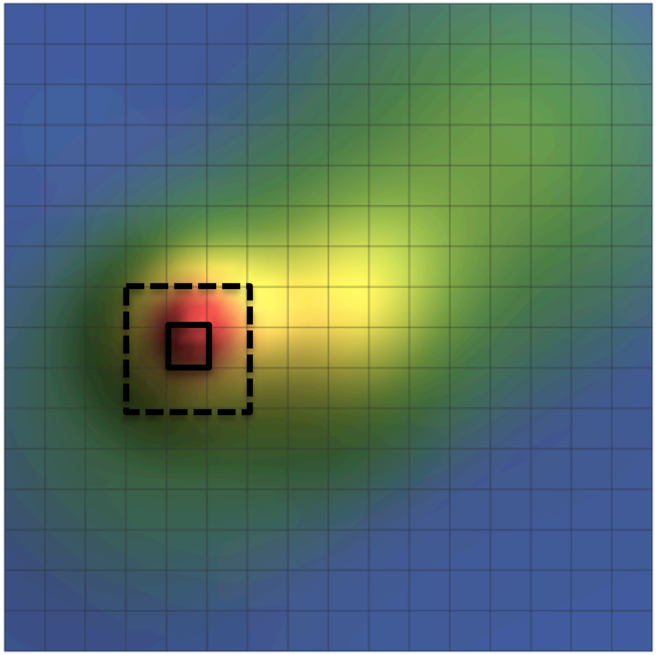


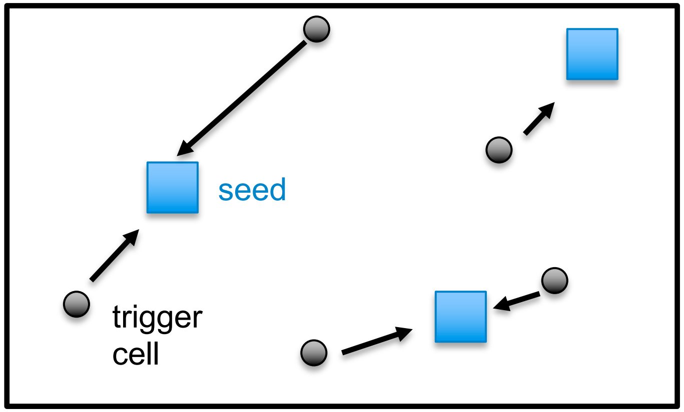


- The threshold selection has overall the best performance
- But possible compromise to use the Best Choice algorithm in the electro-magnetic section, and Super Trigger Cells in the hadronic section

Back-end (off-detector) processing

Purpose: Form 3D clusters to be sent to central CMS Level-1 trigger for decision (CLUE too sophisticated for firmware implementation)





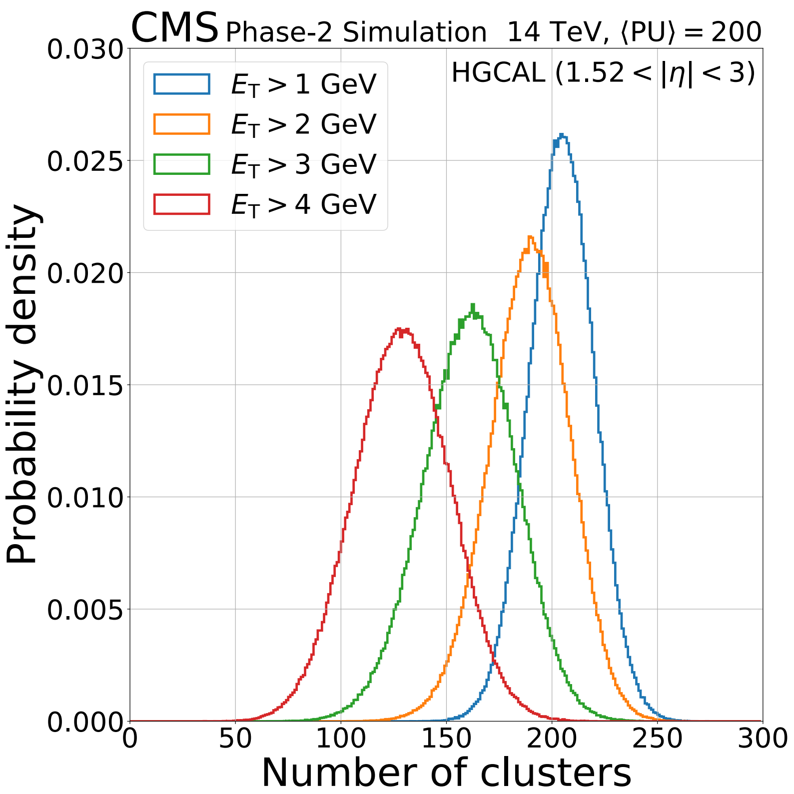
Fill 2D histogram with trigger cells – “Seed finding”

- Nearby TCs from all layers are associated to seeds in *projective geometry to origin* forming 3D clusters
  - Calculate energy, position and ID variables (e.g. width, layer information)
  - Passed to L1 trigger

HGCal trigger system

- The total rate for 200 pileup events is easily accommodated by the downstream L1 trigger processor

- The 3D clusters are then combined with the tracking information (down to $\eta = 2.4$) in the Level-1 trigger
  - Allowing particle flow at the L1 trigger level



Number of 3D clusters with 200 PU

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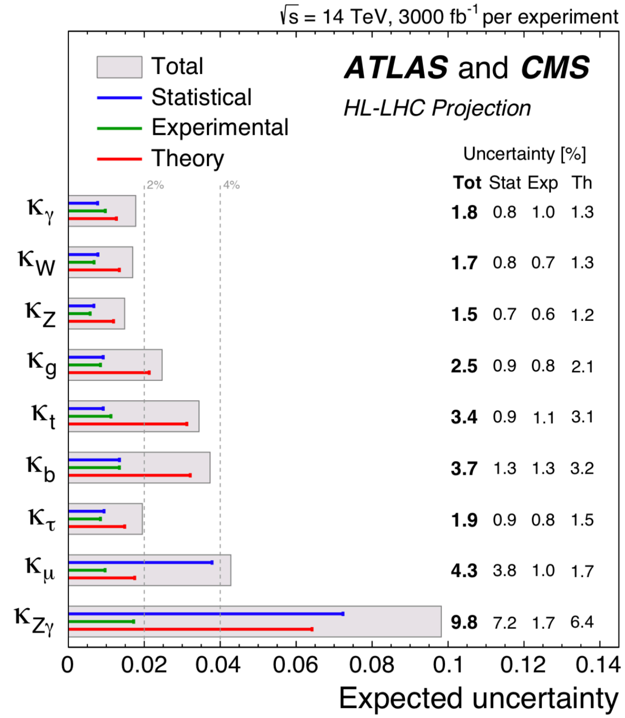
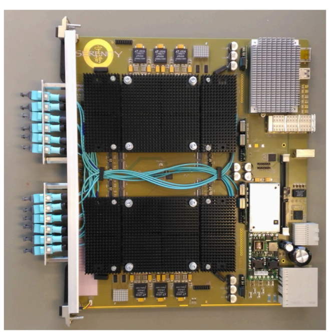
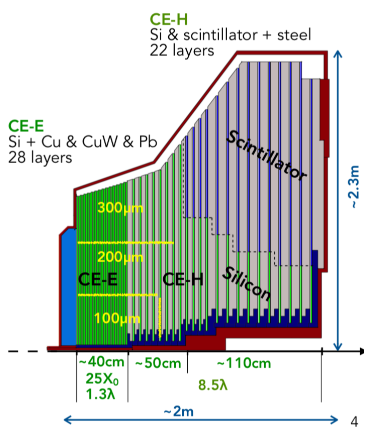
Summary

- Strong physical motivation for upgrading the LHC
- CMS also needs to be upgraded to cope with higher pileup and increased radiation
- The HGCal is an ambitious project to enable the exploration of many interesting phenomena







The CMS HL-LHC upgrade projects close to ending a crucial R&D period with data taking around 7-8 years away

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Additional Material

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Run 2 of the LHC

- 2015-2018
- Proton-Proton centre of mass energy 13 TeV (7/8 TeV in run 1)
- Higher instantaneous and integrated luminosity