A level-1 pixel based track trigger for the CMS HL-LHC upgrade

(Exercise for L1 pixel track trigger simulation)

Chang-Seong Moon

Kyungpook National University

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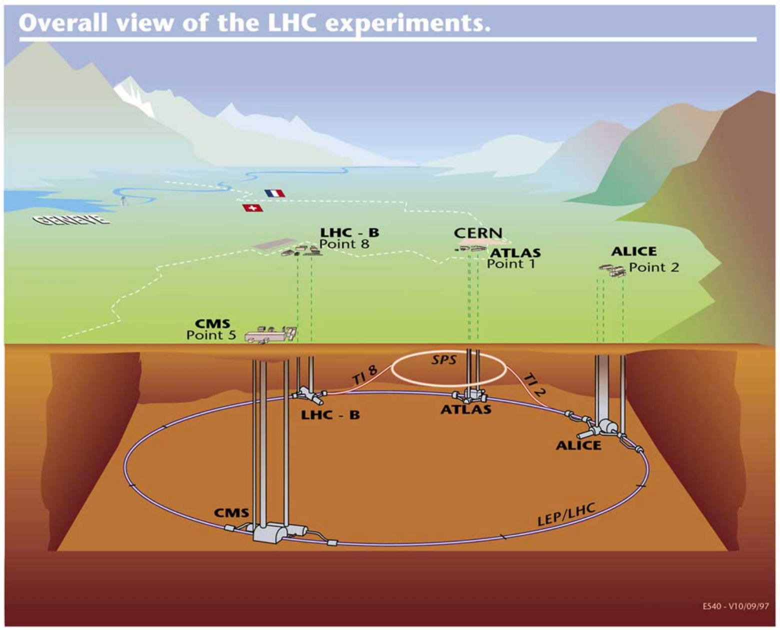
Introduction

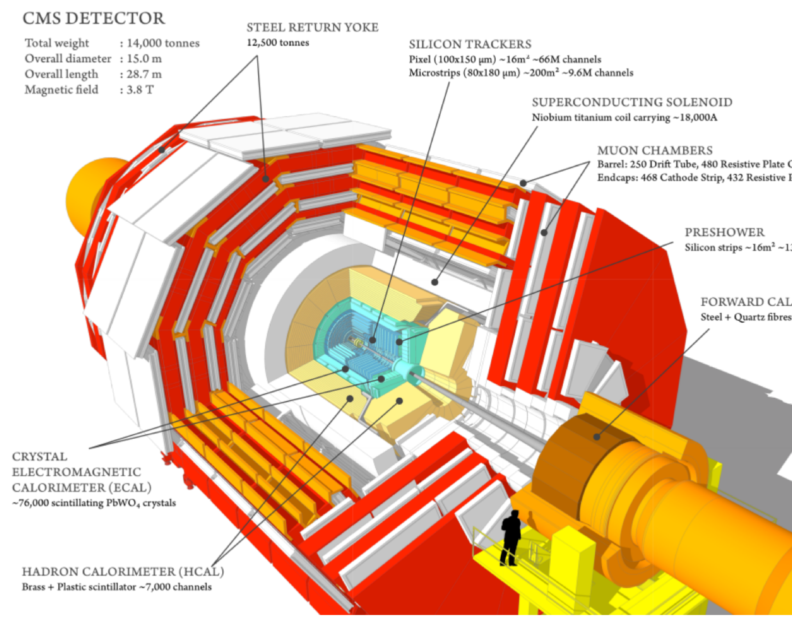
- The current Level-1 Trigger at CMS
  - Maximum bandwidth of 100 kHz and latency of 4.5 μsec
  - Electron/Gamma, Tau, Jet based on calorimeters
  - Muon reconstructed by muon chambers
  - No tracking information at Level-1
- The High Luminosity LHC (HL-LHC) conditions are characterized by:
  - Instantaneous luminosity of 5×10^{34} $cm^{-2}s^{-1}$ and 140 average Pile-up (PU) events
  - Large increase in the rates of the physics processes
- The main goal for the L1 trigger of CMS Phase 2 Upgrade:
  - Maintain or even improve the overall physics potential despite the challenging HL-LHC conditions by:
    - ❑ Avoiding the increase of the trigger thresholds
    - ❑ Refining the selection of physics objects at L1
  - Maximum bandwidth of 750 kHz and latency of 12.4 μsec
- The L1 Track Trigger for Phase 2 Upgrade at HL-LHC: a new L1 key element
  - Self-seeded L1 Track Trigger based on L1 Outer Tracker:
    - ❑ Reconstruct "L1 tracks" with $p_T > 2$ GeV.
    - ❑ Identify z position along beam pipe within 1mm.
  - Feasibility and performances studies for the L1 Pixel Trigger:
    - ❑ How the pixels can further improve some features of the L1 Track Trigger of CMS.

Motivation

- Improvement of some features of the L1 Track Trigger:
  - Higher precision of the vertex resolution at L1
  - L1 electron trigger by matching L1 EM calorimeter tower with pixel hits:
    - ❑ Helps Improving fake electrons rejection
    - ❑ Keeps high efficiency in the high η region
  - L1 b-tagging by combining L1 track with pixel hits:
    - ❑ Increases the chances of triggering on very rare physics processes with b-jets in final state at HL-LHC as for example:
      - Higgs pair production
      - Higgs production in association with a top quark pair
- High selection capability for events from low-mass processes
  - Retain good efficiency for Higgs decay products
    - ❑ Precision measurement of the Higgs coupling and its properties
  - New physics searches
    - ❑ SUSY and Dark Matter (Mono-X search)
    - ❑ Rare decays in B Physics: $B_s \to \phi\phi \to 4$ K's
    - ❑ Lepton Flavor Violation: $\tau \to 3$ μ's
    - ❑ Long Lived Charged particles

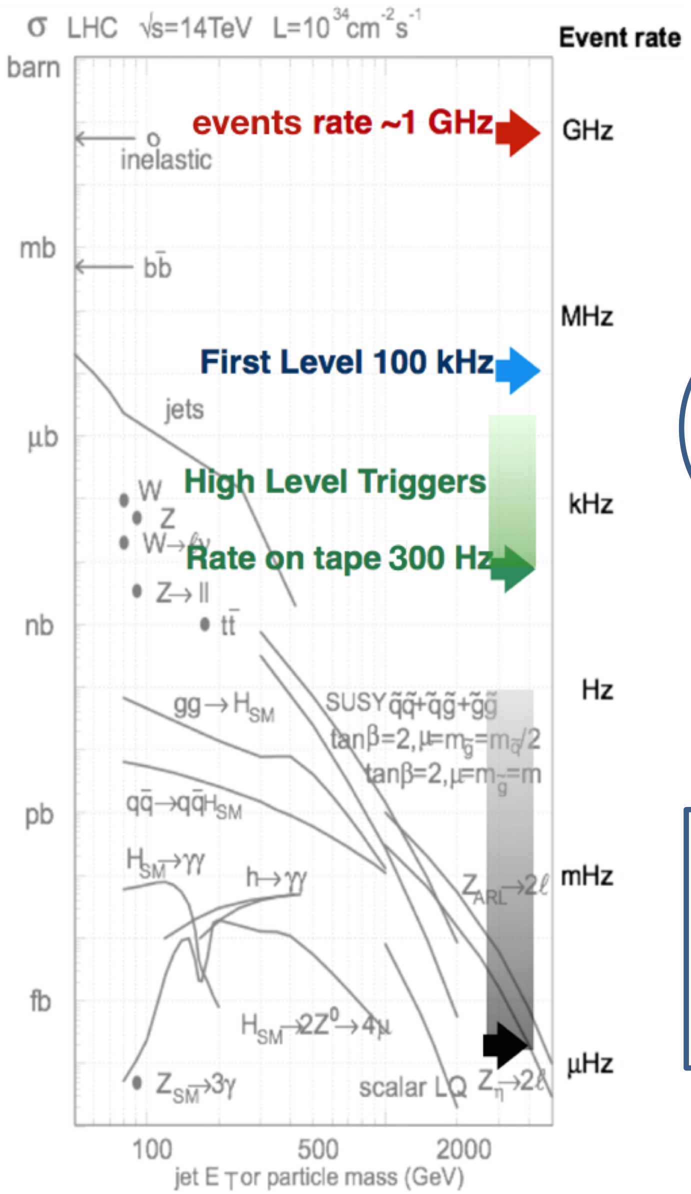
Series of CMS upgrades at CERN LHC

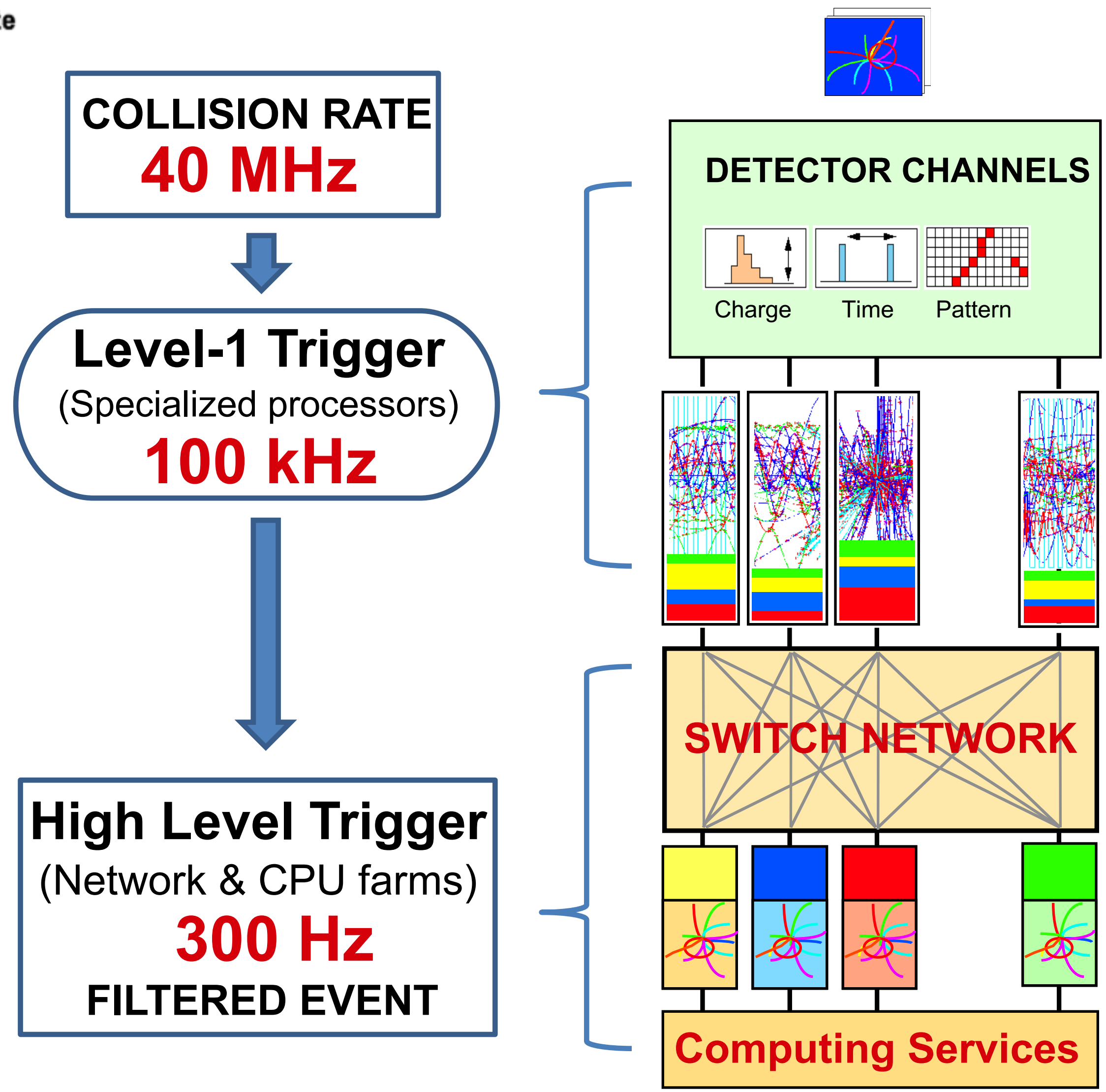




- Run I (2010-12) → 2010-11: 7 TeV (5 fb^{-1}) and 2012: 8 TeV (20 fb^{-1})
  - Bunch-crossing rate: 40 MHz
  - ~20 p-p collisions for each bunch-crossing, Data rate: ~1000 event/sec (Hz) in 2012.
- LHC Schedule
  - The first long shut down (LS1) (2013-14) : Collision energy upgrade (8 → 13 TeV)
  - The second long shut down (LS2) (2018-19) : Muon system upgrade, Collision energy upgrade (13 → 14 TeV)
  - The third long shut down (LS3) (2023-25) : High luminosity LHC upgrade (new CMS pixel and outer tracker) → Phase 2 upgrade

CMS Data Acquisition System



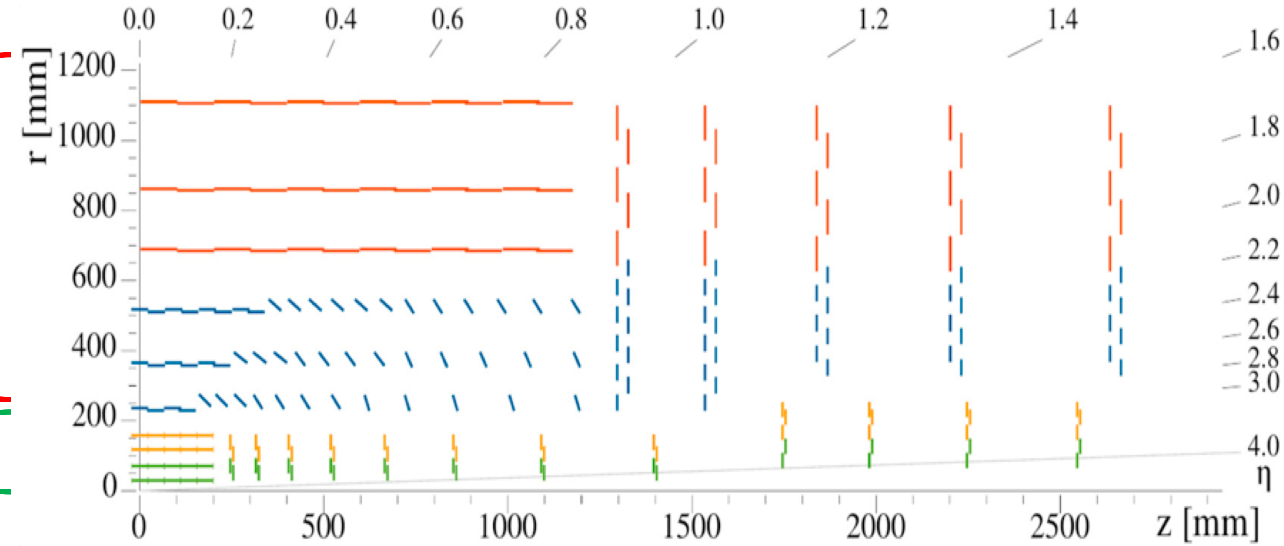


CMS Level-1 Pixel Track Trigger Upgrade R&D project

CMS Tracking system for Phase 2 upgrade

Outer Tracker

Inner Pixel



- **The main goal is to help reducing the total L1 trigger rate** while keeping an high selection efficiency **with pixel detector**.
  - **Quite challenging** objective, **but innovative!** for CMS phase 2 upgrade at HL-LHC
  - **Key and leading role** for developing the L1 pixel trigger algorithm and performing its feasibility studies as well as supervising students in the CMS L1 pixel trigger working group.

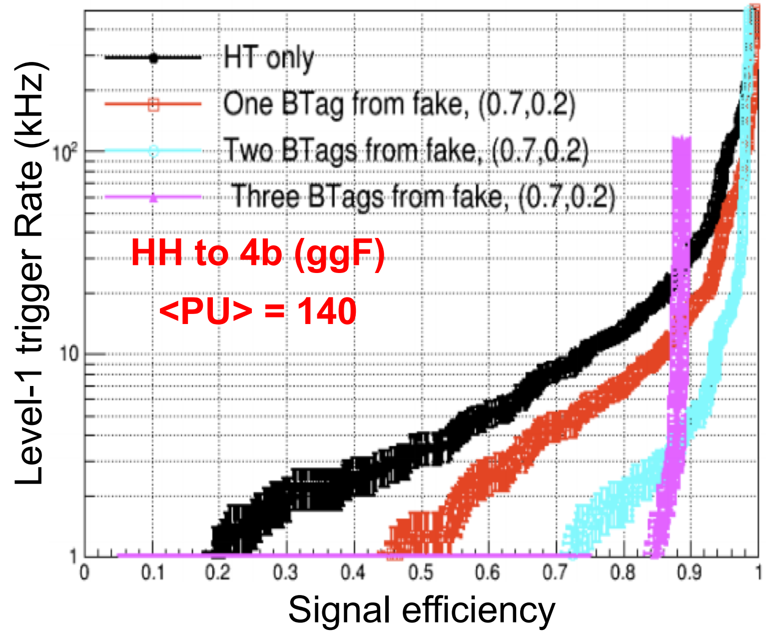
  - Collaborations : CNRS-Paris, INFN-Pisa, LIP-Lisbon, Fermilab, Seoul Nat'l Univ. and Sao Paulo State Univ.

INFIERI European ITN project (FP7-PEOPLE-2012-ITN)

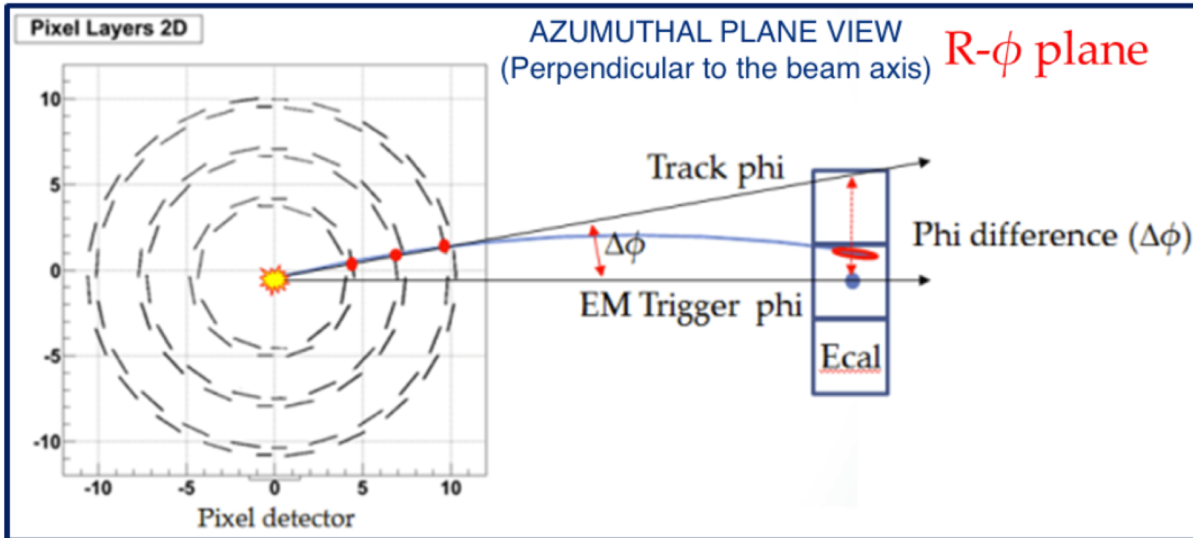
Physics Motivation for the pixel track trigger

- The current Level-1 Trigger at CMS based on calorimeters and muon chambers
  - **No tracking information at Level-1!**
- Significantly increasing the rates of the physics processes at HL-LHC
  - A main goal of the LHC upgrade: **maintain the overall physics acceptance**
  - Intelligent **L1 track trigger** is a key component to reduce trigger rate.
- Significant improvement by requiring 2 or 3 b-tagging with pixels
  - **Triggering the double Higgs events at Level-1**, while reducing the background at a reasonable level.

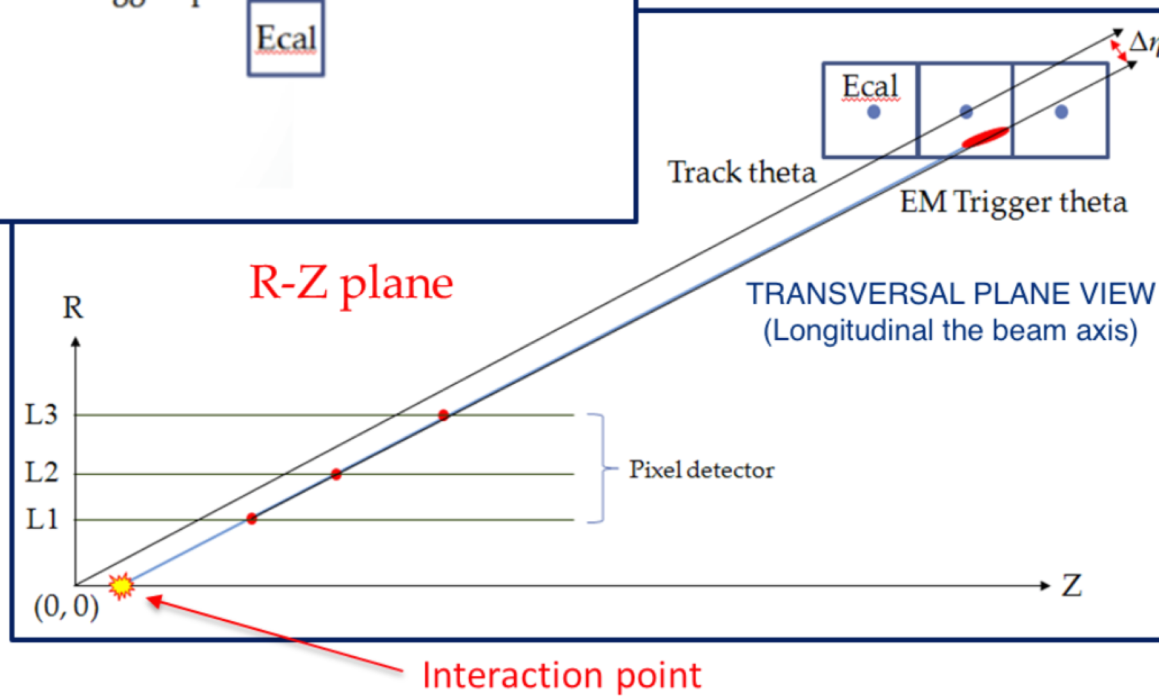
Trigger efficiencies for Higgs pair production vs L1 b-tagging trigger rates for gluon fusion processes



The Pixel Tracking algorithm (PiXTRK)



Improving background rejection by adding vertex detector information



EM cluster matching with regional pixel tracking using a ($\Delta\phi$, $\Delta\eta$) signal window range

In experimental particle physics, **pseudorapidity**, η, is a commonly used spatial coordinate describing the angle of a particle relative to the beam axis. It is defined as

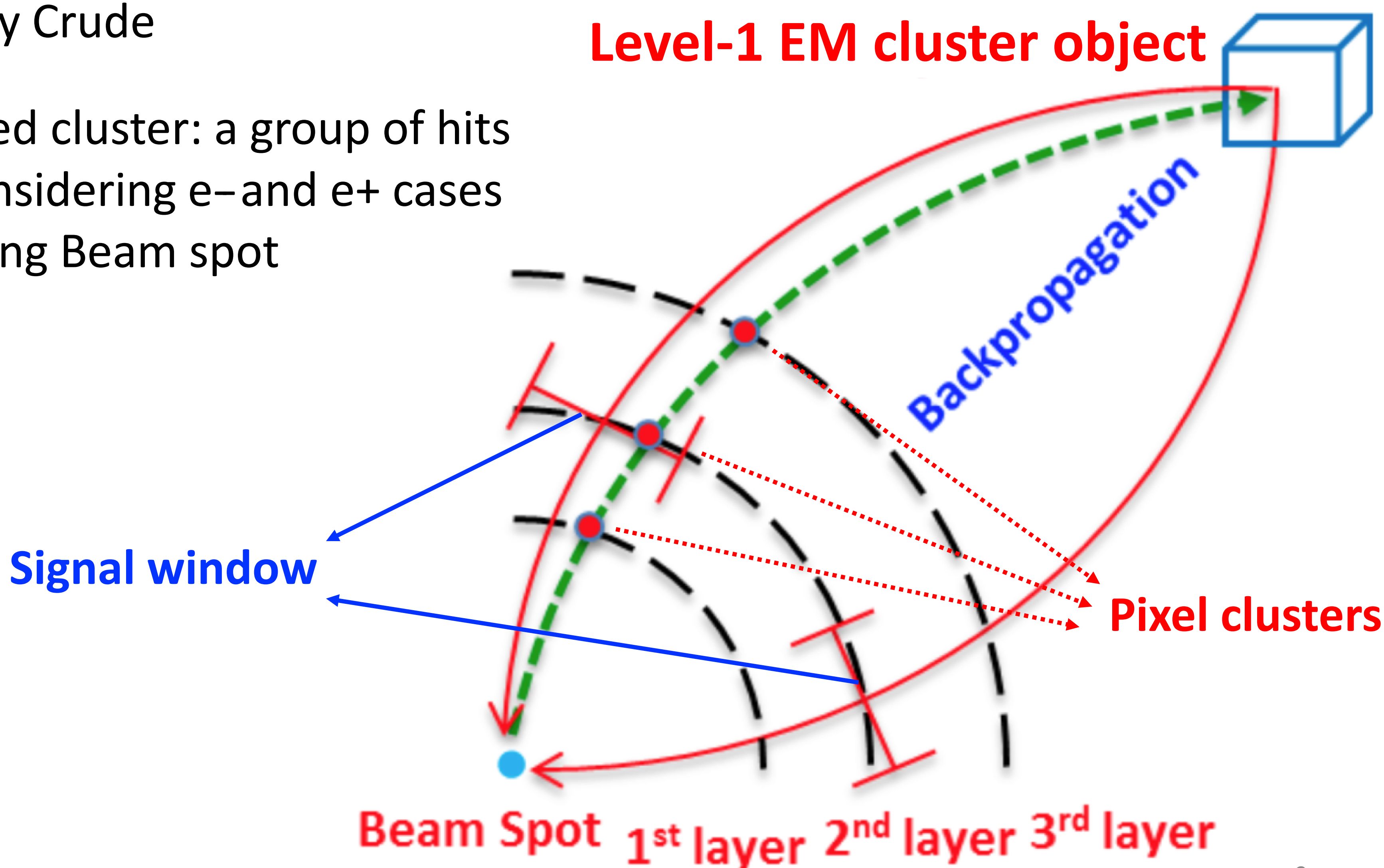
$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

where θ is the angle between the particle three-momentum $\mathbf{p}$ and the positive direction of the beam axis.

Pixel hits matching with Level-1 EM object

Level-1 EM Calorimeter Tower
: Very Crude

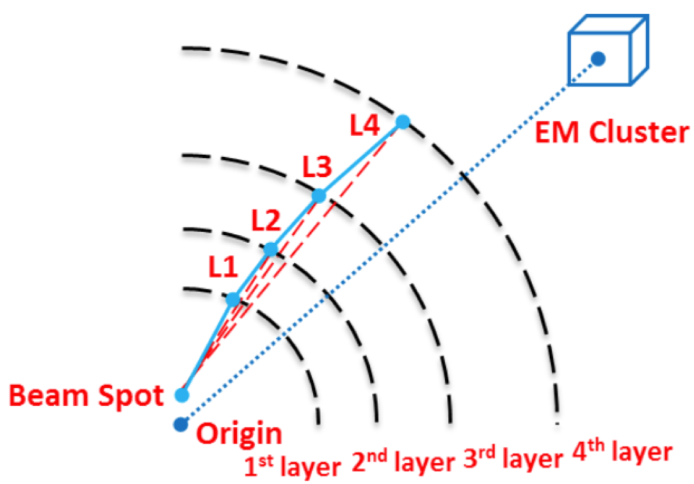
- Used cluster: a group of hits
- Considering e− and e+ cases
- Using Beam spot

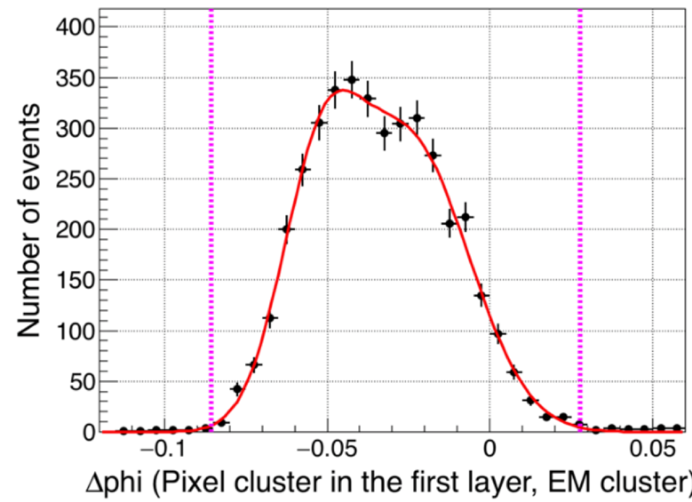


1) Pattern recognition seeded by the L1 EM cluster

1–1) Pattern recognition in the $R-\phi$ transverse plane

First is considered the region of interest (RoI) defined, in the transverse $R-\phi$ plane, by the L1 EM cluster linked to the beam spot (BS). In this region are selected the pixel clusters which, in each layer (L_i, i=1,...,4) are included in a $\Delta\phi$ window defined here by $\Delta\phi < 0.1$, and considering both the cases of electrons and positrons. The selected pixel clusters in each layer are those which are in the $\Delta\phi$ window (figure 4) defined as: $\Delta\phi = \phi(BS, L_i) - \phi(BS, EM)$





Where (BS, L_i) is the pixel segment joining the beam spot with the relevant pixel cluster in the corresponding L_i layer. The segment of (BS, EM) joins the beam spot with the L1 EM cluster. In the case of more than one cluster satisfying the equation 3.1, all the combinations corresponding to all the possible clusters in this region of interest are considered. The pattern recognition proceeds further on for refining the pattern recognition procedure according to the two following steps.

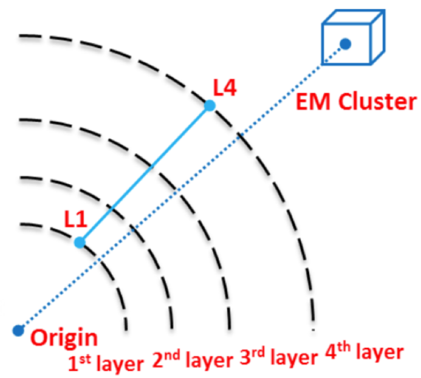
1–2) Refined Pattern recognition seeded by the EM cluster

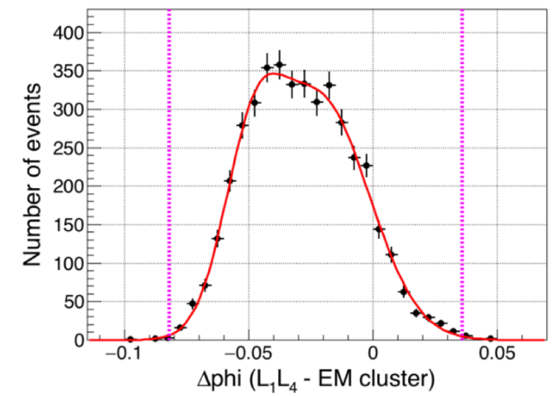
It consists in determining now the $\Delta\eta$, $\Delta\phi$ and ΔR signal windows, in function of EM E_T, for the set of the pixel clusters selected by the condition defined by the equation 3.1, for each layer. The pixel layers are combined 2 by 2 to form all the possible (L_i, L_j) track segments which correspond to each pixel cluster retained in the selection defined by the condition (3.1). It compares the matching of each of these (L_i, L_j) segments with the segment joining the beam spot with the EM cluster in the (η, ϕ) coordinates by defining:

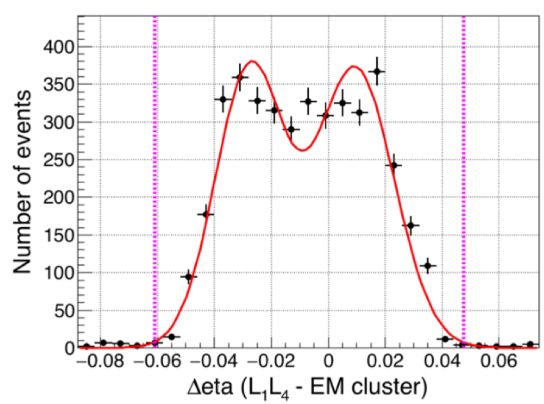
$$\Delta\eta = \eta(L_i, L_j) - \eta(BS, EM)$$

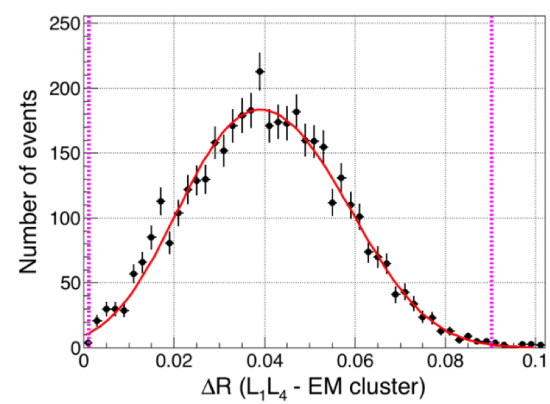
$$\Delta\phi = \phi(L_i, L_j) - \phi(BS, EM)$$

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









Where i, $j = 1, \ldots, 4$ and $i \neq j$. The pixel cluster in each layer is then selected only and only if it passes all the possible signal windows within 3 standard deviations as shown in figure 5.

2) The standalone pattern recognition

This second step aims to still reduce the possible remaining fake pixel clusters. To do so, we now look for all the possible three aligned clusters, with all the remaining pixel clusters in each of the 4 layers including also the beam spot. The $\Delta\phi$, $\Delta\eta$ and ΔR signal windows (figure 6), in function of EM E_T, are now defined by:

$$
\begin{aligned}
\Delta\eta &= \eta(L_i,L_j) - \eta(L_j,L_k) \\
\Delta\phi &= \phi(L_i,L_j) - \phi(L_j,L_k) \\
\Delta R &= \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}
\end{aligned}
\tag{3.3}
$$

Where i, j, k = 0,...,4 with $L_0 = BS$ and $i \neq j \neq k$. The pixel cluster must satisfy all the signal windows requirements within 3 standard deviations. The complete procedure allows achieving a good pattern recognition by giving a complete set of pixel clusters defined by a series of $\Delta\eta$, $\Delta\phi$ and ΔR signal windows. The selected clusters can then be used to perform a track fit reconstruction which is not the purpose of this present series of exercise.

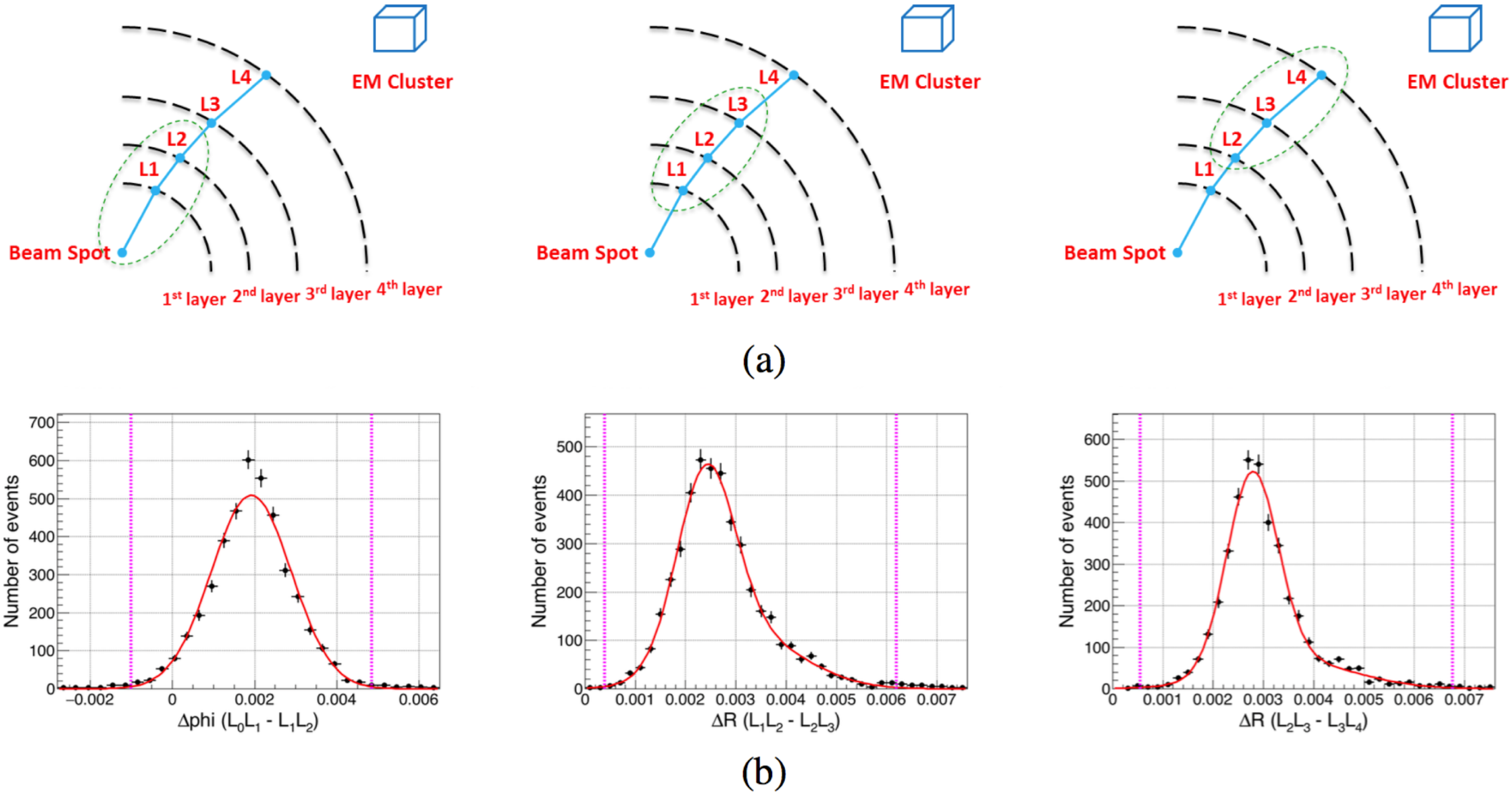
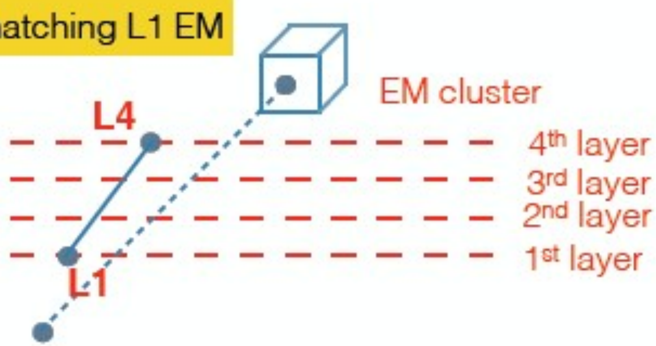


Figure 6. Standalone pattern recognition with pixel clusters: (a) top views shows all possible three aligned clusters cases including also BS. (b) Left plot shows the corresponding $\Delta\phi = \phi(L_0, L_1) - \phi(L_1, L_2)$ to the top left schema. Middle plot shows the ΔR corresponding to the top middle schema and right plot shows the ΔR corresponding to the top right schema. All the distributions include the three sigma boundary and correspond to EM transverse energy (E_T) range from 20 to 21 GeV.

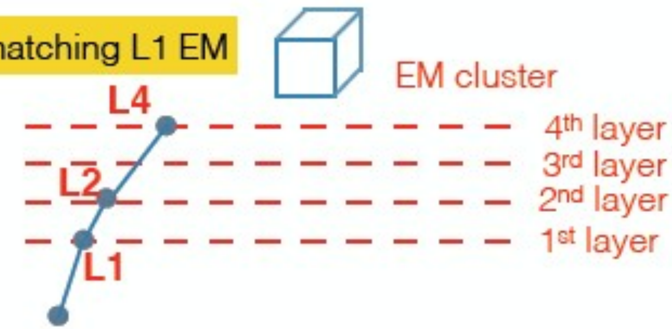
Defining signal windows

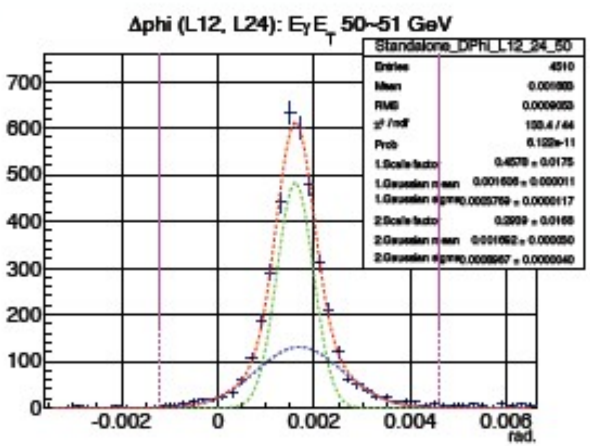
- Note in the L1 Pixel scenario we use PIXEL CLUSTERS and not the PIXEL HITS
- for the cases with pixel clustering on **at least 3 out of 4** layers
  - two different types of signal windows: with/without matching L1 EM cluster
  - define signal window by measuring $\Delta\phi$, $\Delta\eta$, ΔR with simulated single electron events
  - $\Delta\phi$, $\Delta\eta$, and ΔR distribution is measured for each 1 GeV e/γ E_T step, 5~140 GeV

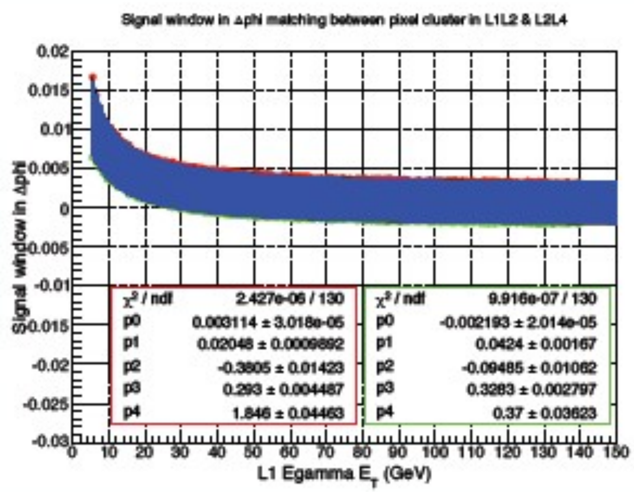
with matching L1 EM



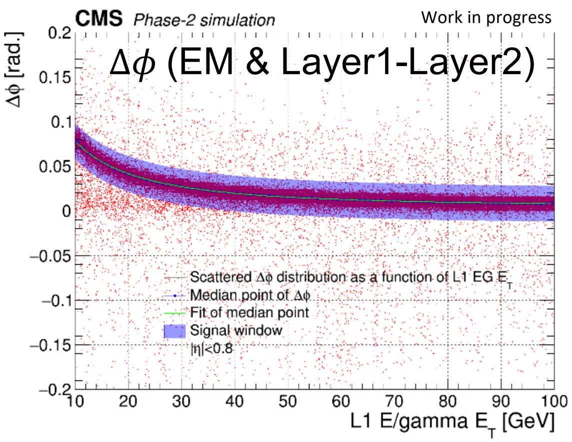
without matching L1 EM

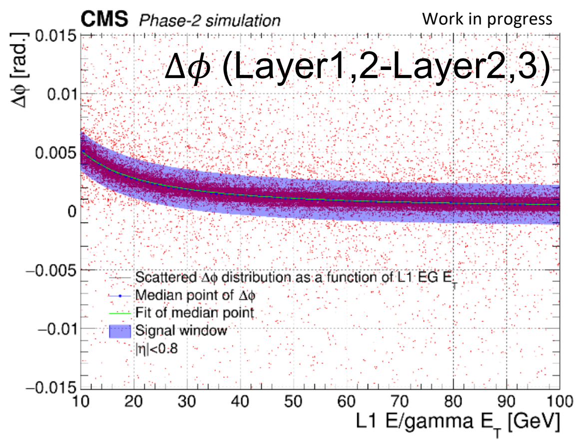


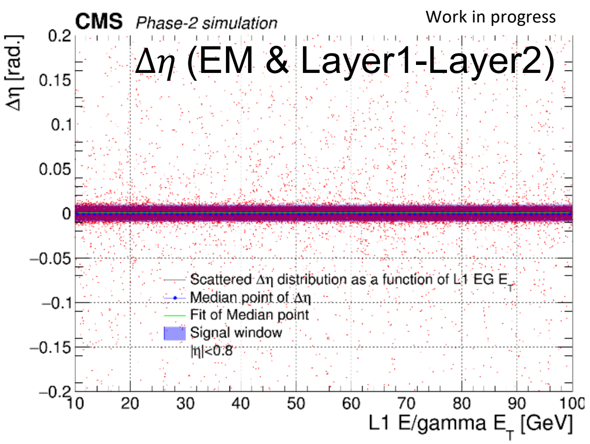


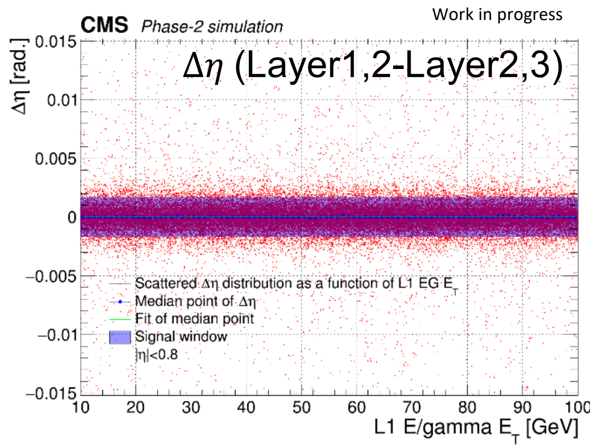


Example of signal windows for $|\eta| < 0.8$





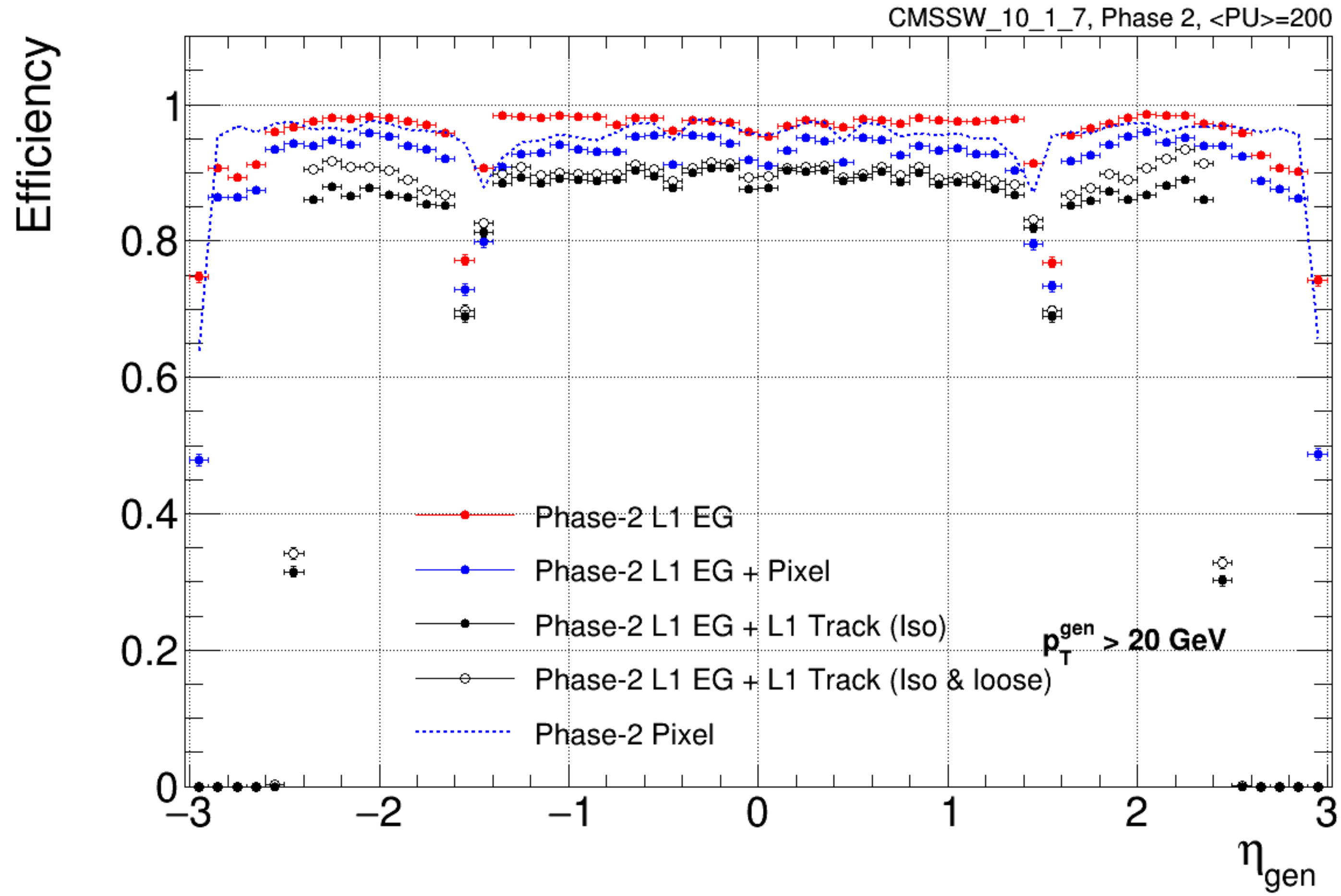




- In each distribution, median points are fitted as a function of L1 EG E_T.
- The signal windows are measured with the fitted functions.

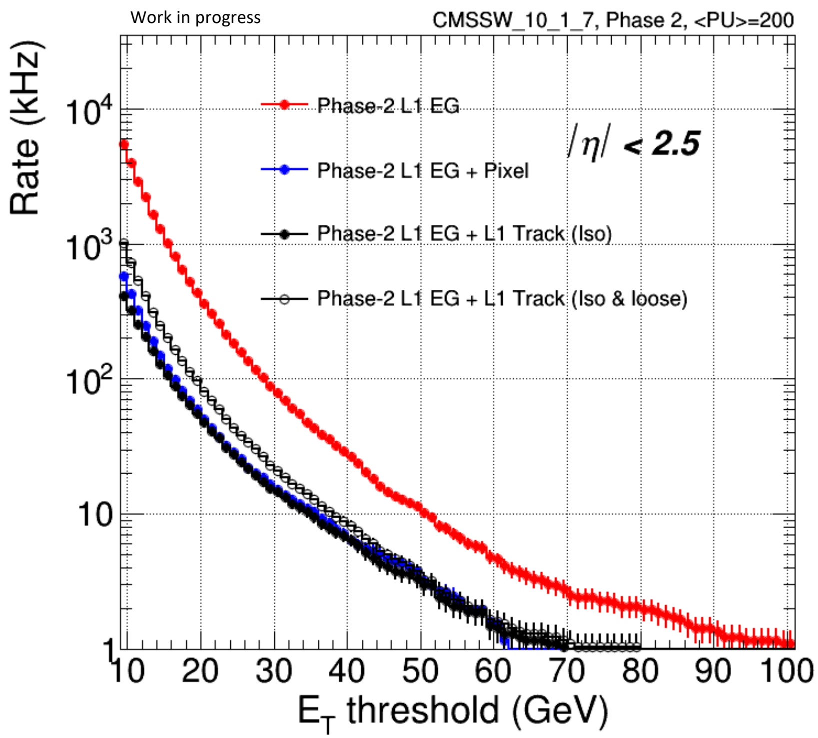
Width of signal window	$\Delta\phi$ window (EM-Pixel)	$\Delta\eta$ window (EM-Pixel)	$\Delta\phi$ window (Pixel-Pixel)	$\Delta\eta$ window (Pixel-Pixel)
$\|\eta\| < 0.8$	0.02	0.01	0.0017	0.0017
$0.8 < \|\eta\| < 1.4$	0.03	0.015	0.003	0.003
$1.4 < \|\eta\| < 3.0$	0.02	0.01	0.0017	0.0017

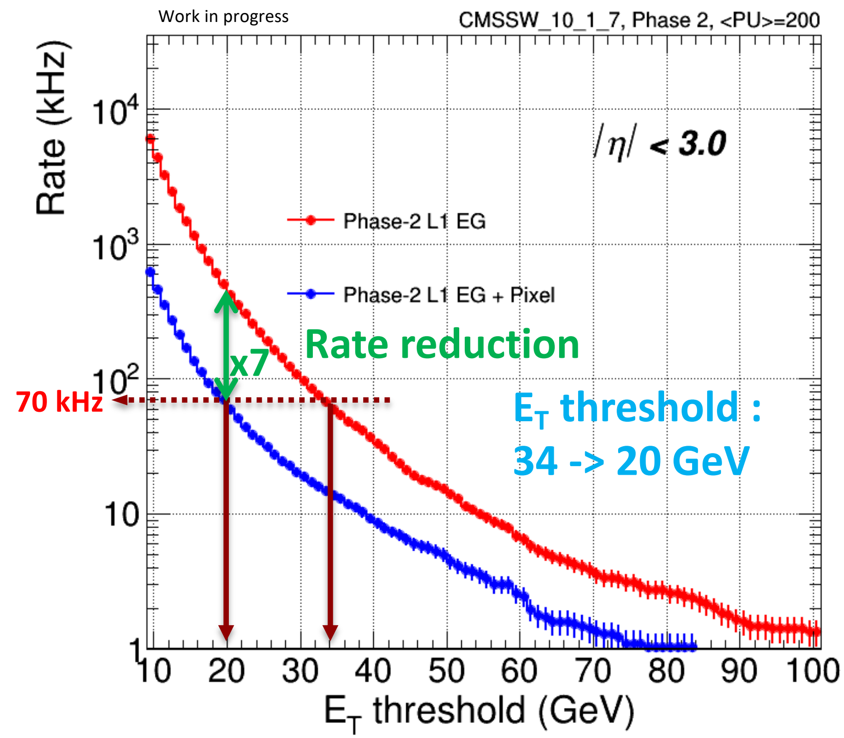
L1 pixel trigger efficiency with 200 pile-up



Level 1 trigger	$\|\eta\| < 1.5$	$1.5 < \|\eta\| < 2.5$	$2.5 < \|\eta\| < 3.0$
L1 EG	97%	95%	88%
L1 EG + L1 Track (Iso)	89%	79%	N/A
L1 EG + Pixel	92%	92%	80%

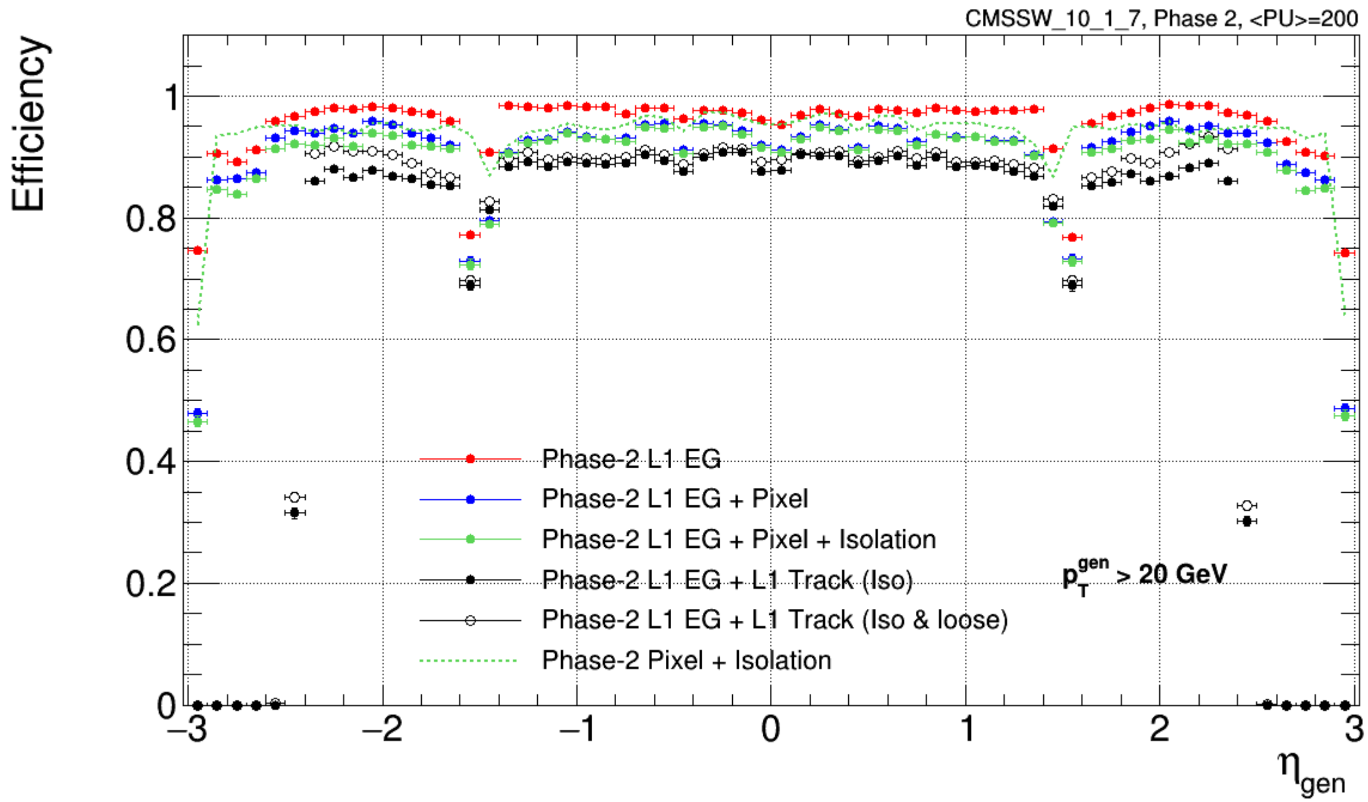
L1 EM trigger rate reduction by PiXTRK





L1 trigger at $E_T = 20$ GeV threshold	$\|\eta\| < 2.5$		$\|\eta\| < 3.0$	
	Rate	Reduction factor	Rate	Reduction factor
L1 EG	436 kHz	-	505 kHz	-
L1 EG + L1 Track (Iso)	**55 kHz**	**7.9**	**N/A**	**N/A**
L1 EG + Pixel	**59 kHz**	**7.4**	**70 kHz**	**7.2**

L1 pixel trigger efficiency including track isolation



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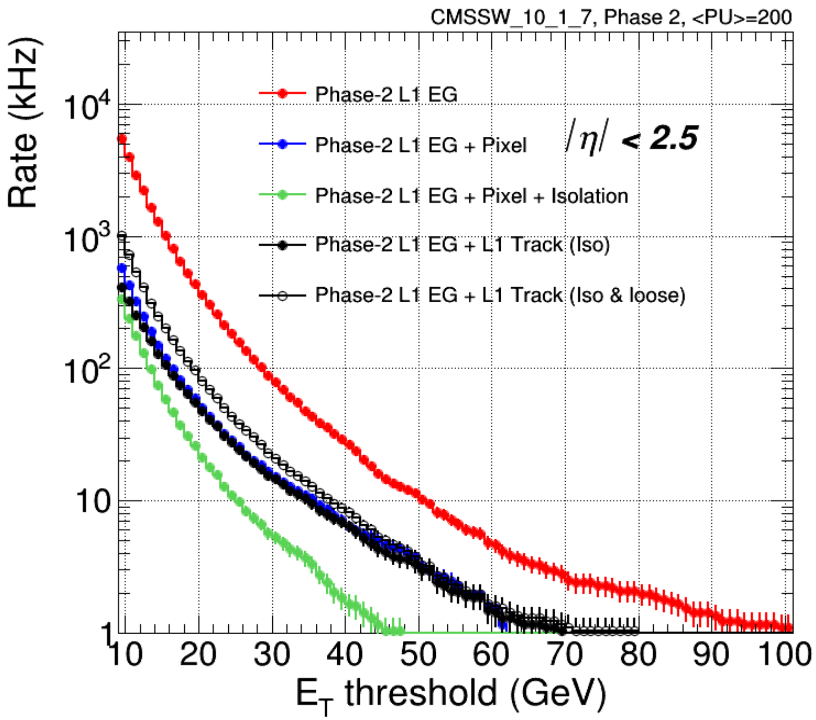
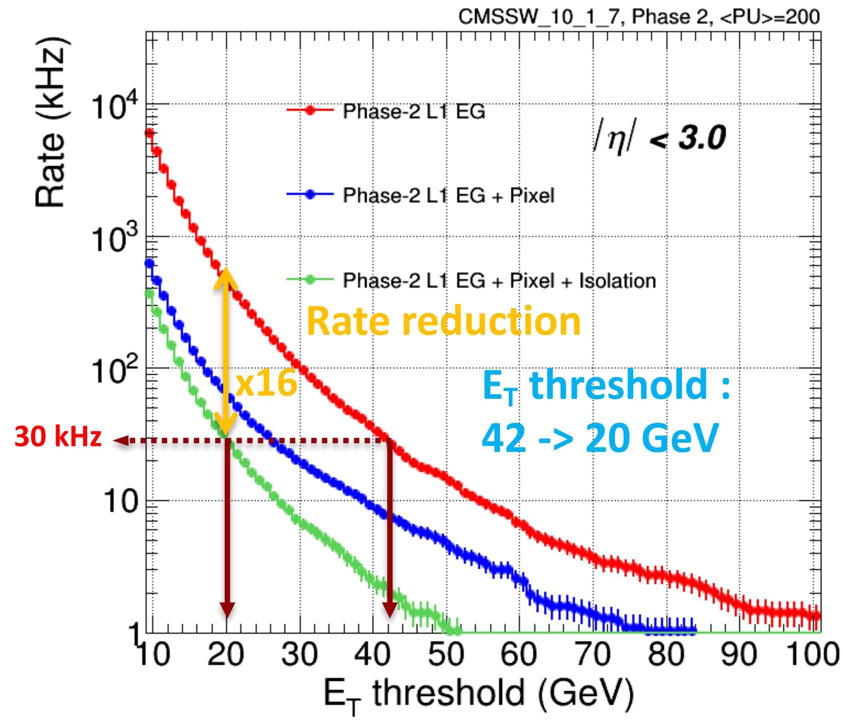
L1 EG	97%	95%	88%
L1 EG + Pixel	92%	92%	80%
L1 EG + L1 Track (Iso)	89%	79%	N/A
L1 EG + Pixel + Isolation	**92%**	**90%**	**79%**

L1 EM trigger rate reduction by PiXTRK with isolation





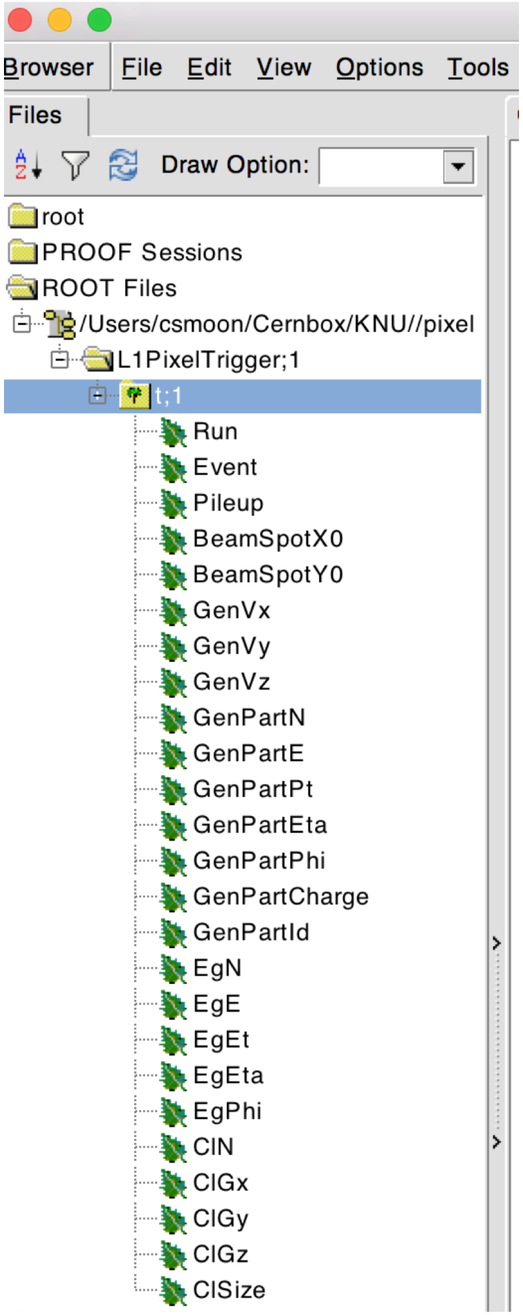
L1 trigger at E_T = 20 GeV threshold	$\|\eta\| < 2.5$		$\|\eta\| < 3.0$	
	Rate	Reduction factor	Rate	Reduction factor
L1 EG	436 kHz	-	505 kHz	-
L1 EG + L1 Track (Iso)	**55 kHz**	**7.9**	**N/A**	**N/A**
L1 EG + Pixel	59 kHz	7.4	70 kHz	7.2
L1 EG + Pixel + Isolation	**26 kHz**	**16.8**	**32 kHz**	**15.8**

Exercises

The exercises for introducing the students to a L1 pixel-based tracking trigger algorithm are made of the following three series of exercises.

Exercise 1

- You will be given a skeleton code test.C and its header file test.h to draw pixel clusters distribution in R-ϕ (X-Y) plane based on main simulated data sample in ROOT file format (pixelTree.root).
- You can make a plot using below commands in ROOT
  - root [0] .L test.C+
    - loading and compiling test.C
  - root [1] test a
    - define test function as a name of 'a'
  - root [2] a.Loop()
    - looping the function 'a' over all events stored in root file



Useful Variables in the simulation sample, pixelTree.root

Where only one electron was created in each event. This is called as *'single electron gun sample'*.
(one electron was produced solely in center of detector and it goes out of detector so that it remains its track and energy in the CMS detector)

GenPart* : Generated (Monte Carlo truth) level particle information

Eg* : indicates kinematic variables for Level-1 (L1) Electromagnetic (EM) Calorimeter cluster object.

*N : Number of events

*Et : Transverse energy *Pt : Transverse Momentum

*Eta : η, *Phi : ϕ

Cl* : Pixel cluster information
*Gx : x position
*Gy : y position
*Gz : z position
*Size : Cluster size

Exercise 1

- Exercise 1-1 : Understanding the Ntuple data structure in the ROOT framework

In the exercise 1-1, the students are introduced to the ROOT-based software framework and the CMS pixel data format.

- Exercise 1-2 : Drawing the pixel geometry in the X-Y plane using pixel clusters on each pixel layer (figure 7 (a))
- Exercise 1-3 : Drawing the pixel geometry in the R-Z plane using pixel clusters on each pixel layer and each disk (figure 7 (b))

In exercises 1-2 & 1-3 (figure7 (a) and (b)), the students learn the CMS pixel detector geometry. Estimate the radius of each pixel barrel layers. you can imagine how small the pixel detector is. The pixel detector is called heart of CMS detector..

Exercise 1

- Exercise 1-4 : Drawing separately the L1 EM cluster η and ϕ distributions (figure 7 (c) and (d))

In exercise 1-4, the students get to also understand the granularity of the EM calorimeter and the size in elementary cells that defines the L1 EM trigger tower (figure7 (c) and (d)). The dimension of the L1 EM tower is instrumental for defining the "region of interest" as the L1 trigger tower size defines the dimension of the seed in this case.

- Exercise 1-5 : Drawing the 2-dimensional plot between the generation-level electron transverse momentum (p_T) vs. the L1 EM E_T (figure 7 (e)).

The last step in the first exercise is to understand the correlation between the electron as defined at the generator-level and the L1 EM cluster that indeed serves to the identification of the electron. The figure 7 (e) shows how the measured transverse energy agrees well with the electron momentum as defined at the generator-level within a given resolution.

Exercise 1

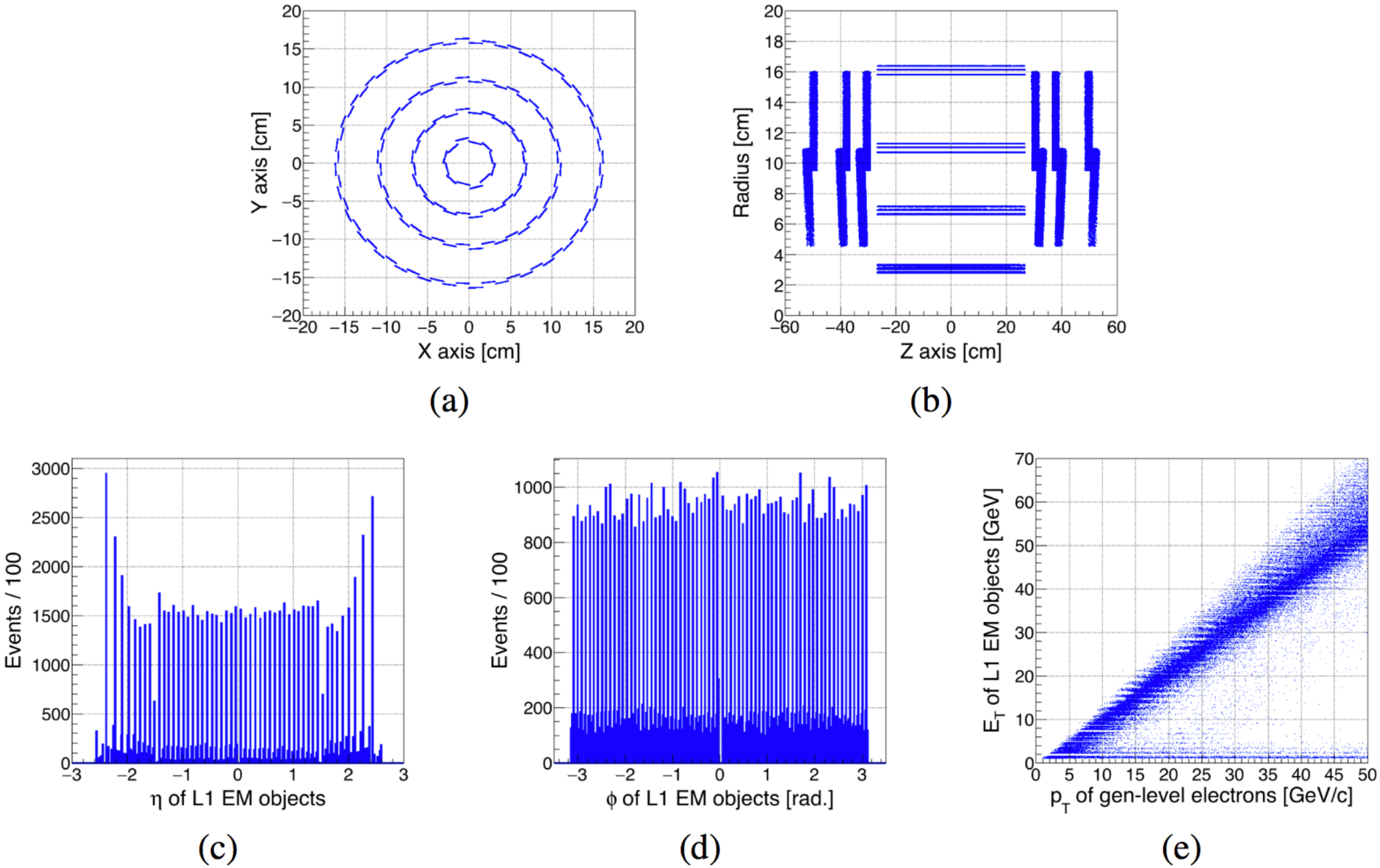


Figure 7. EXERCISE 1 results: Exercise 1-1 (a): view of pixel layers in X-Y plane; Exercise 1-2 (b): view of pixel layers and disks in R-Z plane; Exercise 1-3 (c): η distribution of L1 EM clusters; Exercise 1-4 (d): ϕ distribution of L1 EM clusters; Exercise 1-5 (e): 2-dimensional distribution of gen-level electron E_T vs. L1 EM E_T

Exercise 2

The purpose of the second exercise is to match the track reconstructed with pixel clusters with the generator-level electron and with the L1 EM cluster

- Exercise 2-1 : Transferring the (x,y,z) pixel cluster position to its η and ϕ cylindrical co-ordinates and drawing the corresponding η and ϕ distributions only in the case of the first barrel pixel layer (figures 8 (a) and (b)).

In the exercise 2-1, the students have to simply calculate the η and ϕ angles in cylindrical coordinates from the pixel clusters defined in cartesian coordinates (figures 8 (a) and (b)).

- Exercise 2-2 : Drawing the $\Delta\eta$ and $\Delta\phi$ distributions between the pixel cluster in the first barrel layer and the generator-level electron as previously defined (figures 8 (c) and (d)).
- Exercise 2-3 : Drawing the $\Delta\eta$ and $\Delta\phi$ distributions between the pixel cluster in the first barrel layer and the L1 EM cluster as previously defined (figures 8 (e) and (f)).

Exercise 2

Using the previously obtained η and ϕ coordinates, the $\Delta\eta$ and $\Delta\phi$ distributions defined as the difference between the η (respectively ϕ) coordinate of the pixel cluster on each layer and the η (respectively ϕ) of the generator-level electron or the η (respectively ϕ) of the L1 EM cluster are drawn in the exercises 2-2 & 2-3 (figures 8 (c) and (d)).

This step is for understanding how precisely one can determine the $\Delta\eta$ and $\Delta\phi$ signal windows using the pixel detector and the L1 EM calorimeter (figures 8 (e) and (f)).

Exercise 2

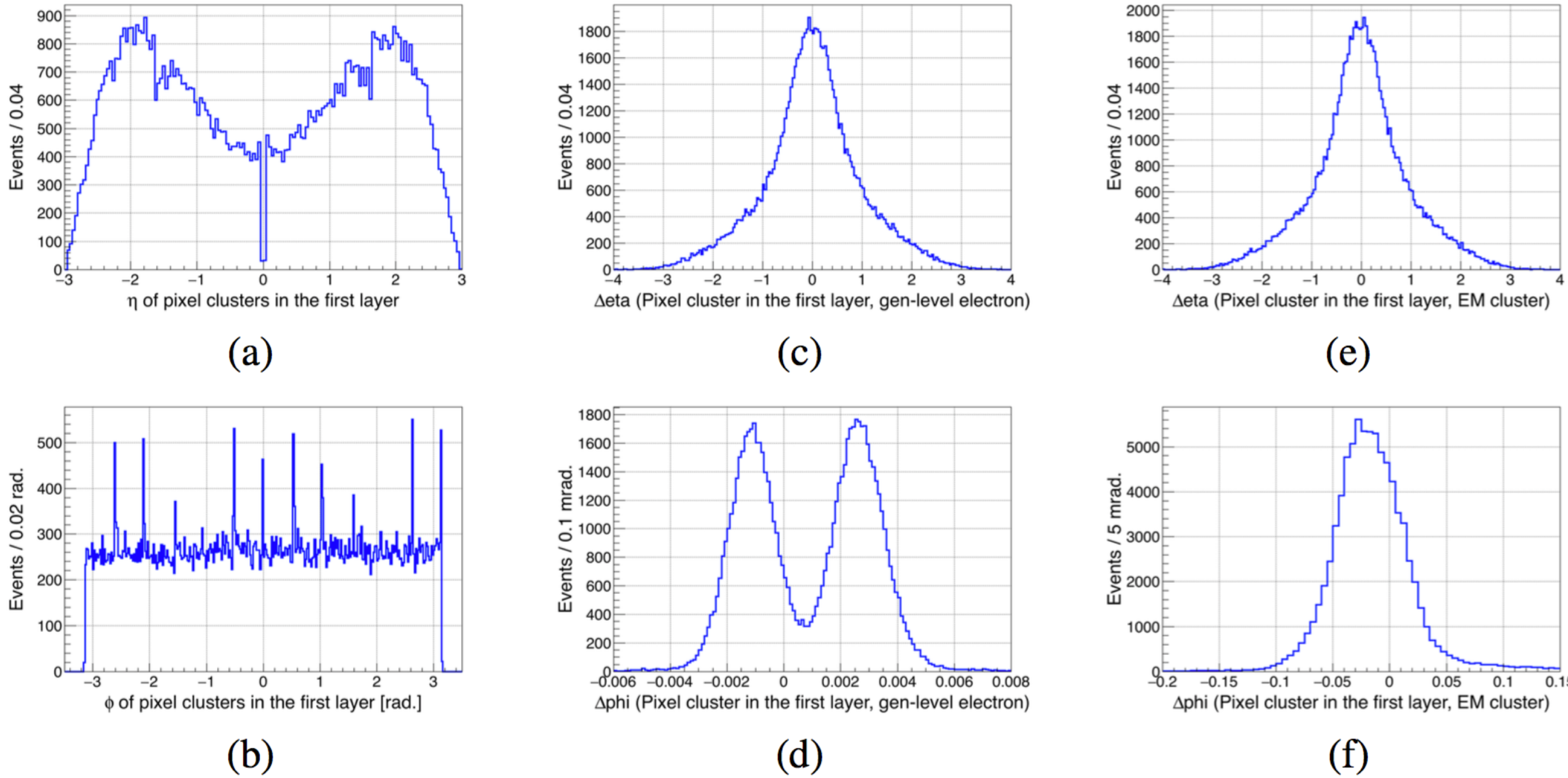


Figure 8. EXERCISE 2 results: Exercise 2-1: η (a) and ϕ (b) distributions of pixel clusters in the first pixel layer; Exercise 2-2: $\Delta\eta$ (c) and $\Delta\phi$ (d) distributions between pixel clusters in the first pixel layer and gen-level electron; Exercise 2-3: $\Delta\eta$ (e) and $\Delta\phi$ (f) distributions between pixel clusters in the first pixel layer and L1 EM cluster

Exercise 3

The goal of the third exercise is to evaluate the size of the signal windows in two cases, one based on tracks segments using only the pixel clusters i.e. *standalone pixel tracking*, the other one using tracks based on pixel clusters matching with the corresponding L1 EM cluster i.e. *pixel track seed by EM cluster*.

- Exercise 3-1 : Drawing the $\Delta\eta$, $\Delta\phi$ and ΔR signal windows in the case of standalone tracking pixel case (figure 9 (a), (b) and (c)).

The first case (pixel standalone tracking) of the third exercise consists in getting the $\Delta\eta$, $\Delta\phi$ and ΔR signal windows using the corresponding pixel clusters in the first, second and third pixel layers. To do so, the students have simply to edit the basic generic source code provided to them. This source code allows extracting from the Ntuple the needed parameters. In this case it is used to compare $\Delta\eta$, $\Delta\phi$ and ΔR angle differences between the track segment defined with the corresponding aligned clusters in the first and second layers and the track segment defined with the corresponding aligned clusters in the second and third layers for determining the corresponding η and ϕ signal windows.

Exercise 3

- Exercise 3-2 : Drawing the $\Delta\eta$, $\Delta\phi$ and ΔR signal windows in the case of the pixel track seed by EM cluster (figure 9 (d), (e) and (f)).

The second case (EM cluster seed case) consists in determining the $\Delta\eta$ (figure 9 (d)), $\Delta\phi$ (figure 9 (e)) and ΔR (figure 9 (f)) distributions computed as the difference in η and ϕ between the pixel track segment defined between corresponding aligned clusters in the first and fourth layers and the η and ϕ of the segment linking the origin (0,0,0) to the L1 EM cluster.

Exercise 3

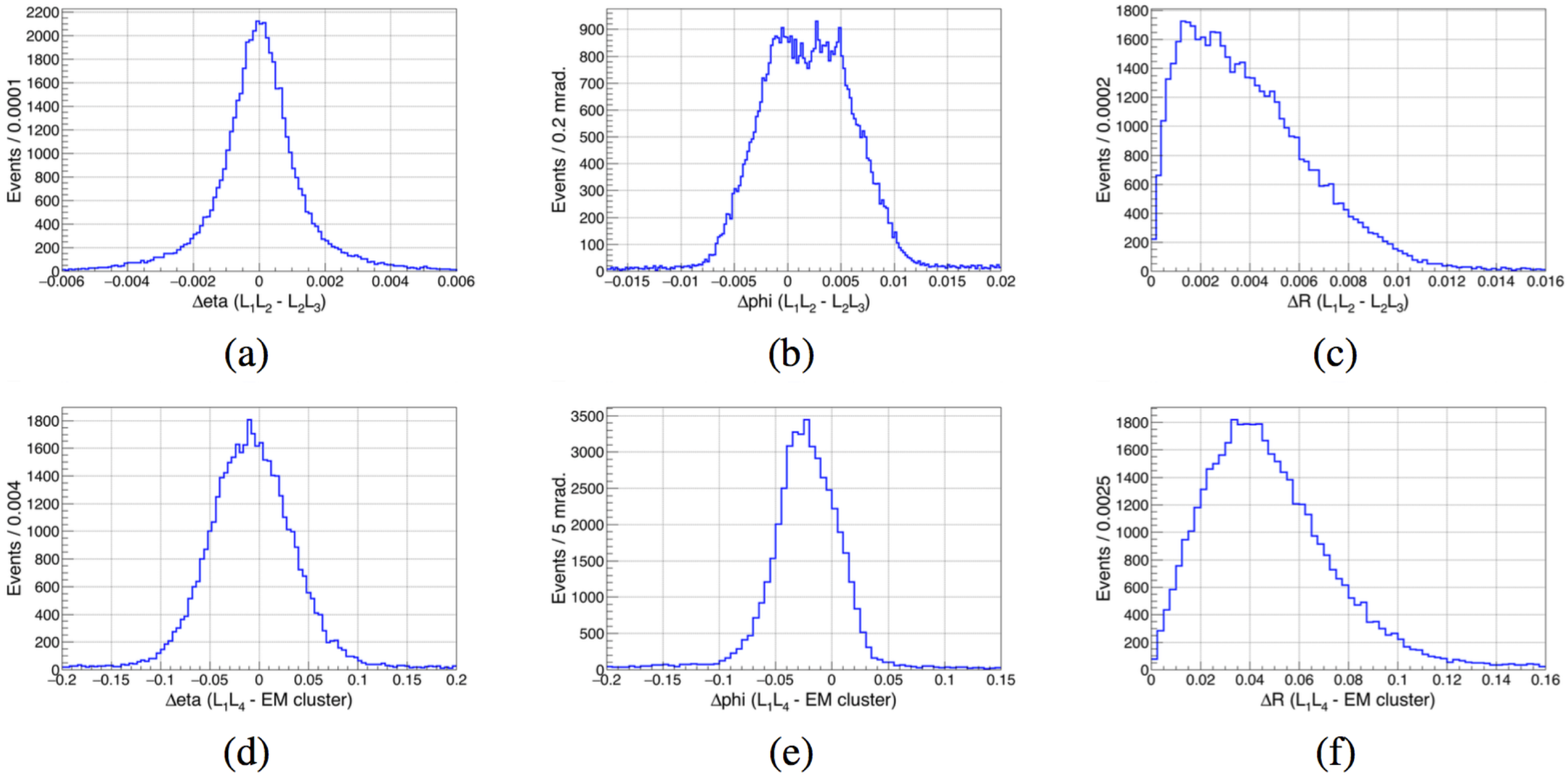


Figure 9. EXERCISE 3 results: Exercise 3-1: $\Delta\eta$ (a), $\Delta\phi$ (b) and ΔR (c) distributions between aligned clusters in the first and second layers and aligned clusters in the second and third layers; Exercise 3-2: $\Delta\eta$ (d), $\Delta\phi$ (e) and ΔR (f) distributions between colinear pixel clusters in the first and fourth layers and L1 EM cluster