# *Development of Level 3 Trigger on Belle II HLT*

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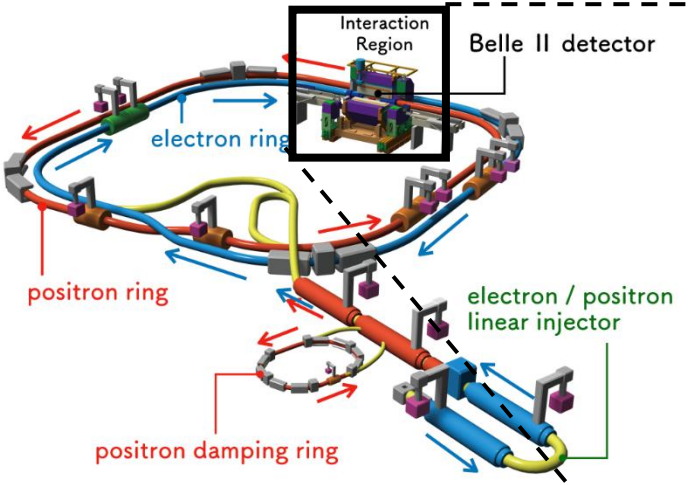
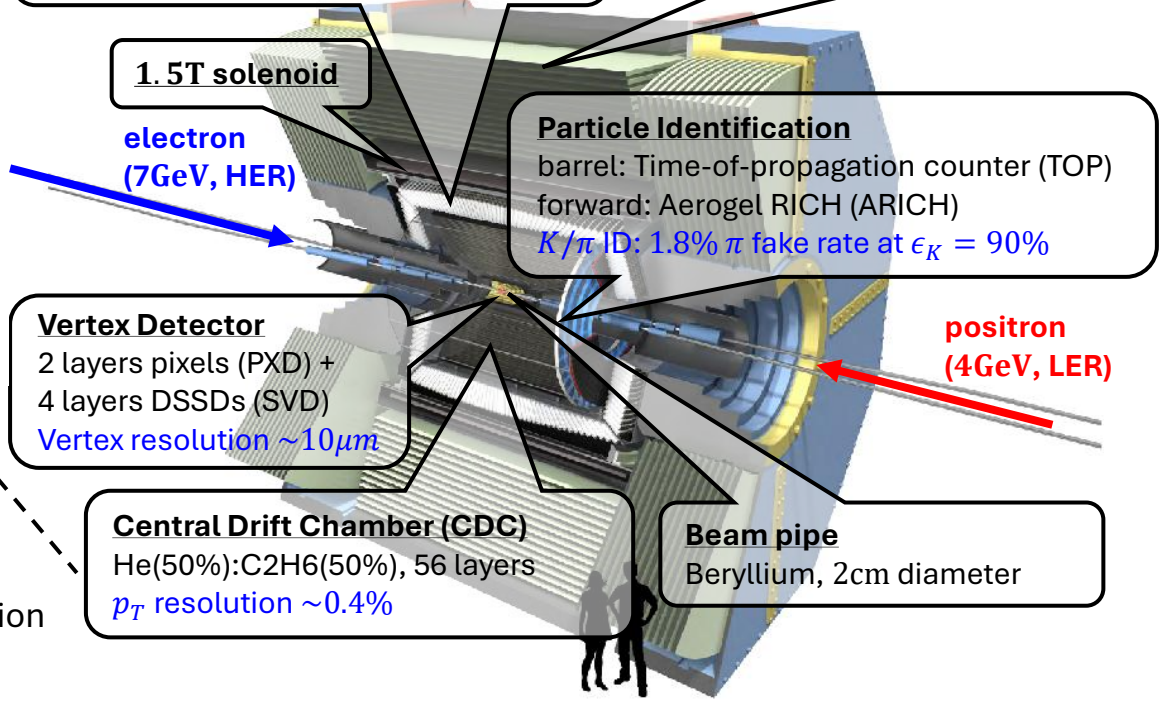
***on behalf of the Belle II DAQ group***


# Belle II experiment and SuperKEKB




- Collisions near $\Upsilon(4S)$ resonance
- Good missing energy reconstruction
  - Clean collision environment
  - Precise beam energy
  - 93% solid angle coverage
- Excellent vertexing and track reconstruction
- Good particle identification
  - Lepton ID and $\pi/K$ seperation



**EM Calorimeter (ECL)**
8k CsI(Tl) crystals, waveform sampling
$e$ID: 0.01% fake rate at $\epsilon_e = 95\%$

**$K_L$ and $\mu$ Detector (KLM)**
RPC + scintillator w/ SiPM's
$\mu$ID: 1% fake rate at $\epsilon_\mu = 95\%$

**1.5T solenoid**

**electron (7GeV, HER)**

**Particle Identification**
barrel: Time-of-propagation counter (TOP)
forward: Aerogel RICH (ARICH)
$K/\pi$ ID: 1.8% $\pi$ fake rate at $\epsilon_K = 90\%$

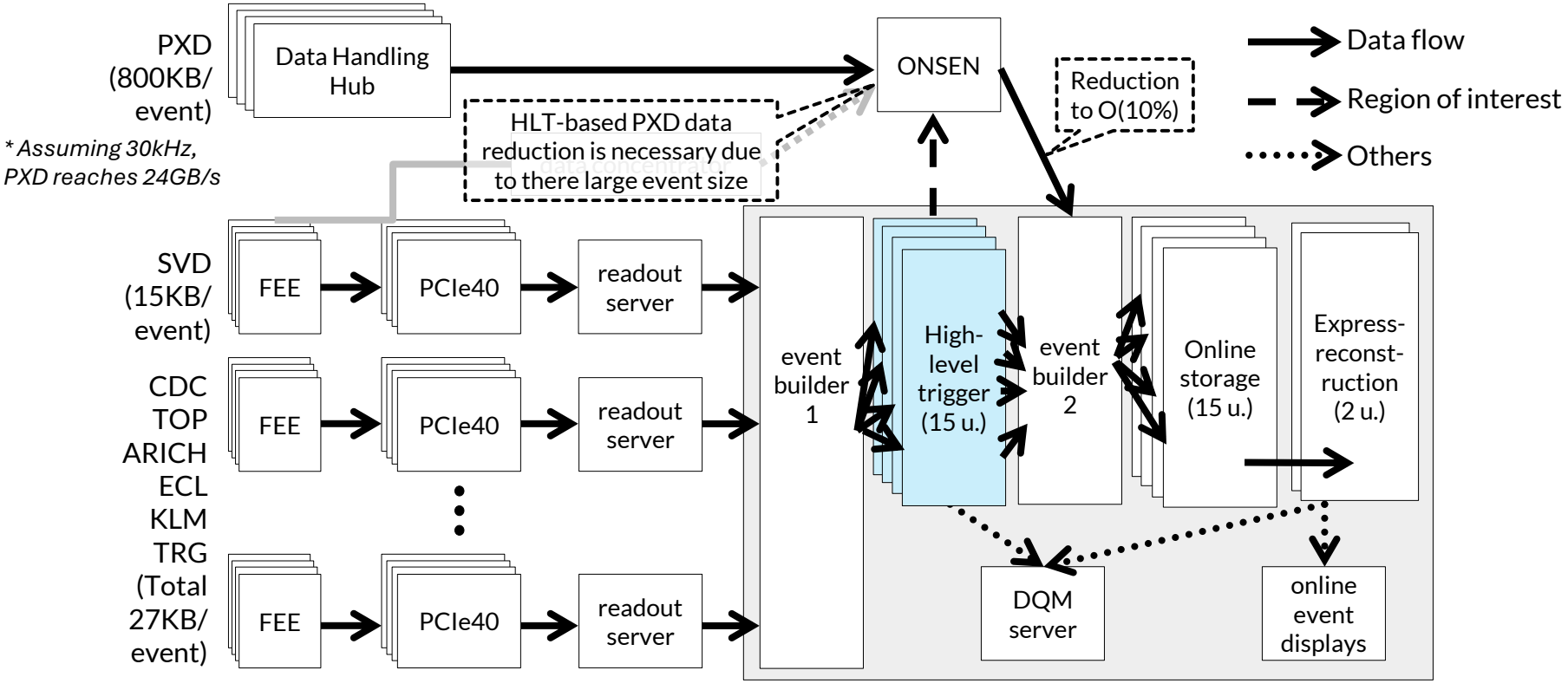
**Vertex Detector**
2 layers pixels (PXD) +
4 layers DSSDs (SVD)
Vertex resolution $\sim 10\mu m$

**positron (4GeV, LER)**

**Central Drift Chamber (CDC)**
He(50%):C2H6(50%), 56 layers
$p_T$ resolution $\sim 0.4\%$

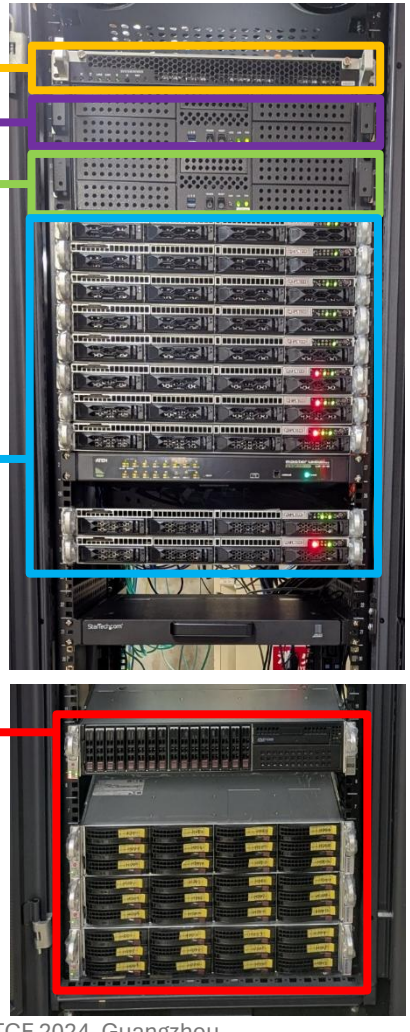
**Beam pipe**
Beryllium, 2cm diameter

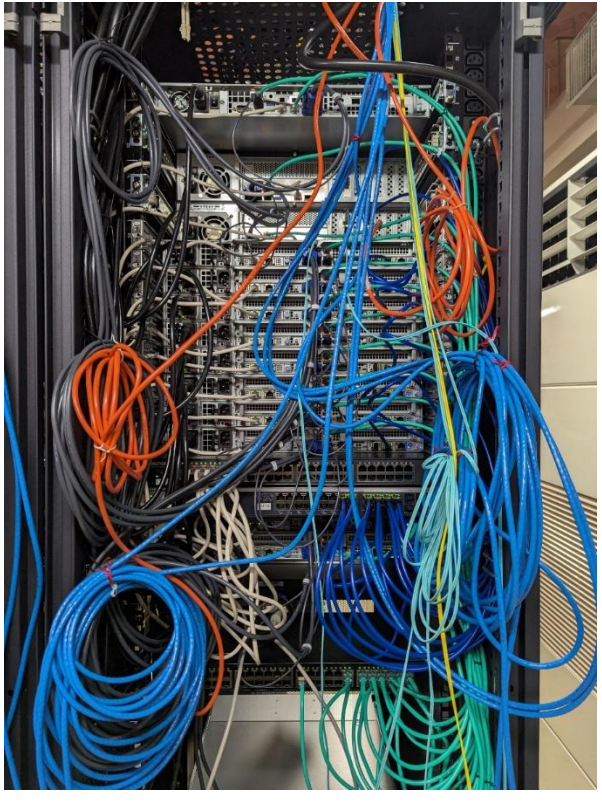
# Belle II data flow overview



# Hardware configuration

- Servers in a single HLT unit
  - 1 control node
  - 1 input node
  - 1 output node
  - 10-20 worker nodes
  - 1 storage node
- 15 HLT units
  - The number of CPU cores ~ 6700
  - **Expect to process up to 20 kHz input trigger rate**





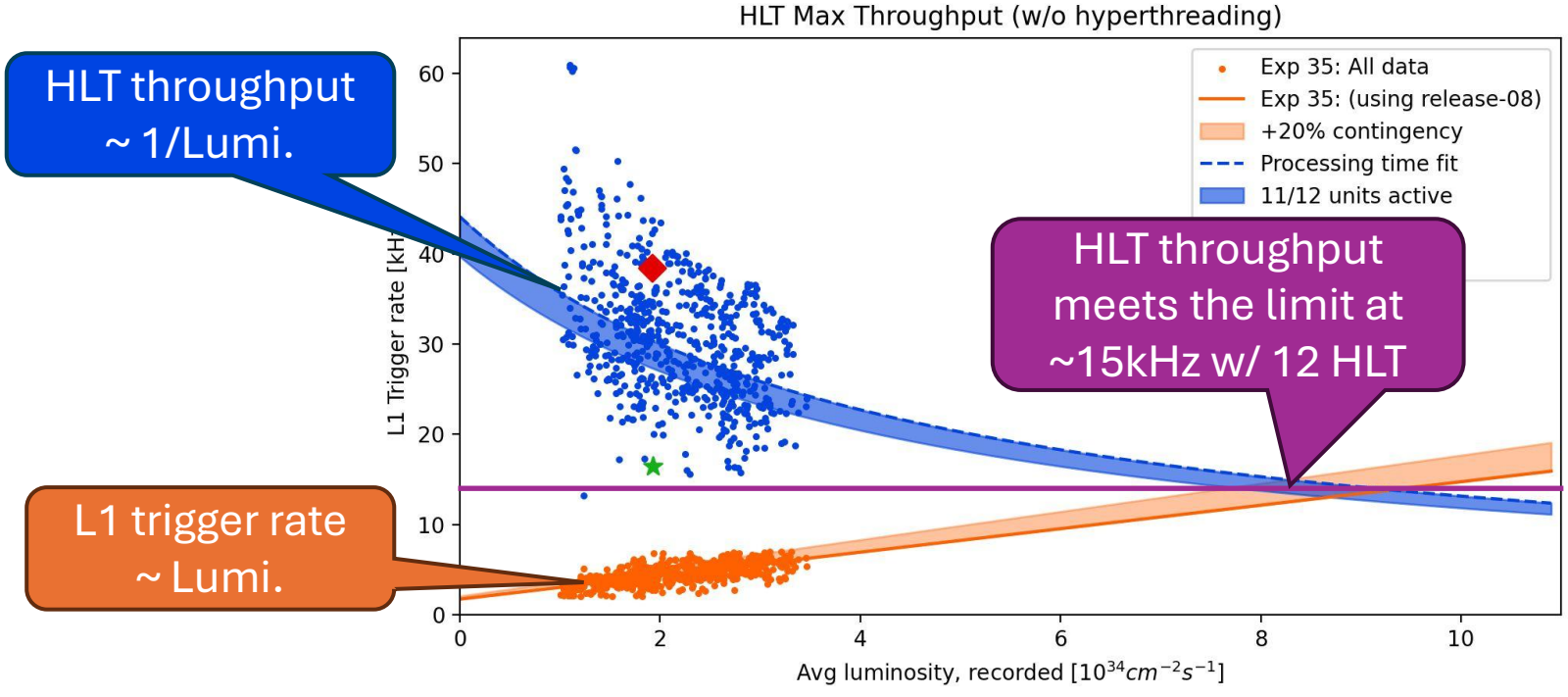
- Network
  - Dataflow: 10Gbps
  - Control: 1Gbps
  - Fully IPMI controllable

# *High-Level Trigger (HLT): Software trigger*

- Unpacking the detector raw measurements
- Reconstructing unpacked data
  - Each subdetector except PXD
  - Combined information like tracking fitting or particle identification
- Tagging events for pre-specified categories
  - Hadronic, Muonic, Bhabha etc.
  - Calibration or luminosity measurements
- Accepting or rejecting (filtering) events
- Generating a set of Regions-of-Interest (RoI) from accepted events
  - Reducing the PXD data to $O(10\%)$
- Online data quality monitoring

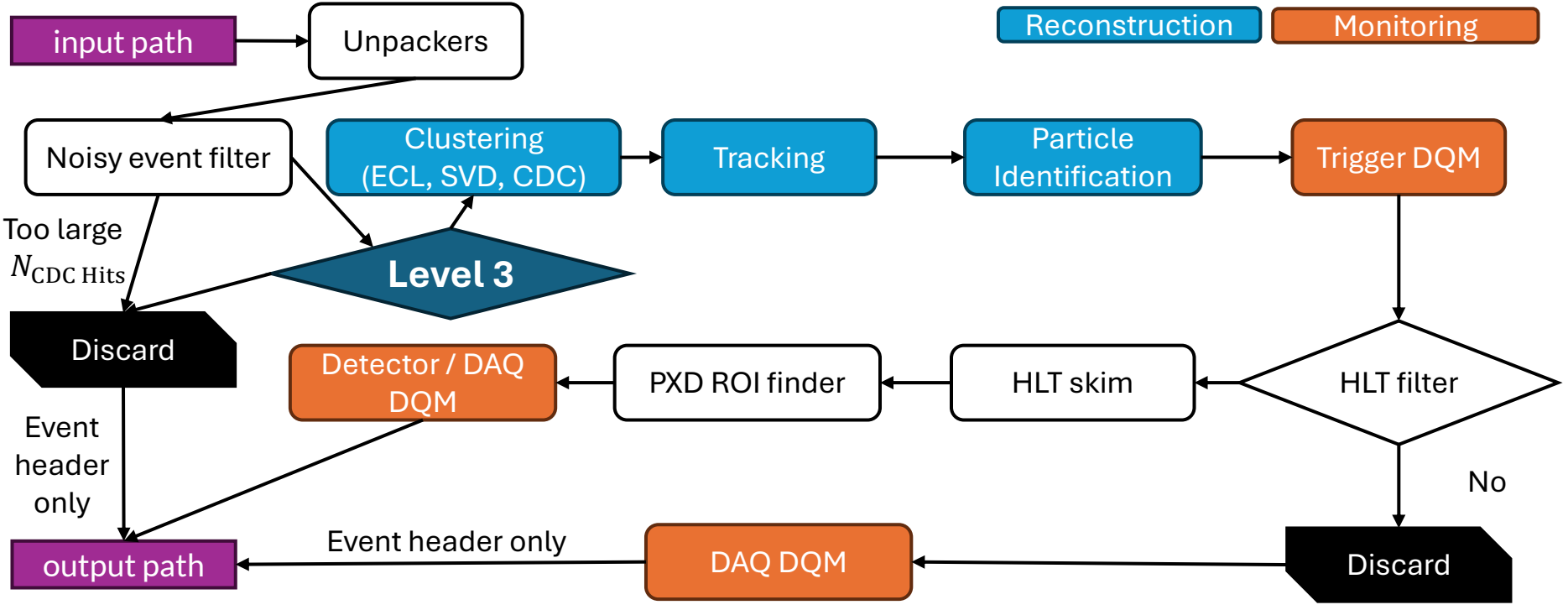
# *HLT performance estimation*

- The estimation is totally varied on the software release version, beam condition, injection timing veto, level 1 trigger prescale, etc.



# *Introduction*

- L3 intended as **“more configurable pre-filter including fast (but not precise) reconstruction of CDC tracks and ECL clusters**



# *Introduction*

- Currently developed version is inherited by Kakuno-san. (~10y ago)
  - The module is known as “Fzisan”. Probably continued from Belle.
- (My L3) project is basically for CPU-only HLT; different to HLT acceleration
  - Mid-term project compared to the heterogeneous HLT.
- The original code is not working on the latest BASF2 (Belle II analysis software framework)
  - Some updates are needed.
  - **One lesson: if the project has never been used in real production, better to write from blank.**
- The coding style is not close to the current tracking or clustering module.
  - **Rewriting the code** for easily asking to the tracking and clustering expert later
  - This is more important than what I think before. Give the highest priority.

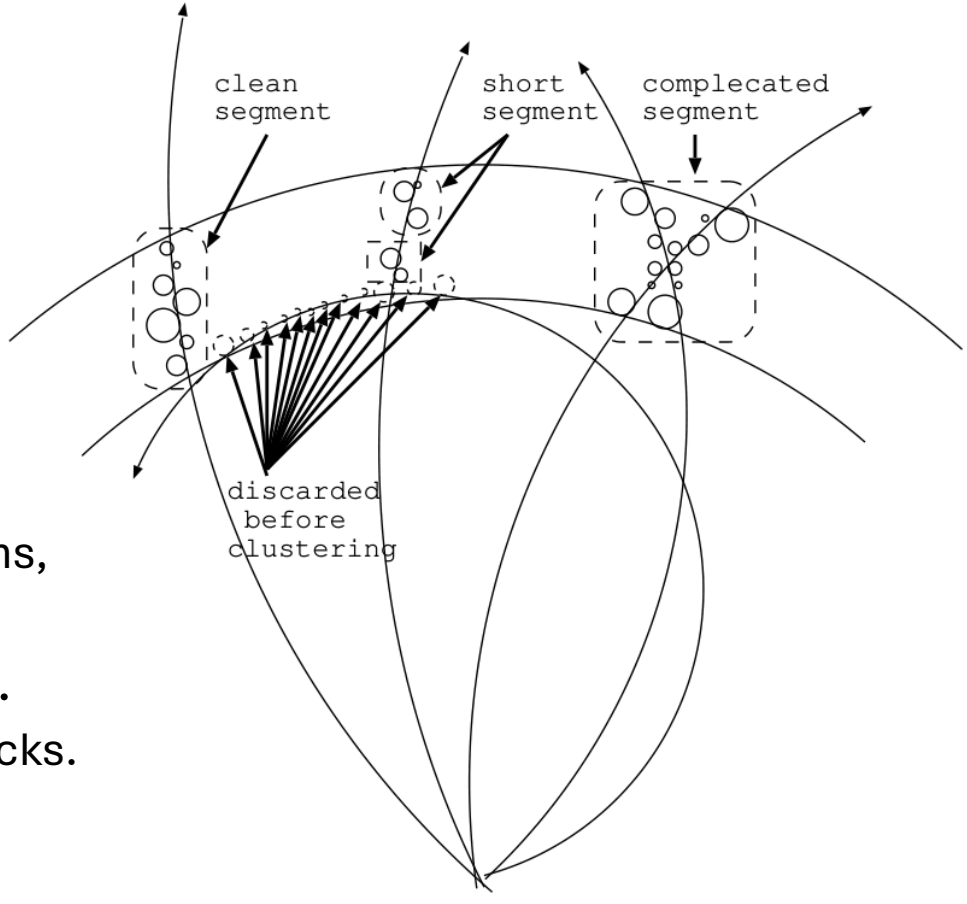
# *Introduction*

- The level 3 trigger introduces fast clustering and fast track finder.
  - After that, a selection can be done by the L3 tracks and L3 clusters.
- In the original code, there is no complex and multiple trigger conditions like the current HLT filter&skim calculator.
  - For now, a single or a few hand-writing conditions can be done by using the number of clusters/tracks, total energy, momentum, etc.

```
addParam("dr_cut", TrackTrigger->drCut(),
         "Minumum |dr| value of a reconstructed CDC track", 1.0);
addParam("dz_cut", TrackTrigger->dzCut(),
         "Minumum |dz| value of a reconstructed CDC track", 4.0);
addParam("pt_cut", TrackTrigger->ptCut(),
         "Minumum transverse momentum of a reconstructed CDC track", 0.3);
addParam("es_cut", m_EsCut,
         "Minumum energy of the seed for a reconstructed ECL cluster", 0.01);
addParam("ec_cut", m_EcCut,
         "Minumum energy of a reconstructed ECL cluster", 0.02);
addParam("min_n_trks", TrackTrigger->minNGoodTrks(),
         "Minumum number of good CDC tracks", 1);
addParam("min_energy", EnergyTrigger->minEnergy(),
         "Minumum threshold of the energy sum of ECL clusters", 4.0);
addParam("find_evt_vtx", m_findEvtVtx,
         "Flag for event vertex finding", 0);
addParam("save_data", m_saveData,
         "=0:HLTTag only, =1:HLTTag+L3Tag, =2:HLTTag+L3Tag+L3Track+L3Cluster", 2);
```

# *L3 Track*

- The L3 tracking consists with segment finding in a super layer, segments linking, and finally tracking fitting.
- Especially, the segment finding is simplified for speed.
  - Discard low $p_t$ segments
  - Discard complicated segment, hits connected more than two connections, without separation
- The tracking is done only with CDC.
  - HLT filter uses both CDC and SVD tracks.



# *L3 Cluster*

- For the fast clustering in ECL, we use slightly different conditions.
  - The cluster is basically a just connected hits.
  - No limitation on the number of local maximum hits in a cluster
  - No limitation on the number of hits in a cluster
  - Neighbor for connected hit is only 4-direction: up, down, left, and right
  - The cluster position is defined as a most energetic hit in the cluster

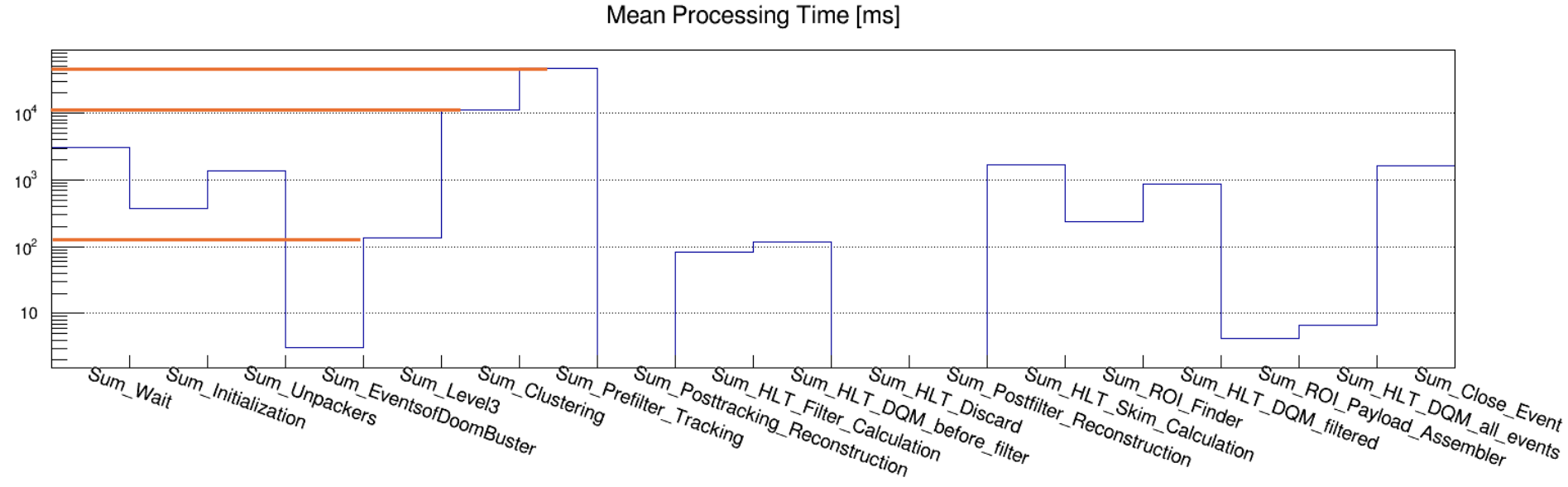
- We may give more conditions in this stage (just an idea yet)
  - Size of cluster, minimum energy cut of a hit or a local maximum hit, …

# *Level 3 monitoring*

- A dedicated DQM module for level 3 is ready, but…
  - For now, only can extract the final objects like the number of tracks/clusters, final momentums, dr, dz, etc.
  - No internal items like drift distance, timing, etc.
- While keeping the dedicated DQM module, make the Level 3 module to record DQM histograms directly.
- The performance (CPU mean processing time, memory usage, etc.) monitoring is included in the test setup.
  - There is no issue on memory consumption.
  - The mean processing time is much faster than my expectation.
  - If we have performance issues, I need to separate the module into the tracking, clustering, and trigger calculating for more detailed checking.

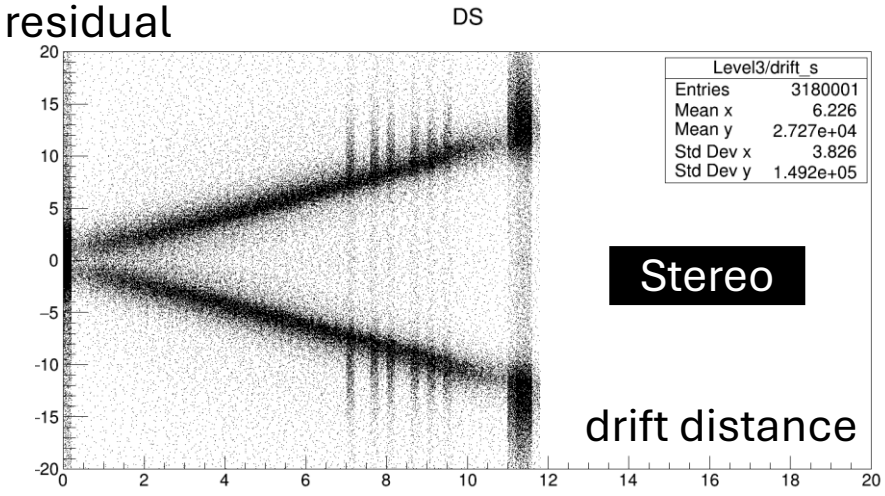
# *Level 3 computing performance*

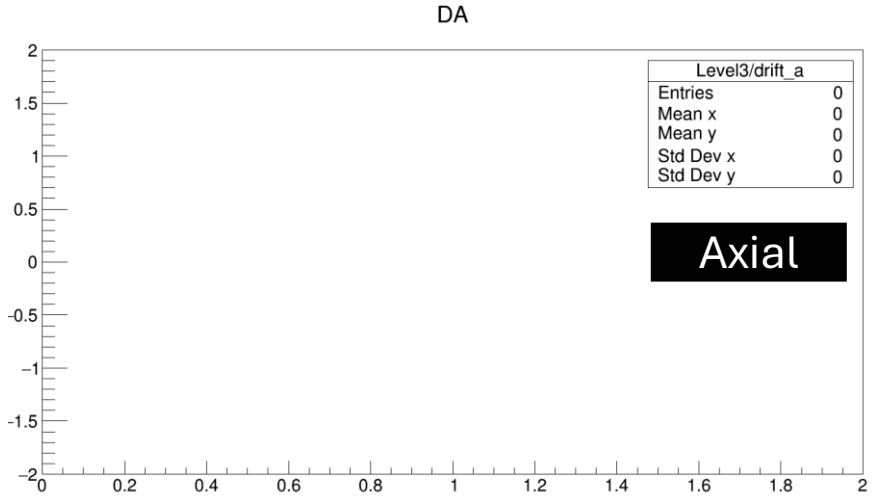
- The level 3 module's mean processing time is very small.
  - The mean processing time of the Level 3 module is very short
  - This is a tentative measurement… more precise study will be prepared.



# *Level 3 reconstruction DQM*

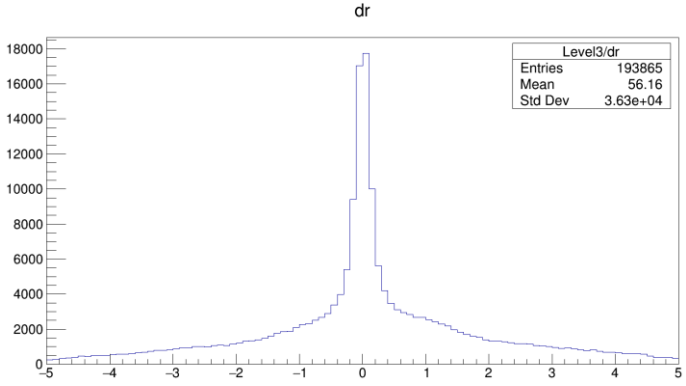
- However, not 100% sure that the tracks and clusters are correctly reconstructed.
- Using the pre-defined DQM set by Kakuno-san, some of DQM hisograms are just empty even if they should exist.
  - For example, the comparison of drift distance (coming from drift time) and residual (distance between CDC hit and reconstructed track), the stereo layer result is shown, but the axial result is empty.

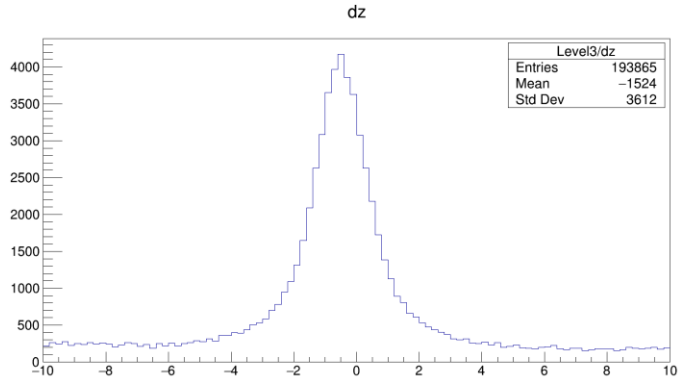


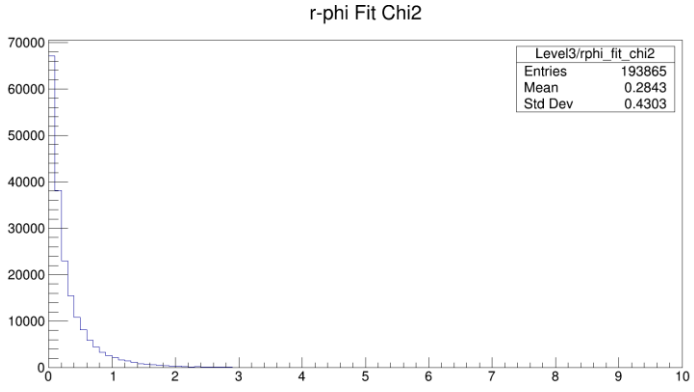



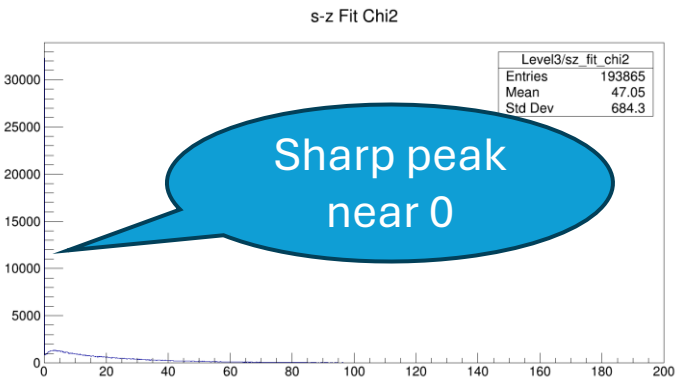
# *Level 3 reconstruction DQM*

- Final results like dr, dz, or track fitting $\chi^2$ are shown correctly.
  - Source code cleaning up is needed for correct understand + asking experts



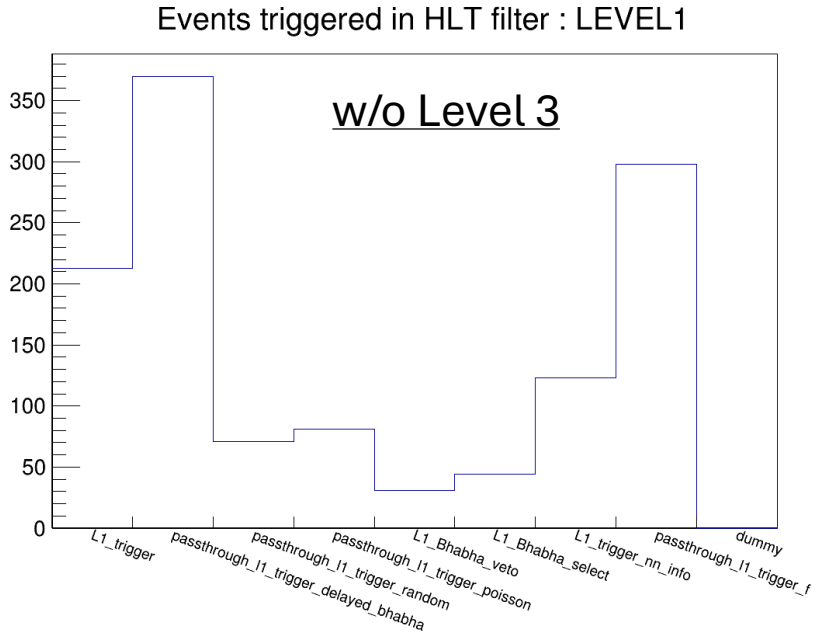



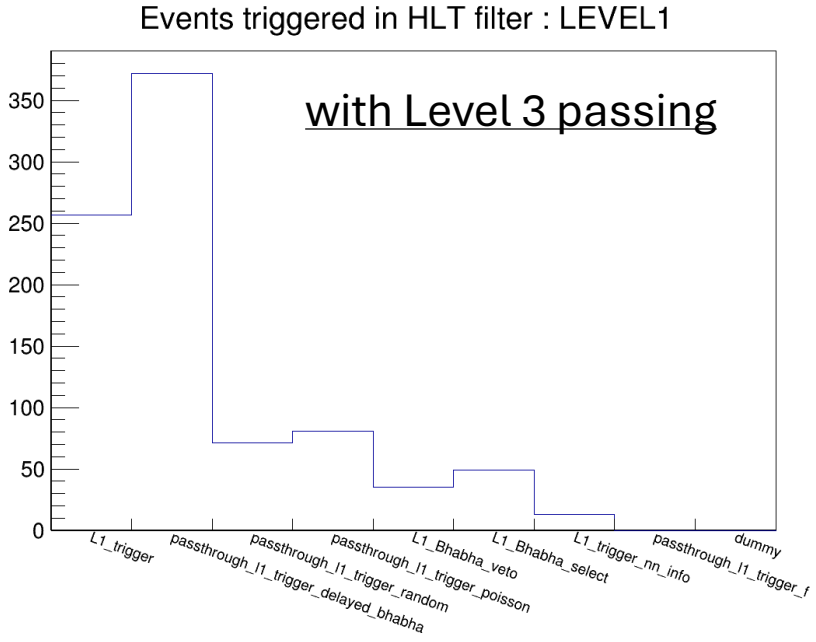



# *Level 1 implementation*

- The level 1 information is installed in the Level 3.
  - The original Fzisan code don't use the level 1 information for selection.
  - Differences in L1_trigger_nn_info and passthrough_l1_trigger_f



# *0 track, 0 cluster trial*

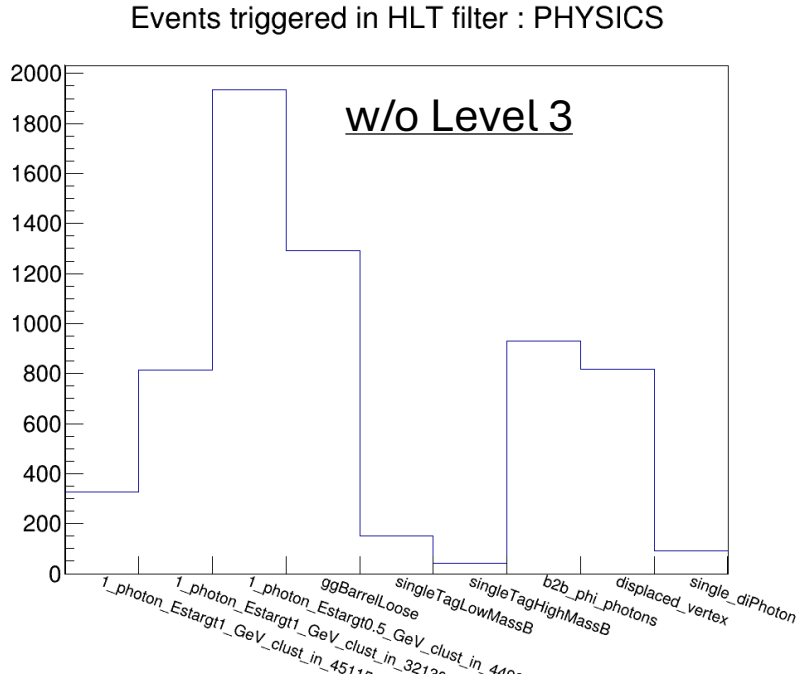
- With the level 1 information, try to give a condition: discard no L3 tracks and L3 clusters if it doesn't have level 1 info.
  - I expect that certain amount of "filtered" data are kept, but....

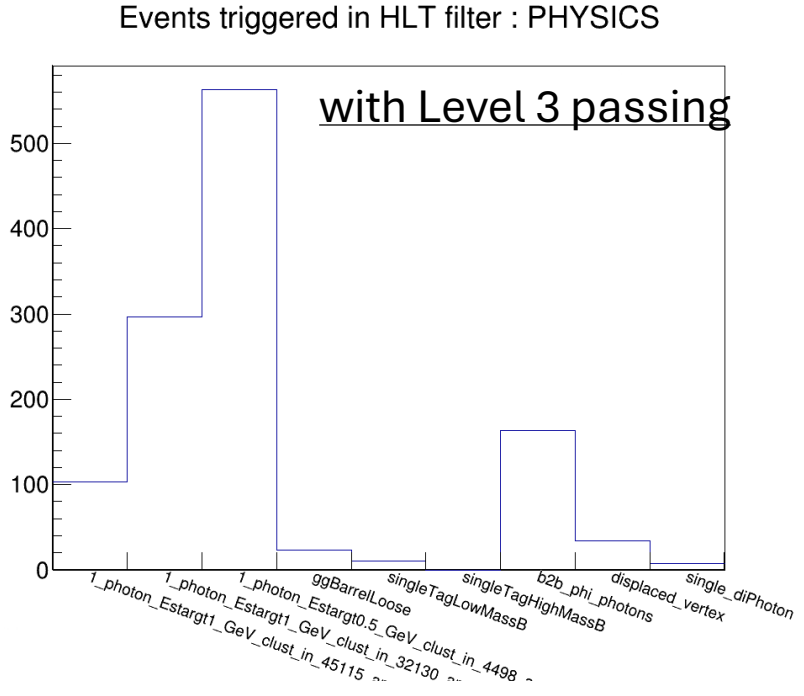
```
bool Level3Module::doCalculation(Belle2::SoftwareTrigger::SoftwareTriggerObject &calculationResult)
{
  if (calculationResult["l1_trigger_delayed_bhabha"] == 1) return true;
  if (calculationResult["l1_trigger_poisson"]        == 1) return true;
  if (calculationResult["bha3d"]                     == 1) return true;
  if (calculationResult["bhapur"]                    == 1) return true;
  if (calculationResult["bhapur_lml1"]               == 1) return true;
  if (calculationResult["l1_bit_f"]                  == 1) return true;
  if (calculationResult["l1_trg_NN_info"]            == 1) return true;

  if (m_l3Tracks.getEntries() == 0 && m_l3Clusters.getEntries() == 0) {
    return false;
  }
  return true;
}
```

Taken from FilterCalculation

# *0 track, 0 cluster trial*

- By checking the filter menu, 10x difference is found for all the trigger menus except to L1-related.
- Need to carefully check the L3 track and cluster reconstruction.



# *0 track, 0 cluster trial*

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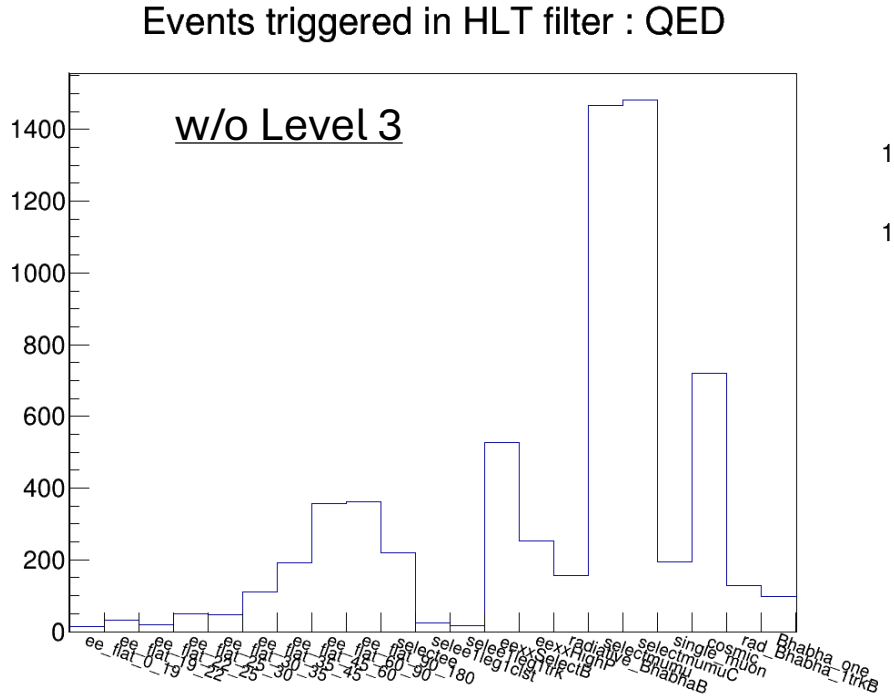
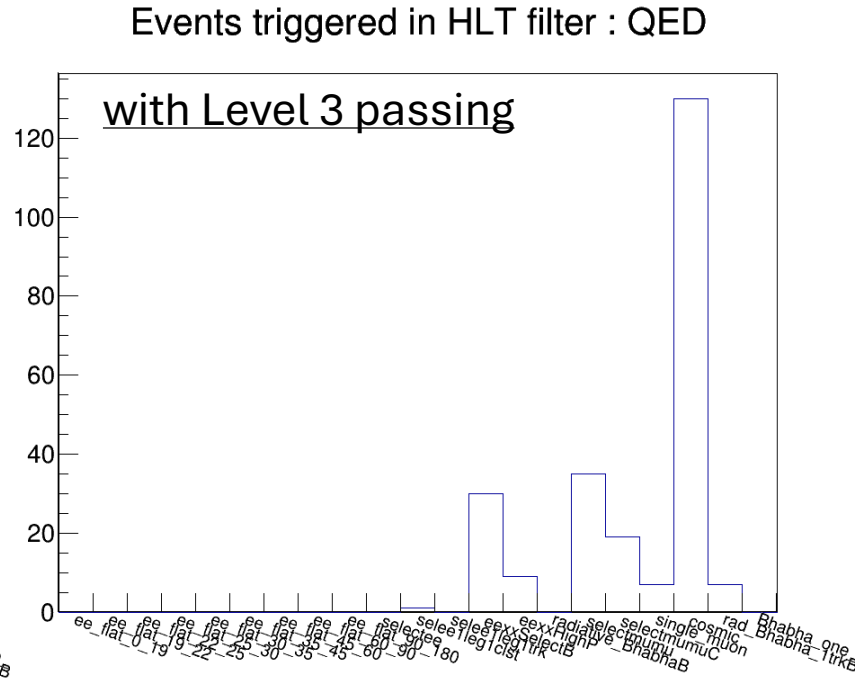


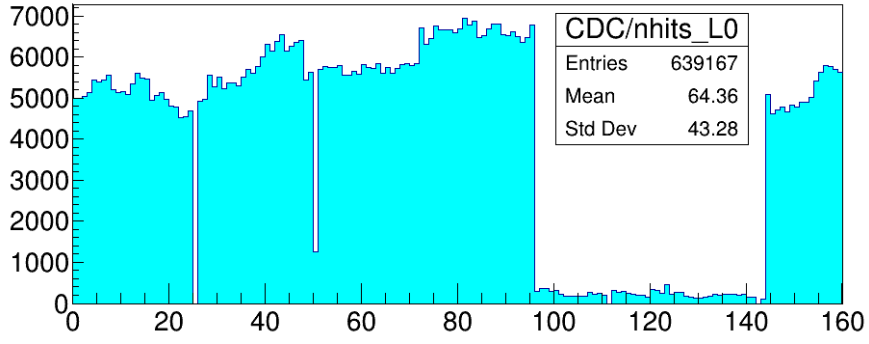



# *Checking CDC DQM*

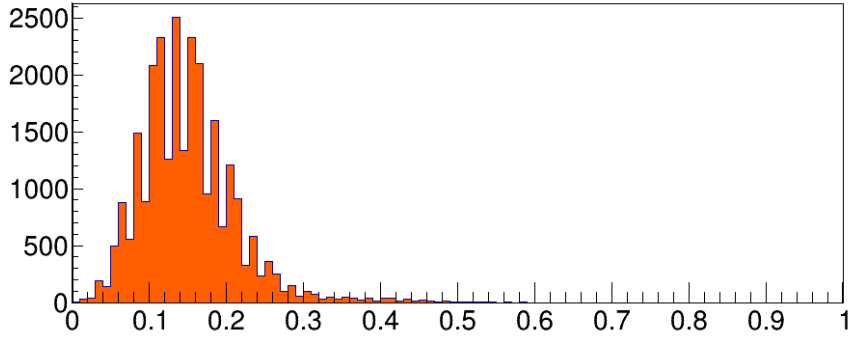
- While nhits of each layer is similar, occupancy shows strange difference.

w/o Level 3

nhits Layer 0

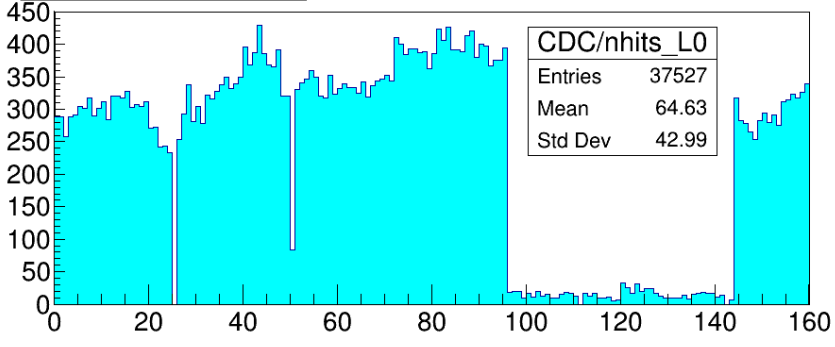



occ. each layer

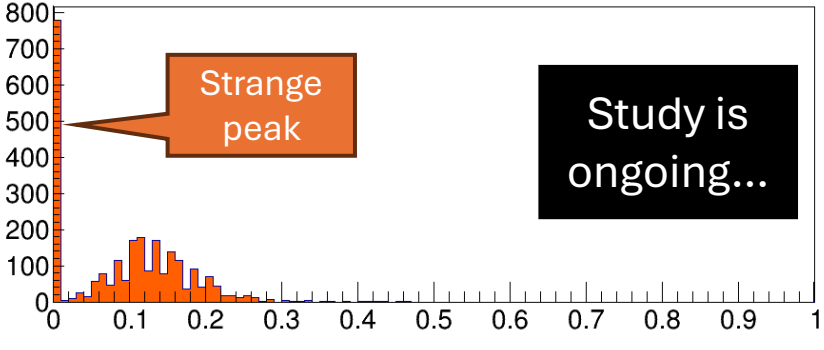


with Level 3

nhits Layer 0

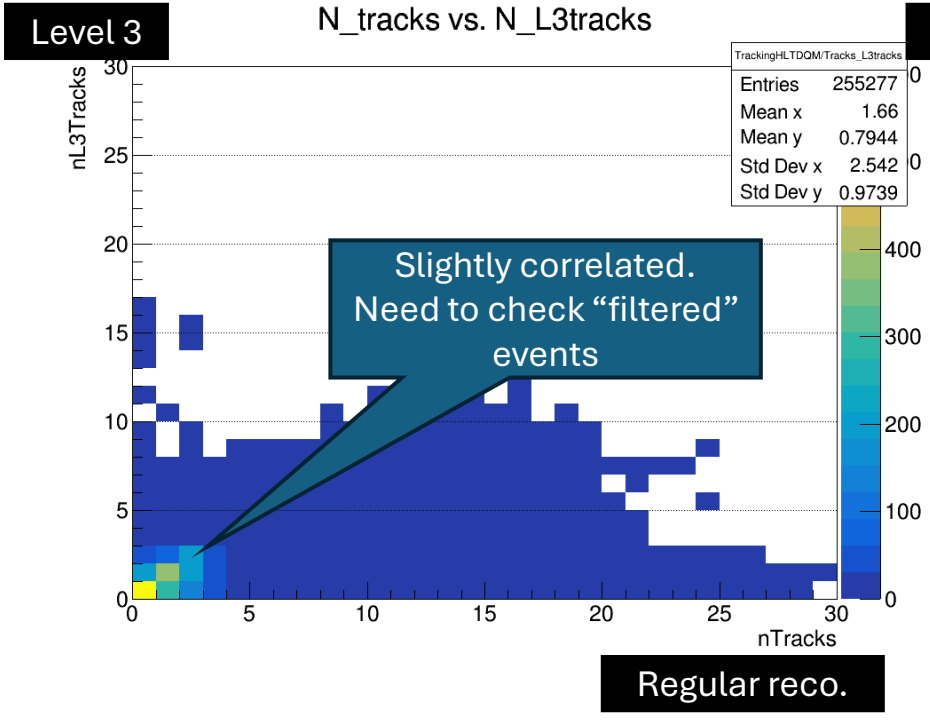


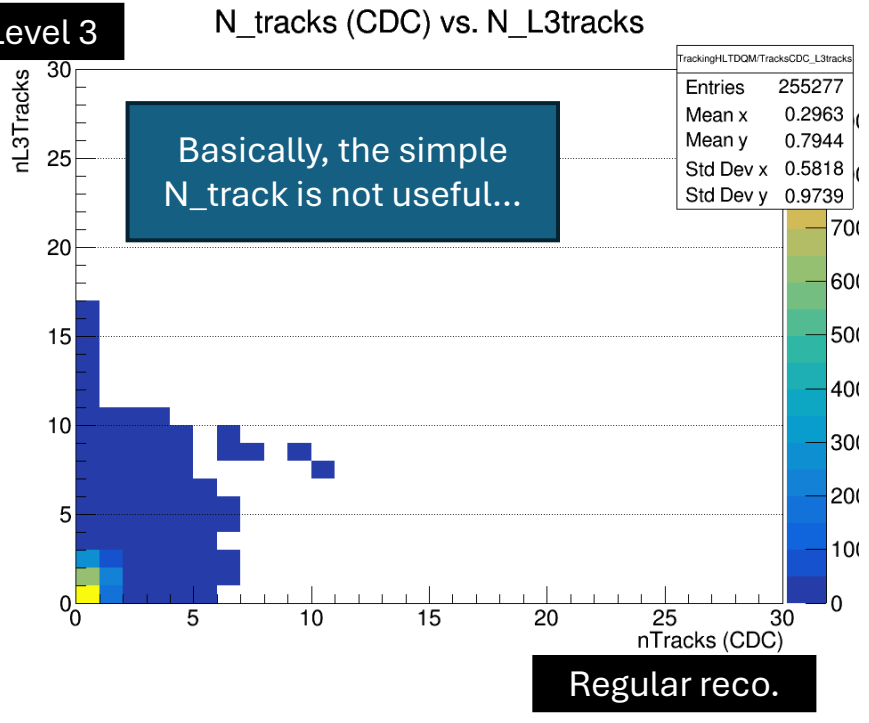

occ. each layer



# *Comparisons: L3 track vs. regular track*

- Compare all tracks / CDC-only tracks with L3 track (beam_reco_monitor)
  - No useful information…



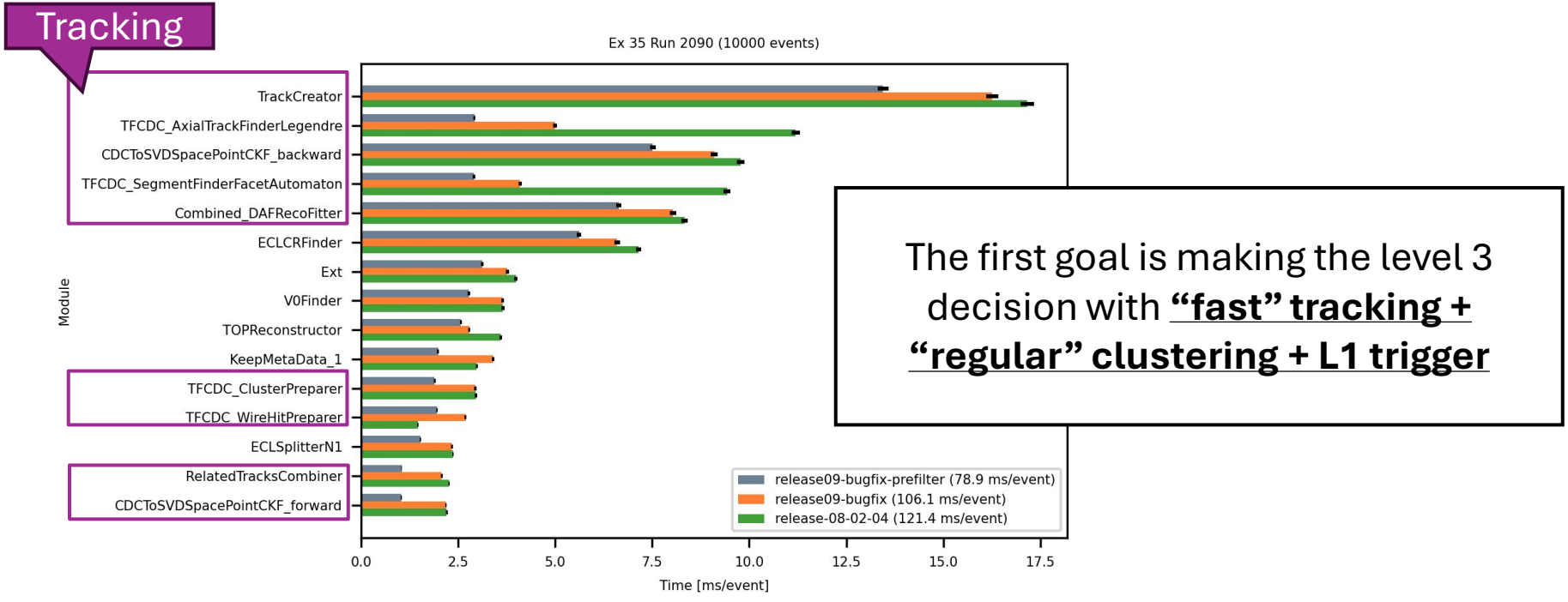
# *Important point*

- HLT already has extensive trigger lines not only for the B-physics but also for the rare/new physics including low multiplicity events.
- 68 lines in 2024c run period.
- **All the data must be kept!**
  - The low multiplicity, rare events simulation and testing is oneof difficult point in the development.
- **Communication with the physics group is important.**

| | | | |
|---|---|---|---|
| ECL - Physics | | | |
| filter Elab gt 0.3 plus 3 others with Elab gt 0.18 plus no clust with Ecms gt 2.0 | 149 ( 32.96%) | 149 ( 32.96%) | 1.0 |
| filter Elab gt 0.5 plus 2 others with Elab gt 0.18 plus no clust with Ecms gt 2.0 | 50 ( 11.06%) | 50 ( 11.06%) | 1.0 |
| filter gel Estargt2 GeV neutral clst 2232 or 130145 not gg2clst ee2clst eelleg eeBremB | 11 ( 2.43%) | 11 ( 2.43%) | 1.0 |
| filter gel Estargt2 GeV neutral clst 32130 not gg2clst eellegiclst eellegltrk eeBremB | 40 ( 8.85%) | 40 ( 8.85%) | 1.0 |
| ECL - Potentially Prescaled | | | |
| filter 0.3lteEstar max clustlt2 GeV plus 2 others gt 0.2 GeV | 1 ( 0.22%) | 199 ( 44.03%) | 100.0 |
| filter 1 electron Estargt1 GeV clust in 45115 and no other clust Estargt0.3 GeV | 3 ( 0.66%) | 21 ( 4.65%) | 10.0 |
| filter 1 electron Estargt1 GeV clust in 32130 and no other clust Estargt0.3 GeV | 1 ( 0.22%) | 31 ( 6.86%) | 100.0 |
| filter 1 Estargt1 GeV cluster no other cluster Estargt0.3 GeV | 0 ( 0.00%) | 66 ( 14.60%) | 200.0 |
| filter 1 photon Estargt1 GeV clust not low not 45115 no other clust Estargt0.3 GeV | 1 ( 0.22%) | 5 ( 1.11%) | 50.0 |
| filter gg2clst | 0 ( 0.00%) | 0 ( 0.00%) | 100.0 |
| filter gel Estargt2 GeV chrg clst 22145 not gg2clst ee2clst eelleg | 2 ( 0.44%) | 65 ( 14.38%) | 50.0 |
| filter ggEndcapLoose | 0 ( 0.00%) | 0 ( 0.00%) | 1.0 |
| filter n2GeVPhotonBarrelgel | 1 ( 0.22%) | 28 ( 6.19%) | 100.0 |
| filter n2GeVPhotonEndcapgel | 0 ( 0.00%) | 10 ( 2.21%) | 50.0 |
| filter Estargt2 GeV cluster | 2 ( 0.44%) | 122 ( 26.99%) | 100.0 |
| filter ECLMuonPair | 0 ( 0.00%) | 12 ( 2.65%) | 10.0 |
| CDC - Physics | | | |
| filter ge3 looseB tracks inc 1 tightB not ee2leg | 38 ( 8.41%) | 38 ( 8.41%) | 1.0 |
| filter 2 looseB tracks inc 1 tightB q==0 pstarmaxlt0.8 GeVc not eexx | 11 ( 2.43%) | 11 ( 2.43%) | 1.0 |
| filter 2 looseB tracks 0.8ltpstarmaxlt4.5 GeVc not ee2leg eellegltrk eexx | 356 ( 78.76%) | 356 ( 78.76%) | 1.0 |
| filter 2 looseB tracks pstarmaxgt4.5 GeVc not ee2leg eellegltrk eellegle eeBremB muonPairVB | 18 ( 3.98%) | 18 ( 3.98%) | 1.0 |
| CDC - Potentially Prescaled | | | |
| filter 2 loose tracks pstarmaxlt0.8 GeVc | 0 ( 0.00%) | 11 ( 2.43%) | 100.0 |
| filter 2 loose tracks 0.8ltpstarmaxlt4.5 GeVc | 3 ( 0.66%) | 357 ( 78.98%) | 100.0 |
| filter 2 loose tracks pstarmaxgt4.5 GeVc | 0 ( 0.00%) | 18 ( 3.98%) | 500.0 |
| filter gel tight track | 0 ( 0.00%) | 451 ( 99.78%) | 1000.0 |
| Targeted Physics Lines | | | |
| filter 1 photon Estargt1 GeV clust in 45115 and no other clust Estargt0.3 GeV | 5 ( 1.11%) | 5 ( 1.11%) | 1.0 |
| filter 1 photon Estargt1 GeV clust in 32130 and no other clust Estargt0.3 GeV | 8 ( 1.77%) | 8 ( 1.77%) | 1.0 |
| filter 1 photon Estargt0.5 GeV clust in 4498 and no other clust Estargt0.3 GeV | 6 ( 1.33%) | 6 ( 1.33%) | 1.0 |
| filter ggBarrelLoose | 0 ( 0.00%) | 0 ( 0.00%) | 1.0 |
| filter singleTagLowMassB | 0 ( 0.00%) | 0 ( 0.00%) | 1.0 |
| filter singleTagHighMassB | 0 ( 0.00%) | 0 ( 0.00%) | 10.0 |
| filter b2b phi photons | 0 ( 0.00%) | 0 ( 0.00%) | 1.0 |
| filter displaced vertex | 0 ( 0.00%) | 0 ( 0.00%) | 1.0 |
| QED / Control Samples | | | |
| filter ee flat 0 19 | 0 ( 0.00%) | 0 ( 0.00%) | 62.0 |
| filter ee flat 19 22 | 0 ( 0.00%) | 0 ( 0.00%) | 36.0 |
| filter ee flat 22 25 | 0 ( 0.00%) | 0 ( 0.00%) | 30.0 |
| filter ee flat 25 30 | 0 ( 0.00%) | 0 ( 0.00%) | 10.0 |
| filter ee flat 30 35 | 0 ( 0.00%) | 0 ( 0.00%) | 36.0 |
| filter ee flat 35 45 | 0 ( 0.00%) | 0 ( 0.00%) | 30.0 |
| filter ee flat 45 60 | 0 ( 0.00%) | 0 ( 0.00%) | 10.0 |
| filter ee flat 60 90 | 0 ( 0.00%) | 0 ( 0.00%) | 4.0 |
| filter ee flat 90 180 | 0 ( 0.00%) | 0 ( 0.00%) | 2.0 |
| filter selectee | 0 ( 0.00%) | 0 ( 0.00%) | 20.0 |
| filter seleelleglclst | 0 ( 0.00%) | 6 ( 1.33%) | 1000.0 |
| filter seleellegltrk | 0 ( 0.00%) | 21 ( 4.65%) | 1000.0 |
| filter eexxSelectB | 2 ( 0.44%) | 13 ( 2.88%) | 4.0 |
| filter eexxHighP | 2 ( 0.44%) | 2 ( 0.44%) | 1.0 |
| filter radiative BhabhaB | 9 ( 1.99%) | 39 ( 8.63%) | 4.0 |
| filter selectmumu | 21 ( 4.65%) | 21 ( 4.65%) | 1.0 |
| filter single muon | 6 ( 1.33%) | 79 ( 17.48%) | 10.0 |
| filter cosmic | 0 ( 0.00%) | 0 ( 0.00%) | 1.0 |
| filter rad Bhabha ltrkB | 0 ( 0.00%) | 1 ( 0.22%) | 4.0 |
| filter Bhabha one cluster | 0 ( 0.00%) | 0 ( 0.00%) | 10.0 |
| Level 1 Passthrough | | | |
| filter L1 trigger | 0 ( 0.00%) | 452 (100.00%) | 1000.0 |
| filter passthrough l1 trigger delayed bhabha | 0 ( 0.00%) | 0 ( 0.00%) | 1.0 |
| filter passthrough l1 trigger random | 0 ( 0.00%) | 0 ( 0.00%) | 1.0 |
| filter passthrough l1 trigger poisson | 0 ( 0.00%) | 0 ( 0.00%) | 1.0 |
| filter L1 Bhabha veto | 0 ( 0.00%) | 0 ( 0.00%) | 10.0 |
| filter L1 Bhabha select | 0 ( 0.00%) | 0 ( 0.00%) | 100.0 |
| filter L1 trigger nn info | 0 ( 0.00%) | 0 ( 0.00%) | 8.0 |
| filter passthrough l1 trigger f | 0 ( 0.00%) | 0 ( 0.00%) | 1.0 |
| filter dummy | 0 ( 0.00%) | 0 ( 0.00%) | 1000.0 |
| Prescaled Vetoes | | | |
| filter eelleg | 0 ( 0.00%) | 0 ( 0.00%) | 1000.0 |
| filter eelleglclst | 0 ( 0.00%) | 0 ( 0.00%) | 1000.0 |
| filter eellegle | 0 ( 0.00%) | 0 ( 0.00%) | 1000.0 |
| filter eellegltrk | 0 ( 0.00%) | 0 ( 0.00%) | 1000.0 |
| filter ee2clst | 0 ( 0.00%) | 0 ( 0.00%) | 1000.0 |
| filter ee2leg | 0 ( 0.00%) | 0 ( 0.00%) | 1000.0 |
| filter eeBremB | 0 ( 0.00%) | 0 ( 0.00%) | 1000.0 |
| filter eexx | 0 ( 0.00%) | 7 ( 1.55%) | 1000.0 |
| filter muonPairVB | 0 ( 0.00%) | 0 ( 0.00%) | 1000.0 |

# *Important point*

- Introducing both new tracking and clustering at the same time is not so easy. (Lesson 2) We must focus on more crucial part.
- In the reconstruction chain, tracking takes more time than clustering.




The first goal is making the level 3 decision with **“fast” tracking + “regular” clustering + L1 trigger**

# *Summary*

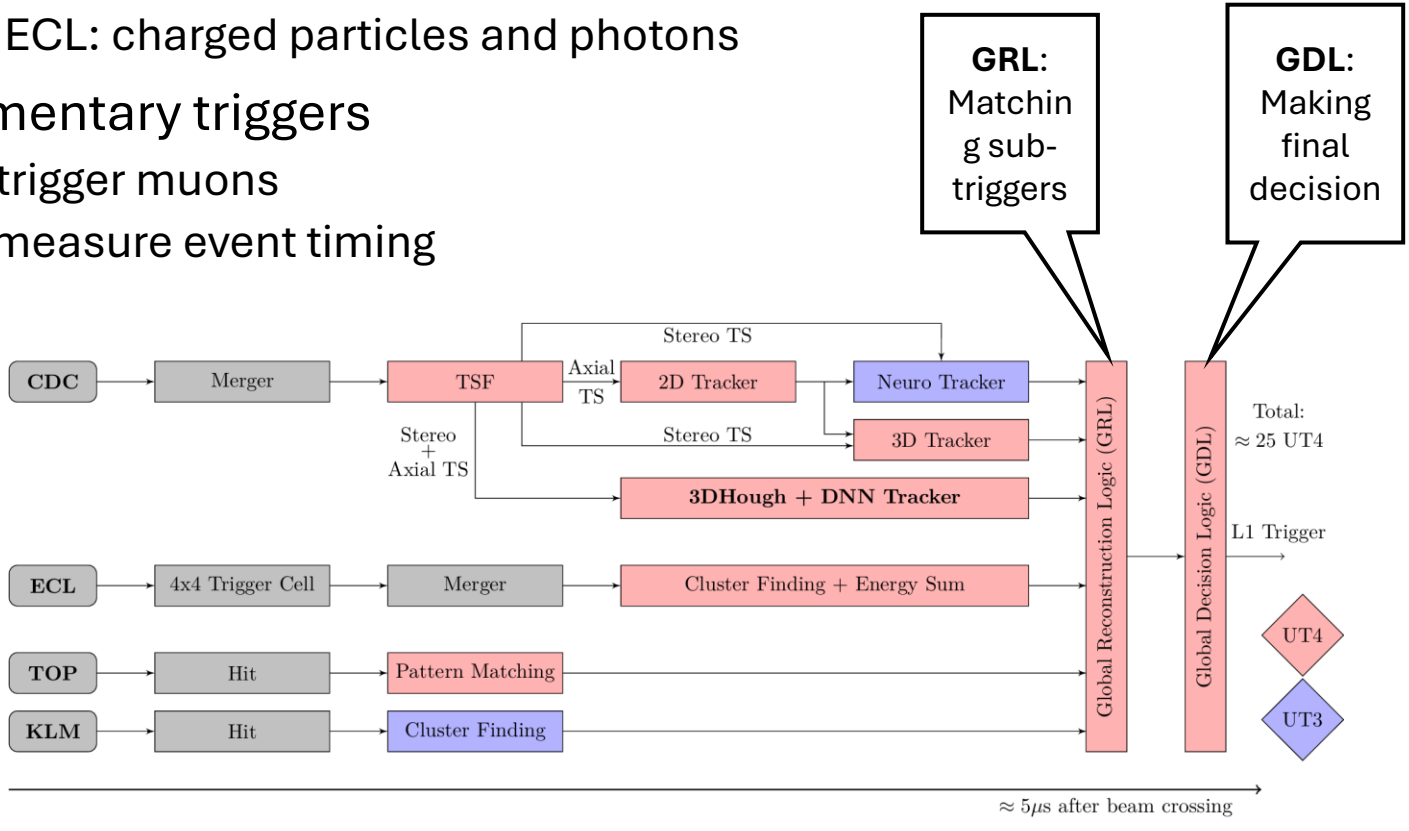
- The Fzisan code is used for developing level 3 trigger.
  - The original development was suspended in 2015.
- Primitive conversion to the latest BASF2 build is done.
- Performance test is good shape, only 0.5% of CPU usage compared to the pre-tracking and pre-clustering.
- However, by checking pre-built histograms, not all the information is shown. More study is necessary.
- Level 1 menu is successfully installed in the Level 3 trigger.
- Tried to 0-track, 0-cluster condition, but too many events are discarded.

- First, we are focusing on the code rewriting for tracking since the tracking is complex and uses more CPU time compares to the clustering.

# *Backup*

# *Level 1 (Hardware) Trigger*

- Main triggers
  - CDC, ECL: charged particles and photons
- Supplementary triggers
  - KLM: trigger muons
  - TOP: measure event timing



# Level 1 (Hardware) Trigger

- Expected event rate at target luminosity ($= 6.0 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$)

| Process | Event rate |
|---|---|
| $e^+e^-$ bunch collision | ~200 MHz |
| Beam background | > ~300 kHz (2022) |
| Bhabha scattering | > ~50 kHz |
| Two photon processes | ~10 kHz |
| $e^+e^- \to \gamma\gamma$ | ~2 kHz |
| $e^+e^- \to q\bar{q}$ $(q = udsc)$ | ~2 kHz |
| $e^+e^- \to \Upsilon(4S)$ | ~1 kHz |
| $e^+e^- \to \mu^+\mu^-$ | ~0.6 kHz |
| $e^+e^- \to \tau^+\tau^-$ | ~0.6 kHz |
| dark sector/new particle | ??? |

physics target

~ 15 kHz

| Item | Requirement | Present status |
|---|---|---|
| Trigger rate | $< 30$ kHz<br>@ $6 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ | ~8 kHz<br>@ $4.7 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$<br>→ reducible by increasing prescale |
| Latency | $4.4\ \mu s$ | $4.4\ \mu s$ |
| Event timing resolution | 10 ns | ~8 ns |
| Efficiency | $> 99\%$ for $B\bar{B}$ pair | $> 99\%$ for $B\bar{B}$ pair<br>$> 95\%$ for $\tau^+\tau^-$ pair<br>+ low multiplicity triggers for dark sector and new physics |

# *Level 1 (Hardware) Trigger*

- A few examples of the trigger conditions (rate from 2021c run)

| Physics target | Condition | Raw rate (kHz) | Exclusive rate (kHz) |
|---|---|---|---|
| $B\bar{B}$ pair | CDC #2track>=3, NNtrack>=1 with \|z\|<20cm >=1 | 1.40 | 1.40 |
| | CDC #2track>=2, NNtrack>=1 with \|z\|<20cm >=1, Δϕ>90deg | 1.03 | 0.47 |
| | ECL #cluster>=4, 2<θid<15 | 0.13 | 0.08 |
| | ECL Energy sum>1GeV, 2<θid<15 | 0.69 | 0.56 |
| $\tau^+\tau^-$ pair | CDC #full track>=1, \|z\|<15cm, p>0.7GeV | 1.74 | 0.96 |
| | CDC #full track>=1, \|z\|<15cm, #short track>=1, Δϕ>90deg. | 0.74 | 0.38 |
| | CDC #full track>=1, \|z\|<15cm, #inner track>=1, Δϕ>90deg. | 0.37 | 0.08 |
| | NCL ≥ 3, at least 1 CL ≥ 500 MeV(Lab)) (withθID= 2 -16) | 0.17 | 0.03 |
| single photon | ECL only one CL ≥ 1 GeV(CM) with θID = 4 - 15 and no other CL ≥ 300 MeV(Lab) anywhere | 0.18 | 0.03 |
| | ECL only one CL ≥ 1 GeV(CM) with θID = 2, 3, or 16 and no other CL ≥ 300 MeV(Lab) anywhere | 0.15 | 0.04 |
| ALP | ECL 170°< ΔϕCM< 190°, both CL > 250 MeV(Lab), no 2GeV(CM) CL in an event | 0.08 | 0.05 |
| | ECL 170°< ΔϕCM< 190°, one CL < 250 MeV(Lab), one CL > 250 MeV(Lab), no 2GeV(CM) CL in an event | 0.34 | 0.28 |