The Belle II Workshop at Ole Miss

The Trigger System of Belle II

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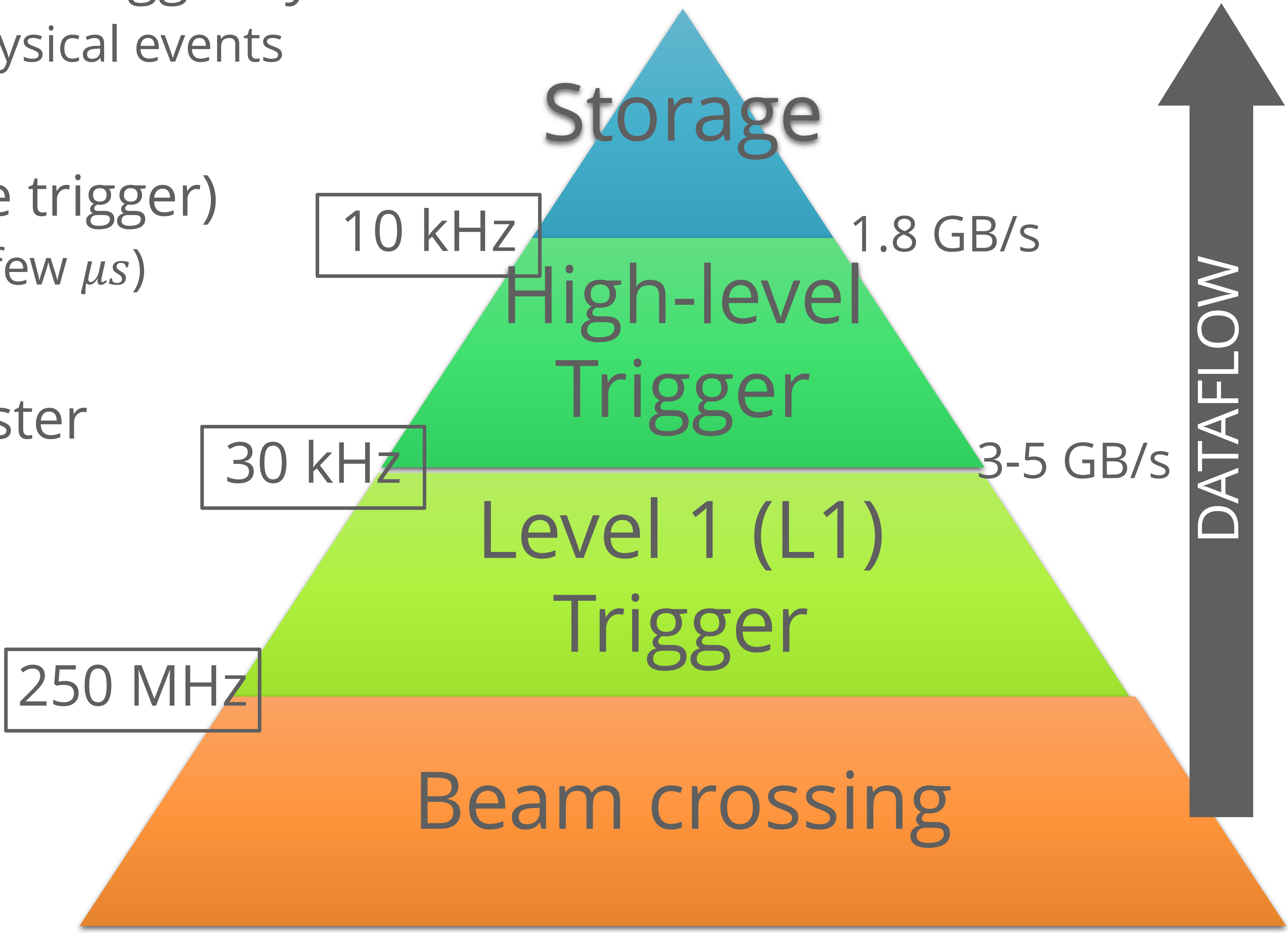
Acknowledgment: this slide is largely based on Koga-san's nice lecture slides in the previous workshop and other TRG members

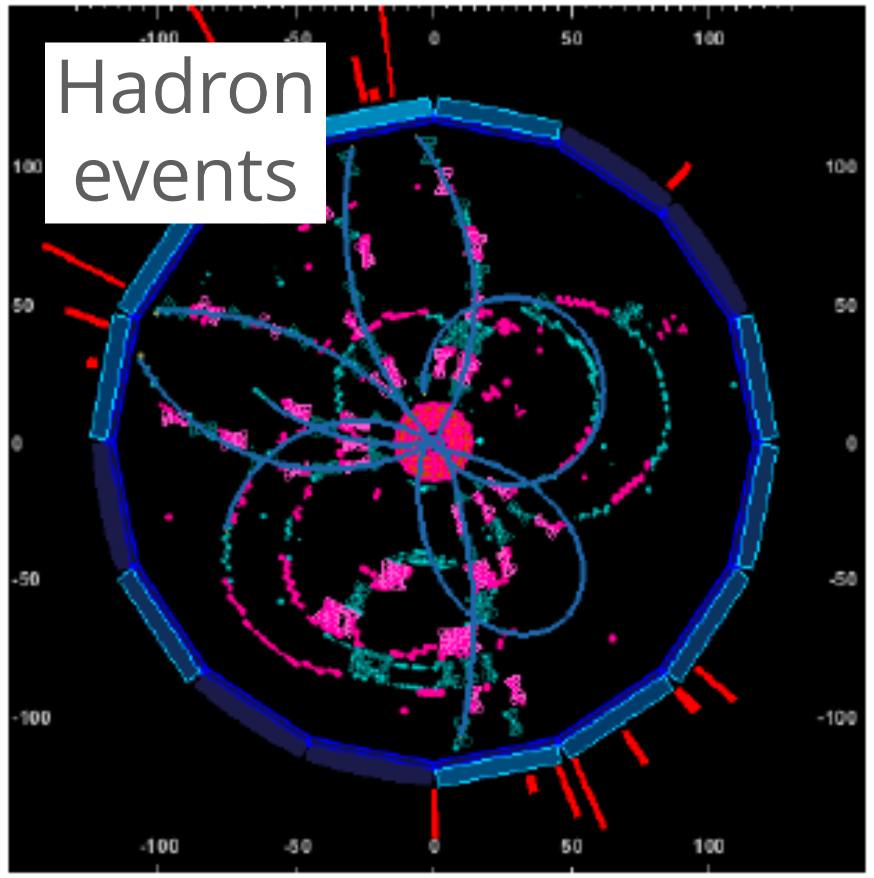
Dataflow in DAQ of Belle II

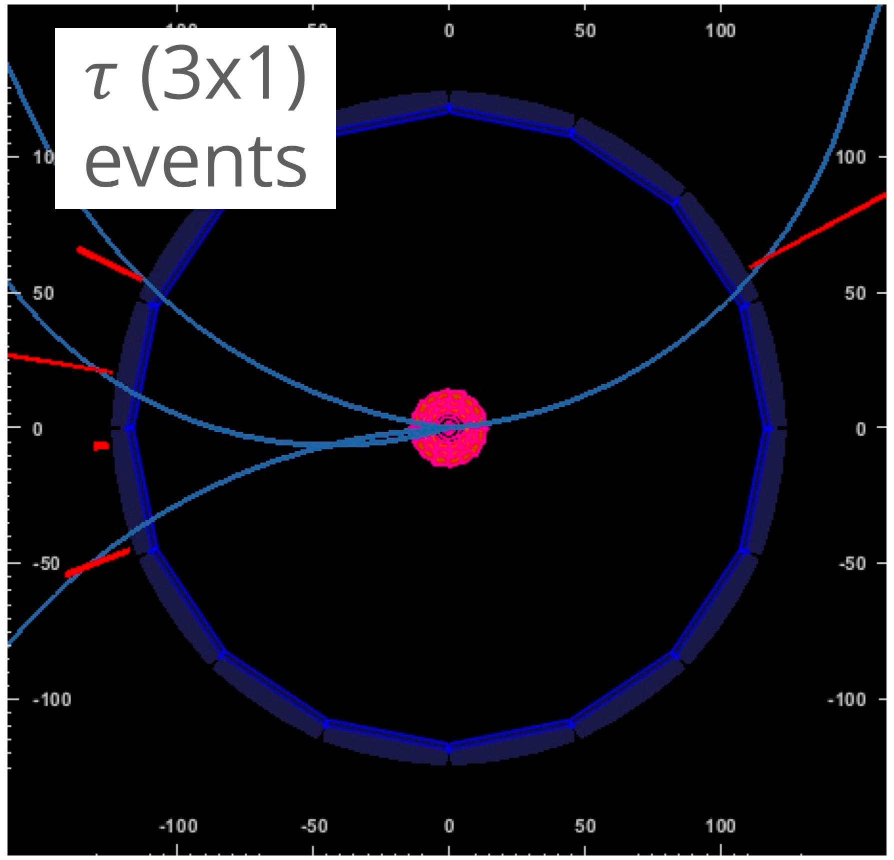
- The Belle II experiment adopts a multi-level trigger system
  - The goal of the trigger system: picking the physical events
- L1 Trigger: An electronic circuit (Hardware trigger)
  - Relatively simple process with low latency (a few μs)
- High-level trigger: A super-computing cluster
  - Accurate and complex processing (i.e., track reconstruction, mass, and so on…)
  - Can add new data from the post-processing
- **Today's main dish: L1 Trigger**

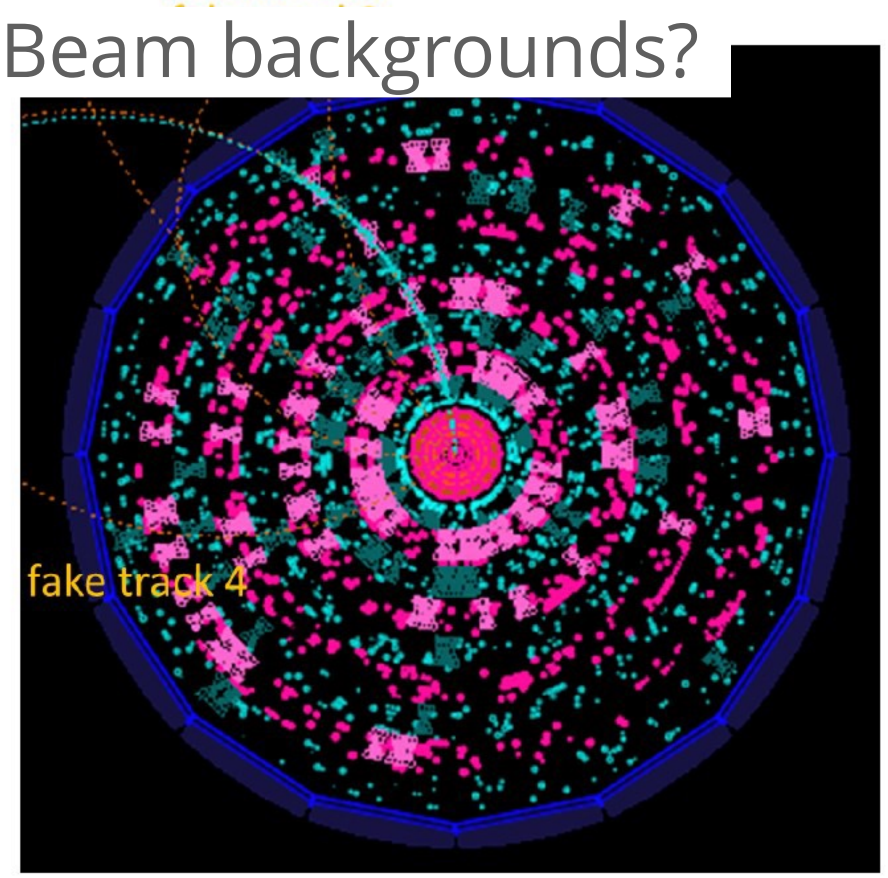


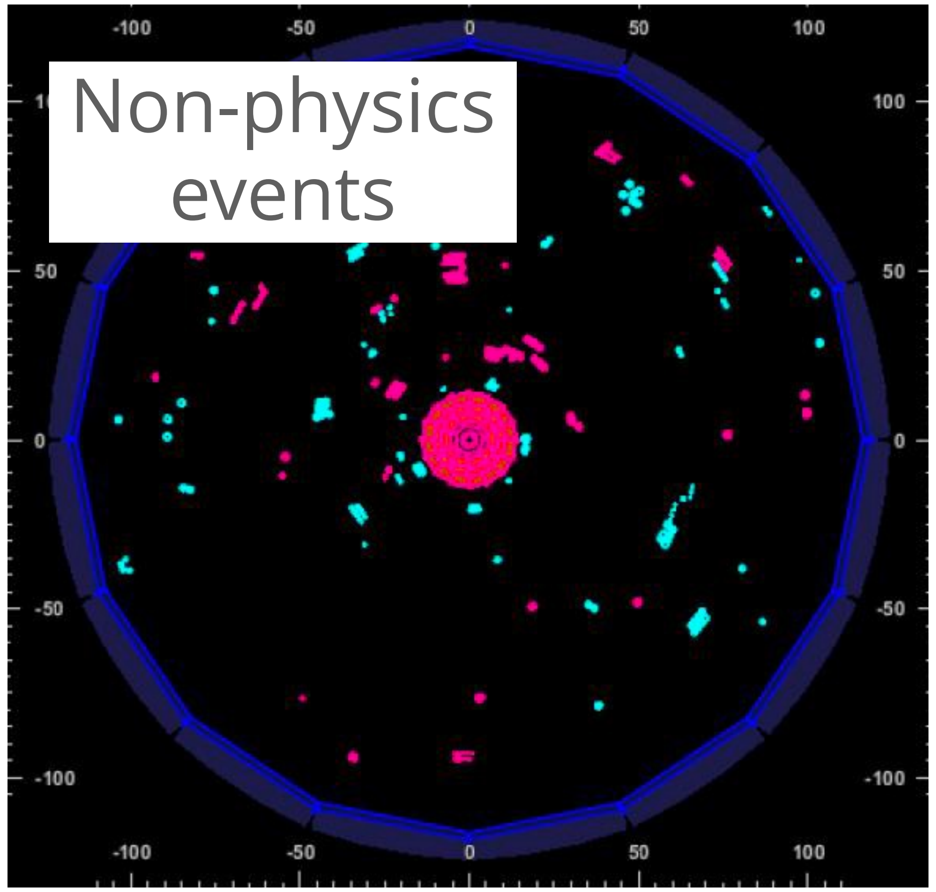
Belle II Data Taking and Trigger

- Belle II consists of seven subdetectors to observe the e^+e^- collision events
  - The rate for the collision: 250 MHz **>>** • The upper limit of the Belle II DAQ throughput: 30 kHz
- We need to screen the collision events to record the data through DAQ properly
  - Judge a large data ($\mathcal{O}(100)$KB or $\mathcal{O}(1)$MB) within low latency ($4\mu s$) 👉 Dedicated circuit needed


Hadron events


τ (3x1) events


Beam backgrounds?


Non-physics events

Should be recorded

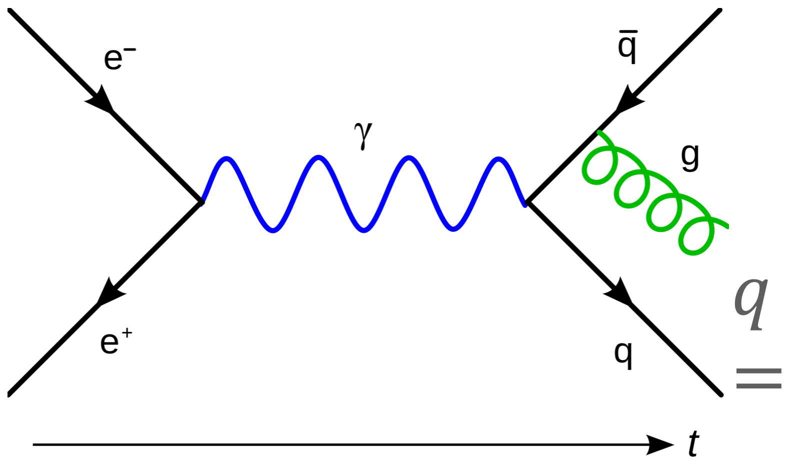
Should NOT be recorded

Phenomena from the e^+e^- Collision

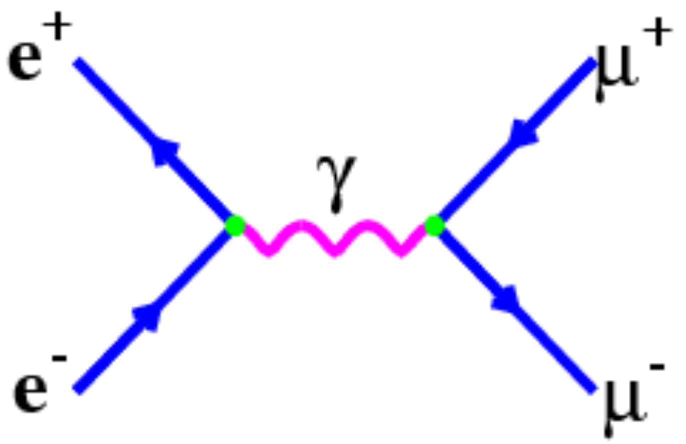
- From the e^+e^- collision, Belle II can see many types of events as follows:

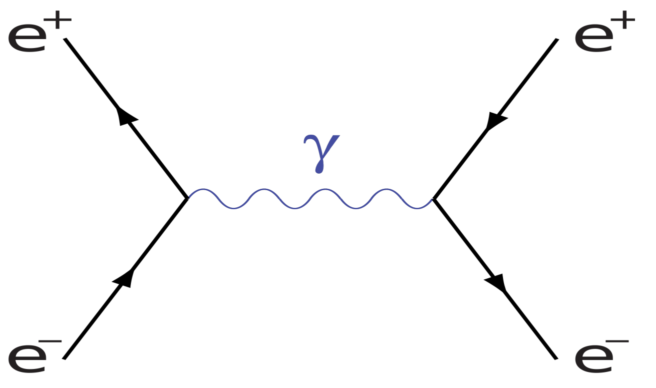
Expected event rate at the target luminosity

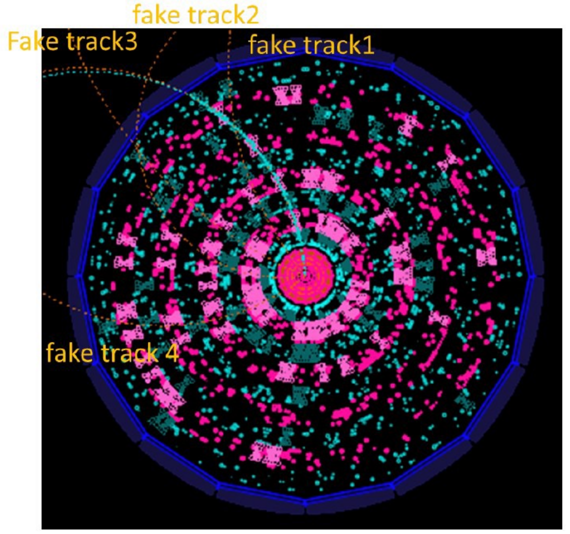
- e^+e^- Collision: ~ 250 MHz
  - Physical events
    - Continuum ($q\bar{q}$ events): ~ 2 kHz
    - $\Upsilon(4S)$: ~ 1 kHz
    - $\mu^+\mu^-$: ~ 0.6 kHz
    - $\tau^+\tau^-$: ~ 0.6 kHz
    - Dark matter? New Physics?: ????
    - Two photons: ~ 10 kHz
    - Bhabha scattering: > 50 kHz
  - Non-physical events
    - Storage Bckg.: > 150 kHz
    - Injection Bckg.: > 1 MHz



$q = u, d, s, c, b$

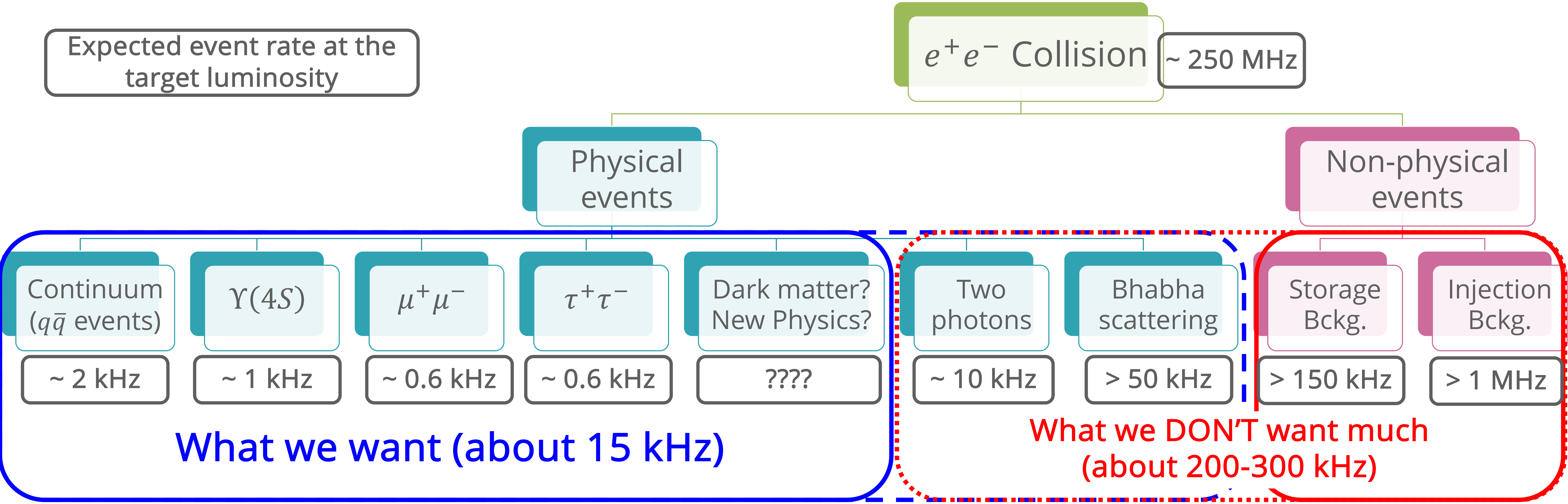






Phenomena from the e^+e^- Collision

- From the e^+e^- collision, Belle II can see many types of events as follows:



Expected event rate at the target luminosity

e^+e^- Collision ~ 250 MHz

Physical events

Non-physical events

Continuum ($q\bar{q}$ events) ~ 2 kHz

$\Upsilon(4S)$ ~ 1 kHz

$\mu^+\mu^-$ ~ 0.6 kHz

$\tau^+\tau^-$ ~ 0.6 kHz

Dark matter? New Physics? ????

Two photons ~ 10 kHz

Bhabha scattering > 50 kHz

Storage Bckg. > 150 kHz

Injection Bckg. > 1 MHz

What we want (about 15 kHz)

What we DON'T want much (about 200-300 kHz)

We should select the events that we are interested in among backgrounds!

Requirement for the L1 Trigger System

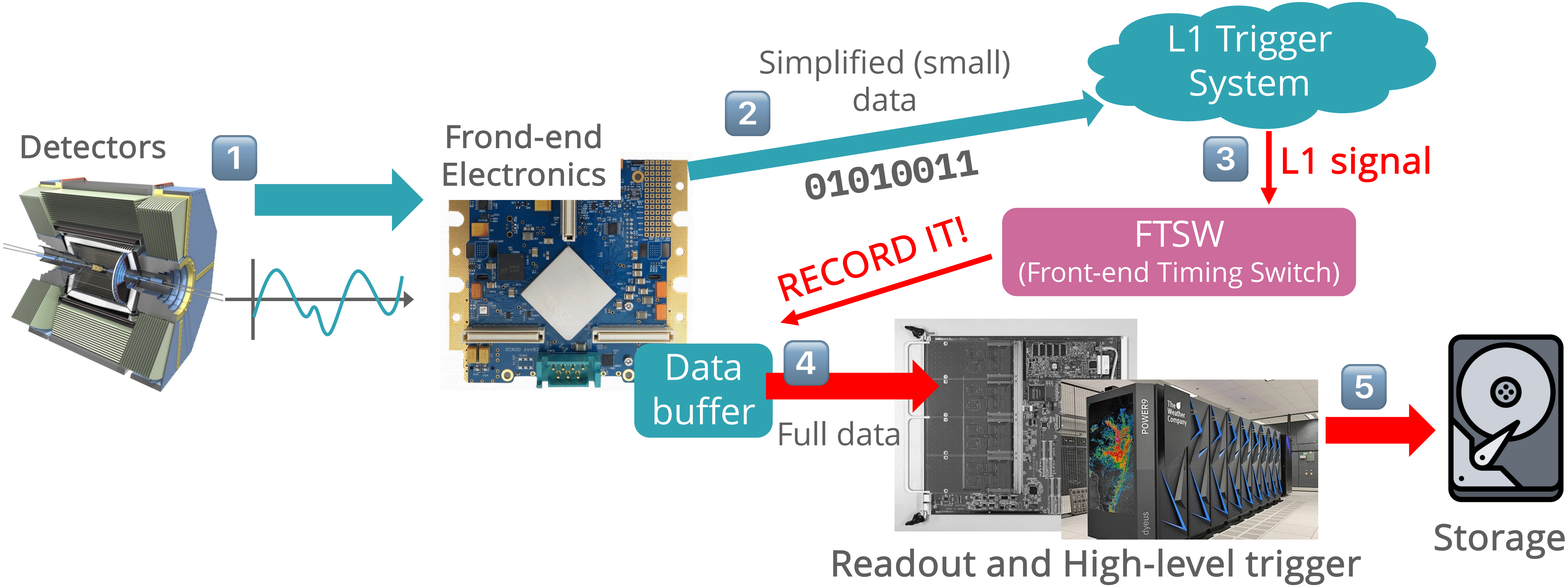
- The mission of the L1 trigger system
  - Issues L1 trigger signal (to indicate the event should be recorded)
  - Provide the event timing (to tell how long before the event has occurred from the L1 signal)

- The target luminosity of Belle II is 40 times higher than that of Belle
  - The maximum trigger rate also increases x40

	Belle	Belle II
Efficiency	Should be 100% for B-meson events	
Maximum Trigger Rate	500 Hz	30 kHz
Latency	2.2 μs	4.4 μs
Deadtime	As small as possible (ideally, evt. separation time 200 ns)	
Event timing resolution	About 16 ns	About 10 ns

- See Belle II TDR (Technical Design Report) for details!: https://arxiv.org/abs/1011.0352

(Simplified) Structure of the Belle II Data-Taking



Detectors

1

Frond-end Electronics

2

Simplified (small) data

01010011

L1 Trigger System

3

L1 signal

FTSW

(Front-end Timing Switch)

RECORD IT!

Data buffer

4

Full data

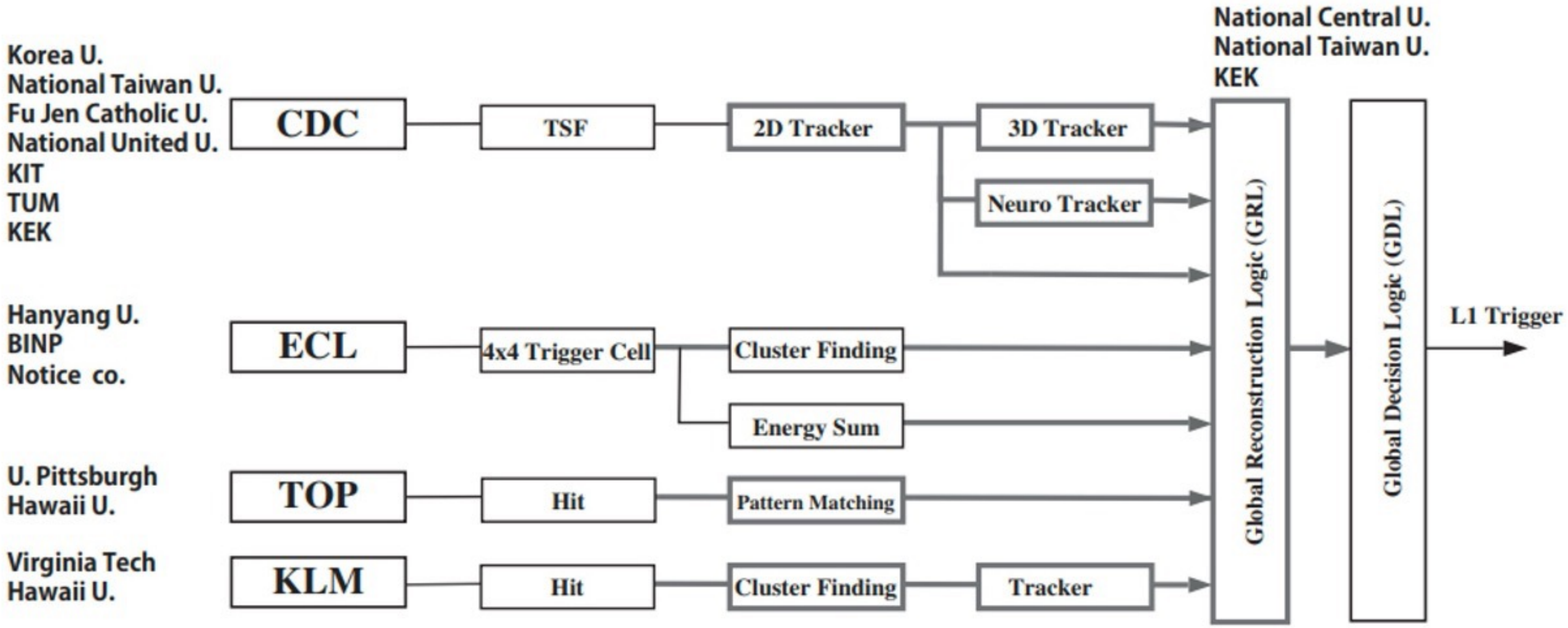
Readout and High-level trigger

5

Storage

The Structure of the L1 Trigger System

- Currently, the L1 trigger system uses signals from the four subdetectors
  - The trigger for each subdetector detects serval features (e.g., tracks, ECL clusters…) individually
- The global logic of GRL and GDL aggregates the individual results from subsystems and issues the L1 trigger signal

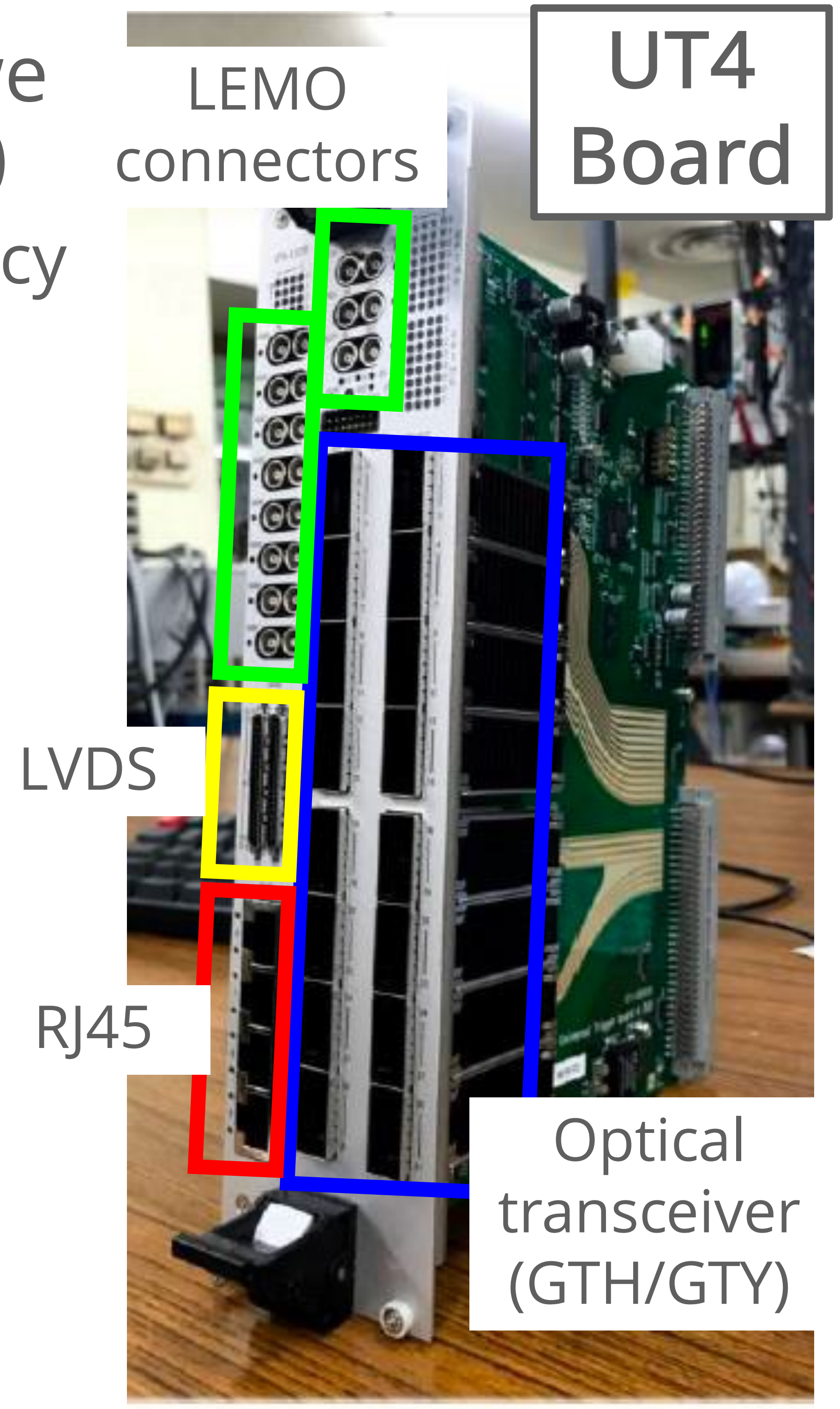


Hardware of the L1 Trigger System

- To configure the electronic circuits that we want to implement, we use a versatile board with FPGA (Field Programmable Gate Array)
  - this also can communicate with detectors with high speed and low latency
- This electronic board is called a UT (Universal Trigger) board.
  - with large FPGA and various interfaces for communication

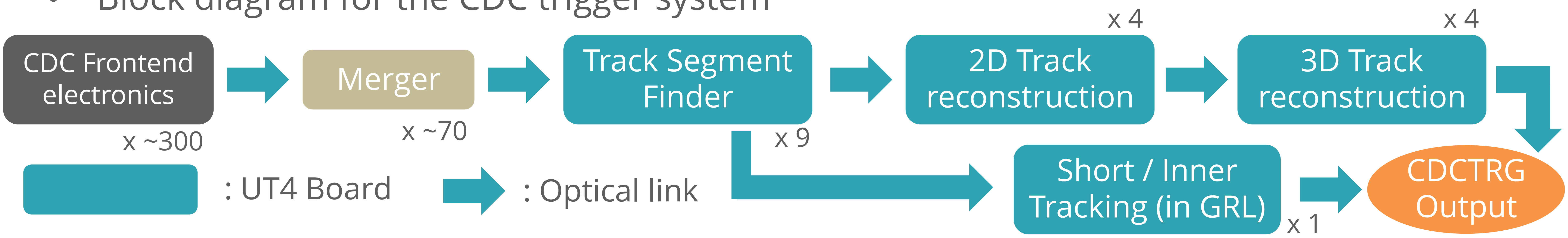
Generation	Year	FPGA	Maximum Bandwidth
UT1 (for testing)	2006	Spartan 3	
UT2 (for testing)	2008	Virtex 5 (LX220T)	
UT3	2011	Virtex 6 (HX565T)	192 Gbps in total
UT4	2018	Virtex Ultrascale (VU080/160/190)	328 Gbps in total

- We make firmware on this board for each trigger module (+ some designated electronics for specific purposes)



CDC Trigger: Finding Charged Particles from IP

- Block diagram for the CDC trigger system



CDC Frontend electronics

x ~300

Merger

x ~70

Track Segment Finder

x 9

2D Track reconstruction

x 4

3D Track reconstruction

x 4

Short / Inner Tracking (in GRL)

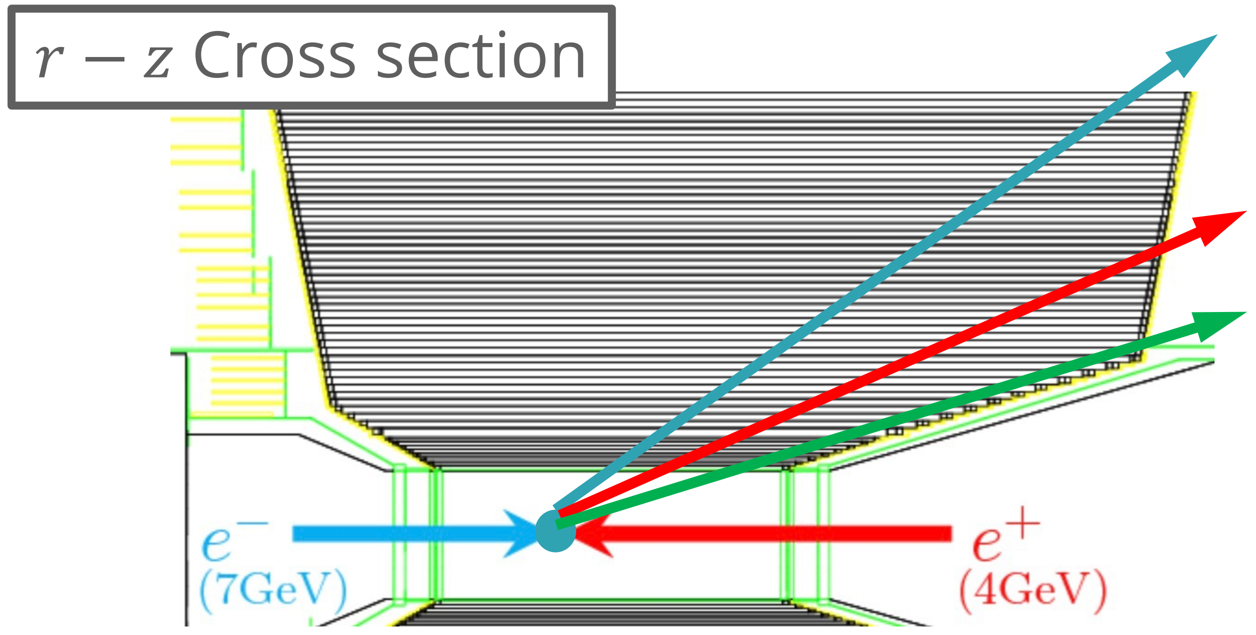
x 1

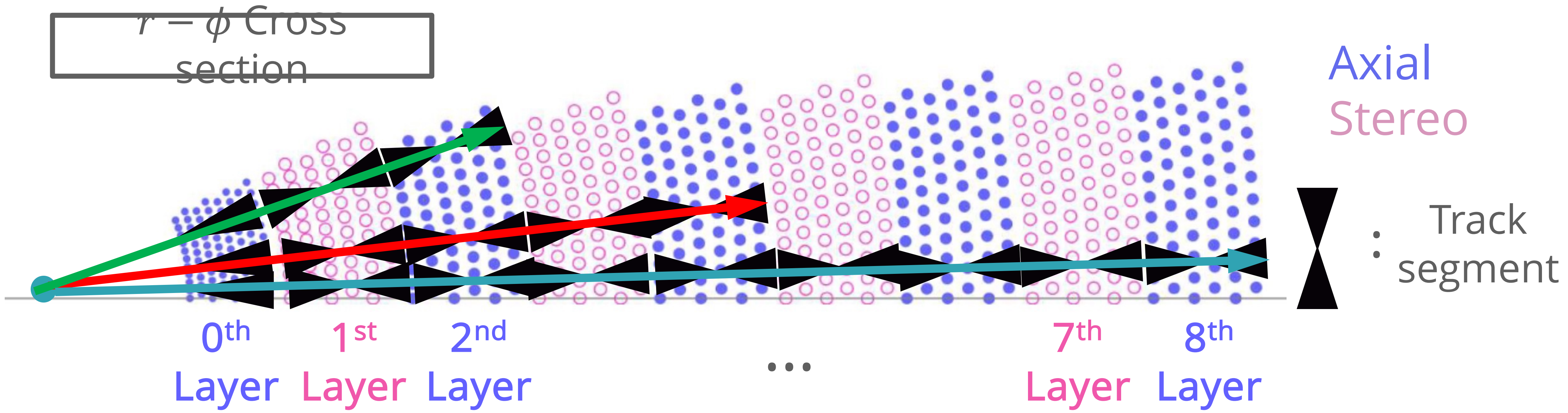
CDCTRG Output

▬ : UT4 Board

➡ : Optical link

- Three types of tracks in the CDC trigger: Full track, Short track, and Inner track



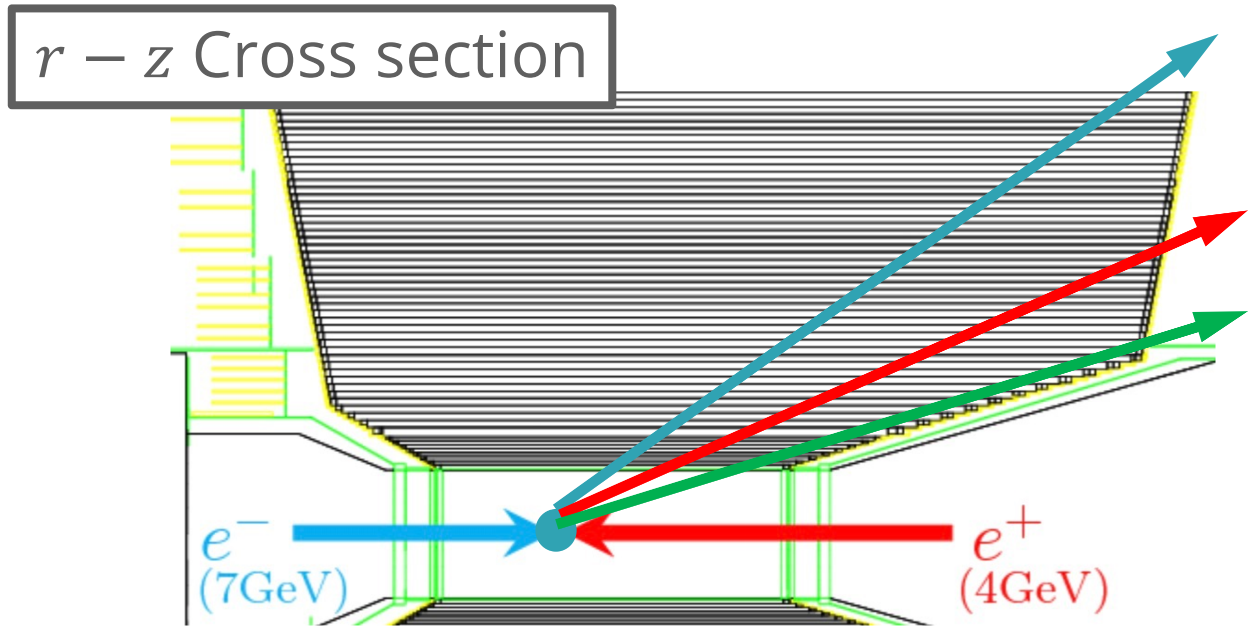


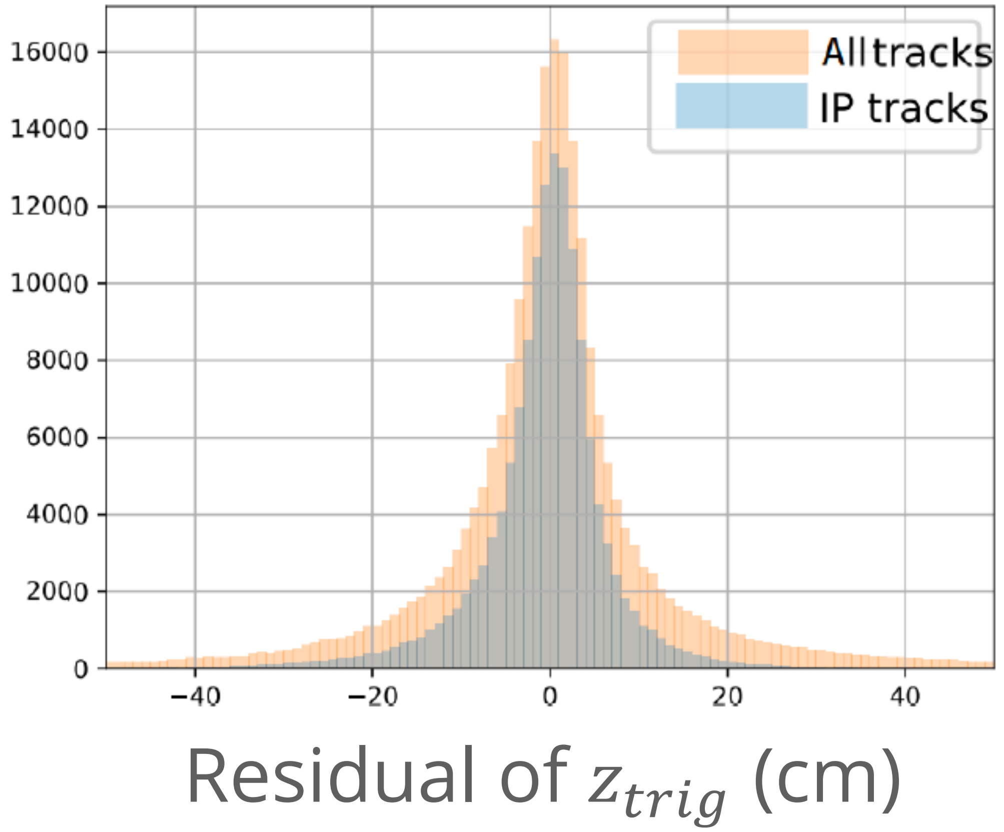
CDC Trigger: Performance

- The CDC trigger can cover the following region

Type	p_t	θ	Trigger rate (2022b)
Full track	> 0.4 GeV	30-125°	~10 kHz
Short track		25-130°	~50 kHz
Inner track		20-140°	> 100 kHz

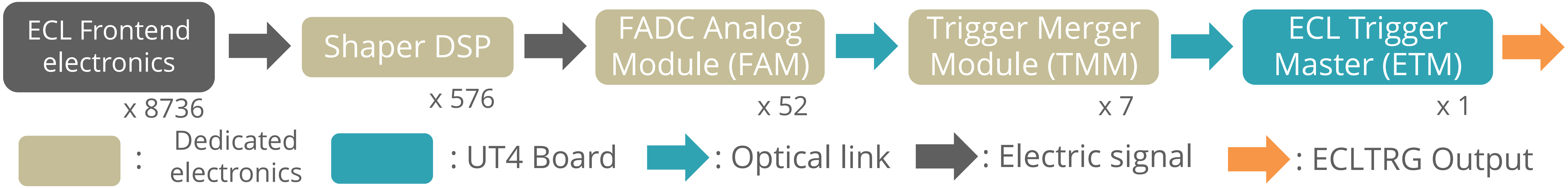
- Current performance:
  - 93-98% tracking efficiency for tracks from IP
  - z resolution: 5-10 cm (only for the full tracks)
  - p resolution: about 0.1 GeV (only for the full tracks)
  - Due to CDC performance degradation by the beam BG, those performances are run-dependent





ECL Trigger: Finding EM Shower at ECL

- Block diagram for the ECL trigger system



ECL Frontend electronics x 8736 → Shaper DSP x 576 → FADC Analog Module (FAM) x 52 → Trigger Merger Module (TMM) x 7 → ECL Trigger Master (ETM) x 1 →

▨ : Dedicated electronics

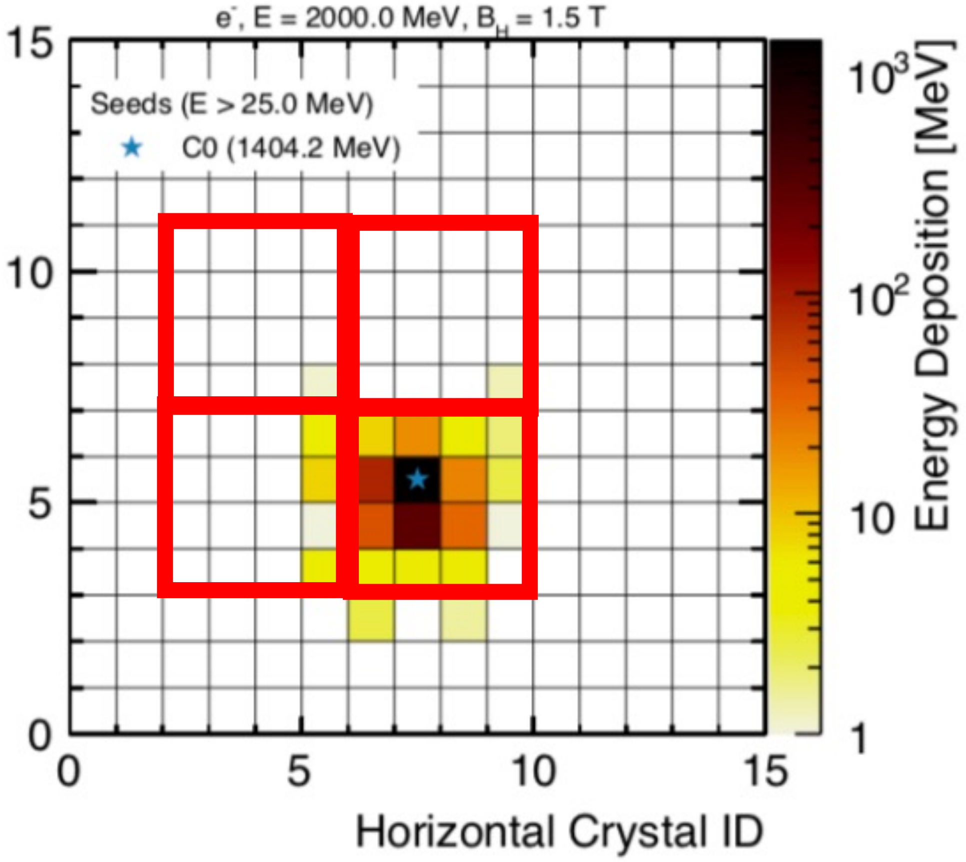
🟦 : UT4 Board

→ : Optical link

→ : Electric signal

→ : ECLTRG Output

- Shaper DSP: Merge & Simplify ECL signals
  - Makes Trigger Cell (TC), which is a minimal unit of ECLTRG
  - TC consists of 4x4 (16) crystals
  - Analog waveform summation of the 16 crystals
  - 8746 CsI(Tl) crystal → 546 TCs
  - Removes the shower shape information

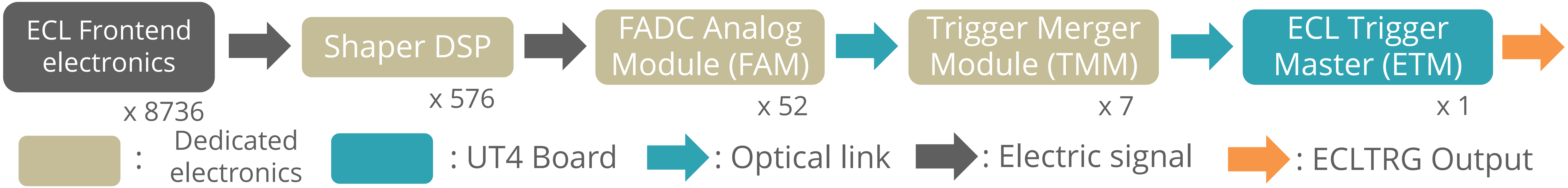


🟥 : Trigger Cell

☐ : ECL crystal

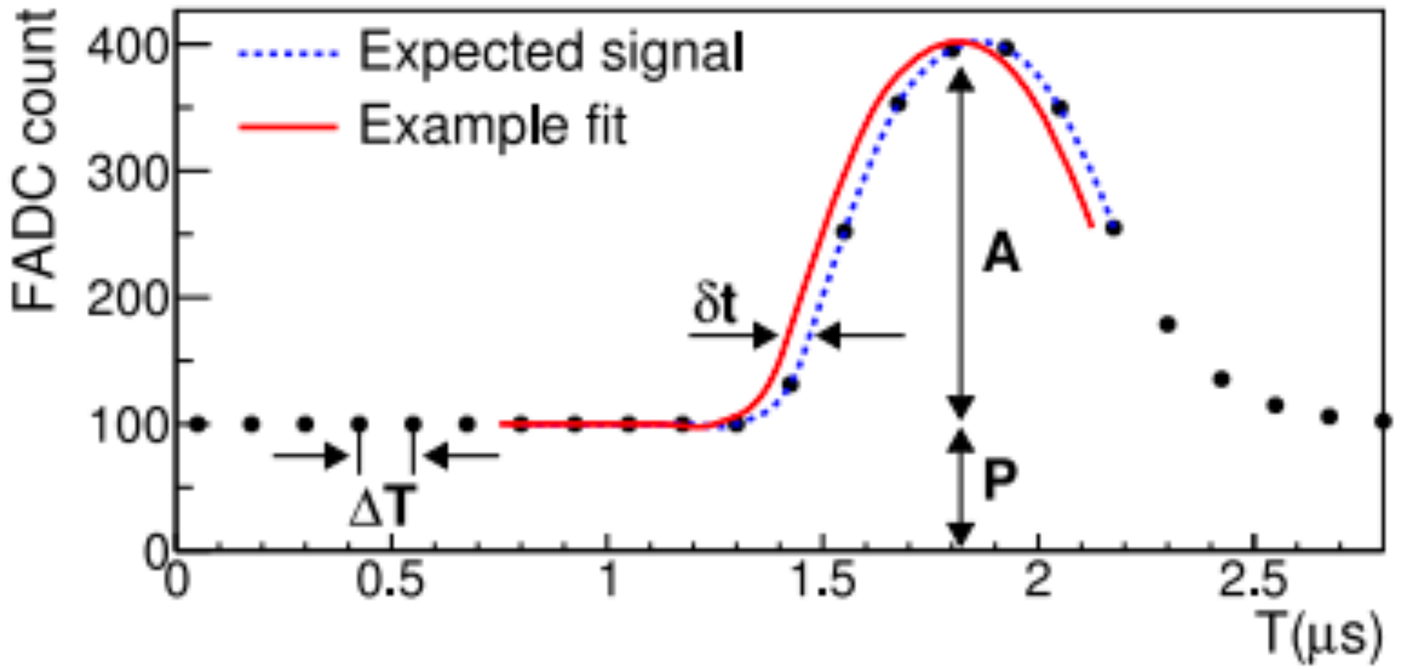
ECL Trigger: Finding EM Shower at ECL

- Block diagram for the ECL trigger system



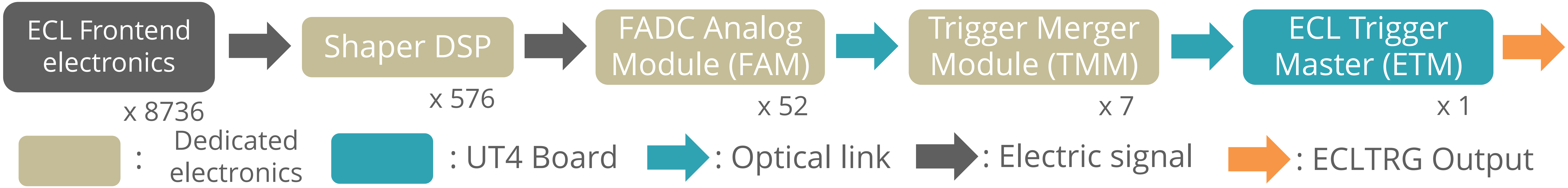
- FAM: Estimate the energy & timing
  - It performs fitting the waveform from ECL
  - Estimates the energy of TC
  - Calculates the timing of TC (When TC has been created?)
  - 8 MHz FADC, 200ns fast shaper

Waveform fitting example:



ECL Trigger: Finding EM Shower at ECL

- Block diagram for the ECL trigger system

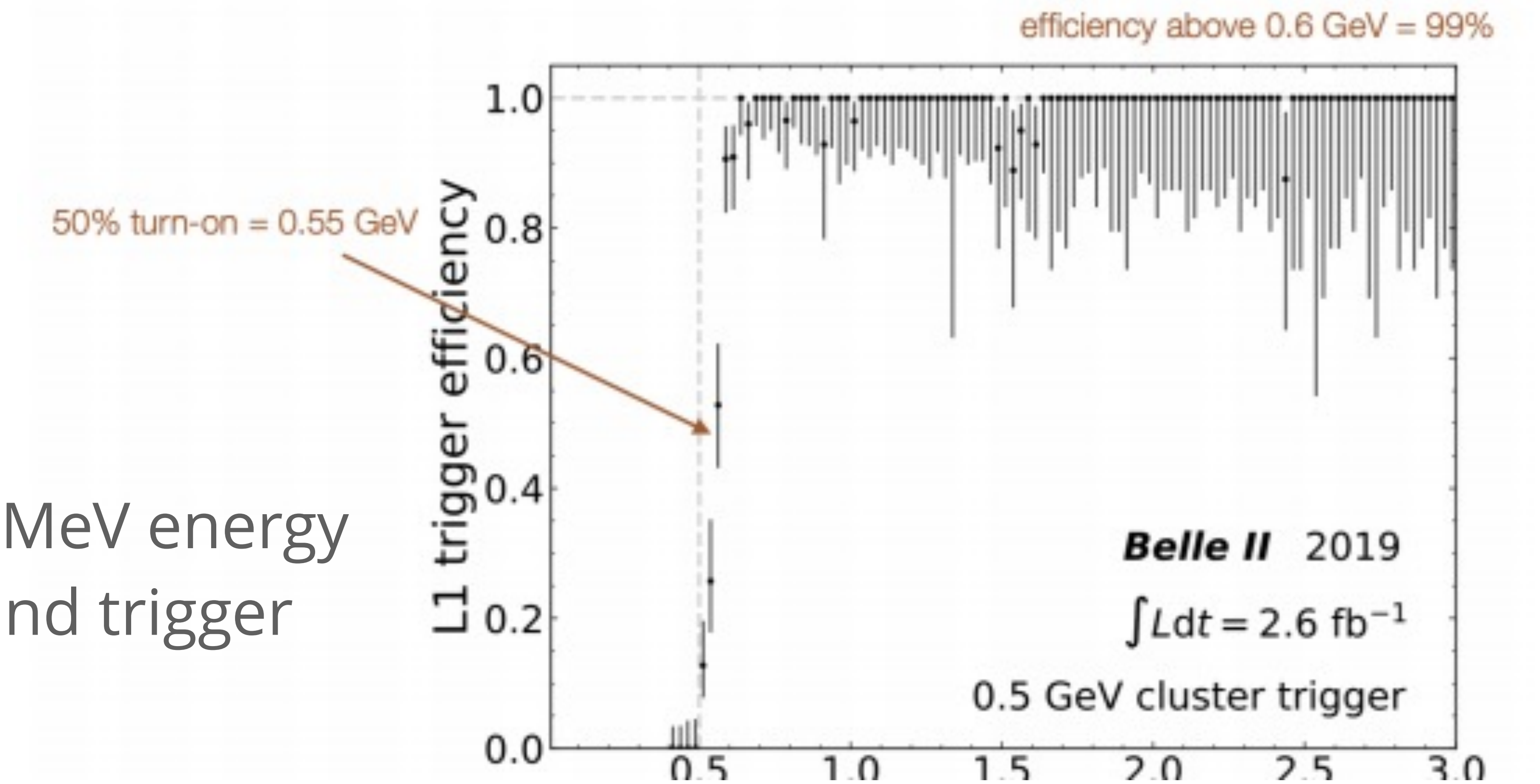


- TMM: Merges data from FAM and send it to ETM
- ETM: Final decision of the ECL trigger
  - It makes a decision for the ECL trigger system
  - Send the ECLTRG summary to GDL and cluster data to GRL

ECL Trigger: Performance

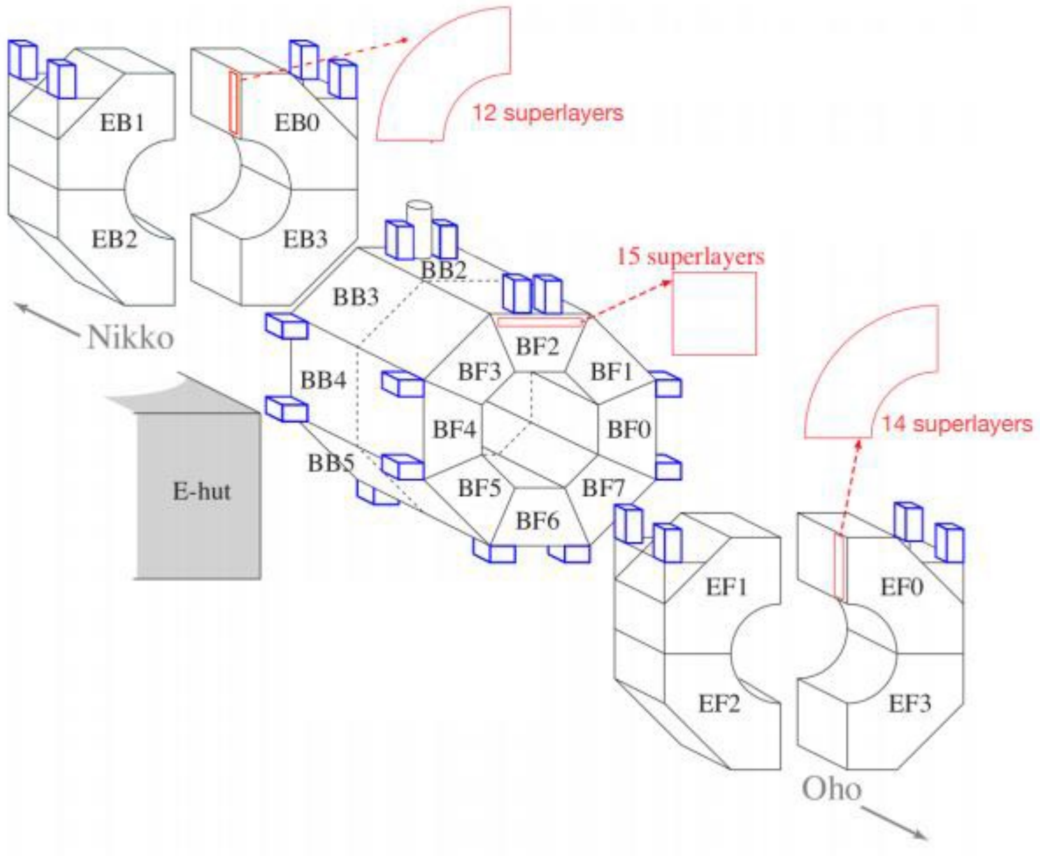
- Acceptance of the ECL trigger:
  - over 100 MeV for all TC
  - The full θ region is covered

- Performance
  - near 100% efficiency for the photons with >100 MeV energy
  - the energy difference between offline analysis and trigger that depends on the energy and angle exists

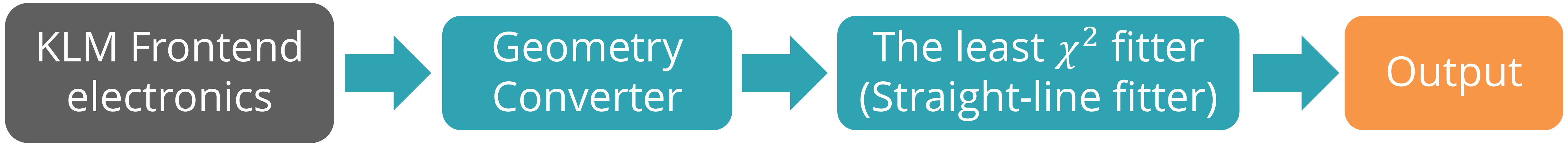


KLM Trigger: Reconstructing Trajectories by Muons

- A straight-line tracking with muon candidates
  - If the number of KLM hits over seven, then it will be judged as a muon candidate
  - Straight-line fitter based on the least-χ^2-fit for the muon track



- Flow-chart for the KLM trigger

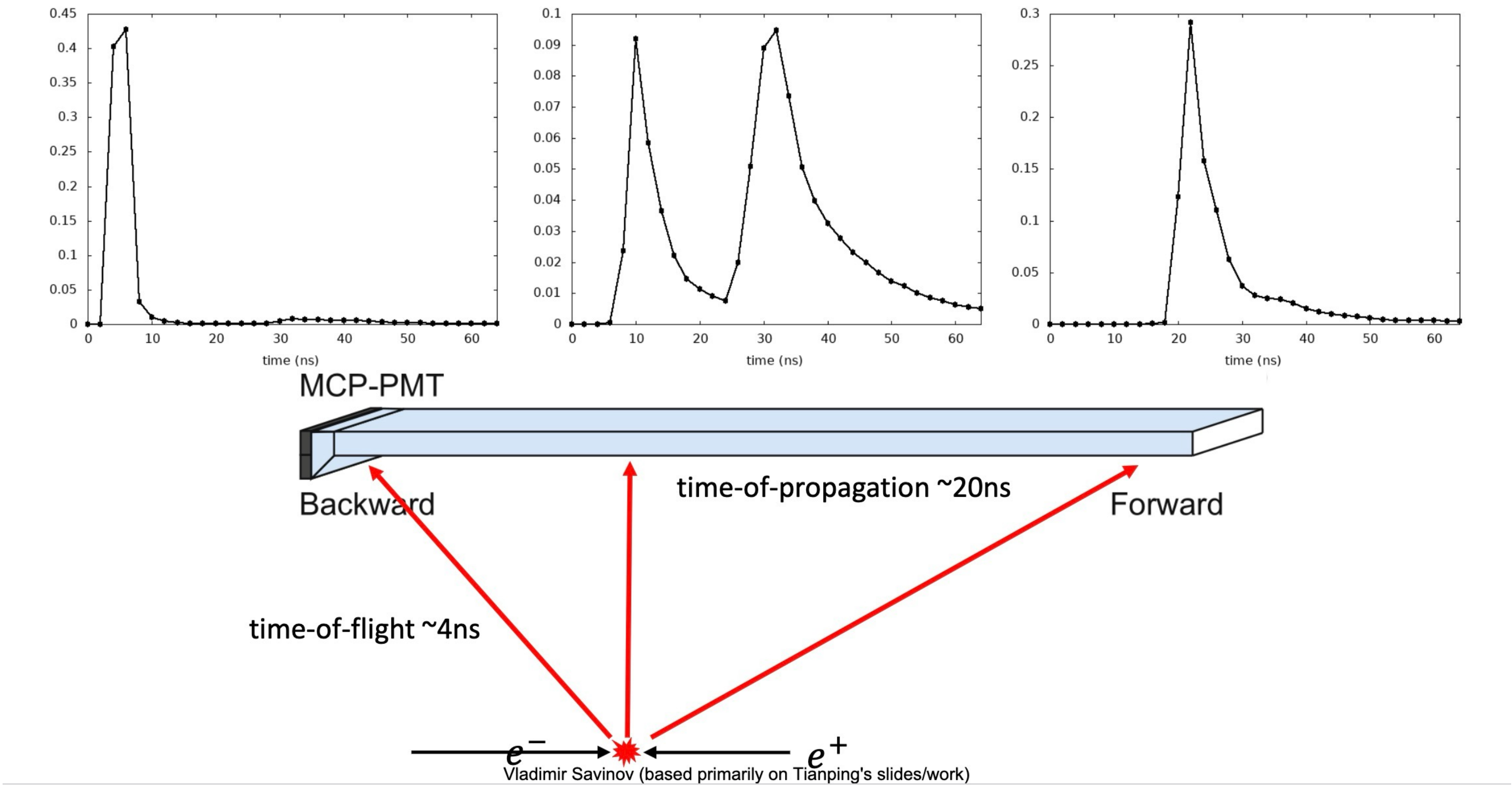


KLM Frontend electronics → Geometry Converter → The least χ^2 fitter (Straight-line fitter) → Output

TOP Trigger: Estimating the Event Timing

- Event timing estimation using the signal from TOP:
  - The pattern of the time distribution of Cherenkov photons depends on the incident position

- Example of principle and flowchart:



Vladimir Savinov (based primarily on Tianping's slides/work)

TOP Frontend electronics

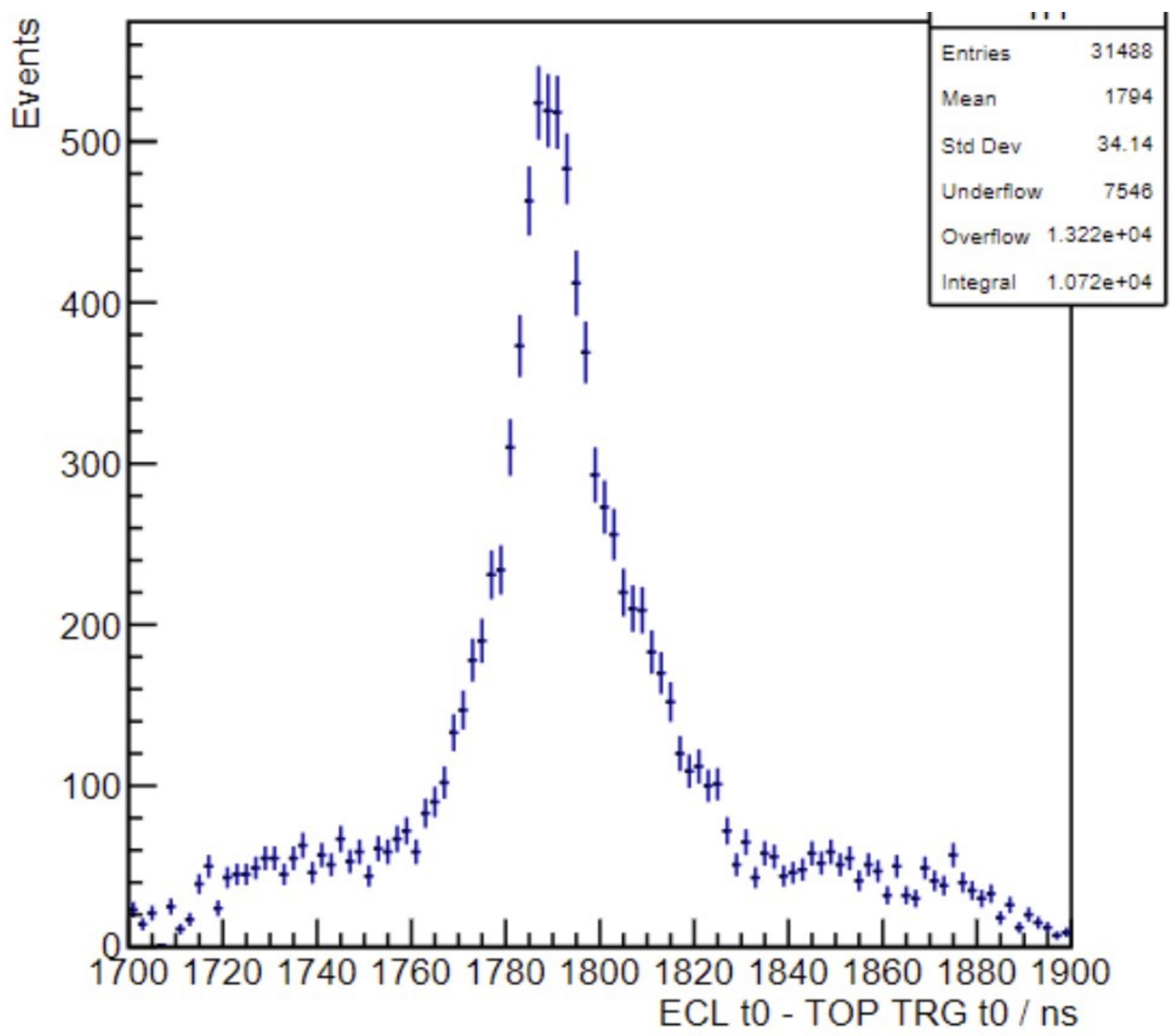
Pattern matching

Incident position on the TOP bar

Collision timing calculation

Timing output

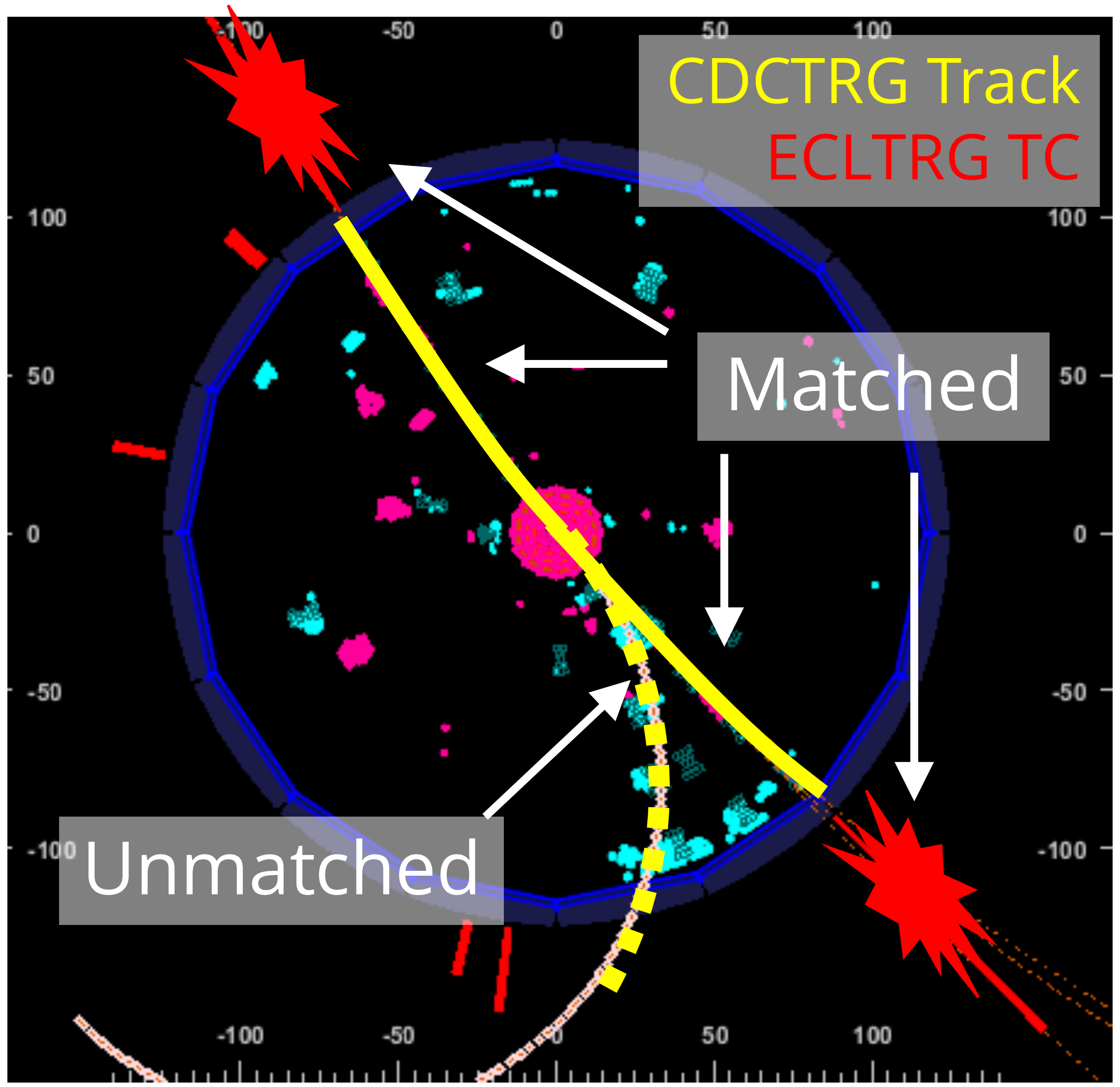
TOPTRG timing distribution



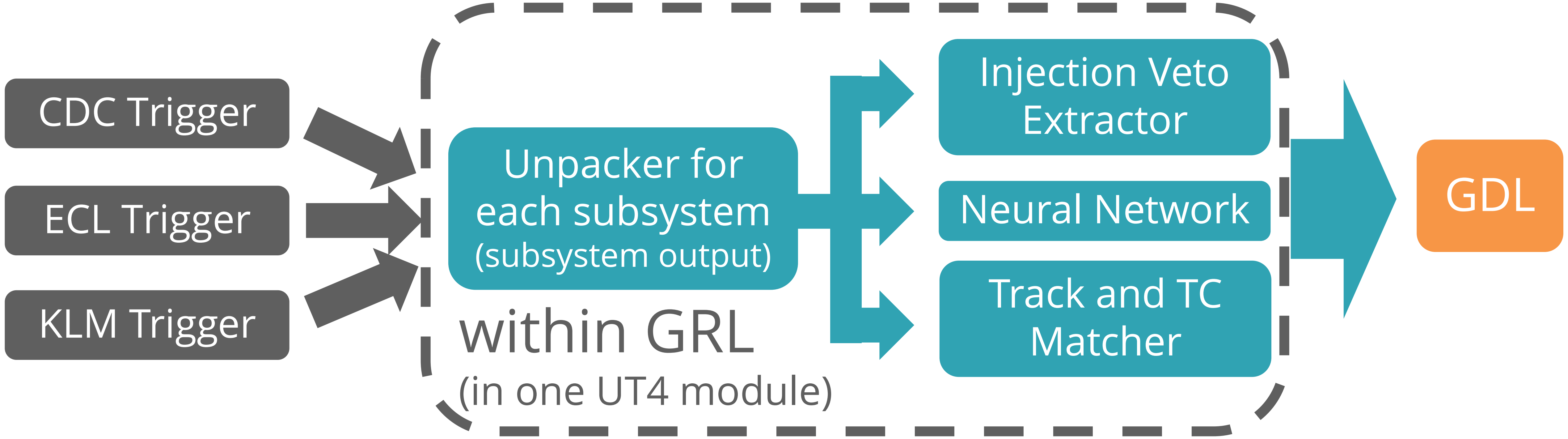
Entries	31488
Mean	1794
Std Dev	34.14
Underflow	7546
Overflow	1.322e+04
Integral	1.072e+04

GRL: Reconstructing Events Globally

- GRL: Global Reconstruction Logic
  - Interconnects the output from individual subsystems and make comprehensive result
  - Physics-specific trigger: Neural network trigger for tau (Now commissioning)

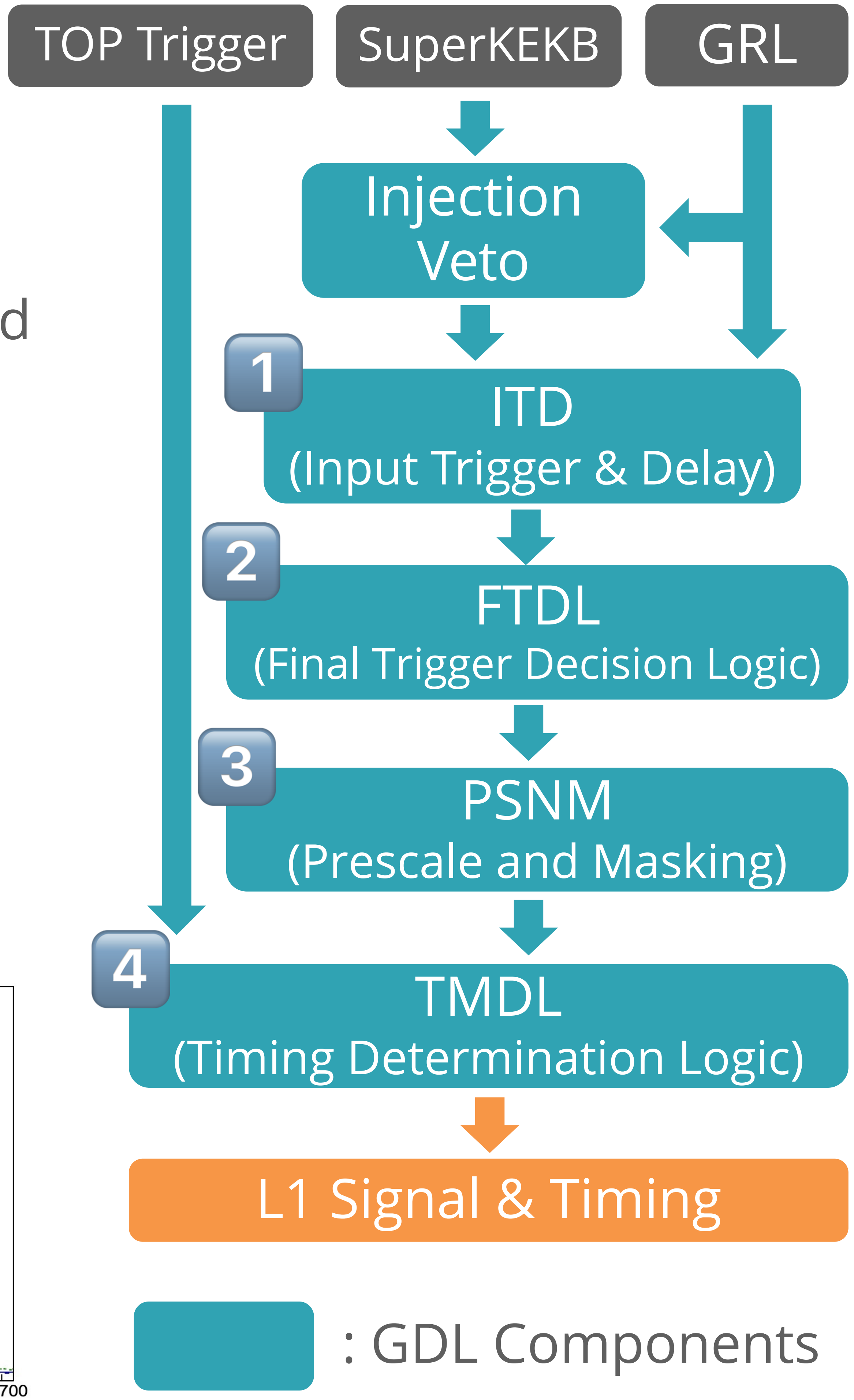


- Block diagram of GRL:



GDL: Making a Final Decision for L1

- GDL: Global Decision Logic
  - Decides the issue of the L1 trigger signal based on GRL and selected subsystems and determines the event timing
- Procedure inside GDL
  1. Applies the delay for the input signal to match the arrival timing
  2. Calculates the logical expression for the L1 trigger signals
  3. Applies the prescale or masking to output bits from FTDL (Prescale: scaling the rate of the output GDL bits)
  4. Find the event timing and issue the L1 signal to FTSW



TOP Trigger

SuperKEKB

GRL

Injection Veto

1 ITD (Input Trigger & Delay)

2 FTDL (Final Trigger Decision Logic)

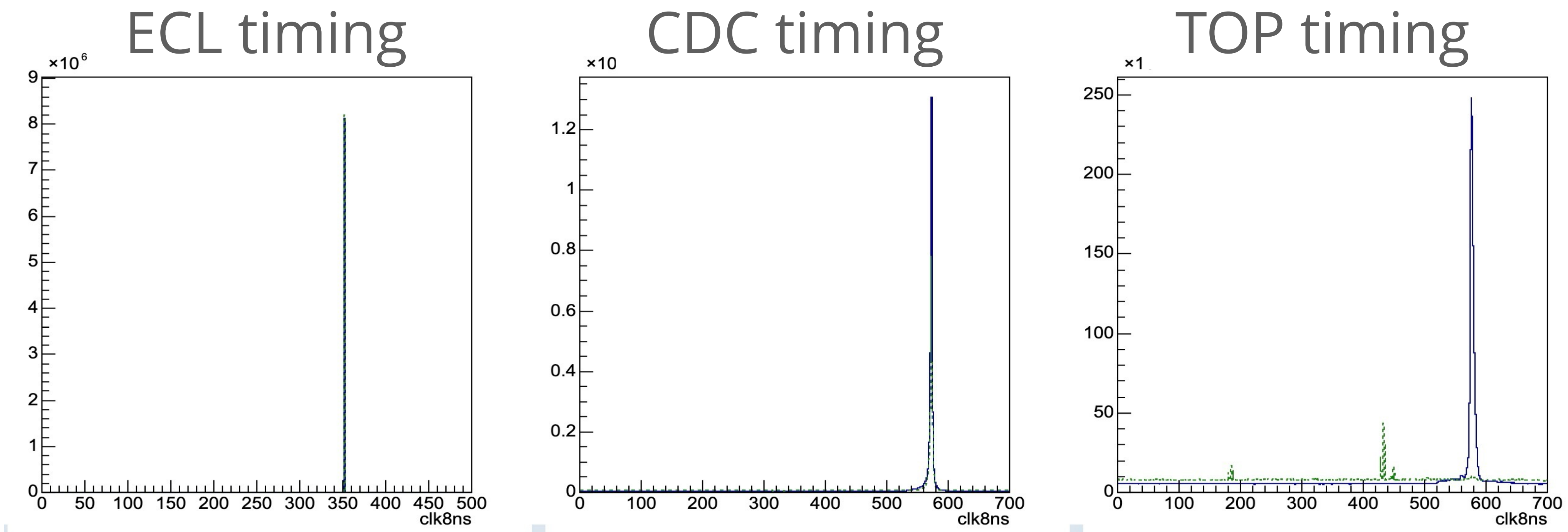
3 PSNM (Prescale and Masking)

4 TMDL (Timing Determination Logic)

L1 Signal & Timing

🟦 : GDL Components

- Event timing distribution:



ECL timing

CDC timing

TOP timing

Event timing (8ns)

Output from Trigger

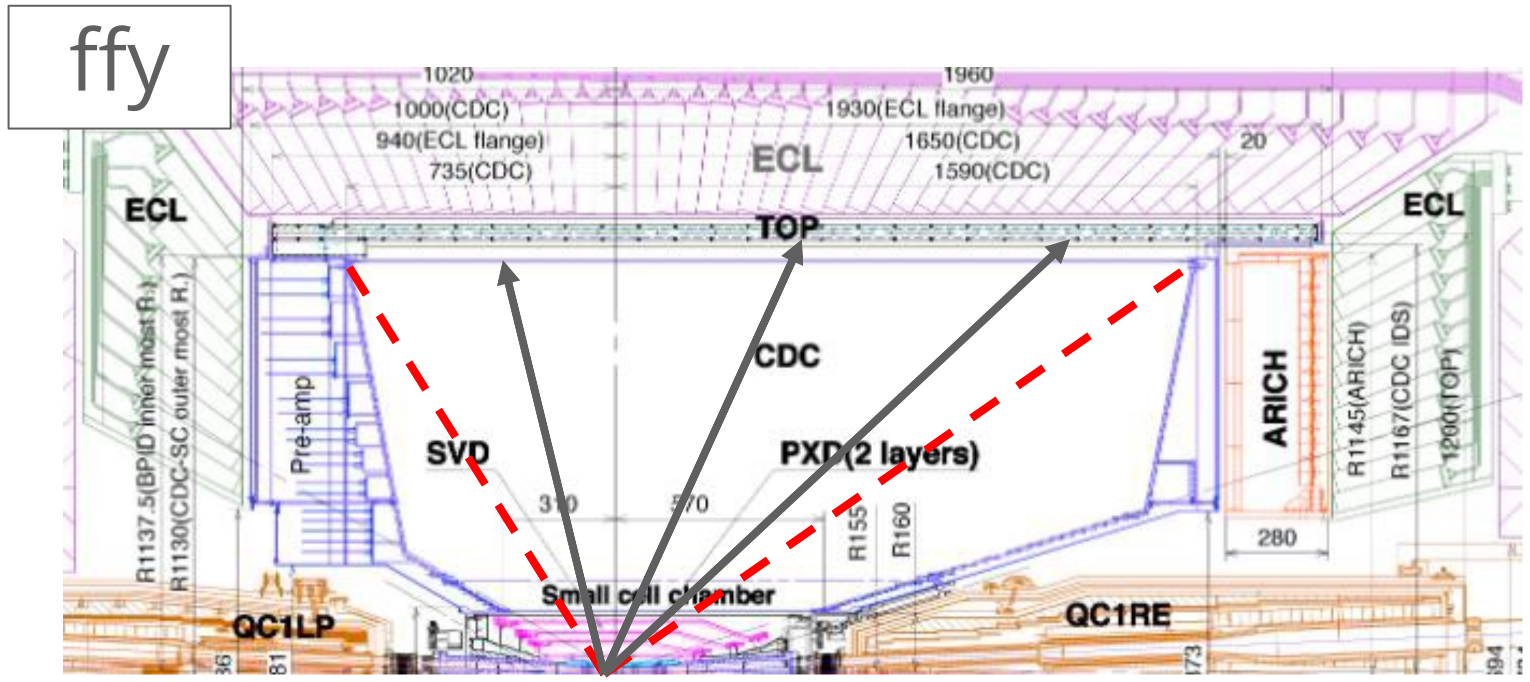
- There are many types of L1 trigger signals to indicate the type of physical events
  - Confluence page: https://confluence.desy.de/display/BI/TriggerBitTable

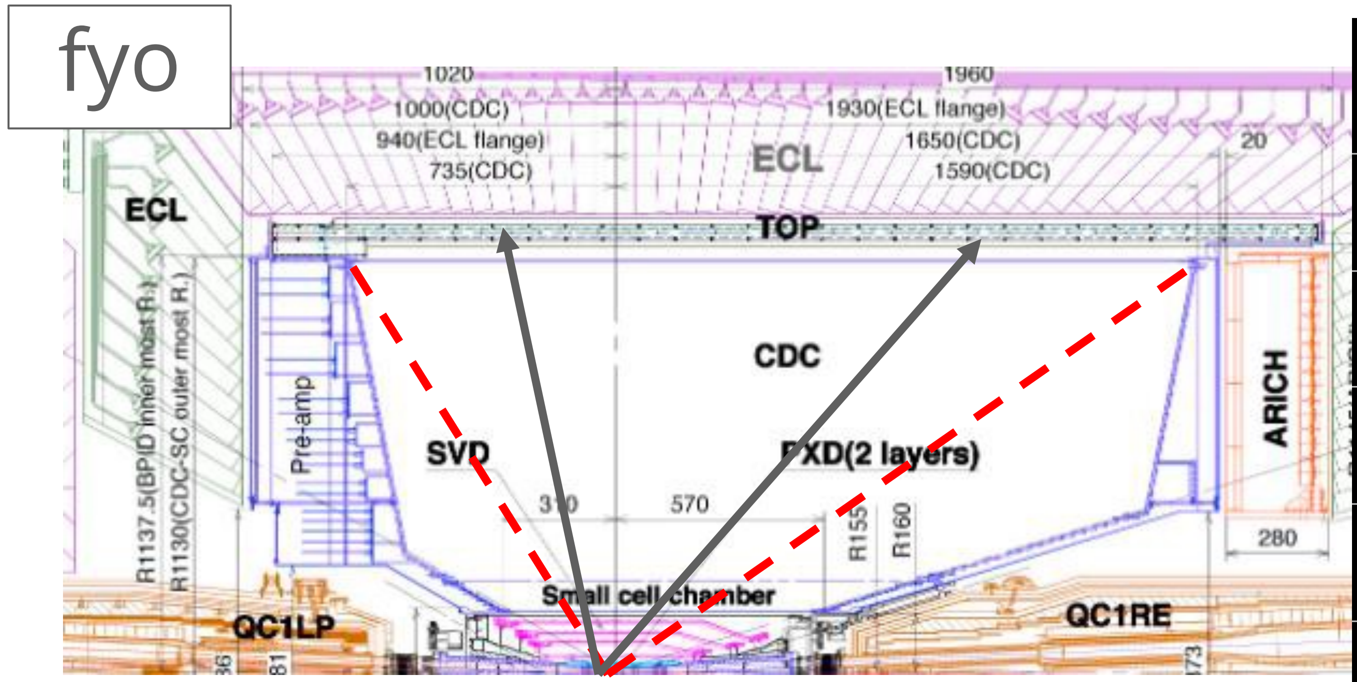
Category	Bit name & Condition	Raw rate
CDC Trigger	ffy: # of full tracks ≥ 3, $\|z\| \leq$ 20 cm and NN track cond. fyo: # of full tracks ≥ 2, $\|z\| \leq$ 20 cm and NN track cond. and $\Delta\phi > 90°$	2.18 kHz 1.77 kHz
ECL Trigger	c4: The number of the trigger cells ≥ 4 hie: Energy summation of all the trigger cells > 1 GeV	0.47 kHz 2.02 kHz
KLM τ and DM	klmb2b, eklmb2b, beklm: Back-to-Back trigger from KLM hits cdcklm, seklm, eclklm: The number of CDC-KLM, ECL-KLM matching ≥ 1	0.51 kHz 1.11 kHz
CDC τ and DM	stt: # of full tracks ≥ 1, $\|z\| <$ 15 cm, $p >$ 0.7 GeV syo: # of full tracks ≥ 1, # of short tracks ≥ 1, $\|z\| <$ 15 cm, $p >$ 0.7 GeV and $\Delta\phi > 90°$	2.93 kHz 1.93 kHz
ECL τ and DM	lml: several combinations of trigger cells and energy eclmumu: Back-to-Back trigger cells with low-energy	3.92 kHz 0.63 kHz
⋮	⋮	⋮
Total L1	**OR combination of all output trigger bits**	**11.5 kHz**

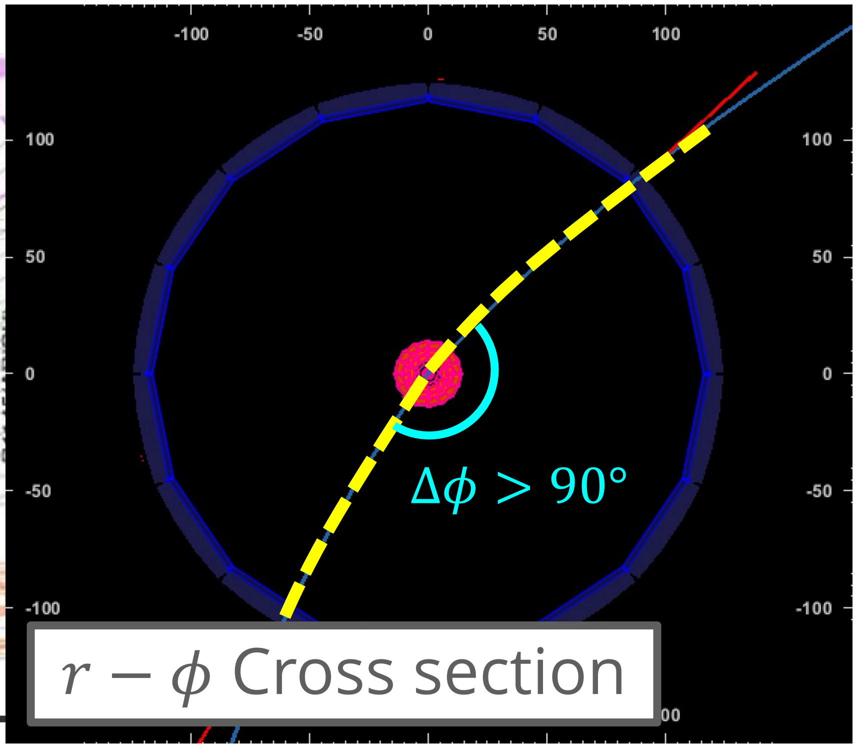
Example of the L1 Trigger Signals (Bits): B-Physics

- There are several conditions to pick the $B\bar{B}$ pair physics

L1 Output (bit) name	Condition	Rate (2021c)
ffy	# of Full track ≥ 3 and (# of NN tracks >= 1 with $\lvert z \rvert \leq 20\text{cm}$)	1.4 kHz
fyo	# of Full track ≥ 2 and (# of NN tracks >= 1 with $\lvert z \rvert \leq 20\text{cm}$) and $\Delta\phi > 90°$	1.03 kHz
c4	# of Trigger Cell ≥ 4 within barrel θ region ($2 < \theta_{ID} < 15$)	0.13 kHz
hie	The summation of TCs $\geq$ 1GeV within barrel θ region ($2 < \theta_{ID} < 15$)	0.69 kHz


ffy


fyo


$r-\phi$ Cross section

Example of the L1 Trigger Signals (Bits): B-Physics

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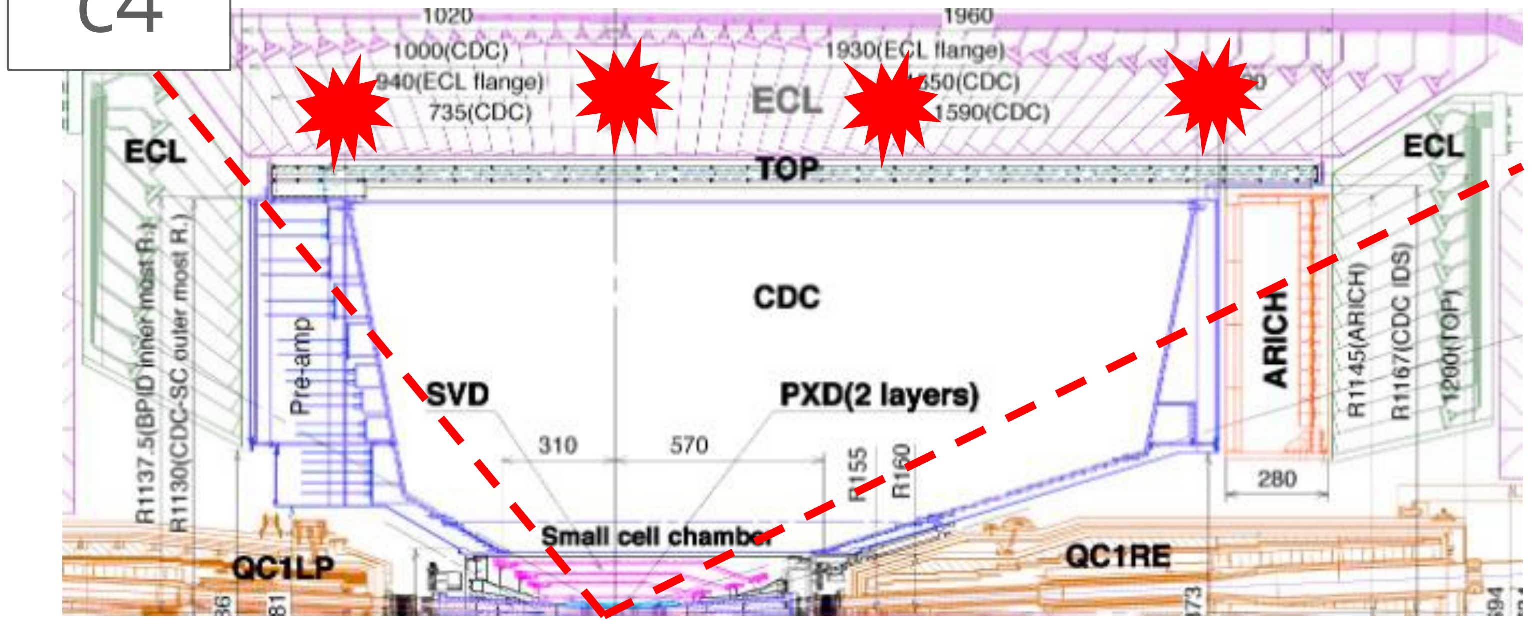
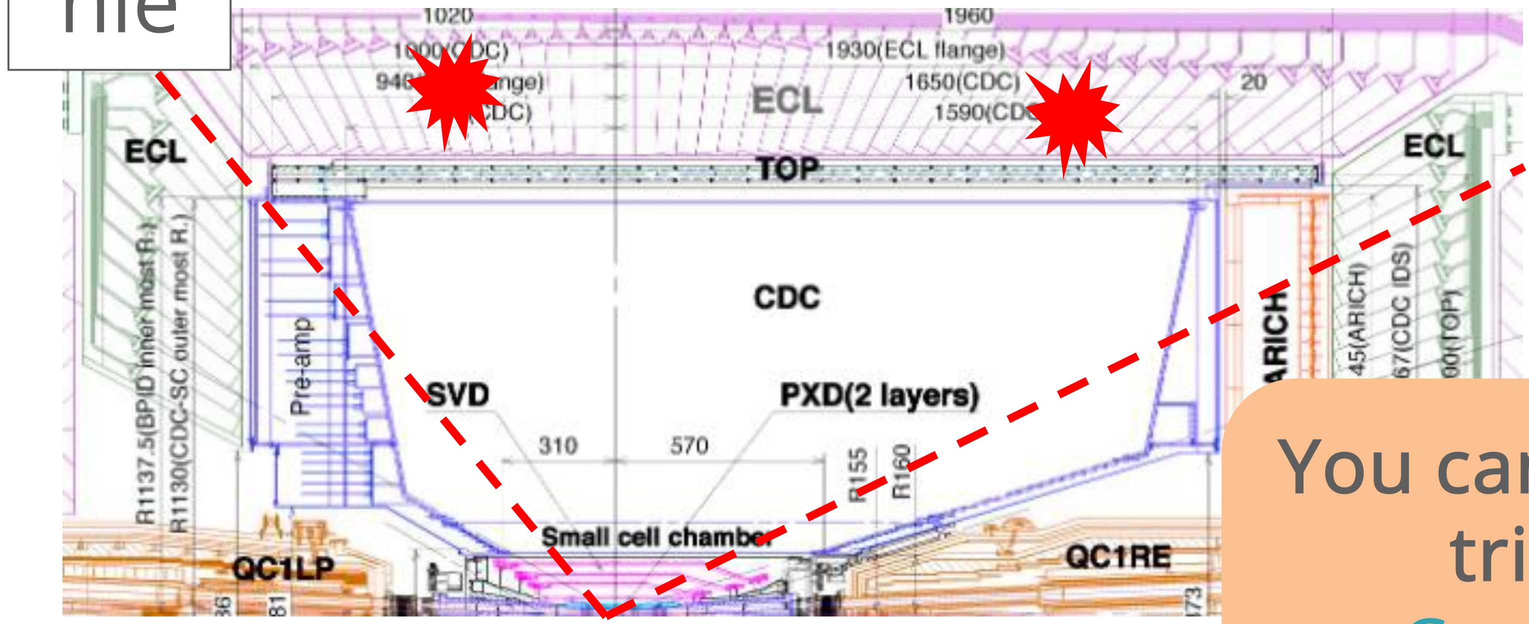
c4



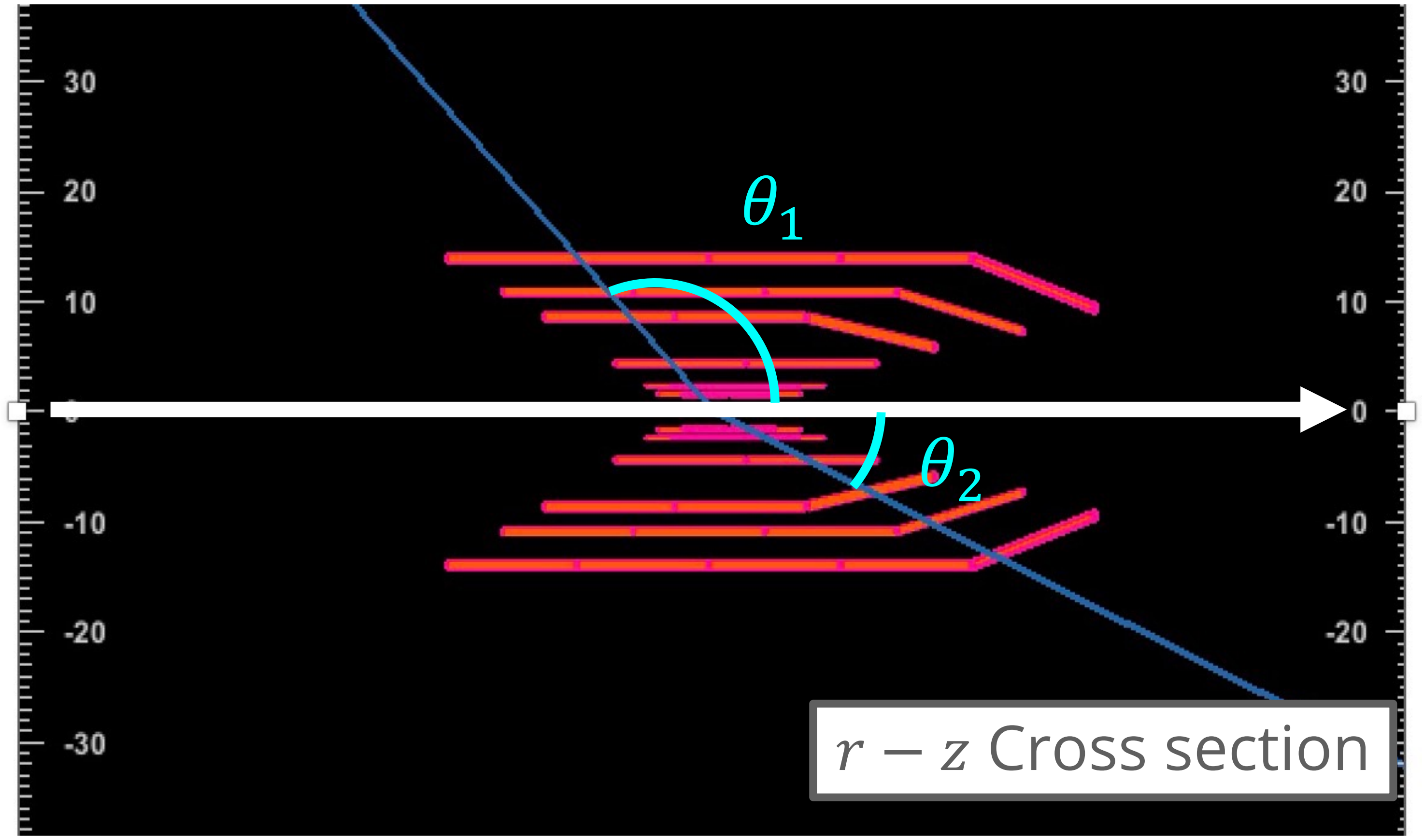
hie



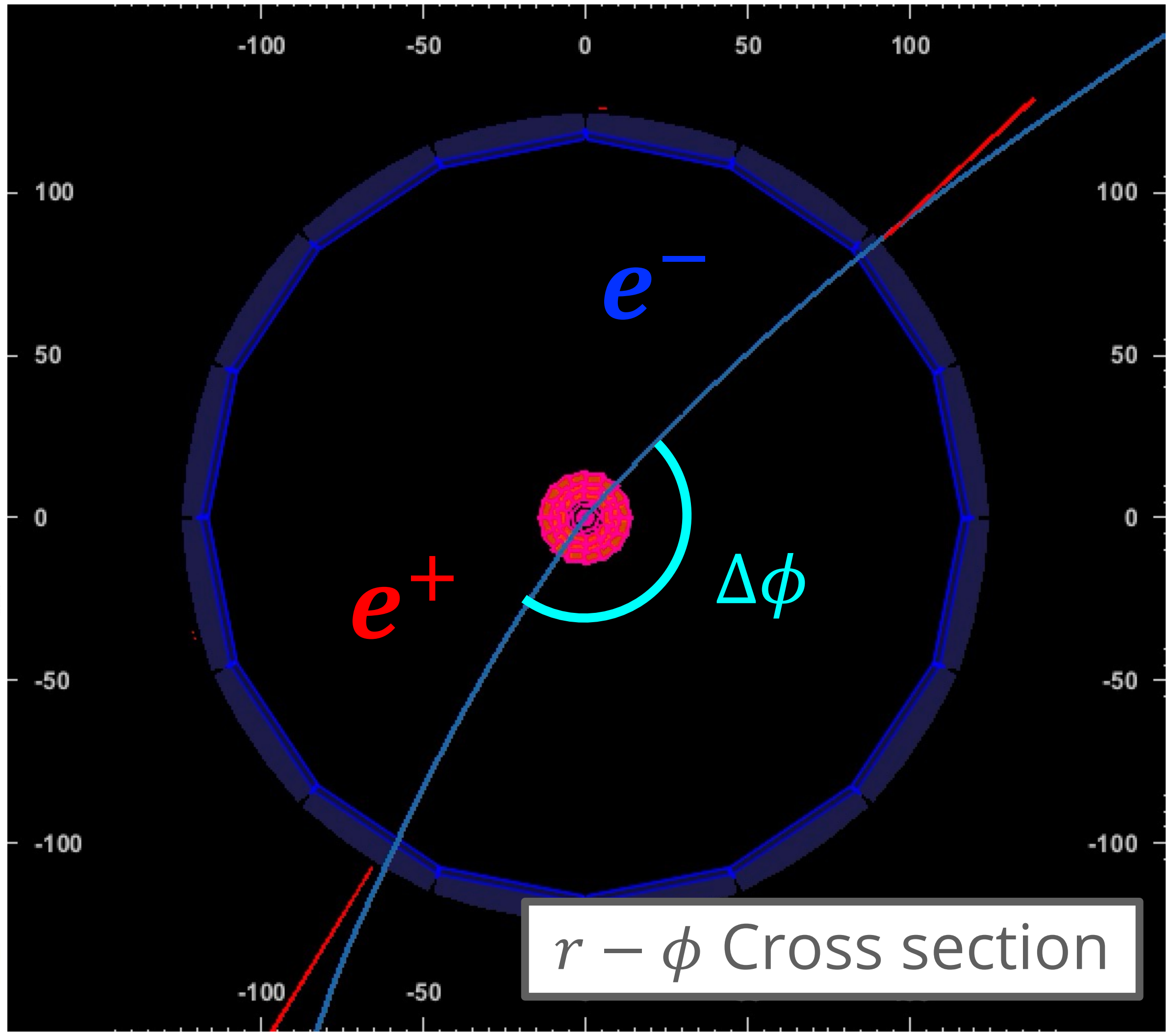
You can check more L1 trigger bits at [Confluence Page (Trigger Bit Table)]

Reducing Trigger Rate: Bhabha Veto

- Bhabha scattering: $e^+(4\ \mathrm{GeV})\ e^-(7\ \mathrm{GeV}) \rightarrow e^+\mathrm{e}^-$ 👉 Very energetic electron & positron
  - ECL can catch signals from those particles
  - We veto these events (suppress the L1 trigger signal even though the conditions are satisfied) to reduce the trigger rate
- Conditions:
  - $E_1 > 4.5$ GeV and $E_2 > 3.0$ GeV : High-energy, and
  - $160° < \Delta\phi < 200°$ and $165° < \theta_1 + \theta_2 < 190°$: Back-to-back
- 80% reduction of the total trigger rate!



$r - z$ Cross section

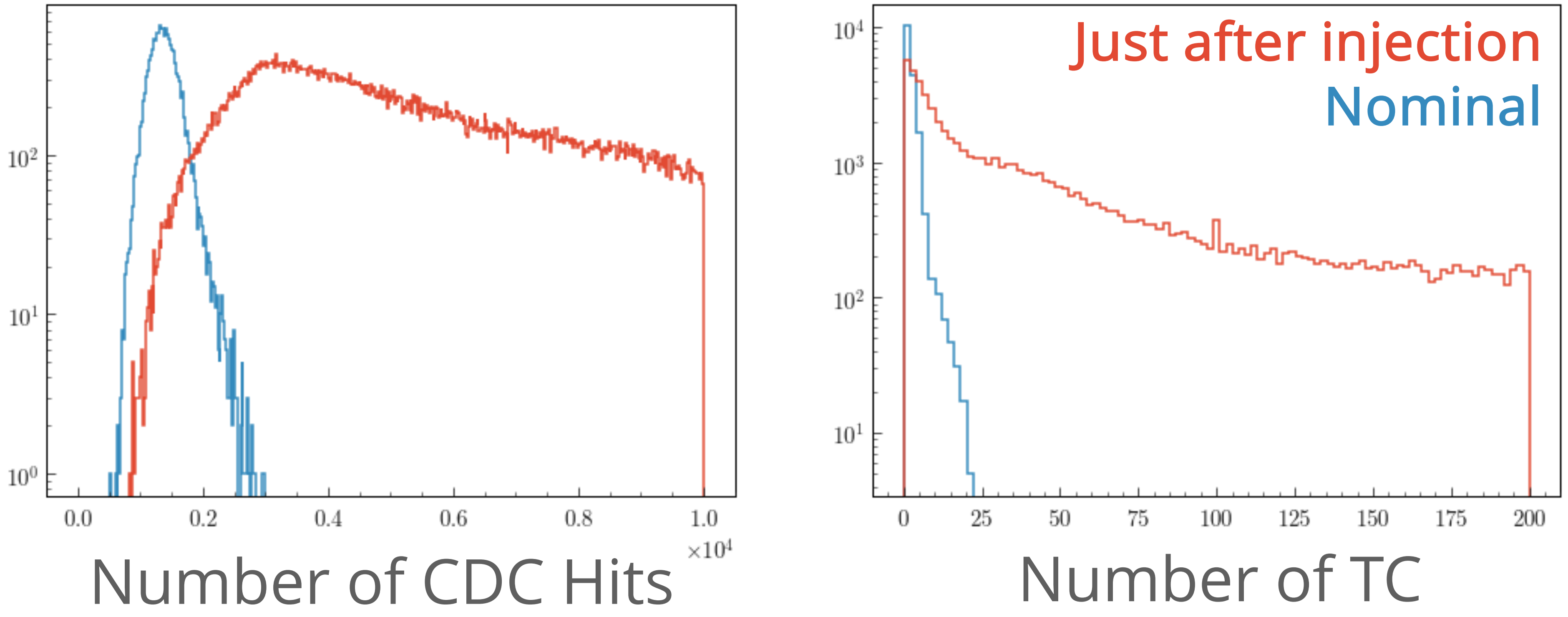


$r - \phi$ Cross section

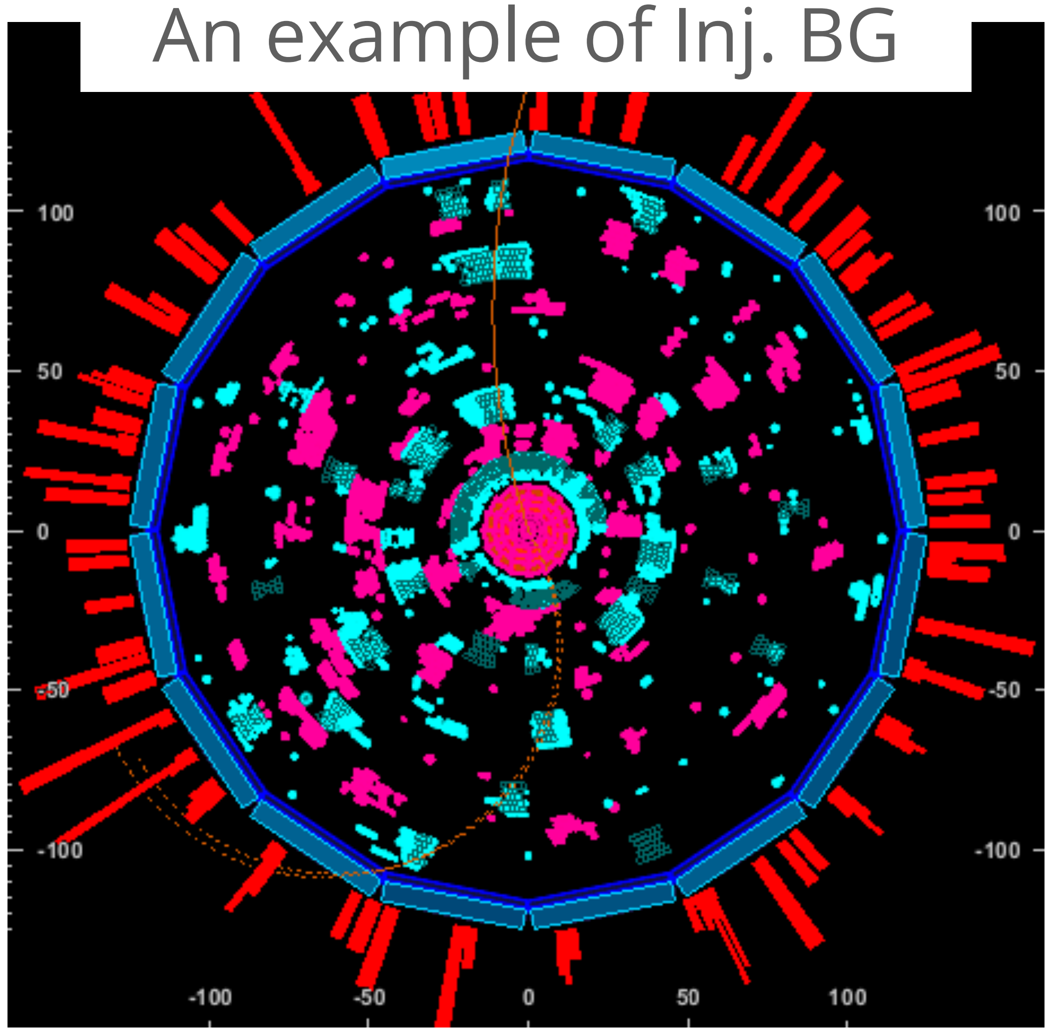
Reducing Trigger Rate: Injection Veto

- Just after the beam injection, we observe a huge background: Injection Background
  - Very high occupancy and trigger rate (over 1 MHz)

- After the pre-injection signal from the accelerator, events with high occupancy are vetoed.
- Without this veto, we cannot operate DAQ during the beam injection



An example of Inj. BG

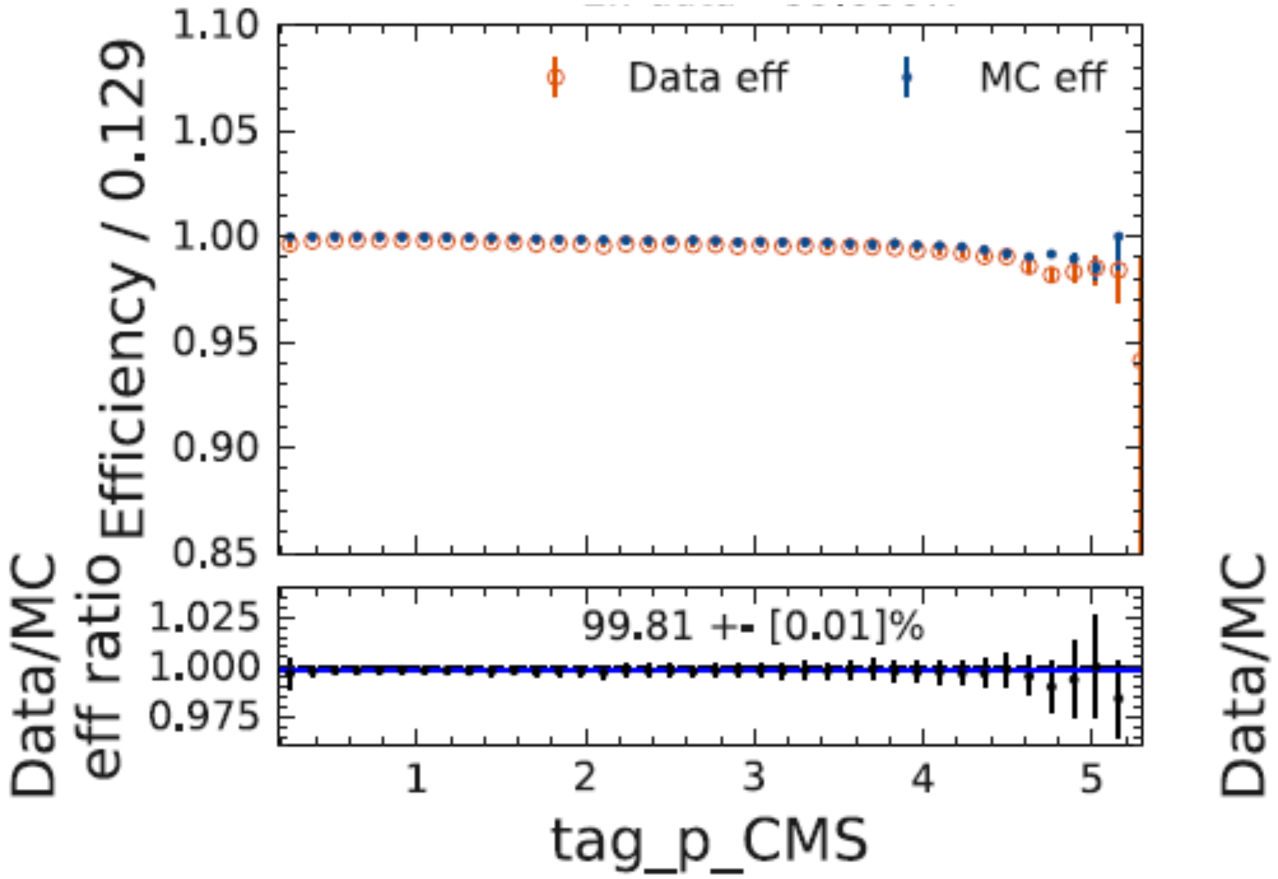


Very high occupancy!

TSIM: The Trigger Simulation

- We implemented a simulation algorithm called TSIM for the trigger logic in basf2.
  - You can estimate the trigger performance also in MC
- Since MC14, most of the trigger logic is implemented on basf2 with good Data/MC agreement, of which the discrepancy is less than 1%.
  - Continuous maintenance is ongoing
- Example of tau 1x1 study:

ECLTRG Efficiency in e mode



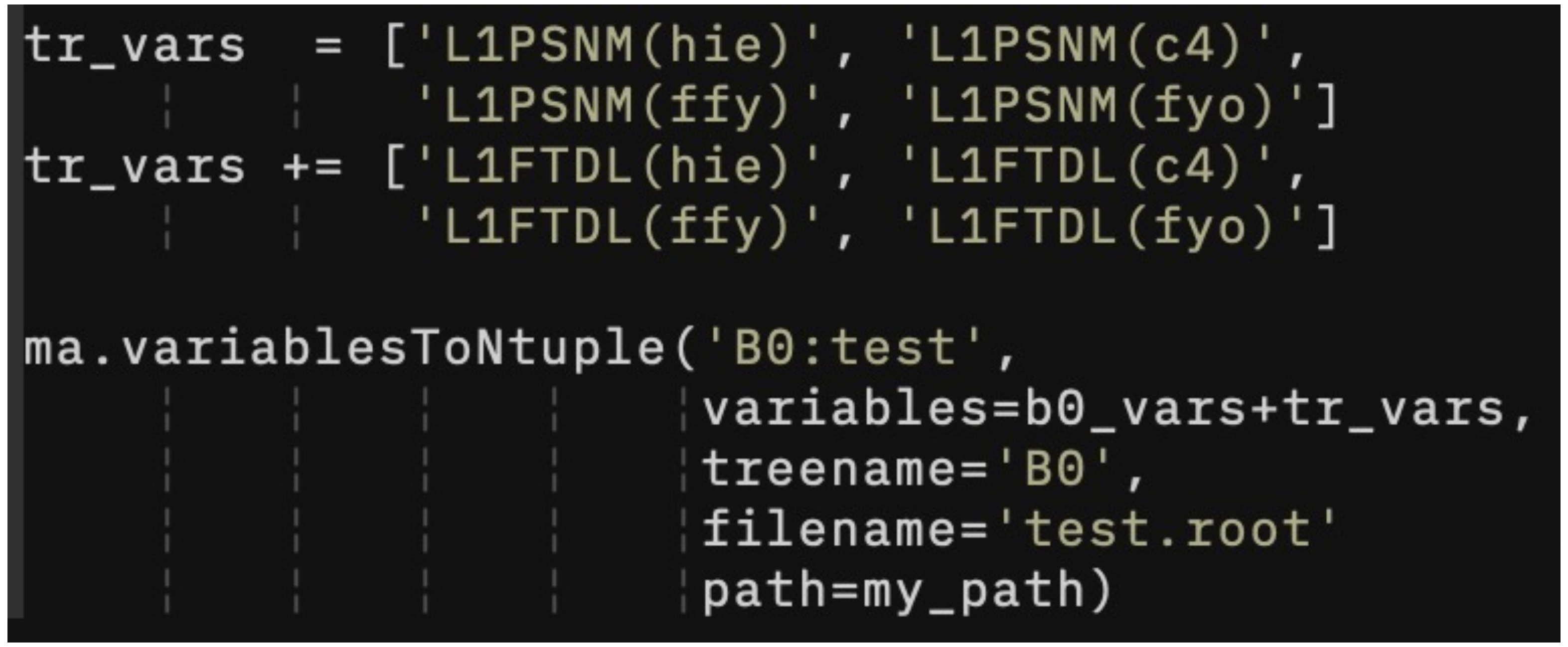
Trigger in Analysis

- We should consider the effects of triggers in the physics analysis and basf2 provides methodologies to estimate the effects
  - Especially, the low-multiplicity analysis will have a large effect by the trigger
- How to access the information?: Use the basf2 variables
  - Example: If `L1PSNM(fyo)==1`, then the event has been triggered by the '`fyo`' bit

Variable name	Description
`L1Input(name)`	The input bit status to the GDL logic with the given name
`L1PSNM(name)`	The output trigger bit status from GDL after the prescale
`L1FTDL(name)`	The output bit status before prescale
`L1Prescale(name)`	Prescale settings

Please be careful when you work with the run-indep. MC as the prescale settings may be different from data

- An example of how using the variables:



```
tr_vars  = ['L1PSNM(hie)', 'L1PSNM(c4)',
            'L1PSNM(ffy)', 'L1PSNM(fyo)']
tr_vars += ['L1FTDL(hie)', 'L1FTDL(c4)',
            'L1FTDL(ffy)', 'L1FTDL(fyo)']

ma.variablesToNtuple('B0:test',
                     variables=b0_vars+tr_vars,
                     treename='B0',
                     filename='test.root'
                     path=my_path)
```

Summary

- The trigger system of Belle II is an FPGA-based signal processing system for the Belle II detectors to catch physically meaningful events

- The system consists of the global logic and four subsystems: CDC, ECL, KLM, and TOP

- Many trigger bits (conditions) are prepared for specific physics (B, τ, or low-multiplicity)

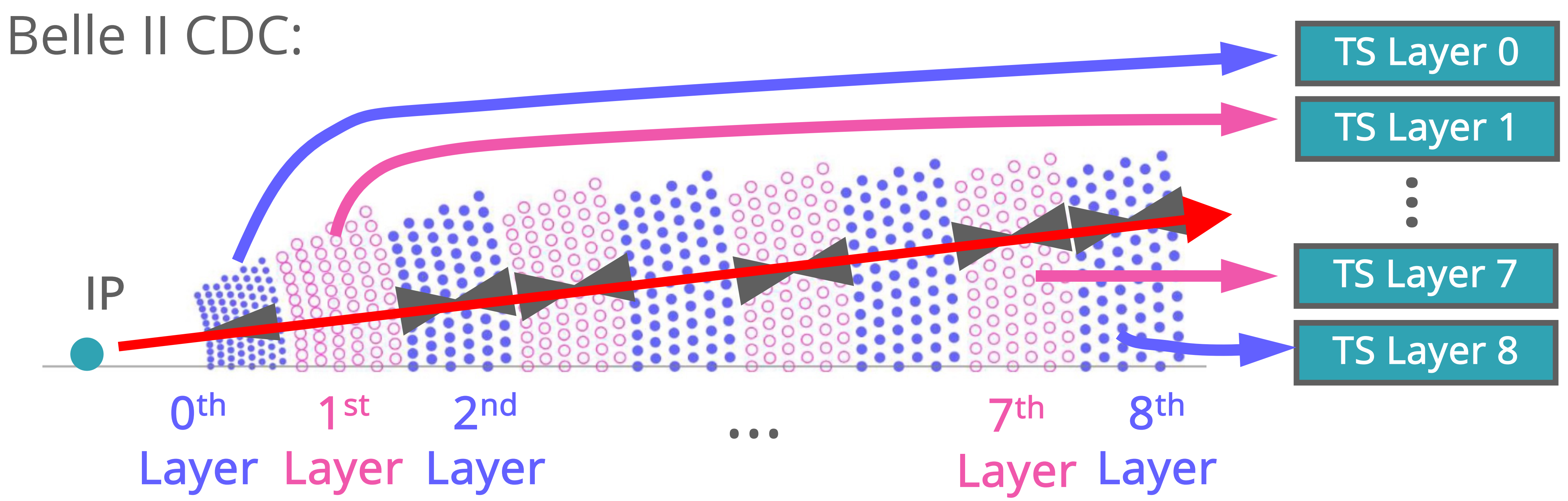
- Good agreement between the experimental data and simulation (MC) in the overall

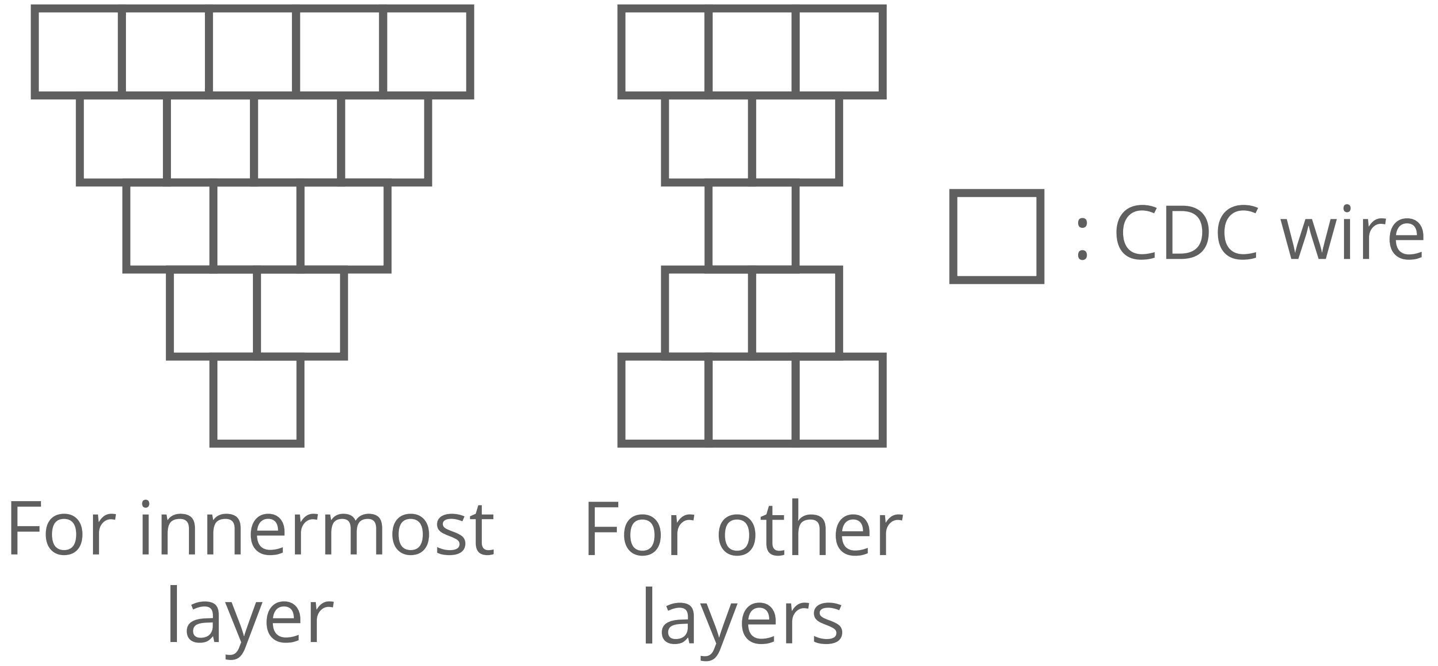
- When you start the physics analysis, you should confirm the effects of the L1 trigger
  - Especially, large effects on the low-multiplicity physics
  - Please consult with the trigger group

Backup Slides

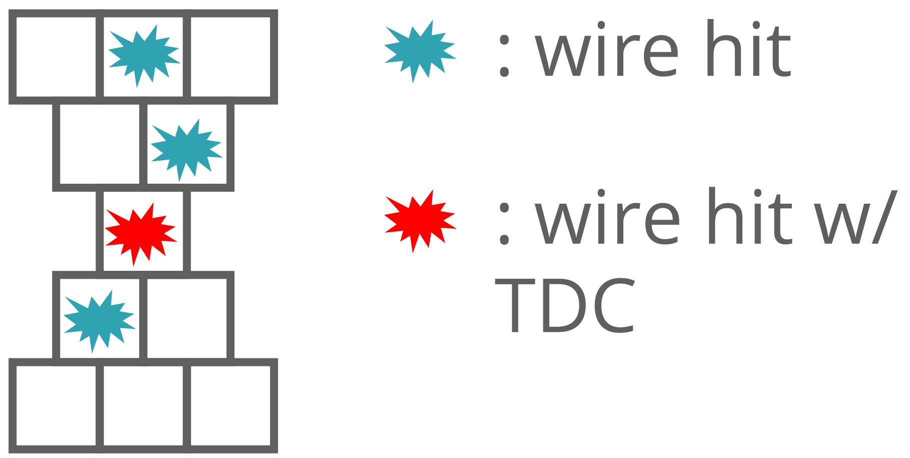
CDC Trigger: Track Segment

- CDC has too many wires ($\mathcal{O}(10000)$) to process them individually 👉 Grouping the wires





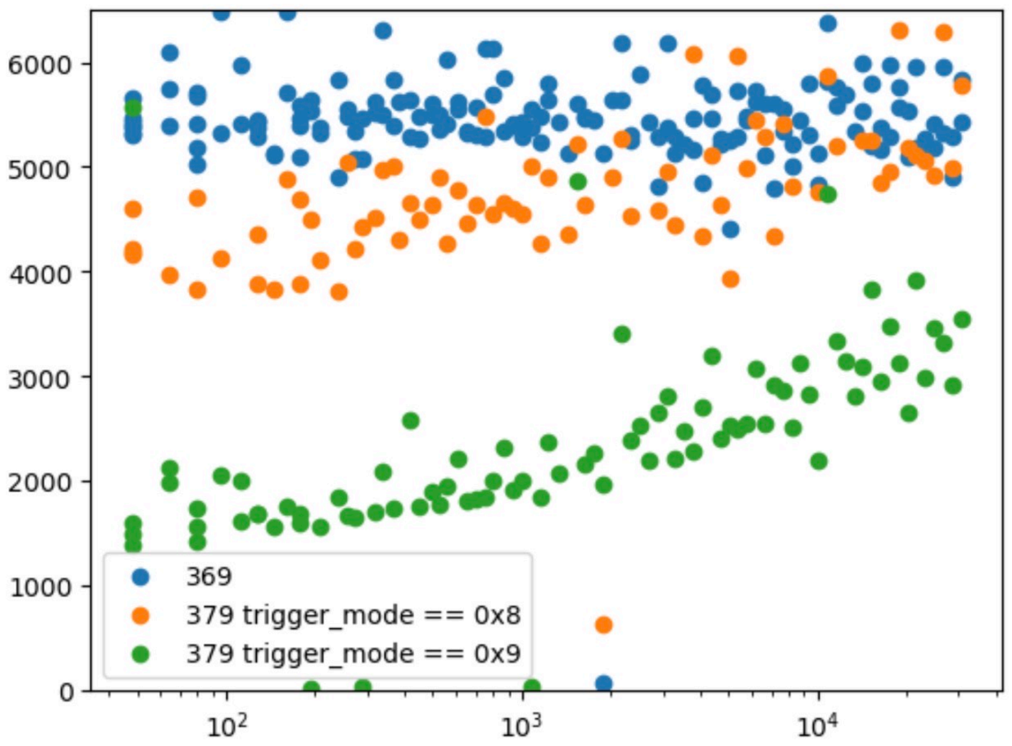
- This group of CDC wires is called the “Track Segment” (TS)
  - a basic element in the CDC trigger system
  - requires 4 radially continuous wire hits ($p_t \geq 0.35$ GeV required)



KLM Trigger: Performance?

- The trigger rate from KLMTRG with the new mode reduced significantly
  - which indicates the background rejection power of the new mode

The internal trigger for SLF



Back-to-Back Trigger for SLF