

Level 1 Trigger at Belle II

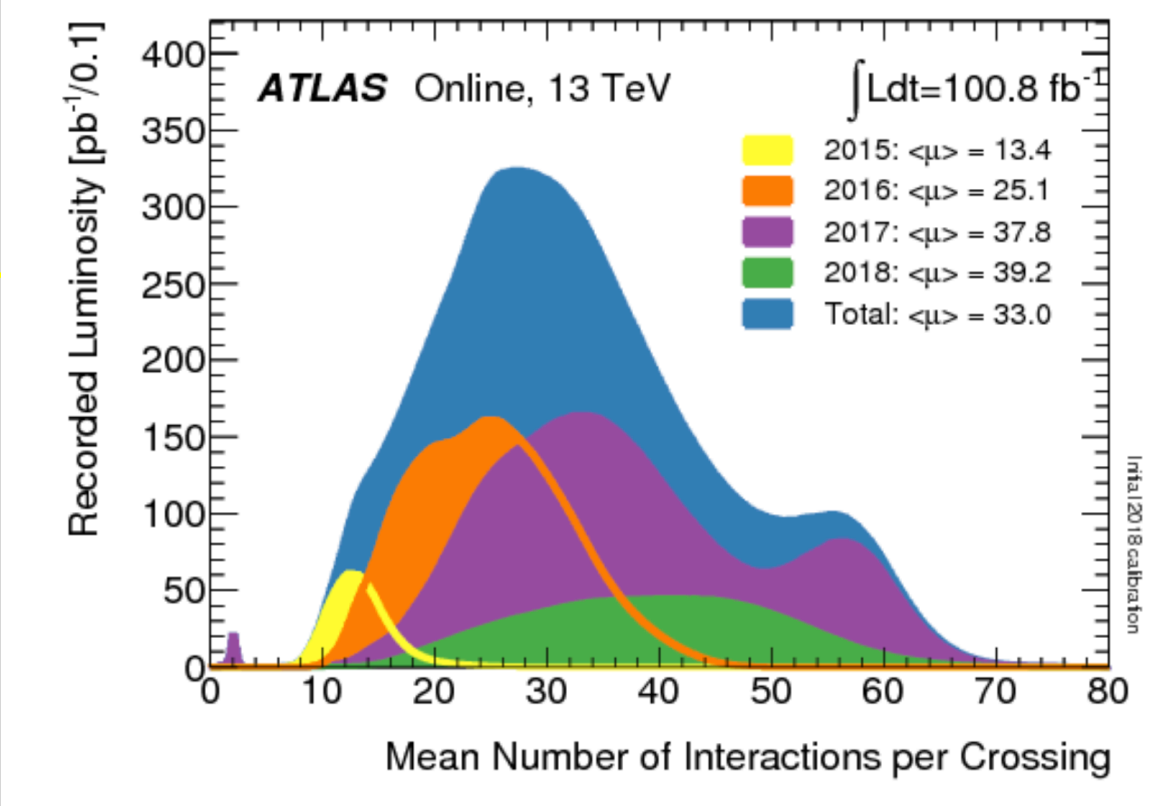
H. Nakazawa (NTU)

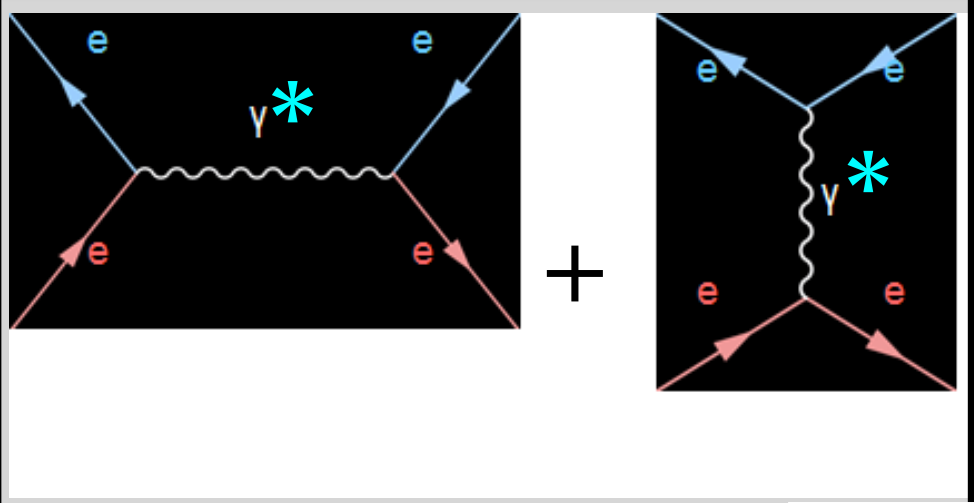
20251022@TRG/DAQ workshop

Physics processes at Belle II

$e^+e^- \rightarrow$	Xsec [nb] in acceptance	Hz @6e35/cm2s	Target
$\gamma(4S) \rightarrow B\bar{B}$	1.1	660	Physics (Hadron)
$q\bar{q}(u\bar{d}s\bar{c})$	3.7	2200	Physics (Hadron)
$\tau^+\tau^-$	0.9	540	Physics (LowMult)
$\mu^+\mu^-$	1.1	660	Physics/Calibration
$e^+e^- X$	13	10000	Physics/Calibration
$e^+e^- (\gamma)$	300	$<1800_{(1/100)}$	Calibration
$r\bar{r} (\gamma)$	5	$30_{(1/100)}$	Calibration
NP	??	??	Physics (??)
Total	>320	20 kHz (w/ PS)	
		~200 kHz (w/o PS)	
		15 Hz (requirement)	
Beam Crossing		250 MHz	

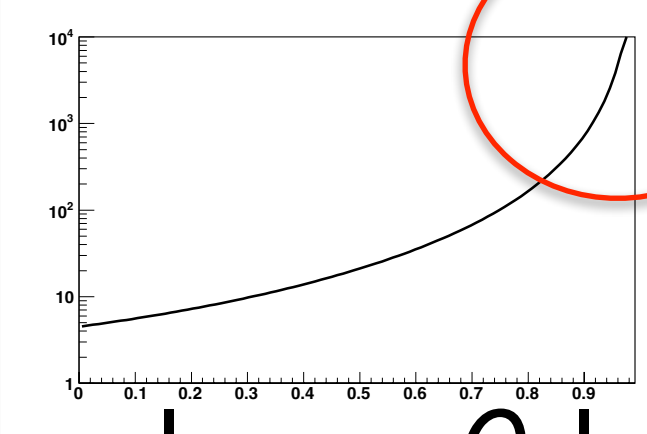
- Physics process / Beam bunch crossing < 0.1%
- Most of the 0.1% is QED “background”
- Hadron+tautau < 0.002% of Beam crossing



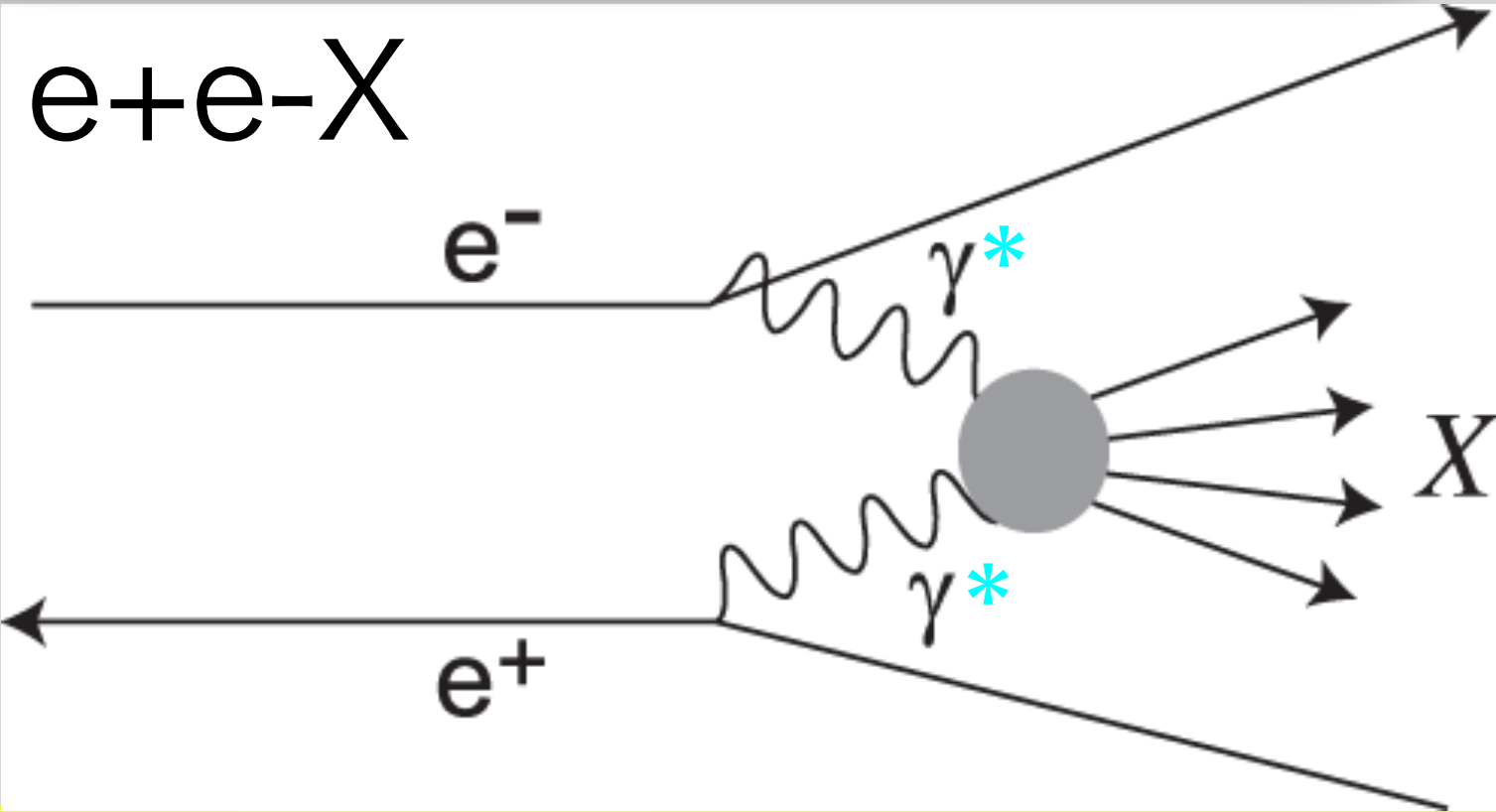


$$= \frac{4 + (1 + \cos\theta)^2}{(1 - \cos\theta)^2} - \frac{(1 + \cos\theta)^2}{1 - \cos\theta} +$$

Bhabha



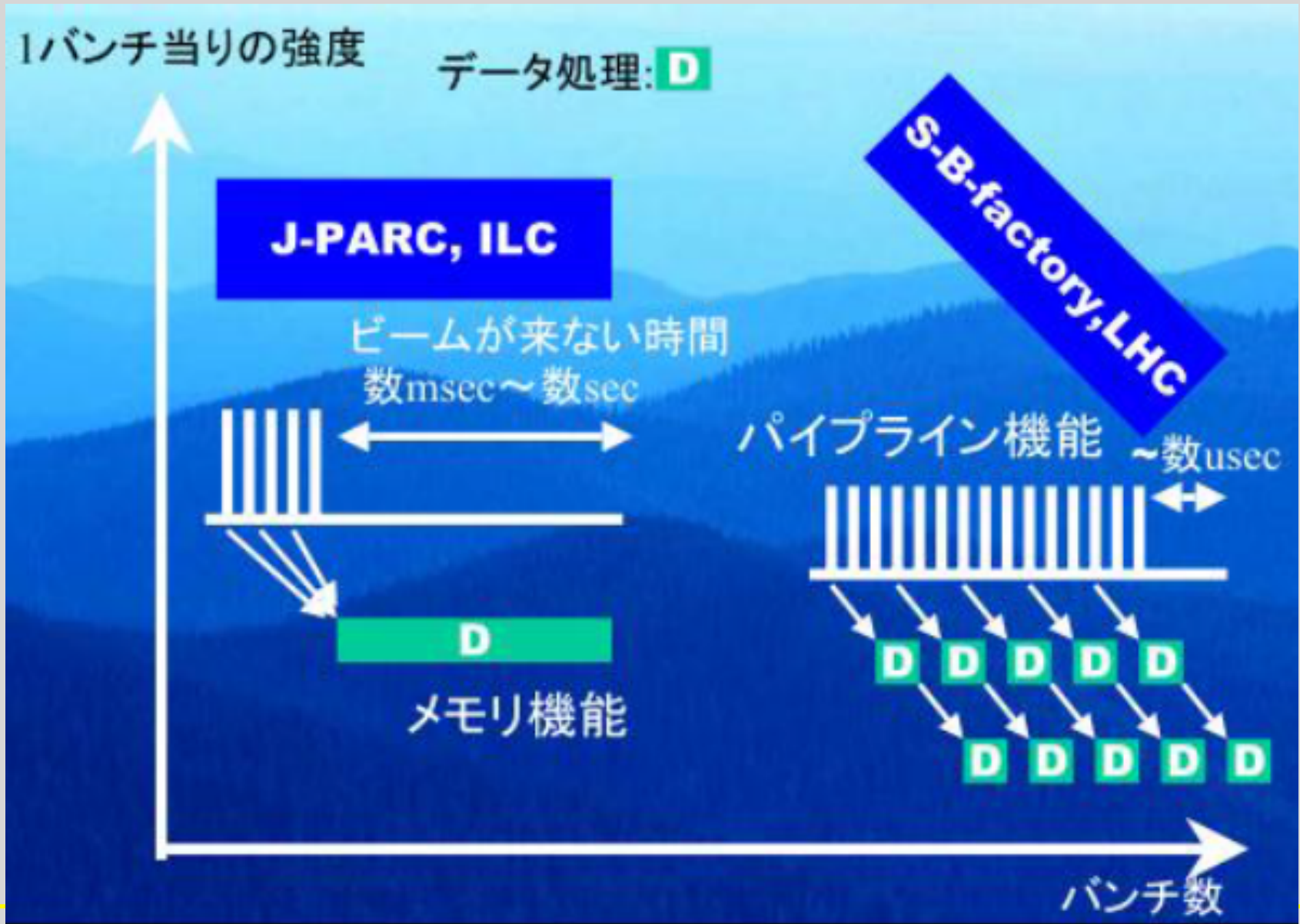
$|\cos \theta|$



Outputs of Belle II Detector

- >300k channels from Belle II Detector
- Each channel just keep outputting its response (wire hit, energy, etc)
- Digitized on FEE near Detector, “0”/“1”.
- Continuous (system clock of 127MHz) data flow
 - Typical data width for physics events, [100 nsec, 2 usec]
 - We want to record only 30kHz times 2 usec = 60 ms = 6%.

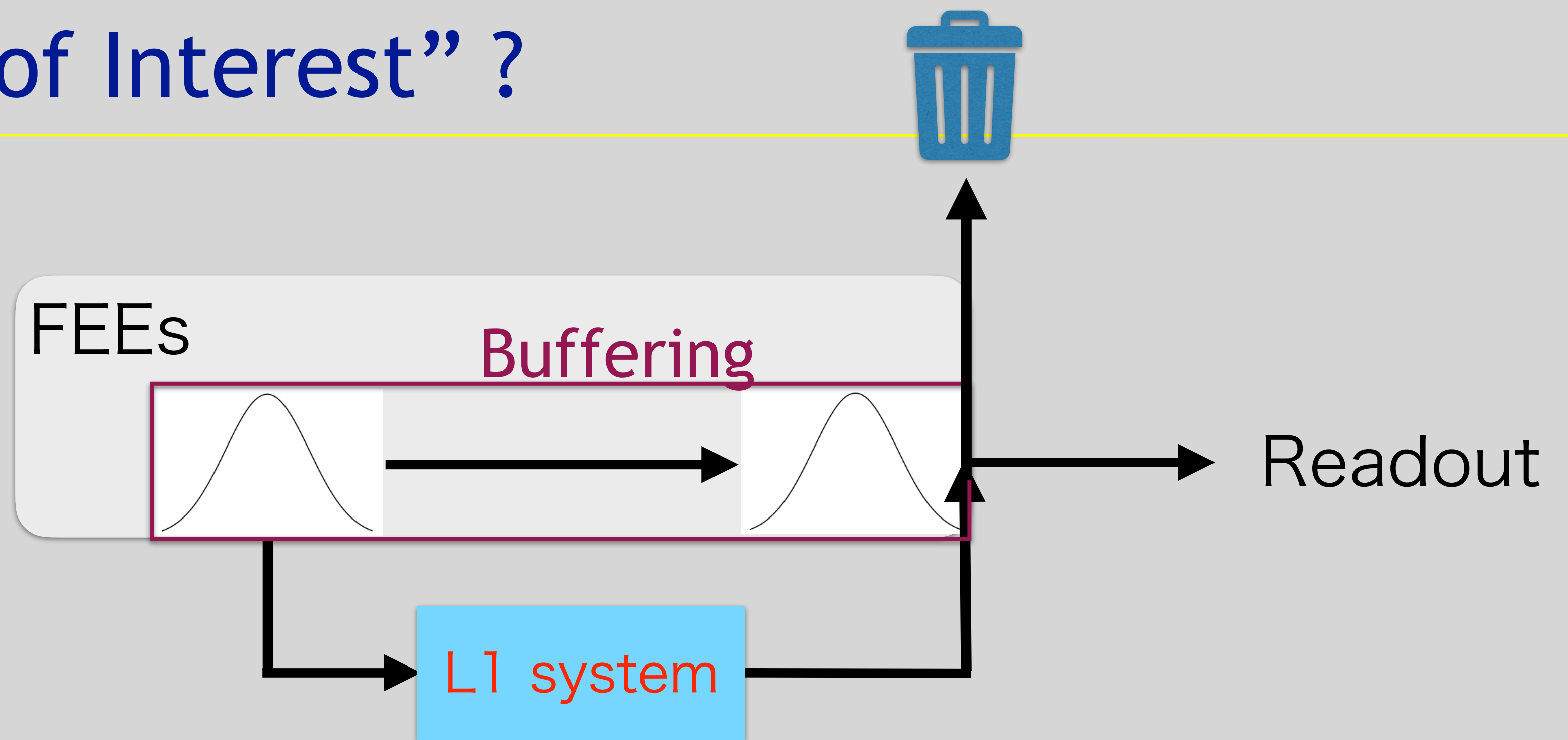
	#ch
PXD	8
SVD	223744
CDC	14336
BPID	8192
EPID	65664
ECL	8736
BKLM	19008
EKLM	16800
TRG	



How do we record the data?

- Record all continuous data flow, and check carefully on PCs with softwares in down stream
 - Triggerless DAQ
 - LHCb, ALICE, EIC adopt this but **Belle II does not.**
 - Requires huge Processing (CPU/GPU) and Storage resources
- Record only “data of interest” to discard unwanted data and reduce data size to be sent to DAQ
 - **L1 (Level 1 Trigger)** system is a dedicate electric circuit (hardware) that extracts only data of interest from continuous data flow, classifies the data (physics or calibration) and scale down calibration process if necessary, and lets the readout system know the timing of recording

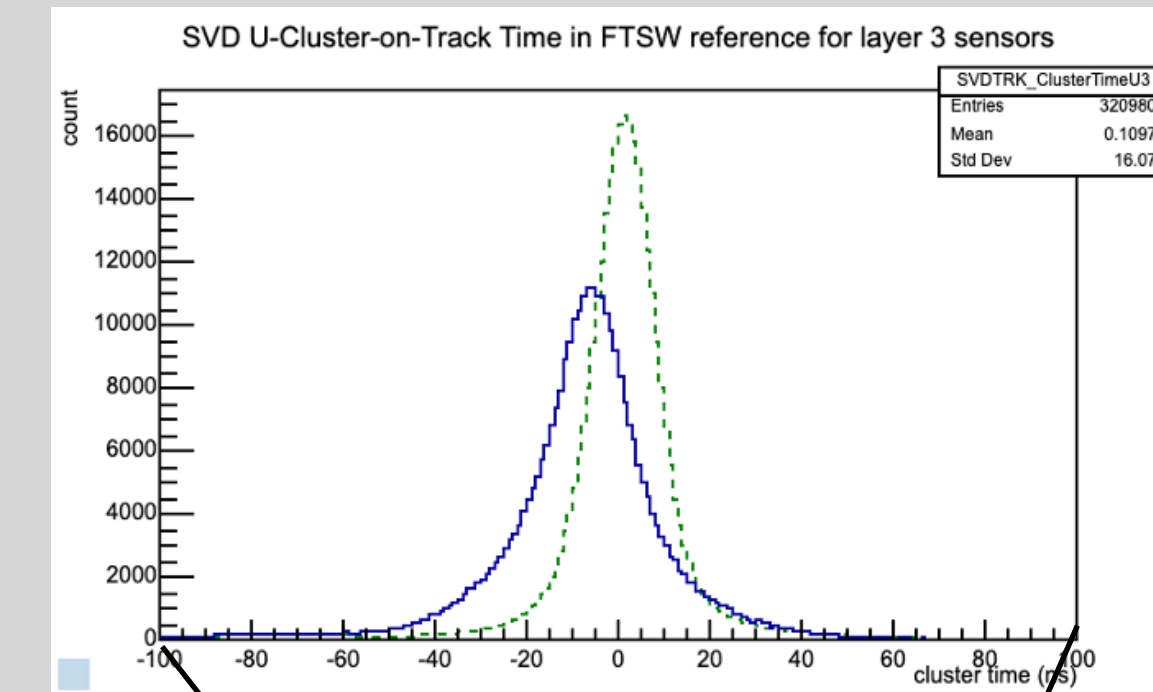
How L1 detects “Data of Interest” ?



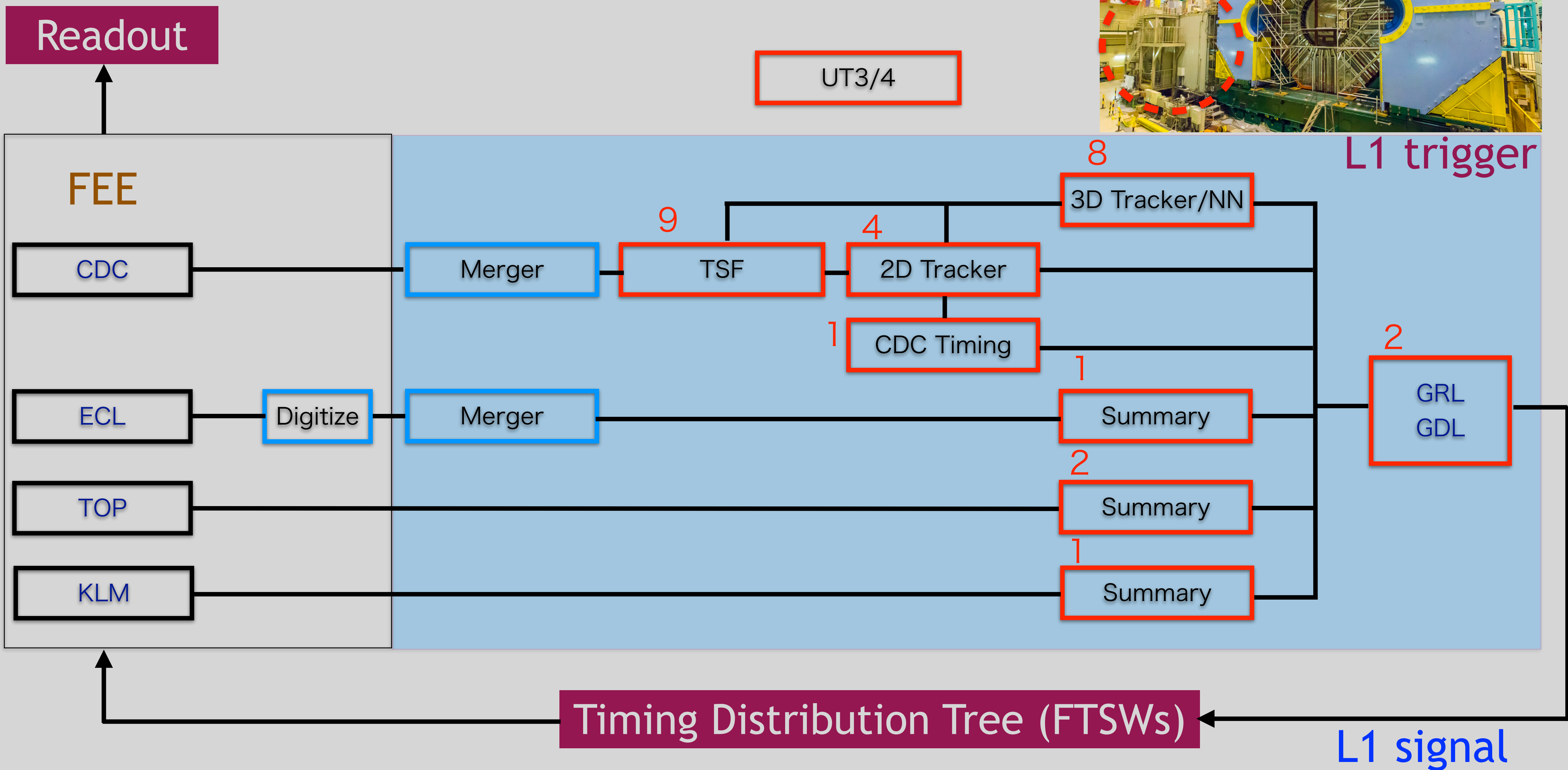
- By analyzing data itself
 - Collects available fast data from subdetector FEEs and do coarse analysis
 - #tracks, #clusters, energy sum, event topology, ... of the event with reduced granularity (TS, TC)
 - Relevant subdetector FEEs have output lines for L1
- L1 takes some time to make decision.
 - All FEEs must hold data in FIFO (ring buffer) until L1 makes decision that the data is necessary or not
- Allowed time length for L1 to consider is limited by Buffer size of the FEEs
- The decision making is done at every 127MHz. ~500 nsec dead time if L1 is fired.

Requirement of L1 Trigger

- High efficiency, ~100% for hadron ($n_{\text{trk}} \geq 3$) events
- Redundant and independent TRG logics
 - Track and Energy trigger
- Max. average rate 30 kHz @ $6 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$
- Good background reduction necessary
- Latency ~4.4 μs . Limited with SVD FEE.
- Event Timing Resolution ~10 nsec. Limited with SVD FEE.



Overview of L1 and surroundings



Universal Trigger Boards, UT3/UT4

- Widely used in L1 system
 - Optical Links
 - LVDS for parallel connection
 - NIM I/O x 11 x 2
 - RJ45 x 4 for Belle2Link
 - JTag for Firmware download
- Transition to UT4 ongoing
 - KLMTRG and NNs are UT3

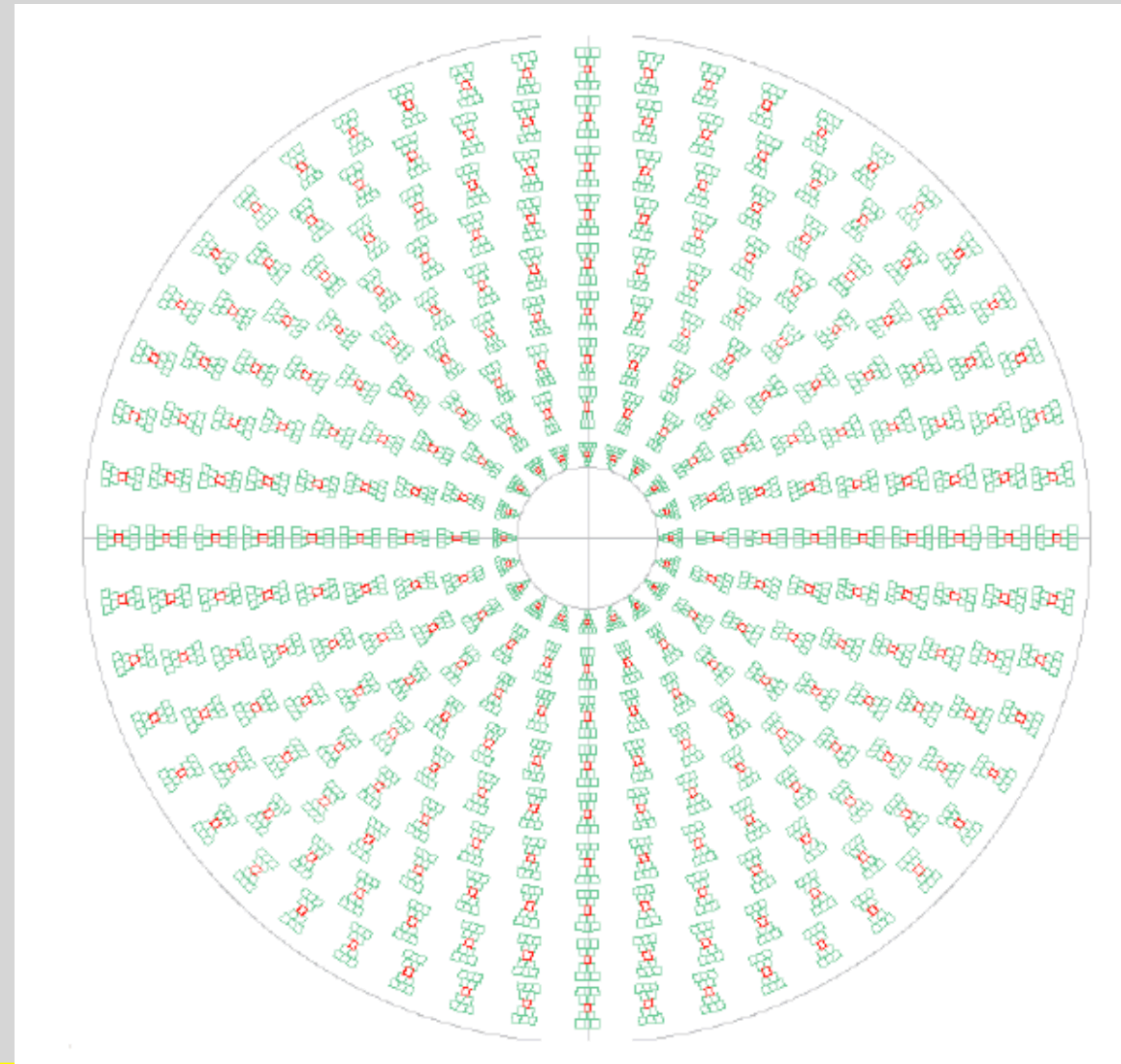
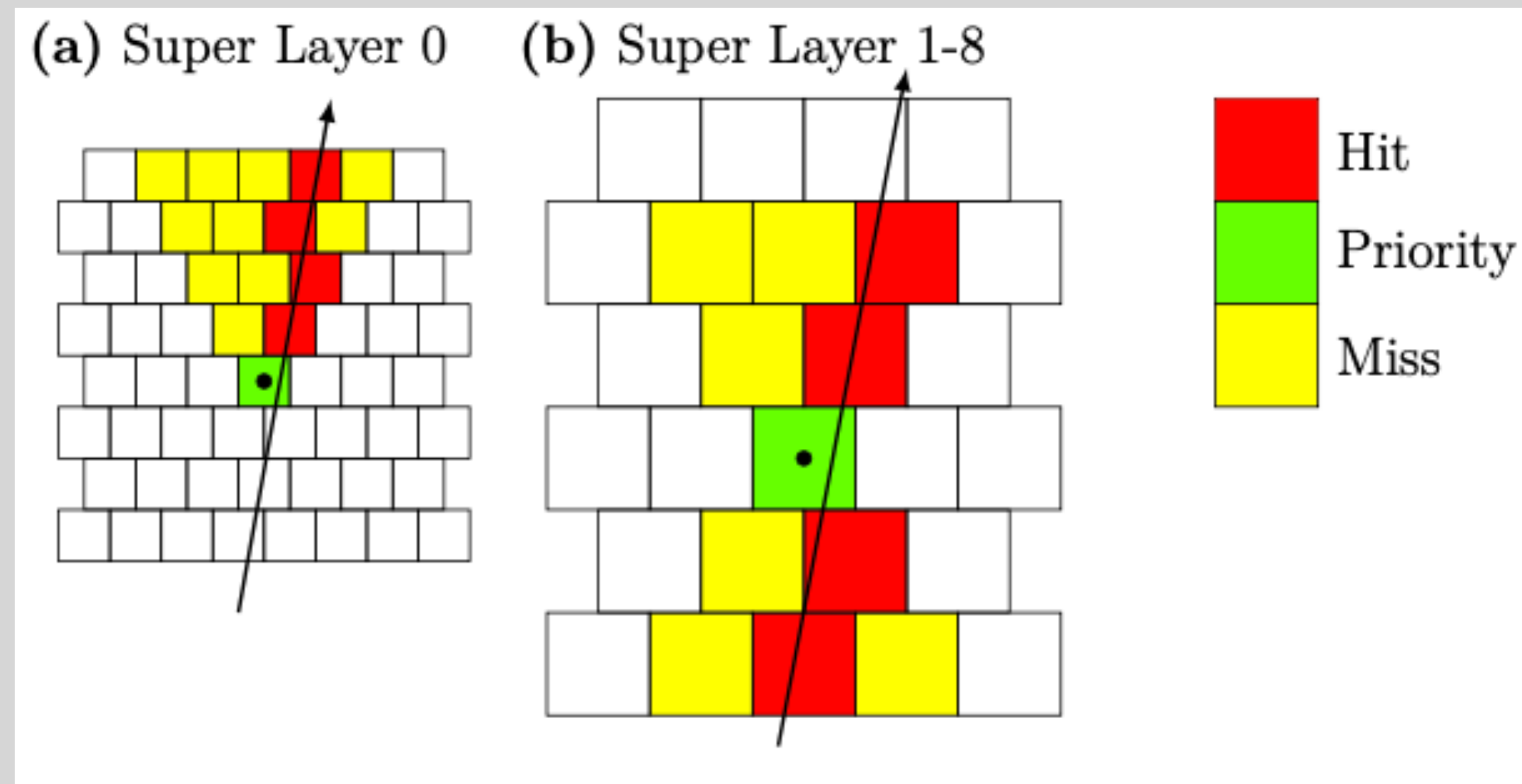
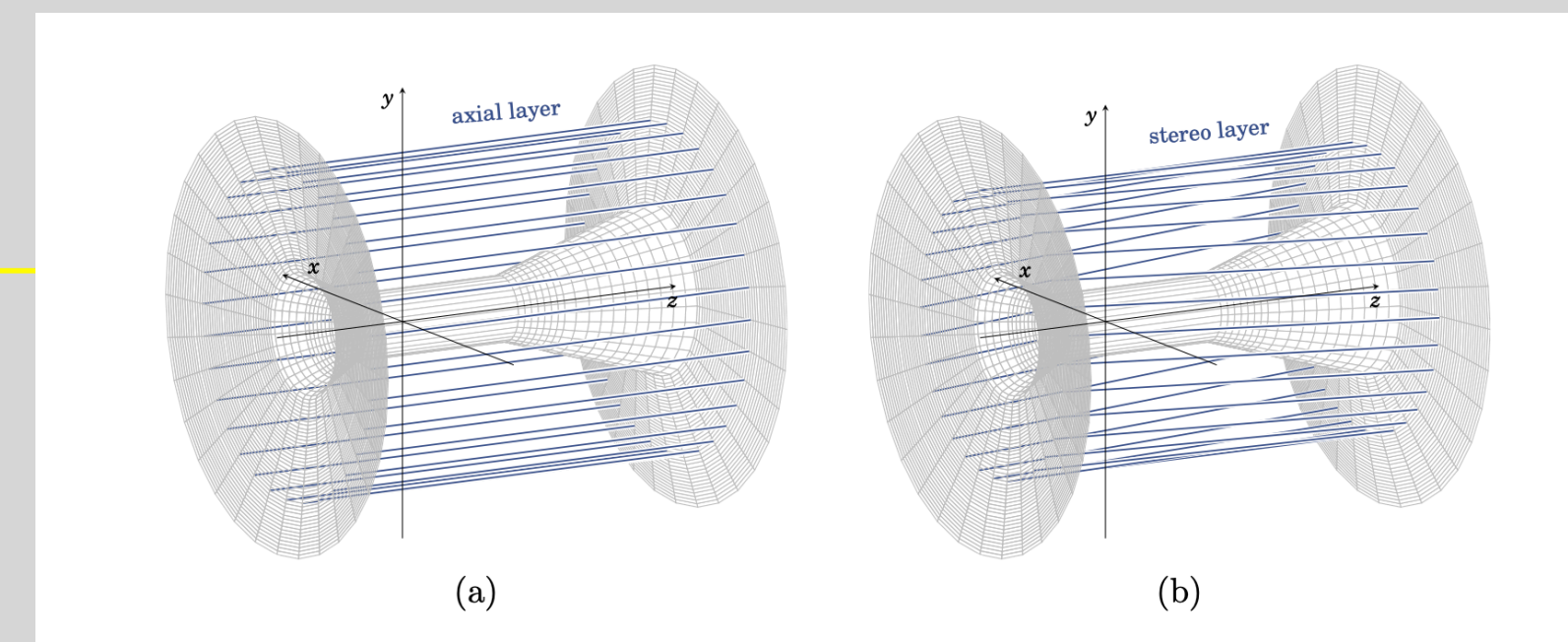


	UT3	UT4
FPGA	Xilinx Virtex6 XC6VHX380/560T	Xilinx Virtex Ultrascale XCVU080/160/190
number of logic cells	382k/580k	975k/2026k/2350k
IO	GTH 5Gbps x24lane	GTY 25Gps X 32lane
	GTX 3Gps x40lane	GTH 12.5Gps X 32lane

Sub Triggers

CDC Trigger: TSF

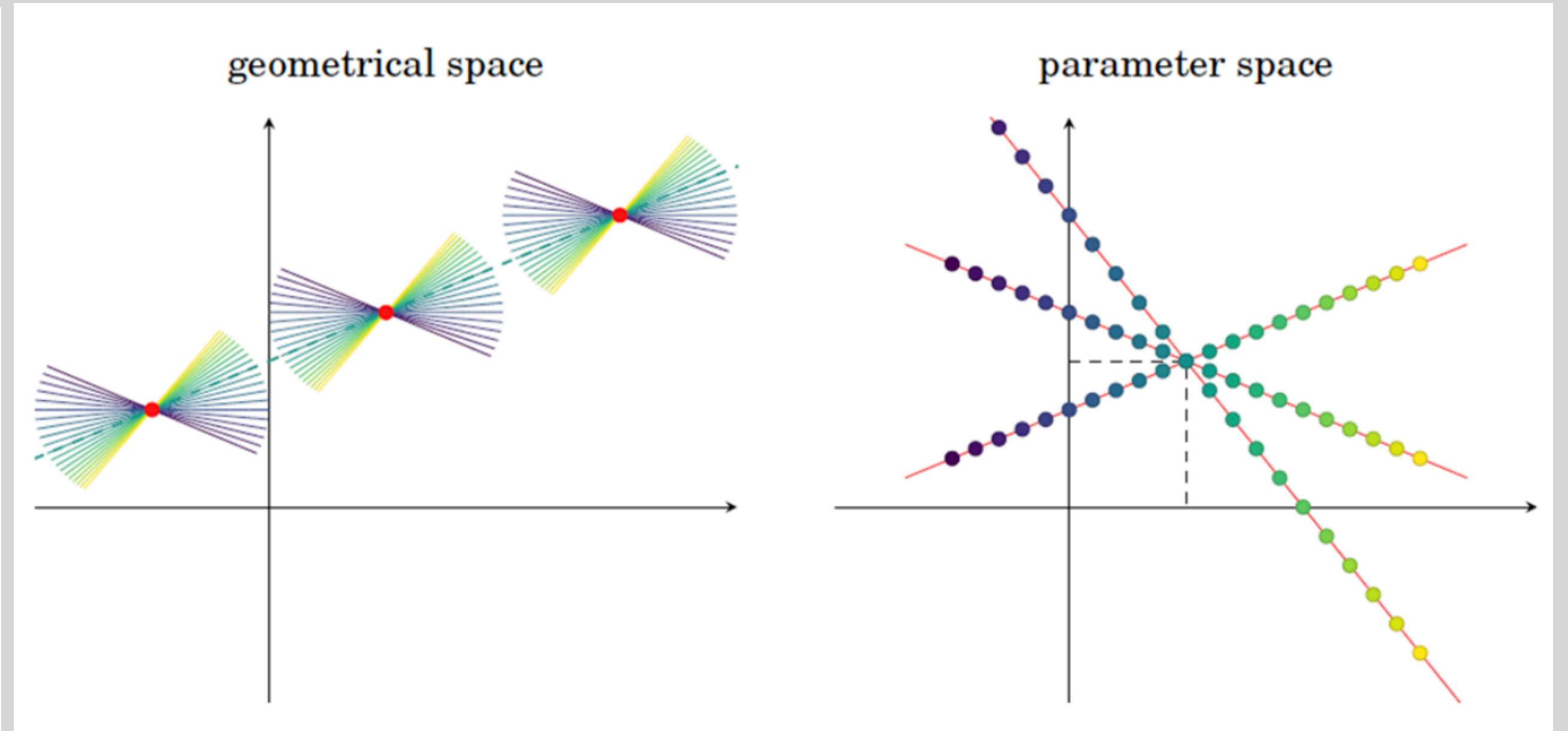
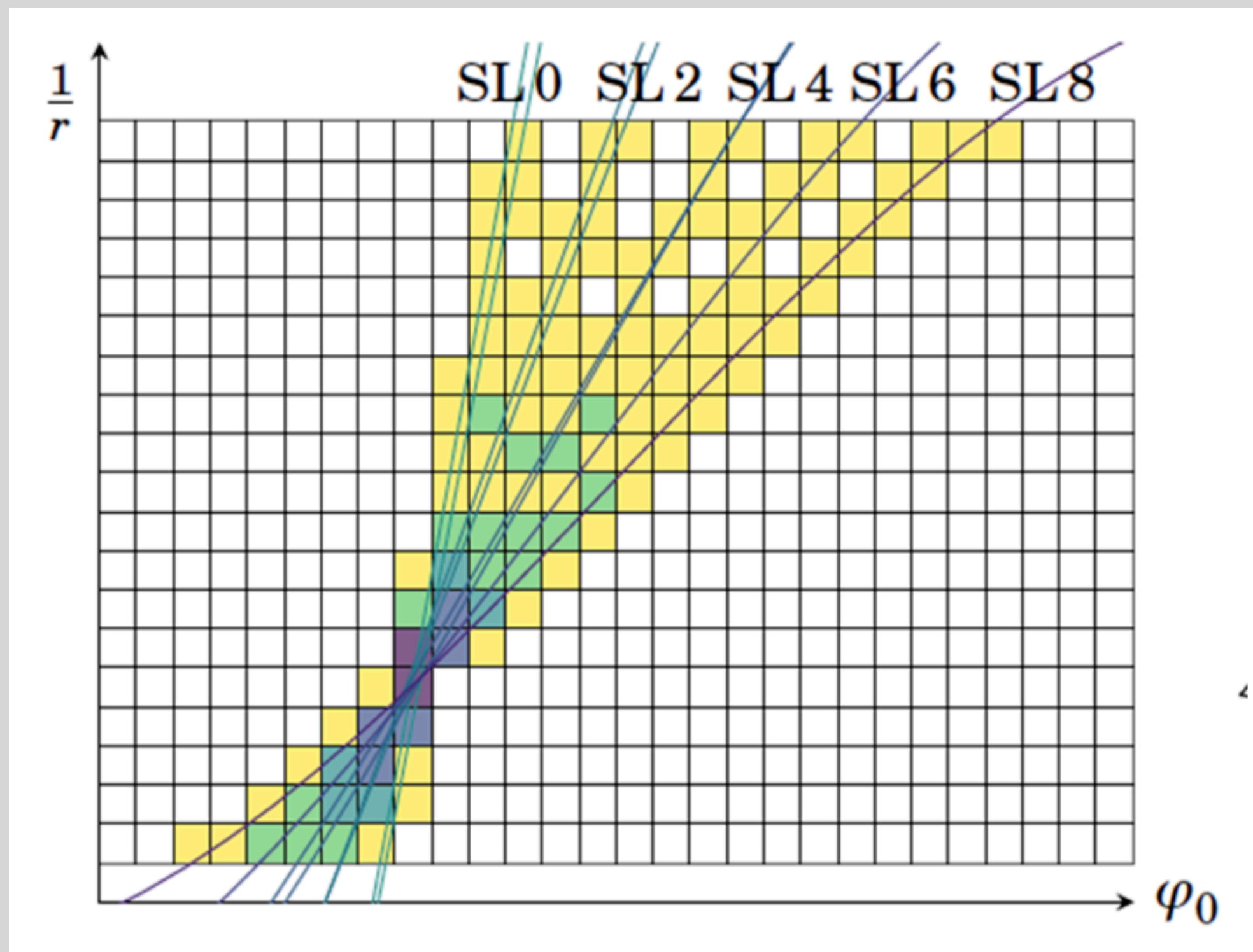
- 14,336 sense wires grouped into nine super-layers (SL) 0 (innermost) to 8 (outermost)
- SL0, 2, 4, 6, 8; Axial. Parallel with z axis
- SL1, 3, 5, 7; Stereo. Tilted slightly ($\pm x^\circ$) to measure z.
- TS: Priority hit and Pre Defined Wire hit pattern from signal track
- Effective for $> 3.0 \text{ GeV}/c$
- Track hit at trigger level
- Pyramid shape in SL0, hourglass shape in SL1-8
- TSF (9 UT4s)



2D Track finder

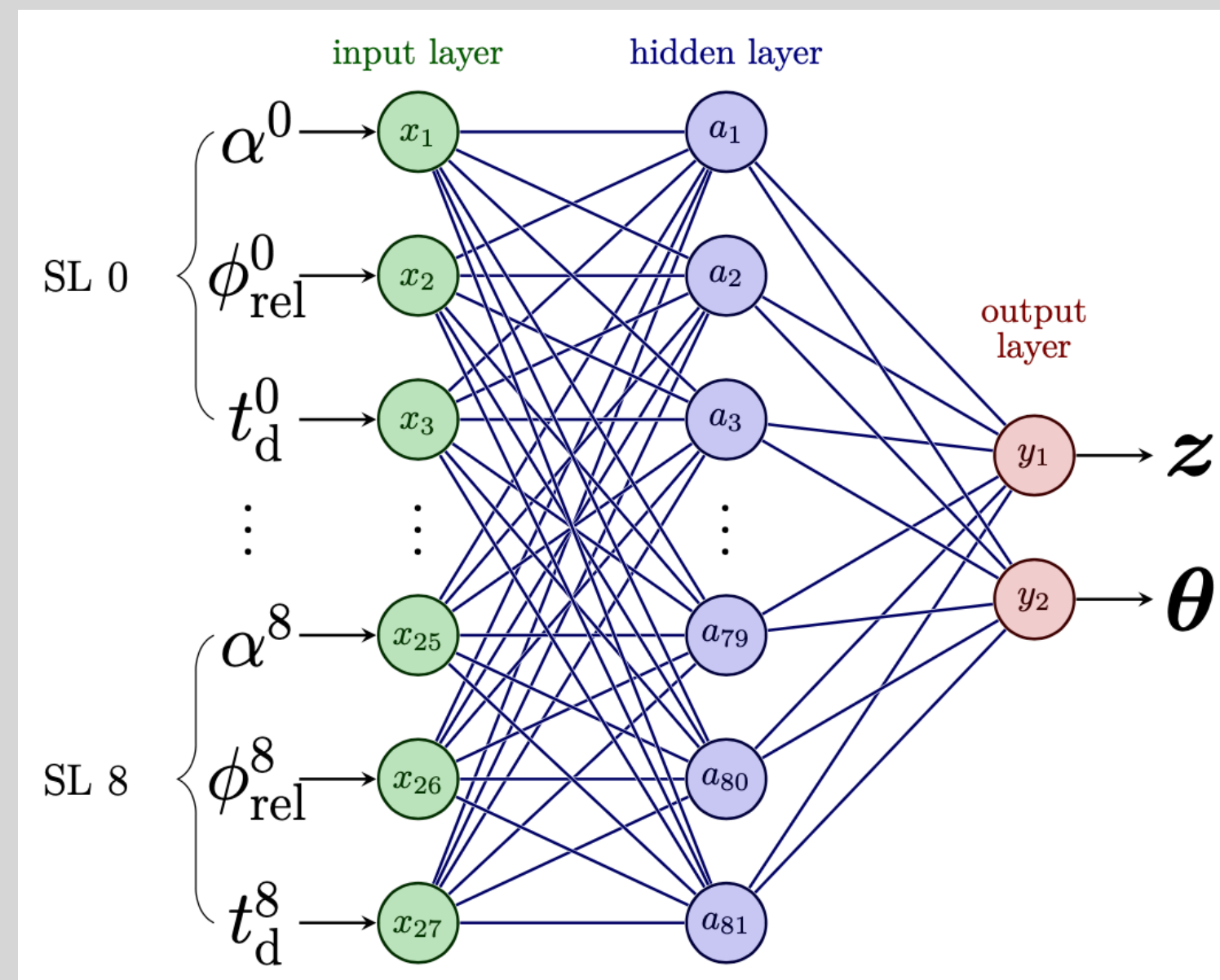
- Only Axial TS, no z information
- Track finding based on Hough Transformation for TS hits
- 1/r-phi plane, assuming a track pass through IP, remaining #parameter is 2 => 2D parameter space.
- 2D track has 2D parameter at intersection of 2D param space

Hough Transformation

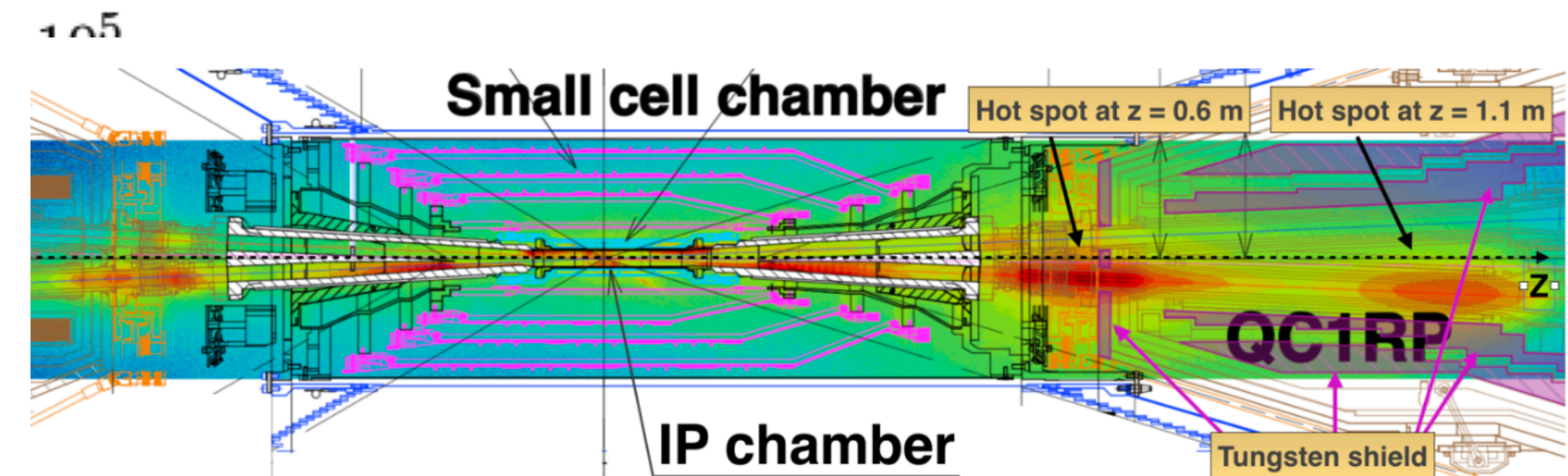
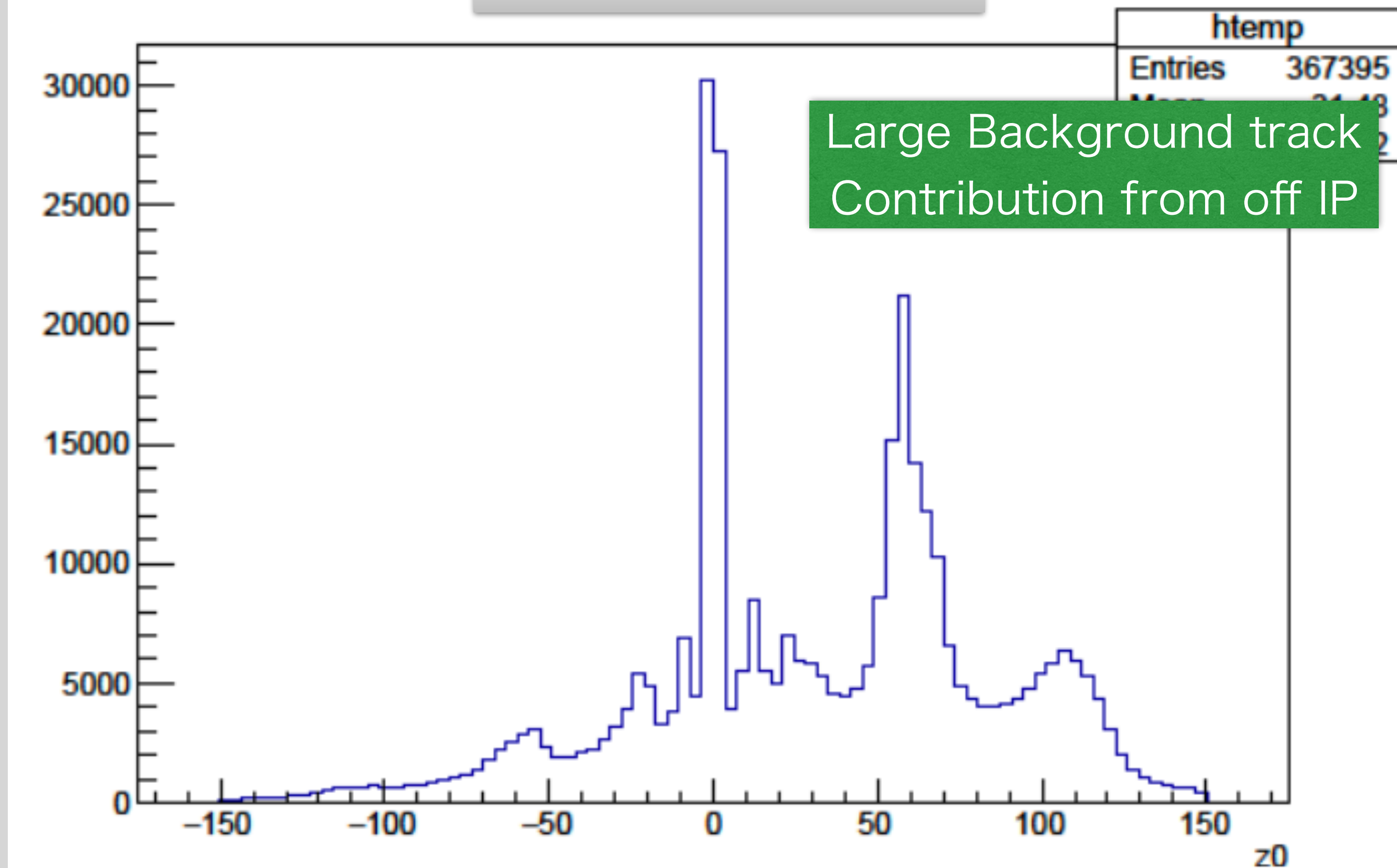


Single Track Trigger

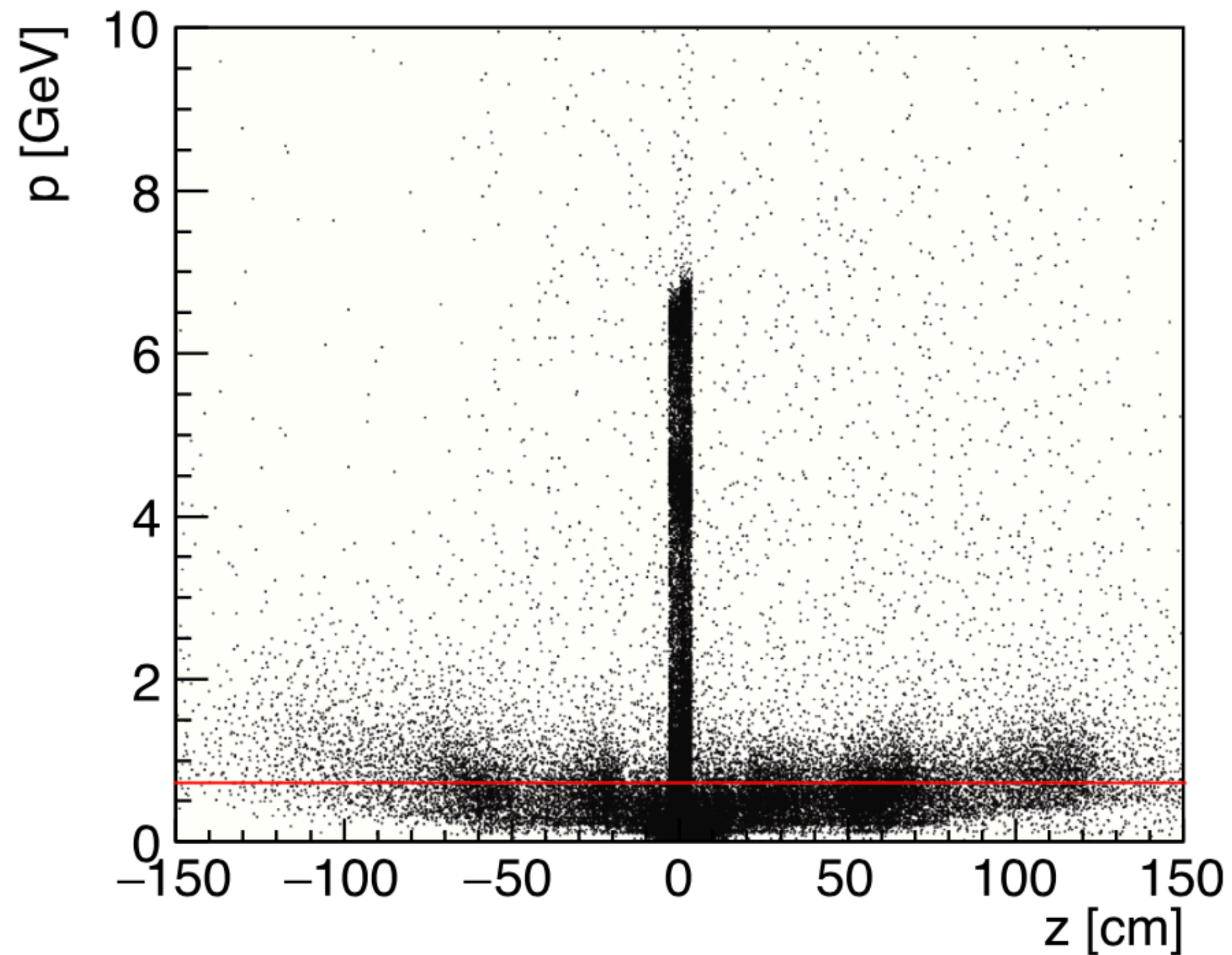
- Z-position and emission angle θ prediction with **Neural Network**
- Using 2D track from 2D track finder and stereo TS hits (priority wire hit timing)
- One hidden layer, 81 nodes
- Training in offline track analysis



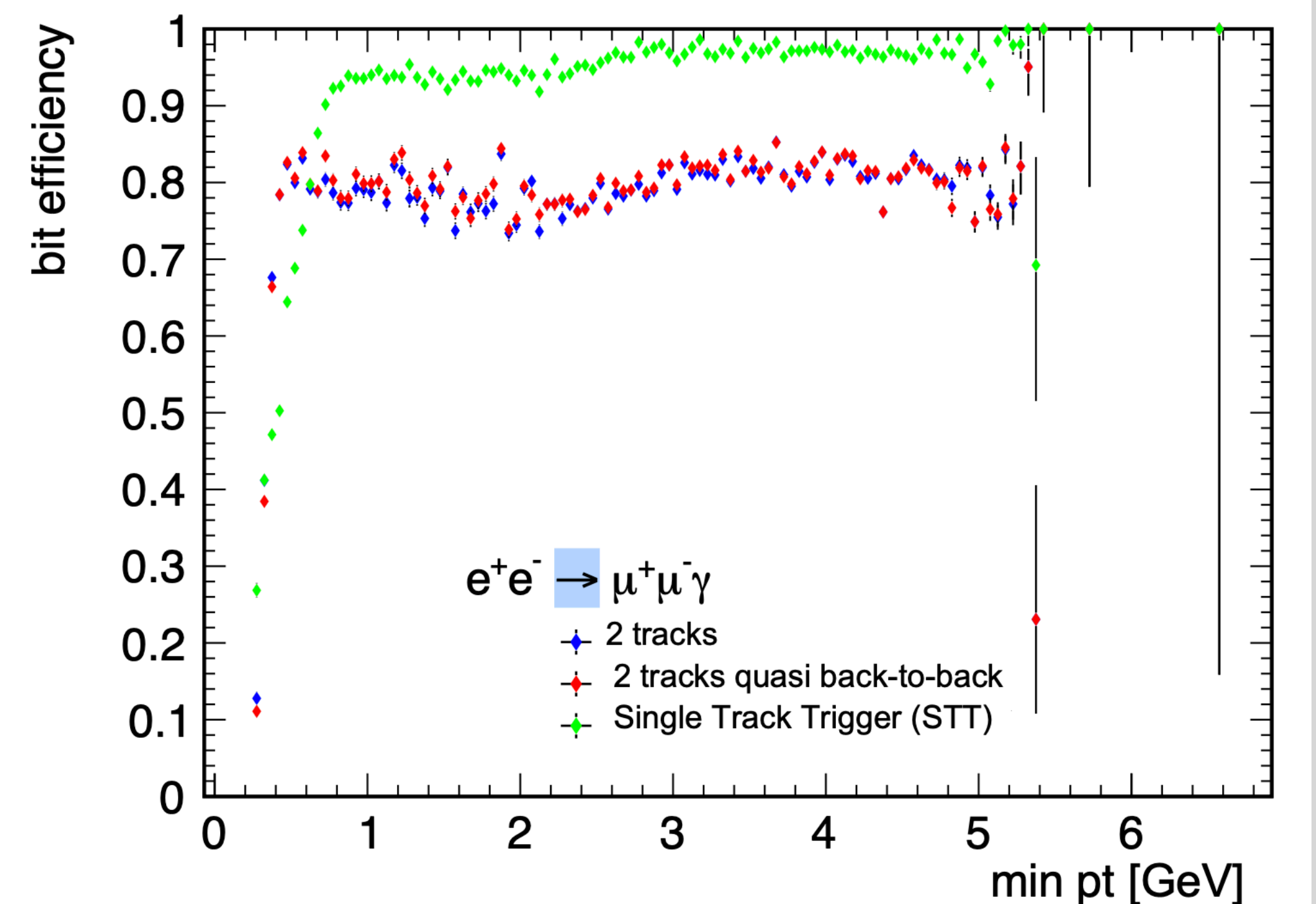
Offline z-vertex



Single Track Trigger



- QED and off IP background seen in $p < 0.7$ GeV/c
- Apply $|z| < 15$ cm
- Provides 2 trigger bits
 - At least one NN track, “y”. Associated with 2 or 3 trk bits.
 - At least one NN track with $p > 0.7$ GeV/c, “stt”

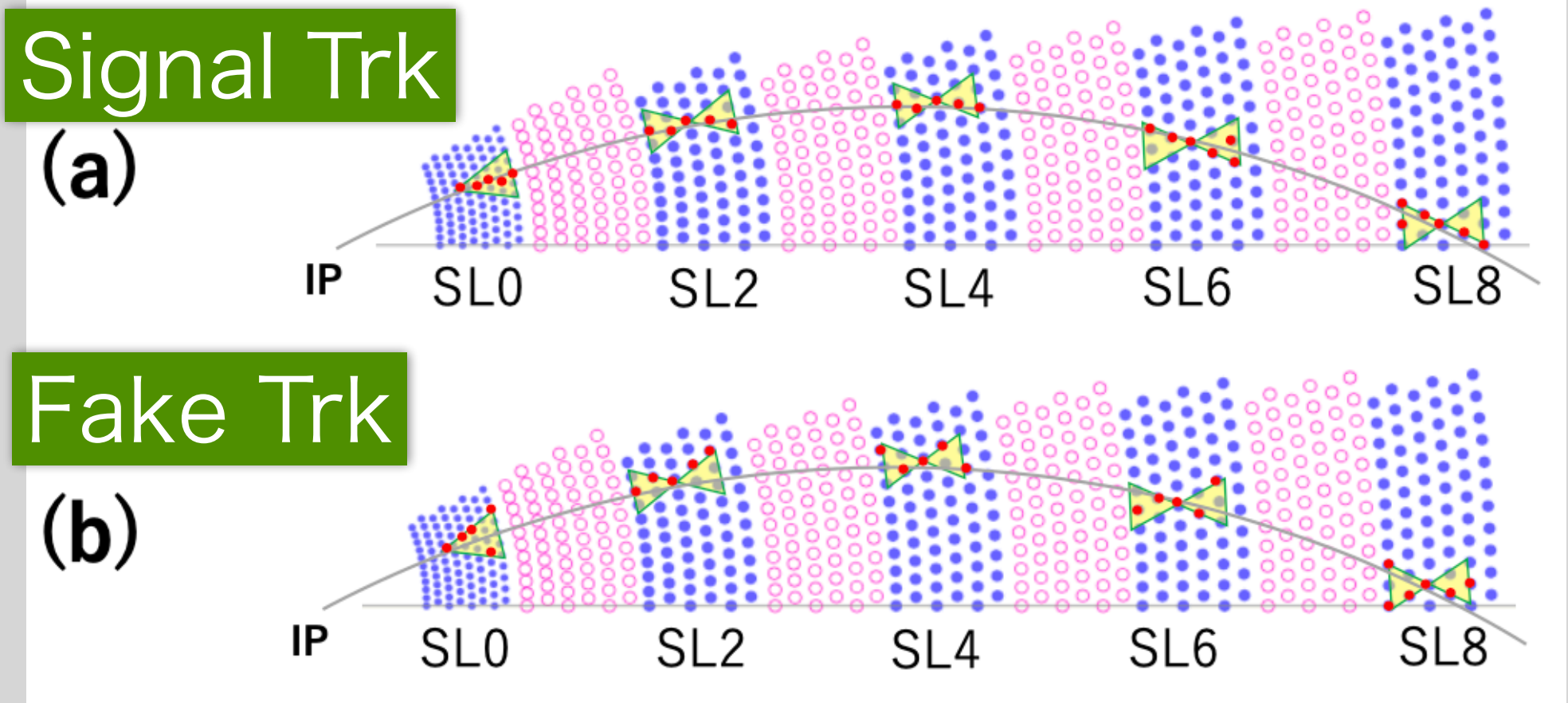


● Much better performance than 2D tracker

The first fully operating global L1 track trigger based on neural networks has been realized.

NIMA

Full hit algorithm: Upgraded 2D Finder



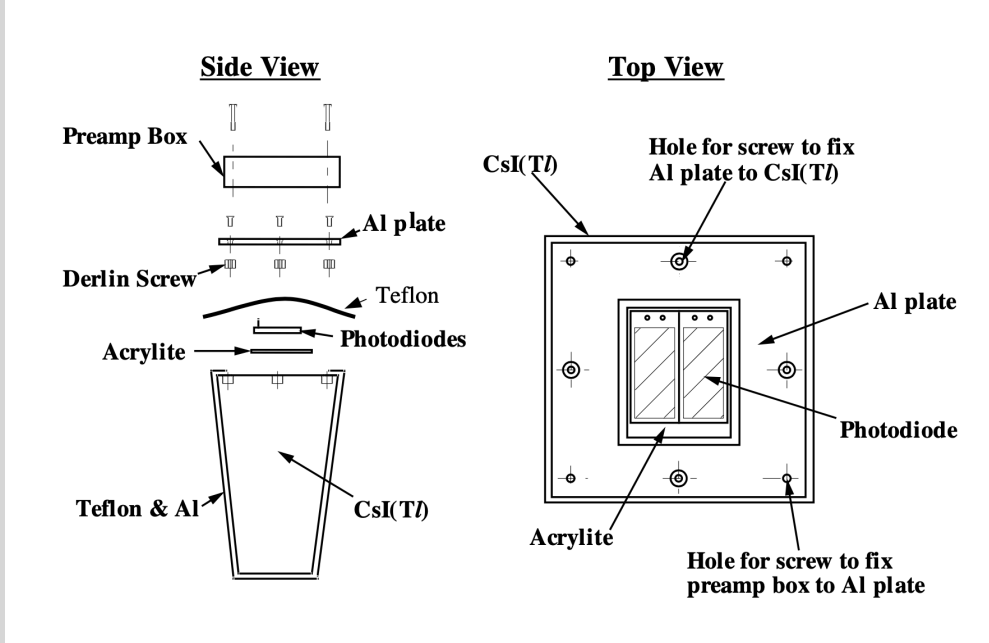
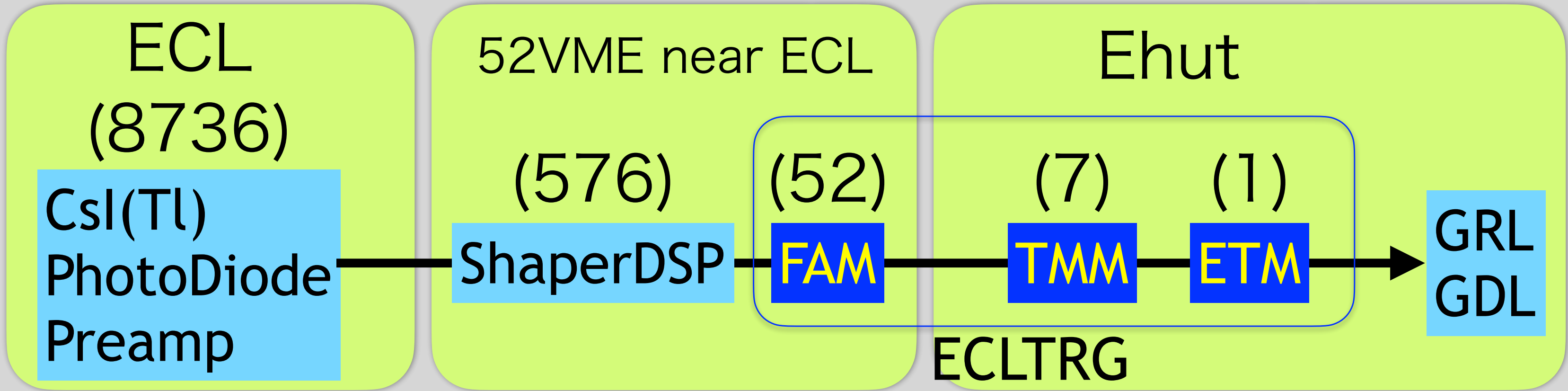
BG=2020

Table 5.2: Comparison between the trigger rates caused by fake tracks of the Full-Hit 2D and of the conventional 2D. The errors are statistical errors calculated by the Clopper-Pearson method.

BG level		trigger rate /kHz (full-hit 2D)	trigger rate (conventional 2D) /kHz
BGx10	4e35	$0.0^{+0.18}_{-0.0}$	$7.0^{+3.7}_{-2.6}$
BGx15	6e35	$0.0^{+0.18}_{-0.0}$	141^{+12}_{-11}
BGx20	8e35	$7.0^{+0.8}_{-0.9}$	695^{+15}_{-15}

- Wire hits of fake track are not aligned with the fake track but satisfies TS pattern matching
- Conventional 2D Track finder does not use hit pattern in TS but use only priority wire info
- Full-hit algorithm where all wire hit is used for track reconstruction allows us significant fake track reduction in future high BG

ECLTRG



➊ Analog sum of 16 crystals taken on FAM to reduce granularity for coarse online analysis with limited time and resources

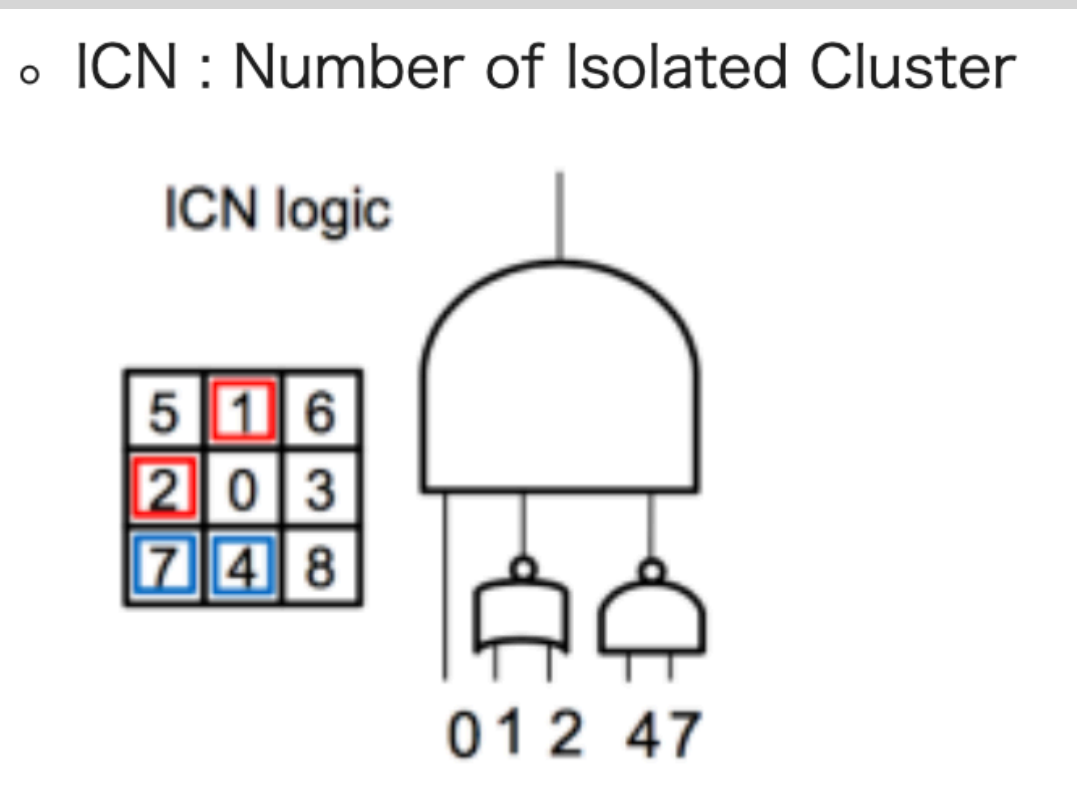
=> TC (Trigger cell)

➋ TMM merges TC info

➌ ETM reconstruct cluster

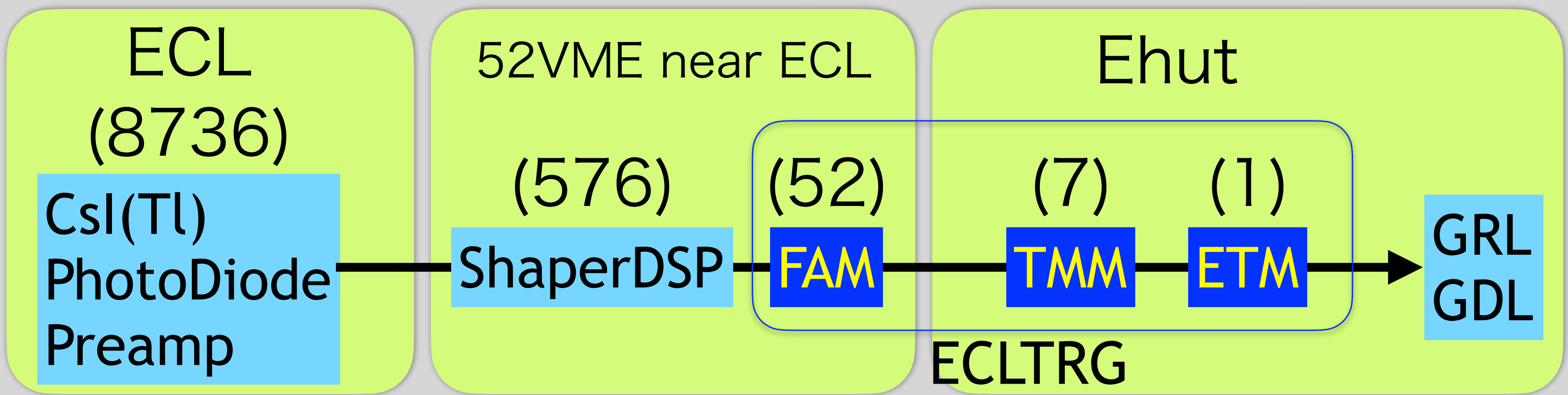
➍ #cluster, Esum, Bhabha, Timing to GDL

➎ TC info (timing/geometry/energy) to GRL



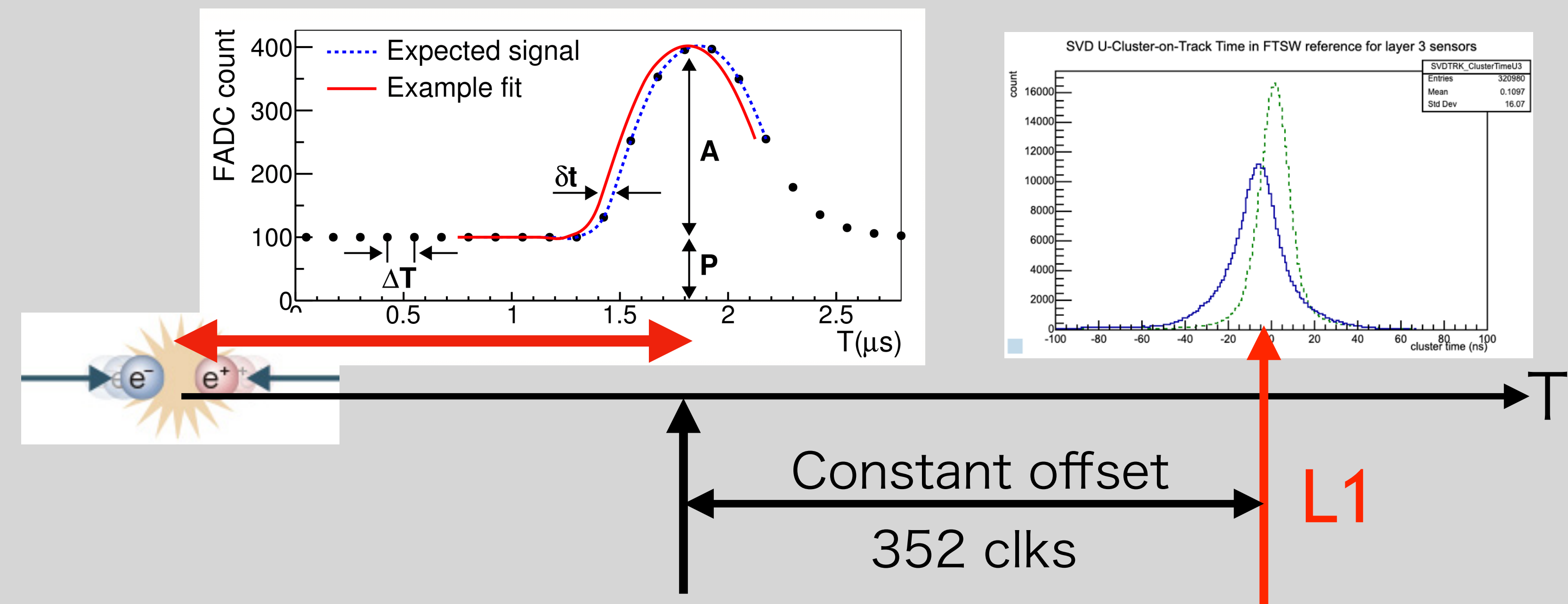
- ➊ Algorithm of clustering for position
- ➋ Timing determined with the central TC
- ➌ Energy of the Cluster is sum of 9 TCs

ECLTRG



- ① Fit energy (ADC) distribution to determine the deposited energy and hit timing of the TC signals
- ② Timestamp of the peak (latency since collision) is obtained by template fit
- ③ Timestamp of the most energetic TC is sent to GDL
- ④ GDL generate L1 signal after constant offset studied beforehand if physics event is detected

Timing Signal Generation on FAM



timestamp:
counter in 0,...,1279 with 127 MHz sysclk
10 usec cycle, one beam revolution

TOPTRG/KLMTRG

● TOPTRG

- 2 nsec precision MCPPMT hits in 16 modules sent from FEE to TOPTRG
- Template fit for each 16 module and geometrical info sent to GRL where matching is taken with CDCTRG
- Timing resolution of 10 nsec achieved
 - Filtered with CDCTRG through matching

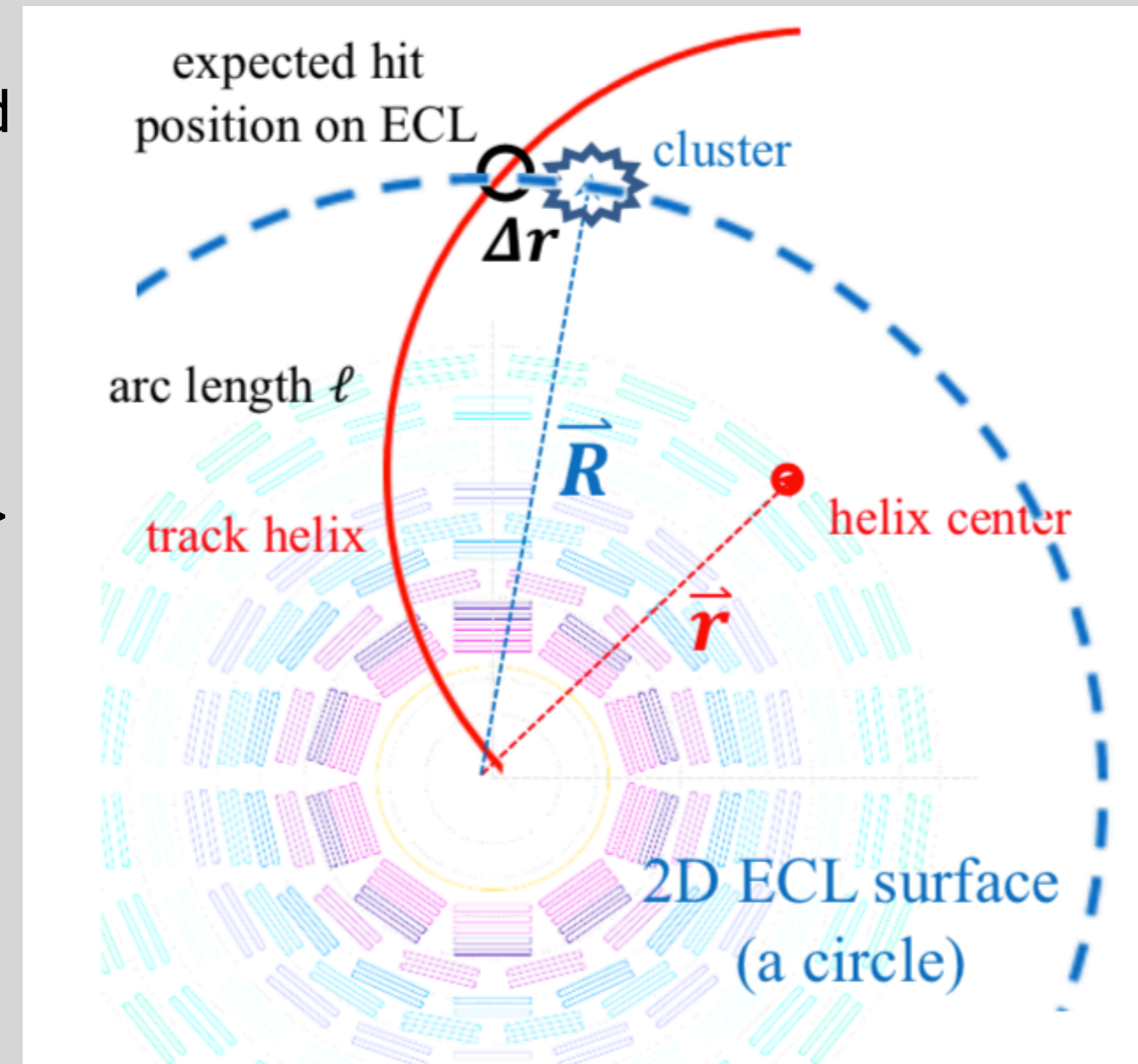
● KLMTRG

- Layer-Counting Trigger (LCT) algorithm
- Sector-based counting. Fired if $\#count > 8$.



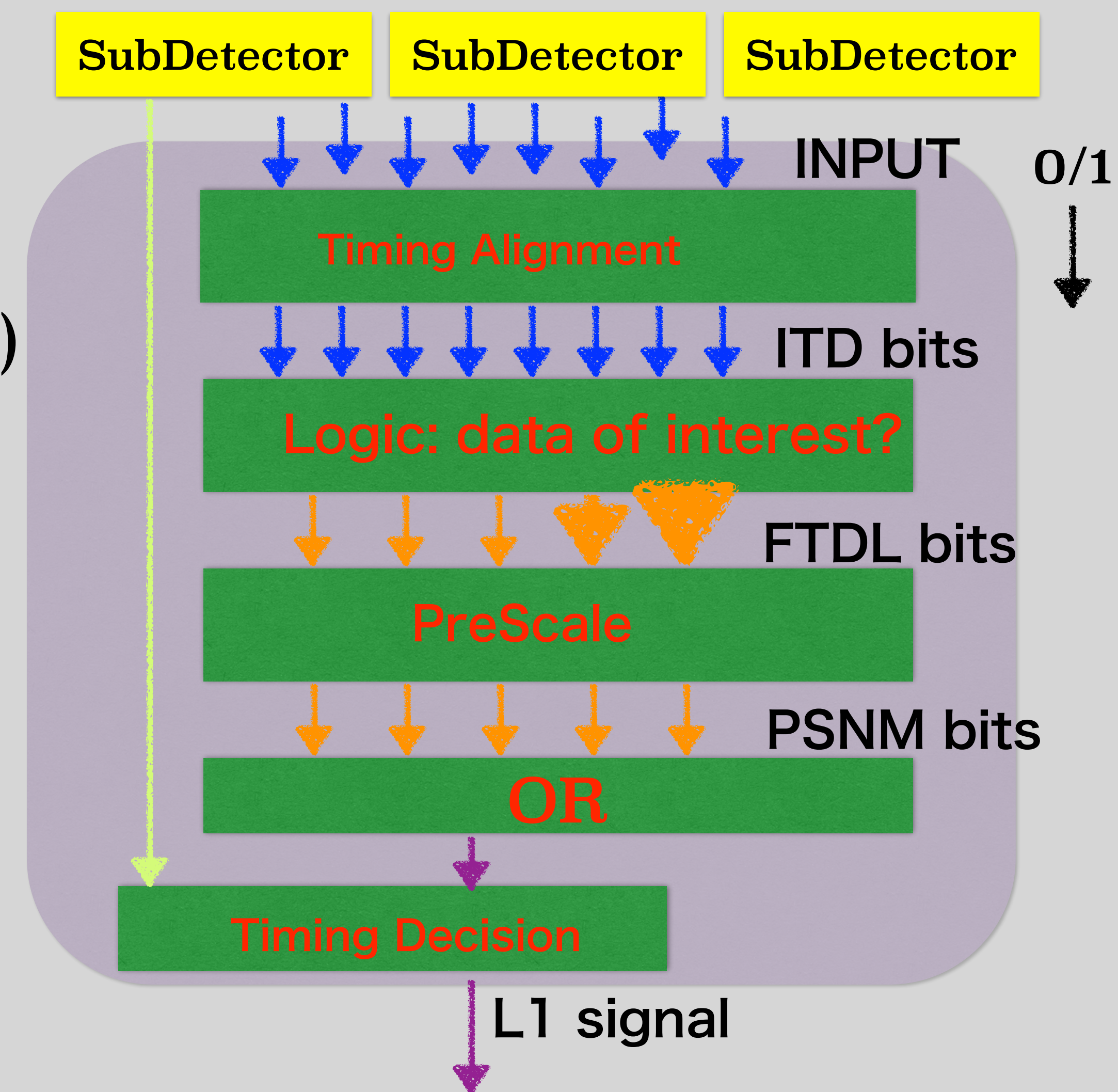
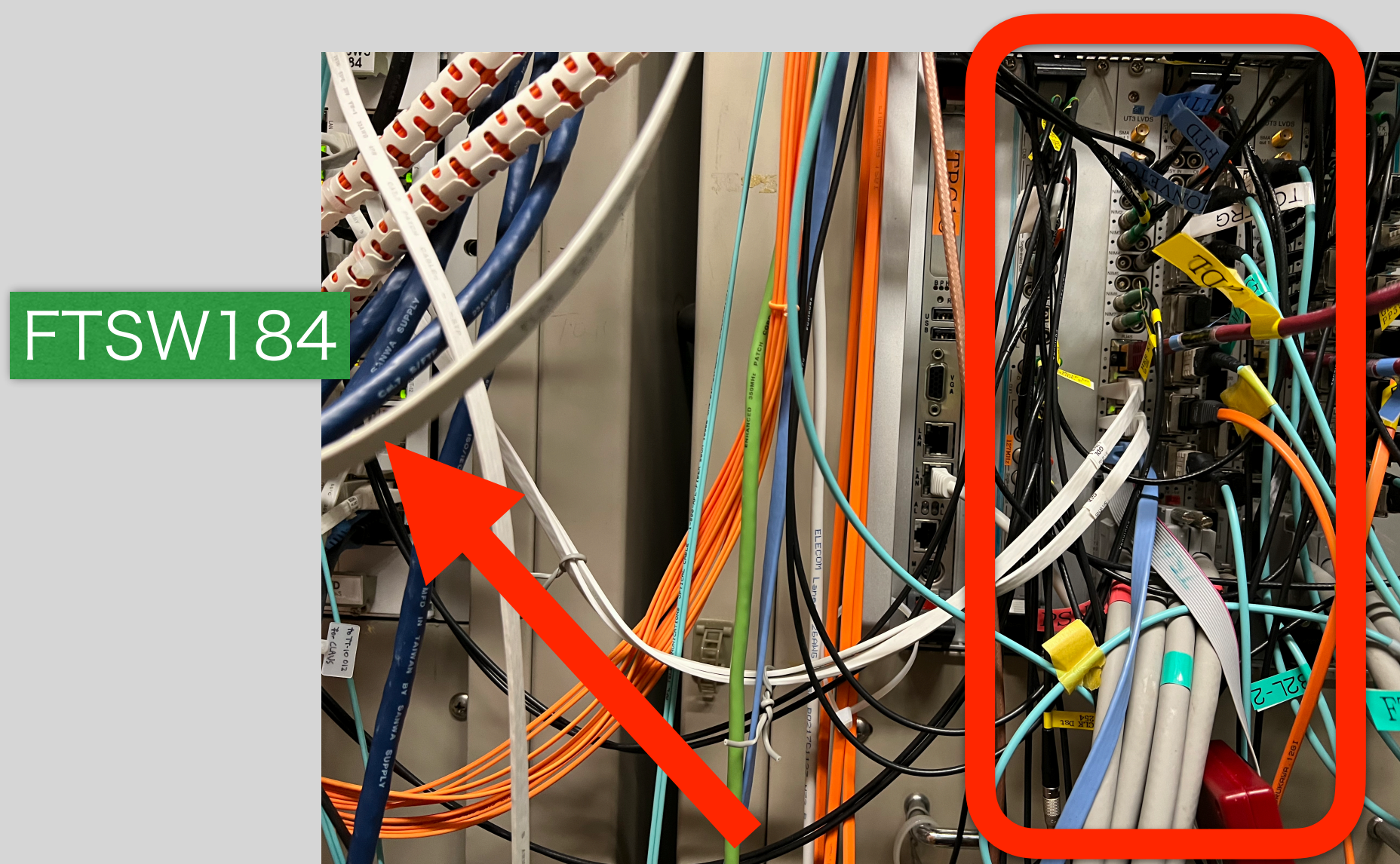
GRL (Global Reconstruction Logic)

- Receives particle level information from subtriggers and take coincidence of the particle in different subtriggers.
 - Trk-Clster, Trk-KLMTRG hit, Trk-TOP
- Latency is tight. LVDS (serial) connection used for GRL -> GDL.
- Generates short track



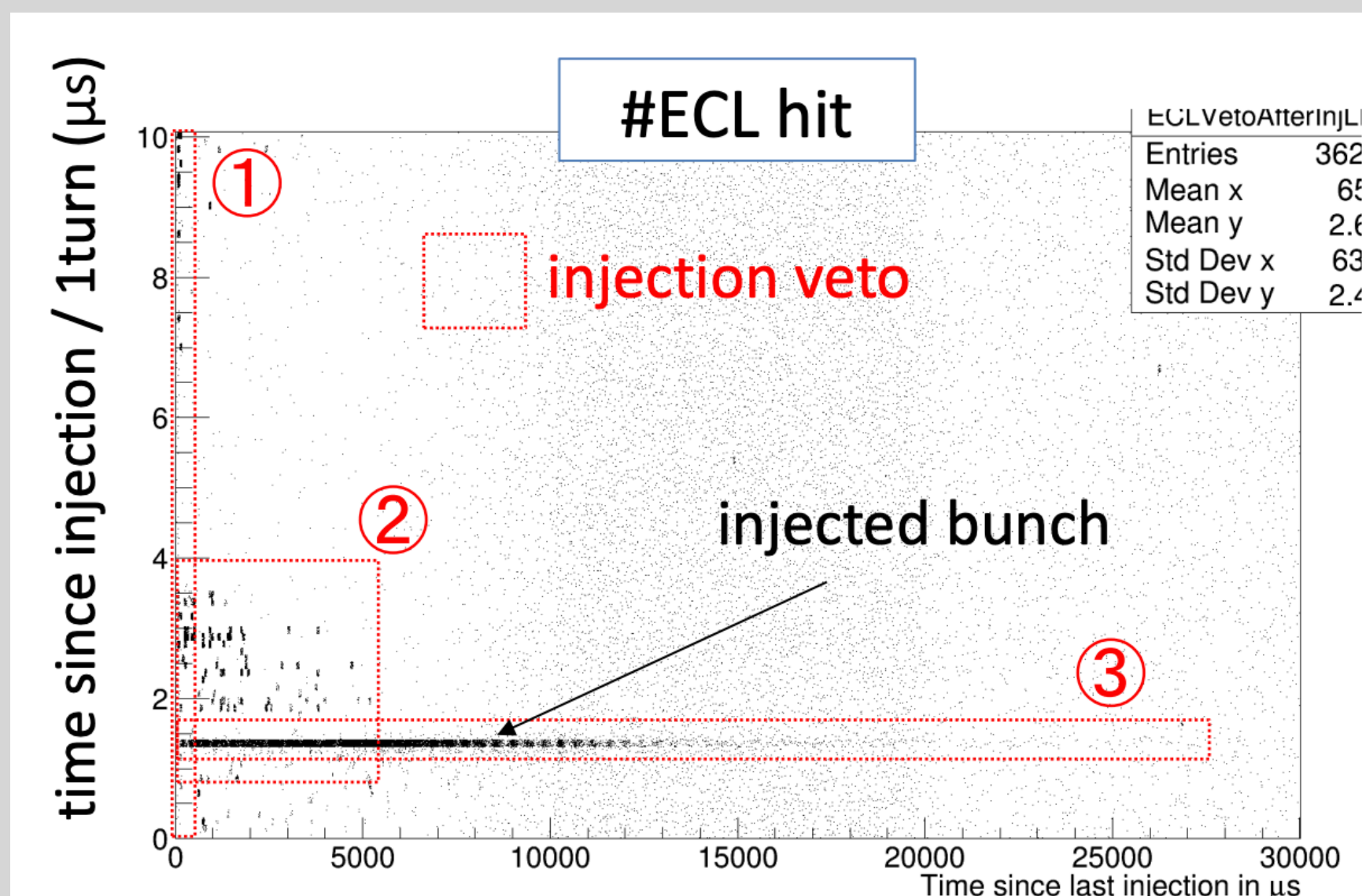
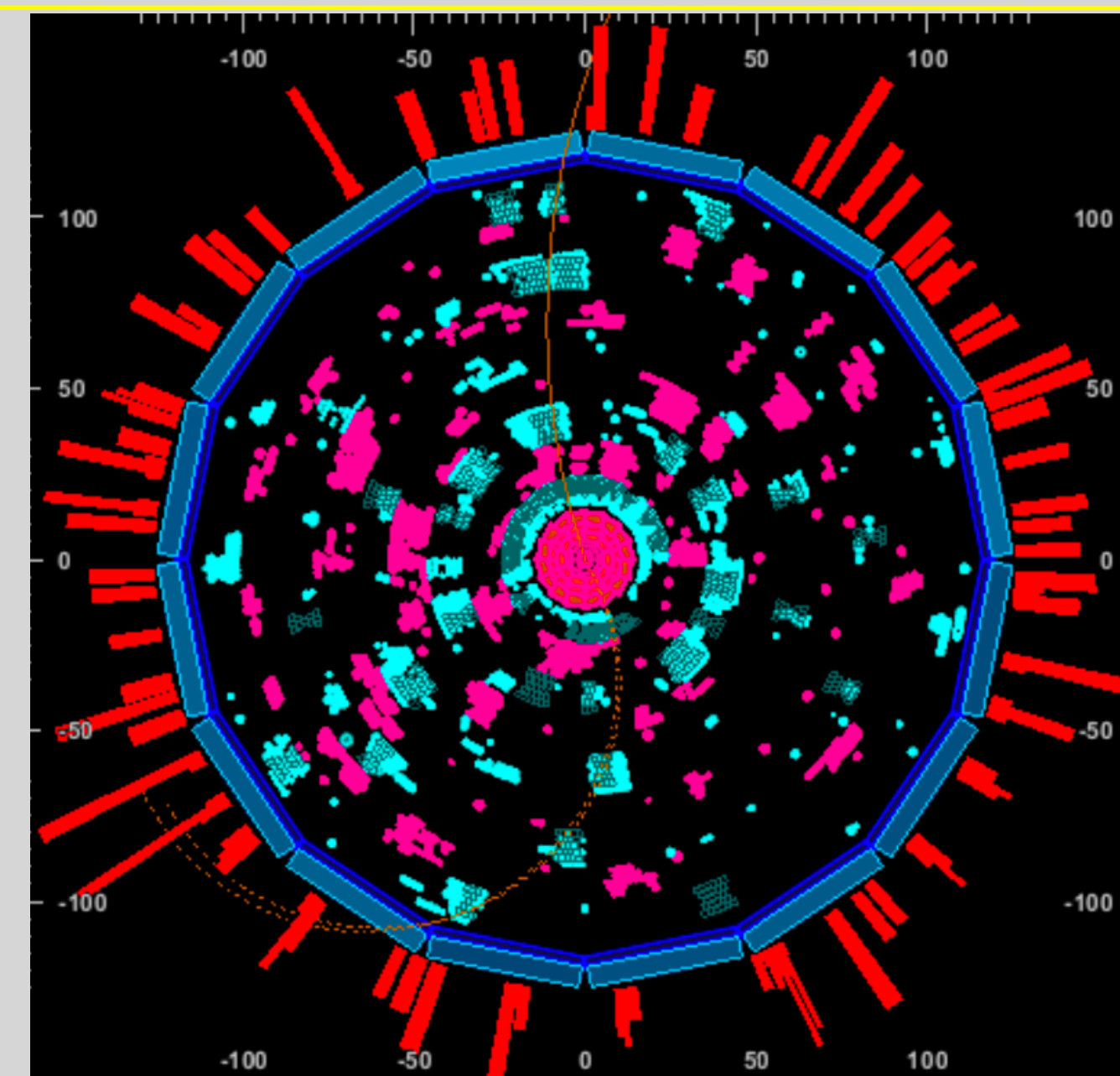
GDL (Global Decision Logic)

- Summary module of L1 system
- Implemented on a UT4
- Issues L1 signal to FTSW (Timing Distribution)



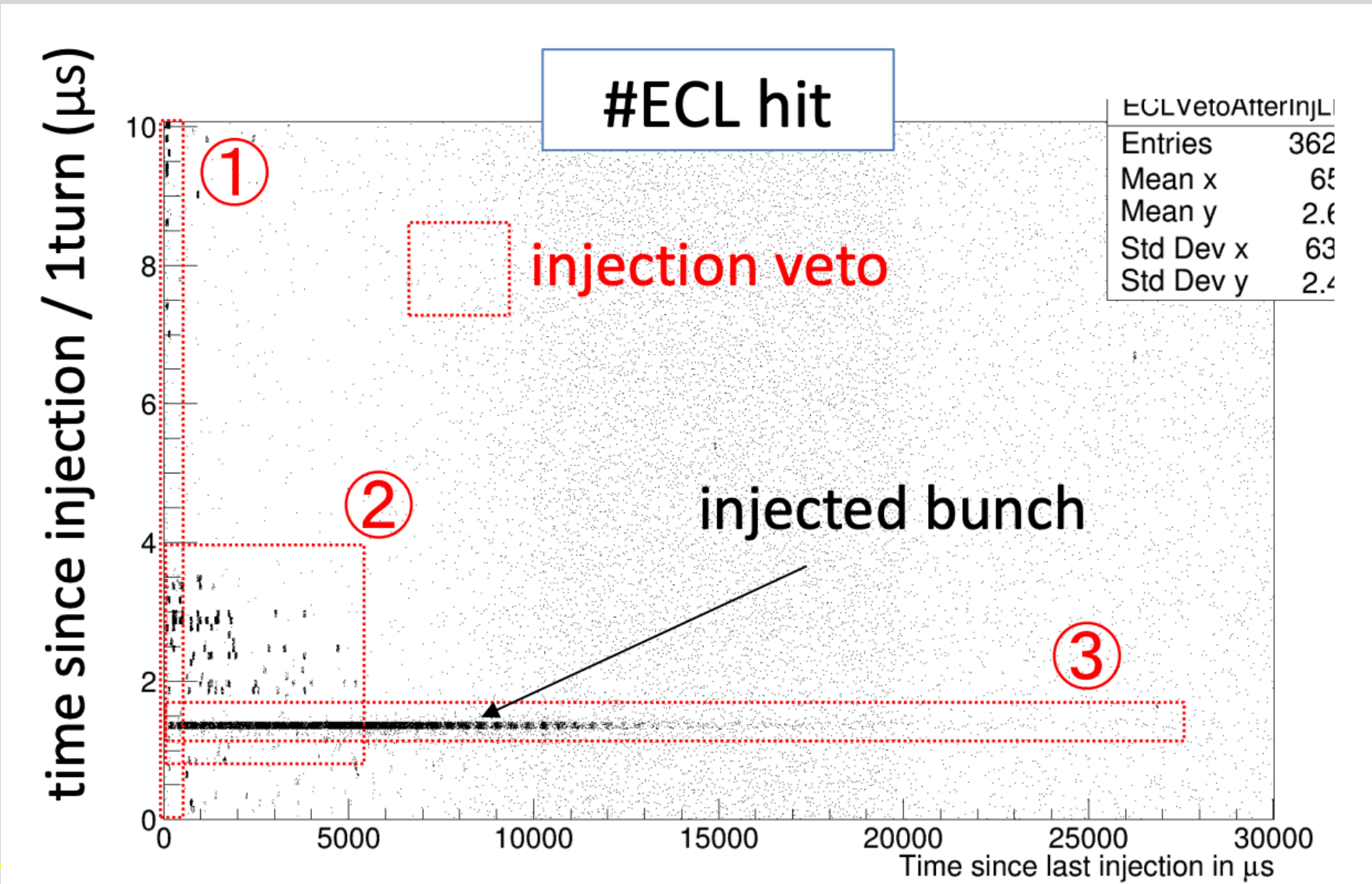
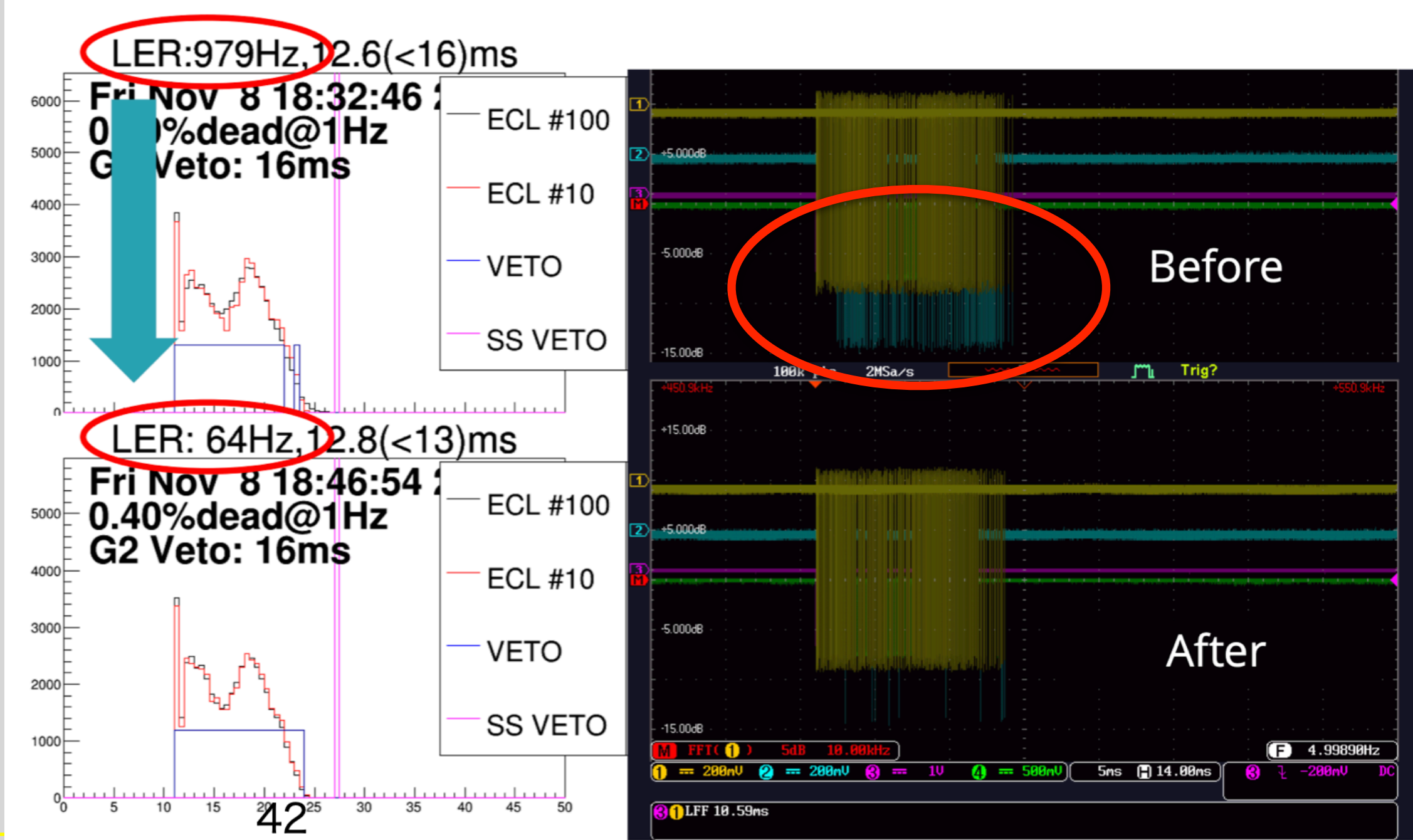
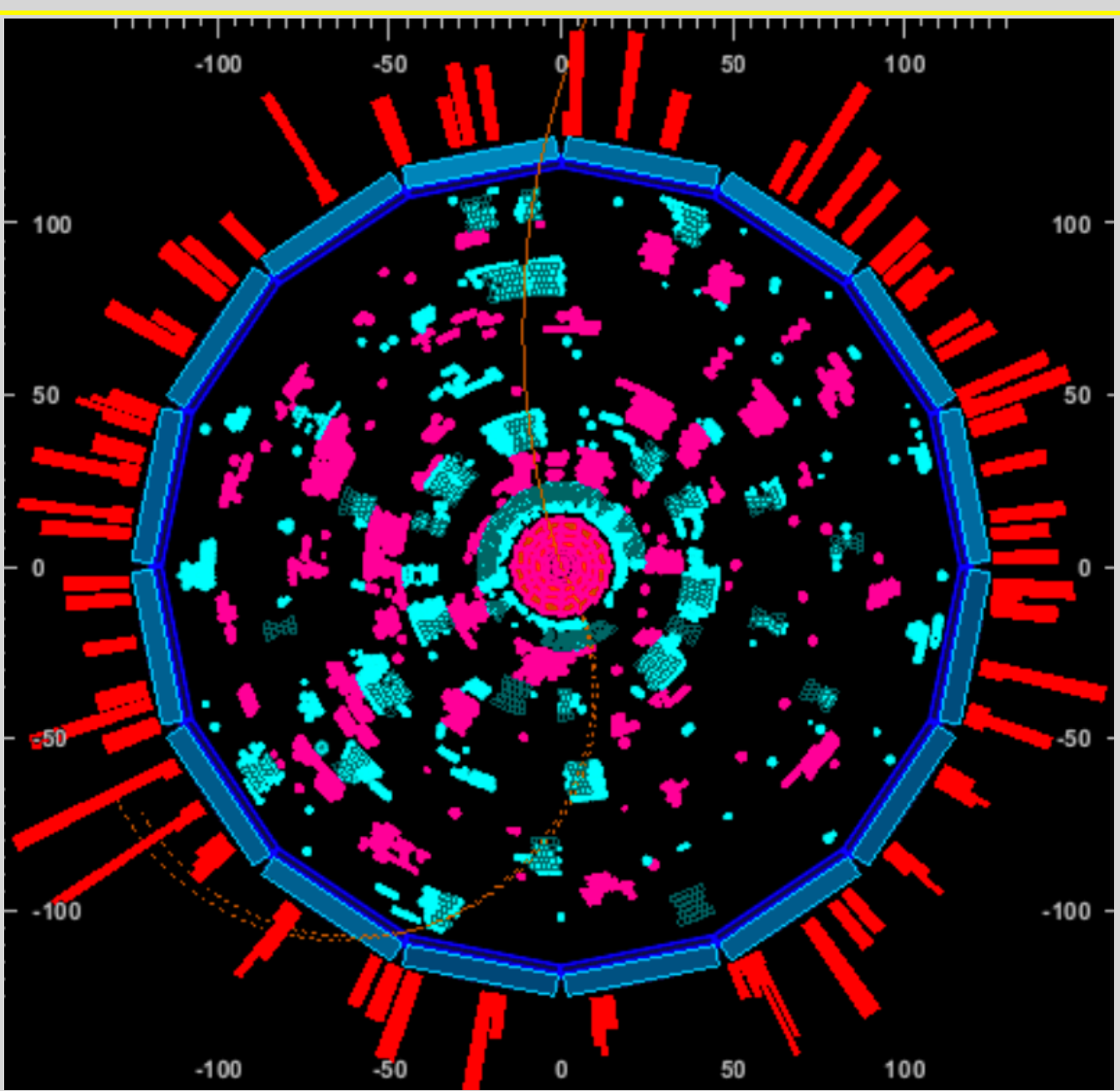
Injection veto

- To Keep beam current, Beam injection is made even during data taking
- Background level surges for short period after injection. We must not take data.
- Injection rate 25 Hz at most. Injection background disappears by the next injection.
- L1 applies veto in the period applying “& !veto” in logic
- Full veto
- Gate veto1: wider time window around injected bunch
- Gate veto1: narrower time window around injected bunch
- SKB provides GDL injection kicker signal through NIM cable
- Time window size and length are adjusted automatically based on data in the past 15 mins and updated at the next run



Injection veto: active injection veto

- Injection veto causes large dead time
 - => Even in veto-period of ①-③, take data (issue L1 signal) if #TC hit and #wire hit is lower than threshold to reduce dead time
- Injection veto is severe in Endcap region, we set partwise threshold for #TC. Leakage of injection background events disappear.



Input Triggers

	nbits	name	
CDC	4	n_ty	#of NN tracks
	4	n_t2	#of 2D tracks
	1	cdc_bb	back-to-back topology
	1	cdc_open90	opening angle
	1	cdc_timing	timing signal
	1	typ	Single Track
ECL	1	e_high	1 GeV or more
	1	e_low	0.5 GeV or more
	1	ecl_3dbha	Bhabha event
	4	n_clus	# of cluster
	1	ecl_timing	timing signal
	1	ecl_lml_1	Single Cluster >2GeV in Brl
	14	ecl_lml_X	Low Multiplicity Analysis

Input Triggers

	nbits	name	
TOP	1	top_timing	Top Timing
KLM	3	n_klm	# of klm hits
	1	klmb2b	Back-to-Back in Brl
	1	eklmb2b	Back-to-Back in Ecp
Random	1	revo	Beam Revolution
	2	rand	Poisson
	3	bhabha_delay	Background overlay data
GRL	4	cdcecl_X	CDC-ECL matching
	2	cdcklm_X	CDC-KLM matching
	1	ecleklm	ECL-EKLM matching

Trigger Outputs: Logic

Output bit		PS	Logic = algorithm
stt	Single track	1	<code>typ & !bha_veto</code>
lml1	1 Cluster	1	<code>ecl_lml_1</code>
ffy	hadron	1	<code>t2 > 2 & ty > 0</code>
fyo	2 track	1	<code>t2 > 1 & cdc_open90 & ty > 0 & !bha_veto</code>
hie	1 GeV	1	<code>e_high & !bha_veto</code>
c4	4 clusters	1	<code>n_clus > 3</code>
Bha3d	Bhabha	100	<code>ecl_3dbha</code>
ggse1	$ee \rightarrow \gamma \gamma$	1	<code>ecl_3dbha & (!trkbha1 & !trkbha2) & bha_intrk</code>
mu_b2b	mu pair	1	<code>klmb2b</code>
revolution	random	1	<code>revo</code>
random		1	<code>rand</code>
bg		1	<code>bhabha_delay</code>

Injection veto applied, “ & !veto”, to all bits

Trigger Efficiency from experiment data

- Experiment data is survival biased.
- Mask with orthogonal trigger, Track $\Leftrightarrow$ Energy.

Energy Trigger Efficiency
With Track mask

$$= \frac{\text{Energy \& Track}}{\text{Track}}$$

Signal Events

Energy Trigger

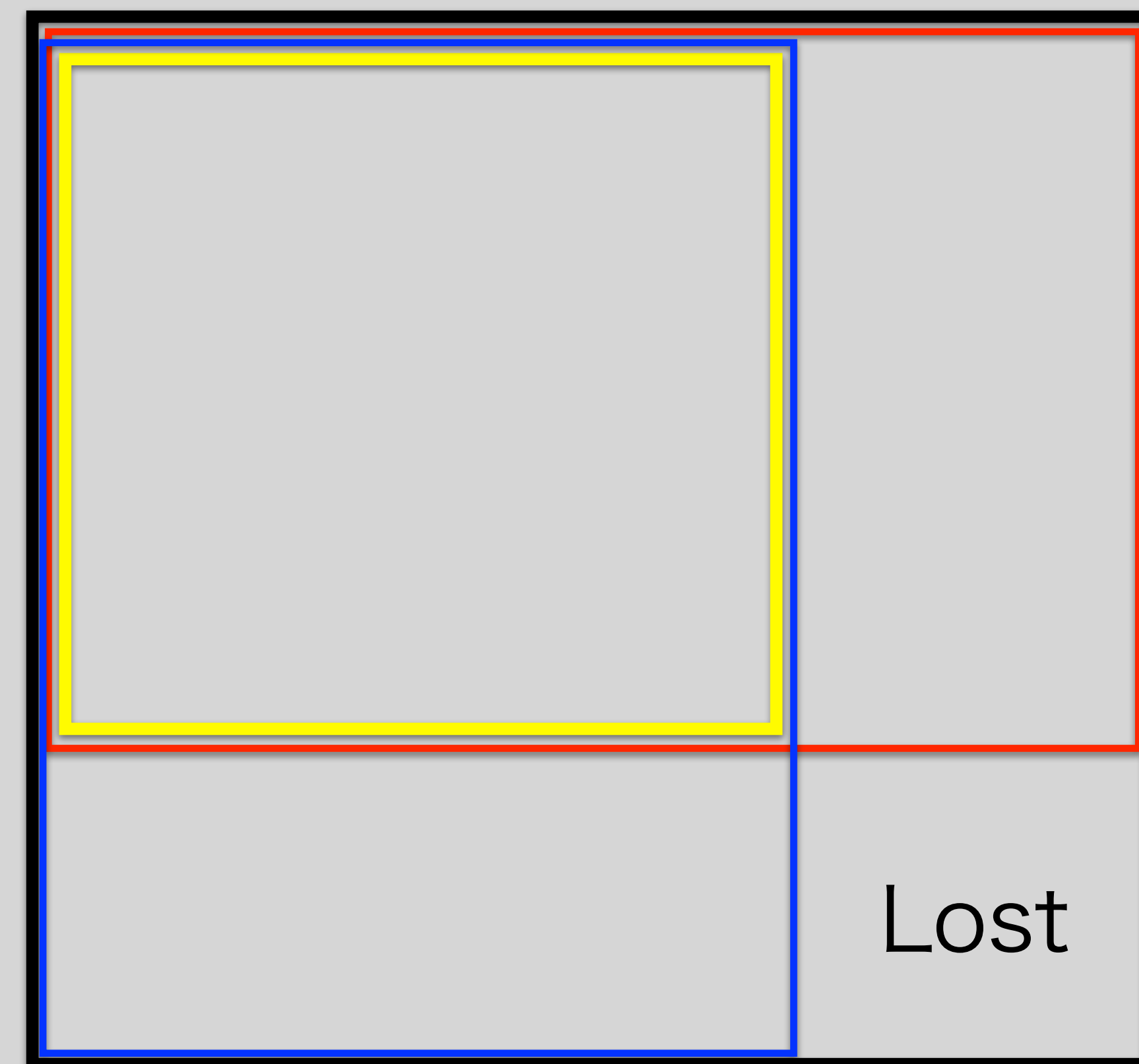
fired

Not

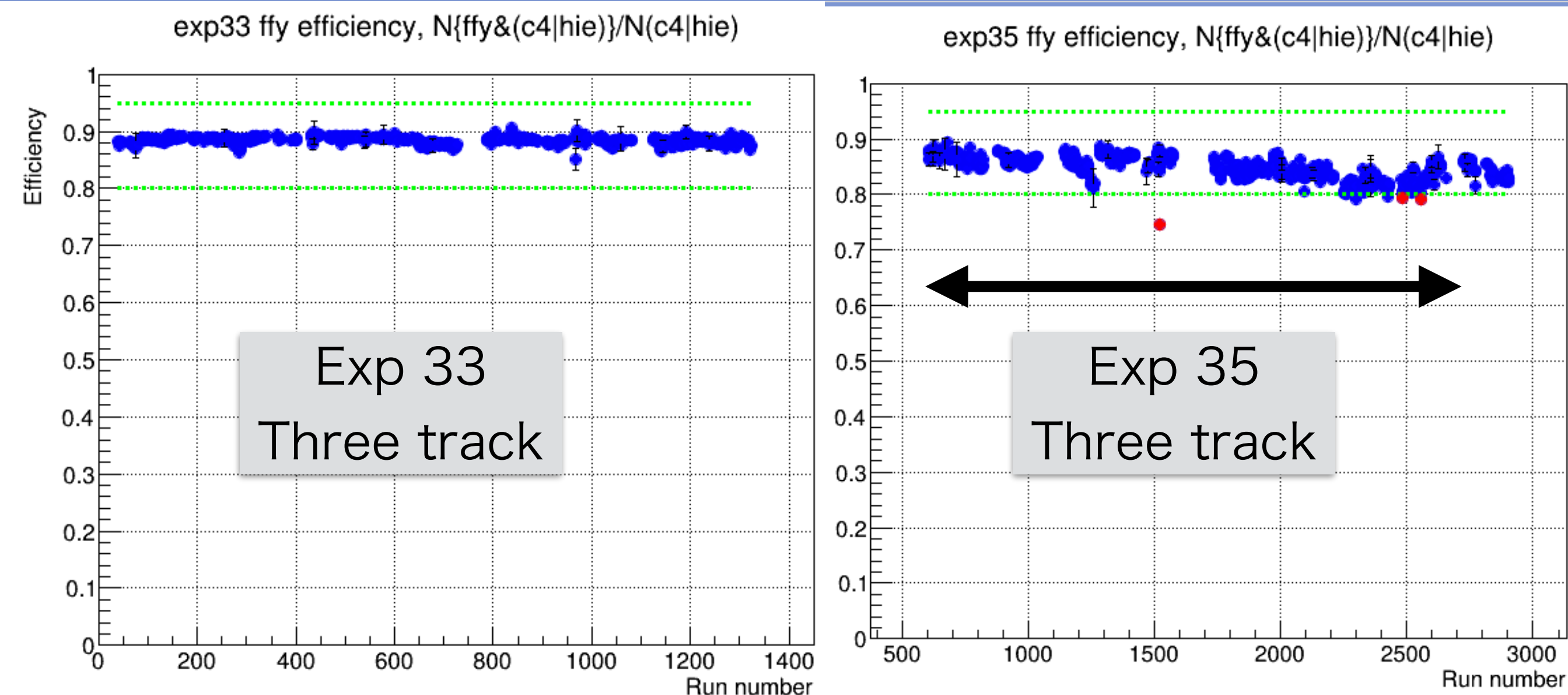
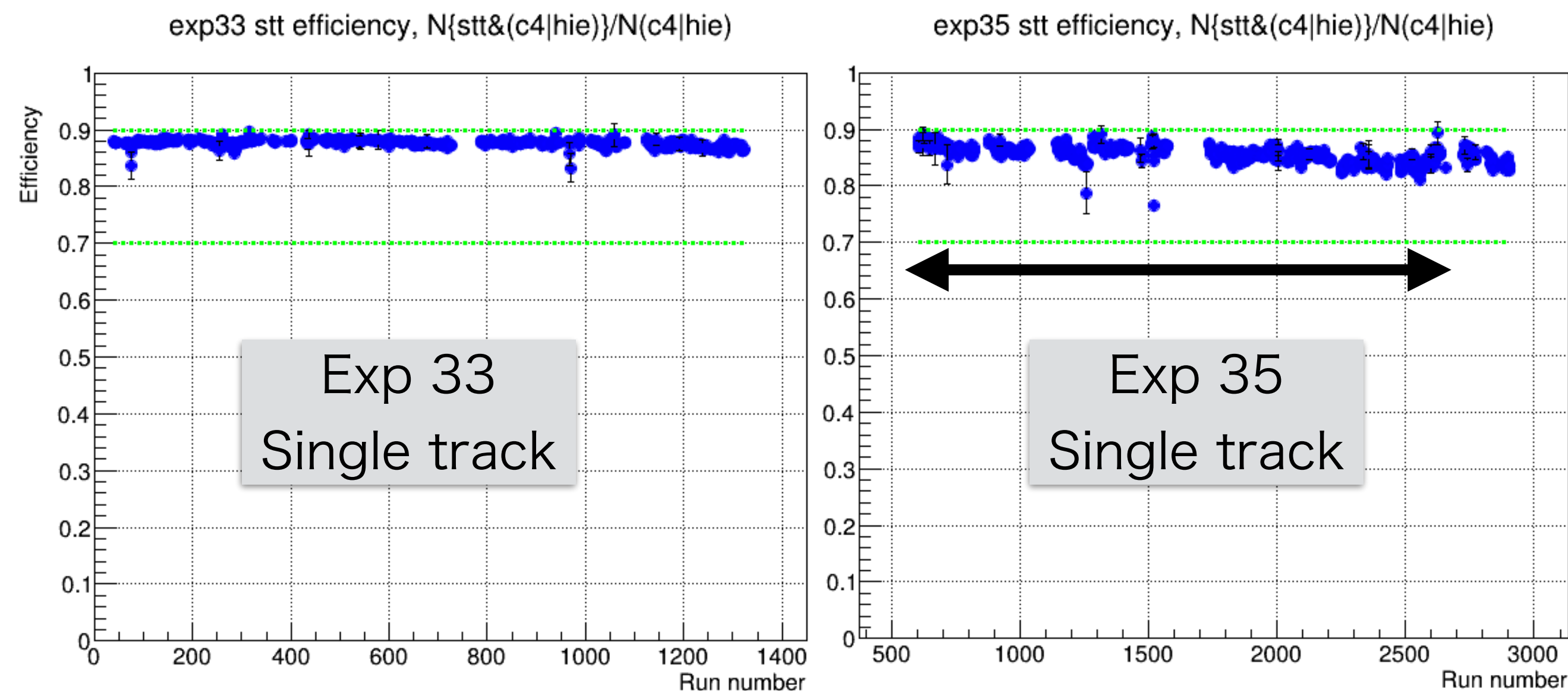
Track Trigger

fired

Not

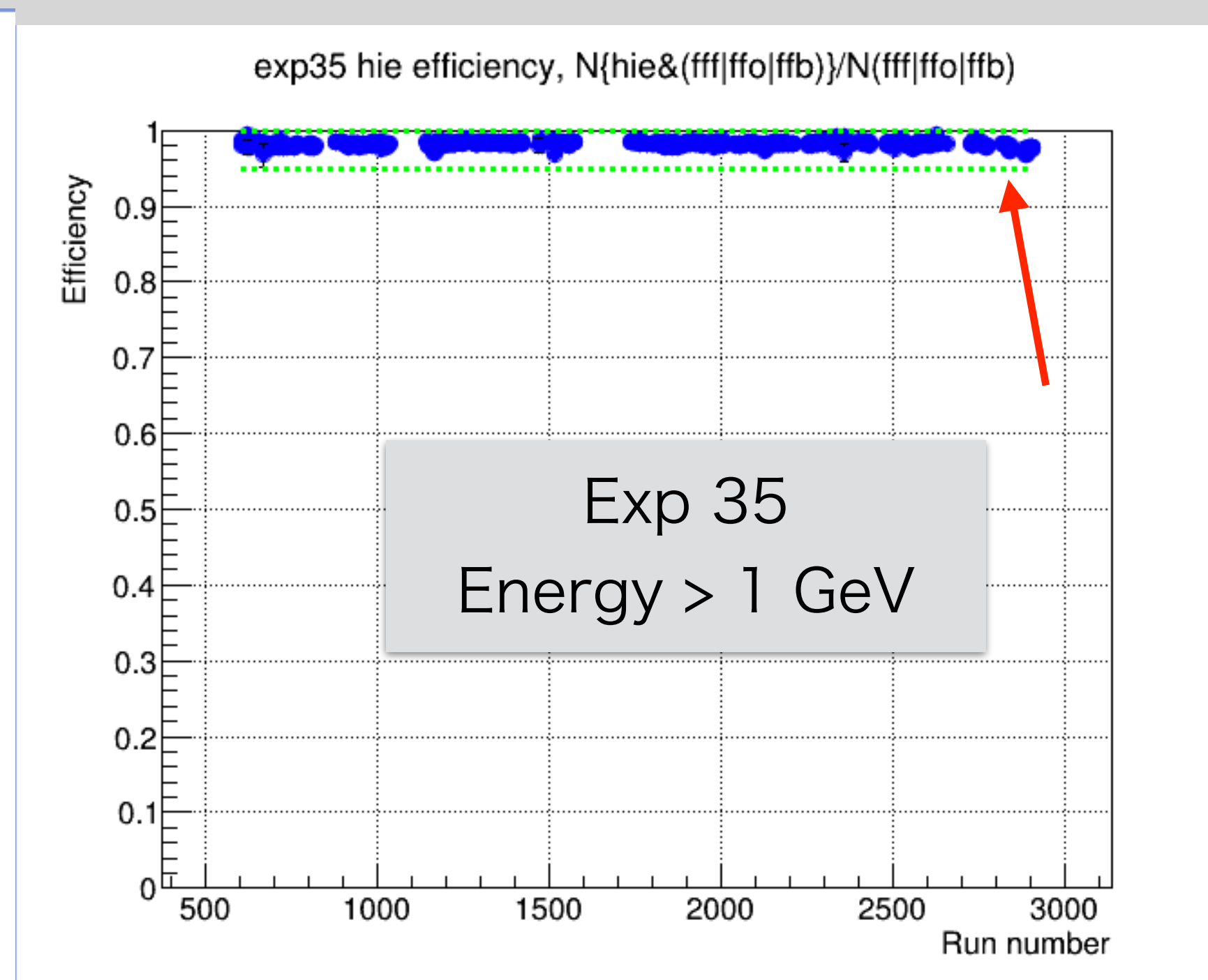
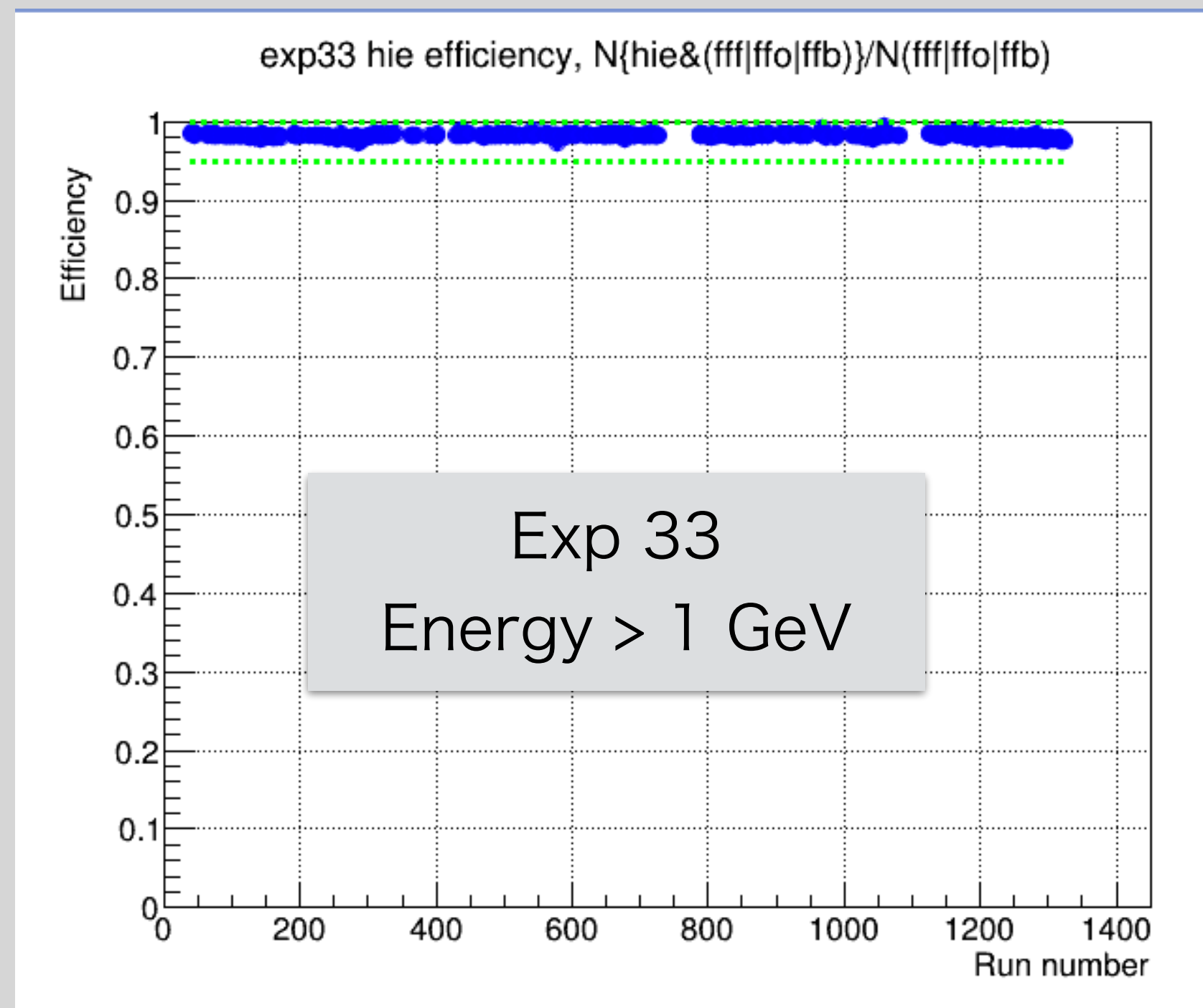


Trigger Efficiency for hadron events: CDCTRG



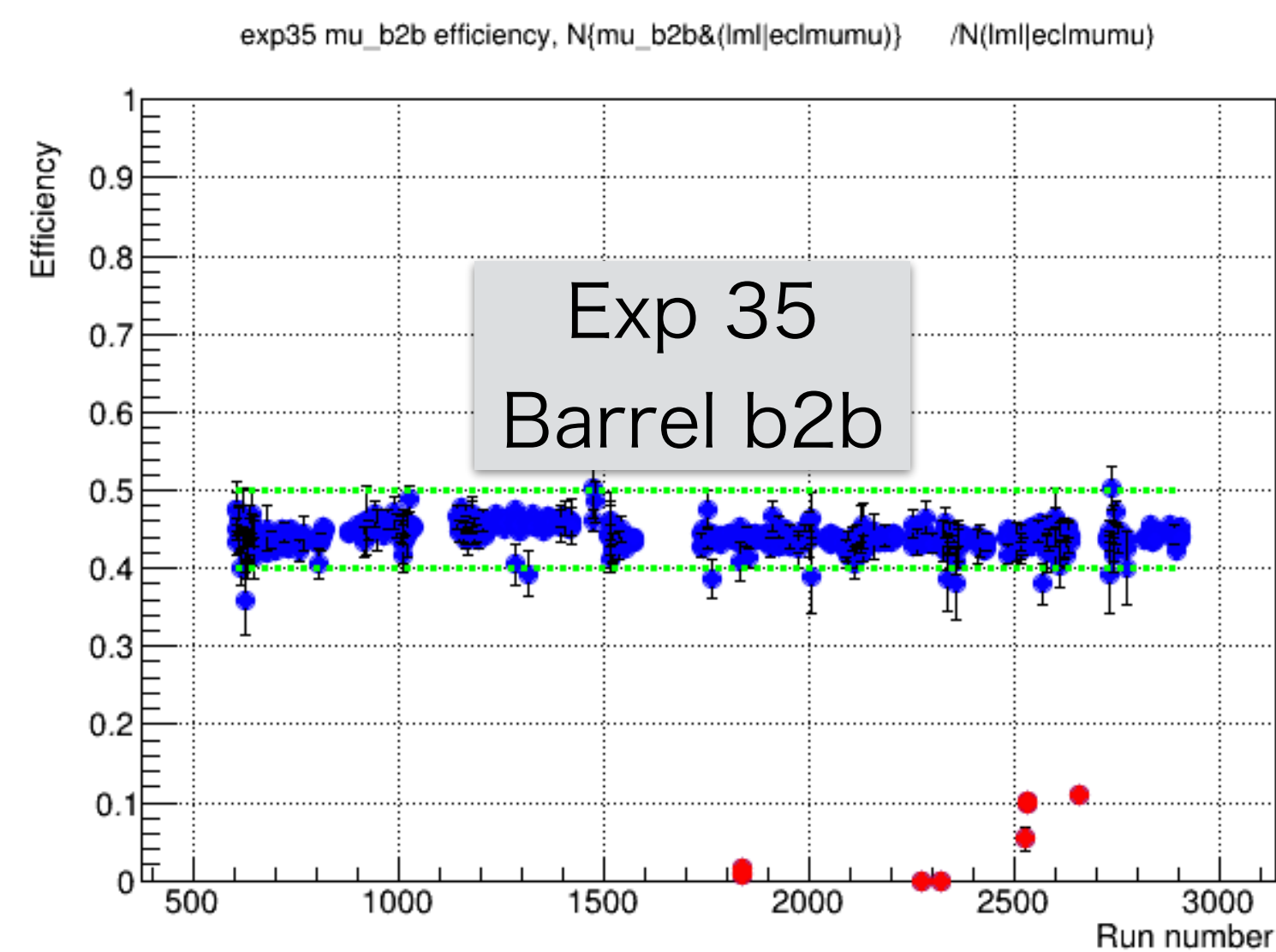
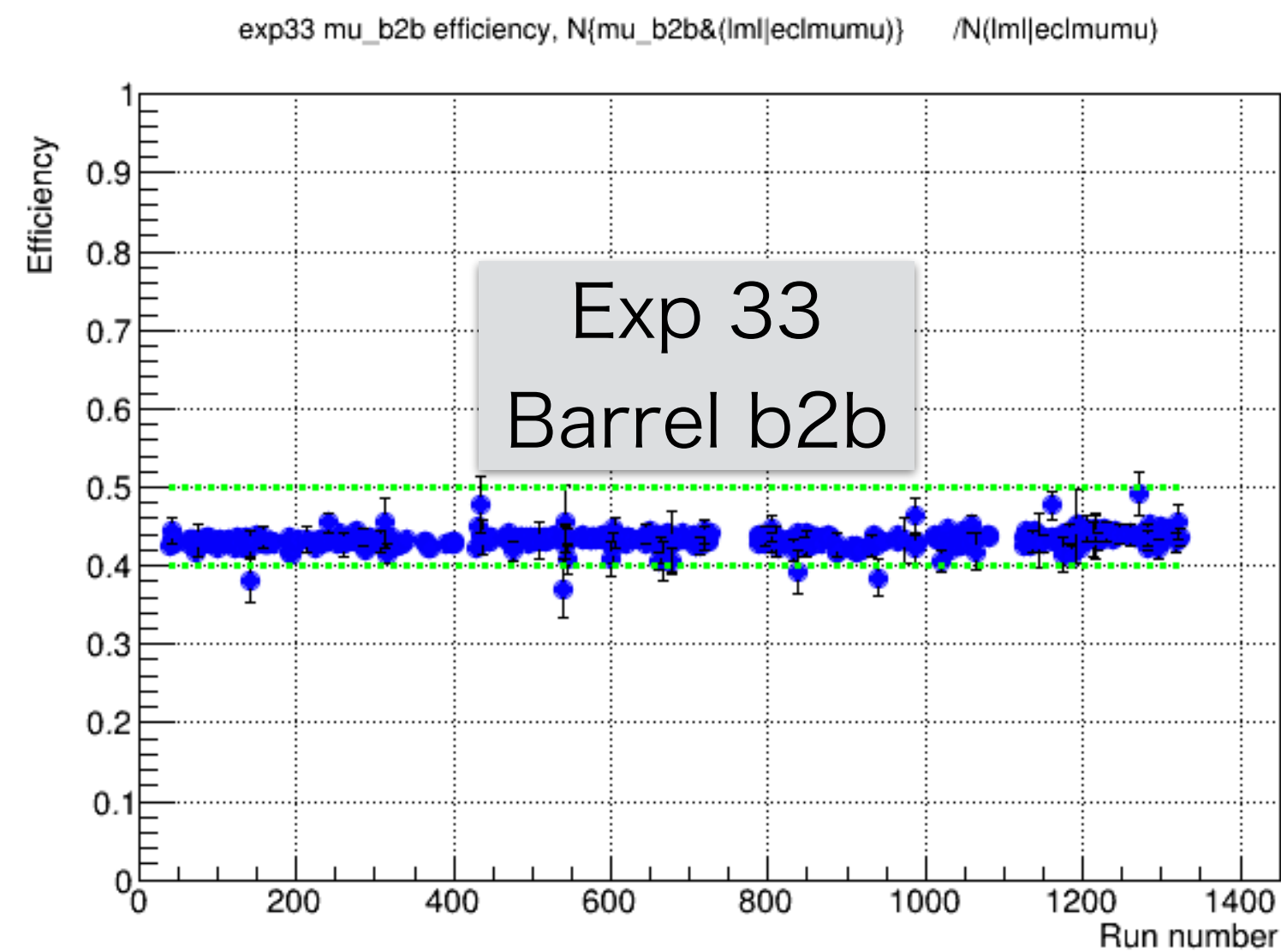
- Efficiency slightly decreased in 2024bc
- Reason unknown but can be due to masked merger or CDC Gas
- Various triggers complement each other. Total inefficiency, $(1-\epsilon_1)(1-\epsilon_2)(1-\epsilon_3)(1-\epsilon_4)\dots$ is negligibly small for hadron events.

Trigger efficiency for hadron events: ECLTRG



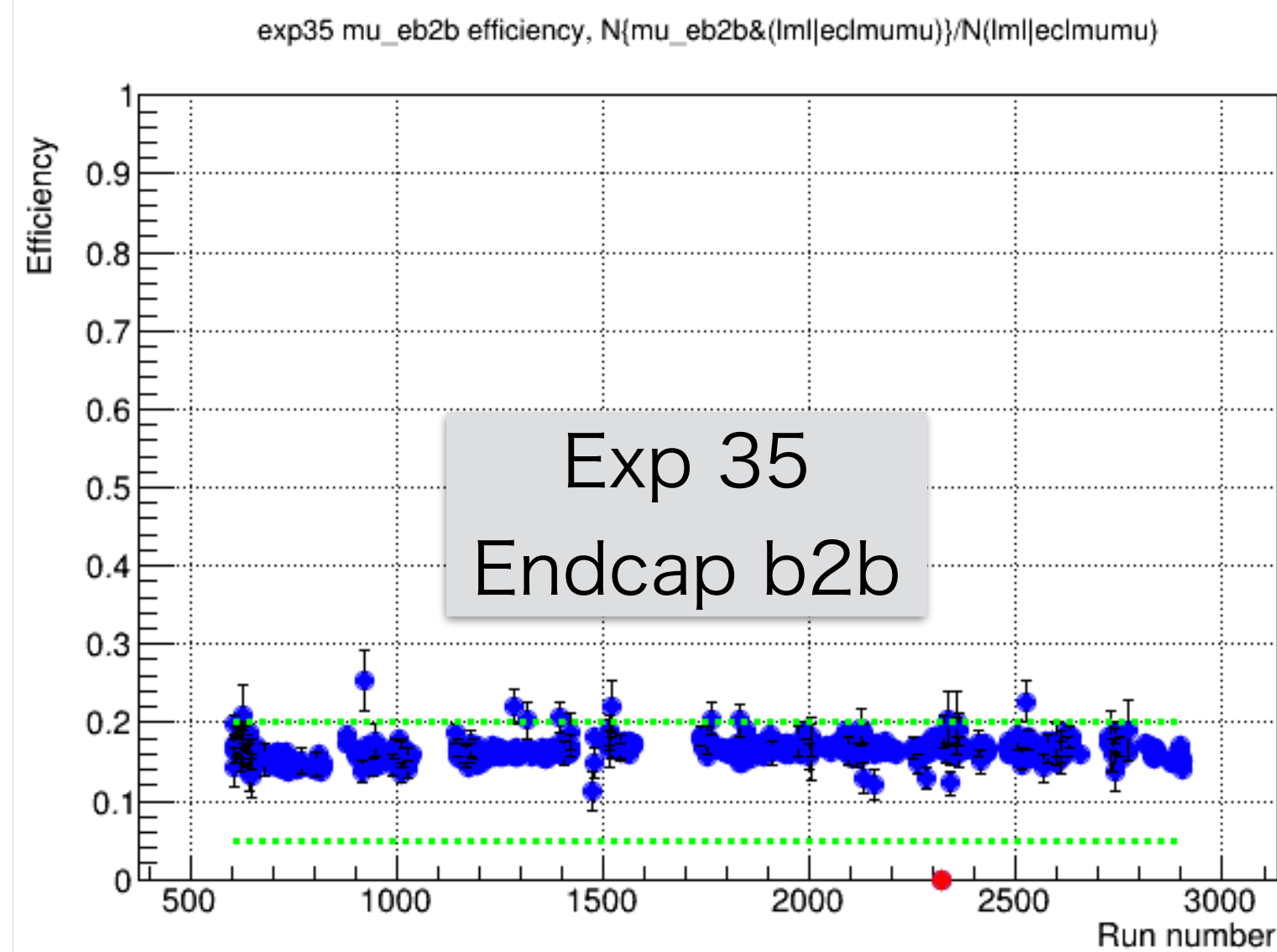
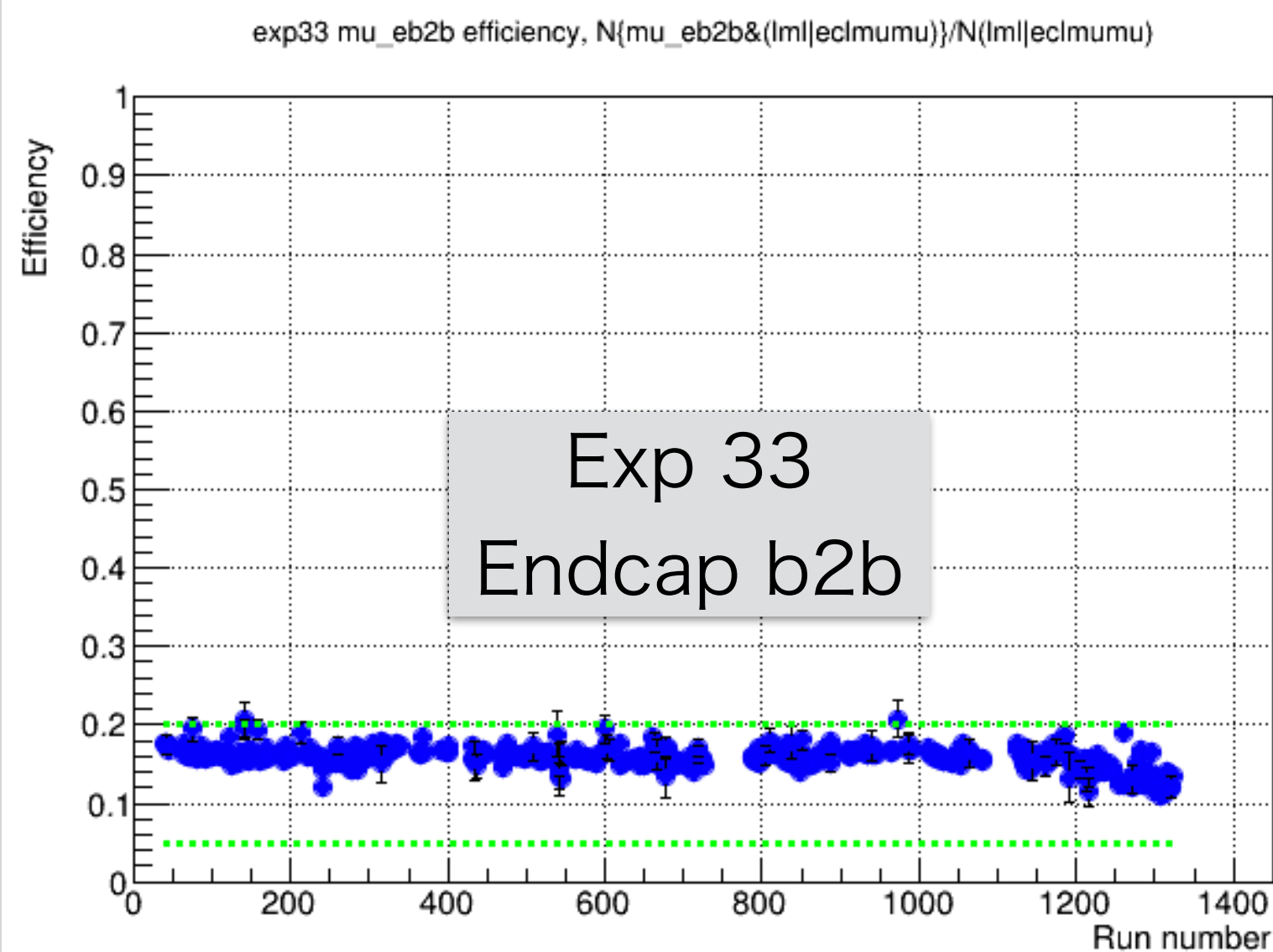
- Basically stable. > 95%.
- Problematic shaperDSP caused low efficiency in Energy sum and cluster counting bits

Trigger Efficiency: KLMTRG

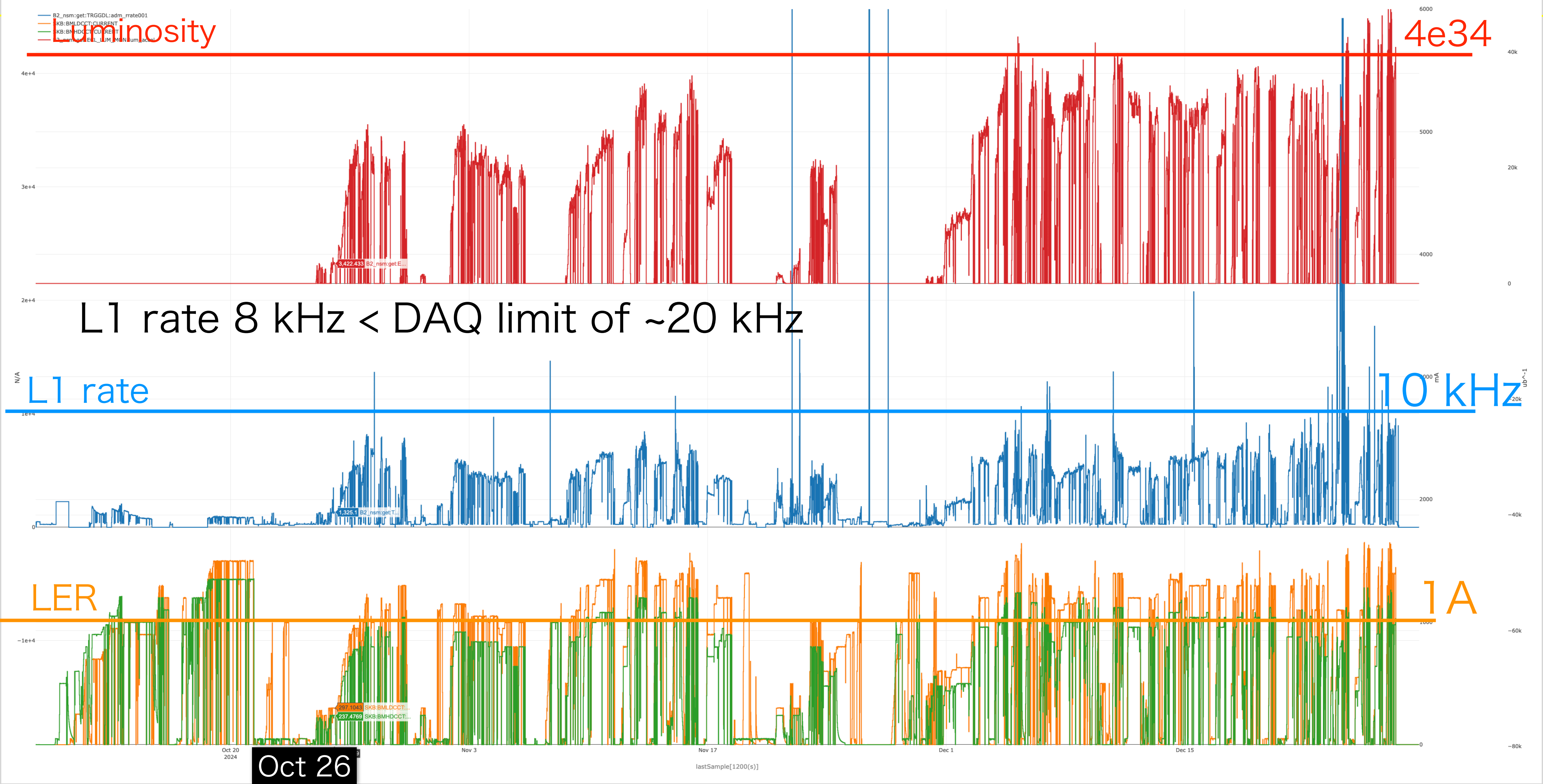


Efficiency OK

Bad runs due to KLMTRG link down
([gitlab](#), [gitlab](#))



L1 rate



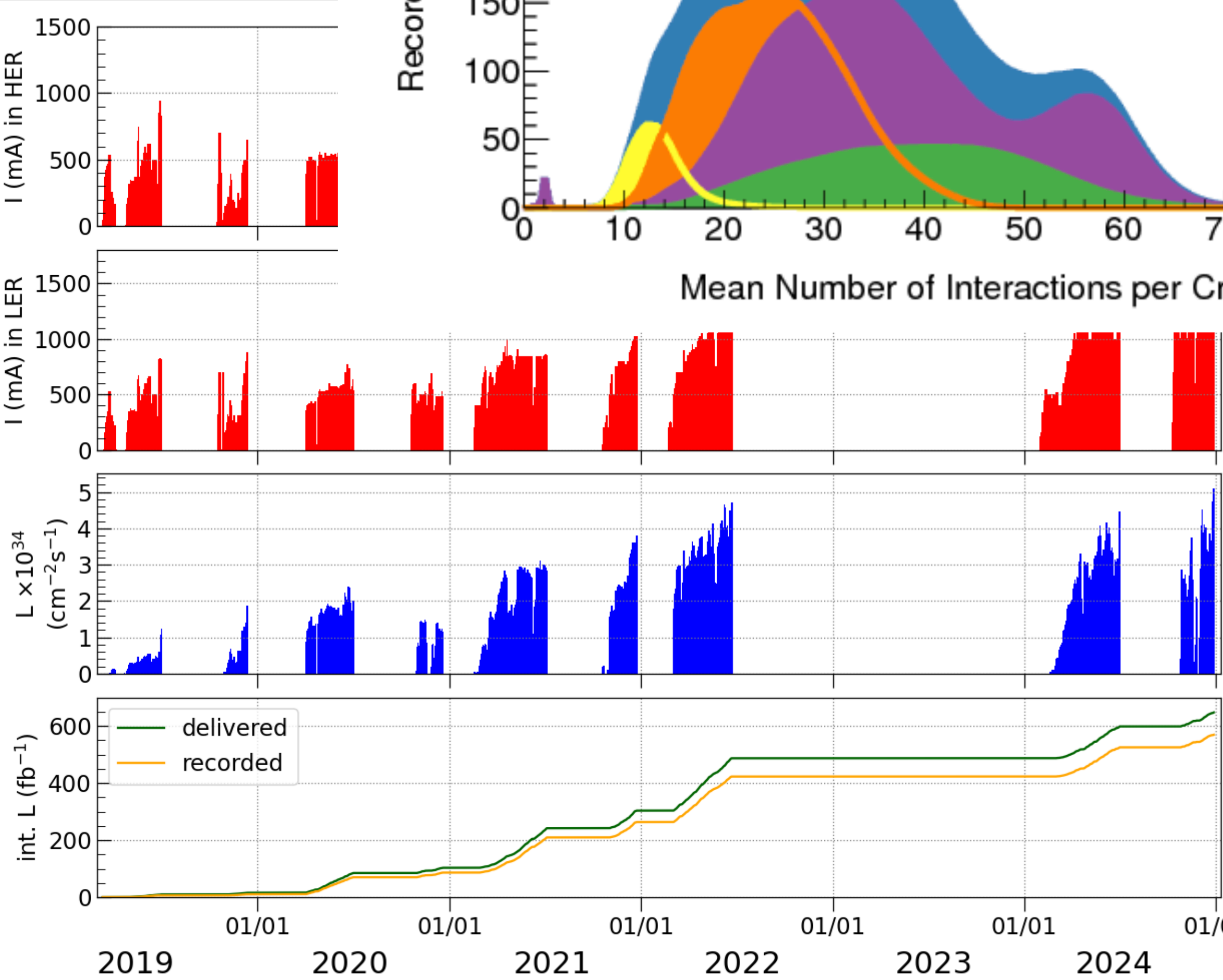
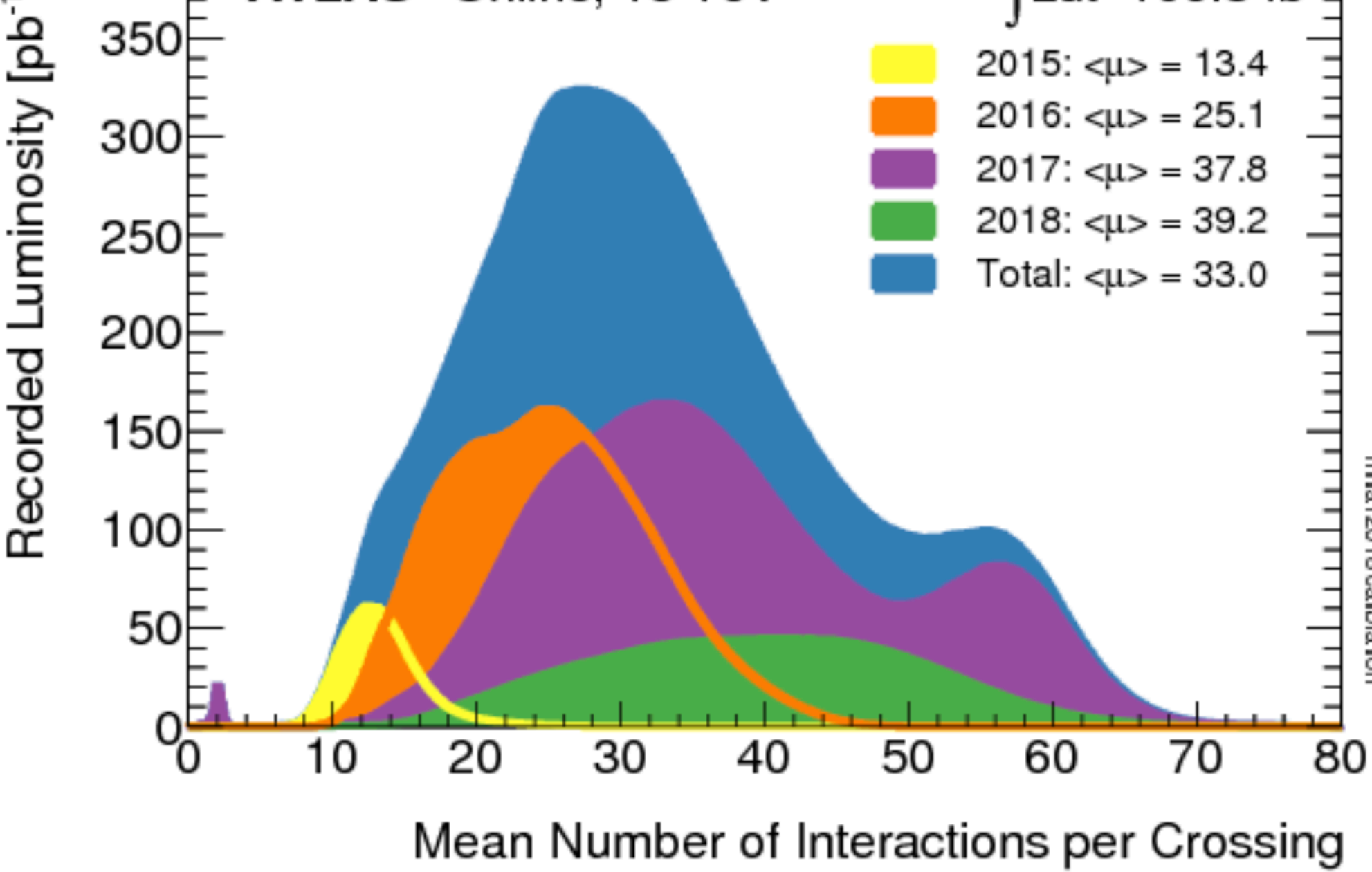
Summary

- L1 Trigger at Belle has worked well.
- Almost 100% efficiency for hadron data taking
 - Independent Triggers complement each other
- Trigger rate well before the DAQ limit
 - Many efforts to reduce background has been made
 - Neuro Trigger, full-hit algorithm, Injection veto, etc.

Machine Parameters

2017/September/1	LER	HER	unit	
E	4.000	7.007	GeV	
I	3.6	2.6	A	
Number of bunches	2,500			
Bunch Current	1.44	1.04	mA	
Circumference	3,016.315		m	
ϵ_x/ϵ_y	3.2(1.9)/8.64(2.8)	4.6(4.4)/12.9(1.5)	nm/pm	() : zero current
Coupling	0.27	0.28		includes beam-beam
β_x^*/β_y^*	32/0.27	25/0.30	mm	
Crossing angle	83		mrad	
α_p	3.20×10^{-4}	4.55×10^{-4}		
σ_δ	$7.92(7.53) \times 10^{-4}$	$6.37(6.30) \times 10^{-4}$		() : zero current
V_c	9.4	15.0	MV	
σ_z	6(4.7)	5(4.9)	mm	() : zero current
V_s	-0.0245	-0.0280		
v_x/v_y	44.53/46.57	45.53/43.57		
U_0	1.76	2.43	MeV	
$T_{x,y}/T_s$	45.7/22.8	58.0/29.0	msec	
ξ_x/ξ_y	0.0028/0.0881	0.0012/0.0807		
Luminosity	8×10^{35}		$\text{cm}^{-2}\text{s}^{-1}$	

https://www-



	SuperKEKB : Dec. 27, 2024		SuperKEKB : May 22, 2022		Unit
Ring	LER	HER	LER	HER	
Emittance	4.0	4.6	4.0	4.6	nm
Beam Current	1632	1259	744	600	mA
Number of bunches	2346		1565		
Bunch current	0.696	0.537	0.475	0.383	mA
Horizontal size σ_x^*	15.5	16.6	17.9	16.6	μm
Vertical cap sigma Σ_y^*	0.375		0.250		μm^{*1}
Vertical size σ_y^*	0.265		0.177		μm^{*2}
Betatron tunes ν_x / ν_y	44.525 / 46.589	45.531 / 43.599	44.525 / 46.589	45.532 / 43.574	
β_x^* / β_y^*	60 / 1.0	60 / 1.0	80 / 0.8	60 / 0.8	mm
Piwinski angle	12.3	12.7	10.7	12.7	
Crab waist ratio	80	60	80	40	%
Beam-Beam parameter ξ_y	0.036	0.027	0.031	0.022	
Specific luminosity	5.8×10^{31}		8.7×10^{31}		$\text{cm}^{-2}\text{s}^{-1}/\text{mA}^2$
Luminosity	5.1×10^{34}		2.5×10^{34}		$\text{cm}^{-2}\text{s}^{-1}$

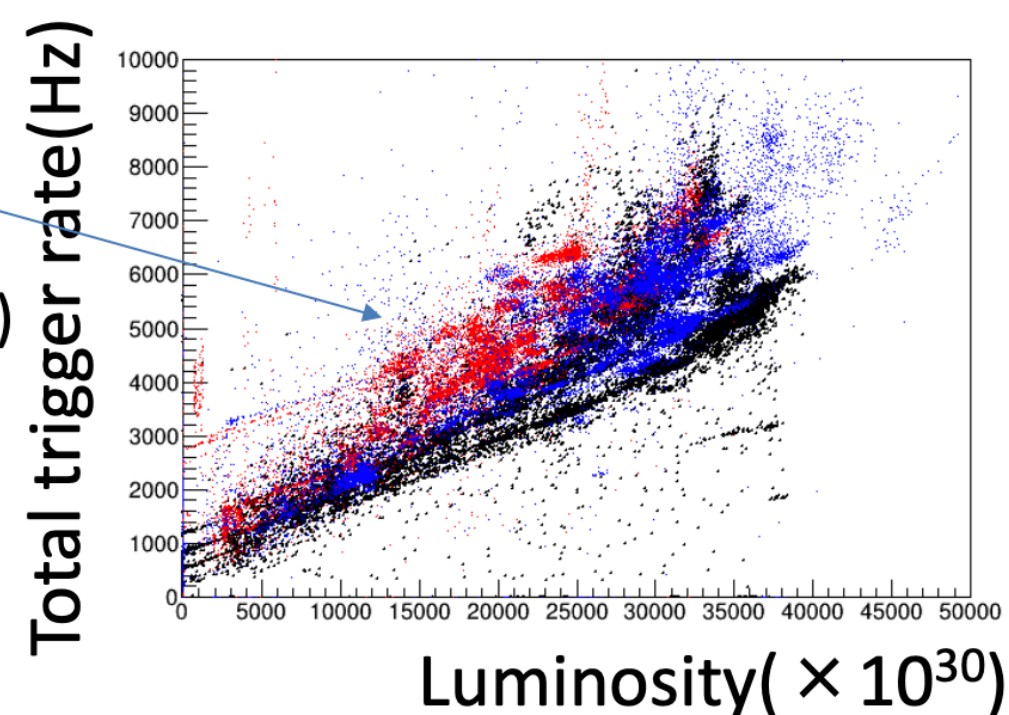
*1) estimated by luminosity with assuming design bunch length
*2) divide *1 by $\sqrt{2}$

Component of L1 rate

T. Koga

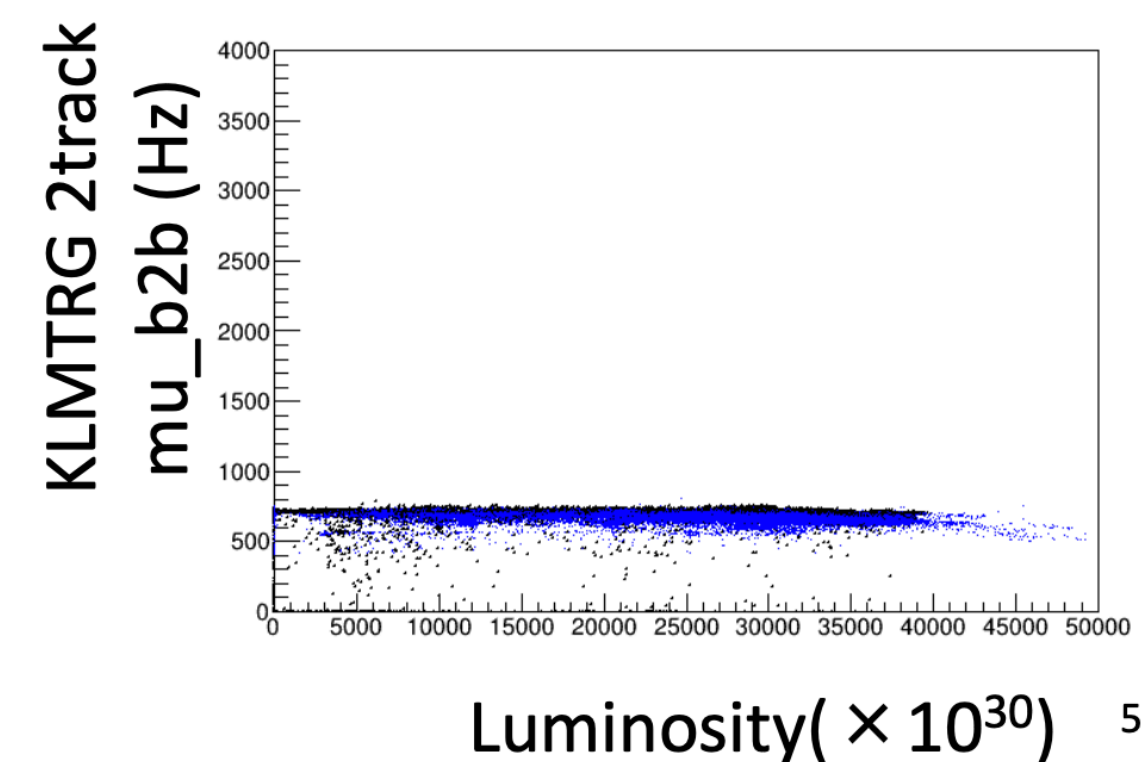
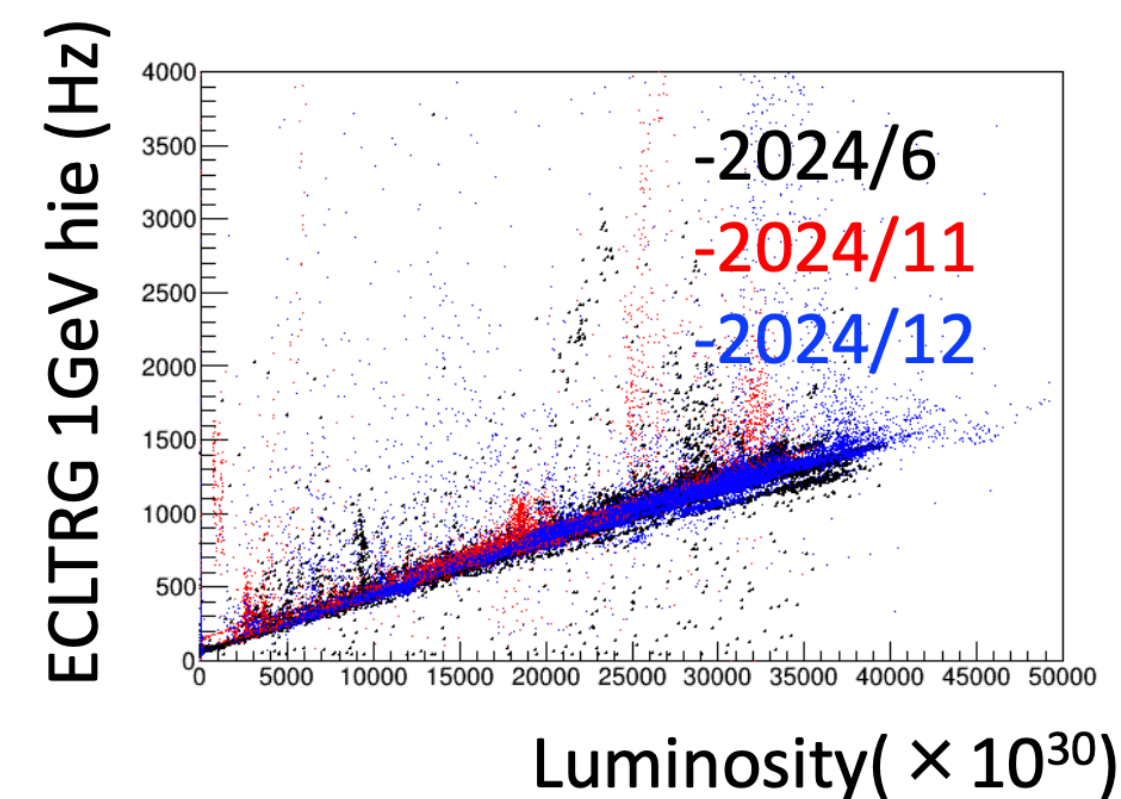
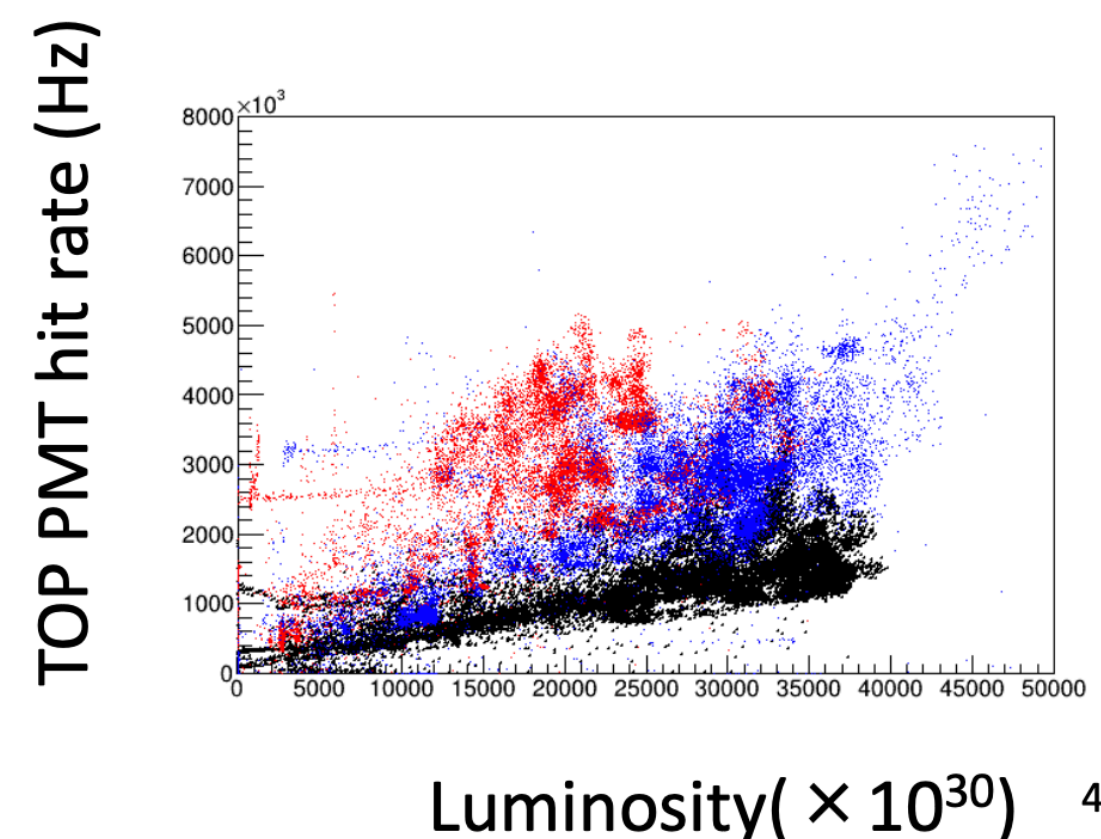
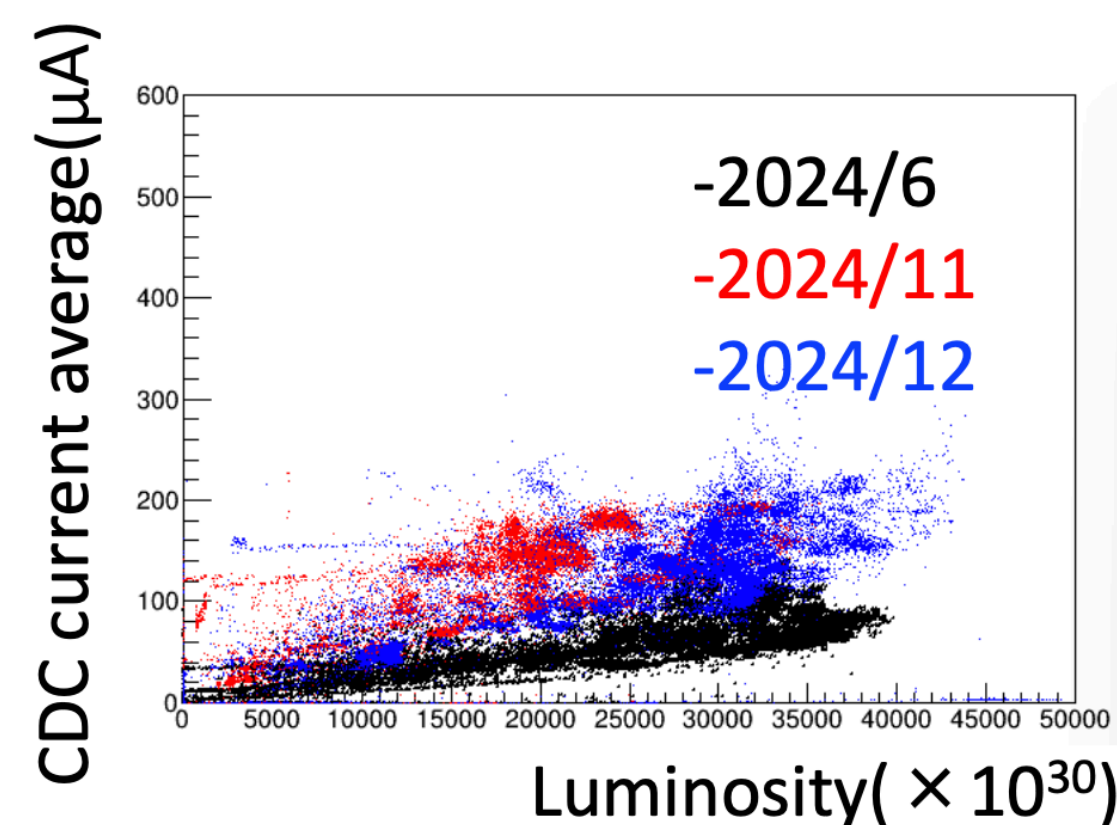
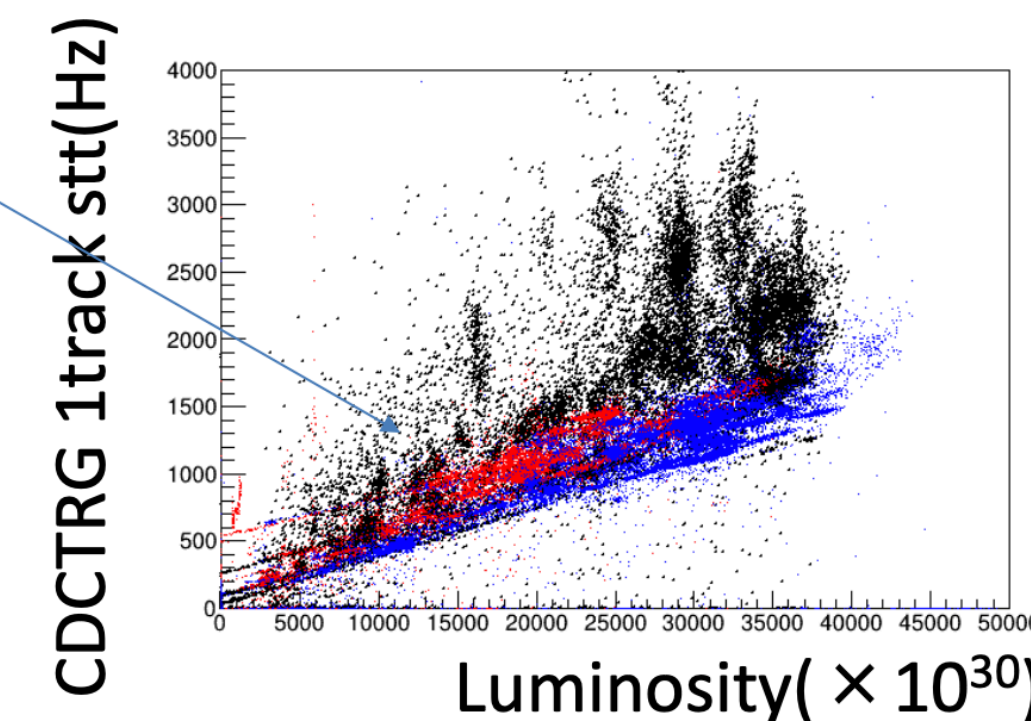
Luminosity vs Total Trigger rate in 2024c

- beamBG is 1.5~4 times larger than 2024ab
- Nevertheless, Trigger rate is 1~1.5 times larger than 2024ab.
(by CDCTRG modification, trigger rate reduced)



Luminosity vs Sub trigger rate in 2024c

- CDCTRG 1track (beamBG dominant) rate per luminosity is smaller than 2024ab: according to ADC cut implemented in 2024c
- ECLTRG 1GeV (Bhabha dominant) rate is same as 2024ab
- KLMTRG 2muon (cosmic dominant) rate is same as 2024ab



1.5 - 4 higher beam background than 2024ab

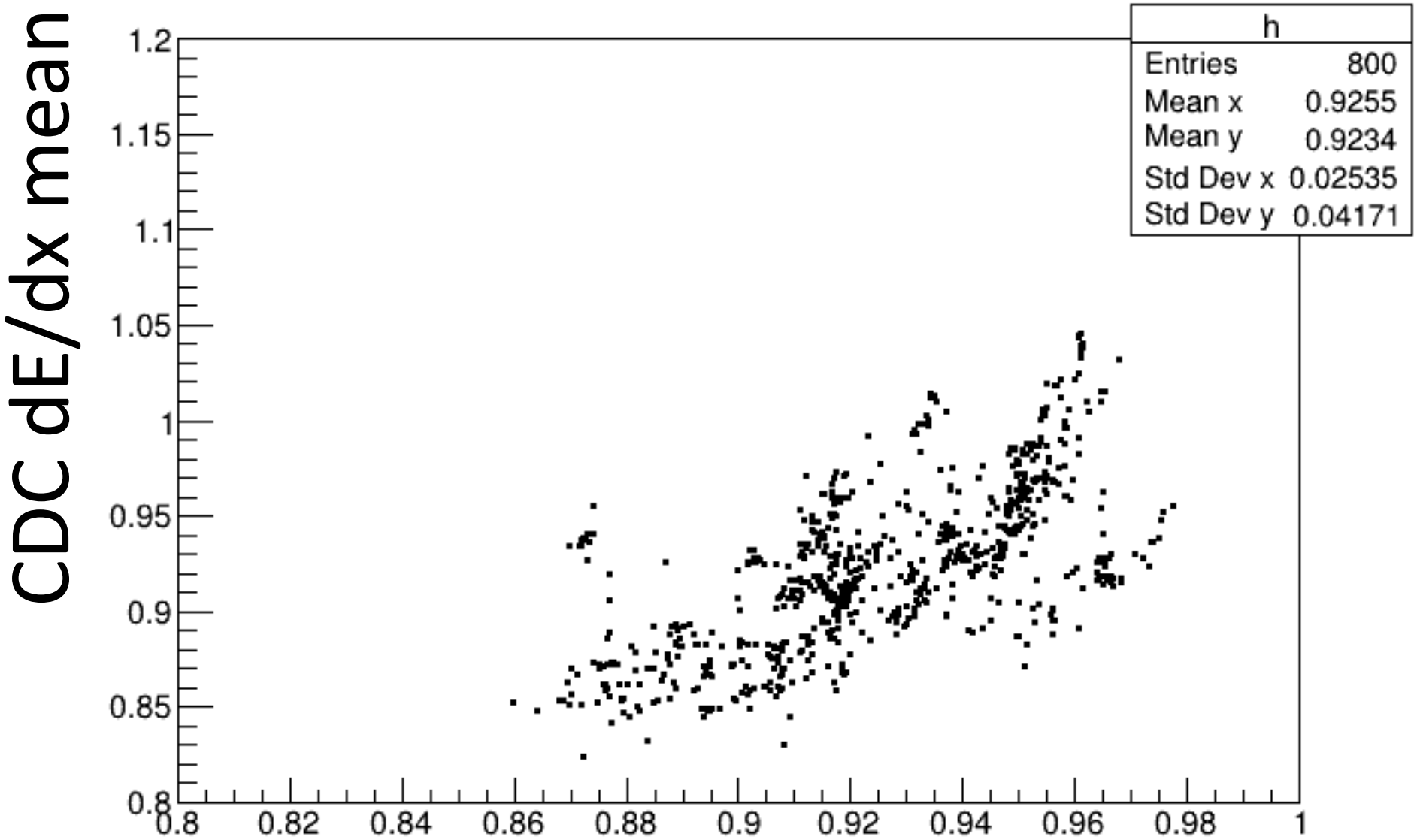
No beam background effect on ECL and KLM trigger rate

1 - 1.5 higher CDCTRG rate than 2024ab thanks to ADC cut introduced 2024c

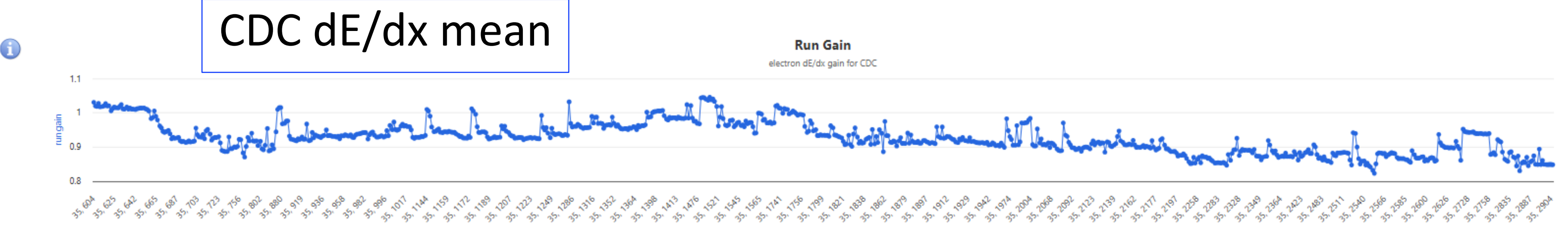
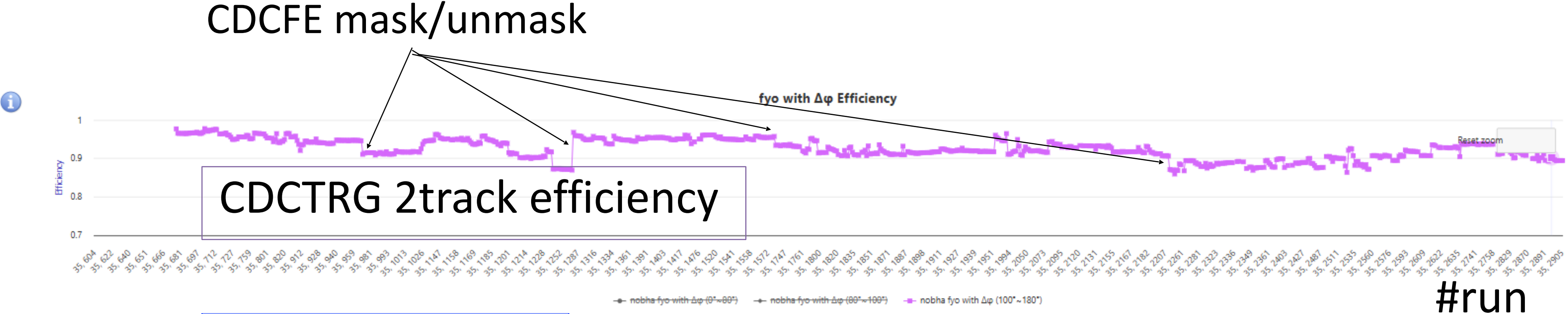
CDCTRG efficiency drop

-CDCTRG efficiency is not stable

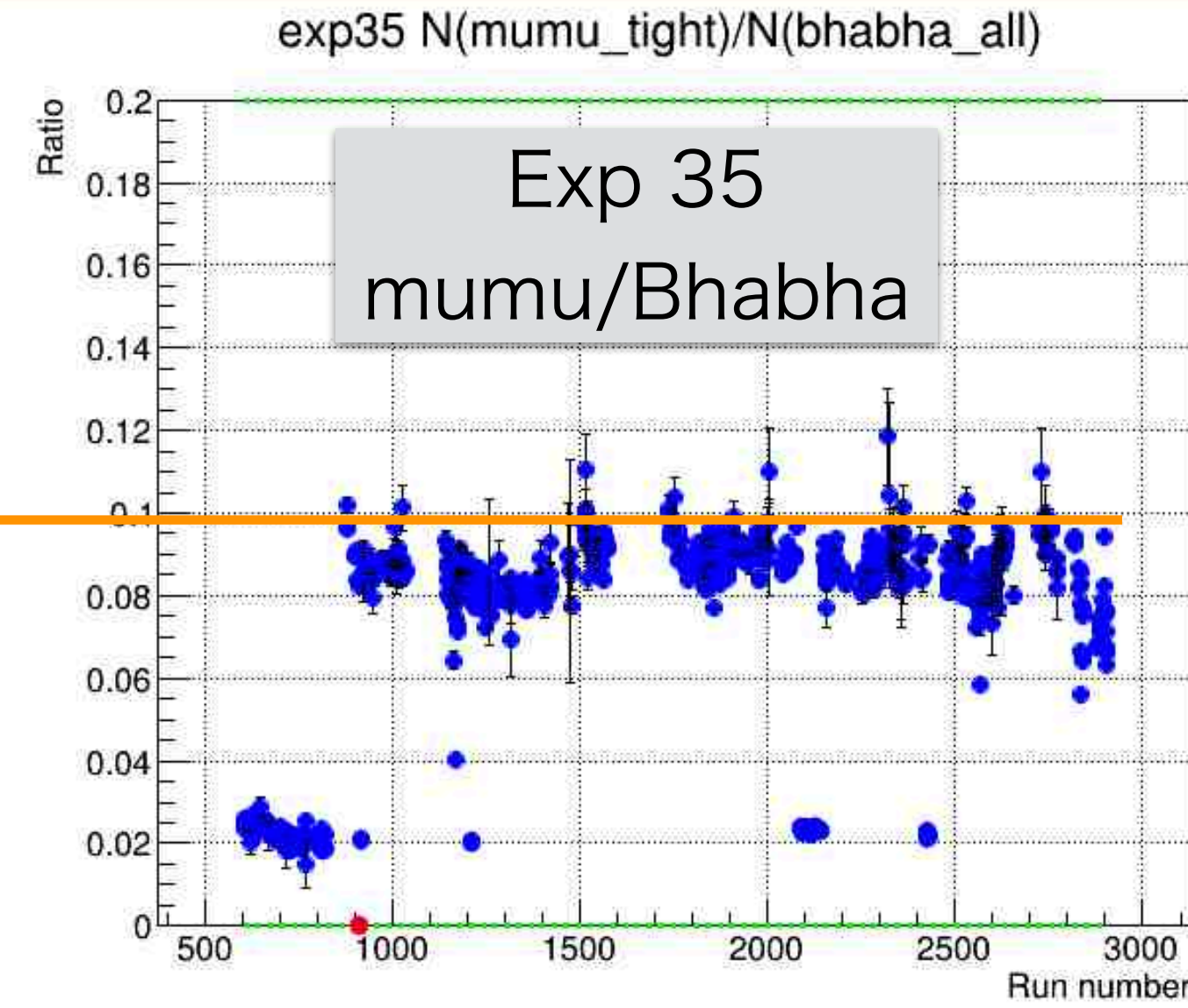
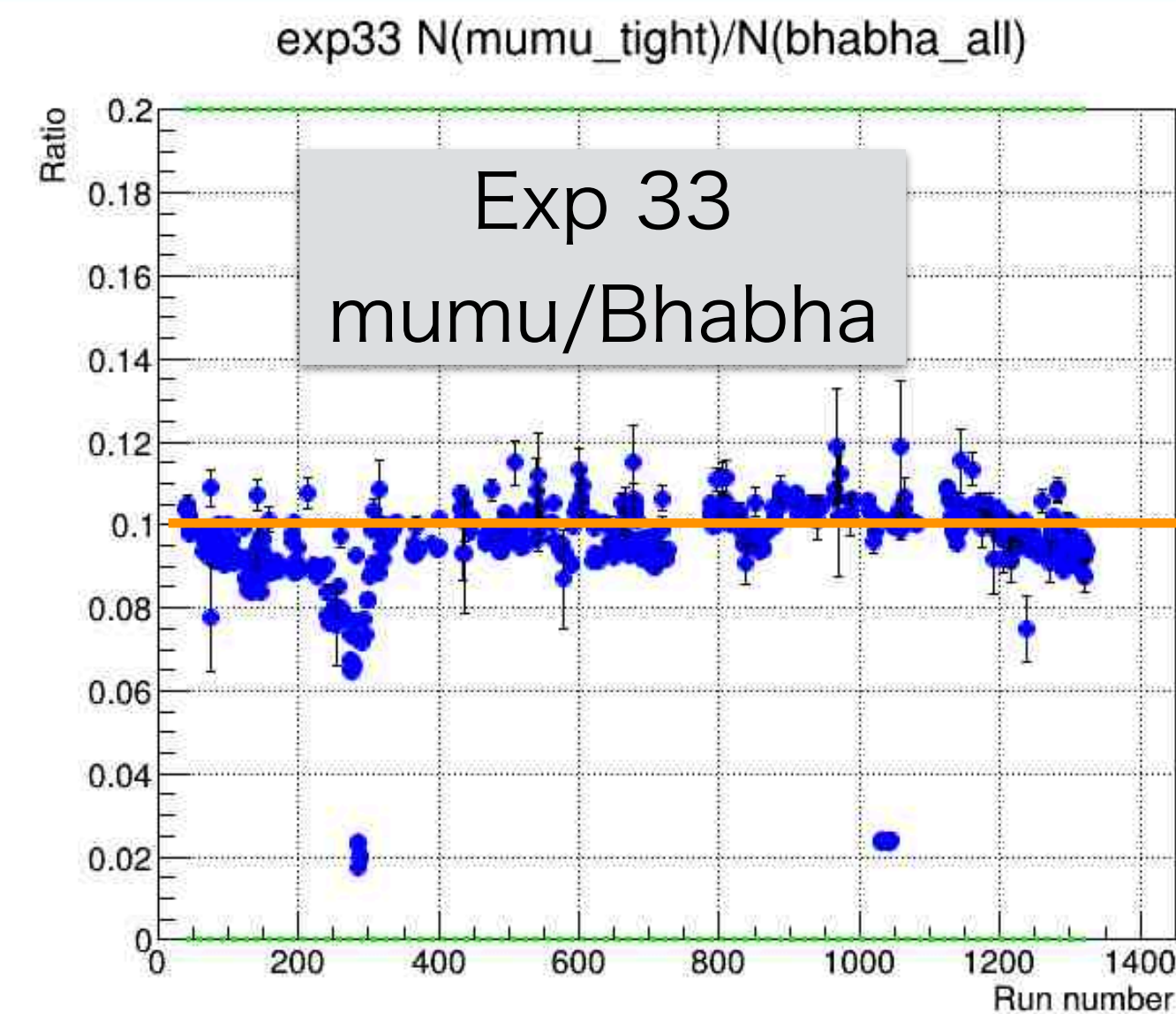
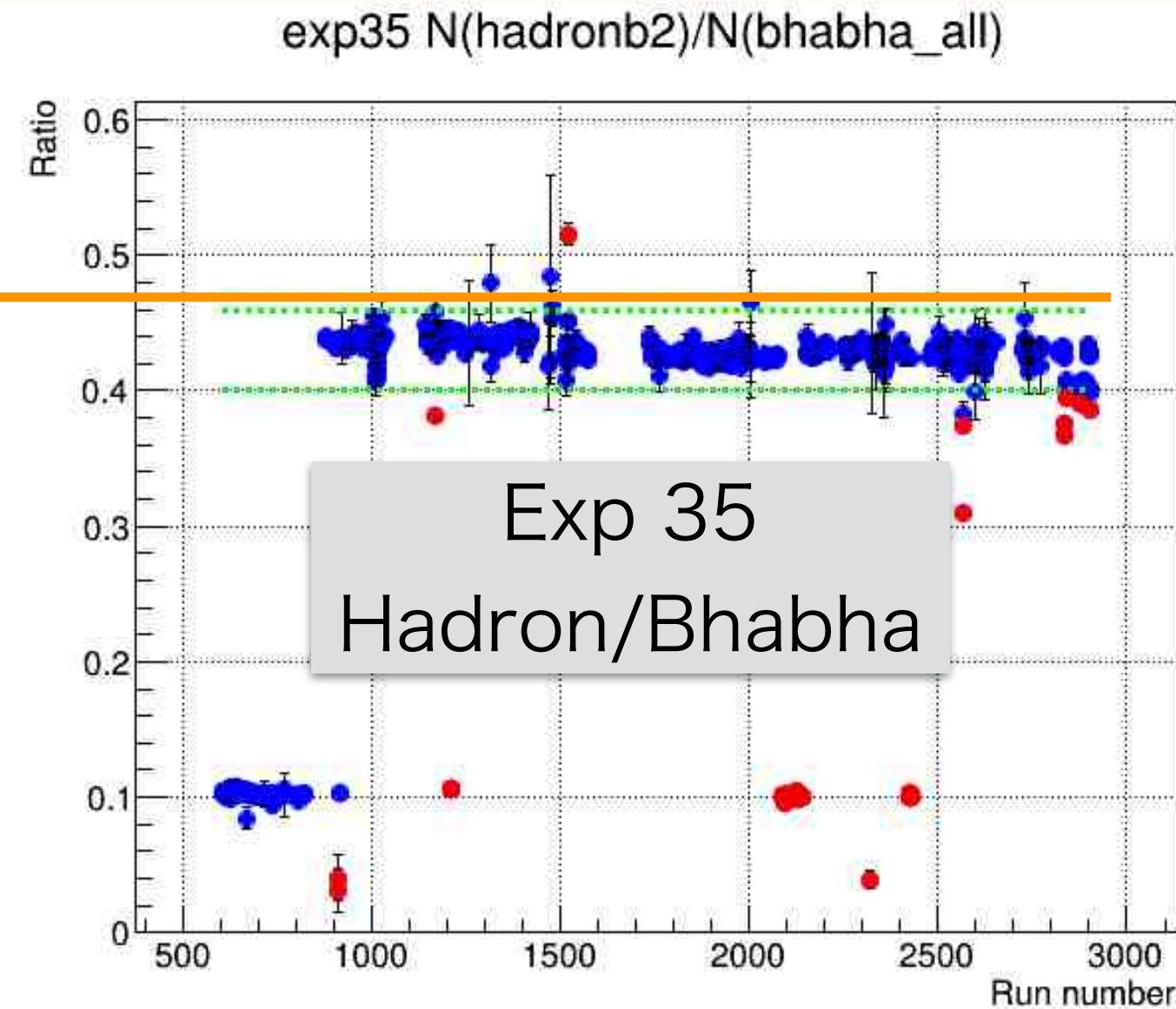
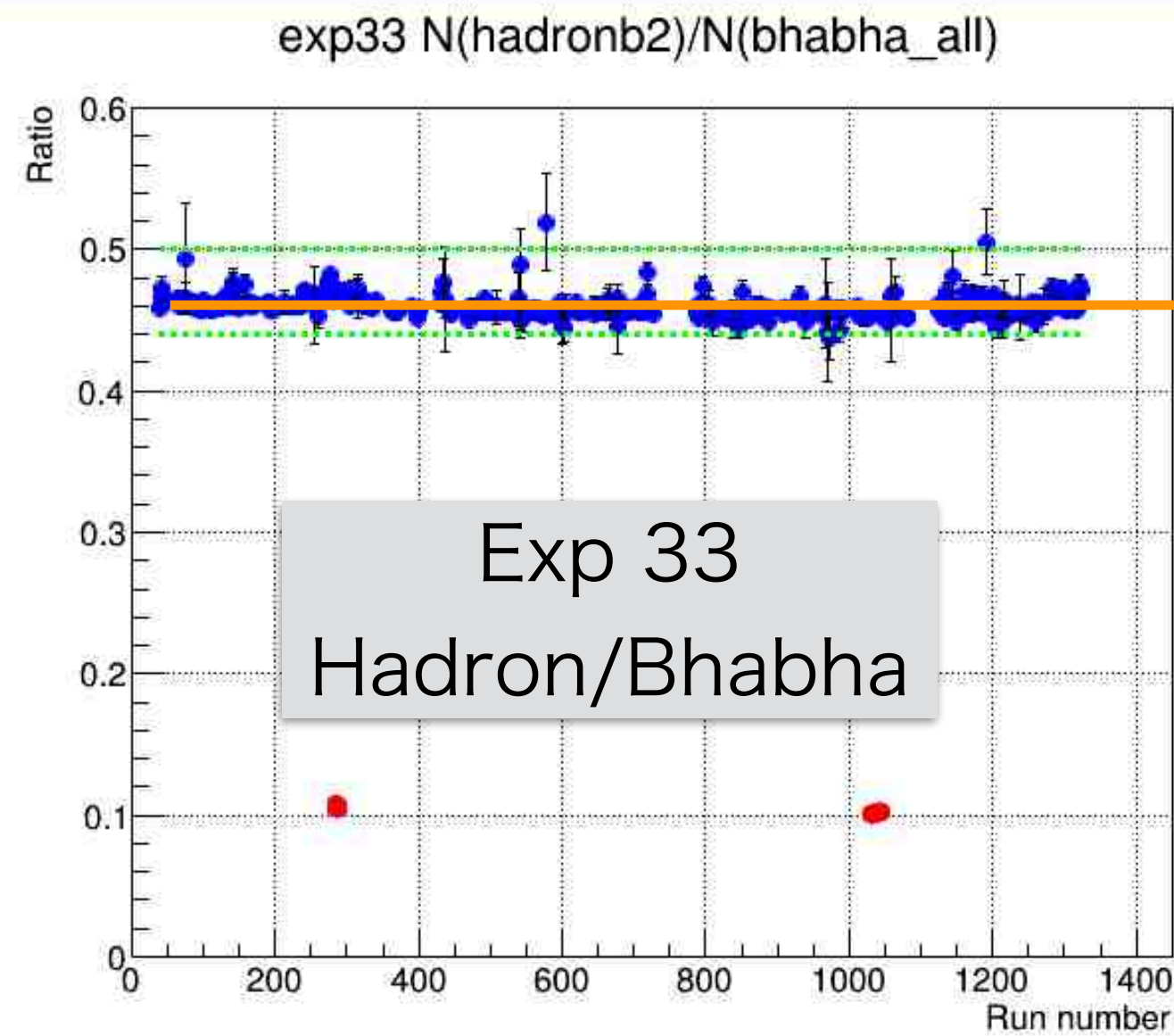
- ~2% by dead CDCFE and MGR
- ~6% by CDC detector gain drop
(large effect if CDC $dE/dx < 0.9$)



CDCTRG 2track efficiency



Skim Ratio



- Both hadron/bhabha and mumu/bhabha decreased
- No impact from Injection background
- HER optics change or update of globaltag might affect this ([gitlab](#))
- Monitor (DQM) from software group needed

Acceptable beam background by TRG

- Roughly say, Trigger rate is linearly proportional to beamBG
- Trigger rate will be 15kHz with “CDC current $\sim 450\mu\text{A}$ ” or “TOP PMT $\sim 9\text{MHz}$ ” equivalent beamBG condition
- With tighter trigger menu, further $\sim 50\%$ reduction of trigger rate is expected

