Belle II Trigger System

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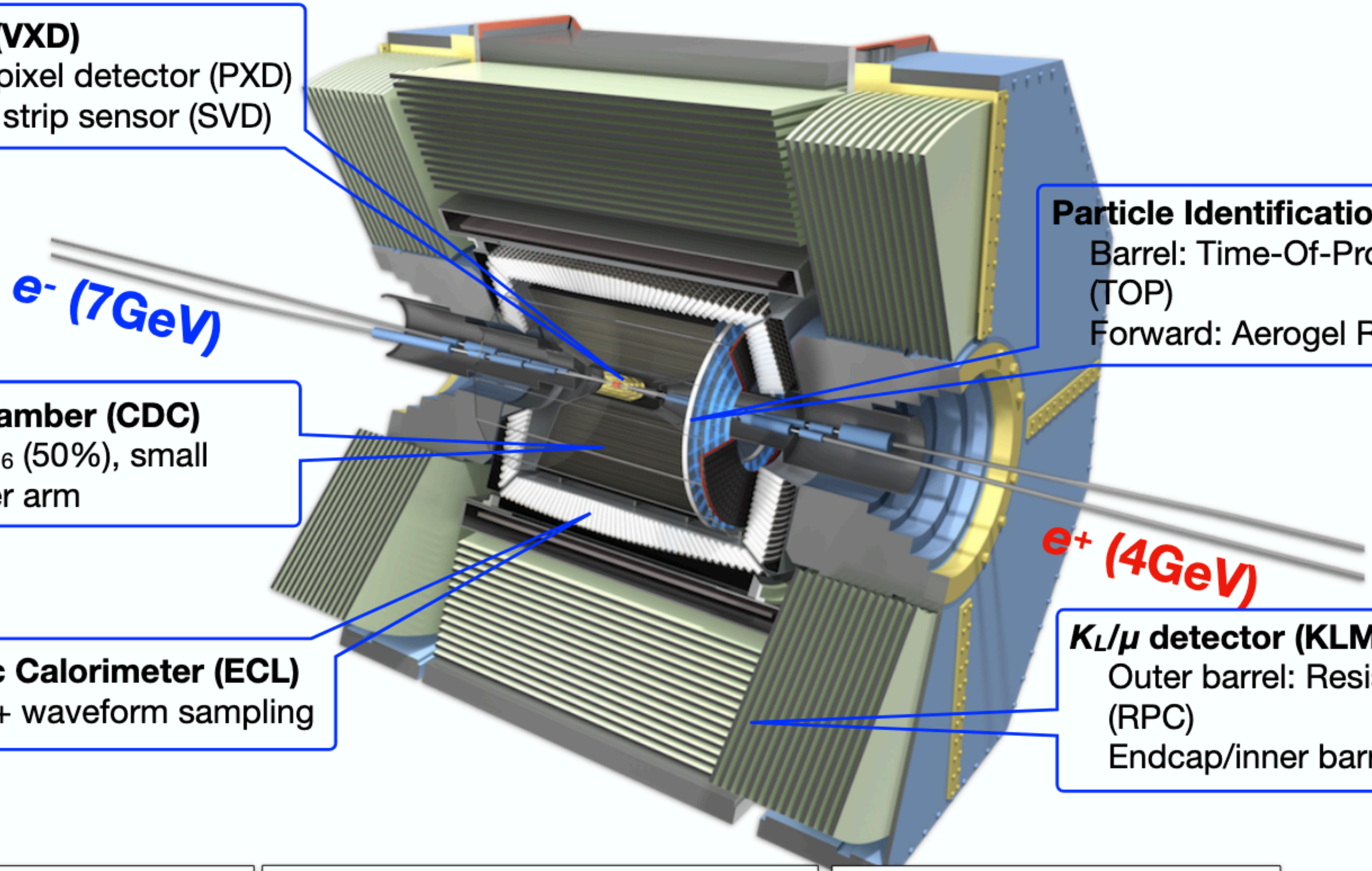
Outline

- Belle II detector
- TRG construction
- Current TRG status
- Developing
- Summary

The Belle II detector

Vertex detector (VXD)
Inner 2 layers: pixel detector (PXD)
Outer 4 layers: strip sensor (SVD)



Central Drift Chamber (CDC)
He (50%), C_2H_6 (50%), small cells, long lever arm

ElectroMagnetic Calorimeter (ECL)
Barrel: CsI(Tl) + waveform sampling

Particle Identification
Barrel: Time-Of-Propagation counters (TOP)
Forward: Aerogel RICH (ARICH)

K_L/μ detector (KLM)
Outer barrel: Resistive Plate Counter (RPC)
Endcap/inner barrel: Scintillator

Level-1 trigger system
CDC+ECL+TOP+KLM
L1 trigger latency 5 μsec

Data acquisition (DAQ) system
Maximum 30 kHz L1 trigger
1MB/event

Computing system
GRID
Tens of PB / year

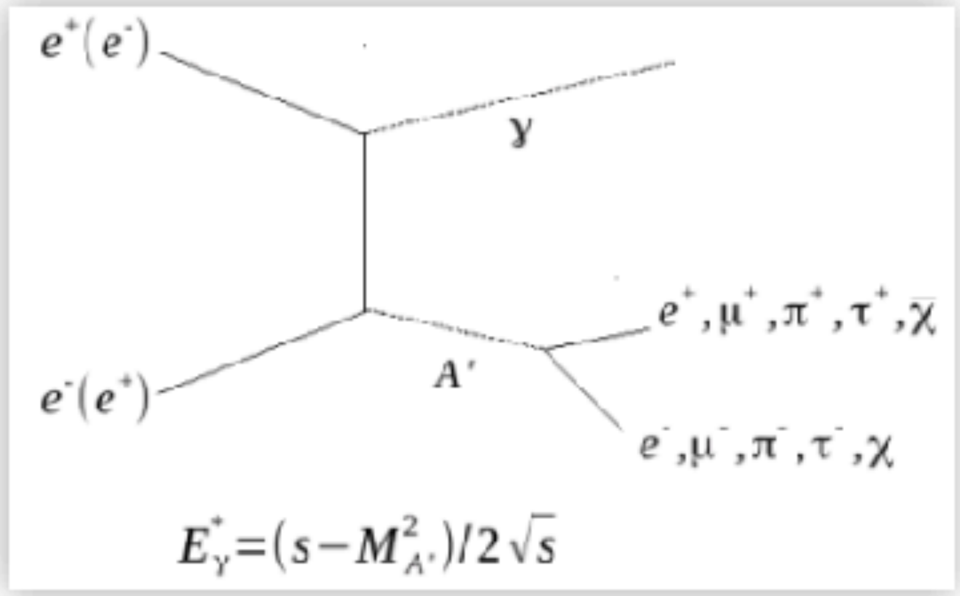
Belle II Physics Mind-map

Image courtesy of Tom Browder

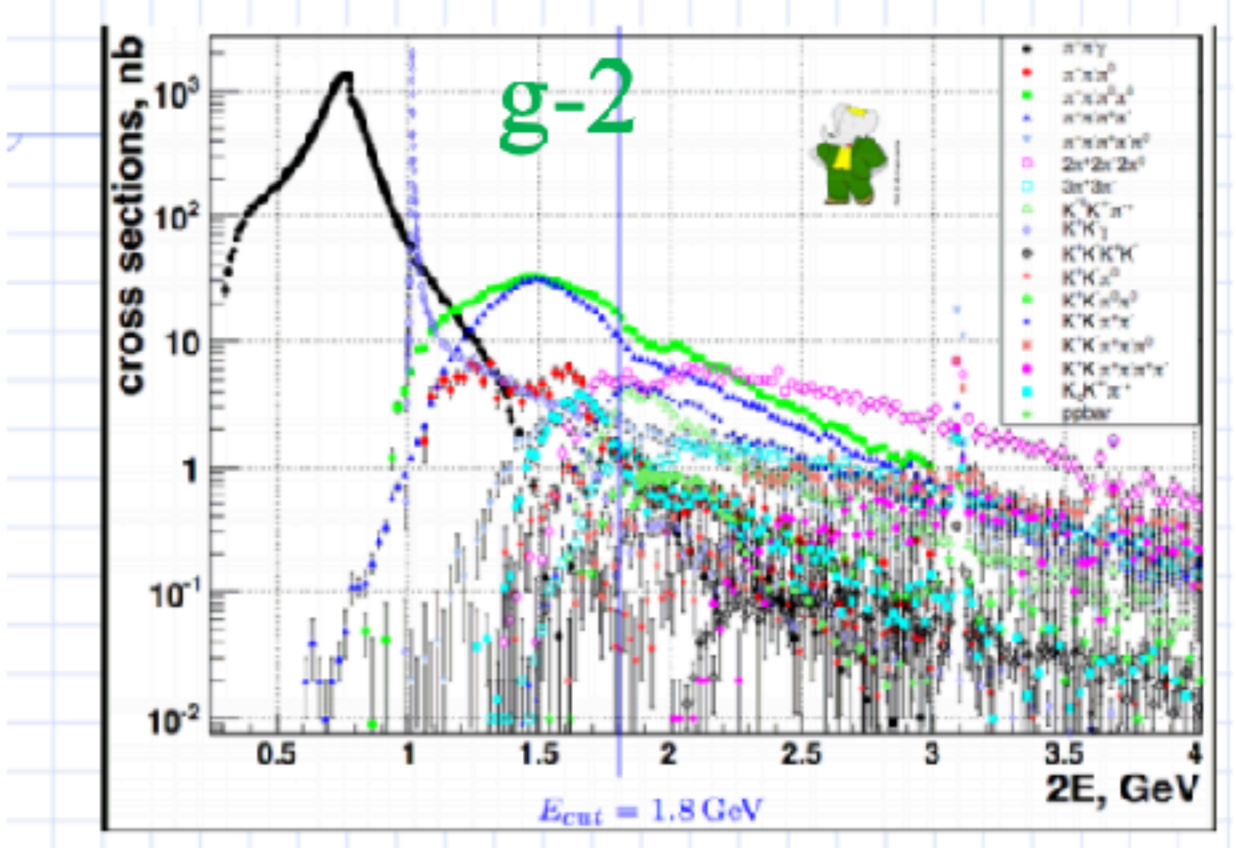
Trigger Challenges

- High luminosity, high background
  - Total physics trigger rate: 15 kHz @ $8.0 \times 10^{35}/cm^2/s$ (designed)
  - Large beam-related, QED background
- Physics process trigger
  - $\Upsilon(4S)$ + continuum, ~100% efficiency
  - Low multiplicity process, challenge trigger

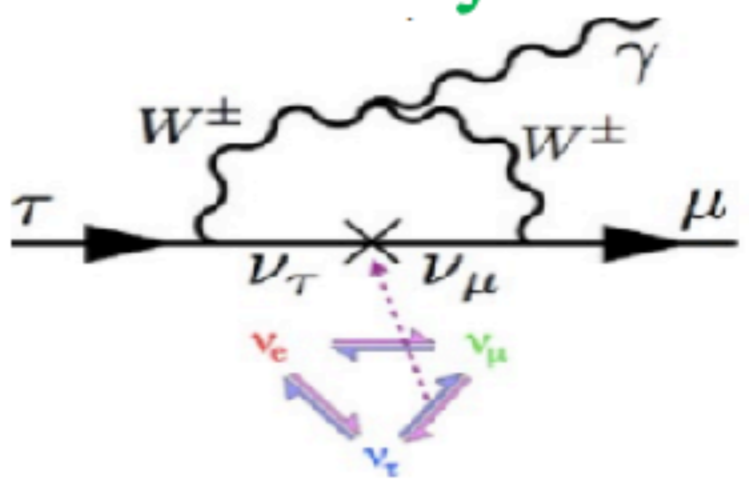
Dark photon



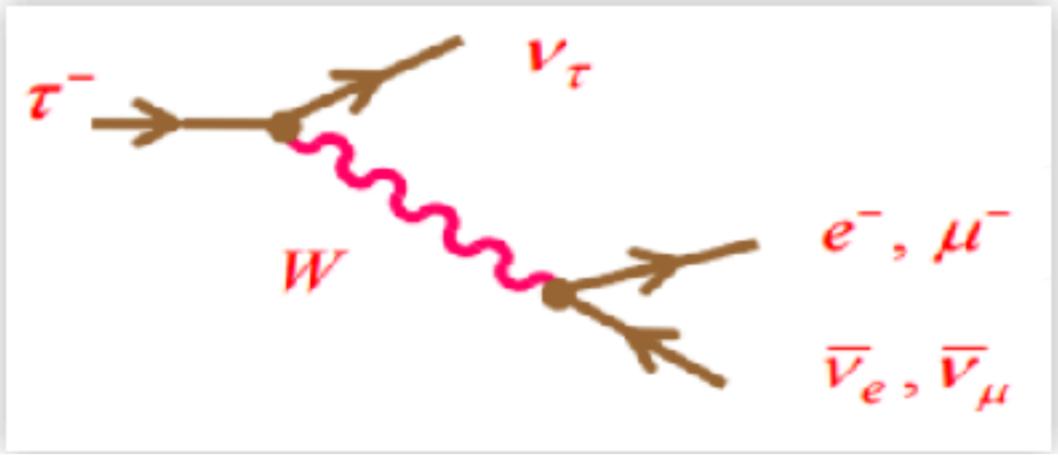
BaBar measurements summary



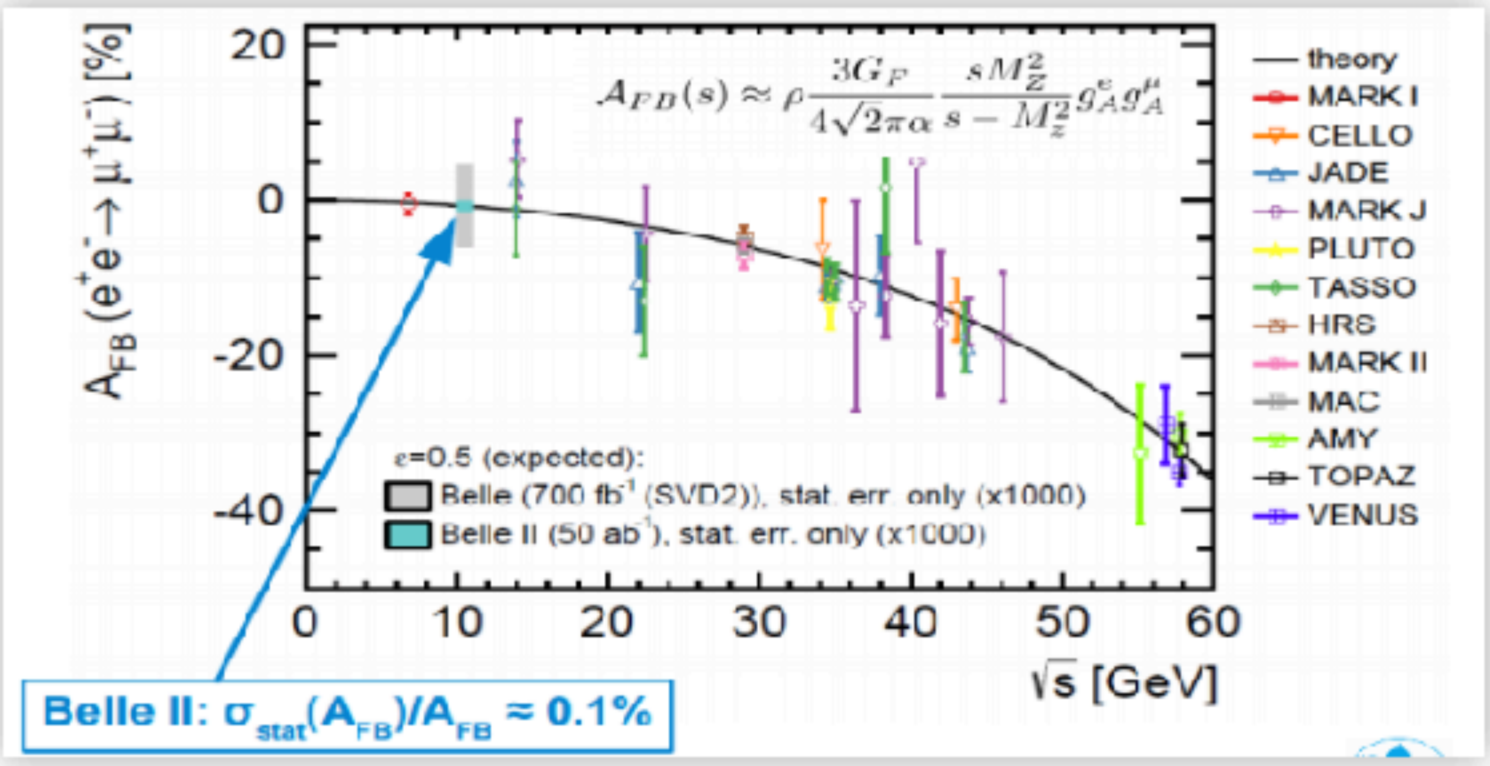
LFV tau decay



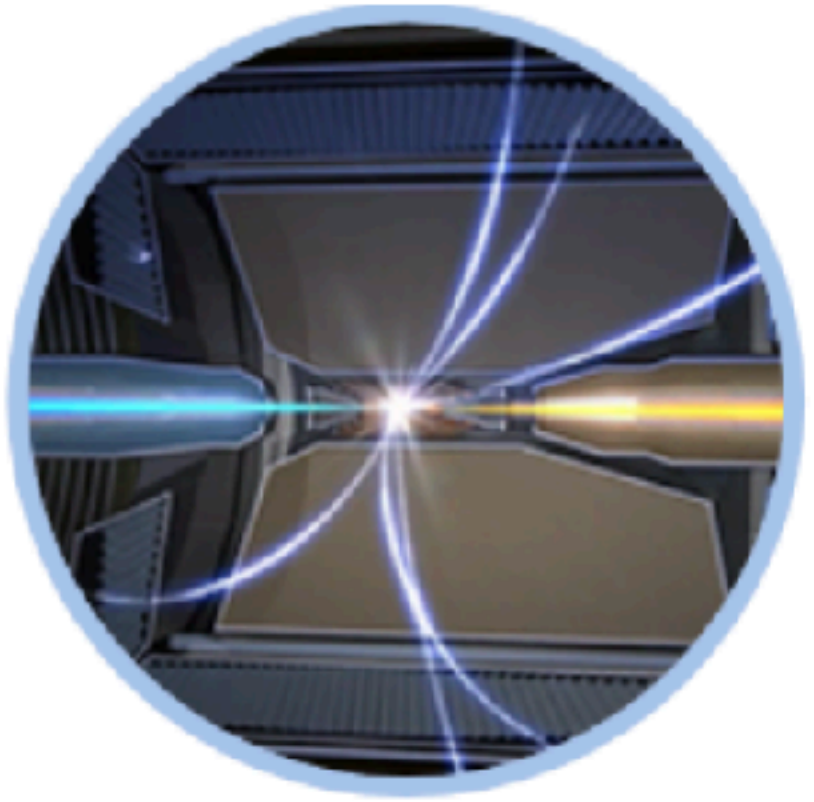
Leptonic tau decay

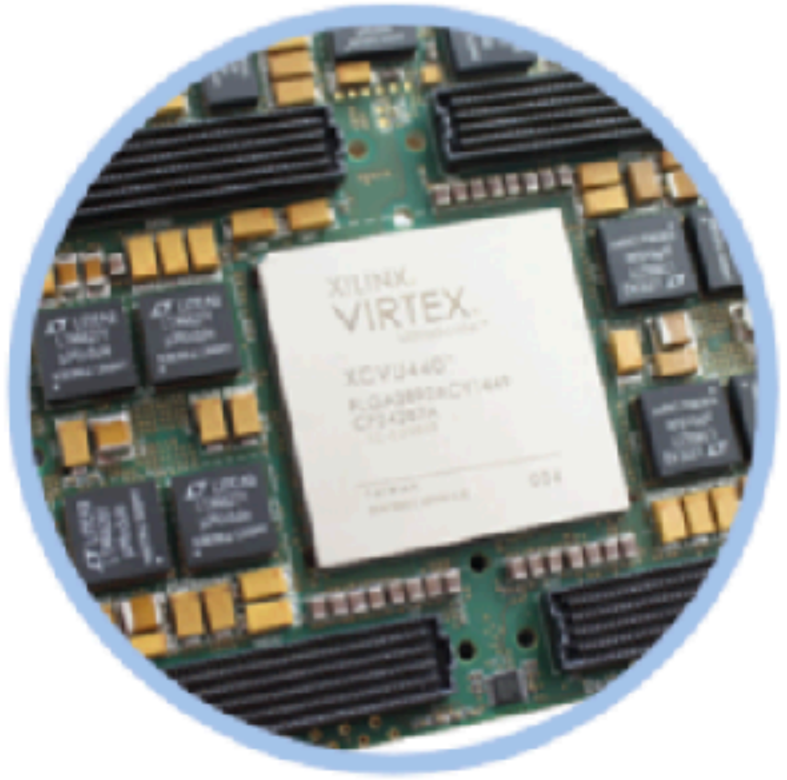


Precision electroweak tests



Belle II TRG pipeline





Collisions:
250 MHz

Level 1 Trigger:
30 kHz, 5 μs Latency

High Level Trigger:
5-10 kHz, 1.8 Gb/s

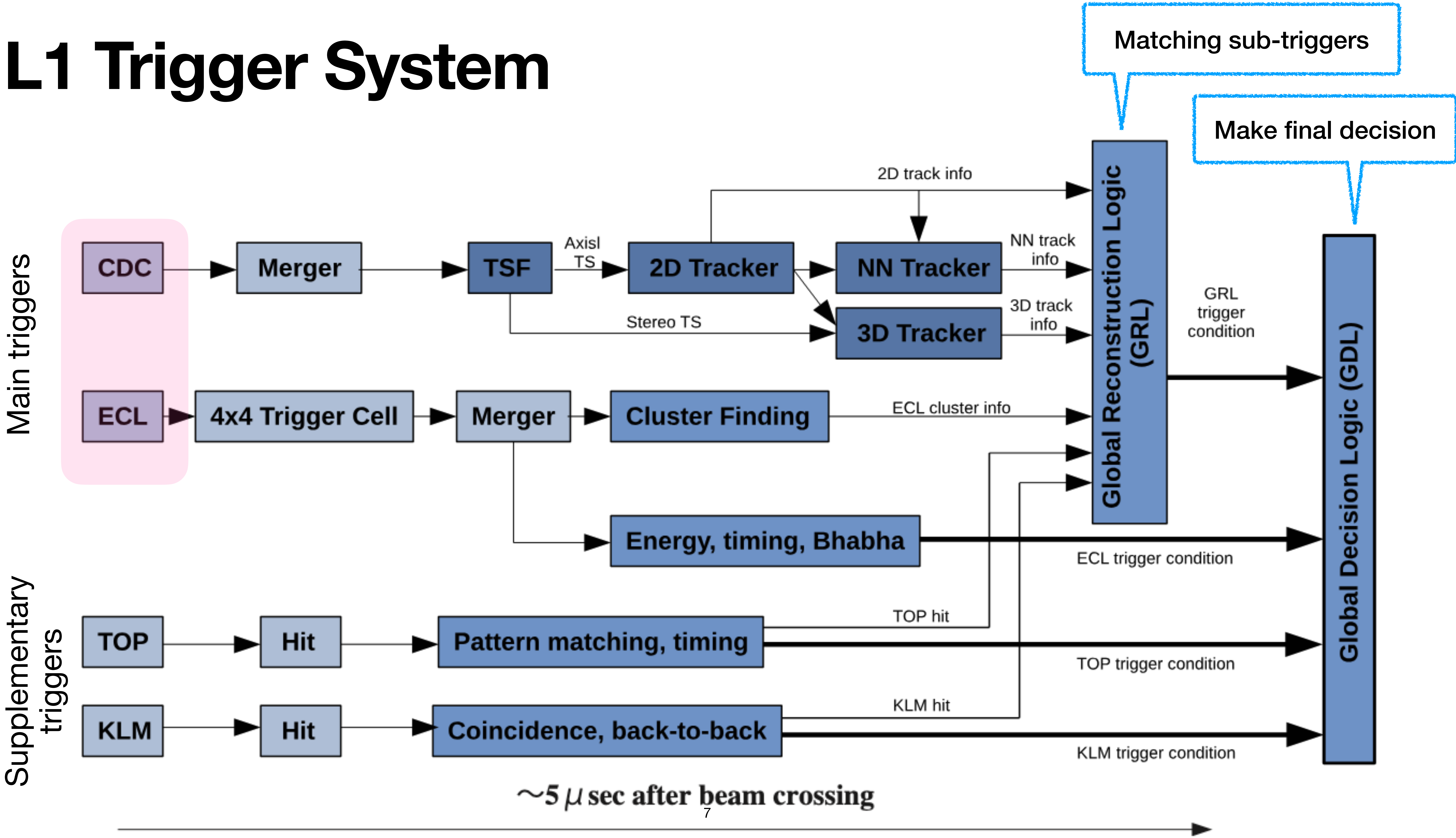
Expected trigger rate @ $\mathscr{L}_{\mathrm{ins}} = 6.0 \times 10^{35}\ \mathrm{cm}^{-2}/\mathrm{s}$

bhabha	B-physics	qq-bar	two photon	di-muon	di-tau	di-gamma	dark sector
> 50 kHz	1 kHz	2 kHz	10 kHz	0.6 kHz	0.6 kHz	2 kHz	??

dominate

Physics Target ~ 15 kHz, ~100% efficiency of $B\bar{B}$ events

L1 Trigger System



-Universal FPGA board developed for Belle II

-QSFP optical transceiver (GTX,GTH,GTY)

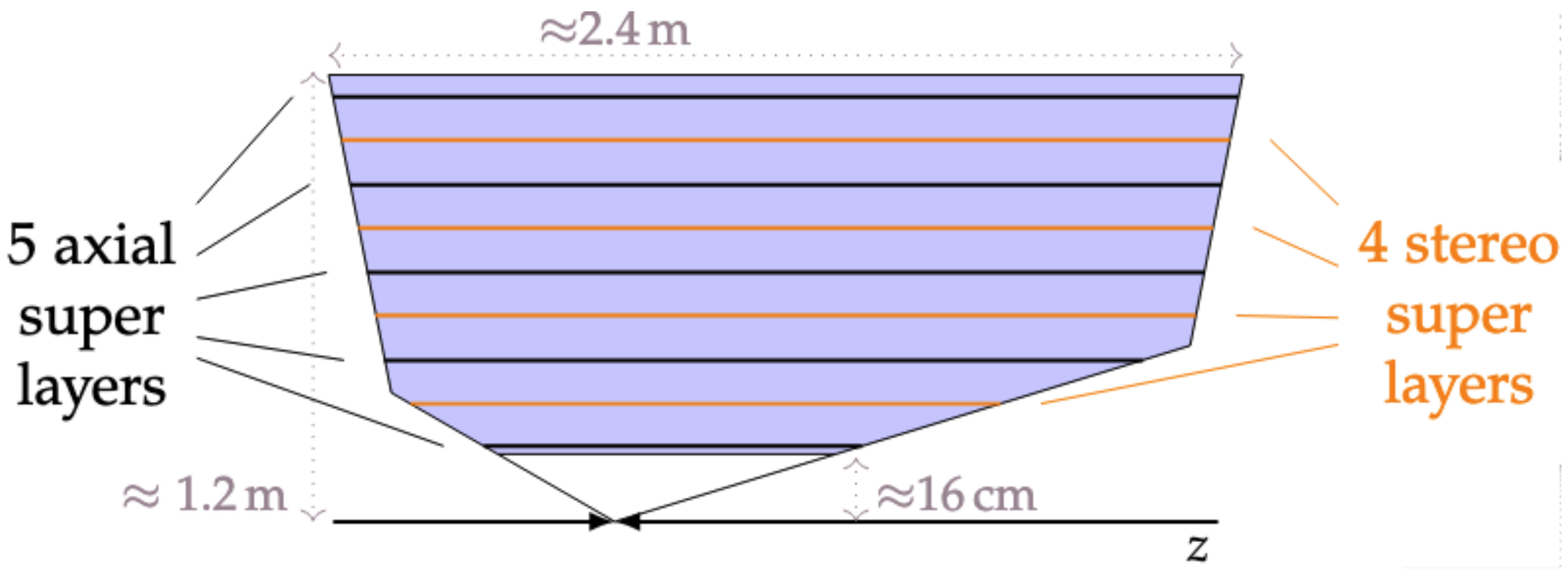
-Register access through VME

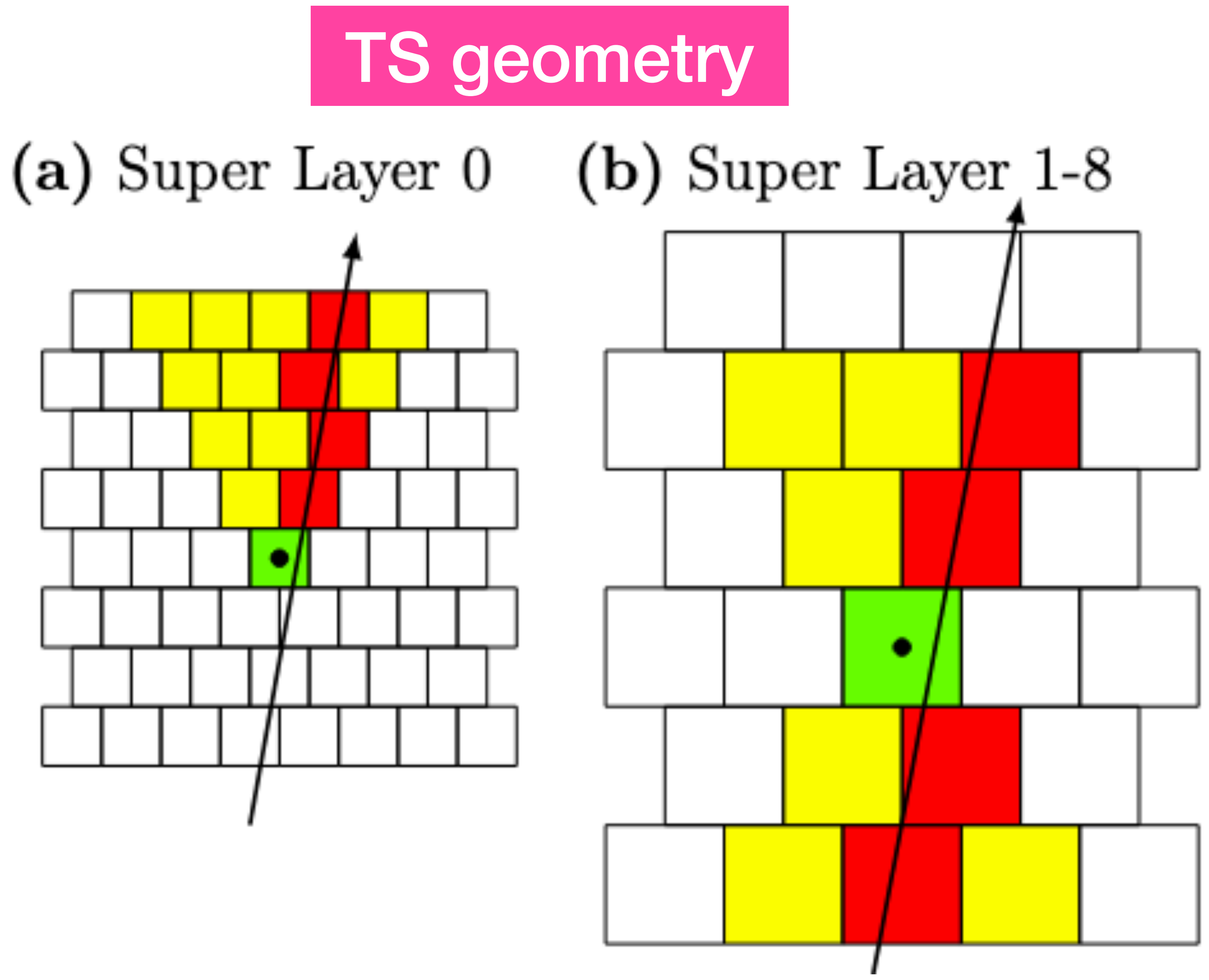
-Total ~30boards, common in subtrigger

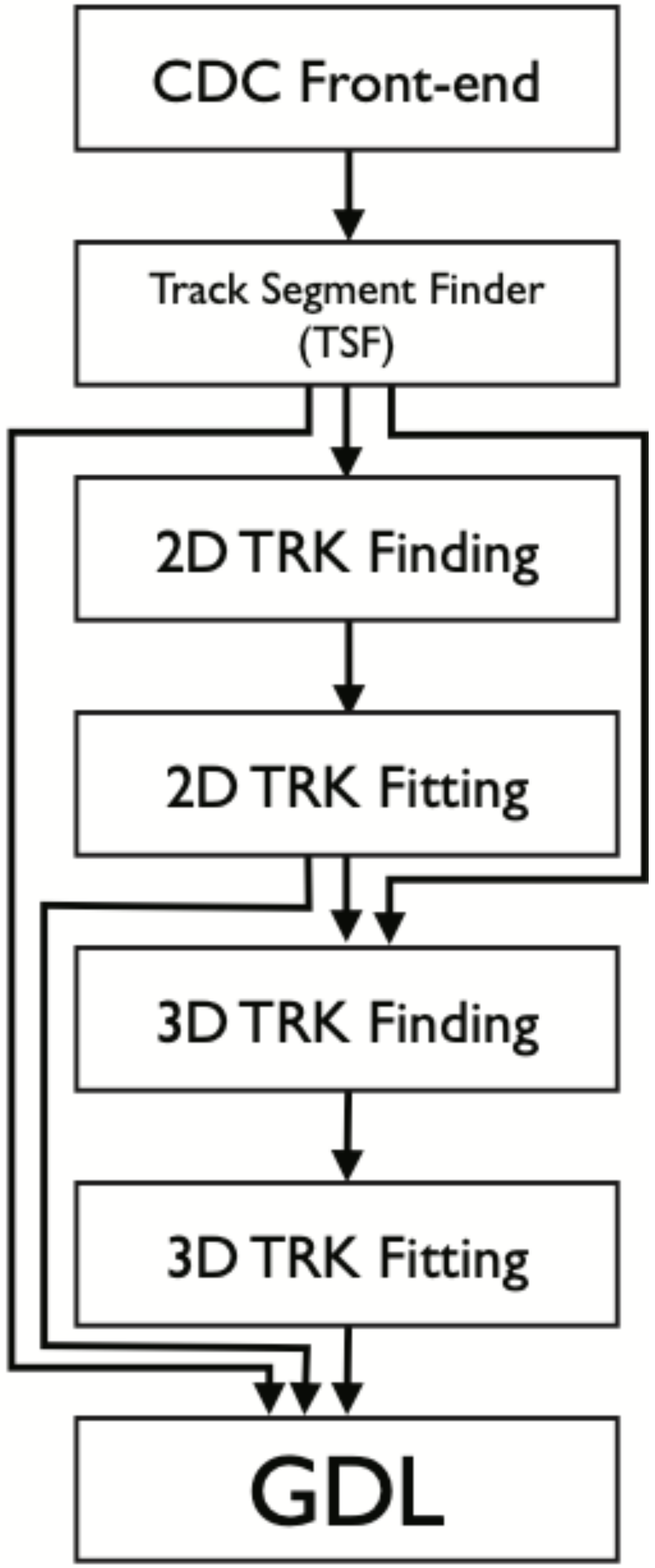
UT	3rd generation	4th generation
FPGA	Xilinx Virtex6 XC6VHX380/565T	Xilinx Virtex Ultrascale XCVU080/160
Logic gate	382k/580k	975k/2026k
IO	GTH 11Gbps × 24lane GTX 6Gbps × 40lane NIM, LVDS, RJ45 JTAG, VME bus	GTY 25Gbps × 32lane GTH 15Gbps × 32lane NIM, LVDS, RJ45 JTAG, VME bus

CDCTRG

Provides the charged track information



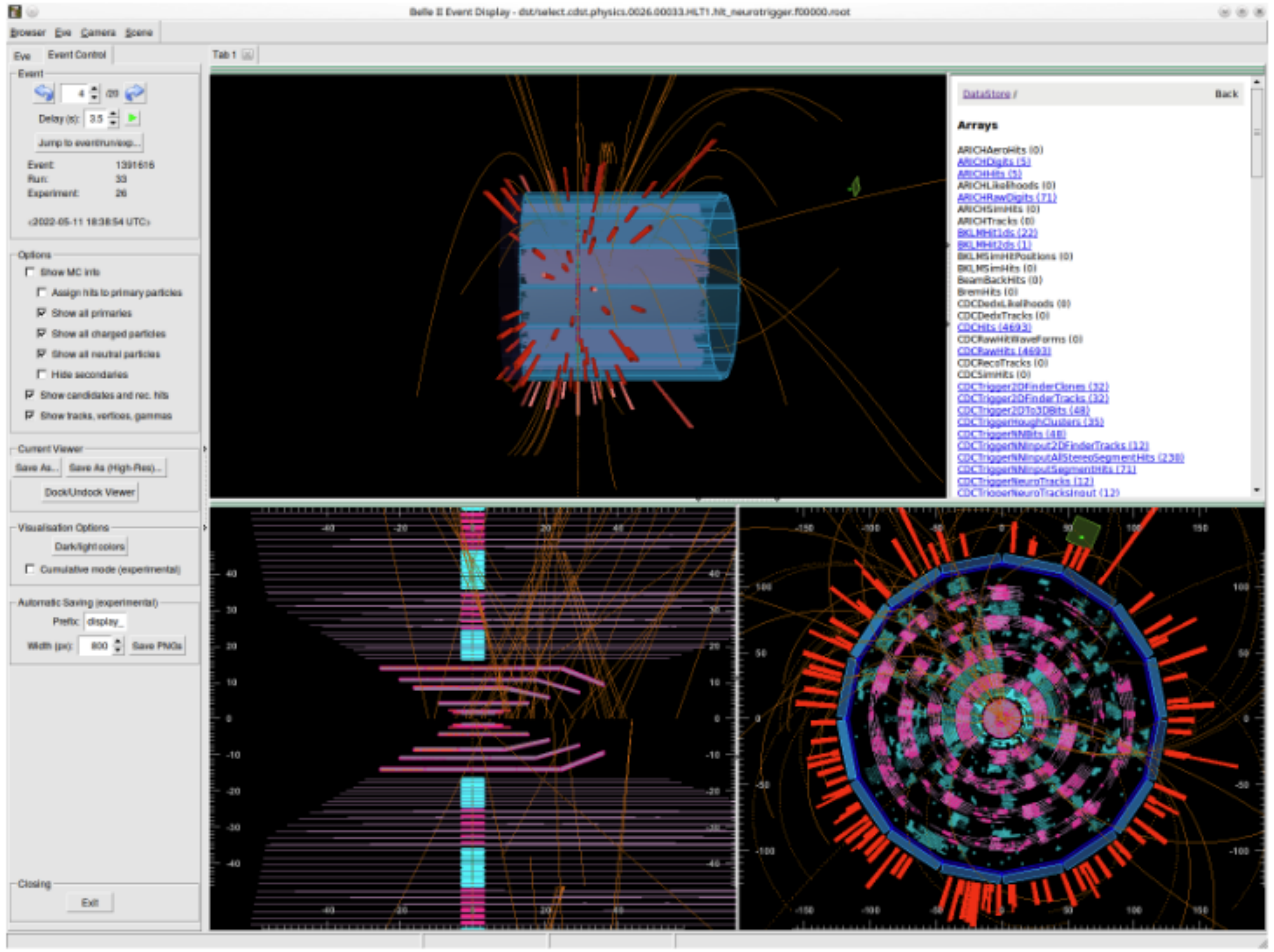


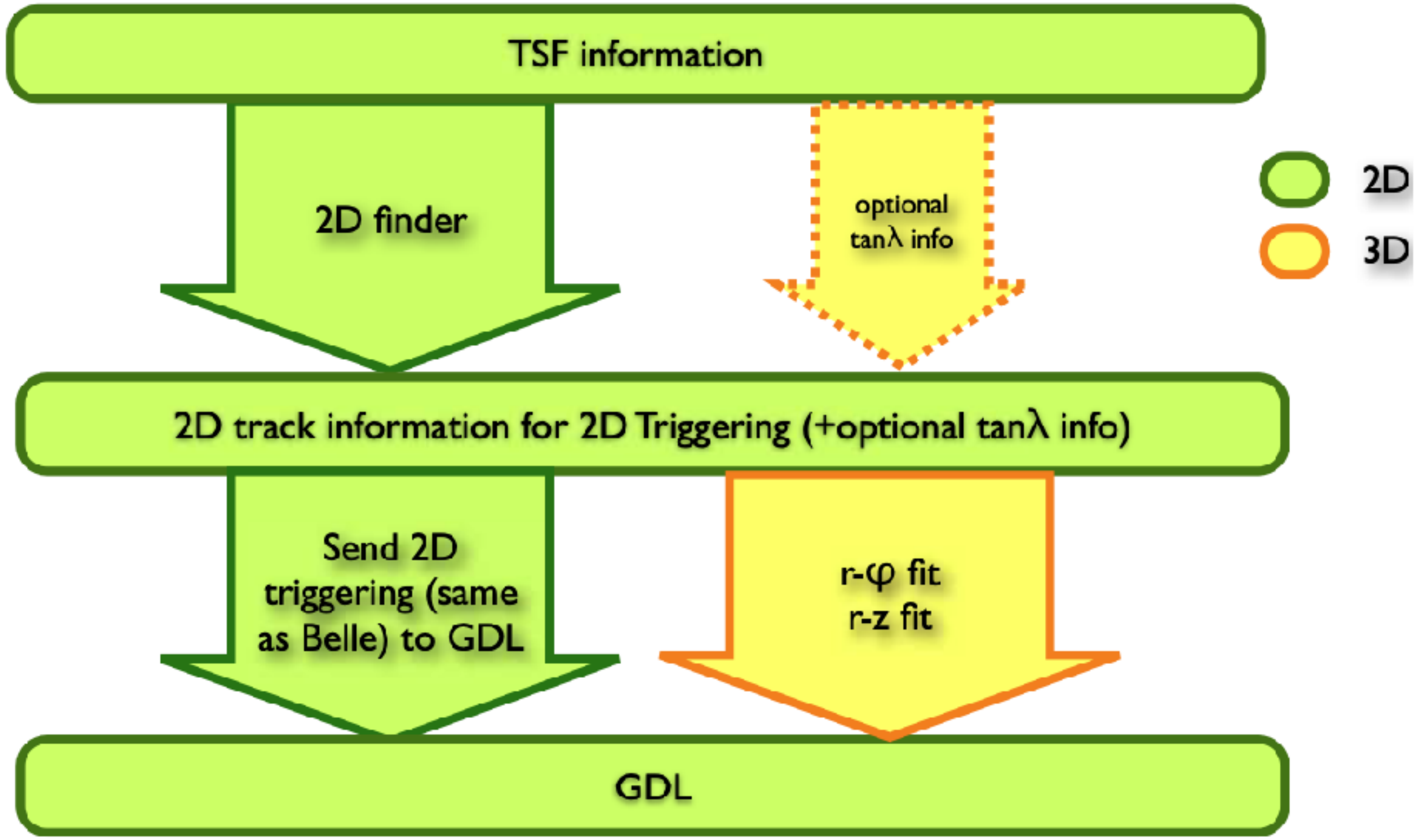


Wire hit information sent to TSF; 2336 TS in total.

TS hit is determined by look-up method.

Use conformal and Hough transformation to search for 2D tracks

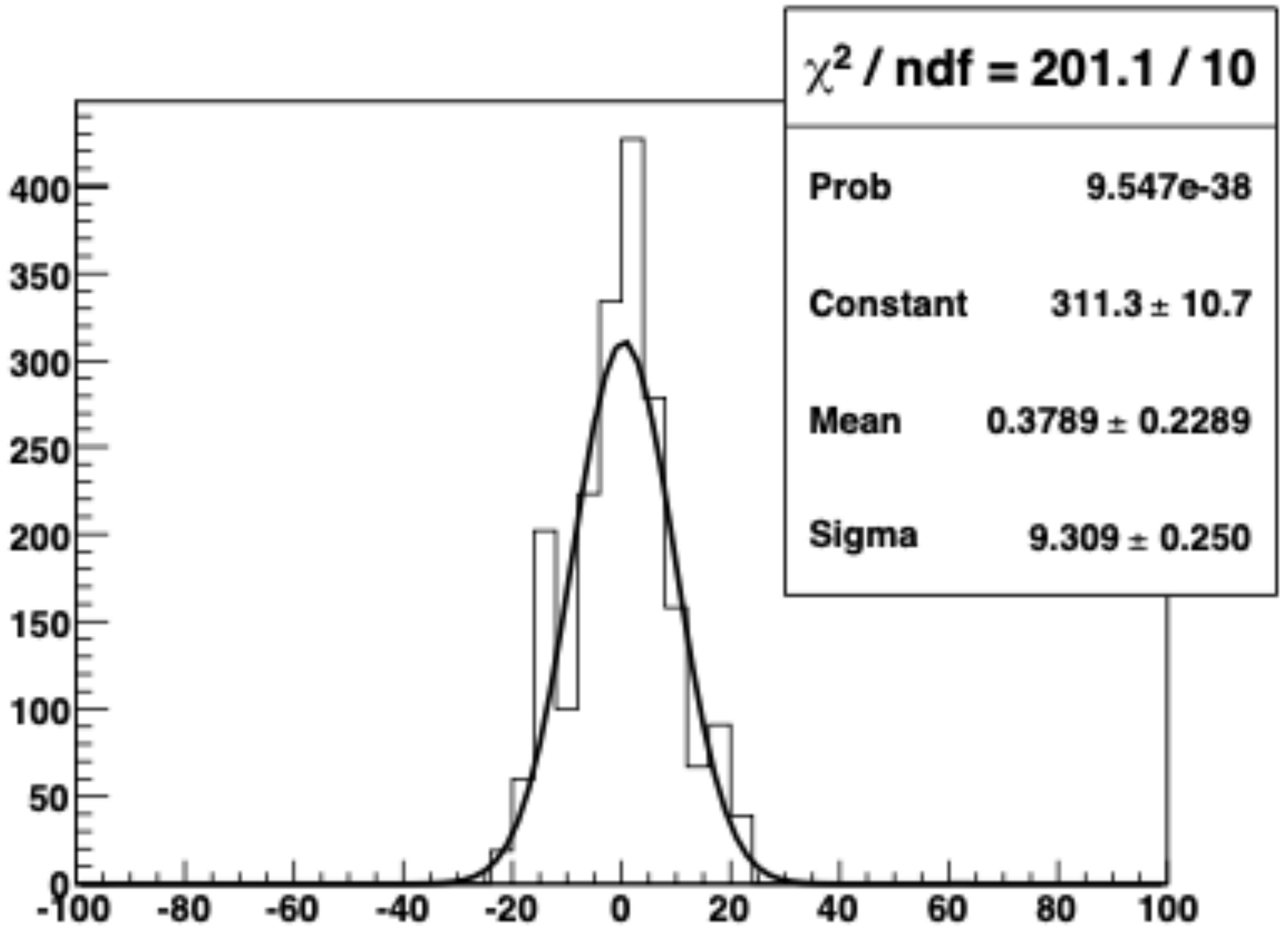




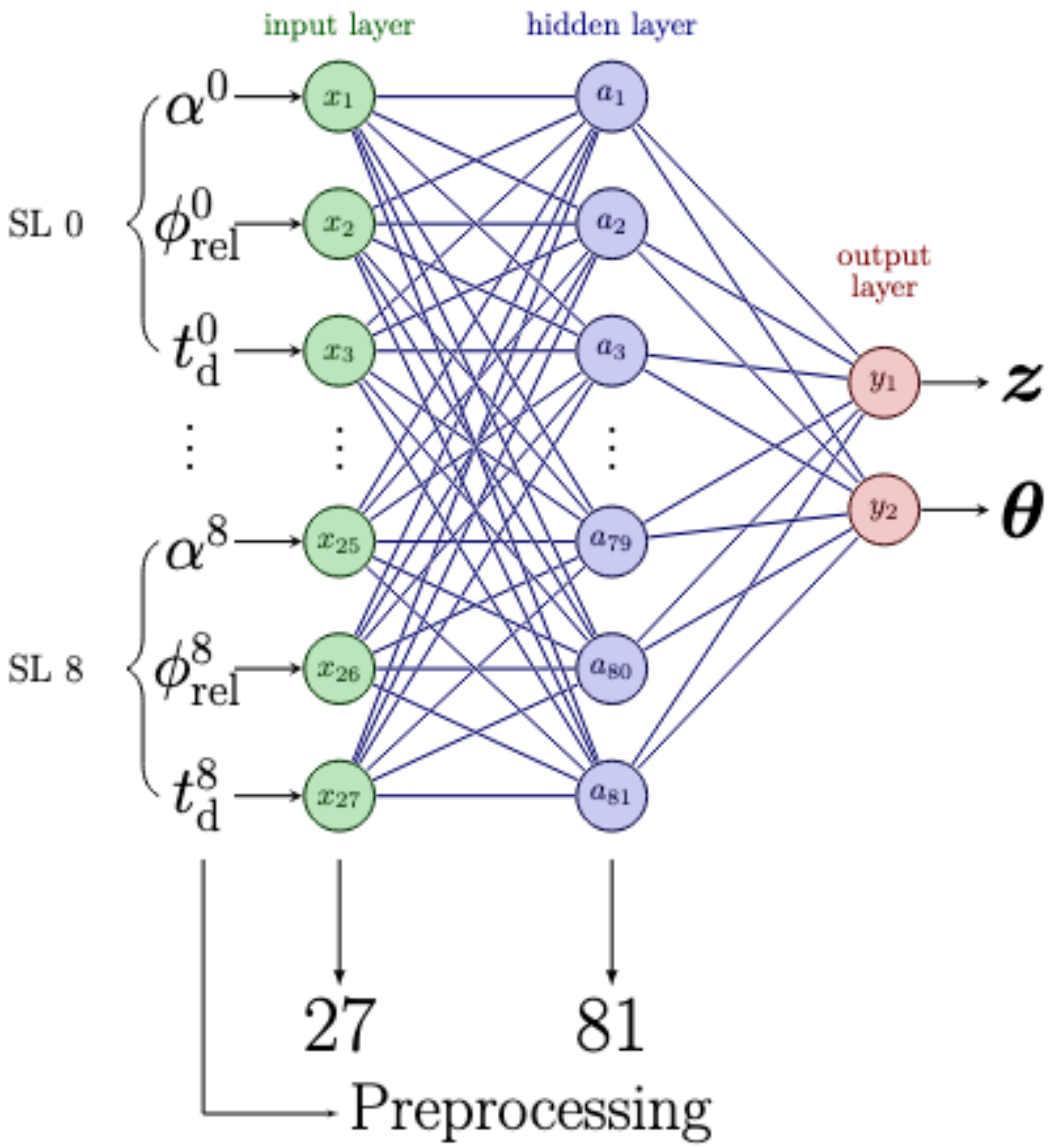
High Background: Large number of fake 2D track candidates.

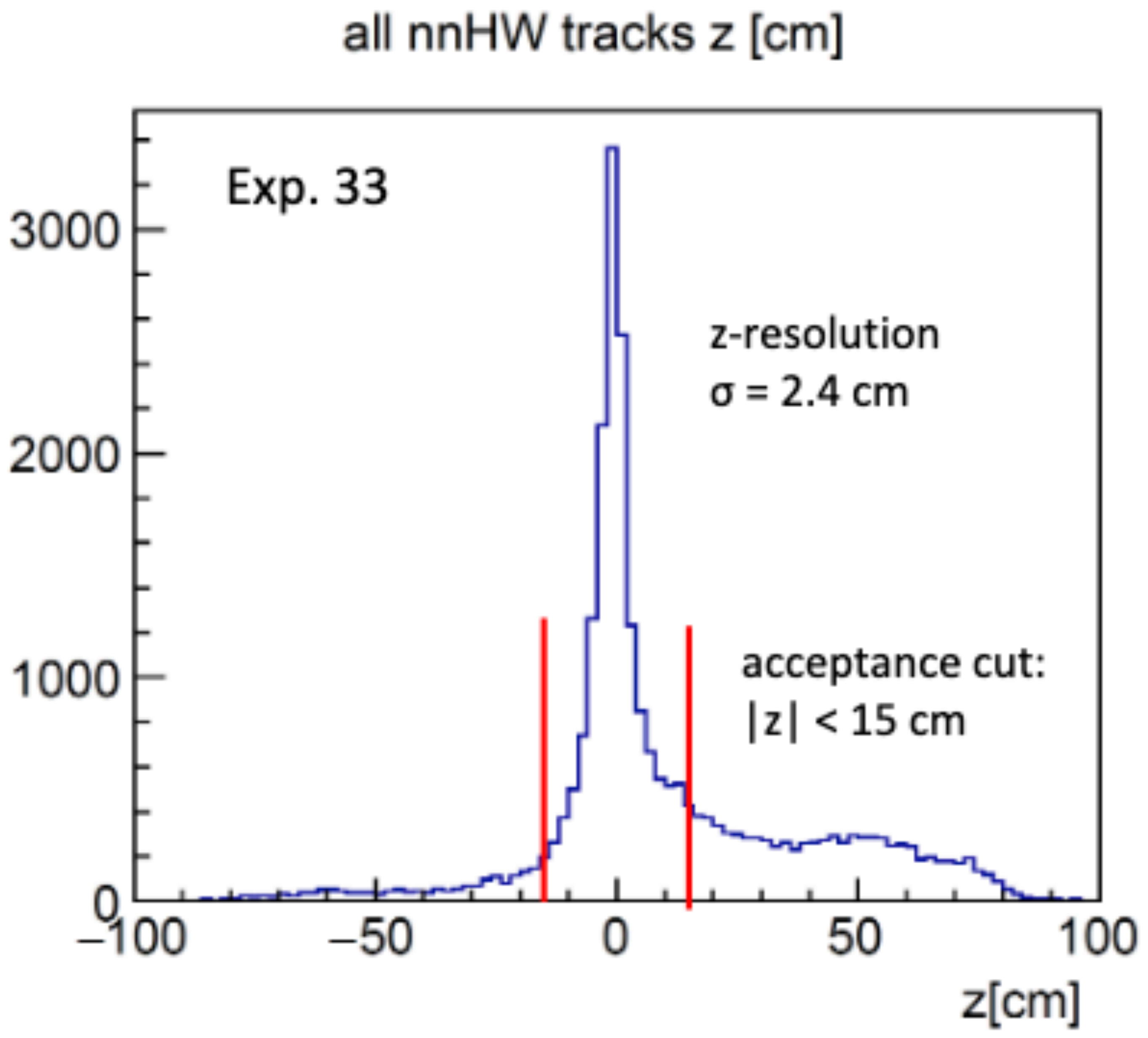
2-step 3D fitter: $r - \phi$ fit; $r - z$ fit

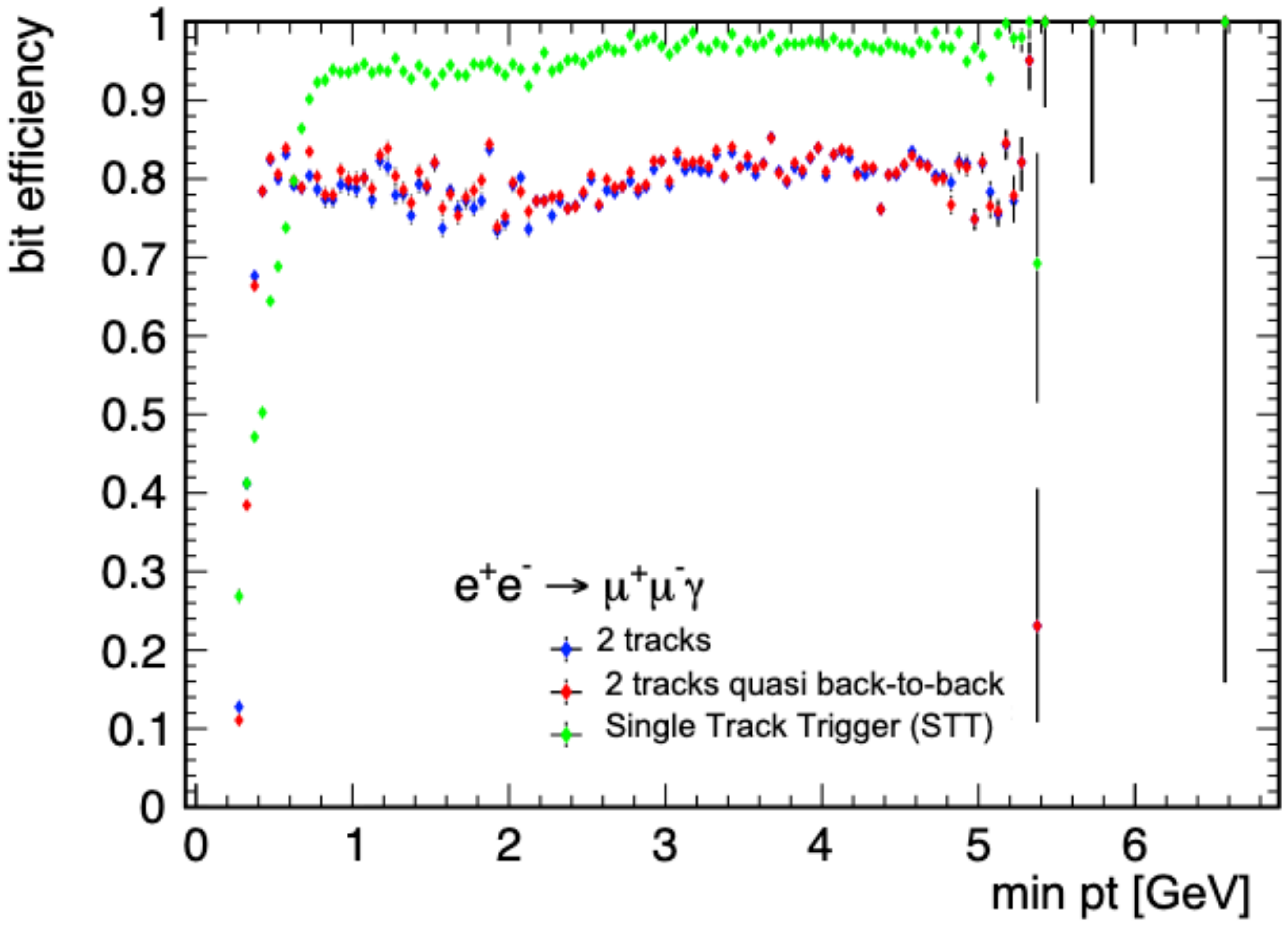
z_0 resolution ~10 cm



Neural network track trigger







Single-Track-Trigger:
$|z| < 15\,\mathrm{cm}$ and $p > 0.7\,\mathrm{GeV}$ (via θ)
(S. Bähr et al., arXiv:2402.14962,
NIMA 1073 (2025) 170279

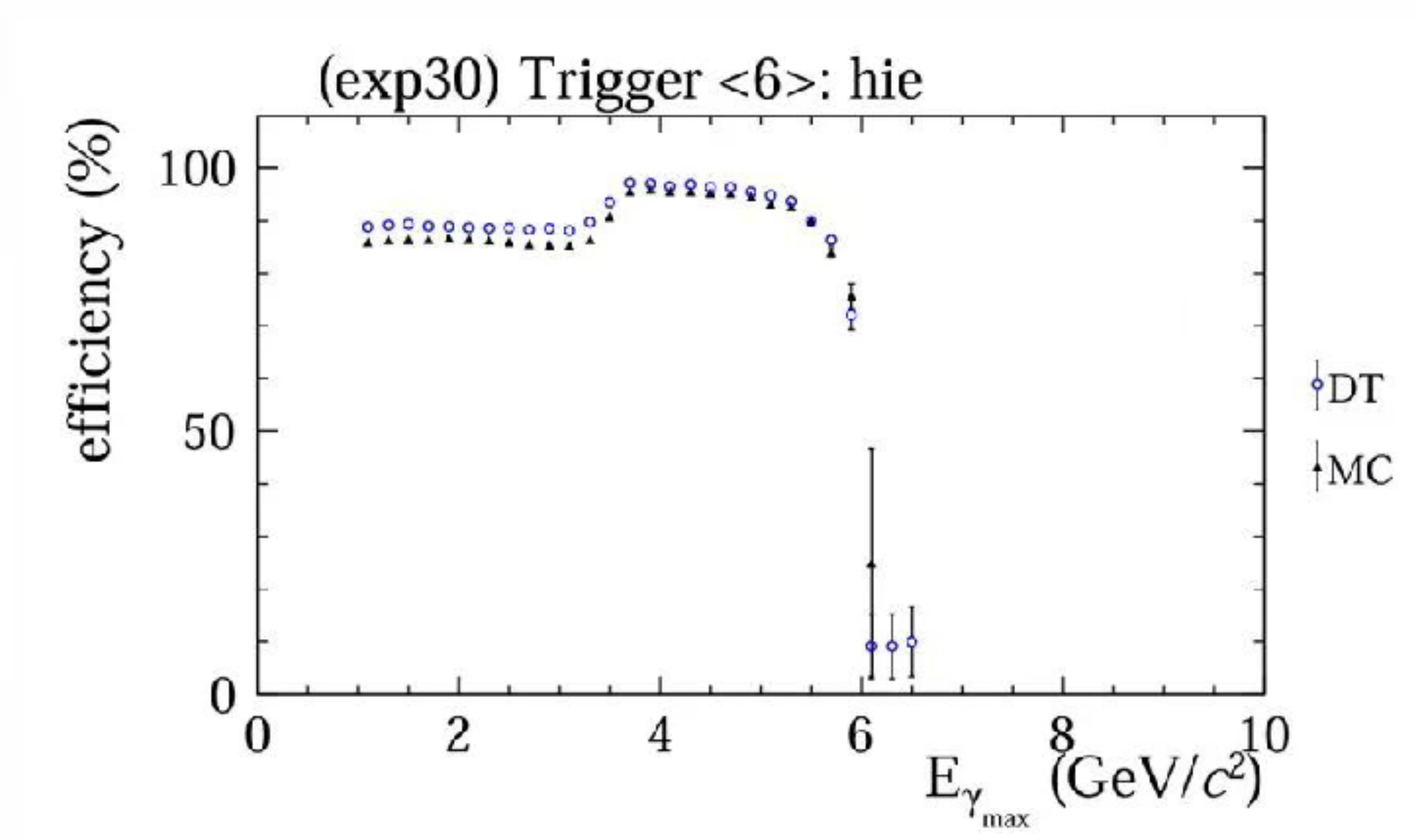
Better z_0 resolution with NN 3D track

Formally used in Belle II

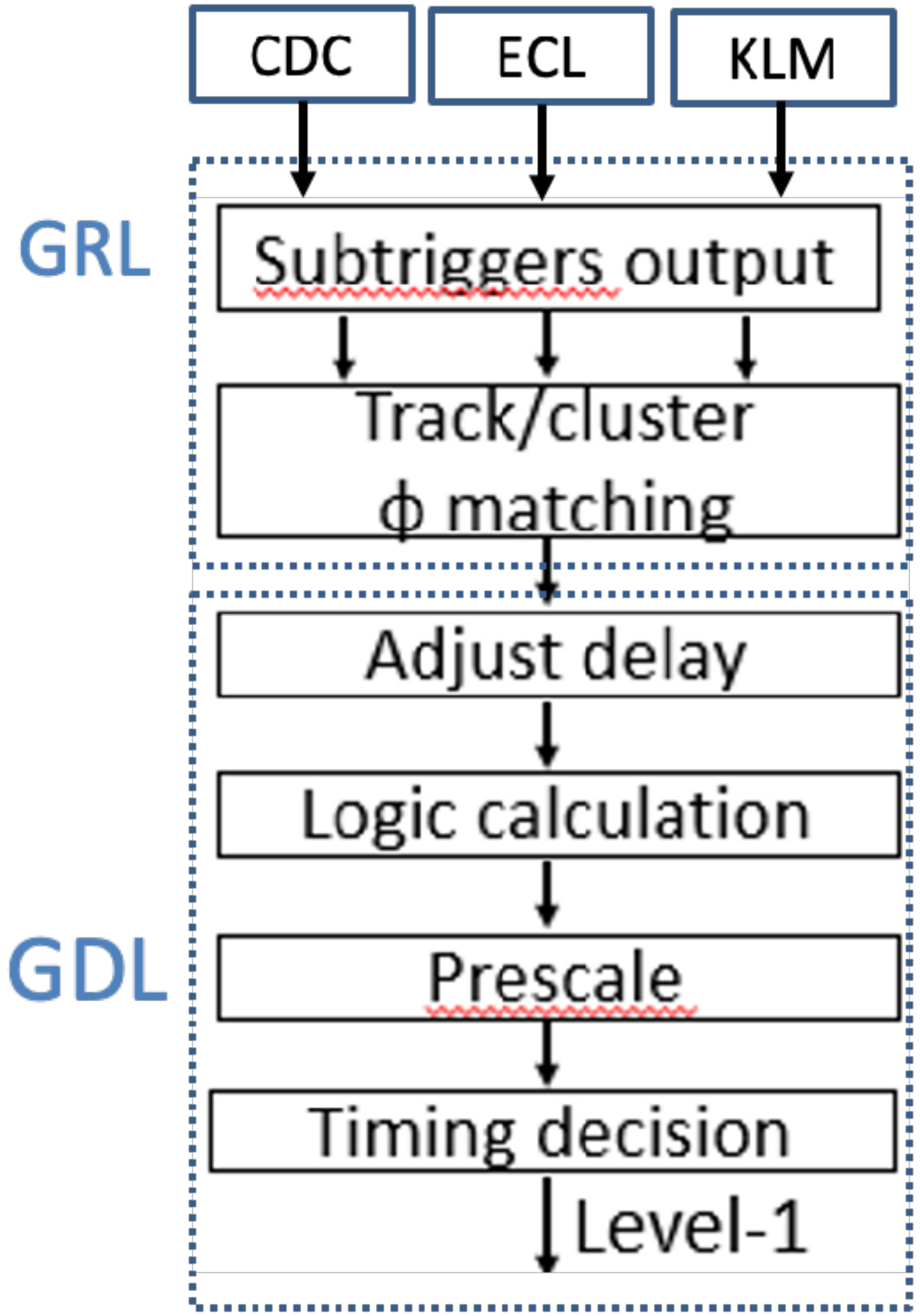
ECLTRG

- Generate fast signals for both neutral- and charged-particle
- Good timing resolution: ~7 ns determined by the most energetic trigger cell (TC)
- Two main schemes:
  - Total energy, sensitive to physics events with high electromagnetic energy deposit (i.e., hie)
  - Cluster counting, sensitive to multi-hadronic physics events (i.e., c4)
  - Also provide bhabha and $\gamma\gamma$ trigger

hie: Basic ECL trigger. Requires sum of trigger towers >1GeV, with 100 MeV threshold per tower.
- tower ≈ 4×4 crystals.
- sum is over θ_{ID}^{L1} range [2,15]
- Bhabha veto



Physics trigger



For example, bhabha events identification:

Two ECL clusters after fast reconstruction

$$\sum \theta_{CM} \in [165,\ 190],\ \Delta\phi_{CM} \in [160,\ 200]$$

(E1 > 3 GeV & E2 > 3 GeV) or (E1 > 4.5 GeV || E2>4.5 GeV)

Yes or No

One bit is sent

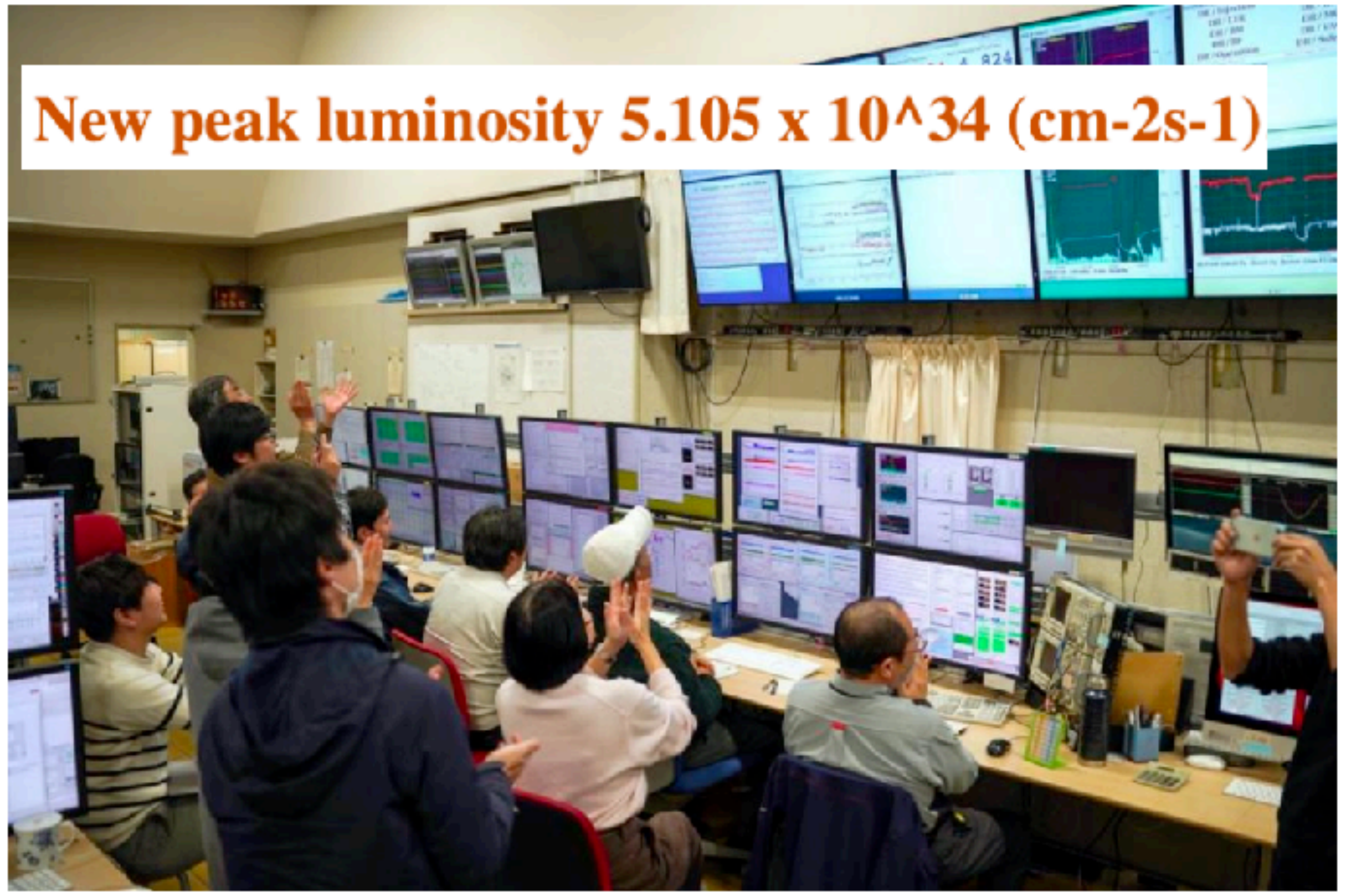
-GDL: Global decision logic
- -calculate if trigger condition (output bit) is satisfied or not with subtrigger input
- -apply prescale
- -If one of trigger bit satisfied, provide Level1 signal to take data

Now in Belle II have ~160 pre-defined trigger bits targeting to different physics events.

Close and frequent communication with physicists.

Challenge: High trigger rate and DAQ saturation

The Level-1 trigger rate has **reached a maximum exceeding 10 kHz.**
The luminosity was **less than one-tenth of the target luminosity.**



Revealing potential risks of **DAQ saturation** in future operations.

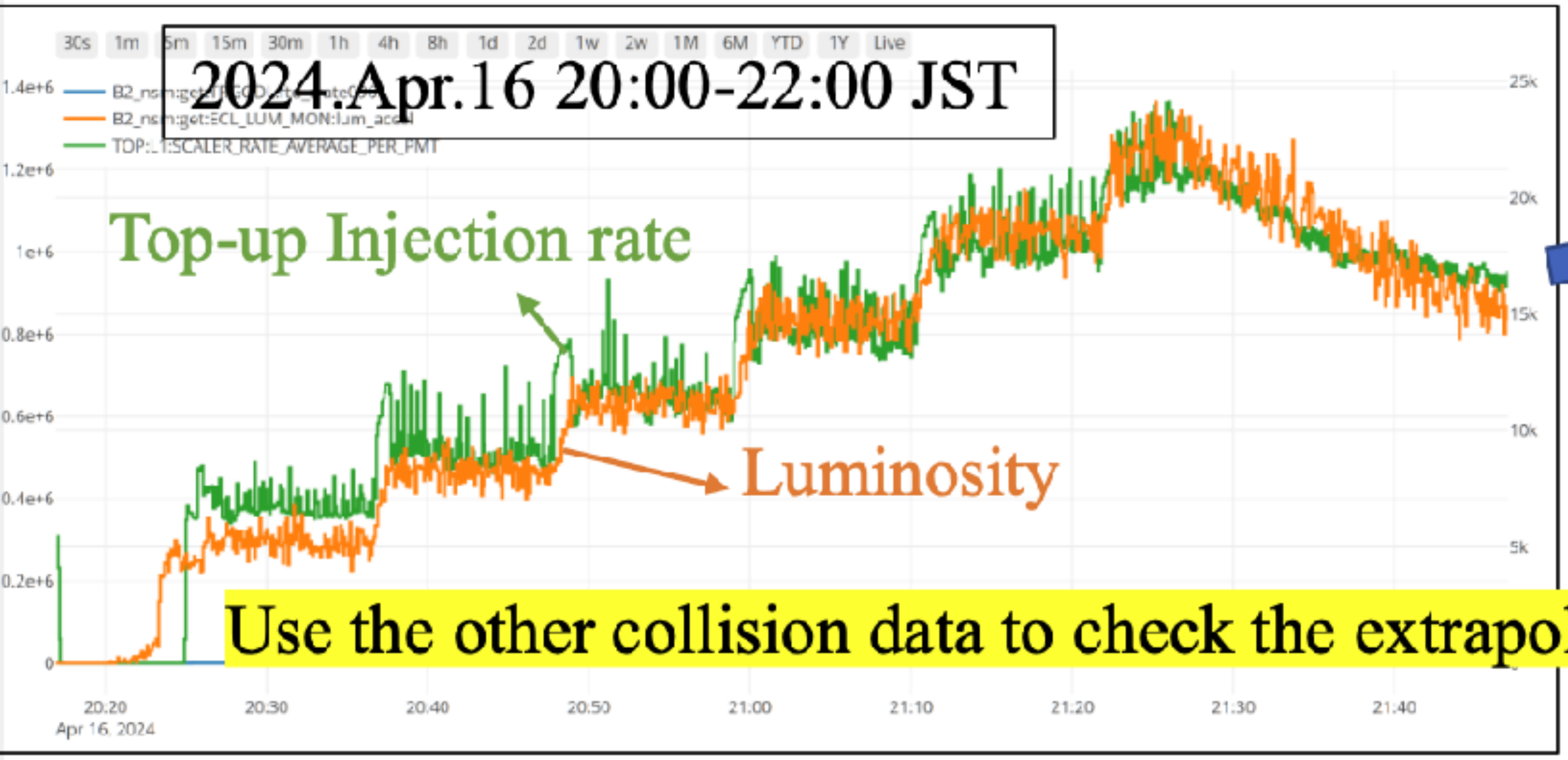
Date	L	**L1-Trigger**
Exp20 Run905	$\sim 2.0 \times 10^{34} cm^{-2}s^{-1}$	~ 11 kHz
2024c	$\sim 3.2 \times 10^{34} cm^{-2}s^{-1}$	~ 6 kHz
Before-LS2	$\sim 2.8 \times 10^{35} cm^{-2}s^{-1}$	**Requirement < 30 kHz**
LS2	$\sim 6.0 \times 10^{35} cm^{-2}s^{-1}$	**Requirement < 30 kHz**

To facilitate future data acquisition, we must ensure that TRG system:
① **operates in a high-performance status**
② **and will not exceed the trigger limitation.**

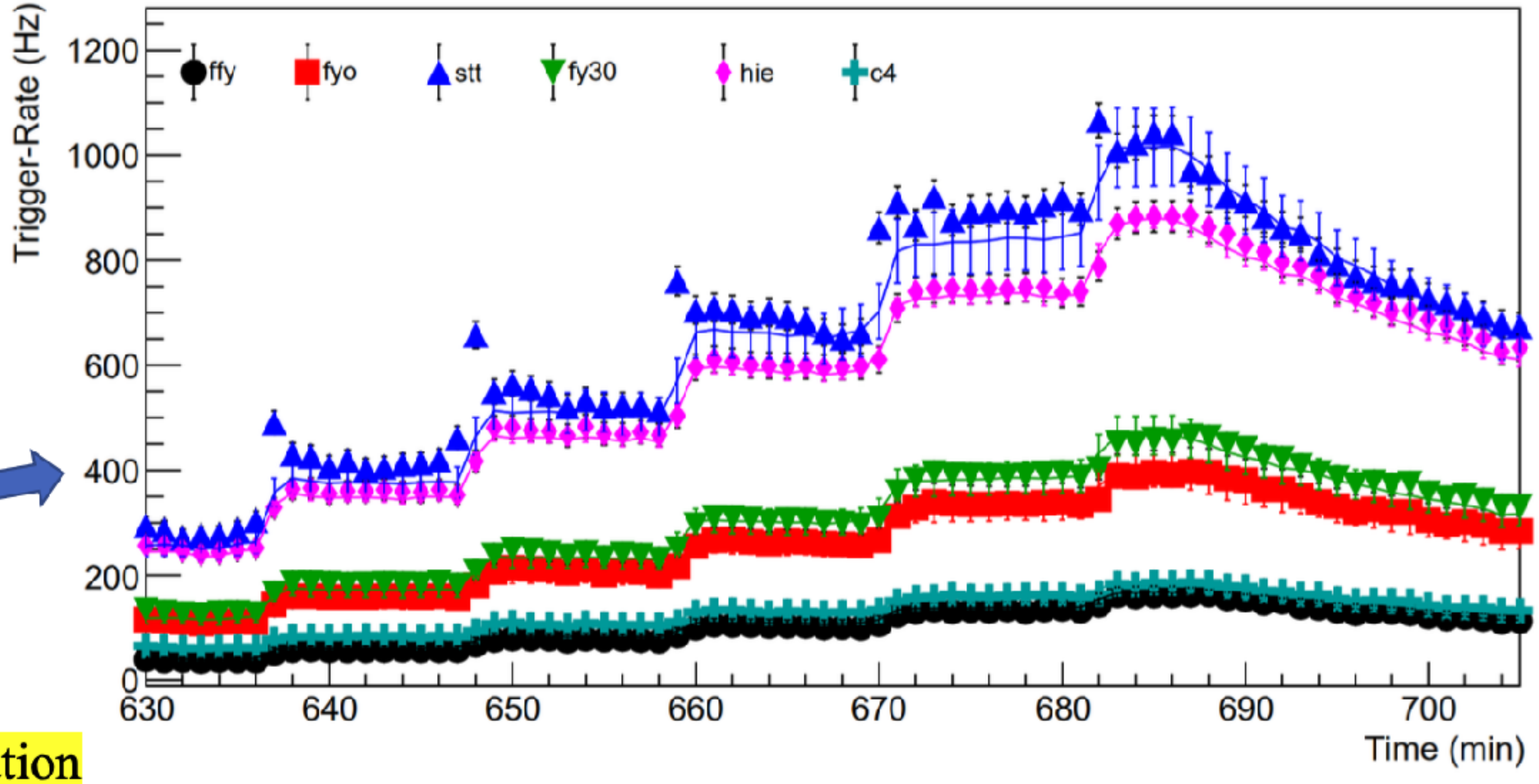
TRG Rate extrapolation

Extrapolation: $\mathcal{R}_{\mathrm{bit}} = \overline{D} + \boldsymbol{T}^{\mathbf{LER}} \times \left(\frac{I^2}{n_{\mathrm{b}}\sigma_{\mathrm{x}}^{*}\sigma_{\mathrm{y}}^{*}\sigma_{\mathrm{z}}^{*}}\right)^{\mathrm{LER}} + \boldsymbol{T}^{\mathbf{HER}} \times \left(\frac{I^2}{n_{\mathrm{b}}\sigma_{\mathrm{x}}^{*}\sigma_{\mathrm{y}}^{*}\sigma_{\mathrm{z}}^{*}}\right)^{\mathrm{HER}} + \boldsymbol{B}^{\mathbf{LER}} \times (I\overline{P}_{\mathrm{eff}})^{\mathrm{LER}} + \boldsymbol{B}^{\mathbf{HER}} \times (I\overline{P}_{\mathrm{eff}})^{\mathrm{HER}} + \boldsymbol{\kappa} \times \mathcal{L}$

*The dots with shapes are experimental trigger rate.
*The curves with statistical errors are extrapolation.



Use the other collision data to check the extrapolation



$$\mathcal{R}_{\mathrm{L1}} = \Sigma f_i \times \mathcal{R}_i$$

where $\mathcal{R}_i$ is the individually extrapolated rate for the i^{th} bit and the factor $\boldsymbol{f_i} \equiv \frac{\mathcal{R}_i^{\mathrm{Exclusive}}}{\mathcal{R}_i^{\mathrm{Raw}}} \in [0,1]$ quantifies effective trigger rate after overlap exclusion. $\boldsymbol{\mathcal{R}_i^{Raw}}$ **is the raw rate** of the individual trigger measured in the experiment, while $\boldsymbol{\mathcal{R}_i^{\mathrm{Exclusive}}}$ **is obtained by excluding events that trigger simultaneously with other bits.**

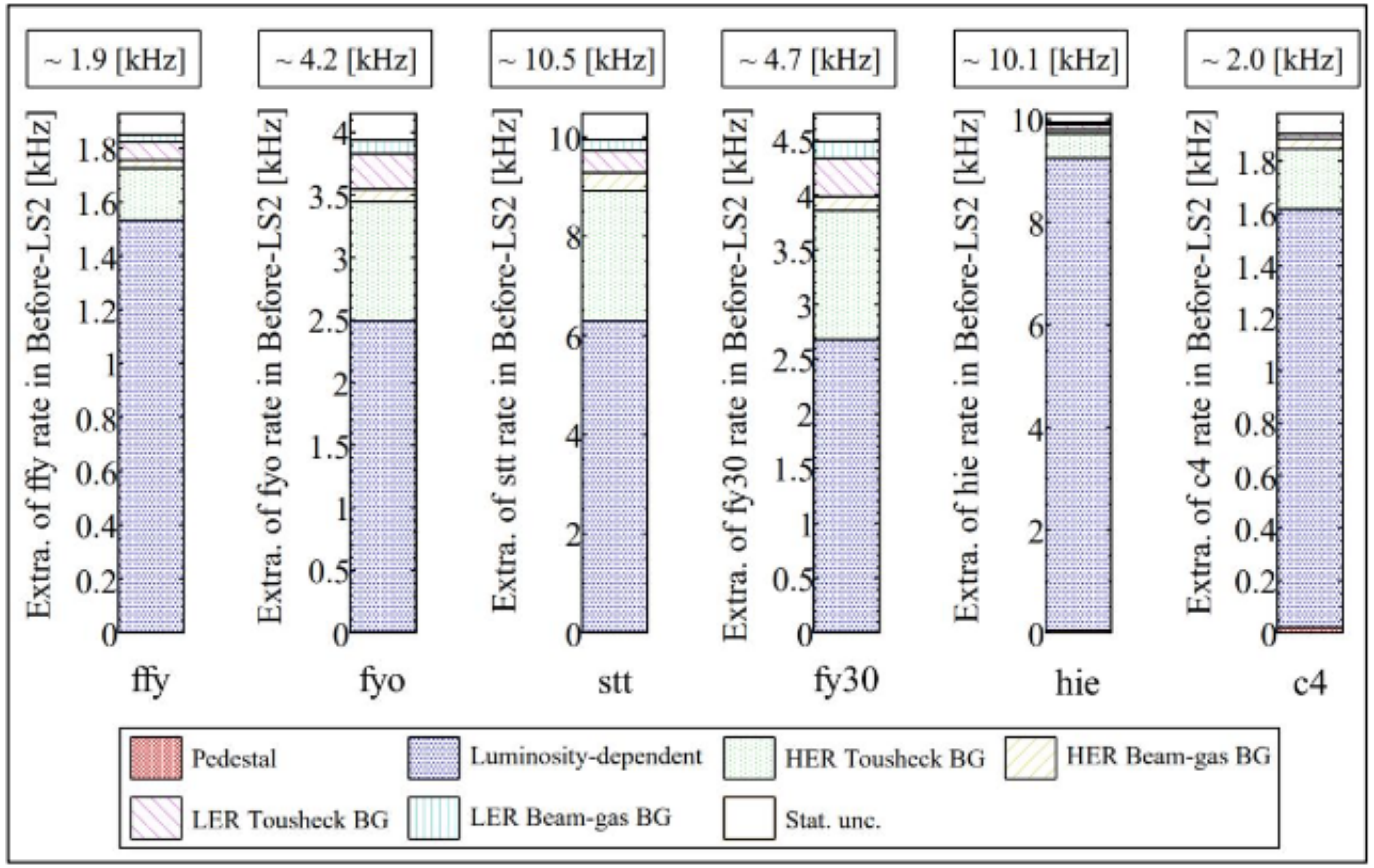


Fig. The extrapolation to Before-LS2

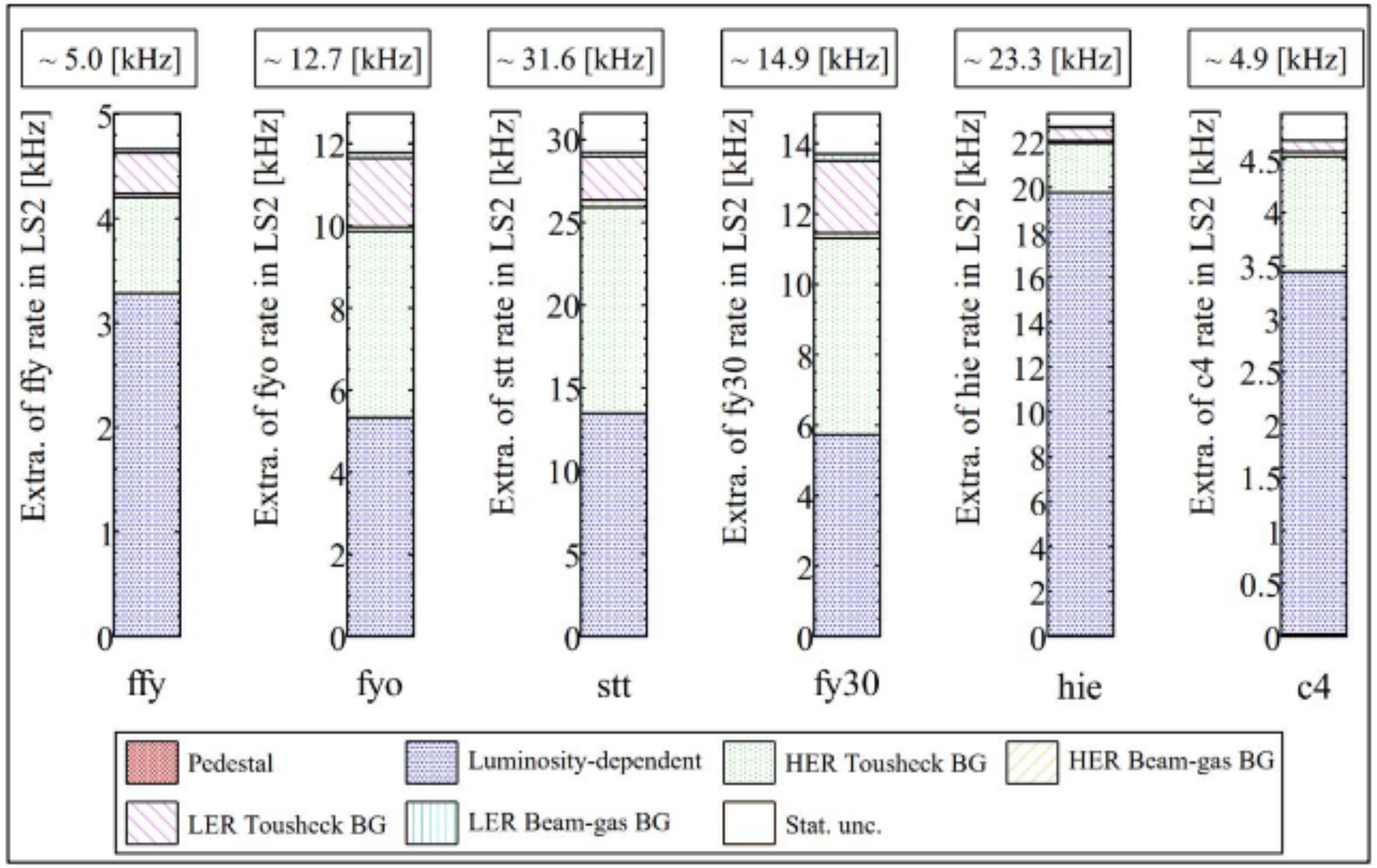


Fig. The extrapolation to LS2

$\mathcal{R}_{\mathrm{L1}}$ ~13kHz @ $2.8 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$(Before-LS2)

$\mathcal{R}_{\mathrm{L1}}$ ~32kHz @ $6.0 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$(LS2)

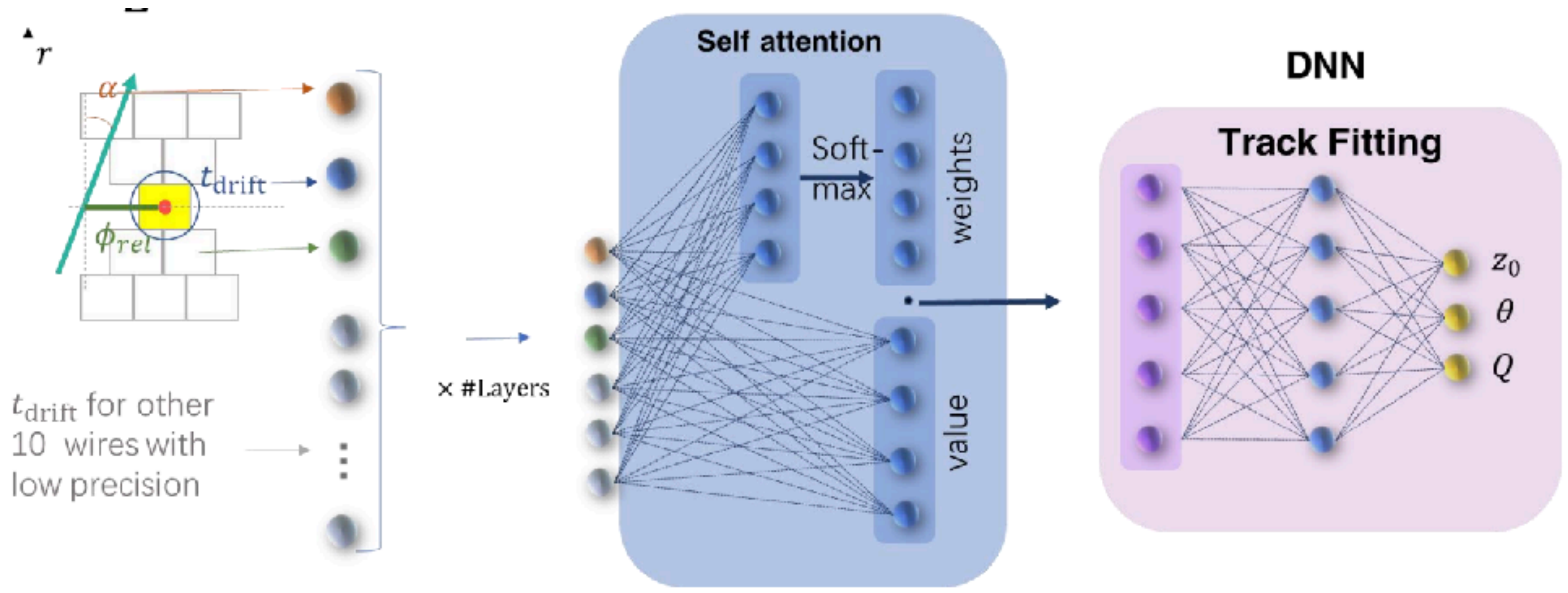
CDCTRG

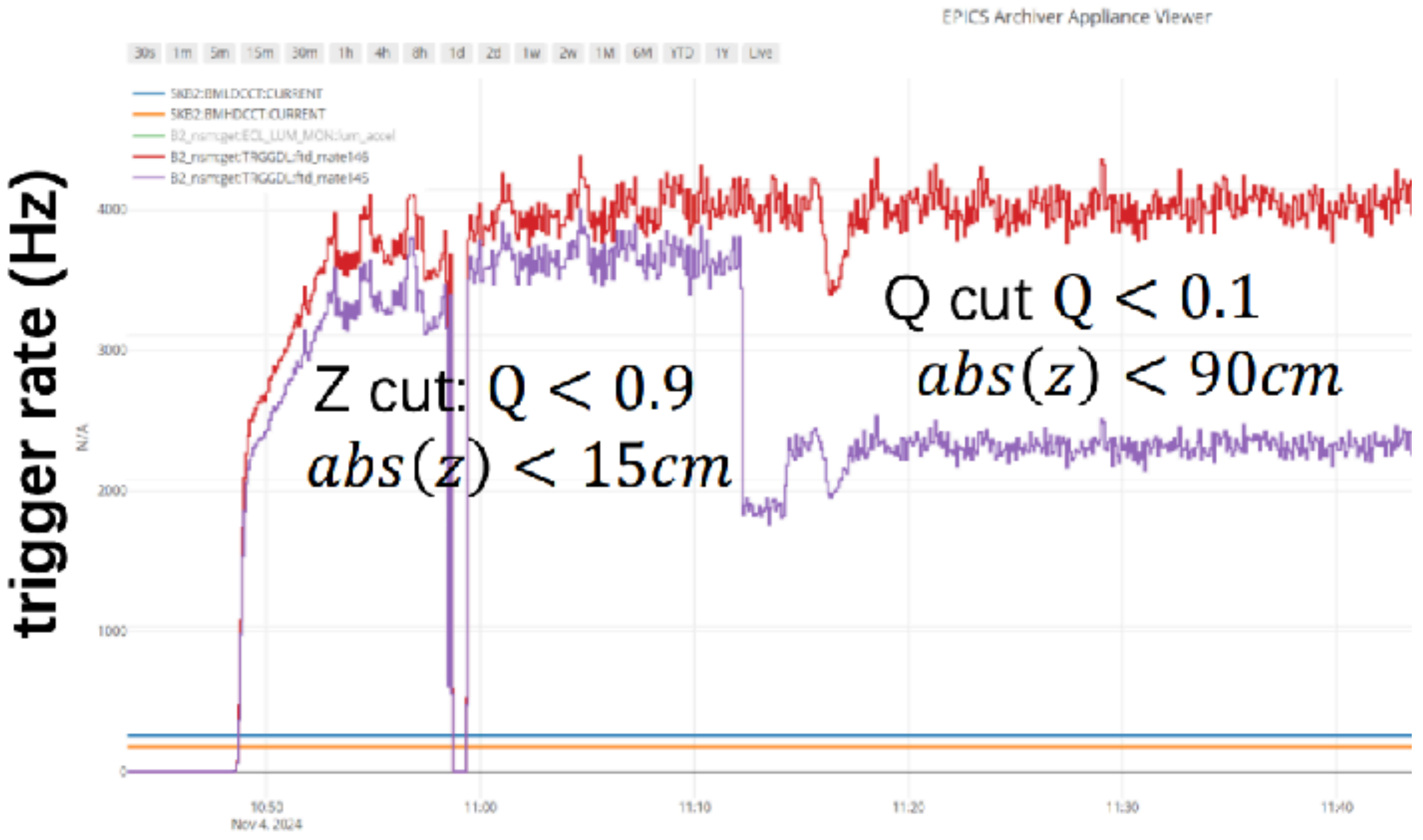
DNN track

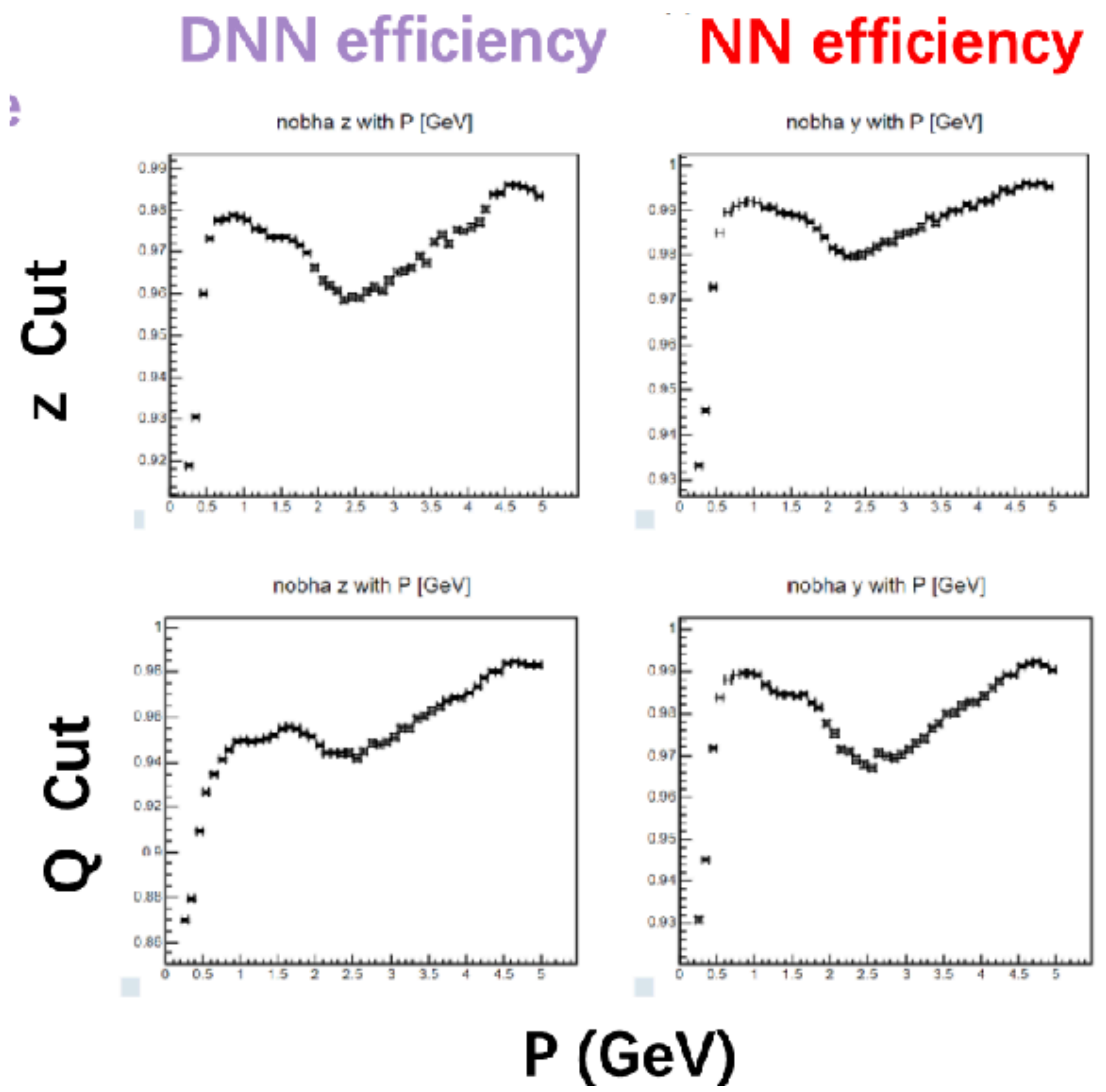
DNN track trigger is developed with

- Additional inputs
- New architecture
- Higher complexity and higher depth
- New output Q

71 inputs: α, t_{drift}, ϕ_{rel} from 9 SLs & extra t_{drift} from 4 stereo SLs

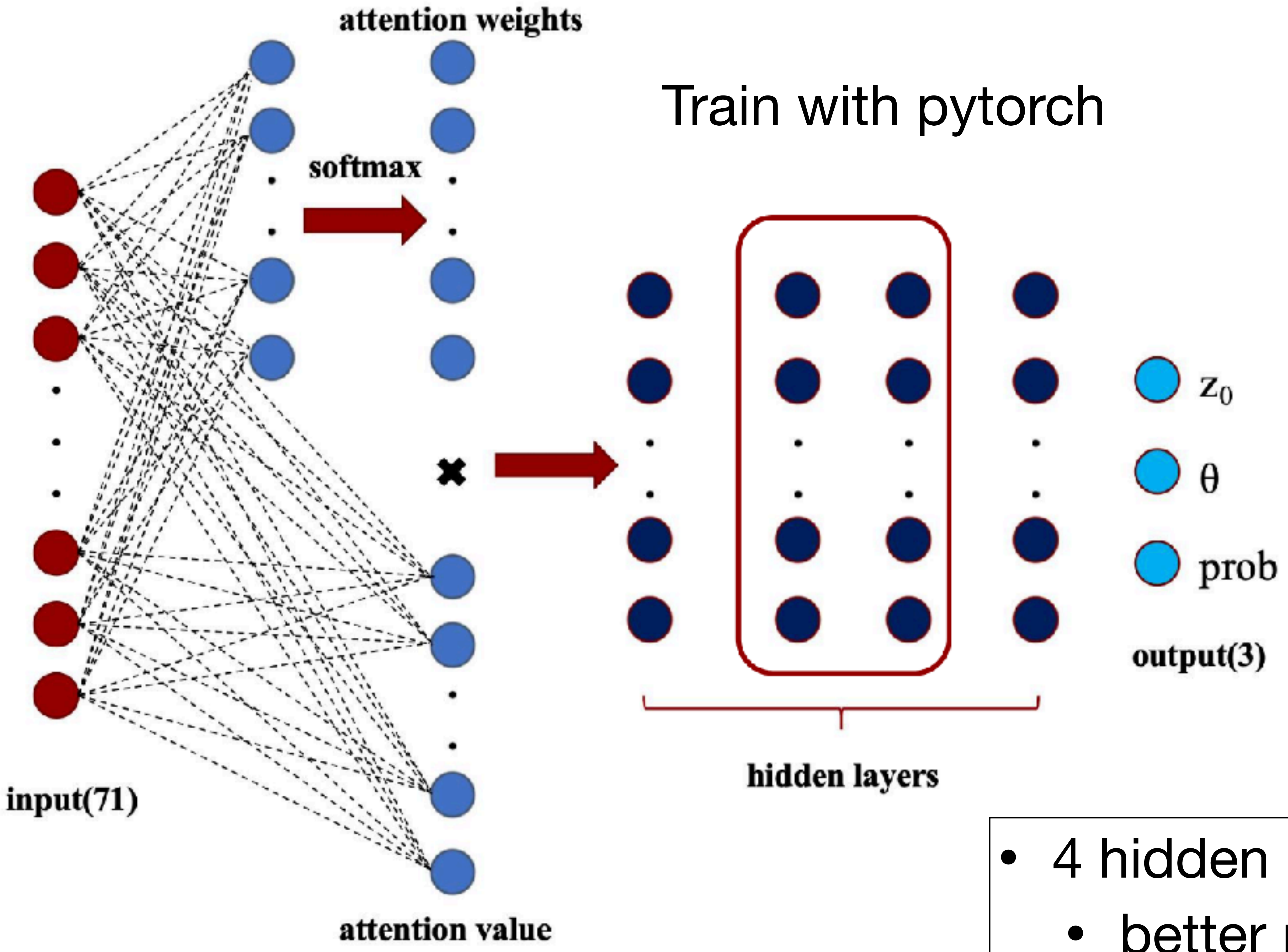




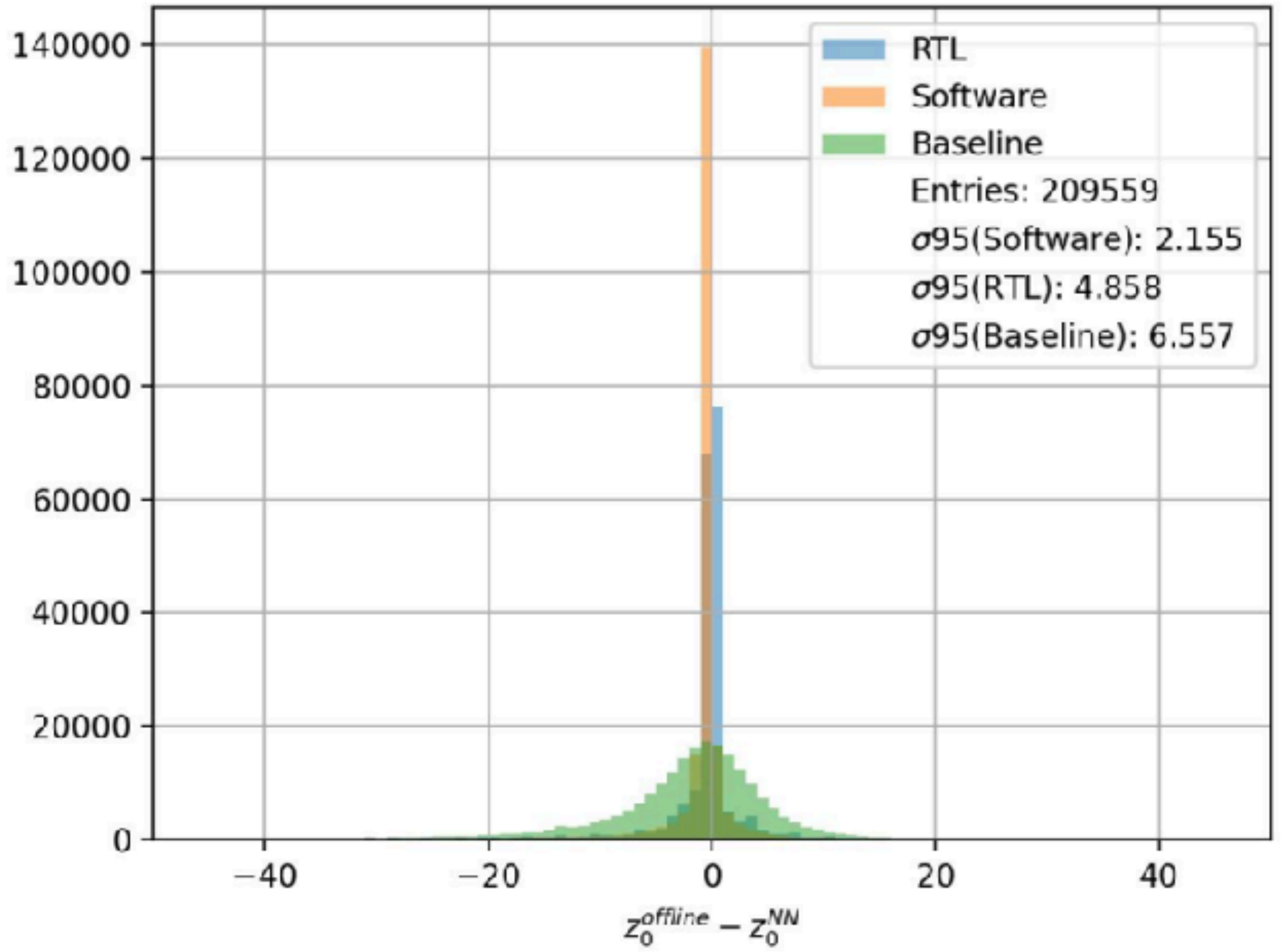


CDCTRG

DNN track



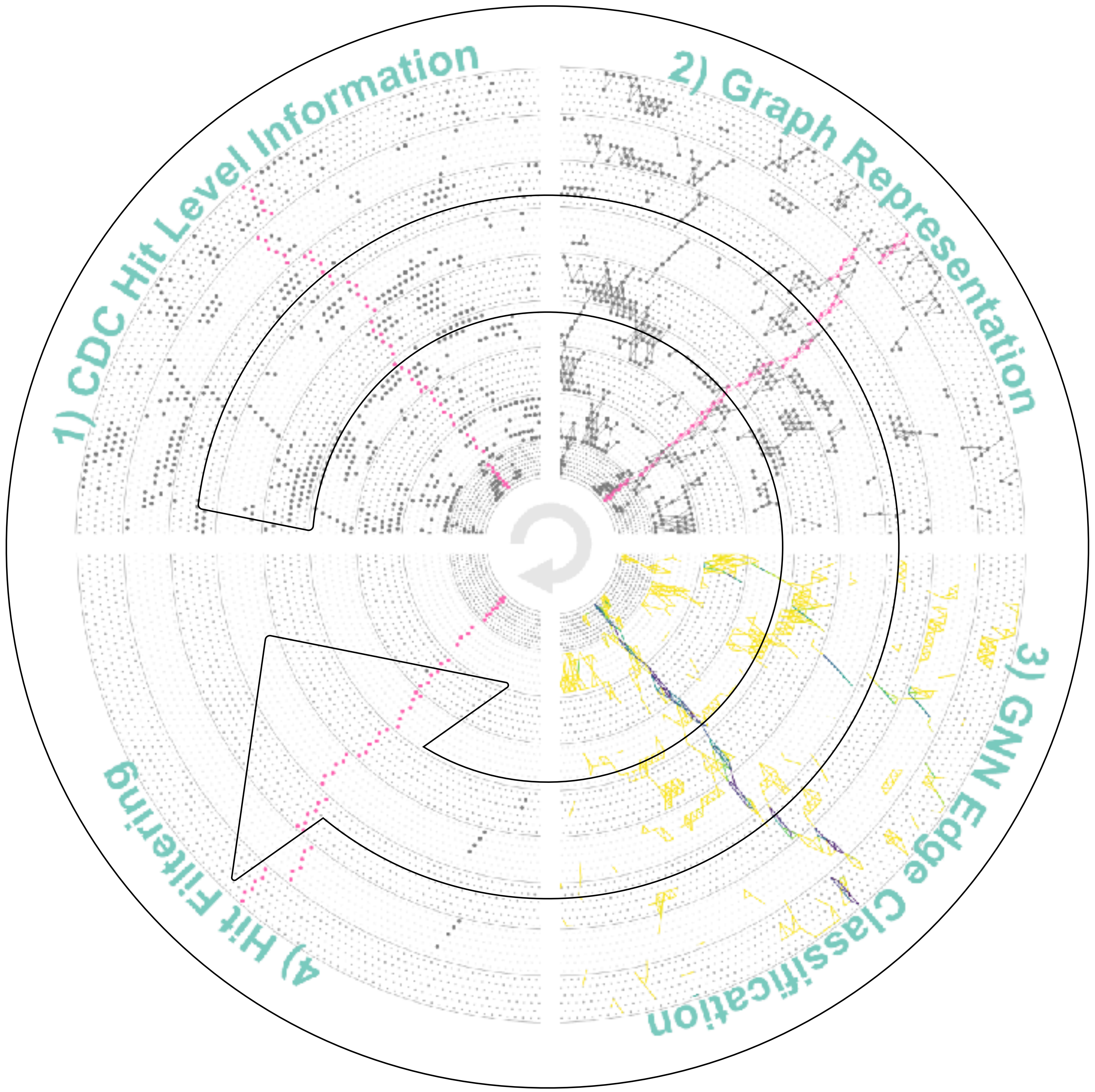
Train with pytorch



	Initial	quantization
LUT	858308(95.38%)	686,780(76.32%)
DSP	572(29.06%)	318(16.16%)
latency	637.8 ns	582.7 ns

- 4 hidden layers
  - better performance
- Per channel symmetric quantization
  - optimize hardware resources and reduce latency

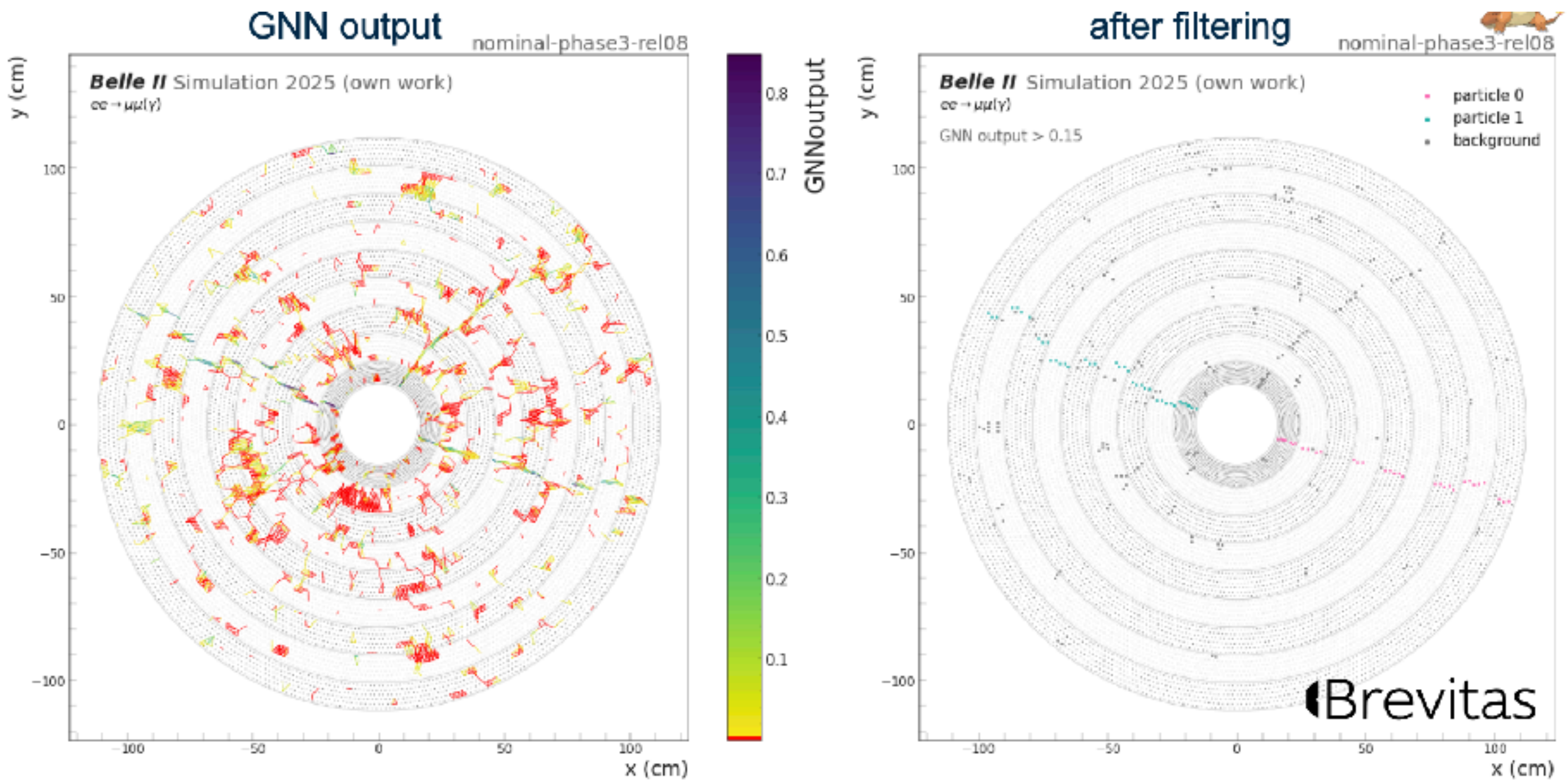
CDCTRG hit cleanup



Target: clean up background CDCTRG hits

Plug before Track Segment Finder (TSF)

- Quantisation (NeuraLUT || Brevitas) needed to fulfill hardware constraints.
- Results looks promising and stable.



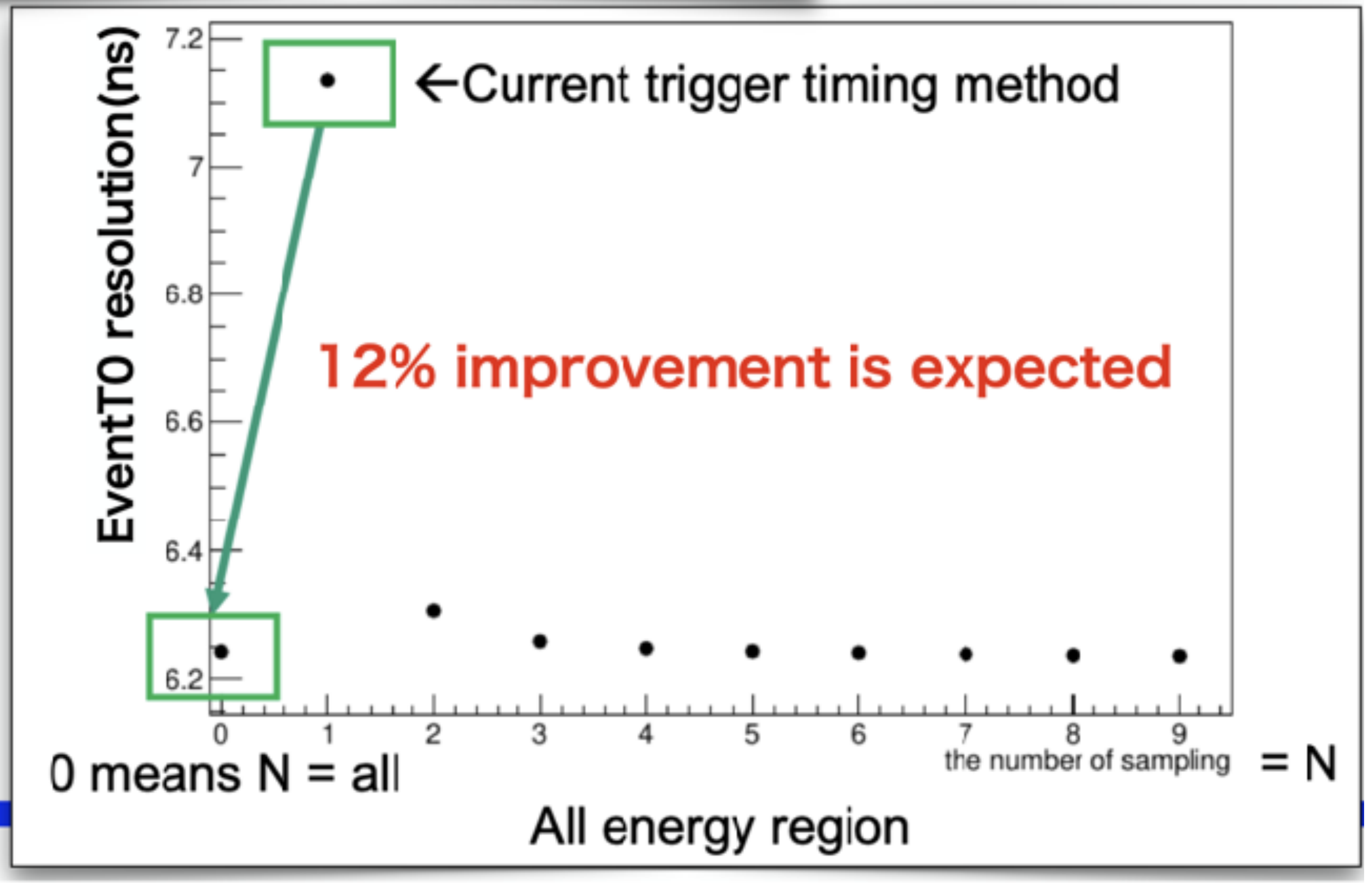
In developing/testing/debugging

ECLTRG

New event timing logic

- Target: "good" resolution of L1 timing for SVD to reduce dead time
- Event timing in ecltrg was determined by timing of most energetic TC
- Check the resolutions for energy weighted TC timing by varying N(TC)

$$(\text{trigger timing}) = \frac{\Sigma_i^N E_i t_i}{\Sigma_i^N E_i}$$



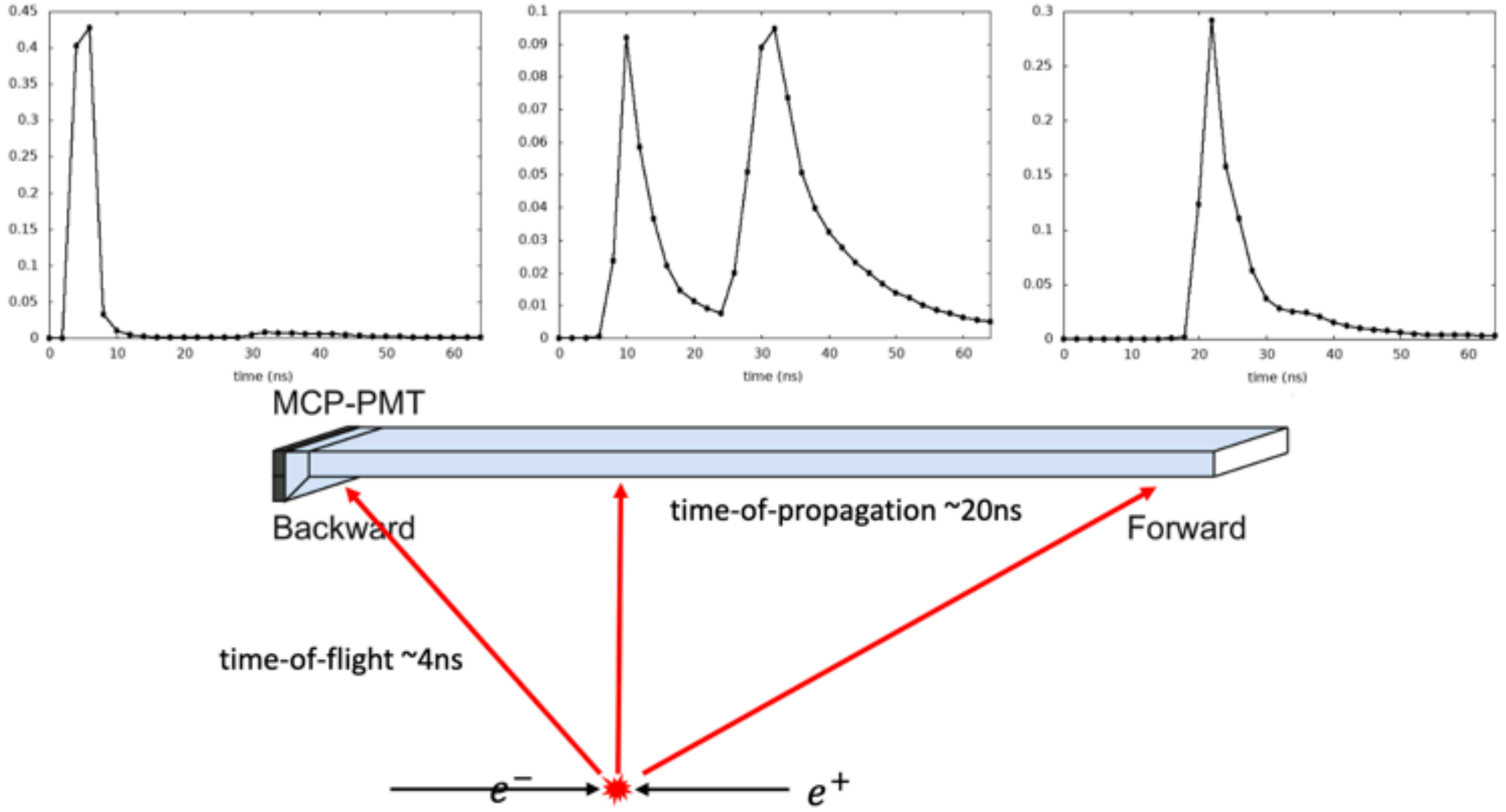
Firmware

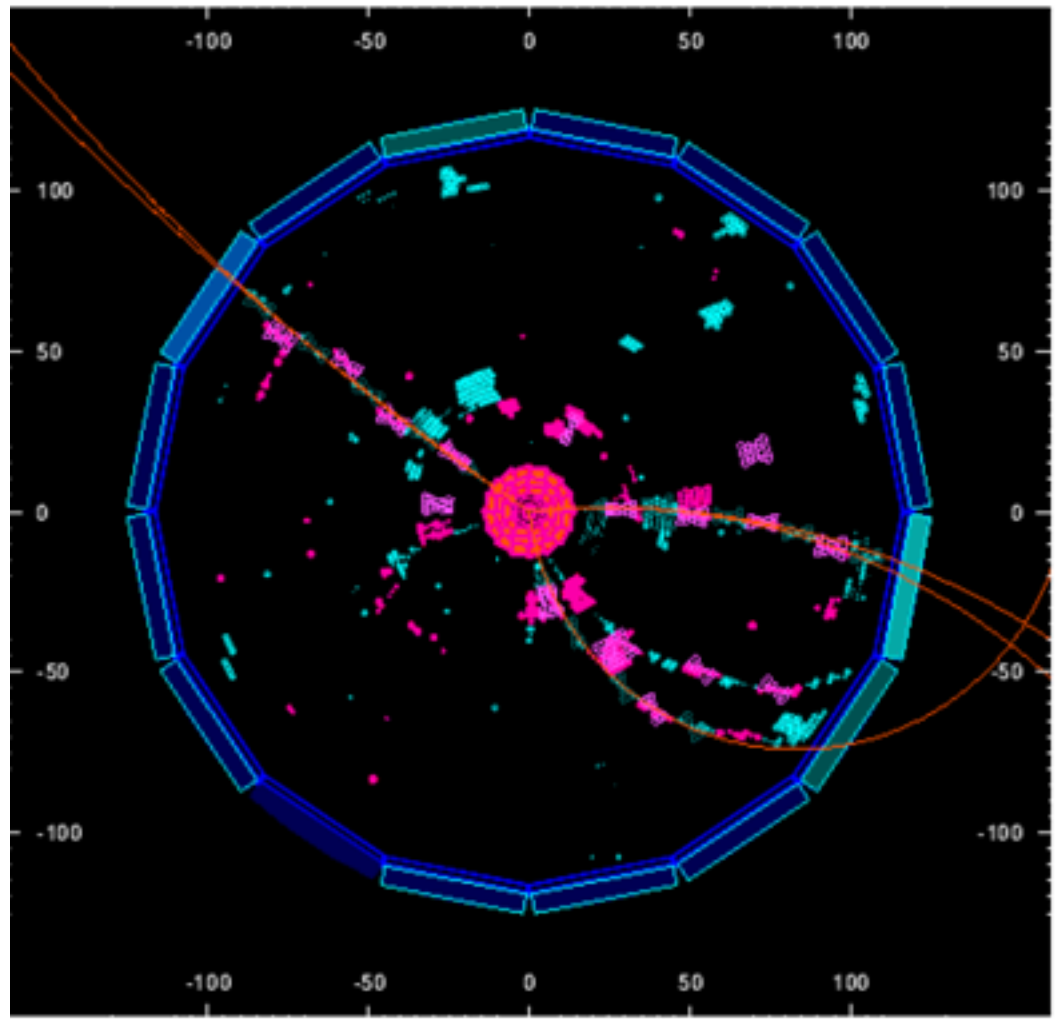
- Meets requirements of latency and timing closure
- Test bench: consistent with simulation

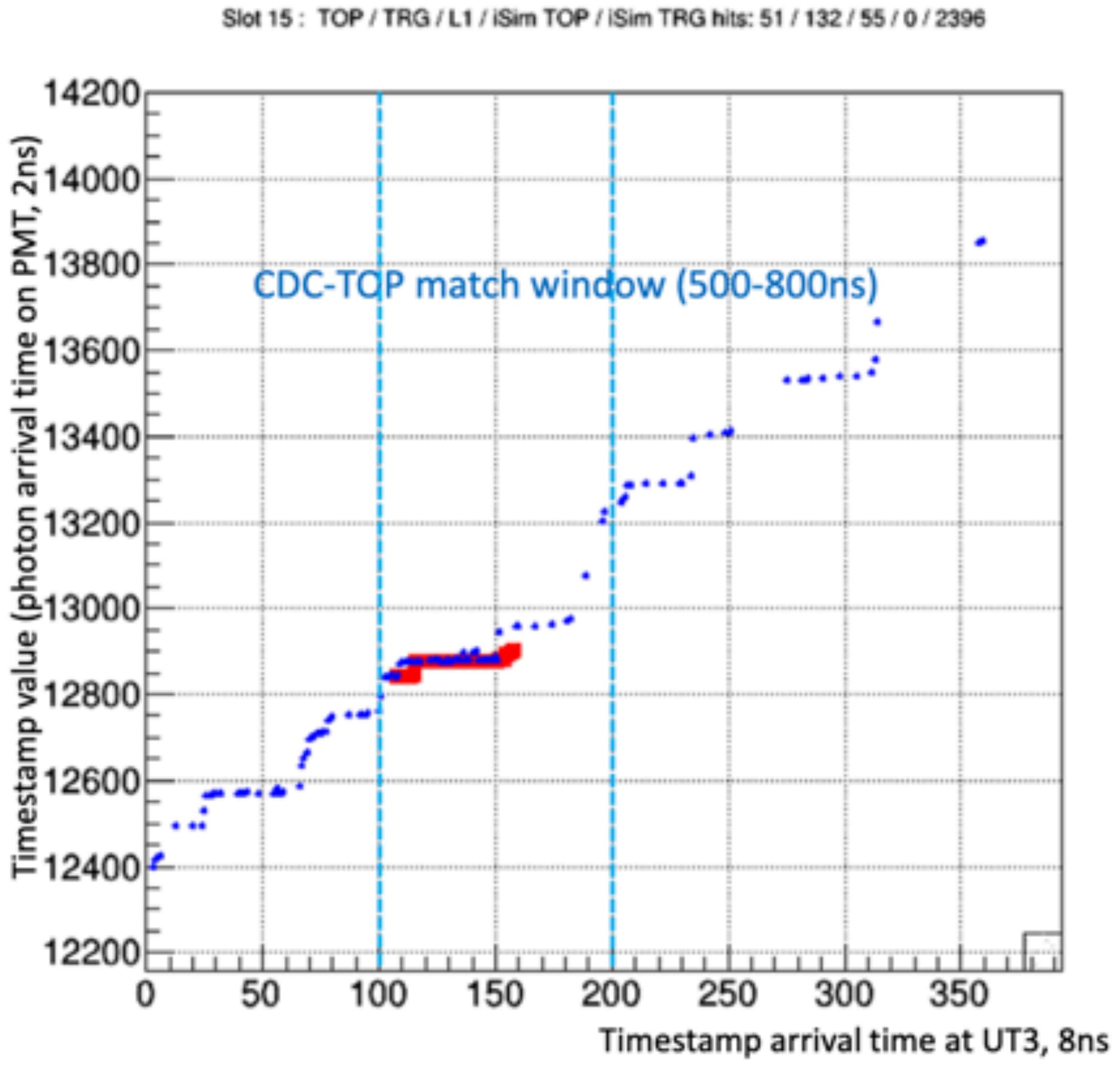
TSIM

- Results are consistent with expectation.

TOPTRG







Fast and precise measurement of collision timing (t0), to suppress out-of-time hits and reduce data volume.

- TOP Trigger efficiency for cosmic events is ~ 93%
- For hadronic events is only ~ 34% because of beam background photons
- Match with track information from 2D TRG track
  - TOP Trigger efficiency for hadronic events improves to ~ 70%
  - Future
    - Use 3D track; ML based approach
    - Need to run FW faster - More progress needed

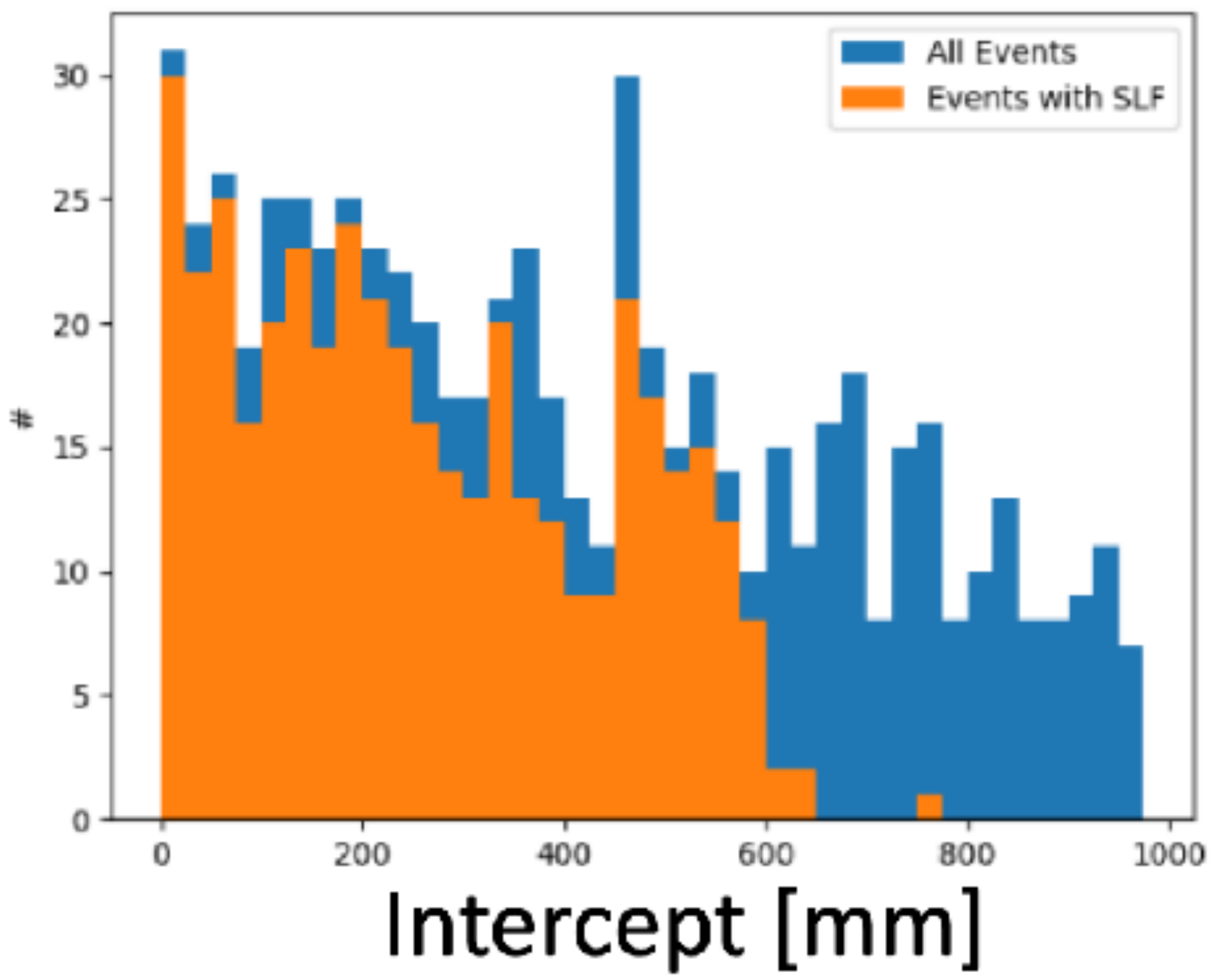
KLMTRG

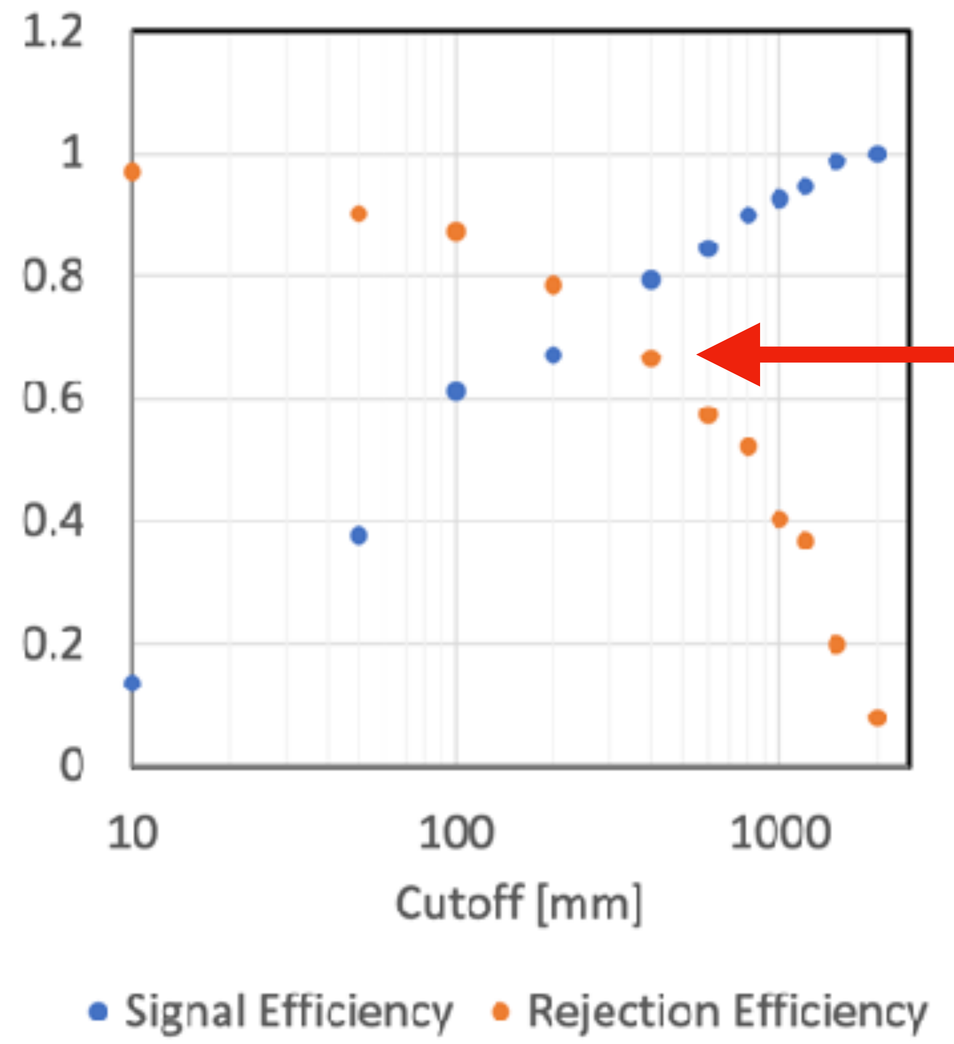
Used to take μ^+ pair events, necessary for calibration.

New algorithm, Straight line fitter (SLF):

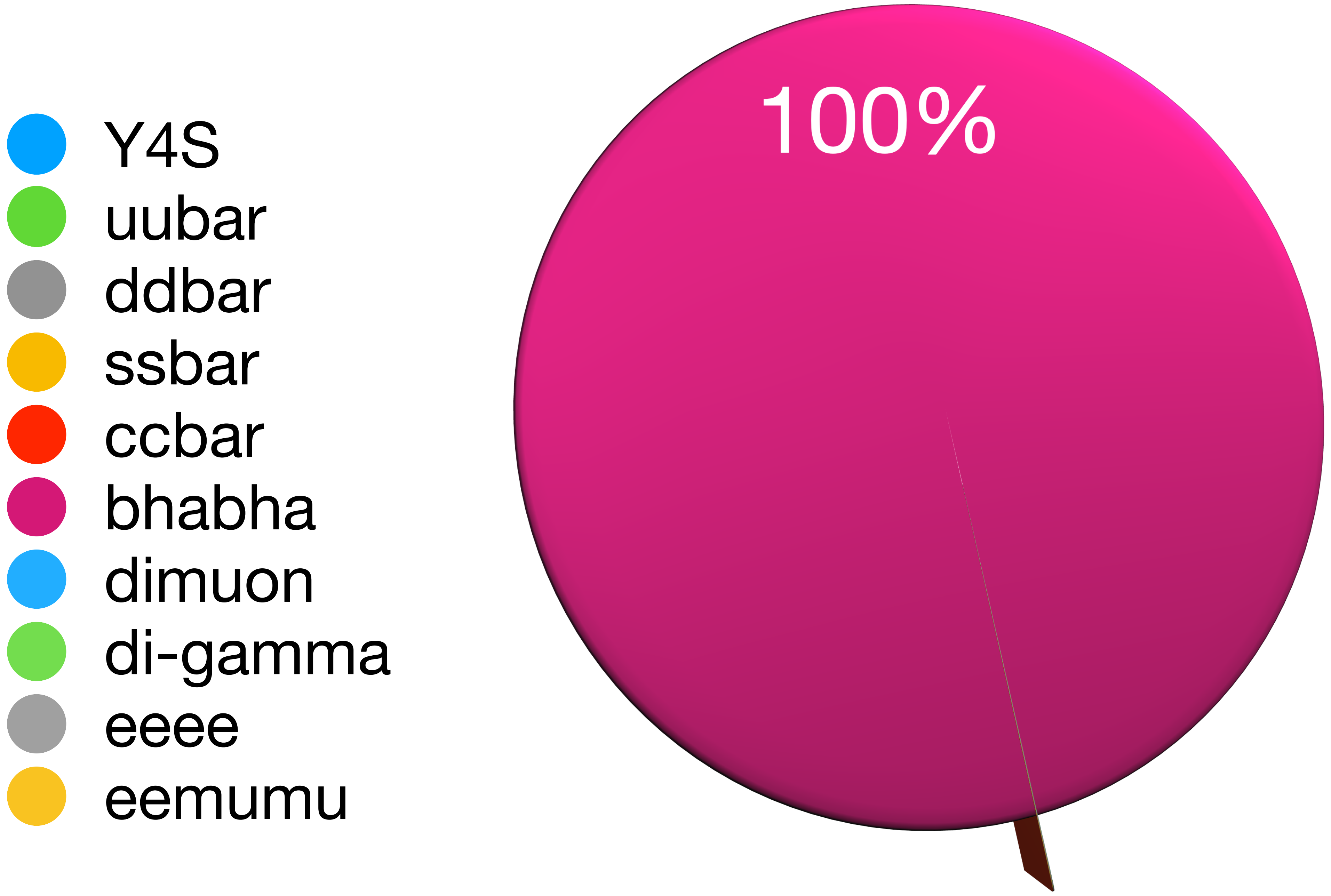
Target: ~2 times smaller cosmic rate while keep same muon efficiency

- Histogram of Events as function of the Intercept
- Events with SLF show a steep drop-off after 600 mm

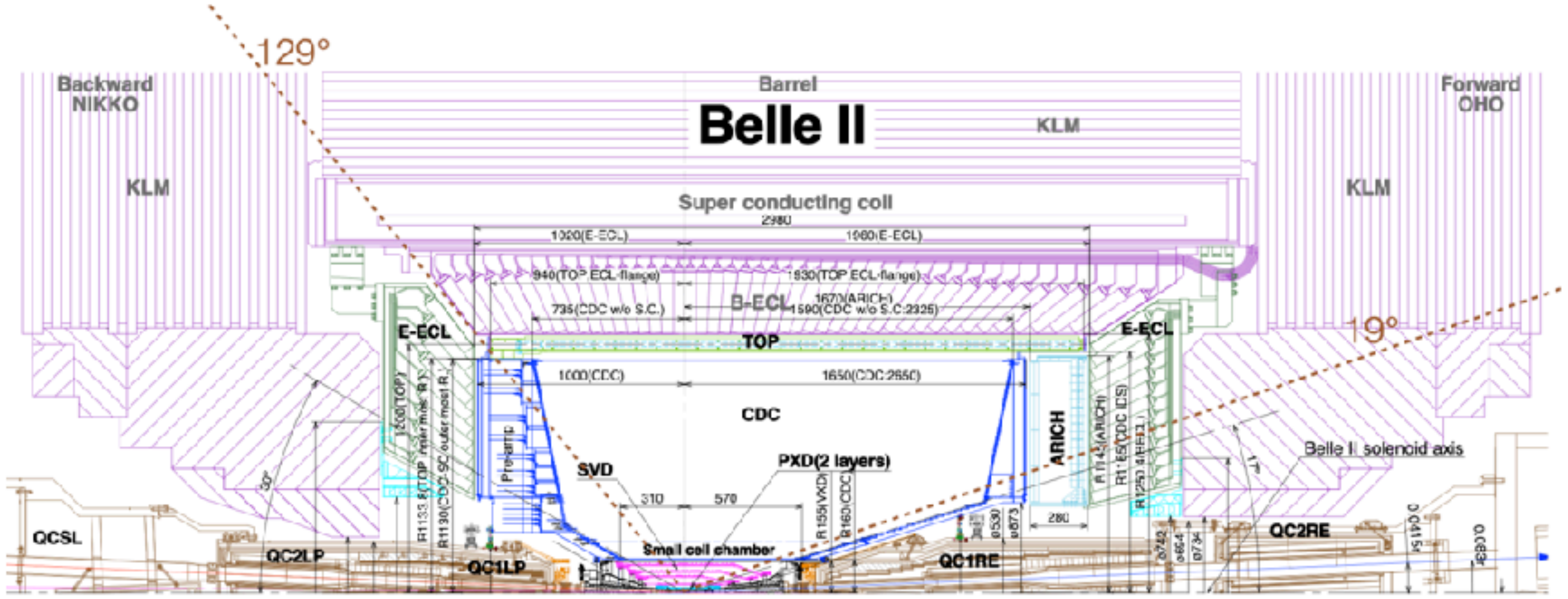




At a cutoff of ~500 mm, the internal trigger rate is reduced by a factor of ~2.

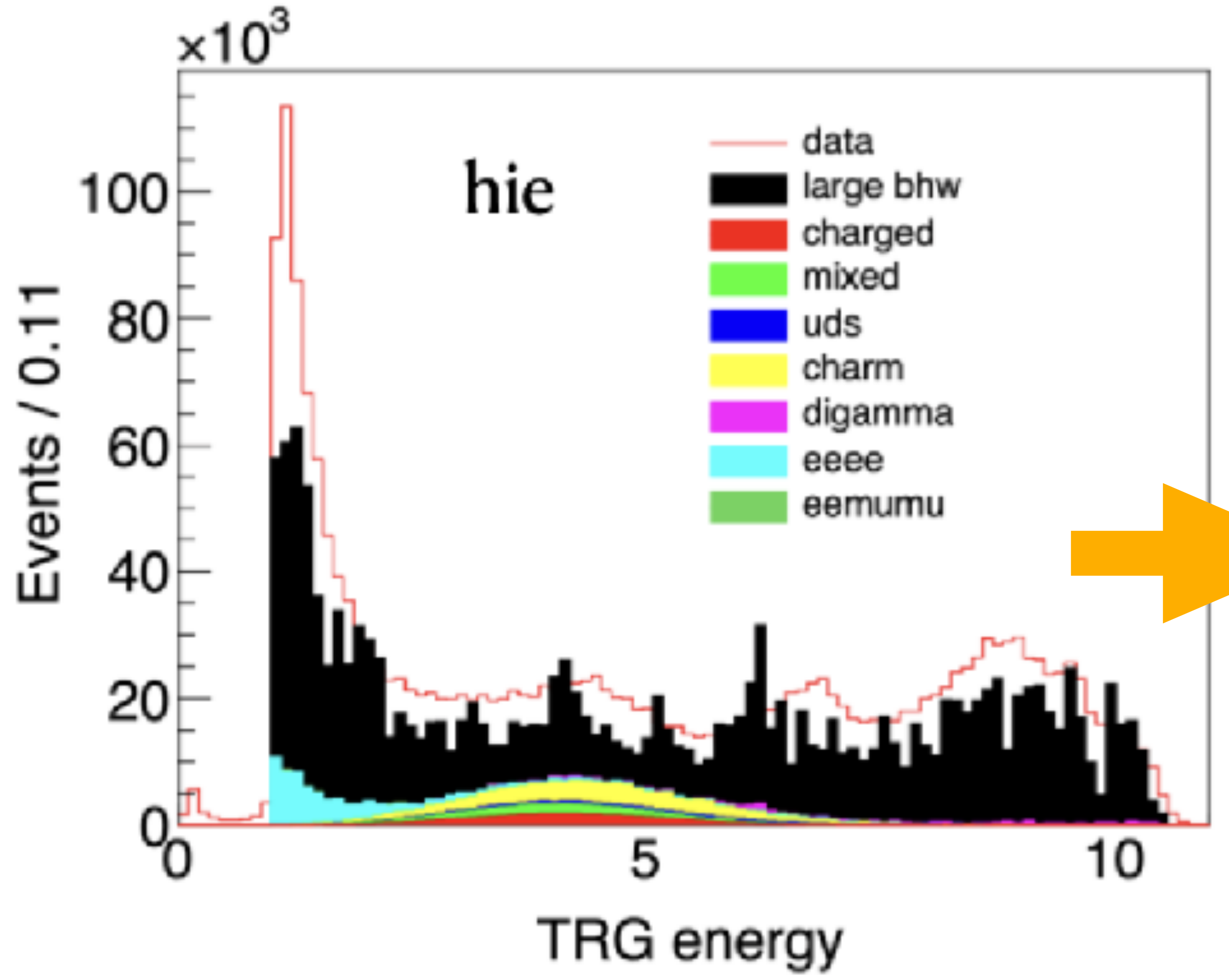


- **hie**: Basic ECL trigger. Requires sum of trigger towers >1GeV, with 100 MeV threshold per tower.
  - tower ≈ 4×4 crystals.
  - sum is over θ_{ID}^{L1} range [2,15]
  - Bhabha veto



Cross section of bhabha will increase to 1.23×10^5 nb when $0.5^\circ < \theta_e^* < 179.5^\circ$

Significant effect to ECL trigger;
Needs optimization.



bit logics	bhabha	taupair	eeee	data
hie	1531	735879	2628	2950
fff|ffo|c4|hie	1601	856847	3506	4476
newhie	510	695997	1173	1640
fff|ffo|c4|newhie	558	823458	2165	3185

TRG rate reduced 1/2 while keep high trg rate to physics events.

newhie = hie && 1-cluster-veto && 2-clusters-veto

Not on F-endcap

Second energetic (Edep > 0.5 GeV) photon not on endcap

GRL

ML for τ events

input variables

Energy
$\{E_1, \ldots, E_6\}$ (12 bits, LSB = 5.5 MeV)

Azimuthal Angle
$\{\theta_1, \ldots, \theta_6\}$ (7 bits, LSB = 1.6025°)

Polar Angle
$\{\phi_1, \ldots, \phi_6\}$ (8 bits, LSB = 1.6025°)

Average Cluster Time
$\{t_1, \ldots, t_6\}$ (8 bits, LSB = 1 ns)

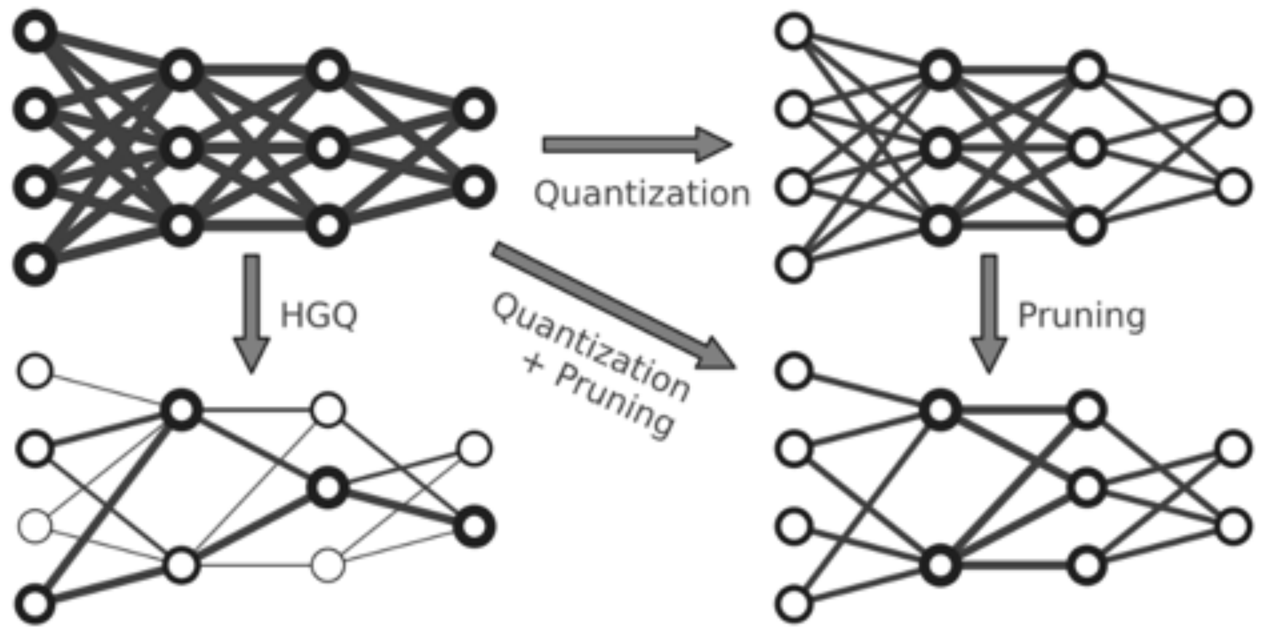
dataset

Exp 35 Run 2191, identify signal with offline preselection

Hidden layer

- 64 Nodes per Layer
- Dense + ReLU Activation

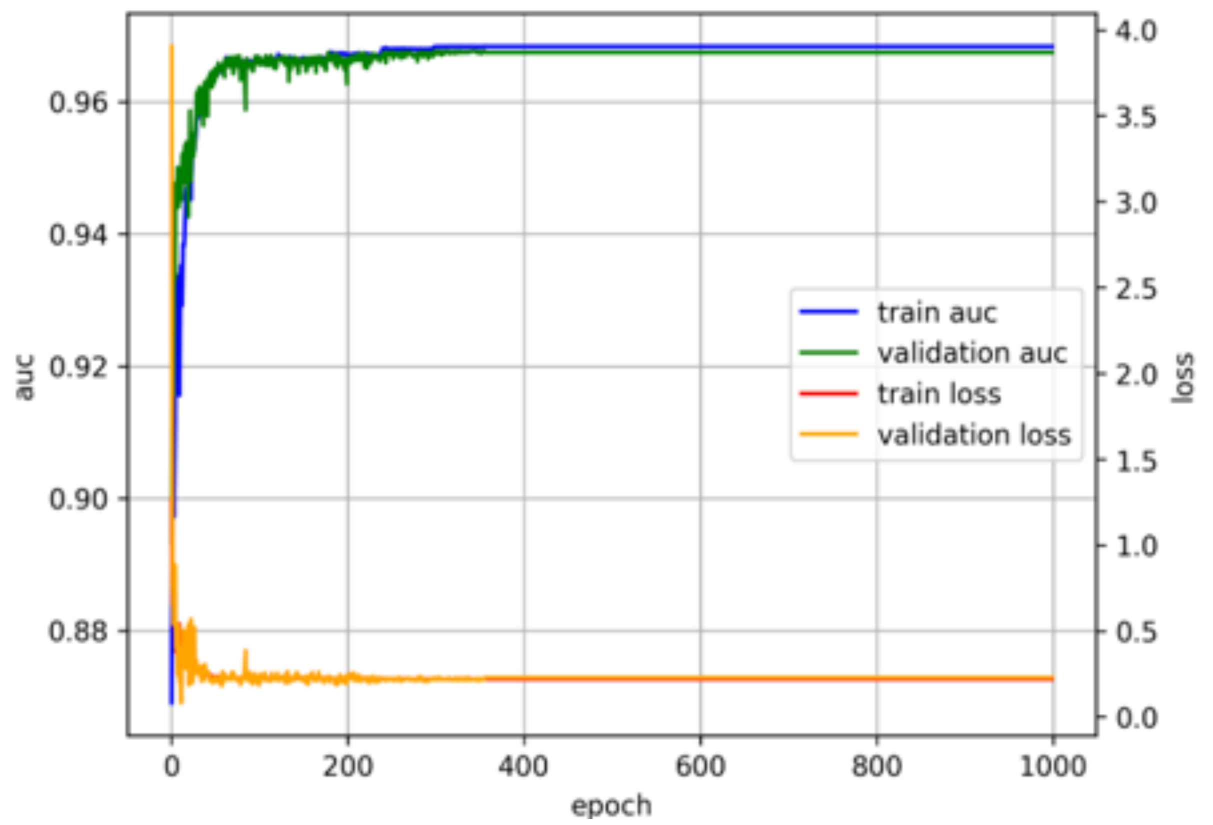
High-Granularity Quantization

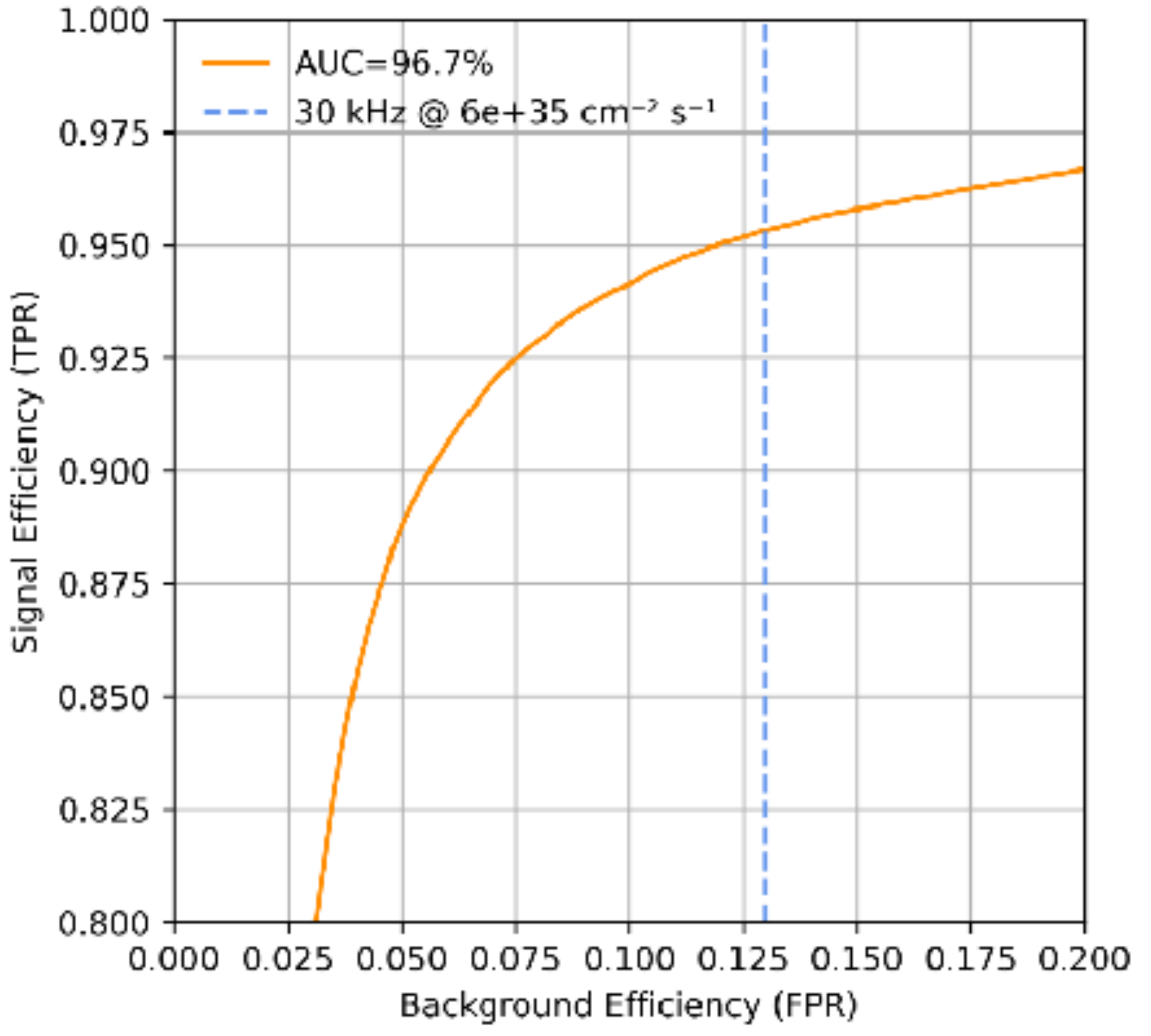


Resource utilization $\sim \mathcal{O}(1\%)$

Latency $\sim \mathcal{O}(10\text{ ns})$

output





Firmware validation & Software validation ongoing

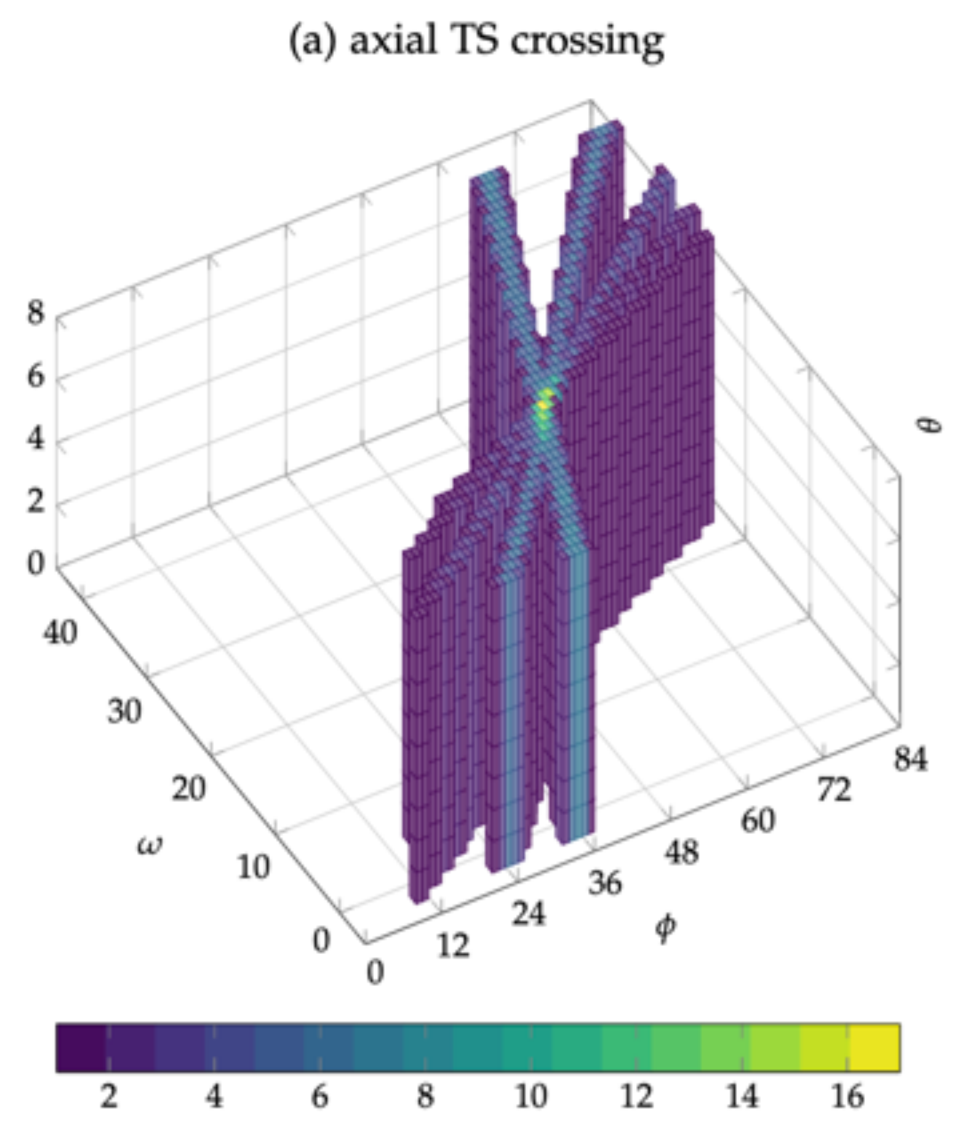
Summary

- Belle II TRG system is running stably.
- Many approaches are explored to reduce the trigger rata. Especially, neural network technologies now firmly established on the first trigger level, uniquely used in Belle II. Many new features incoming:
  - CDC TRG DNN 3DHough
  - New ECLTRG timing Logic with multiple clusters;
  - KLMTRG SLF is ready.
  - NN based tau events trigger on GRL.
  - CDC GNN-based hit cleanup
  - CDC displaced vertex trigger (DVT)
  - Reducing beamBG with data-driven template and ML and TOPTRG
  - Algorithm on Versal AI-engine
  - VTXTRG studies

Back up

CDCTRG

3D Hough Track finder & DNN



Target:

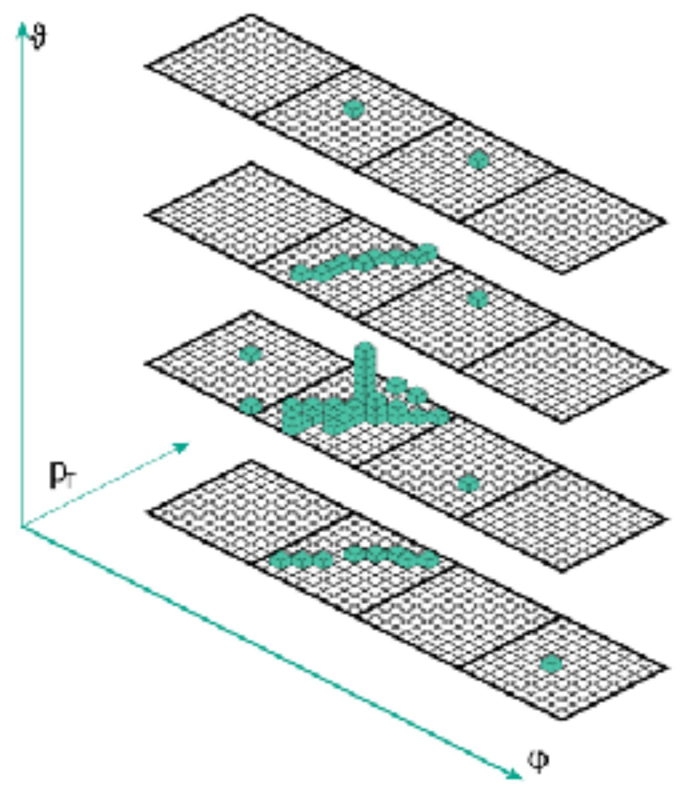
- New 3D Hough Finder + DNN to replace present single-layer NN Trigger
- Reduce TRG rate ~30% (current: 2D)

Software:

- 3DHough algorithm has been optimized
- DNN architecture is done
- Better efficiency and background rejection than 2DFinder, extension of polar angular range

Firmware:

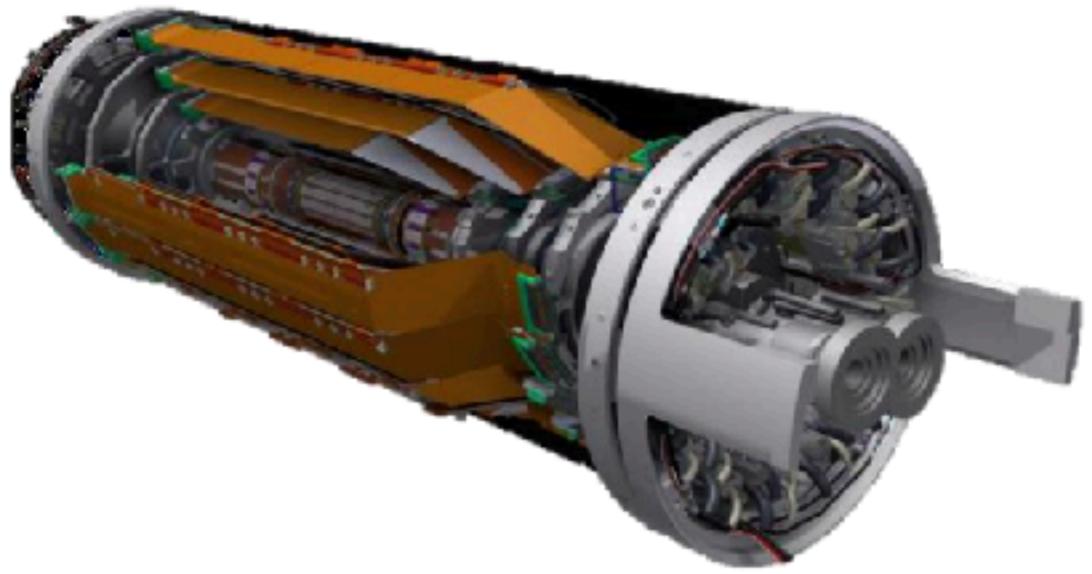
- Each possible Hough curve in grid is pre-calculated
- Use look-up tables to generate the Hough curve



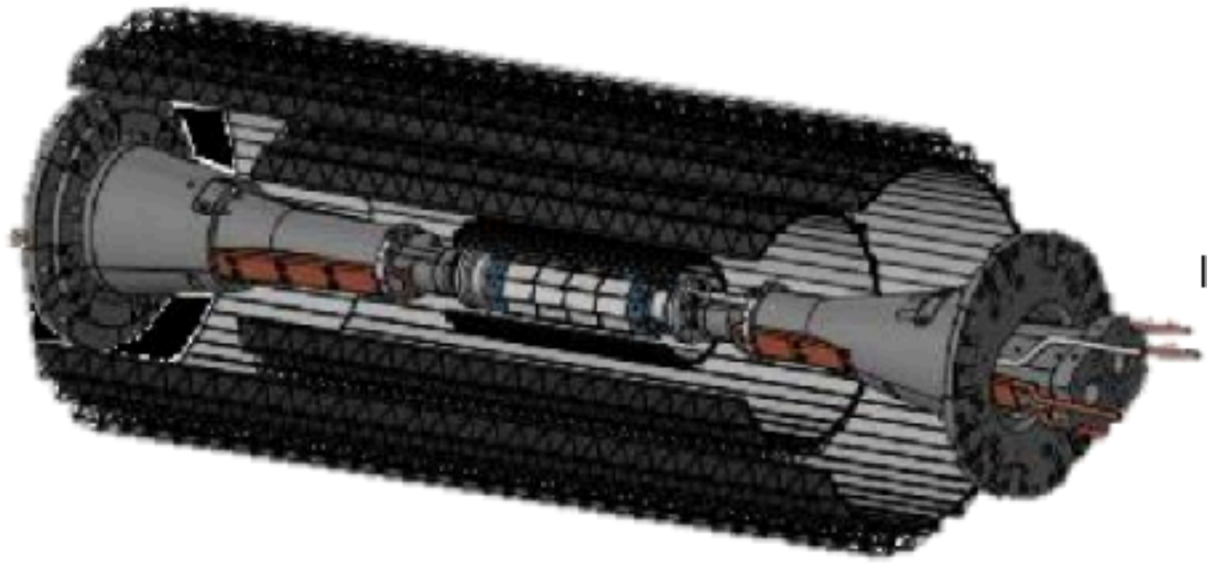
Combination	Efficiency $\geq (3, 2)$	Rejection $\geq (3, 2)$
Across the board: 0.25	98.44%	81.41%
Across the board: 0.5	95.78%	90.93%
Optimization: Equal	94.63%	95.70%
Optimization: 3×Eff.	97.08%	91.45%
Optimization: 6×Eff.	98.50%	85.51%
Optimization: 3×Rej.	90.71%	98.13%
Optimization: 6×Rej.	87.16%	99.00%

VTX TRG

Current inner vertex detector (VXD)

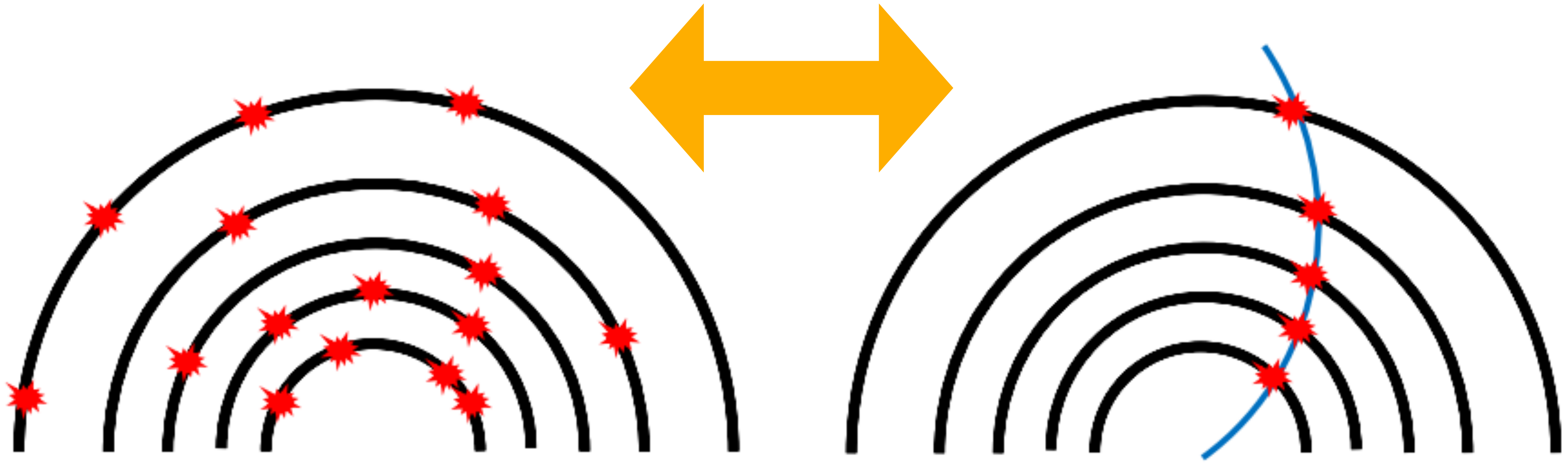


Future inner vertex detector (VTX)



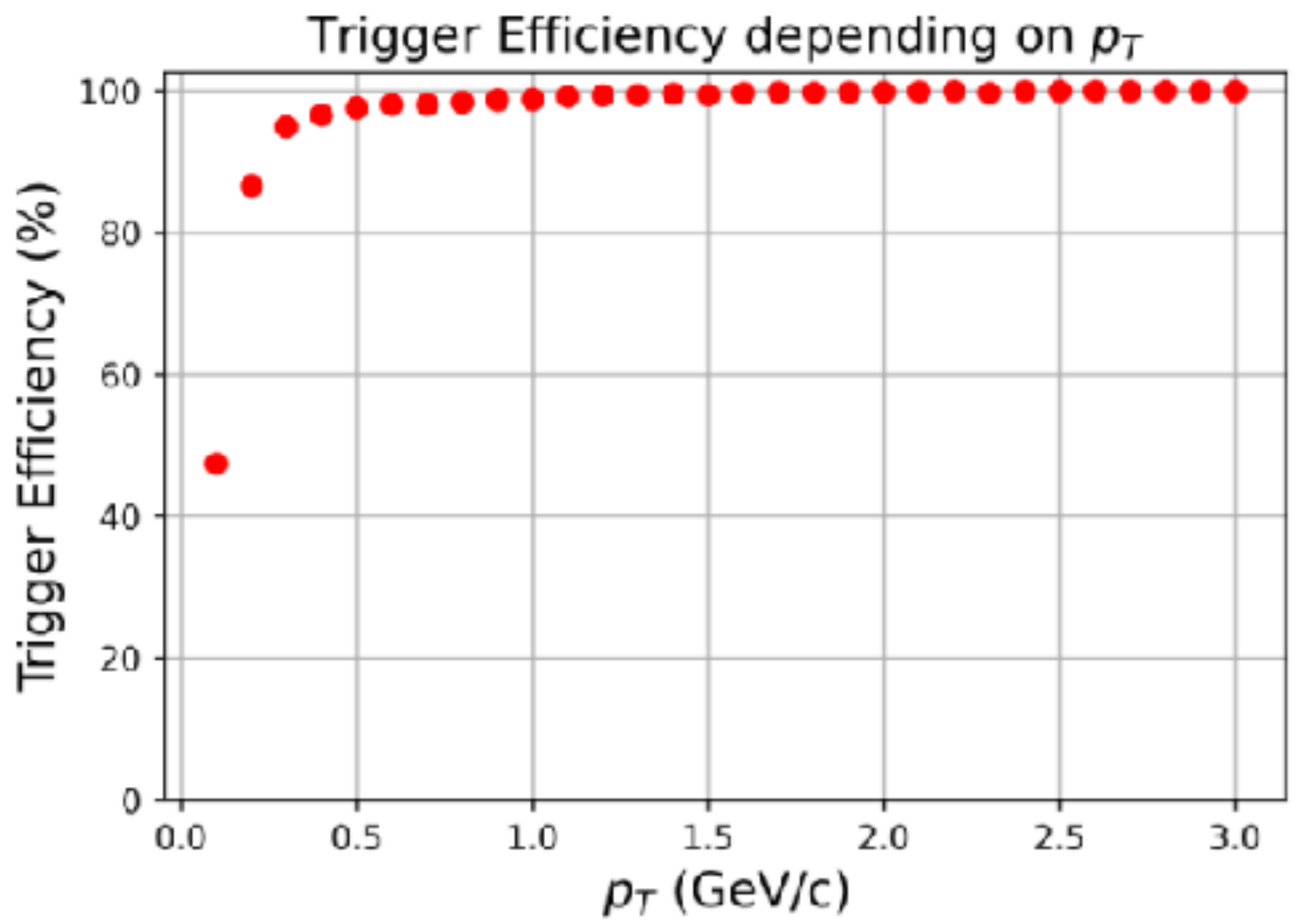
	inner VTX		outer VTX		
Layer	1	2	3	4	5
Ladder	6	10	30	40	31
Sensor per Ladder	4	4	12	16	2×24
Distance to IP (mm)	14.1	22.1	69.1	89.5	140.0
Max Hit Rate (MHz cm^{-2})	120	51.6	6.4	2.1	1.2

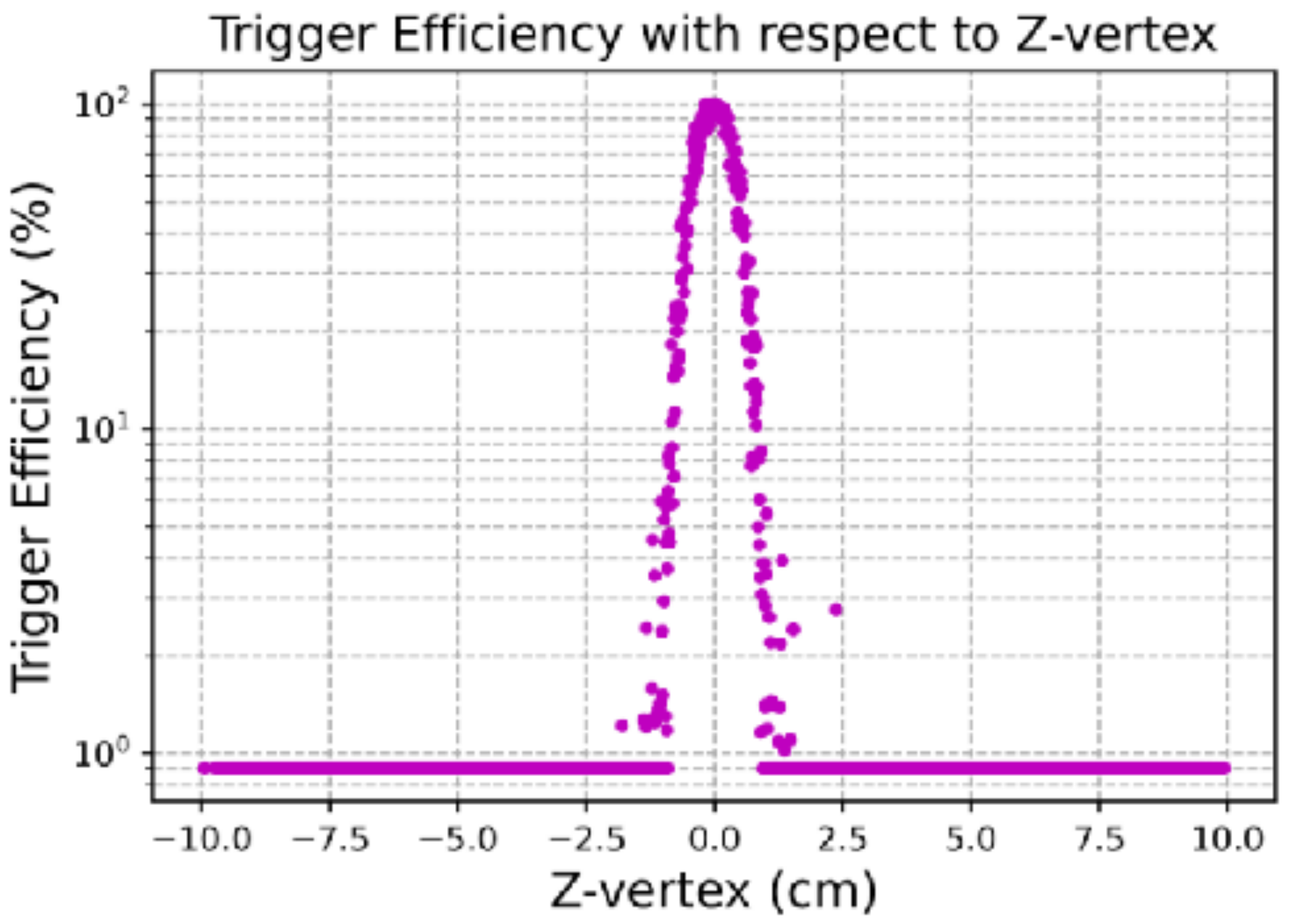
Table 2.1: VTX characteristics with OBELIX sensor



VTXTRG will provide: (θ, ϕ, z_0)

High efficiency, very good z_0 resolution





Huge background, CDC-VTX matching will be needed.