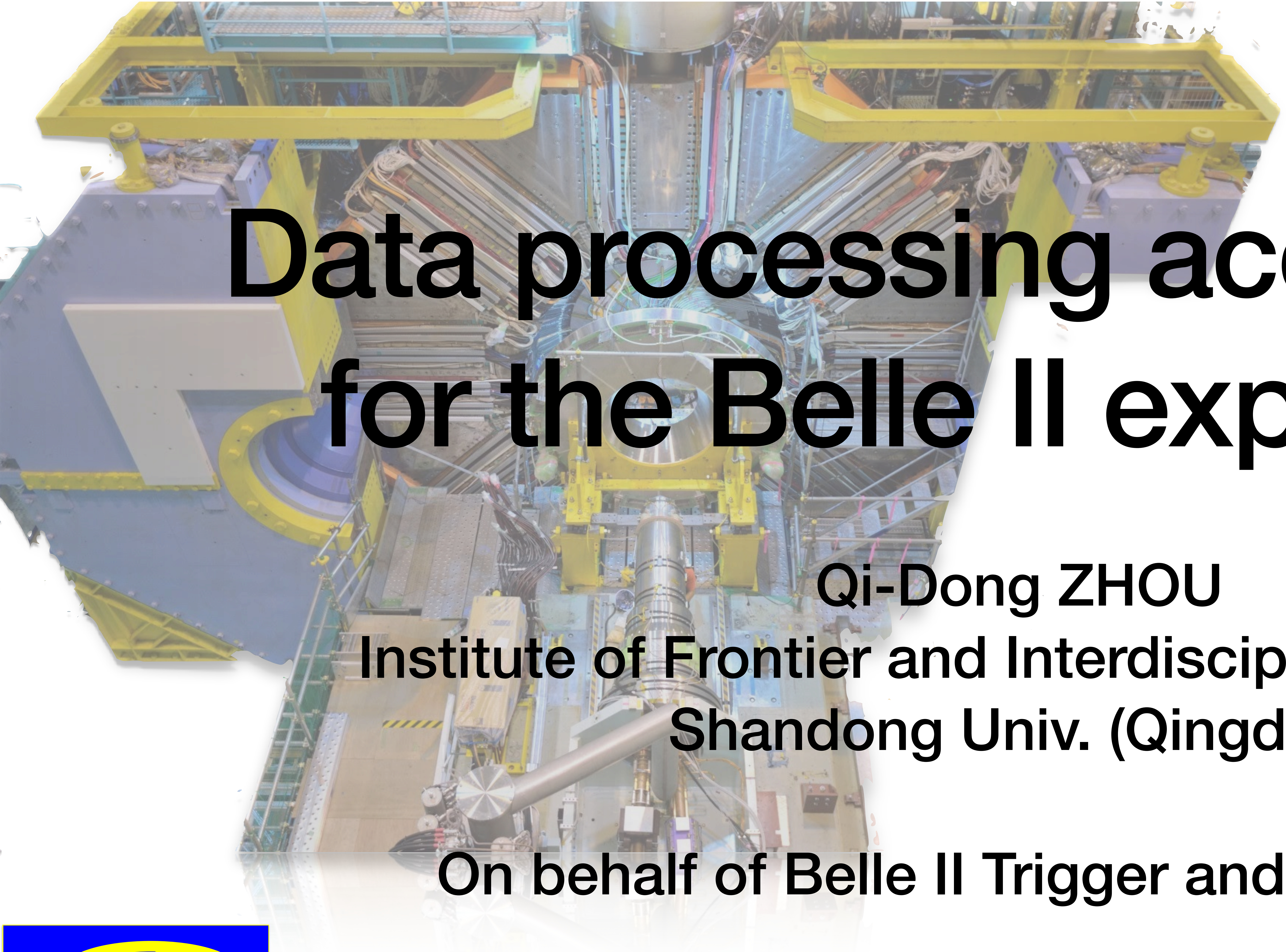


# Data processing acceleration for the Belle II experiment


Qi-Dong ZHOU

Institute of Frontier and Interdisciplinary Science,

Shandong Univ. (Qingdao)

On behalf of Belle II Trigger and DAQ group



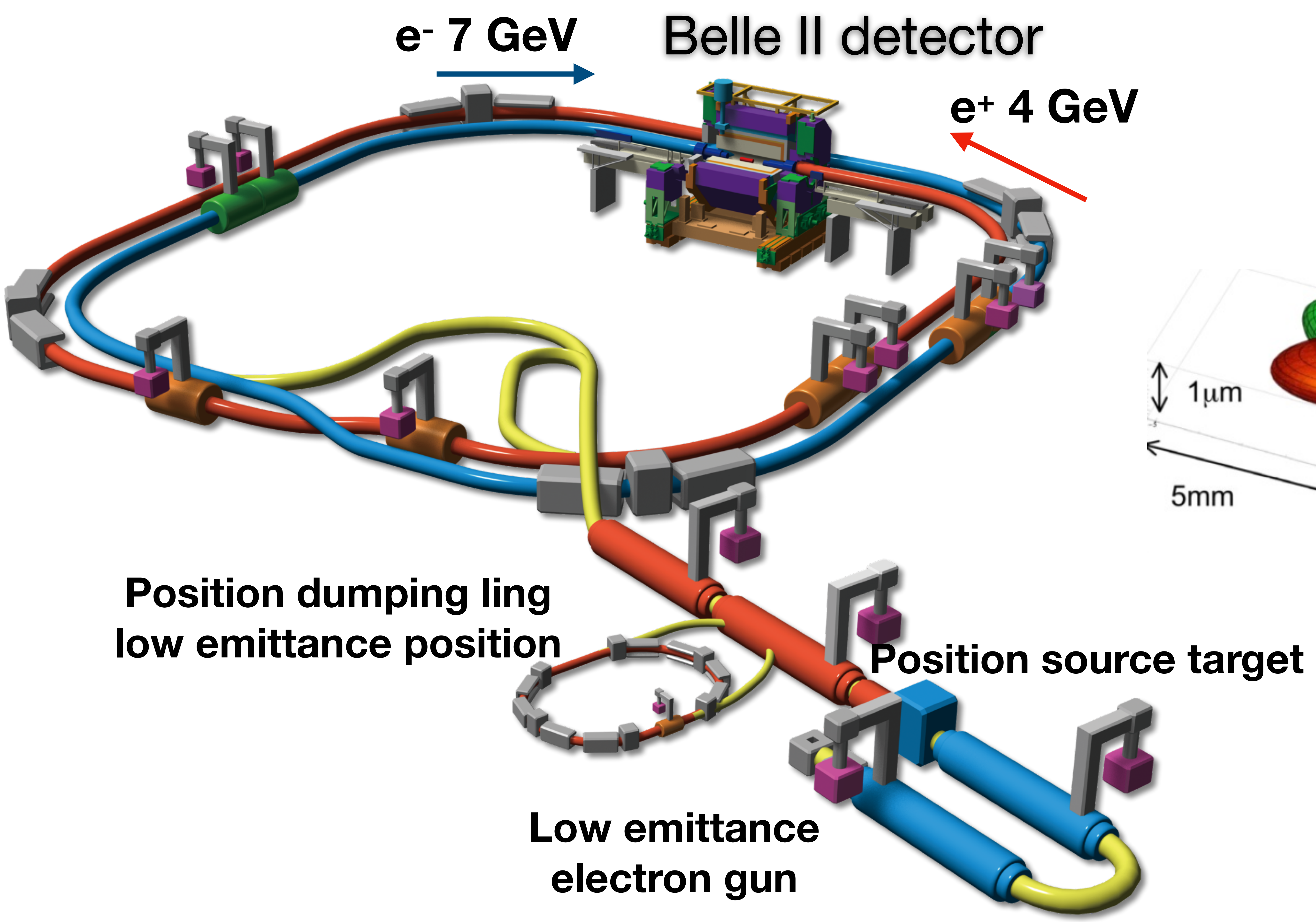
2-4 Dec. 2024, Tokyo

Streaming Readout Workshop SRO-XII

# Luminosity frontier: SuperKEKB

# Luminosity frontier: SuperKEKB

- Asymmetric $e^+e^-$ collider
  - $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$
  - very clean and well-known initial state

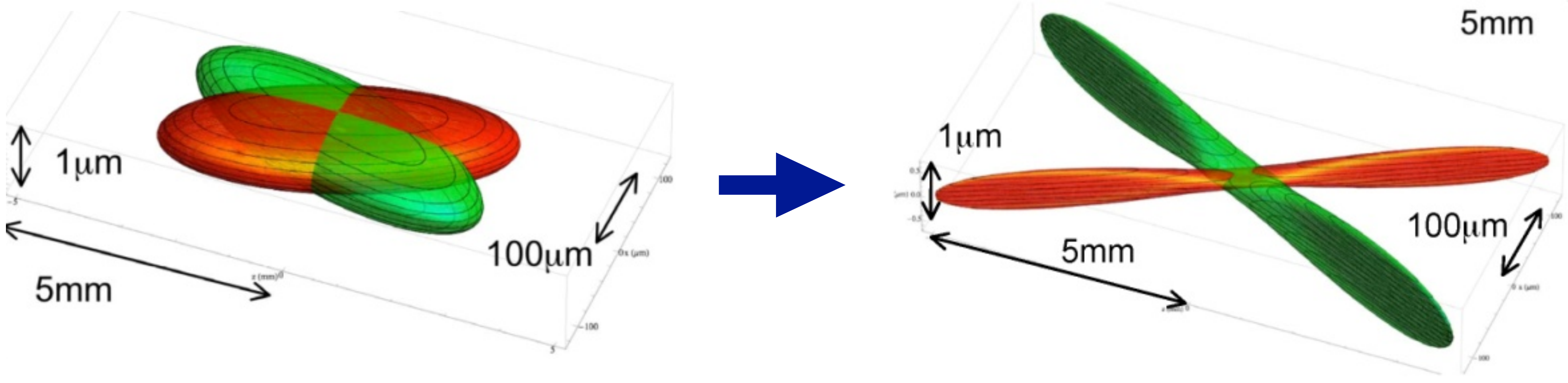



Beam current: KEKB x ~1.5

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\left(\frac{R_L}{R_y}\right)$$

Beam squeeze: KEKB / ~20

**Nano beam scheme**




Target: L = 60 x $10^{34}$ $cm^{-2}$ $s^{-1}$
Achieved : 4.7 x $10^{34}$ $cm^{-2}$ $s^{-1}$ (Record)

- Data:
  - **531** $fb^{-1}$ (Belle II) <-> 980 $fb^{-1}$ (Belle)

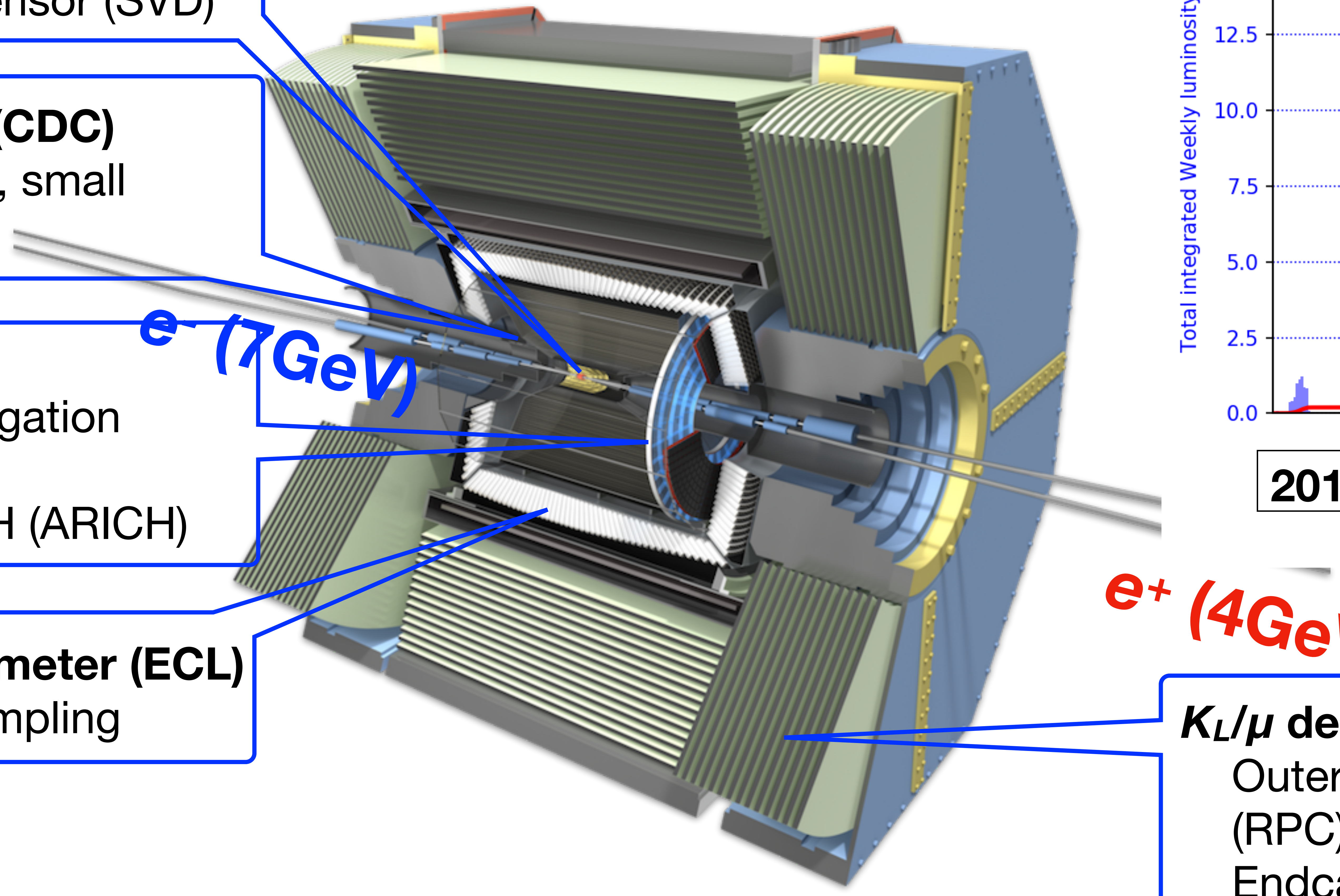
# Belle II detector and dataset

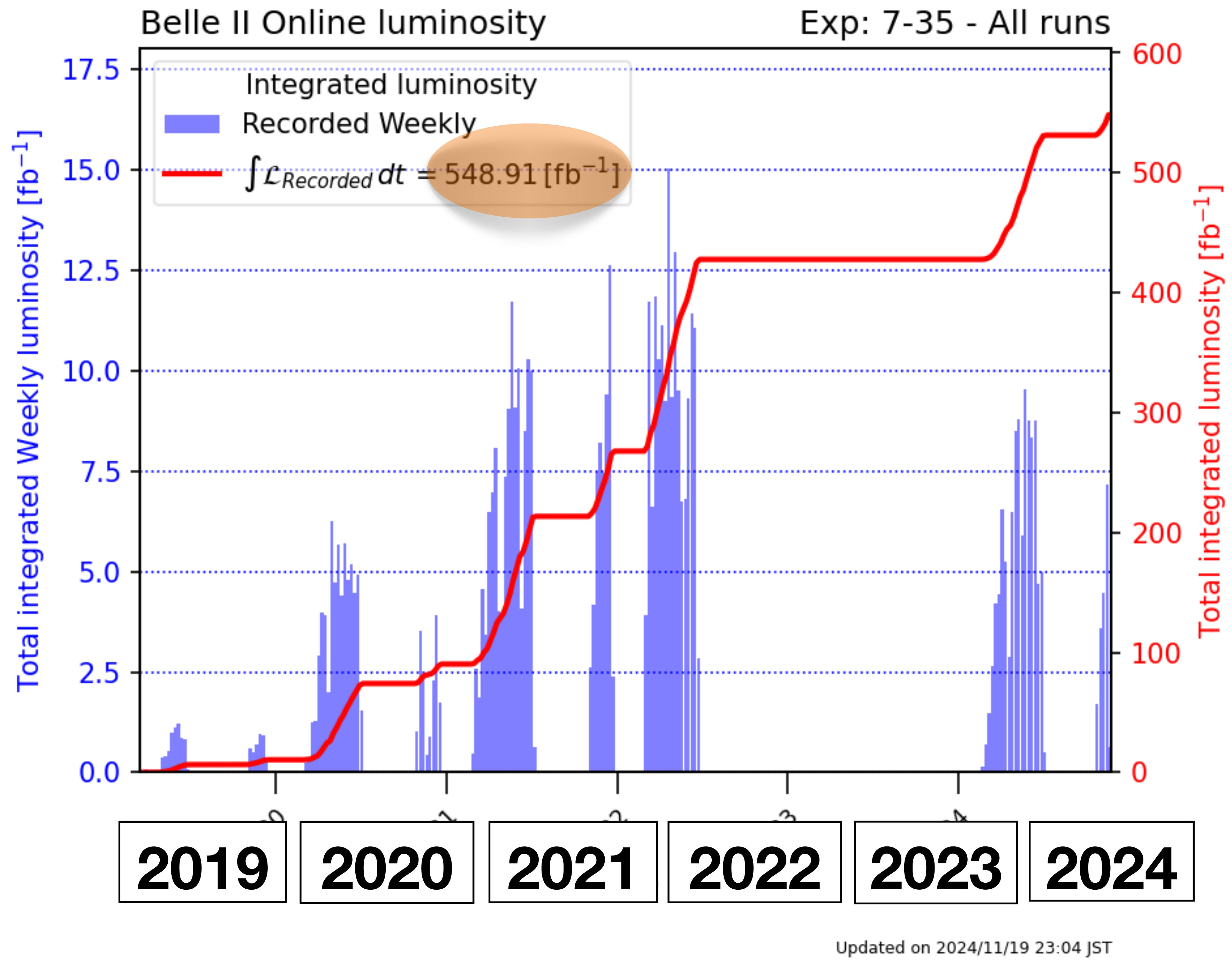
**Vertex detector (VXD)**
Inner 2 layers: pixel detector (PXD)
Outer 4 layers: strip sensor (SVD)

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

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

**ElectroMagnetic Calorimeter (ECL)**
CsI(Tl) + waveform sampling




**$K_L/\mu$ detector (KLM)**
Outer barrel: Resistive Plate Counter (RPC)
Endcap/inner barrel: Scintillator

- Features:
  - Near-hermetic detector
  - Vertexing and tracking: σ vertex ~ 15μm, CDC spatial res. 100μm $\sigma(P_T)/P_T$ ~ 0.4%
  - Good at measuring neutrals, $\pi^0$, $\gamma$, $K_L$… $\sigma(E)/E$ ~ 2-4%

# Belle II trigger strategy

- Design requirements: ~100% for $\Upsilon(4S)$->*BB*(hadronic decay), Tau/Charm, Exotics
  - No dead-time -> pipeline
  - Single photon trigger
  - Single track trigger
- Max. trigger rate: 30 kHz @ 6 x $10^{35}$ $cm^{-2}$ $s^{-1}$
  - Physics trigger ~15 kHz
- Latency limit: ~5 usec (SVD APV25 buffer structure)
  - A fixed latency of about 4.4 usec
- Event timing resolution: 10 nsec

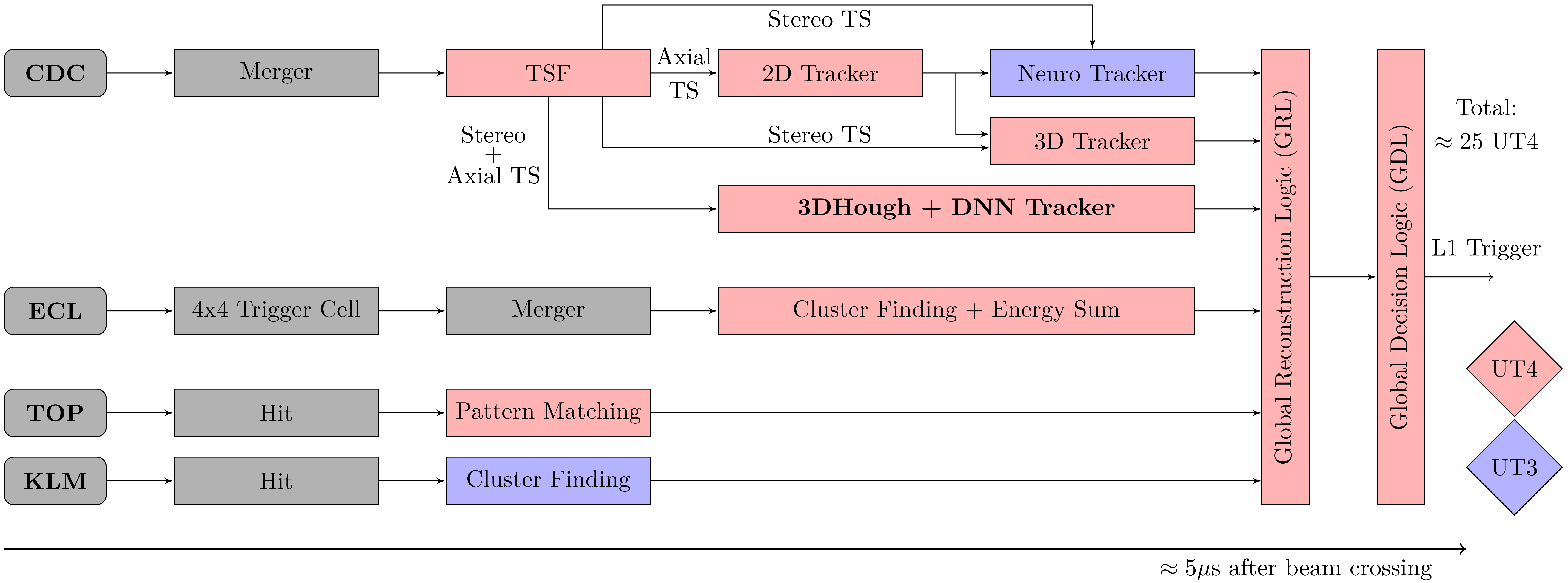
| Process | σ(nb) | Rate@L=6x$10^{35}$ (kHz) |
|---|---|---|
| Bunch. cross. | - | 2x$10^5$ |
| Beam bkg | - | 300-600 |
| Bhabha | 44 | 50 |
| Total->L1 | - | 200350->~15 |

| Process | σ(nb) | L1@L=6x$10^{35}$ (kHz) |
|---|---|---|
| Bhabha | 44 | 0.35* |
| Two photon | 13 | 10 |
| Upsilon(4S) | 1.2 | 0.96 |
| Continuum | 2.8 | 2.2 |
| μμ | 0.8 | 0.64 |
| ττ | 0.8 | 0.64 |
| γ-γ | 2.4 | 0.019* |
| Total | 67 | ~15 |

# Belle trigger system

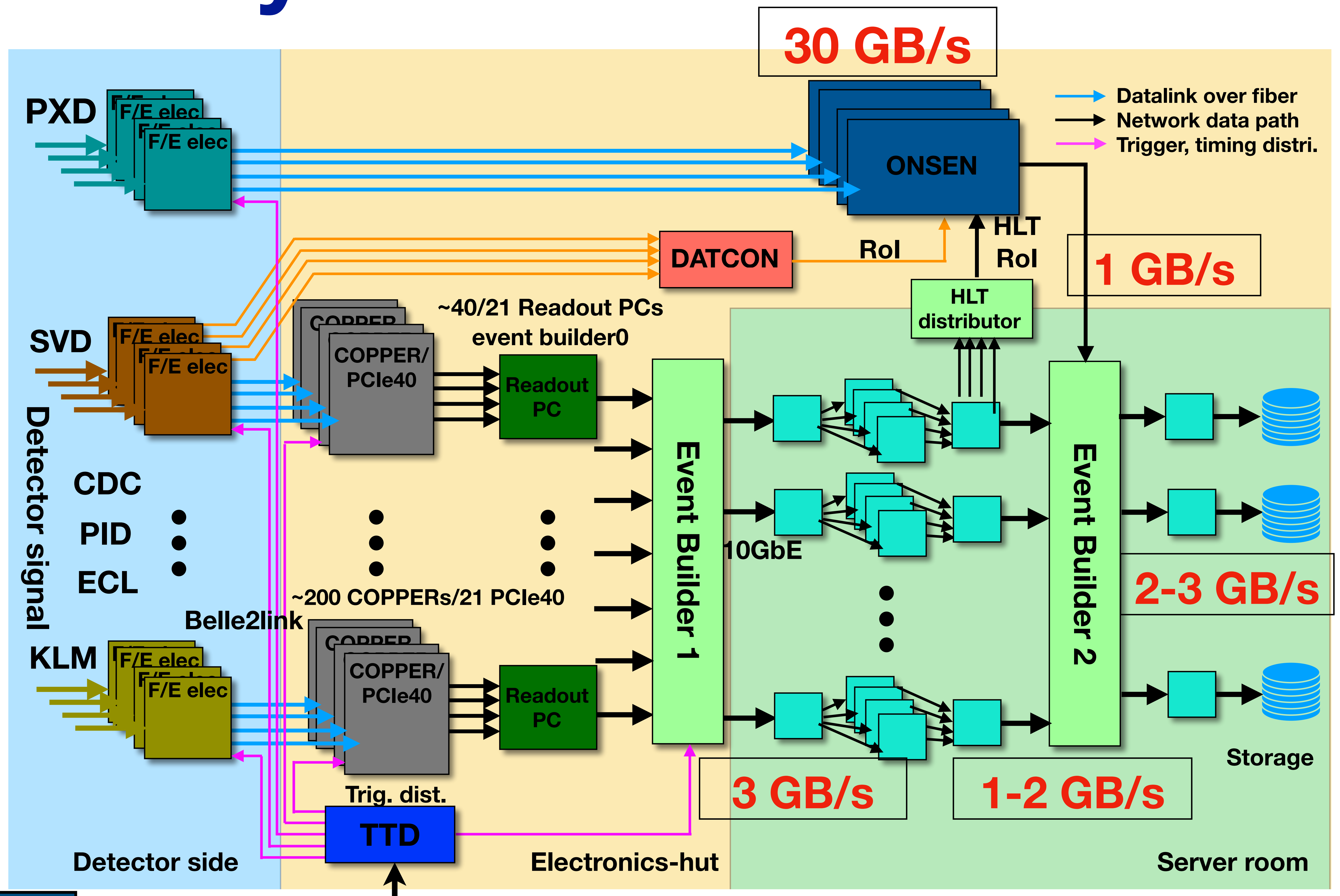
- CDC, ECL: main triggers for tracks and clusters
- KLM: trigger muon
- TOP: event timing
- GRL: matching of sub-triggers
- GDL: final trigger decision

- Challenges:
  - low multiplicity trigger vs. background
  - High track trigger vs. crosstalk
  - Drawback of track trigger at endcap
  - Latency budget vs. transmission and logics
  - …



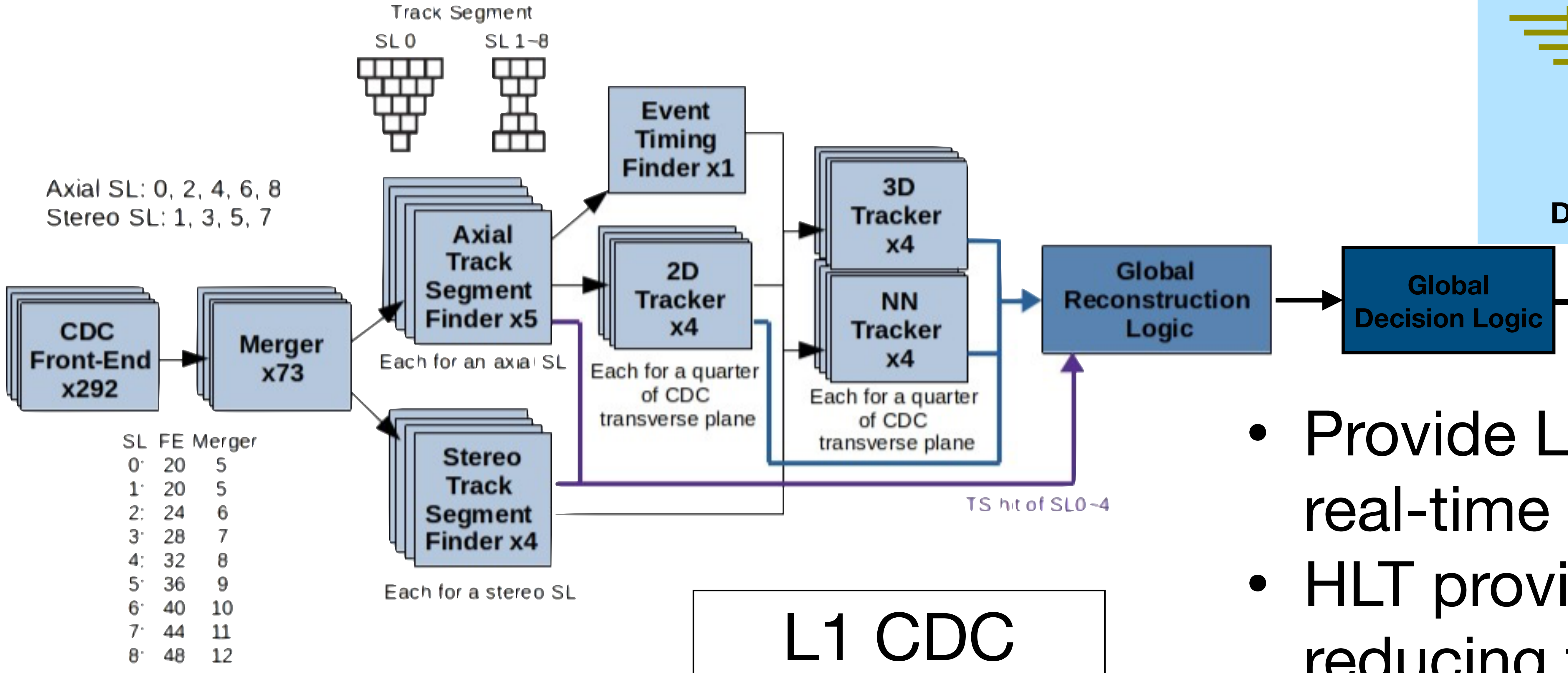
# Belle II TDAQ system

- Unified common readout system (except for PXD)
- Unified timing and trigger distribution (TTD) system
- A pipeline readout
- To handle 30 kHz level 1(L1) trigger with O 1% dead time under raw event size of 1 MB




High level trigger(HLT)

Example: CDC

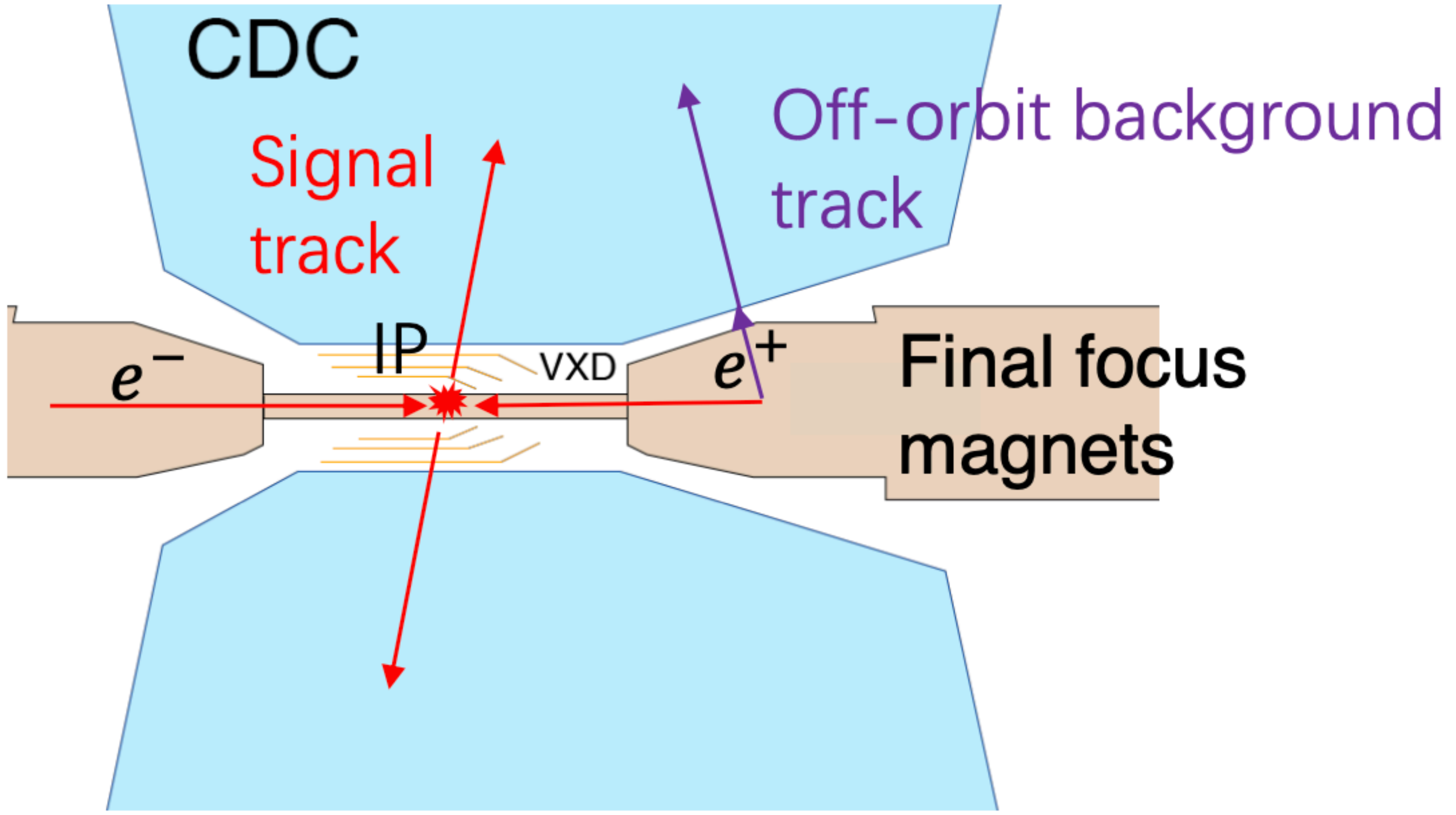


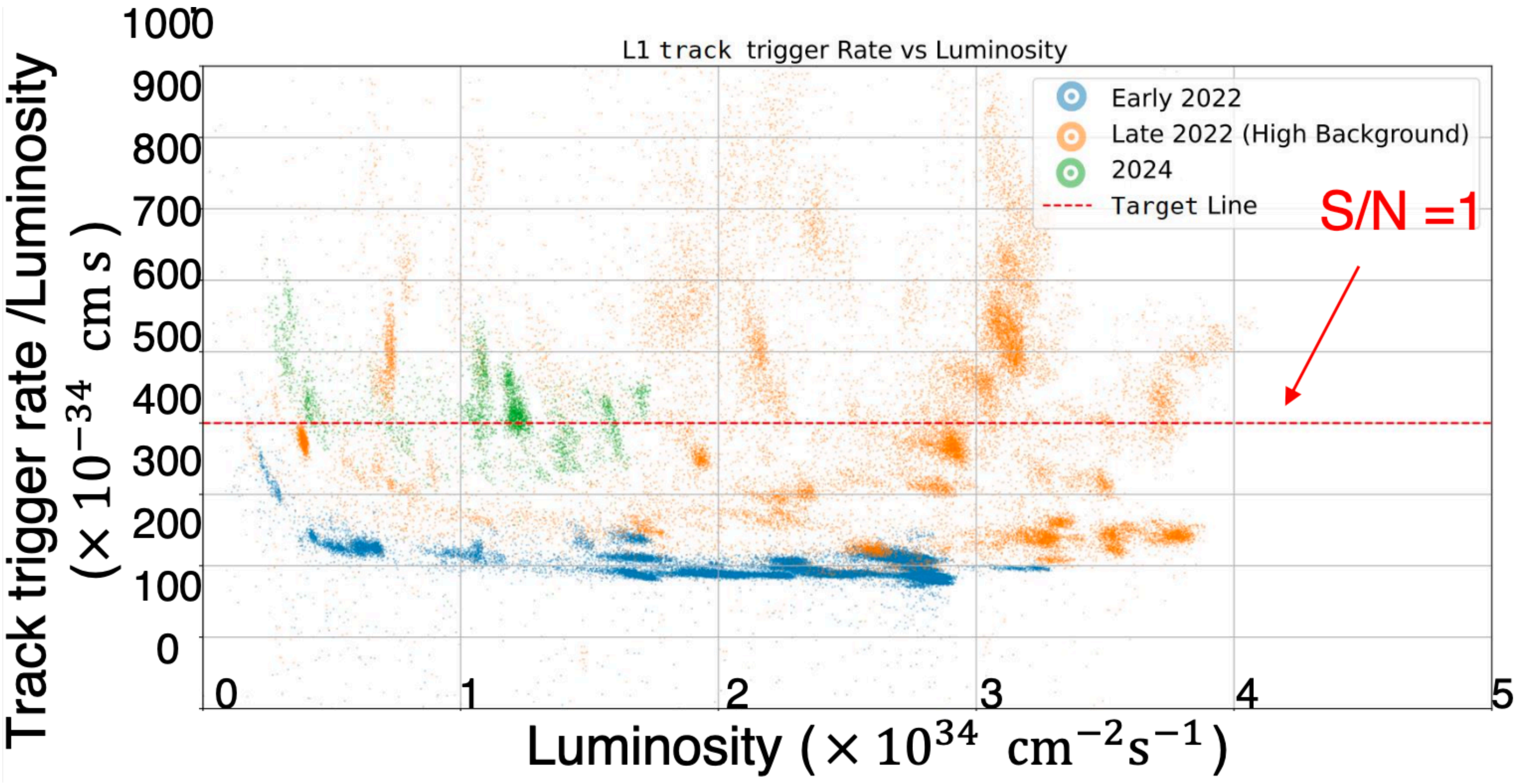

L1 CDC trigger logic

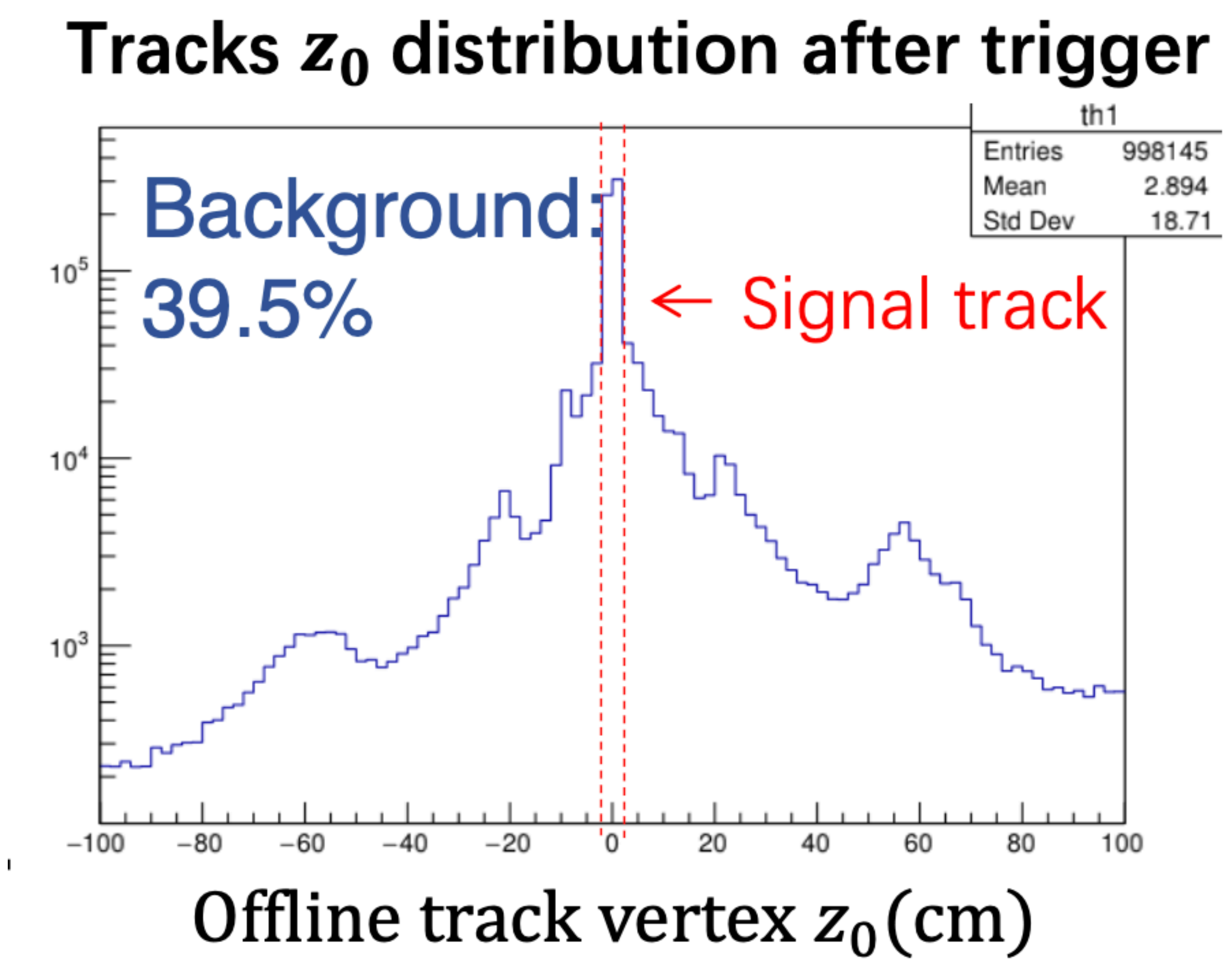
- Provide L1 trigger signal to DAQ using FPGA chips for real-time processing on detector raw data.
- HLT provide Region of Interest (RoI) to PXD for significantly reducing the data size.
  - Latency O sec.

# Motivation of Neural Network for L1 Track trigger

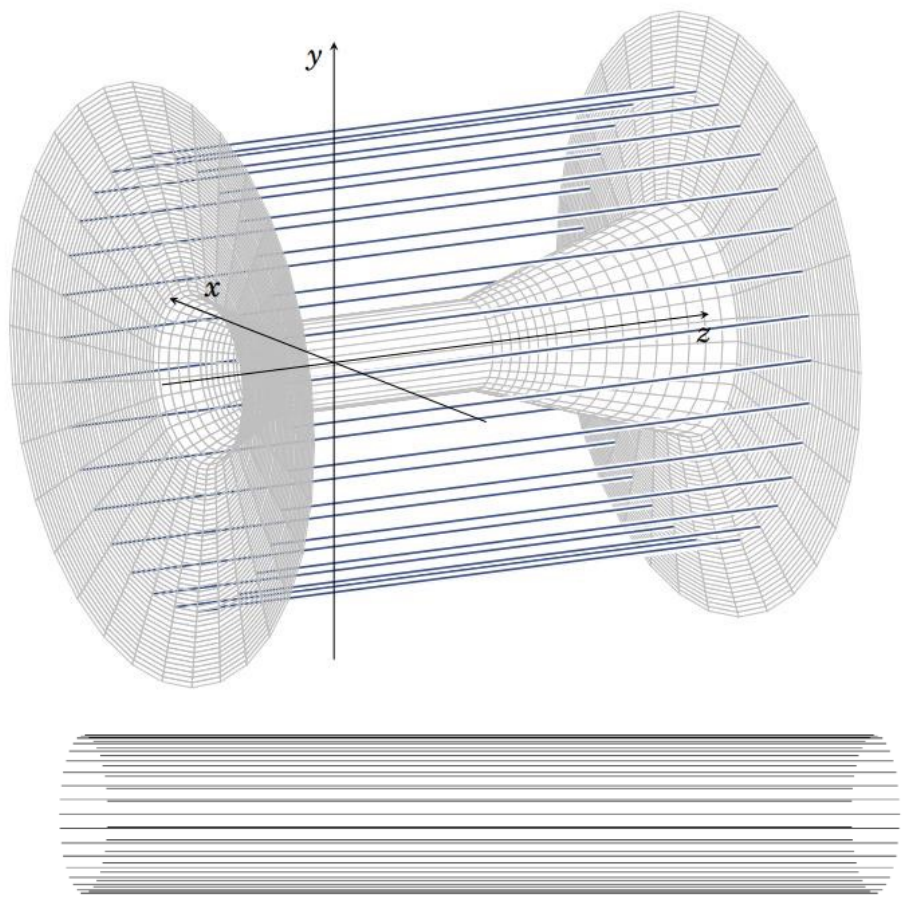
- DAQ system is designed to handle 30 kHz
  - Physical trigger ~15 kHz, require S/N = 1
- L1 trigger rate depends significant on background condition
- Advanced CDC algorithm to further suppress background
- A fixed latency of about 4.4 usec



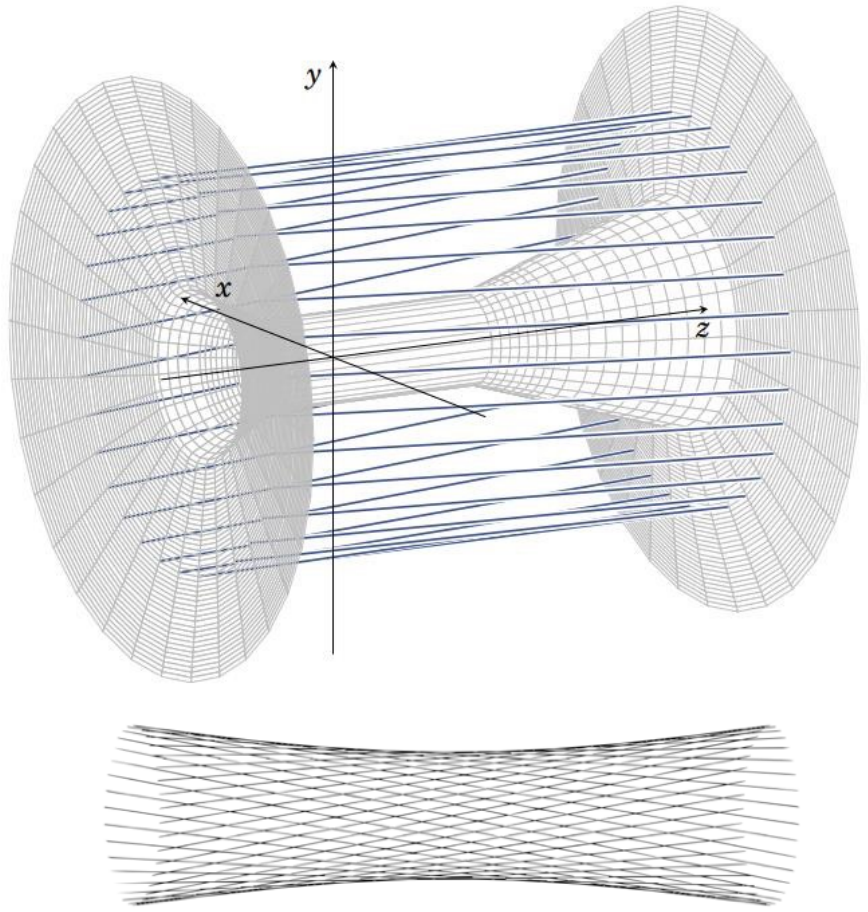



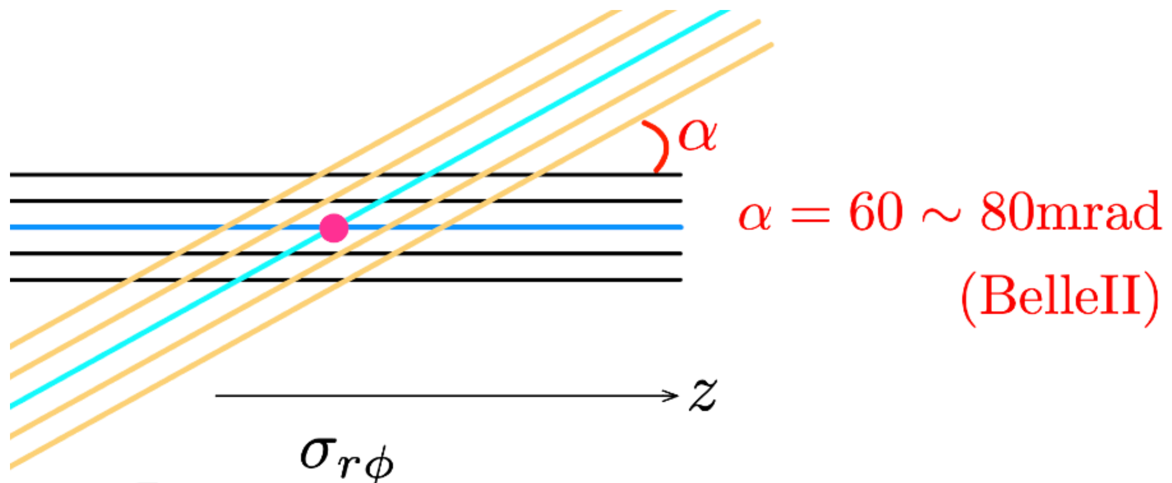
# Basics of L1 CDC trigger




Axial wire

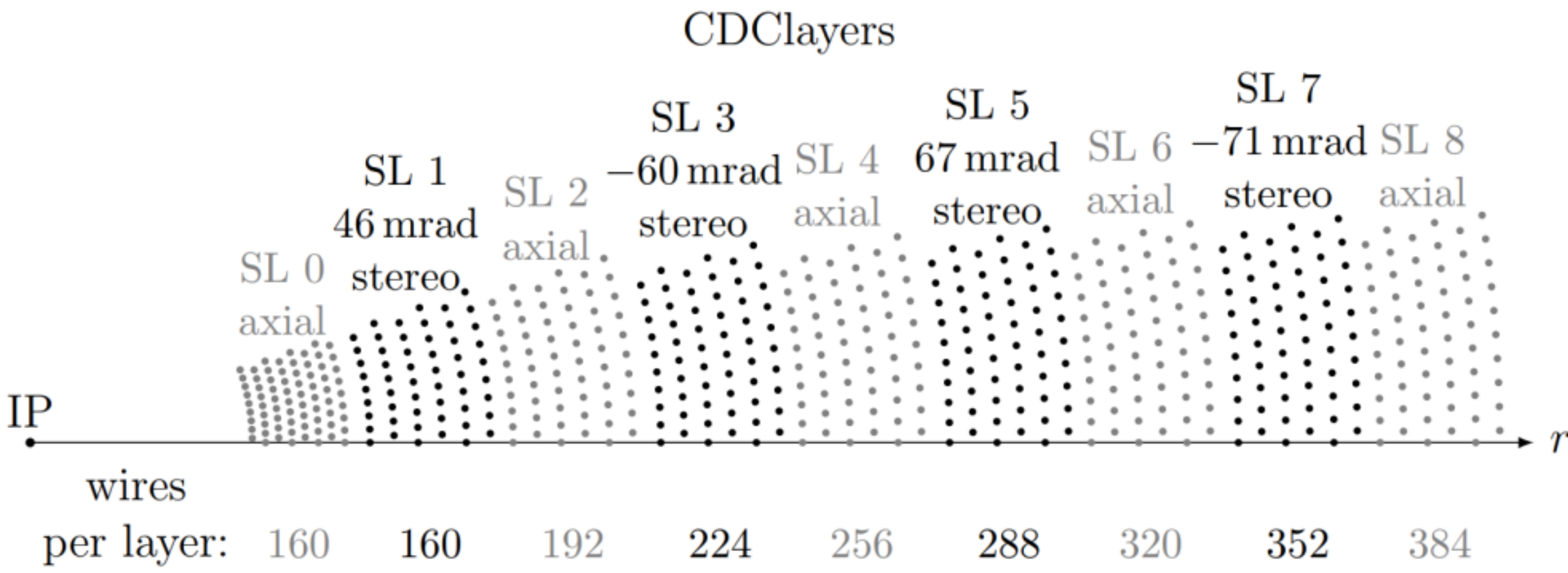


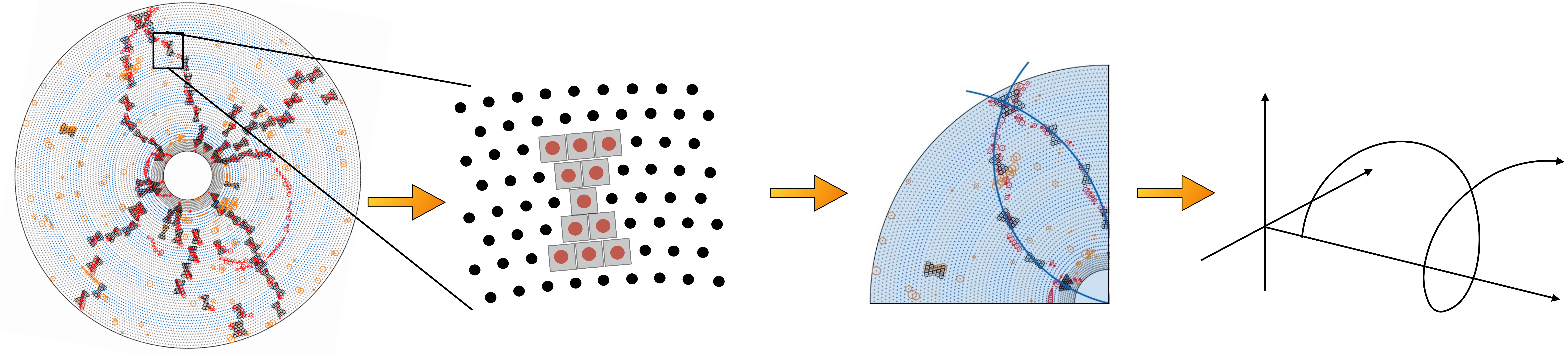

Stereo wire




$$\sigma_z = \frac{\sigma_{r\phi}}{\sin\alpha}$$

$$\sigma_z = 1.9 \sim 2.5\text{mm}(\sigma_{r\phi} = 0.15\text{mm})$$



CDC 2D hit map

Track Segment (TS) Finder in every super layer

Build 2D track with axial hits using Hough transformation

3D Track trigger base on 2D track and Stereo TS

# Neural Network z-trigger

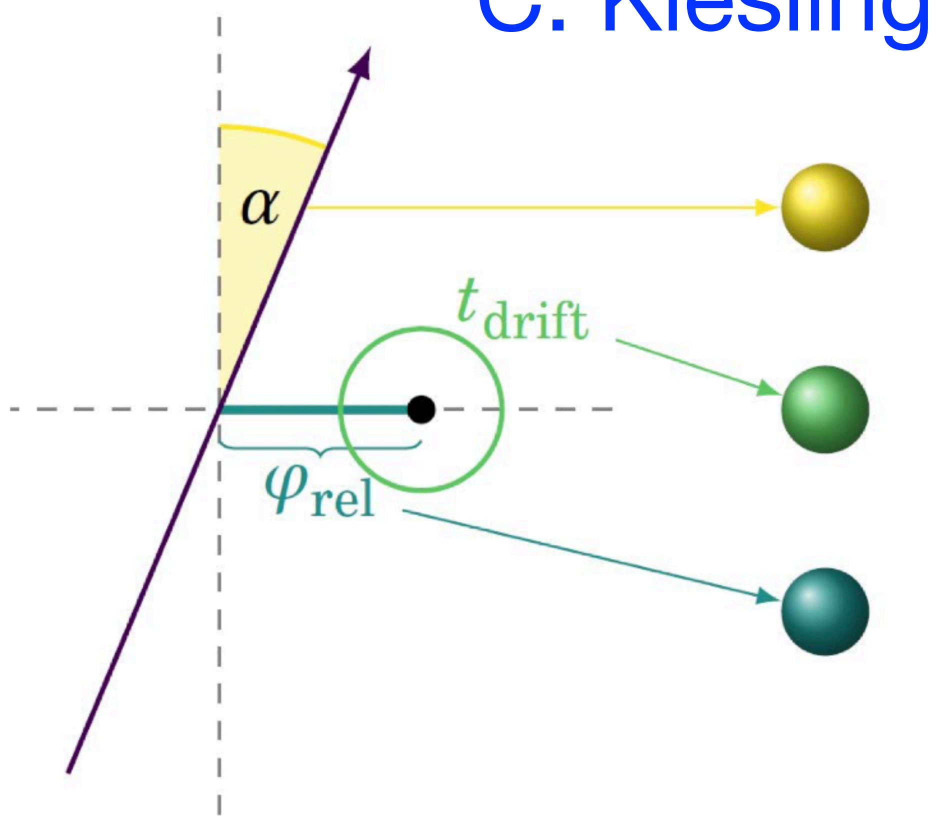
Karlsruhe Institute of Technology

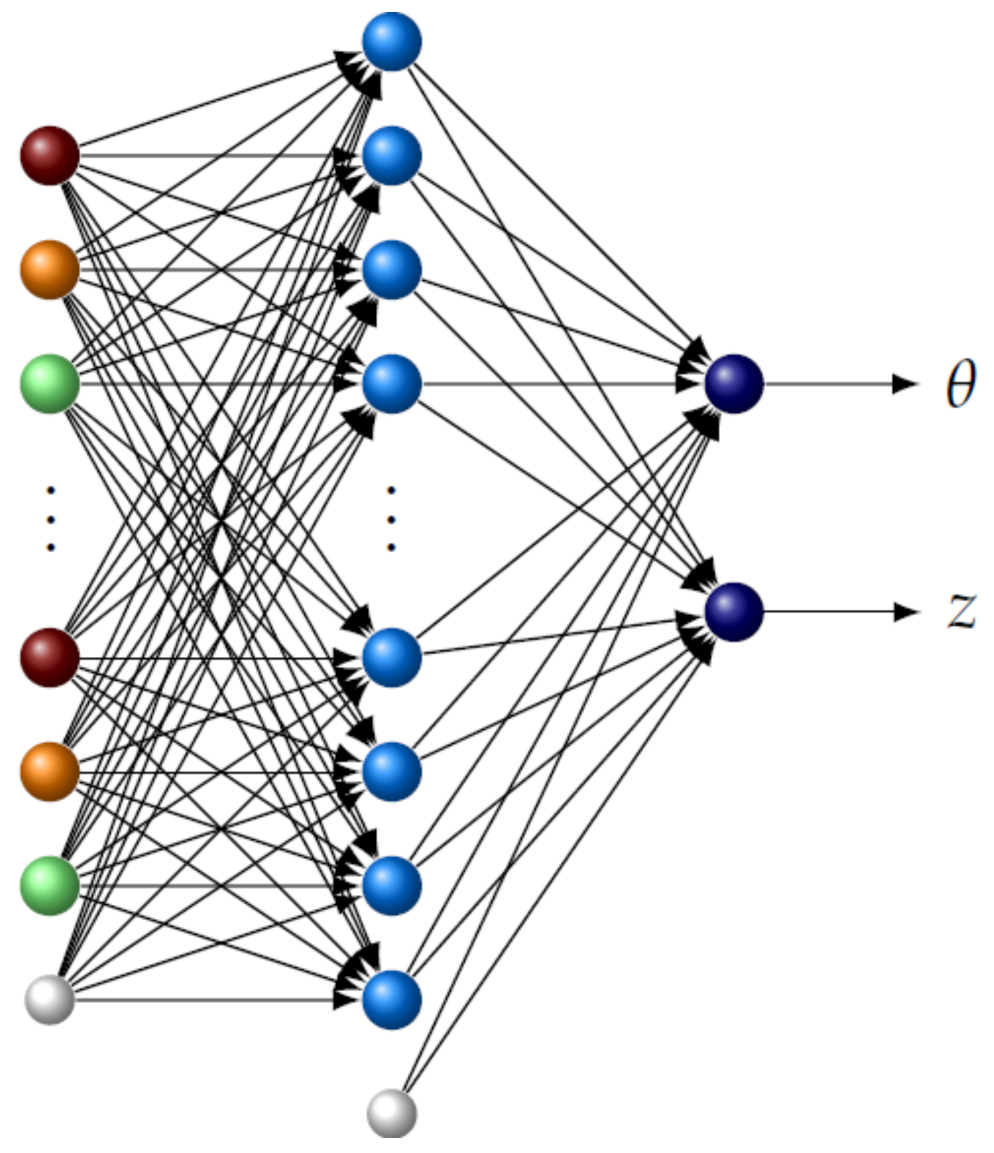
MAX-PLANCK-GESELLSCHAFT

SOKENDAI

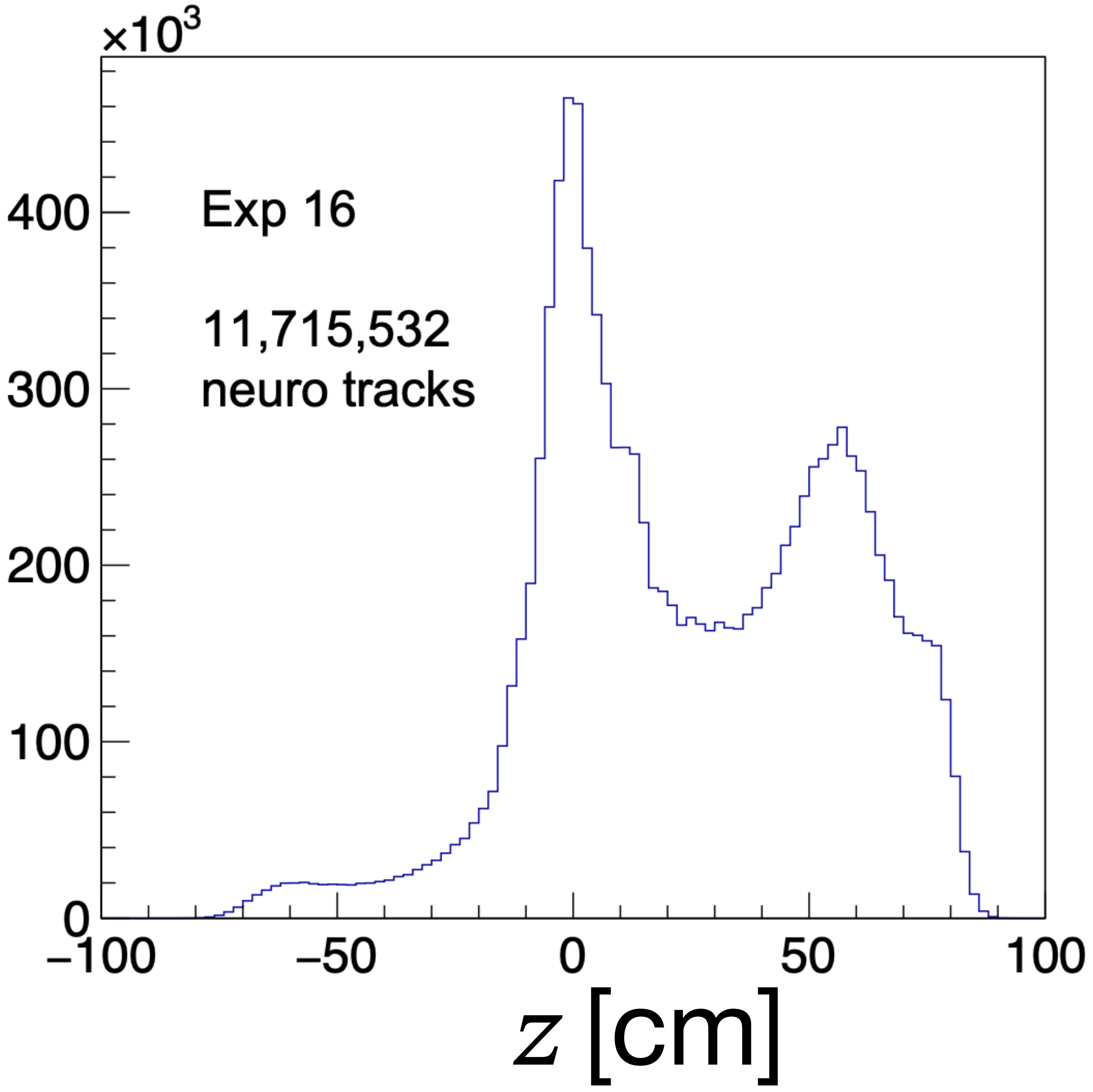
- Pioneer of NN on **HARDWARE** for Belle II trigger
- Inputs: **Drift time $t_{drift}$**, **wires relative location $\phi_{rel}$**, **Crossing angle $\alpha$** for priority wires
- Outputs: track vertex $z_0$, track $\theta$
- Selected 1 Track Segment per one Super Layer
- Networks trained with real data from May-June 2020

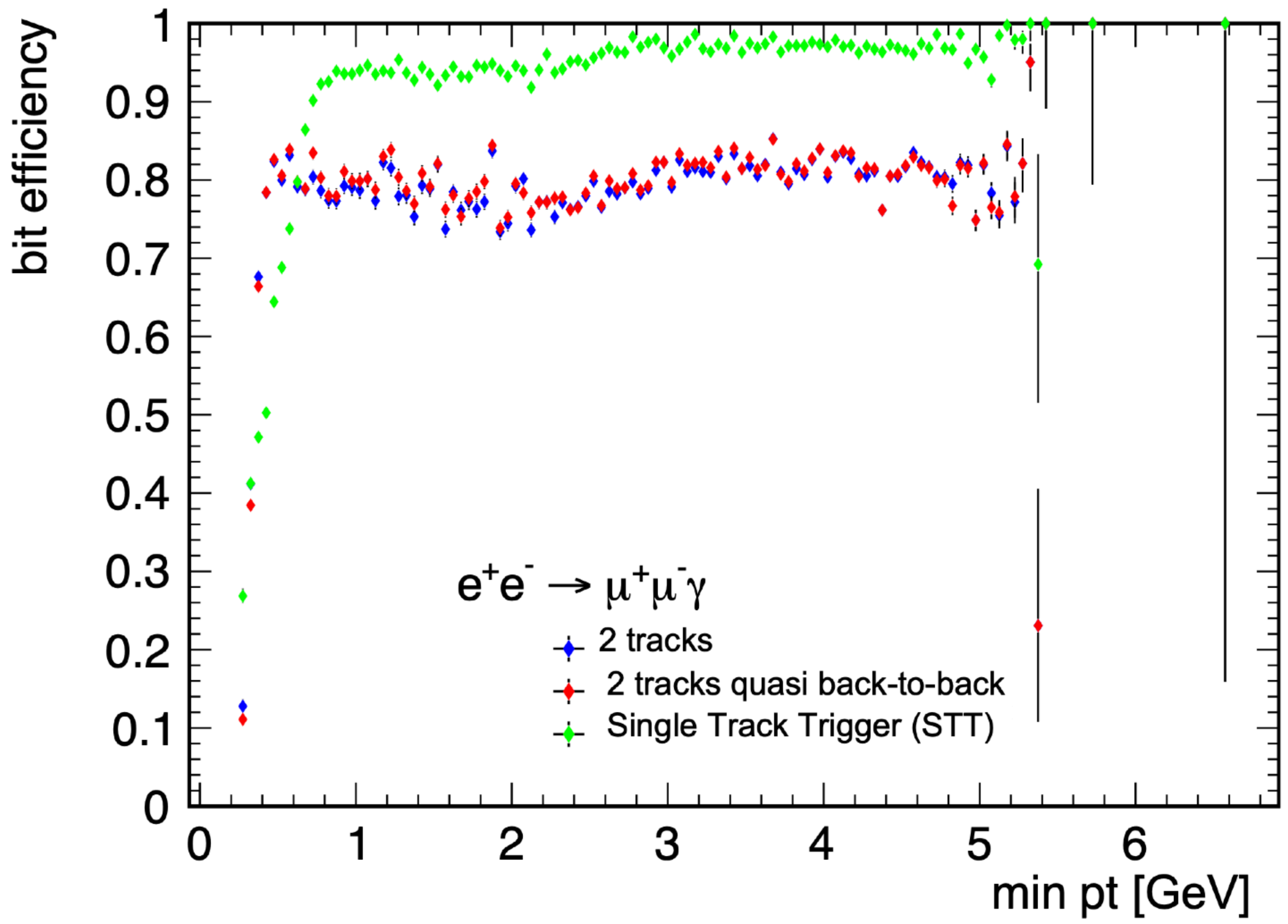
C. Kiesling (MPI) @ ACAT 2024




arXiv:2402.14962 (submitted to NIMA)



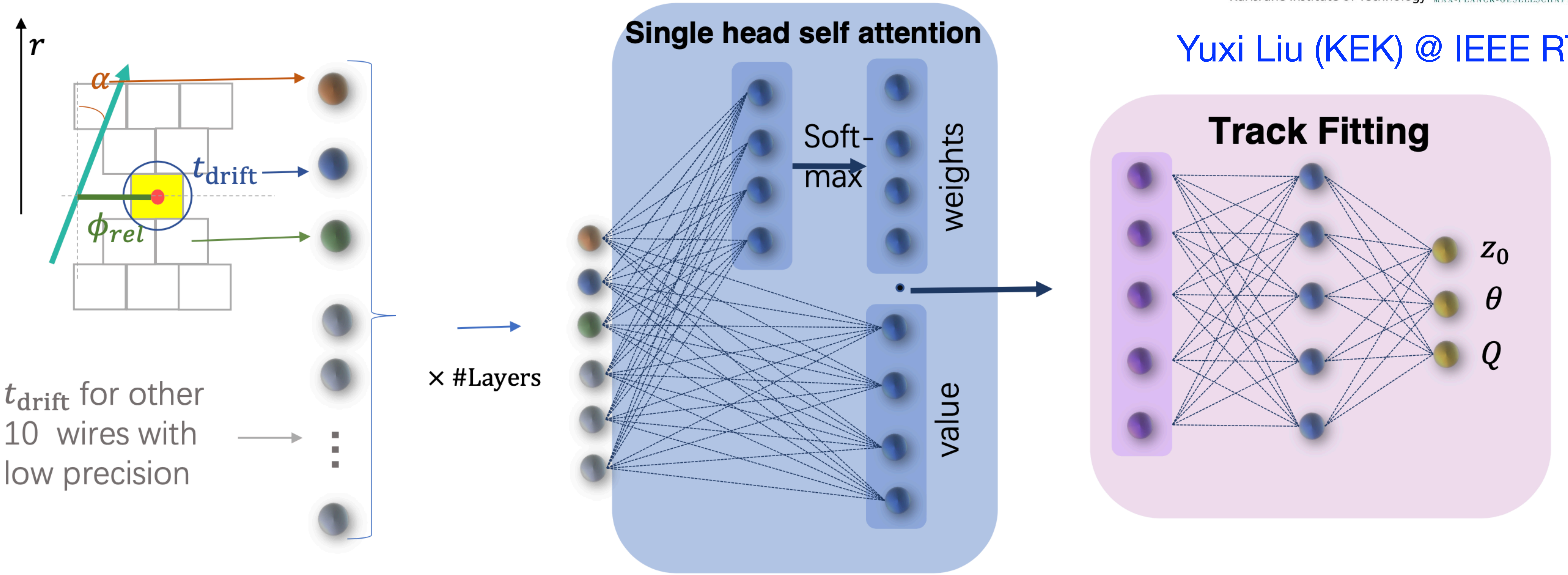




- Backgrounds still high
- Fake background

- Upgrade plan in trigger group:
- Track finding in **3D Hough space**
- network architecture: “deep-learning” + additional inputs

# Deep Neural Network

Yuxi Liu (KEK) @ IEEE RT 2024




- Inputs: **Drift time $t_{drift}$**, **wires relative location $\phi_{rel}$**, **Crossing angle $\alpha$** for priority wires + **Drift time for all other wires**
- Introduce the **self-attention architecture** to “focus” on certain inputs
- Output track vertex $z_0$, track $\theta$ and **signal/ background classifier output** ($Q$)

| Parameter | #Attention value | #hidden nodes | #hidden layer | activate | precision | Total multiplier |
|---|---|---|---|---|---|---|
| Values | 27 | 27 | 2 | Leaky Relu | Float 16 | 4,185 |

# Development flow of DNN on FPGA

Software → Hardware → FPGA

Keras + TensorFlow
PyTorch

- Machine Learning model
- Parameter

hls4ml

- C/C++ transition

Vivado™ HLS

- Translate into Verilog/VHDL FPGA language

VIVADO

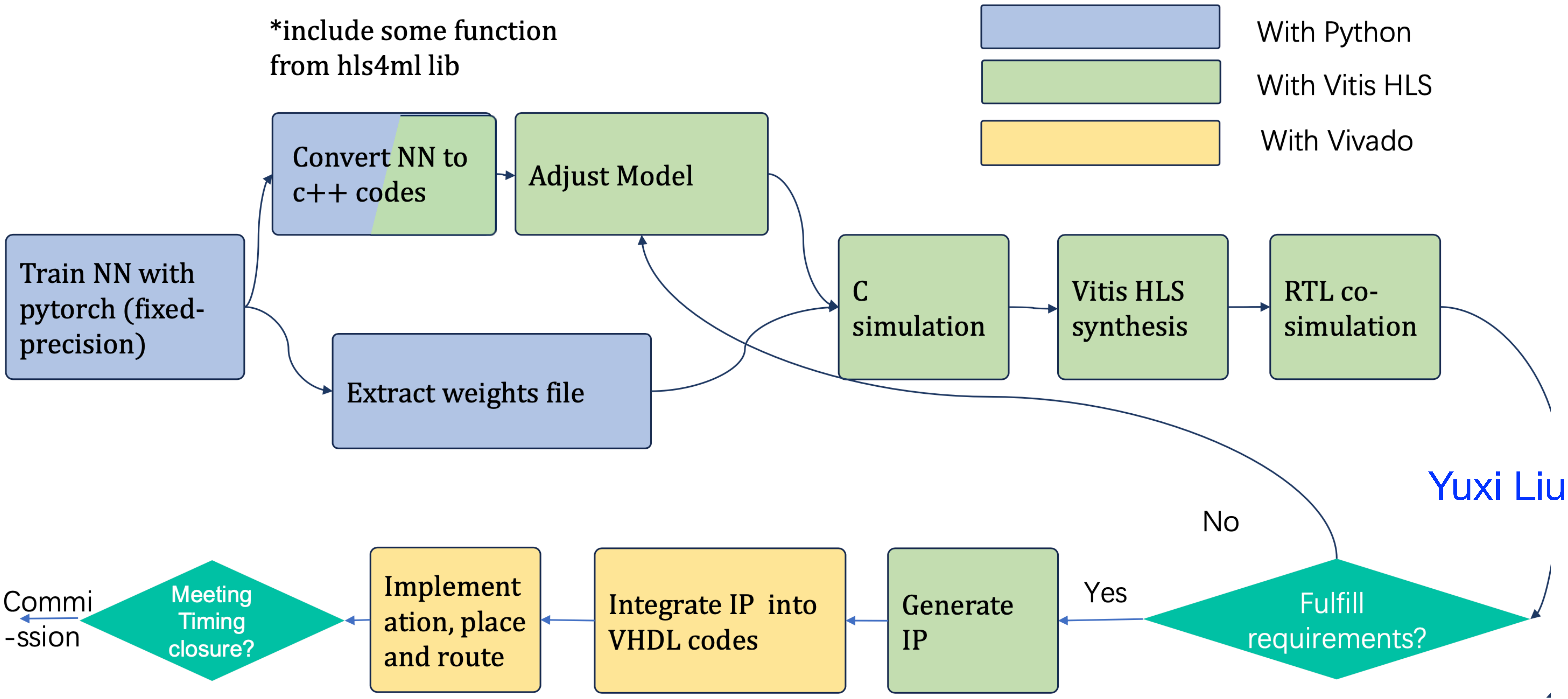
- Start fitter

- Evaluation

**Belle II UT4**

Xilinx UltraScale
XCVU080, XCVU160
25 Gbps with 64B/66B

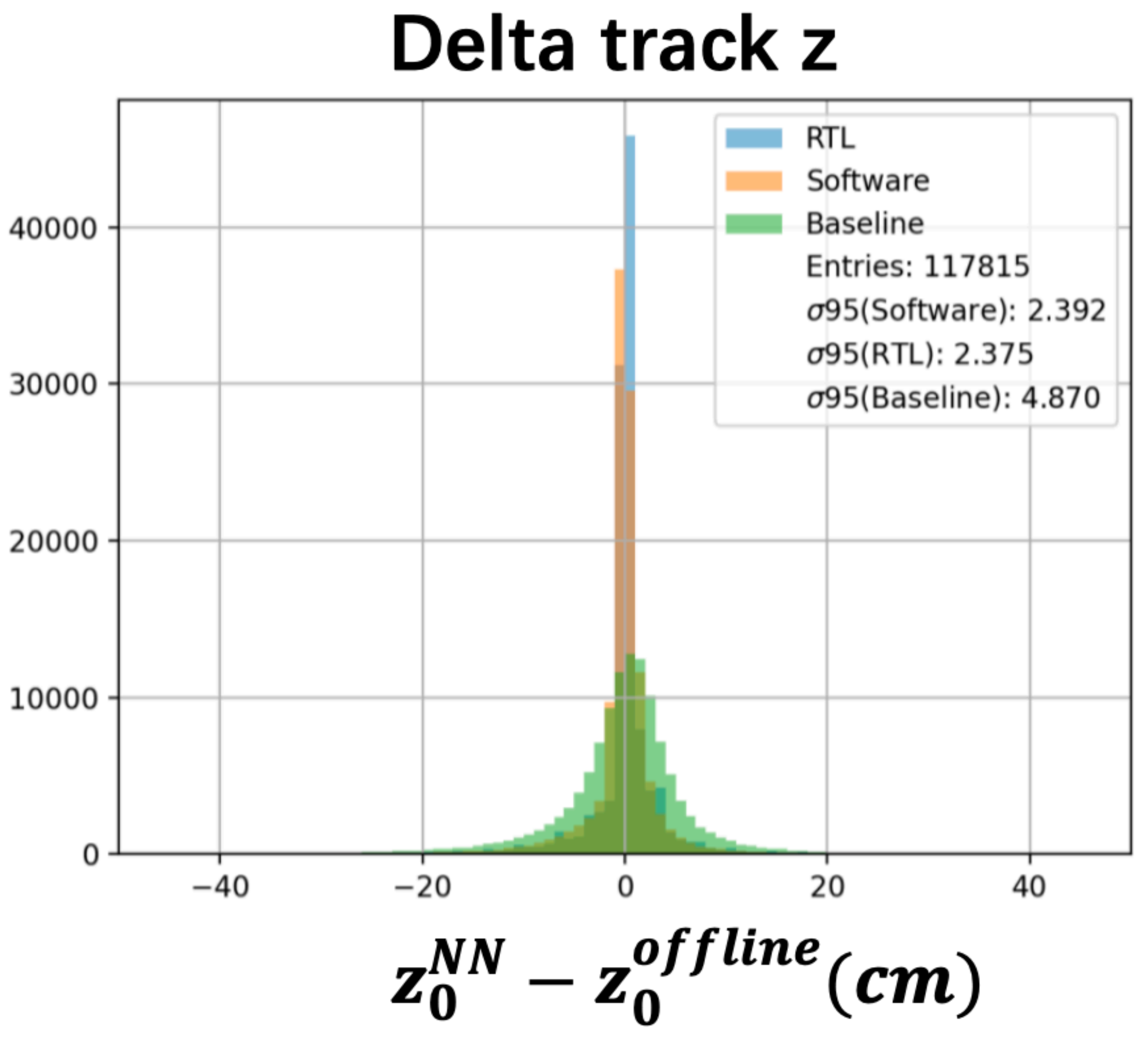
*include some function from hls4ml lib

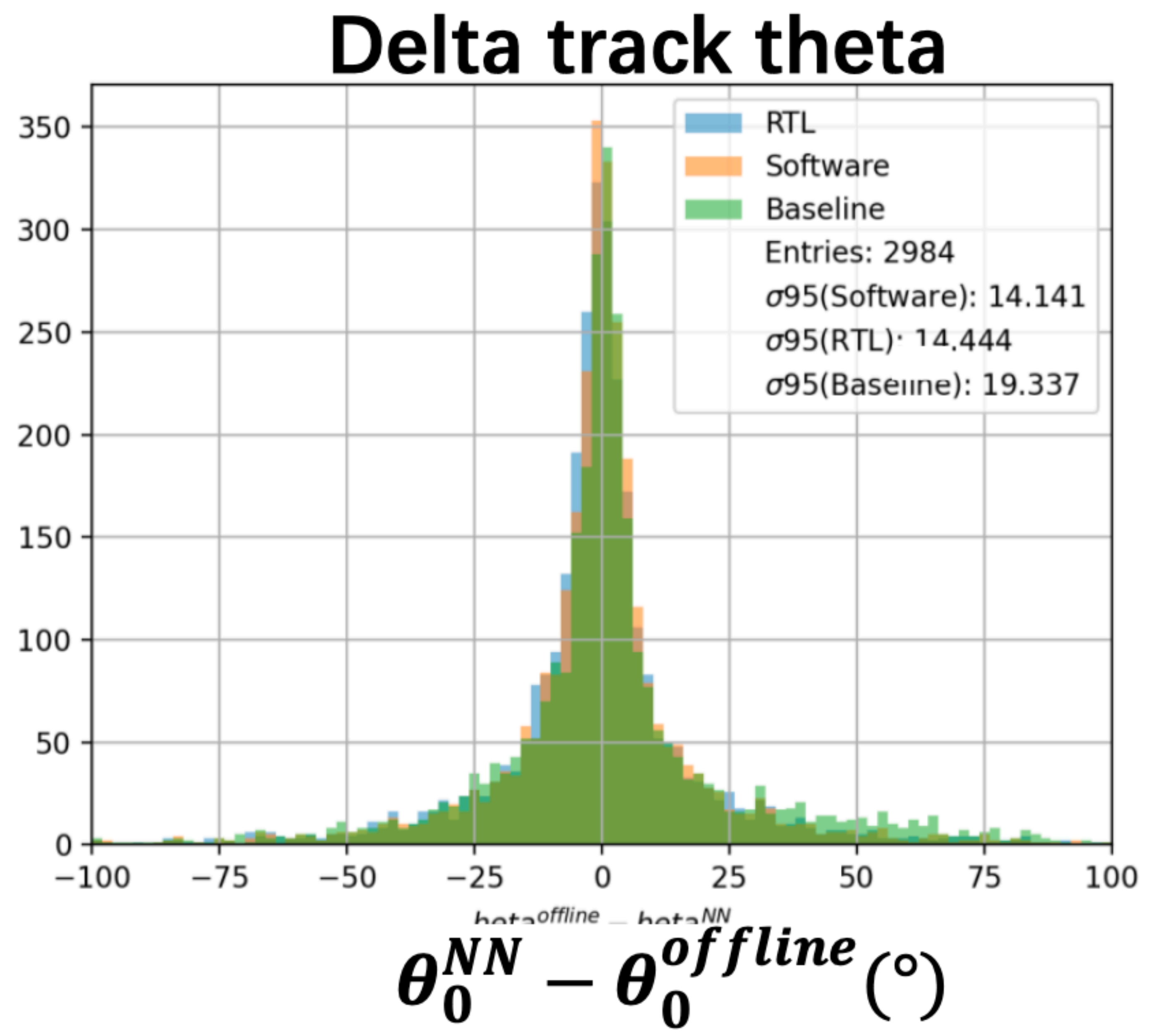


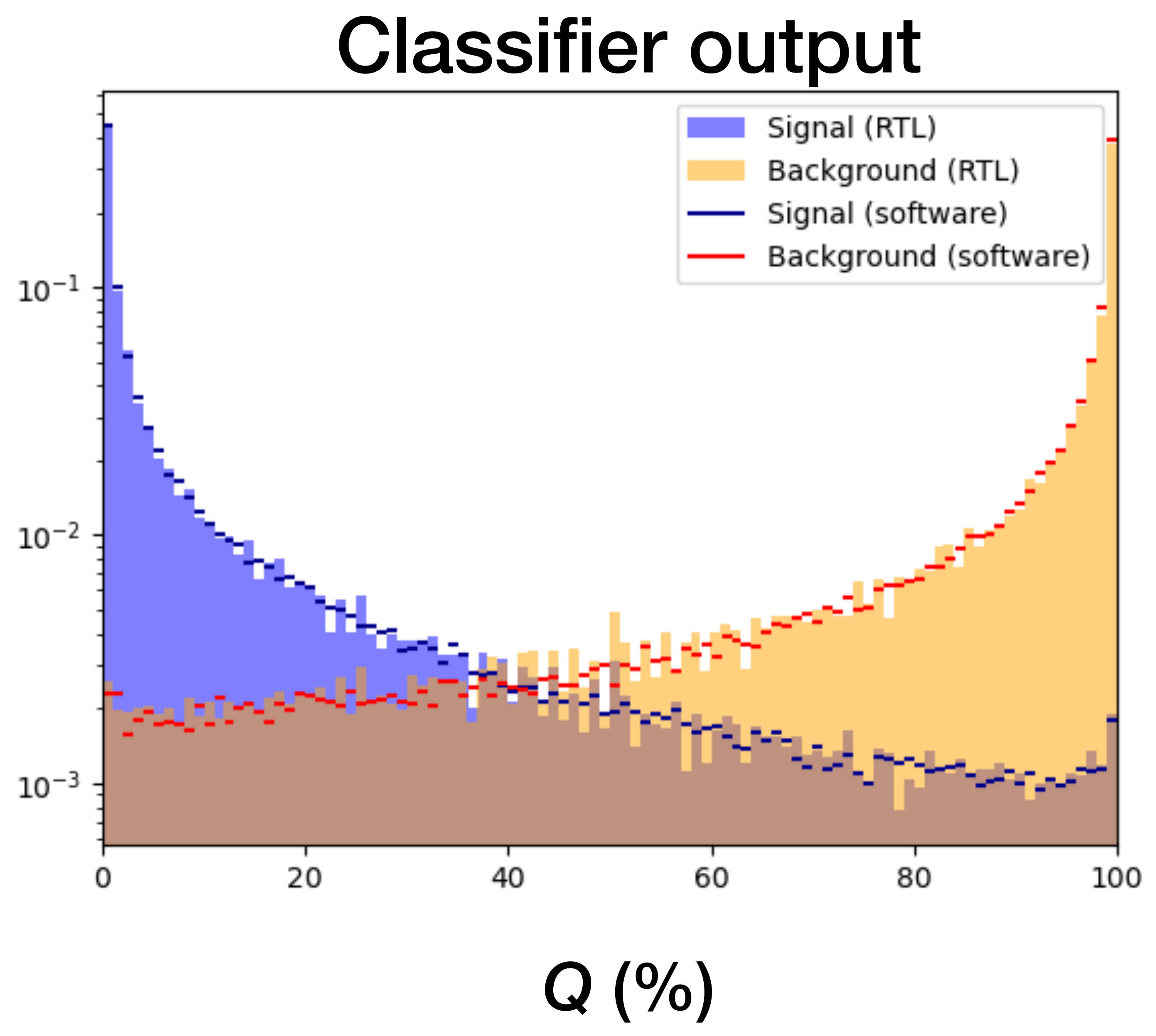

Yuxi Liu (KEK) @ IEEE RT 2024

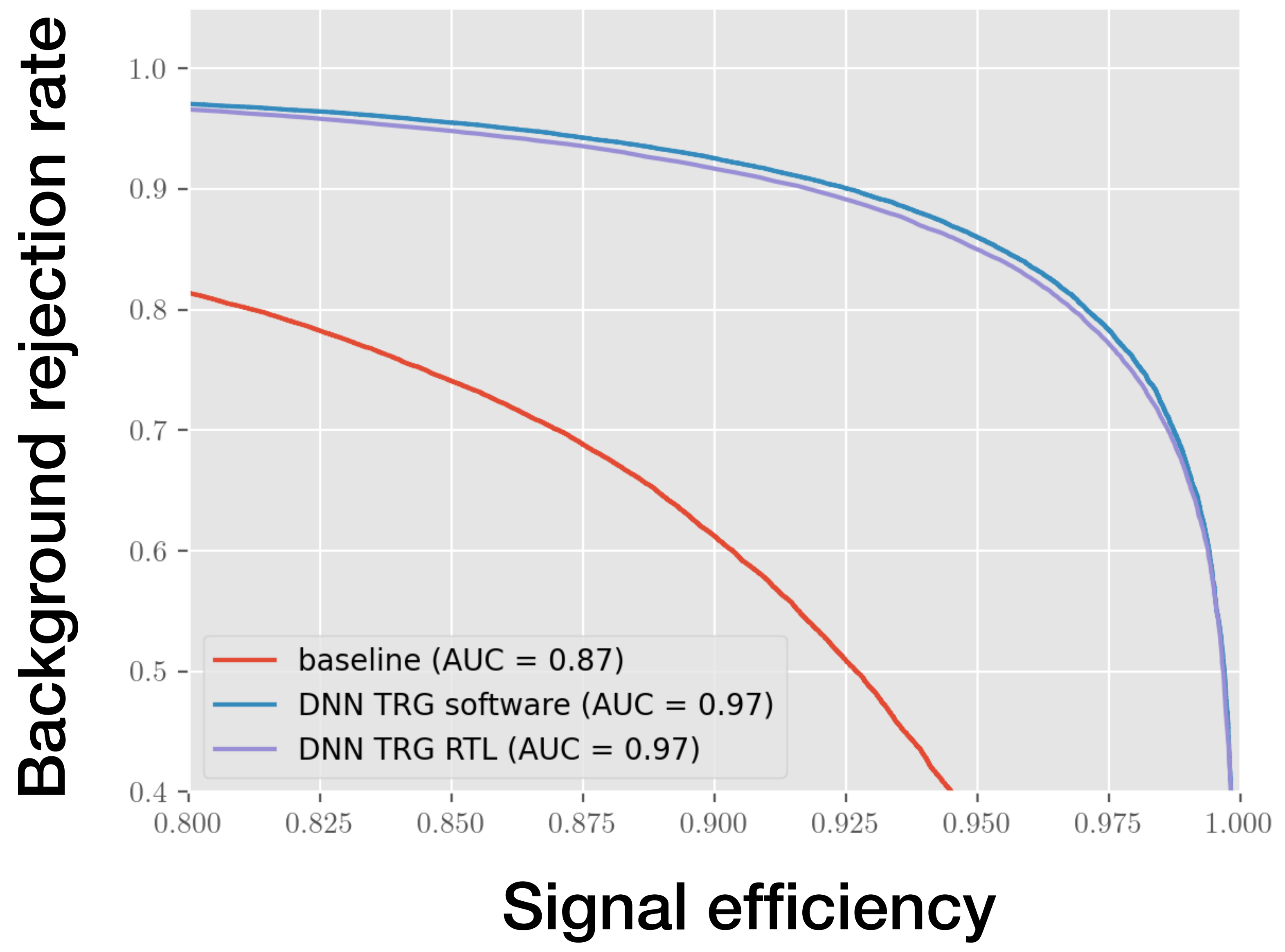
# Simulation performance of DNN

Yuxi Liu (KEK) @ IEEE RT 2024



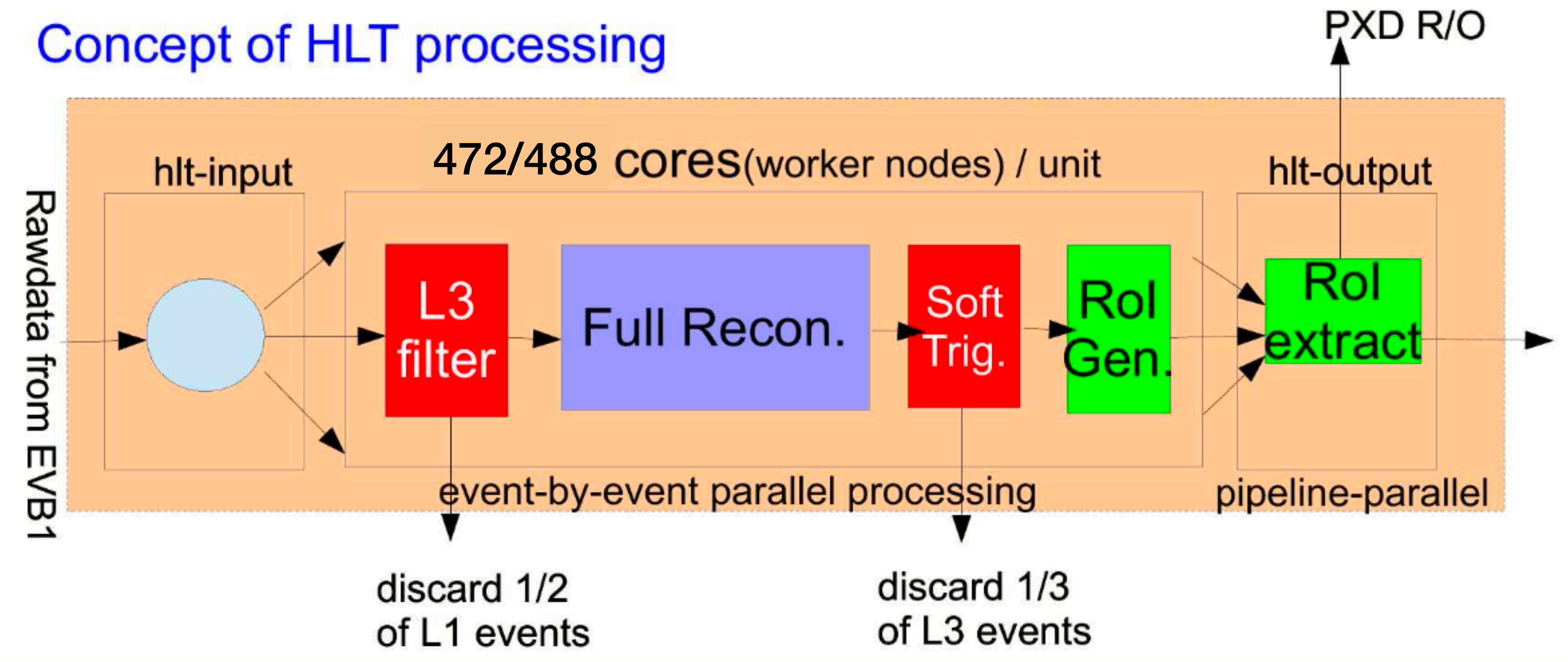



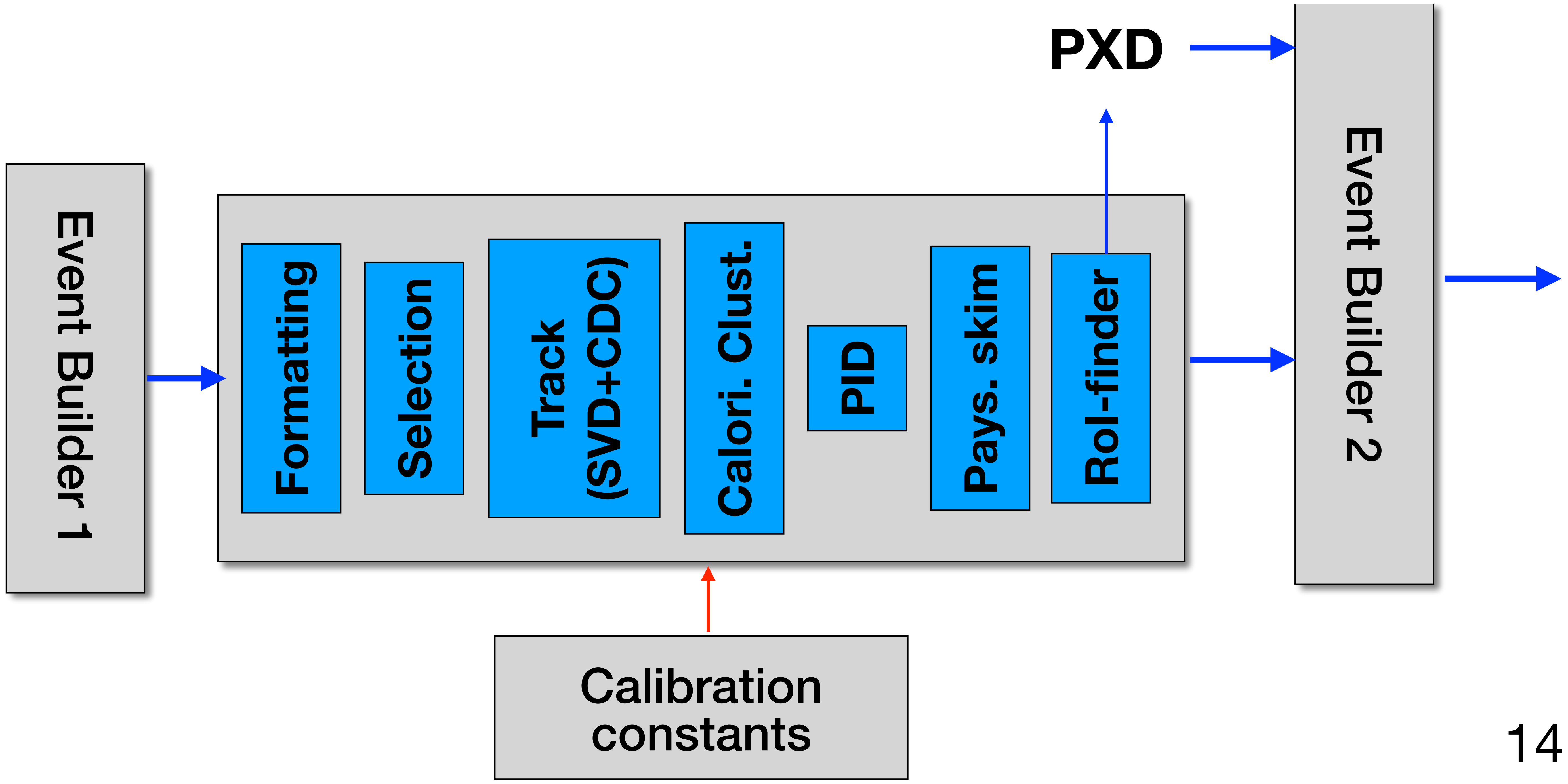

- Latency : 76 clock = 592.8 ns ;require: < 600ns
- FPGA resource (UT4: Virtex UltraScale XCVU160) usage:
  - DSP: ~70%, LUT: ~50%, others <30%
- AUC do not get large drop comparing RTL and software simulation
- At signal efficiency ~95%
  - Background rejection rate ~85%

- DNN trigger with **HARDWARE** under commissioning, close to operate

# Overview of high level trigger system at Belle II

- Full event reconstruction (same as offline processing)
- Crude calibration constant
- 13 HLT units, in total ~6200 CPU cores (design: 7000 cores)
- Data processing: ~ 2.1kHz/ HLT unit w/ hyper-threading
- Event size at HLT in the last run period: ~150 kB/event
- PXD event size = 1MB/event, 10 times larger than the rest of detectors
- Region of interest (RoI) method is effective to reduce the data size
- ROI
  - **Tracking software** running on HLT nodes

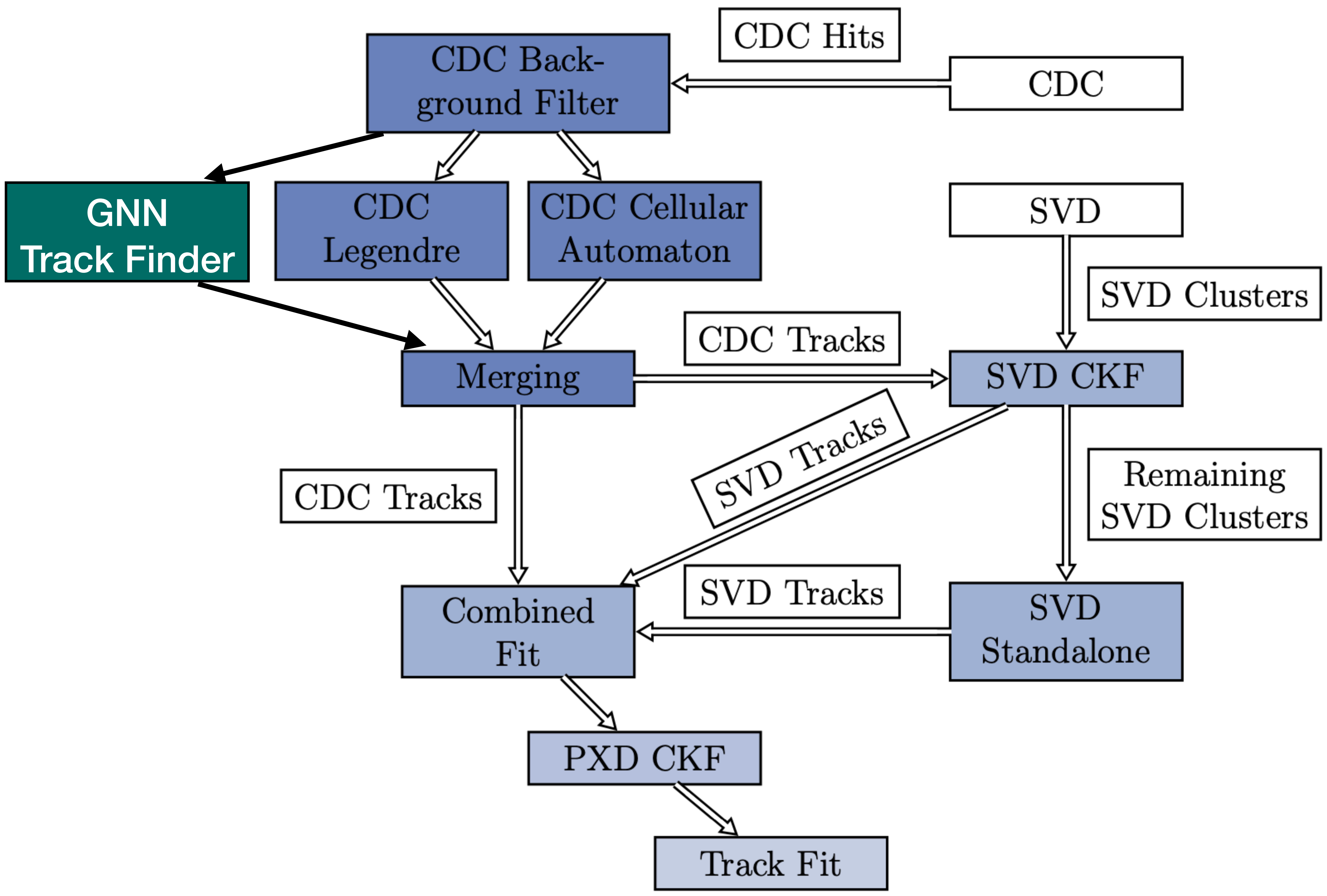


# GNN based CDC track finder

- <u>Motivations of introducing a GNN track finder (**SOFTWARE**)</u>
- Low efficiency for displaced vertices
  - Efficiency decrease as displacement increase
  - Important signature for new physics search
- Higher background
- CDC wire inefficiencies
  - Bad wires or electrics
  - Decreased efficiency

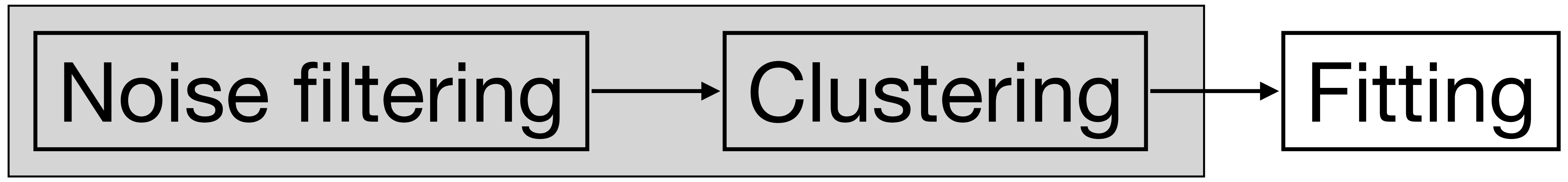
Comput.Phys.Commun. 259 (2021) 107610



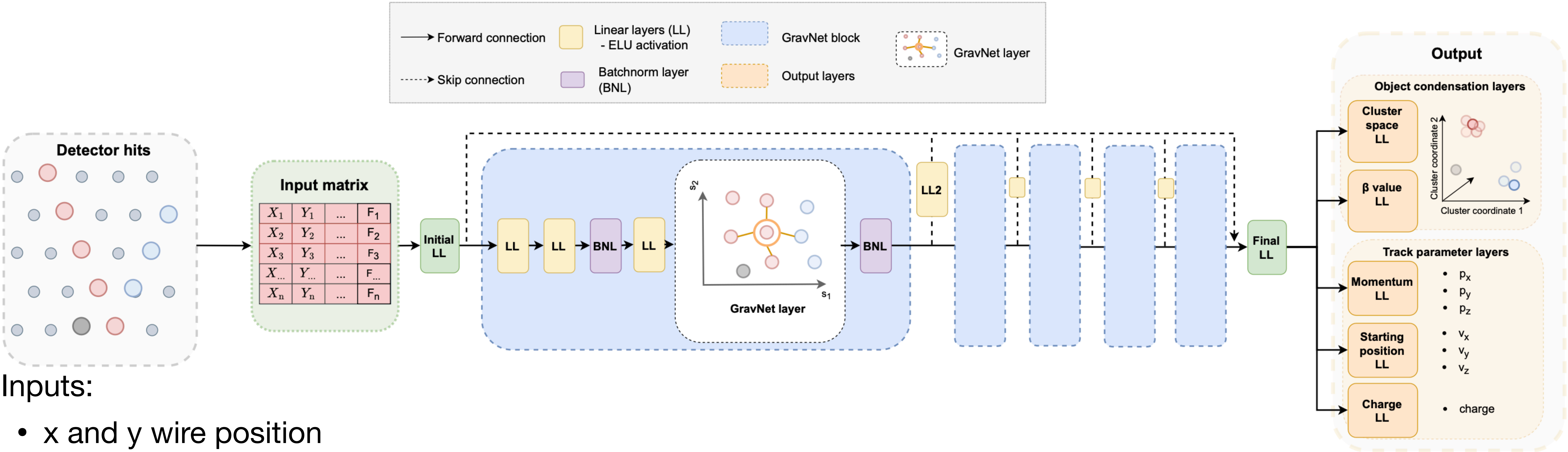

- Modular structure for track finding, with flexible of reconstruction sequence

# GNN for offline track finding

- Find track parameters: momentum, starting position and charge
- Find unknown number of tracks → Object Condensation (arXiv:2002.03605)
- Computing resource and time constraint may reducible



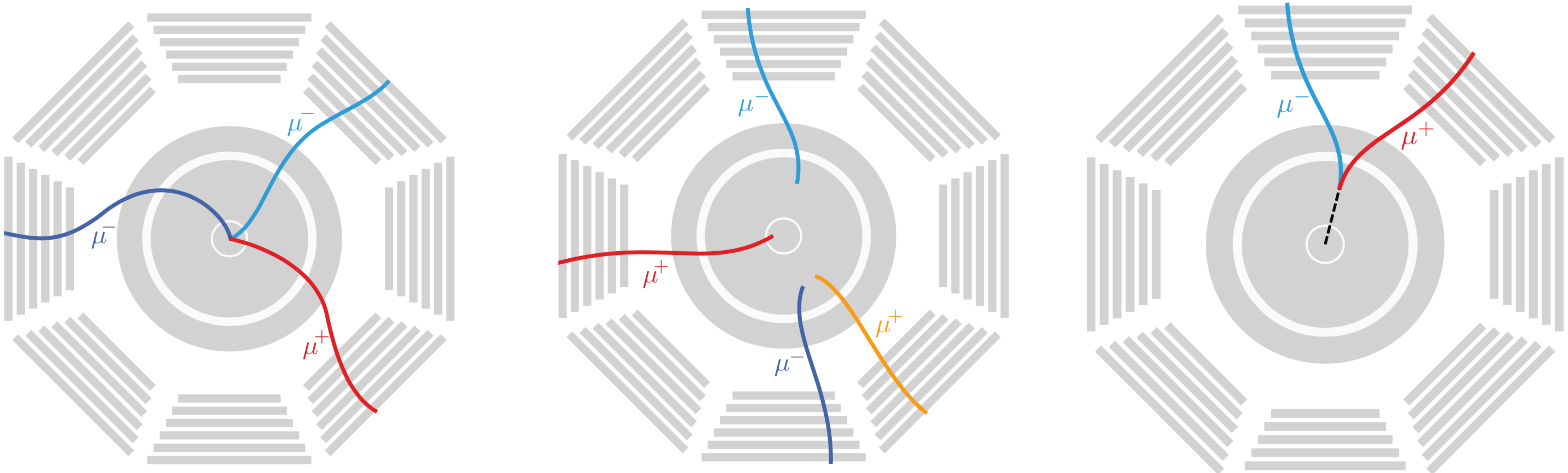

L. Reuter et. al. (KIT) BELLE2-NOTE-TE-2024-008




- Inputs:
  - x and y wire position
  - TDC and ADC of signal information
  - layer, superlayer, and layer info. with suprlayer
- Adjustable Parameters
  - 797,812 trainable parameters (3MB weight files)

# Training of GNN

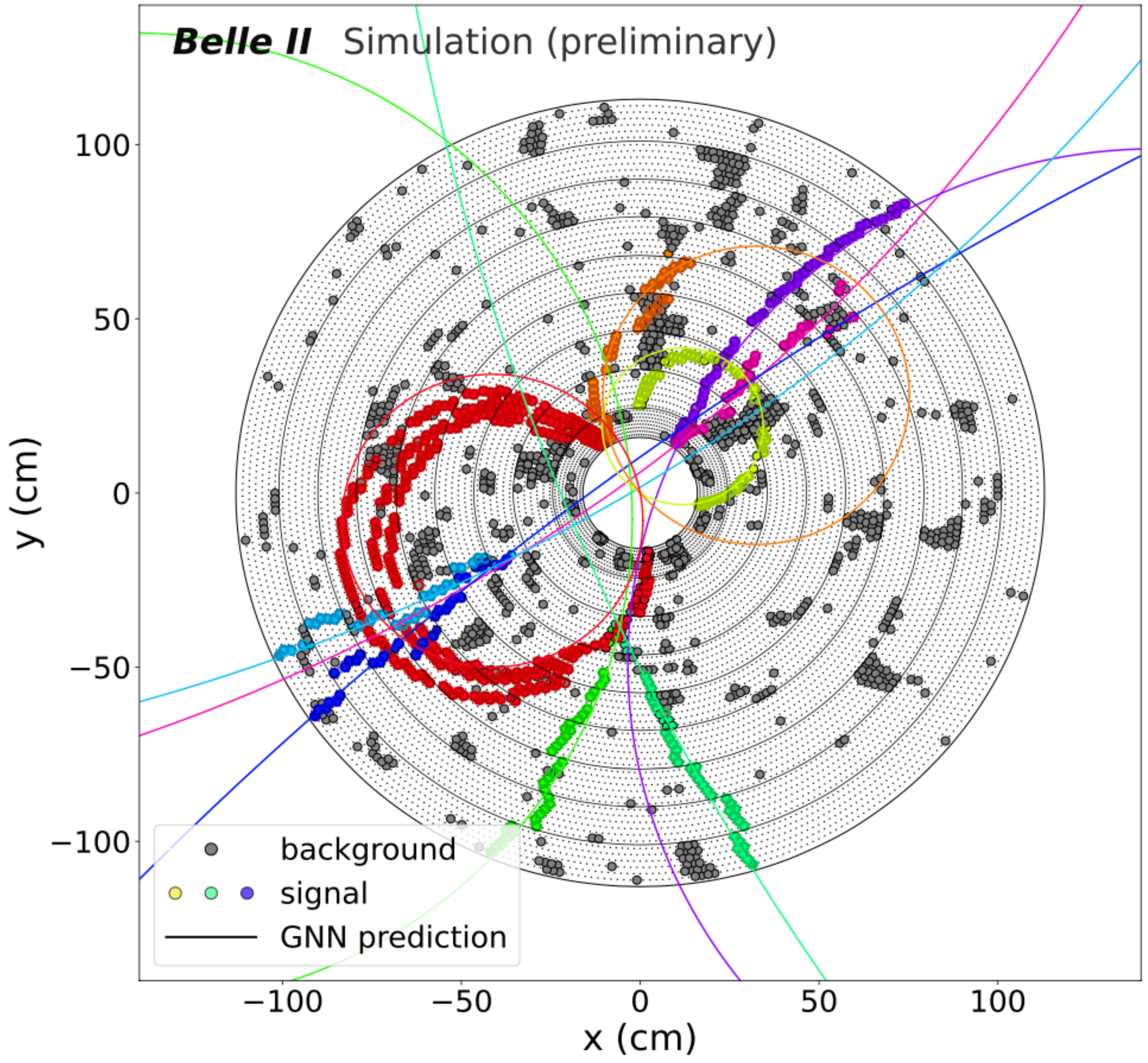
- Simulate 1 million events with over 4 million tracks
  - Train: Validation = 4 :1
- Training samples contain different topologies that cover all interested event features, to not bias the model, **no conservation laws involved here!**
  → crucial step to be agnostic about the physics processes
- Sample features
  - Low momentum tracks forming circles in the CDC ($P_t$ < 0.4 GeV) <-> High momentum tracks
  - Short tracks <-> tracks penetrate all CDC layers
  - Small opening angle <-> well isolated two tracks
  - …



# Performance of GNN

- Efficiency of displaced vertex tracks improved from 85.4% with a fake rate of 2.5%, compared to 52.2% and 4.1%
  - The other performance similar as original algorithm
- Momentum $p_x$ , $p_y$ , $p_z$ starting position $v_x$ , $v_y$ , $v_z$ ,charge
  - Provide initial inputs for GENFIT
- GNN prediction is drawn according to the track parameters predicted by the GNN
- Plan to added as additional track finder for Belle II

L. Reuter et. al. (KIT) BELLE2-NOTE-TE-2024-008



# Motivations of trigger-DAQ upgrade

Physics

- Tau trigger efficiency now is >95% (to be pre-scaled if luminosity is high)
- Low multiplicity trigger efficiency (to be pre-scaled pre-scaled if luminosity is high)
- Low-momentum track trigger efficiency
- “Anomaly” trigger
  - Design a special trigger line for some specific physics channel
- Trigger efficiency of displaced vertex

Current hardware limitation:

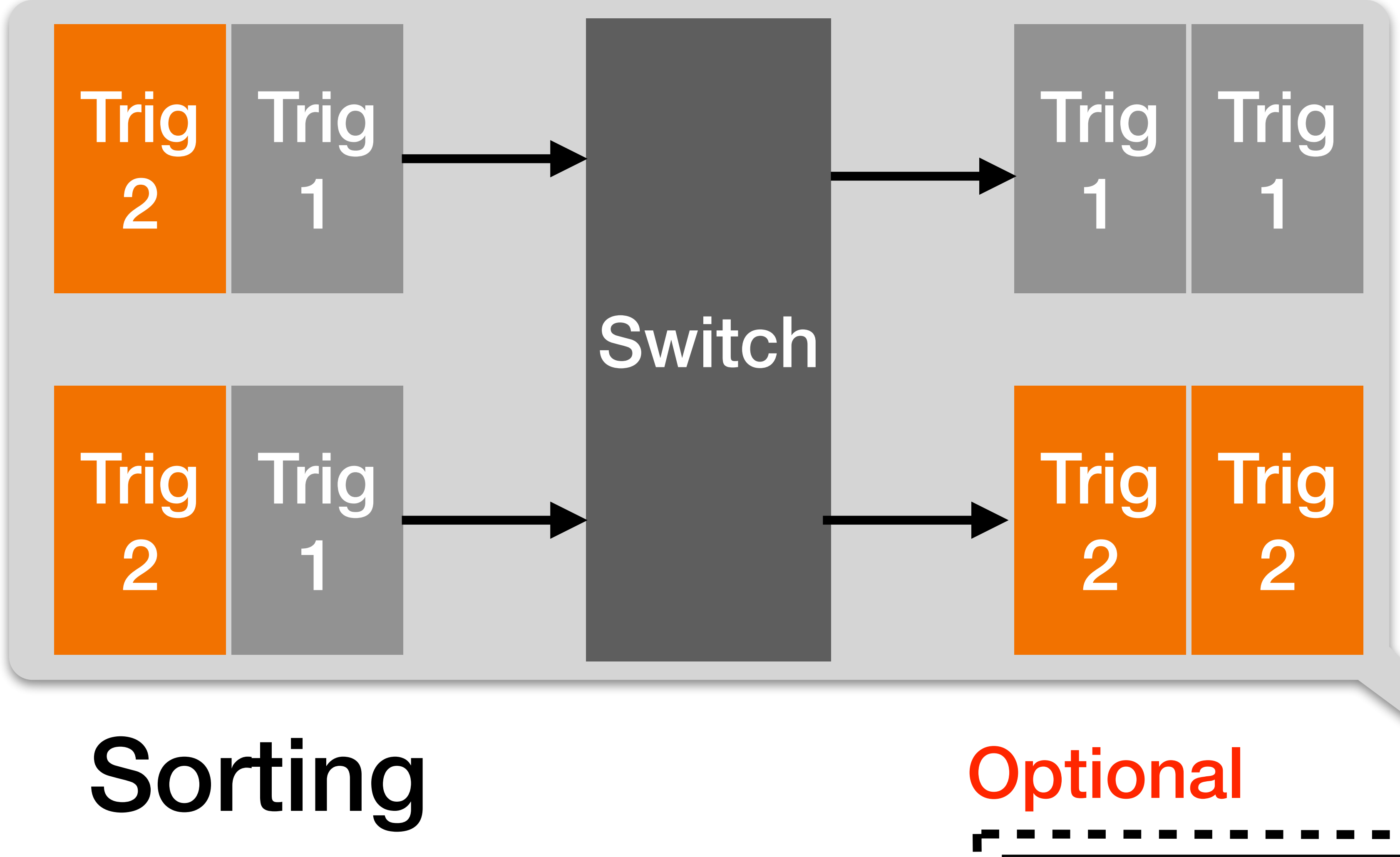
- DAQ system is designed to handle 30 kHz
  - L1 latency 4.4 us (SVD APV25 buffer)
    - CDC DNN trigger latency ~500 ns, latency already limited more large model
- L1 trigger rate will reach to ~20 kHz at $0.9\text{x}10^{-35}$ $cm^{-2}$ $s^{-1}$ (13 HLT units, w/o hyperthreading), planed full HLT: 15 units (7000 CPU cores)
- TTD system: VME bus limit,  no more than 3 triggers within 80 clock (624ns)

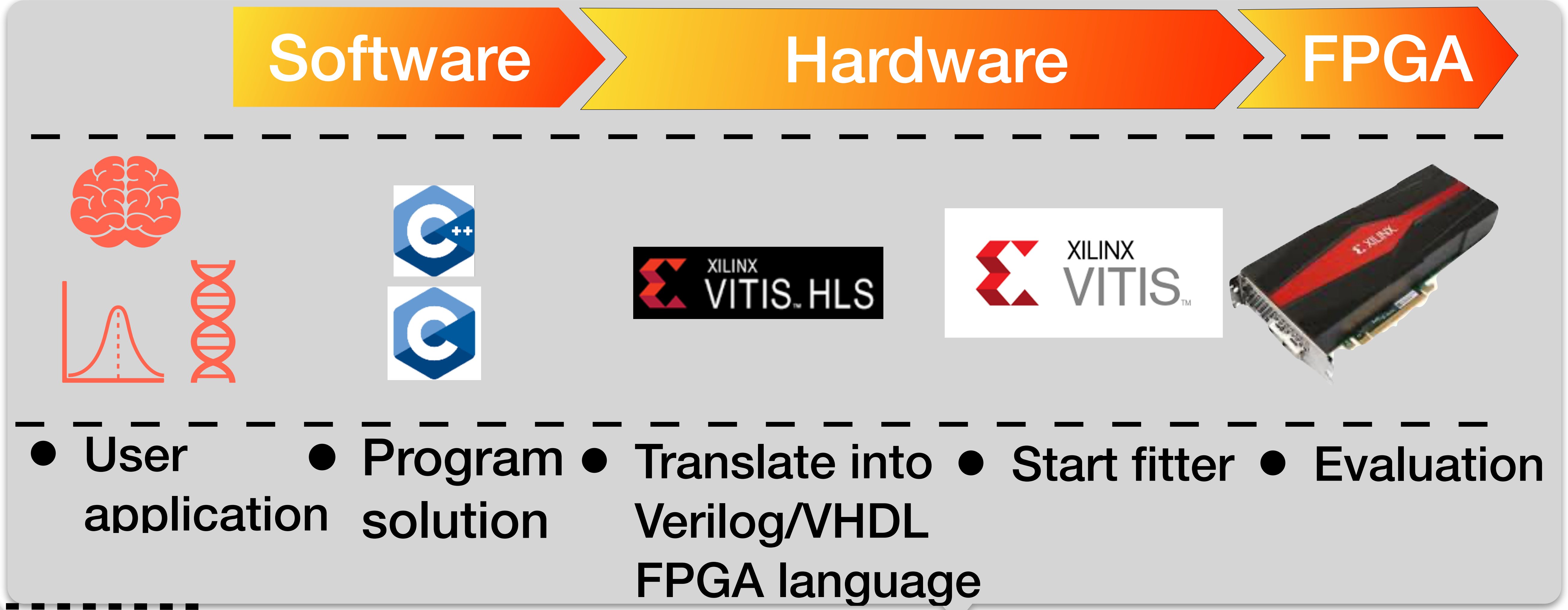
Vertex detector is planed to be upgraded during long shutdown 2 (after 2028)

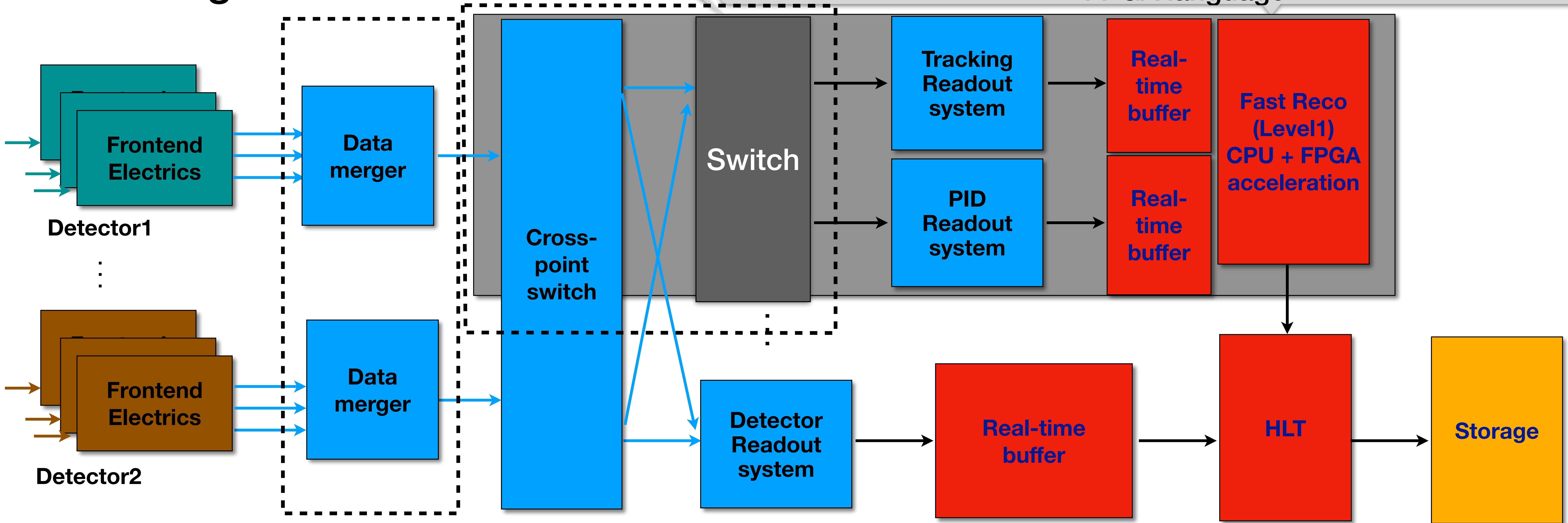
- Latency limit target: 5 us -> 10 us (5.2 us KLM, 9 us TOP, considering upgrade)
- New TTD hardware: VME bus -> Ethernet
- New trigger board (UT5): Versal ACAP

# Idea of upgrade trigger and DAQ system

Proposed on Belle II trigger DAQ workshop 2022

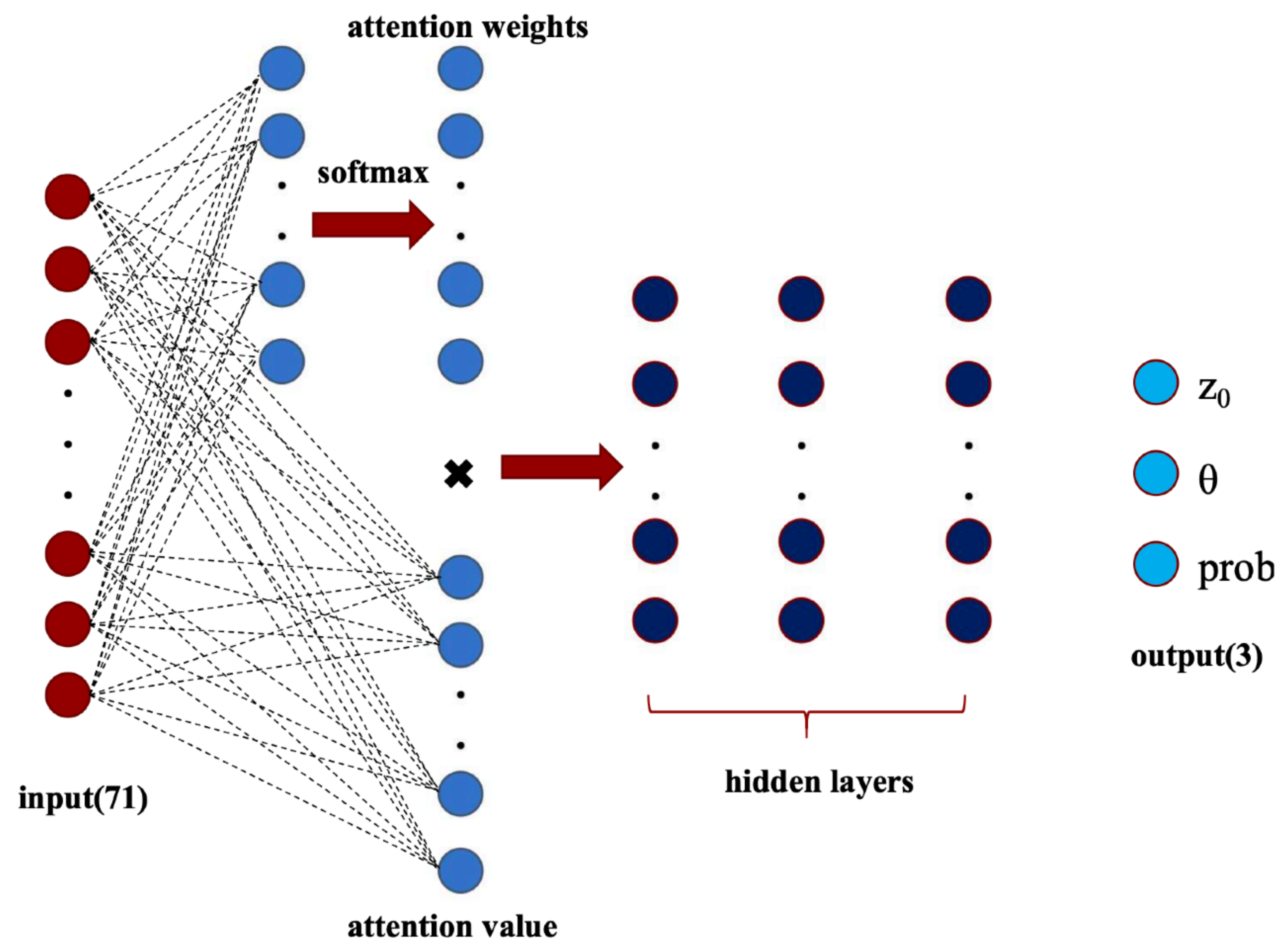


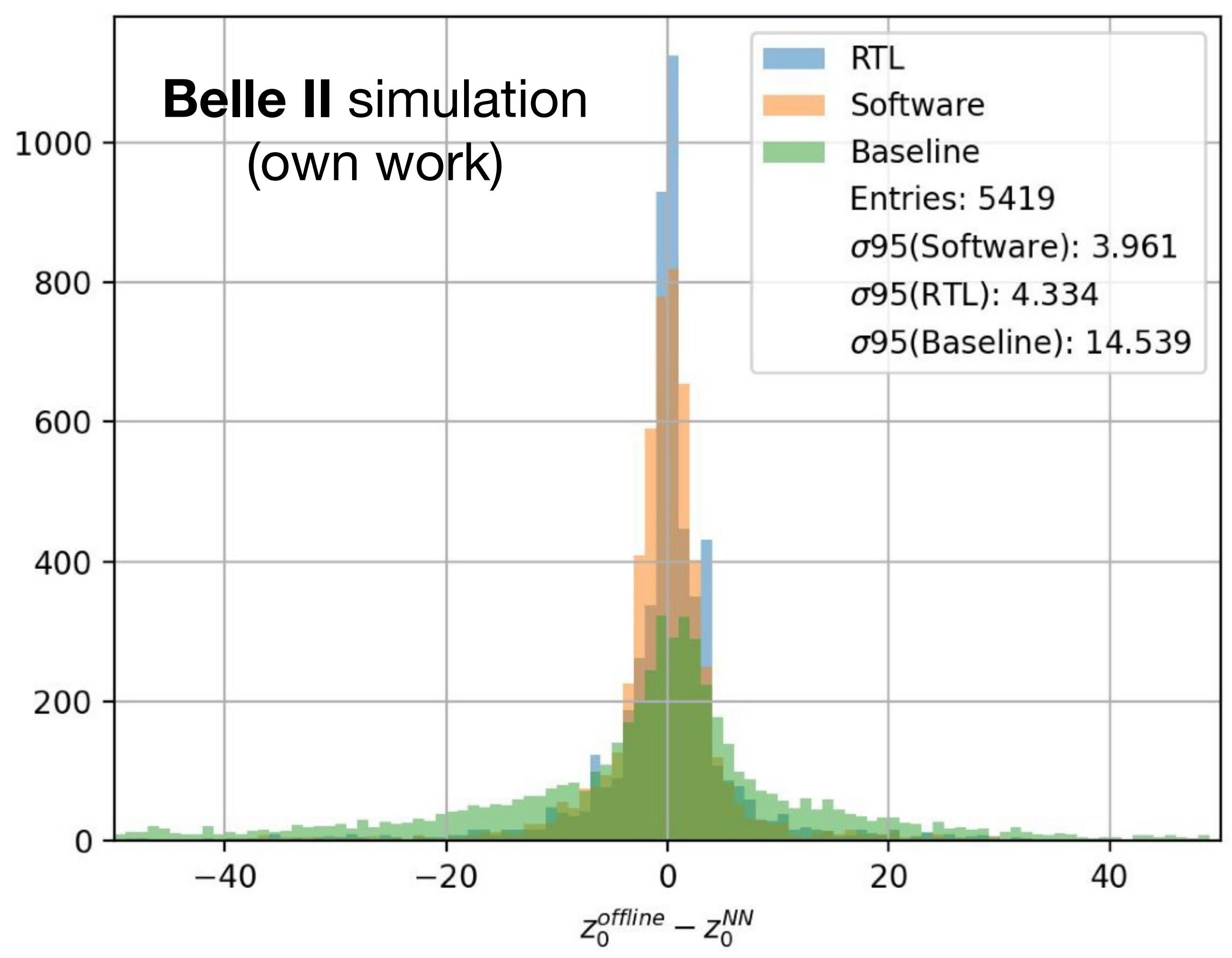



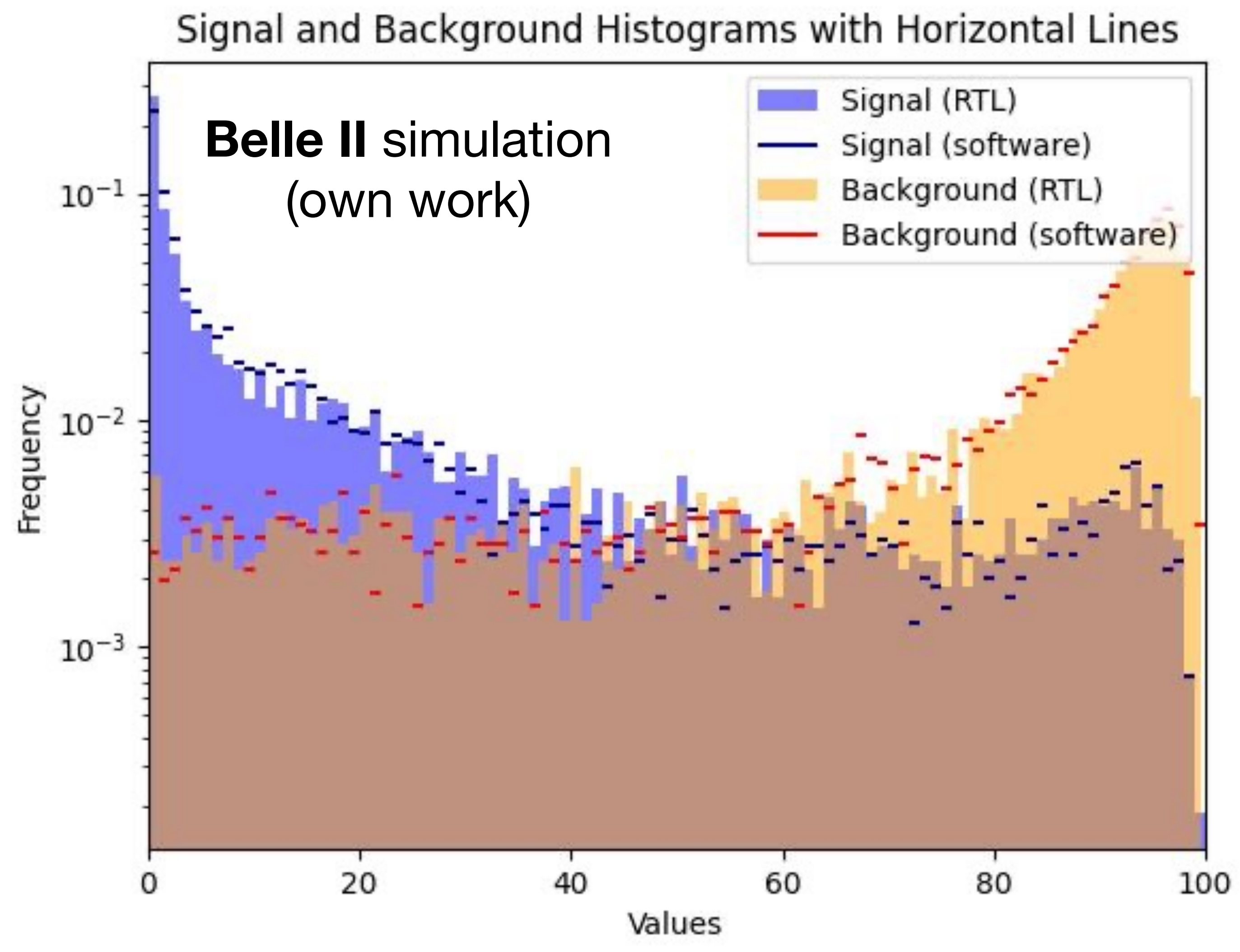
# Improvement try for CDC track trigger

- Develop a algorithm improve the performance for the upgrade (10 usec latency)
  - Start from optimization of DNN model
- Modify the number of hidden layers and learning rate
  - Hidden layer: 2 -> 4, learning rate: $1e^{-2}$ -> $1e^{-3}$
  - Others keep the same
  - No improvement
  - Latency: 76 clock (592.8 ns) -> 82 clocks (640 ns)
- Next step, change the inputs (CDC hits info.), instead of 2D track parameters



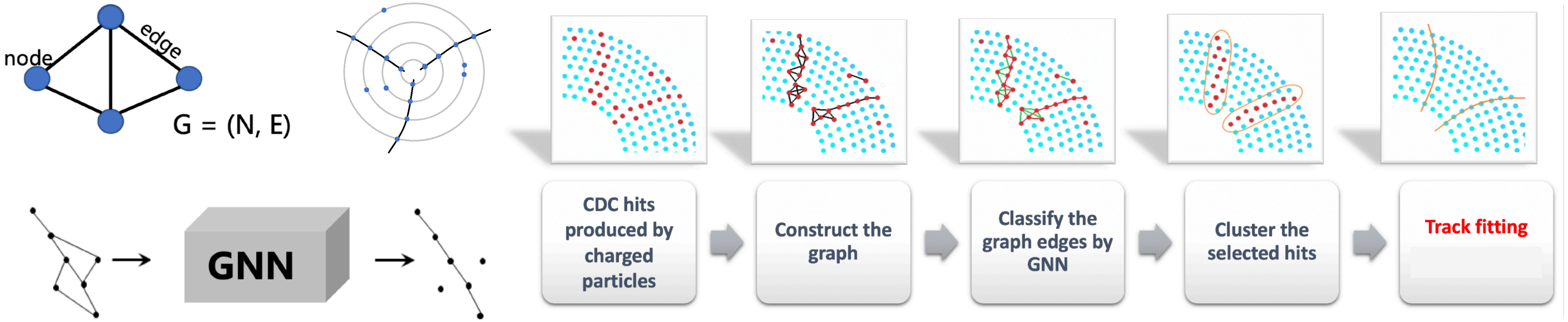

Shangshang Zhang (SDU)

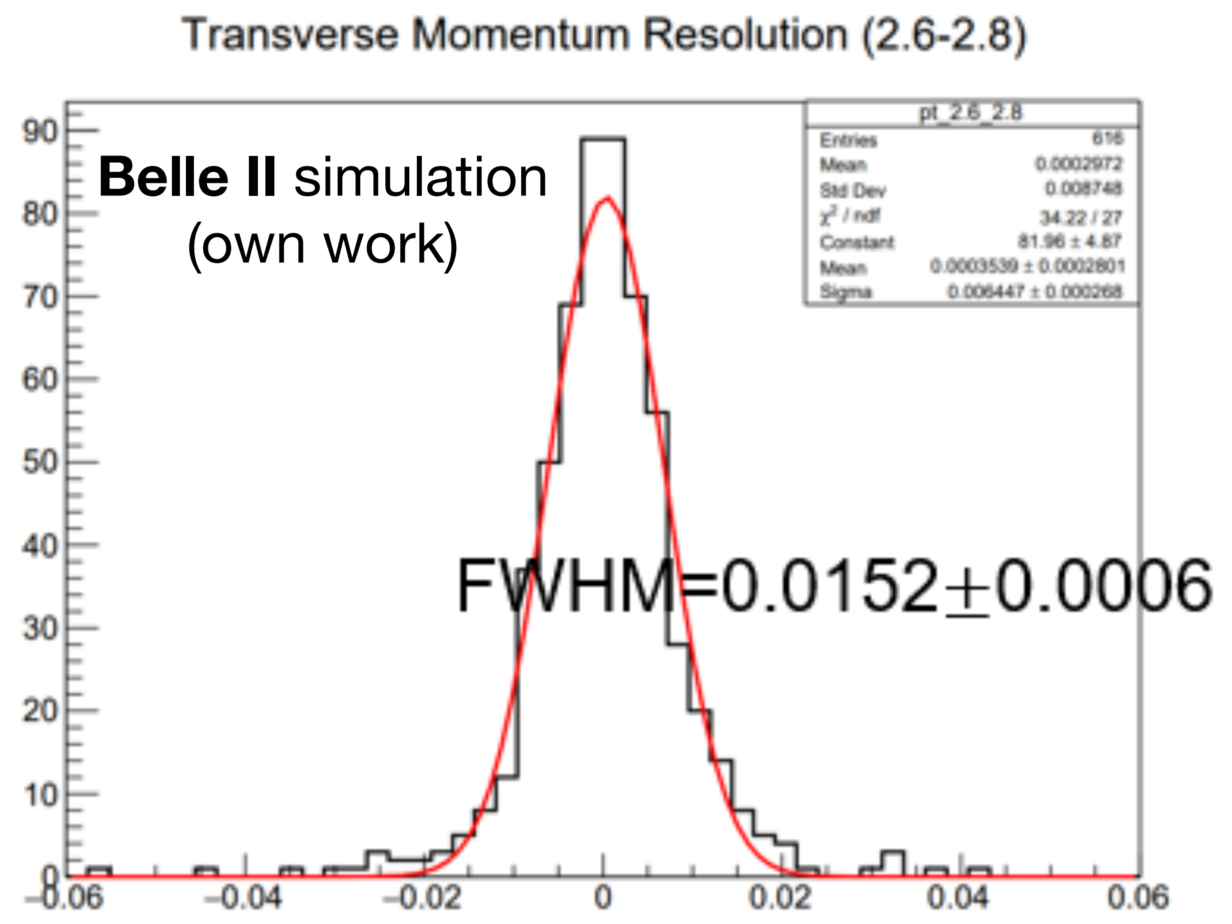


# GNN for CDC track background filtering

- Developed a GNN algorithm (based on X. Q. Jia (SDU) et al. BESIII's algorithm) for Belle II CDC hits clean up
  - Inputs: TDC, position coordinates r, ϕ

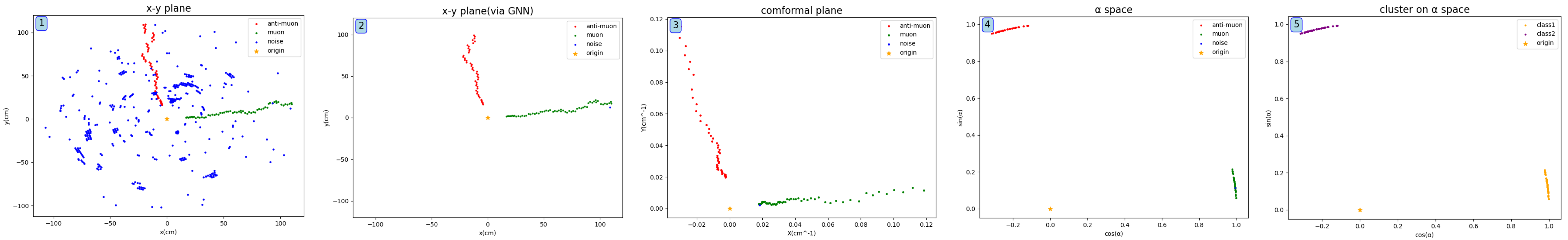
Xiaoqian Hu (SDU)




$(P_t^{pred} - P_t^{MC})/P_t^{MC}$

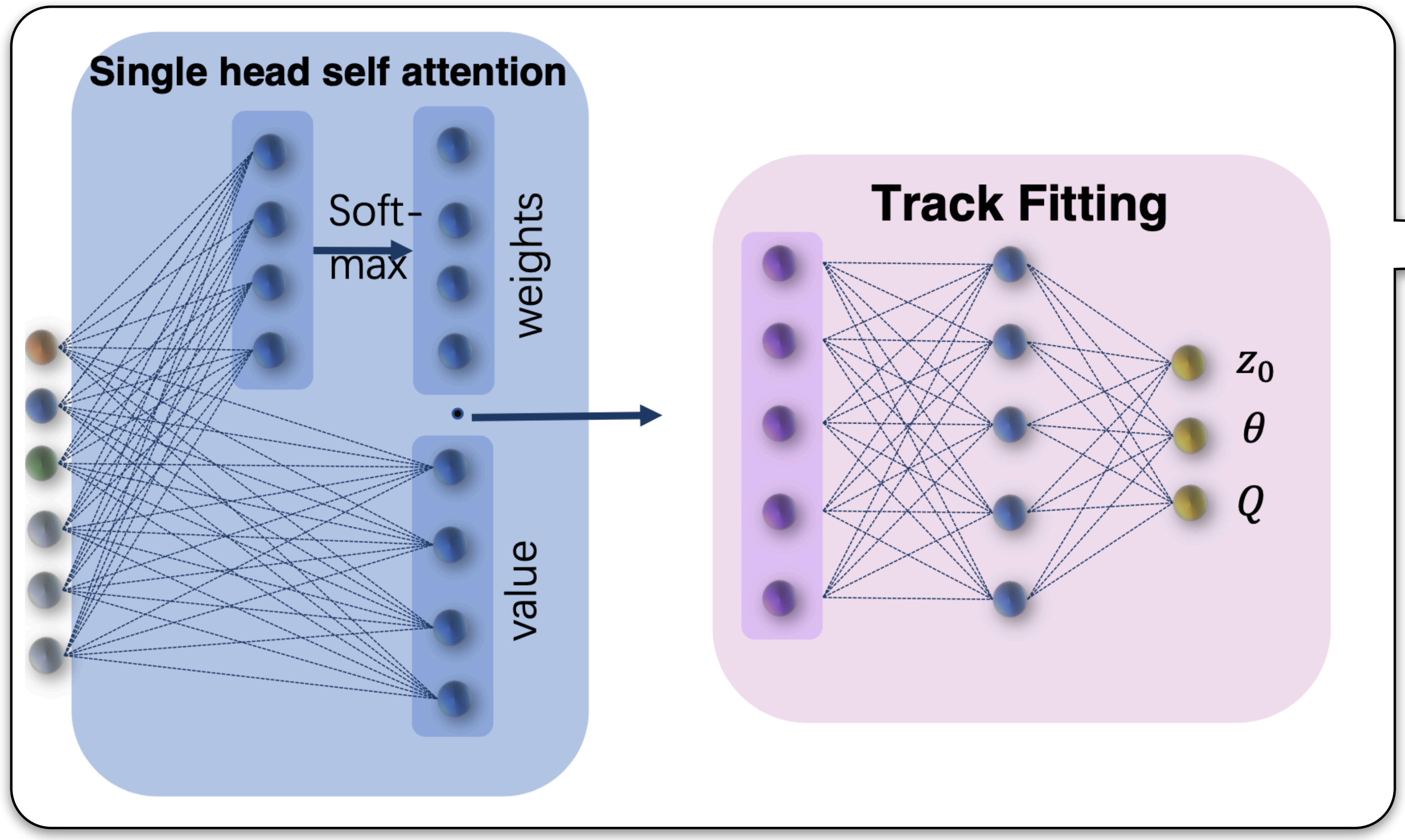
**Belle II** simulation (own work)

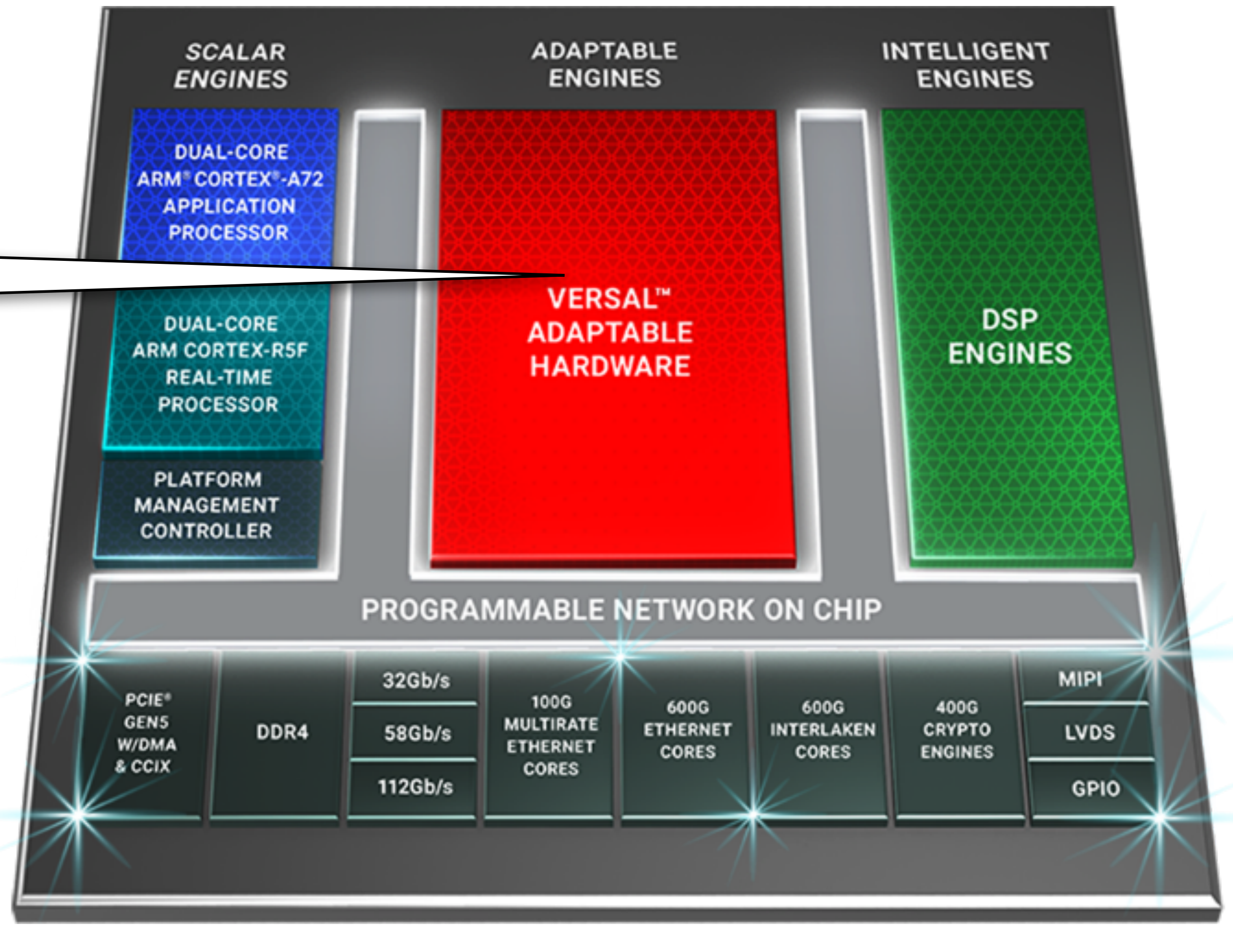


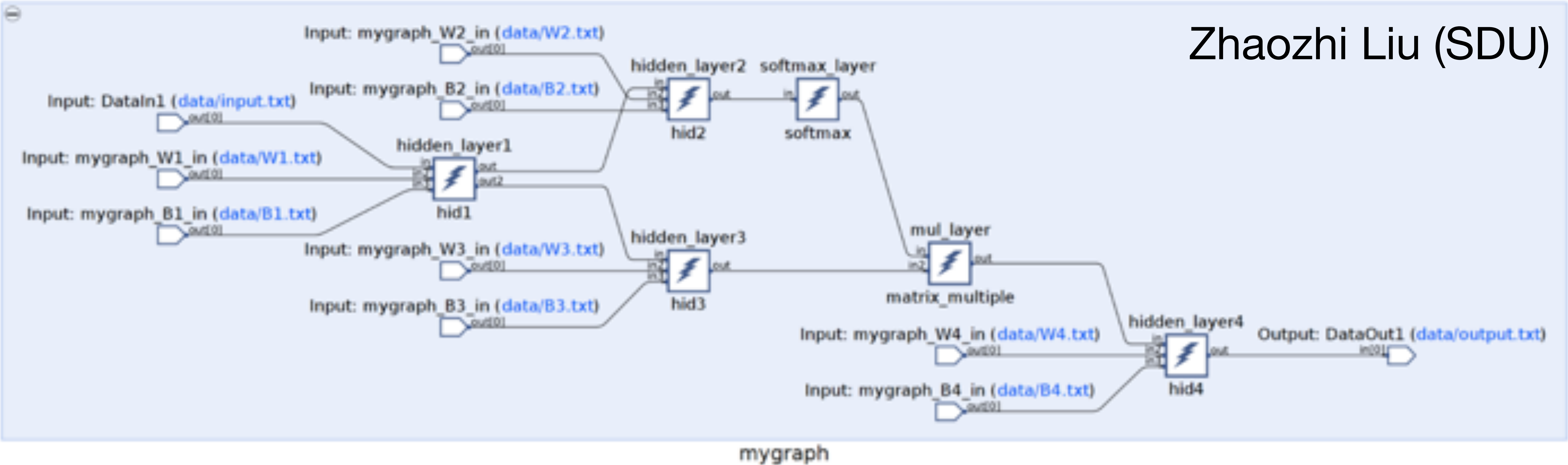

μ+ μ- (particle gun) GNN noise filtering Transform space Transform α space DBSCAN clustering

# NN acceleration on Versal ACAP

- Real-time graph building algorithm enables GNN implementation on FPGA for Belle II
  M. Neu et al. Comp. Soft. BigSci. 8, 8(2024)
- R&D of a new general FPGA device using the Versal ACAP
  - Heterogenous acceleration (VCK190, VCK5000 evaluation kit)
    - AI engine, DPU




Zhaozhi Liu (SDU)

# Summary and prospects

- Belle II TDAQ system was designed to handle 30 kHz level 1 trigger
- NN and DNN with hardware based CDC L1 track trigger to improve background rejection
- GNN with software based offline CDC track finder to improve the efficiency of displaced vertex tracks
- Not covered in the talk: GNN with hardware based clustering trigger for Belle II is under commissioning
- Upgrade of vertex detector, trigger board, possible detector electrics during LS2
    - Idea about upgrade of trigger and DAQ system
    - ML based developments on going for the upgraded system