Progress on the MDC Track Reconstruction for STCF L1 Trigger Pre-Research

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On behalf of STCF Trigger Working Group

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Outline

1. **STCF trigger system preliminary design**
2. MDC track reconstruction algorithm
    - 2D tracking and reconstruction
    - Time reconstruction
    - 3D reconstruction
3. Summary

STCF overview

☐ **Super Tau-Charm Facility:**

- ➢ A new generation of **high-luminosity electron-positron collider**
- ➢ Center-of-mass energy: **2-7 GeV**
- ➢ Peak luminosity: **>0.5×10^{35} $cm^{-2}s^{-1}$ at 4 GeV**
  - Two orders of magnitude higher than BEPCII
- ➢ Collision data: more than **1 ab^{-1}/y**
- ➢ With potential to further **increase luminosity** and **beam polarization**

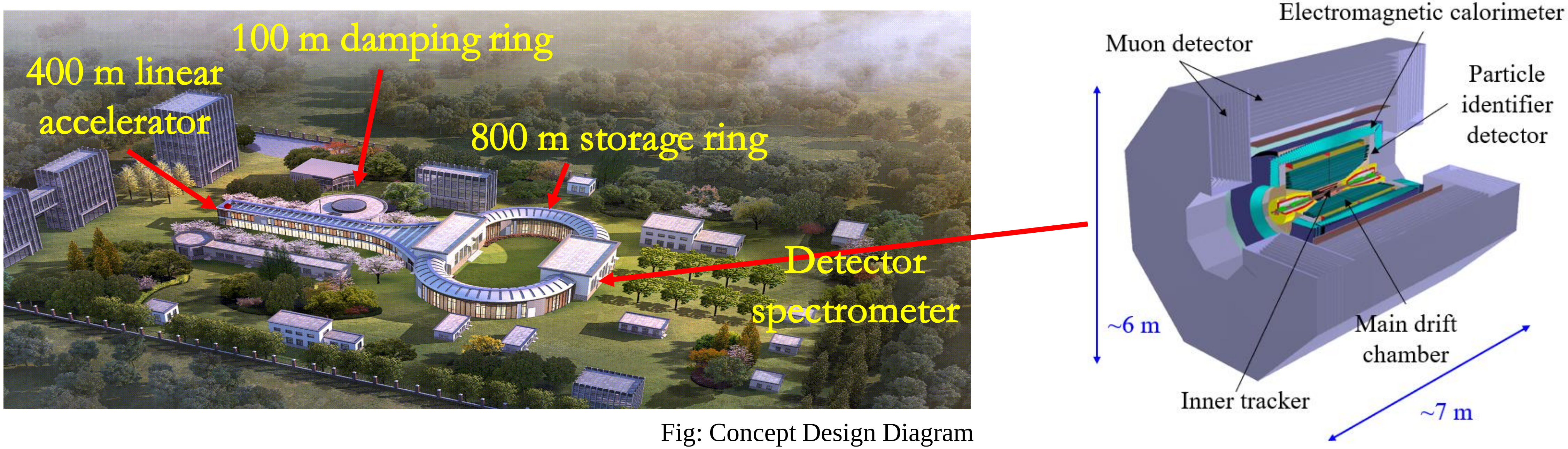


Fig: Concept Design Diagram

Requirements for trigger system

High trigger rate (~ 1 MHz)

Low latency

Maintain the long-term stable operation of experiment

Good background suppression capability

Distinguish of multi-physics events in 1 trigger window

❑ **High luminosity in STCF generates:**

- ➢ **High physics event rate:** over **400 kHz**
- ➢ **Large data size: 30 GB/s at 1 times background** raw data
- ➢ **High background:** ~ **400 kHz/channel** in MDC
  ~ **1 MHz/channel** in ECAL

❑ **Trigger system:**

- ➢ Identifying physics events from massive background
- ➢ Ensure very high physics event trigger efficiency：>99%
- ➢ Reducing the pressure in data acquisition and transmission

STCF trigger system preliminary design

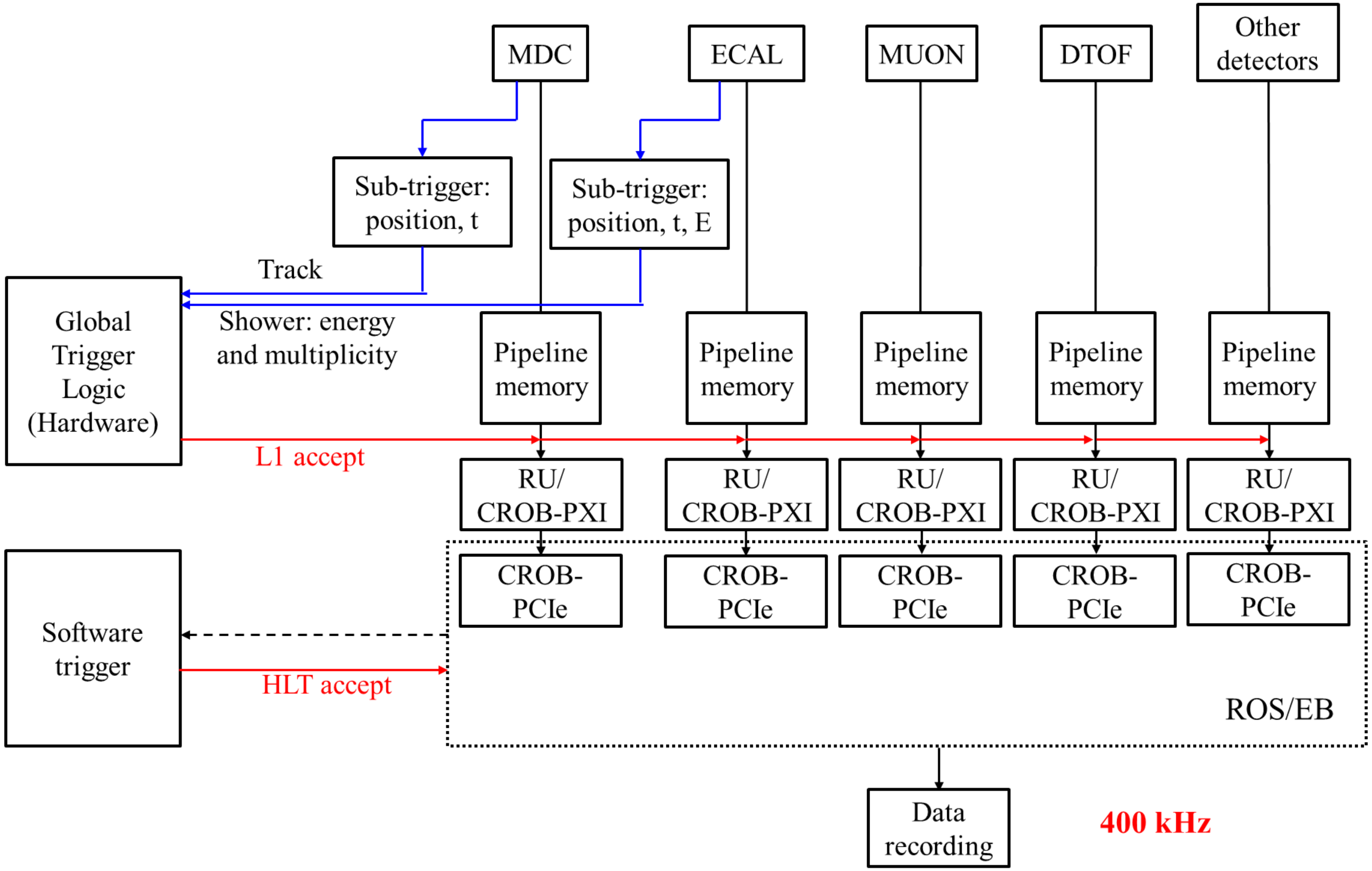
Two-stage trigger system:

☐ **Level 1 Trigger:**

- Identifying physics events window
- Based on FPGA platform
- Latency ~ 5 μs

☐ **High Level Trigger (HLT):**

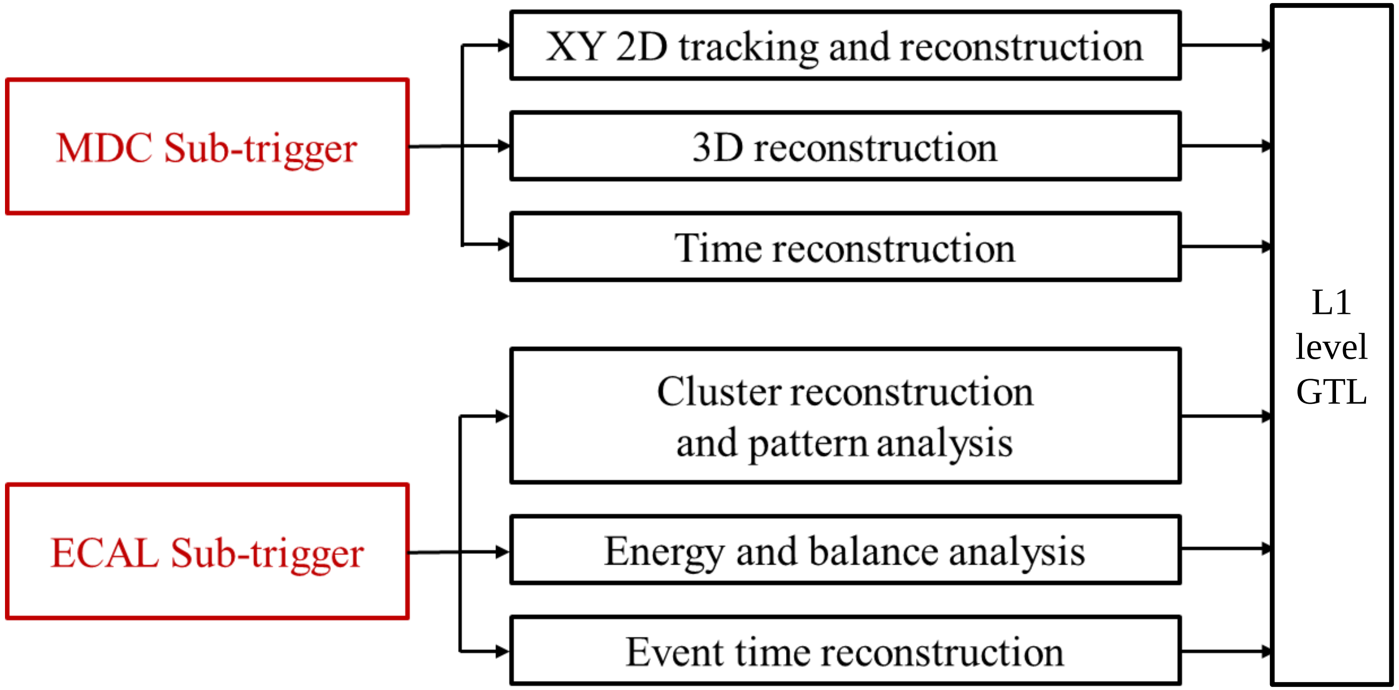
- Suppressing backgrounds in each time window
- Based on server cluster



400 kHz

Preliminary design of L1-level trigger

- **ITK:** high background
- ✓ **MDC:** key tracking detector
- **RICH:** complex Cherenkov ring reconstruction
- **DTOF:** auxiliary in Endcap
- ✓ **ECAL:** key calorimeter, fast response
- **MUON:** auxiliary for μ/π/n/K_L



MDC Sub-trigger

XY 2D tracking and reconstruction

3D reconstruction

Time reconstruction

ECAL Sub-trigger

Cluster reconstruction and pattern analysis

Energy and balance analysis

Event time reconstruction

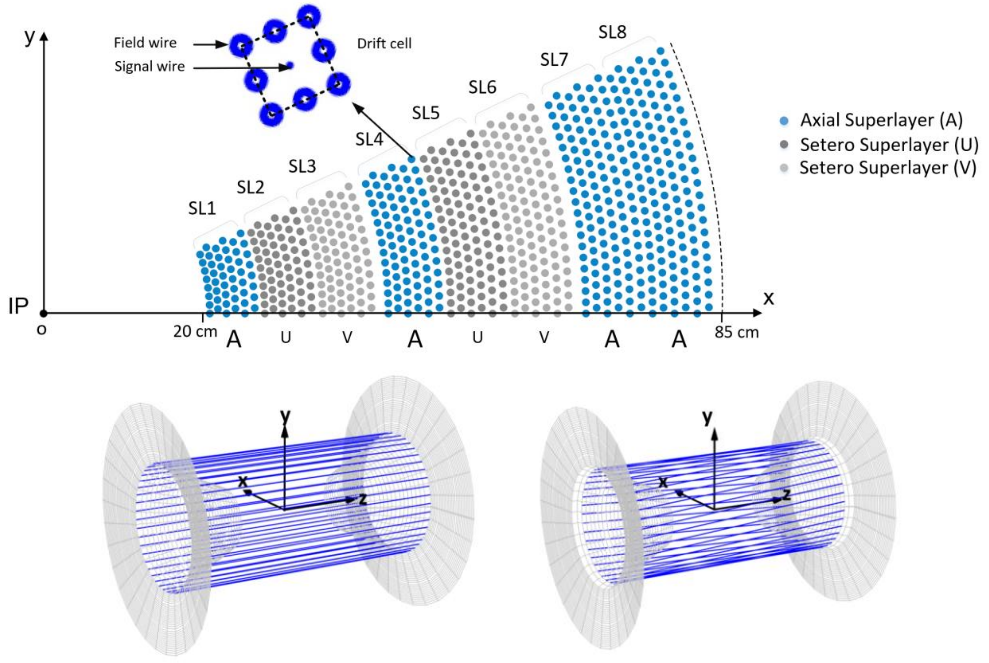
L1 level GTL

MDC sub-trigger

☐ Baseline design:

- 48 layers of small cell
- **1,4,7,8---**axial superlayers

  2,3,5,6---stereo superlayers



Axial wires

Stereo wires

Fig.1: Layout of the MDC signal wires.

☐ Region division:

- Barrel & Endcap
- Long track: Exits after passing through the Barrel.
- Short track: Exits at the Endcap.

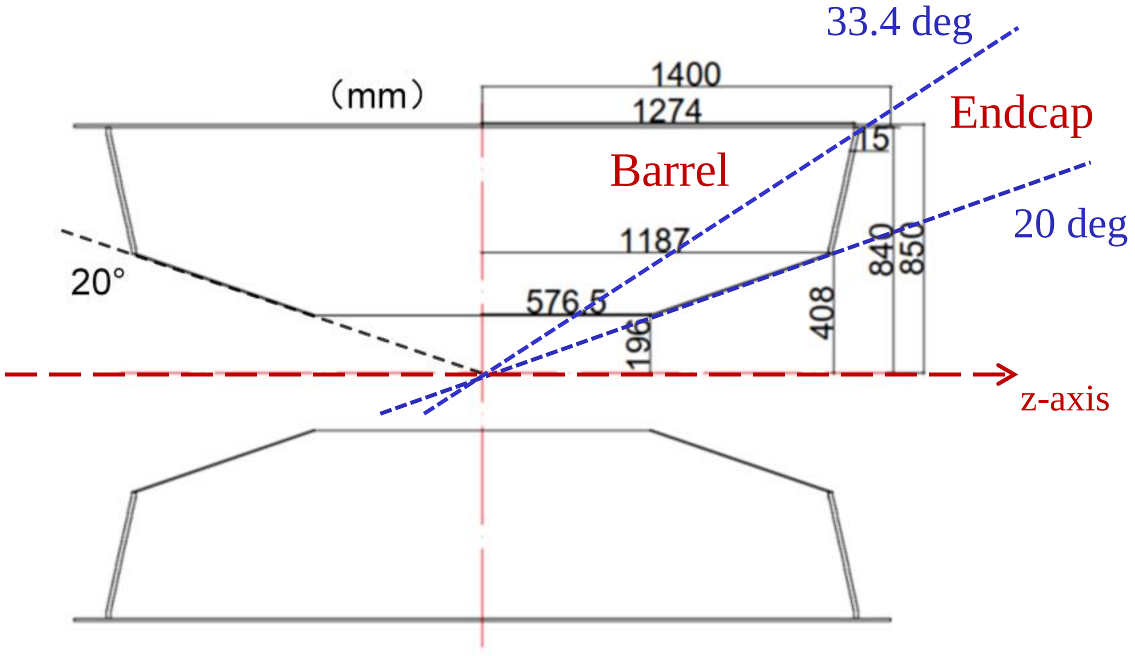


Fig.2: MDC geometric structure

MDC sub-trigger

☐ Requirements for the MDC trigger algorithm:

- **Challenges:**
  - High background
  - Coordination between sub-detectors

- **Needs:**
  - Information of charged particles：p_t, Φ, θ, ρ, *z-vertex*
  - Time at which particles hit MDC：t_s

- **Implementation:**
  - 2D tracking and reconstruction & 3D reconstruction
  - Time reconstruction

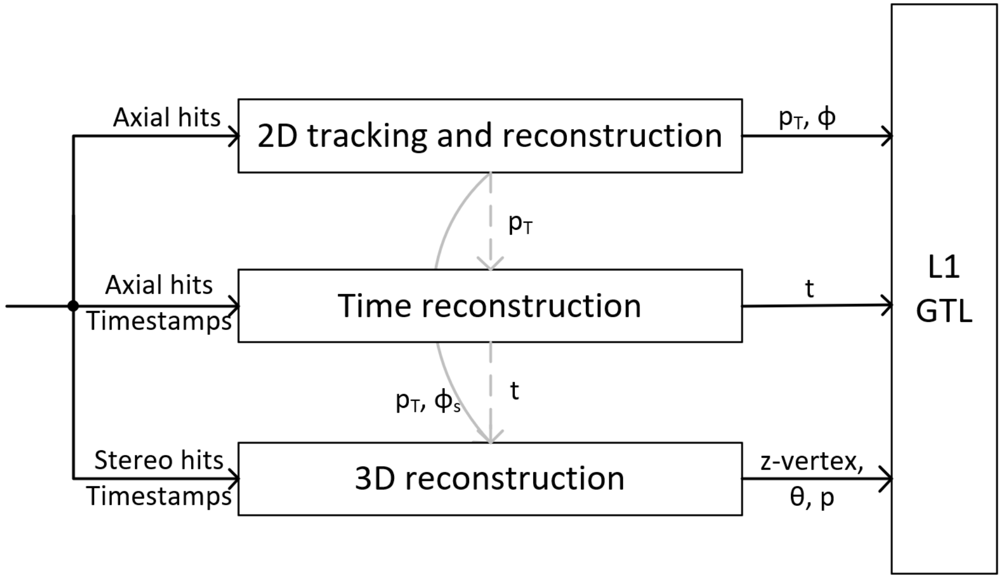


Fig: Data flow of MDC sub-trigger.

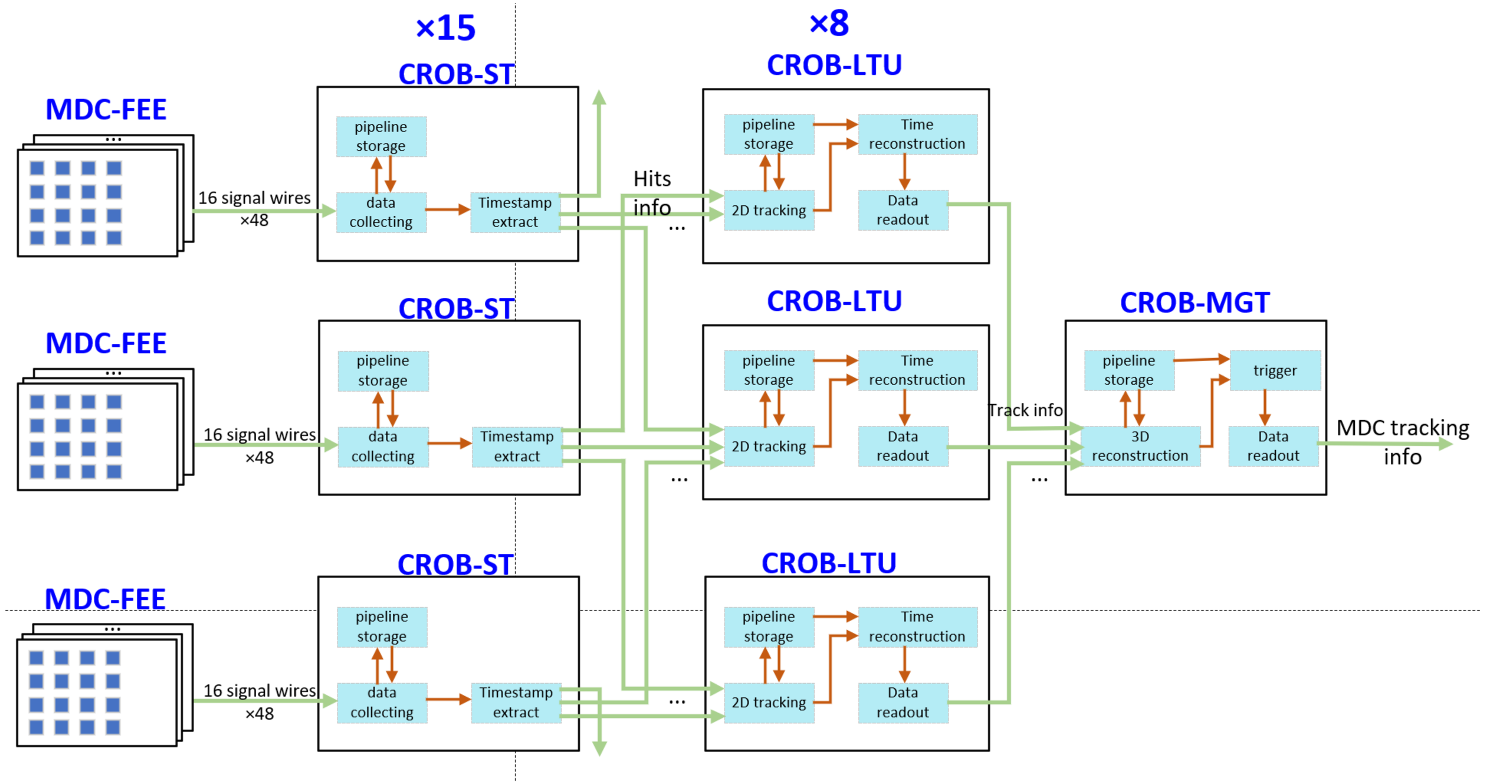


Fig: a schematic diagram of the hardware structure

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    - 2D tracking and reconstruction
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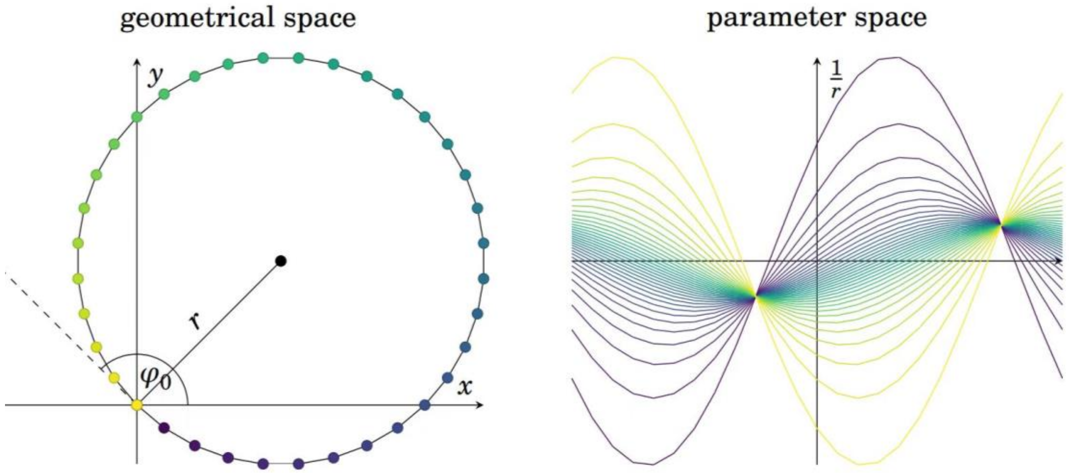
2D tracking and reconstruction

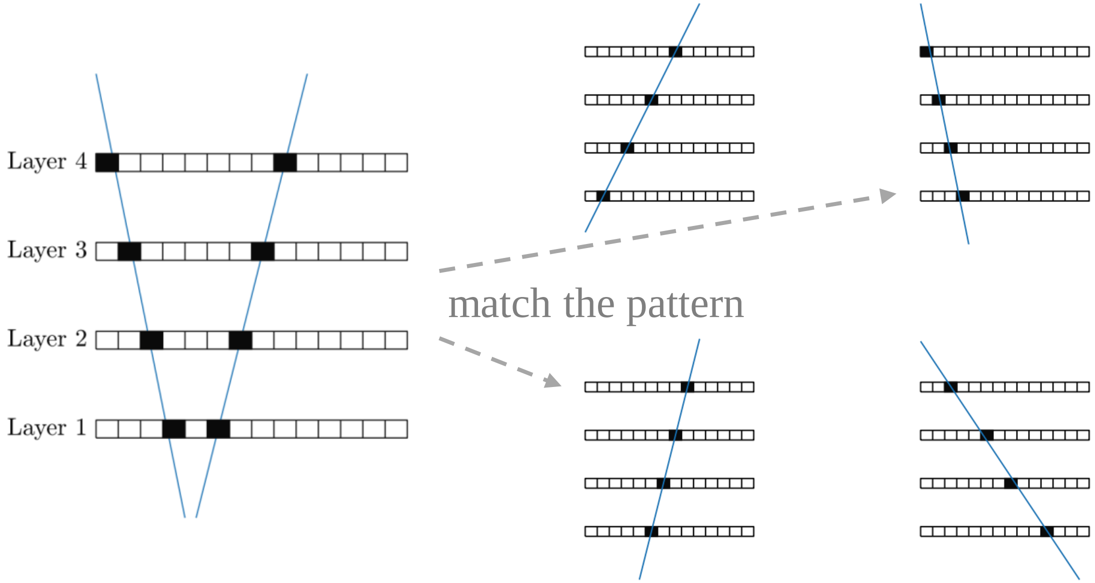
☐ Method selection:

- Hough transform：
  - Complex calculations
  - Cannot achieve Track trigger logic < 1 μs

- Pattern matching：
  - ✓ Simple and easy to implement
  - ✓ **achieve Track trigger logic < 1 μs**

replace →





2D tracking and reconstruction

☐ Pattern matching operation:

- **Generate pattern banks** through simulated data

  Write into distributed storage units on the FPGA
- **Match event data** with the pattens

  Implement high-speed parallel processing with FPGA logic

☐ Three stages:

- **Track segment (TS) finding:** reduce the input, reject background hits
- **Track finding:** pattern matching---fast but sketchy
- **Estimation of track parameters:** matching with an accurate pattern bank

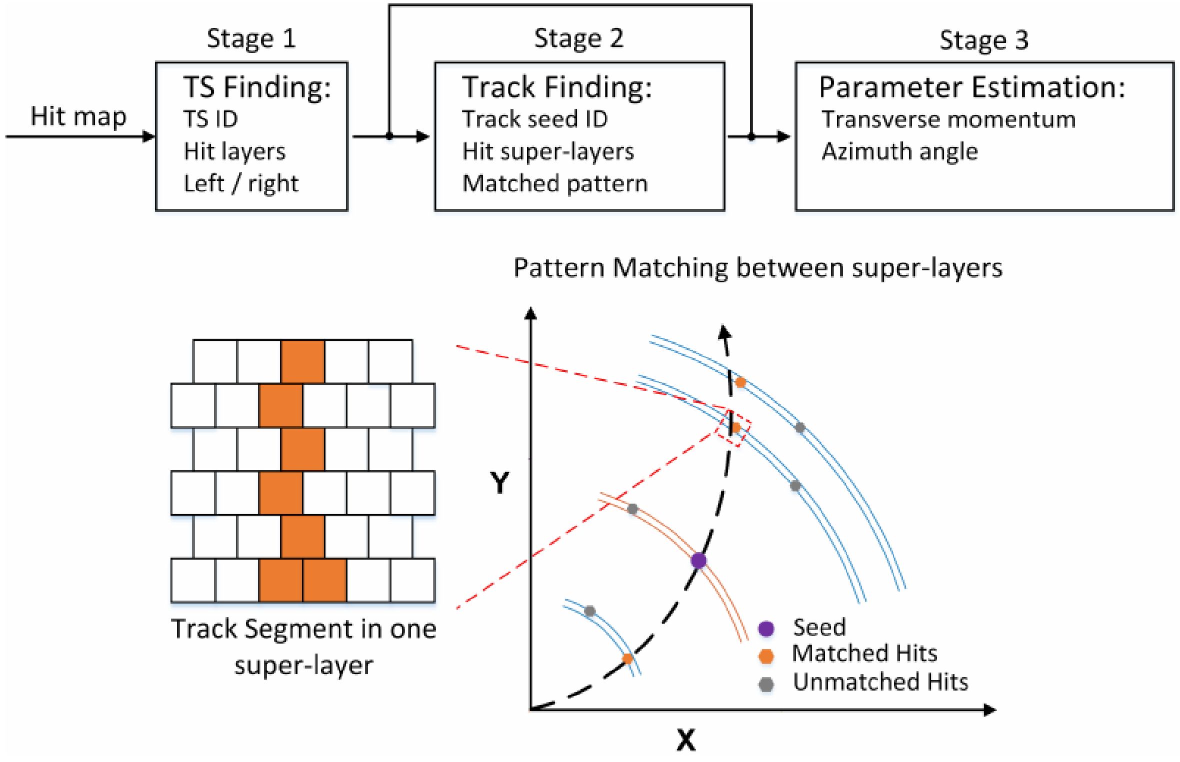


Fig: The components and process of the track reconstruction algorithm.

2D tracking and reconstruction

Track segment finding:

- **Undivided TS:** for track finding
- **Divided TS:** for parameter estimation

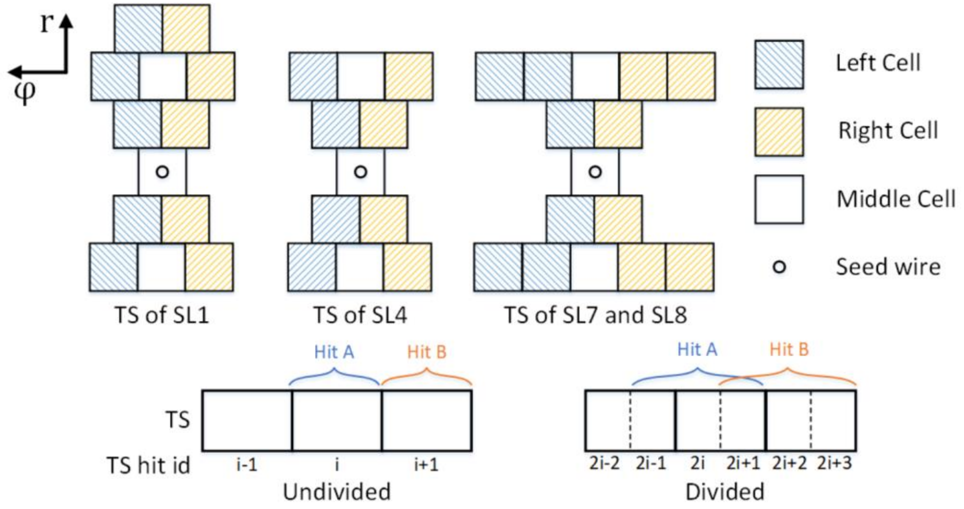


Fig.1: Configurations of three types track segments in different super-layers.

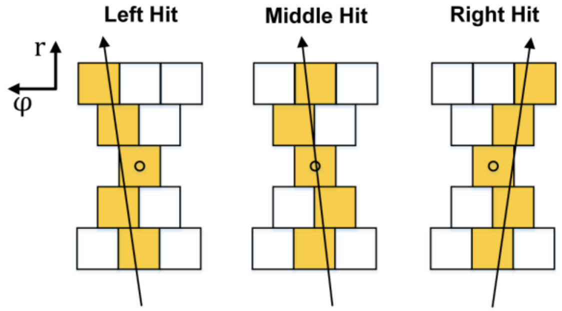


Fig.2: Three examples of segment hits classified by passing side.

Pattern matching

- Track finding: merged patterns for fast tracking

  total number: **784**
- Track reconstruction: accurate patterns
  - total number: ~**7800**
  - p_T > **170 MeV**

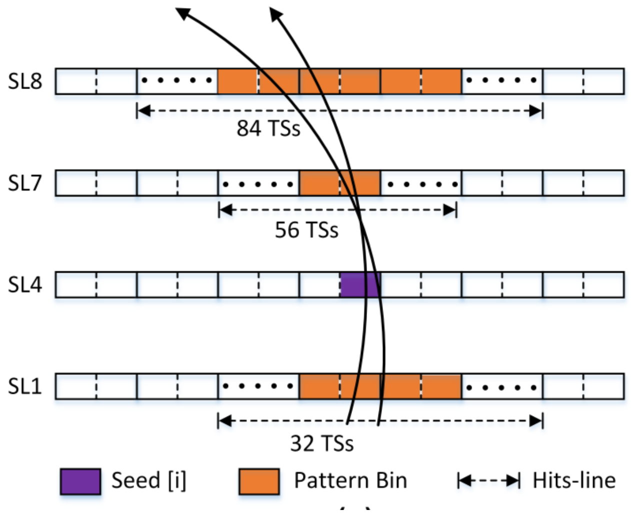


Fig.3: The granularity of patterns in track finding.

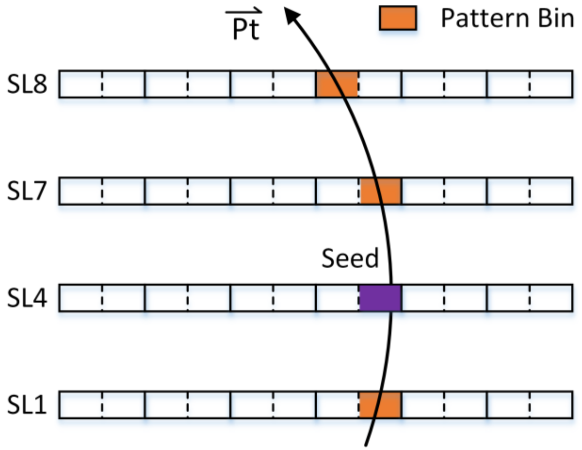


Fig.4: The granularity of patterns in pt reconstruction.

2D tracking and reconstruction

☐ Track efficiency

- Single track
  - Track finding: $p_T > 130\text{MeV} \quad \theta > 30°$
  - Parameter estimation: $p_T > 170\text{MeV} \quad \theta > 30°$

    $\Delta p_T/p^2_T \sim 0.1$
- Physics event
  - The cut of θ: reason for 90% lost events

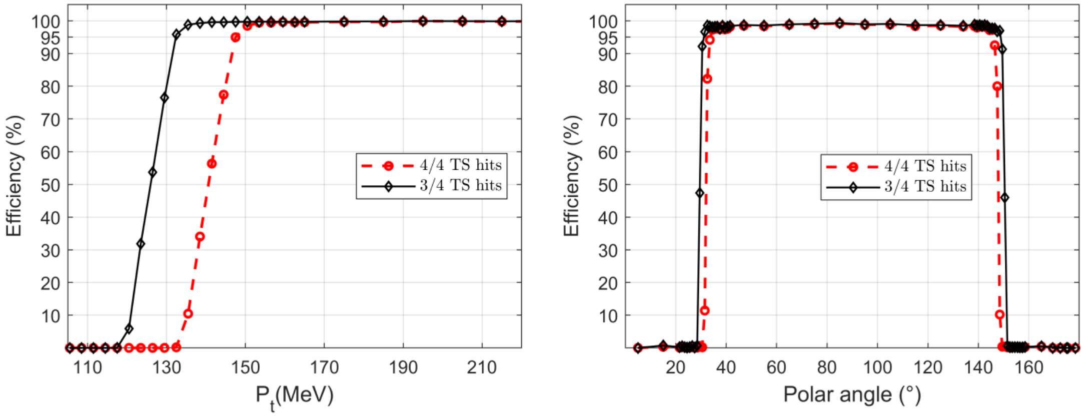


Fig.1: The track finding efficiency in different thresholds.

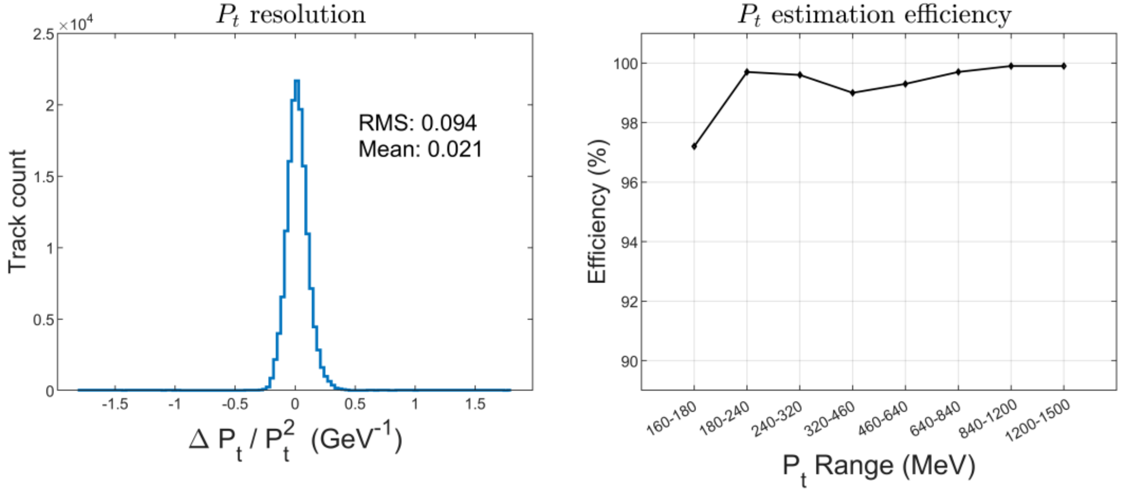


Fig.2: p_T resolution and reconstruction efficiency for single track

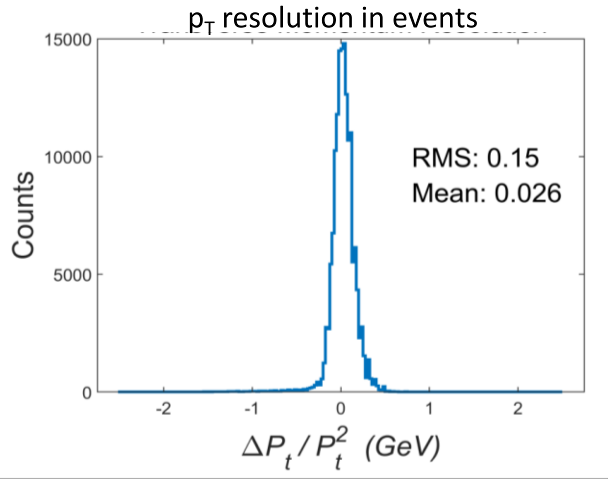


Fig.3: p_T resolution of track reconstruction in physics events

2D tracking and reconstruction

- Track efficiency - The cut of θ: reason for 90% lost events

☐ Optimization: Short Track Reconstruction

- For data with hits only in the first and fourth superlayers
- Introduce hits from the second and third superlayers to select short tracks (hits account for the θ error caused by the z-vertex offset)
- <u>Still under development</u>
- Preliminary tracking results:
  - Single track: Efficiency ~ **98% (1505/1540)**
  - Background in physics events: Misidentification rate ~ **41% (1829/4463)**

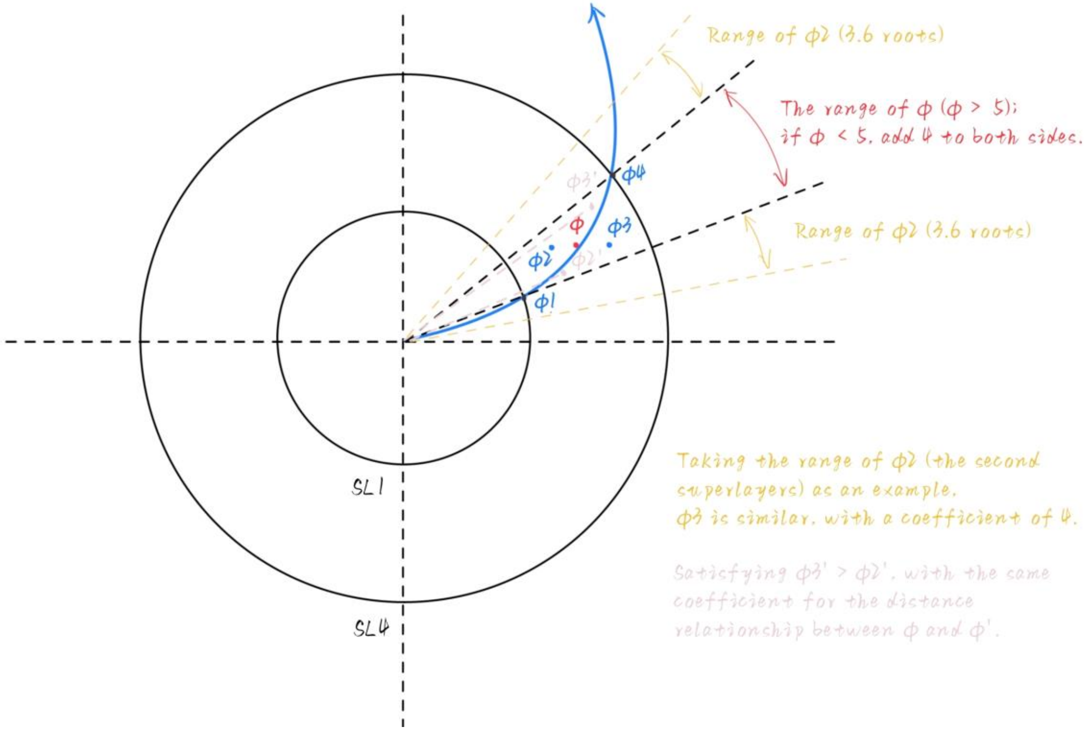


Fig: Track finding rules

2D tracking and reconstruction

☐ φ reconstruction

IP： $\varphi_0 = \varphi_4 - \arcsin\left(\frac{r_4}{2\rho}\right)$

EMC： $\varphi_e = \varphi_4 - \arcsin\left(\frac{r_4}{2\rho}\right) + \arcsin\left(\frac{r_e}{2\rho}\right)$

$$\rho = \frac{p_t(Gev)}{0.3B} \quad (\mathrm{m})$$

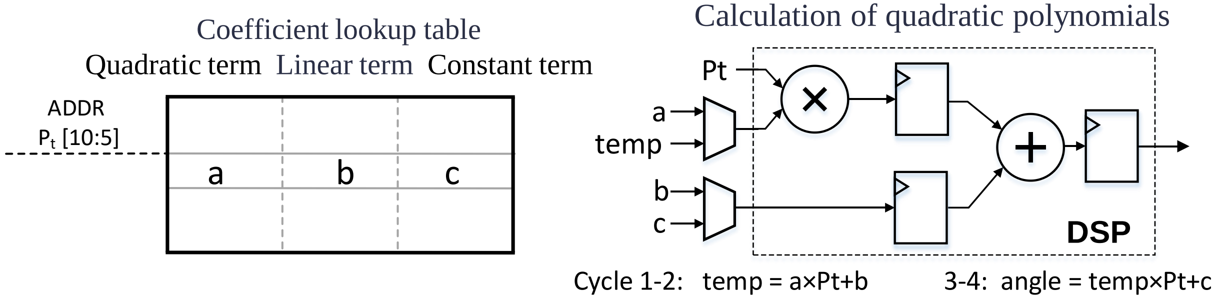
Piecewise interpolation →

☐ FPGA implementation

$$\varphi = \varphi_4 + \Delta\varphi$$

Resource friendly

$$\Delta\varphi = a \times p_t^2 + b \times p_t + c$$


Coefficient lookup table

Quadratic term Linear term Constant term

Calculation of quadratic polynomials

Cycle 1-2: temp = a×Pt+b 3-4: angle = temp×Pt+c

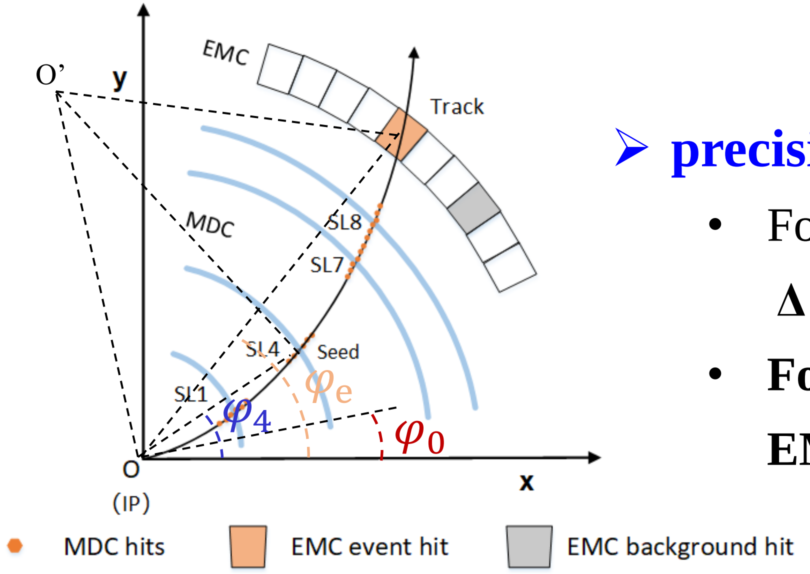
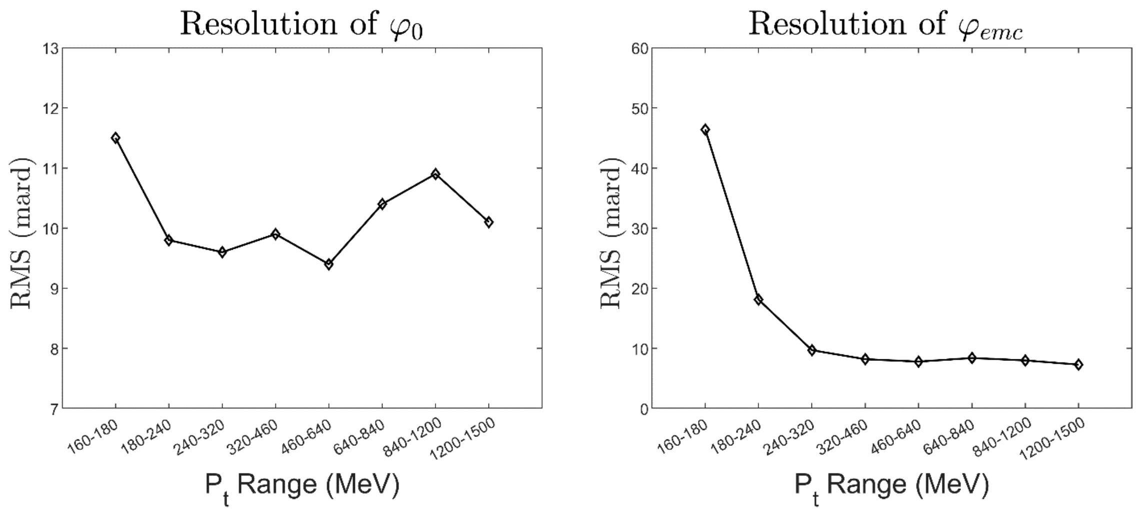


Fig.1: Calculating the φ by the seed location and estimate of pt.

➢ precision

- For tracks with p_t > 180 MeV, $\Delta\varphi_e$ < **20 mrad**
- **For track matching with EMC, 50 mrad is OK**


Resolution of φ_0

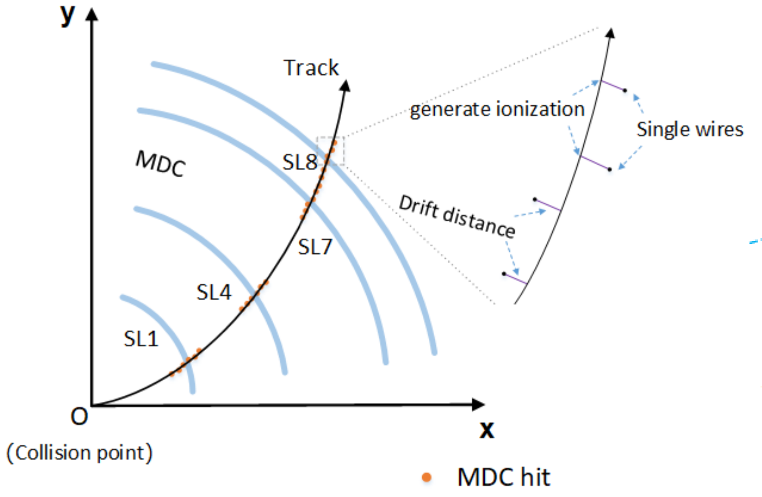
Resolution of φ_{emc}

Fig.2: φ resolution for single track

Time reconstruction

☐ Purpose of time reconstruction:

- TS generation time t_s + drift time t_{drift} = single wire hit time T
- suppress background
- Distinguish adjacent physics events



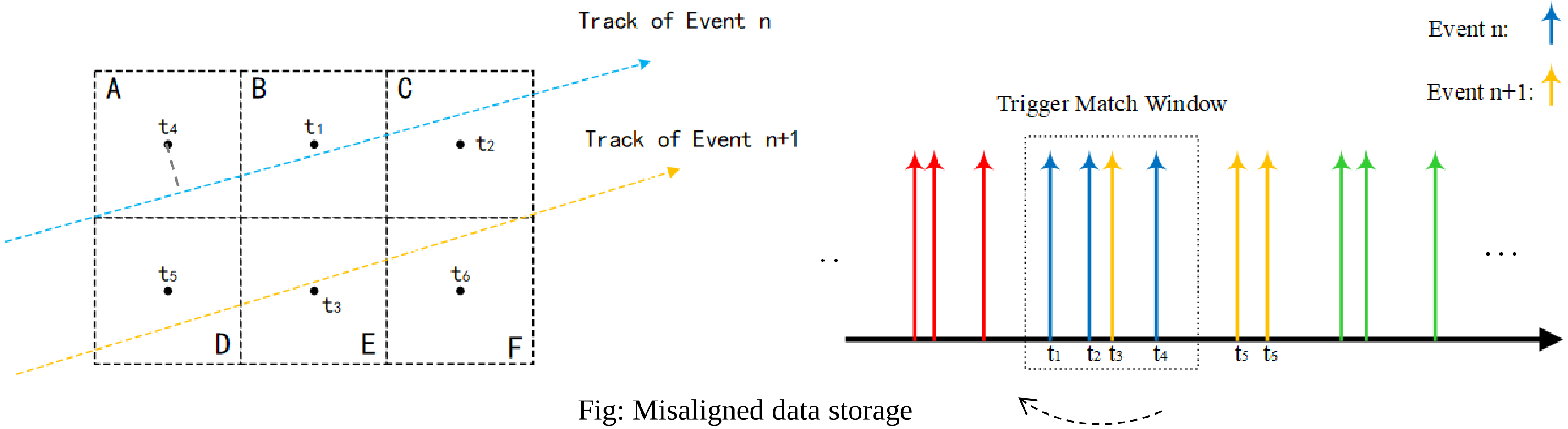
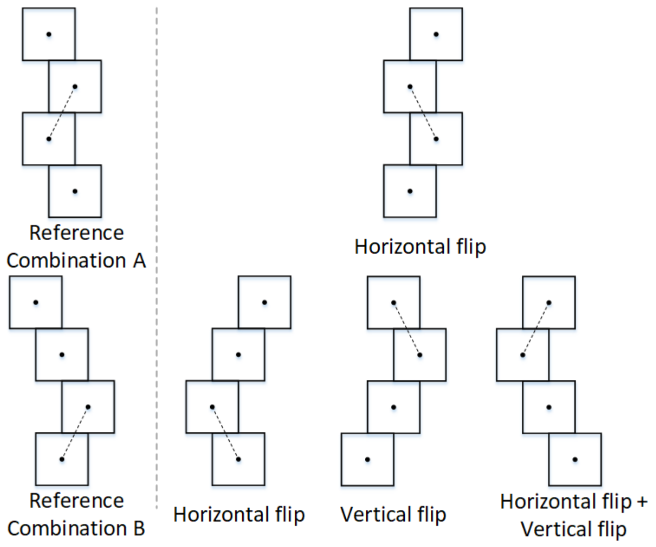


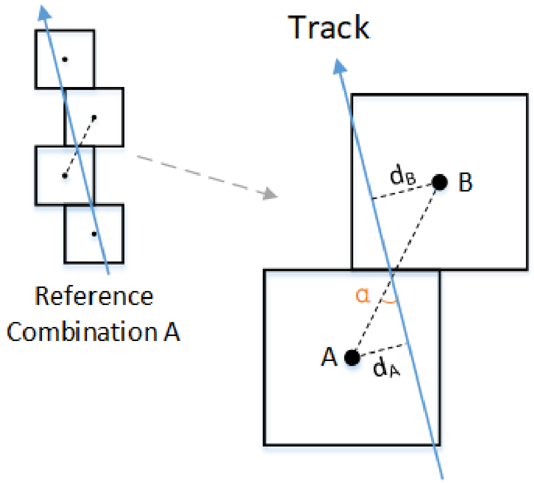
Fig: Misaligned data storage

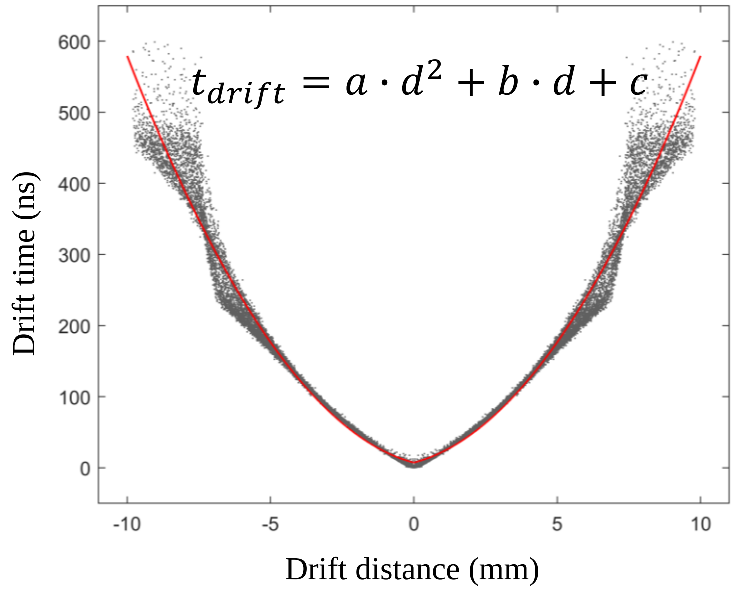
Time reconstruction

☐ Reconstruct the hit time using track parameters

- Estimate the track segment as a straight line
- Calculate the drift distance based on the reconstructed track parameters, and then obtain the drift time
    - FPGA pipeline computation
- Combine the timestamp to calculate the generation time of the track segment
- The track time is the average value of the times of each track segment







Time reconstruction

☐ Track time reconstruction

  - Calculate the median
  - Abandon TS whose time deviates significantly from the median
- Test with single tracks
  - For tracks with $p_T > 180$ MeV: efficiency > 80%， $\Delta t < 8$ ns

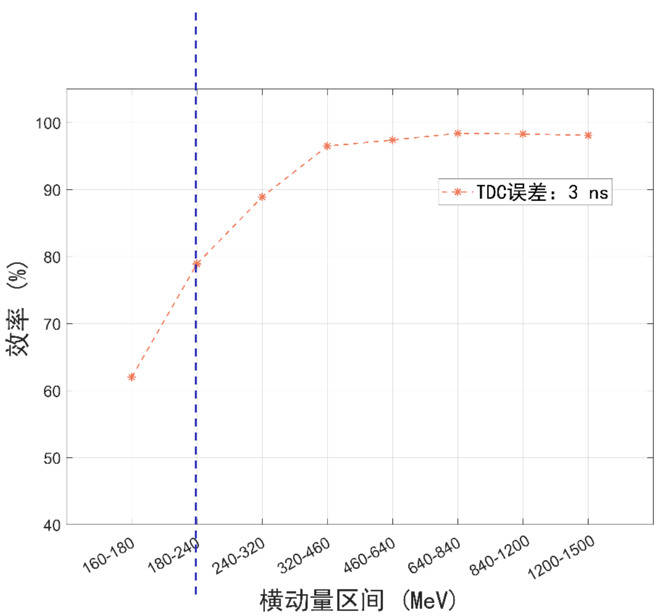


Fig.1:Reconstruction efficiency of single track.

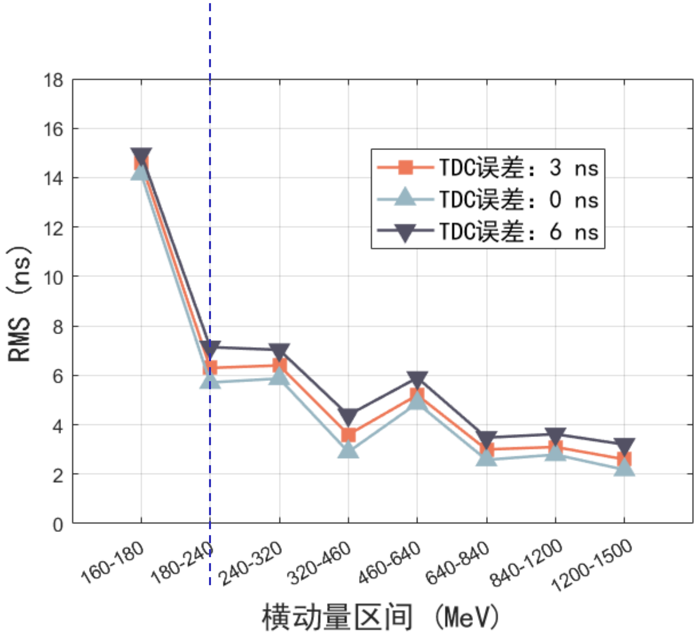


Fig.2:resolution of single tracks.

3D reconstruction

☐ Main content of 3D reconstruction

✓ **Z-vertex reconstruction**

- Resolution of about 3 cm
- Support for |z| < 10 cm truncation, and an error of ±3σ
- over 97% of background tracks can be eliminated

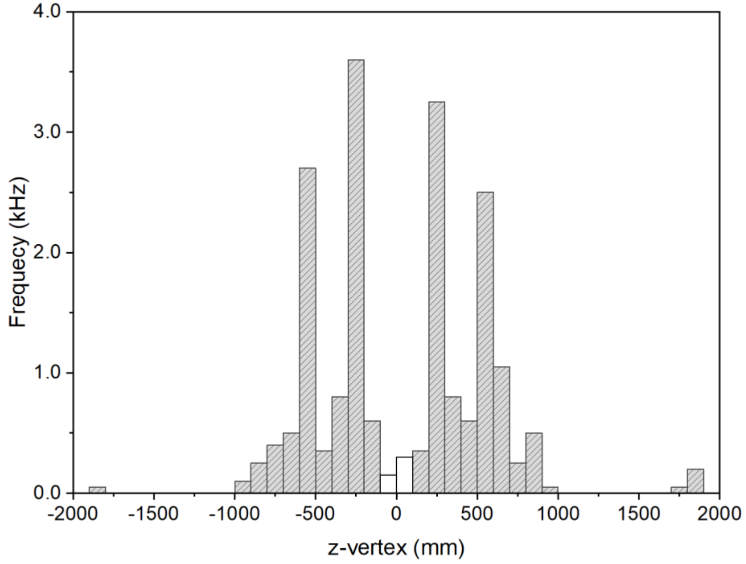


Fig: The *z*-vertex distribution of background tracks selected by the two dimensional reconstruction algorithm.

Z-vertex reconstruction

☐ Stereo TS finding

- 1 superlayer ---2 seed wires

  Position + timestamp

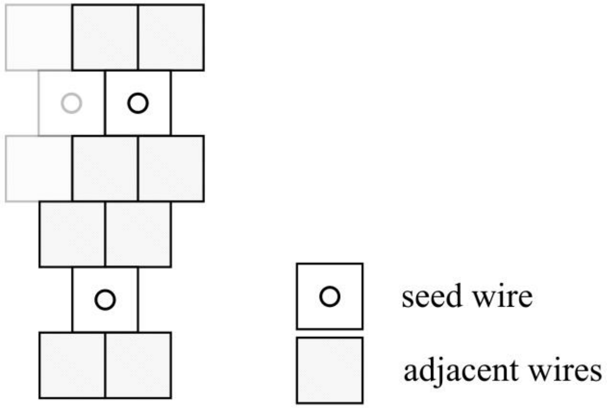
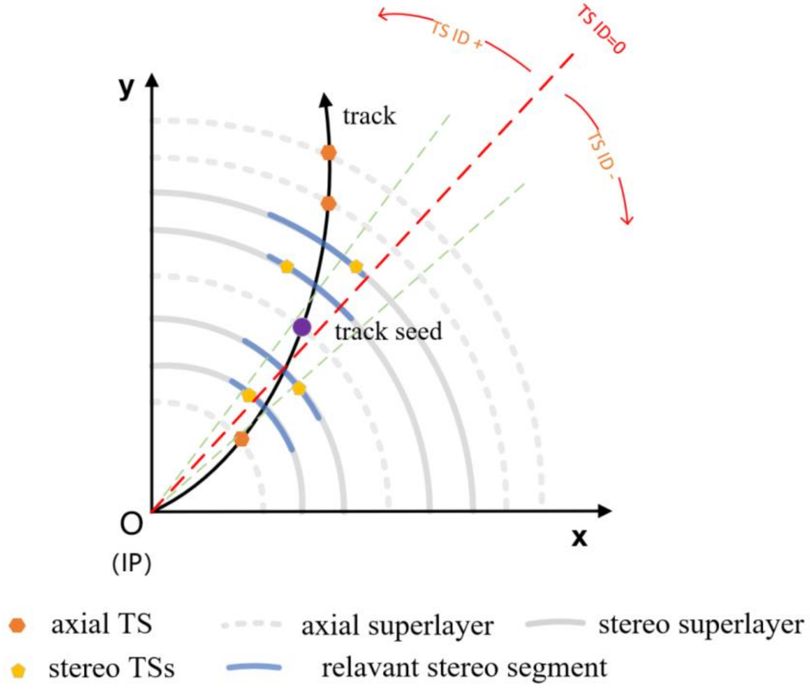


Fig: Stereo SLs

☐ Track finding

- Matching stereo TS with an existing track
- Sectorization and Normalization



Z-vertex reconstruction

☐ MLP training

- **Multi-layer fully connected neural network (MLP)**
- Input: track segment numbers and timestamps for 8 superlayers
- Output: z-vertex in various p_t regions

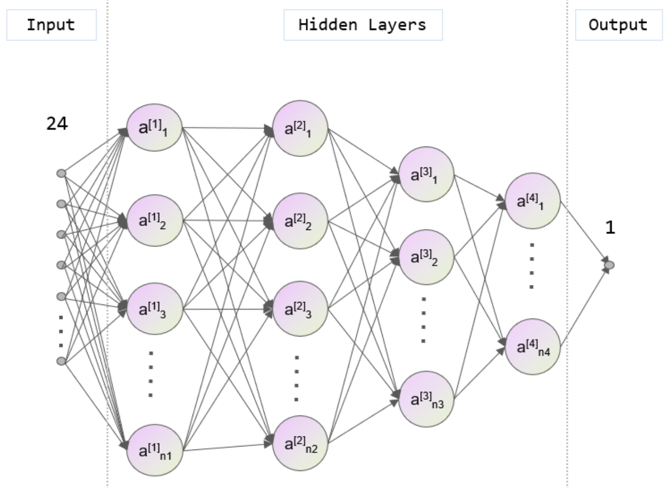


Fig.1: The basic structure of an MLP model.

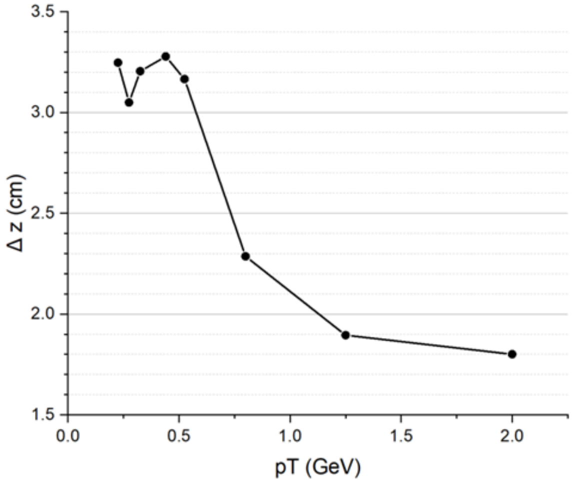
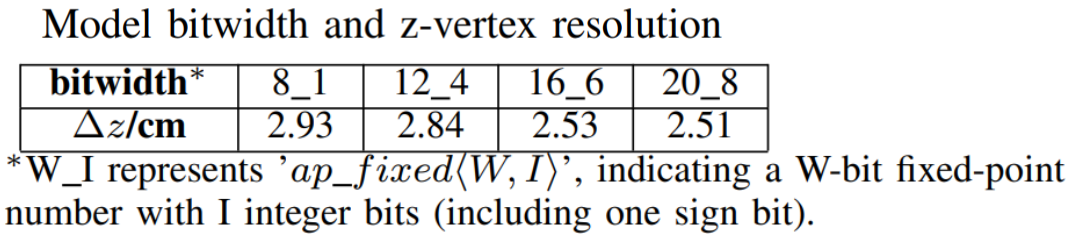


Fig.2: Z-vertex resolution at different pt

☐ Quantization & FPGA resource optimization

- Qkeras

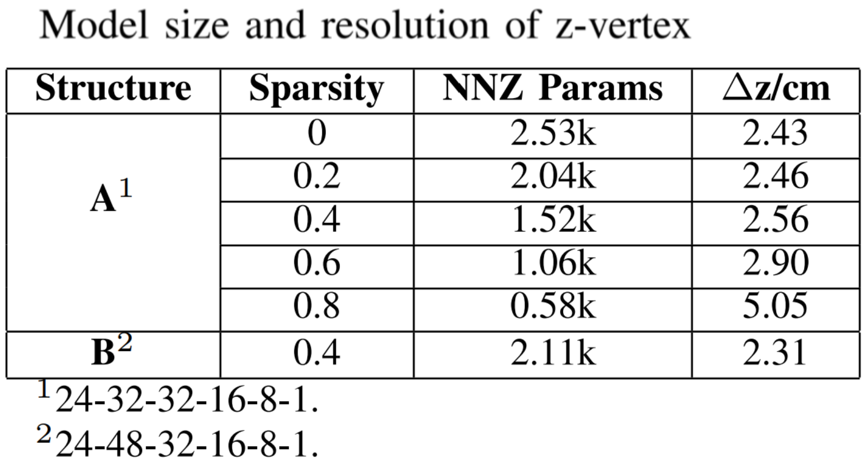


Model bitwidth and z-vertex resolution

bitwidth*	8_1	12_4	16_6	20_8
Δz/cm	2.93	2.84	2.53	2.51

*W_I represents '$ap\_fixed\langle W, I\rangle$', indicating a W-bit fixed-point number with I integer bits (including one sign bit).

- Pruning



Model size and resolution of z-vertex

Structure	**Sparsity**	**NNZ Params**	**Δz/cm**
A^1	0	2.53k	2.43
	0.2	2.04k	2.46
	0.4	1.52k	2.56
	0.6	1.06k	2.90
	0.8	0.58k	5.05
B^2	0.4	2.11k	2.31

[1] 24-32-32-16-8-1.

[2] 24-48-32-16-8-1.

Z-vertex reconstruction

☐ Further resource optimization

- **1 MLP for all tracks**
- Training with High Granularity Quantization (**HGQ**)
  - Certain parts of the network can accommodate lower precision without compromising performance.
  - Fine-tune the per-weight and per-activation precision.

- Latency: 60 clk
- Interval (Dead time): 2 clk
- FPGA resource:

  DSP: 71%

  FF: 29 %

  LUT: 19%

→

- Latency: 40 clk
- Interval (Dead time): 1 clk
- FPGA resource:

  DSP: 4%

  FF: 4%

  LUT: 17%

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Algorithm Summary

1. 2D tracking and reconstruction (J/ψ -> anything)
   - $\Delta p_T / p_T^2 \sim 15\%$ Latency = 339 ns
2. Time reconstruction (single track)
   - $\Delta t < 16$ ns Latency = 207 ns
3. Z-vertex reconstruction (clear single track)
   - $\Delta z \sim 3$ cm Latency (MLP) = 125 ns

Further Work Plan

☐ Algorithm Optimization

- Un-identification of high-p_t track in Endcap
  - 3 hits tracking as a complement to 4 hits tracking requiring further optimization
- Continue advancing short track reconstruction.
- Distinguish of cross tracks

☐ Engineering Principle Prototype Testing

- Port the FPGA GBT protocol and establish the data link.
- Validate the MDC hardware reconstruction algorithm.
  - 2D reconstruction algorithm
  - 3D reconstruction algorithm
  - Time reconstruction algorithm
- Purpose:
  - Conduct on-board hardware logic test to verify the reliability of timing.
  - Ensure consistency between actual test results and simulated behavior.

Thanks