MDC Track Reconstruction for the Pre-Research of STCF L1 Trigger

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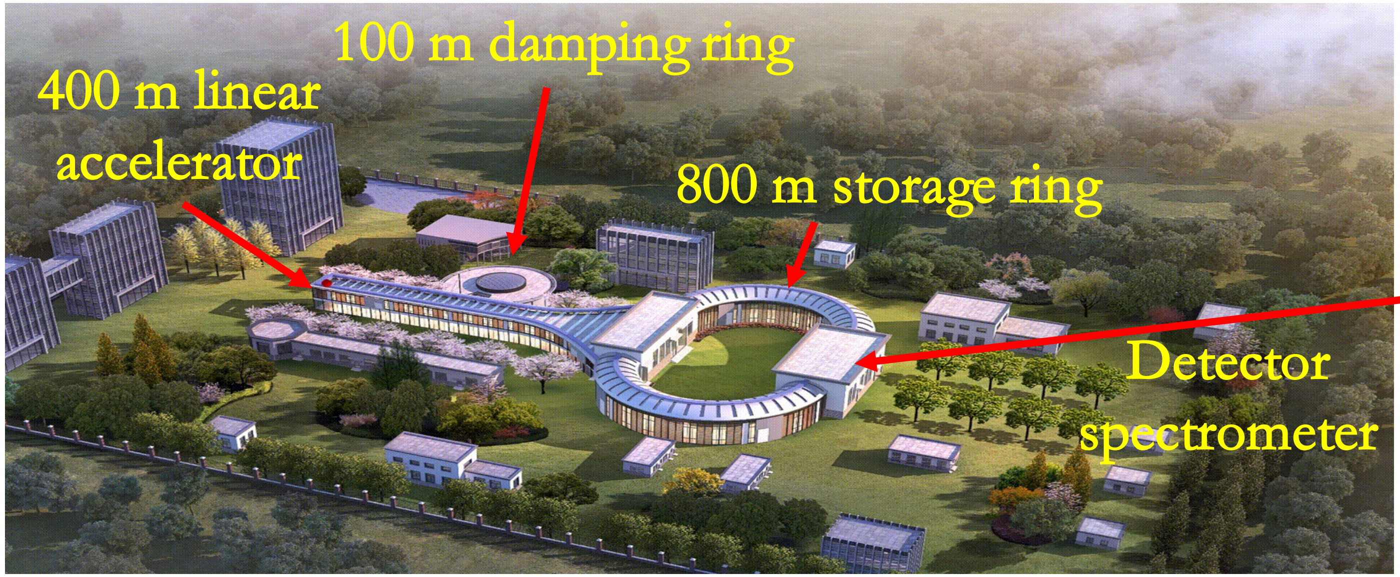
Outline

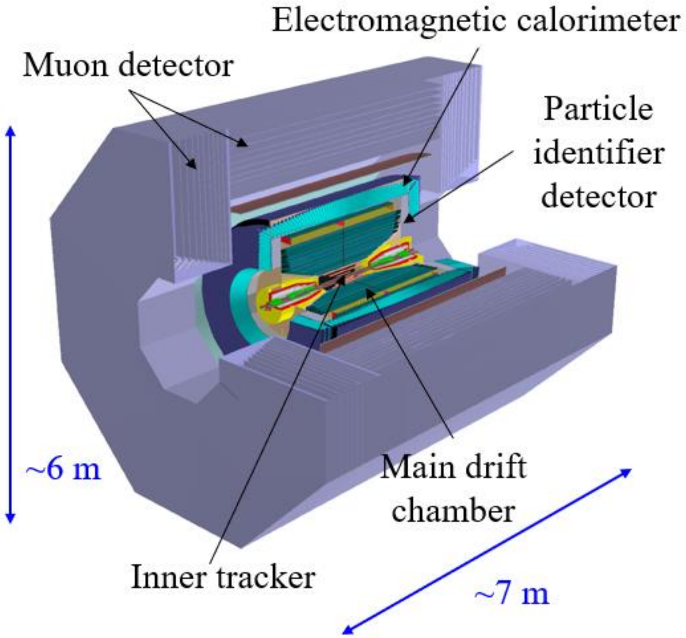
1. **STCF trigger system preliminary design**
2. MDC track reconstruction algorithm
   - 2D tracking and reconstruction
   - Time reconstruction
   - 3D reconstruction
3. Summary

STCF overview

Super Tau-Charm Facility:

- A new generation of high-luminosity **electron-positron collider**
- Center-of-mass energy: **2-7 GeV**
- Peak luminosity: **$>0.5\times10^{35}$ $cm^{-2}s^{-1}$ at 4 GeV**
- Collision data: more than **1 ab^{-1}/y**
- With potential to further **increase luminosity** and **beam polarization**





Requirements for trigger system

Requirements for trigger system in STCF

High trigger rate (~ 1 MHz)		Low latency
Very high physics event trigger efficiency (>99%)	Good background suppression capability	Distinguish of multi-physics events in 1 trigger window

High luminosity in STCF synchronous generates:

- **High physics event rate:** over **400 kHz**
- **Large data size:** over **200 GB/s** raw data
- **High background:** ~ **400 kHz/channel** in MDC
  ~ **1 MHz/channel** in ECAL

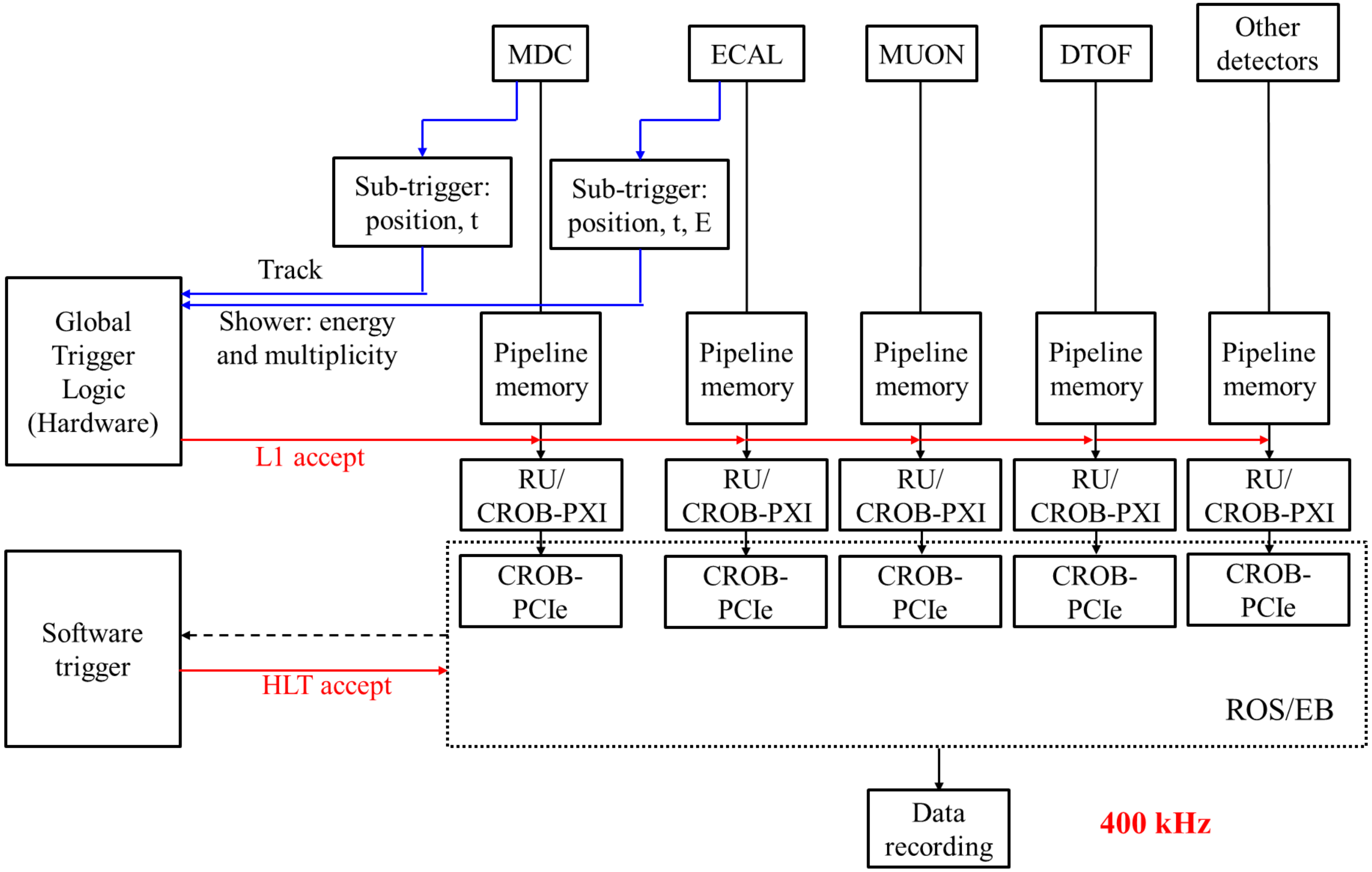
Trigger system:

- Identifying physics events from massive background
- Reducing the pressure in data acquisition and transmission
- Maintain the long-term stable operation of experiment

STCF trigger system preliminary design

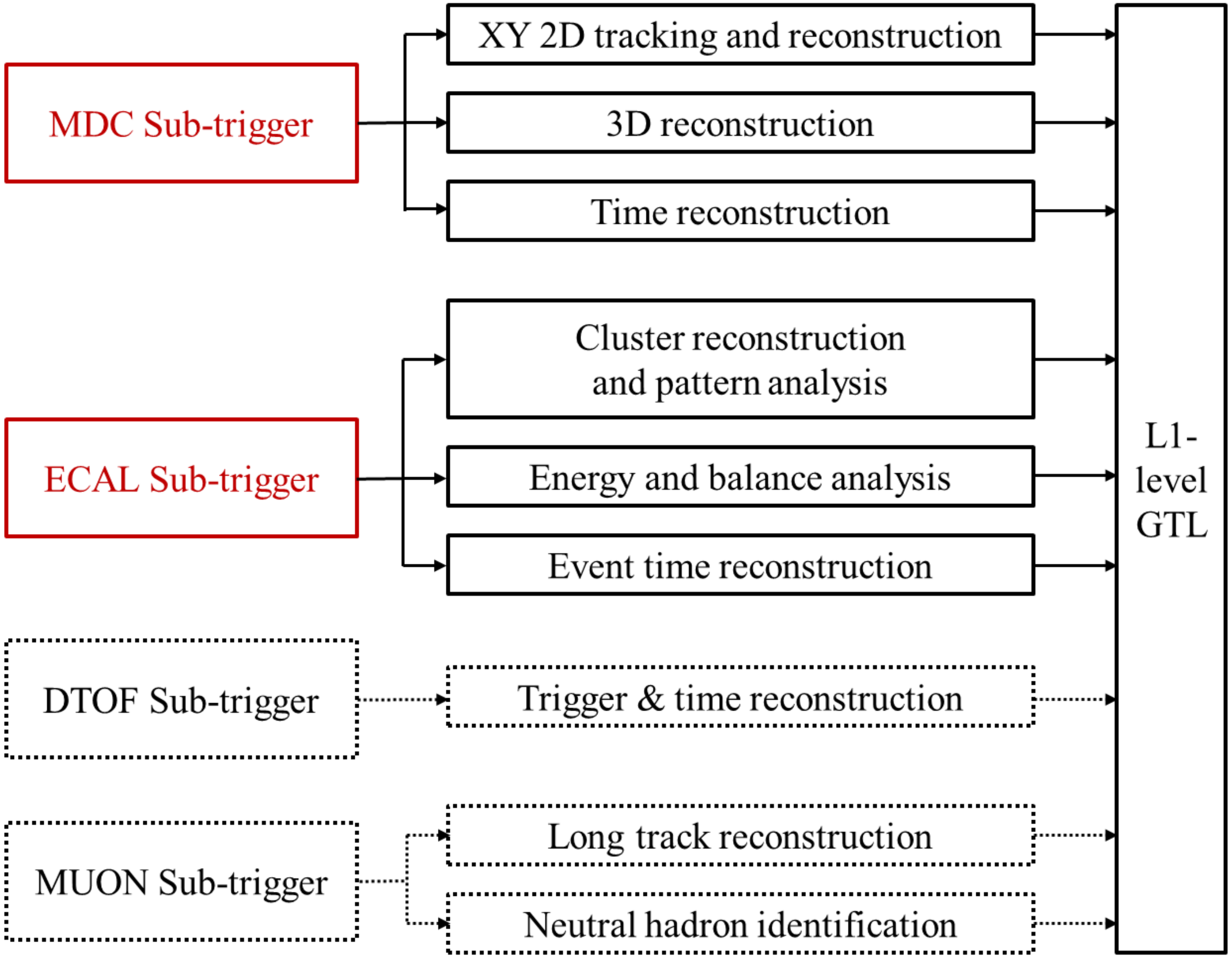
Two-stage trigger system:

- **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



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 $\mu/\pi/n/K_L$



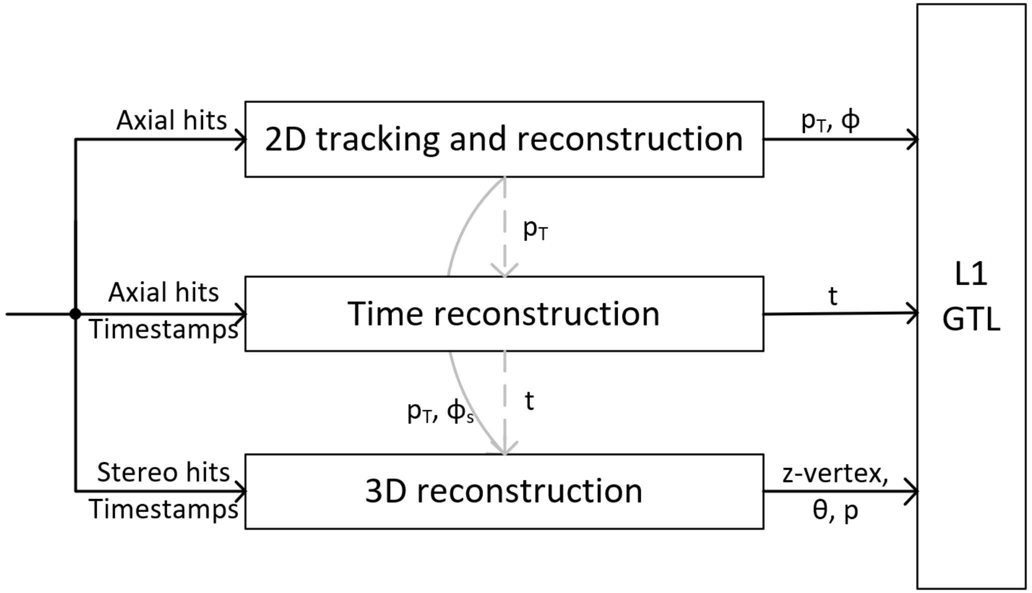
MDC sub-trigger

Data flow of MDC sub-trigger:

- **2D tracking and reconstruction:** transverse momentum, azimuthal angle

  Time reconstruction: track time --- events piling up (18% in 500ns)

  3D reconstruction: z-vertex (polar angle, momentum)



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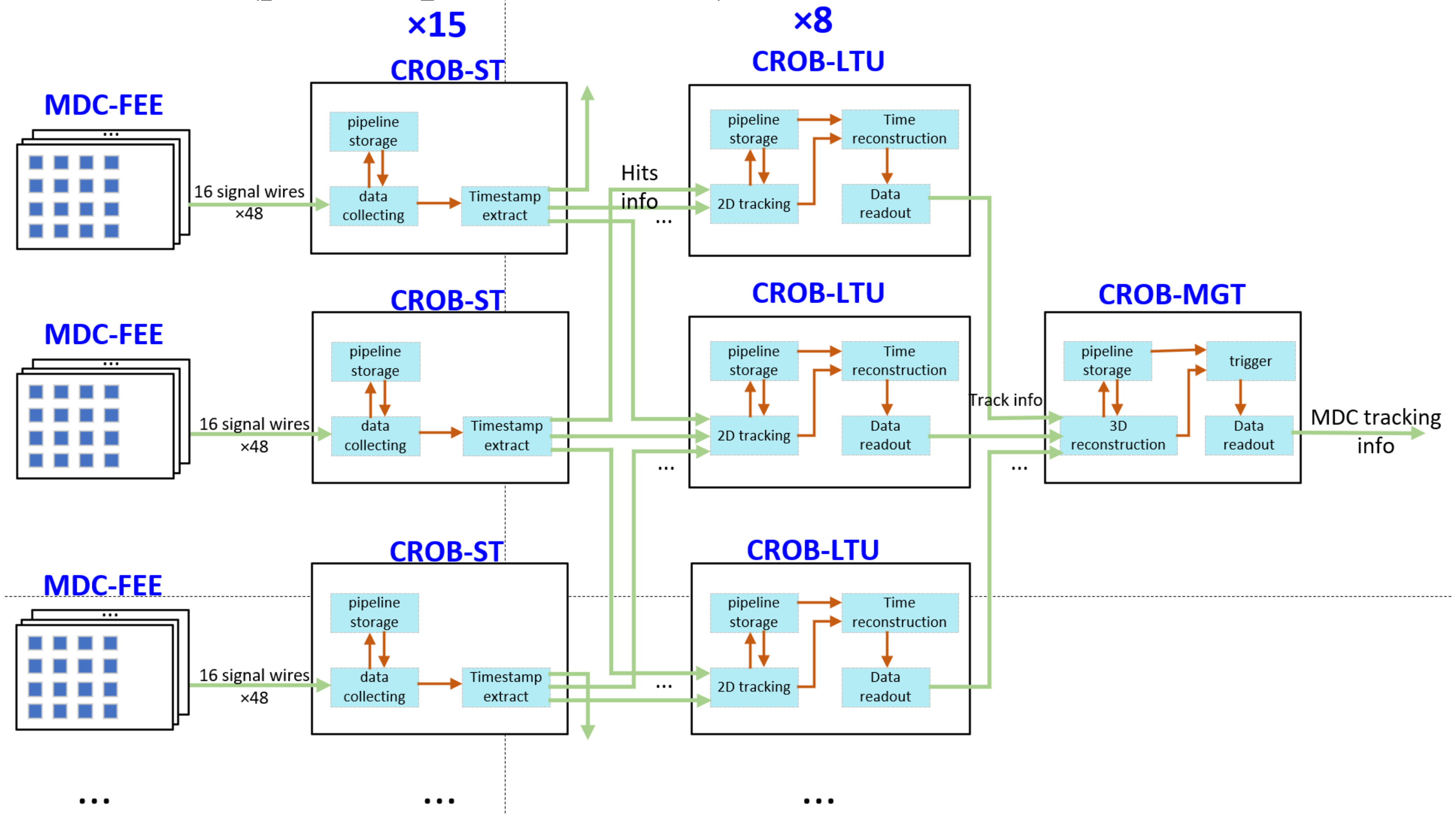

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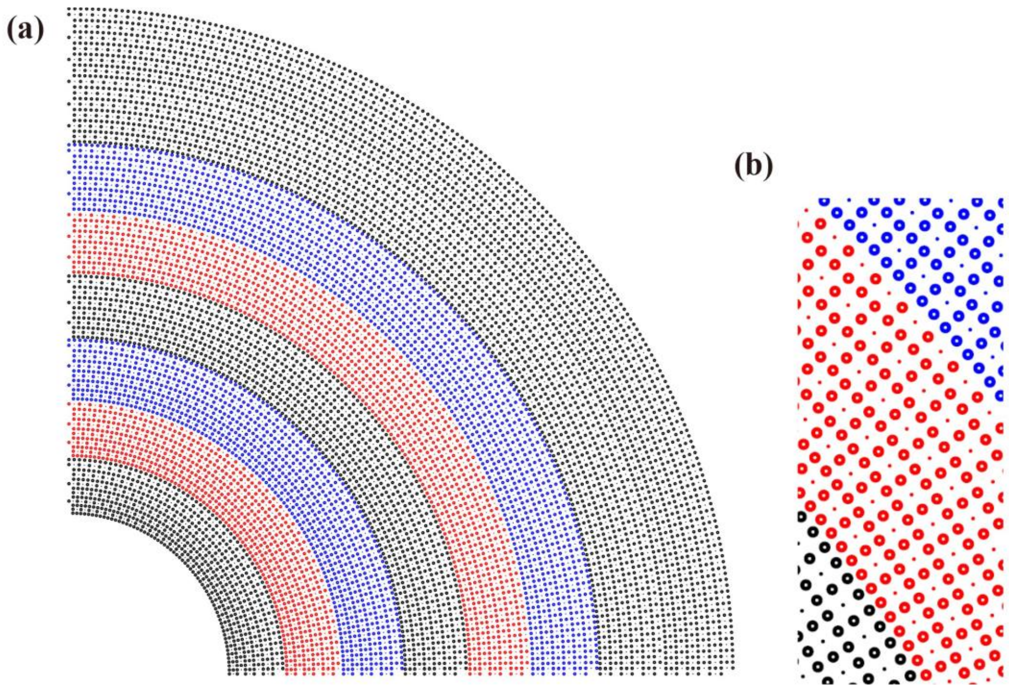
STCF MDC design

Baseline design:

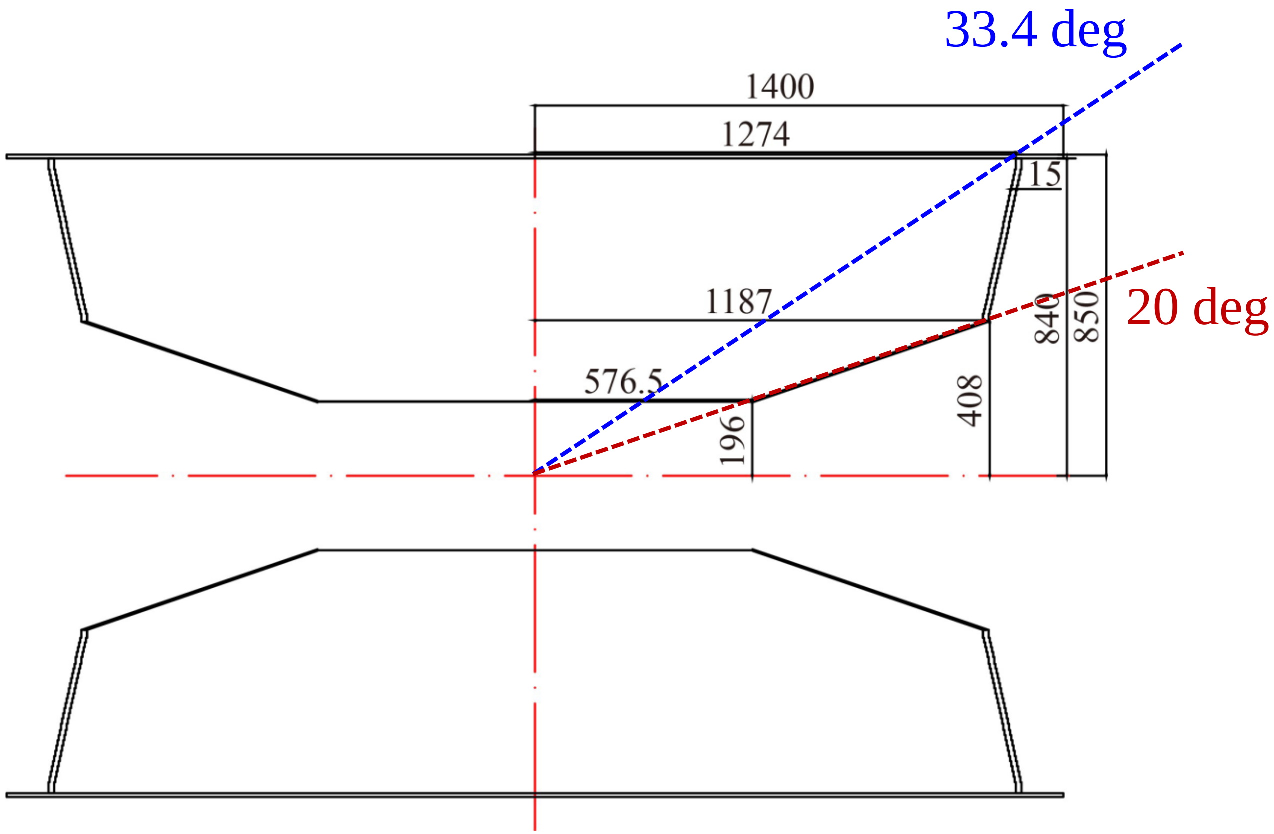
- 48 layers of small cell
- **1,4,7,8---**axial superlayers

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



Region division:

- Barrel: 33.4 deg – 90 deg
- Endcap: 20 deg – 33.4 deg



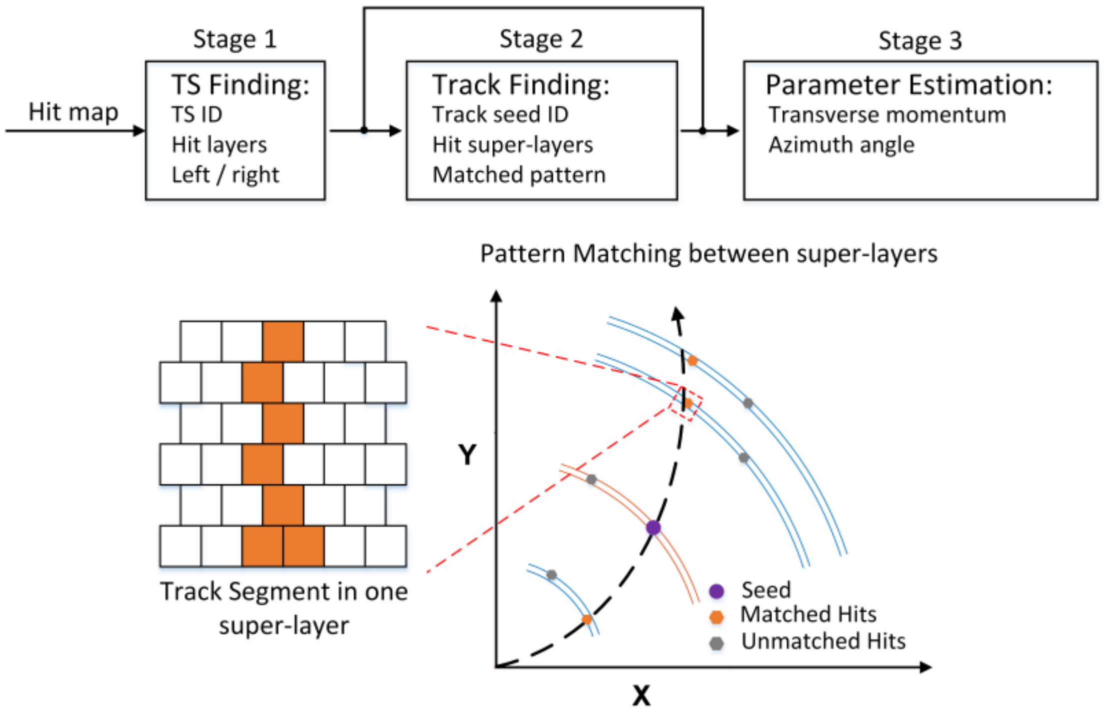
2D tracking and reconstruction

Pattern matching:

- 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



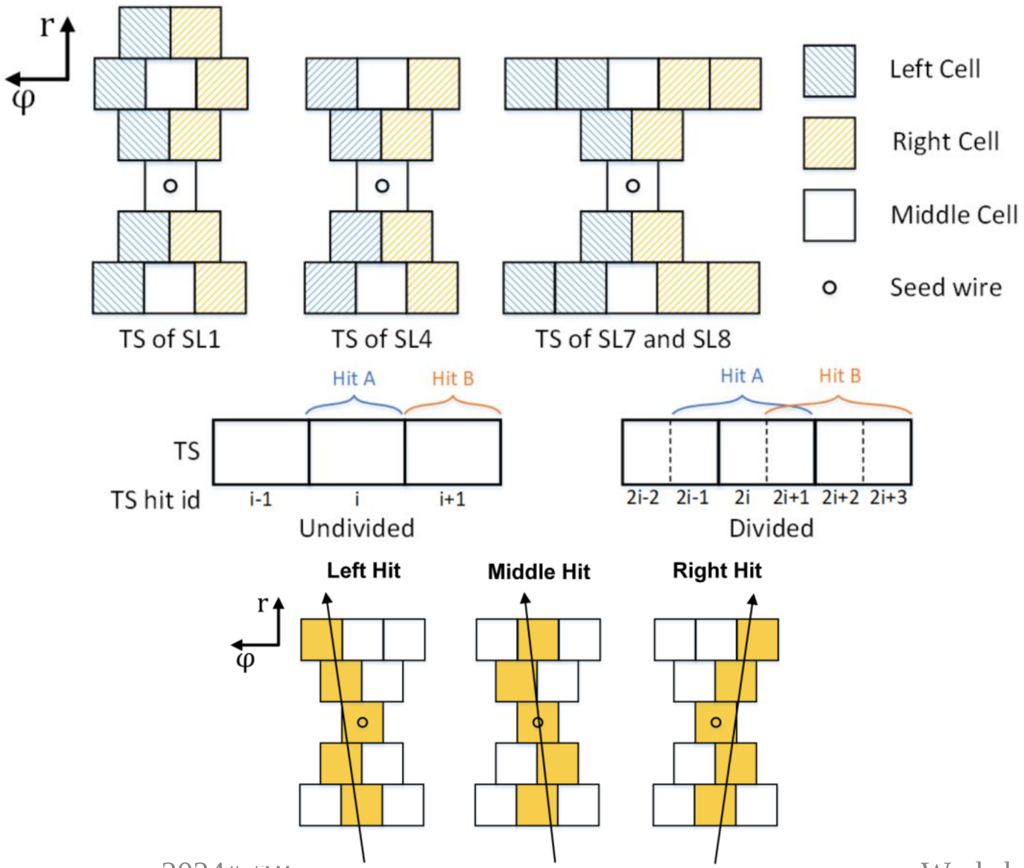
Three stages:

- **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

2D tracking and reconstruction

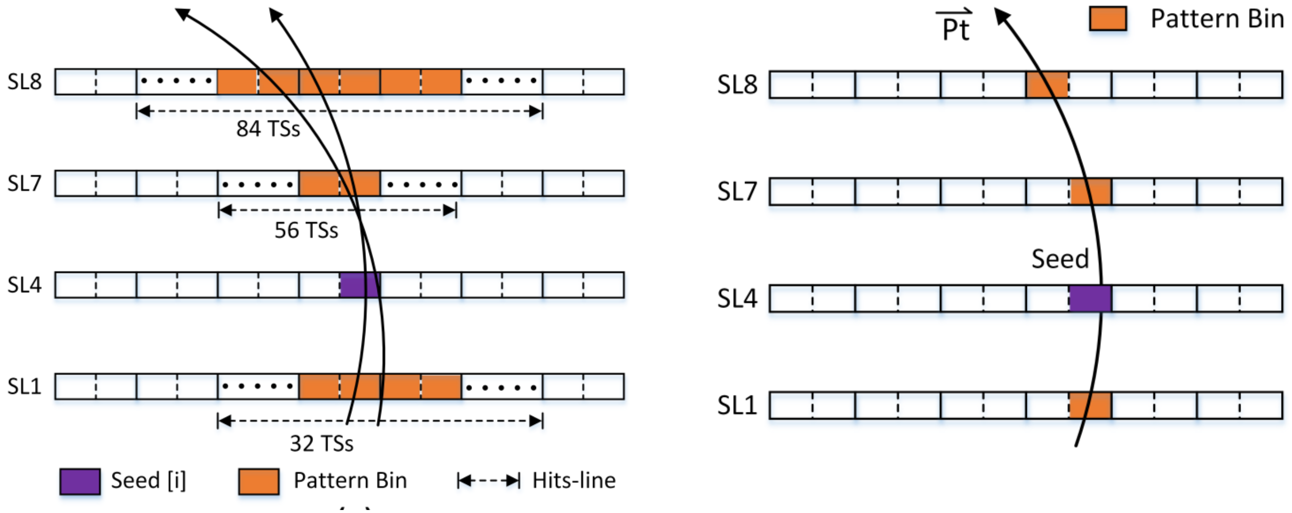
Track segment finding:

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



Pattern matching

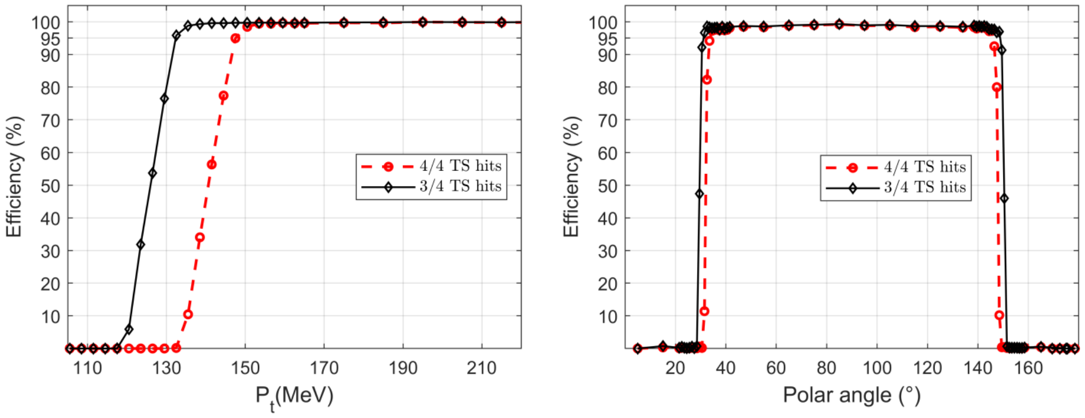
- Track finding: merged patterns for fast tracking
  total number: **784**
- Track reconstruction: accurate patterns
  - total number: ~**7800**
  - $p_T >$ **170 MeV**



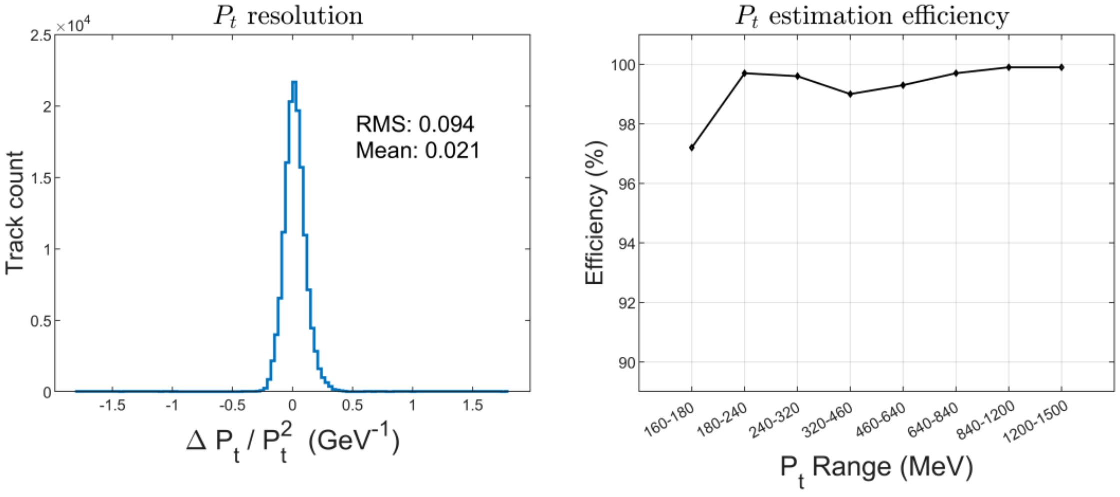
2D tracking and reconstruction

Track efficiency

- Single clear track
  - Track finding: $p_T > 130\text{MeV}$ $\theta > 30°$
  - Parameter estimation: $p_T > 170\text{MeV}$ $\theta > 30°$
    $\Delta p_T/p^2_T \sim 0.1$
- Physics event
  - The cut of θ: reason for 90% lost events



The track finding efficiency in different thresholds.



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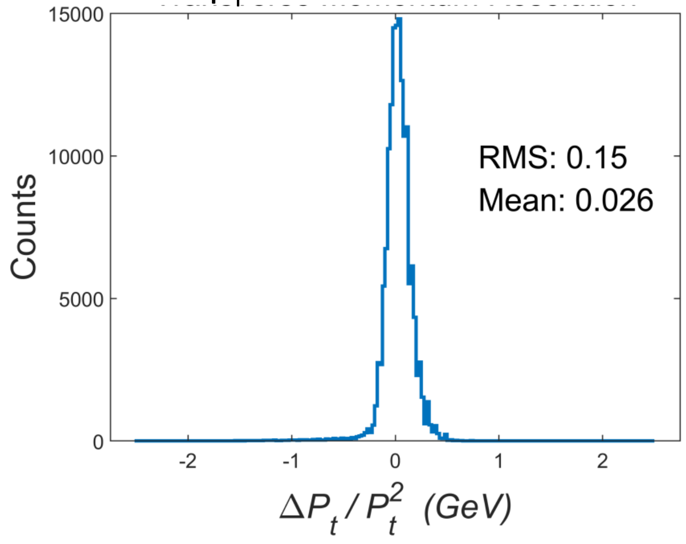


混有噪声情况下 $J/\Psi \rightarrow Anything$ 事例中寻迹模块性能.

径迹条数	寻迹效率	事例平均坏径迹数	寻迹成功 ≥1 事例比例	寻迹成功 ≥2 事例比例
1	98.4%	0.07	98.4%	-
2	98.1%	0.05	100%	96.2%
3	96.6%	0.12	100%	99.7%
4	95.8%	0.13	100%	100%
5	94.3%	0.22	100%	100%
>5	92.6%	0.23	100%	100%

混有噪声情况下 $J/\Psi \rightarrow Anything$ 事例横动量重建模块性能.

径迹条数	重建效率	事例平均坏径迹数	重建成功径迹 ≥1 事例比例	重建成功径迹 ≥2 事例比例
1	93.1%	0.15	93.1%	-
2	92.6%	0.13	98.7%	86.5%
3	89.6%	0.24	99.9%	95.5%
4	87.9%	0.26	99.9%	98.9%
5	86.5%	0.33	100%	99.8%
>5	84.5%	0.35	100%	100%

2D tracking and reconstruction

φ reconstruction

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

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

$\rho = \frac{p_t}{0.3B}$

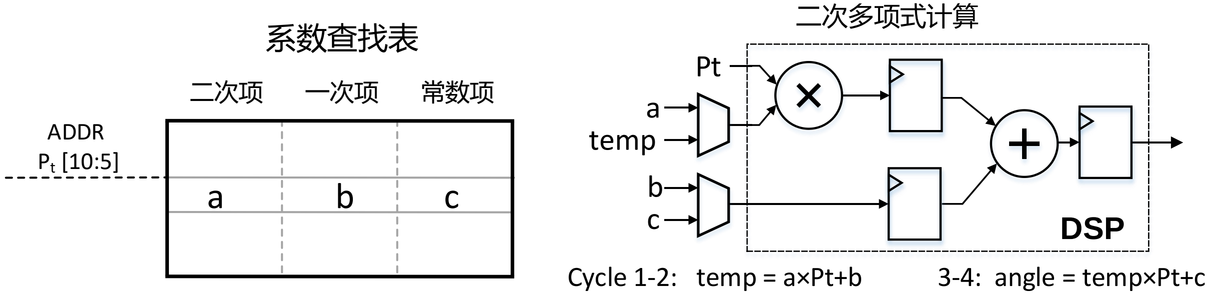
Piecewise interpolation →

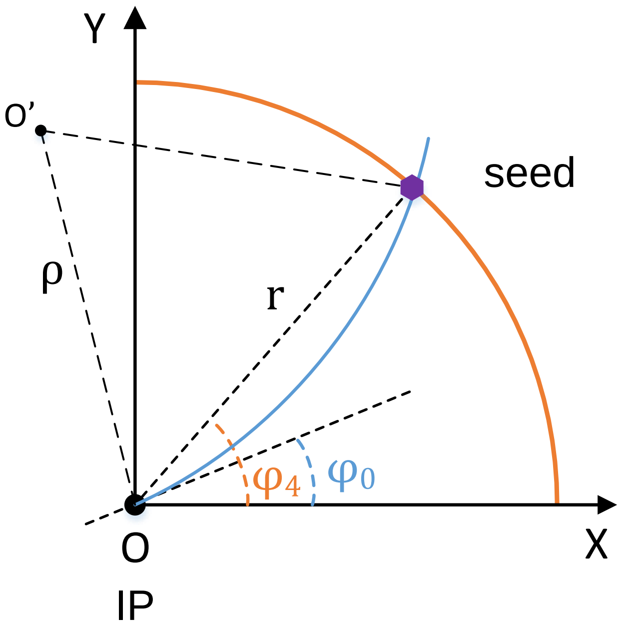
FPGA implementation

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

Resource friendly

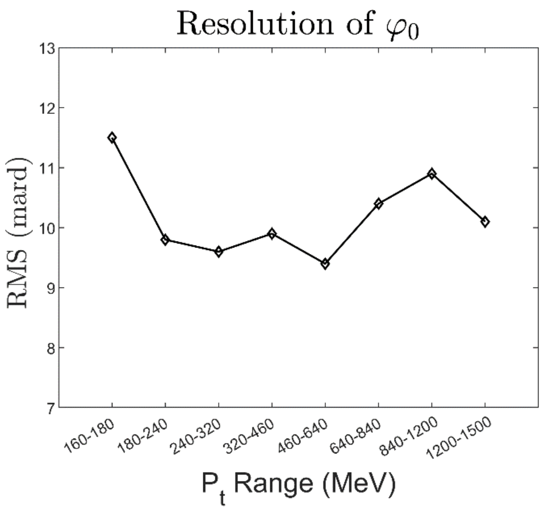
$\Delta\varphi = a \times p_t^2 + b \times p_t + c$

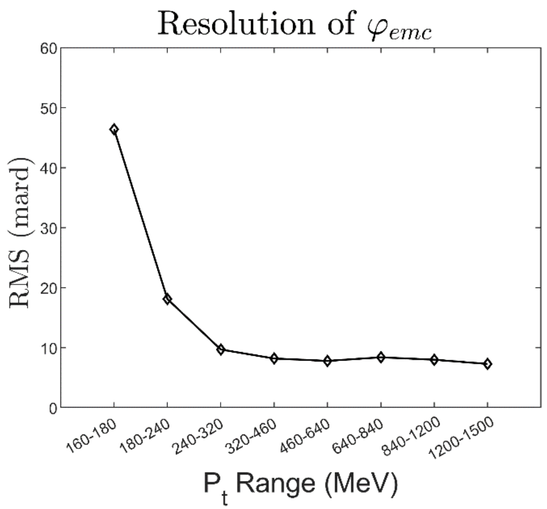




For tracks with p_T > 180 MeV,
Δ φ_e < 20 mrad

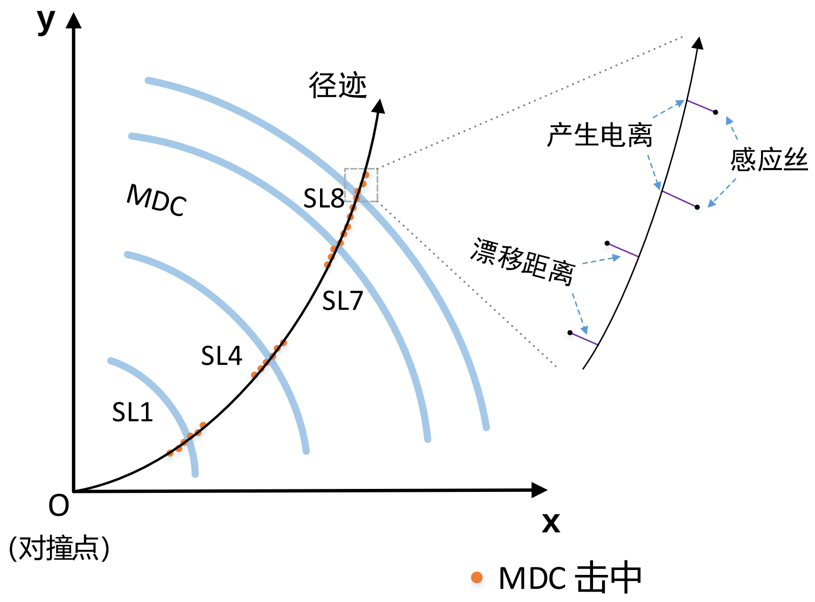
For track matching with EMC, 50 mrad is OK

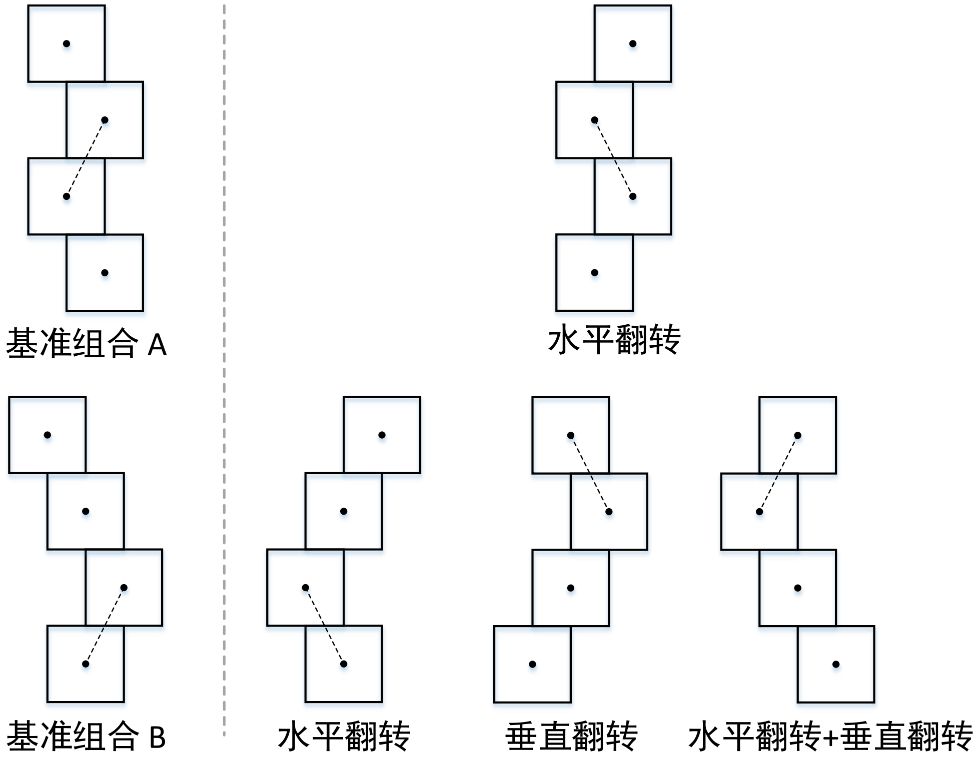




Time reconstruction

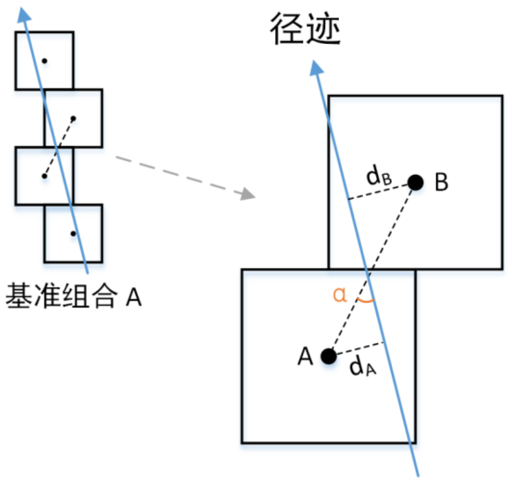
- 利用径迹参数重建击中时间
  - 将径迹段近似为直线
  - 利用径迹重建得到的参数计算漂移距离,从而得到漂移时间
    - FPGA流水线计算
  - 结合电子学Timestamp时间计算径迹段产生时间
  - 径迹时间为各径迹段时间的平均值





Time reconstruction

Time calculation



$$T_A = t_s + t_{driftA}$$
$$T_B = t_s + t_{driftB}$$
$$t_{driftA} - t_{driftB} = T_A - T_B$$

$$t_{drift} = a \cdot d^2 + b \cdot d + c$$

$$t_{driftA} - t_{driftB} = [a \cdot (d_A + d_B) + b] \cdot (d_A - d_B)$$

$$l_{AB} \cdot sin\alpha = d_A + d_B$$

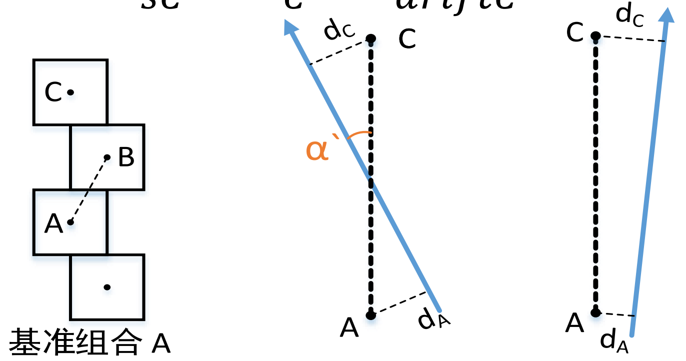
$$\alpha = \arcsin\left(\frac{r}{2\rho}\right) + \arcsin(0.5)$$

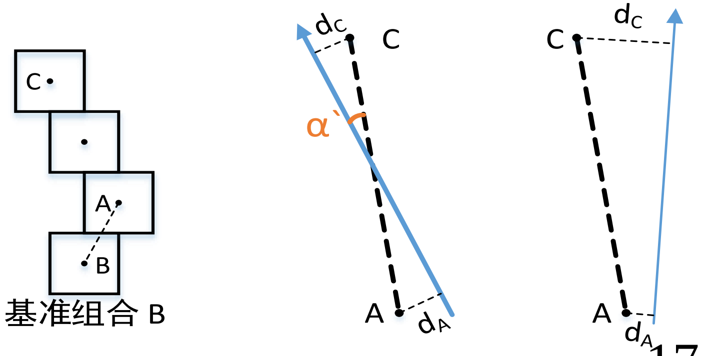
Check with another hit

- Abandon 5% TSs

$$\mathrm{d}_C = |l_{AC} \times sin\alpha' - d_A|$$

$$t_{sA} = T_A - t_{driftA}$$
$$t_{sC} = T_C - t_{driftC}$$



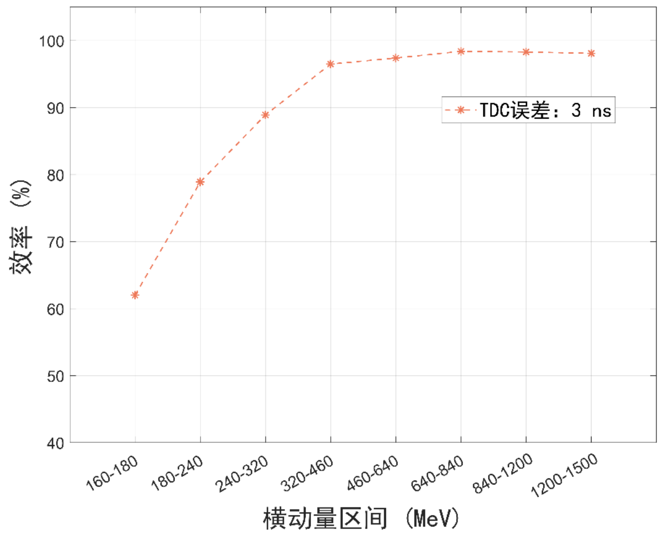


Time reconstruction

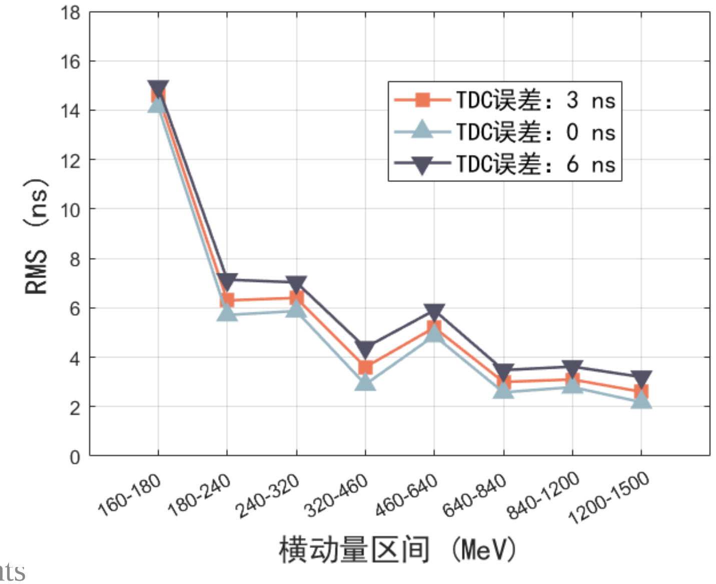
Track time reconstruction

- 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



横动量区间 (MeV)	5% 筛选阈值 (ns)	1% 筛选阈值 (ns)
160-180	66.3	121.0
180-240	15.7	42.1
240-320	17.2	39.2
320-460	15.0	25.2
460-640	14.9	24.8
640-840	12.3	19.8
840-1200	12.6	19.9
1200-1500	12.2	18.7

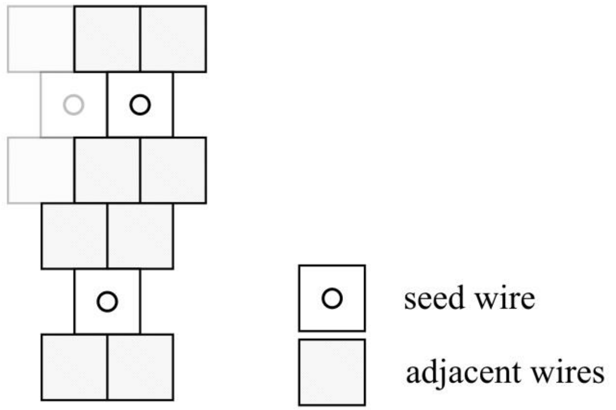


Z-vertex reconstruction

Stereo TS finding

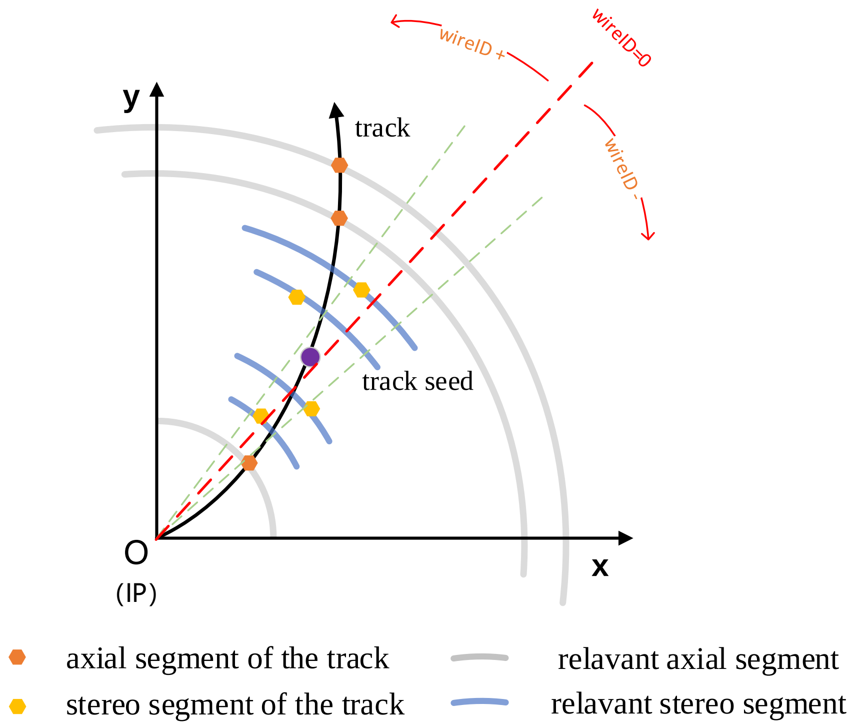
- 1 superlayer ---2 seed wires

  Position + timestamp



Track finding

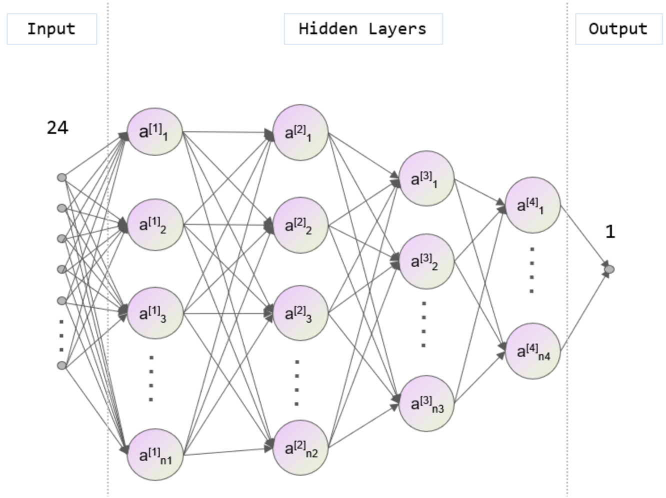
- Matching stereo TS with an existing track
- Sectorization and Normalization

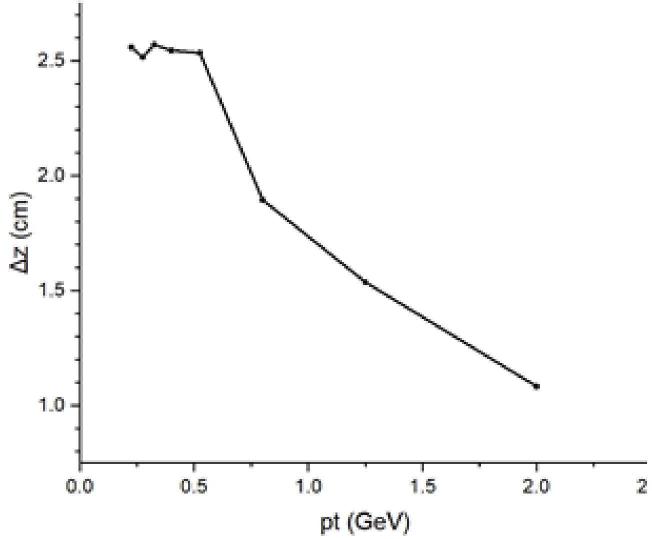


Z-vertex reconstruction

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





Quantization & FPGA resource optimization

- Qkeras

Model bitwidth and resolution of z-vertex

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**)

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

  DSP: 97%

  FF: 64%

  LUT: 44%

→

- Latency: 37 clk
- Interval (Dead time): 1 clk
- FPGA resource:

  DSP: 3%

  FF: 5%

  LUT: 13%

Able to be implemented in an XCKU060

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Summary

1. 2D tracking and reconstruction (J/ψ -> anything)
   - Track efficiency > 96% $\Delta p_T / p_T^2 \sim 15\%$ Latency = 339 ns
2. Time reconstruction (single track)
   - Efficiency ~ 80% $\Delta t < 16$ ns   Latency = 207 ns
3. Z-vertex reconstruction (clear single track)
   - $\Delta z \sim 3$ cm   Latency (MLP) = 111 ns

- Un-identification of high-p_T track in Endcap
  - 3 hits tracking as a complement to 4 hits tracking
  - Further optimization is needed
- Short track tagging
  - Un-reconstructed short track will be sent to GTL with related TS information
- Distinguish of cross tracks

Thanks