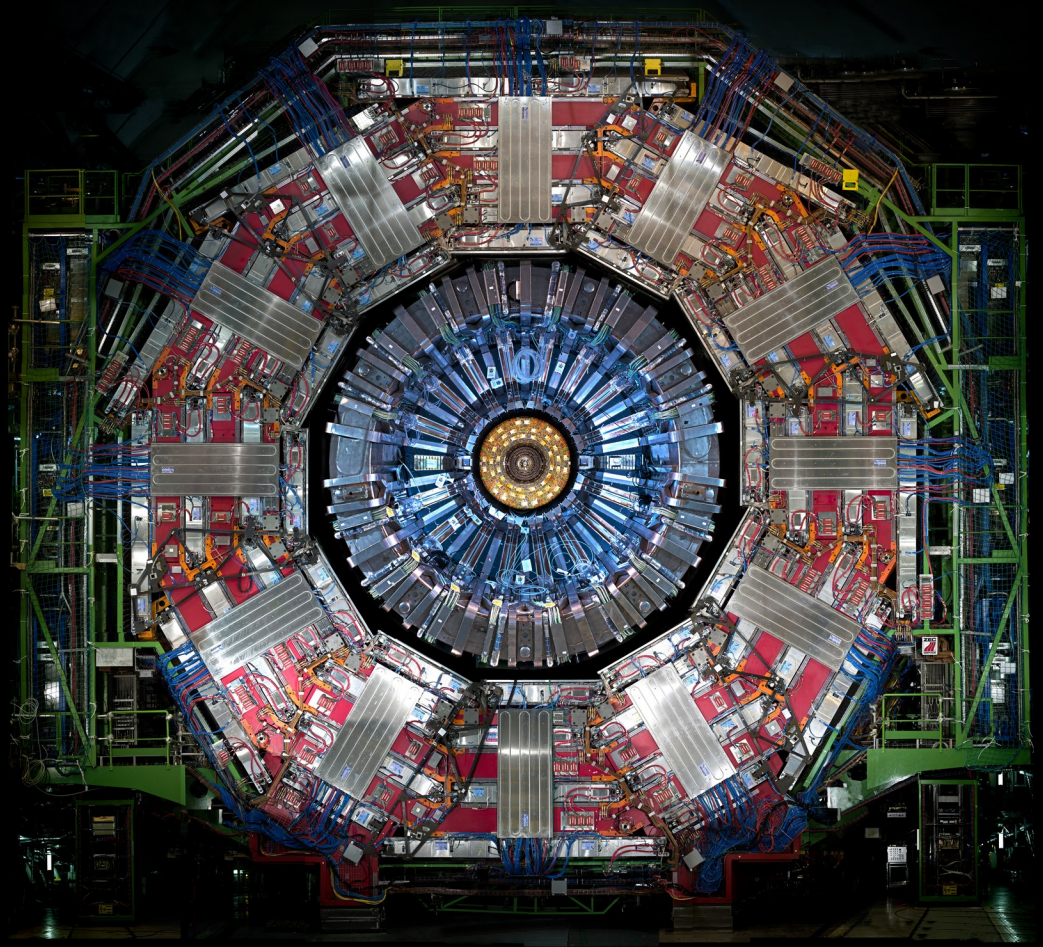
Karlsruher Institut für Technologie

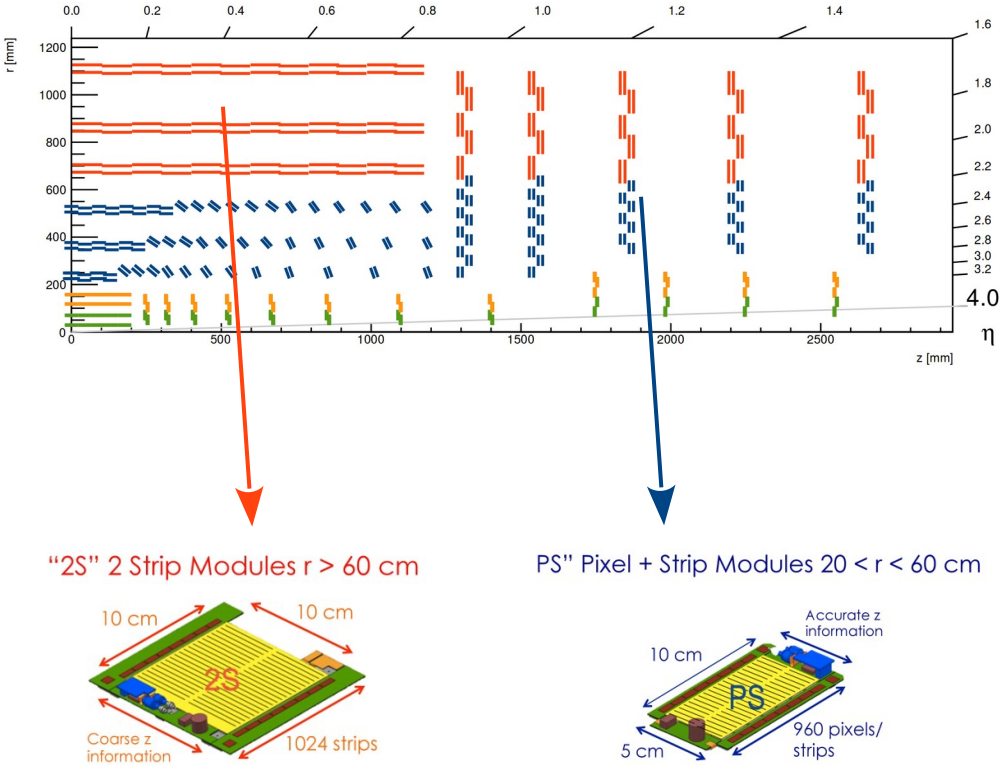
Low-Latency Track Triggering in High-Energy Physics

Dr.-Ing. Luis Ardila-Perez



HL-LHC CMS Tracker Upgrade

- High occupancy → **New silicon detector**



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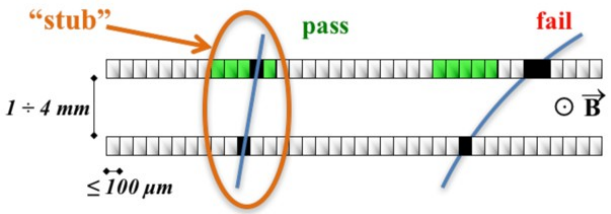
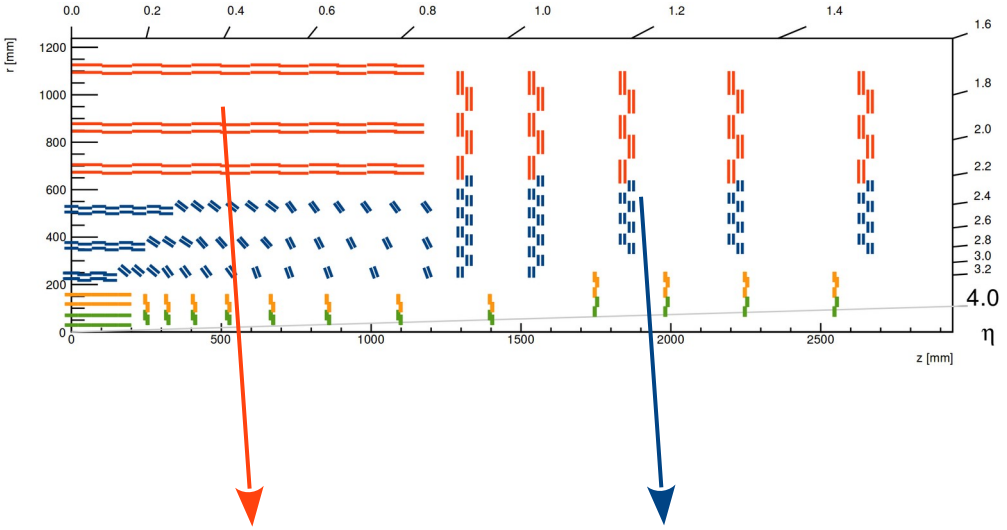
  - Only hit pairs with $\mathbf{p_T > 2\ GeV}$ (“stubs”) are forwarded off-detector



  - Average 15 000 stubs every 25 ns stub bandwidth **~50 Tb/s**



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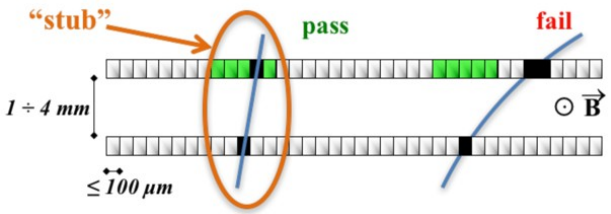
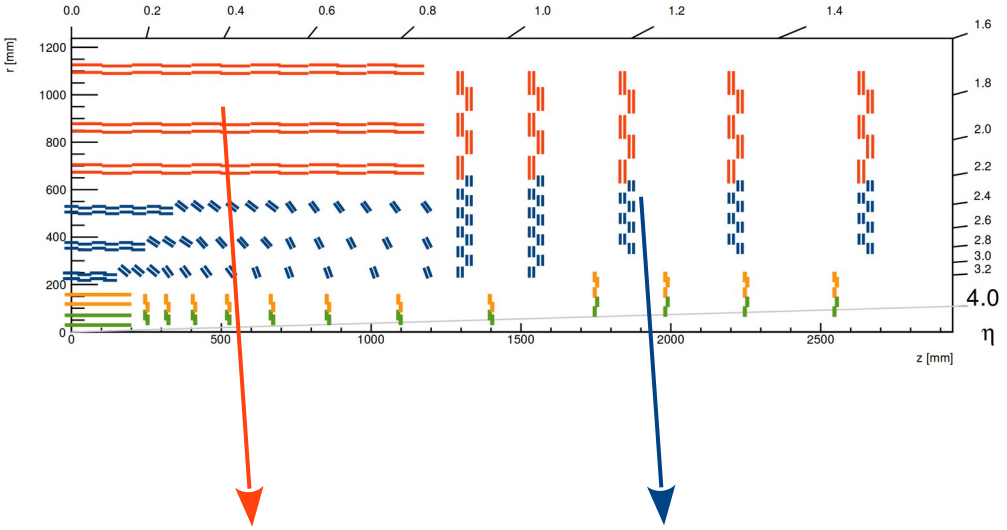
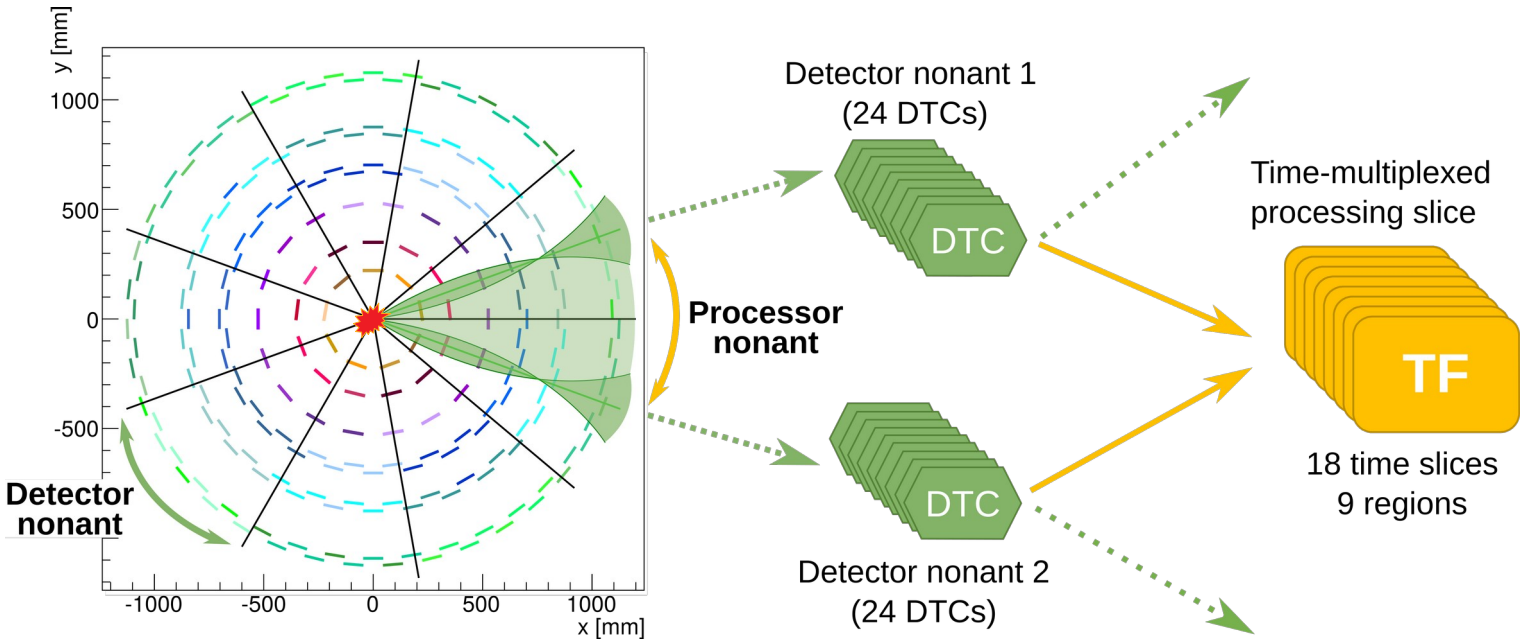


  - Average 15 000 stubs every 25 ns stub bandwidth **~50 Tb/s**
- Increased data rate → **New read-out electronics system**
  - Capable of **reconstructing tracks** at the collision rate
  - With a total latency of **4 µs**

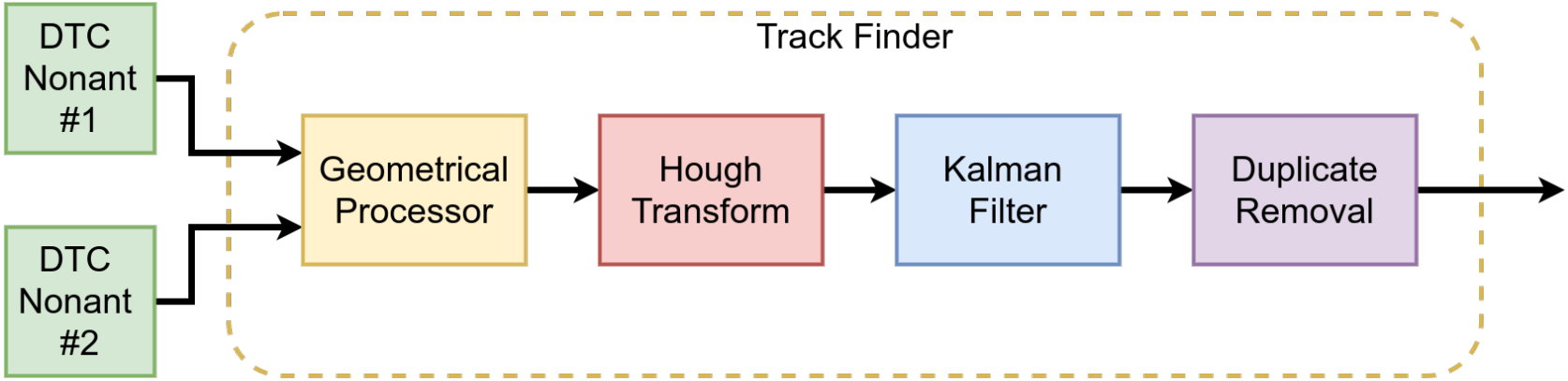


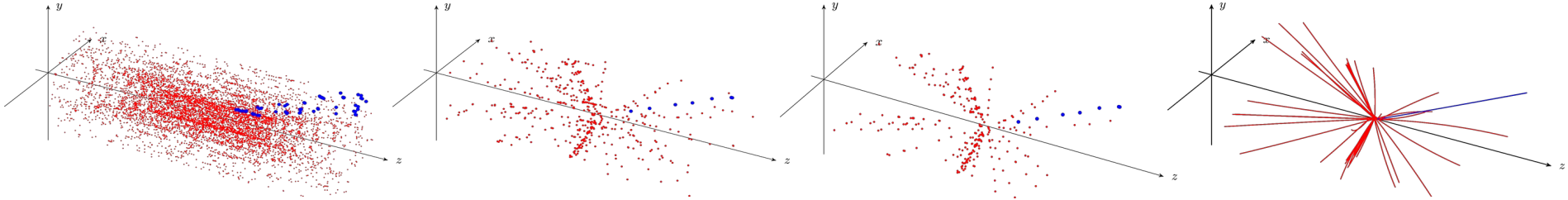
Track Finder Approach - Algorithms



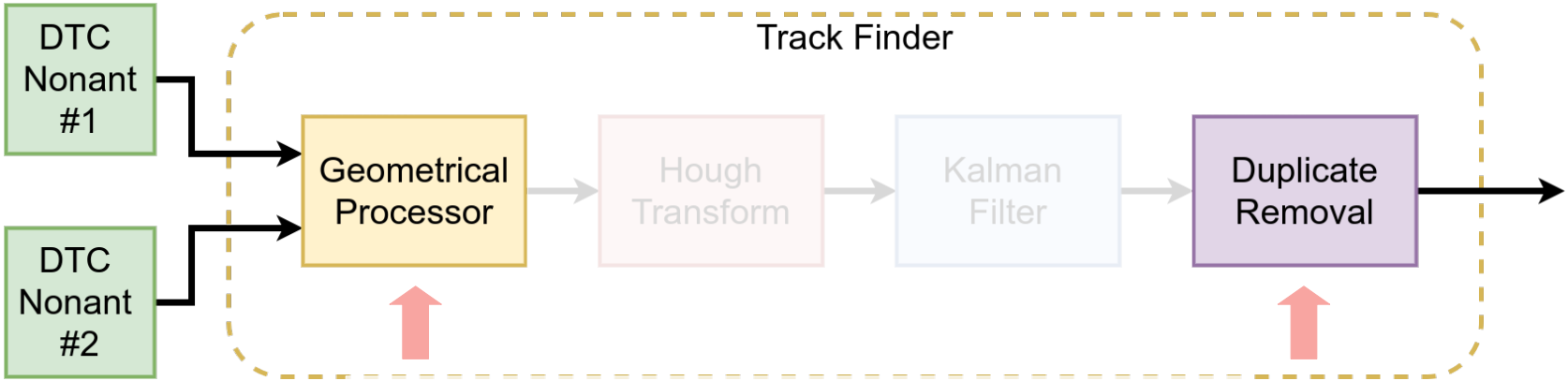
- **DTC** reads the detector modules and performs time-division multiplexing
- **TF** reconstructs the tracks for one event

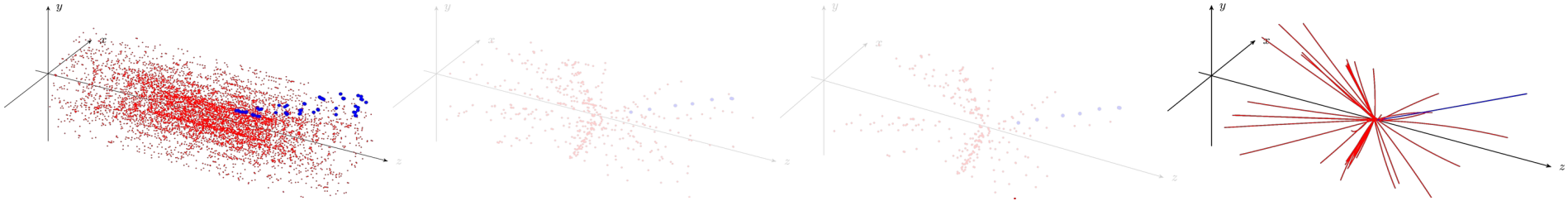
Track Finding Algorithm





Track Finding Algorithm

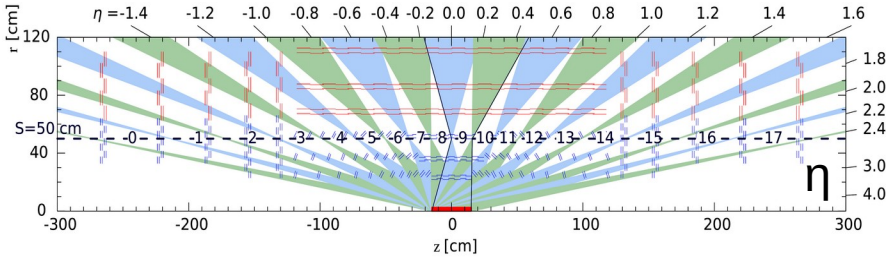




My Contribution

Contributions to the Track Finder Algorithm

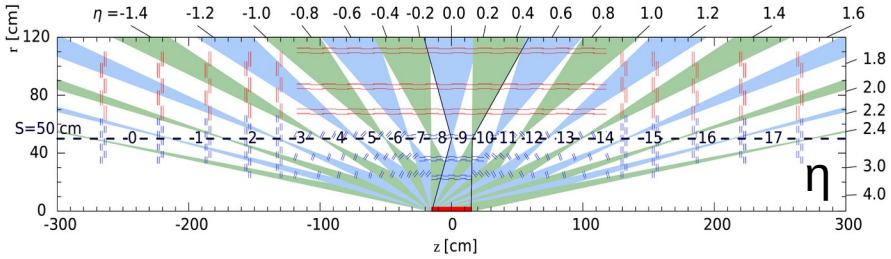
Geometrical Processor



- Detector division in finer sub-sectors in η and φ
- Optimized for similar data rate per sector
- **Latency reduced by a factor of 2** (58 ns) compared to other work
- **Resource saving** of 25 % less DSPs & 30 % less FPGA area

Contributions to the Track Finder Algorithm

Geometrical Processor



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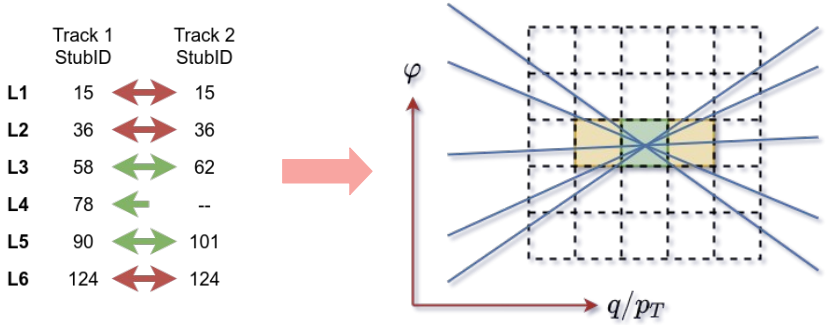
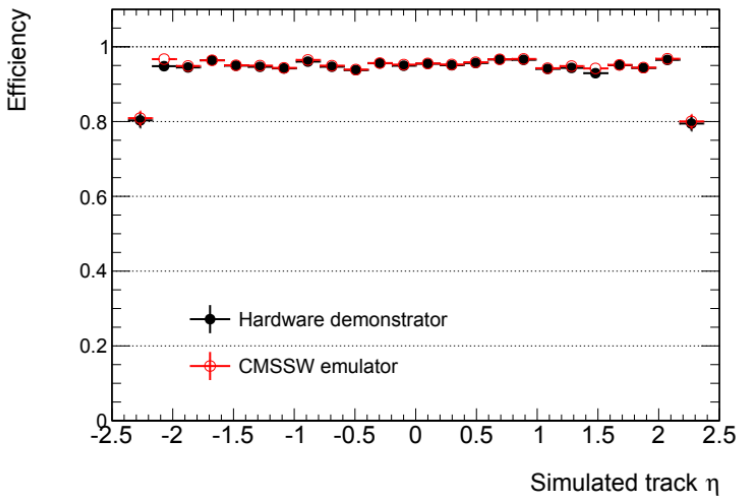
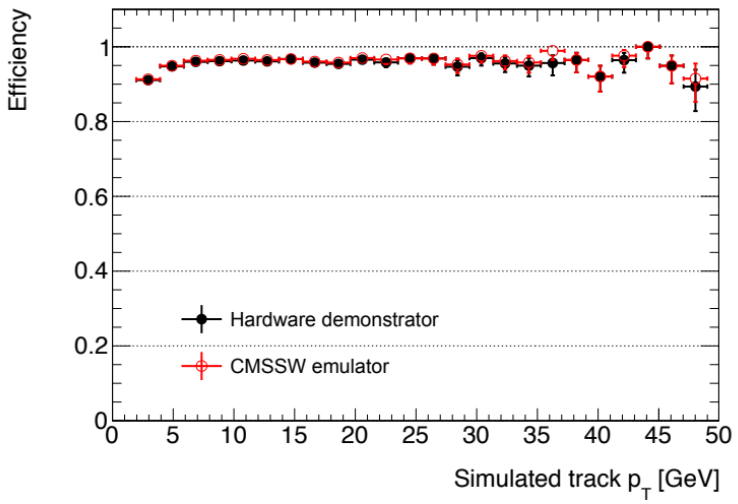
Duplicate Removal



- It uses only **1 % of the resources** used for the pair-wise comparison approach
- Contributes to the latency with only four clock cycles ~17 ns
- Remove duplicates without losing efficiency

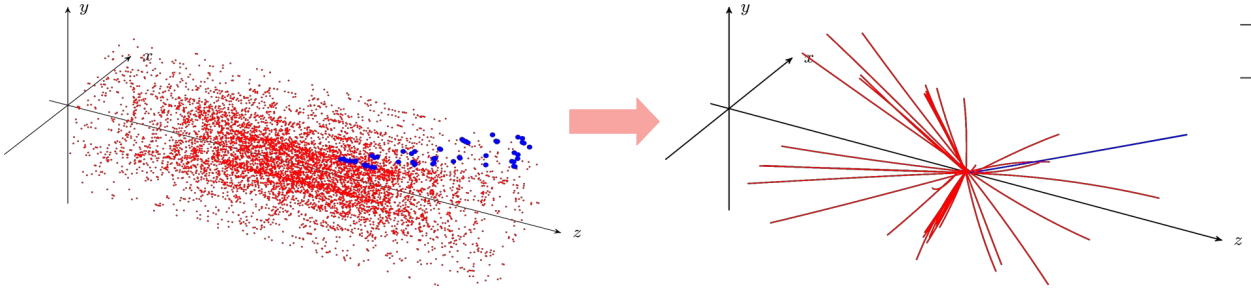
Track Finder Results

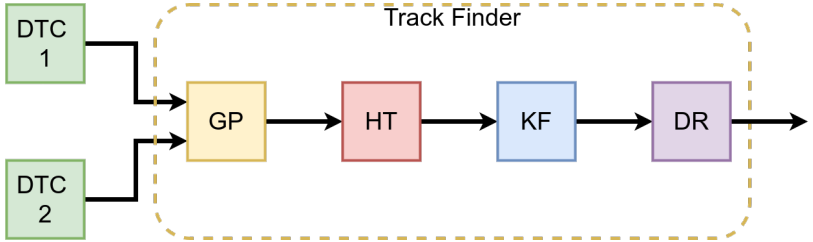


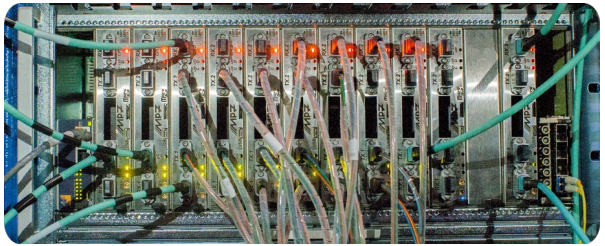


- Average track finding efficiency **> 95 %** (for tracks > 3 GeV)

Track Finder Demonstrator Latency



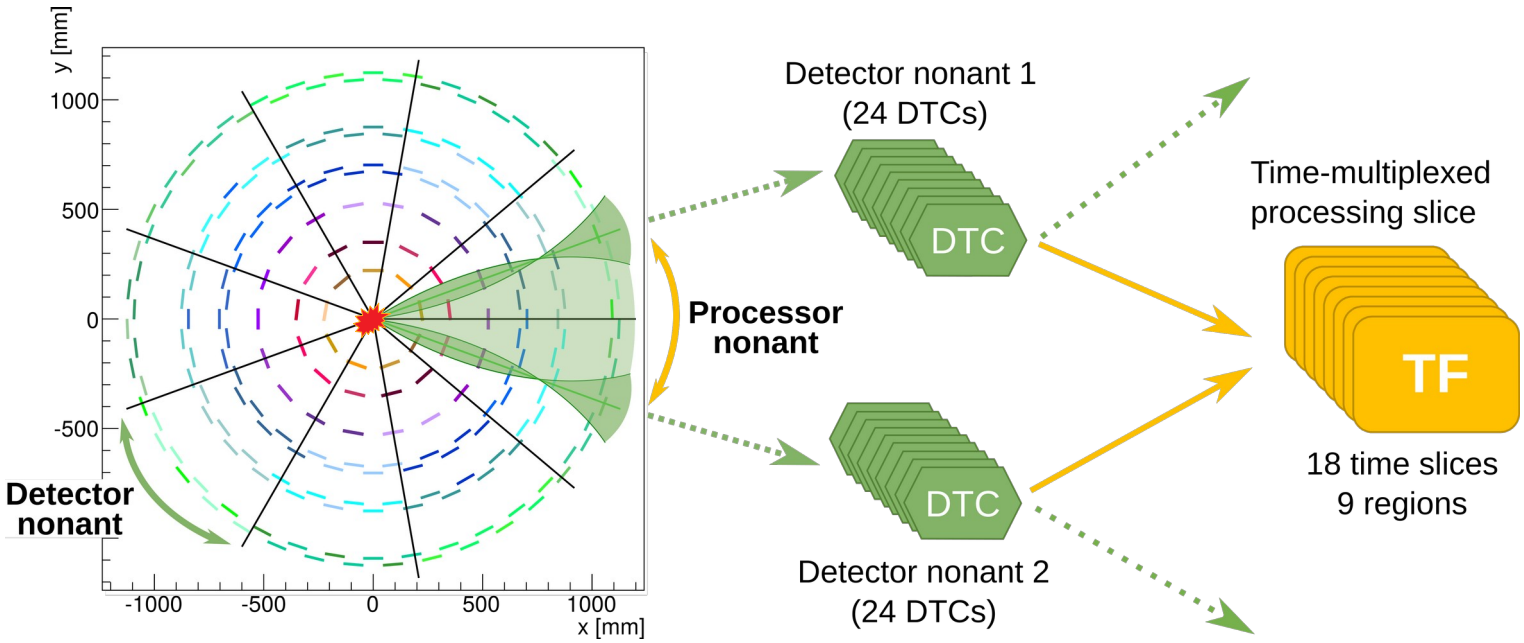




System latency	Latency [ns]
SERDES + optical length 1	143
Geometric Processor	251
SERDES + optical length 2	144
Hough Transform	1025
SERDES + optical length 3	129
Kalman Filter	1641
Duplicate Removal	17
SERDES + optical length 4	129
Total: First out - First in	3479
Last out - First out	225
Total: Last out - First in	3704

< 4 µs requirement fulfilled!

Tracker Finder Approach - Hardware

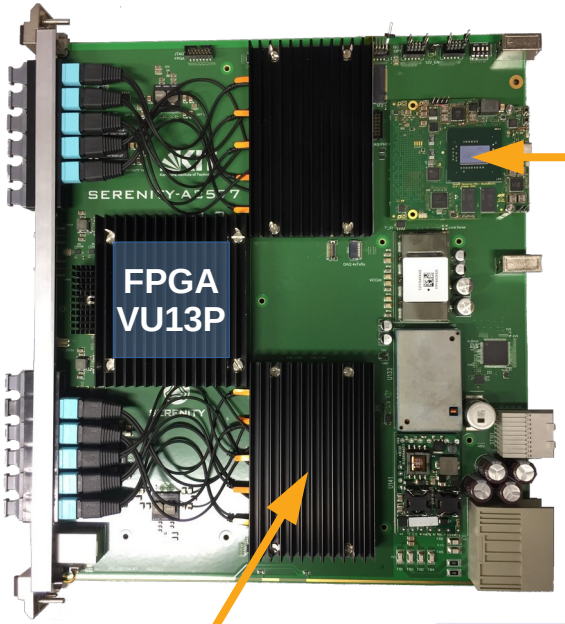


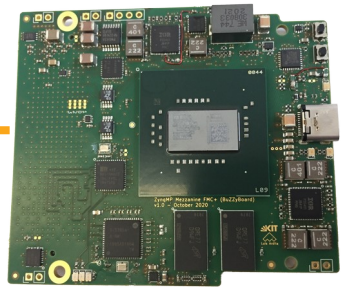
~15 000
Detector Modules

216
Detector, Trigger & Control Boards

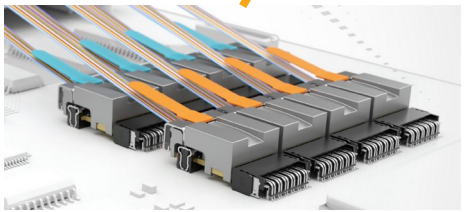
162
Track Finder Boards

‘Serenity’ ATCA Board

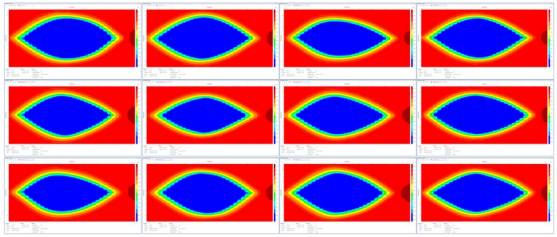




ZynqUS+ Mezzanine



Samtec Firefly



PRBS31 – LPM

- Board compatible with several high-end FPGAs (Xilinx VirtexUS+)
- Capable of handling up to 3.1 Tb/s of data bandwidth
- 124 high-speed optical channels @ up to 25 Gb/s
- Excellent optical performance 1E-12 Bit Error Rate (BER)
- Management mezzanine based on a heterogeneous computing device (Xilinx ZynqUS+)

Conclusions

- Demonstrated that reconstruction of tracks under the tight latency requirements of the CMS L1-trigger system is possible
- The reconstruction algorithm was fully implemented in hardware (FPGAs)
- Optimizations of such algorithms were fundamental for the overall scaling up of the system
- The ‘Serenity’ ATCA board has an enormous processing capability which greatly exceeds the requirements
- ‘Serenity’ is currently foreseen to be used at CMS in several sub-detector systems: Tracker, HGCal, L1-Trigger, MTD, & BRIL

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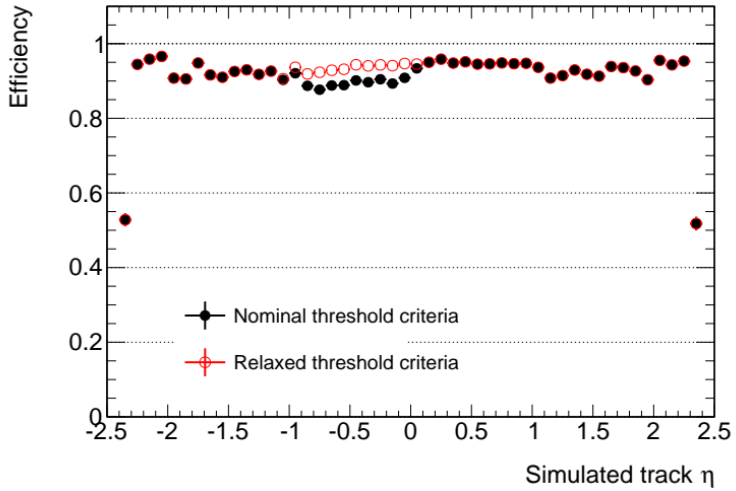
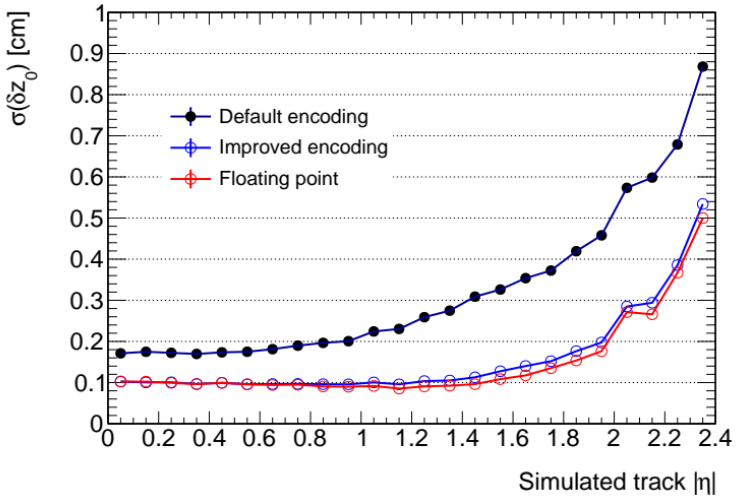
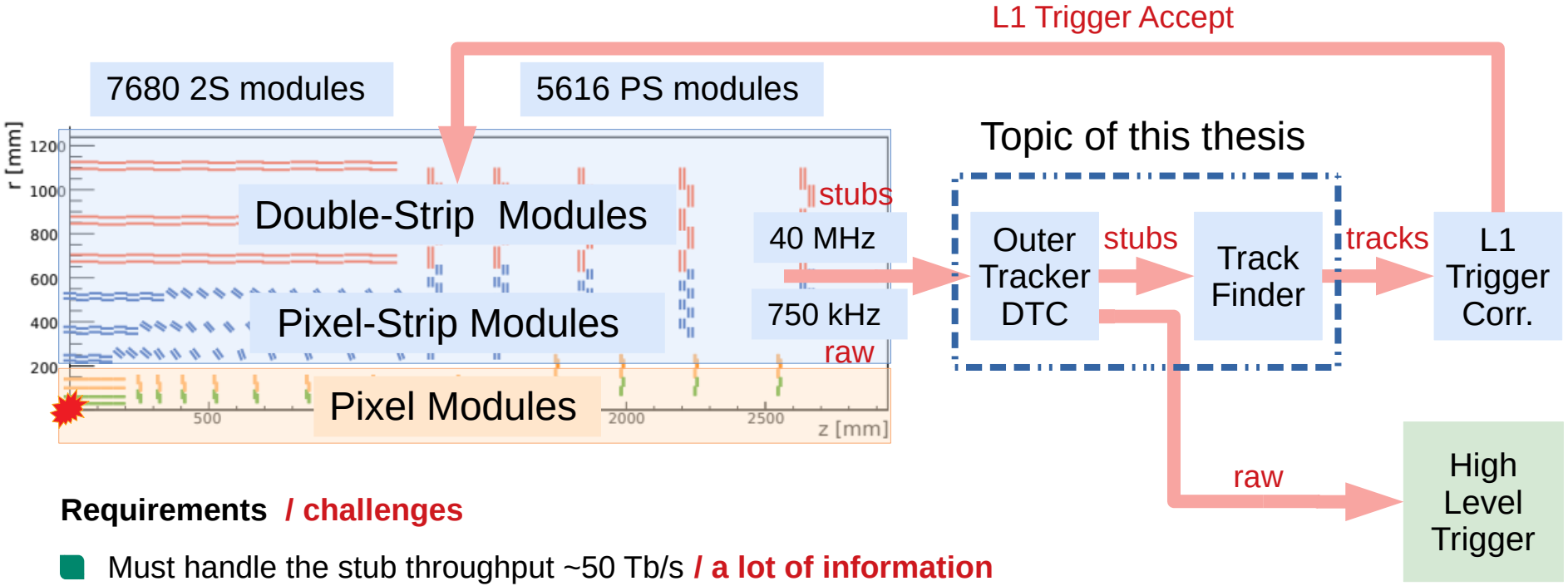


- Robustness of the system over module failures
- Efficiency can be recovered by reducing the number of layers required to form tracks on the affected region



- z_0 resolution **~1 mm** (barrel)
- p_T resolution **~1 %** (barrel)

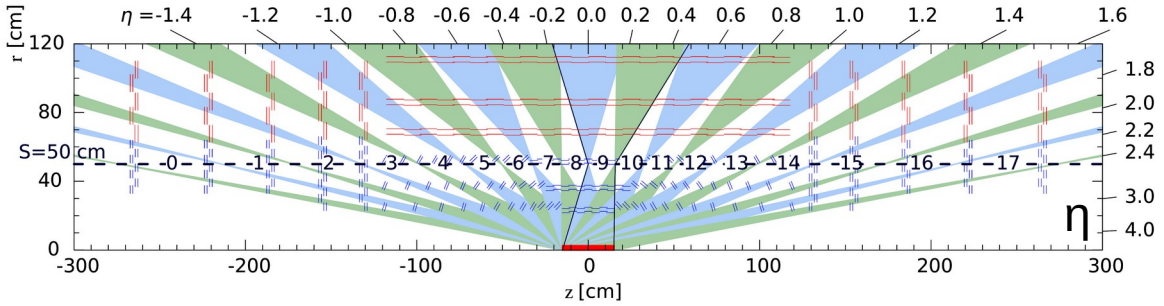
Back-End Electronics System

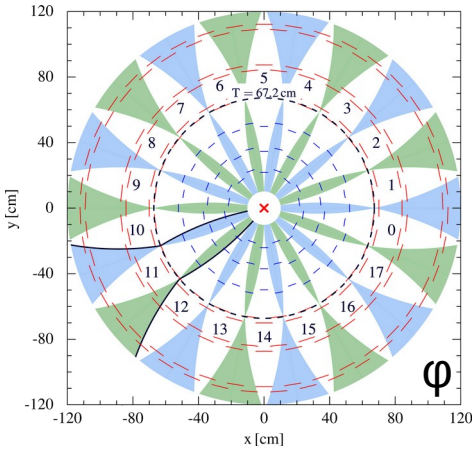


Requirements / challenges

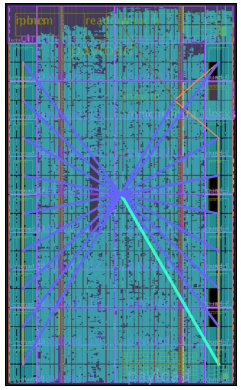
- Must handle the stub throughput ~50 Tb/s **/ a lot of information**
- Must be capable of reconstructing tracks at the collision rate **/ possible?**
- Total allowed latency for (DTC + Track Finder) is 4 µs **/ fast**

Geometrical Processor (GP)

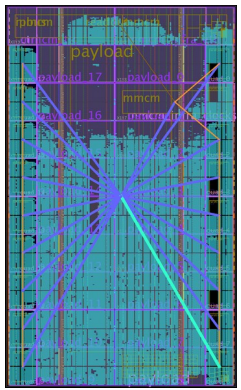




Other work
MaxJ HLS



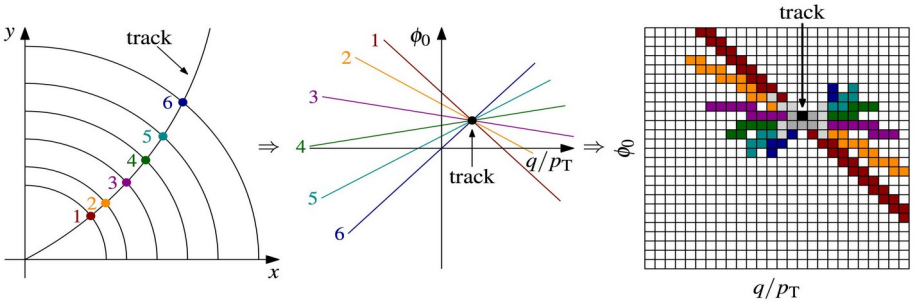
This work
VHDL



- Detector division in finer sub-sectors in η and φ
- Shaded area duplicates data across neighboring sectors
- Optimized for similar data rate per sector
- “Bend filter” reduces output data rate of next stage (HT) by a factor of 4
- Latency reduced by a factor of 2 (58 ns) compared to other work
- Resource saving of 25 % less DSPs & 30 % less FPGA area (V7-690)

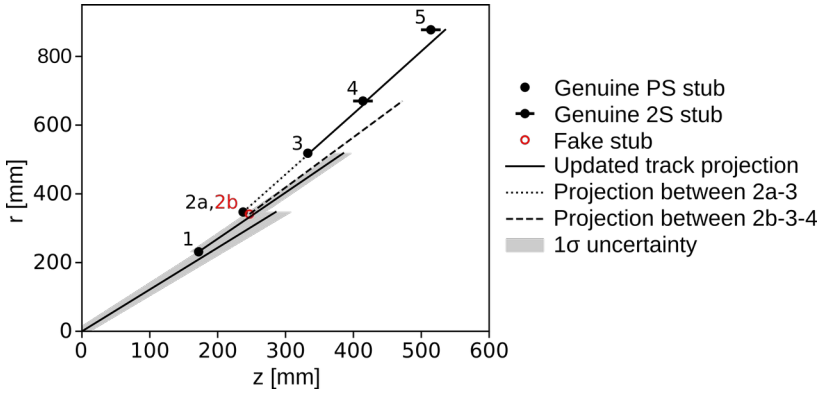
Duplicate Tracks Formation

Hough Transform



- Due to resolution effects ~40 % of track candidates are duplicates
- Every cell in the HT is independent from the others
- A “pair-wise” comparison of tracks in search for stubs in common was developed but not optimal

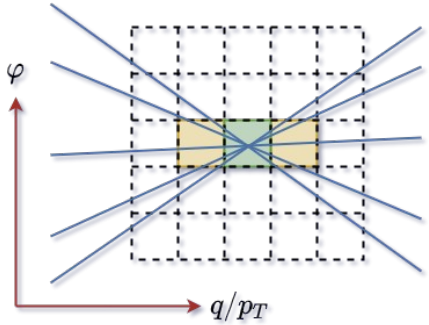
Kalman Filter

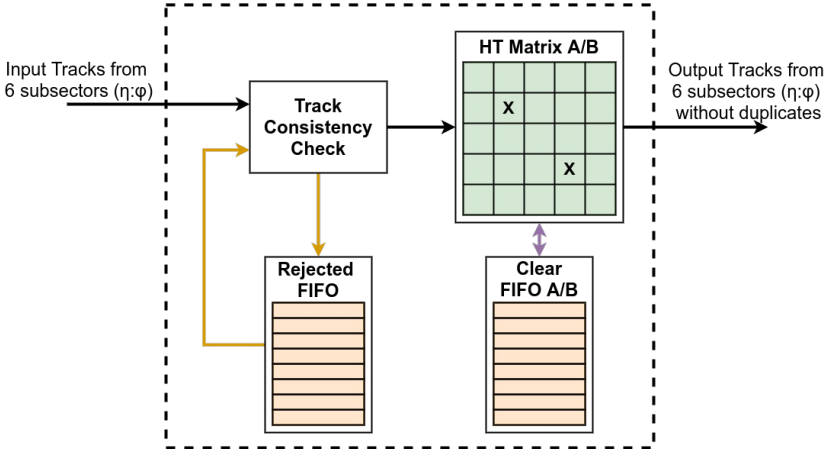


- Able to remove fake stubs and refine the projection
- Not able to remove duplicated tracks
- ~50 % output tracks are duplicates

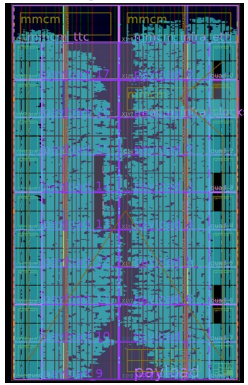
Duplicate Removal

	Track 1 StubID		Track 2 StubID
L1	15	↔	15
L2	36	↔	36
L3	58	↔	62
L4	78	←	--
L5	90	↔	101
L6	124	↔	124

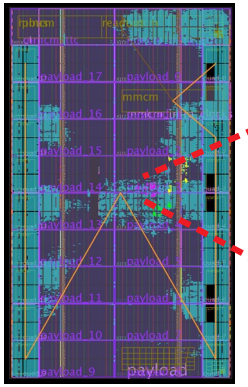


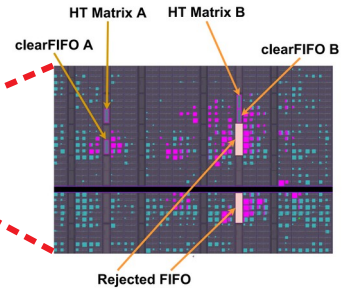


Pair-wise Comparisons



Based on HT-space



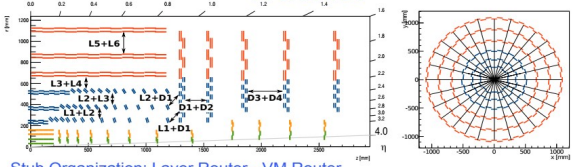


- Looks only at a single track
- It uses only 1 % of the resources used for the pair-wise comparison approach (V7-690)
- Contributes to the latency with only four clock cycles ~17 ns
- Remove duplicates without losing efficiency

Reconstruction Algorithms

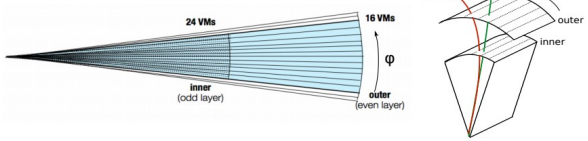
Data Flow

Tracklet



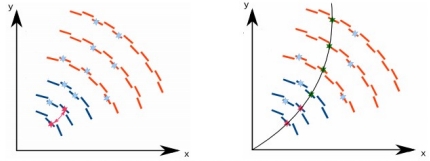
Stub Organization: Layer Router - VM Router

Sorts input stubs into each layer/disk and splits processing module into virtual modules (VM)



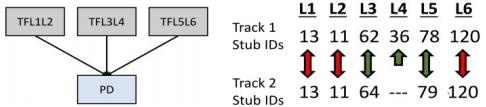
Seeding: Tracklet Engine - Tracklet Calculator

Forms a tracklet from pairs of stubs in adjacent layers according to the VMs, then calculates exact tracklet parameters for each pair



Projections and fitting: Match Engine/Calculator & Linearized χ2 fit

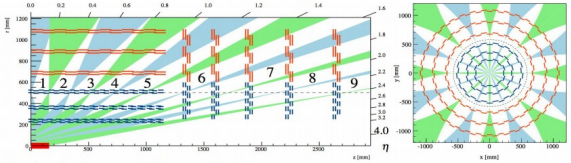
Looks for stubs within a window around the projected track and fits it



Duplicate Removal

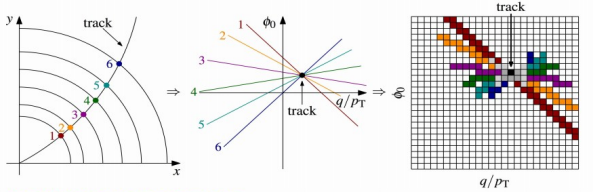
Compares tracks pairwise and eliminates those with less than 3 unique stubs

TMTT



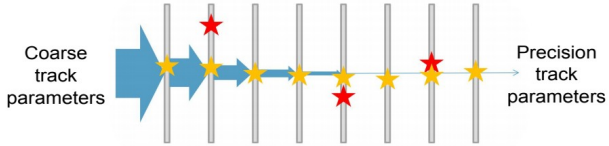
Sector Assignment: Geometric Processor

Processes stub data, and sub-divides the nonant into 36 finer sub-sectors



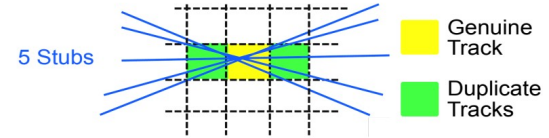
Track Finding: Hough Transform

Track finder that identifies groups of stubs consistent with a track in the r-φ plane



Track Fitting: Kalman Filter

A candidate cleaning and precision fitting algorithm



Duplicate Removal

Uses precise fit information to remove duplicate tracks generated by the HT