An FPGA-Based Track Finder for the L1 Trigger of the CMS Experiment at the High Luminosity LHC

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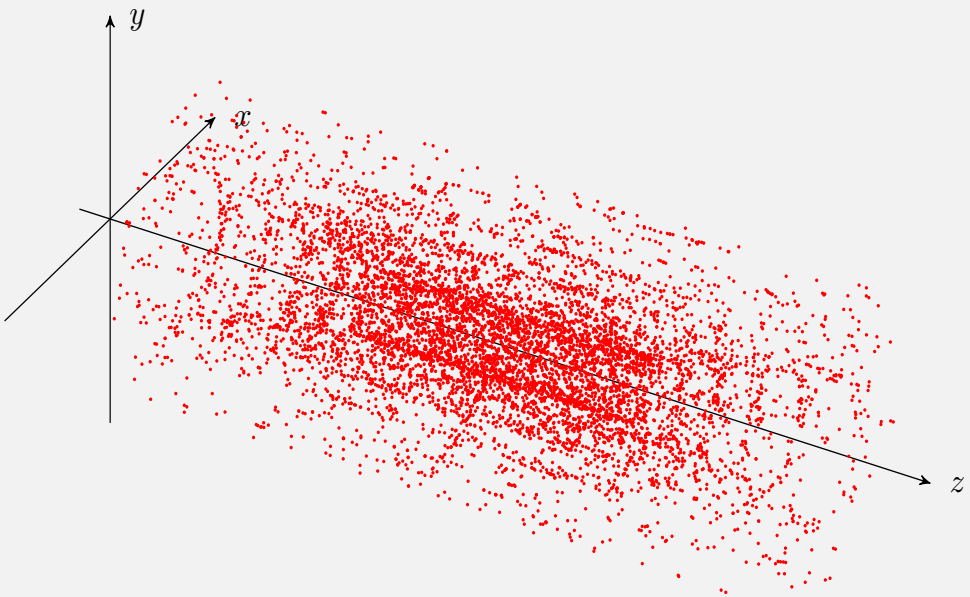
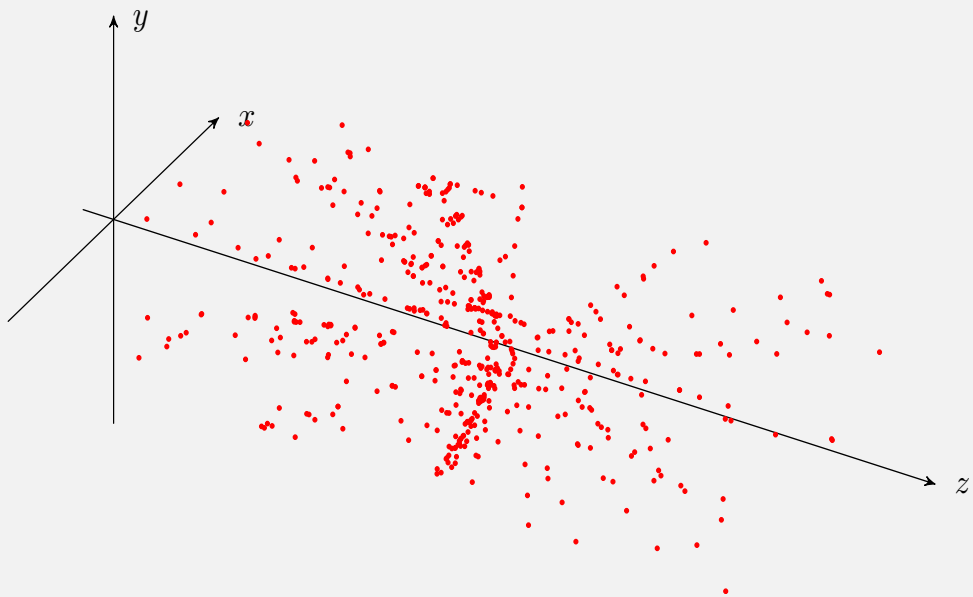
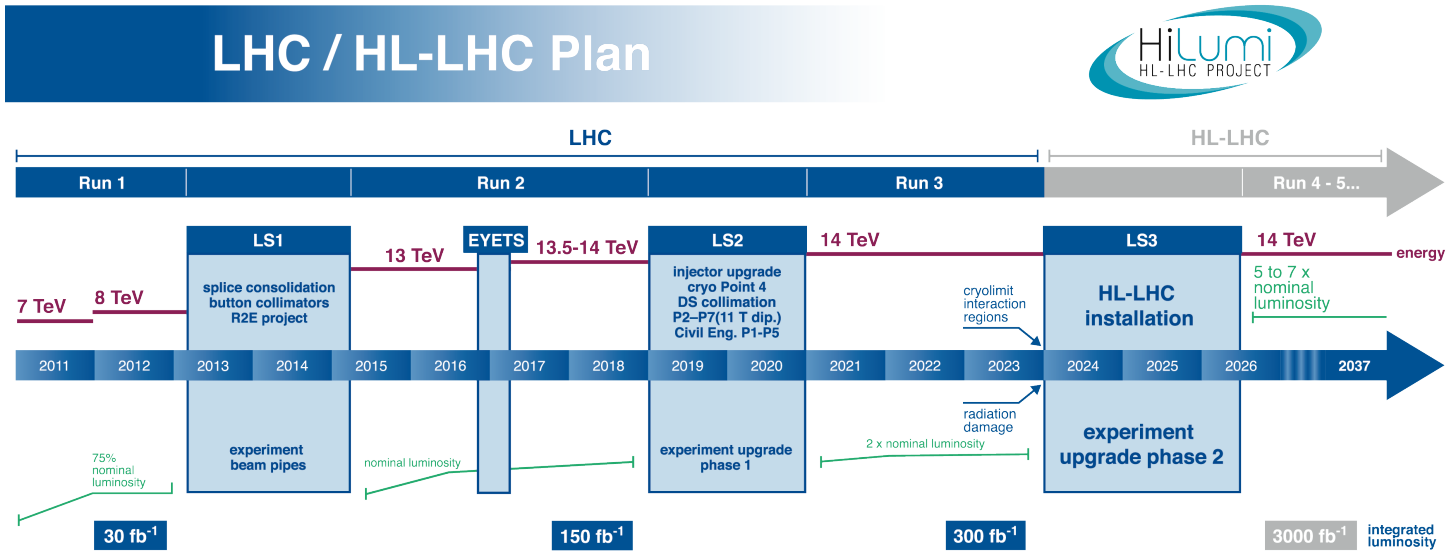
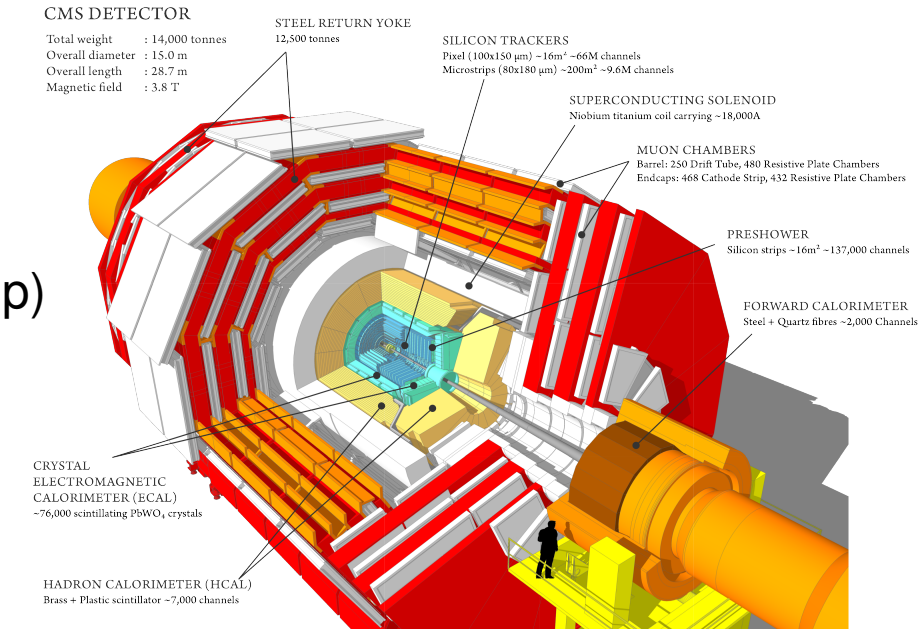




High Luminosity LHC

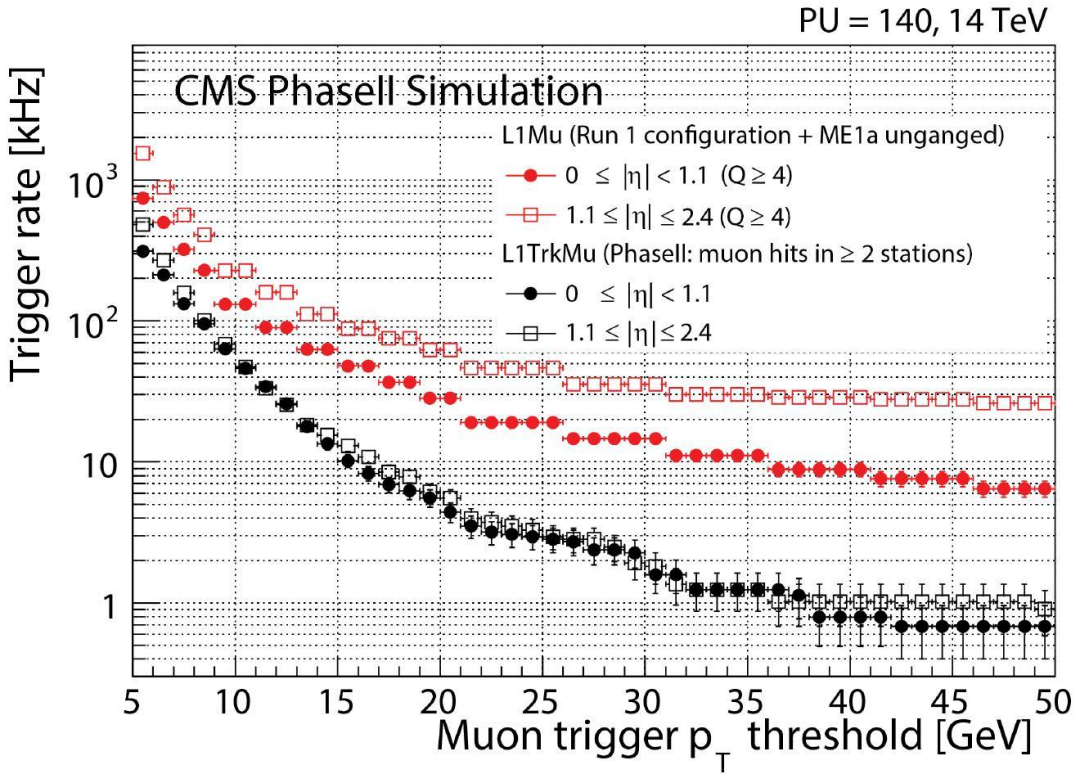


- HL LHC starts 2026
- 5 to 7 times nominal luminosity
  - but same collision frequency
  - up to 200 collisions in one event (pile-up)
- massive challenge for L1 trigger of CMS
  - $\sim$ 100 Tb/s input bandwidth
  - reduction from 40 MHz to 750kHz
  - within 12.5 µs



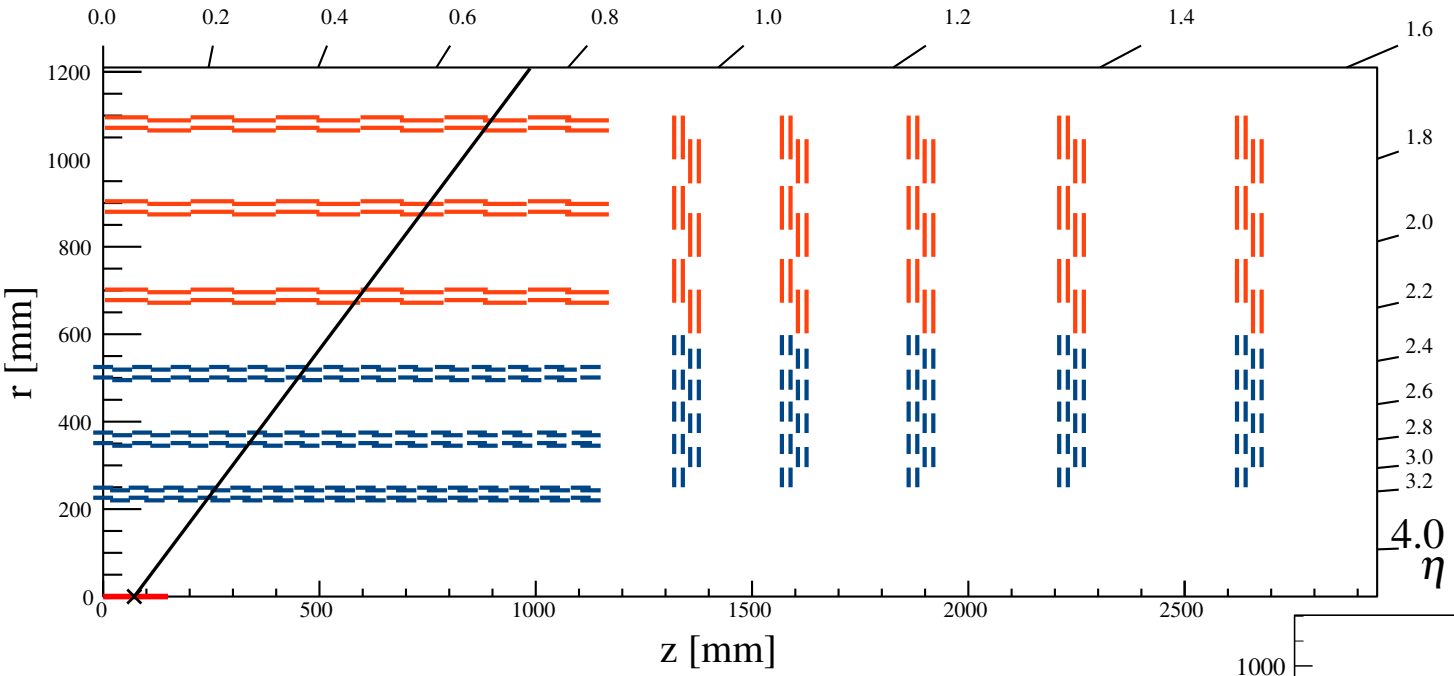
Track Trigger Motivation

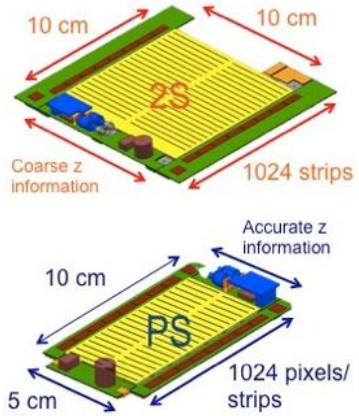
- current L1 trigger uses information from calorimeters and muon chambers only
- one example: single muon trigger rate under high luminosity conditions



- curve for L1 muons flattens for aimed trigger rates around 14 kHz
- additional tracker information is necessary to retain trigger capability

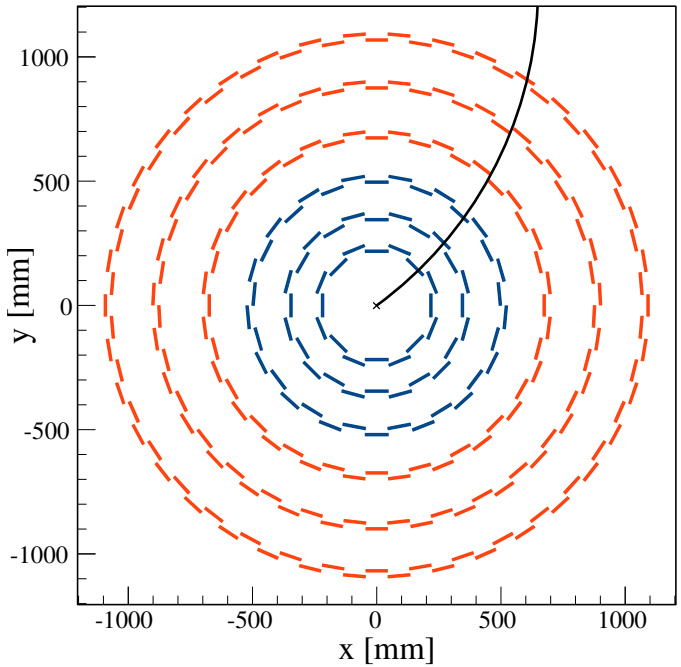
Phase II Outer Tracker



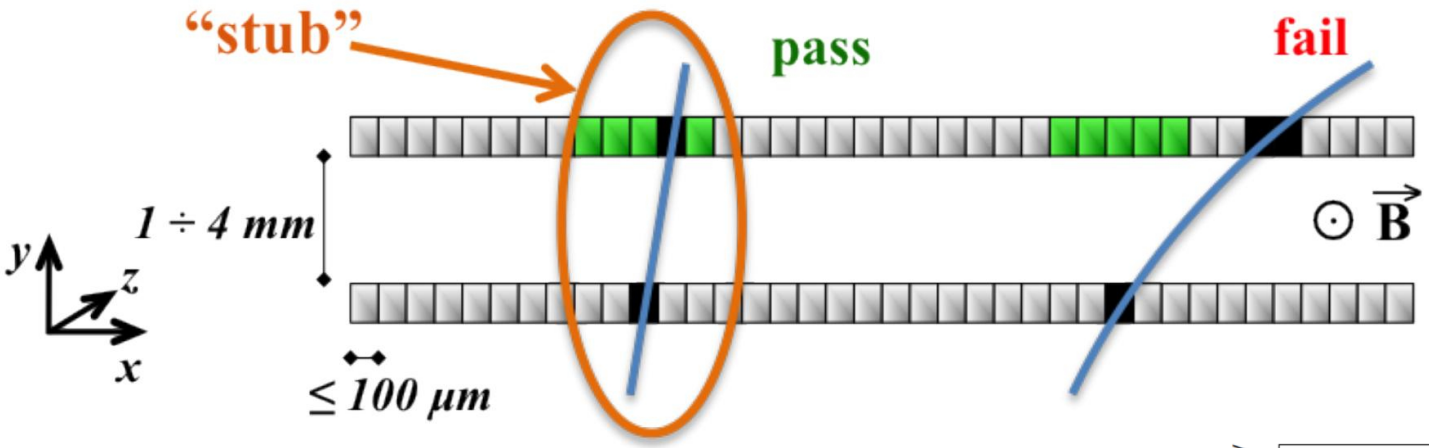


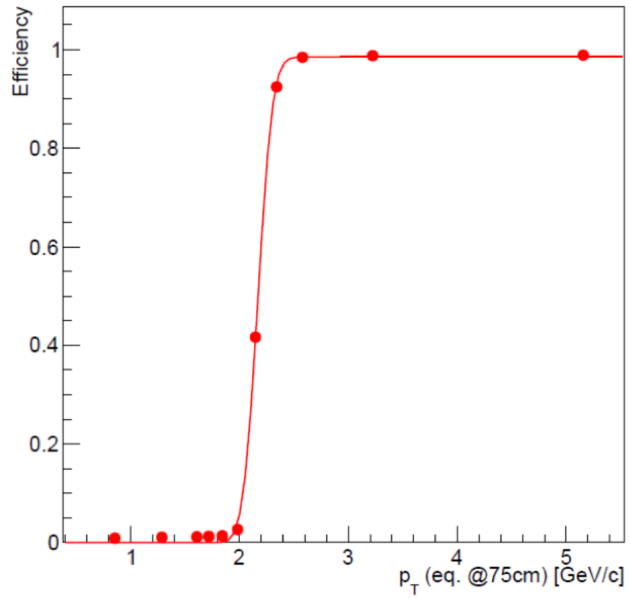
- tracks are straight in *r*-*z* & bent in *r*-ϕ

- 15 354 sensor modules, 260 million channels, 216 m^2 sillicon
- 6 barrel layers in the center and 2×5 endcap disks
- two types of stacked sensor modules:
  - strip-strip (5 cm×90 µm)
  - pixel-strip (1.6 mm / 2.5 cm×100 µm)
- constructed to enable L1 tracking above 2-3 GeV



Stubs

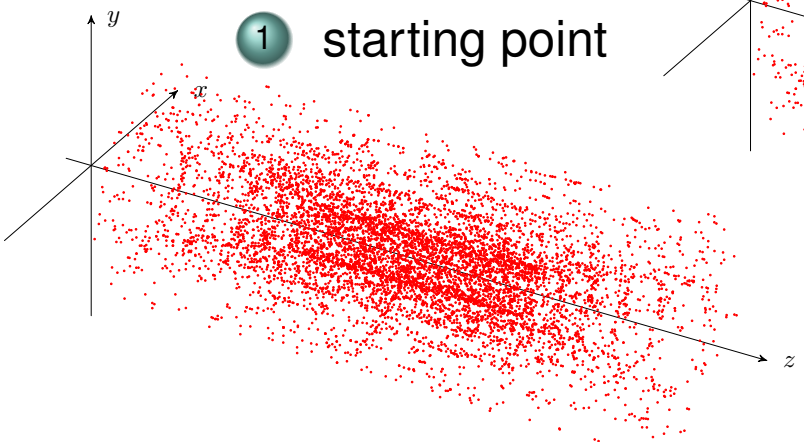




- "p_{T} module" is first stage of data reduction
- rough p_{T} estimation possible
- cut at 2-3 GeV leads to a reduction factor of ~ 10
- outer tracker data volume out ~ 20 k stubs @ 40 MHz (~ 25 Tbps)

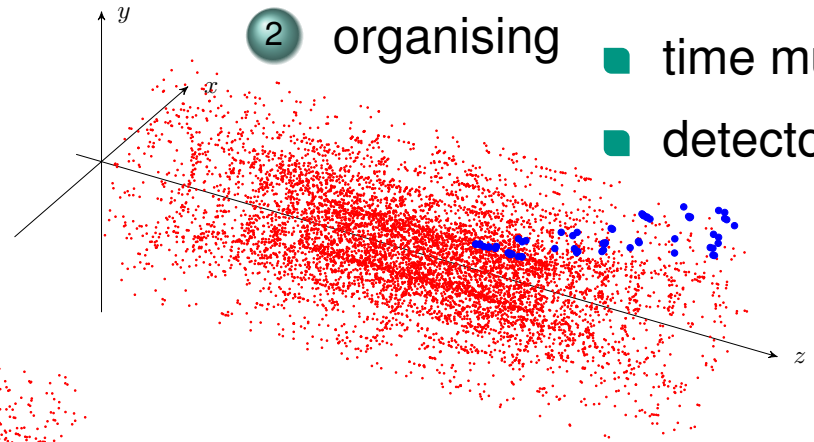
Tracking Concept

1 starting point

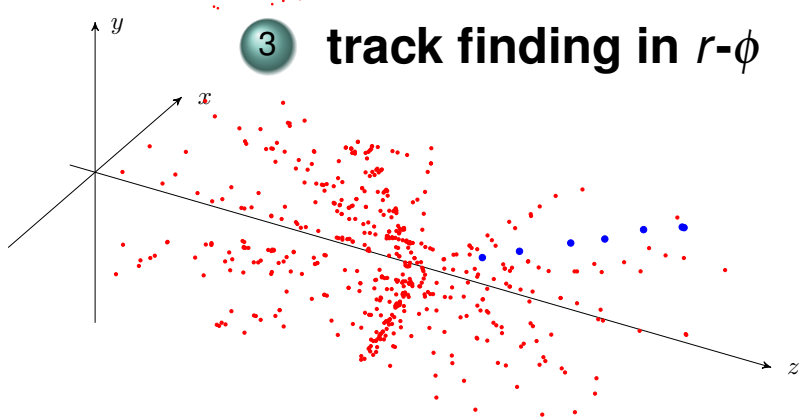


2 organising

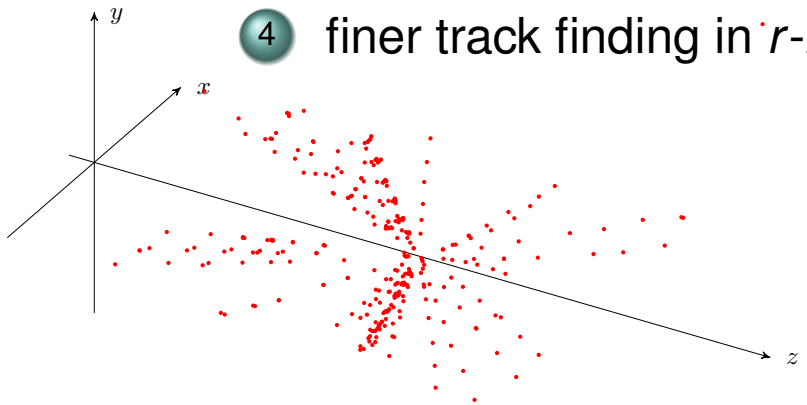
- time multiplexing (36)
- detector segmentation (288)



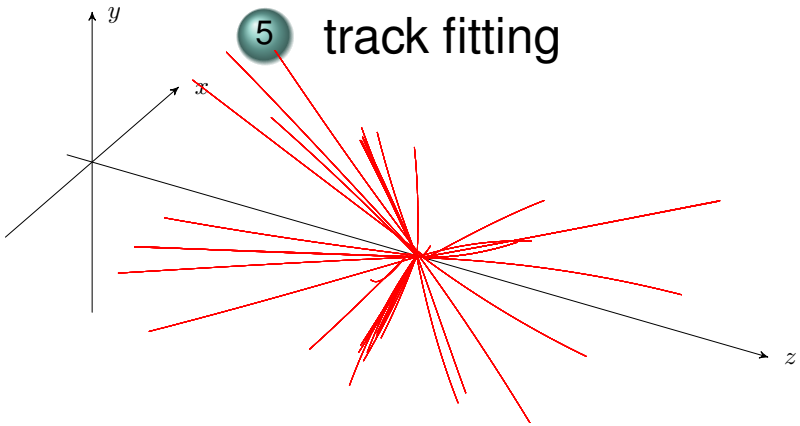
3 **track finding in r-ϕ**



4 finer track finding in r-z

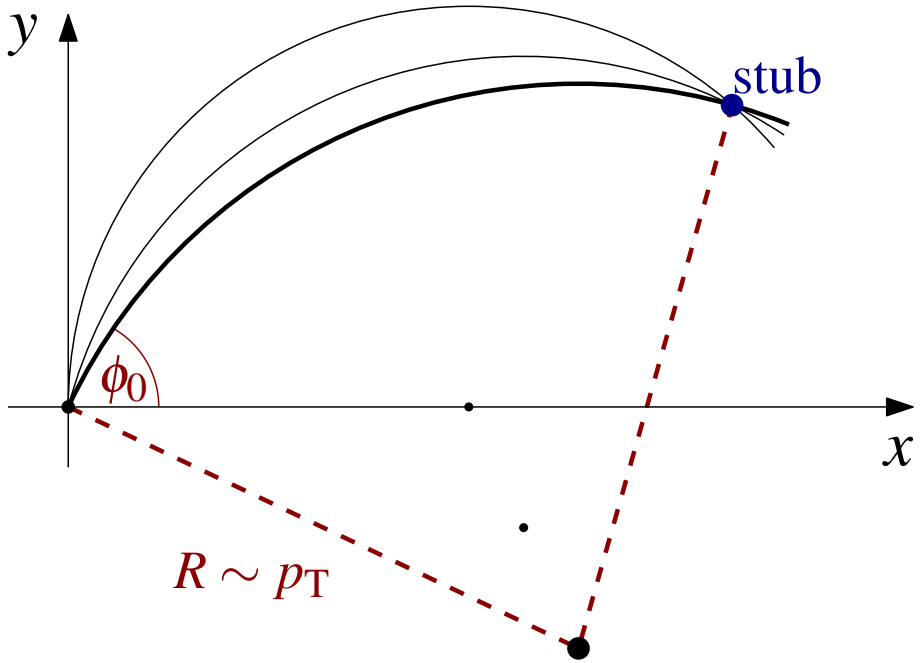


5 track fitting



Hough Transform – Theory

- search for primary tracks in the r-ϕ plane
- infinite amount of different circles (ϕ_0, R) possible between origin and single measured stub position (r, ϕ)

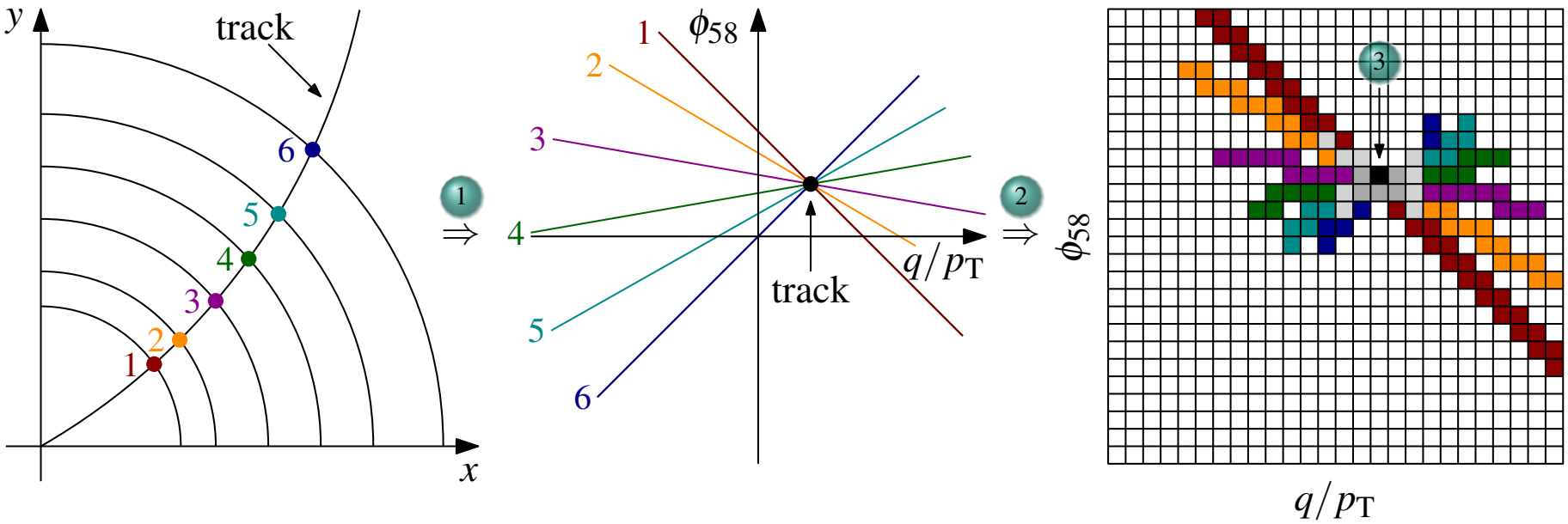


- but track parameters are correlated

$$\phi_{58} \approx \phi + \frac{q}{p_T} \times r_{58} \qquad (\phi_{58} \text{ and } r_{58} \text{ are slightly transformed variables})$$

- **stub positions corresponds to straight lines in the track parameter plane**

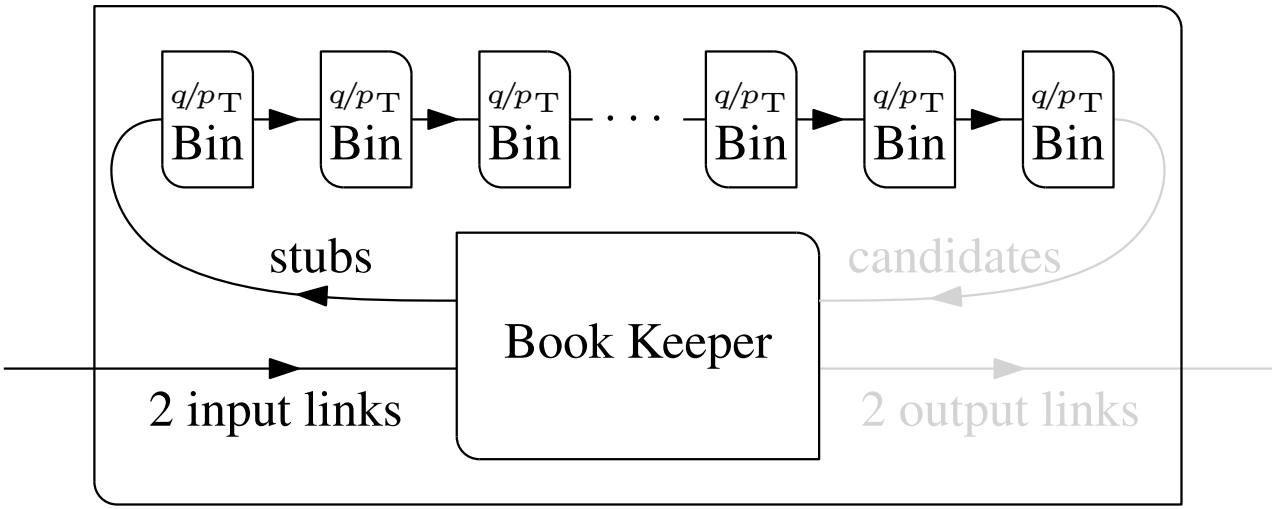
Hough Transform – Algorithm

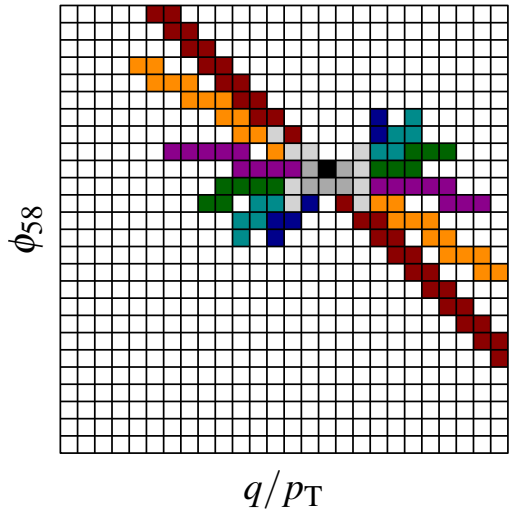


1. for each stub calculate ϕ_{58} for each q/p_T
2. fill the stub into corresponding cells of a 32×32 track parameter array
   - ignore q/p_T values which are inconsistent with the p_T estimate of the stub
3. define cells with stubs from at least 5 different layers as track candidates

FPGA-Based HT Implementation – Overview

- each detector segment will be processed by one array
- array is implemented as a pipeline, it processes one stub per clock cycle (240 MHz)
- first step is the filling of the array
- second step is the readout of track candidates





- Book Keeper unpacks stub data from 2 input links, which then propagate to each of the 32 q/p_T Bins in turn
- track candidates found by the Bins propagate back to the Book Keeper, which transmits them over two links

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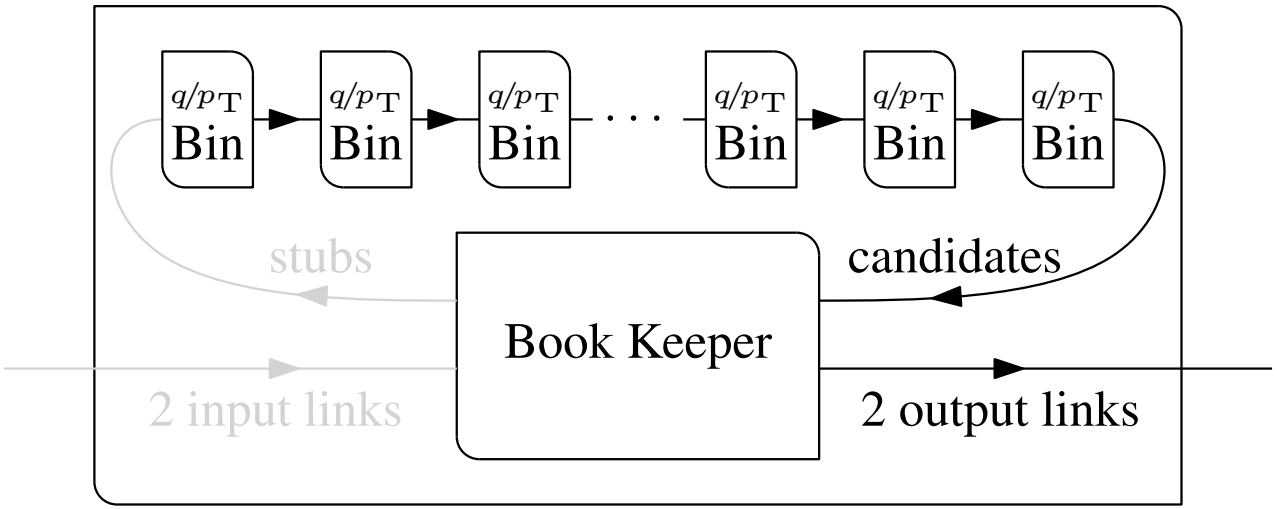

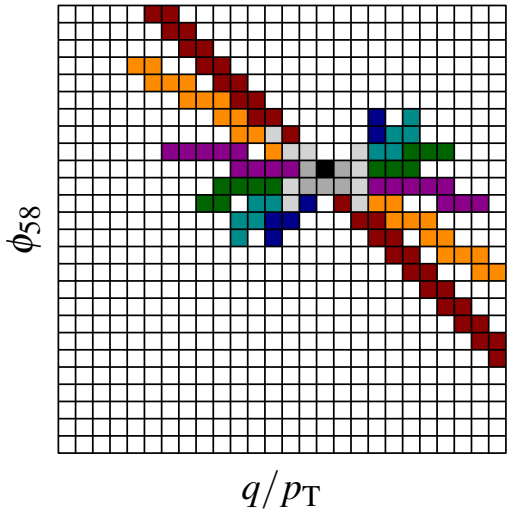

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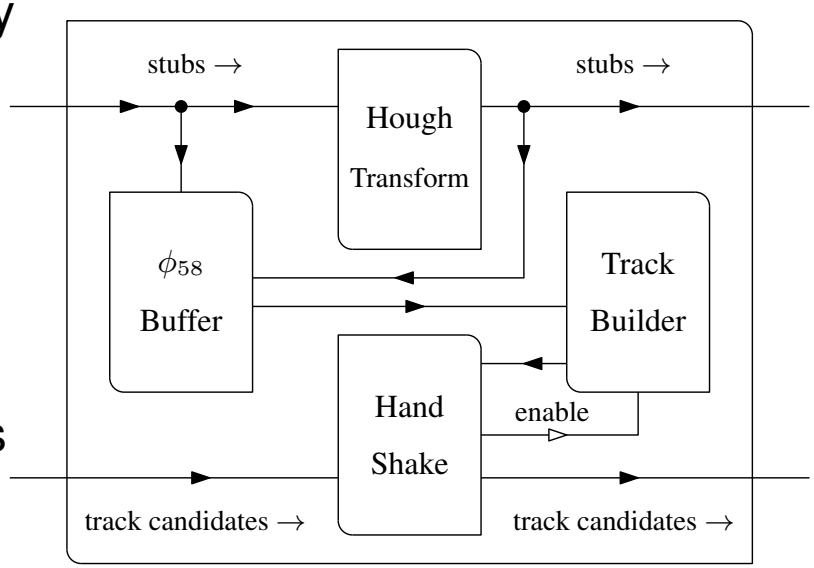
FPGA-Based HT Implementation – Bin

- each Bin represents a q/p_{T} column in HT array



Hough Transfrom

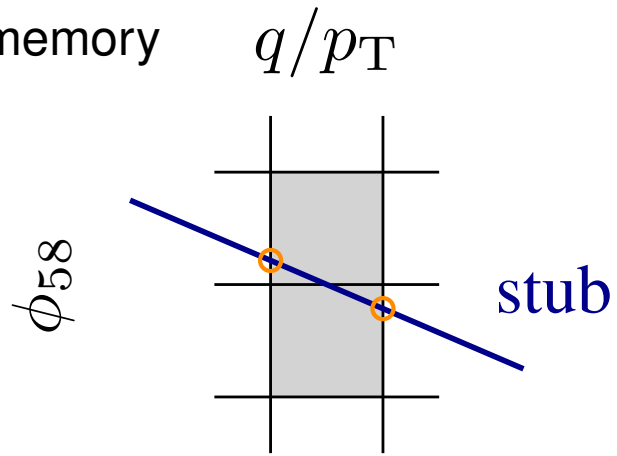
- gets ϕ_{58} at left boundary
- calculates ϕ_{58} at right boundary

ϕ_{58} Buffer

- duplicates a stub when it belongs to two cells
- sends one stub with exactly one ϕ_{58} value

Track Builder

- histograms stubs in ϕ_{58} cells using a segmented memory with a page for each ϕ_{58} value
- marks pages with stubs from at least 5 different layers for read-out

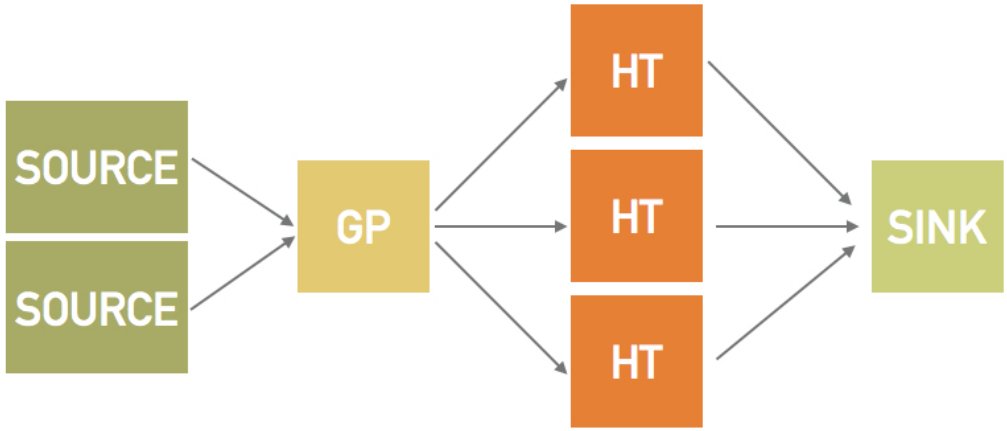


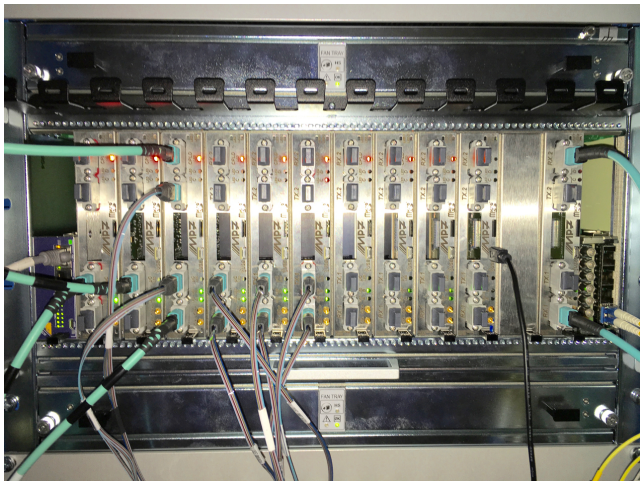
Hand Shake

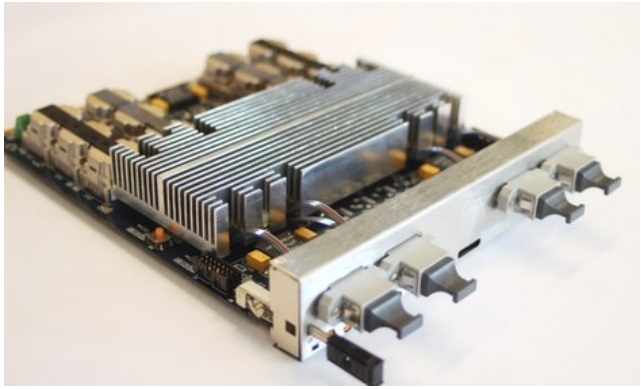
- controls the read-out of track candidates

Hardware Demonstrator

- covers an octant in ϕ of the tracker, subdivided in 36 detector segments (4 ϕ × 9 η)
- processes each 36th event (time multiplexing)

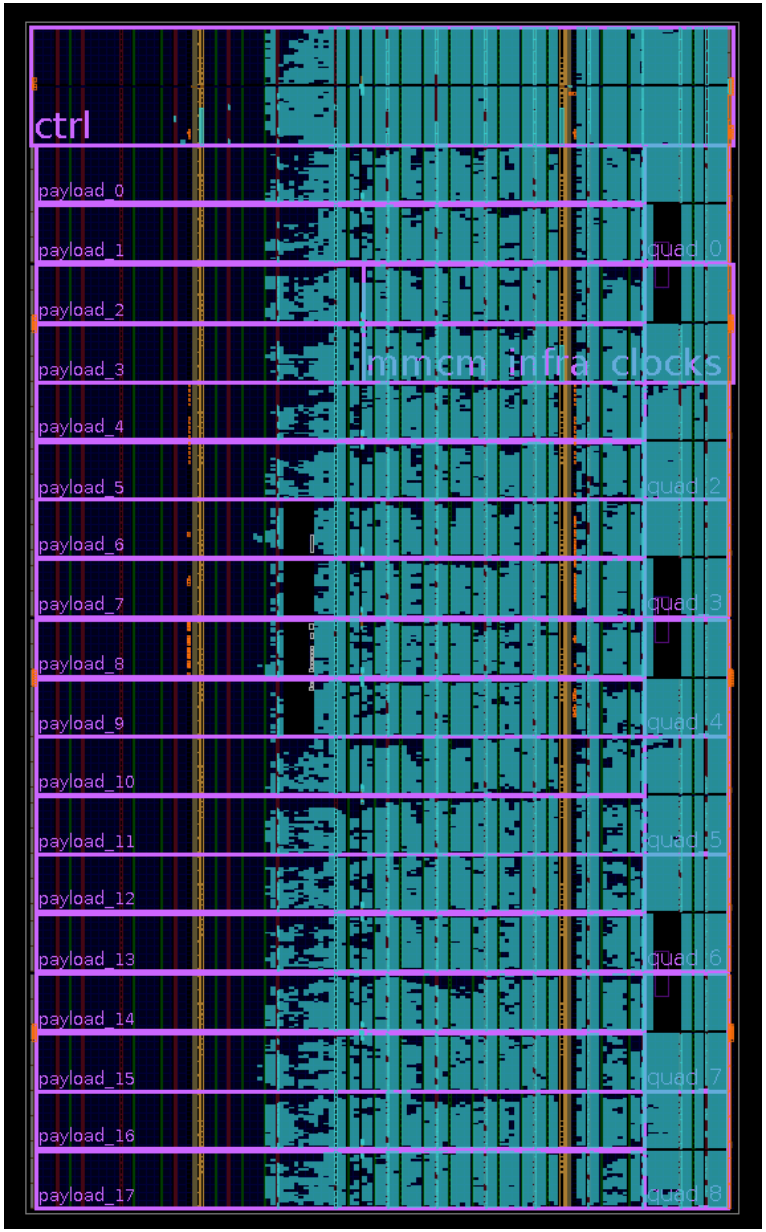




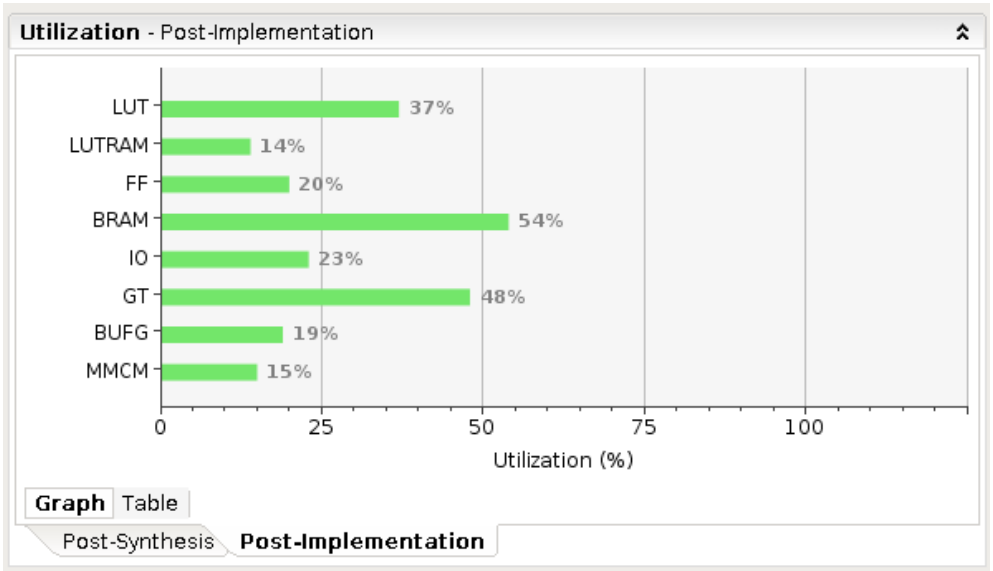


- each block corresponds to a MP7 board:
  - mTCA
  - Virtex 7 690 FPGA
  - 72 I/O fibers up to 12.5 Gbps each
- Source emulates the front-end
- Geometrical Processor (GP) multiplex stubs in η and ϕ segments
- HT boards perform the Hough Transformation

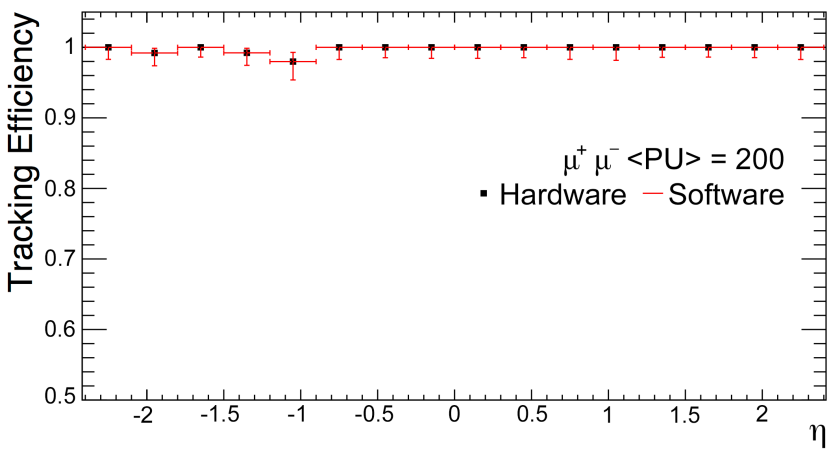
Floorplan & Utilization of one HT MP7

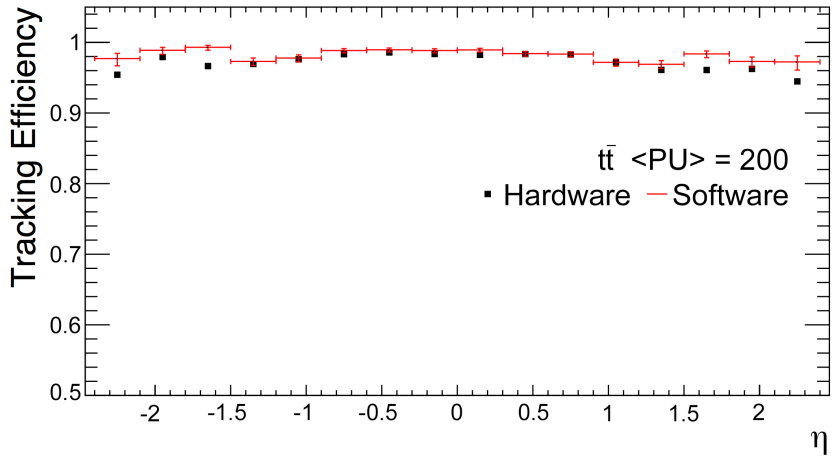


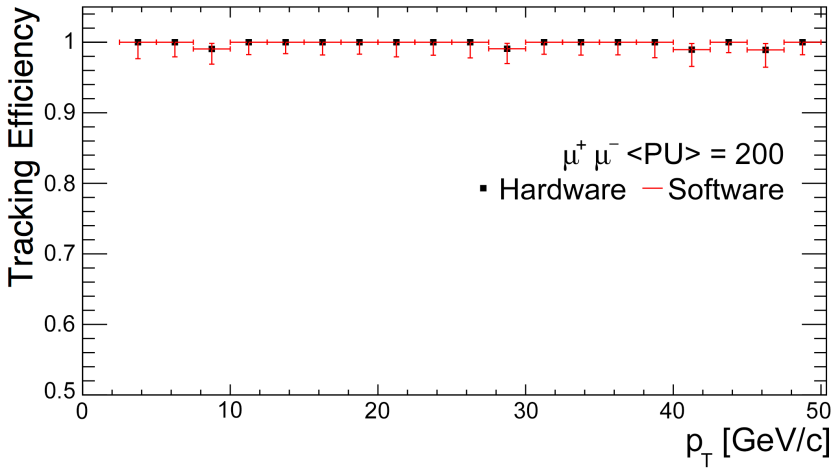
- one octant contains 36 segments (4 in ϕ and 9 in η)
- 18 HT arrays implemented in one MP7 board
- at least 2 MP7's needed

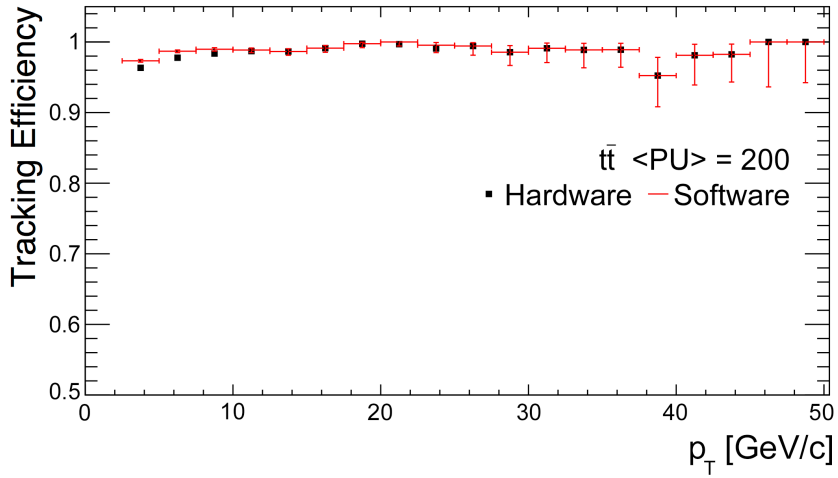


Hough Transform – Results



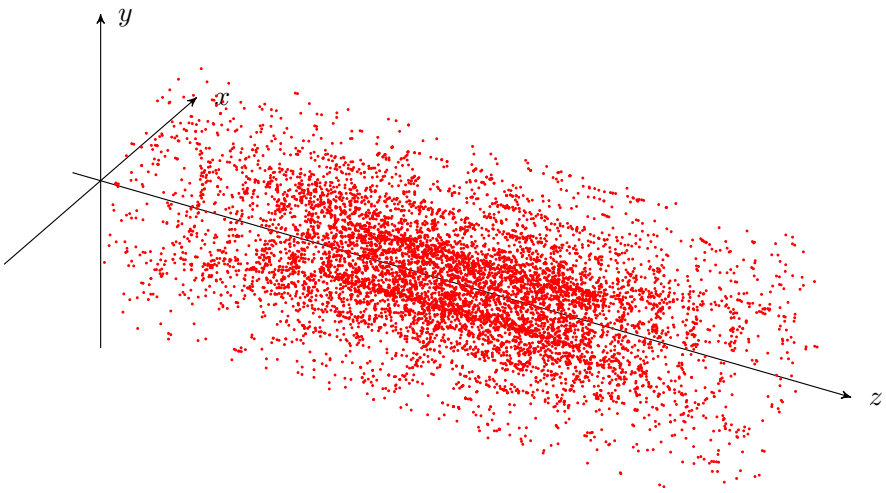


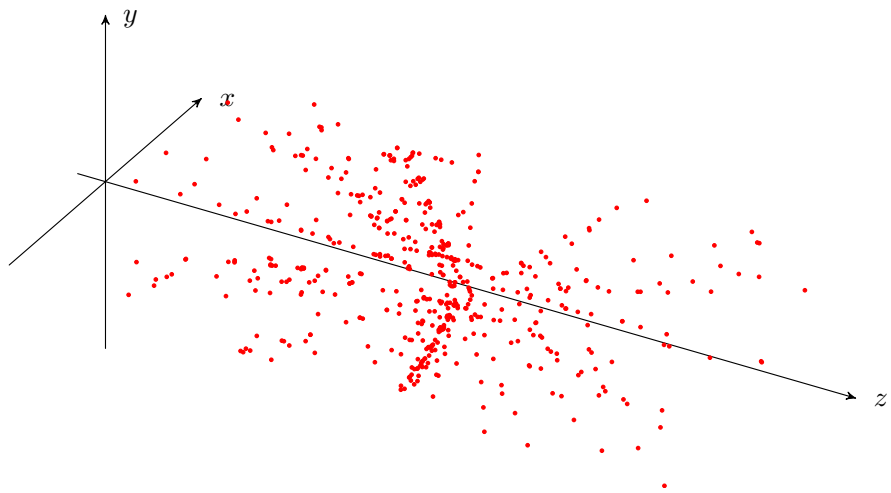




- high tracking efficiency
- good agreement between s/w and h/w

Hough Transform – Results





- data reduction by one order of magnitude
- latency of the HT measured at 1.092 µs
- total algorithmic latency (HT + GP) measured at 1.372 µs
- total latency from Source to Sink including serdes and links measured at 1.855 µs
- well in 4 µs budget for track reconstruction

Summary

- high luminosity conditions present a challenge for the trigger
- CMS plans to reconstruct tracks at first trigger level
- L1 tracking is a completely new handle, never done before
- ability to perform L1 track finding under high luminosity conditions has been demonstrated with current technology
- high track finding efficiency within 1.5 µs achieved using the Hough Transformation
- track filtering using *r*-*z* information and track fitting are in progress