HL-LHC Upgrades and the Track Trigger

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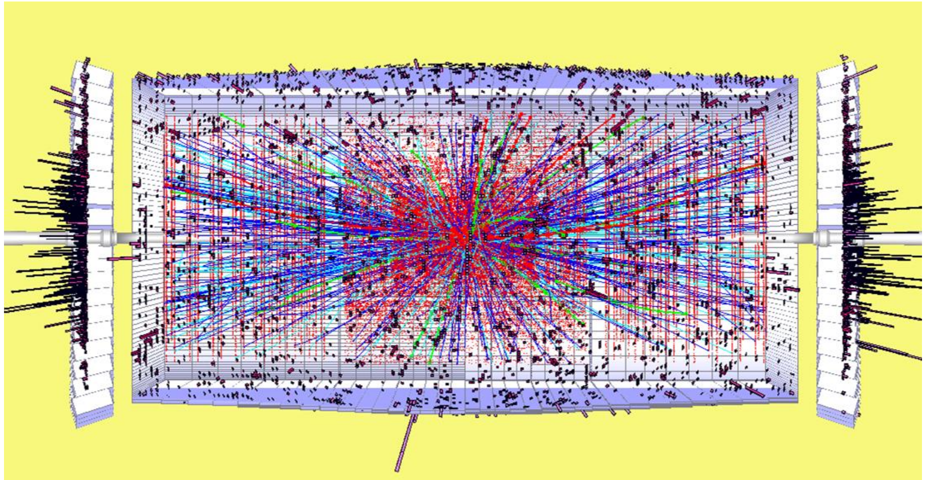
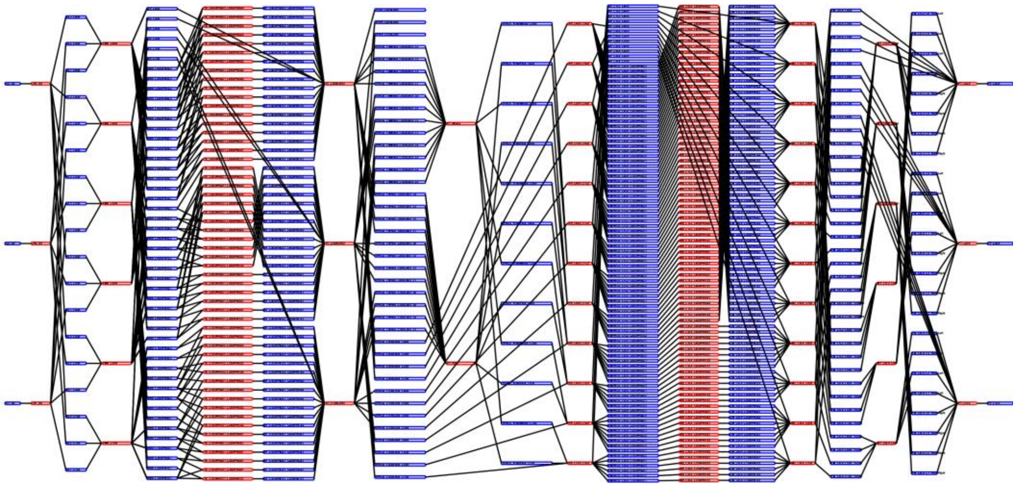
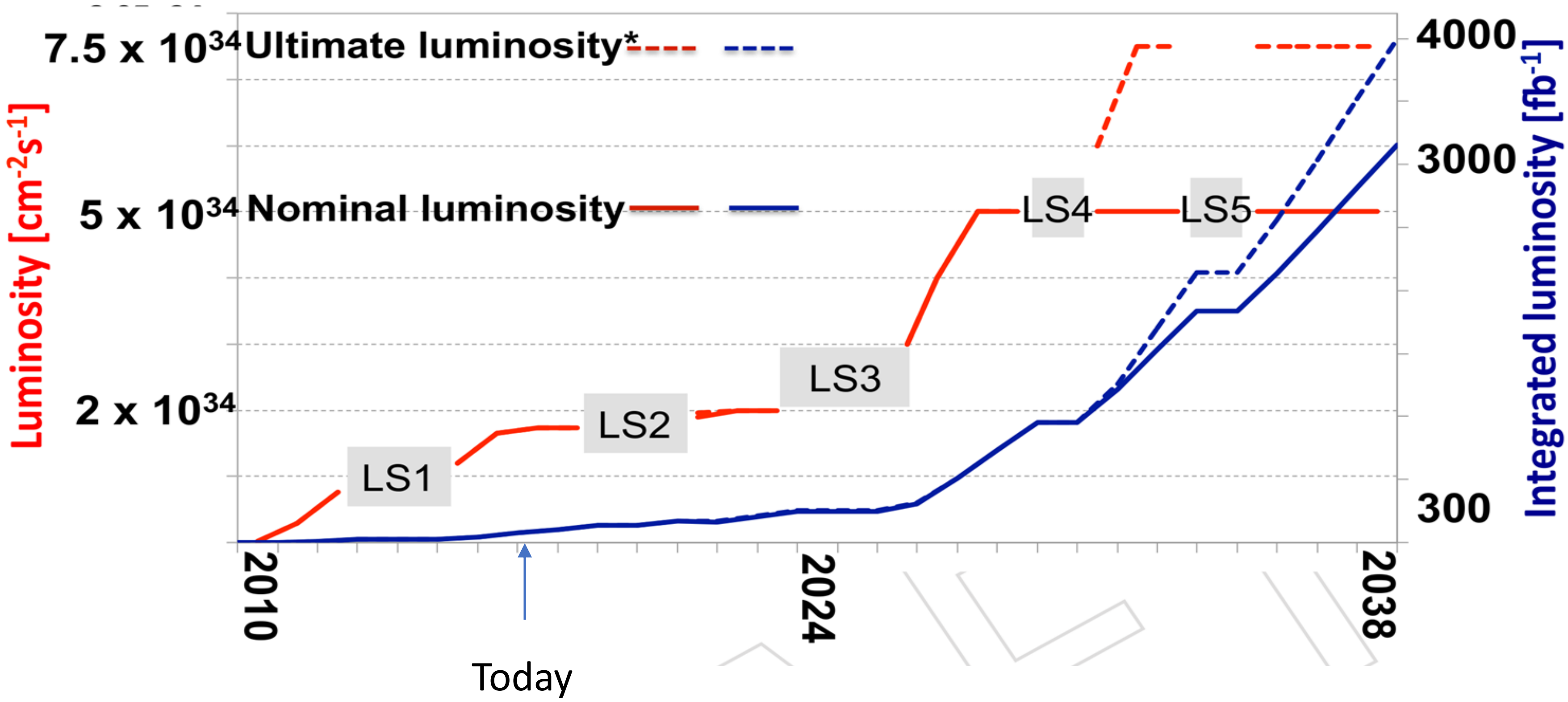
Dec. 13, 2016





Upgrades to the LHC

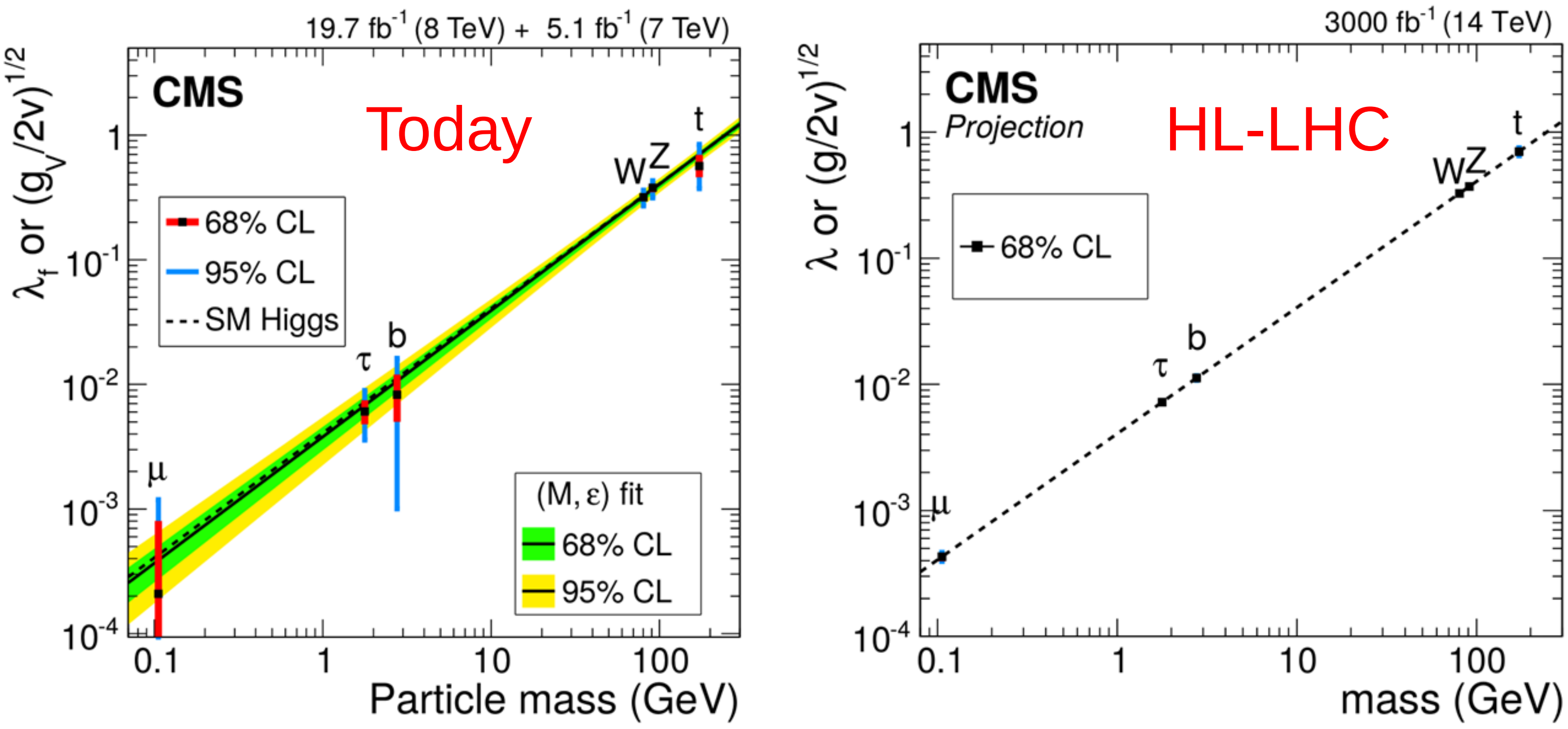
- High Luminosity LHC: 200 proton-proton interactions every 25



While taking data now we are also preparing for the future

Higgs Studies @ HL-LHC

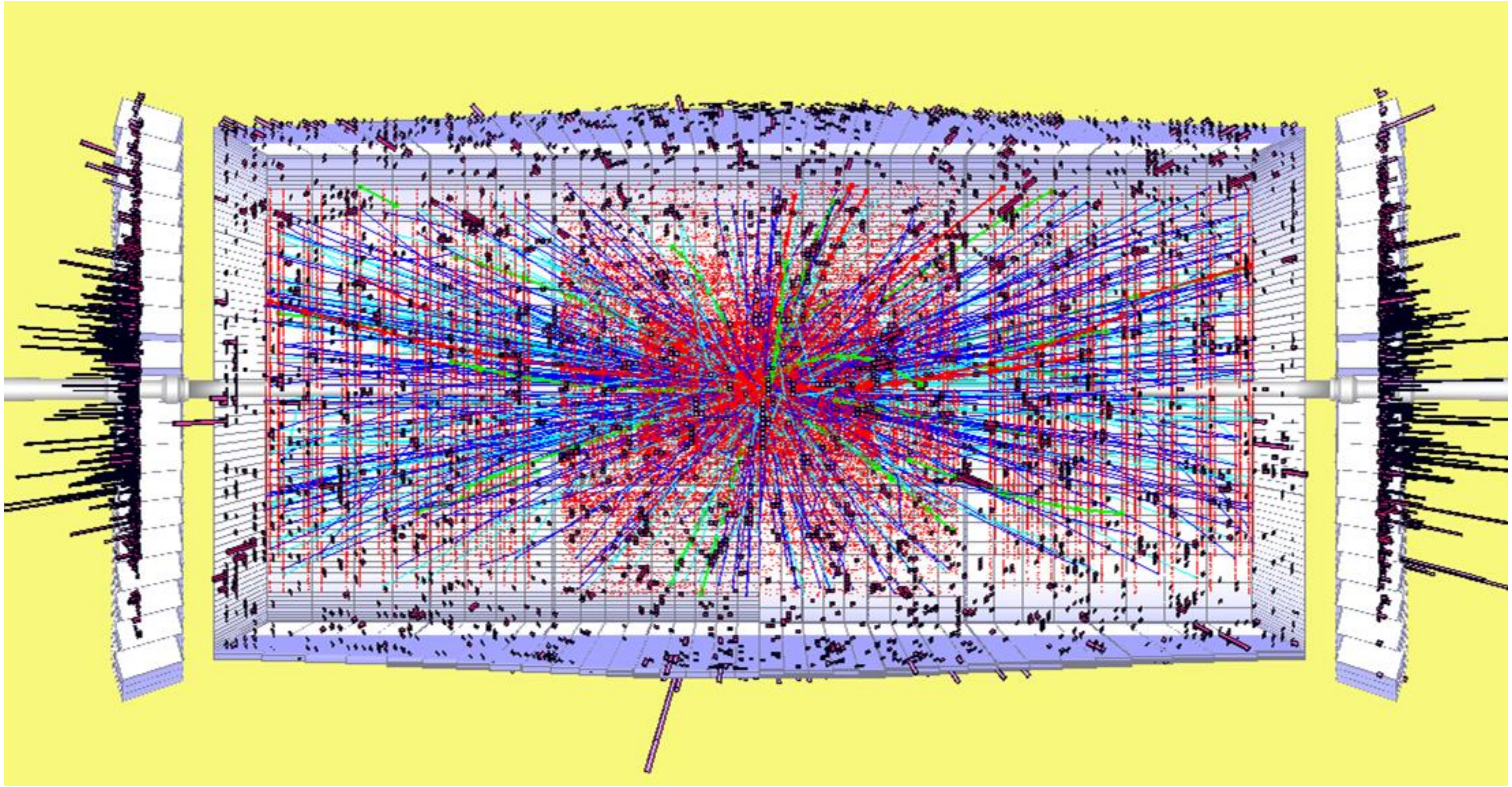
- Detailed exploration of the Higgs discovered during Run 1 is one of the main motivations, e.g. precise coupling strengths:



Is the Higgs responsible for mass generation?

HL-LHC Challenges

In 2025 the LHC will collide protons at a rate of 140 to 200 proton-proton collisions every 25 ns: ~5-8 billion collisions a second!



Radiation hardness – survival of detectors

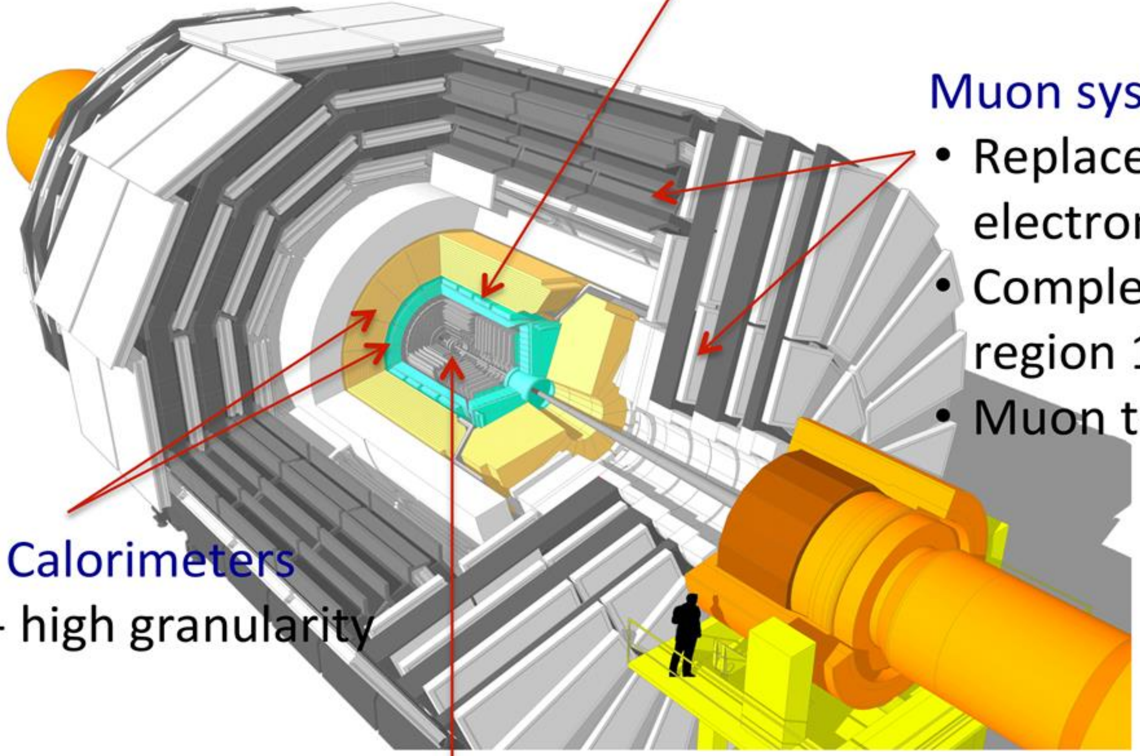
Data rate – data needs to be read out and processed

Performance – resolution, efficiency etc.

Upgrades of the CMS Detector

Trigger/HLT/DAQ
- Track information at L1-Trigger
- L1-Trigger: 12.5 μs latency - output 750 kHz
- HLT output ≃7.5 kHz

Barrel EM calorimeter
- Replace FE/BE electronics
- Lower operating temperature (8∘)



Muon systems
- Replace DT & CSC FE/BE electronics
- Complete RPC coverage in region $1.5 < \eta < 2.4$
- Muon tagging $2.4 < \eta < 3$

Replace Endcap Calorimeters
- Rad. tolerant - high granularity
- 3D capability

Replace Tracker
- Rad. tolerant - high granularity - significantly less material
- 40 MHz selective readout (Pt≥2 GeV) in Outer Tracker for L1-Trigger
- Extend coverage to η = ~4

Trigger Challenge

Each collision at the HL-LHC generates about 4 MB of data, @ 40MHz this means 160 TB/s – 1 petabyte in 6s. We can not readout or store this amount of data.

Most events are not interesting; we use the trigger to filter out the interesting events. We have to stages:

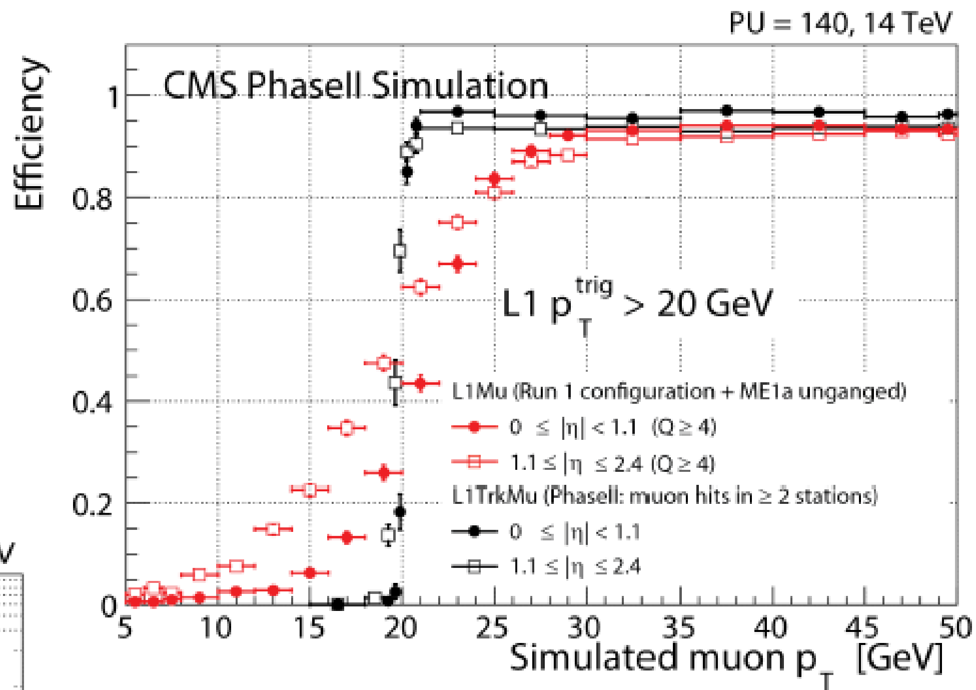
L1 Trigger (40 MHz → 750 kHz) – hardware trigger based on reduced readout of Calorimeter, Muon, and Outer Tracker

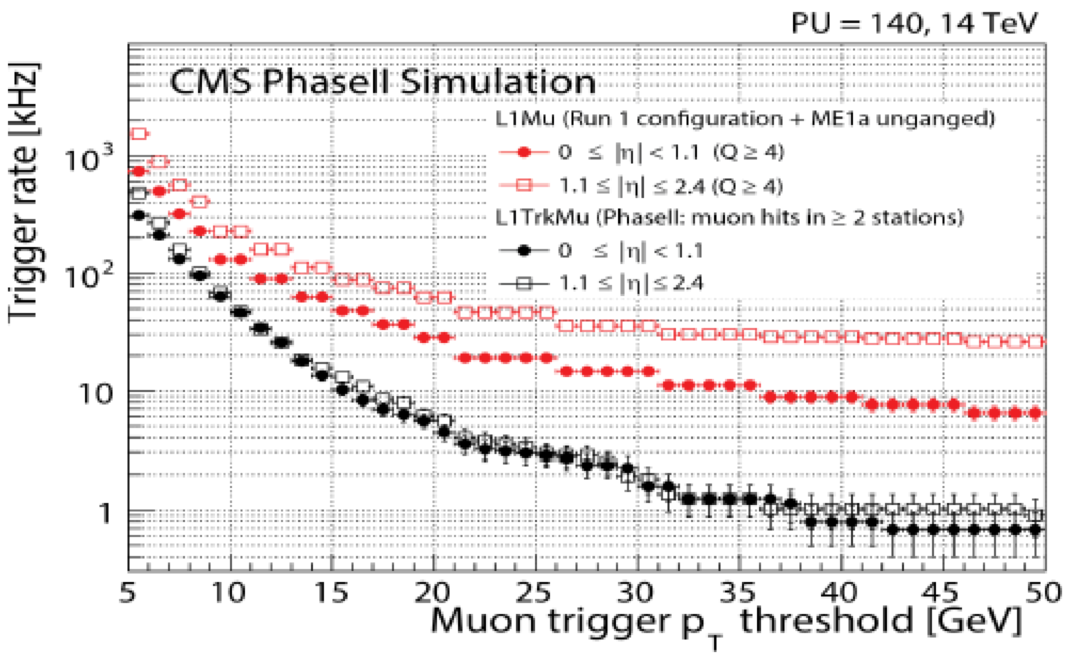
Outer Tracker is new in the L1 Trigger for HL-LHC

High-level Trigger (750 kHz → 7.5 kHz) – Software based trigger with access to full event data

Use of Tracking in the Trigger

- Track matching to muon candidates has high efficiency
- Muons+L1Tracks provide much sharper threshold

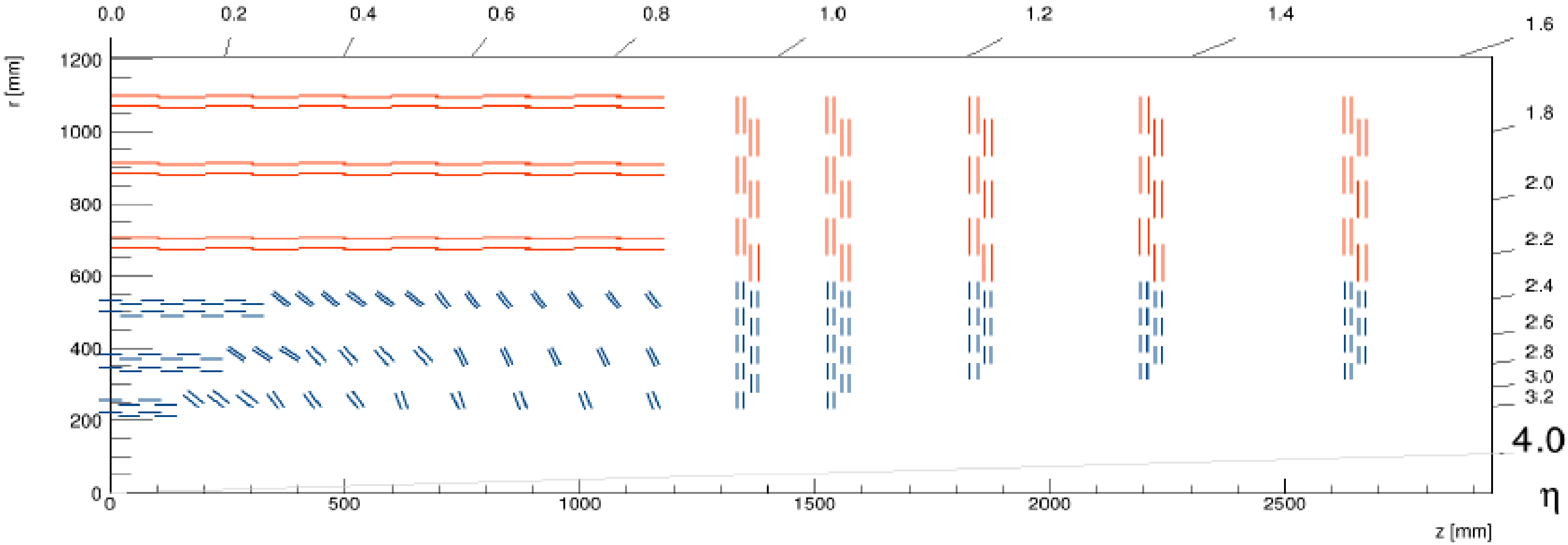




- Sharp threshold allows a significant rate reduction:
  - Factor ~10 reduction @20 GeV

Tracking at L1 is also powerful tool for electrons, taus, jets, photons as detailed in the CMS TP: https://cds.cern.ch/record/2020886

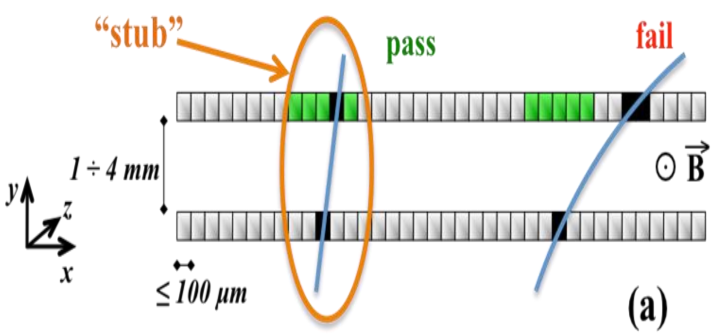
CMS Tracker Trigger



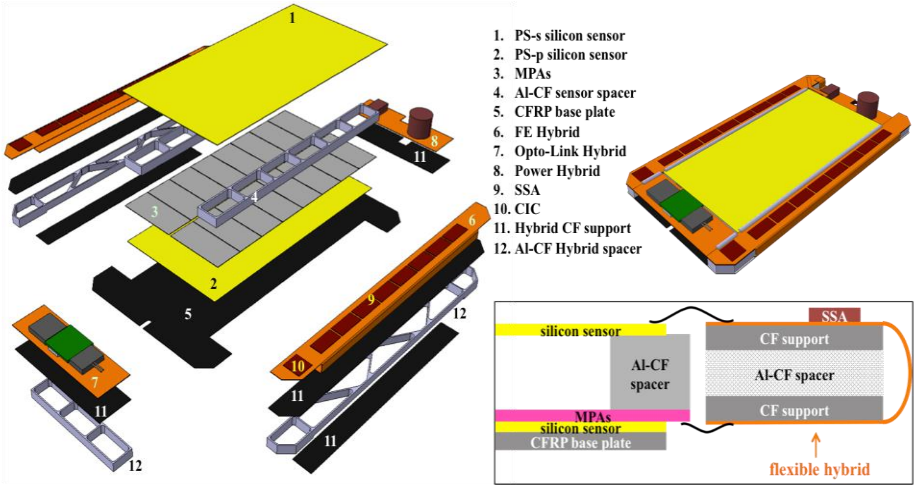
¼ of Outer Tracker

6 Layers

5 Disks



Need O(14,000) Modules
Each module 10 Gbits/s



Reduce data volume to ~100 Tbits/s
About 10,000 stubs every 25 ns (40 MHz)

Challenge: Reconstruct about 200 tracks every 25 ns – within ~4 μs

Track Trigger Goals

The goals of the track trigger are challenging:

- Tracking in full CMS tracking detector ($|\eta|<2.5$)
- Find tracks with p_T>2 GeV
- Process every BX
- Latency <5 μs

A system like this has never been built before (and more challenging than what e.g. ATLAS are planning)

Track Trigger Implementation

Three major R&D projects with different approaches:

- Tracklets - conventional road search
- Time Multiplexed - Hough transform based binning
- Associative Memory - ASIC assisted parallel lookup

The first two of these are based only on processing in FPGAs. These algorithms make use of the processing power in modern FPGA.

The third approach makes use of an ASIC to do the patter finding a CAM (Content Addressable Memory).

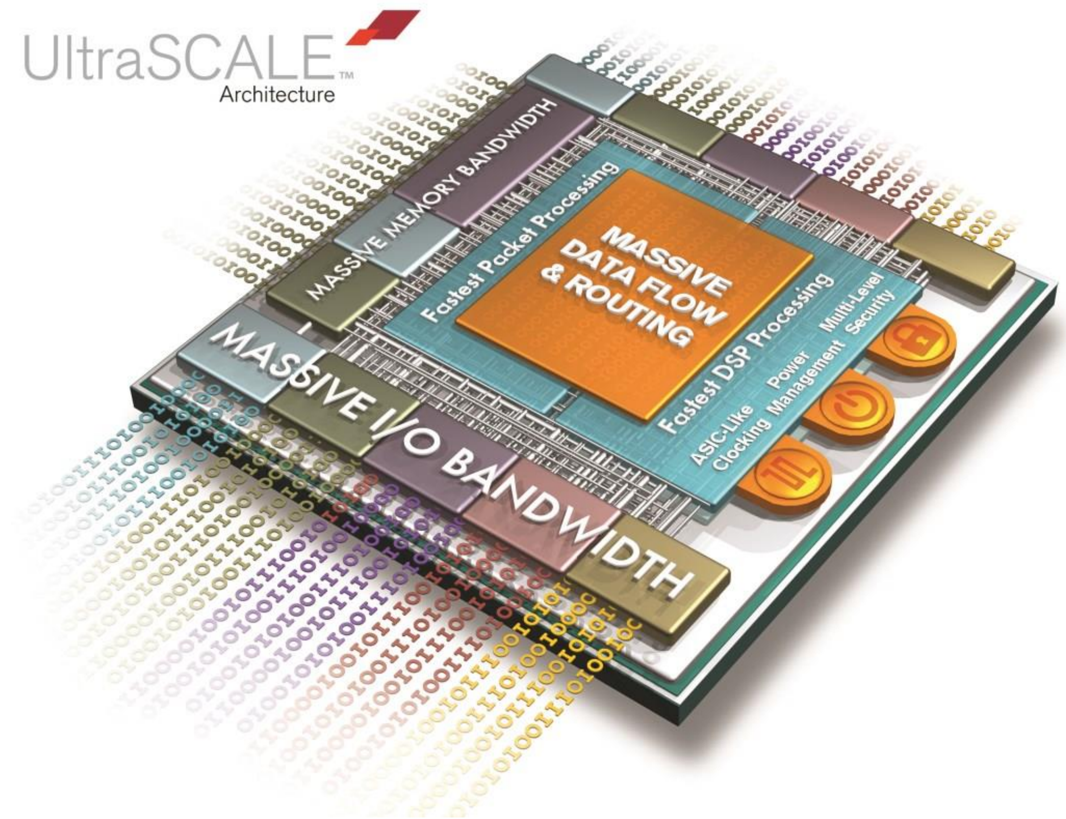
Last week we had a review of these approaches during the tracker upgrade week. All approaches has made great progress and each shown to provide a viable solution.

Field Programmable Gate Array

Most (off-detector) electronics for fast signal processing in HEP is now done using FPGAs

Allows similar performance to ASICs – but the flexibility to be reprogrammed

Performance improvements over the last ~10 years has been remarkable



- 5,000 Digital Signal Processors: >8x10^{12} multiply-and-add per sec
- 120 Transceivers – each up to 33 Gbits/s: 5.8 Tbits/s
- 4,000 18 kbit memory blocks
- 4,000,000 Logic blocks

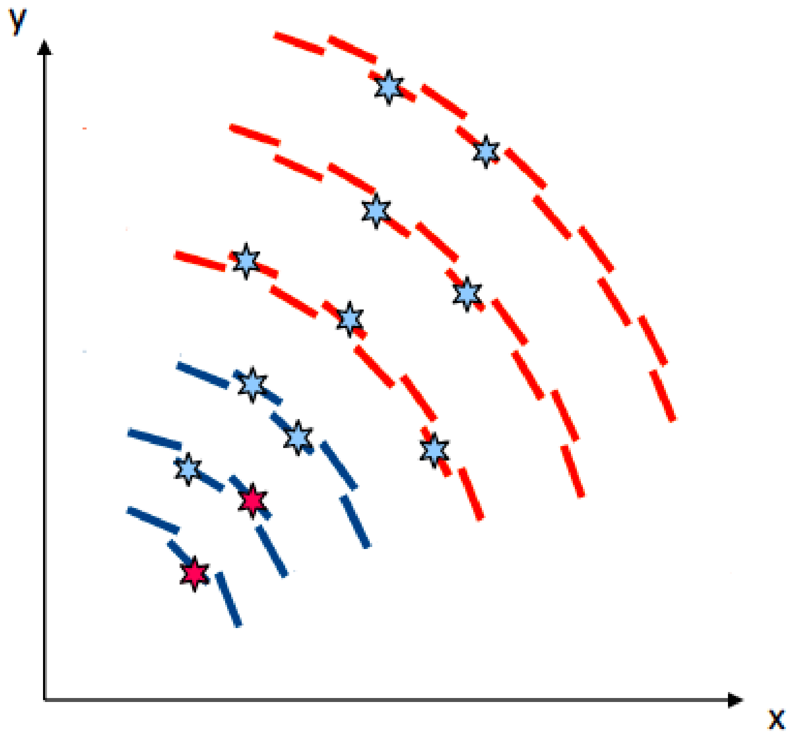
Resources allow us to keep up with HL-LHC data (but cost $$$$)

Tracklet Approach

- I'll show a few slides from the tracklet approch to illustrate the work and challenges that we are addressing

Tracklet Based Track Finding

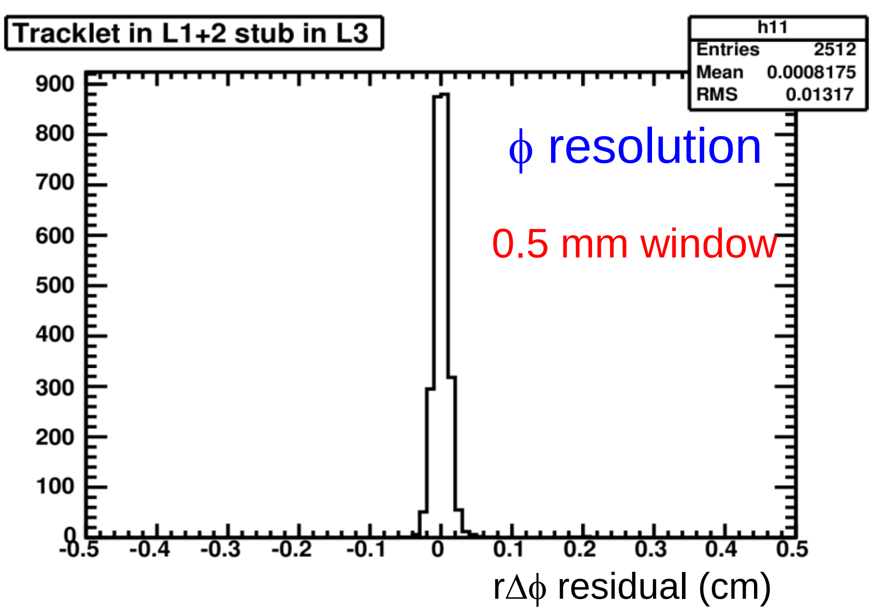
- Form track seeds, tracklets, from pairs of stubs in neighboring layers

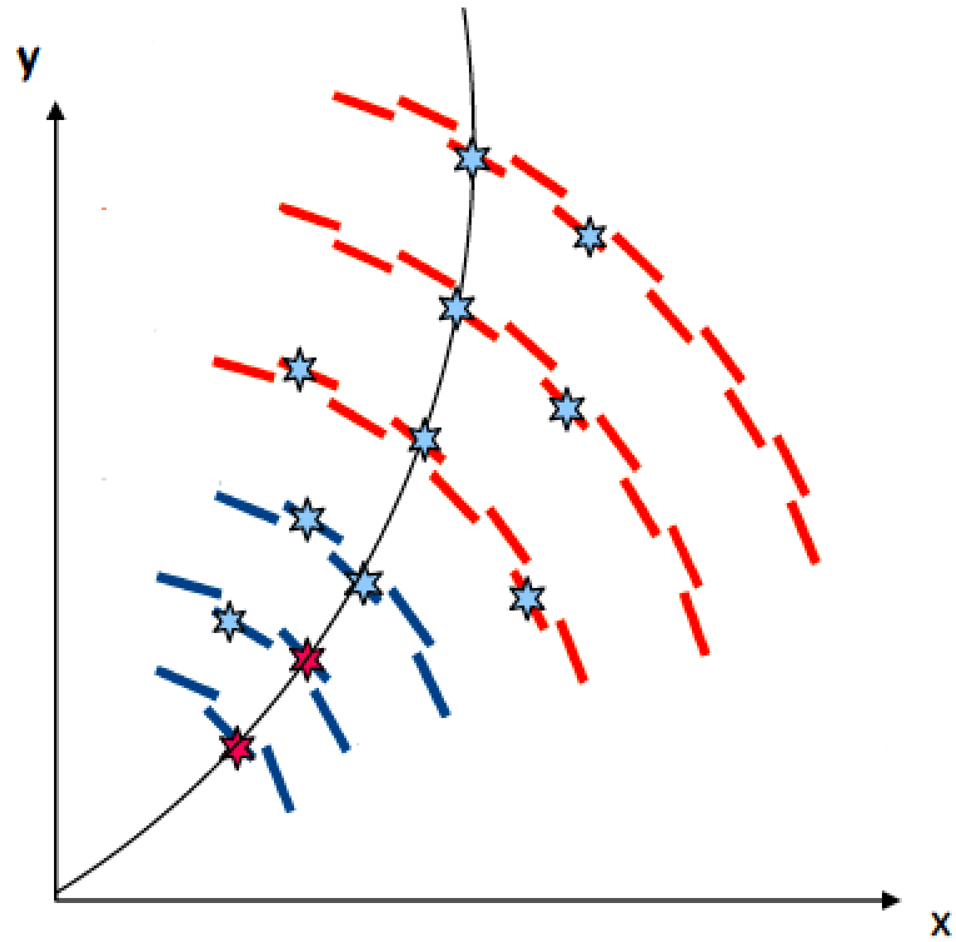


Tracklet Based Track Finding

- Form track seeds, tracklets, from pairs of stubs in neighboring layers
- Match stubs on road defined by tracklet and IP constraint

Matching resolutions for tracklets in L1+L2 projected to L3

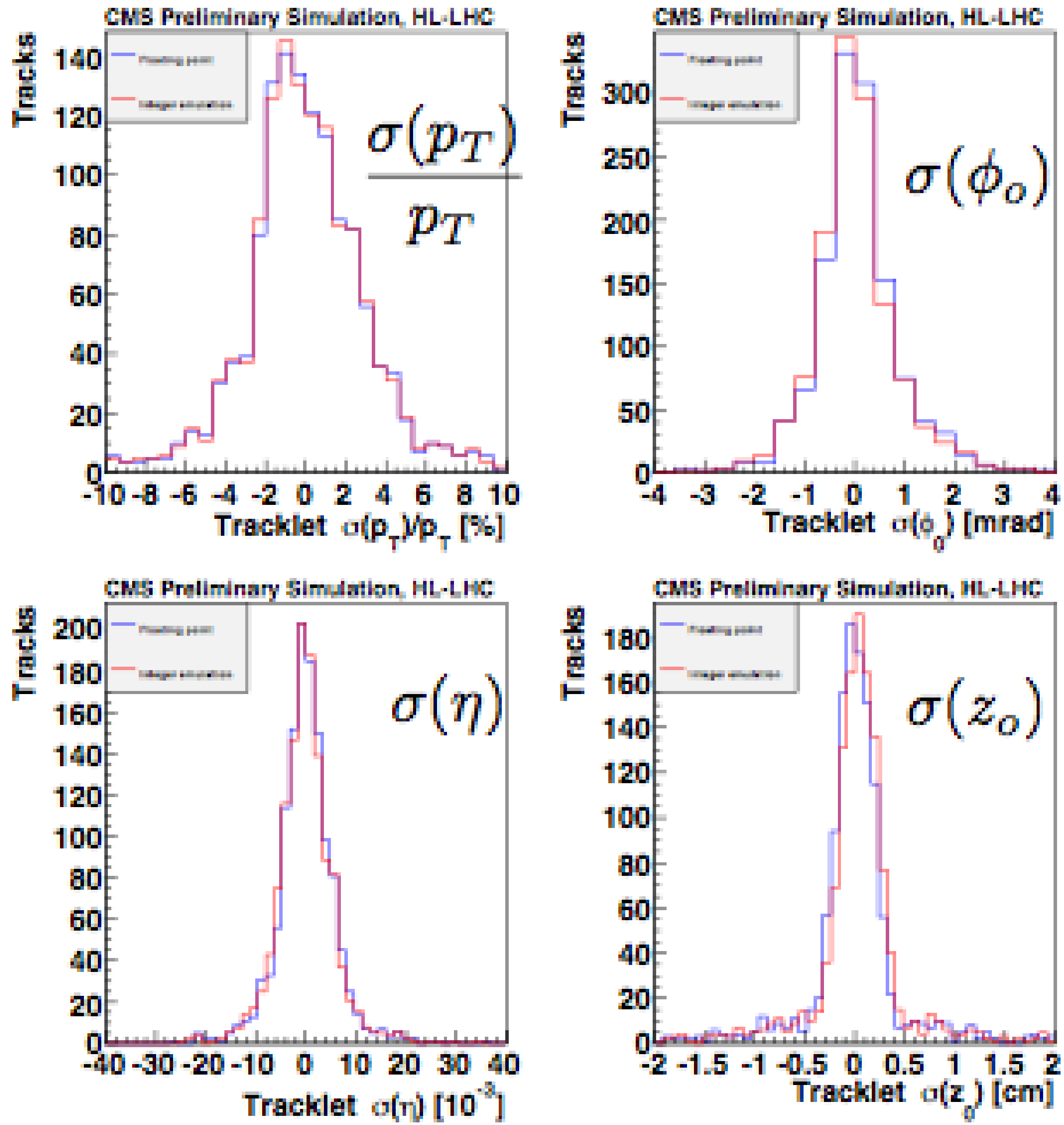




Tracklet parameter resolutions

Already tracklets have good track parameter resolutions

Important for projection stage!

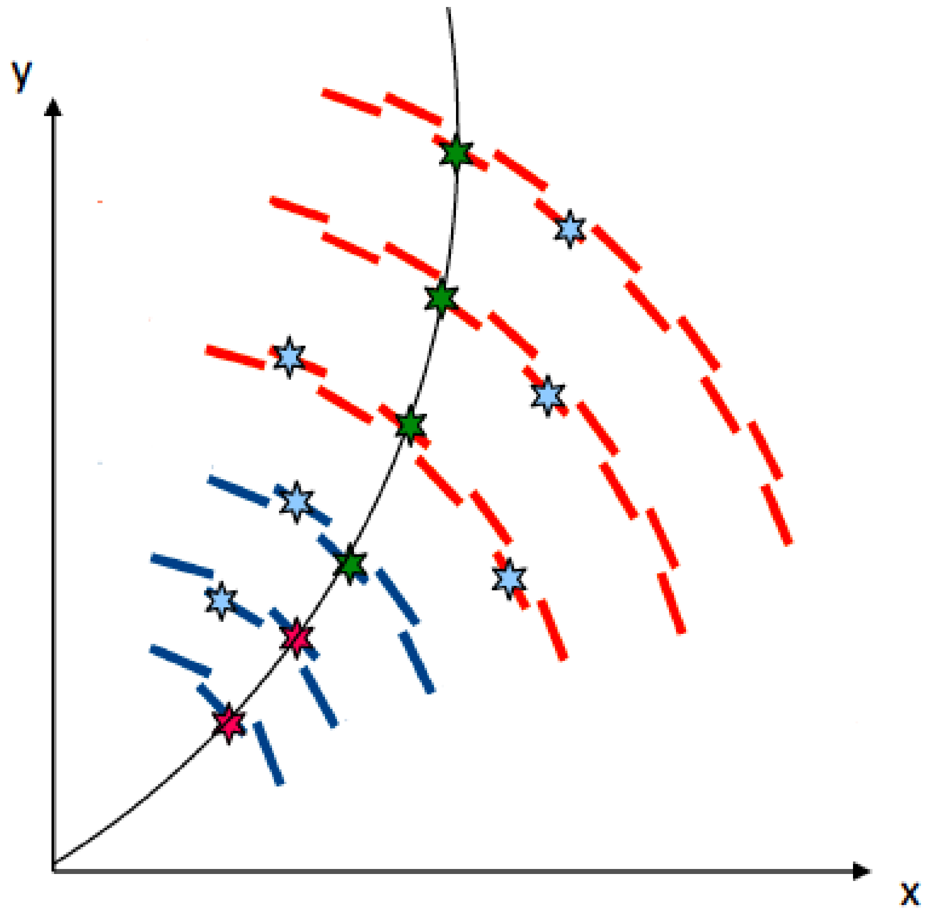


Floating-point calculation

Integer emulation

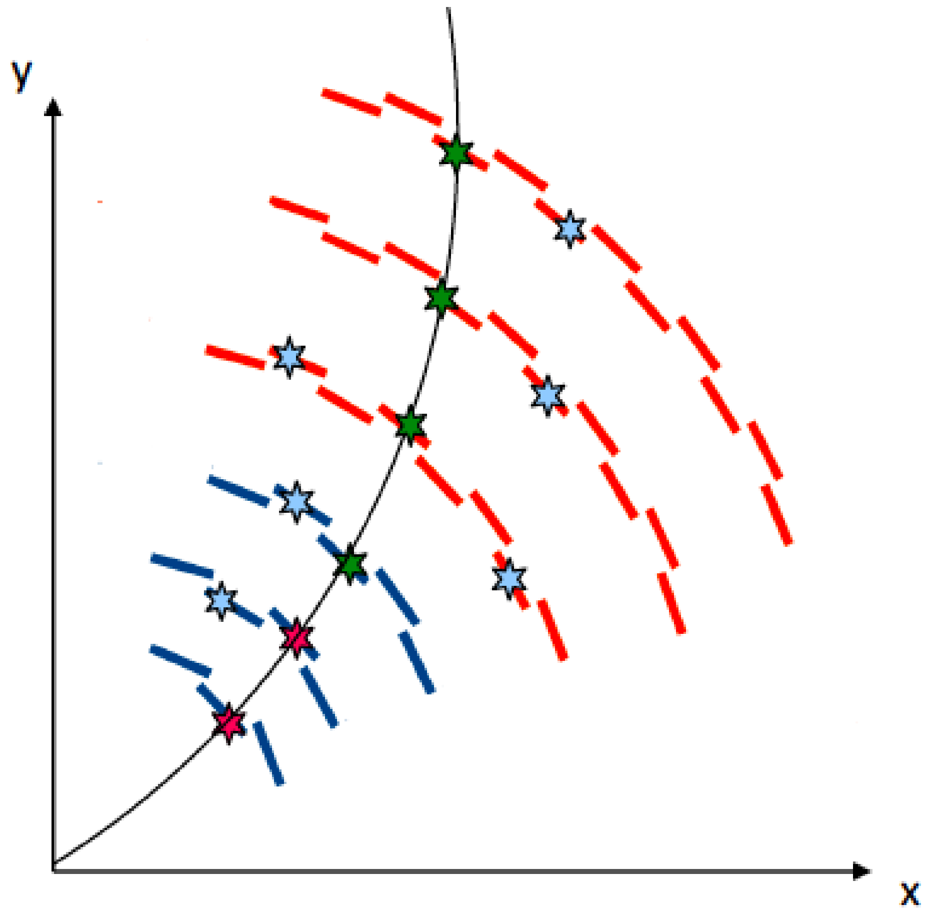
Tracklet Based Track Finding

- Form track seeds, tracklets, from pairs of stubs in neighboring layers
- Match stubs on road defined by tracklet
- Fit the hits matched to the tracklet using a linearized χ^2 fit
  - Fit track if 2 or more matches stubs
  - Tracklet parameters good – linear fit works very will
  - Only fit – no hit filtering



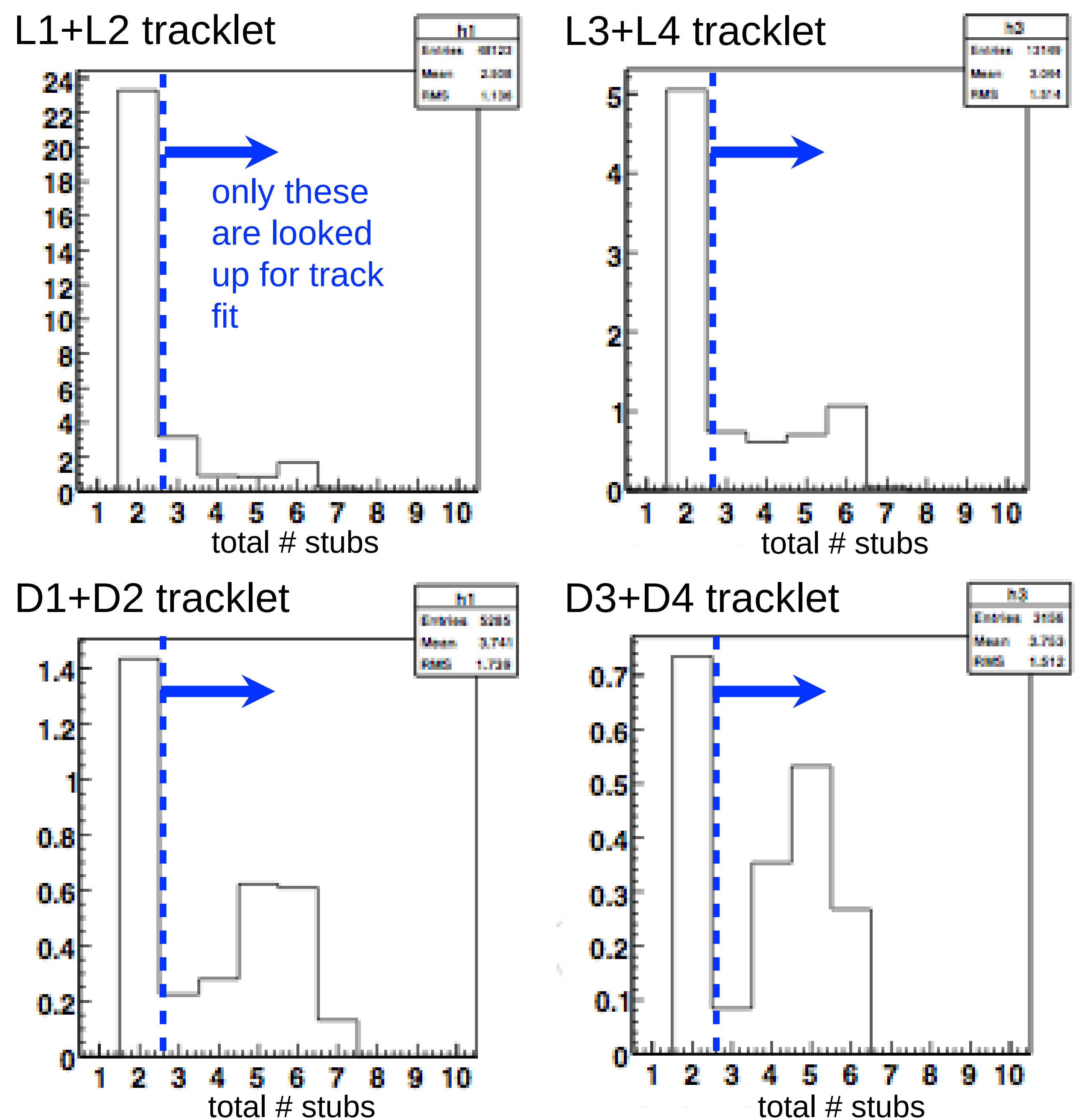
Tracklet Based Track Finding

- Form track seeds, tracklets, from pairs of stubs in neighboring layers
- Match stubs on road defined by tracklet
- Fit the hits matched to the tracklet using a linearized χ^2 fit
- Seeding is done in parallel in different layers
- Duplicate tracks are removed if they share 2 or more stubs



Track fit & tracklet rejection

- Track fit start from list of matches
  - Tracklet + ≥ 1 matched stubs
  - Fit improves tracklet parameters
- Fake tracklets w/o any matches are therefore not looked at for fitting stage
- Fake tracklets efficiently rejected!



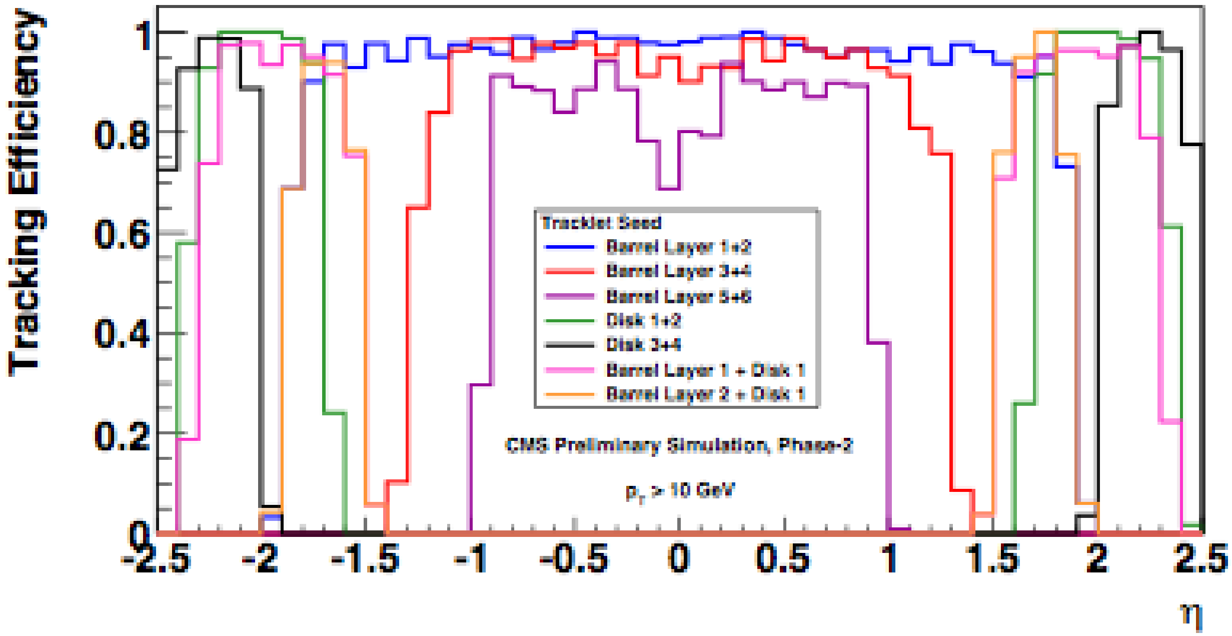
Tracklet formation (2)

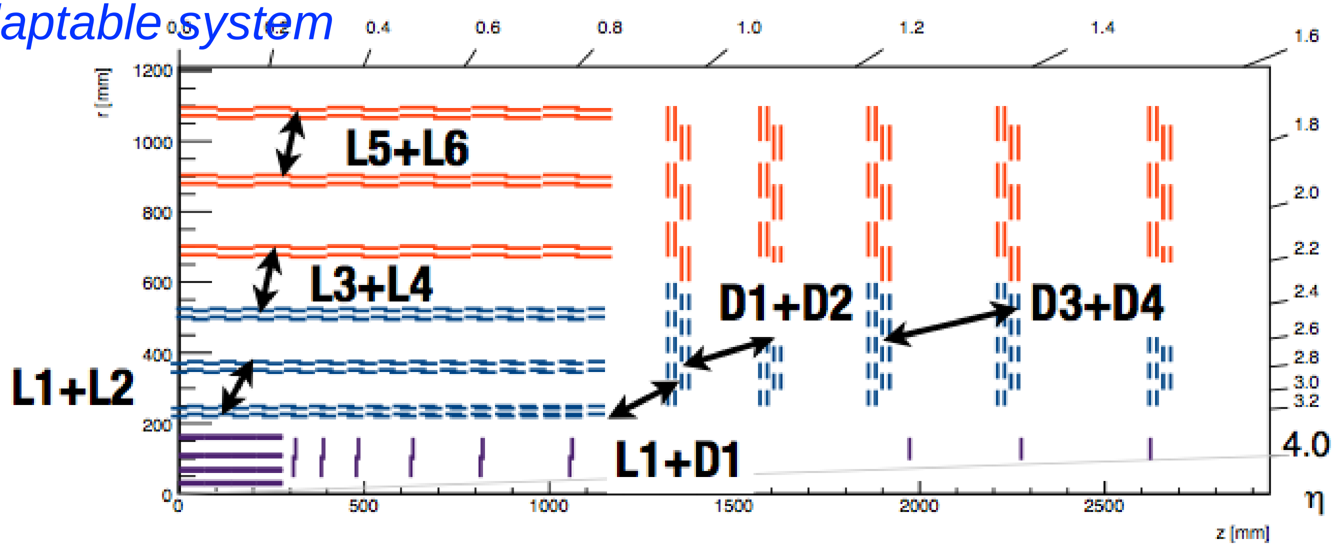
Seed multiple times in parallel to ensure good coverage & redundancy

Current configuration

- Barrel: L1+L2, L3+L4, L5+L6
- Disk: D1+D2, D3+D4
- Overlap: L1+D1
  - *Adaptable system*

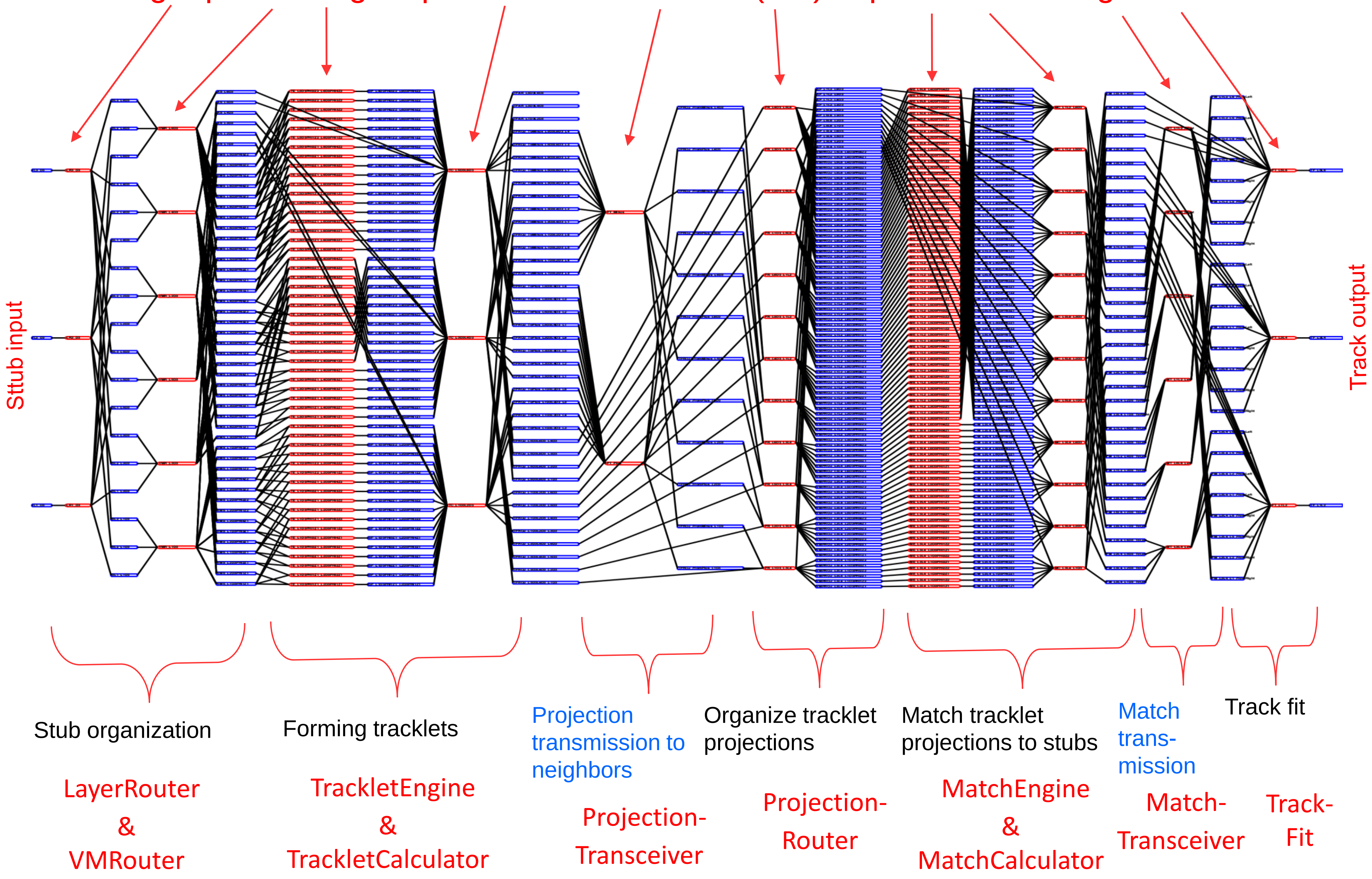
Efficiency for single muons (using firmware emulation)





Firmware Implementation (1/4 of barrel)

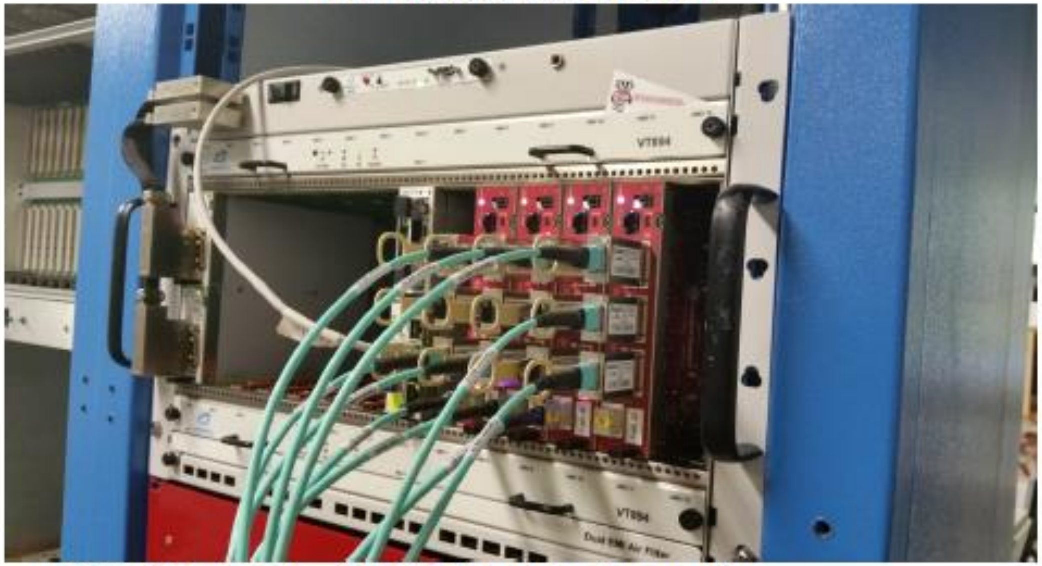
Eight processing steps + two transmission (red) implements the algorithm



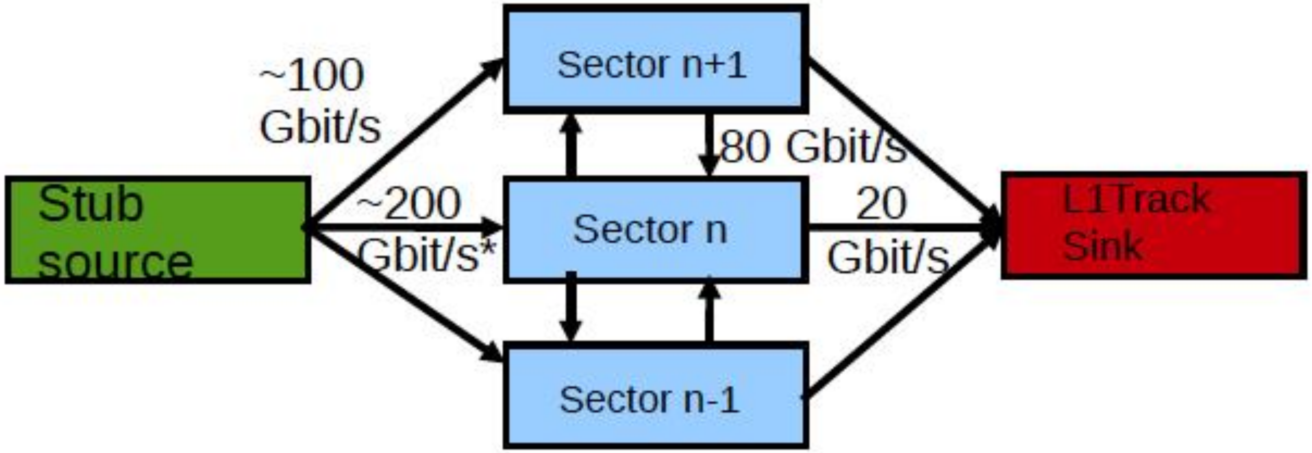
Tracklet Teststand

- Goal: Establish overall viability of tracklet approach.
  - Firmware/Algorithm
  - I/O Tests (input, neighbor, output)
  - Latency
  - Stress tests with data volumes
- Setup:
  - TFirmware/Algorithm
  - I/O Tests (input, neighbor, output)
  - Latency
  - Stress tests est crate at CERN
  - Four µTCA cards (CTP7)
    - 4th acting as data source/sink.
    - Each board has a Xilinx Vertex-7 FPGA and a Zynq chip.
    - Core sector board + 2 neighbors
  - AMC13 card for clock dist.

Test crate at CERN



µTCA boards (CTP7) developed by University of Wisconsin for the current 2016 Level-1 Trigger upgrade.



Summary

- Since the concept for the upgraded CMS tracker started to form in 2008 to 2010 CMS has a come a long way to proving all the concepts:
  - Many of the challenges in building the p_T modules has been solved, and prototype modules has proved the concept in test beams
  - The track trigger demonstrators has proved the feasibility to build a track trigger that meets the primary goals

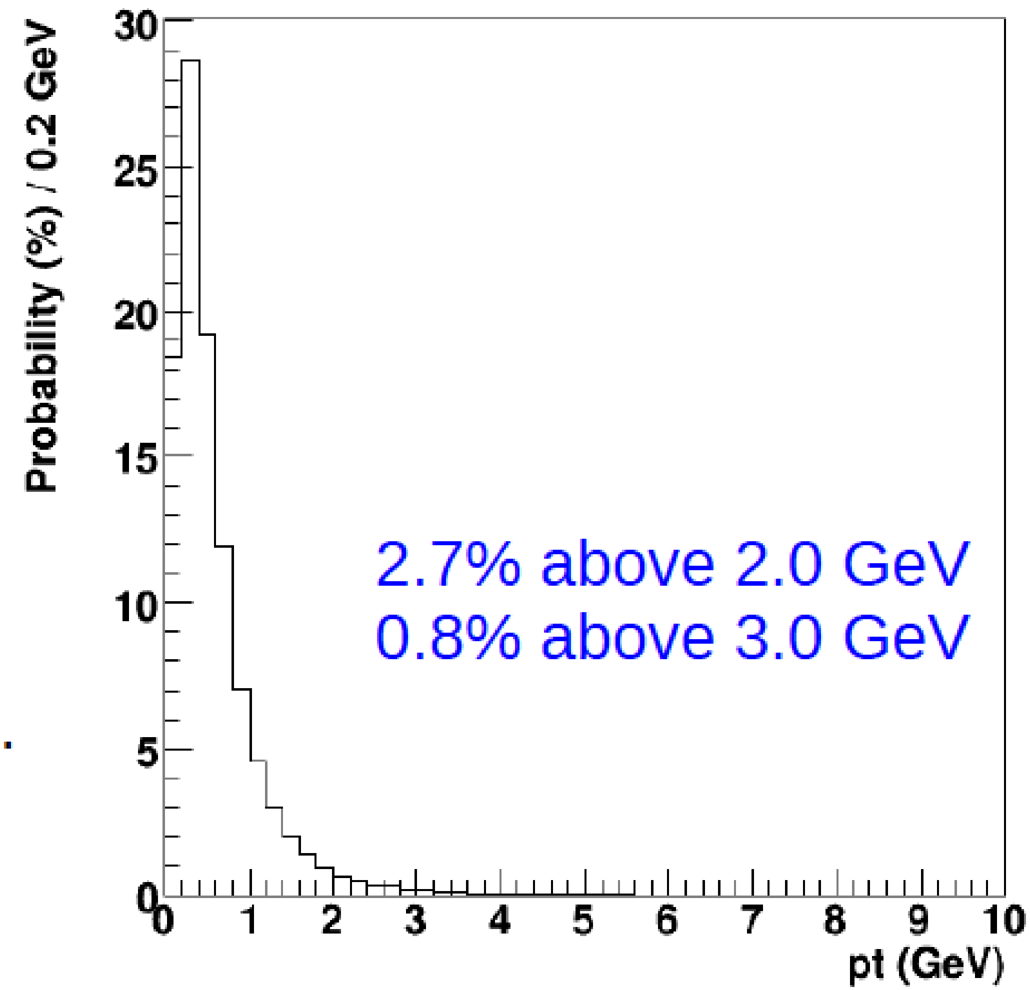
- There are still many challenges and significant work needed to implement the track trigger
  - Trigger algorithm studies needs to better define the track trigger requirements; optimization in latency vs. threshold vs. efficiency vs. cost is a significant undertaking over the next few years
  - Build online and offline software system for track trigger
  - Building/Installing/Commissioning the hardware and algorithms

Backup

Minbias Events

- 14 TeV minbias:
  - 6.5 charged particles, mostly pions, per unit of rapidity or 33 charged particles in the tracking volume $|\eta|<2.5$
  - With 140 PU → 4600 charged particles per bunch crossing.
  - Soft spectrum – peaks at p_T of about 200 MeV.
- The average min bias event has $33 \times 2.7\% = 0.89$ tracks with $p_T > 2.0$.
  - For PU=140 we expect ~125 tracks with $p_T > 2.0$.

p_T distribution in 14 TeV minbias



Data volume:

- In 140 PU average of about 12,000 stubs/BX
- Each stub is ~36 bits
  - At 40 MHz BX rate we have 17 Tbits/s

Only ~5% of stubs are from tracks with $p_T > 2\text{GeV}$