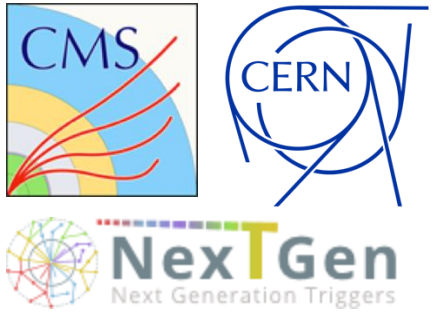

Tracking at 40 MHz
The CMS tracker and trigger upgrades for HL-LHC

Christopher Brown

RAL PPD Seminar

30/10/2024

Hardware

CMS & CMS Phase-2

Tracker

Trigger

Trigger

Track Finding

Triggering with Tracks

Physics

Parameter Residuals

Physics Reach

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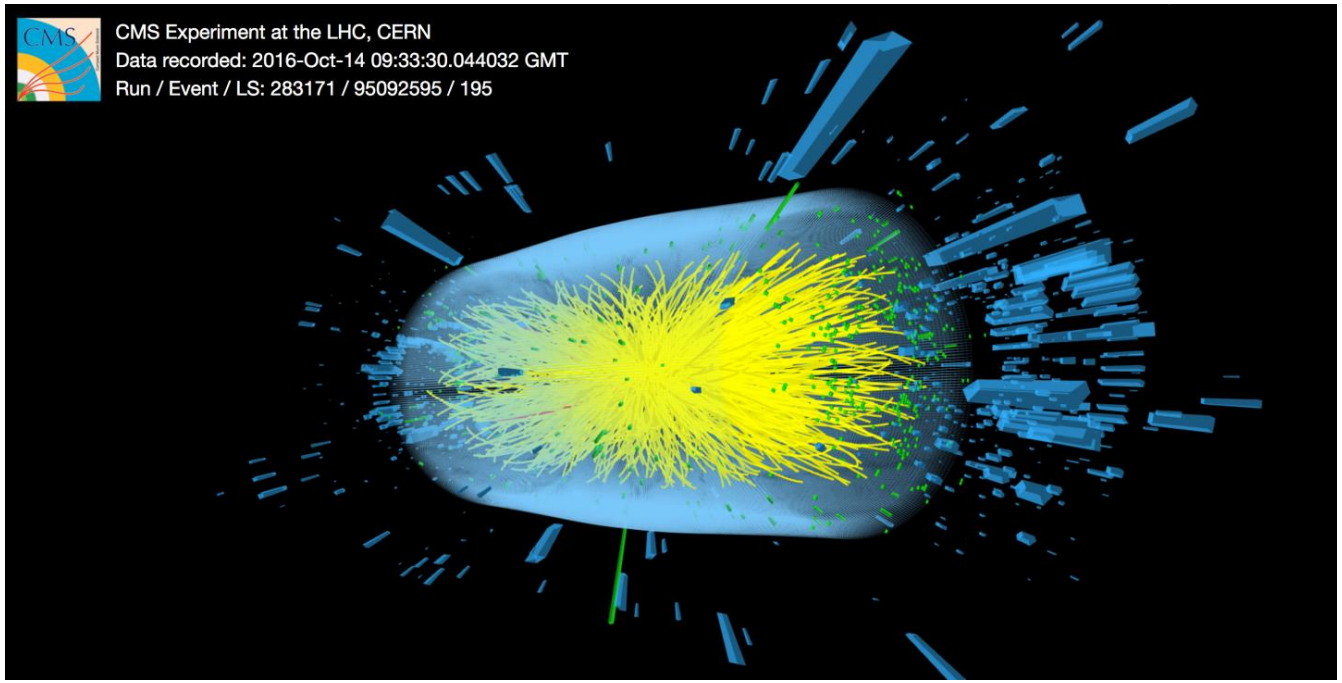
A Brief Introduction to CMS Track Finding

- Proton-proton at 40 MHz, thousands of charged particles in every single event
- Reconstruction of charged particle trajectories and vertices
- Need high granularity pixel detectors for vertex finding
- Radiation hard materials, 10-15 years between replacement
- Low material budget to reduce multiple scattering and electron bremsstrahlung
- Large magnetic fields, fitting curved particle trajectories



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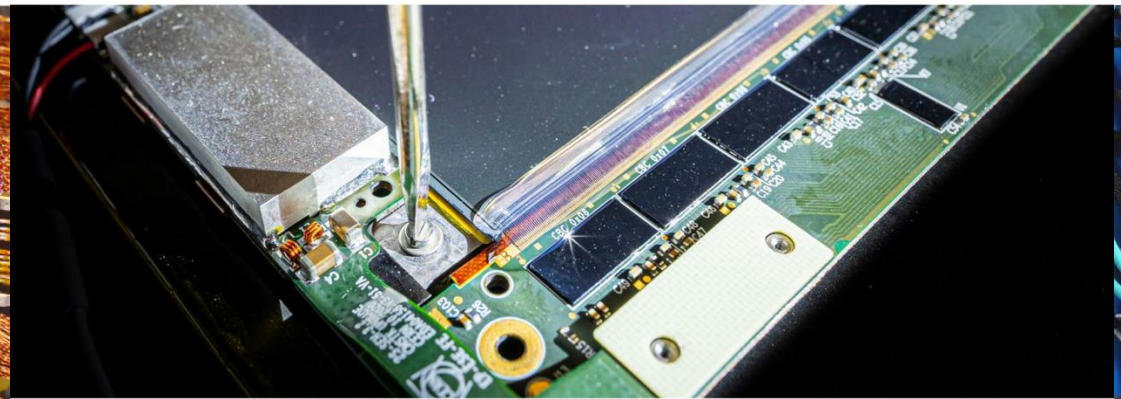
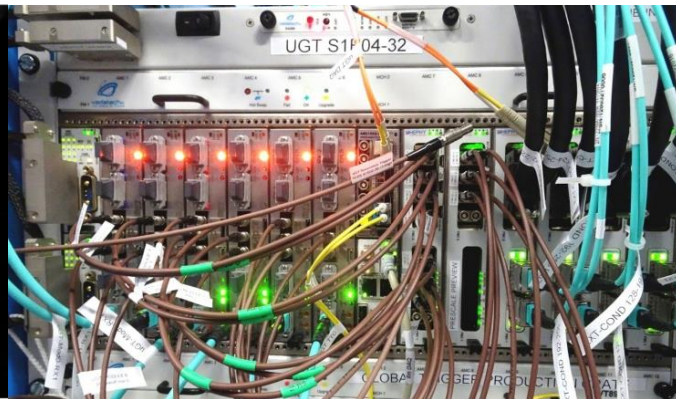
A Brief Introduction to Track Finding and Trigger Jargon

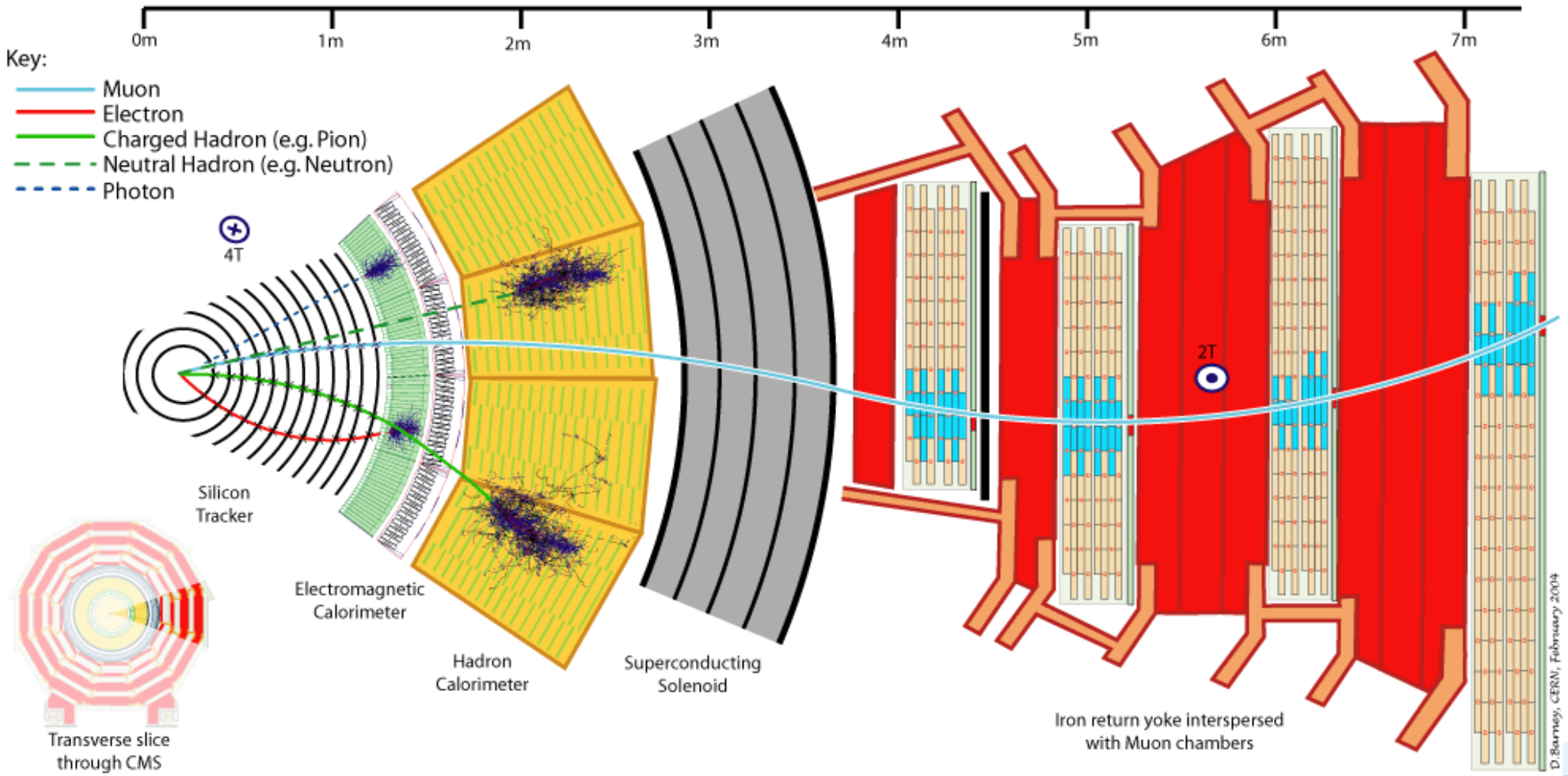
- Pileup – simultaneous proton-proton interactions per bunch crossing, LHC currently ~60, rising to 200 in HL-LHC
- Pixel detector – Silicon detector divided into micrometre pixels, innermost detectors, highest granularity
- Strip detector – Silicon detectors with readout strips, good measurement in one direction only, cheaper, lower datarate
- Pseudorapidity (η) – Angle from beamline, logarithmic
- p_T – Transverse momentum, momentum in the r-φ plane
- Module – Detector element containing the silicon sensor, readout electronics, power and other infrastructure
- Hit – Single point of a particles' trajectory where it interacts with the detector
- Stub – Small part of a particles' trajectory from two hits used to seed reconstruction

Hardware

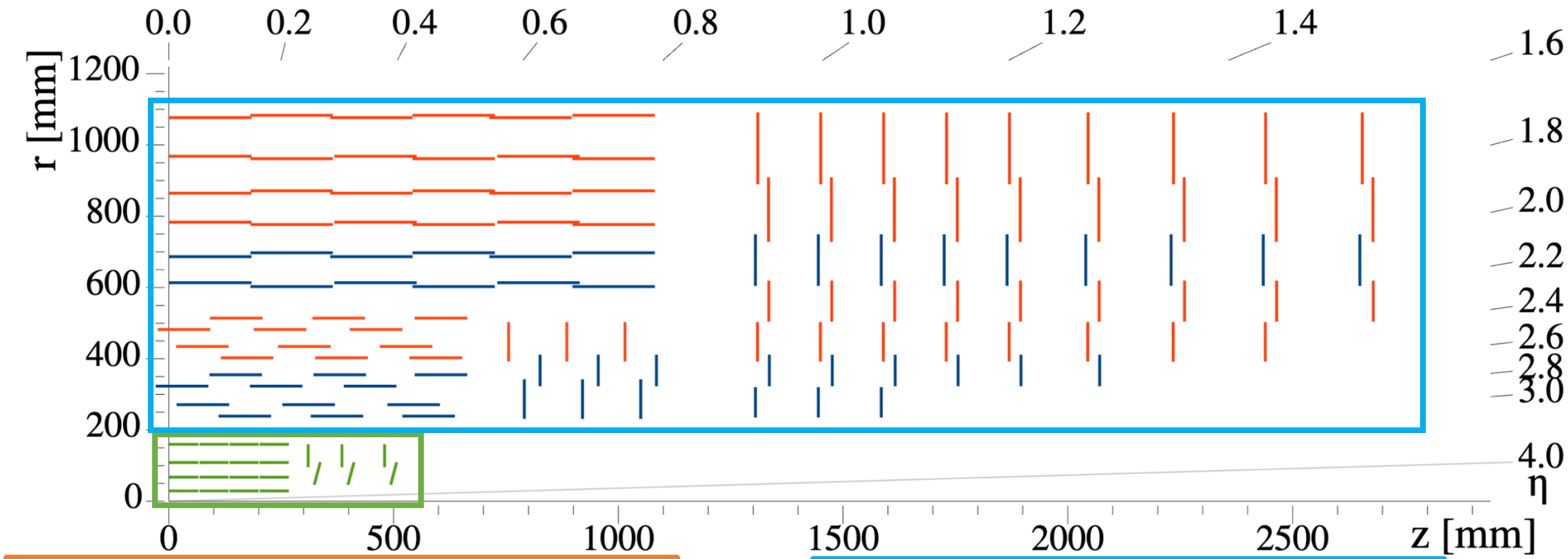




A Brief Introduction to CMS



CMS Tracker – Phase 1



Inner tracker
- $|\eta|$ up to 3
- Pixel sensors 150 x 100 μm^2 pixels
- Layer 1 replaced in 2021

Outer tracker
- Instrumented up to $|\eta| = 2.4$
- Double sided modules
- Single sided modules

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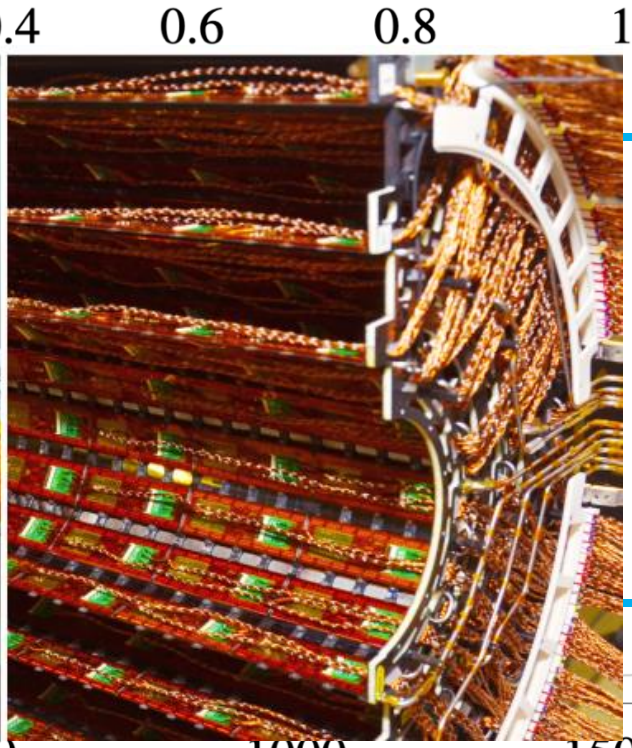
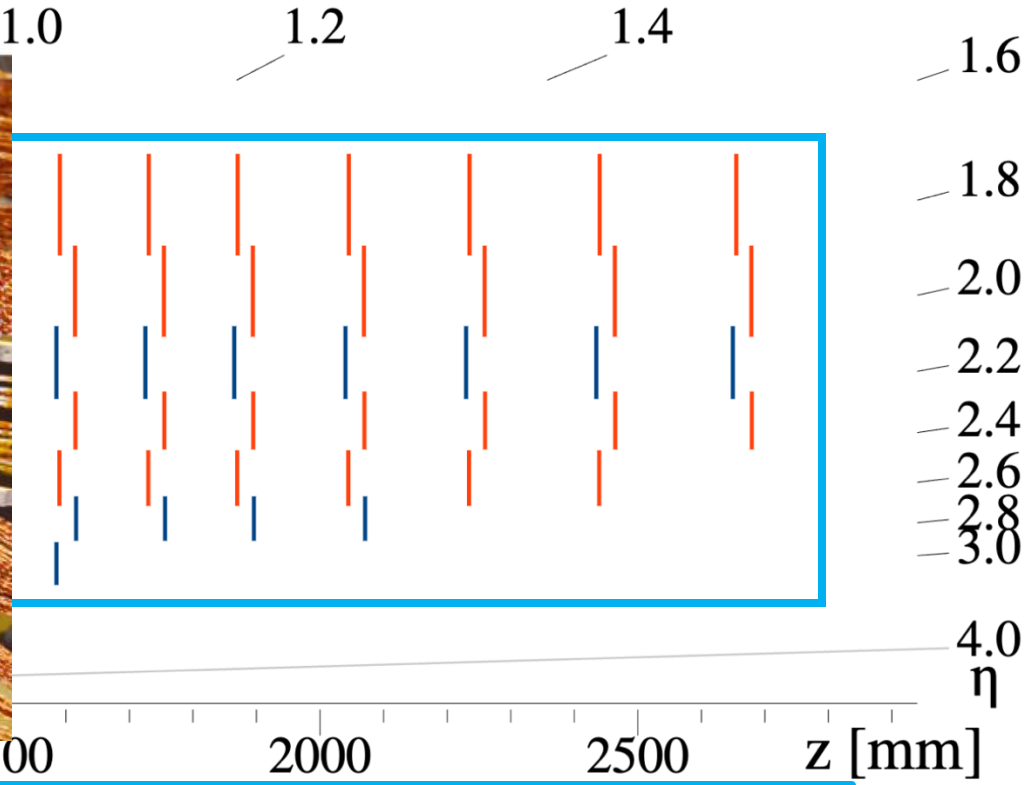
CMS Tracker – Phase 1





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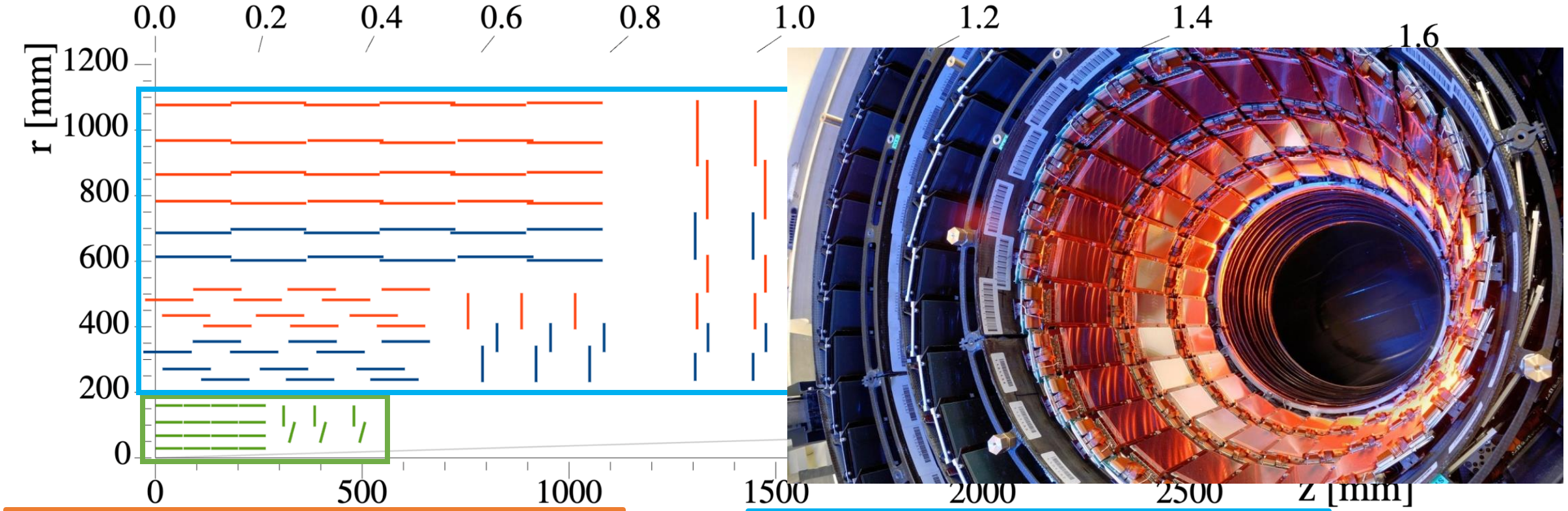
CMS Tracker – Phase 1



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- Single sided modules

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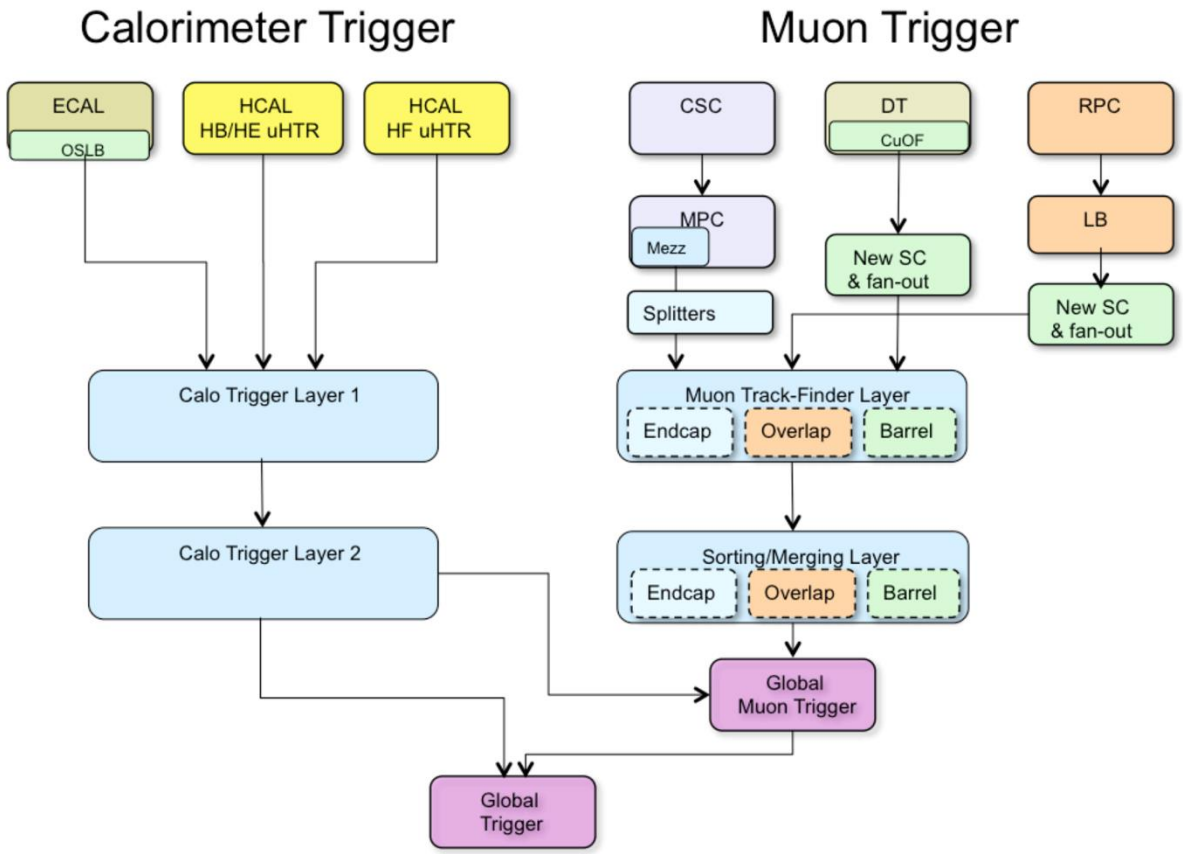
CMS Level-1 Trigger – Phase 1



CMS Trigger
2 – stage
Level-1 HW trigger, low granularity
4μs, 110 kHz rate, 99.7% rejection

Calorimeter Trigger
5 x 5 calorimeter super clusters
Jets and sums
Electron and photon isolation

Muon Trigger
Muon track reconstruction
BDT for p_T regression

Global Trigger
128 different algorithms
Single bit output, keep or discard
Autoencoder anomaly detection

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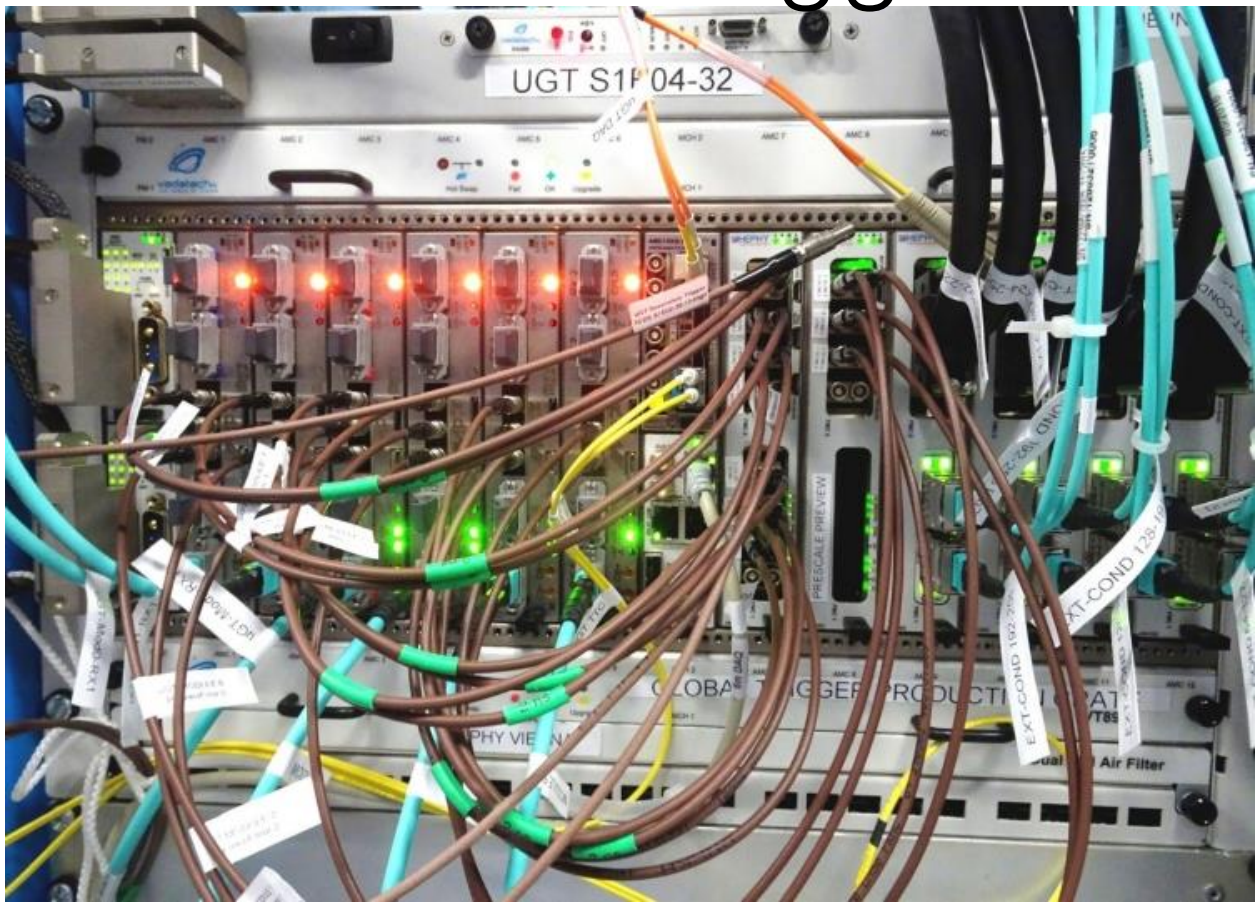
CMS Level-1 Trigger – Phase 1



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Muon track reconstruction
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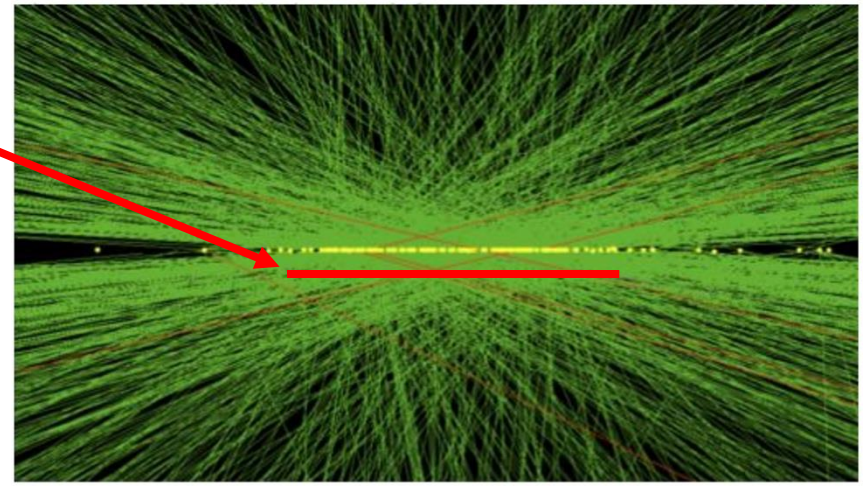
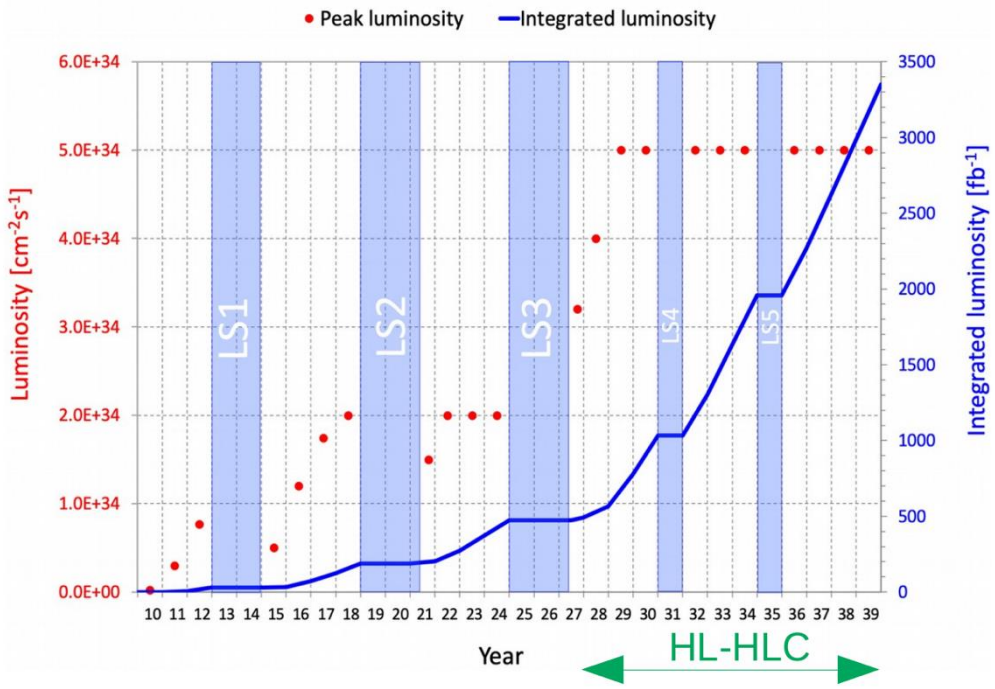
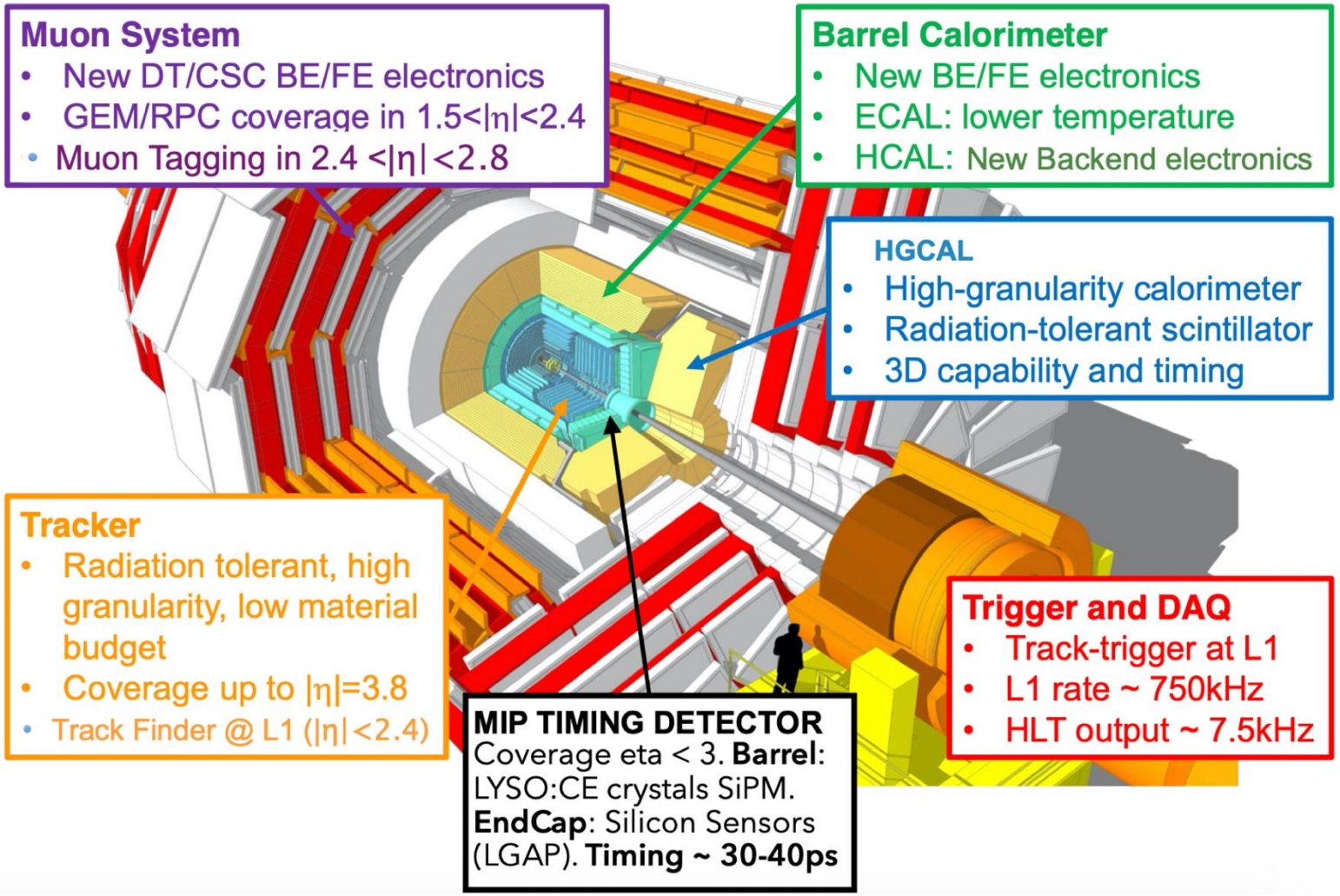
HL-LHC



- 3000-4000 fb^{-1} over the HL-LHC lifetime
- Good for rare BSM physics searches and SM precision measurements
- Simultaneous proton-proton interactions per bunch crossing (pileup) rising to 200 at 40 MHz
- Current era CMS cannot cope without loss in physics performance
- Radiation damage too high for current CMS tracker and endcaps
- CMS needs to be upgraded and the Level-1 trigger is a major part of these upgrades



CMS Phase-2 Upgrade



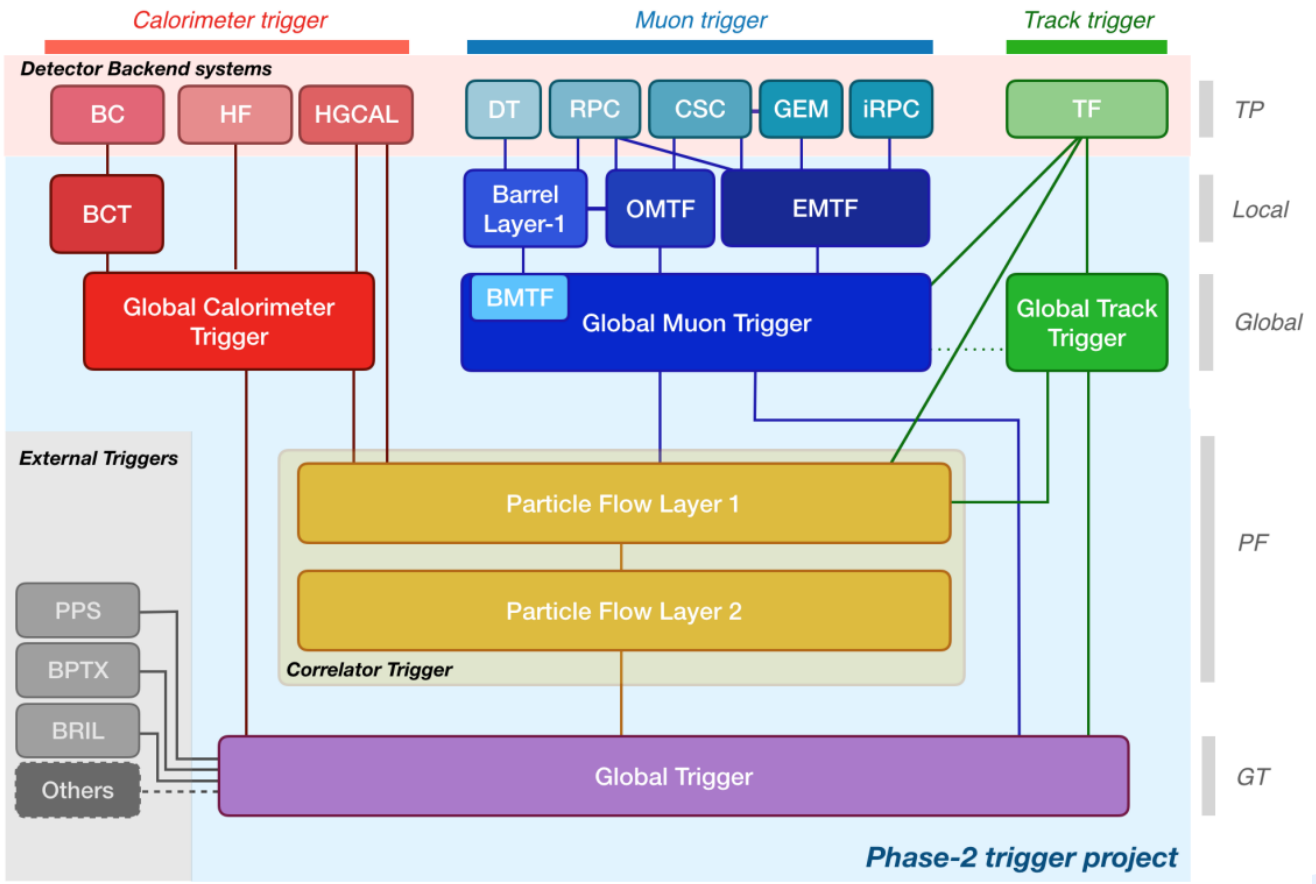
Brand new tracker
Brand new endcap calorimetery
Brand new muon system
Brand new timing layer
Brand new Level-1 Trigger
Basically a new detector

CMS Phase-2 Upgrade

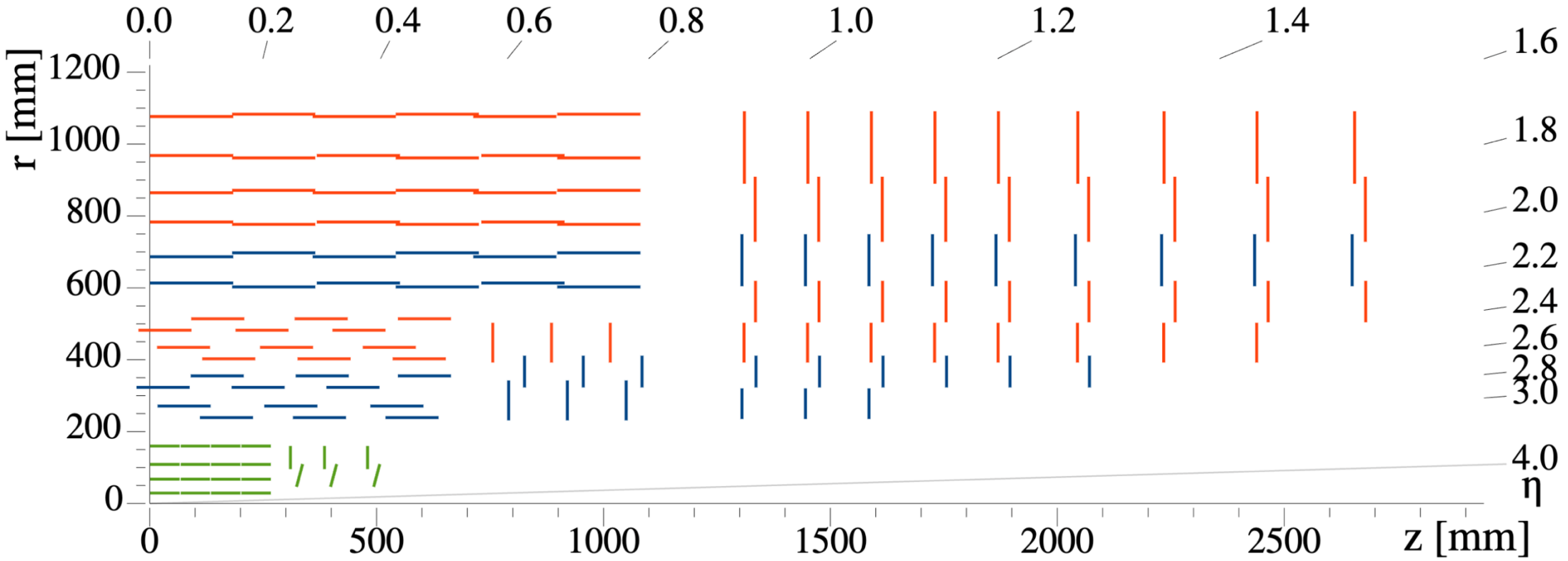
Without tracking finding the rate would be 4 MHz to maintain the same physics selectivity

Level–1 Trigger

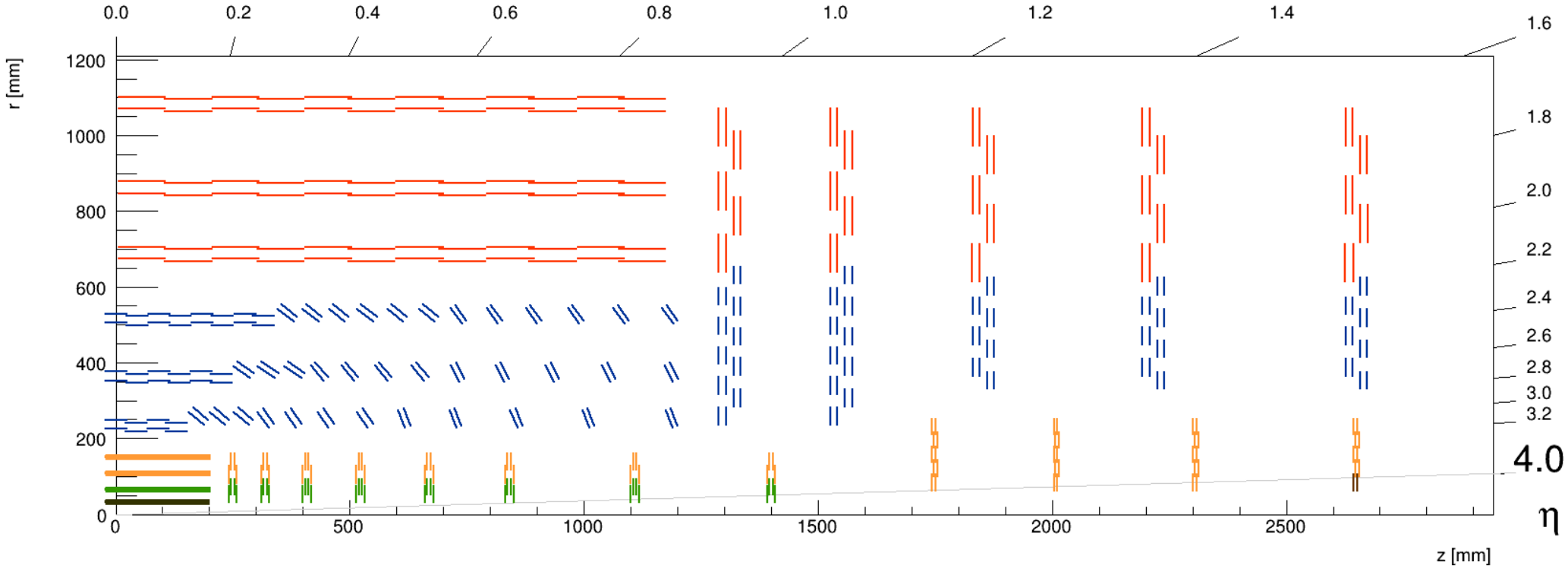
- ~110 kHz → 750 kHz rate
- ~4 μs → 12.5 μs latency
- Big FPGAs → flexibility
- Upgraded HGCal and Calorimeter backend electronics, high granularity at L1
- Tracks from outer tracker at L1, full 40 MHz readout
- Can perform PF and vertex finding for particle per pileup identification



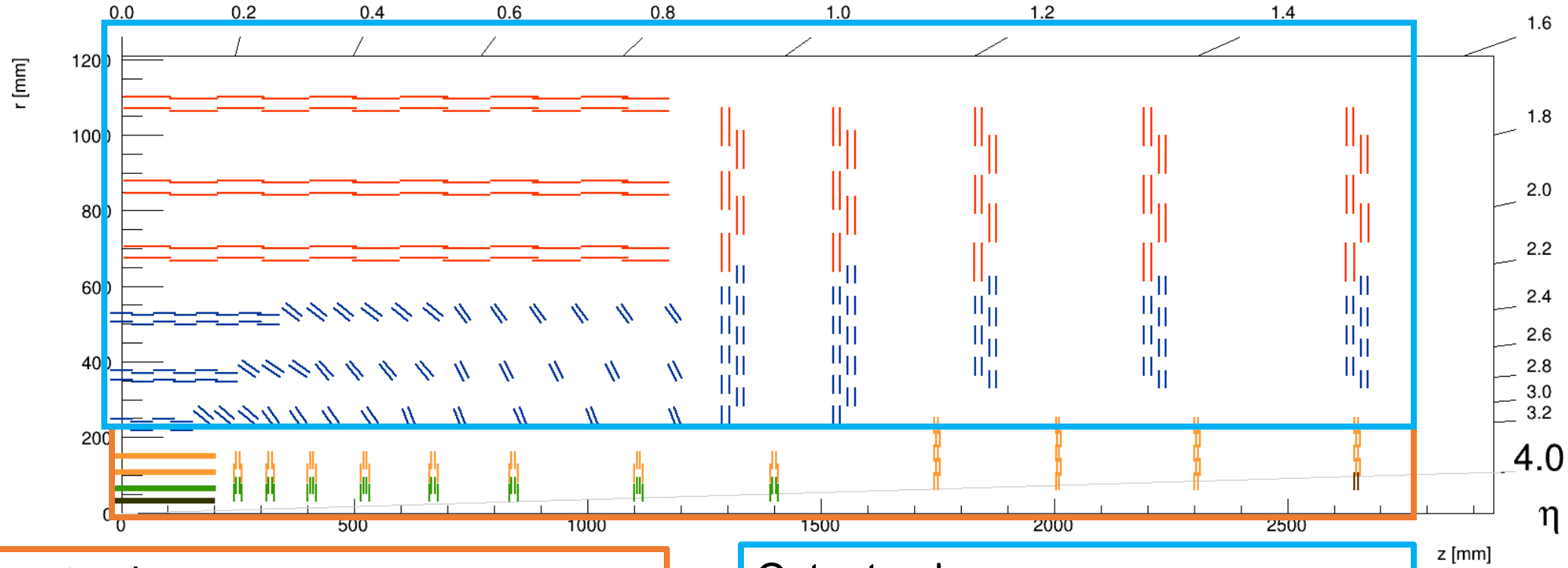
CMS Phase-1 Tracker



CMS Phase-2 Tracker



CMS Phase-2 Tracker



Inner tracker

- $|\eta|$ up to 4
- Pixel sensors 25 x 100 μm^2 pixels
- Replaceable 3D pixel inner layer

Outer tracker

- Instrumented up to $|\eta| = 2.8$
- Tilted geometry

PS modules → pixel-strip modules

2S modules → two strip modules

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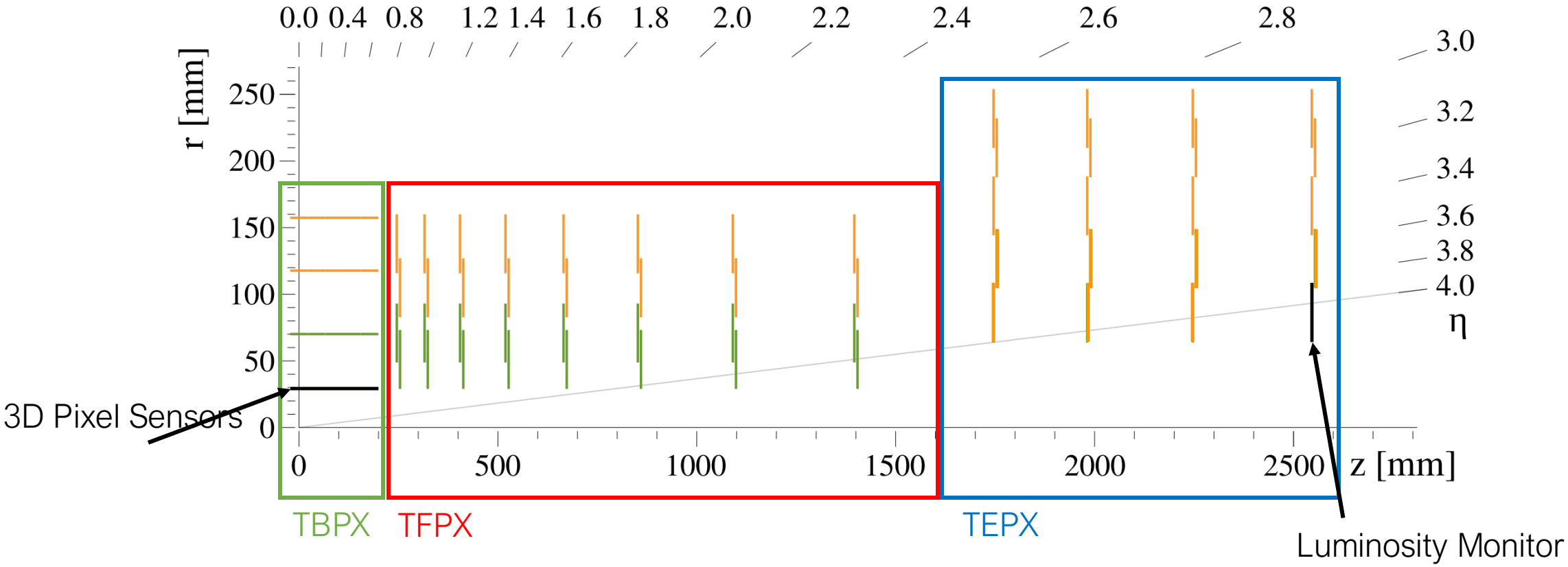
Inner Tracker



3892 Modules, 1x2 or 2x2 readout chips
TBPX – Tracker Barrel PiXel 4 Layers
TFPX – Tracker Forward PiXel 8 small double disks
TEPX – Tracker Endcap PiXel 4 large double disks

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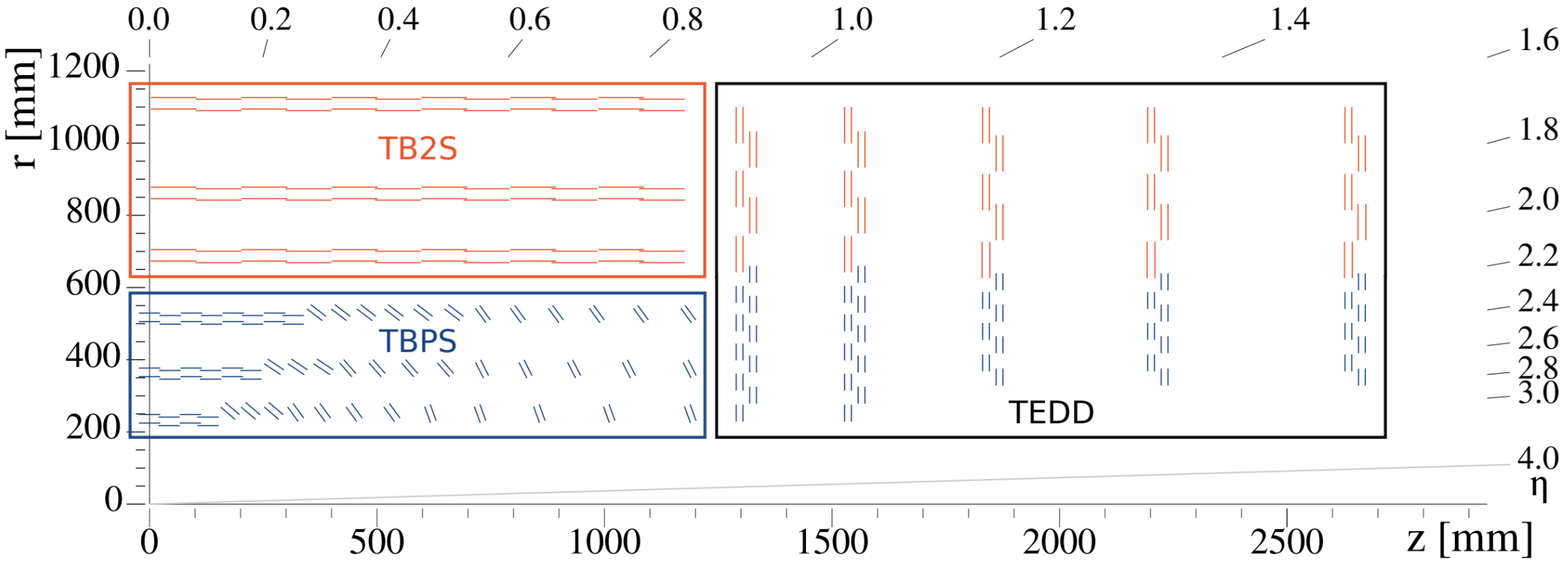
Outer Tracker

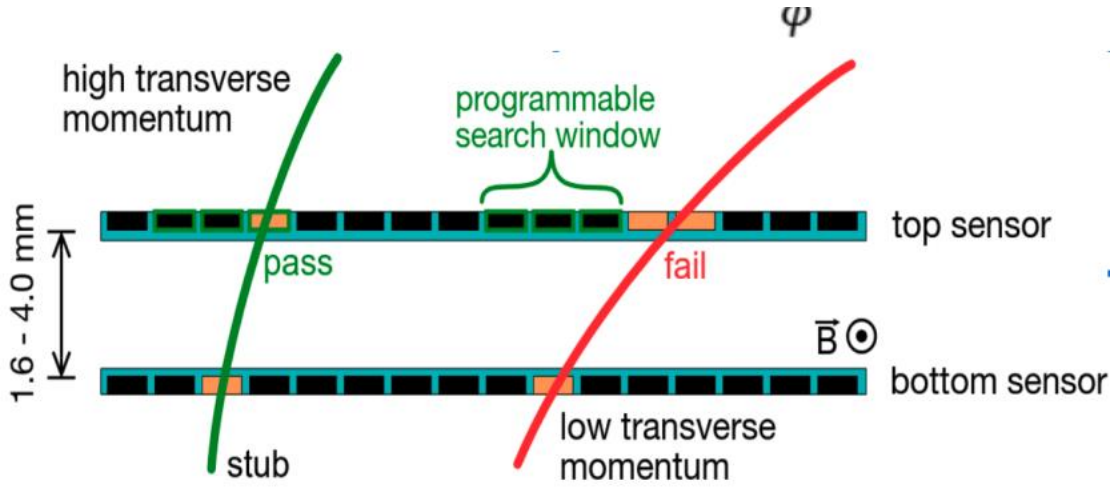


Two types of module Pixel Strip (PS) and Two Strip (2S)
Tracker Barrel PS TBPS
Tracker Barrel 2S TB2S
Tracker Endcap Double Disks TEDD

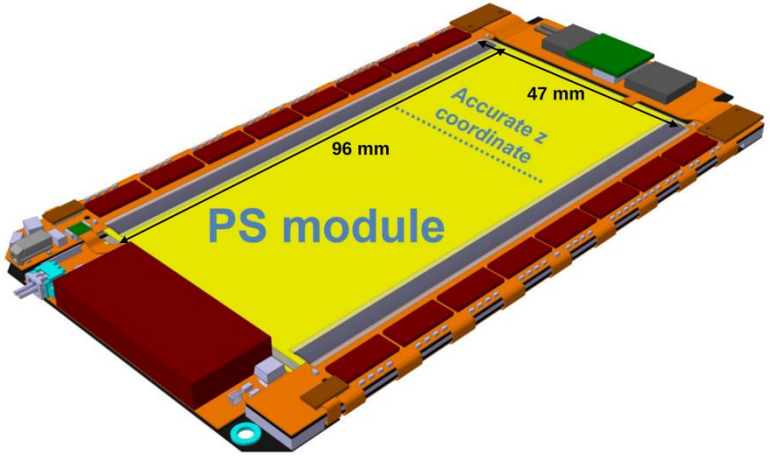
Outer Tracker – p_T Modules

p_T modules

- 2 closely spaced layers of silicon
- Tuneable window give on module p_T cut
- Both types of outer tracker module contain p_T modules
- Can't have stereo strips → but need precise z_0 coordinates so use pixel-strip modules
- Reduces data rate enough for track finding at 40 MHz
- 1 mm z_0 resolution allows a vertex to be found in 200 pileup

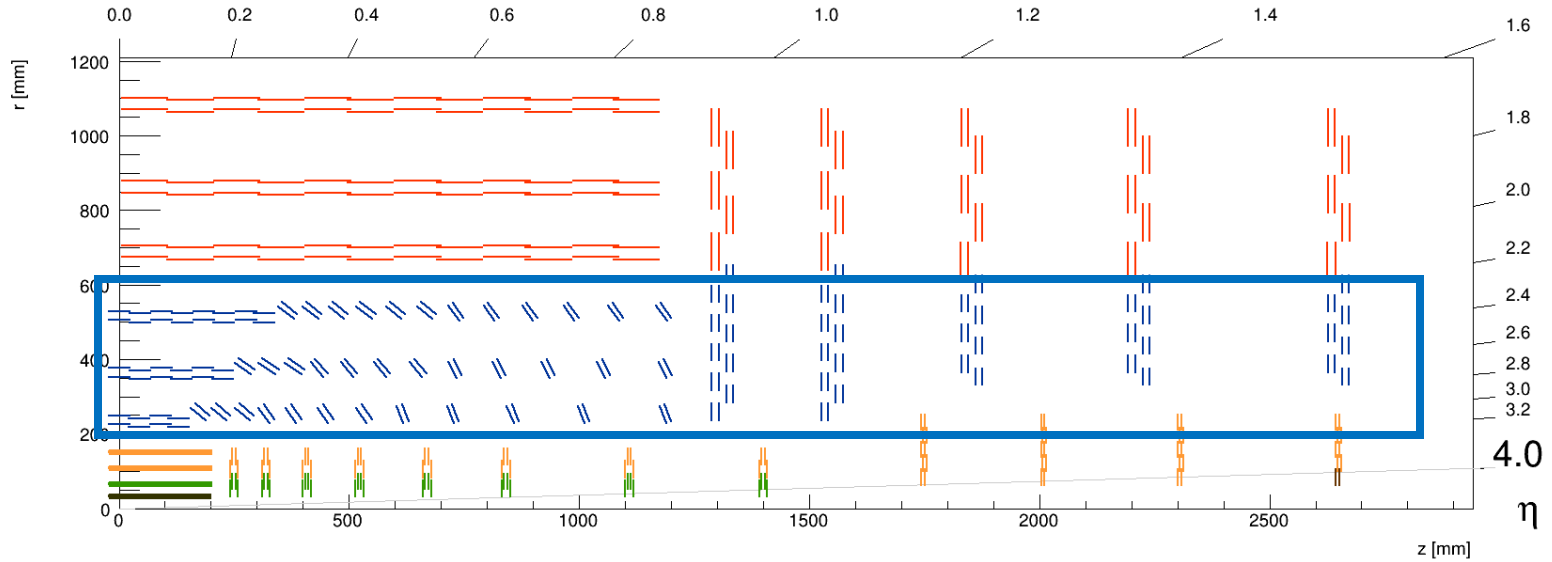


Tracker Upgrade

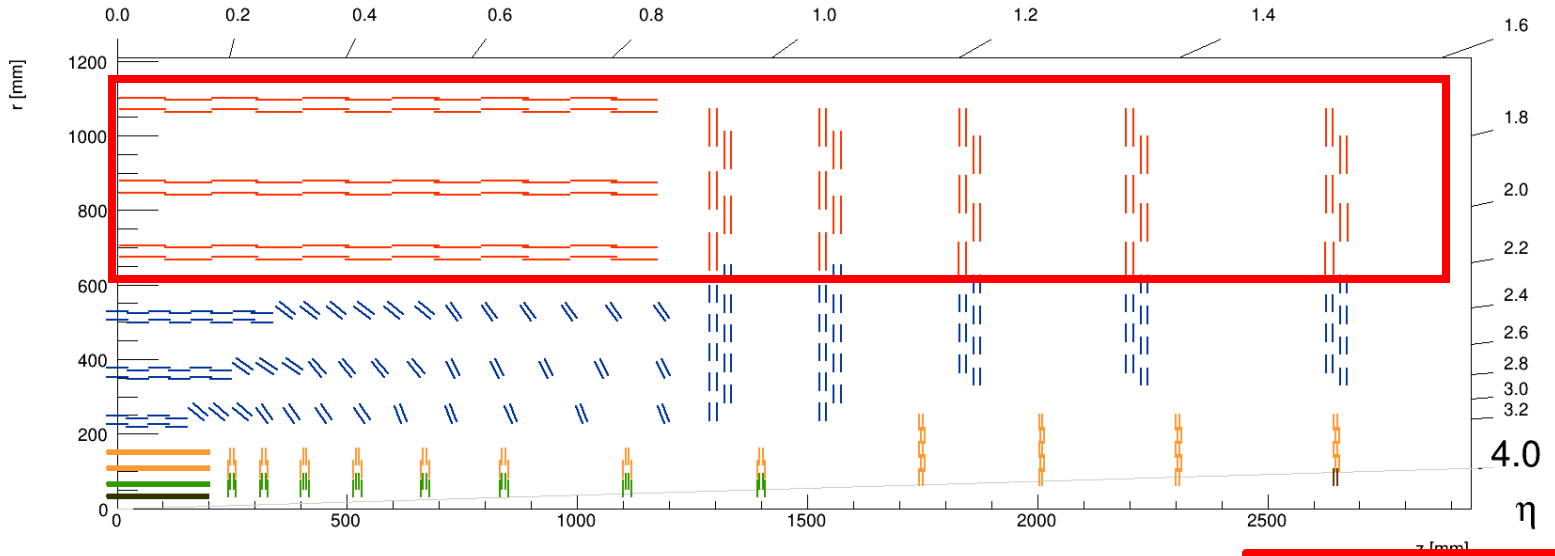


PS Modules

- One Pixel, one strip layer
- 1.47 mm long, 100 µm wide pixels give z_0 resolution for a track of 1 mm
- 100 µm pitch strip sensor
- Angled barrel region increases efficiency

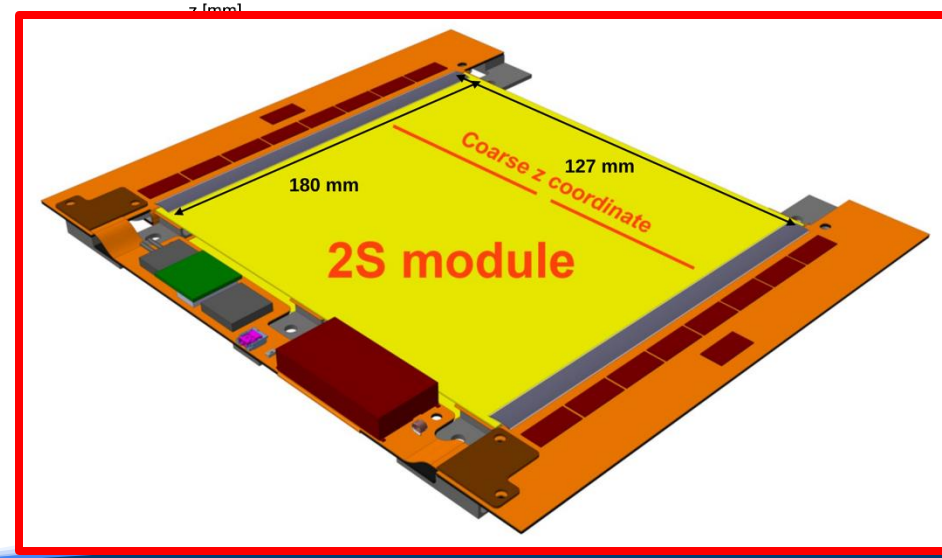


Tracker Upgrade

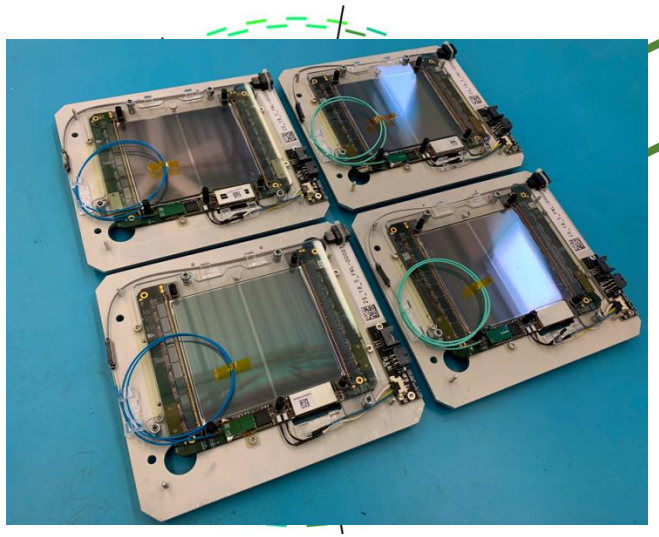


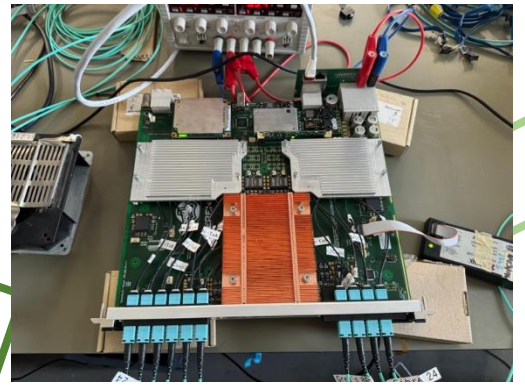
2S Modules

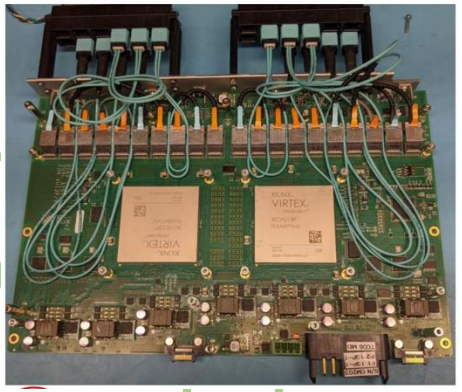
- Two strip sensor layers
- 90 μm pitch
- High resolution in ϕ, poor resolution in z (η) in the barrel (endcap)
- Lower occupancy and bandwidth motivates their use in the outer layers

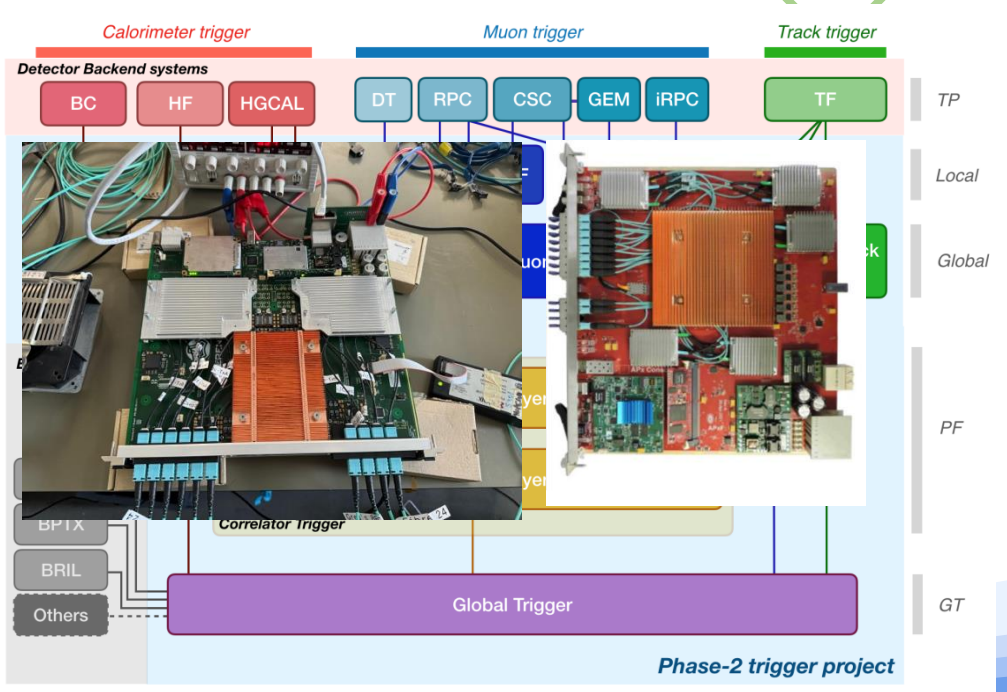


Readout System

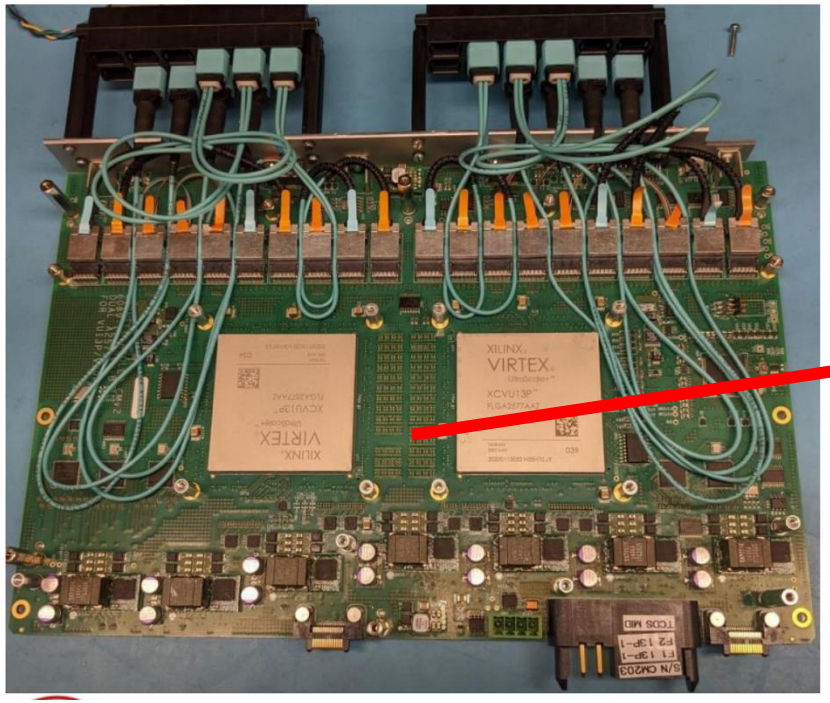


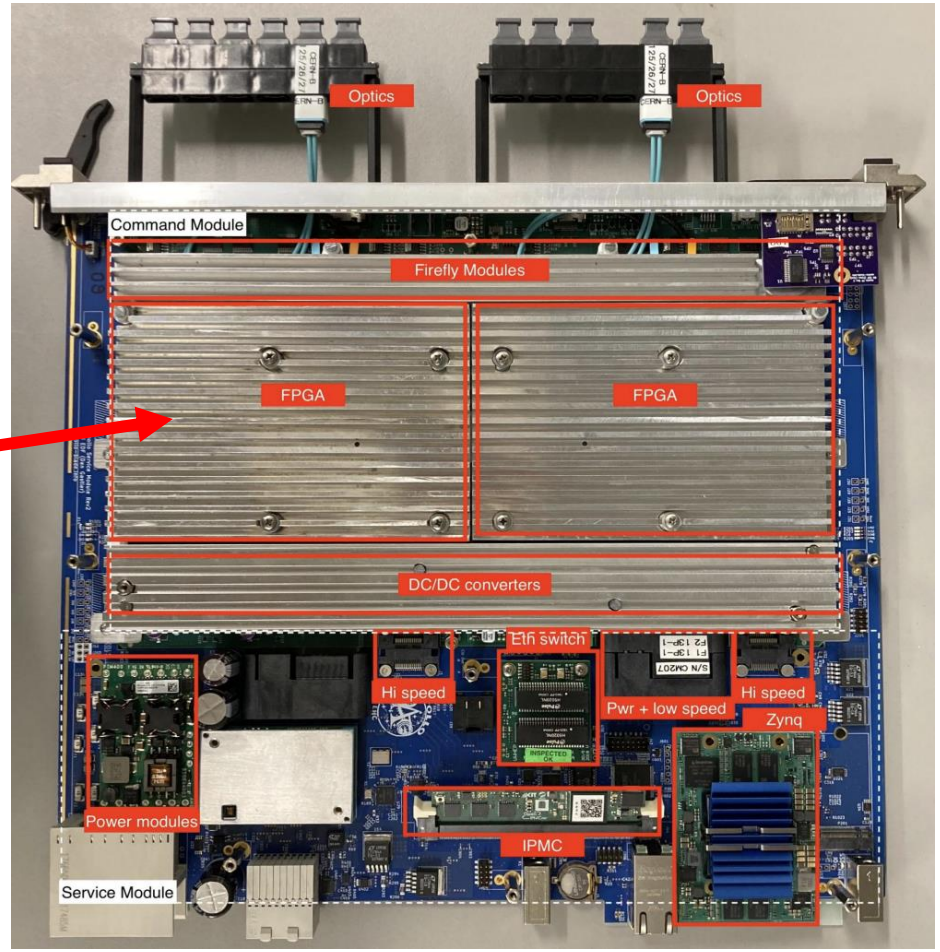






Trigger ATCA Boards

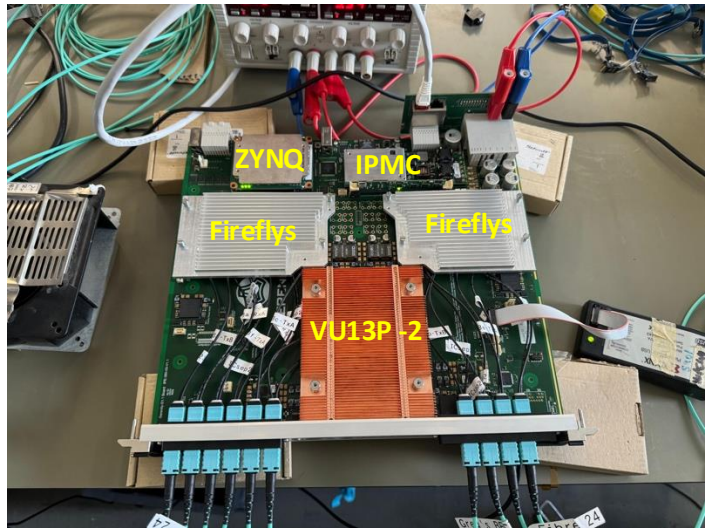




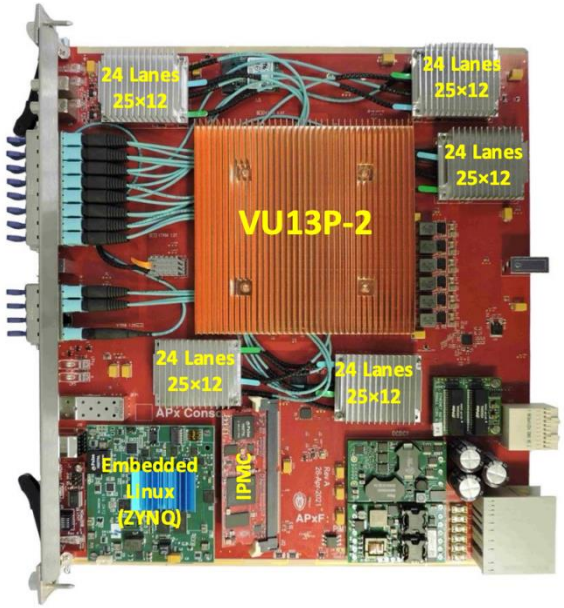
Apollo Board

Track finder processor
Inner tracker readout
Dual VU13P FPGAs, track finder algorithm split between the two

Trigger ATCA Boards



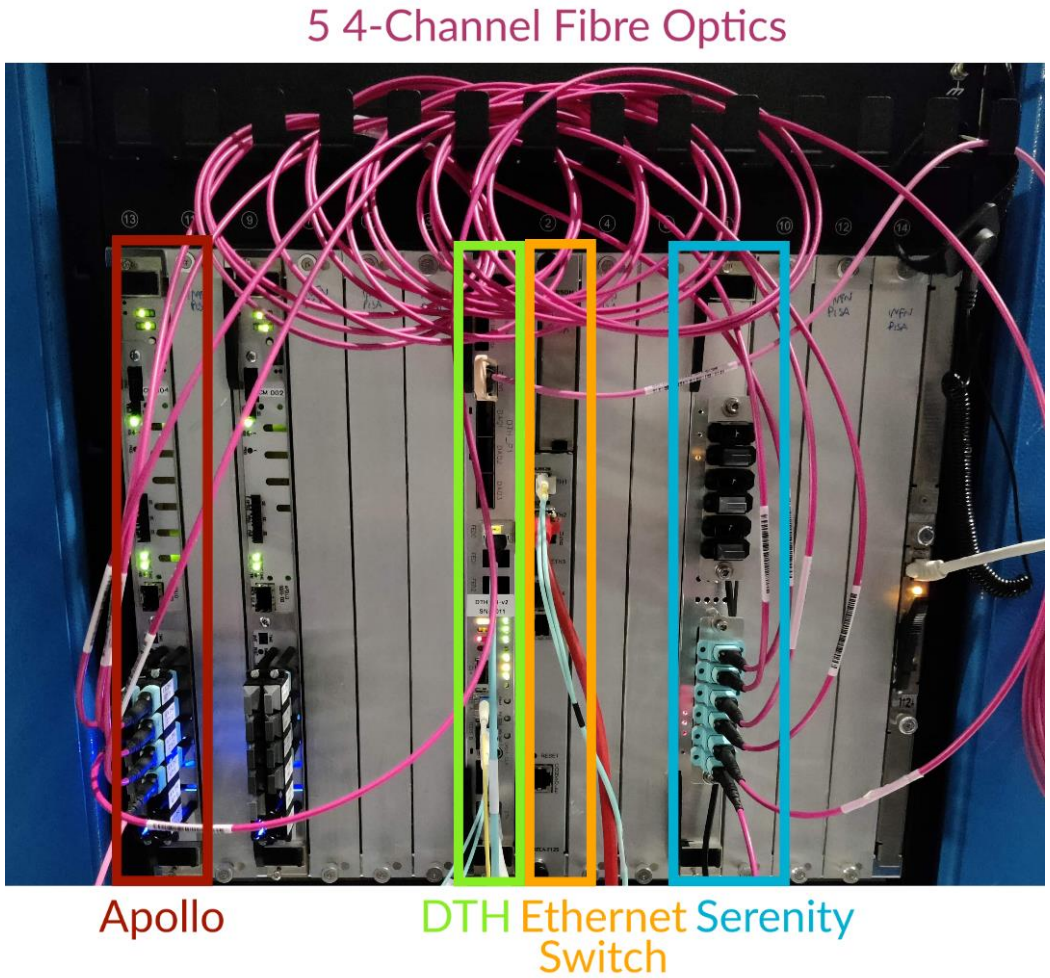
Serenity S1 board
Reading out outer tracker stubs
Level-1 trigger
UK + KIT



APx board
Level-1 trigger
Wisconsin

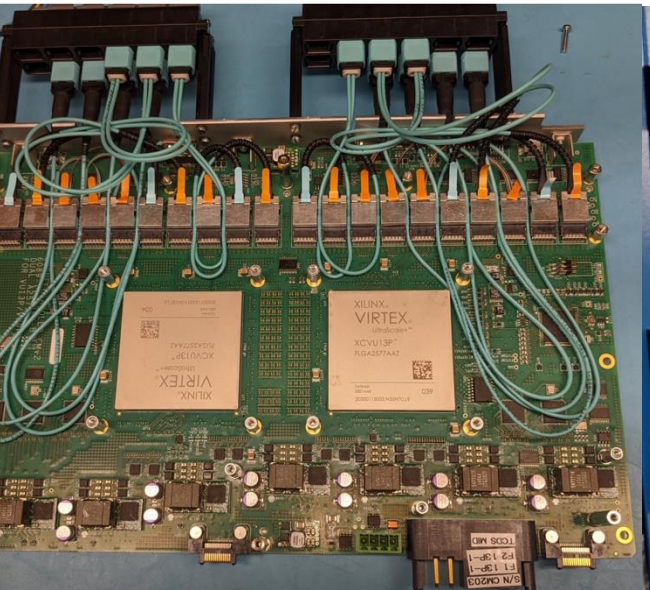
Single VU13P FPGA
Onboard Zynq CPU
IPMC for board control
Firefly optics giving 63 Tb/s Input
> 250 boards in trigger system

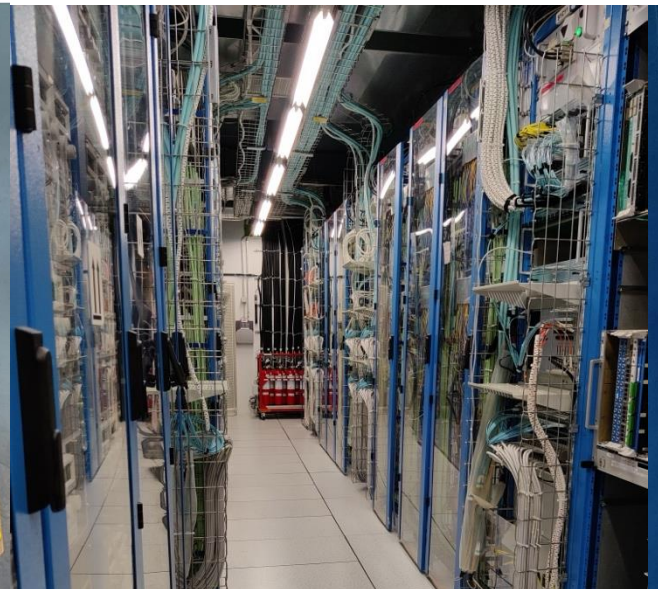
Trigger ATCA Boards

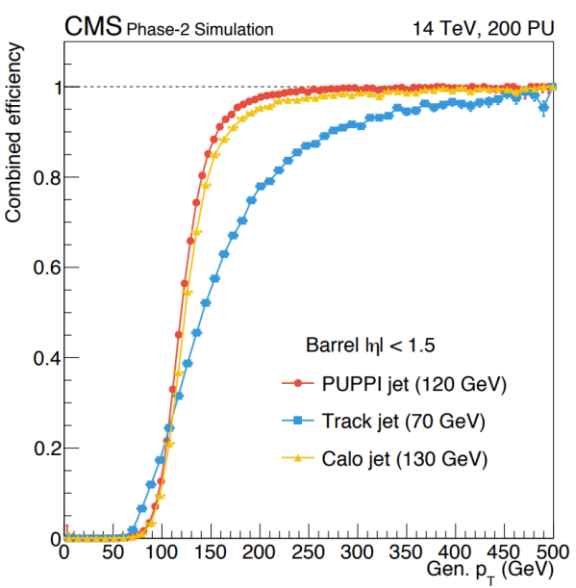


DTH - CMS DAQ and TCDS Hub providing common clock for boards
Ethernet switch for rack management
Online software for board control and monitoring

Trigger


XILINX
VIRTEX
XCVU13P




CMS Phase-2 Simulation
14 TeV, 200 PU
Combined efficiency
Barrel |η| < 1.5
PUPPI jet (120 GeV)
Track jet (70 GeV)
Calo jet (130 GeV)
Gen. p_T (GeV)
0
0.2
0.4
0.6
0.8
1
0
50
100
150
200
250
300
350
400
450
500

Upgraded tracker for Track finding at 40 MHz

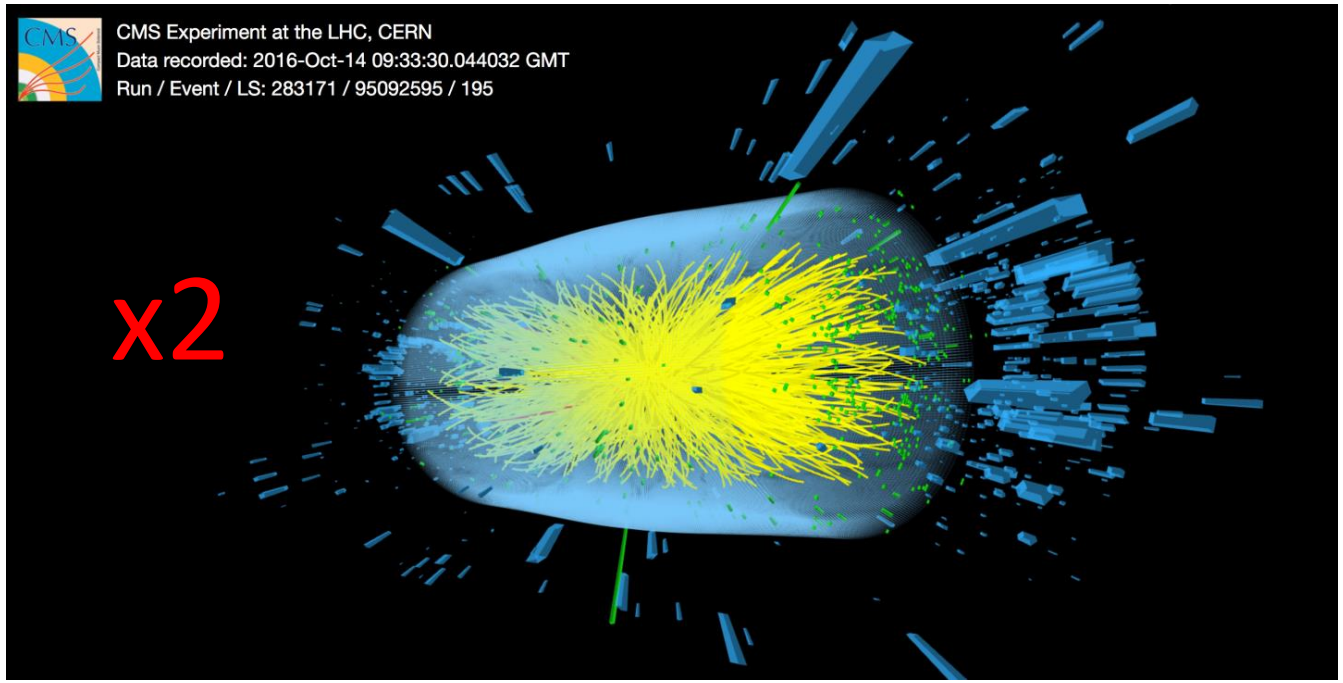
Track finding constraints

200 PU at 40 MHz processing

5 μs to receive data and produce tracks

Need to be able to reconstruct a vertex

Need to be able to pass tracks to downstream algorithms e.g. particle flow



Upgraded tracker for Track finding at 40 MHz

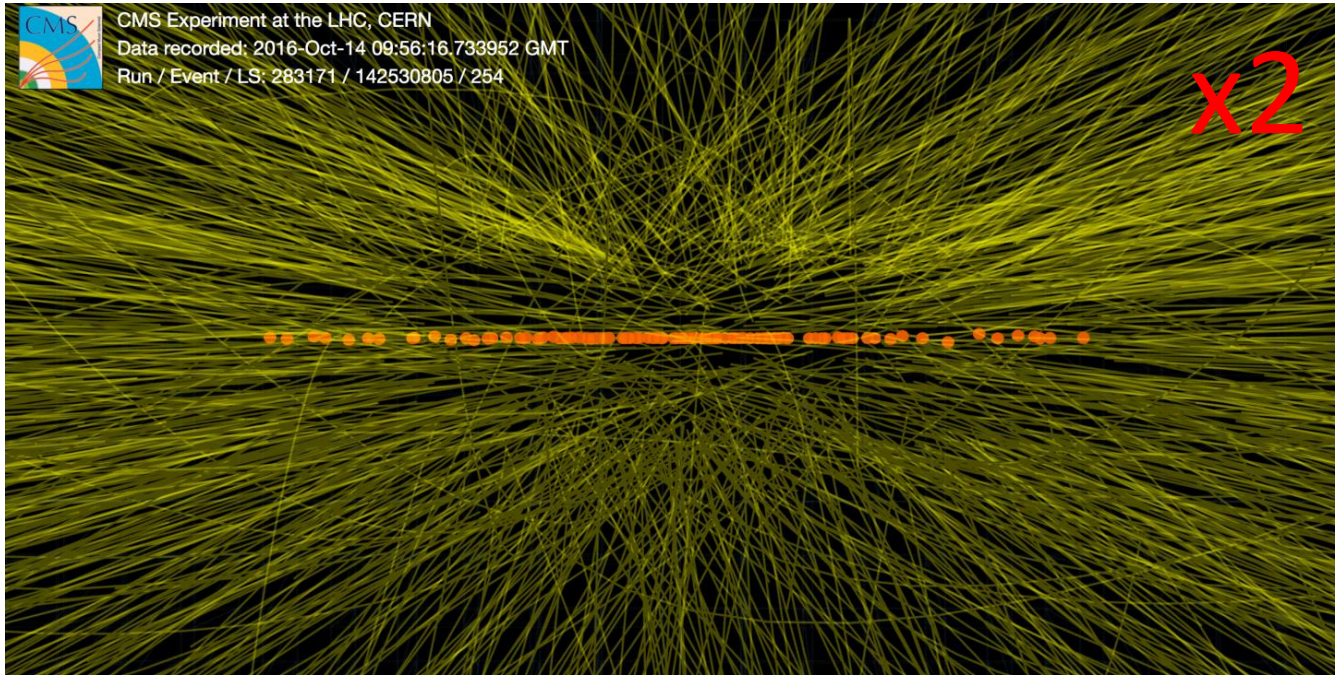
Track finding musts

200 PU at 40 MHz processing
- Highly parallelised algorithm, time and space

5 μs to receive data and produce tracks
- 1 μs stub processing, 4 μs track finding

Need to be able to reconstruct a vertex
- 1 mm track resolution in z_0

Need to be able to pass tracks to downstream algorithms e.g. particle flow
- well reconstructed p_T, η, φ, z_0, quality variables



Upgraded tracker for Track finding at 40 MHz

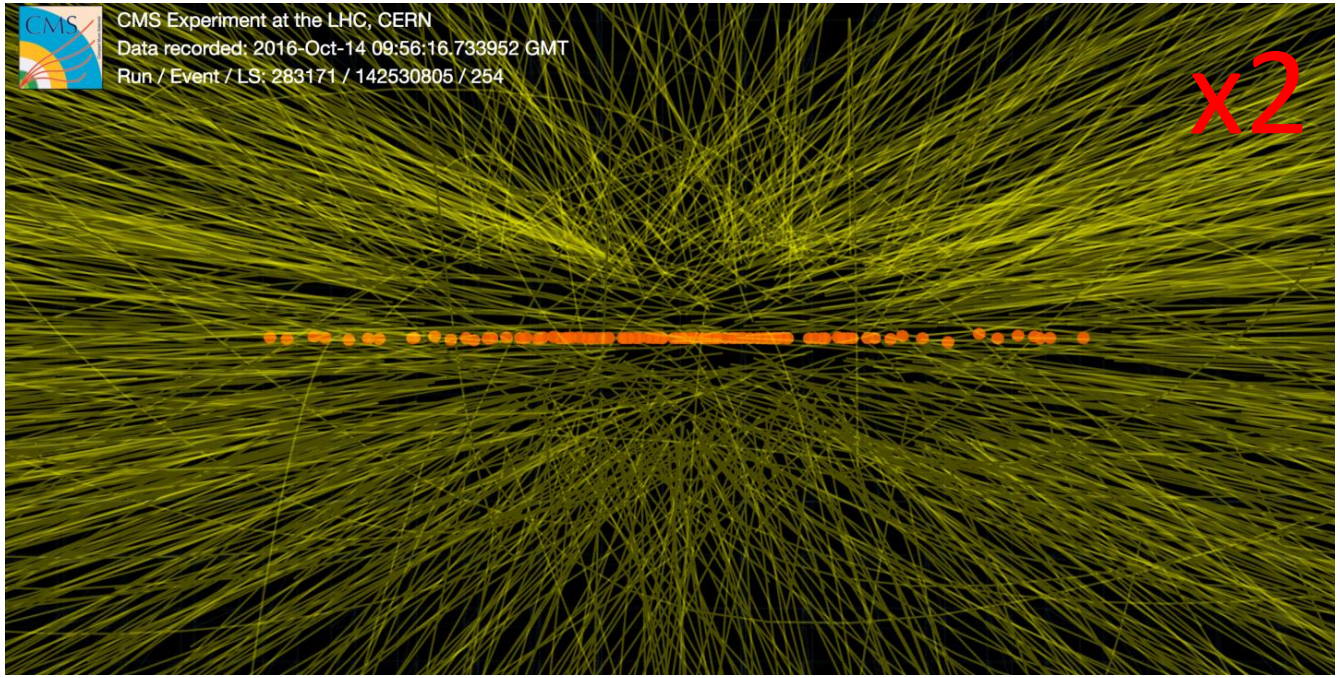
Track finding wants

High and flat efficiency for tracks across $|\eta| < 2.4$

Low fake rate (tracks not matched to real particles)

Robust to breaking detector

Displaced track finding

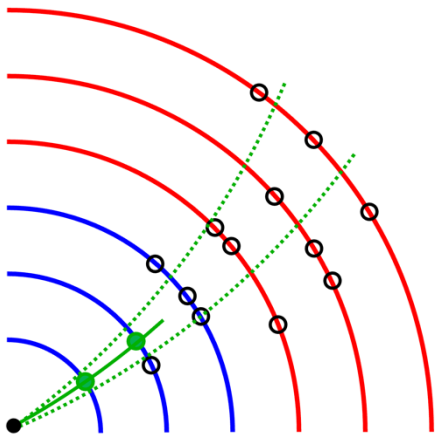


Hybrid Algorithm

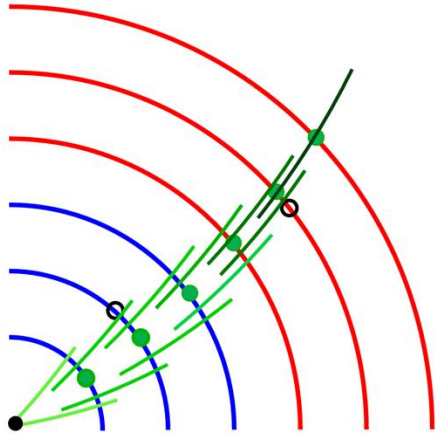
Reconstruct all tracks $p_T > 2$ GeV, $|\eta| < 2.4$
4 μs to process over 10,000 stubs and form $\mathcal{O}$ (100) prompt tracks per event

Hybrid algorithm

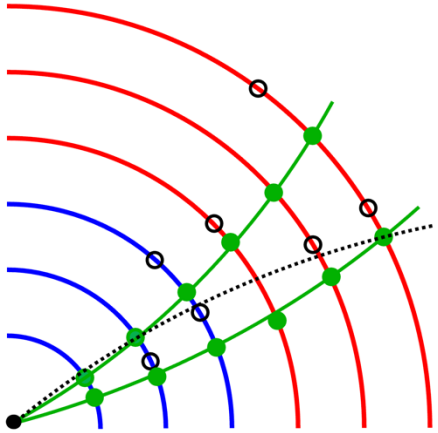
1. Road search algorithm based on tracklet seeds
2. Kalman filter for identify best stub candidates and track parameters
3. Boosted decision tree to evaluate track quality



1.

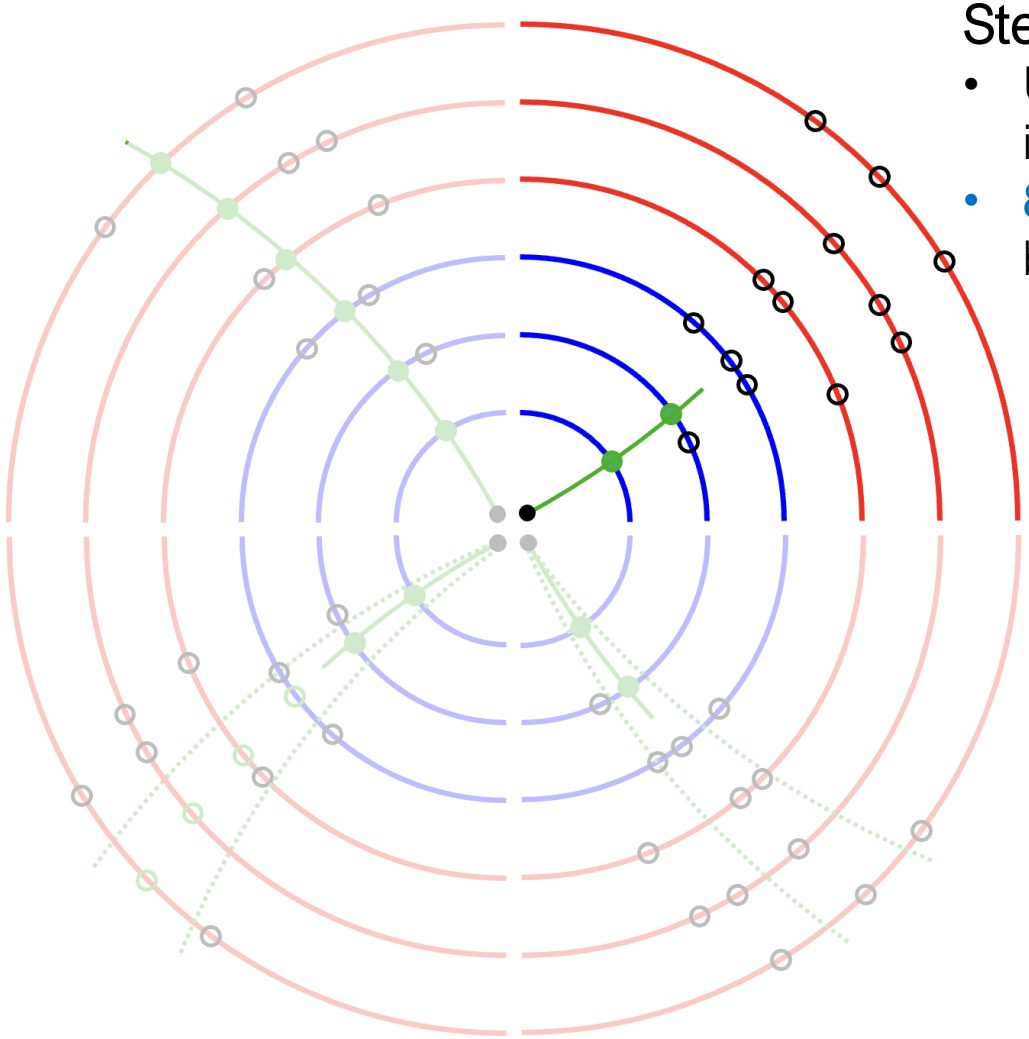


2.



3.

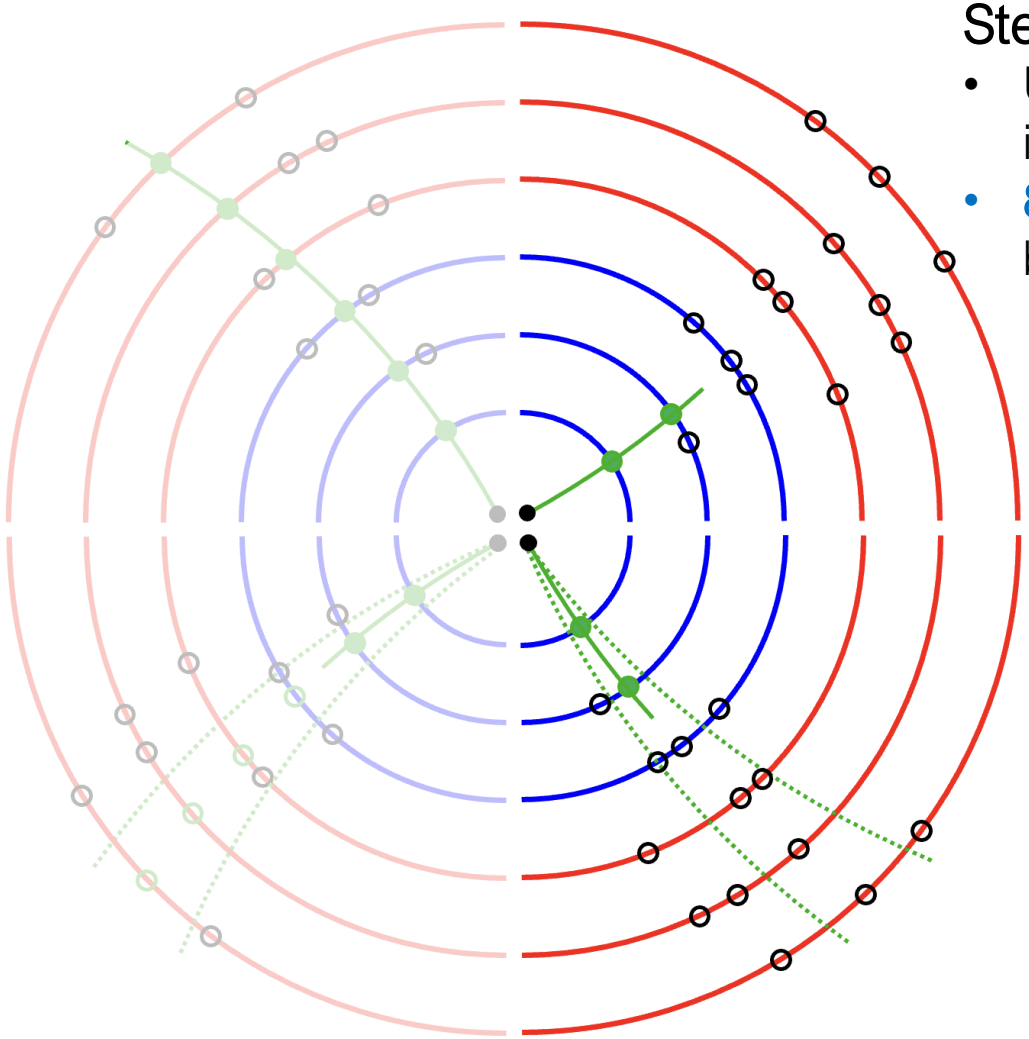
Hybrid Algorithm - Tracklet



Step 1

- Use two stub seeds to create initial tracklets
- 8 different combinations of barrel and endcap layers

Hybrid Algorithm - Tracklet



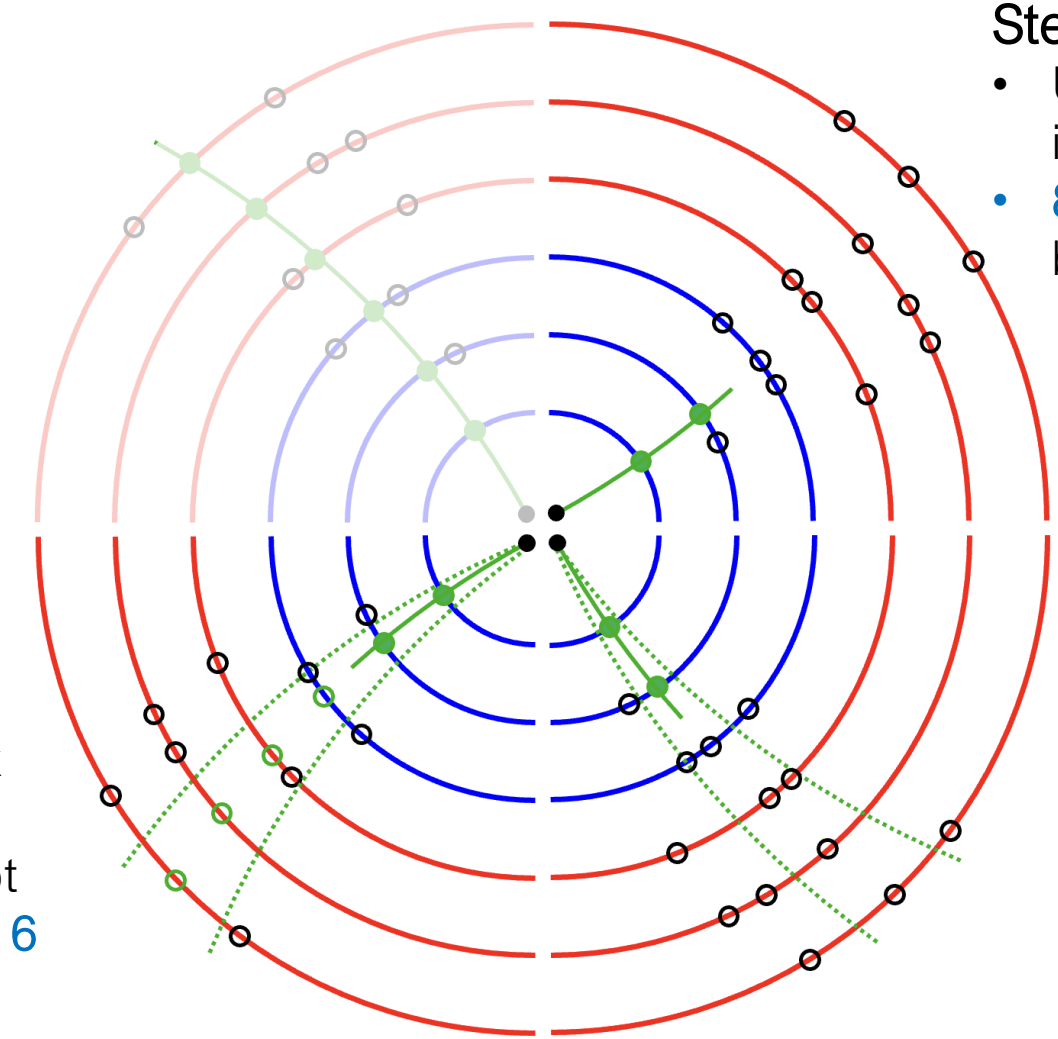
Step 1

- Use two stub seeds to create initial tracklets
- 8 different combinations of barrel and endcap layers

Step 2

- Project track candidates outwards/inwards
- Based on a beamspot constraint
- Create a search window for more stubs

Hybrid Algorithm - Tracklet



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- Add matching stubs to track candidate
- Smallest residual stub is kept
- Minimum 4 stubs, maximum 6 stubs for a track

Hybrid Algorithm - Tracklet

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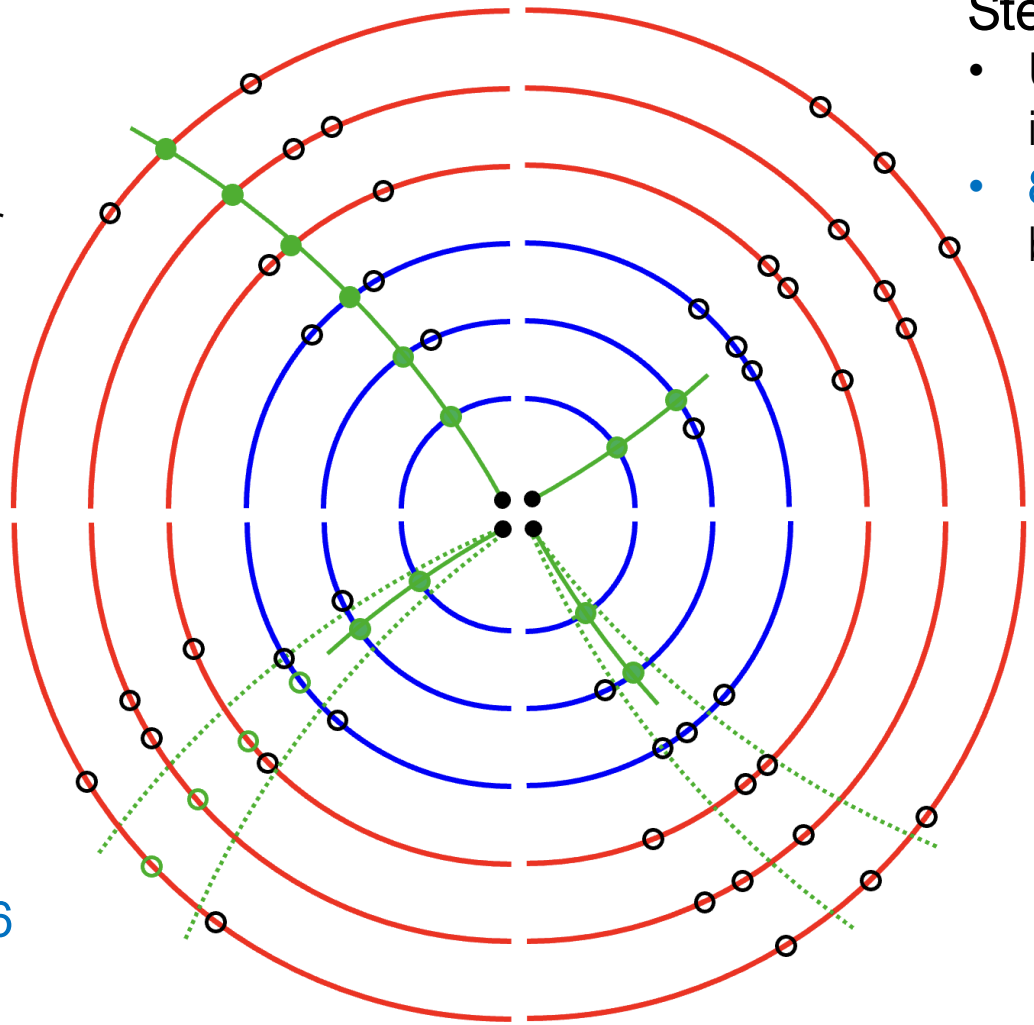

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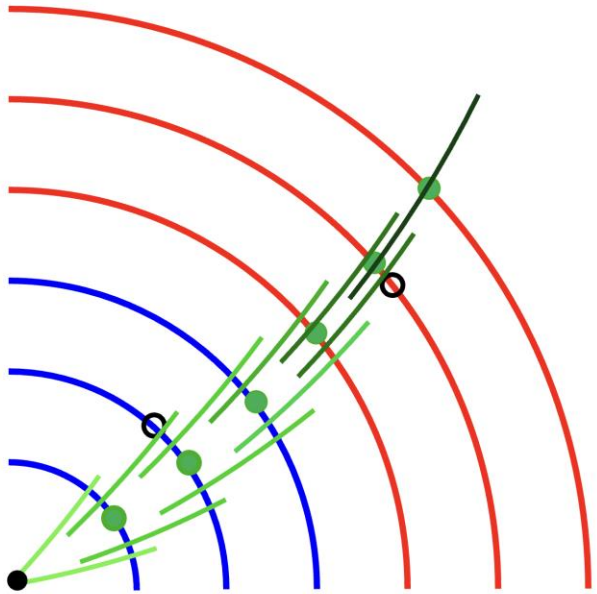
- Based on a beamspot constraint
- Create a search window for more stubs

Step 3
- Add matching stubs to track candidate
- Smallest residual stub is kept
- Minimum 4 stubs, maximum 6 stubs for a track

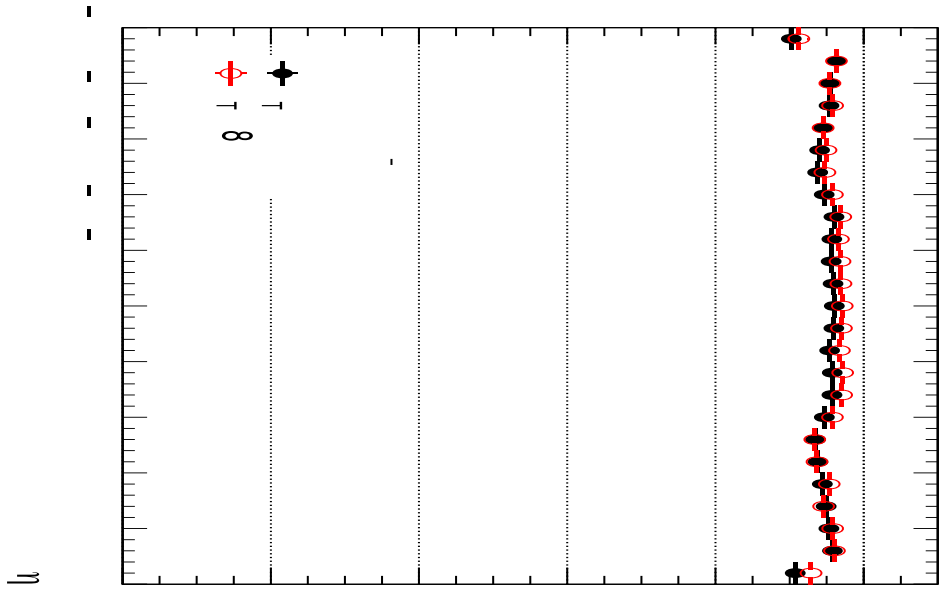
Step 4
- Pass track candidates downstream to track merger and Kalman Filter

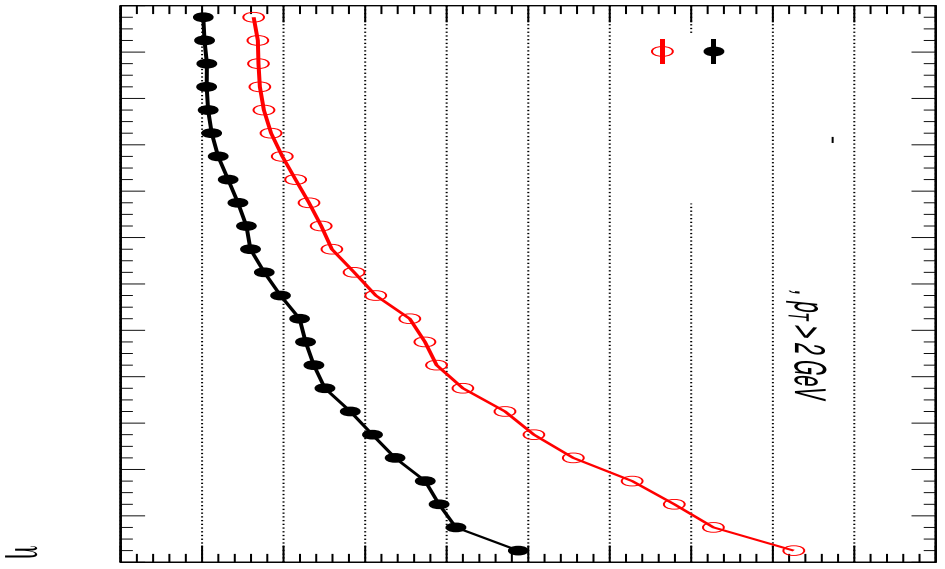
Hybrid Algorithm – Kalman Filter

- Takes track candidates and track residuals to form Kalman filter state and covariance matrix respectively
- Stubs are iteratively added a layer at a time in a state propagation and state update
- State propagation estimates the track in the next layer
- State update uses the recorded stubs and their uncertainties to improve the track state, removing any tracks with incompatible stubs
- Track fit iteratively improves as stubs are added



Hybrid Algorithm - Performance

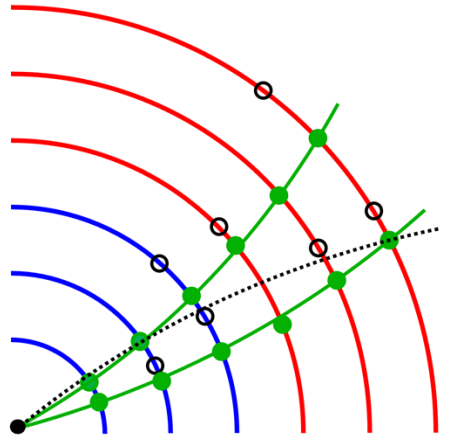




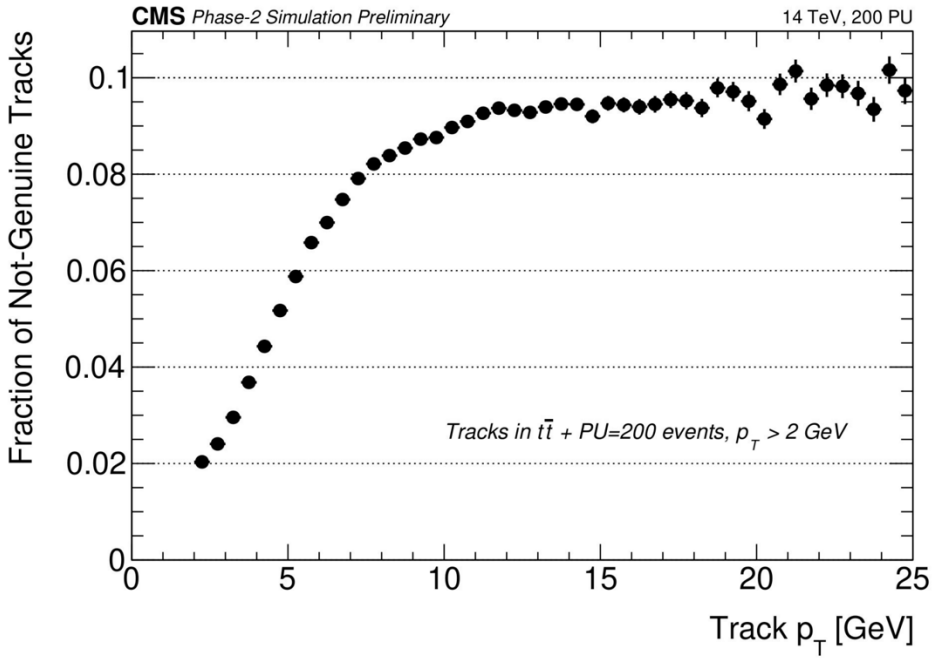
High efficiency across η
Transition regions see fewer layers crossed so slight dip in efficiency at η = 1

1 mm z_0 resolution for tracks → good enough for vertex association in 200 PU
Worse resolution in η because of barrel geometry

Hybrid Algorithm – Track Quality

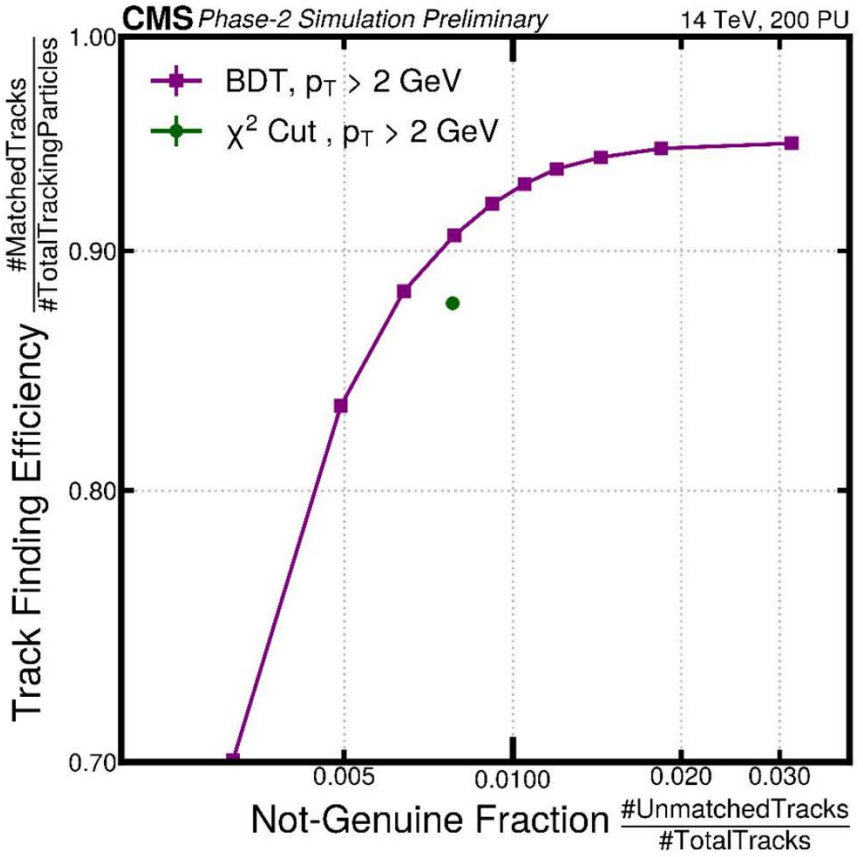


- High fake rate → tracks not coming from genuine charged particles
- Issue for algorithms such as E_T^{miss} where single high p_T tracks can reduce efficiency
- Kalman Filter calculated χ^2 fit parameters
- Can use these to reduce fake tracks → handle for downstream algorithms

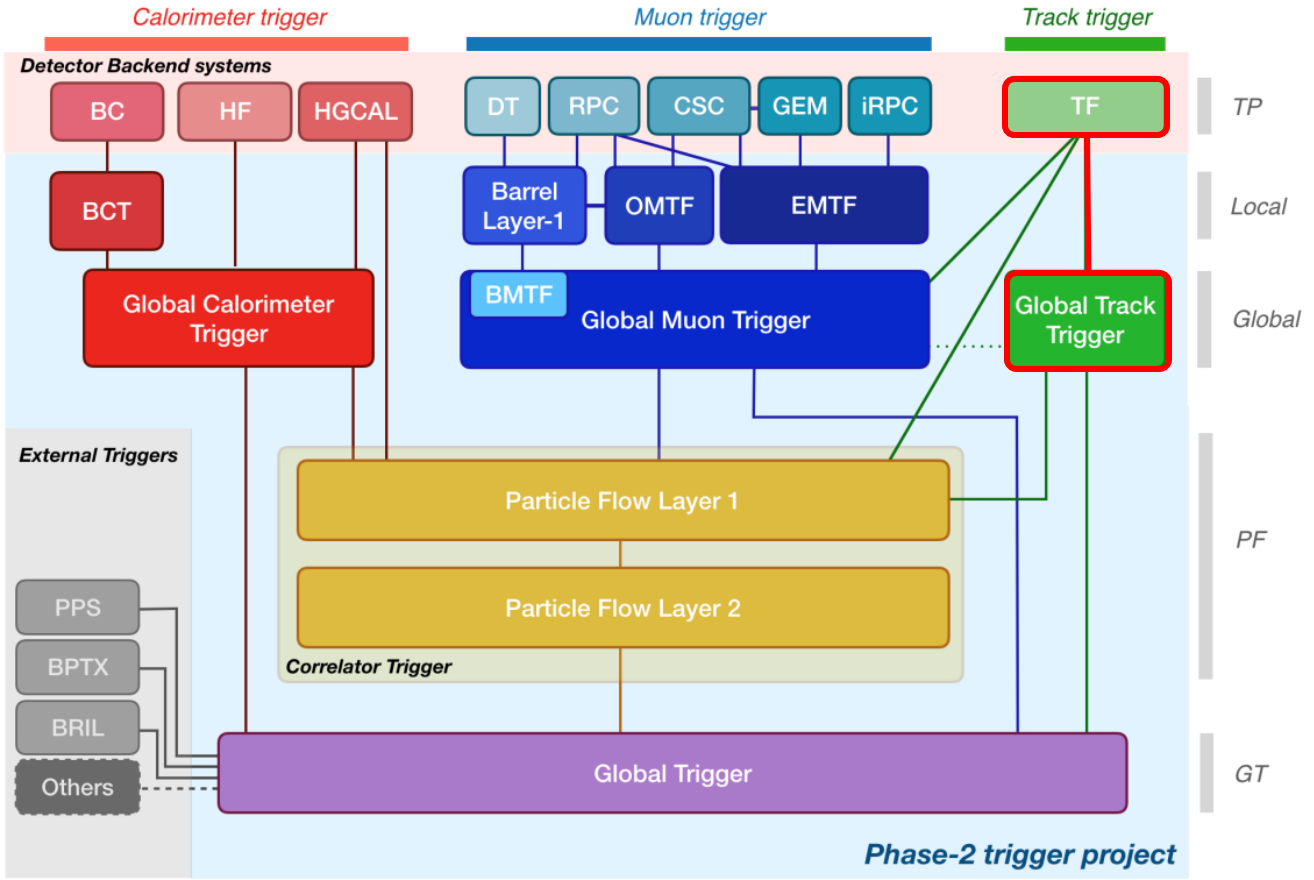


Hybrid Algorithm – Track Quality

- Complex dependence of χ^2 in different η and z_0 regions
- Single cut on χ^2 cannot account for these interdependencies
- Simple boosted decision tree (60 trees, 3 deep) can improve identification
- Can be retrained and tuned as track finding evolves
- Single value for downstream users

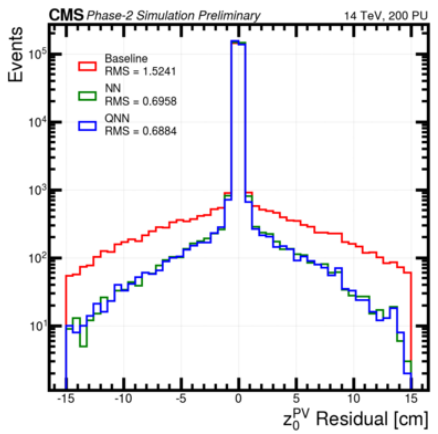


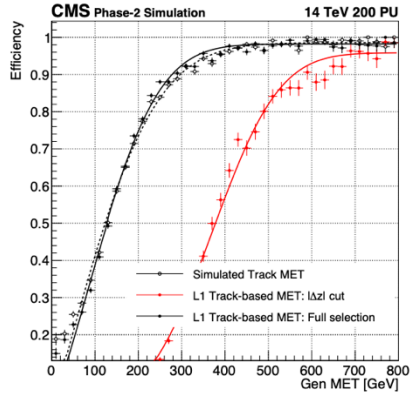
Tracks in the L1 trigger

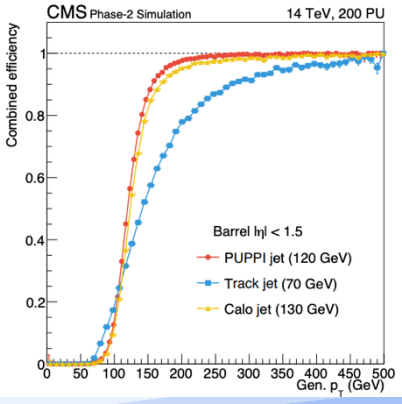


Global Track Trigger

- Event level quantities
- Vertex Finding
- Track-based E_T^{miss}
- Track-based Jets
- Exotic decays e.g. W→3π







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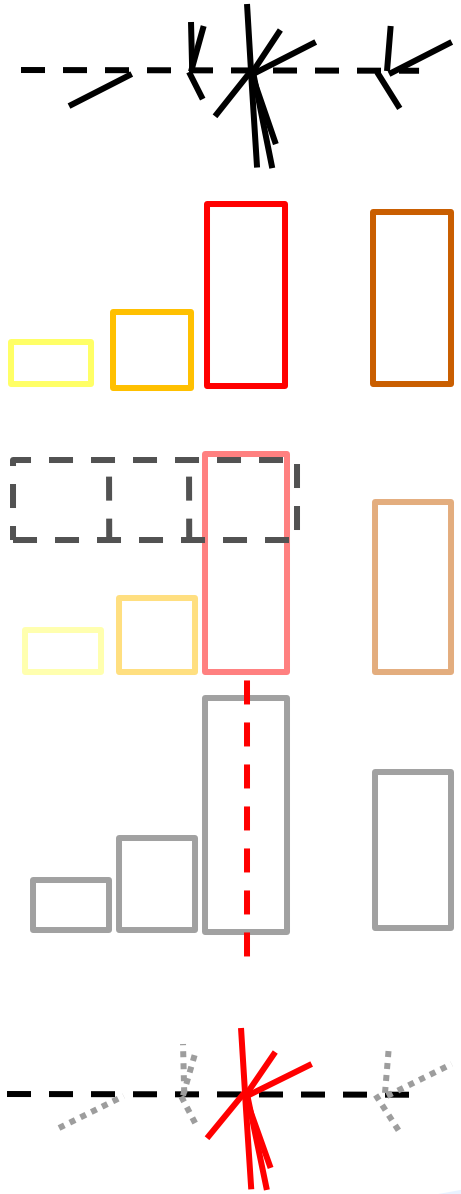


Vertex Finding

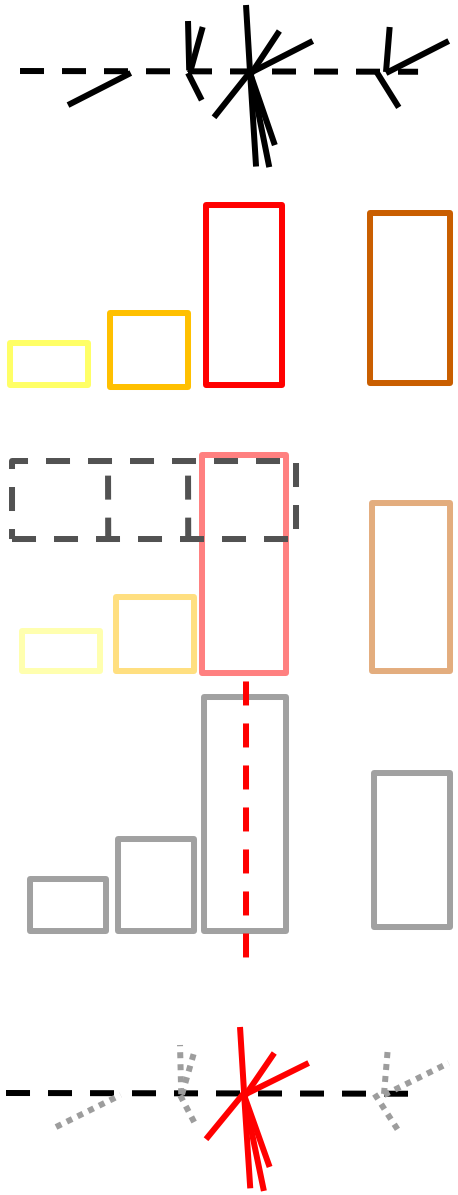
Baseline

p_T weighted histogram

3-bin sliding window sum

z_0 peak finder

z_0 window track-to-vertex association



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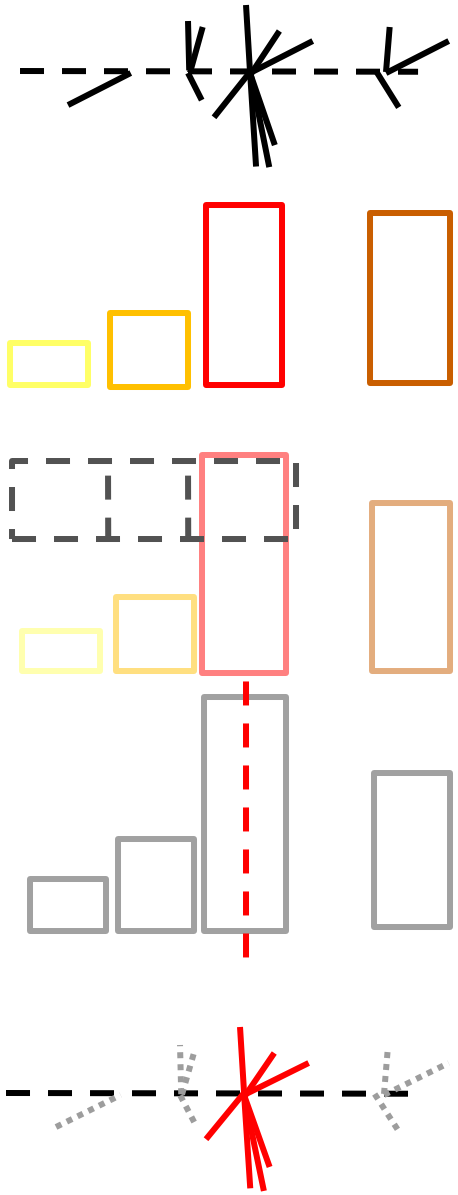

End-to-end Neural Network

DNN learnt weighted histogram

Vertex Finding

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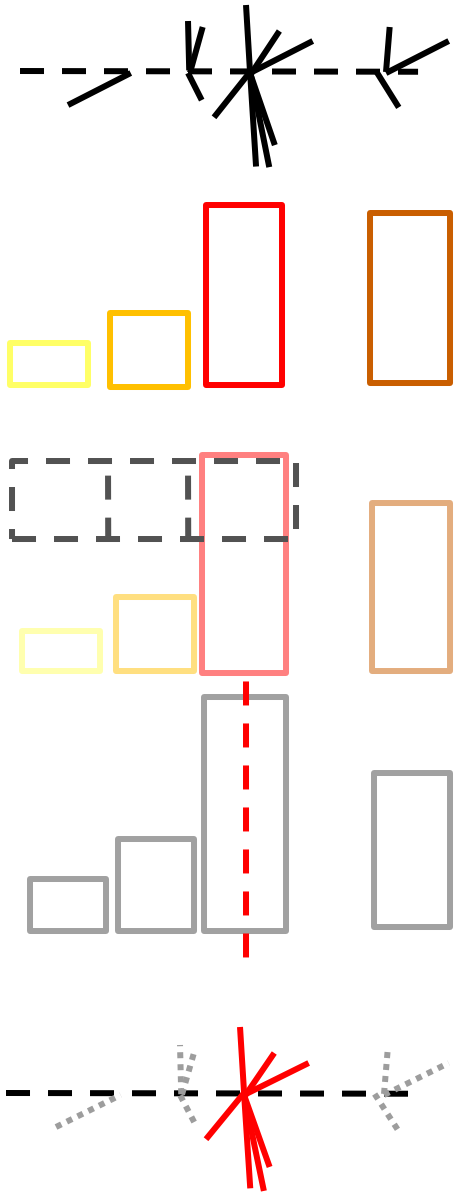

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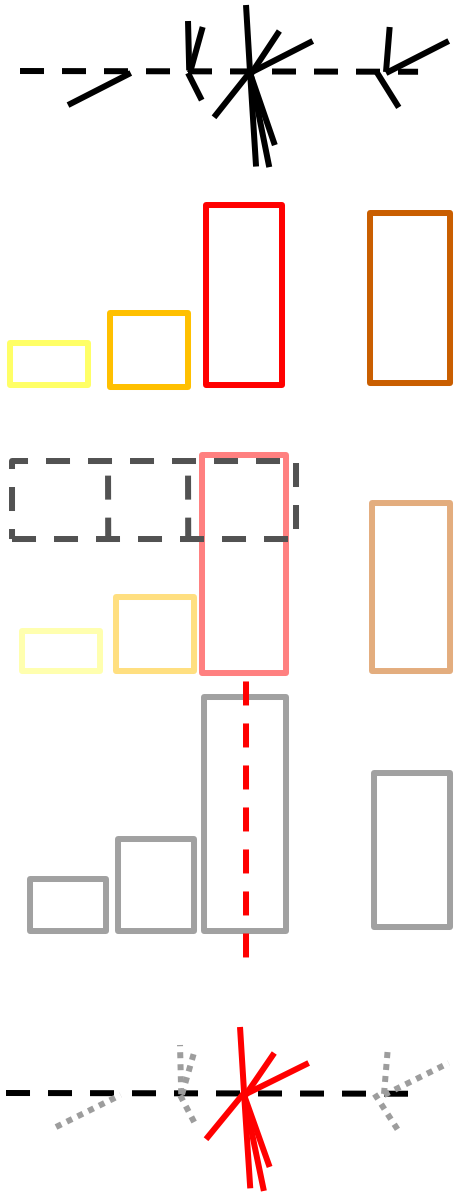

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Vertex Finding

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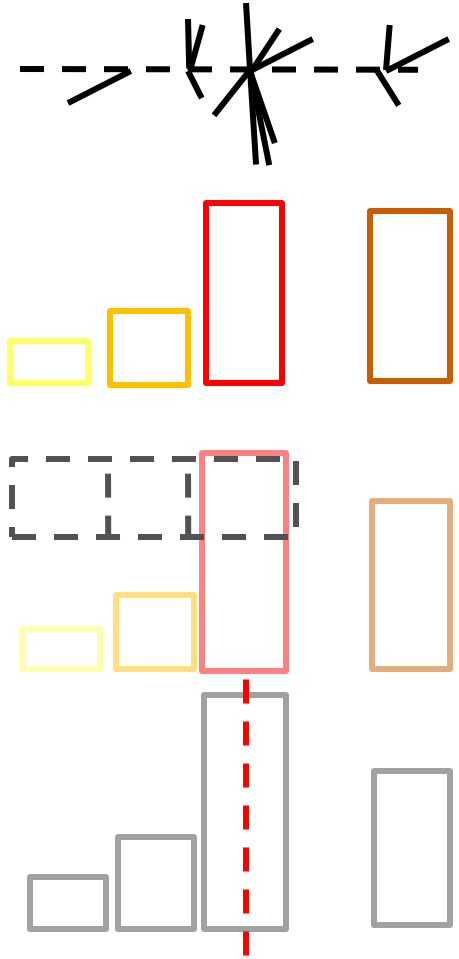
p_T weighted histogram		DNN learnt weighted histogram
3-bin sliding window sum		3-bin 1D CNN
z_0 peak finder		z_0 peak finder
z_0 window track-to-vertex association		DNN for classifying PV tracks

Vertex Finding

End-to-end vertex finding for the HL-LHC

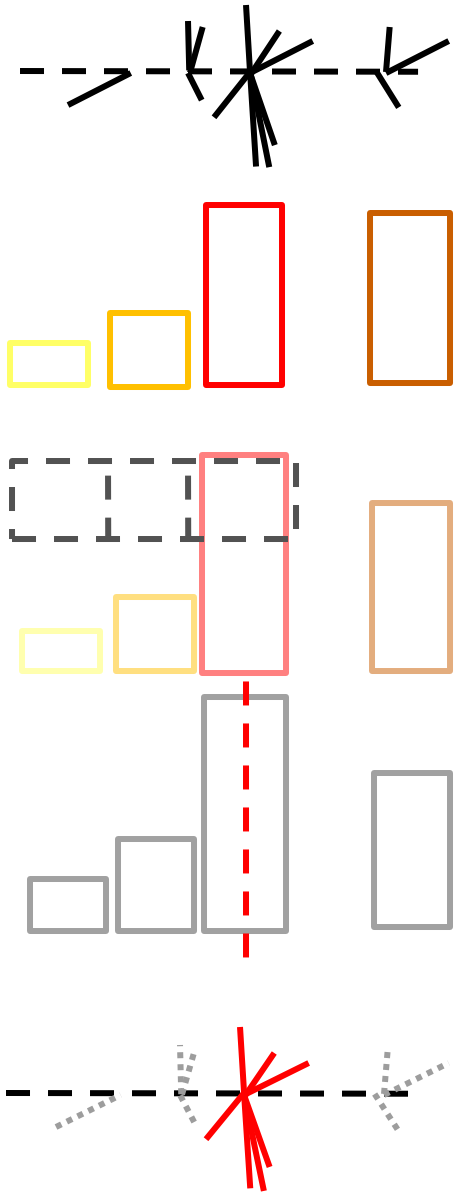
Baseline

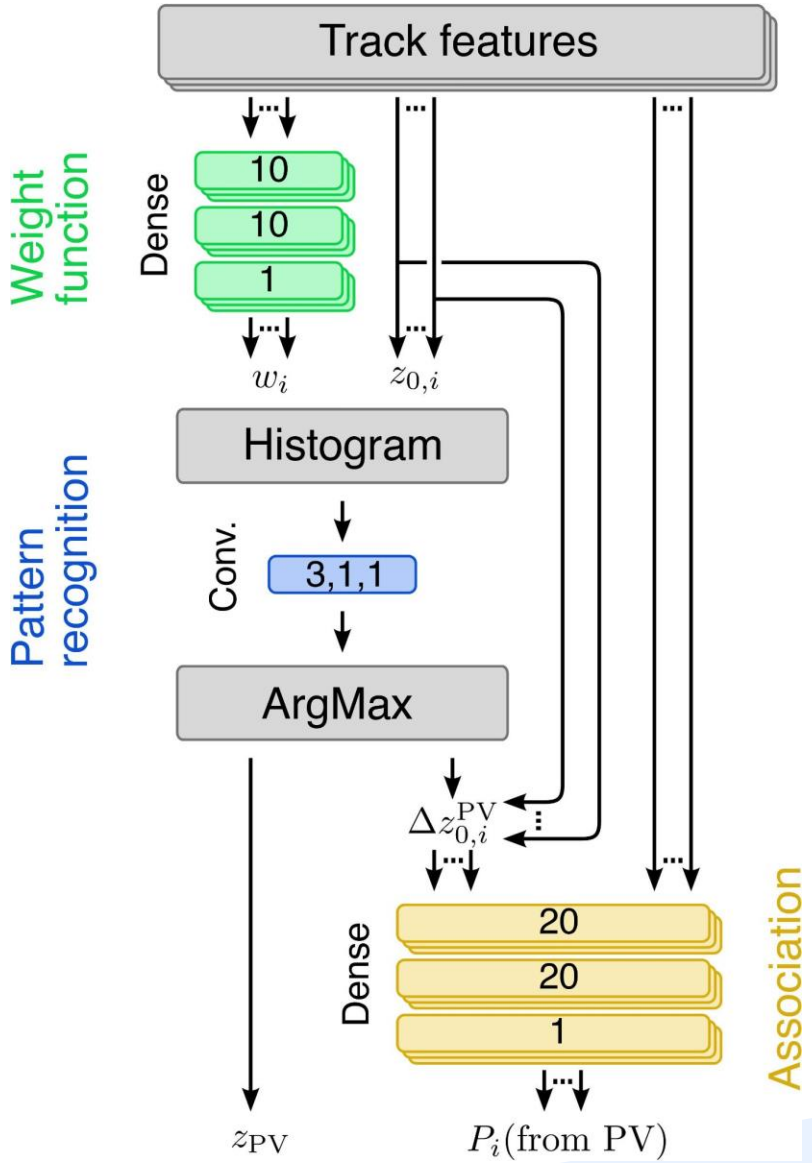
p_T weighted histogram

3-bin sliding window sum

z_0 peak finder

z_0 window track-to-vertex association





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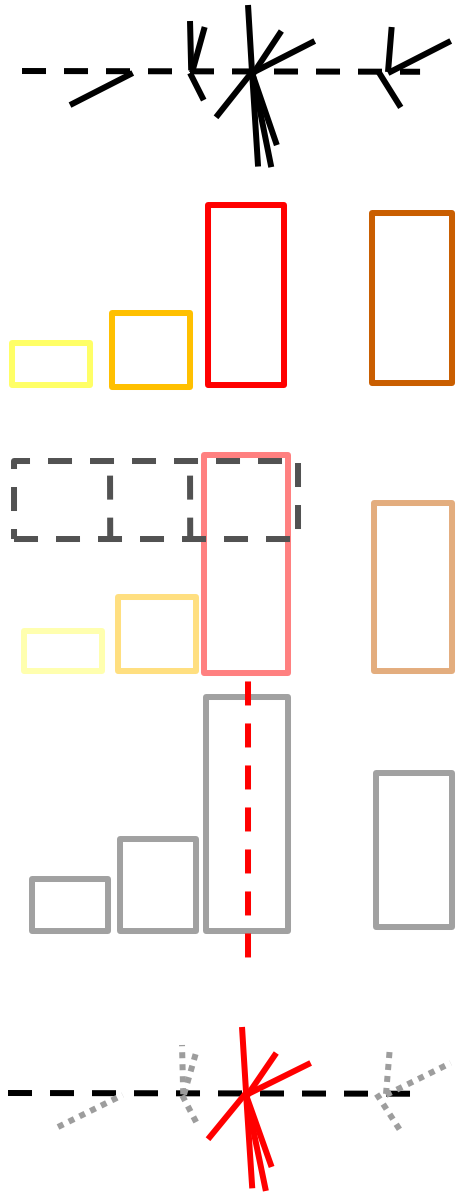
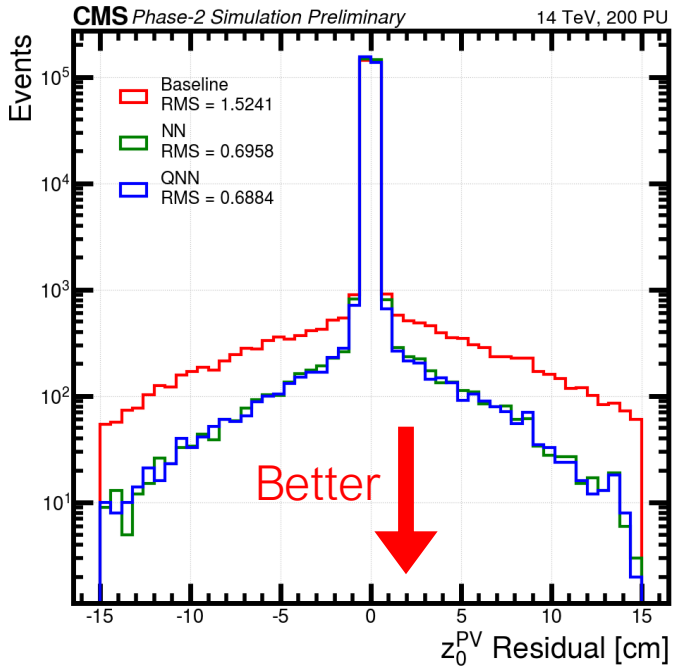
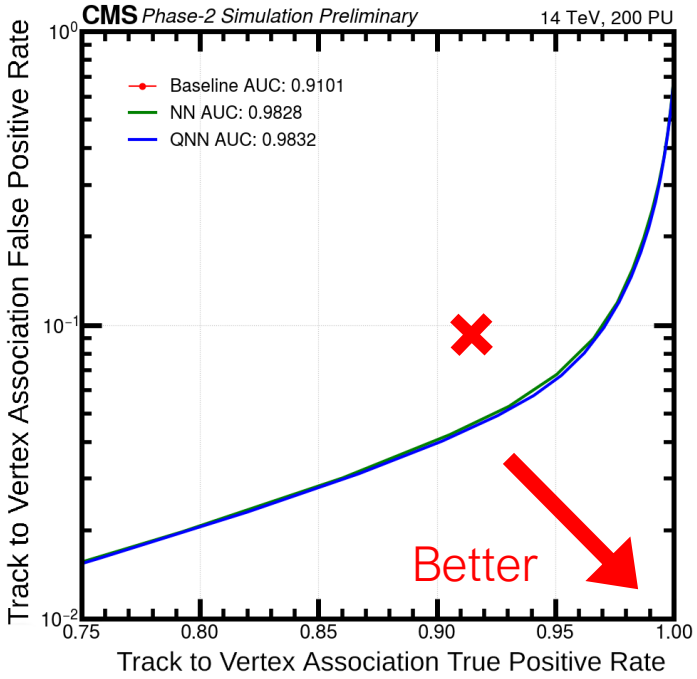
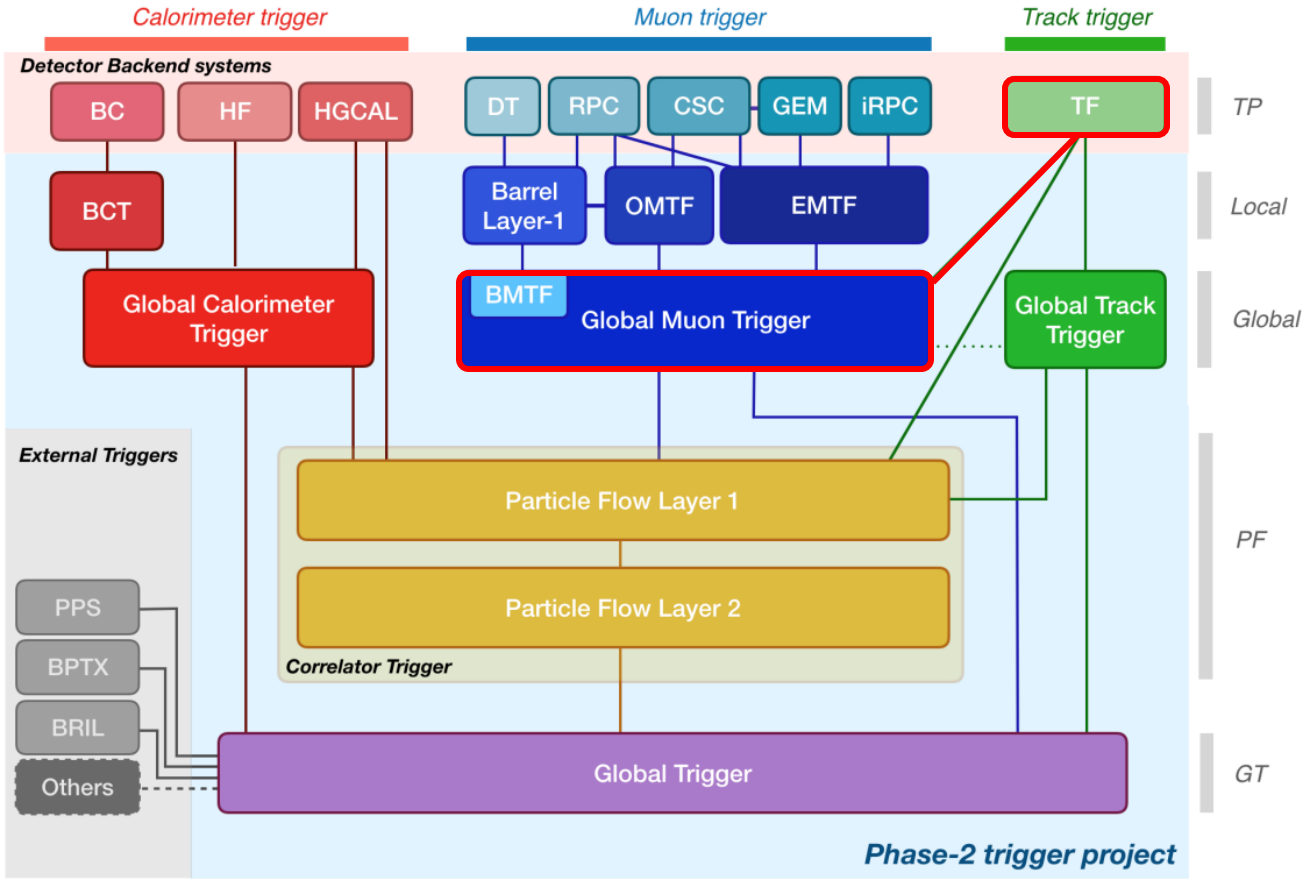




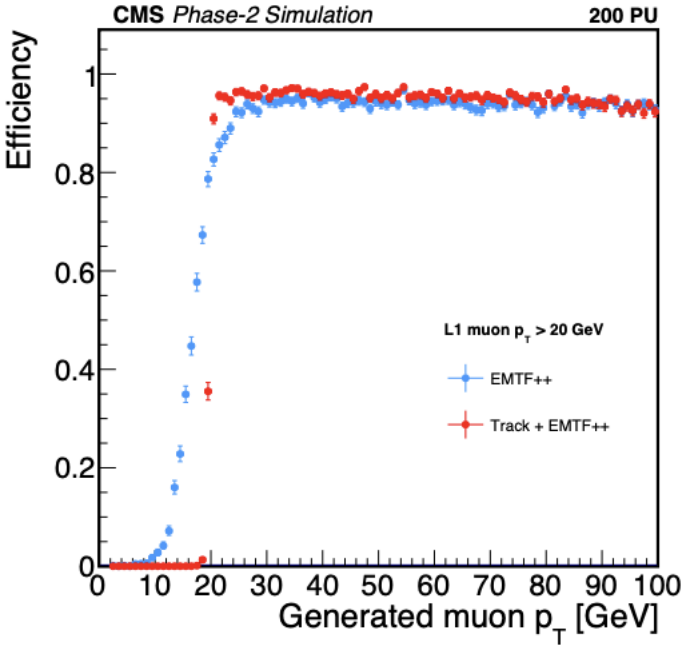


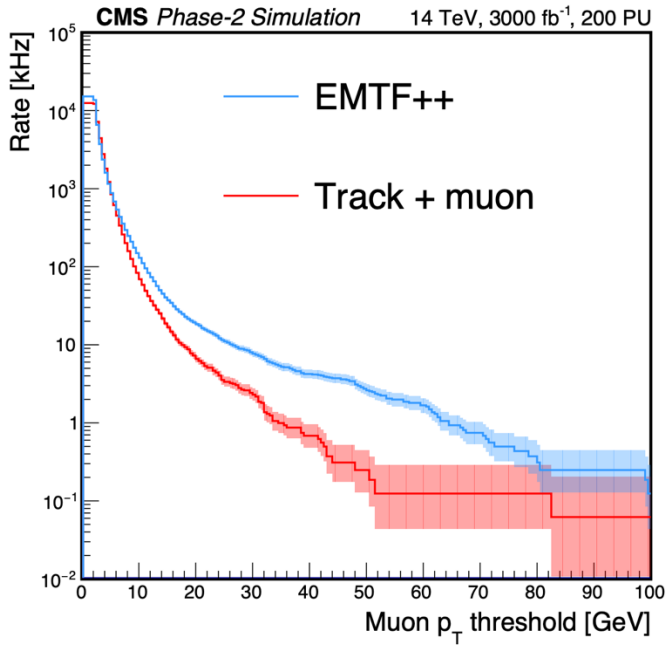
Tracks in the L1 trigger



Muon Trigger

- Link track and muon objects based on η φ cuts
- Sharper turn ons, higher efficiency
- Lower rate, higher purity
- Also match muon stubs to tracks needed for overlap regions





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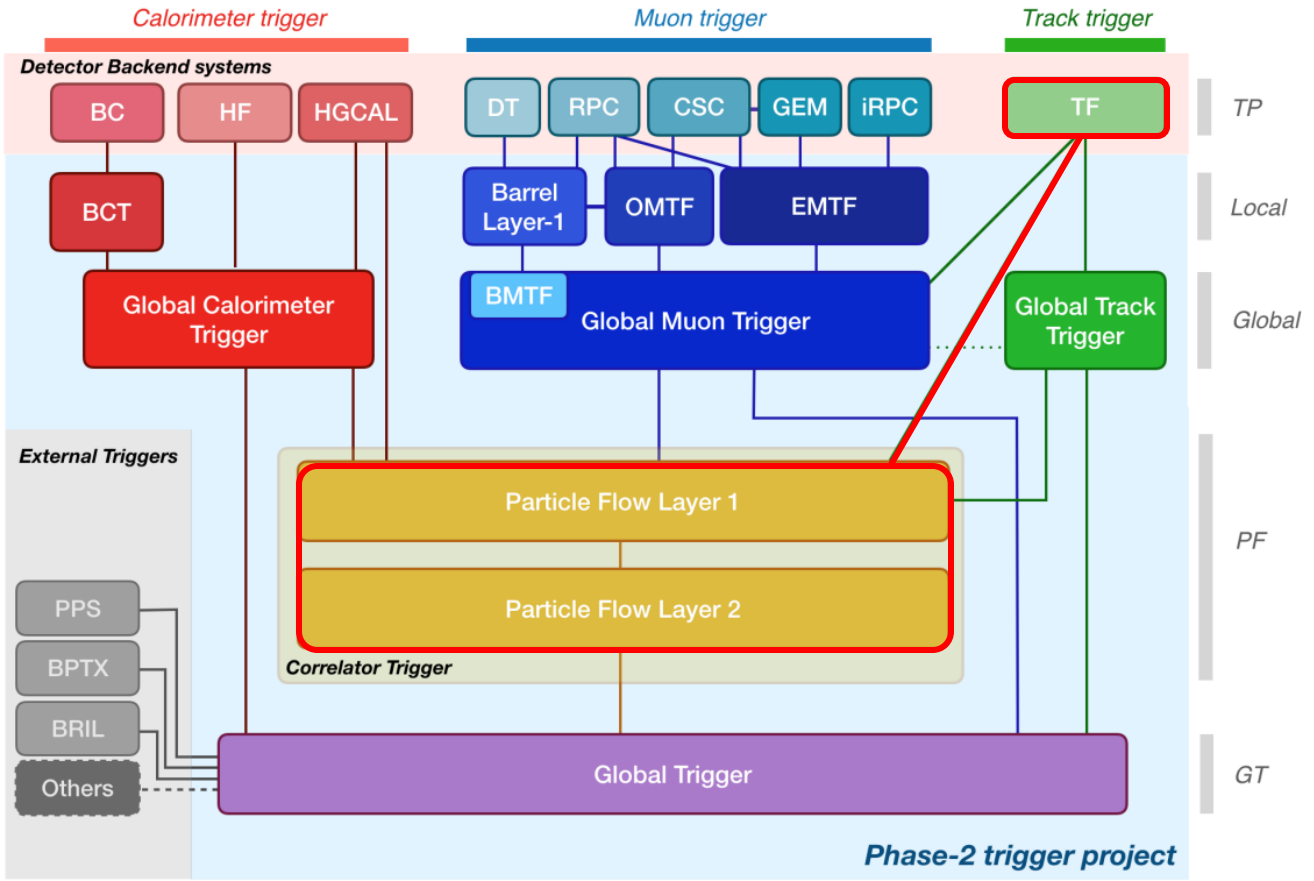
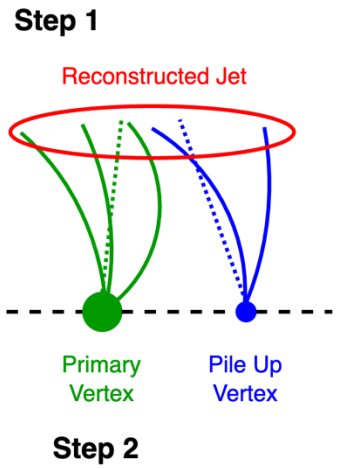
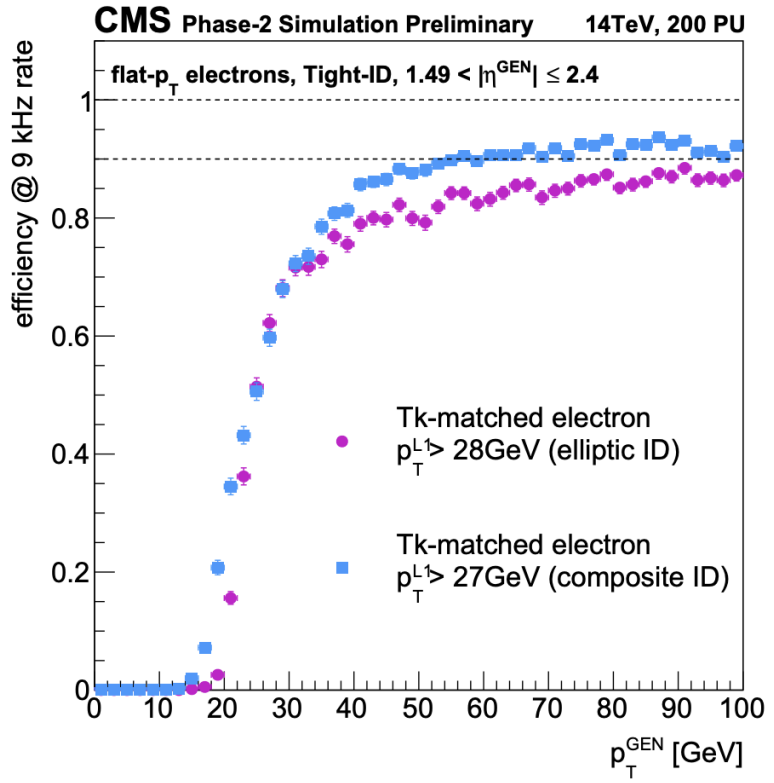


Correlator Trigger

- 2 layers
- First layer performs particle flow and pile up per particle identification (PUPPI)
- Linking objects from multiple subsystems
- Use vertex to weight PF candidates as coming from primary vertex or PU
- Reduces number of candidates in downstream algorithms
- Reduces impact of high PU on downstream algorithms
- Track matched electron ID, BDT boosts performance

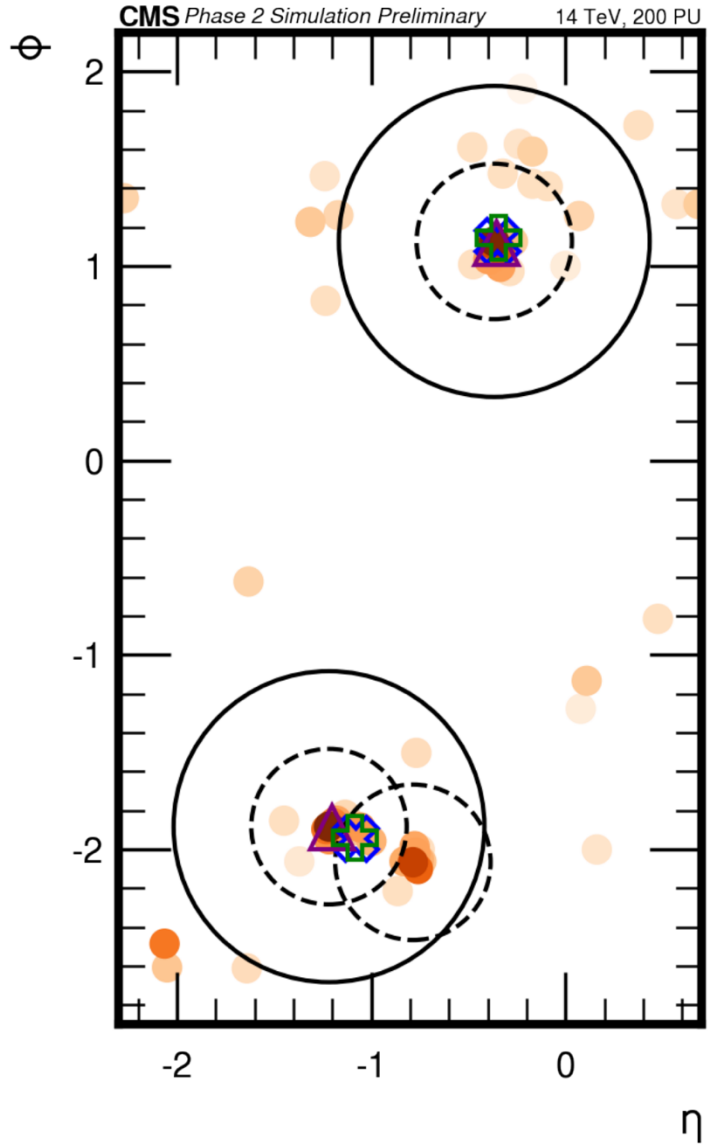


Step 2



Correlator Trigger

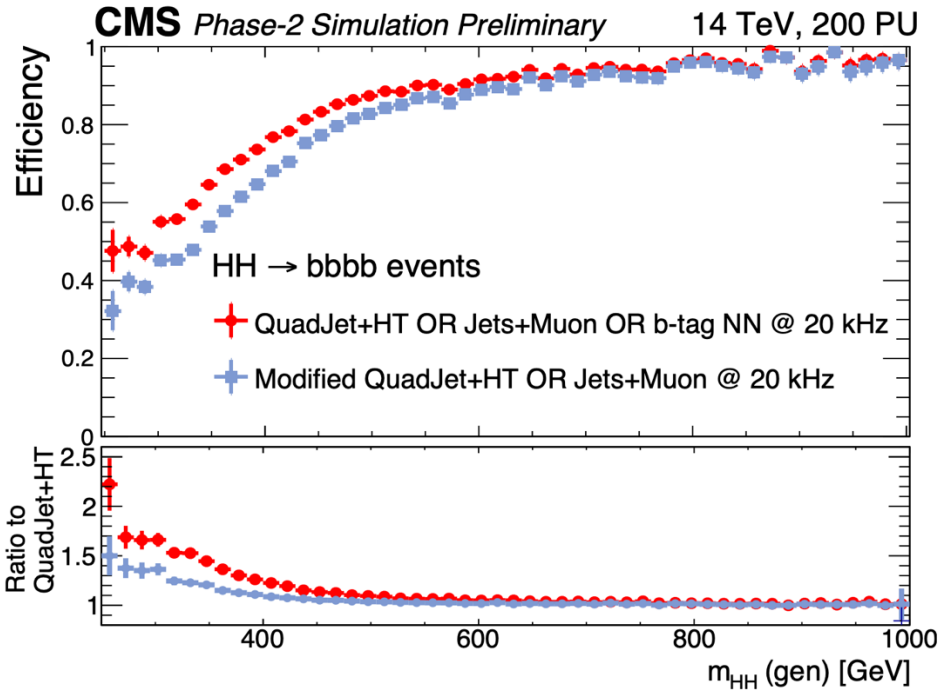
- Second layer performs jet reconstruction, E_T^{miss} calculations, e/γ isolation, τ tagging
- Better reconstruction due to PUPPI
- Objects to trigger on sent to global trigger
- Time to do complex jet tagging using neural networks

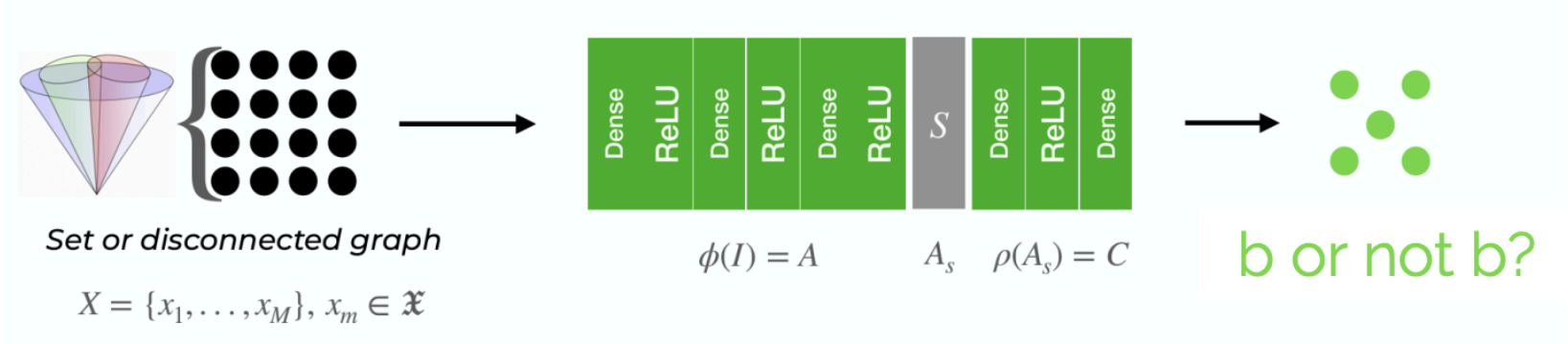


Jet Seeded cone algorithm for HL-LHC

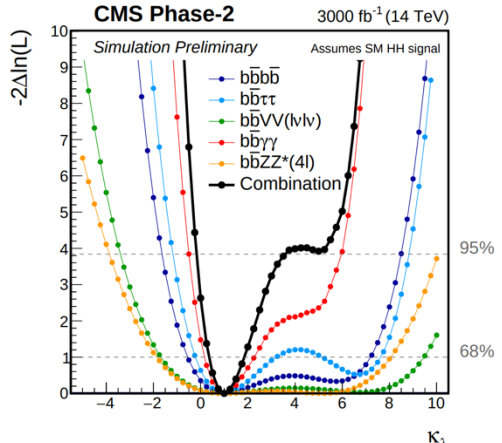
Jet Tagging

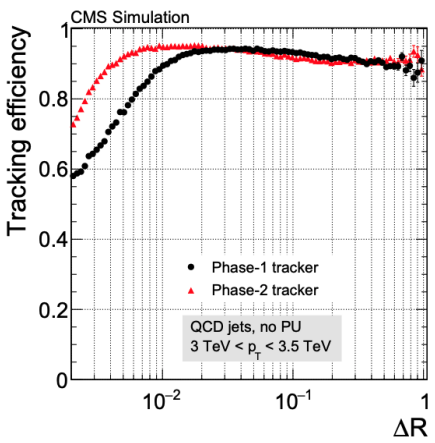
- Useful to understand jet origin
- Downstream global trigger can have event type specific taggers
- B-jet taggers obvious starting point
- Tau taggers also implemented
- Future:
  - Single deepset model
  - Multijet classifiers
  - Regress jet p_T

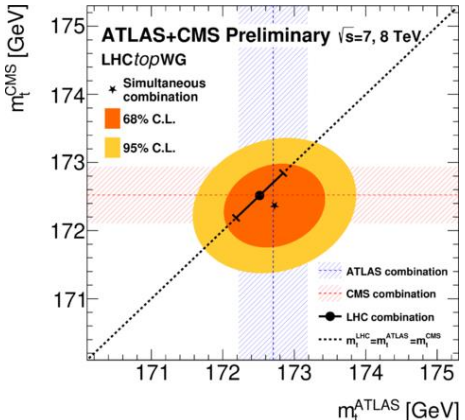


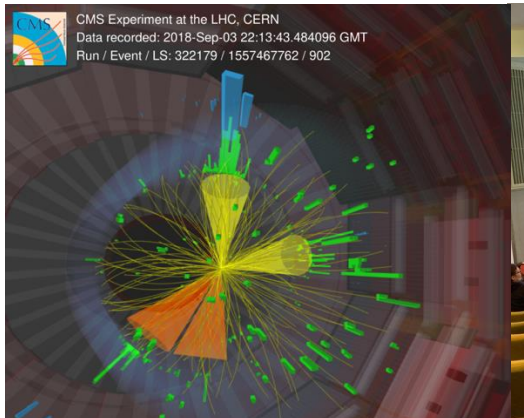


Physics


CMS Phase-2
3000 fb-1 (14 TeV)
Simulation Preliminary
Assumes SM HH signal
bb̄bb̄
bb̄ττ
bb̄VV(lνlν)
bb̄γγ
bb̄ZZ*(4l)
Combination
95%
68%
-2Δln(L)
κλ

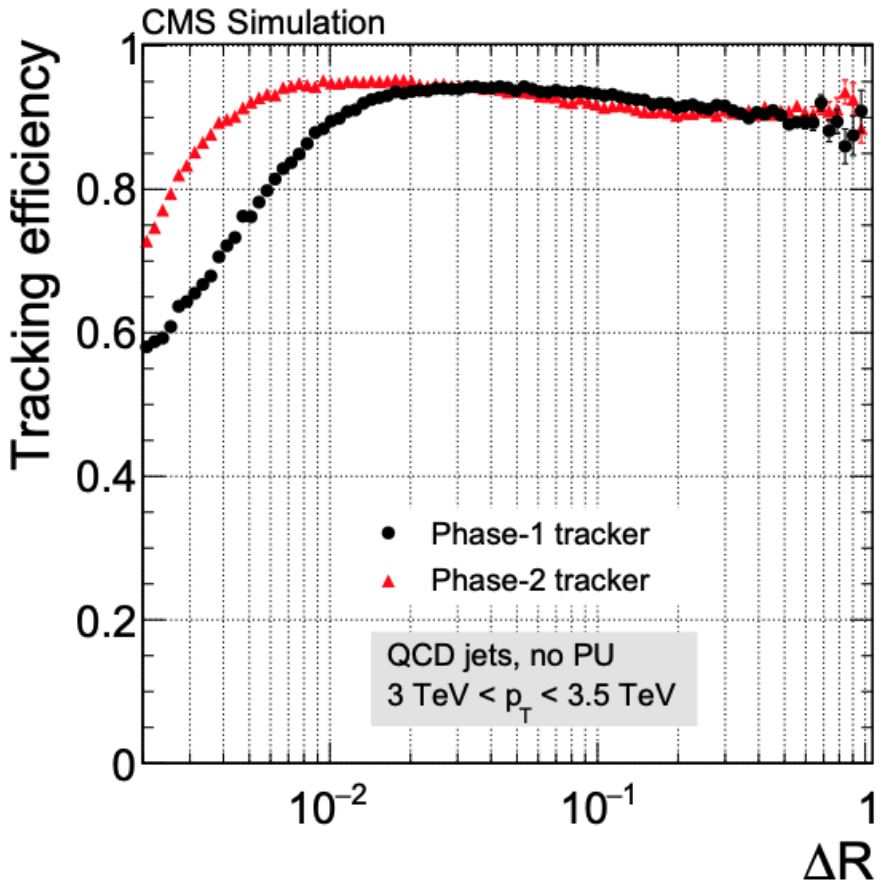

CMS Simulation
Tracking efficiency
Phase-1 tracker
Phase-2 tracker
QCD jets, no PU
3 TeV < pT < 3.5 TeV
ΔR


ATLAS+CMS Preliminary √s=7, 8 TeV
LHCtopWG
Simultaneous combination
68% C.L.
95% C.L.
ATLAS combination
CMS combination
LHC combination
mtCMS [GeV]
mtATLAS [GeV]


CMS Experiment at the LHC, CERN
Data recorded: 2018-Sep-03 22:13:43.484096 GMT
Run / Event / LS: 322179 / 1557467762 / 902

Upgraded Tracker for Physics

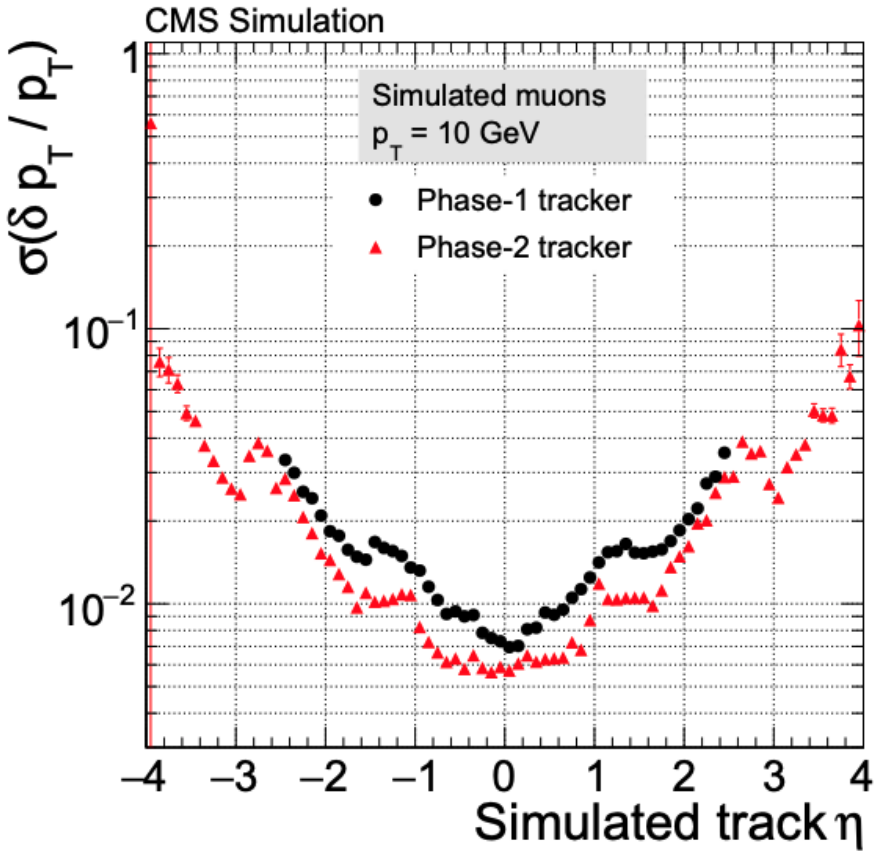
Higher granularity in pixels means better two track separation
Better efficiency in jets

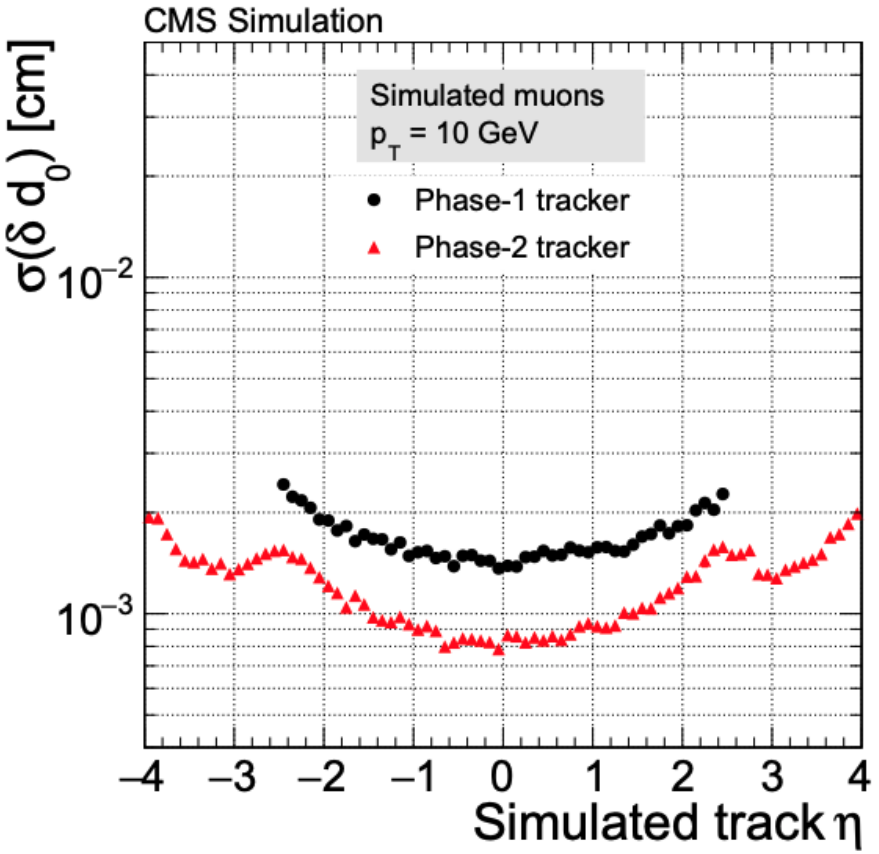


Upgraded Tracker for Physics

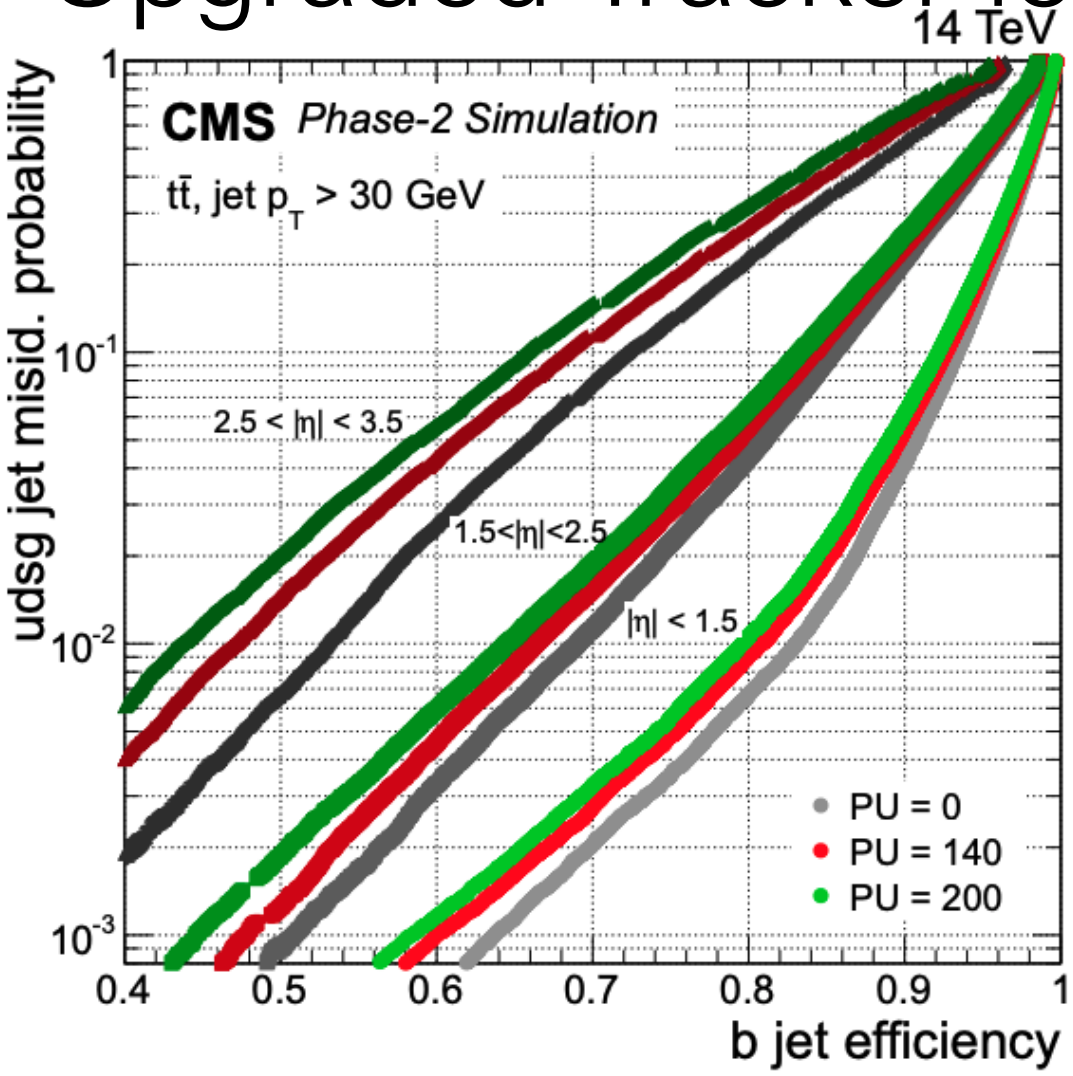
Higher granularity in pixels means better resolution in track parameters

Increased η coverage



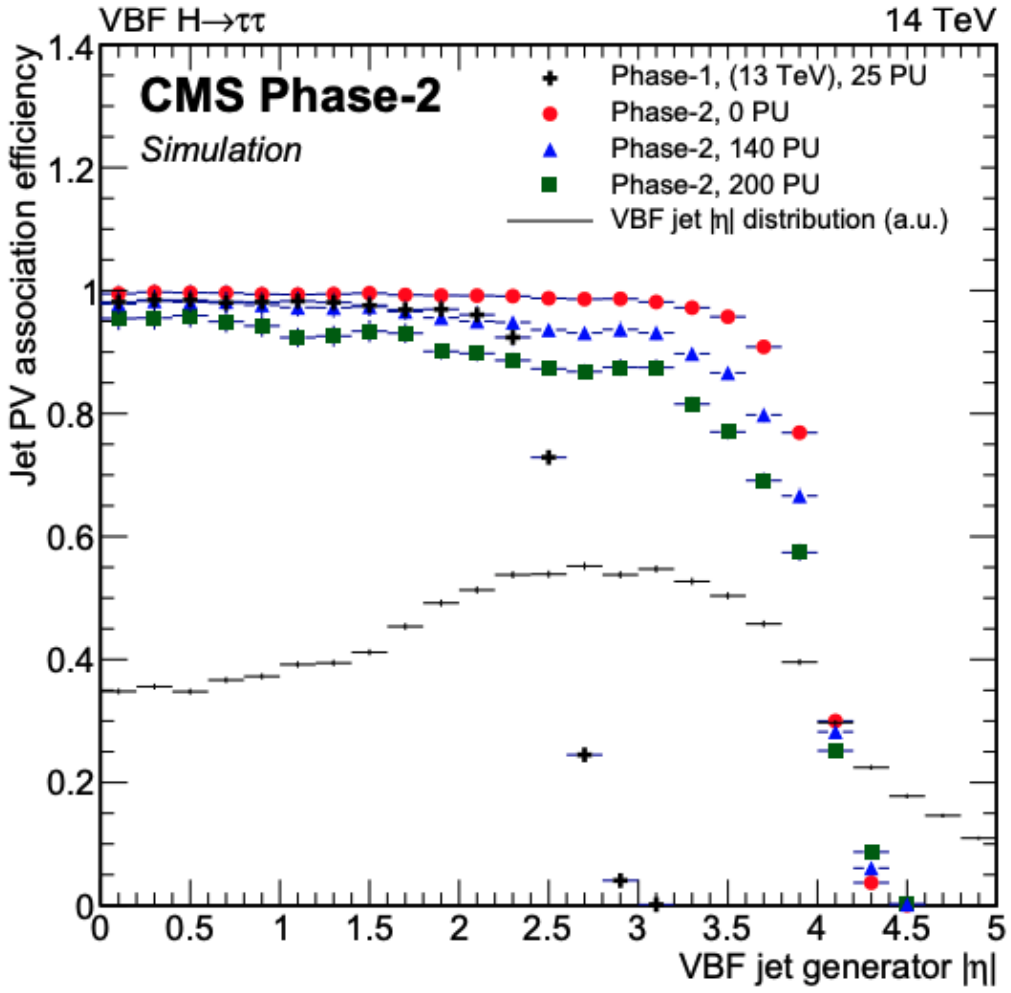


Upgraded Tracker for Physics



b-jet efficiency remains high across different PU scenarios
Drops off at high η, but Phase-1 didn't have these lines at all

Upgraded Trigger for Physics

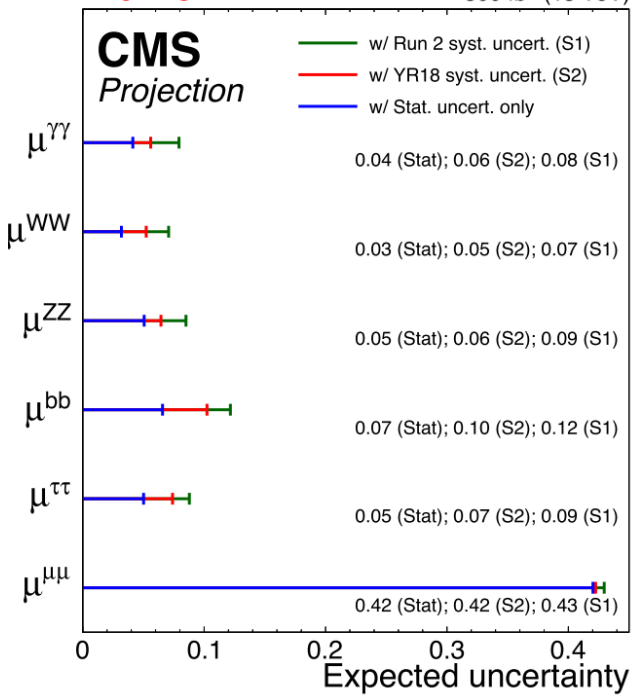


VBF reconstruction efficiency increased versus Phase-1, at least as good at 140 PU in barrel region

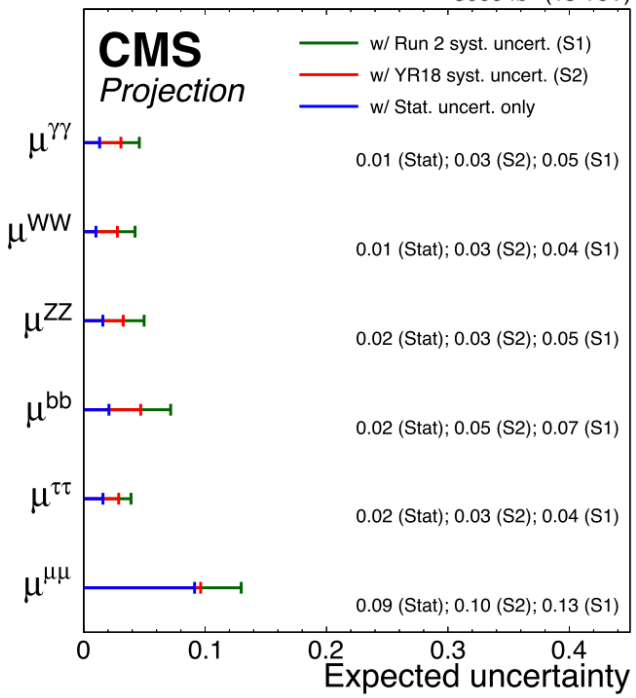
Tracker complements HGCAL VBF reconstruction

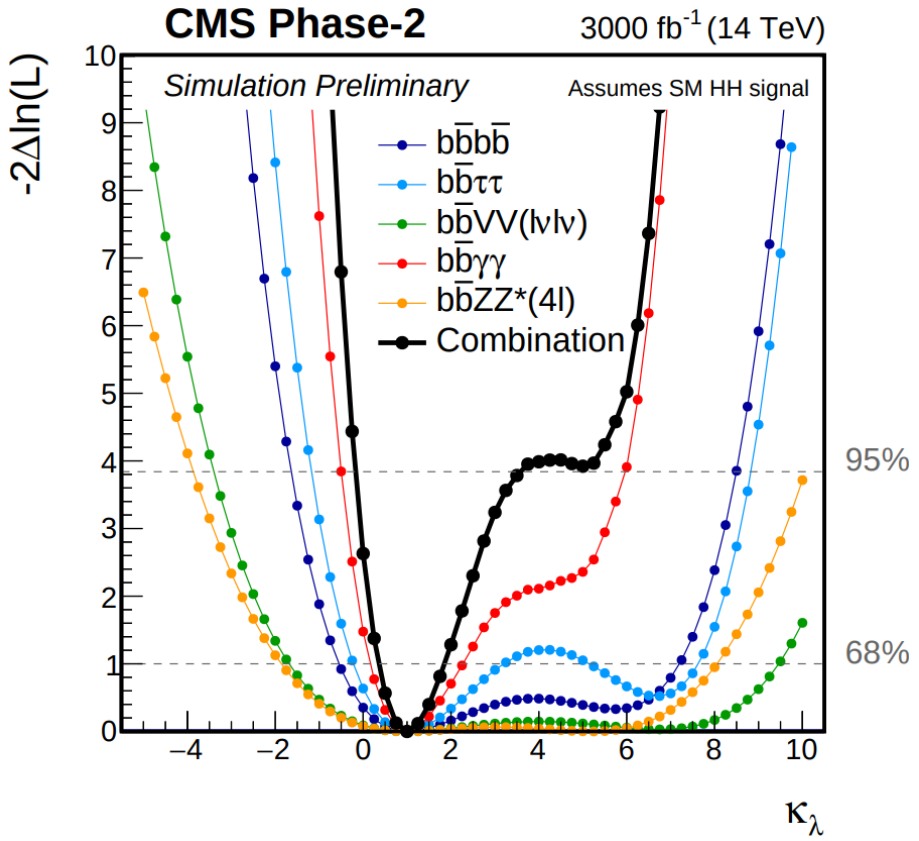
Upgraded Trigger for Physics

Run 3



HL-LHC





Higgs precision era of LHC

Di-higgs observation should be possible with full HL-LHC dataset, ATLAS + CMS

Conclusion

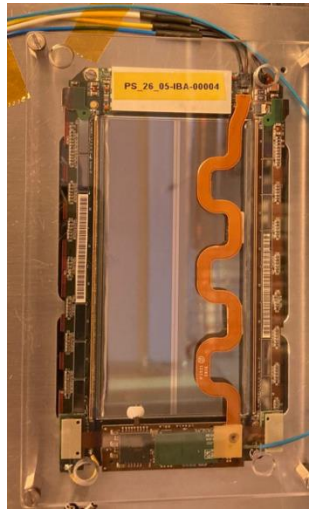
Upgrading the tracker is essential for the CMS HL-LHC upgrade

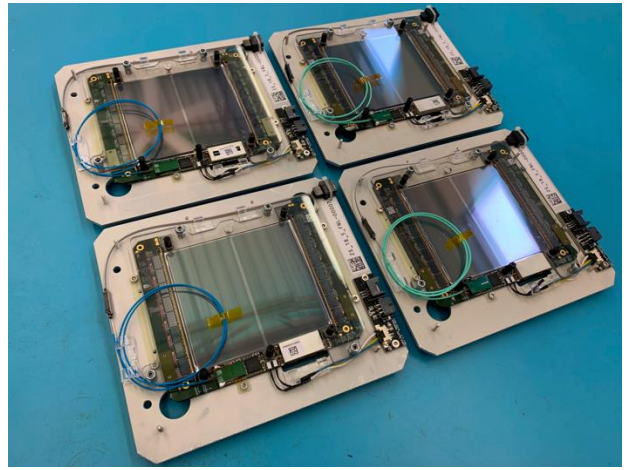
Tracking at Level-1 trigger algorithm nearing completion

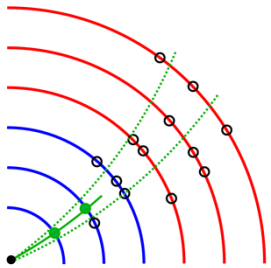
Particle Flow and PUPPI possible at Level-1

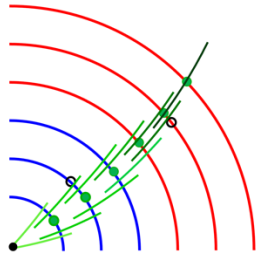
New ML techniques used to boost performance

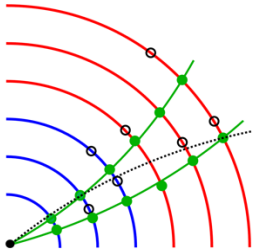
Up to the physicists to start thinking of what analyses and measurements we can make

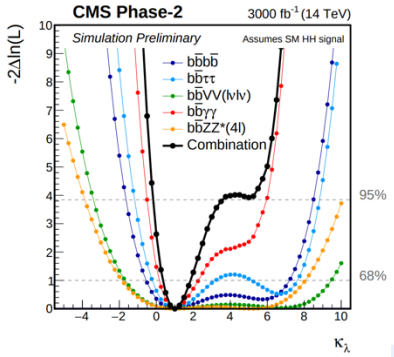




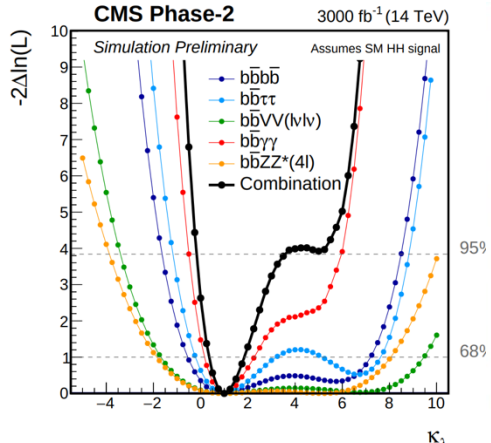


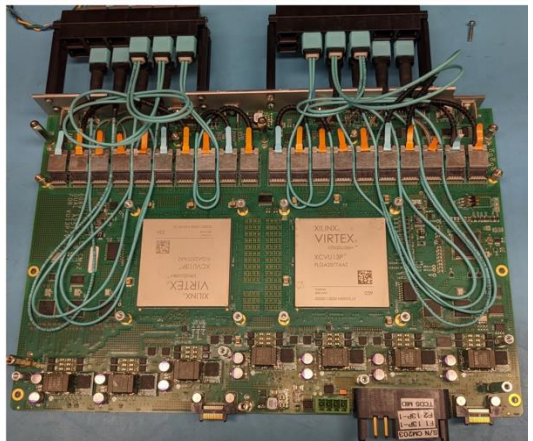


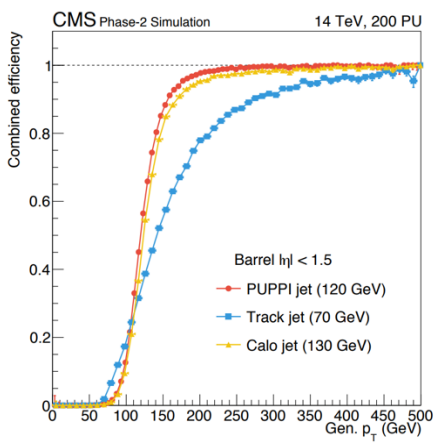


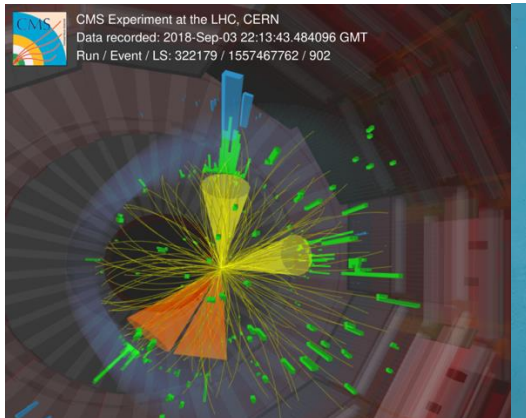


Backup


CMS Phase-2
3000 fb-1 (14 TeV)
Simulation Preliminary
Assumes SM HH signal
bb̄bb̄
bb̄ττ
bb̄VV(lνlν)
bb̄γγ
bb̄ZZ*(4l)
Combination
-2Δln(L)
95%
68%
κλ




CMS Phase-2 Simulation
14 TeV, 200 PU
Combined efficiency
Barrel |η| < 1.5
PUPPI jet (120 GeV)
Track jet (70 GeV)
Calo jet (130 GeV)
Gen. pT (GeV)


CMS Experiment at the LHC, CERN
Data recorded: 2018-Sep-03 22:13:43.484096 GMT
Run / Event / LS: 322179 / 1557467762 / 902

Inner Tracker Modules

3D pixels inner most layer, lower leakage current so can maintain performance after large radiation doses
- Replaceable

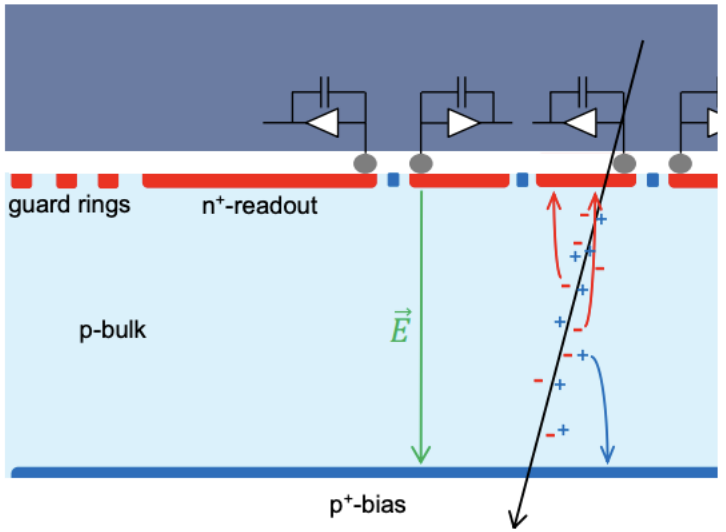
Planar sensors for the rest

CROC Readout chip codeveloped with ATLAS in the RD53 collaboration

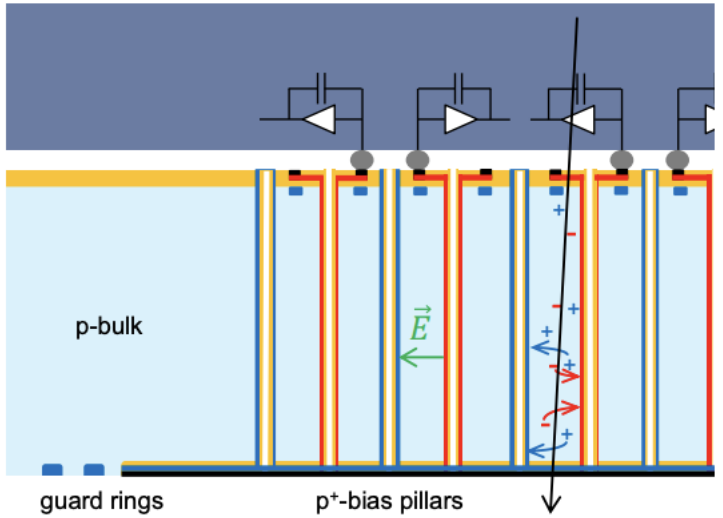
-35 ℃ operating temperature

> 98% hit efficiency, < 1 % pixel noise

Planar



3D



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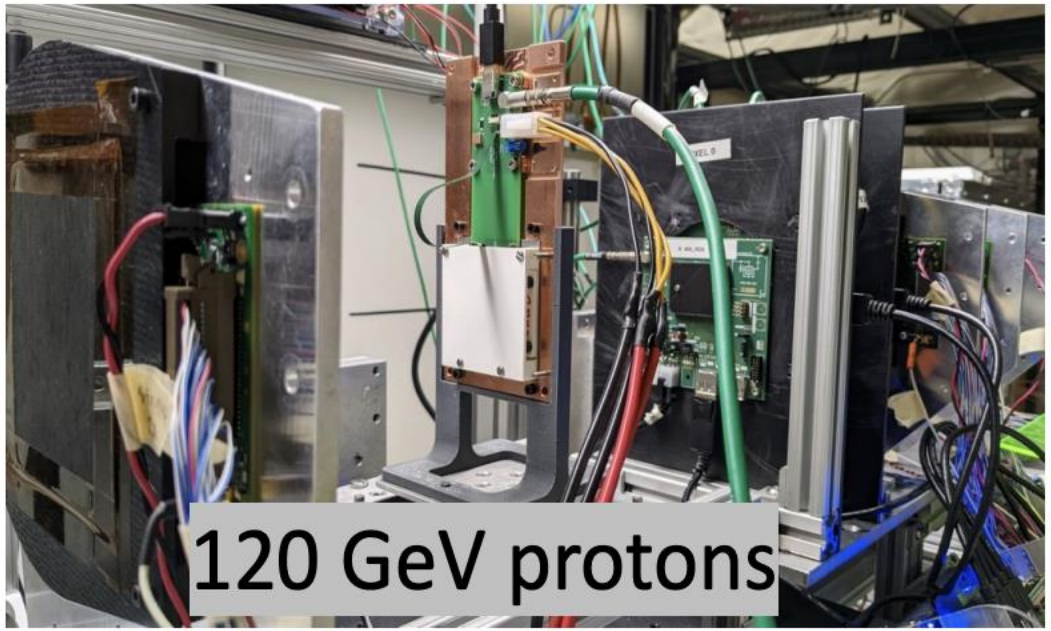
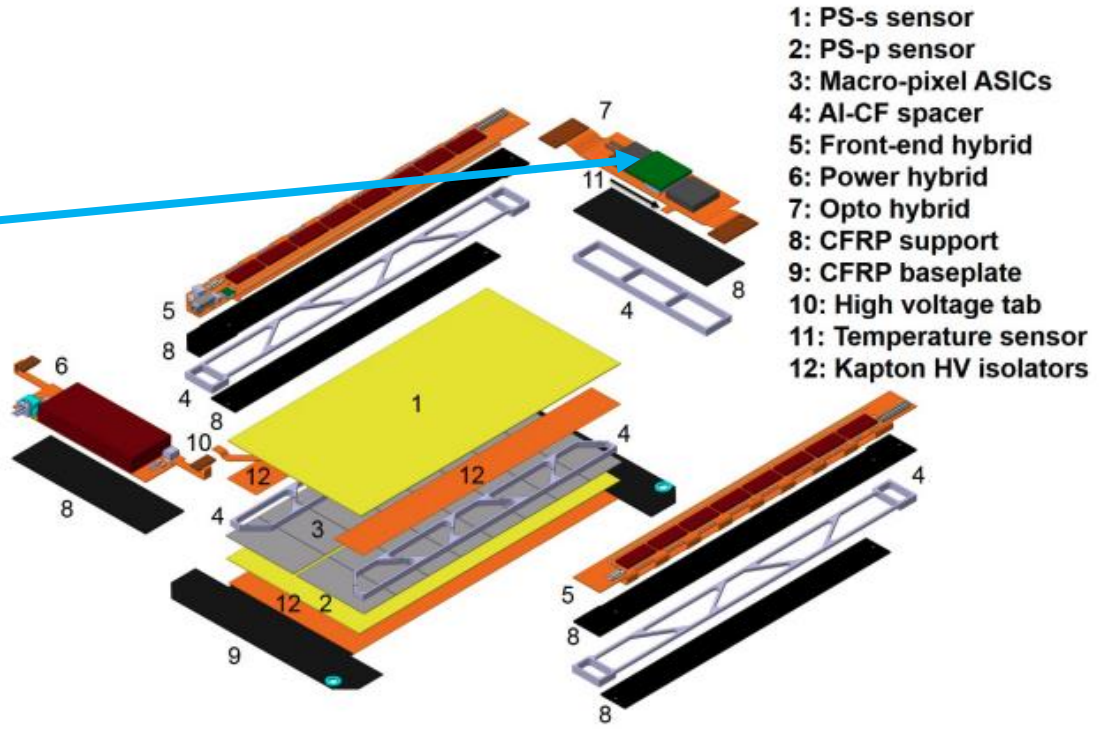
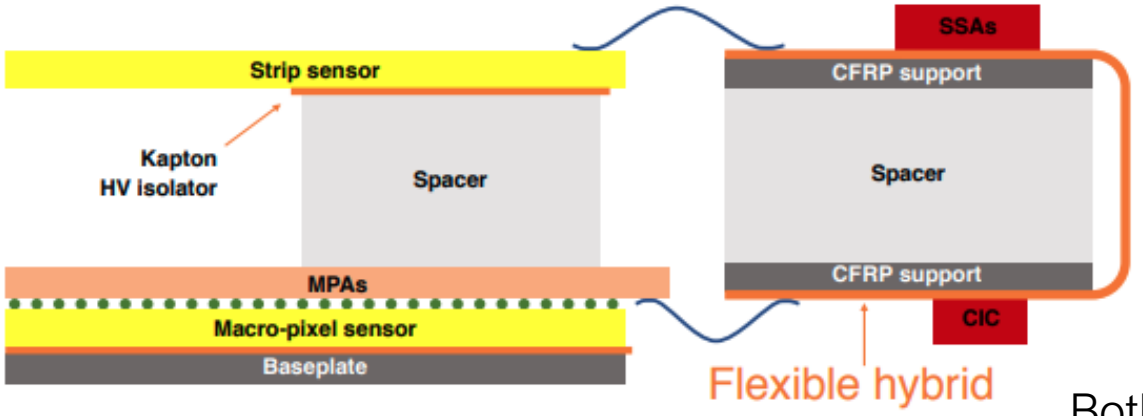


TBPX 2x2 module in FNAL testbeam

PS Module

Optics on module
Low power Gigabit Transceiver (LpGBT)



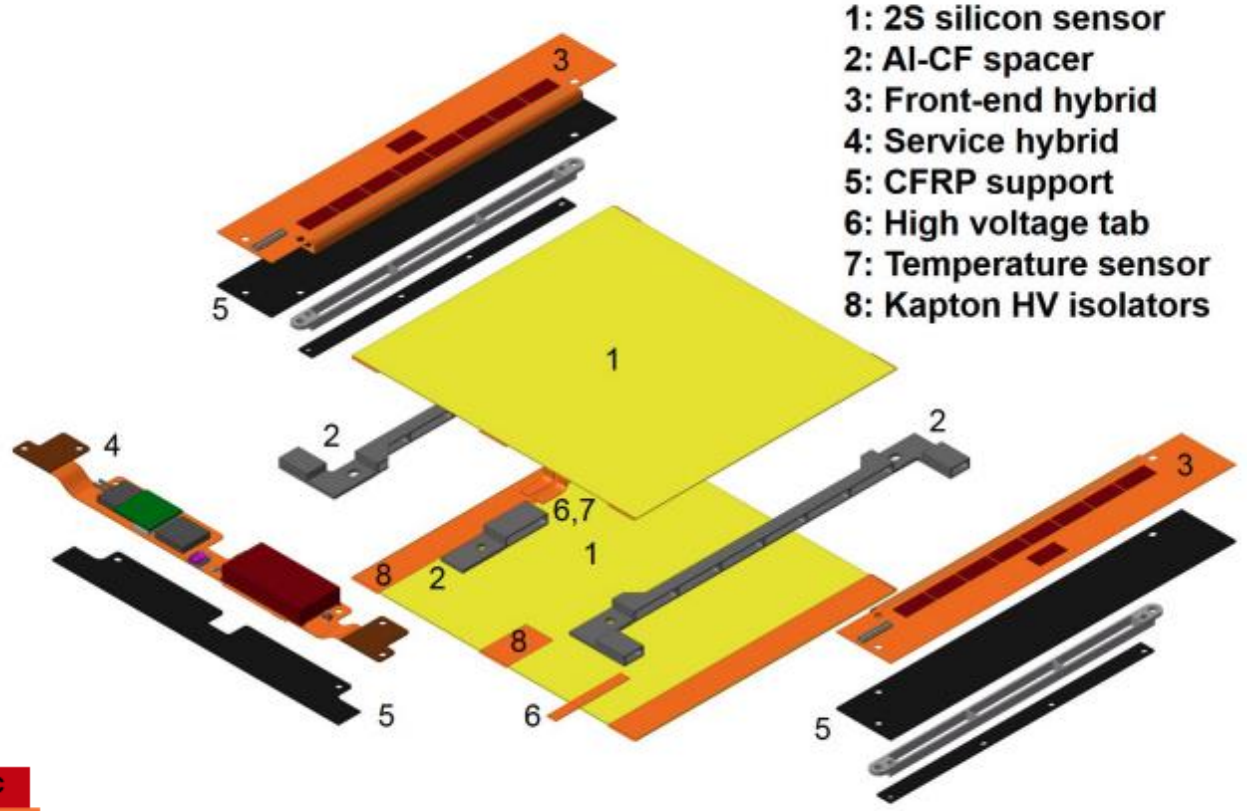


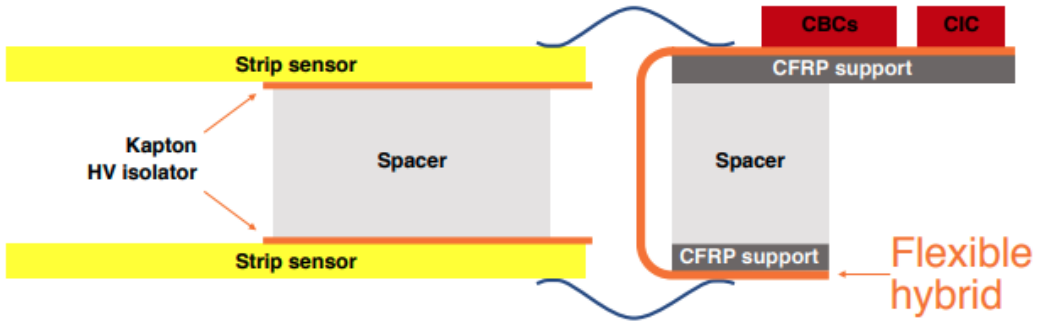
Both sensors wire-bonded to same hybrid needed for sensor-sensor communication

PS Module

- 5616 PS Modules needed
- Assembly process well defined
- Difficult to align top and bottom modules with precise spacing
- Multiple days per module assembly
- Pre-production 2024
- Tests ongoing with preliminary noise results within expectation
- Testing down to -35°C

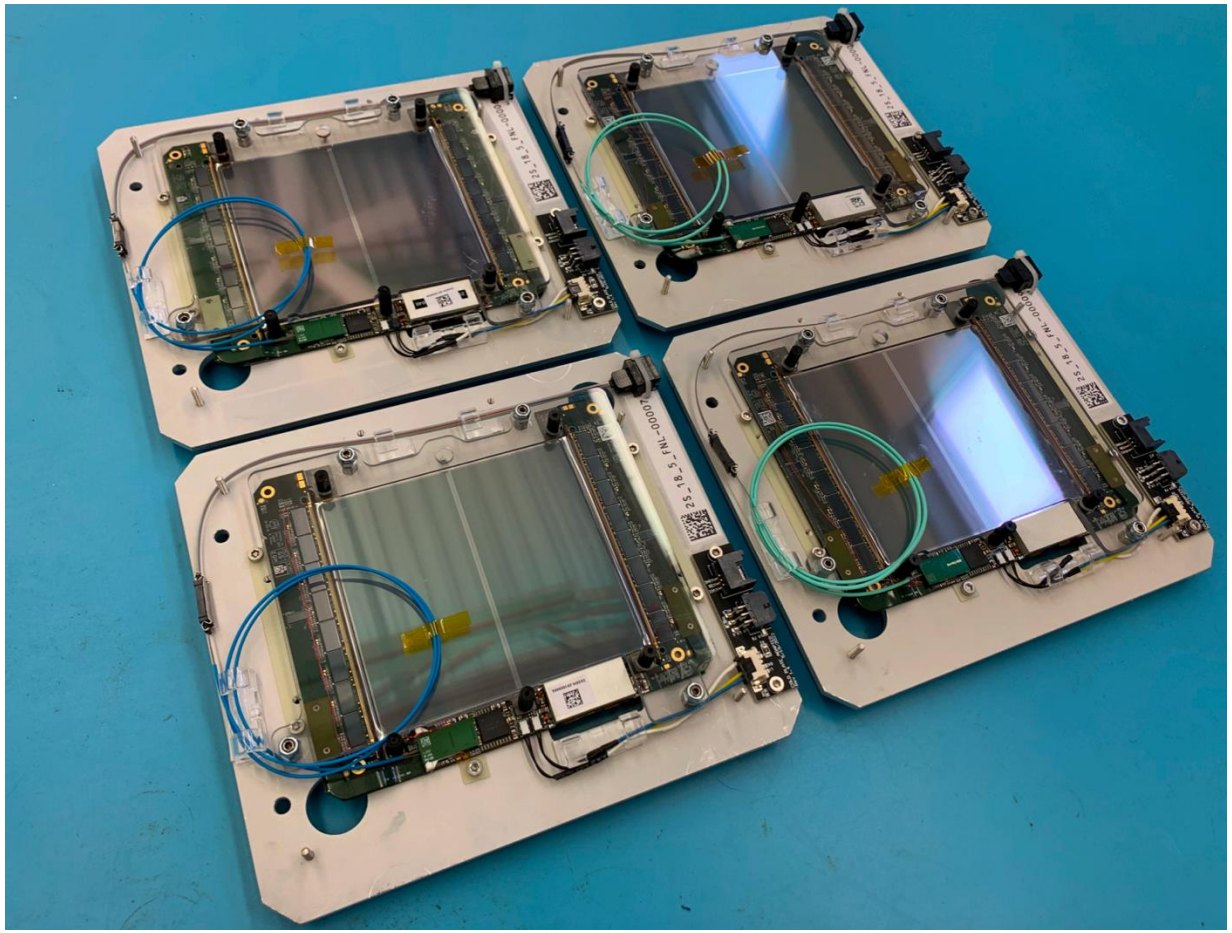
2S Module


1: 2S silicon sensor
2: Al-CF spacer
3: Front-end hybrid
4: Service hybrid
5: CFRP support
6: High voltage tab
7: Temperature sensor
8: Kapton HV isolators
1
2
3
4
5
6
6,7
8


Strip sensor
Kapton
HV isolator
Spacer
Strip sensor
CBCs
CIC
CFRP support
Spacer
CFRP support
Flexible
hybrid

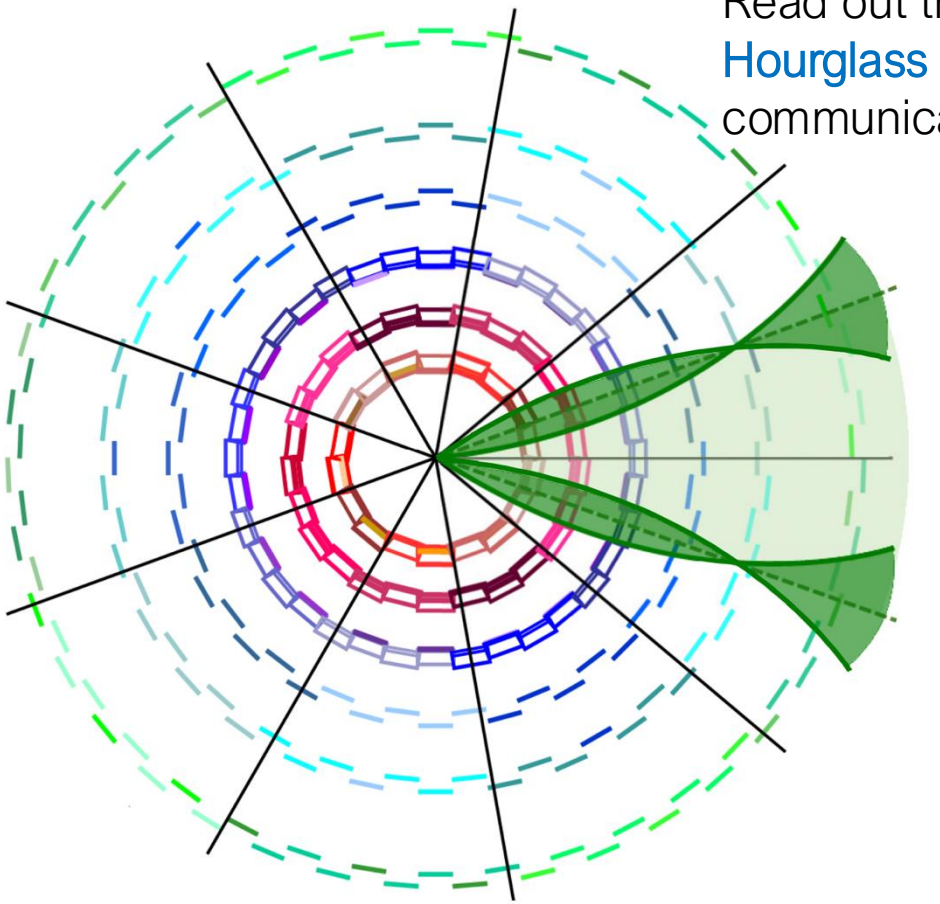
2S Module

- 7680 2S Modules needed
- Difficult to create folded over hybrid
- Assembly process being defined
- Multiple days per module assembly
- Preproduction 2024



c.brown19@imperial.ac.uk

Tracks for Level-1 → System Overview



Read out tracker in nonants
Hourglass shape avoids inter-nonant communication

Track Finder Processor
- 18 boards per nonant
- New event every 450 ns
- 4 μs to process tracks

Data Trigger and Control
- 24 boards per nonant
- Stub pre-processing, distribute stubs to track finder
- Forwards rest of data on L1 accept