Track reconstruction in Level 1 trigger for the Phase 2 upgrade of the CMS detector

Compact
Muon
Solenoid
experiment at
CERN's LHC

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Large Hadron Collider

Large hadron collider (LHC):

- 26.7 km circumference
- 175 m depth
- 1200 dipoles
- 1.9 K temperature
- 13.0 TeV
- ~2800 bunches
- 40 MHz collision rate

Physics motivation:

- Search for the Higgs boson particle
- Precision measurements of W, Z and top
- Rare decays of b – hadrons
- Beyond Standard Model:
  -- SuperSymmetrry
  -- Extra dimensions
  -- Leptoquark
  -- ….

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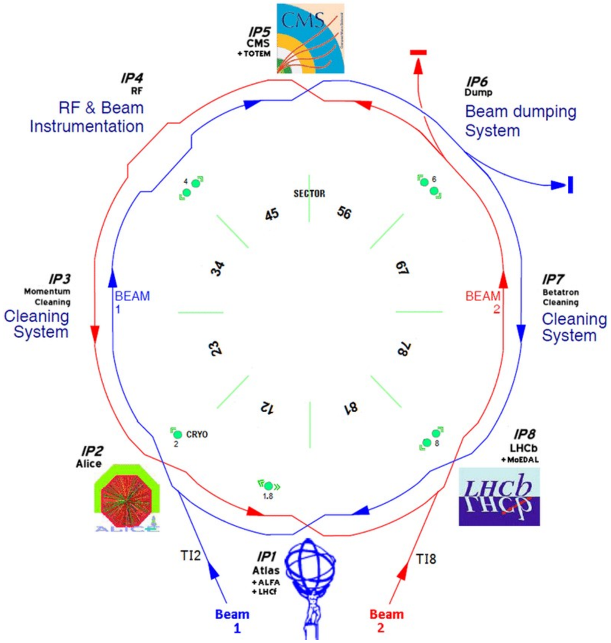
- Precision measurements of W, Z and top → arXiv:1701.07240 and many more
- Rare decays of b – hadrons → arXiv:1307.5025 and many more
- Beyond Standard Model:
  - -- SuperSymmetrry
  - -- Extra dimensions
  - -- Leptoquark
  - -- ….

No hint of BSM phenomena (yet)

Experiments at LHC

- Beams collide in 8 interaction points (IP)
- 4 IP have a detector which corresponds to a different collaboration
- Experiments: ATLAS, ALICE, CMS, LHCb



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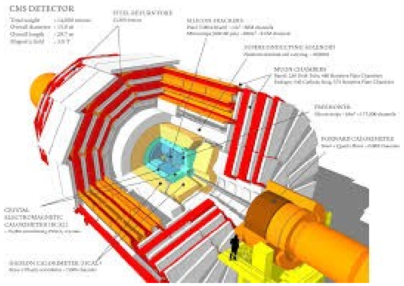
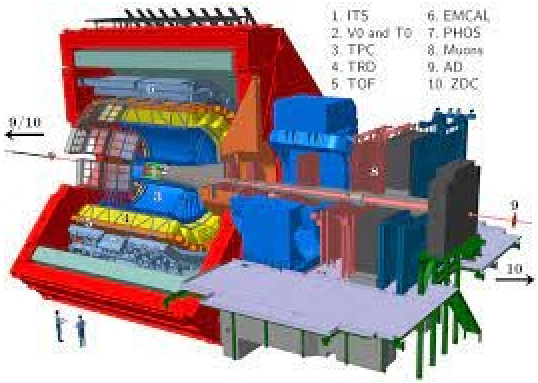
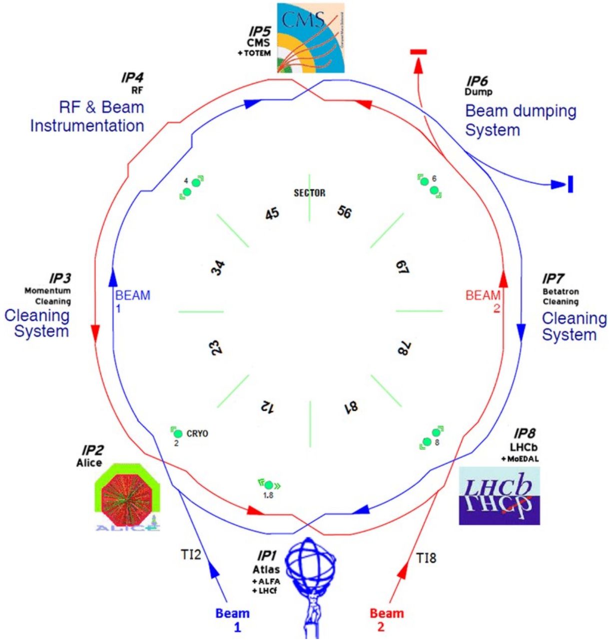
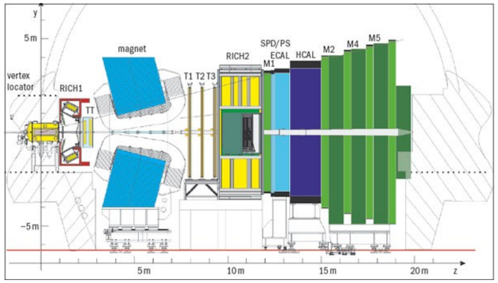


- CMS: Compact Muon Solenoid
- Large general-purpose Detector

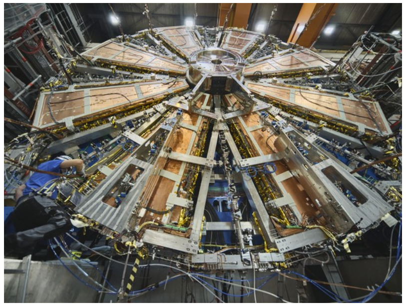






- LHCb
- Specialized b-physics experiment
- Designed primarily for CP violation measurements

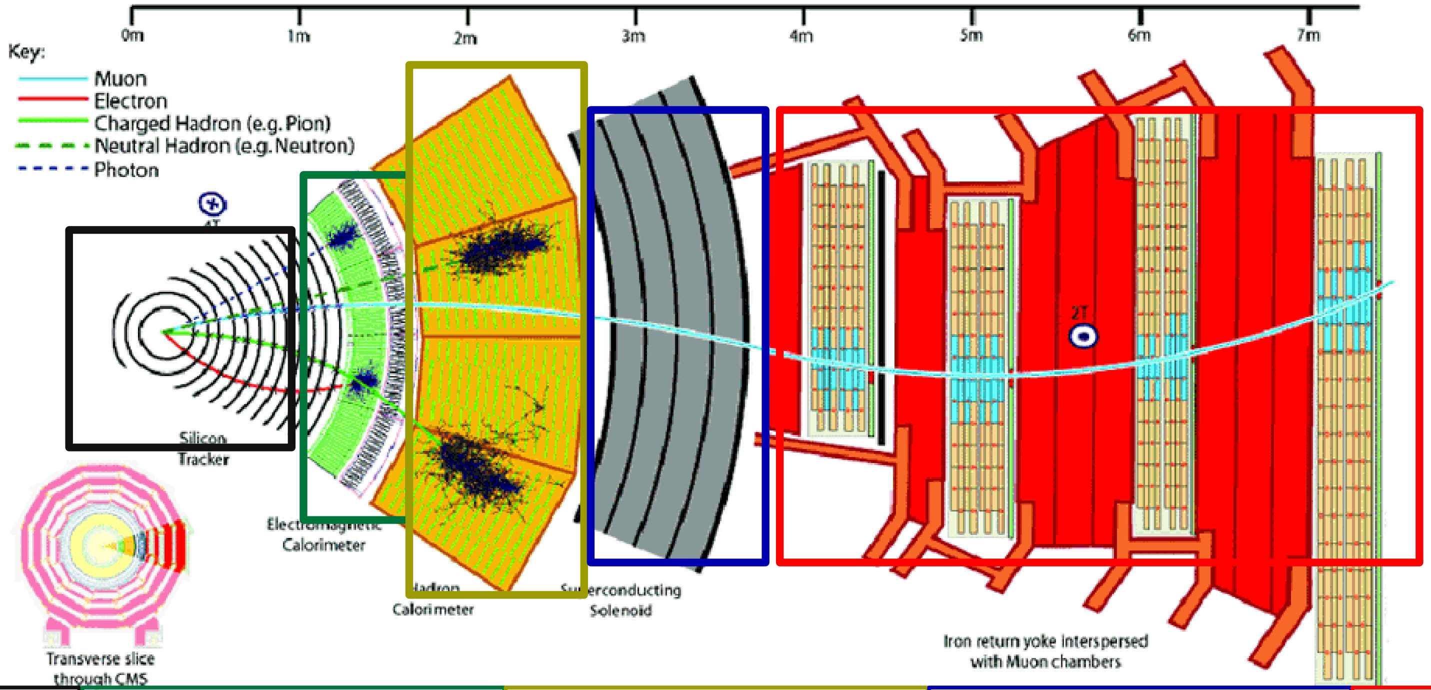
- ALICE: A Large Ion Collider Experiment
- Specialized in heavy-ion (Pb-Pb) collisions
- Designed primarily for quark–gluon plasma measurements



- ATLAS: A Toroidal LHC Apparatus
- Large general-purpose Detector

The CMS Detector

TDR



Tracker:
- Pixels in the core
- Silicon strips around
- In 2017 an extra inner layer added
- Total 14(15) layers in Barrel(endcaps)
- Reconstructs the trajectory of charged particles
- Excellent measurement of position

ECAL:
- Homogeneous calorimiter
- Lead tungstate (PbWO) scintillator
- 61,200 crystals in barrel
- 1,700 crystals in endcap
- Measures the energy of e and γ
- Very good energy resolution

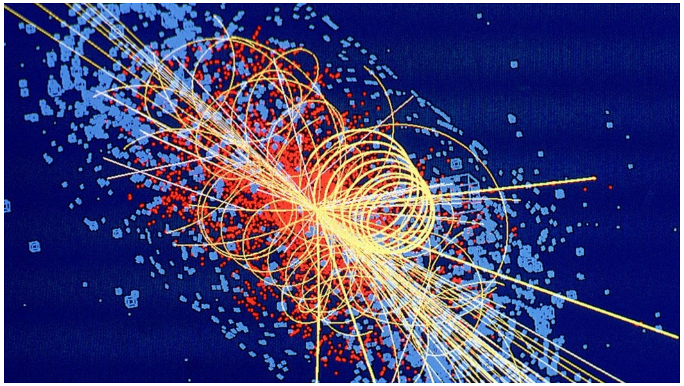
HCAL:
- Heterogeneous calorimiter
- Interleaved heavy material with scintillator layers
- Measures the energy of hadrons
- Indirect measurement of non-interacting particles (like ν)

Magnet:
- Central device
- Large solenoid magnet
- Field up to 4T
- Bends charged particles to measure their momentum

Muon:
- Position exploits that muon are penetrating particles
- Very clean signatures
- Gaseous detectors of three types
- Drift tubes (barrel), CSC (endcap), RPC (barrel+endcap)

Trigger overview

Current Trigger architecture



Collisions
40 MHz

Excessive amount of data! Technically cannot be stored entirely and also most events interesting. Need a way to select the interesting subset

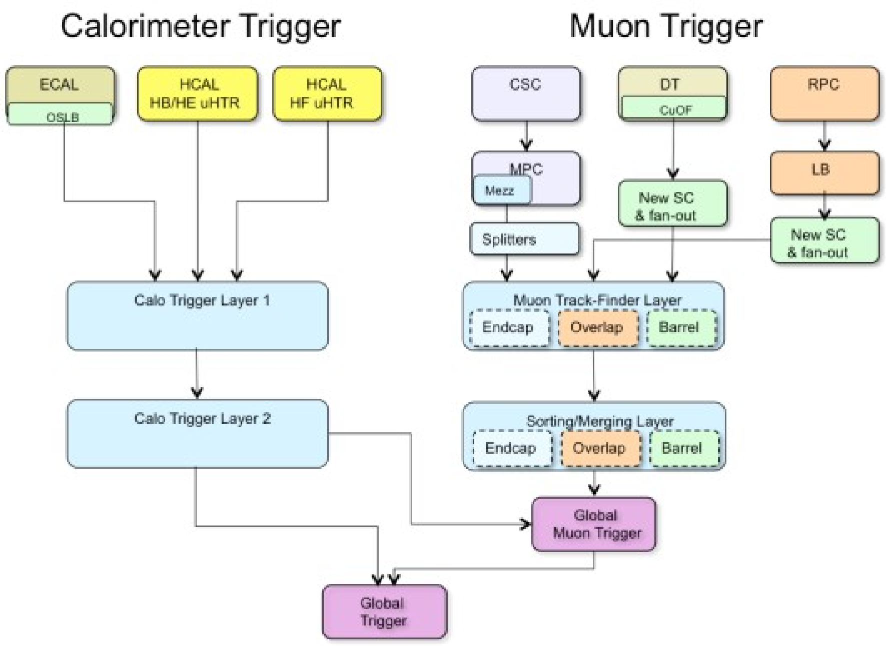
Level 1 100kHz

HLT ~1.2kHz

Trigger: A system that selects events very fast

Divided in two parts L1 (very fast, coarse, hardware-based) and HLT (computing farm less fast more precise)

Level 1 trigger: Selecting events in ~4µs



Architecture:
- Inputs from Calorimeters and Muon chambers
- Not using tracker
- ECAL and HCAL feed the calorimeter trigger
  - e/γ, Jet E_T measured
  - MET, HT calculated
- Muon chambers feed the Muon trigger
  - Builds muon tracks
  - Divided in subsystems based on the geometry (BMTF, EMTF, OMTF)
- Global trigger takes jets, muons as input and calculates higher level quantities. Then it checks for interesting events

General:
- All Level1 trigger is hardware-based in order to cope with the timing constraints (<4µsec)
- The bandwith is 100kHz and is dictated by the electronics (cannot change)
- L1 objects are coarse → usually we cut looser than in offline
- L1 is a crucial system for any experiment: events rejected in this stage cannot never be retrieved. Is the 1st stage of all analysis

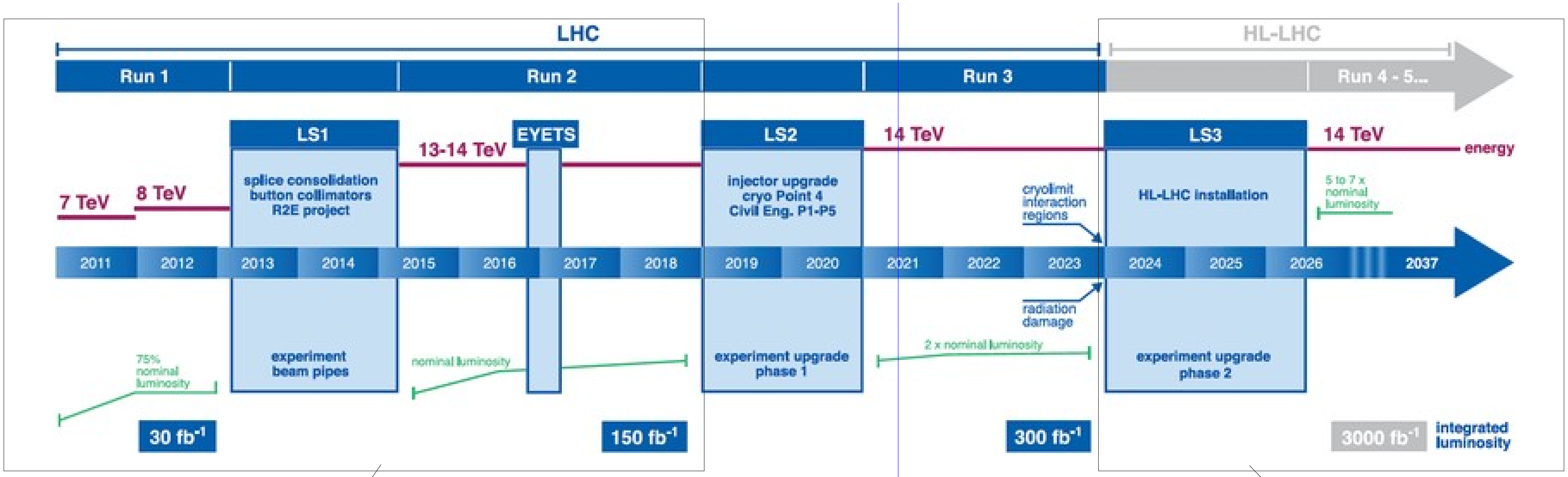
Phase 2 upgrade

LHC operations

Number of events: N = σ L

σ = Cross section
L = Luminosity

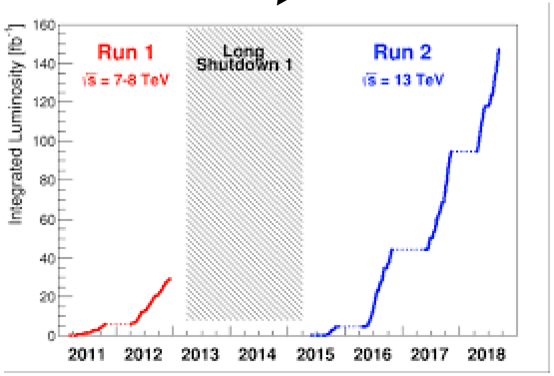
To discover rare processes (like BSM) we need luminosity

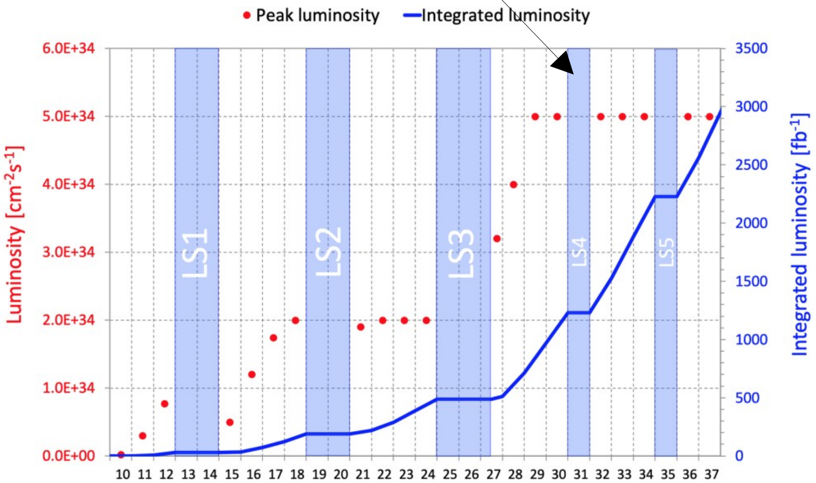


past

now

future

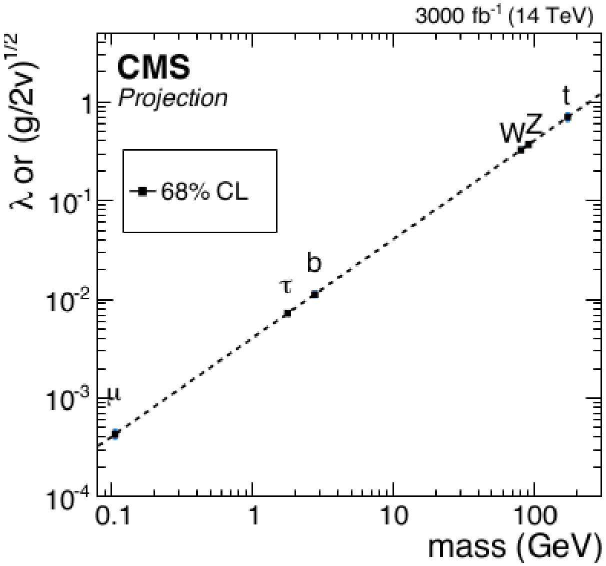




HL-LHC physics motivation

Higgs measurements:

- Improve precision on Higgs couplings measurement
- Search for rare decays (H → cc etc)
- DiHiggs searches to improve the Higgs self coupling measurement
- Explore exotic models for BSM Higgs



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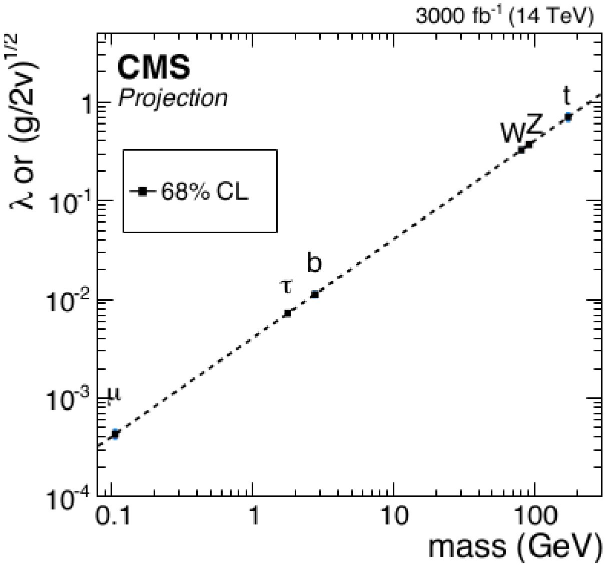

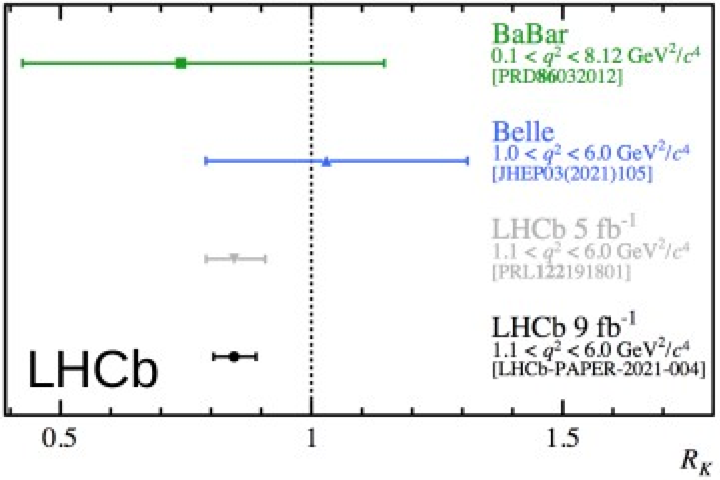

Sensitive searches to NP:

- Rare processes (like FCNC) are sensitive to BSM phenomena due to small SM contribution
- Increasingly interesting topic

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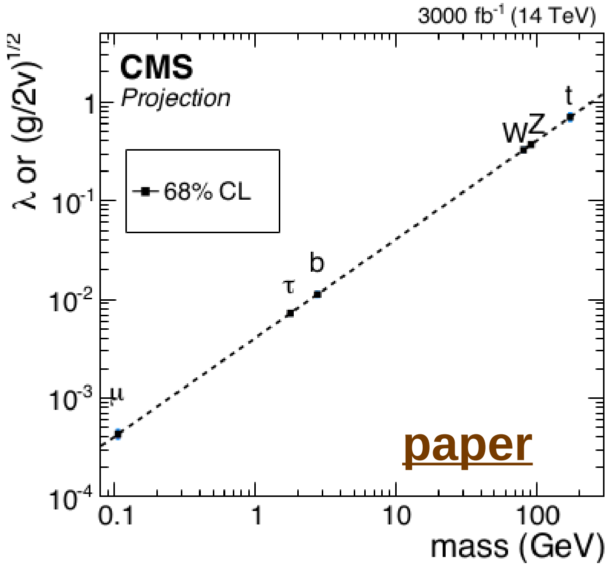

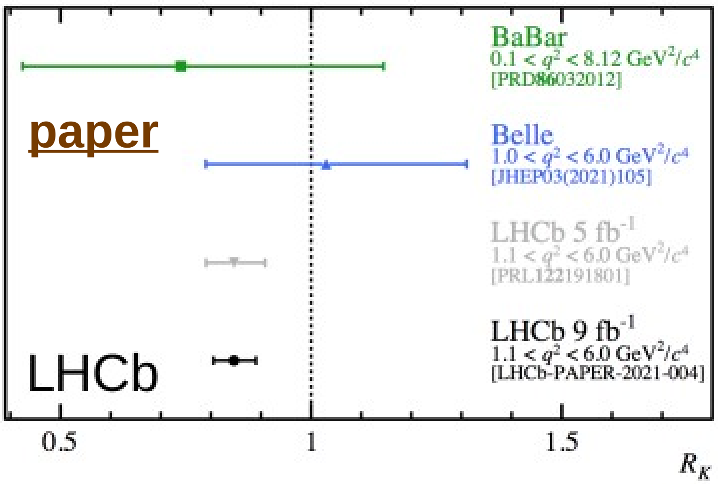

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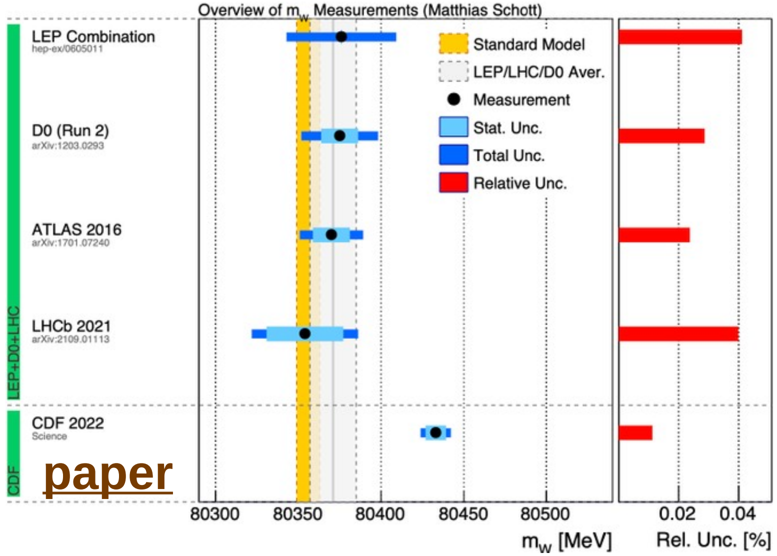
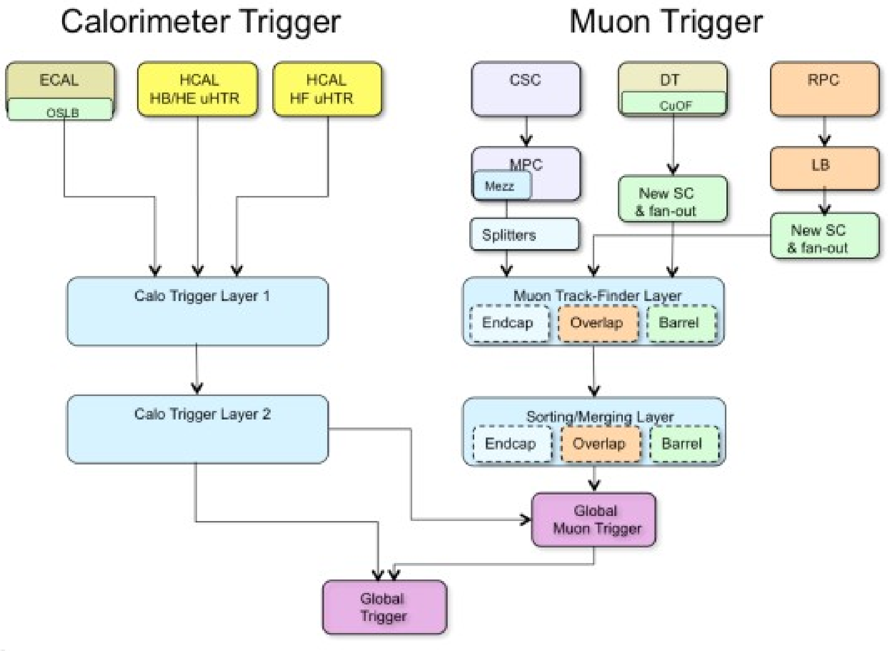
Precision measurements:
- Large datasets → reduced statistical uncertainties
- Detector improvements → reduced systematic uncertainties

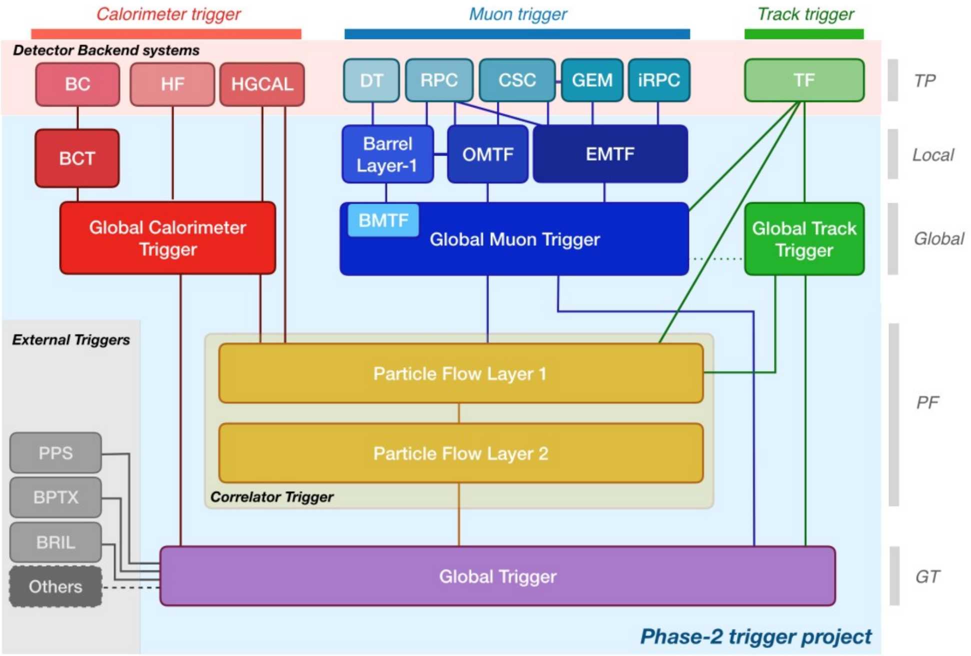


L1 Upgrade for phase 2

Phase 1



Phase 2



	L1 latency	L1 rate	HLT rate
Phase 1	4 μsec	100 kHz	1.2 kHz
Phase 2	12.5 μsec	750 kHz	7.5 kHz

Problem: Even with the increased rate, if the architecture remain the as is in Phase 1, the trigger thresholds will increase so much that W, Z, H and B measurements will be impossible

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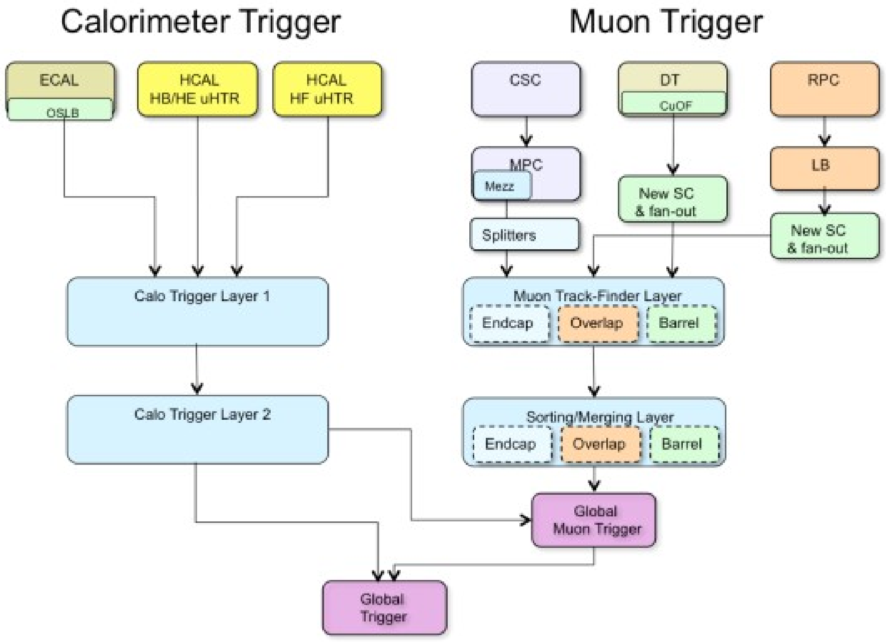

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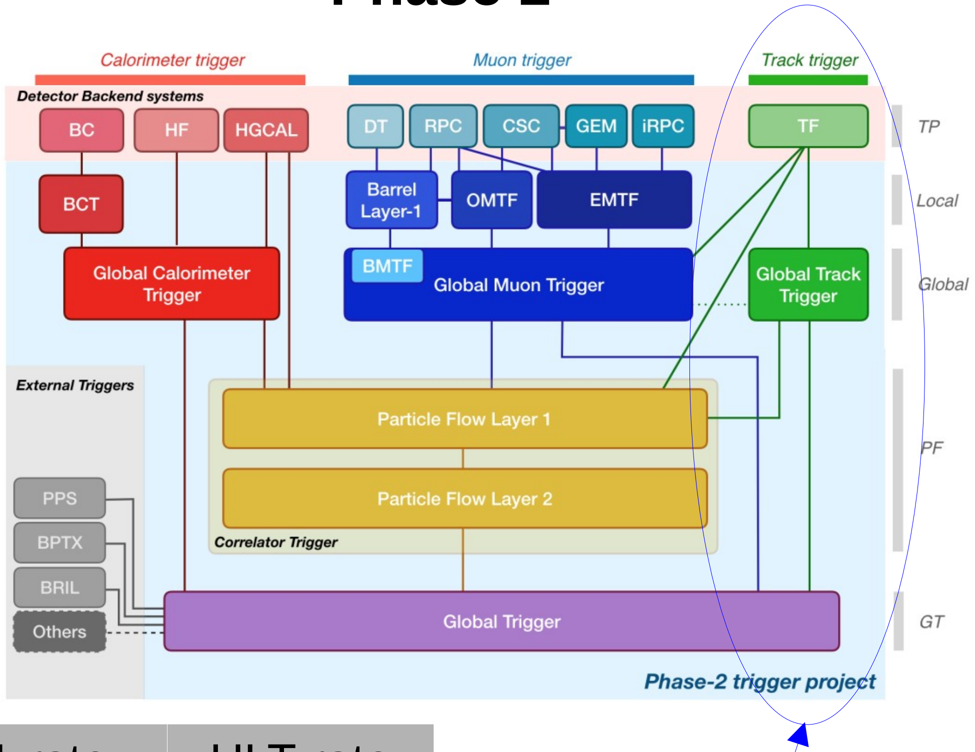

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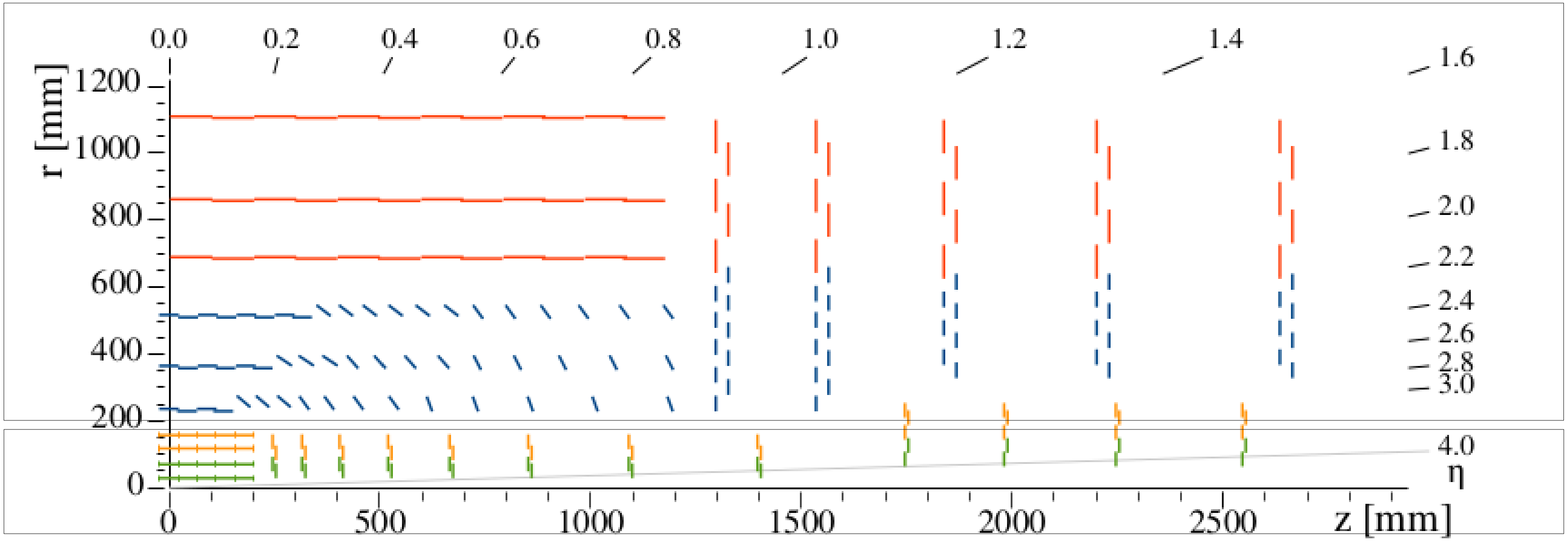
Solution: In Phase 2 L1 architecture is upgraded with a new detector: the L1 tracker

L1 track reconstruction

New track detector

Phase 2 tracker:

- Both inner and outer tracker will be replaced to increase granularity
- Outer tracker (where occupancy is lower) will be used at L1
- L1 trigger possible by the inclusion of **p_T modules**



Outer tracker (Used in L1)

Inner tracker

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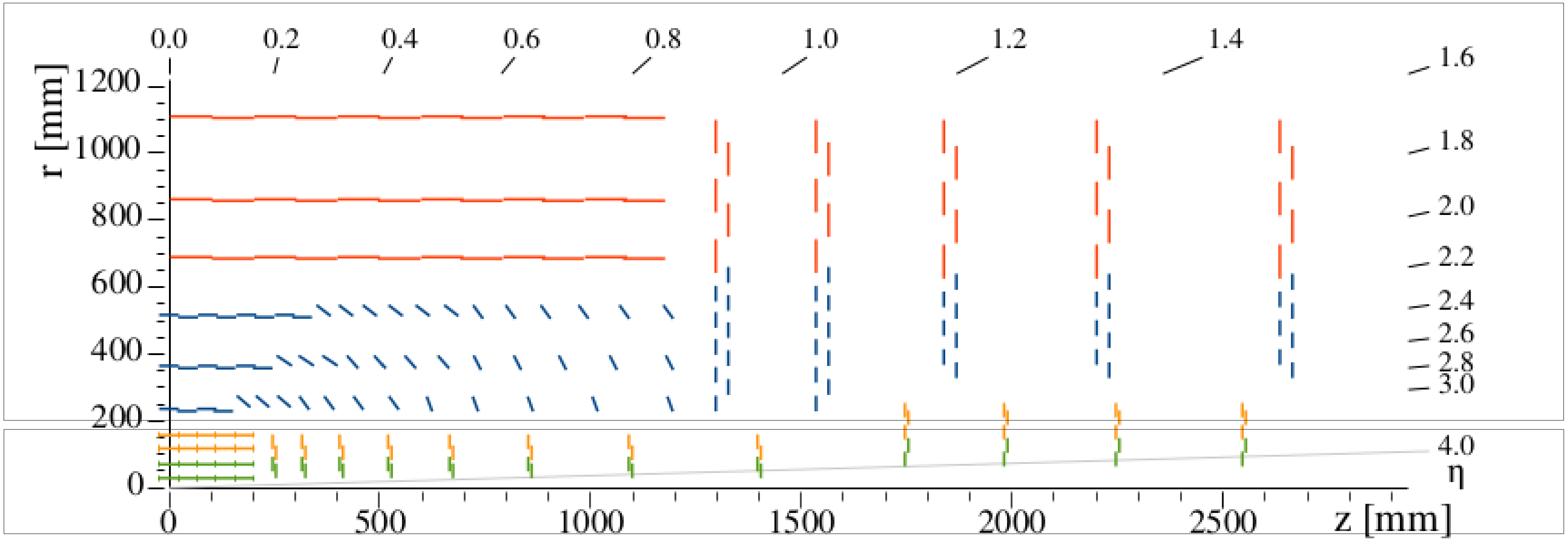


Outer tracker (Used in L1)

Inner tracker

p_T modules: tracker layers with two detectors close to each other

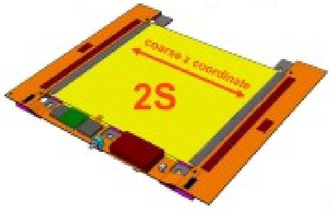
The two types of p_T modules

PS modules (pixel-strip)

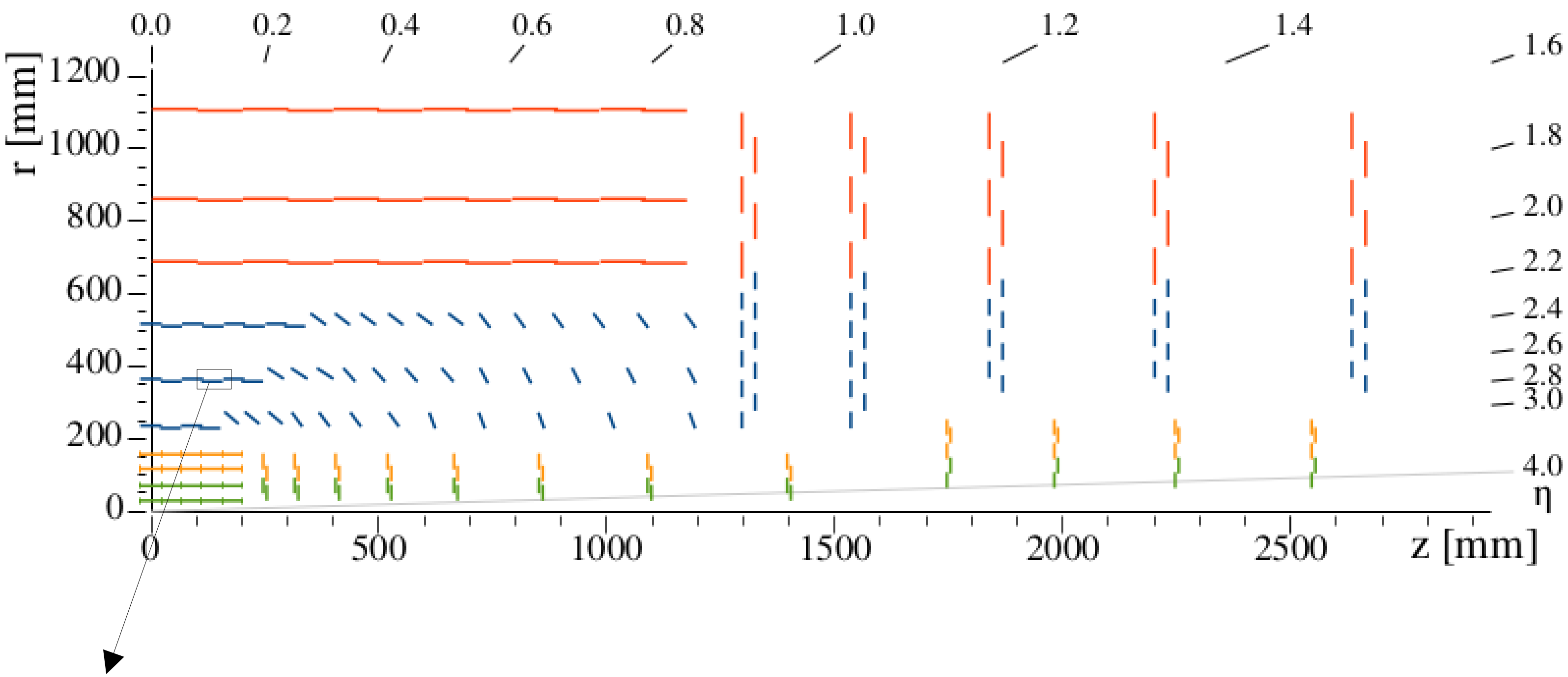
- Top sensor: 2x2.5 cm strips, 100 μm pitch
- Bottom sensor: 1.5 mm x 100 μm pixels

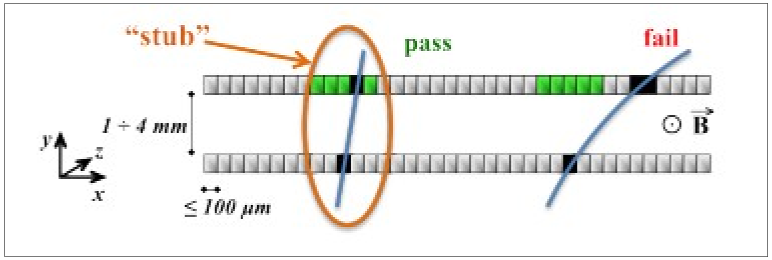
2S modules (strip-strip)

- Strip sensors 10x10 cm²
- 2x5 cm long strips, 90 μm pitch



Creating stubs





Stubs:

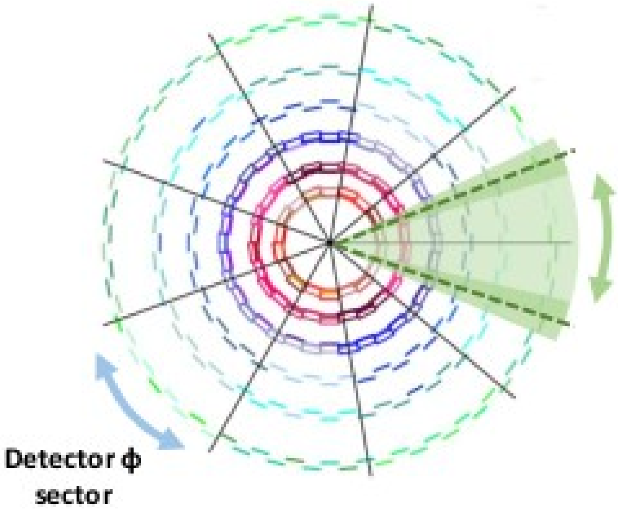
- Connected pair of hits in the detectors of the p_T modules
- Must be consistent with particle of p_T>2 GeV

Output stubs:

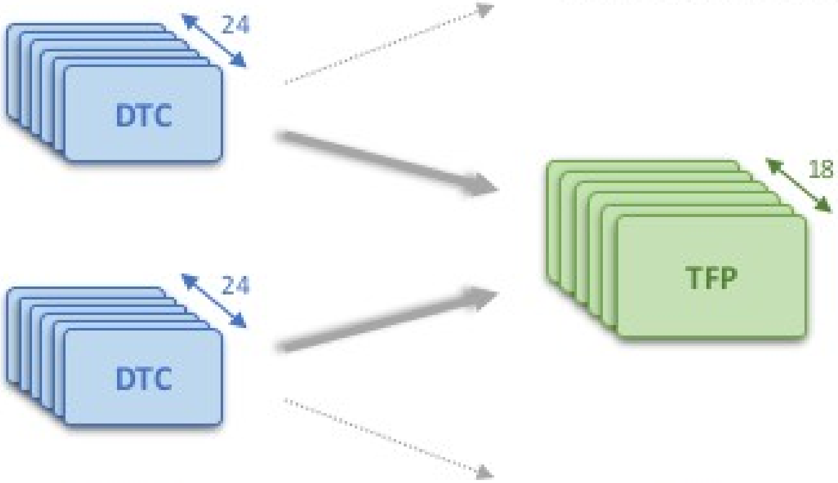
- 15k stubs per bunch crossing
- 30 Tbits / sec

L1 Tracking system

L1 timing requirements:
- L1 track reconstruction must take at most 4 μsec
- Whole L1 timing budget is 12.5 μsec
- To cope with the tight timing requirement → L1 track reconstruction is parallelized



Geometrical parallelization:
- Detector divided in 9 segments in φ (nonant)
- Track-finding works in 9 nonants, shifted from the tracker
- Stubs of each tracker nonant are pre-processed by 24 Data Trigger and Control (DTC) boards
- DTC send stubs to the Track Finding Processor (TFP) boards

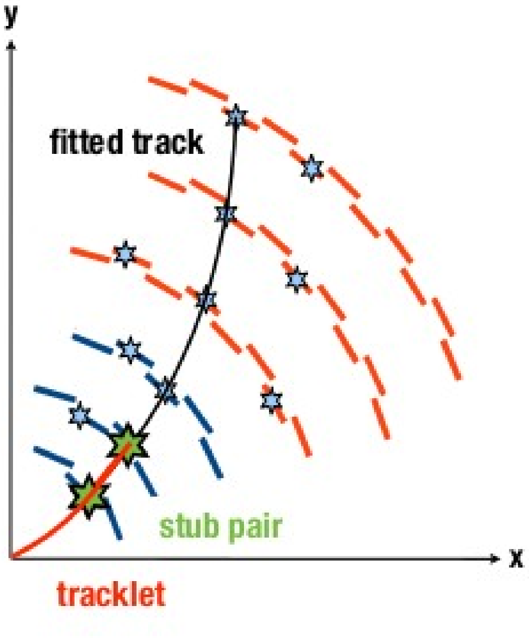


Timing parallelization:
- Due to the large time needed for track reconstruction, TFP needs more time than 4μsec
- Therefore multiple TFP are processing different events from the same nonant
- This is called time-multiplex
- L1 track time-multiplex works with factor of 18 (ie each TFP receives new event / 18 bunch crossings)

Algorithm overview

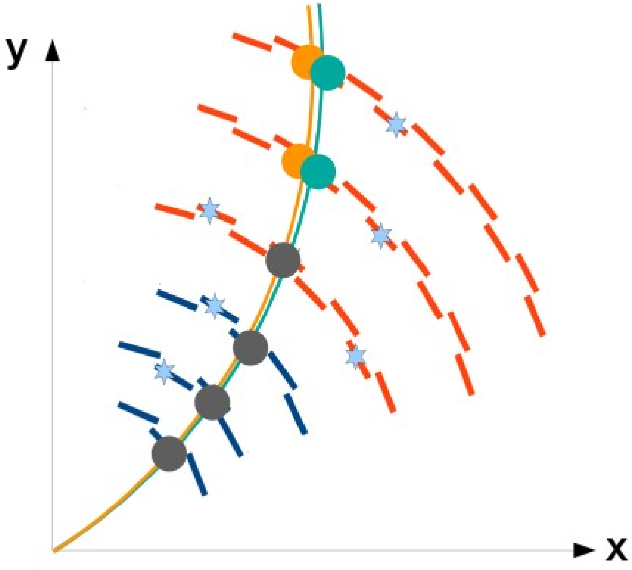
Three independent algorithms were proposed. Finally, merged two most prominent efforts in the so-called “hybrid” algorithm.

Step 1



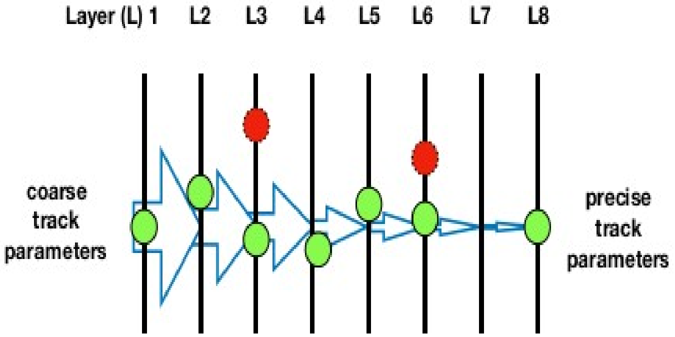
Tracklet step:
- Starts track finding
- Selects stubs for track candidate

Step 2



Cleaning step:
- Merge duplicate tracklets

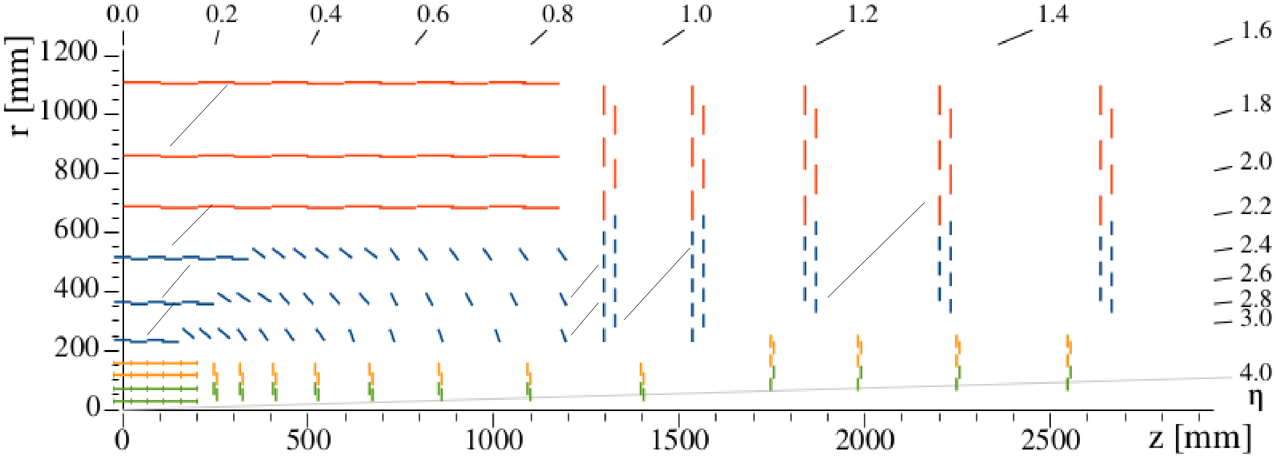
Step 3

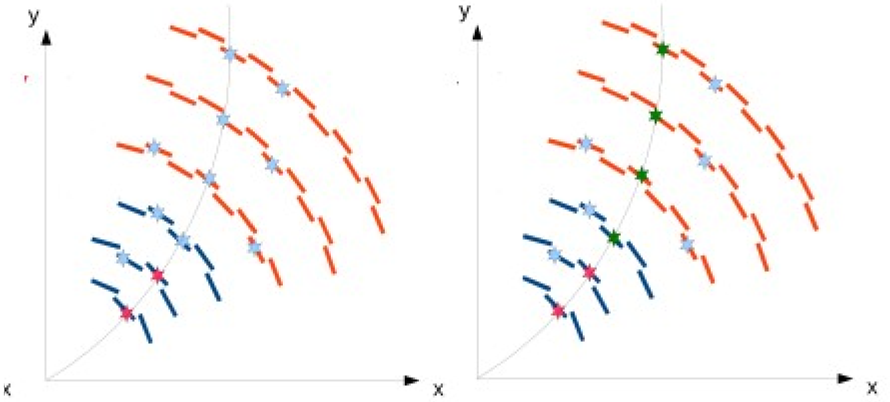


Fitting step:
- Stubs are fitted in a single track
- Kalman filter is used
- This is the best track of L1

Track building

Creating trackles:
- Tracklets: pair of stubs in sequential layers or disks.
- Seeds: tracklets in specific combinations of layers
- Seeds are tested in parallel
- Only tracklets with p_T>2GeV considered as seeds

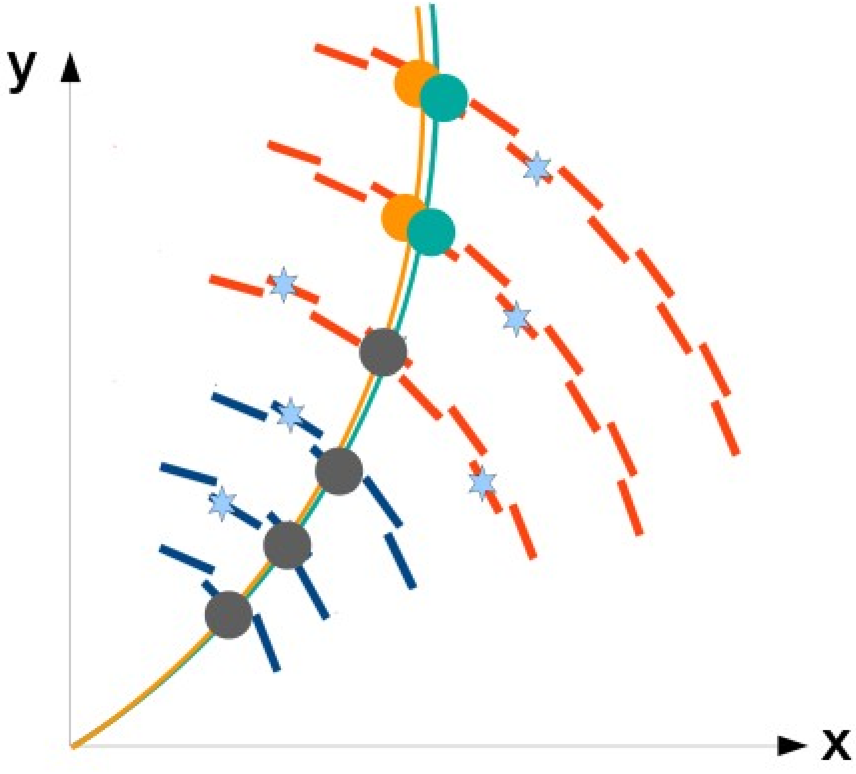




Track building:
- Starting from seed
- Extrapolate to next/previous layers
- Predefined windows are used
- Compatible stubs are considered as part of the same track
- Hypothesis of a track from primary vertex

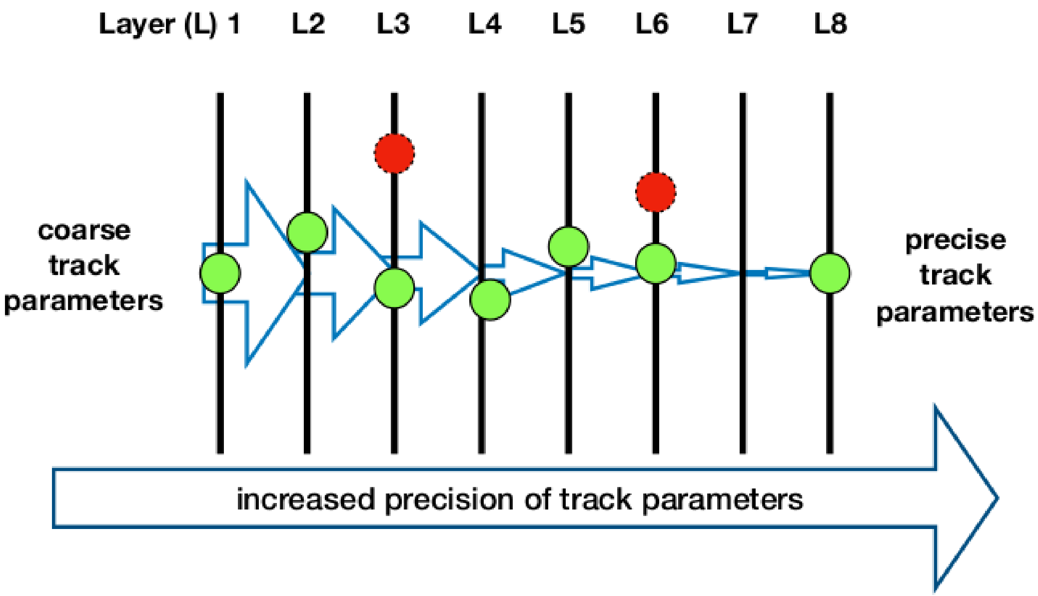
Duplicate removal

- The same charged particle can create multiple seeds
- A redundancy approach (all seeds considered independent) ensures high efficiency
    - -- Unavoidable side effect: creation of multiple L1 tracks from the same original particle
- Existence of random stubs complicates the situation
- Tracks sharing three or more stubs are considered duplicates and merged

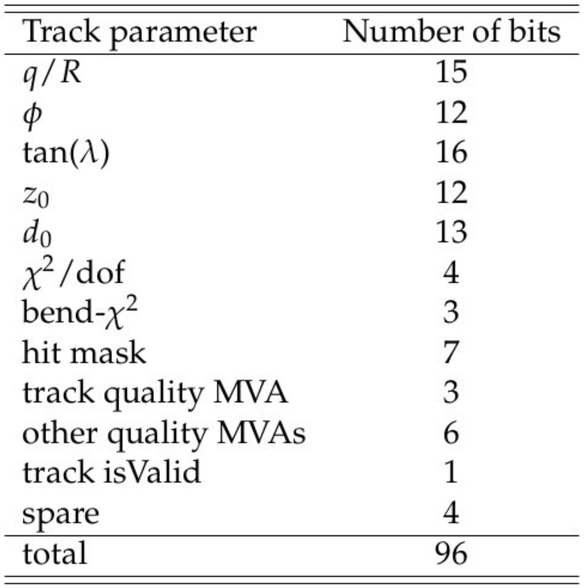


Track fitting

- Code based on Kalman Filter
- Start from the seed and sequentially add stubs layer-by-layer
- In every stub addition the track is updated
- Use a χ^2 test to reject fake tracks or incorrect stubs in a genuine track
- 4 parameter fit: p_T, η, φ, z



Tracks are represented by a word of 96 bits



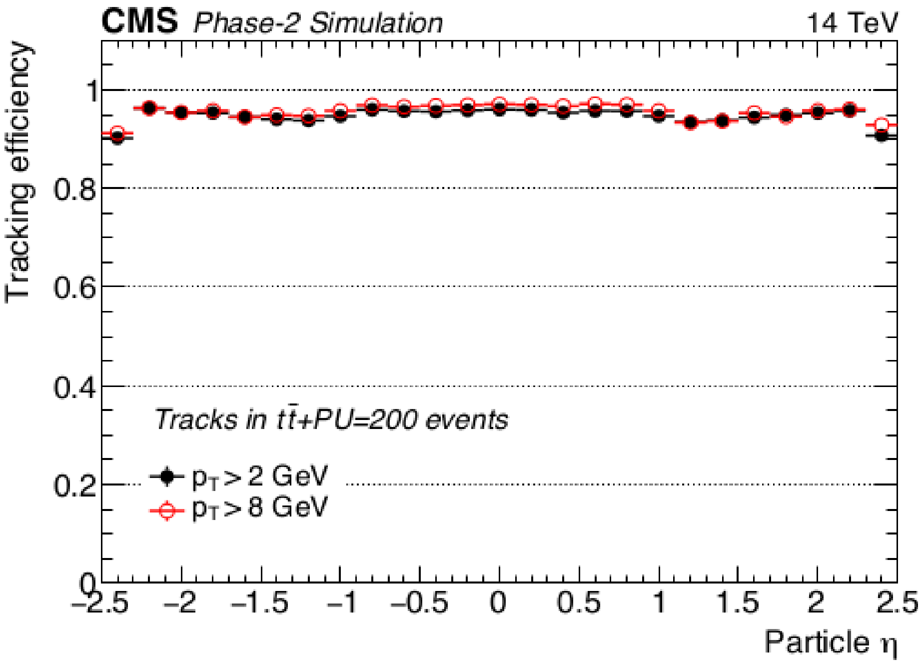
Track parameter	Number of bits
q/R	15
ϕ	12
$\tan(\lambda)$	16
z_0	12
d_0	13
χ^2/dof	4
bend-χ^2	3
hit mask	7
track quality MVA	3
other quality MVAs	6
track isValid	1
spare	4
total	96

TDR

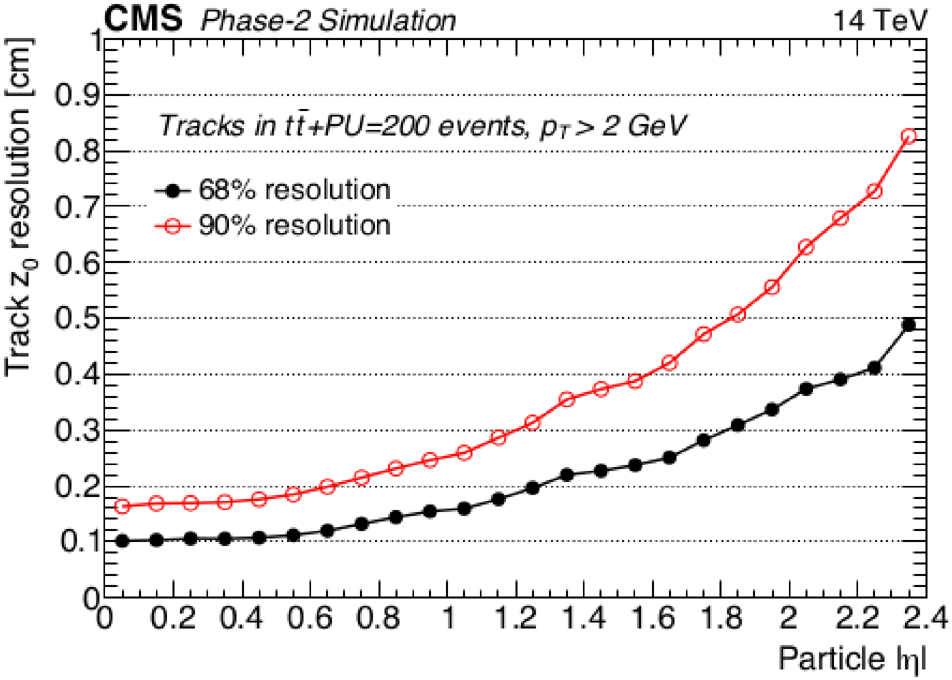
Performance

- Few examples of the L1 track performance

High efficiency across η



Precise z0 resolution for vertex association

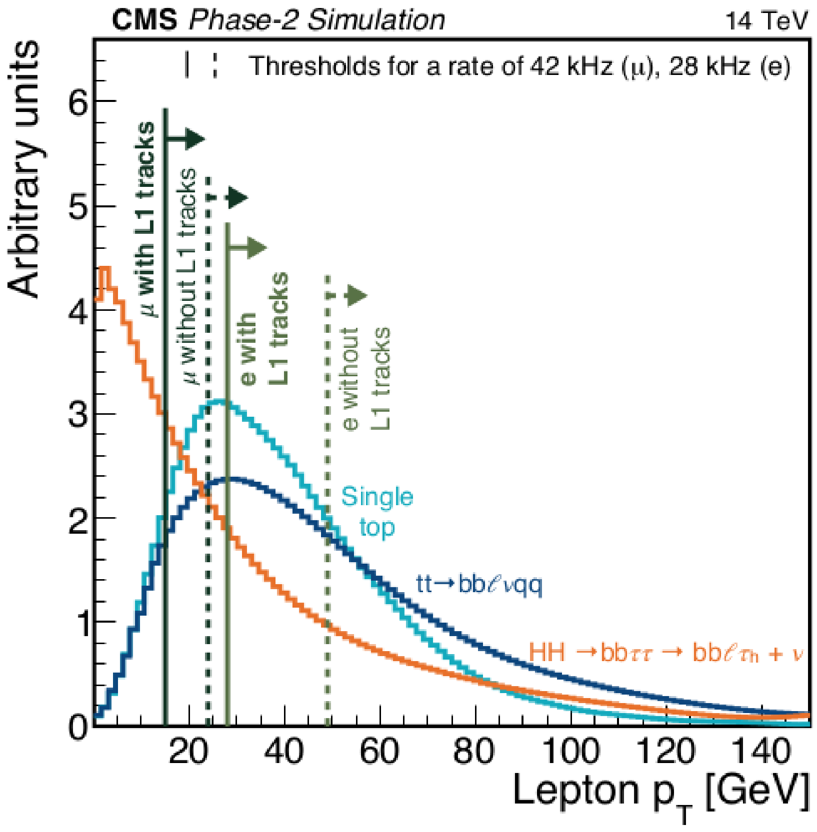


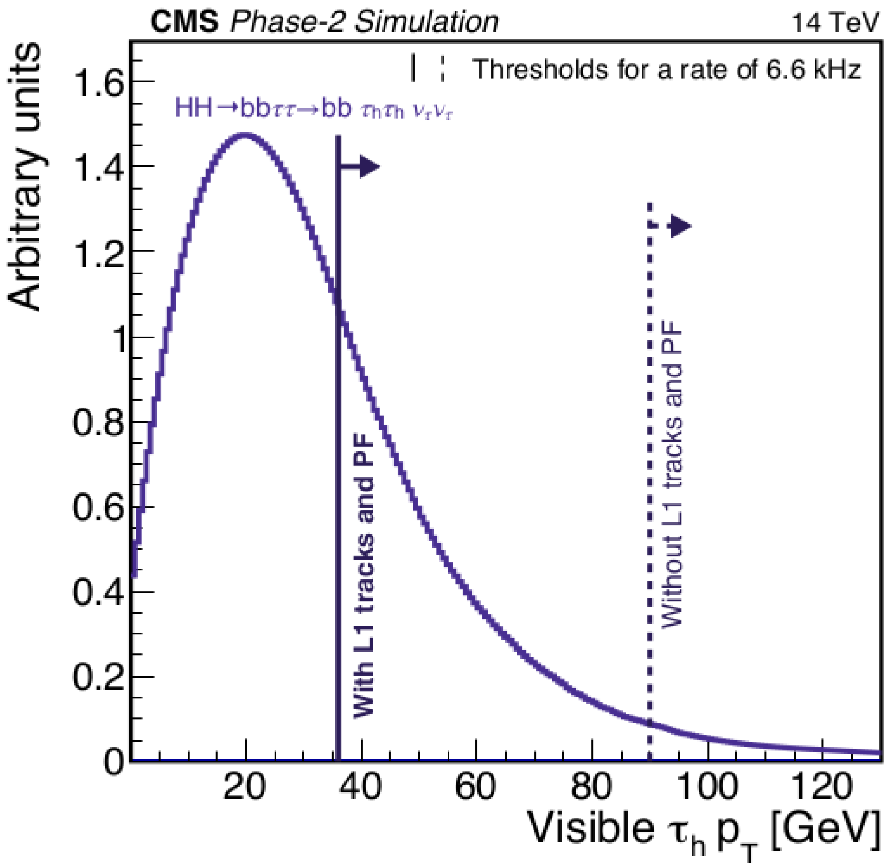
TDR

L1 track impact on thresholds

- Usage of L1 tracks in the trigger:
  1) Combining tracks with other objects improves p_T precision
  2) Provide extra handles like track Isolation
  2) Implementation of advanced Particle Flow techniques similar to the offline

p_T thresholds significantly reduced





TDR

Displaced track reconstruction

- Displaced L1 tracks: A new window to a (mostly) unexplored phase space
  - Run 2 displaced analysis used mostly on prompt L1 triggers reducing the sensitivity

Two modifications are needed to build displaced tracks:

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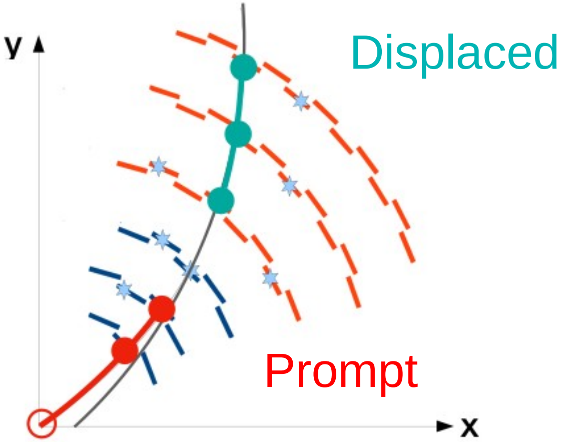
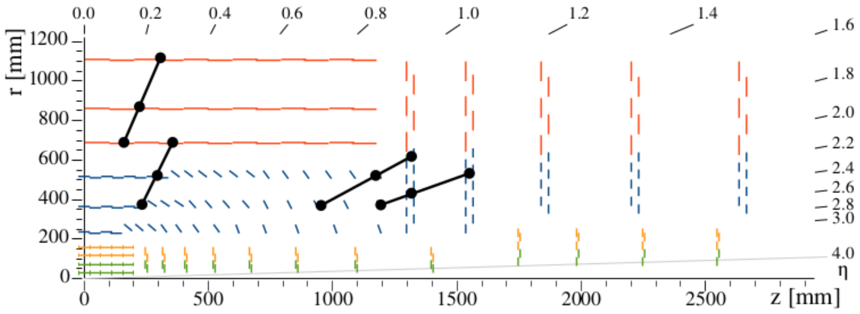
1) Seeding modification
   - Seeds of hybrid algo optimized for prompt tracks (as first stub the center of CMS is used)
   - In displaced tracking the center cannot be used, seeds are required to have three stubs





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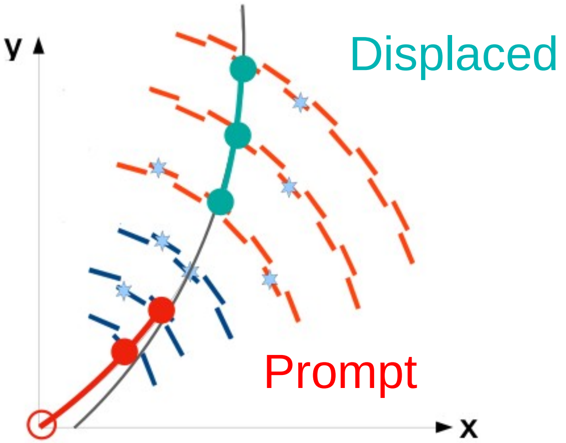
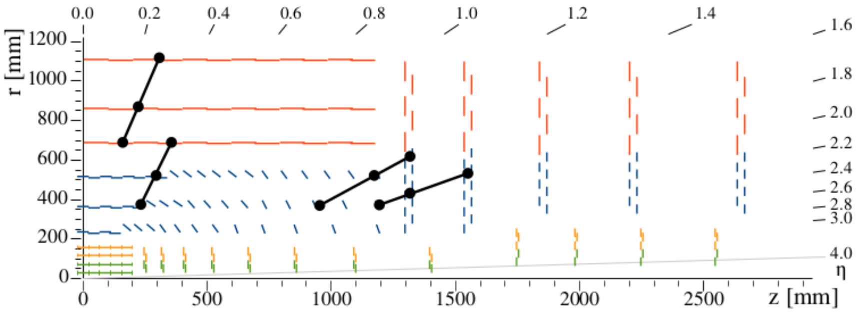


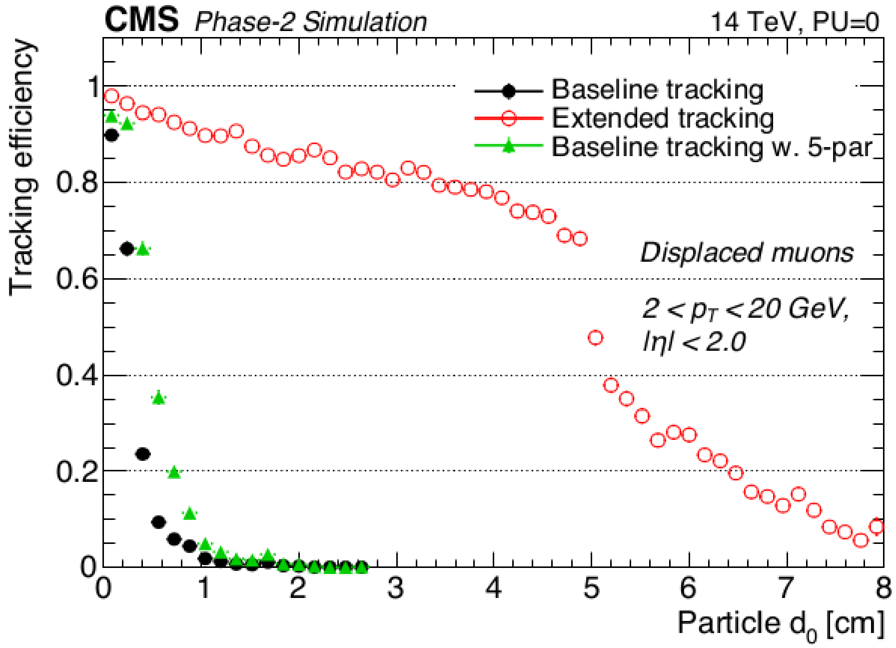


2) Fitting modification
   - Prompt tracks use a four-parameter fit (displacement is not needed by definition)
   - Displaced tracks need the addition of transverse impact parameter, d_0, so the fit is promoted to five-parameter

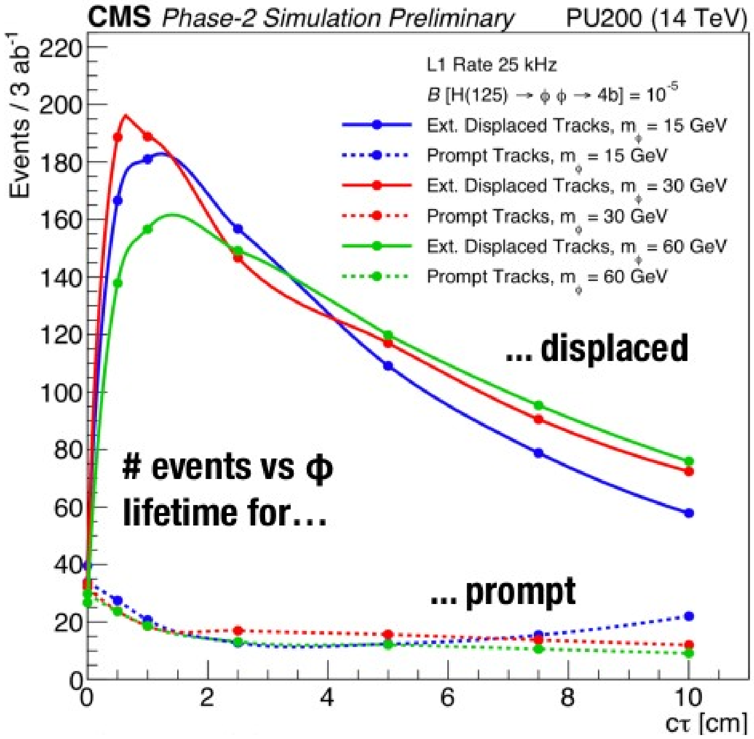
The displaced version of the hybrid algorithm is called “extended”

Extended tracking performance

Efficiency with a simple displaced muon gun as a function of d_0



Yields measured for an exotic Higgs to φ decay (φ displaced scalar)



 # events vs Φ lifetime for…

... displaced

... prompt

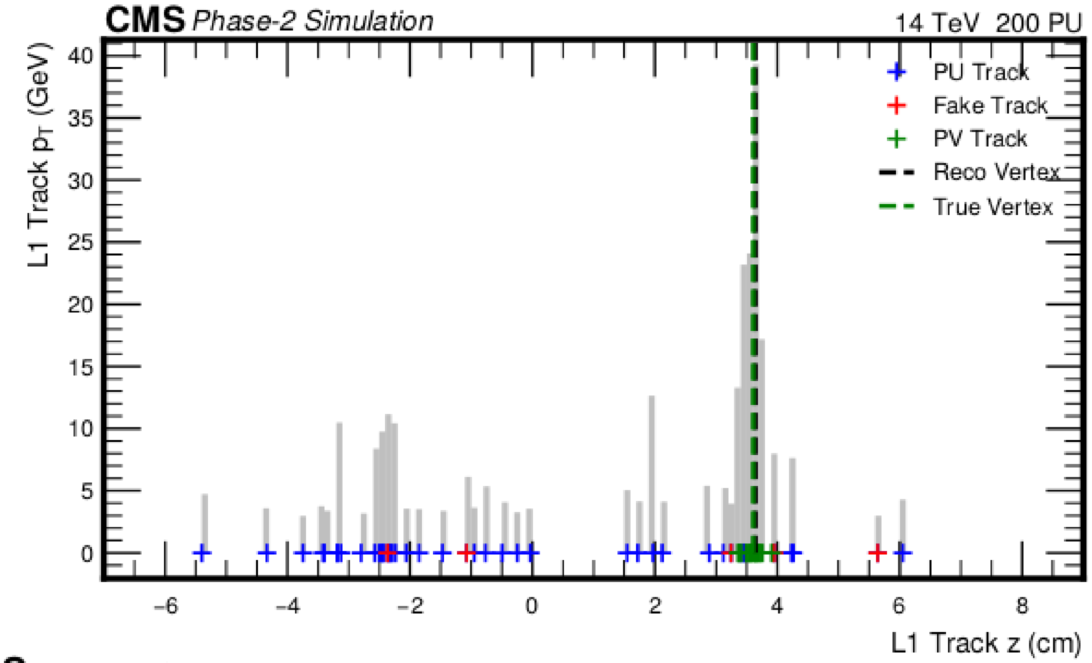
TDR

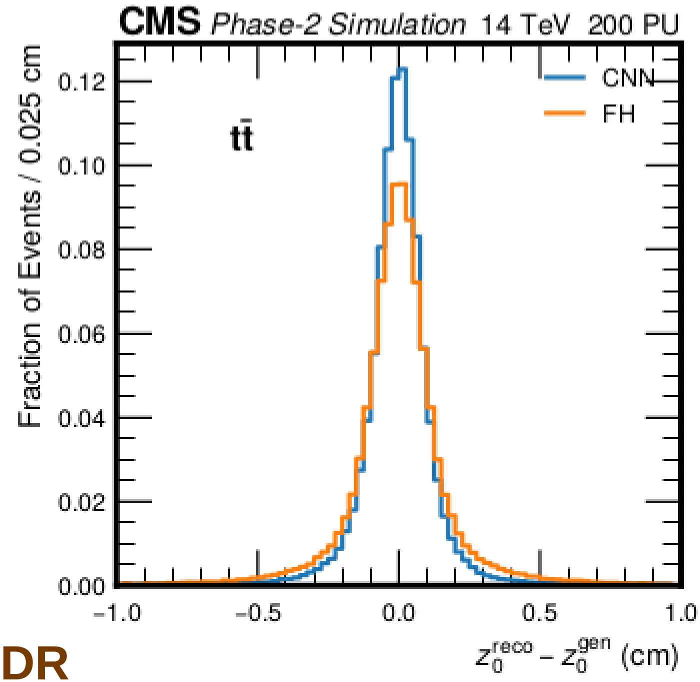
Higher level objects with L1 tracks

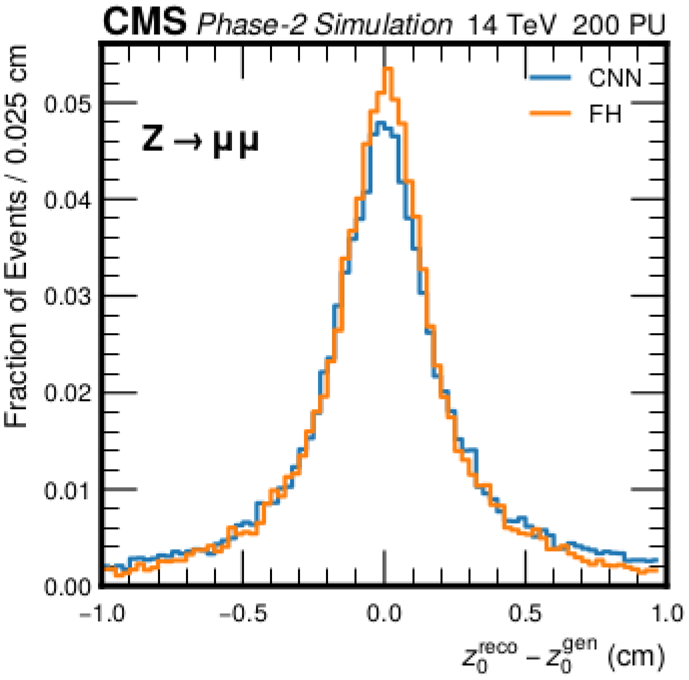
Primary vertex reconstruction

Algorithm of vertex reconstruction (FastHisto):

- Select tracks passing quality cuts
- Tracks sorted in bins of z (like histogram Filling)
- Each track is weighted based on p_T
- The weighted average in z is the vertex position
- As primary we consider the vertex with highest scalar sum of p_T







Performance of z position resolution is better for tt events than for Z. This is because tt is more energetic (ie more tracks)

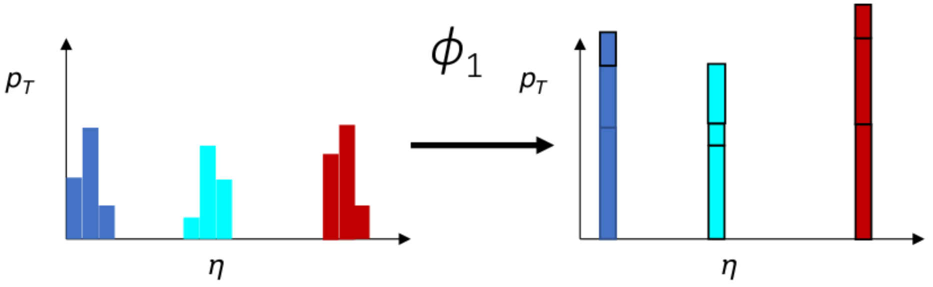
TDR

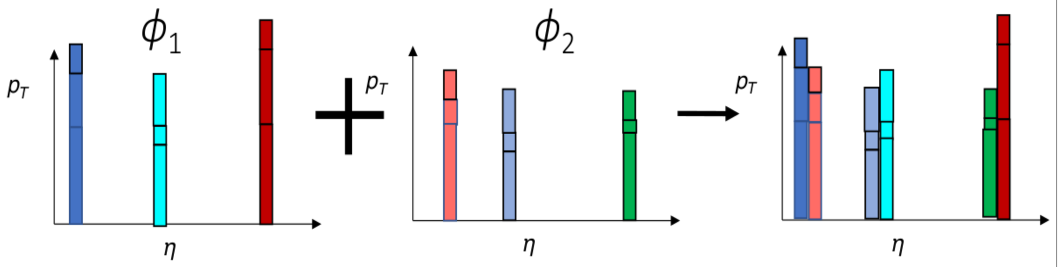
New type of jets: Trackjets

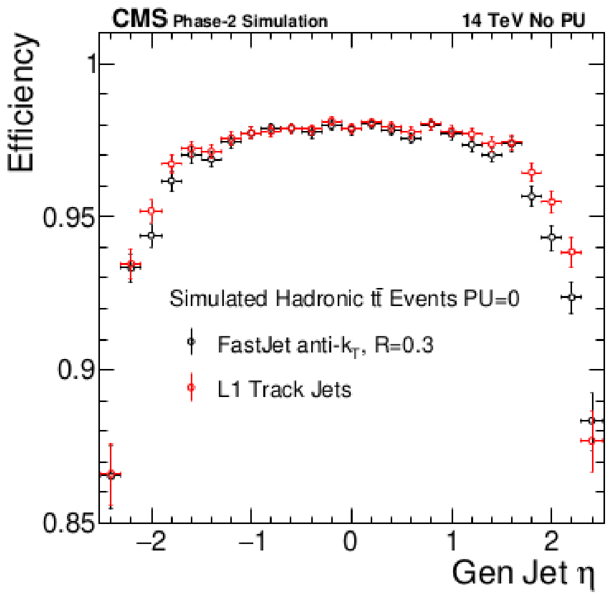
Algorithm

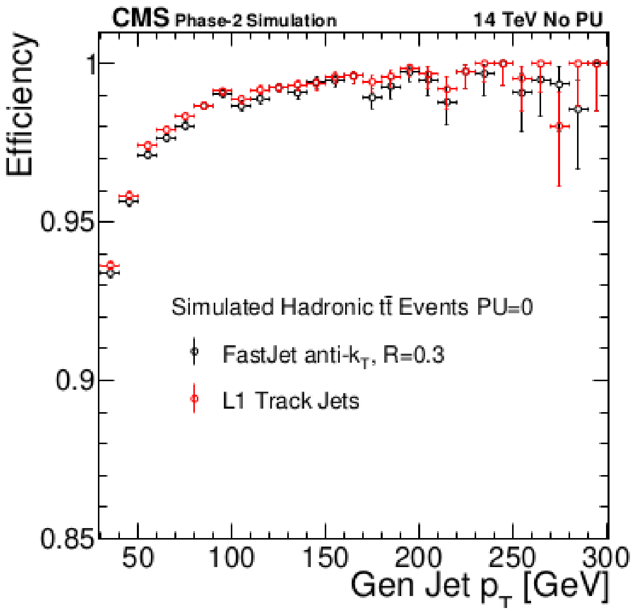
Step1: Divide in φ segments; bin tracks in η to create clusters

Step2: Bin the step 1 clusters in φ to create the final jets. Merge very close jets









TDR

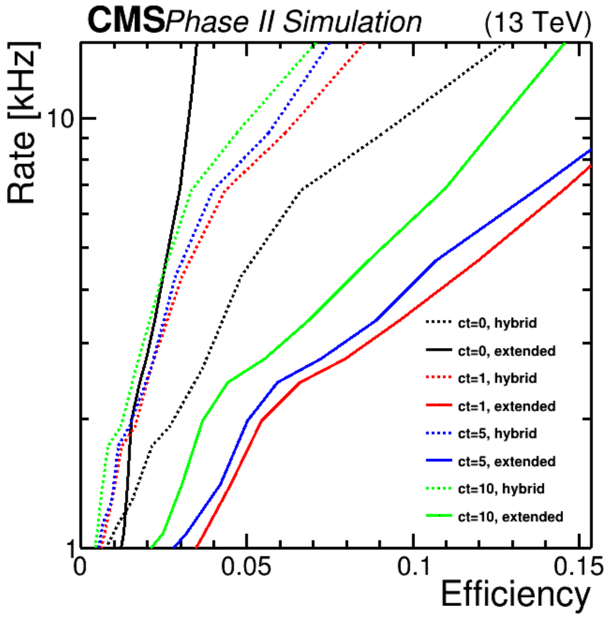
Displaced trackjets

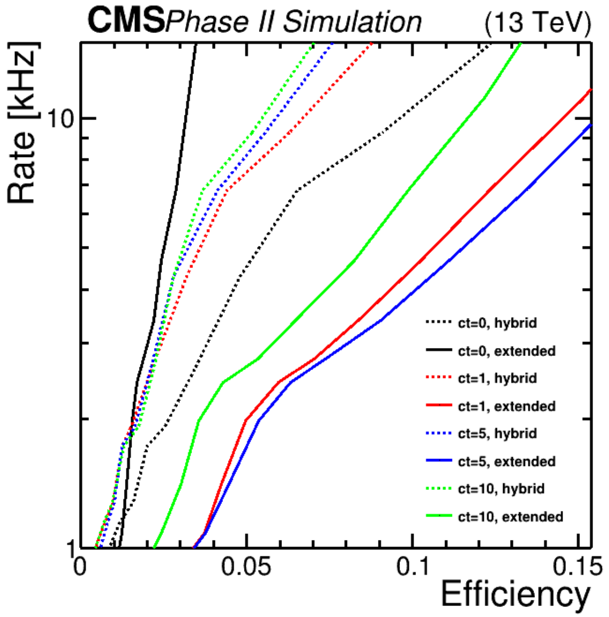
Using extended tracks for jet clustering → create displaced track jets

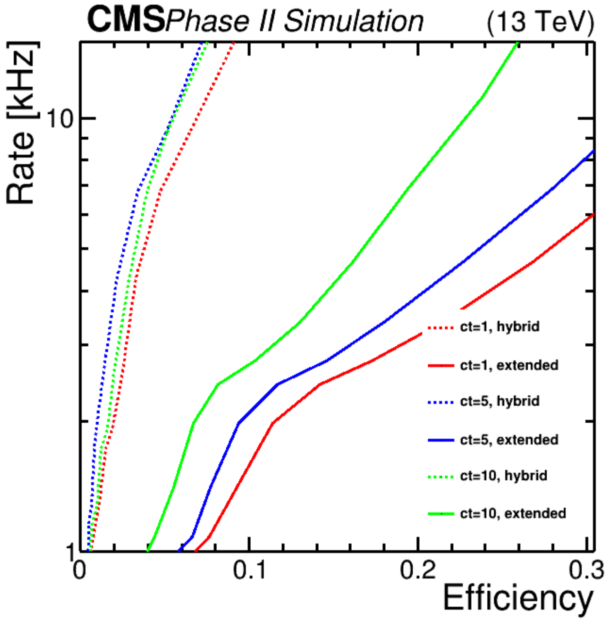
Samples:

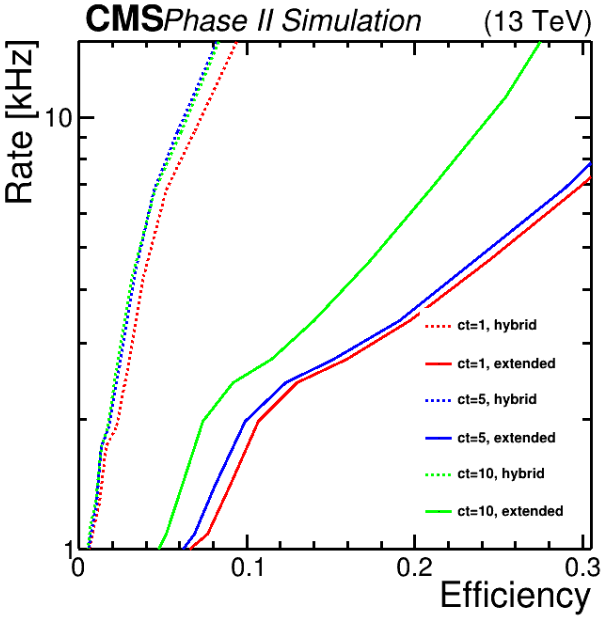
- Decay: H → 2Φ → 4b
- ct: 0, 1cm, 5cm, 10cm
- m(H)=125GeV, 250GeV
- m(Φ)=30GeV, 60GeV

ROC curves (Efficiency vs Rate) for hybrid vs extended trackjets


m(H)=125 GeV, m(Φ)=30 GeV


m(H)=125 GeV, m(Φ)=60 GeV


m(H)=250 GeV, m(Φ)=30 GeV


m(H)=250 GeV, m(Φ)=60 GeV

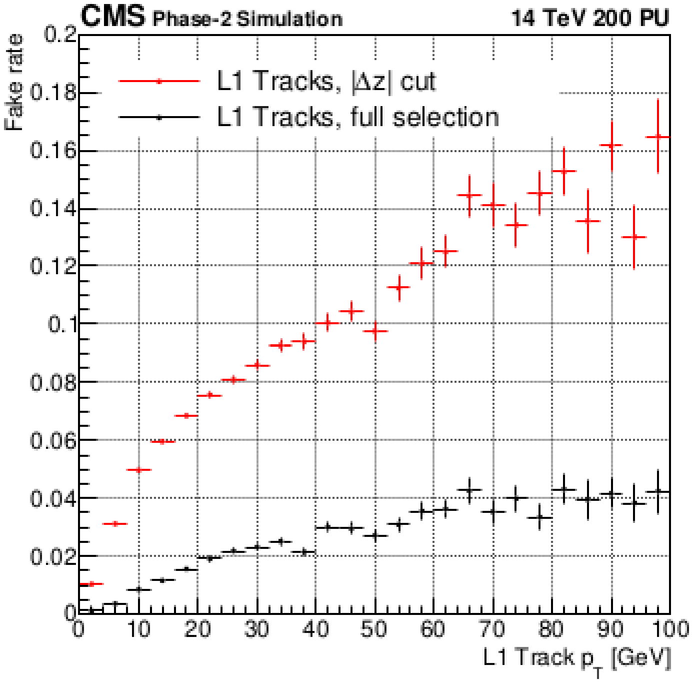
TDR

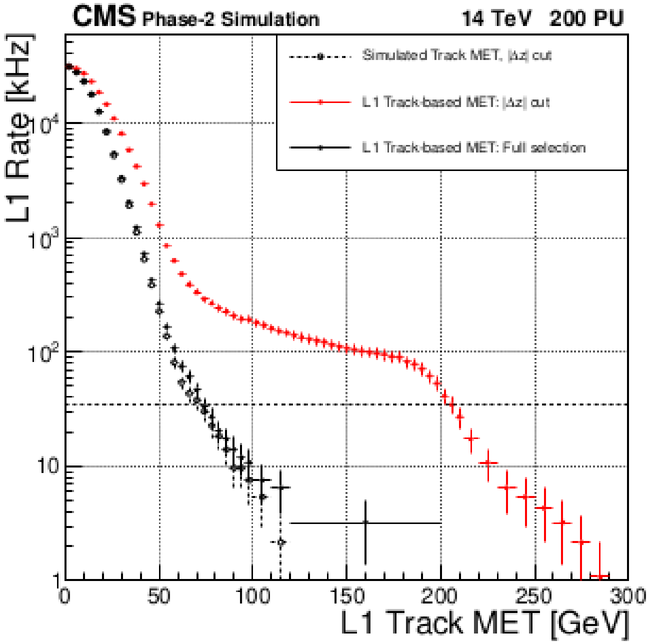
Track-based Missing Energy

Missing Transverse Energy (MET) can be calculated using L1 tracks only:

$$\mathrm{MET} = \Sigma\, \mathbf{p_T(trk)}$$

- Selection cuts for this track must be optimized carefully
- Tracks from random hit combinations can have very high p_T
  - -- In general those tracks are rare with respect to the total number of tracks
  - -- But if Δz cut between PV and tracks is applied, it becomes dominant
  - -- Additional quality cuts to make MET measurement more accurate





TDR

Summary

- Status of Phase 1:
  - Many very interesting measurements and searches
  - LHC has found any hard evidence of BSM
  - **We need to keep pushing the detector/accelerator limits!**

- Phase 2 Upgrade will enable us to:
  - Search even more exotic signatures
  - Make precision measurements
  - Discover rare decays

- The biggest change for L1 trigger for the Phase 2 is the track reconstruction:
  - Very time-consuming procedure
  - Requires the implementation of a complex system
  - The benefits are many:
    - Rate reduction in all thresholds (ie more interesting events)
    - New objects like trackjets
    - Exotic signatures like displaced tracks
    - Can even trigger on rare decays like $B_s \rightarrow \varphi\varphi \rightarrow KKKK$ in L1

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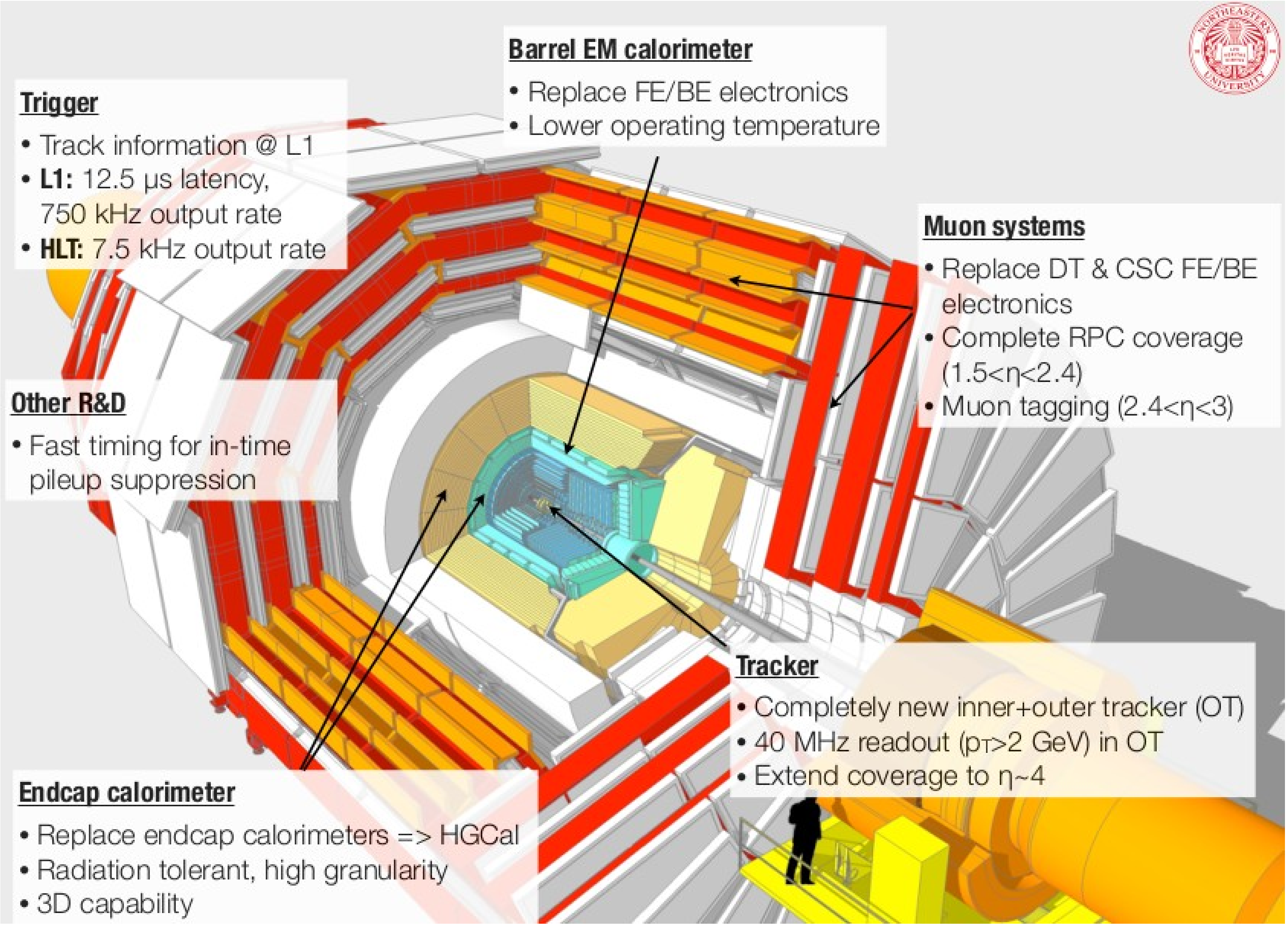
Back up

CMS detector



Trigger
- Track information @ L1
- **L1:** 12.5 μs latency, 750 kHz output rate
- **HLT:** 7.5 kHz output rate

Barrel EM calorimeter
- Replace FE/BE electronics
- Lower operating temperature

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

Other R&D
- Fast timing for in-time pileup suppression

Tracker
- Completely new inner+outer tracker (OT)
- 40 MHz readout ($p_T>2$ GeV) in OT
- Extend coverage to $\eta\sim4$

Endcap calorimeter
- Replace endcap calorimeters => HGCal
- Radiation tolerant, high granularity
- 3D capability

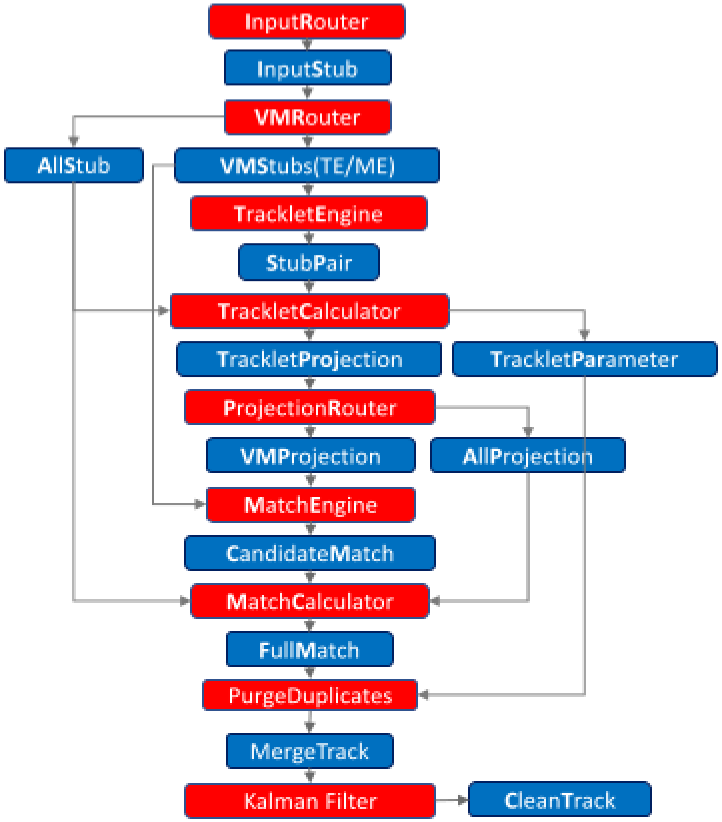
Hardware implementation

Processing modules: Implement the track finder

Memory modules: Store and share information

Tracklet builder and layer projector are written in HLS

Klaman filter is written in VHDL



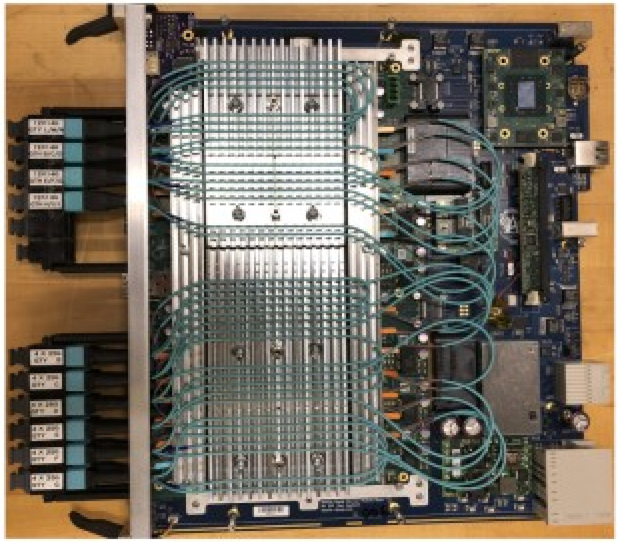
Slice tests on-going

- Hardware for track-finding based on ATCA platform (CMS standard for HL-LHC upgrade)
- Demonstration of algorithm in progress

Test stand @ CERN
with Apollo & Serenity blades

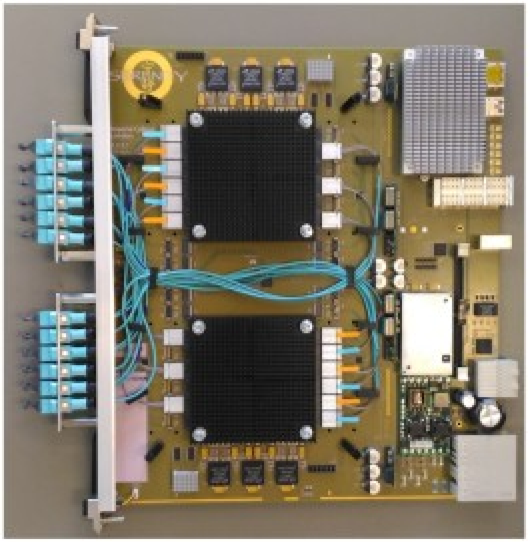
Apollo: track finding processing boards

- *Service Module* provides infrastructure components
- *Command Module* contains two large FPGAs, optical fiber interfaces & memories

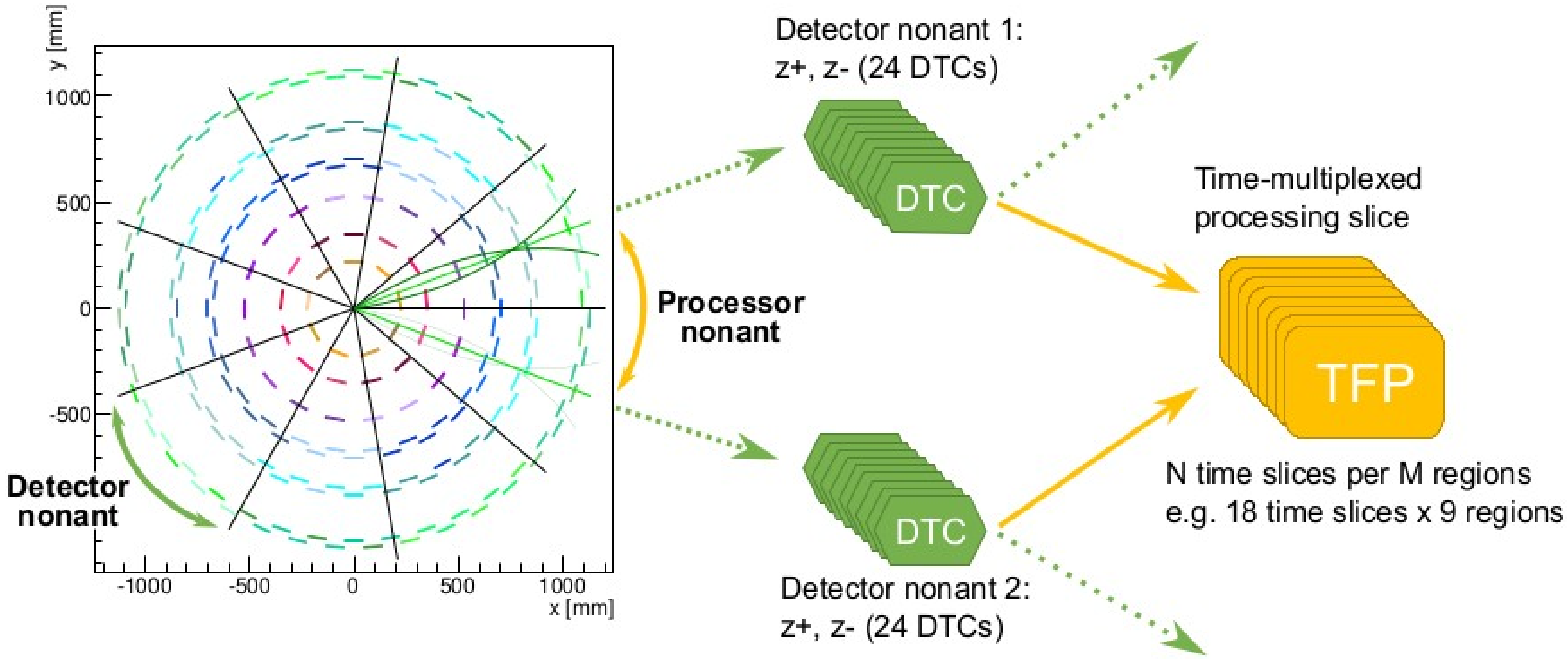


Serenity: DTC processing

- Carrier card provides services
- Daughter cards host FPGAs for data processing



DTC & TFP



Outer tracker

DTC = Data Trigger & Control boards

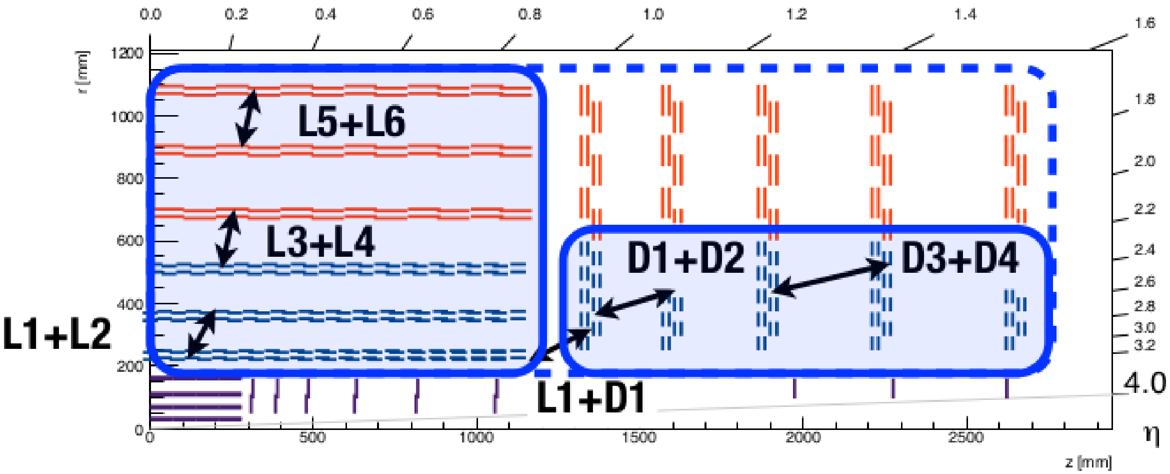
TFP = Track Finding Processor boards

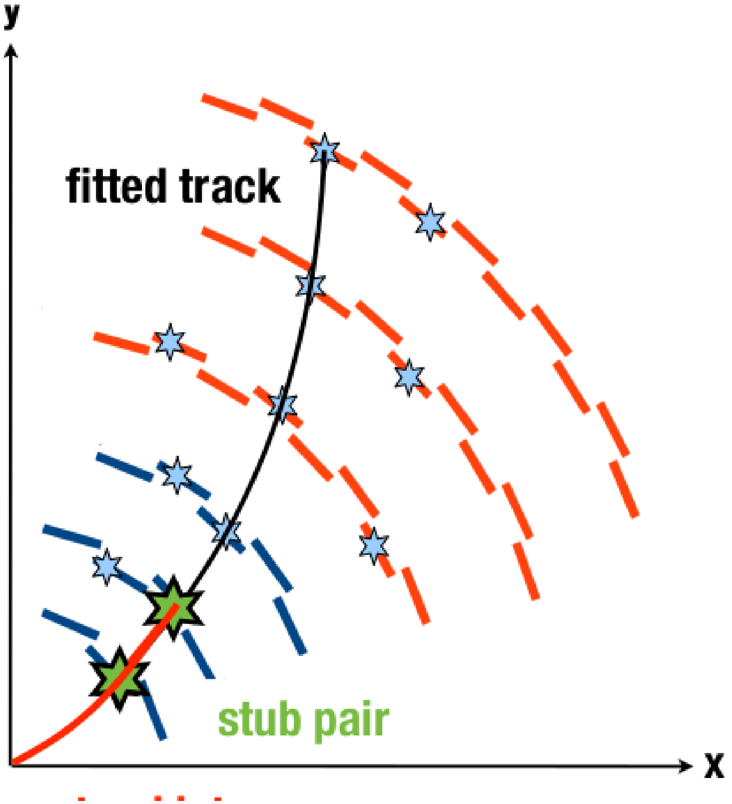
DTCs perform stub pre-processing & distribute stubs to TFP boards (+ communicates with detector modules, forwards full event data upon L1 accept, etc.)

- new event received every 450 ns
- total system: 162 TFP boards

Tracklet algo

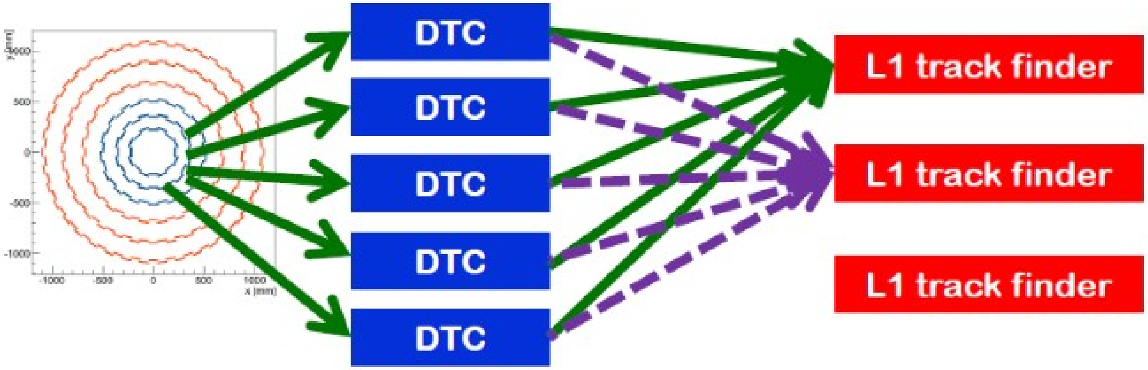
- **Seed** by forming tracklets
  - Pairs of stubs in adjacent layers/disks
  - Initial tracklet parameters from stubs + beamspot constraint
- **Project** to other layers/disks & match with stubs
  - Inside-out & outside-in
  - Calculate residuals used in fit
- **Fit** stubs matched to trajectory
  - Linearized X^2 fit
- Remove **duplicate** tracks based on shared stubs





Hough transform

- Fully time-multiplexed architecture where all module data for given BX send to a single track finder processor board



- Pattern recognition using Hough transform + track fitting (all in FPGA)