Level-1 Track Finding at CMS for the HL-LHC

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on behalf of the CMS Collaboration

Connecting the Dots 2020. April 2020.

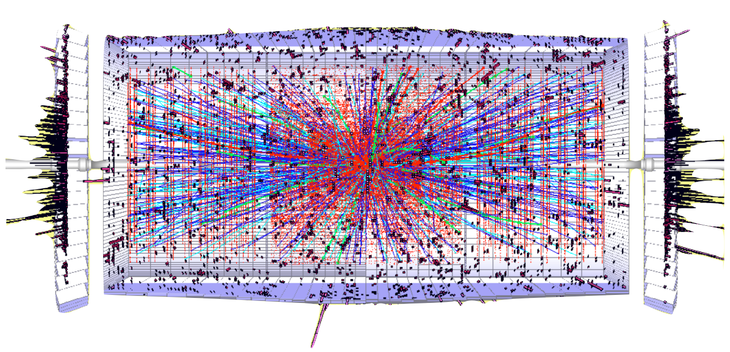
Introduction

- Upgrade to High-Luminosity LHC (HL-LHC) in 2025-2027 will significantly increase instantaneous luminosity
  - Datasets of up to 4000 fb^{-1} for CMS & ATLAS
- *Experimentally challenging conditions!*

Instantaneous Luminosity

LHC (design): **10^{34} $cm^{-2}s^{-1}$**
LHC (Run-2/3): **2 x LHC**
HL-LHC: **7.5 x LHC**

- CMS detector upgrades for HL-LHC includes **tracking in L1 trigger**
  - Full-detector track reconstruction operating at 40 MHz input rate
  - Based on unique concept of double-sided p_T modules
  - Additionally, exploring "extended" capability to reconstruct displaced tracks e.g. due to long-lived particles
- Will show here latest results from the evolved CMS L1 track finding system

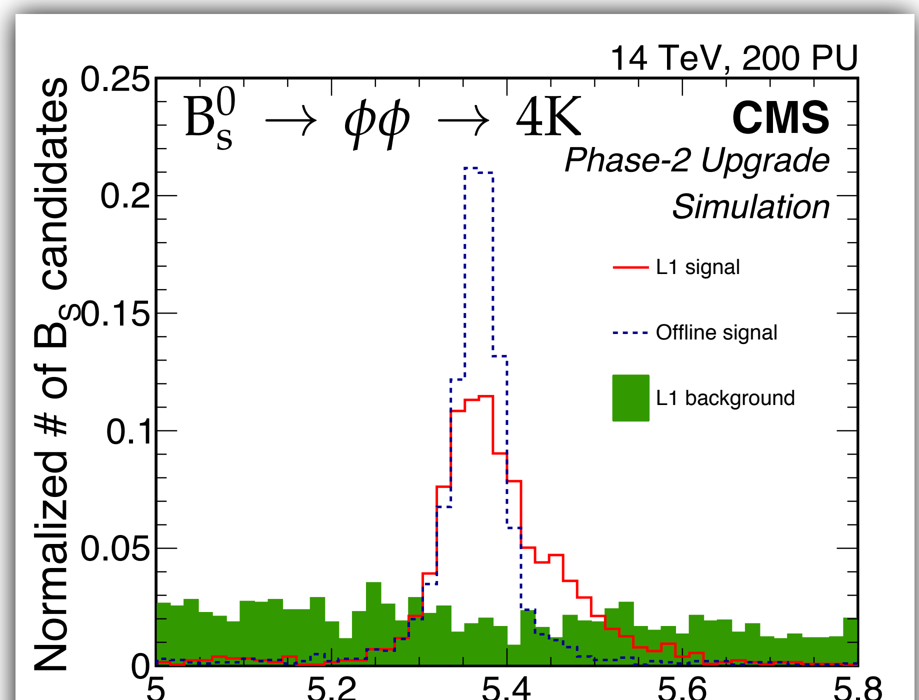


Motivation

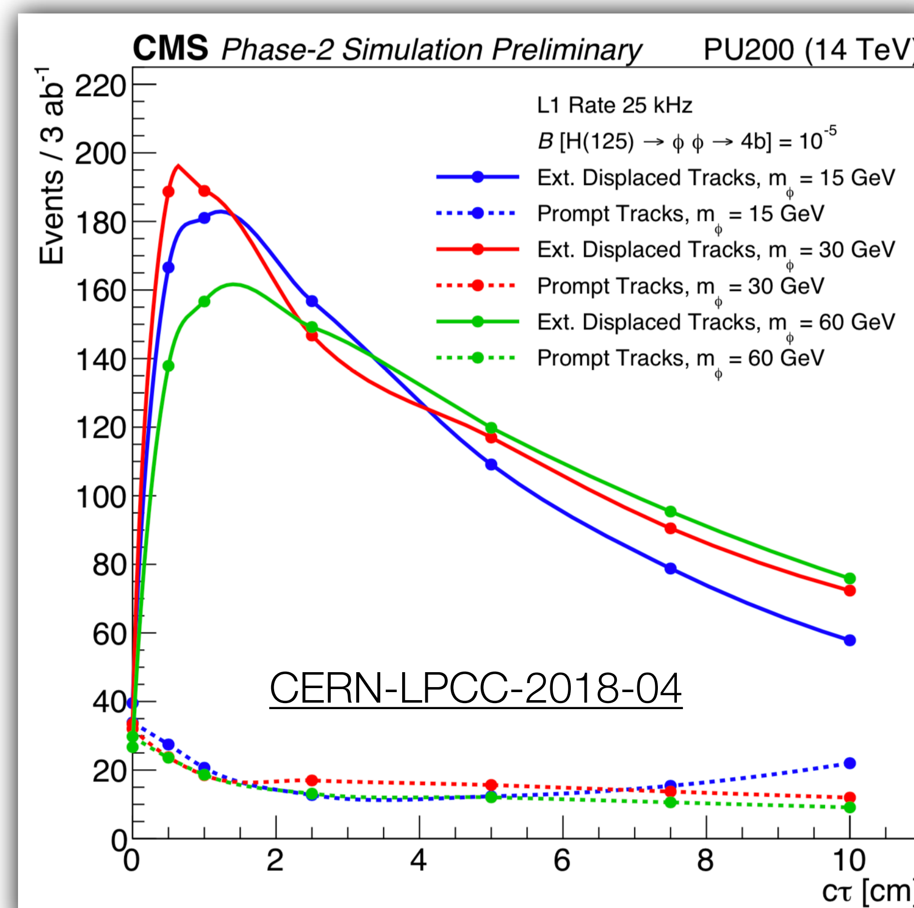
- Large HL-LHC datasets enable exciting physics opportunities
  - Precise measurements of Higgs boson properties & couplings
    - *Probe self-coupling through HH production*
  - Extend discovery reach in BSM searches
  - Search for rare SM processes, possibly enhanced by BSM physics

Maintain ability to trigger on physics at electroweak scale

- *Additionally, probe processes with new sensitivity thanks to upgraded detectors*



CMS-TDR-014



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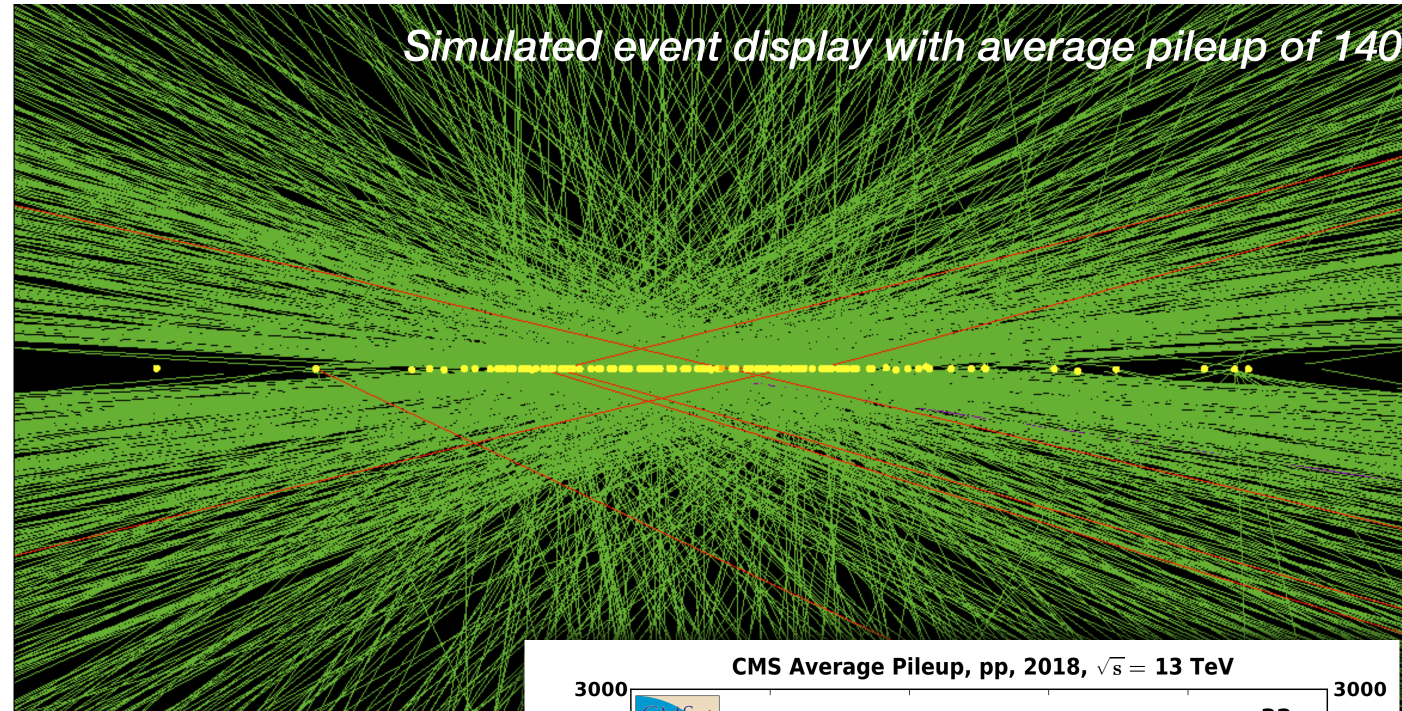
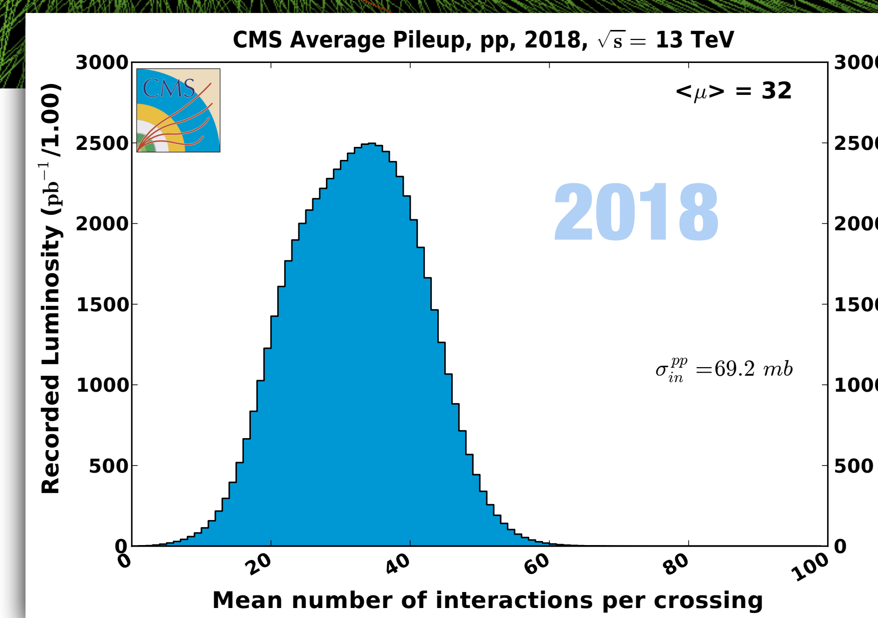
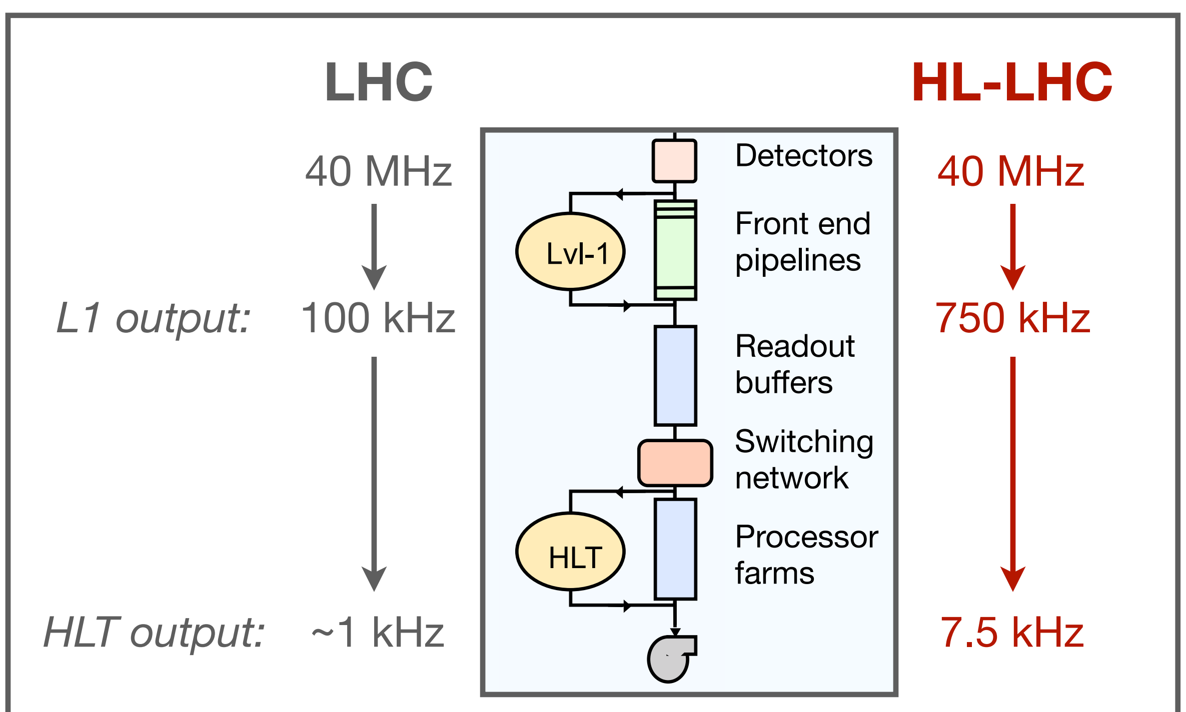
Challenges

- Price to pay for high luminosity — extreme **pileup**
  - At HL-LHC, expect on average **200** overlapping *pp* collisions
- Particularly challenging for trigger system
  - Inclusion of tracking central to mitigating effects of pileup

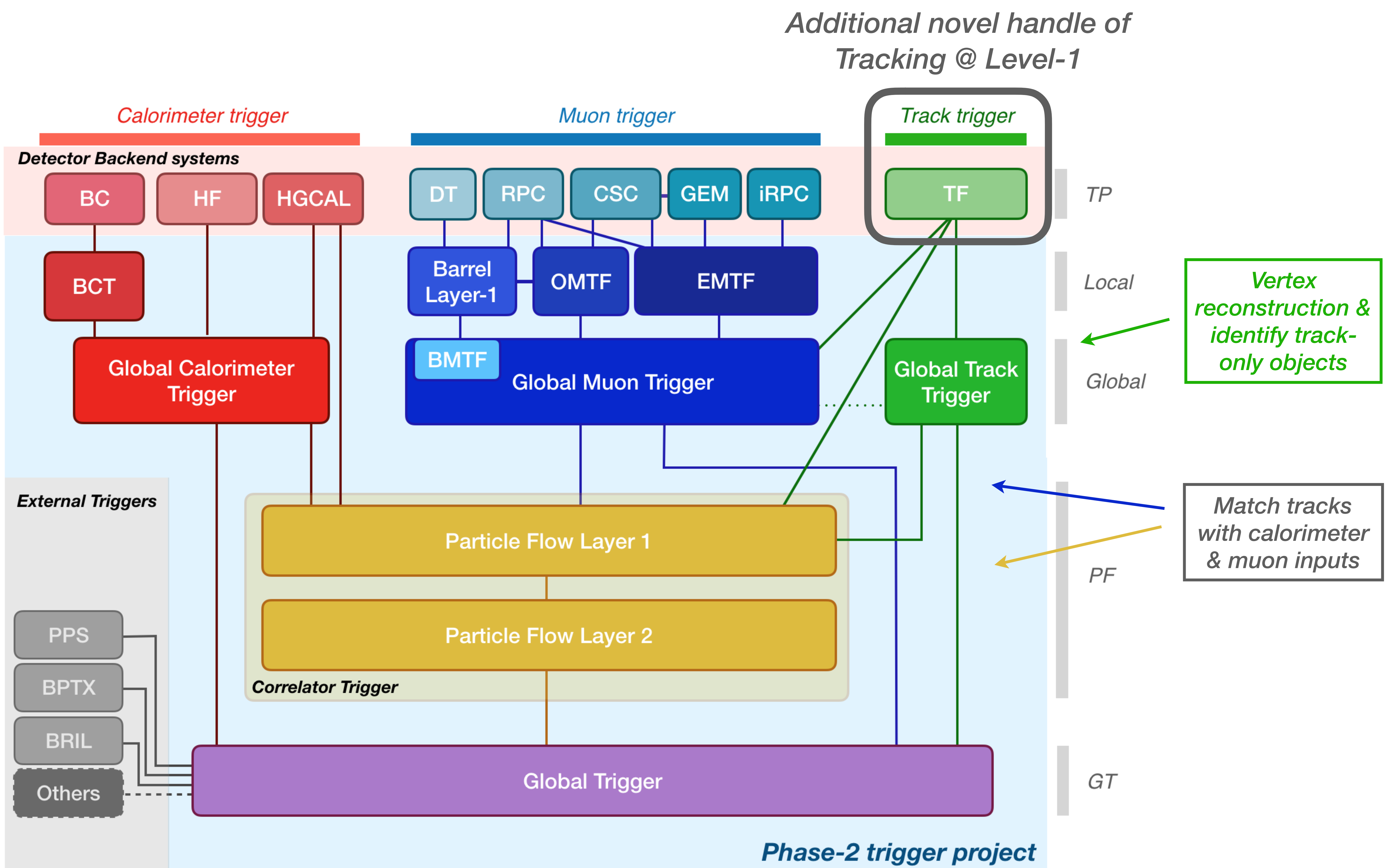






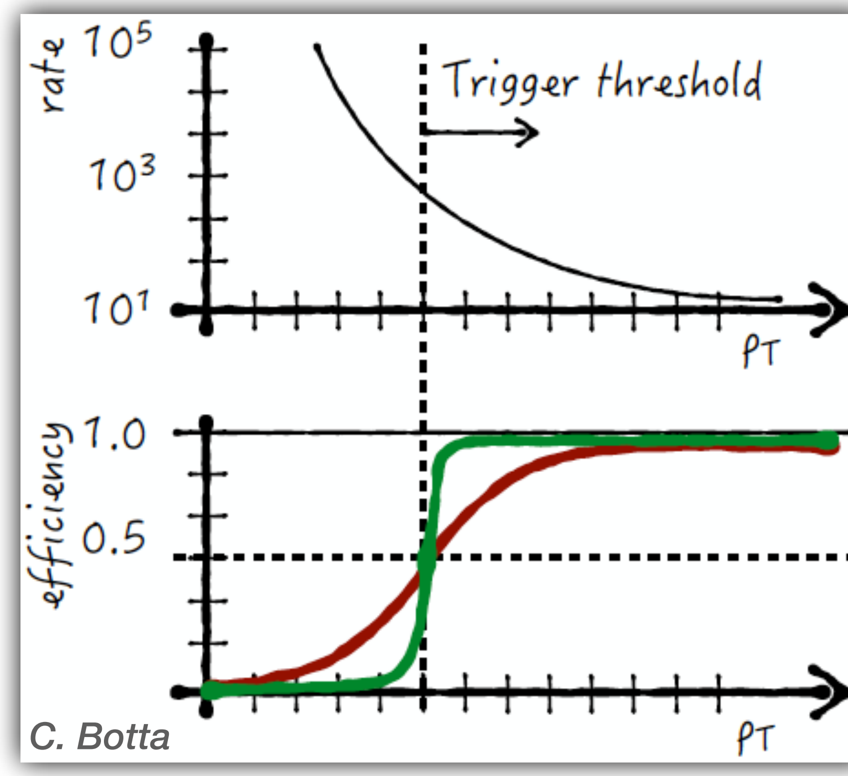
- Trigger system reduces 40 MHz collision rate to data rate that can be read out & written to disk
- w/o tracking, L1 output for PU=200 is ~4000 kHz

CMS L1 trigger for HL-LHC

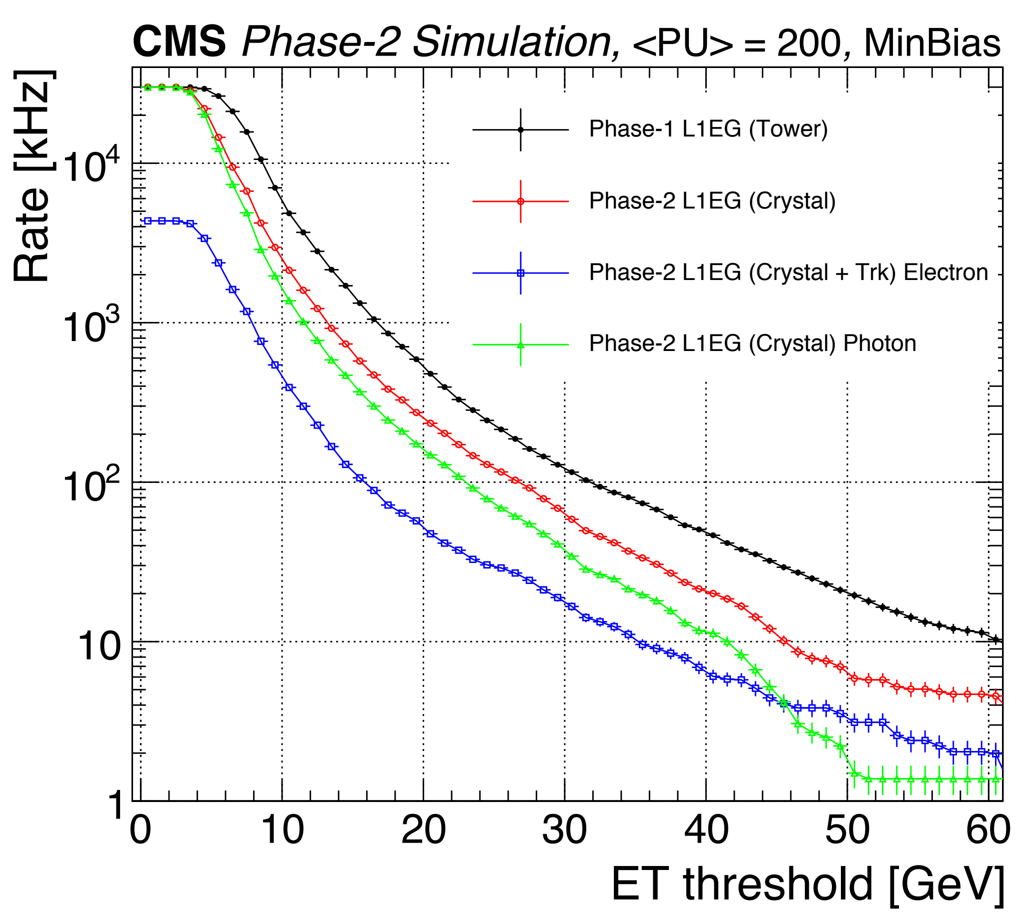


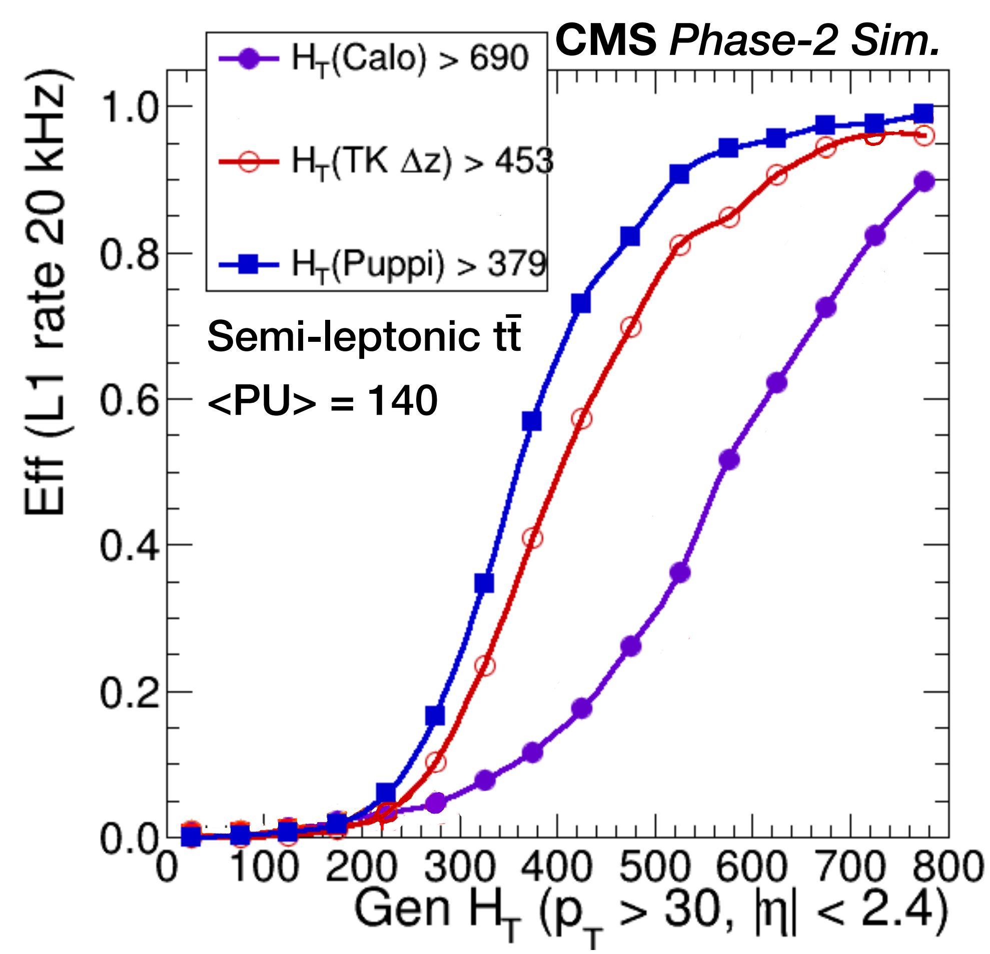
Using tracking @ L1

- Typical handle to control event rates at trigger level — increase momentum thresholds
  - Increasing thresholds limits physics potential + alone insufficient

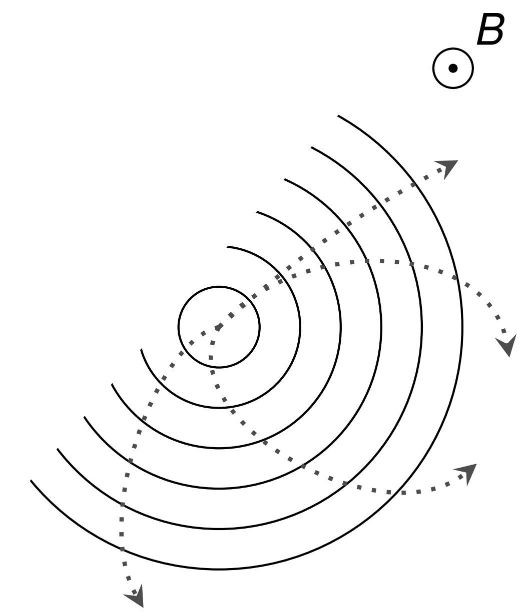


- Tracking provides…
  - Improved muon p_T measurement, e/γ/τ identification, vertex association for hadronic triggers …





CMS tracker for HL-LHC



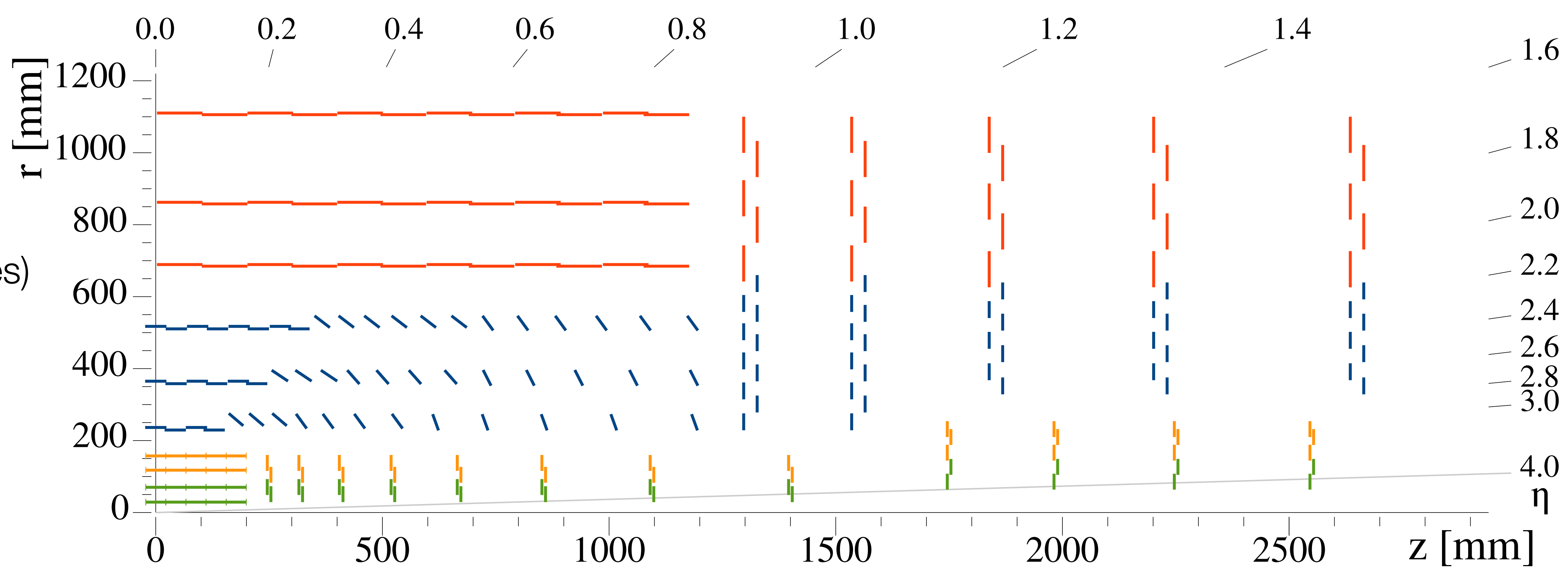
- New all silicon outer tracker + inner pixel detector
  - Increased granularity for HL-LHC occupancies
  - Tracking in hardware trigger, identify particles with $p_T > 2$ GeV

Outer Tracker

(**PS** vs **2S** modules)
=> used at L1

Inner Pixel

(**1x2** vs **2x2** chip modules)
=> not used in L1

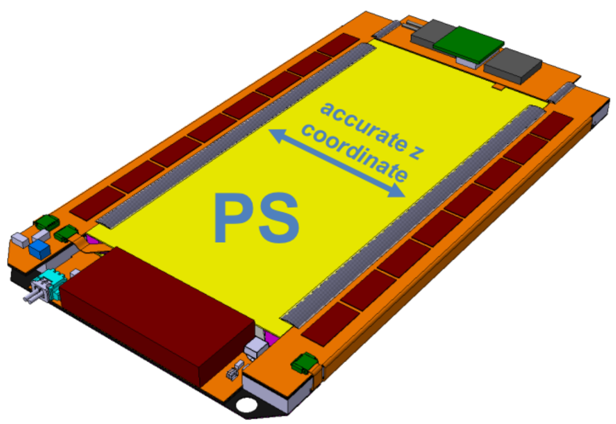


p_T module concept

- Modules provide p_T discrimination in front-end electronics through hit correlations between two closely spaced sensors
- Realized in two module types: **PS** & **2S**

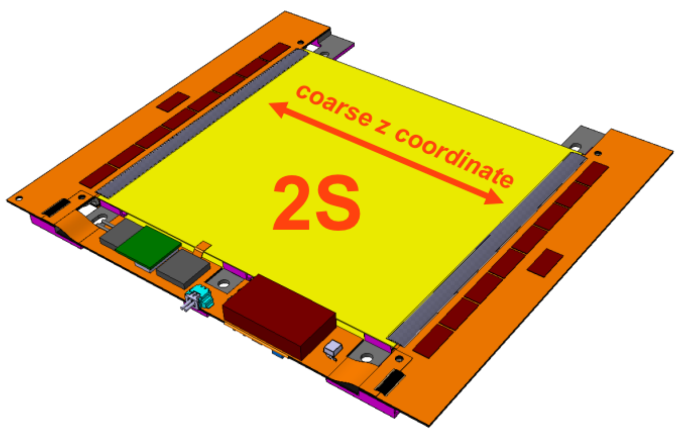
PS modules (pixel-strip)

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

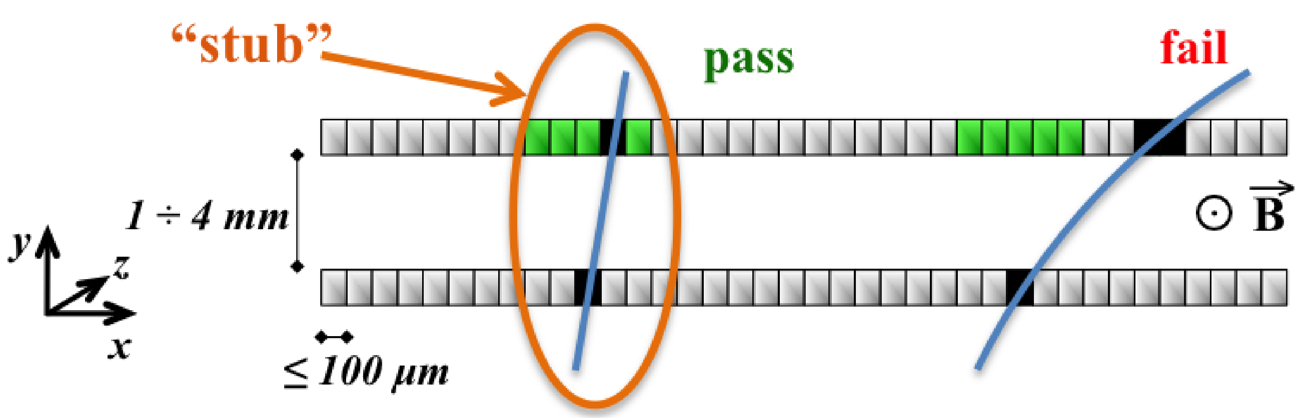


2S modules (strip-strip)

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



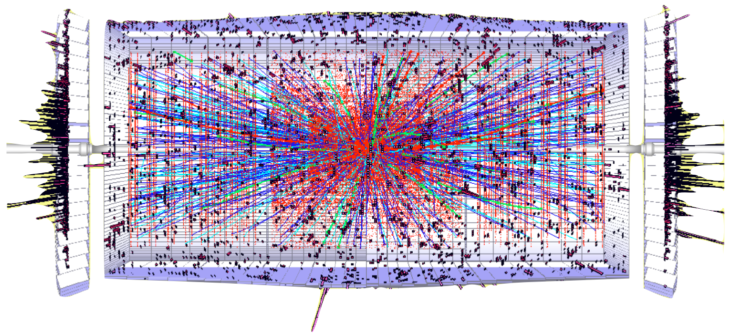
- **Stubs:** Correlated pairs of clusters, consistent with ≥ 2 GeV track
  - Data reduction at trigger readout (by factor 10-20)
  - *Stubs form input to track finding*



Tracking @ L1

- Reconstruct trajectories of charged particle with p_T > 2 GeV, |η| < 2.4
  - At HL-LHC, expect ~7000 charged particles / BX
  - ~200 trajectories with p_T > 2 GeV

BX = bunch crossing



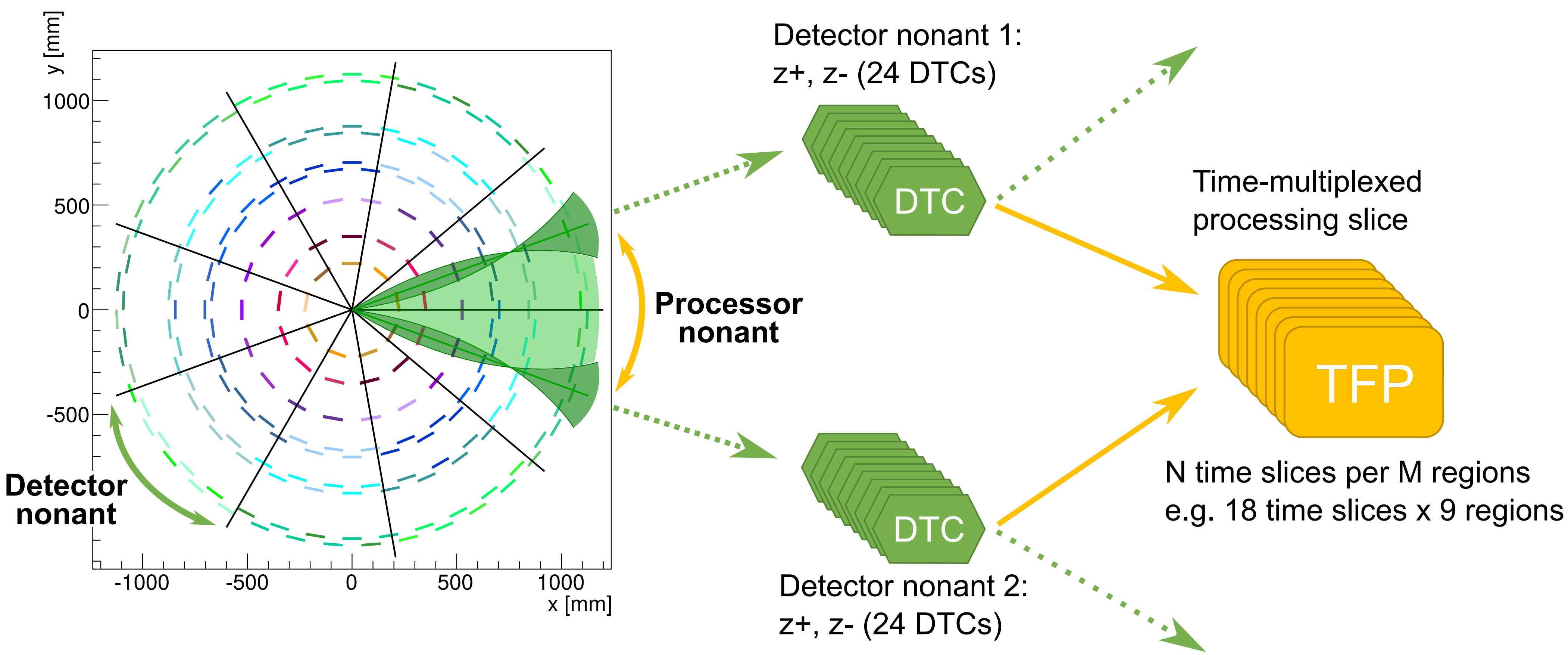
- Challenges
  - _Combinatorics_ from 15-20K input stubs / BX
  - _Data volumes_ of up to ~50 Tbits/s
  - *L1 trigger decision within 12.5 μs, ~4 μs available for track finding*
    - ***A track trigger operating at 40 MHz with <10 μs latency has never been built***

- Utilize extensive parallel processing to tackle above challenges
- CMS utilizes a fully FPGA-based system
  - Off-the-shelf hardware
  - Programmable => flexibility

FPGA = field programmable gate array

System architecture

- Outer tracker divided in 9 ϕ sectors, time multiplexing factor of 18



Outer tracker

DTC = Data Trigger & Control boards

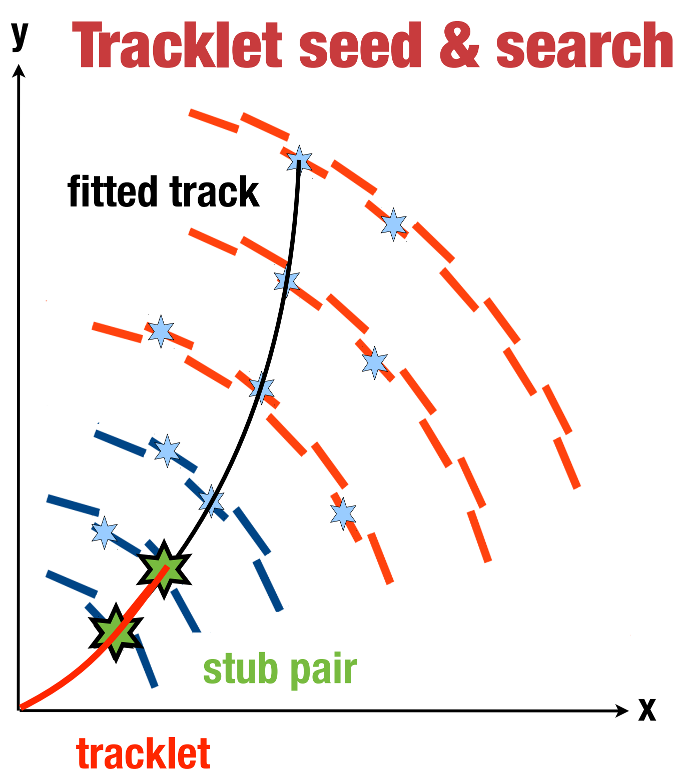
TFP = Track Finding Processor boards

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

Algorithm overview

- Different algorithms have been explored at CMS for L1 track finding
  - Similar performance & demonstrated feasibility, detailed in Phase-2 Tracker TDR
- *Hybrid* algorithm combines ideas from legacy algorithms
  - Road-search algorithm based on "tracklet" seeds
  - Kalman Filter used to identify best stub candidates & provide track parameters



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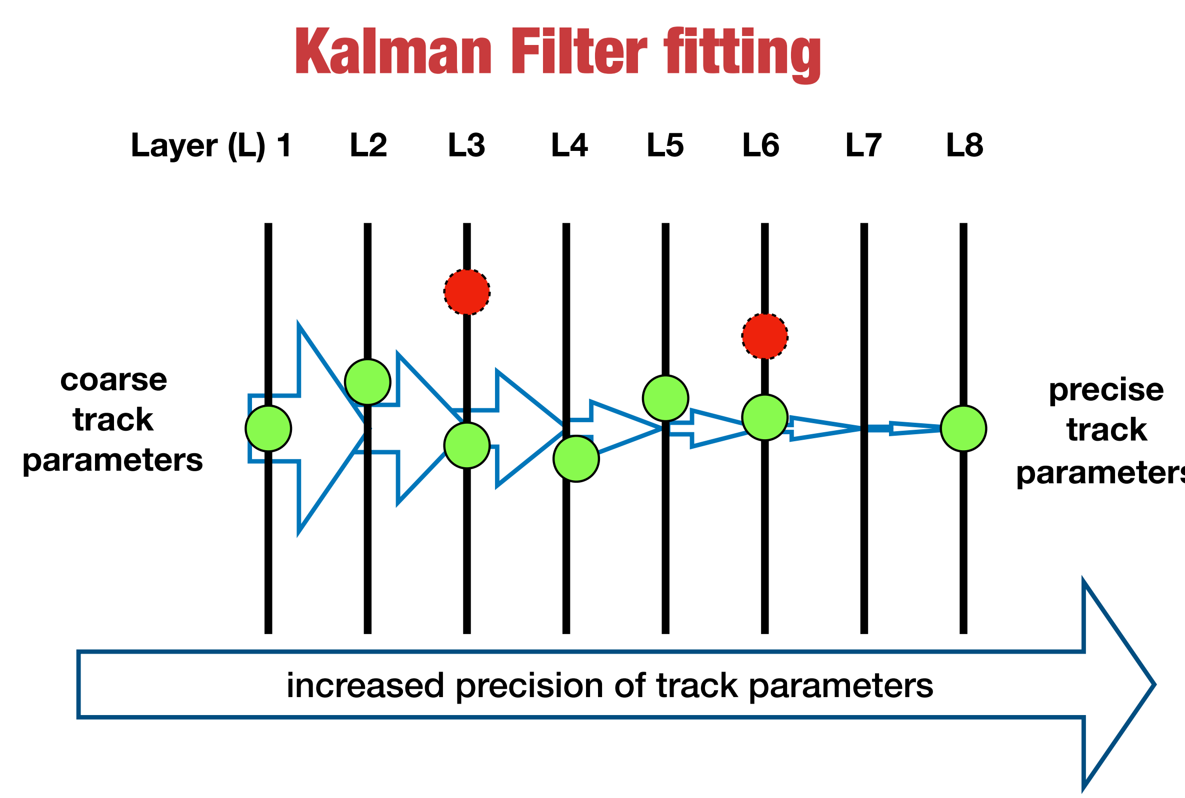
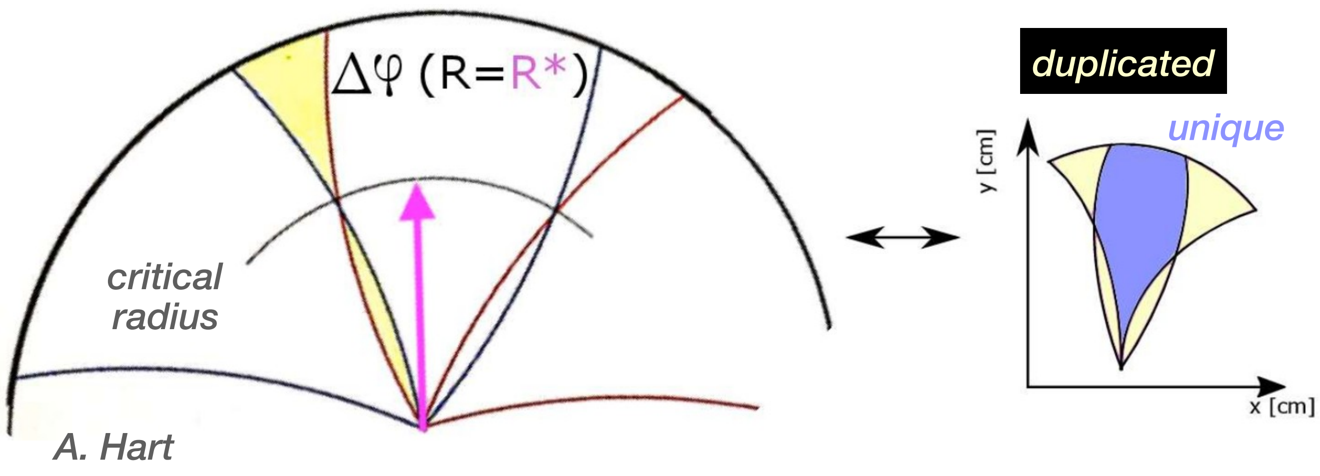
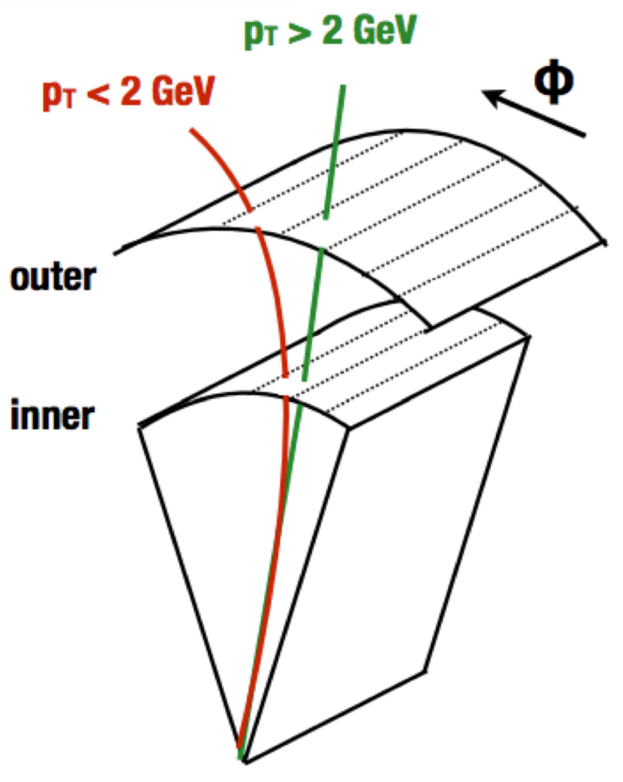


Parallelization

- Extensive parallelization in space & time (time multiplex of 18)
- Detector divided into 9 hourglass-shaped ϕ sectors
  - Hourglass shape prevents tracks above given p_T threshold from entering >1 sector => <u>no cross-sector communication required!</u>
  - Critical radius tuned to minimize overlap of stubs

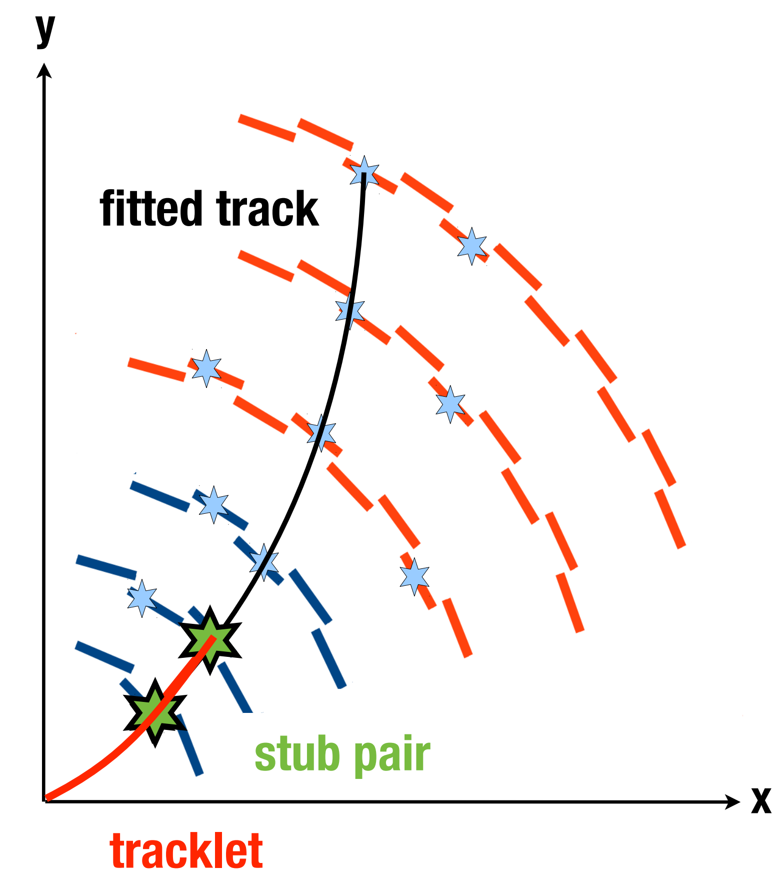


- Within-sector parallel data processing
  - Divide ϕ sector into "virtual modules"
  - Throughout algorithm, only consider combinations compatible with >2 GeV => <u>key to minimize combinatorics & simplify firmware</u>



Seeding & propagation

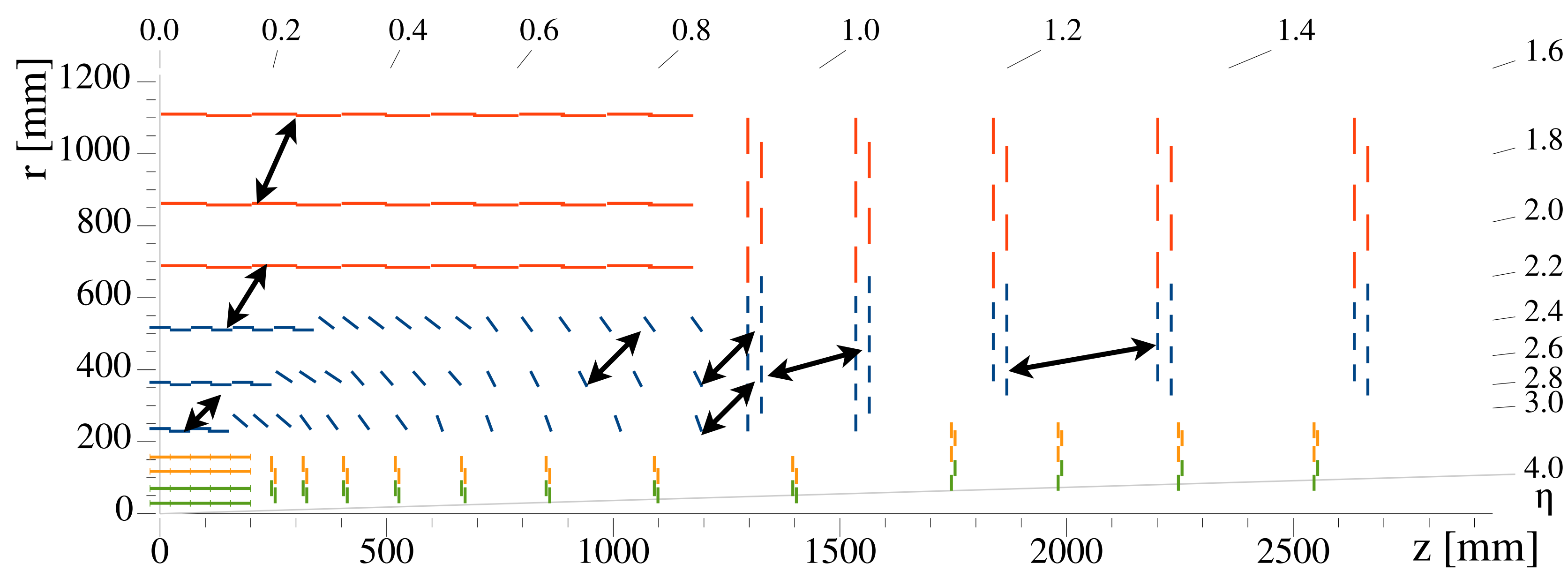
- **Seed** by forming tracklets
  - Pairs of stubs in adjacent layers/disks
  - Initial tracklet parameters from stubs + beam spot constraint
    - *Only combinations w. $p_T > 2$ GeV kept*
- **Project** to other layers/disks & match with compatible stubs within pre-defined windows
  - Inside-out & outside-in (more than 1 match allowed)
  - Calculate residuals used in fit



Central η:
L1+L2, L3+L4, L5+L6

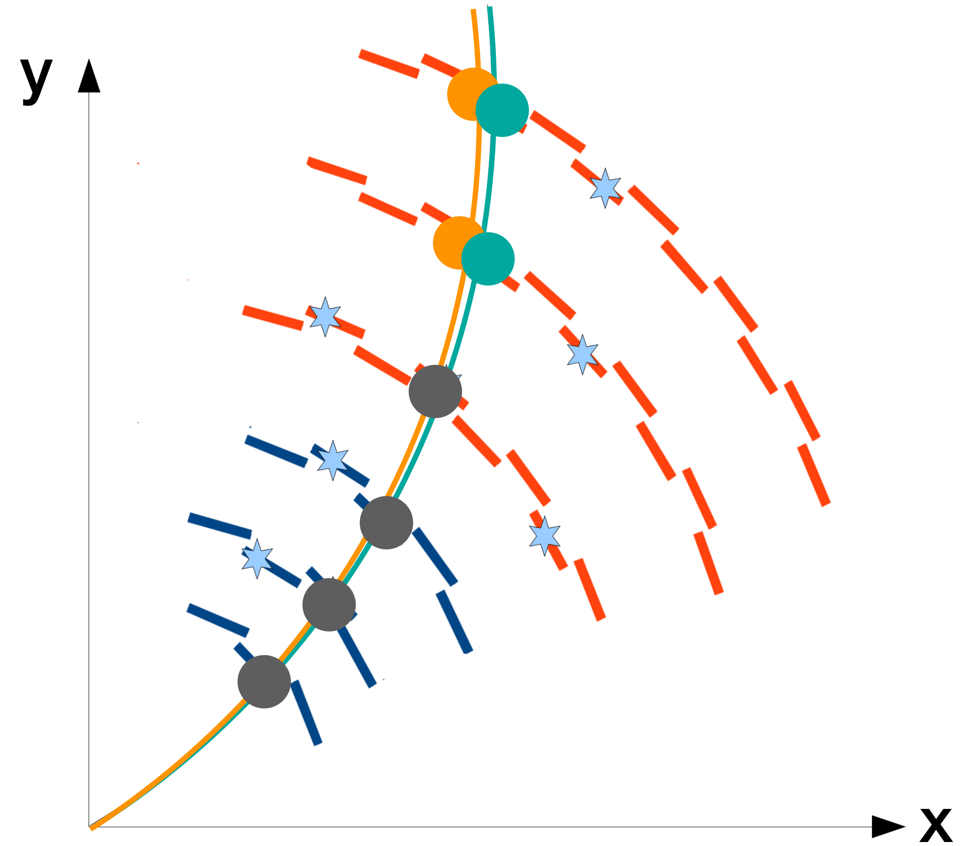
Barrel-disk overlap:
L1+D1, L2+D1, L1+L2

Disks:
D1+D2, D3+D4



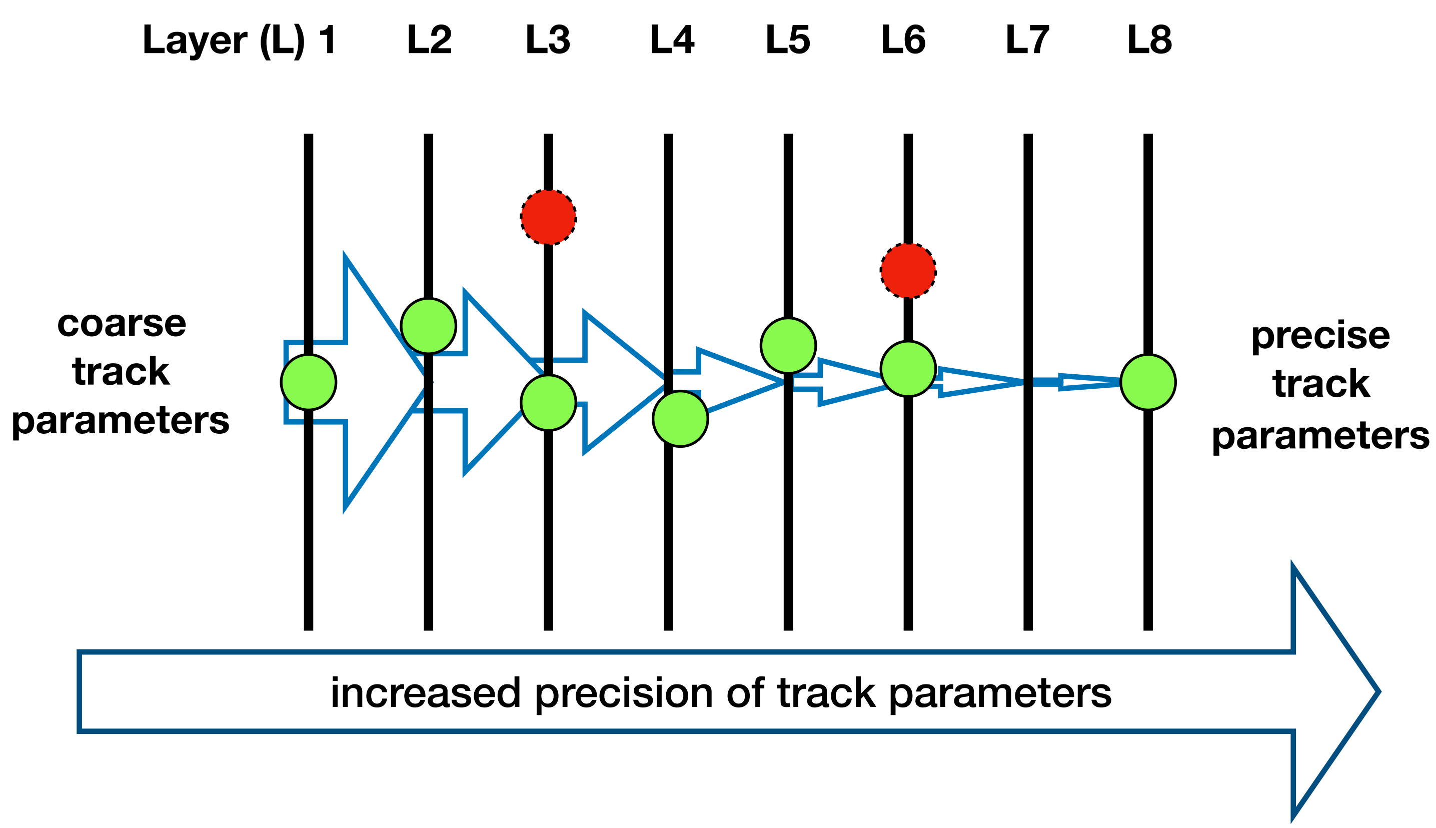
Duplicates & merging

- By construction, pattern recognition produces duplicate track candidates for a given charged particle
  - Redundancy in seeding (L1+L2 vs L3+L4, etc) ensures high efficiency, but leads to a given particle found >1 time
  - Additional duplicates may originate from tracks with combinatorial stubs
- Duplicates are removed by merging track candidates prior to fitting
- Currently, algorithm merges tracks sharing ≥ 3 stubs



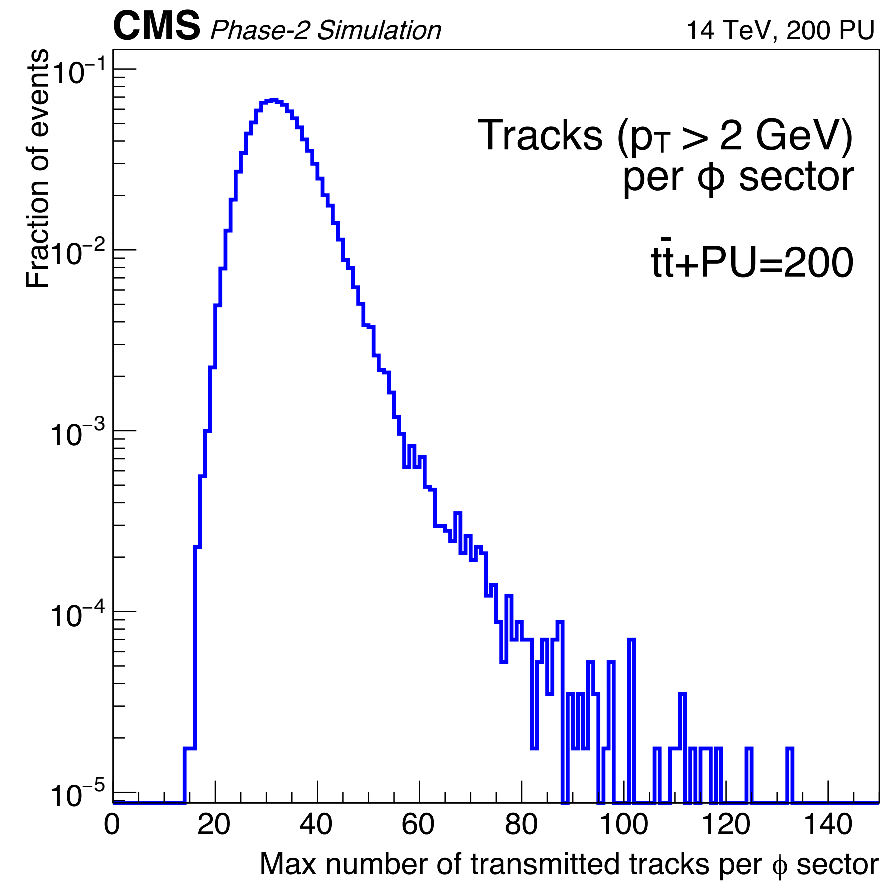
Track fitting

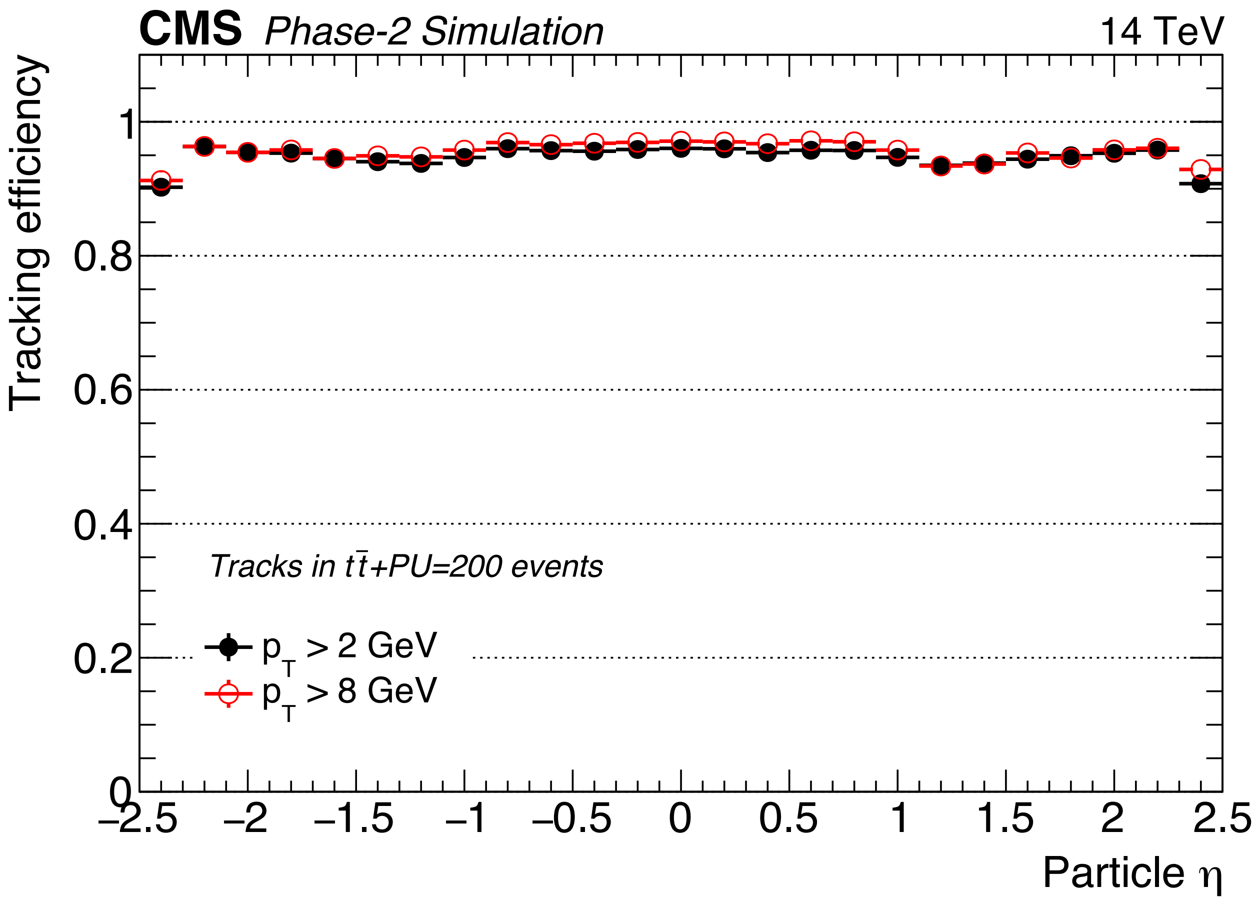
- Final track fitting uses Kalman Filter algorithm
- Iterative track fitting
  - Initial estimate of track parameters & their uncertainties from **tracklet seed**
  - Stub used to update helix parameters (weighted average)
    - *No need to fit stubs from seed*
  - χ^2 calculated, used to reject false candidates & incorrect stubs on genuine candidates
  - Repeat until all stubs are added
- Default is 4-parameter track fit — can be extended to additionally fit for d_0

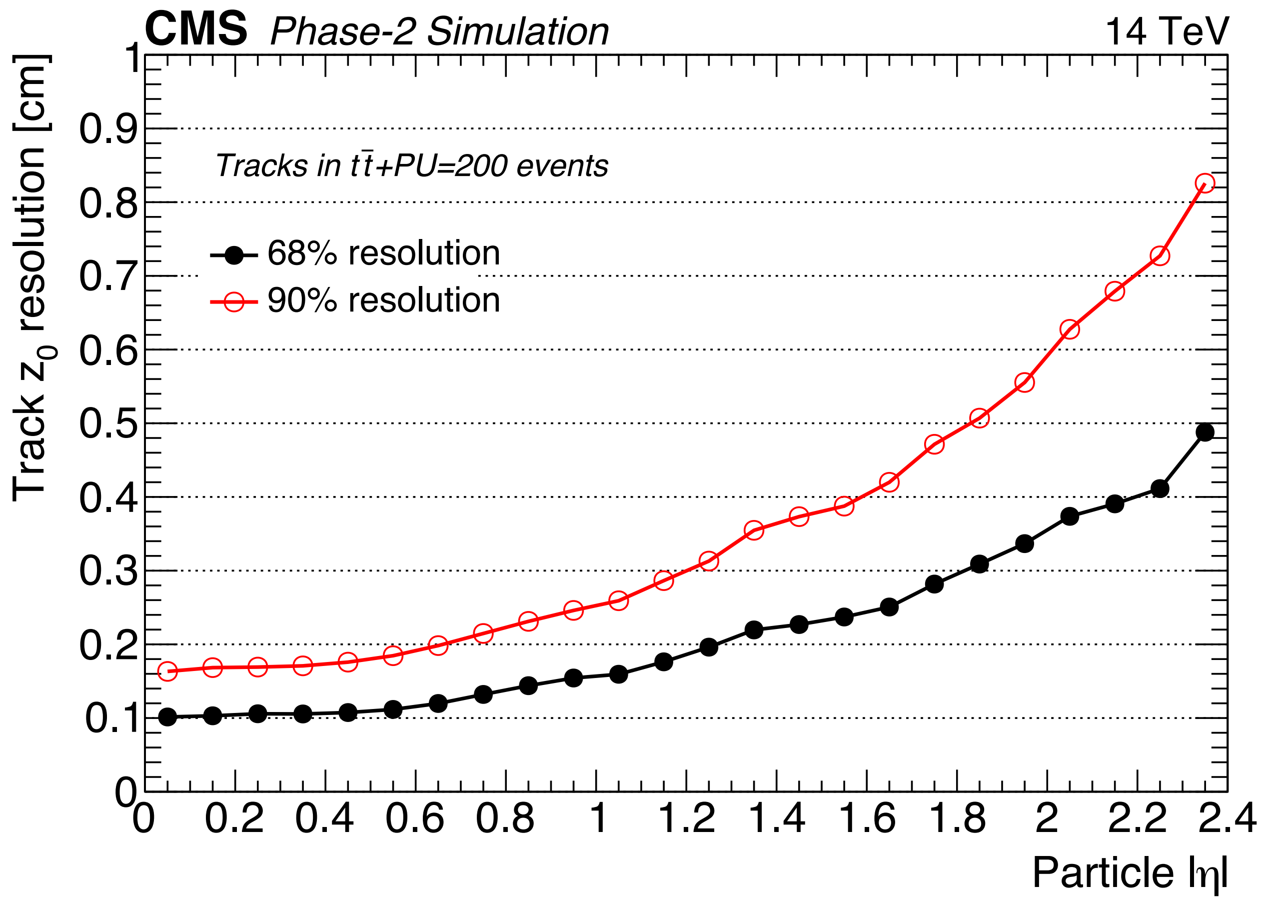


Performance

- Examples of expected L1 tracking performance based on simulation
  - High efficiency across p_T/η
  - Precise z_0 resolution for vertex association

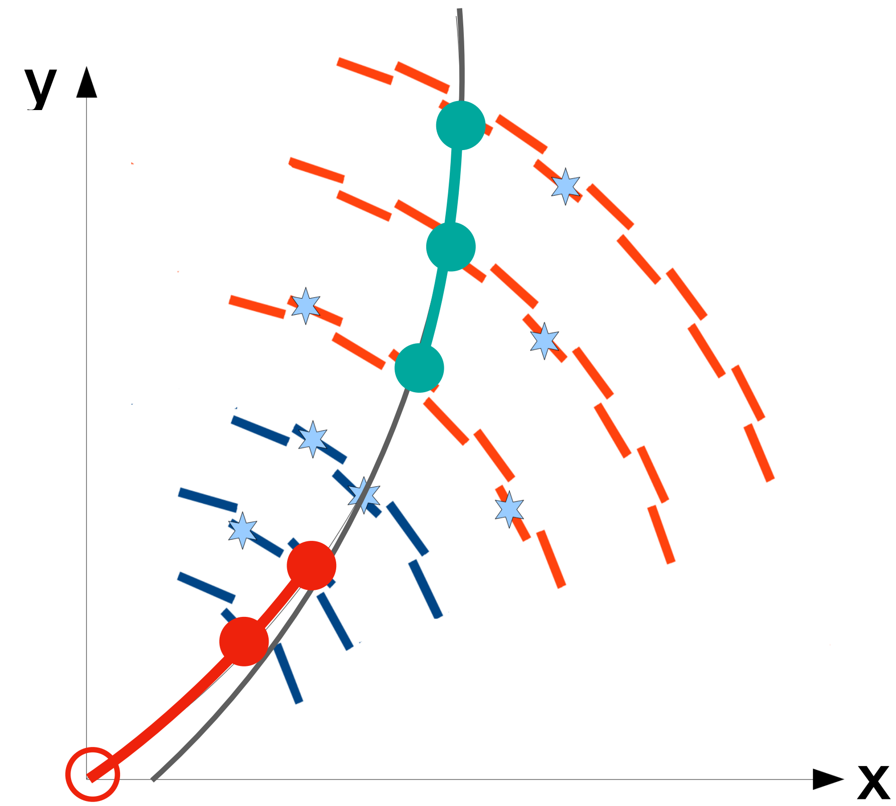






Displaced tracking

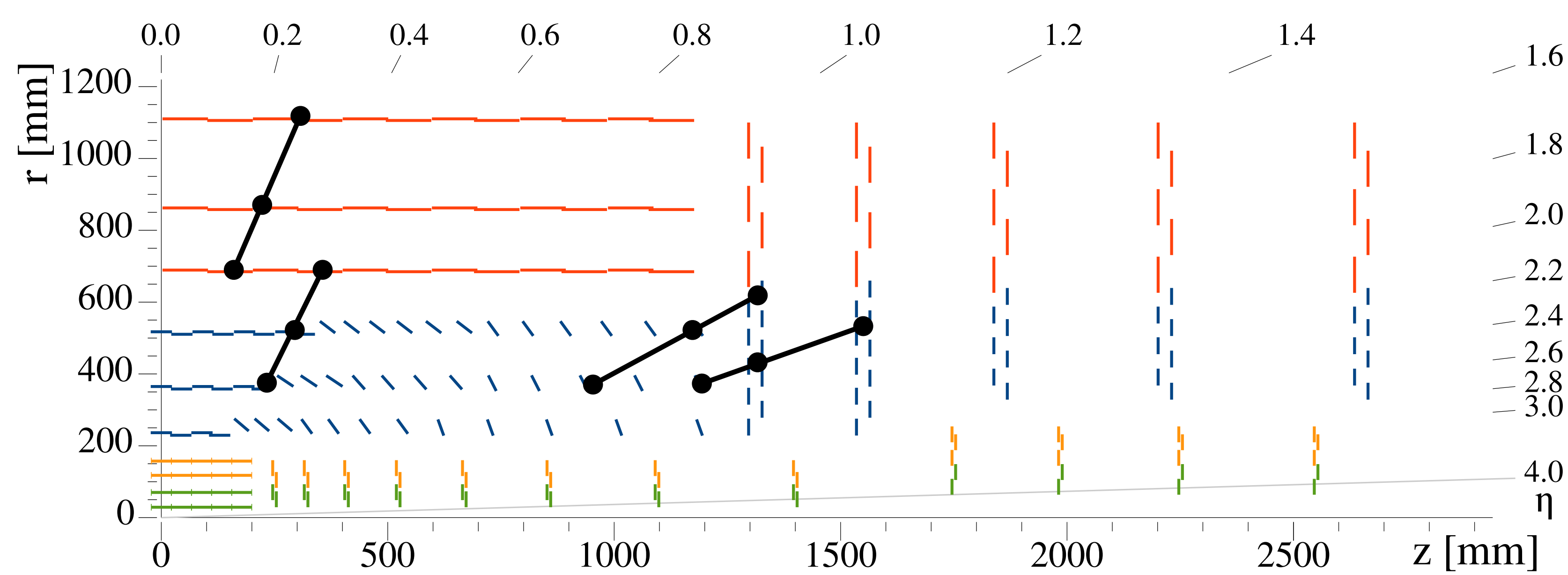
- Actively exploring an *extended tracking* setup to include capability of reconstructing long-lived particle trajectories



- How? Modified seeding
  - ***Prompt*** — tracklets (2 stubs + origin)
  - ***Displaced*** — triplets (3 stubs)
  - Displaced seeds propagated to other layers/disks similar as prompt to find matching stubs

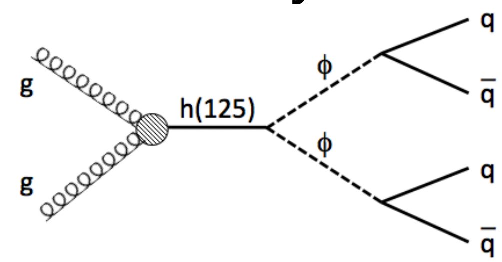
- How? 5-parameter Kalman Filter fit

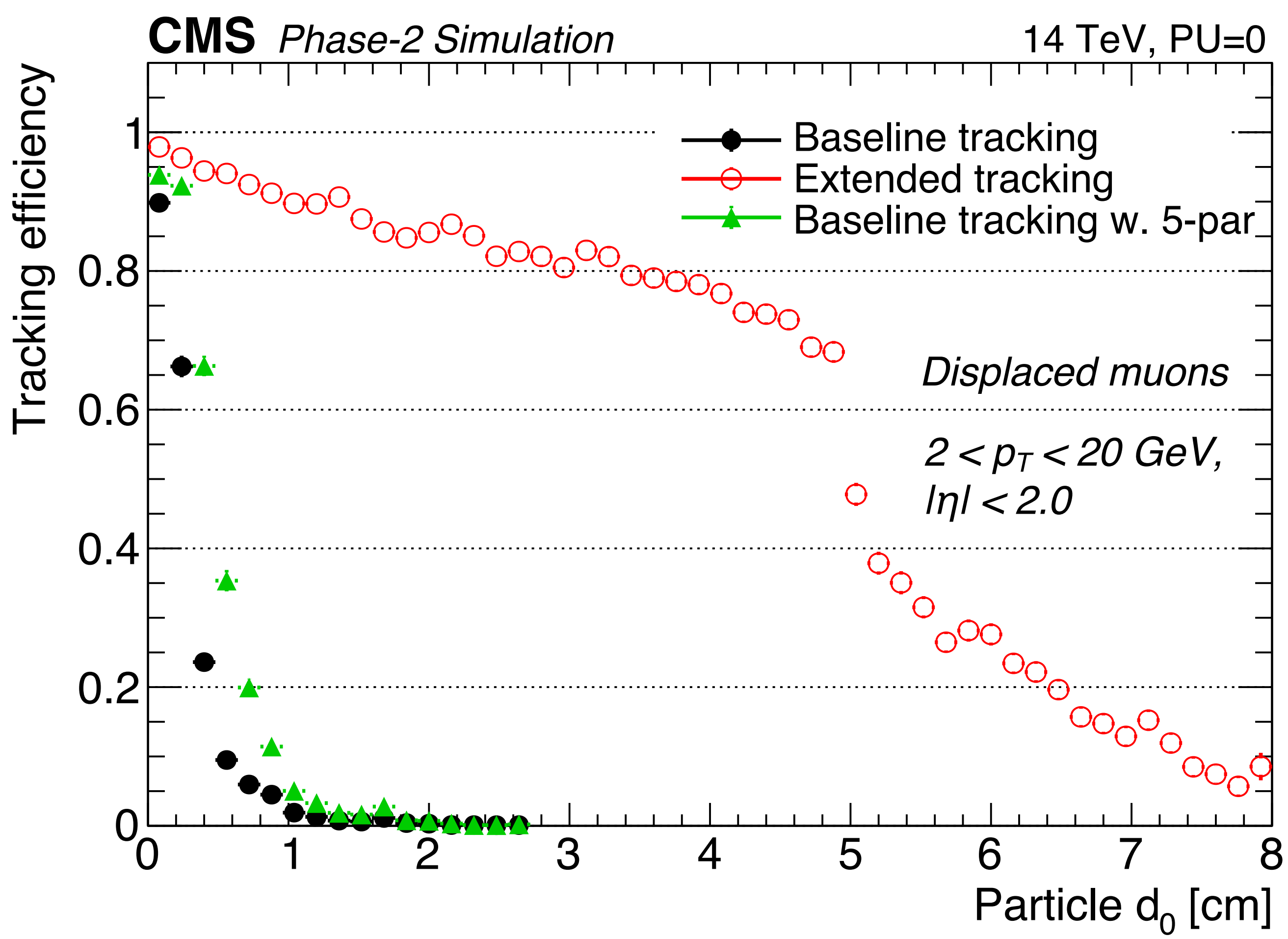
Triplet seeds:
L4L5L6, L2L3L4, L2L3D1, L2D1D2

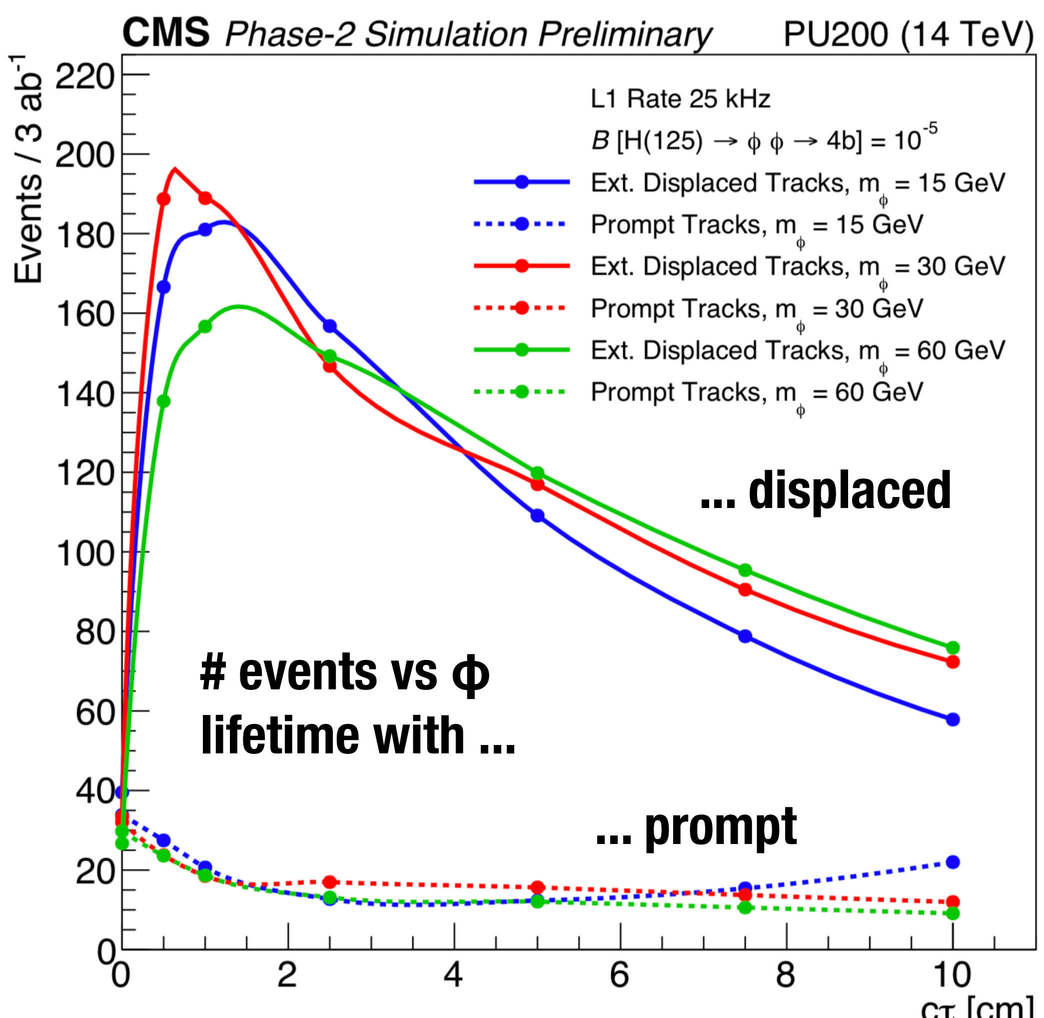


Displaced performance

- Extended tracking recovers efficiency for large d_0 particles
  - Increase in track rate ~40% (conservative estimate)
- As example studied in context of triggering on exotic Higgs boson decays
  - H => ϕϕ => 4 jets, where ϕ is long-lived







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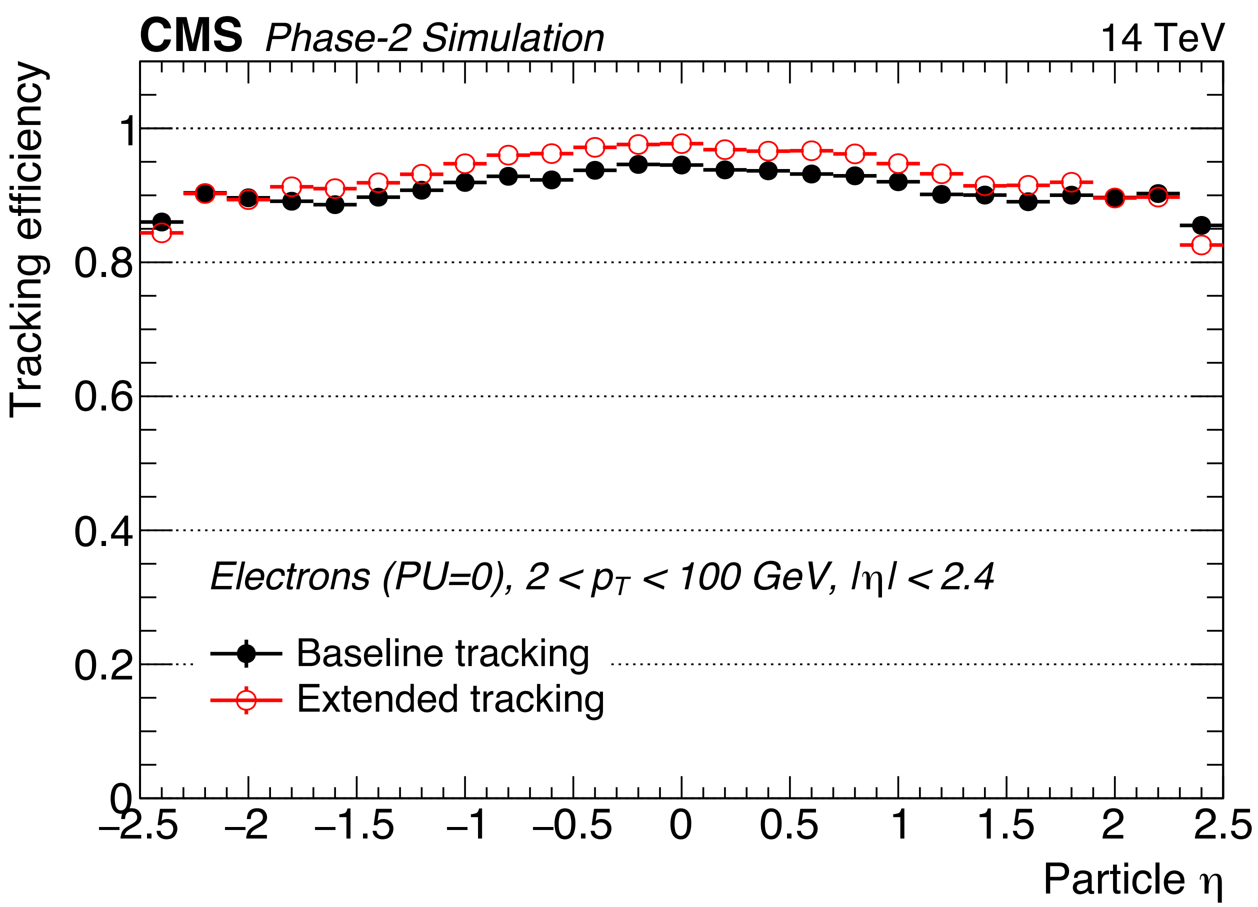
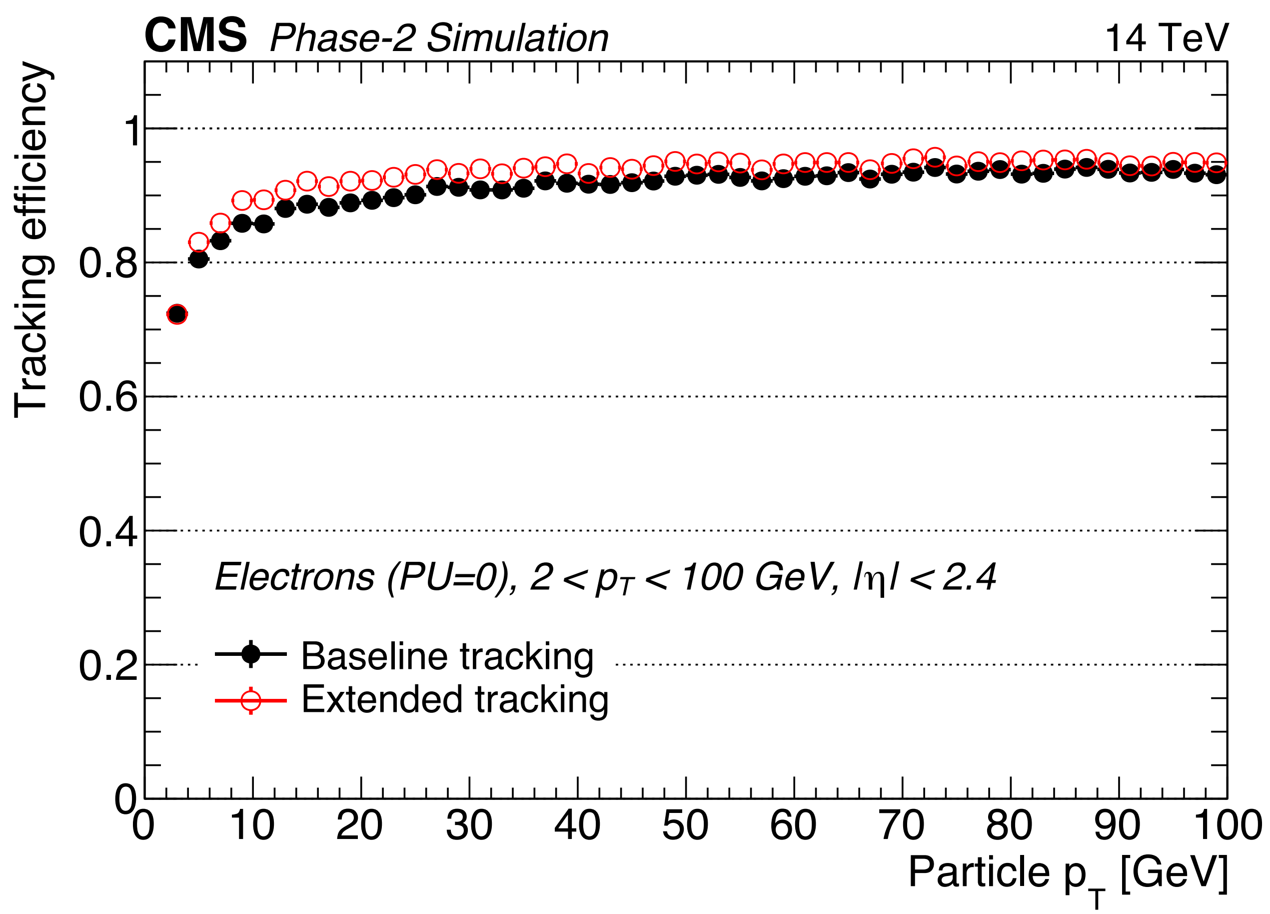
Electron performance

- Electron tracking particularly challenging due to bremsstrahlung (no Gaussian Sum Filter or similar employed at L1)
- Displaced tracking may increase efficiency for electrons
  - Compare baseline vs extended tracking => initial results promising

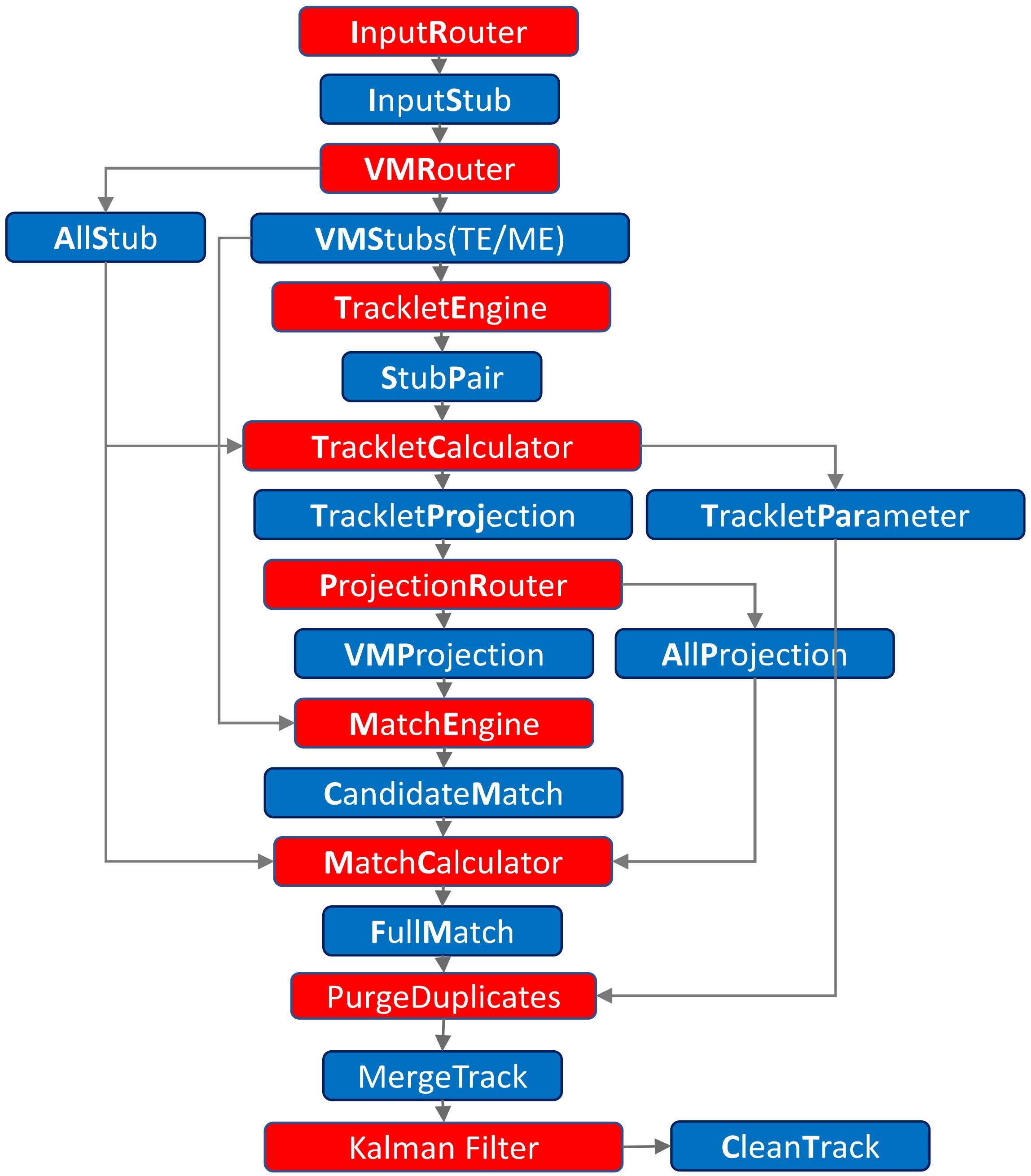




- *Work ongoing to understand additional resource usage & latency impacts*

Hybrid implementation

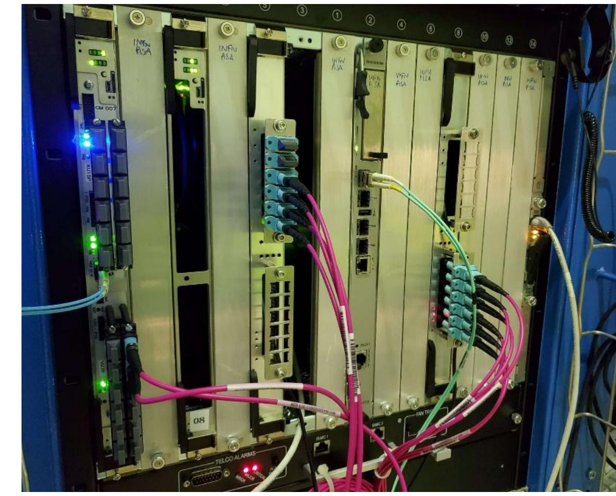
- Firmware implementation
  - Stub organization
  - Tracklet formation
  - Projections
  - Stub matching
  - Duplicate removal (merging)
  - Track fitting
- Implemented as dedicated **processing modules** with **memory modules** storing data between steps
  - Seeding & propagation steps implemented using Xilinx Vivado HLS
  - Kalman filter largely implemented in VHDL
  - Top-level modules connected in VHDL



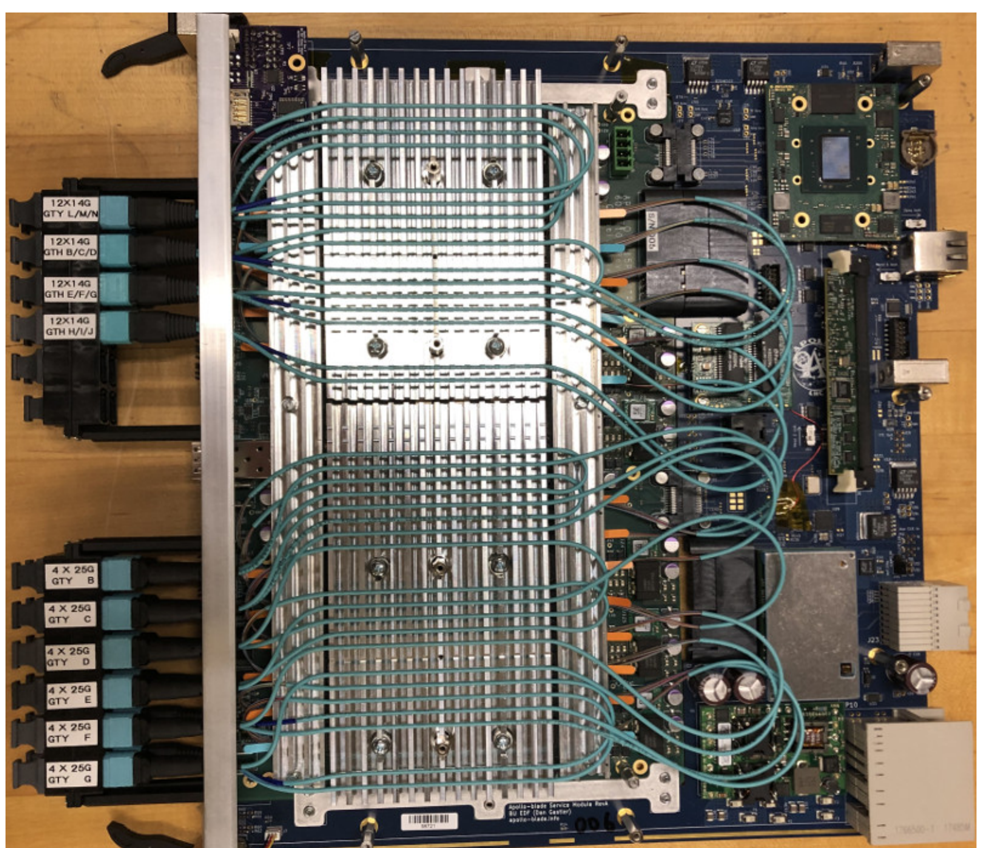
Hardware demonstration

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

Test stand @ CERN
with Apollo & Serenity blades

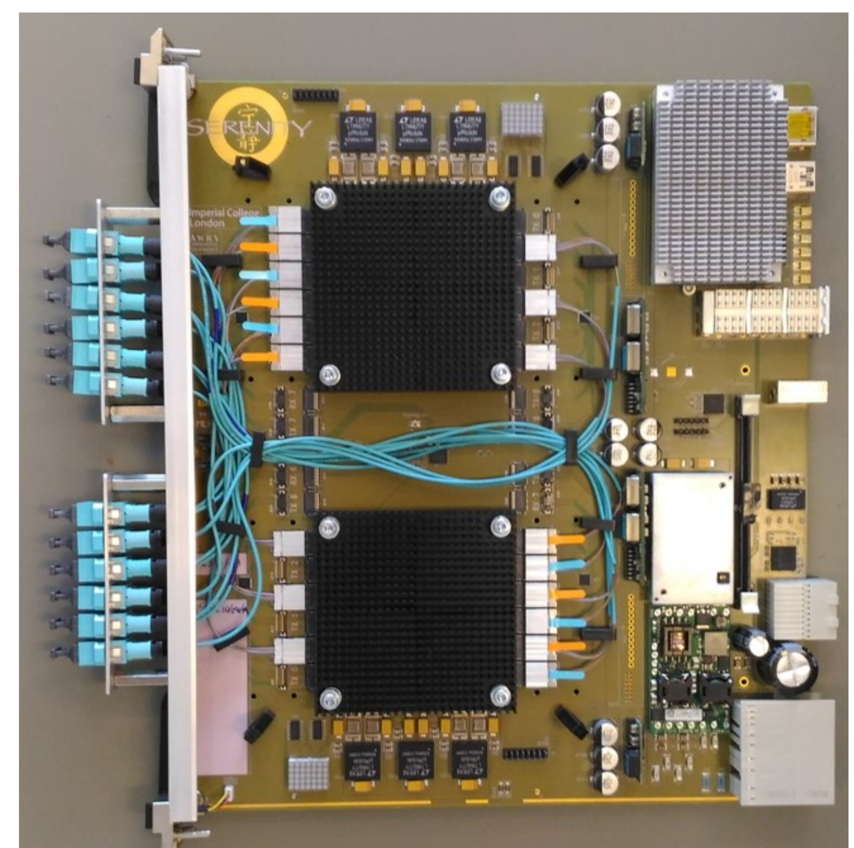


Apollo: track finding processing boards
- *Service Module* provides infrastructure components
- *Command Module* contains two large FPGAs, optical fiber interfaces & memories



arXiv:1911.06452

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



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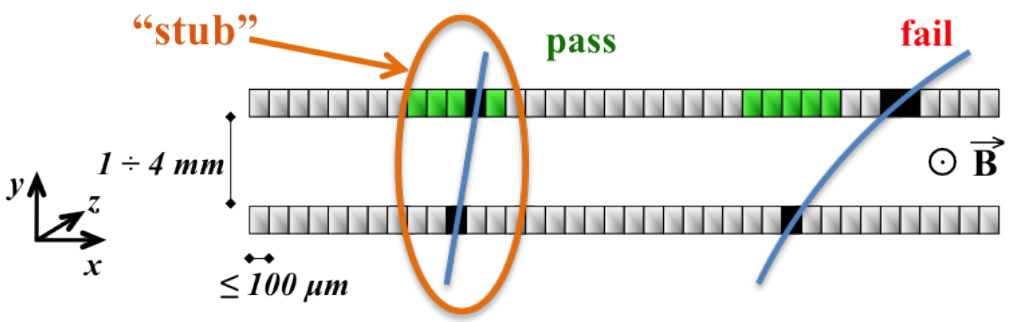
Summary

- Incorporating tracking in L1 trigger is critical to achieve required event rate reductions for CMS at HL-LHC
  - Key to achieve physics goals

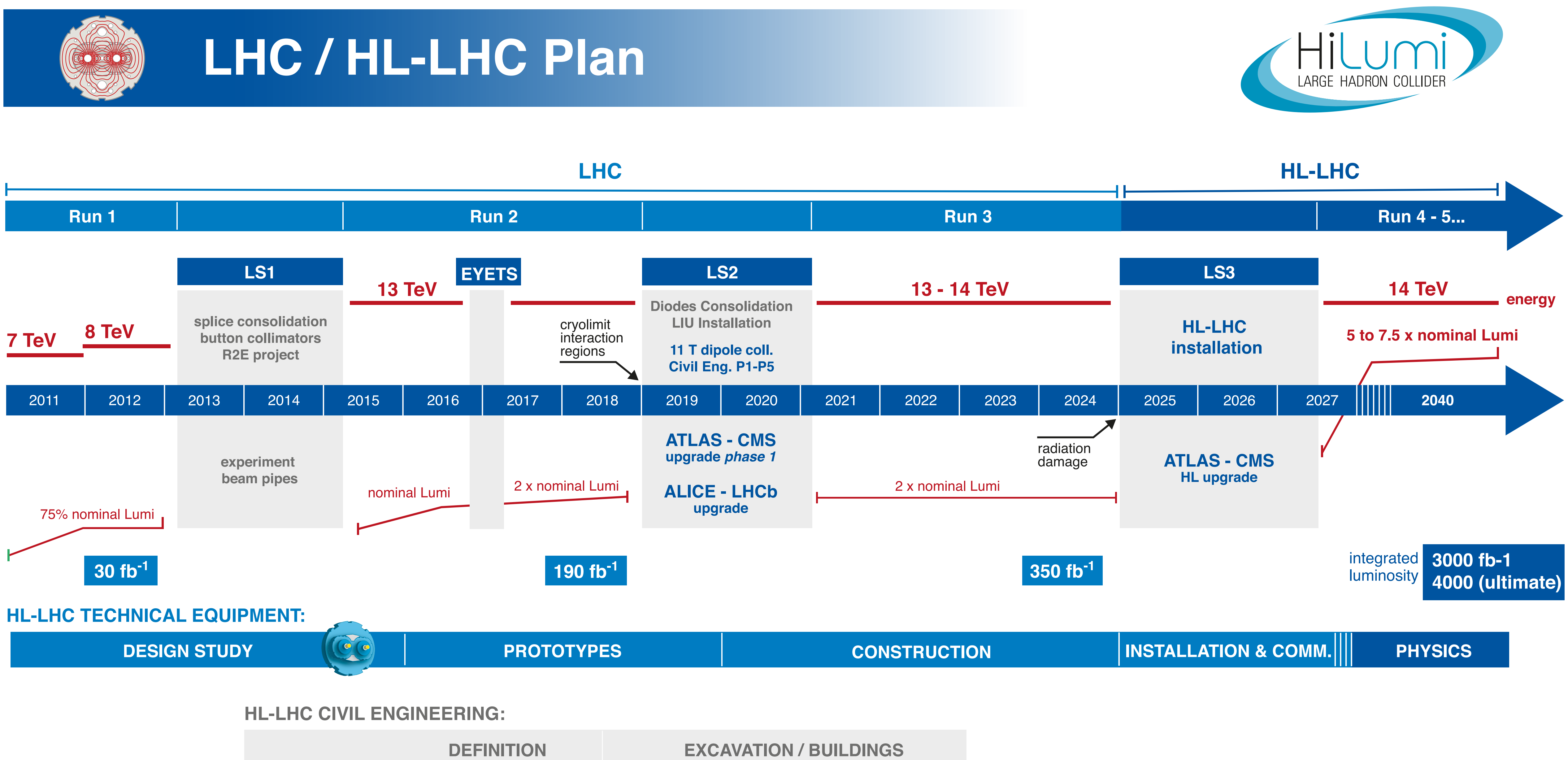


- Track finding performed with **hybrid algorithm**
  - Combines road-search tracklet algorithm with Kalman Filter fit
  - Extension to *displaced tracking* brings feasibility of probing physics scenarios involving long-lived particles
    - *Potential gains also for electron tracking*
  - System design based on off-shelf electronics (FPGA)
  - Legacy demonstrators showed feasibility of systems w. required performance

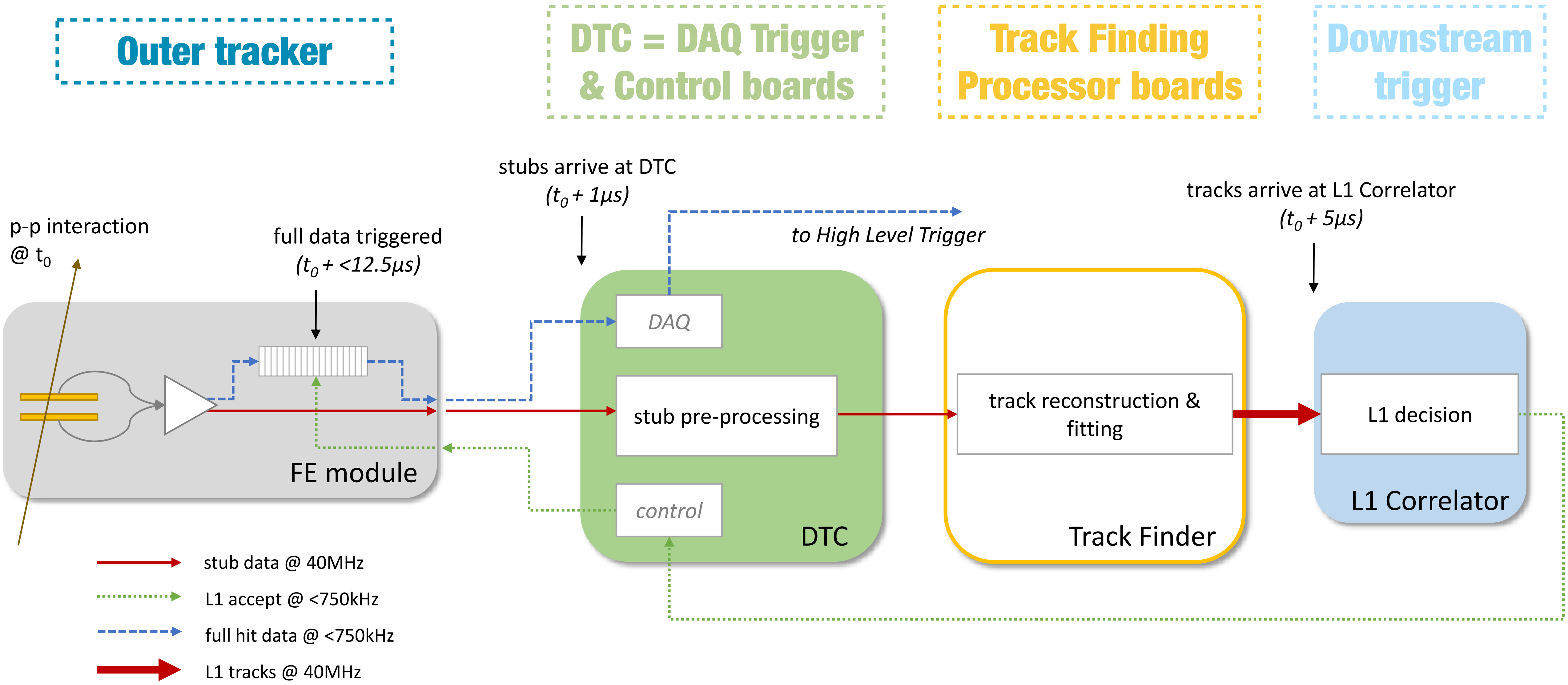
- *Working toward specifications of final system & next-level demonstrators*

BACKUP

Accelerator schedule



Data flow


Outer tracker
DTC = DAQ Trigger & Control boards
Track Finding Processor boards
Downstream trigger
p-p interaction @ t_0
full data triggered (t_0 + <12.5μs)
stubs arrive at DTC (t_0 + 1μs)
to High Level Trigger
tracks arrive at L1 Correlator (t_0 + 5μs)
FE module
DAQ
stub pre-processing
control
DTC
track reconstruction & fitting
Track Finder
L1 decision
L1 Correlator
stub data @ 40MHz
L1 accept @ <750kHz
full hit data @ <750kHz
L1 tracks @ 40MHz

Additional performance plots

- Track rate as function of p_T, comparing *all* reconstructed tracks vs after applying set of quality criteria with # of truth-level trajectories