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

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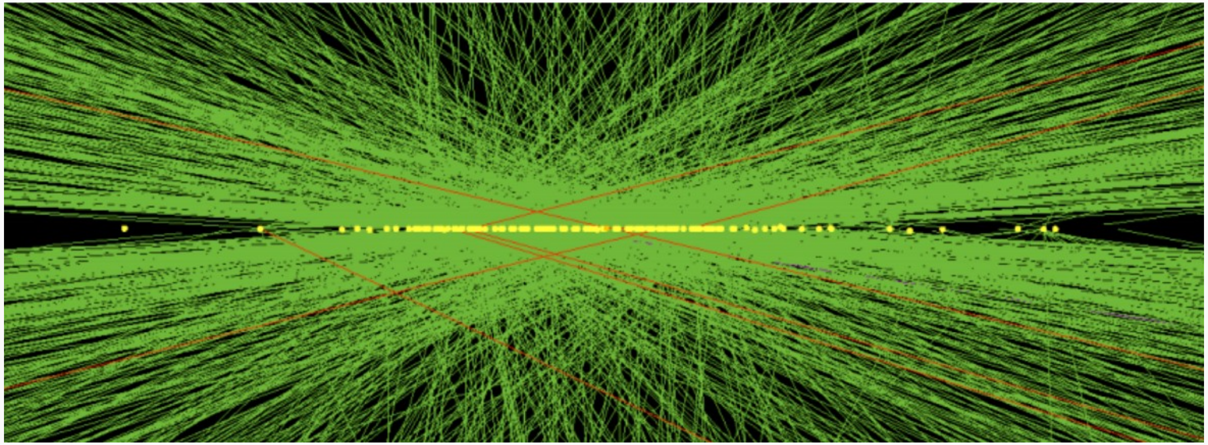
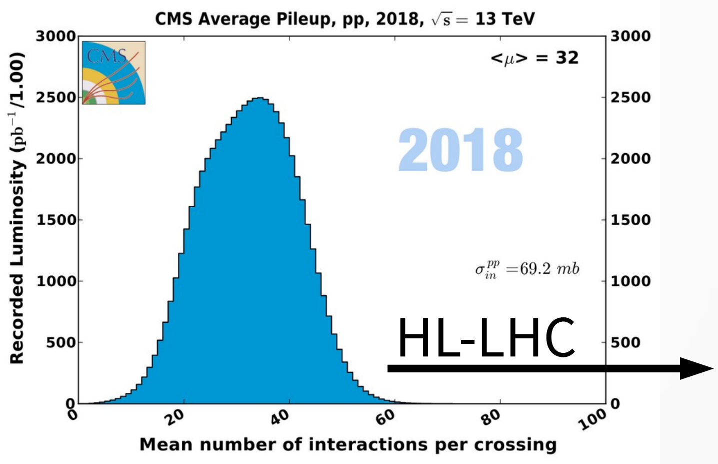
The High-Luminosity LHC

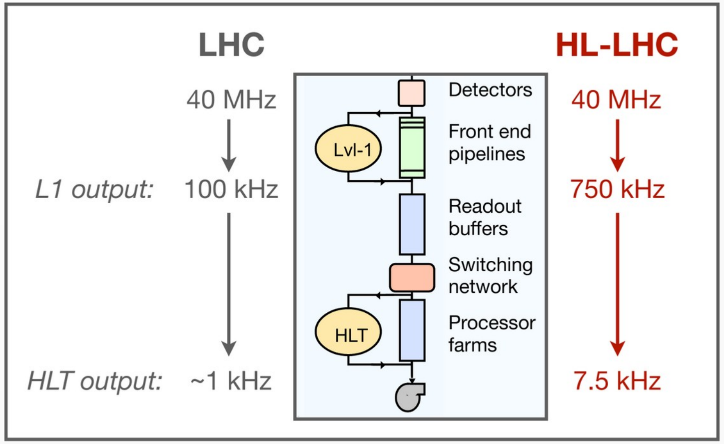
- The High-Luminosity LHC (HL-LHC) upgrade in 2025-2027 is expected to achieve luminosities up to 7.5×10^{34} cm^{-2} s^{-1}:
  - Great opportunities for physics
  - Very challenging at every stage, from triggering to data analysis
- How do we ensure that we get the most out of this data?
  - A key component of the strategy for CMS is to introduce tracking in the Level-1 (L1) trigger
  - Here we show the latest results from the L1 tracking system currently being developed



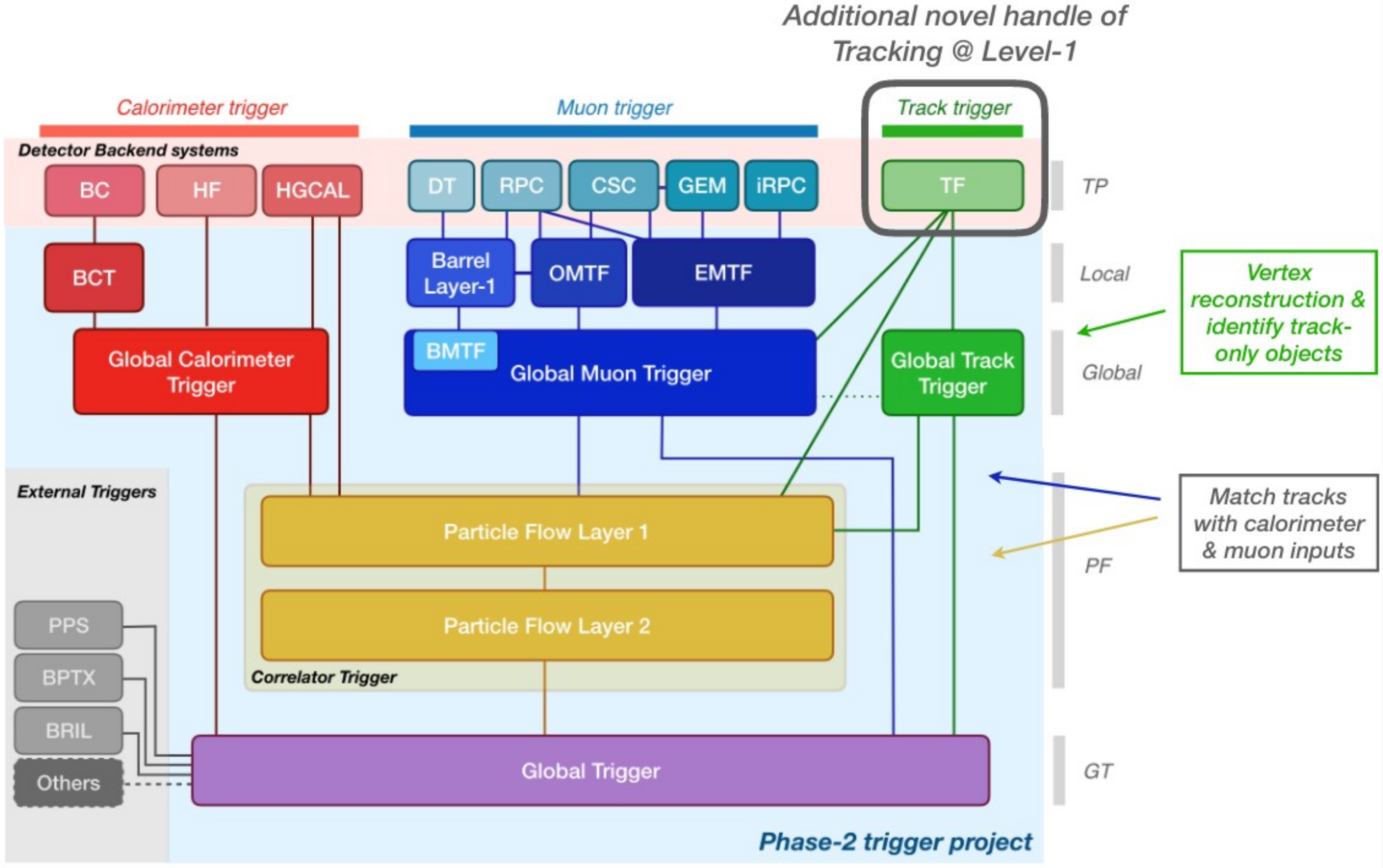
Triggering with 200 pileup

- Many exciting possibilities with ~4000 fb^{-1} datasets expected from the HL-LHC:
  - Precision measurements of the Higgs boson and its interactions, including the self-coupling
  - Extended discovery reach for beyond-the-standard model (BSM) physics
  - Observe rare standard model processes that could be sensitive to BSM physics
- The cost of these physics possibilities is huge amounts of pileup:
  - Expect an average of 200 overlapping pp collisions per bunch crossing
- Trigger system has to reduce the 40 MHz input rate to ~7.5 kHz:
  - Tracking at L1 is central to accomplishing this
  - Without tracking, L1 output would be ~4000 kHz at 200 PU





L1 trigger for HL-LHC



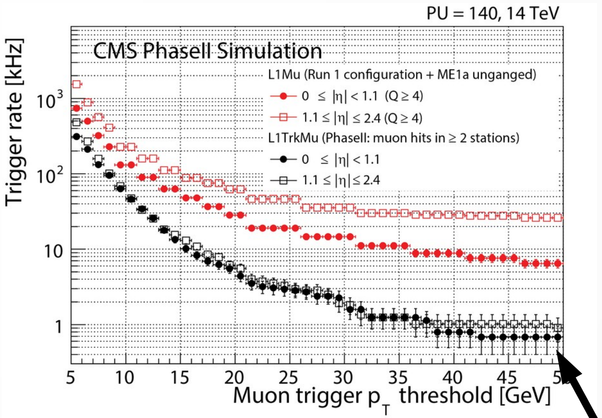
Additional novel handle of Tracking @ Level-1

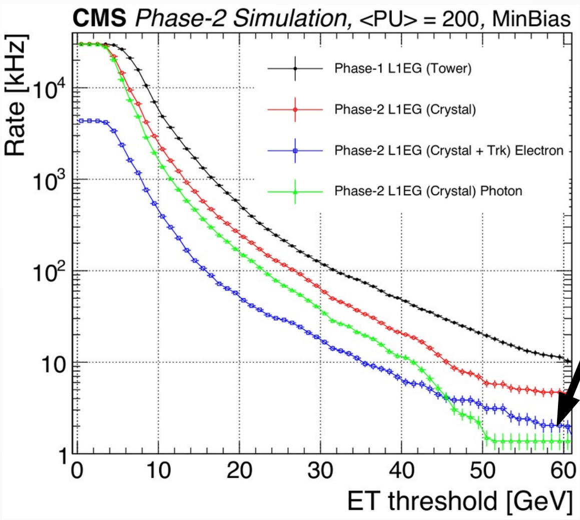
Vertex reconstruction & identify track-only objects

Match tracks with calorimeter & muon inputs

Tracking at L1

- Usually, in order to reduce trigger rates, we increase momentum/energy thresholds:
  - This can obviously hurt physics potential
  - Also insufficient by itself at HL-LHC rates
- L1 tracking provides a powerful alternative:
  - Improved muon p_T resolution
  - Better e/γ/τ identification
  - Ability to associate tracks with vertices





L1 tracking reduces rates

CMS tracker for HL-LHC

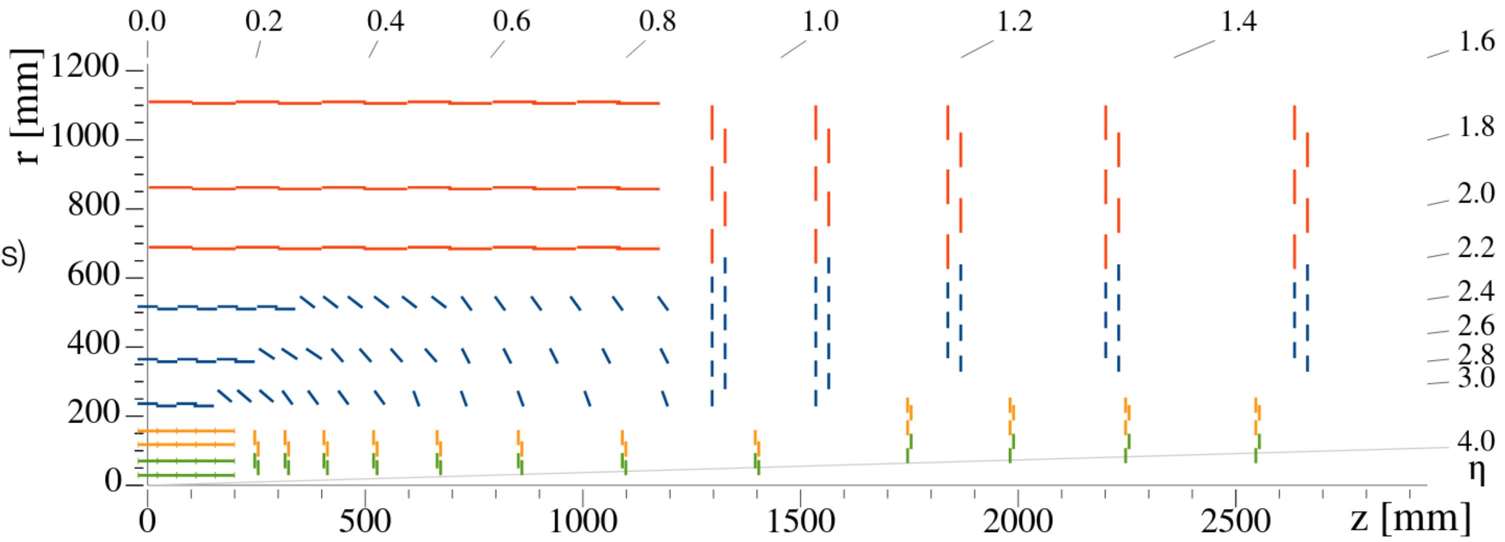
- New pixel and outer tracker:
  - All silicon as with the current CMS tracker
  - Increased granularity in order to handle increased occupancies

Outer Tracker

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

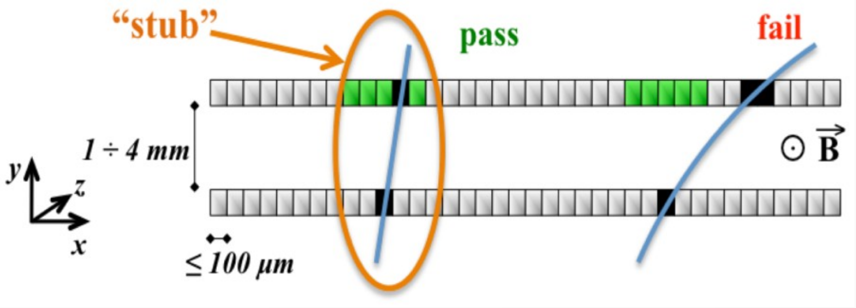
Inner Pixel

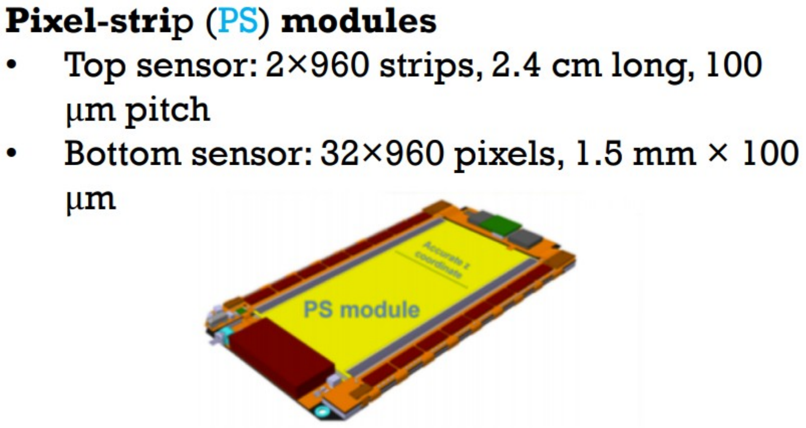
(**1x2** vs **2x2** chip modules)
=> not used in L1



p_T modules

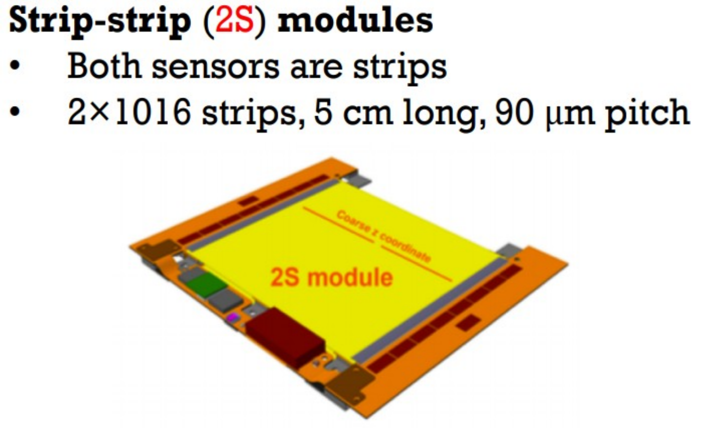
- Two-sided modules in outer tracker enable front-end p_T discrimination:
  - Pairs of clusters inconsistent with a $p_T > 2$ GeV track rejected
  - Data reduction of 10-20
- Stubs formed from correlated pairs of clusters consistent with a $p_T > 2$ GeV track:
  - These are the inputs to the L1 tracking algorithm





Pixel-strip (PS) modules

- Top sensor: 2×960 strips, 2.4 cm long, 100 µm pitch
- Bottom sensor: 32×960 pixels, 1.5 mm × 100 µm



Strip-strip (2S) modules

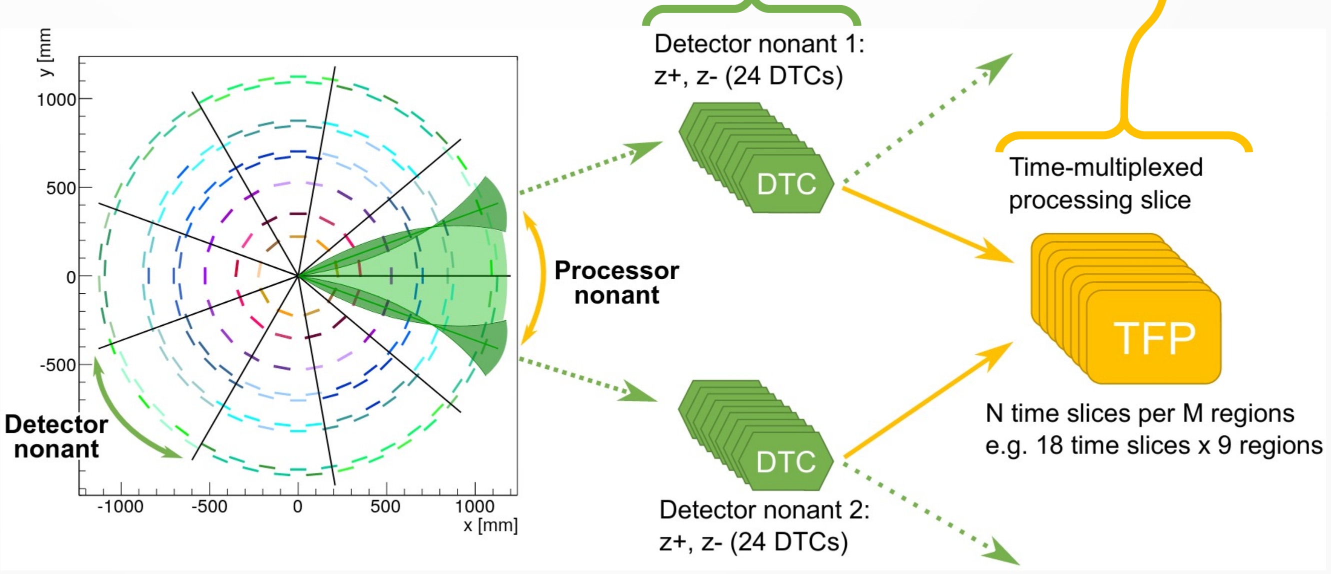
- Both sensors are strips
- 2×1016 strips, 5 cm long, 90 µm pitch

Track finder architecture

- Parallelized in time and space:
  - Time multiplexing factor of 18
  - Detector divided into nine ϕ sectors; stubs shared between sectors, but not tracks

Data, Trigger & Control (DTC) boards perform stub pre-processing and distribute stubs to TFP boards

Track Finding Processor (TFP) boards receive a new event every 450 ns

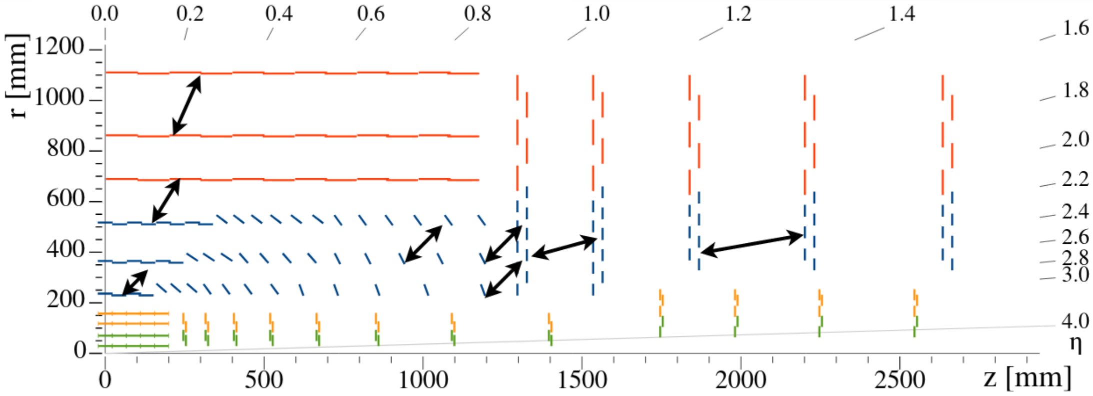


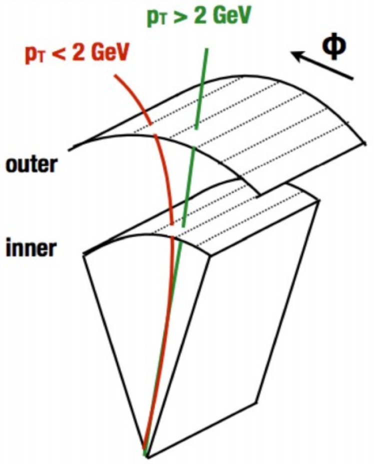
Track seeds

Central η:
L1+L2, L3+L4, L5+L6

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

Disks:
D1+D2, D3+D4

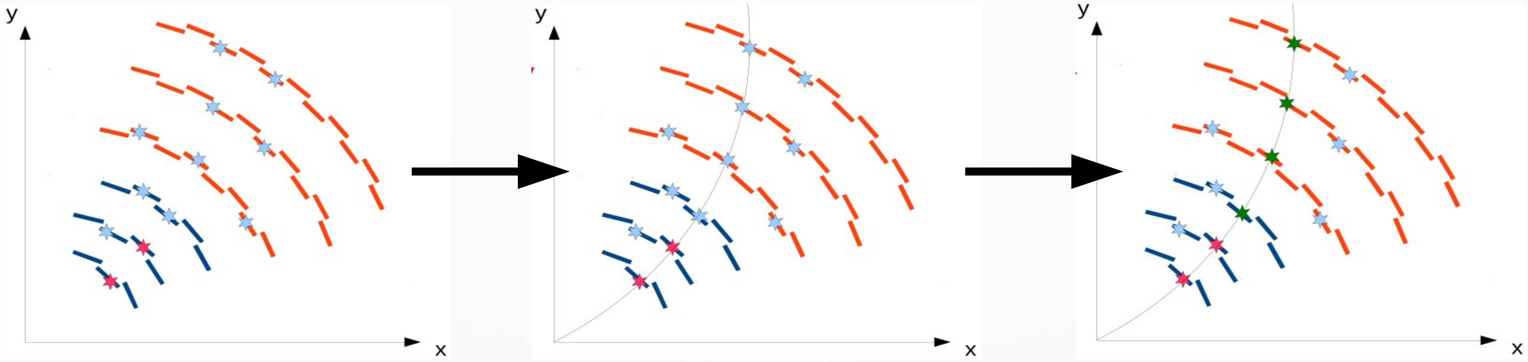




- Tracks seeded by stub pairs in certain layer/disk combinations
- Only stub pairs consistent with p_T > 2 GeV are kept:
  - Tracker layers coursely segmented into virtual modules (VM)
  - Only VM pairs consistent with p_T threshold are even connected in the firmware to reduce the combinatorics

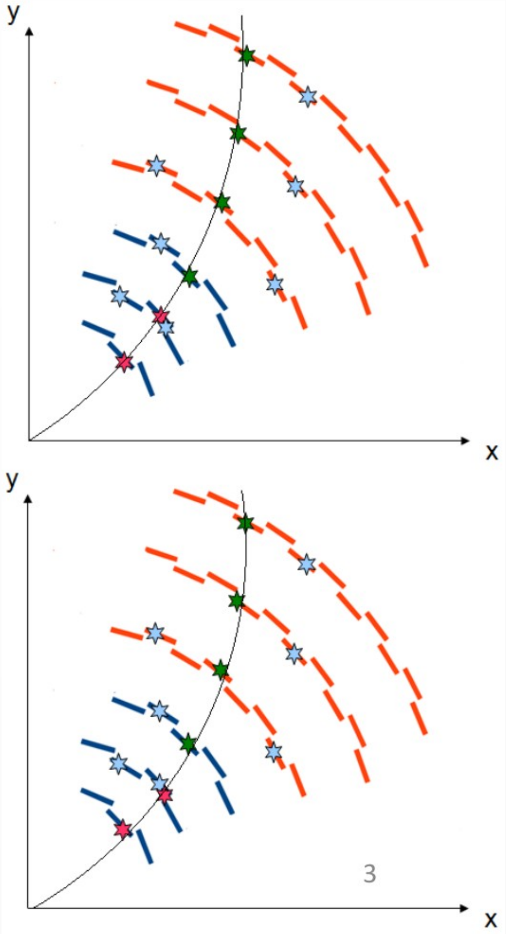
Matches in other layers/disks

- From these seeds, helix parameters and projections to other layers/disks are calculated:
  - Assume tracks originate from beamline
- The projections are used to calculate residuals and match stubs in additional layers/disks:
  - This yields full tracks that are the inputs to the final track fit



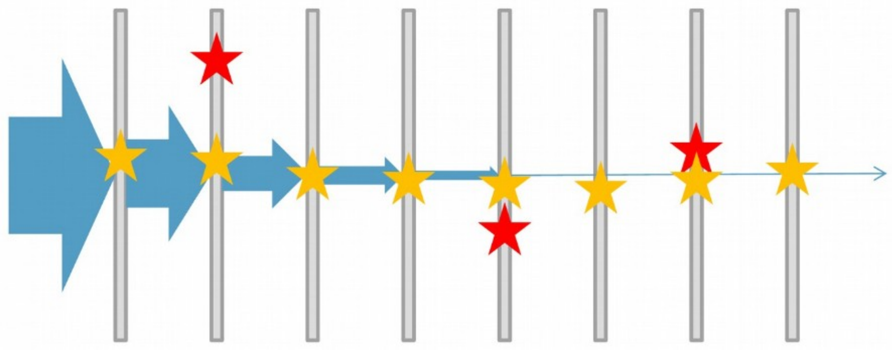
Duplicate removal

- The pattern recognition naturally produces duplicate tracks for a given charged particle:
  - Most come from redundancies in the seeds:
    - e.g., a central charged particle will usually be seeded three times: L1L2, L3L4, L5L6
  - Some come from nearby stubs in a given layer yielding very similar tracks
- These have to be removed before track fitting:
  - Currently merge any tracks that share ≥3 stubs



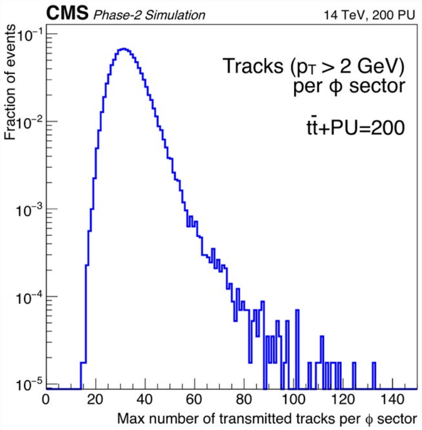
Kalman filter fit

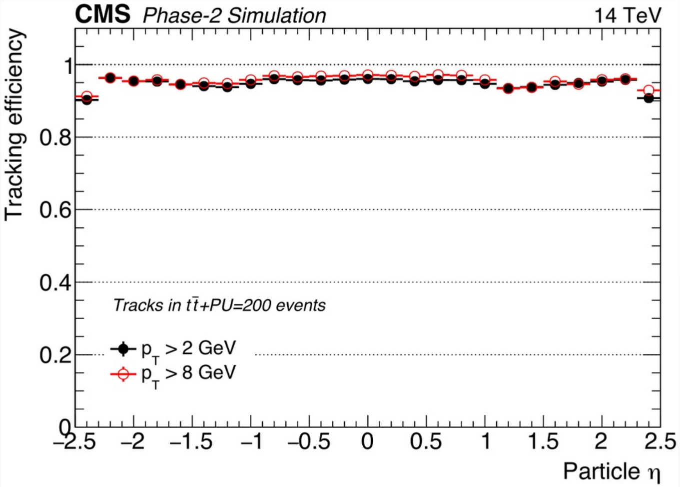
- The final fit of the tracks is done with a Kalman filter:
  - Roughly similar to what is done in the offline tracking of CMS
  - Starts with coarse helix parameters from the seed
  - Adds stubs one by one, updating the helix parameters with greater and greater precision
- By default, there is a beamline constraint and four track parameters are fit:
  - Can easily remove this constraint and also fit for transverse impact parameter (d_0)

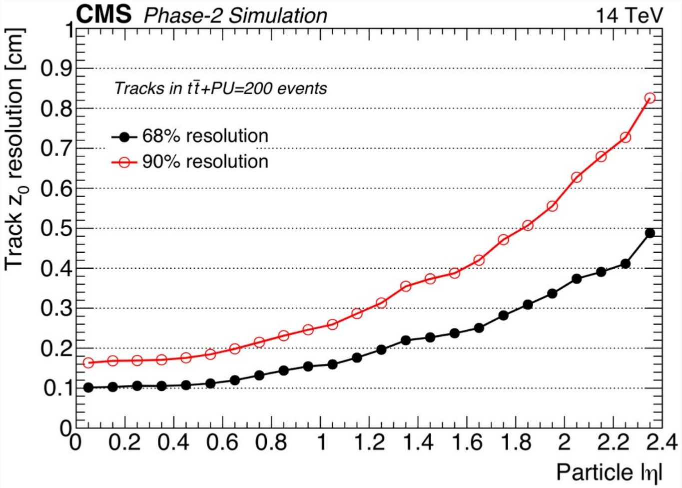


L1 tracking performance

- Expected performance of L1 tracking:
  - High efficiency across the entire tracker
  - Good z_0 resolution:
    - Critical for vertex association and PU mitigation



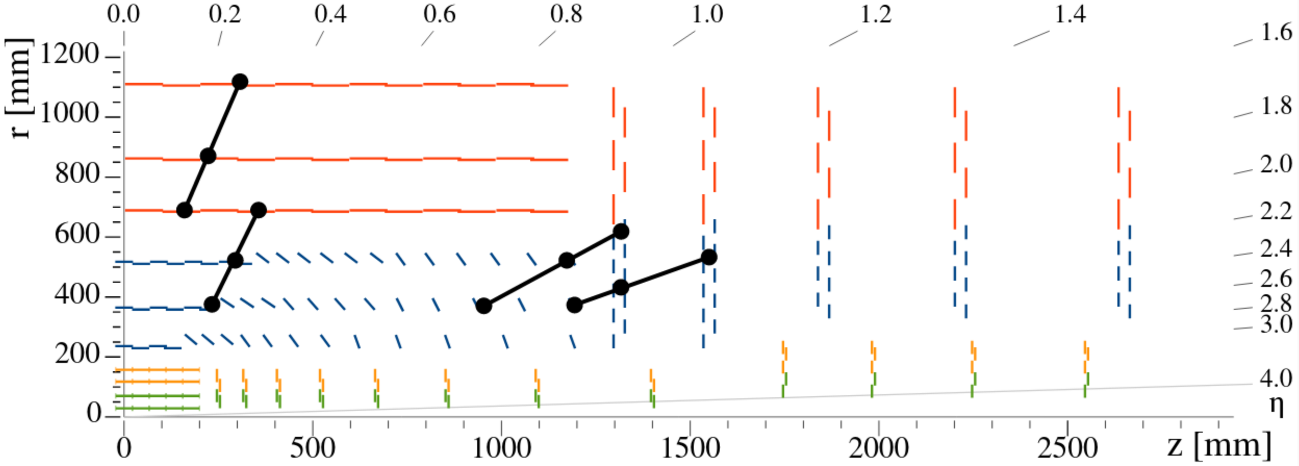




Displaced tracking

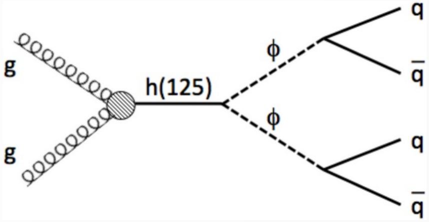
- Displaced tracks at L1 is an exciting extension to the baseline algorithm currently under active development
- Achieved via two additions/modifications:
  - Seeds: three triplet seeds added; projected to additional layers without a beamline constraint
  - Fit: transverse impact parameter added to fit; 5-parameter Kalman filter fit

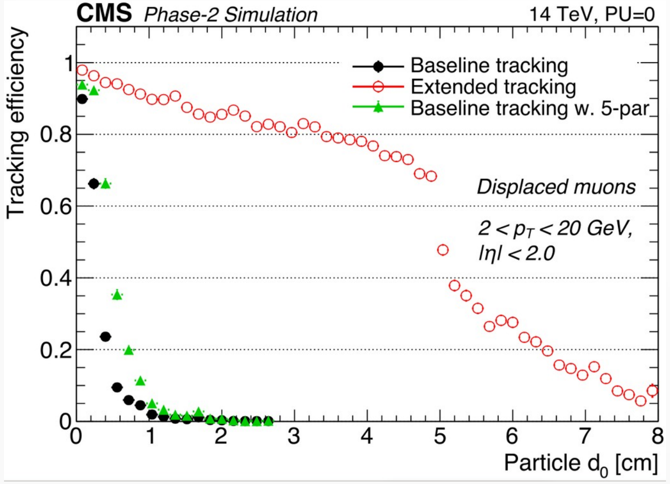
Triplet seeds:
L4L5L6, L2L3L4,
L2L3D1, L2D1D2

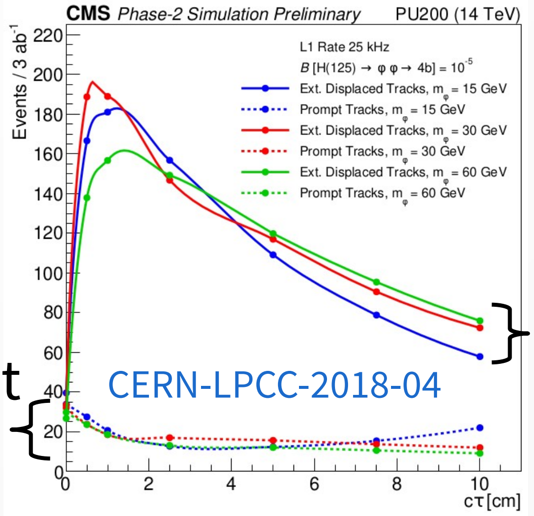


Displaced tracking

- Initial results promising:
  - Displaced tracks reconstructed with good efficiency up to $|d_0|$~5 cm
  - Overall track rate increases by ~40% (conservative estimate)
- Greatly increases sensitivity of Higgs boson decays to exotic long-lived particles:
  - H→φφ→4 jets, where φ is a new long-lived scalar
  - Challenging without displaced L1 tracking because of the low H_T of the signal







CERN-LPCC-2018-04

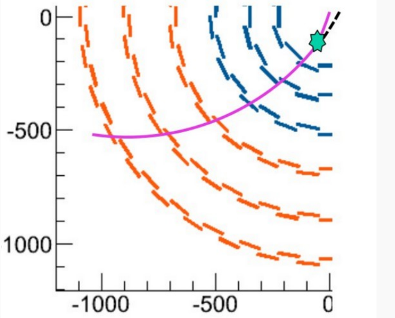
Only prompt tracks

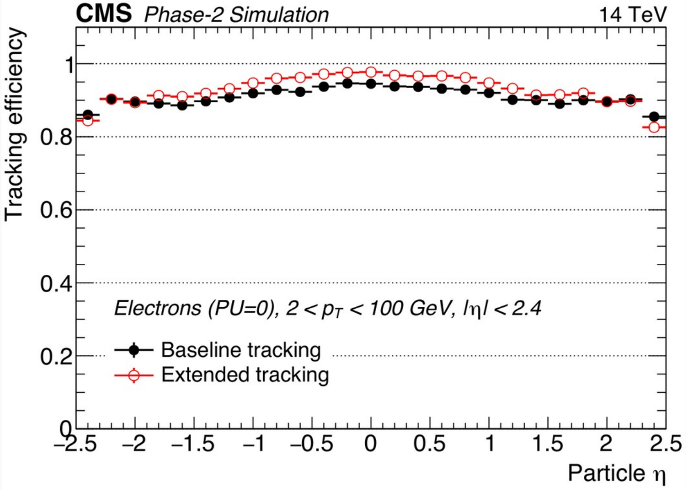
With displaced tracks

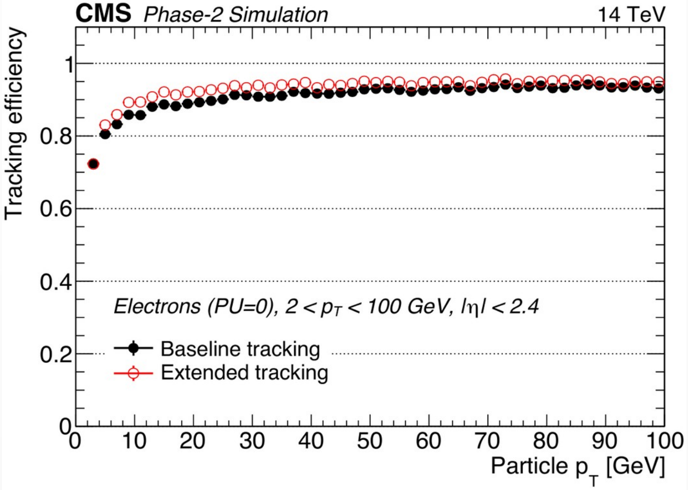
Electron performance

- Electron tracking challenging due to large bremsstrahlung:
  - Mitigated in offline software with a Gaussian sum filter, which is not employed in the L1 trigger
- Electrons can appear as displaced tracks if most of the bremsstrahlung occurs before the outer tracker:
  - Displaced tracking can recover some of these tracks

Brem in the inner tracker:
- With PV constraint: no track at all
- Displaced long track with OK χ^2

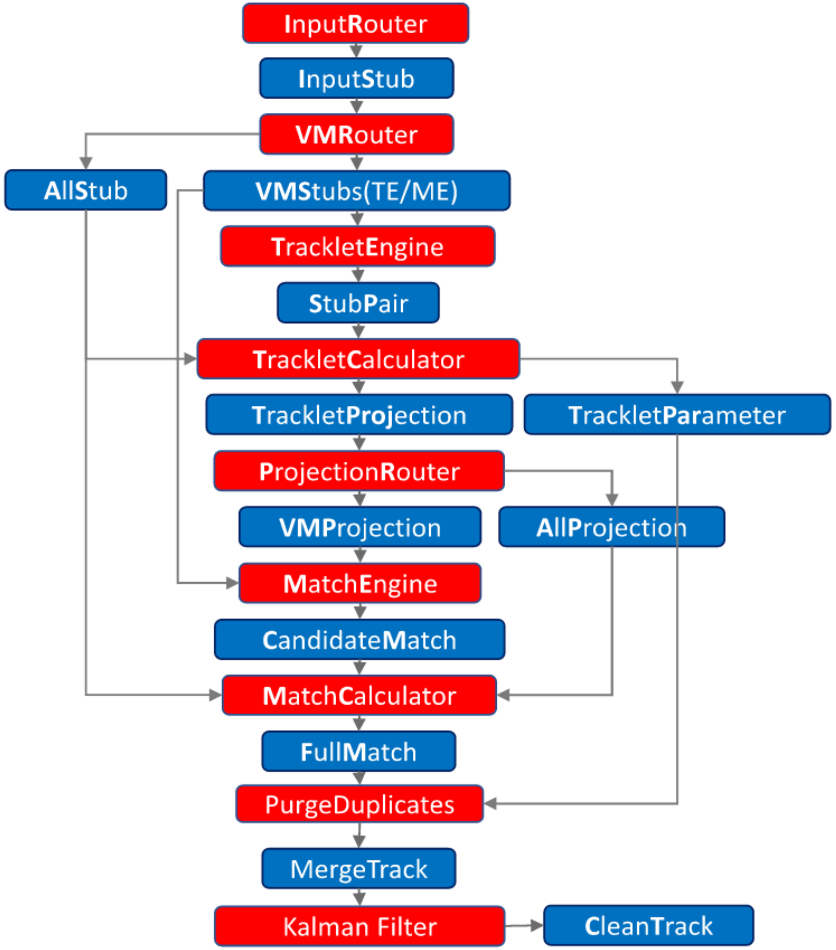






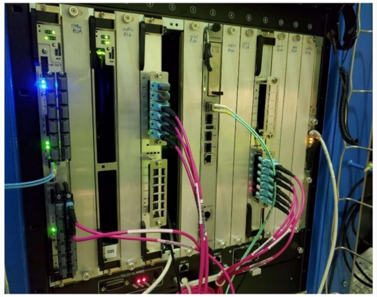
Firmware implementation

- Track finding algorithm implemented as an FPGA design
- Firmware organized as a series of **processing modules** with **memory modules** between each step:
  - Most processing modules implemented in Xilinx Vivado HLS (C++)
  - Kalman filter largely implemented in VHDL
  - Individual processing and memory modules connected together in a top-level VHDL module



Hardware demonstration

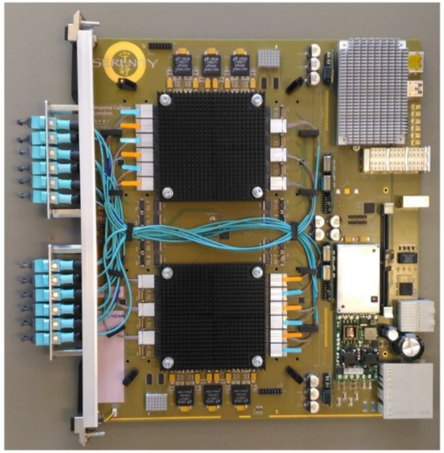
Test stand @ CERN
with Apollo & Serenity blades



- Track-finding hardware based on ATCA platform, the CMS standard for HL-LHC upgrades
- Multiple subchains of processing modules have been tested successfully already

Serenity: DTC processing

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



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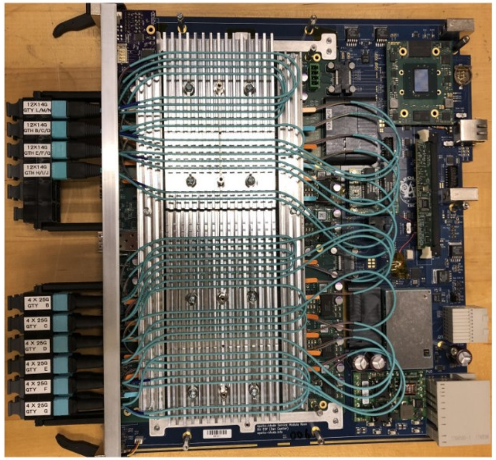
Apollo: track finding processing boards

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



arXiv:1911.06452

Conclusion

- L1 tracking is a key part of the strategy in CMS for making the most of the challenging data that will be delivered by the HL-LHC
- The algorithm combines a road search for pattern recognition with a Kalman filter fit:
  - Simulations shows that the algorithm performs very well
  - Implemented as an FPGA design with processing modules written in Xilinx Vivado HLS and VHDL
  - Multiple subchains of processing modules have been successfully demonstrated in actual hardware
- The focus now is on finalizing the system specifications, and demonstrating more extensive chains of modules in hardware