The Phase-2 Upgrade of the Hardware Trigger of CMS at the LHC

(for HL-LHC = "High-Luminosity LHC")

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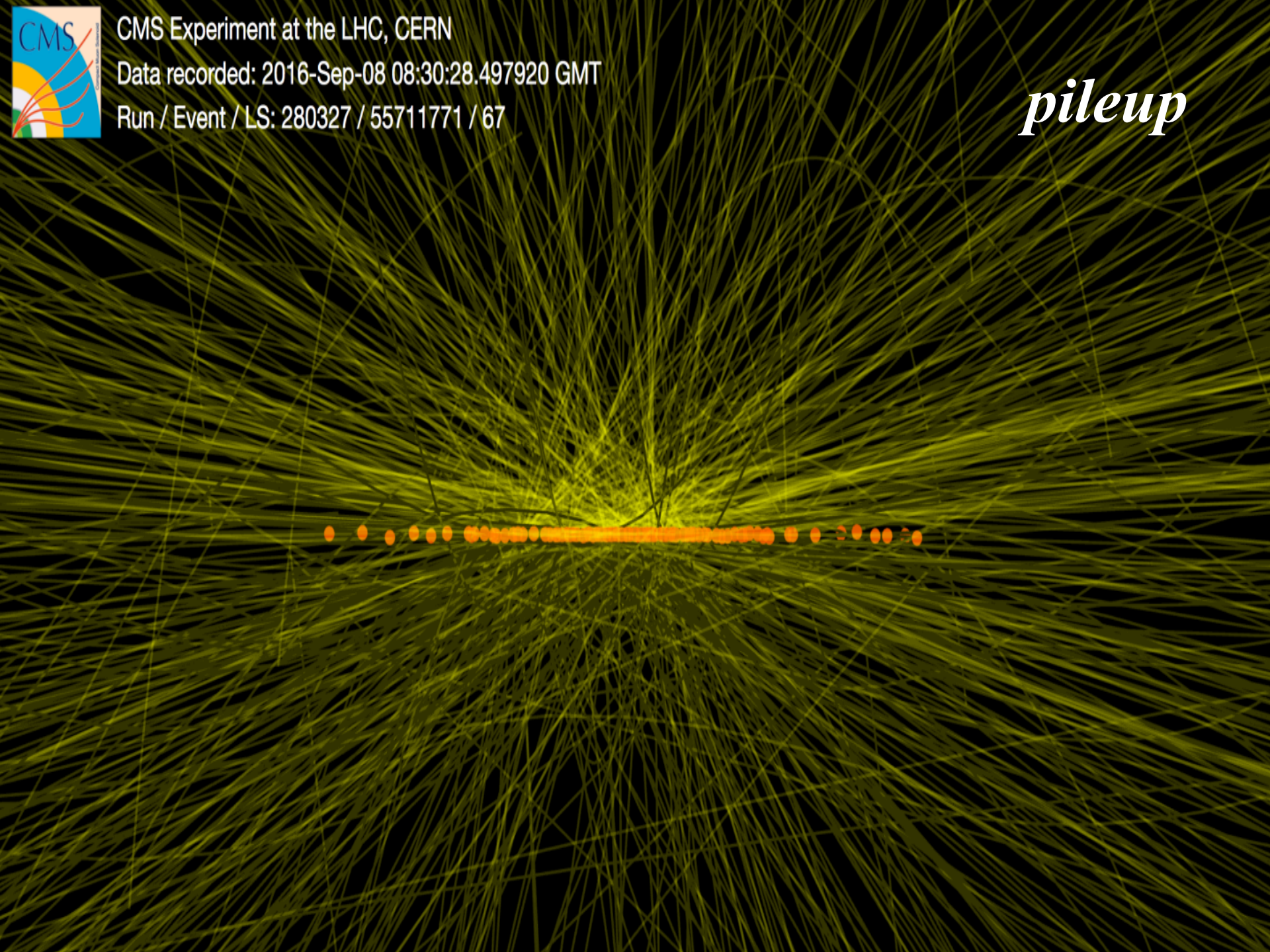
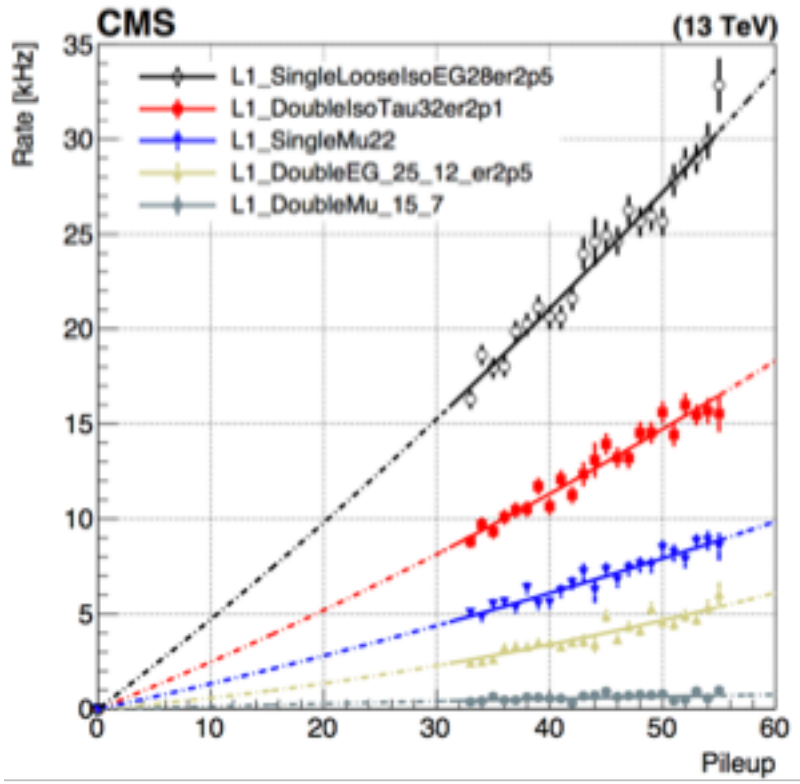
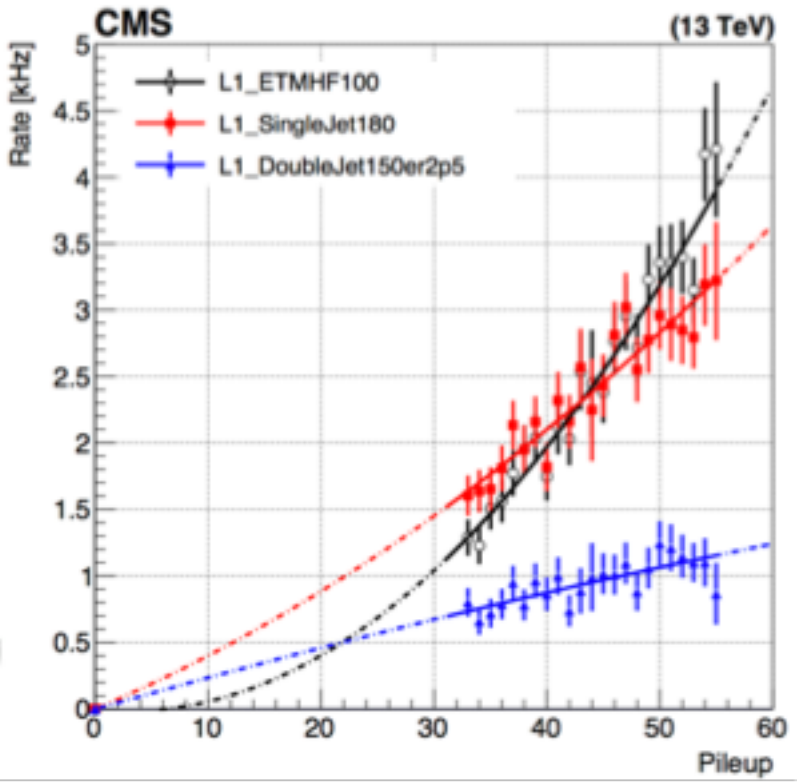
HL-LHC program

- precision measurements of standard model parameters
  - including Higgs particle
- BSM searches
  - "beyond-the-standard-model" physics, "new" physics
- both need much higher luminosity than now
  - "pileup" of 200
    - » simultaneous interactions in a single bunch crossing
  - 7.5×10^{34} cm^{-2} s^{-1}
  - 3000 fb^{-1} over the full experimental run (until 2035)
- if keeping current system: much higher p_T threshold
  - higher threshold in "transverse momentum" → lose sensitivity
- also: new signatures
  - displaced vertices, long-lived particles (timing!)
  - (no new physics has been found with conventional signatures)


CMS Experiment at the LHC, CERN
Data recorded: 2016-Sep-08 08:30:28.497920 GMT
Run / Event / LS: 280327 / 55711771 / 67
pileup

Pileup effect

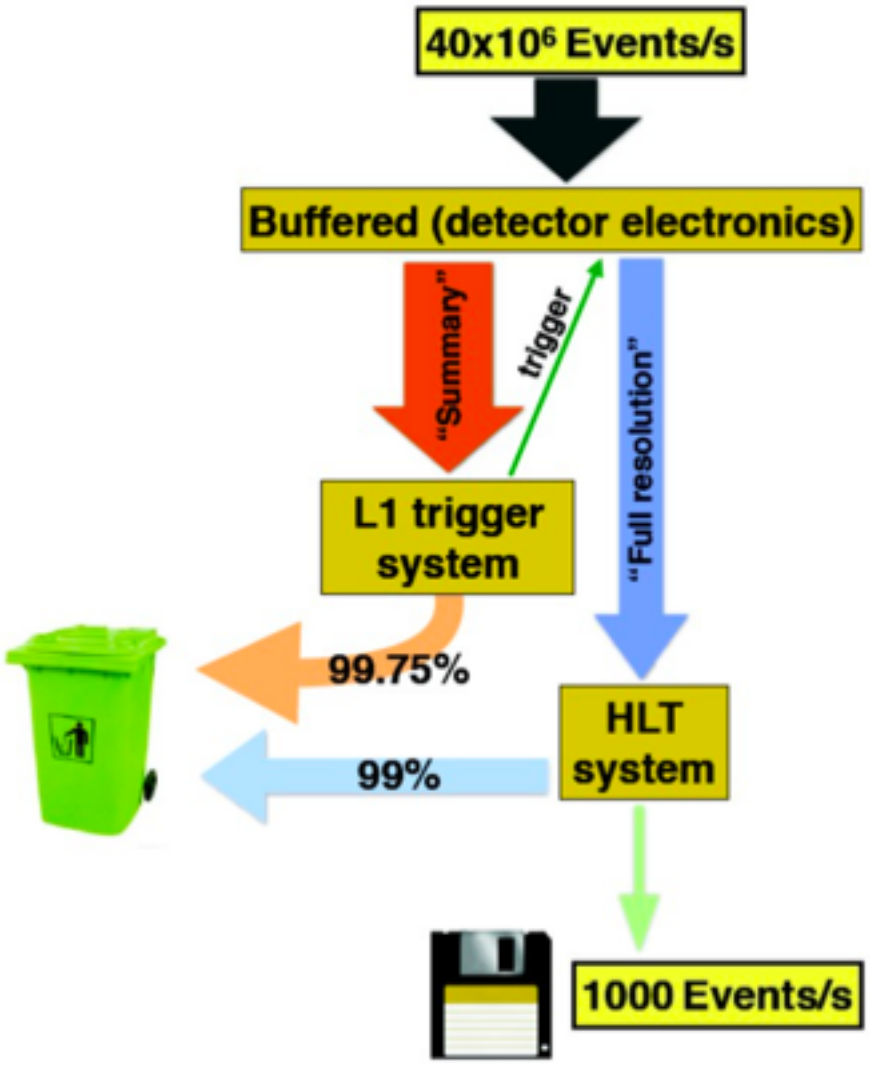




effect of higher pileup on trigger rates is in some cases much stronger than linear!

- for total energy sum, missing transverse momentum, multi-object triggers

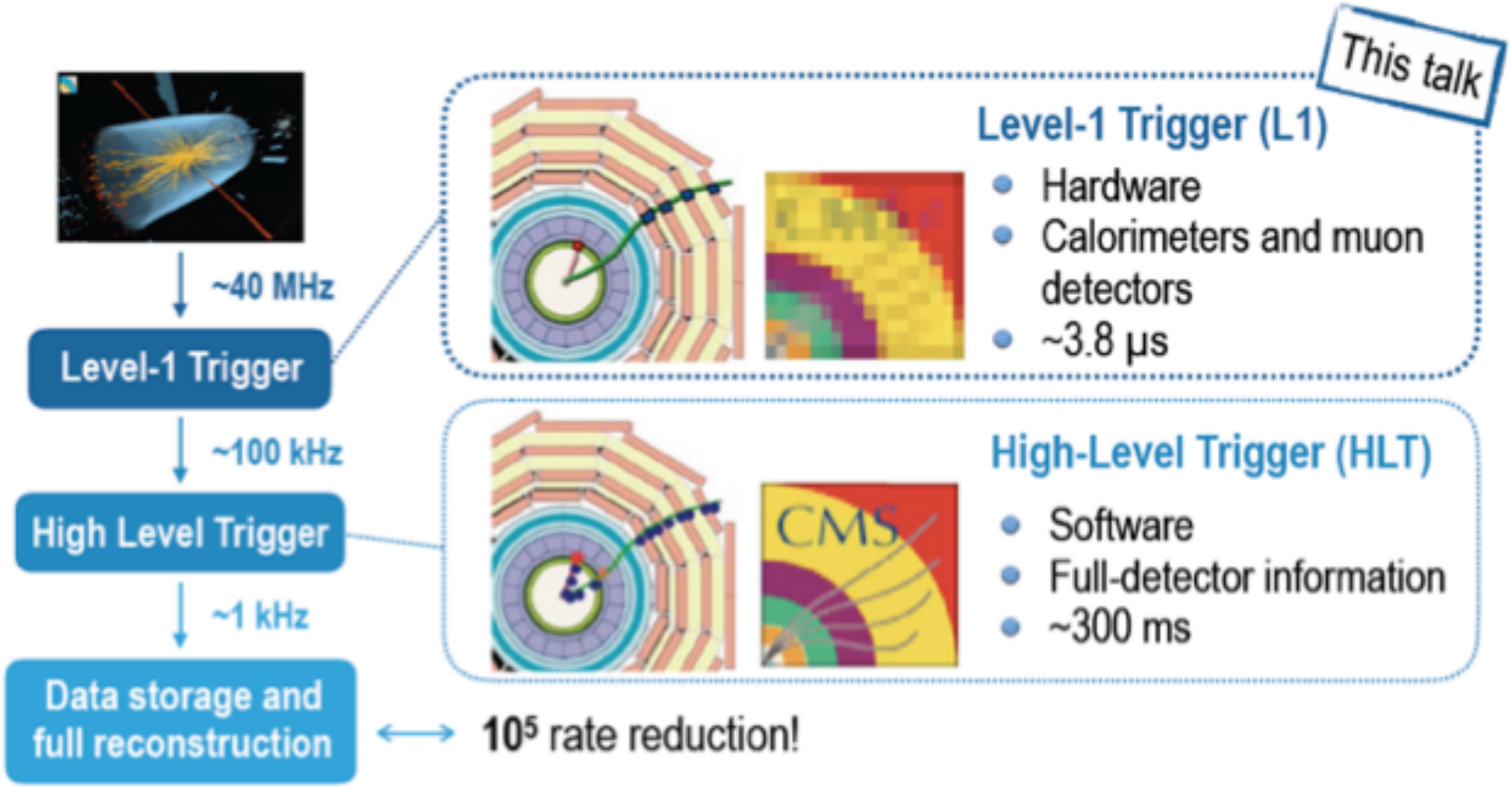
Rate reduction



currently:

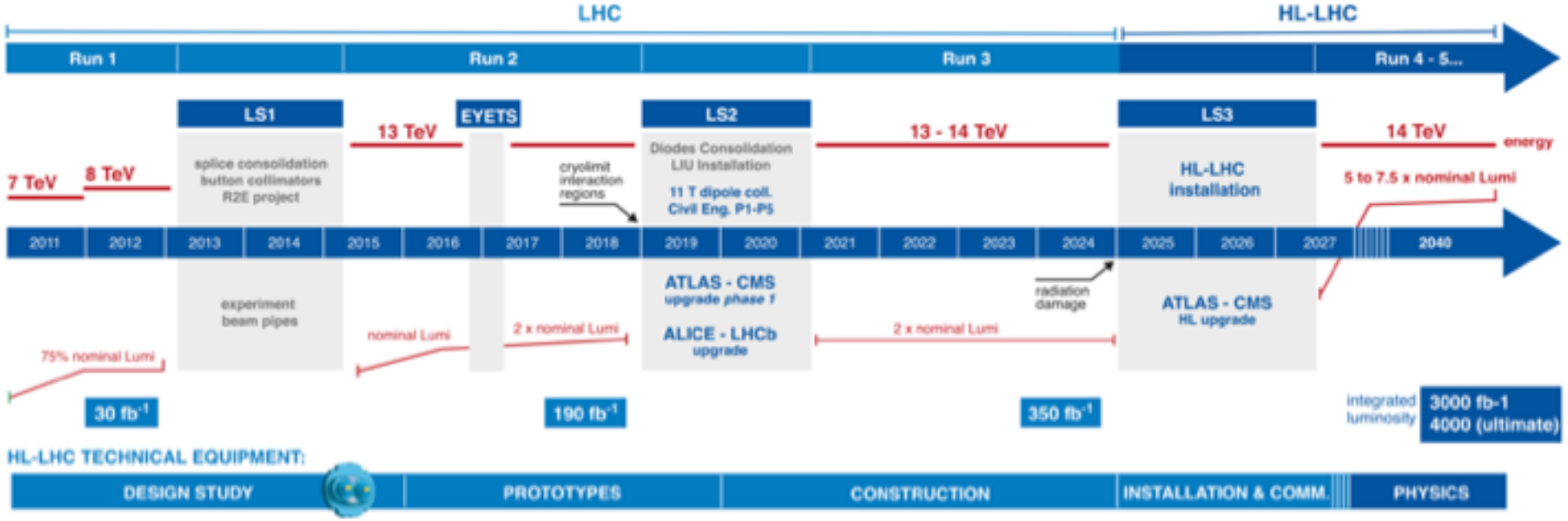
- L1: 40 MHz → 100 kHz
  - "Level-1 trigger"
  - hardware trigger
- HLT: 100 kHz → 1 kHz
  - "High-Level Trigger"
  - computer farm

Trigger stream vs full data



Slide from Alexei N. Safonov

LHC / HL-LHC Plan



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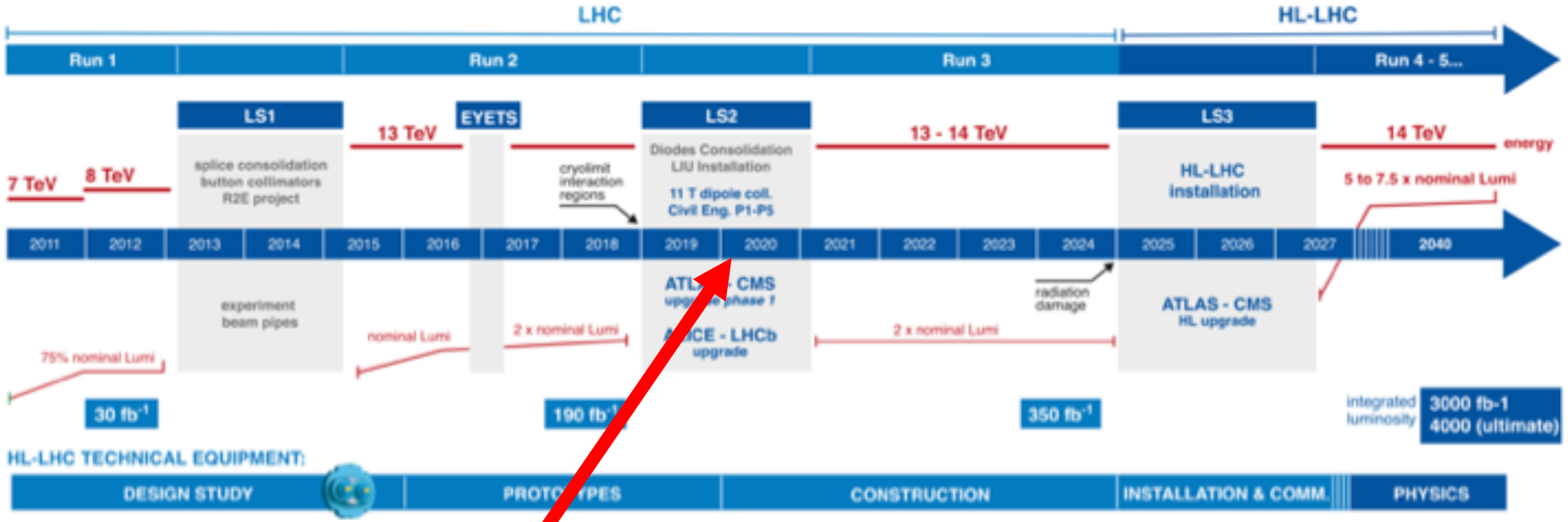
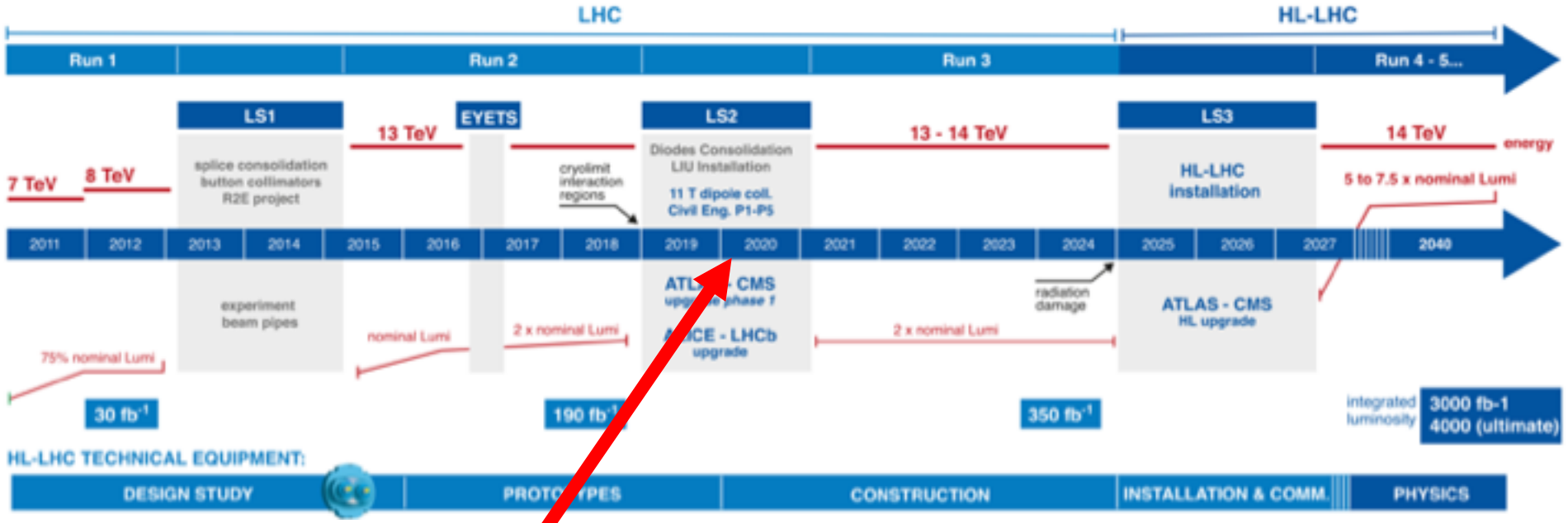


we are here

LHC / HL-LHC Plan



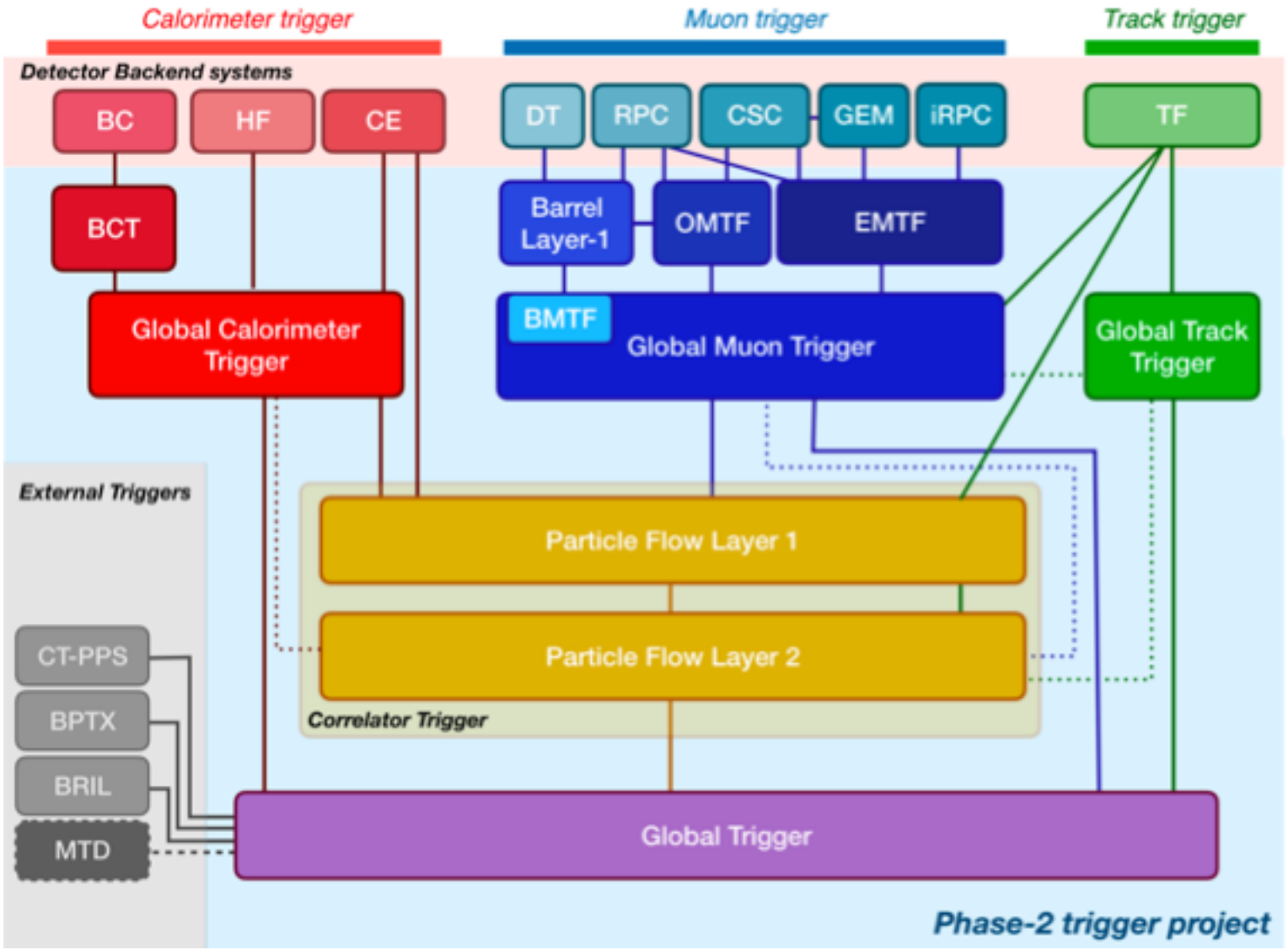
we are here

- Level-1 trigger system will be completely rebuilt for HL-LHC ("Phase-2 upgrade")
- certain aspects can and will be tested in the current setup in Run 3

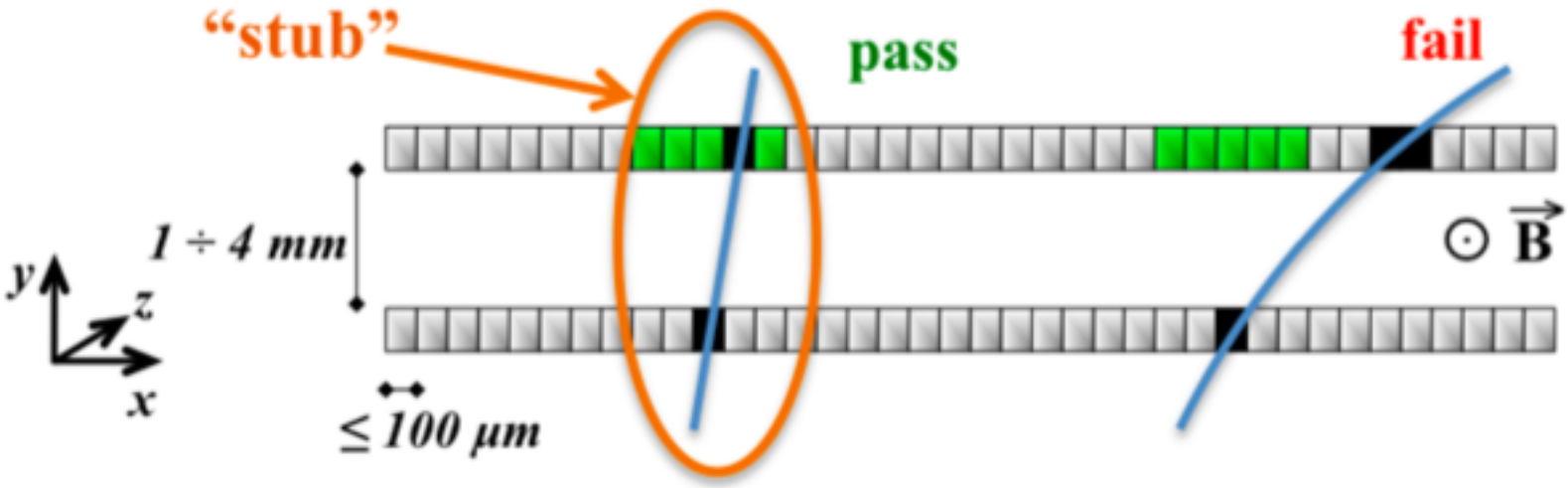
Upgrade strategy

- tracker trigger
  - use particle flow approach at Level-1
  - so far, silicon tracker was not in Level-1 trigger
  - new detector needed to make this possible
- trigger rates increase:
  - L1: 100 → 750 kHz
  - HLT: 1 → 7.5 kHz
- latency increase
  - 3.8 → 12.5 μsec
- better trigger granularity
  - high-granularity endcap calorimeter ("HGCAL")
    - » new detector
  - ECAL towers → single crystals

Architecture

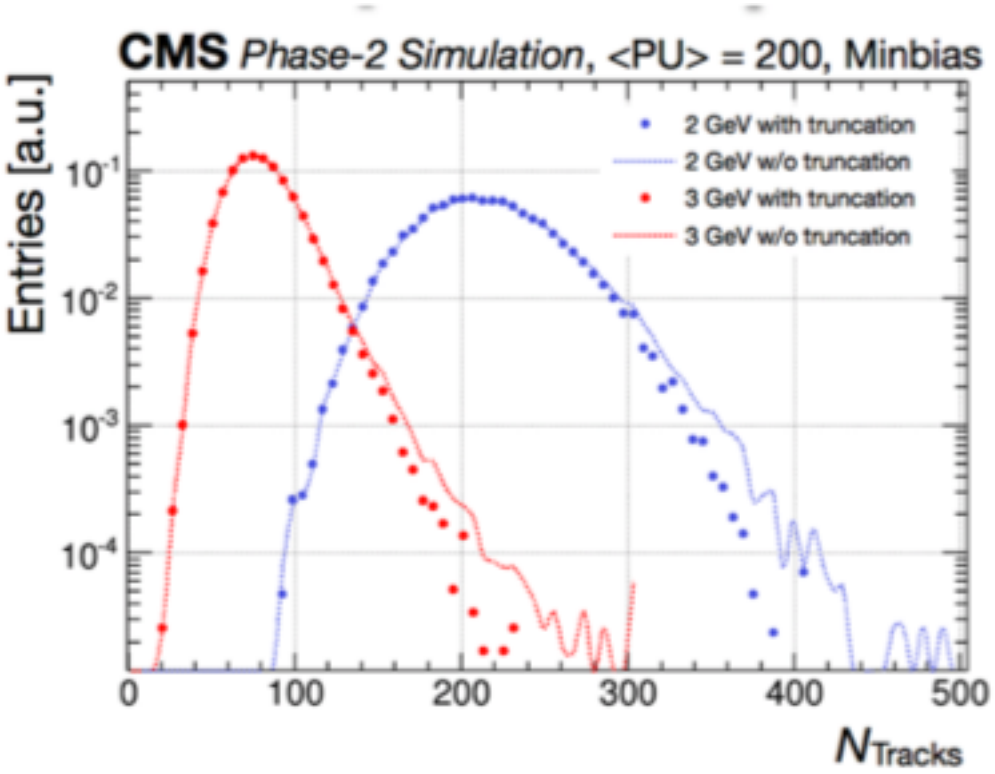


Tracker Trigger (1)



- cannot send all hits to trigger at 40 MHz
- → local "intelligence" needed to reduce rate
  - only tracks with $p_T > 2$ GeV are sent to tracker trigger

Tracker Trigger (2)

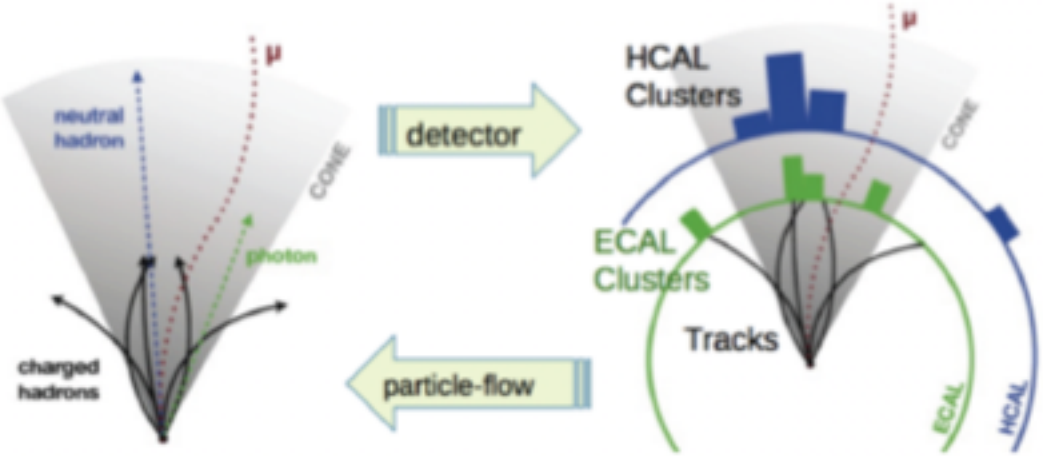


most tracks have low p_T

- need not be sent to L1 trigger
- at a pileup of 200, an average of 200 tracks will be forwarded to trigger correlator

Tracker Trigger (3)

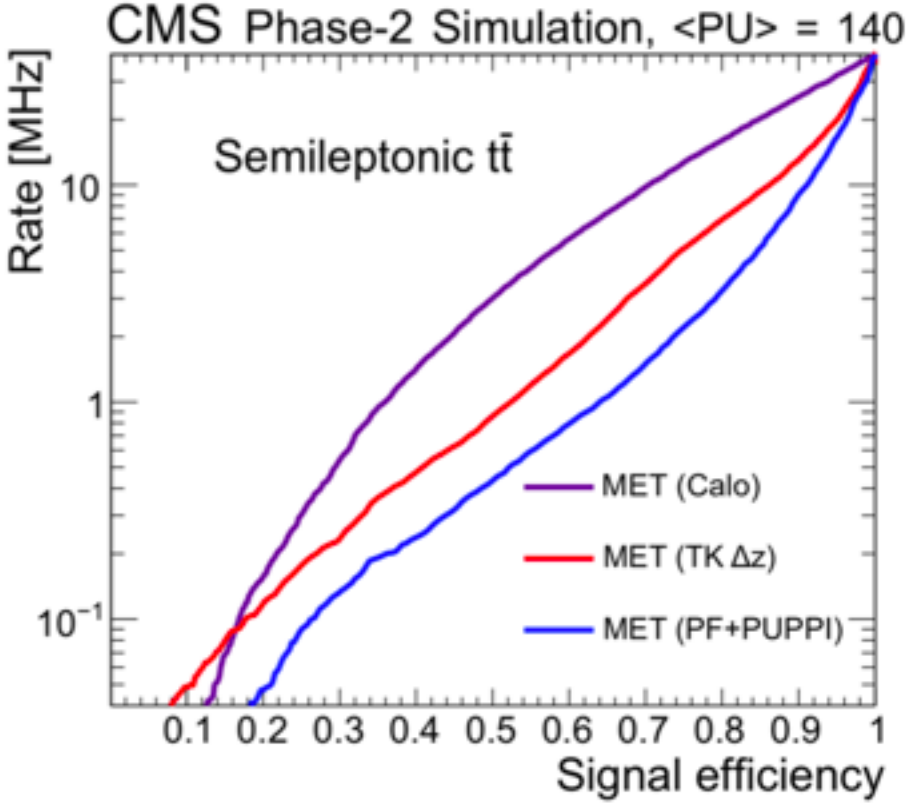
- Track-finding algorithm
  - stubs as input
  - hybrid algorithm: tracklet seed and road search algorithm (Kalman filter)
- "Particle Flow" approach now possible at Level-1 trigger
  - use information from all detectors

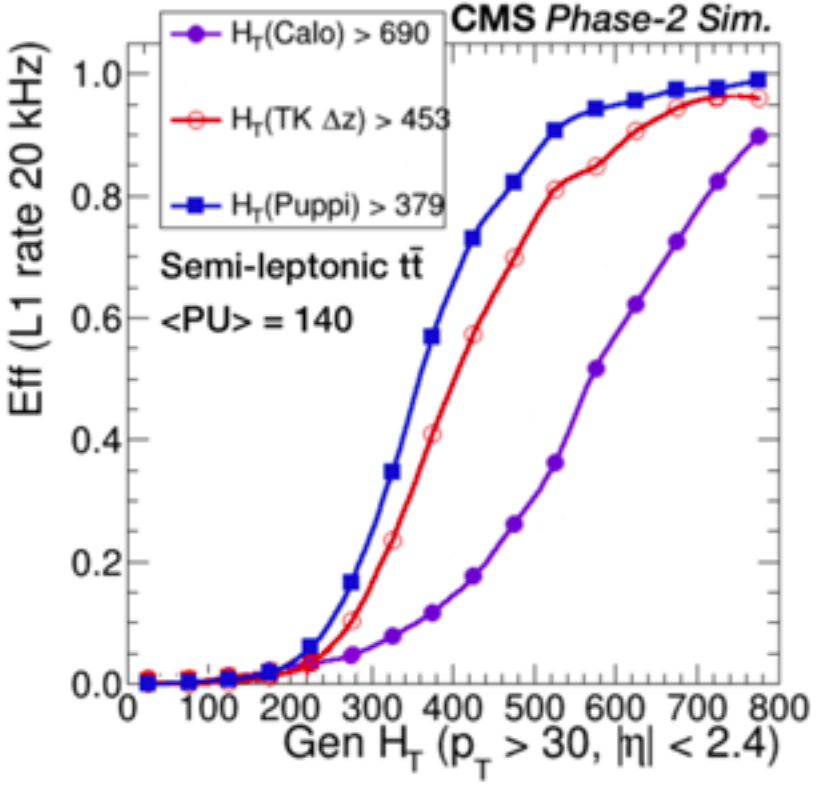


- advanced pileup mitigation techniques
  - "PUPPI" = "PileUp Per Particle Identification"

Tracker Trigger (4)

Example: semileptonic top – anti-top events ($t\bar{t}$)





Rate vs. efficiency of trigger on missing transverse momentum (MET)

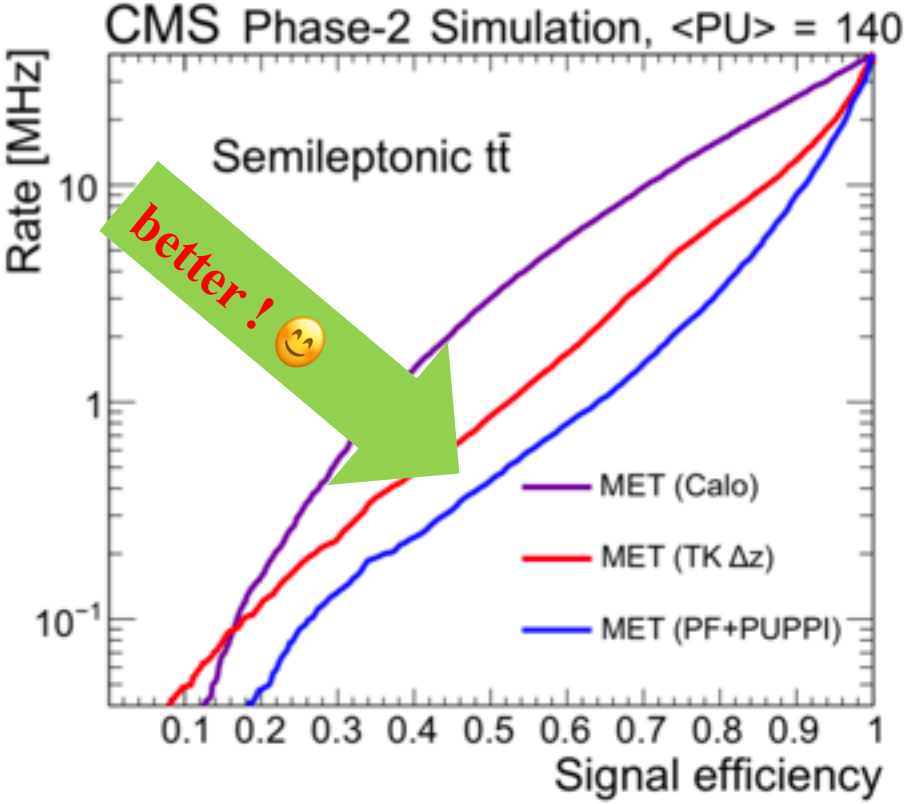
- *also called "missing transverse energy"*
- *calorimeter only / raw tracker information / particle flow and pileup-suppression (PUPPI)*

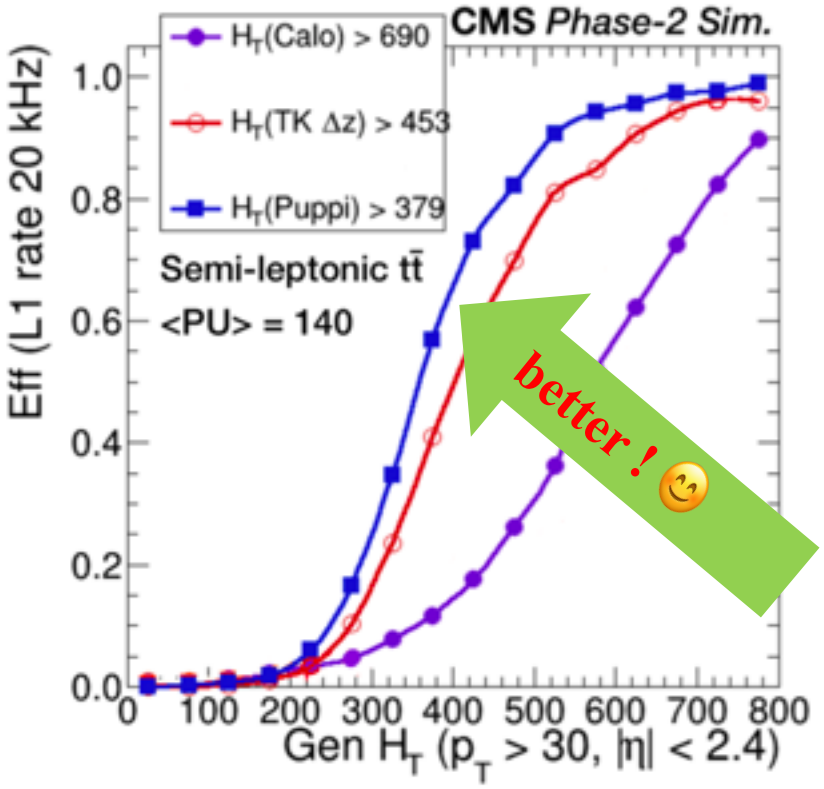
H_T: vectorial energy sum of jets

- *turn-on curve for a fixed Level-1 rate of 20 kHz*

Tracker Trigger (4)

Example: semileptonic top – anti-top events ($t\bar{t}$)





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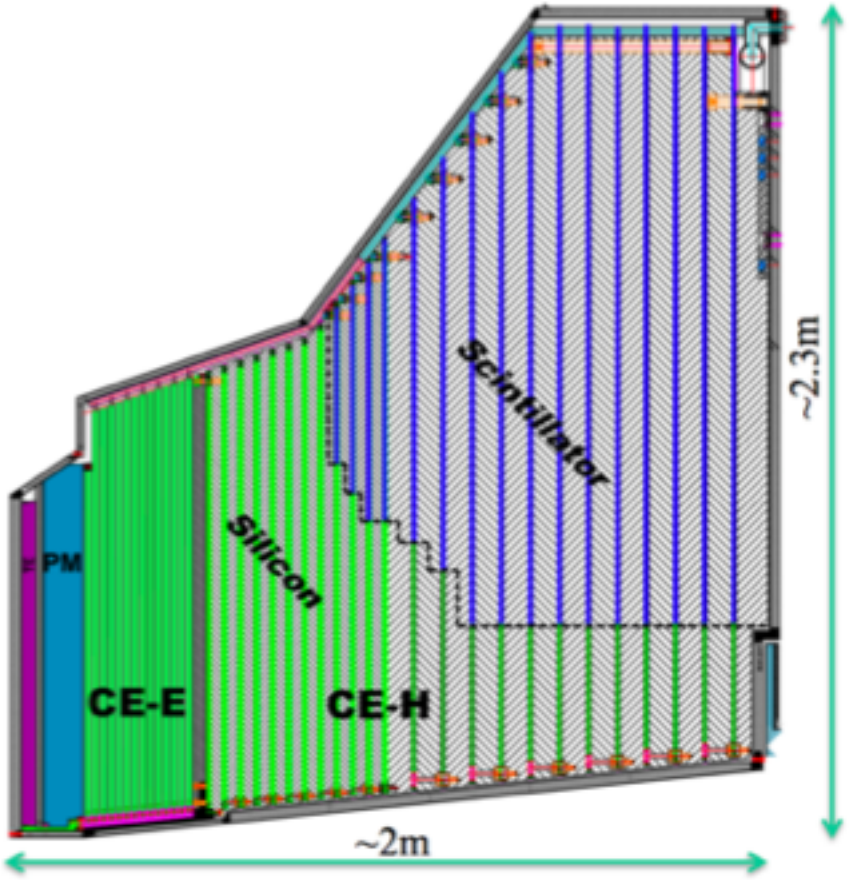
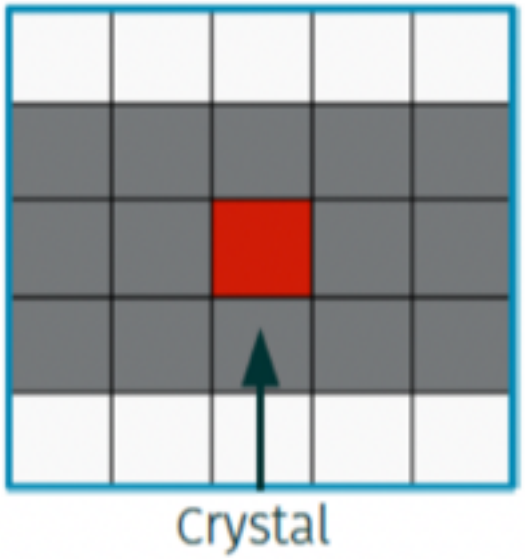
High Granularity Calorimeter (HGCAL)

- completely new subdetector
  - higher radiation in forward region
- sampling calorimeter with silicon (radiation hard) and scintillator
- 14 layers used at L1 in the EM section, 24 in HCAL section
- 3D high granularity allows Particle-Flow reconstruction
- longitudinal segmentation helps to disentangle pileup events
  - longitudinal layer-by-layer readout
- trigger primitives: 3D clusters
  - too much information for L1 trigger
  - compromise between number of clusters and amount of information per cluster



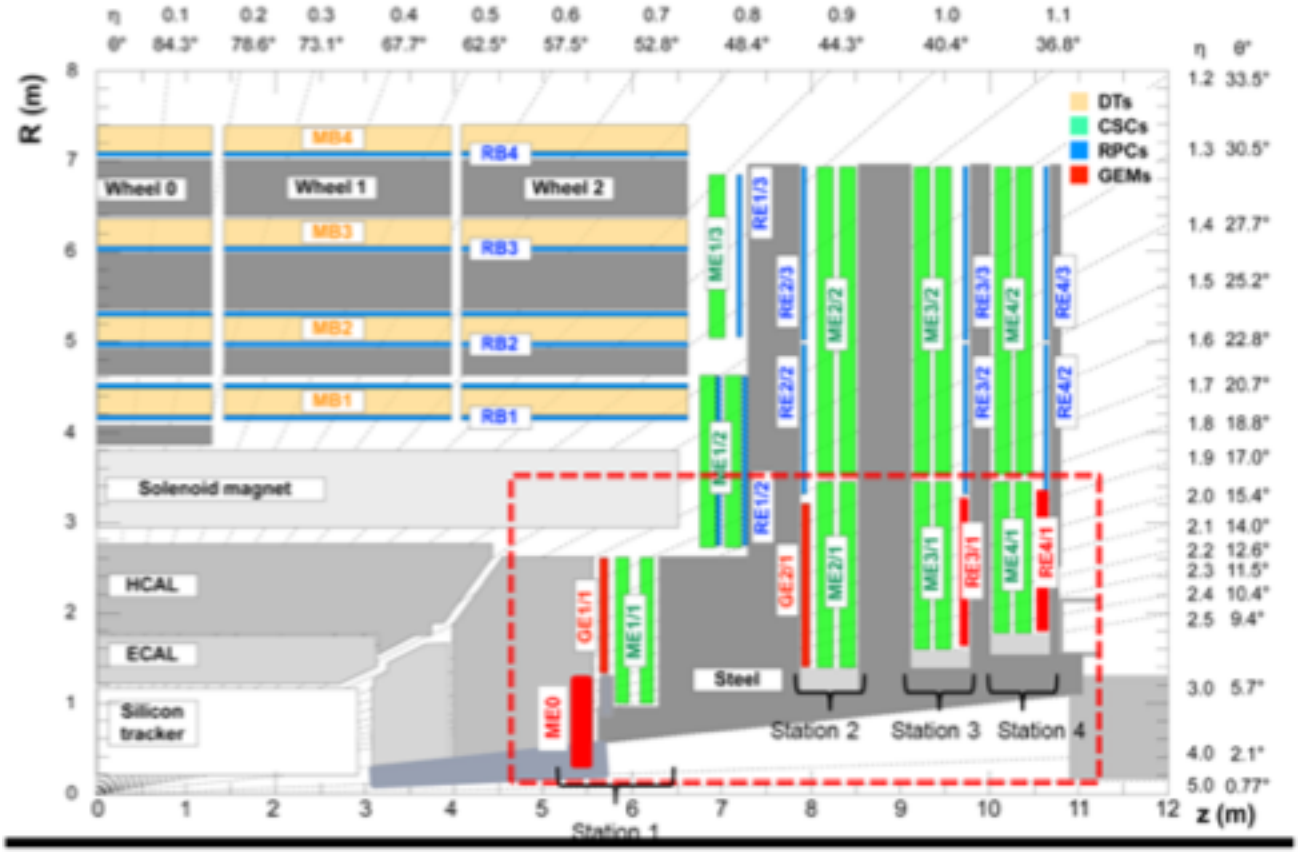
Electromagnetic calorimeter (ECAL) in the barrel

- so far, only information from "trigger towers" (5 x 5 crystals) has been available at L1-trigger
- upgrade electronics to use single-crystal information
  - 16 bits x 61200 crystals ~ 39 Tb
- → better efficiency at half the rate



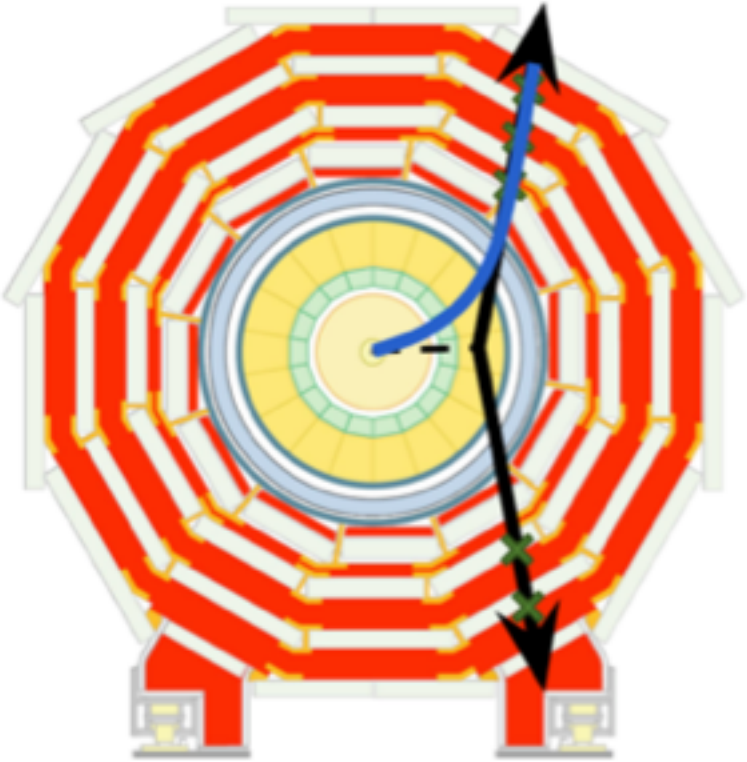
Muons

- additional muon detectors in forward region
- improved algorithms
  - allowing for vertices that are displaced from beam



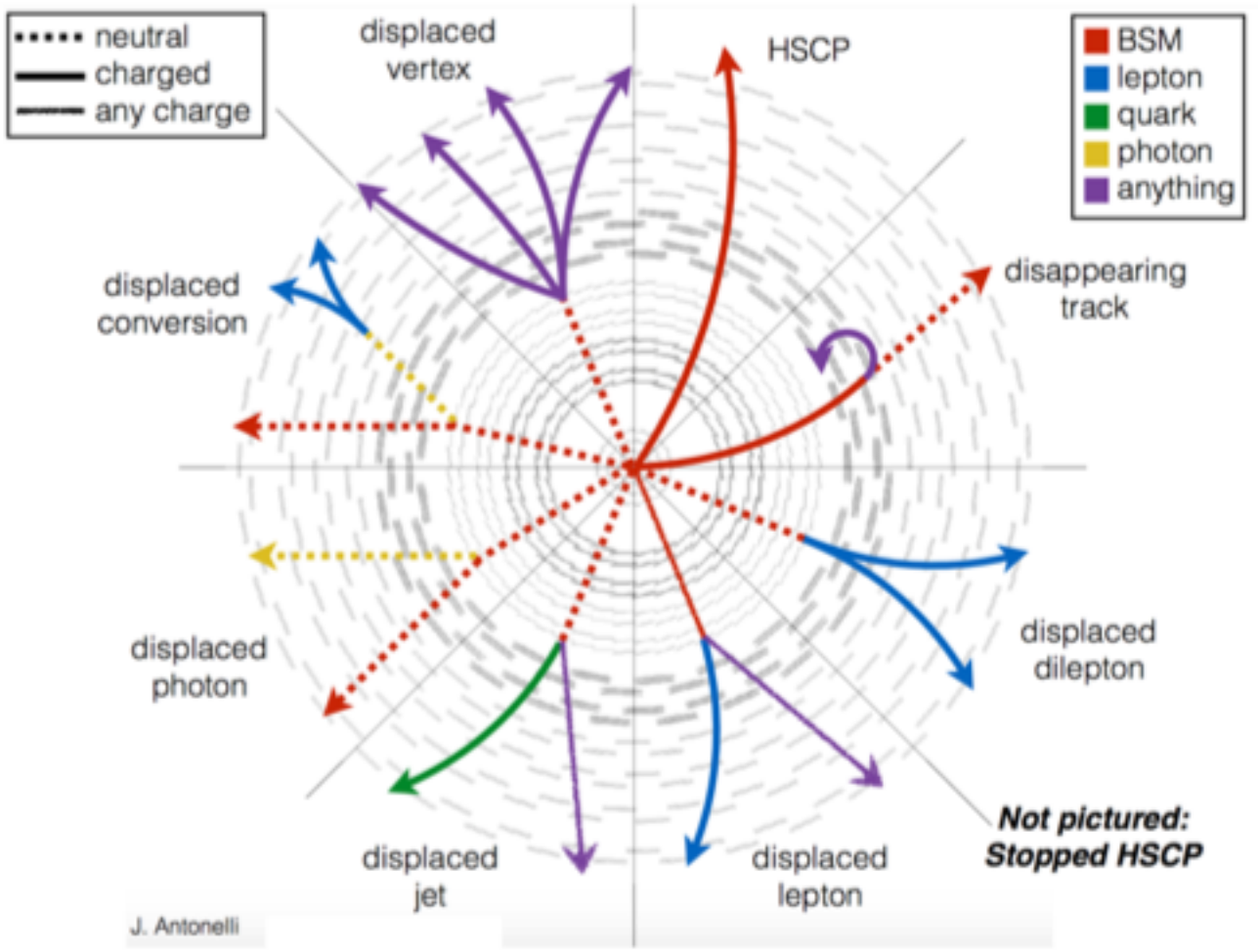
Displaced vertices / "long-lived particles (LLP)" (1)

- some physics scenarios predict relatively long-lived new particles
  - could appear as decay vertices displaced from beam axis
- so far CMS had no efficient Level-1 trigger for such events

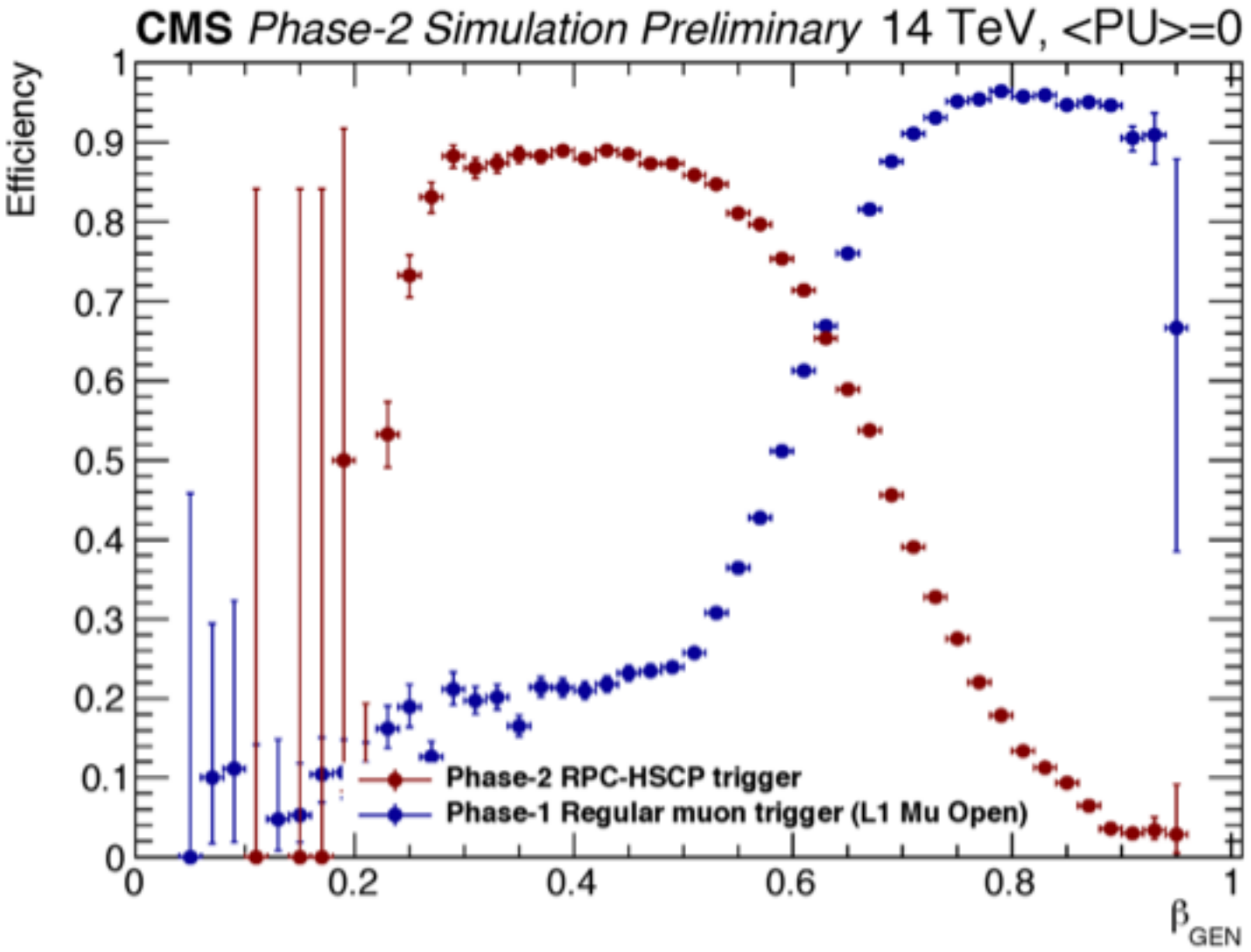


- high-momentum (straight) ***displaced*** track would correspond to lower momentum (bent) track when forced (by Level-1 trigger algorithm) to come from beam axis
- relaxing this requirement can result in high background rates
- new techniques needed
  - for example, muon reconstruction by Kalman filter without beam-axis requirement
  - "unconstrained" vertex fit
  - will be introduced already in Run 3
  - also use timing information

Displaced vertices / "long-lived particles (LLP)" (2)

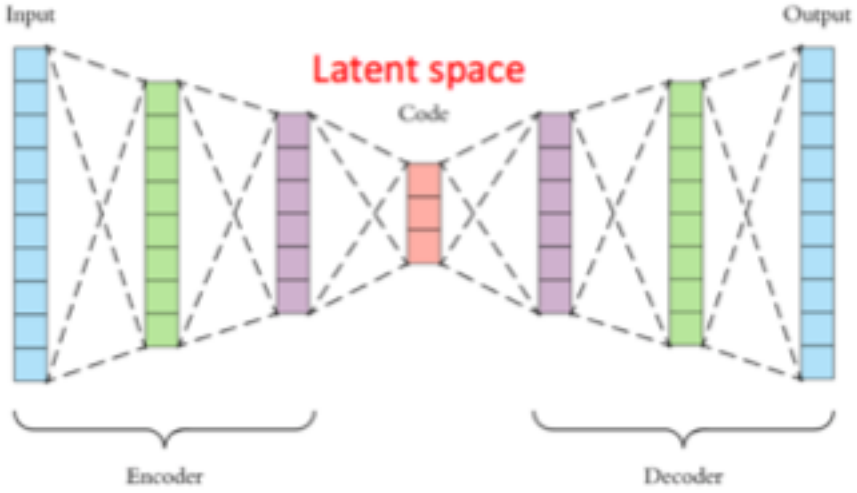


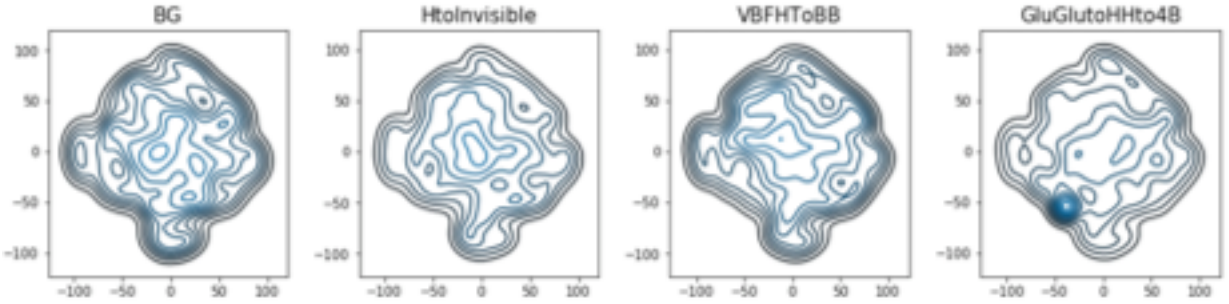
Muon timing for long-lived particles



Anomaly Trigger

- we do not know what "New Physics" looks like
  - it should be different from standard-model physics
- → "anomaly detection" by machine learning
- idea:
  - reduce data volume ("encode") in "Latent space"
  - try to reconstruct original data ("decode")
  - look for differences
  - can "train" with (abundant) measured data





Graphs from Zhenbin Wu

And if we did not trigger? "Scouting"!

- for certain analyses, need lots of statistics but can make do with reduced data
- → record only trigger-level information (without full detector data)
  - has already been done in CMS ("scouting") and also in ATLAS ("trigger-level analysis")
- or even more statistics and less data volume: "40-MHz scouting"
  - record part of the input information to the Level-1 trigger, for each bunch crossing

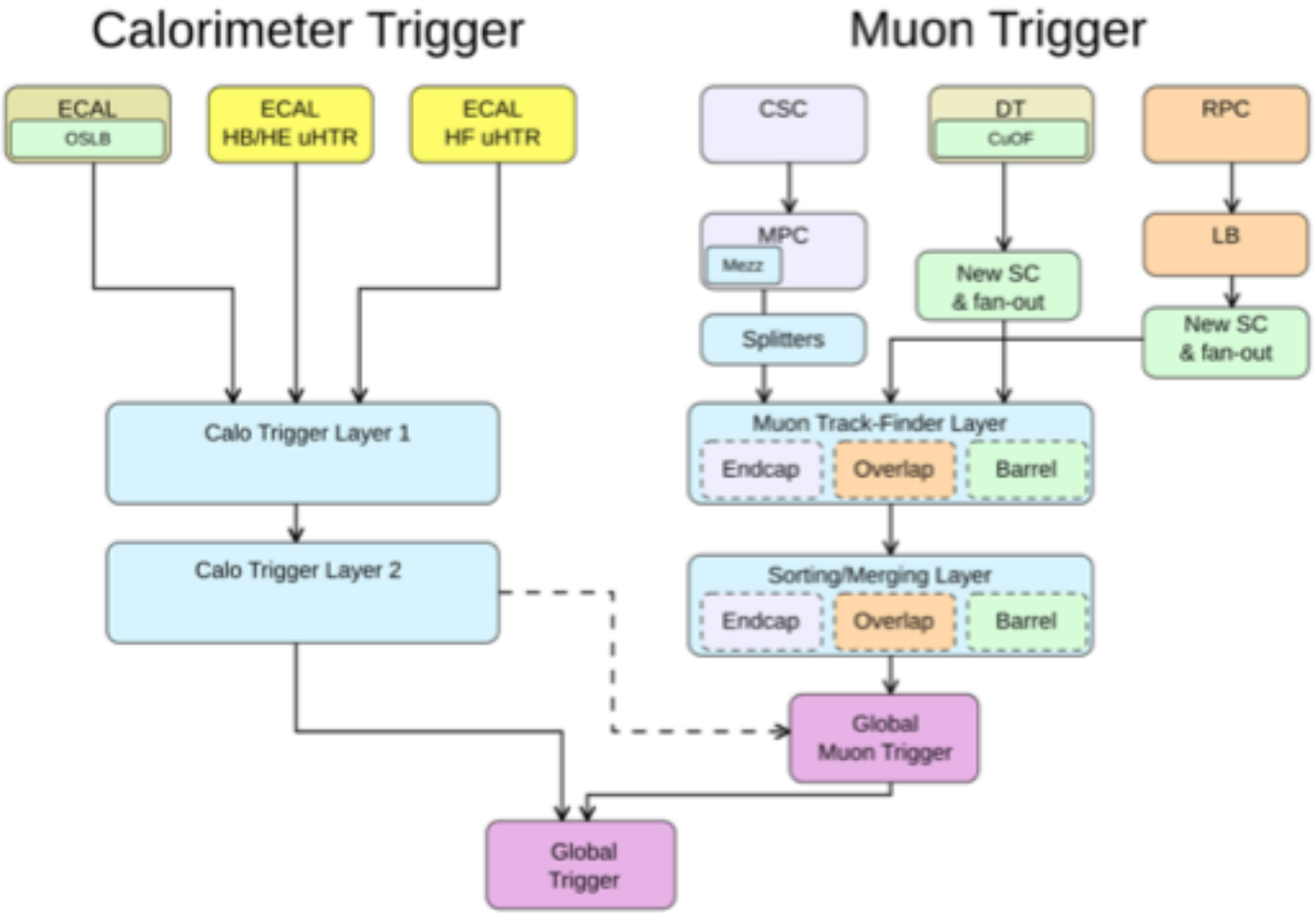
Conclusion

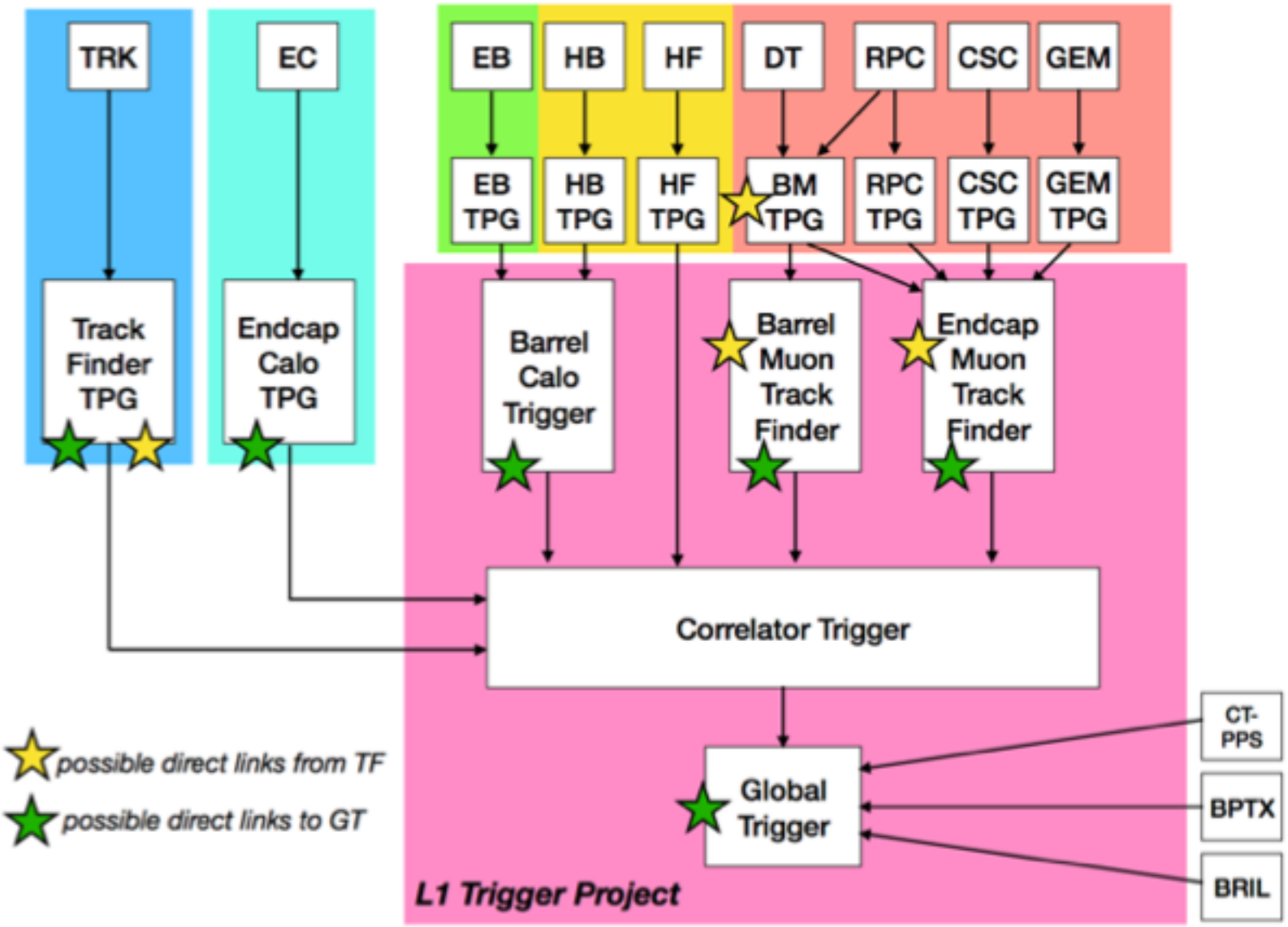
To make optimum use of the HL-LHC, we need more powerful, novel

- detectors
- trigger electronics
- trigger algorithms

BACKUP

The current Level-1 Trigger




TRK
EC
EB
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HF
DT
RPC
CSC
GEM
EB TPG
HB TPG
HF TPG
BM TPG
RPC TPG
CSC TPG
GEM TPG
Track Finder TPG
Endcap Calo TPG
Barrel Calo Trigger
Barrel Muon Track Finder
Endcap Muon Track Finder
Correlator Trigger
Global Trigger
CT-PPS
BPTX
BRIL
possible direct links from TF
possible direct links to GT
L1 Trigger Project

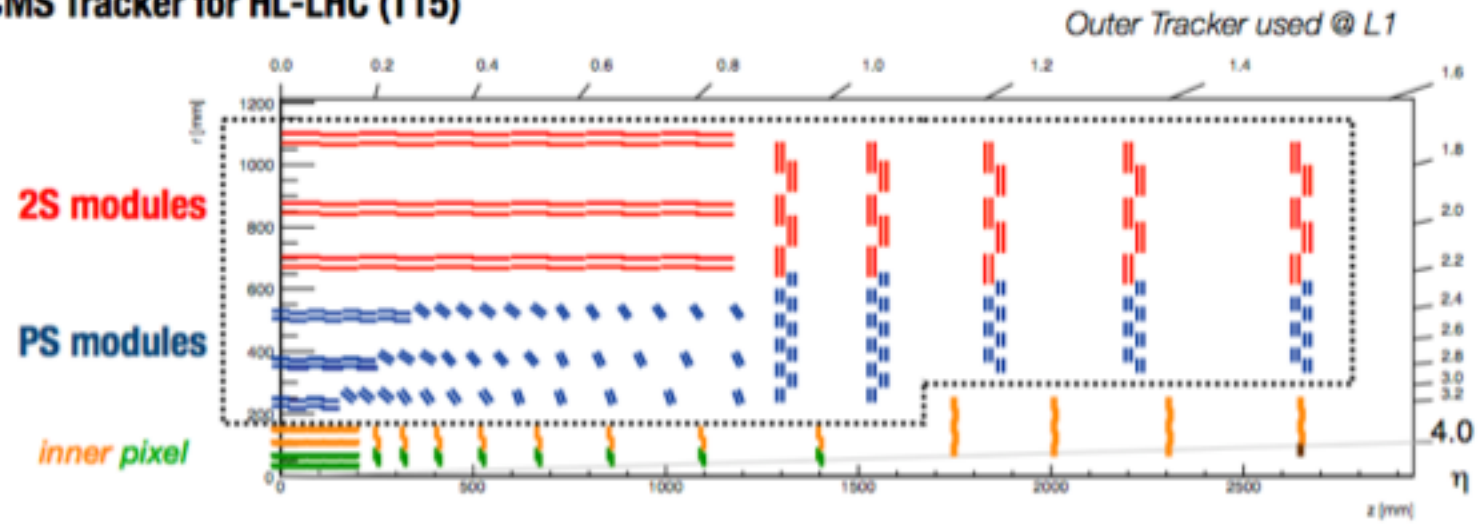
Things not covered

- HCAL depth, timing
- lumi levelling

Introduction

- Full-detector tracking @ 40 MHz for HL-LHC, utilizing unique "p_T modules"
- Baseline to identify prompt tracks with $p_T > 2$ GeV, $|\eta| < 2.4$
  - *Extended: add capability to reconstruct displaced tracks*
- Tracks propagated to L1 trigger for correlation with calo/muon inputs

CMS Tracker for HL-LHC (T15)



http://cms-tklayout.web.cern.ch/cms-tklayout/layouts/recent-layouts/OT616_IT613/index.html

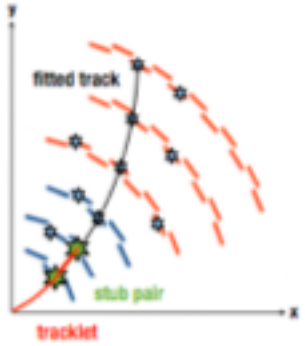
2

from: *Louise Skinnari*

L1 tracking hybrid algorithm

- Form tracklet seeds from adjacent layers/disks + beam spot constraint
  - *Extended (displaced) tracking: "triplet" seeds w/o beam spot constraint*
- Project & find matching stubs in other layers/disks
- Track candidates sharing stubs are merged prior to fitting
- Track fitting using Kalman Filter to identify best stub candidates & provide final set of track parameters
  - *Default uses 4 parameter fit, displaced — 5 parameter fit to include d_0*

Tracklet seed & search



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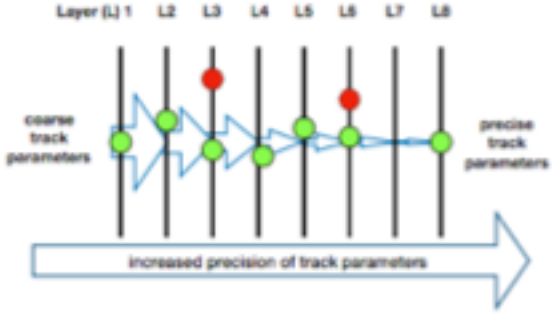
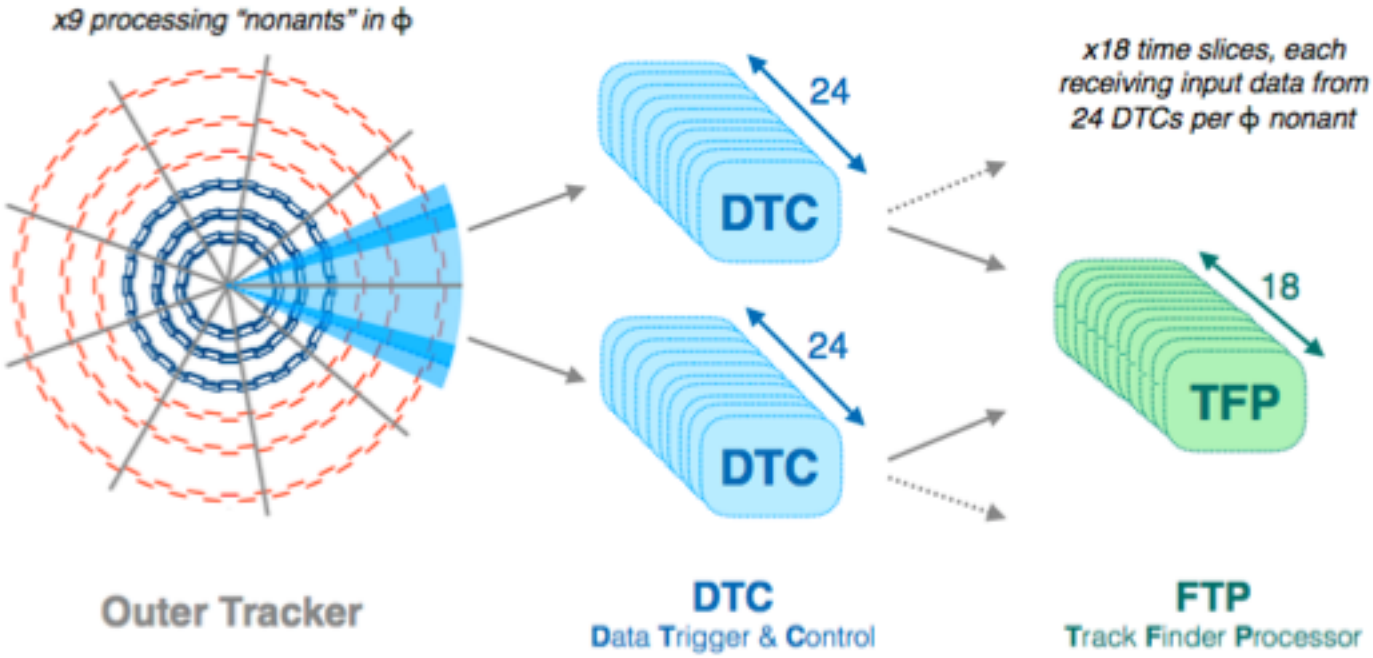


Kalman Filter fitting

from: *Louise Skinnari*

L1 tracking architecture

- System architecture with extensive parallel processing
- Detector sub-divided into 9 ϕ sectors with time multiplexing (TMUX) of 18



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