Status and prospects of the CMS experiment for LHC Run 3 and beyond

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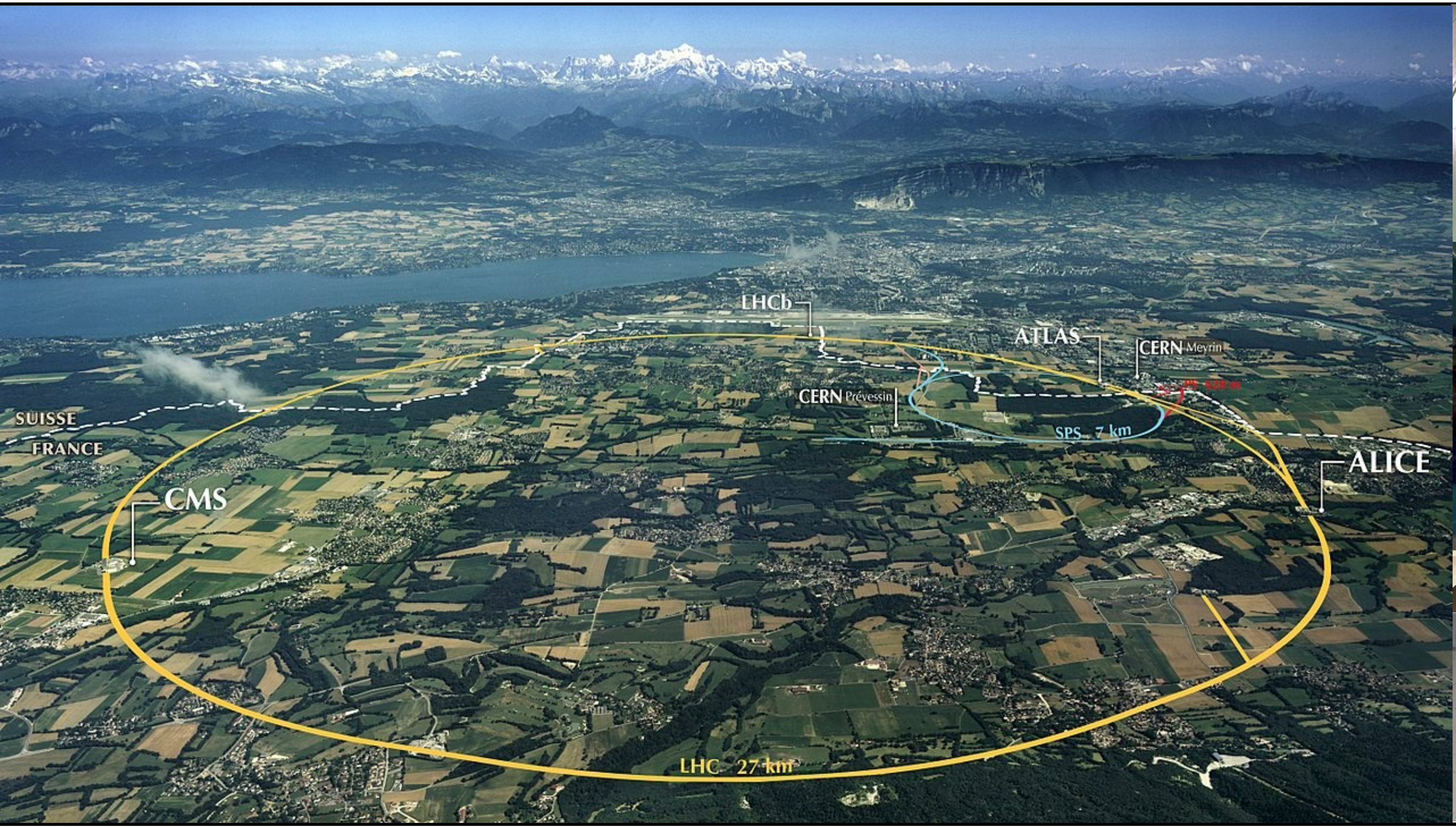
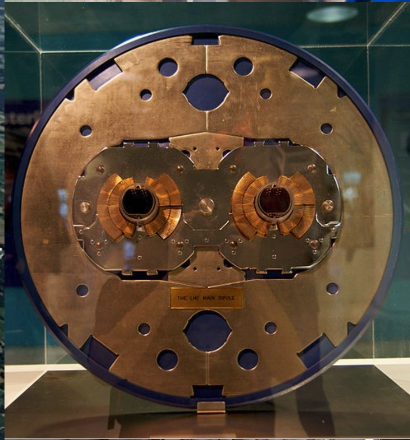
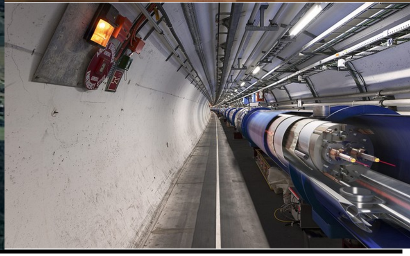
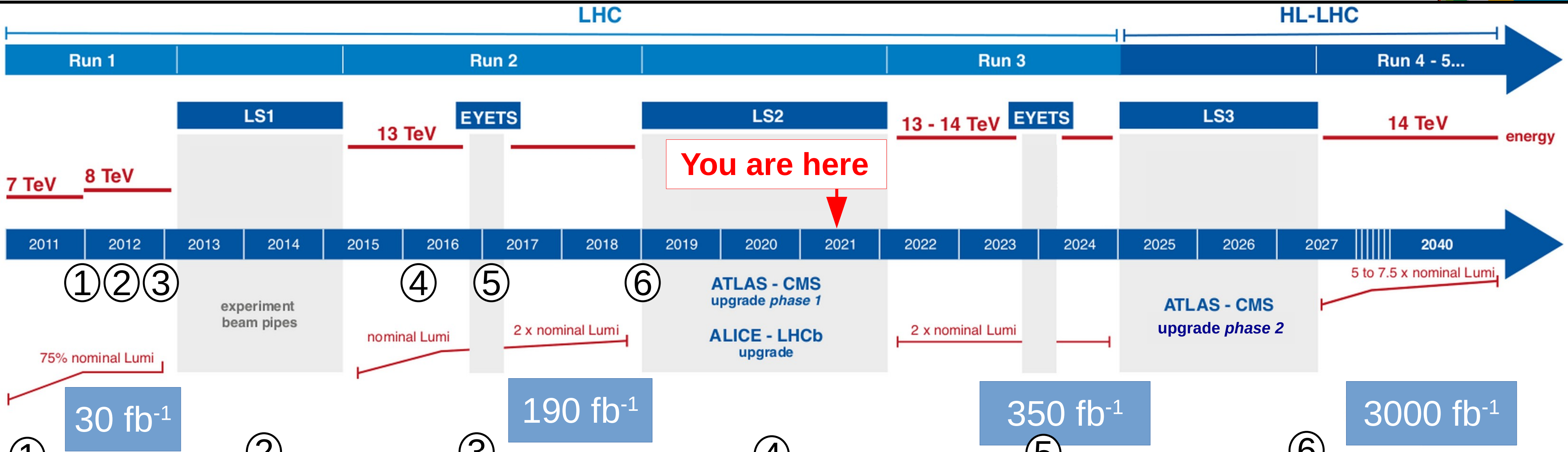
The Large Hadron Collider

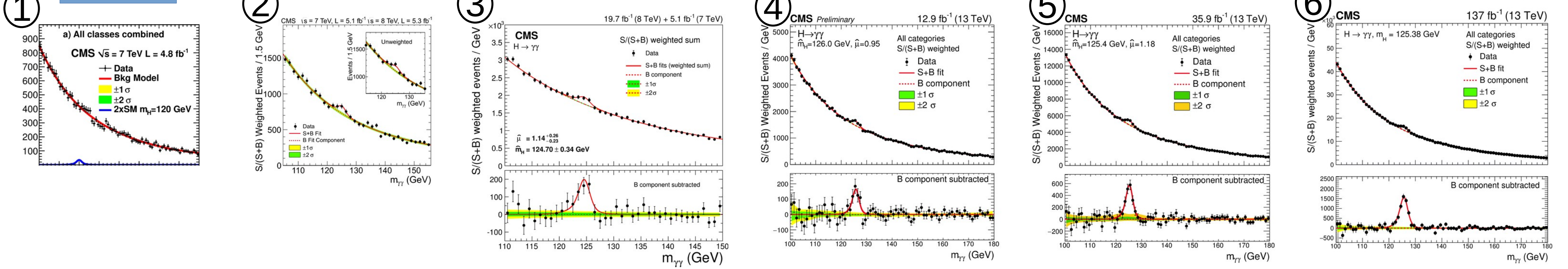




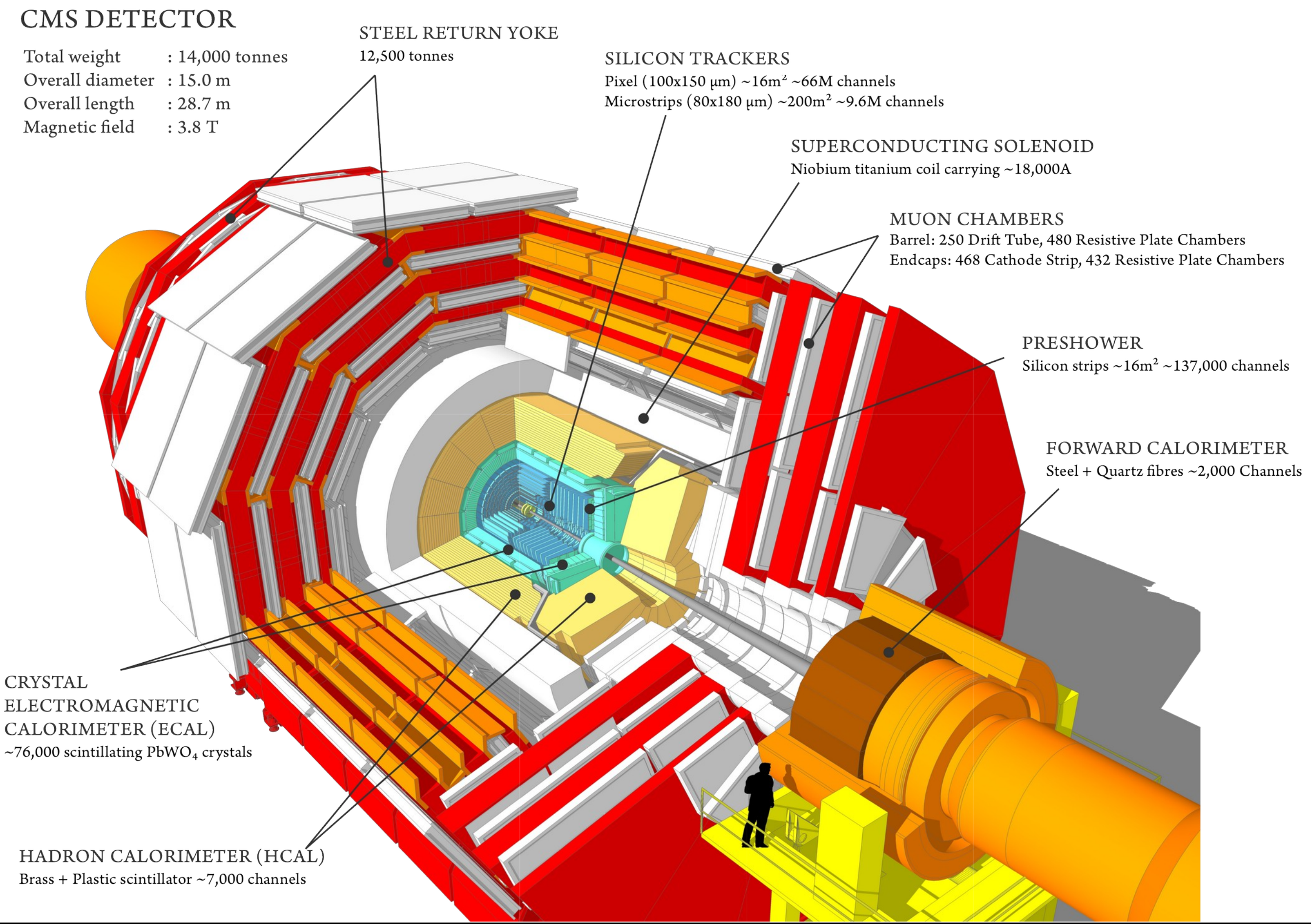


The Large Hadron Collider



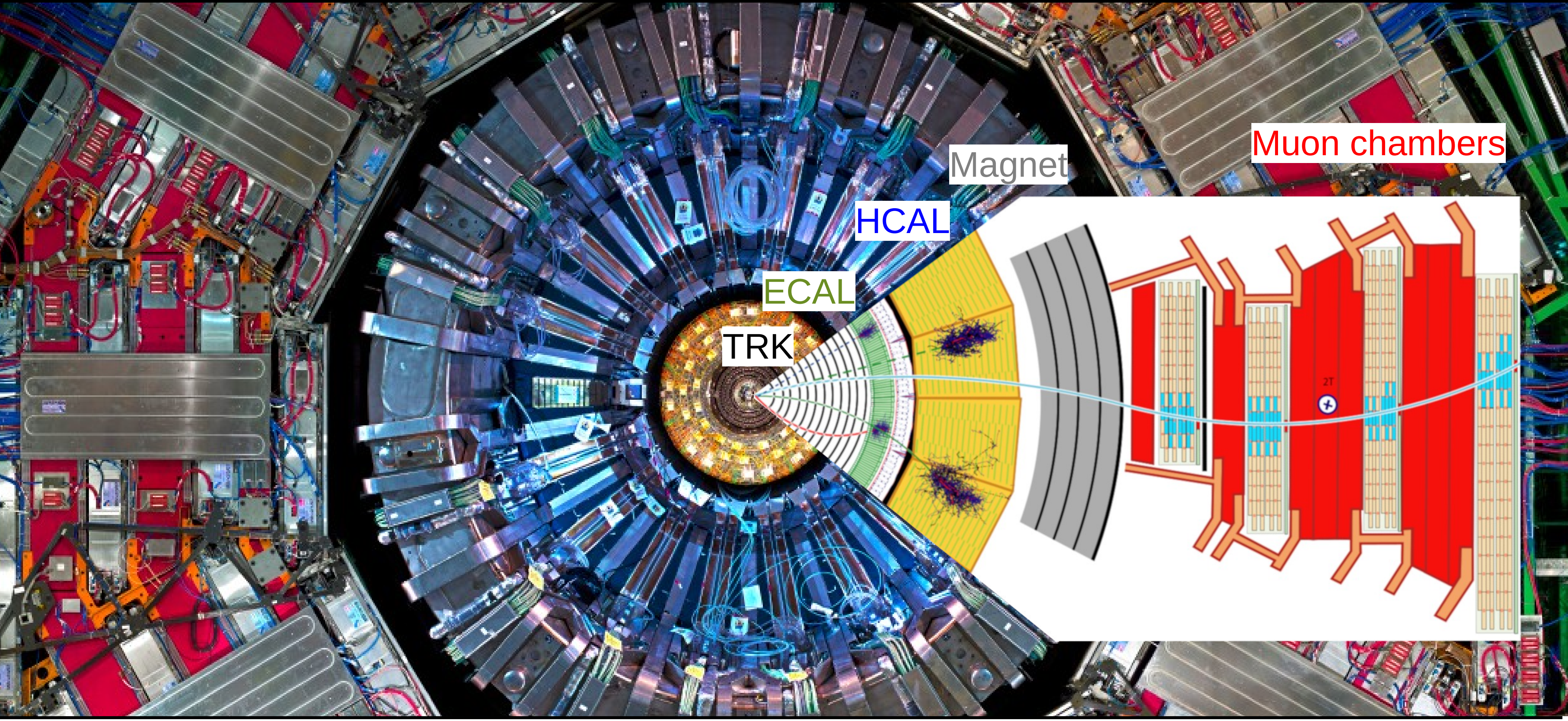


The CMS experiment

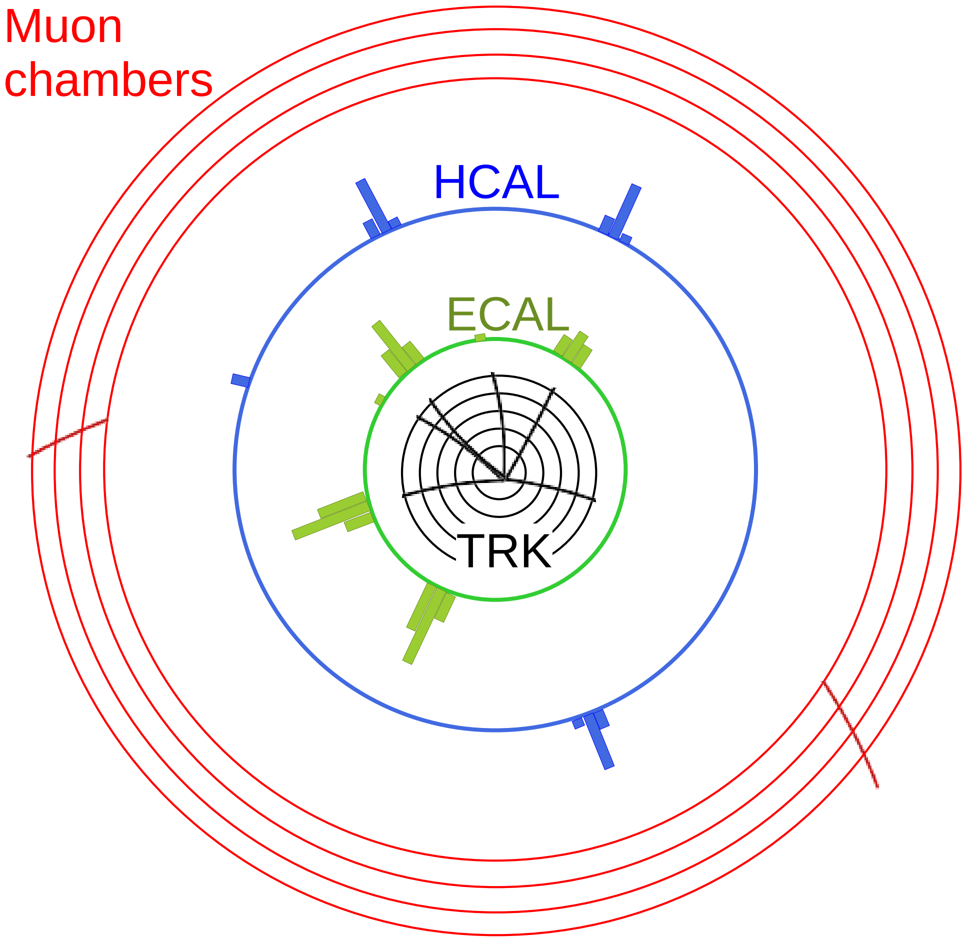


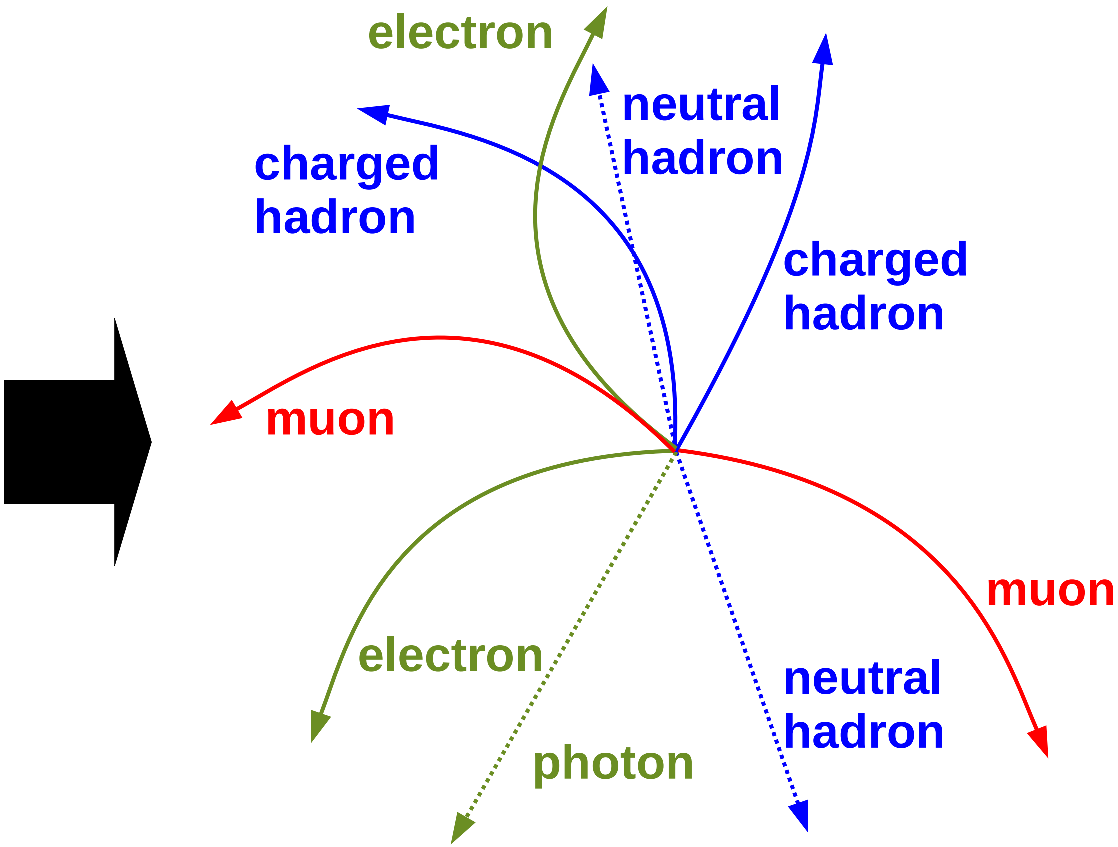
- Silicon tracker:
  - Pixel & Strip
- Electromagnetic calorimeter (ECAL)
  - $PbWO_4$ crystal
- Hadronic calorimeter (HCAL)
- Superconducting solenoid
  - B = 3.8T
- Muon chambers

The CMS experiment

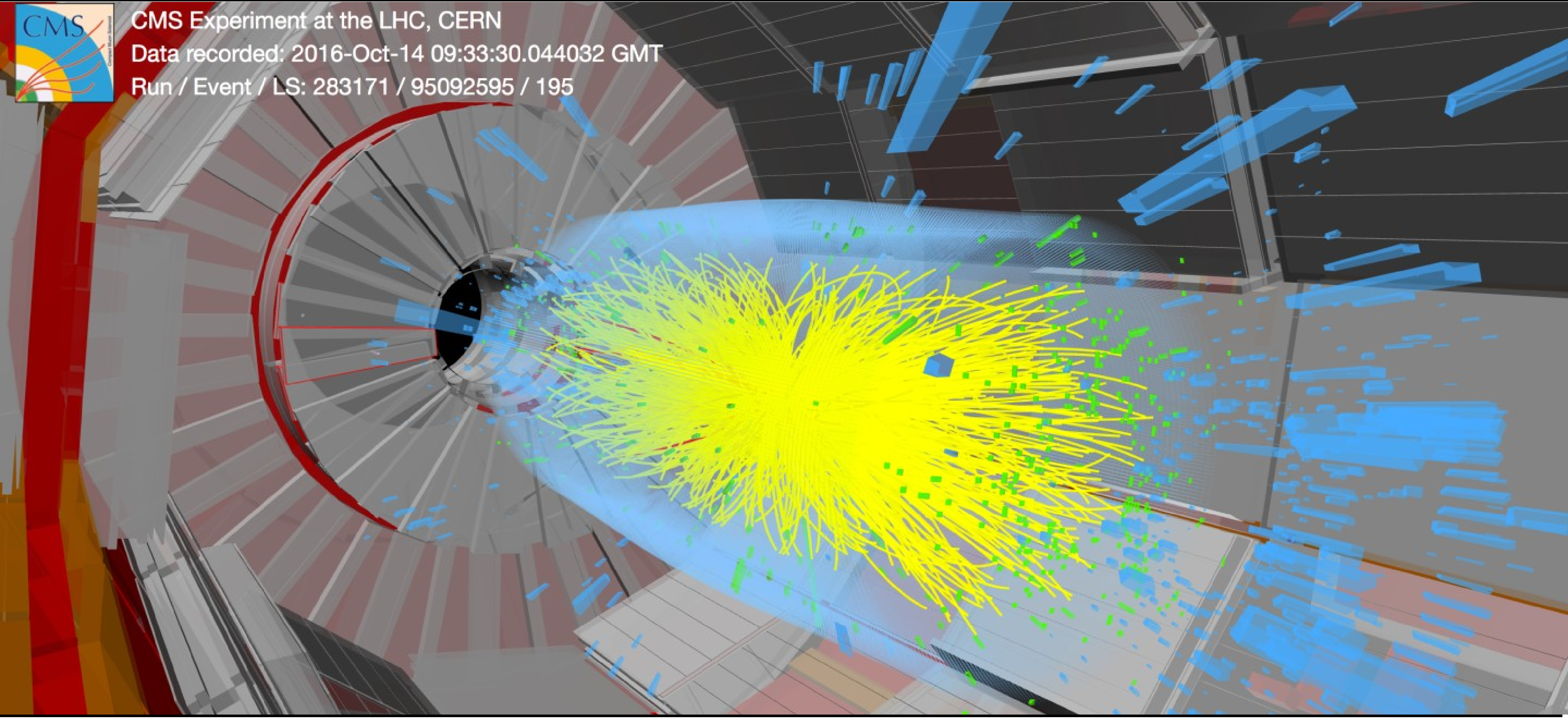


Particle Flow



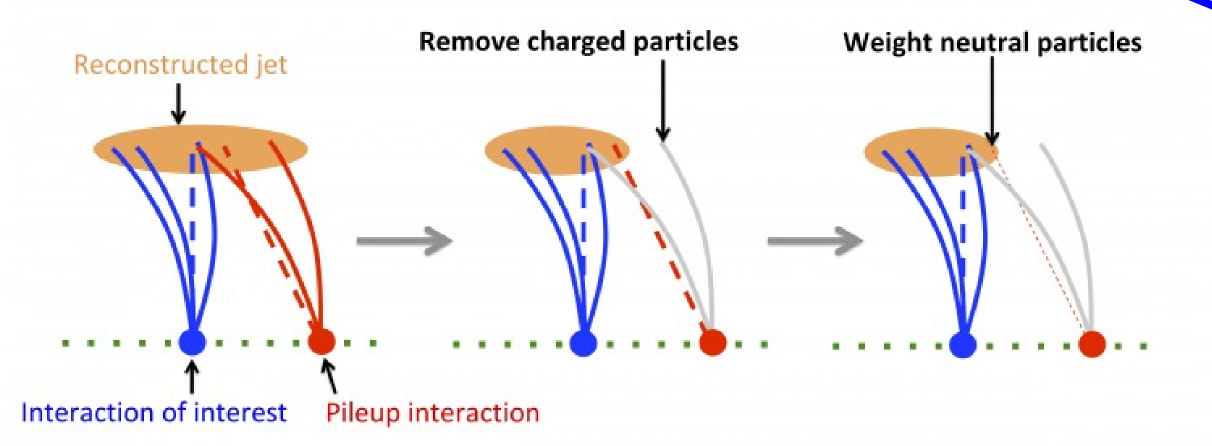


Pileup

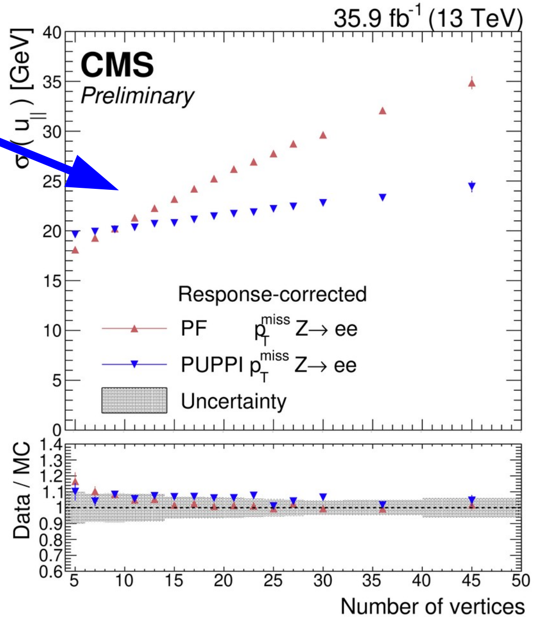

CMS Experiment at the LHC, CERN
Data recorded: 2016-Oct-14 09:33:30.044032 GMT
Run / Event / LS: 283171 / 95092595 / 195

Pileup

- Pileup mitigation:
  - Removal of charged particles originated from the pileup interaction;
  - Reduced weight for neutral particles which are “close” to the charged pileup particles (PUPPI).

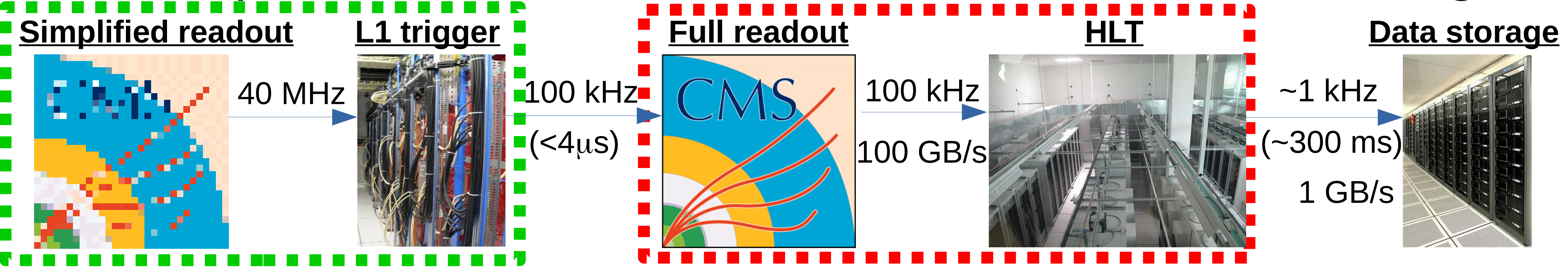


Missing transverse energy resolution



Trigger and data acquisition

- **Hardware** trigger (L1): 40 MHz → **100 kHz**
  - simplified readout (**no tracker**), small latency.
- **Software** trigger (HLT): 100 kHz → **~1 kHz**.
  - full event readout available (~1MB/event);
  - simplified reco: ~30k CPUs → 300ms/event **on average**.



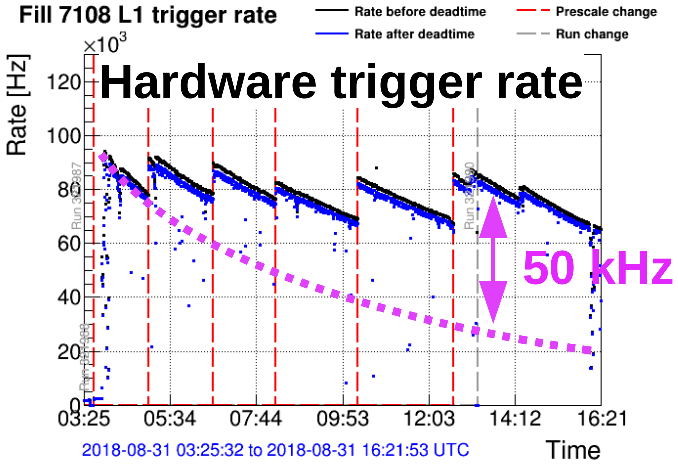
Unconventional data taking

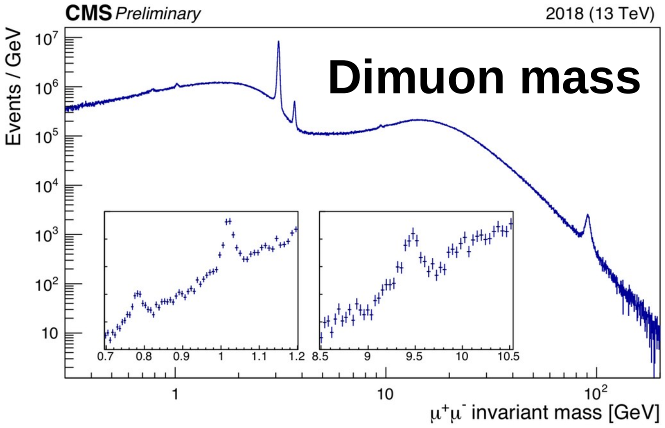
- Trigger limit at 1 kHz because of prompt offline **reconstruction** & available **space** on disk/tape.
- We go beyond the 1-kHz limit in two ways:
  - “data **parking**” → offline reconstruction is delayed.
  - “data **scouting**” → saving only the objects reco’d at trigger level
    - no offline reconstruction;
    - smaller event size (~1 MB → few kBs).

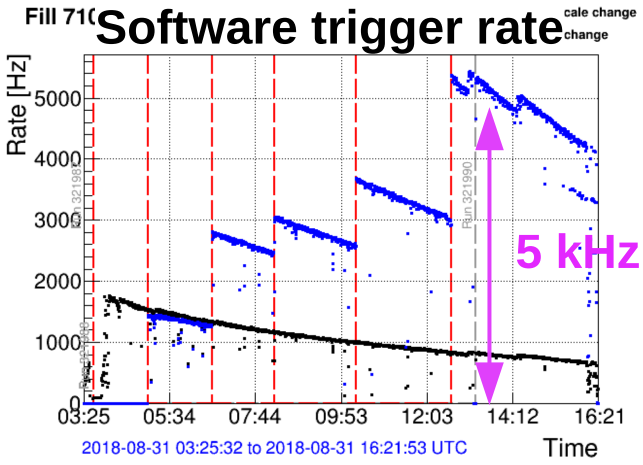
Trigger	Threshold sum jet p_T	Peak rate
“Normal” (offline reco)	> 1050 GeV	~ 10 Hz
Scouting (PF objects)	> 410 GeV	~800 Hz
Scouting (only jets)	> 250 GeV	~3000 Hz

Data parking

- In 2018, CMS collected **10 billions** of events with **unbiased B hadron** decays,
  - Triggered by the displaced muon from another B hadron decay.
- Data analyses are ongoing…





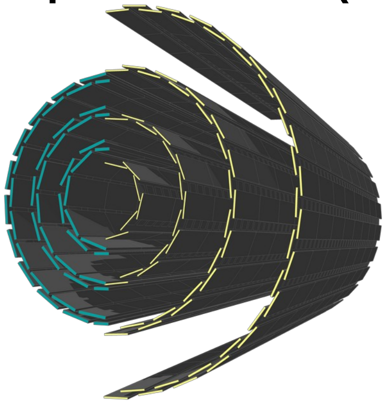


Run-3

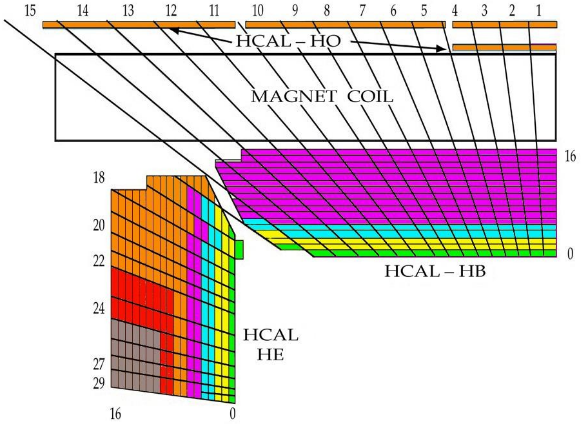
Upgrade for Run-3

- Several upgrades anticipated to 2017.
- Pixel detector:
  - replacement of the innermost layer (250 fb^{-1});
  - replacement of the DCDC converters.
- HCal: Hybrid photo diode → SiPM
  - lower noise, increase of the **longitudinal segmentation** (from 1 to 4 in the barrel)
- Installation of new muon detectors (gas electron multiplier (GEM)).

New pixel detector (2017)

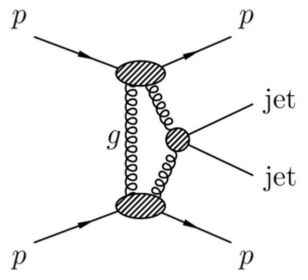


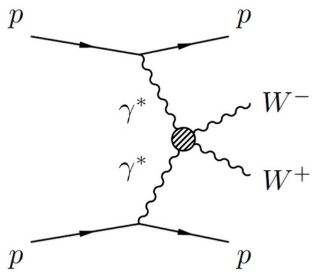
Higher granularity for HCal

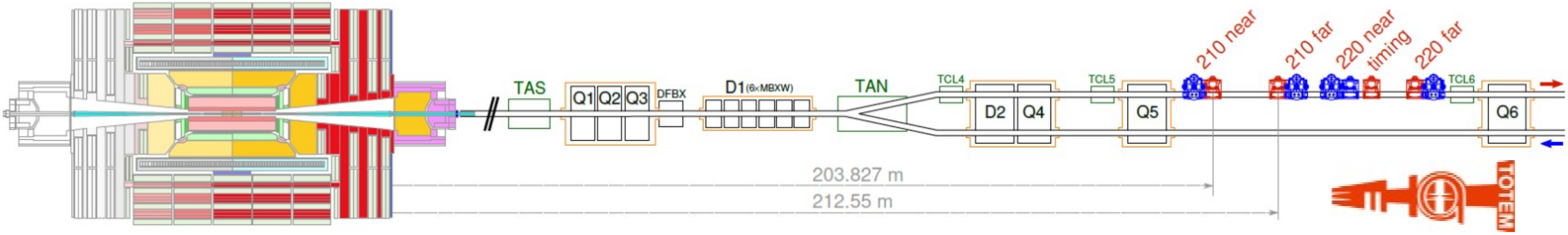


Precision Proton Spectrometer (PPS)

- TOTEM experiment integrated in CMS:
  - allows CMS to detect pp → X + pp (**intact protons**!),
    - longitudinal initial state momentum is known.
  - located ~200m from the interaction point;
  - LHC magnets used to measure the proton momentum;
  - very close to the beam line (~1 mm).

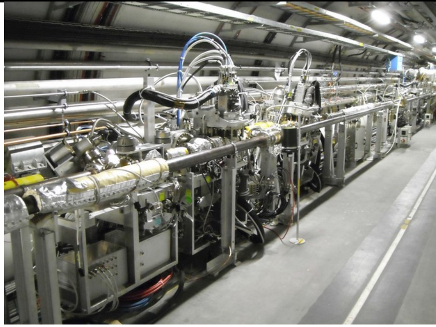


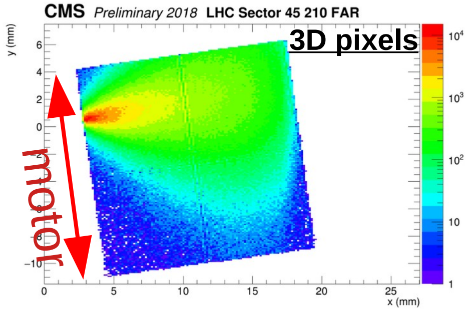


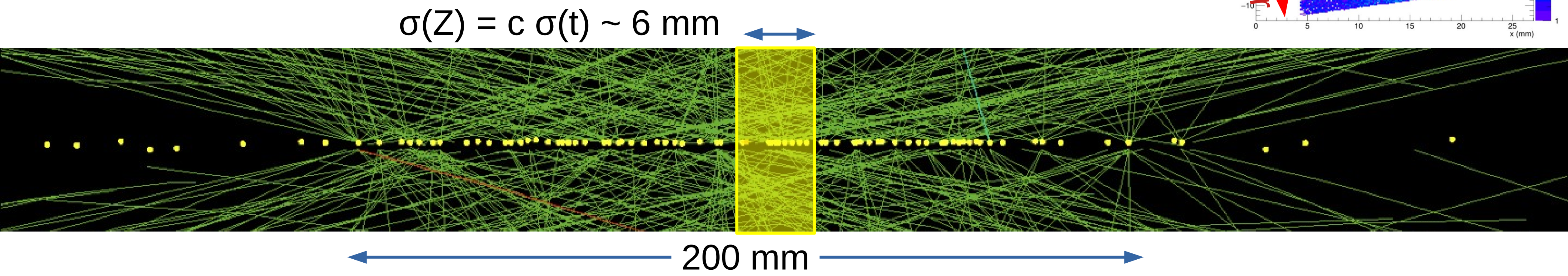


Precision Proton Spectrometer (PPS)

- **Tracking** detector (3D pixels) → proton momentum:
  - resolution goal: 10 – 30 μm,
  - step motor → reduction of radiation damage.
- **Timing** detector (diamond) → primary vertex position:
  - resolution goal: 20 – 30 ps.
- Fully ready in **Run-3**, partially tested in Run-2.

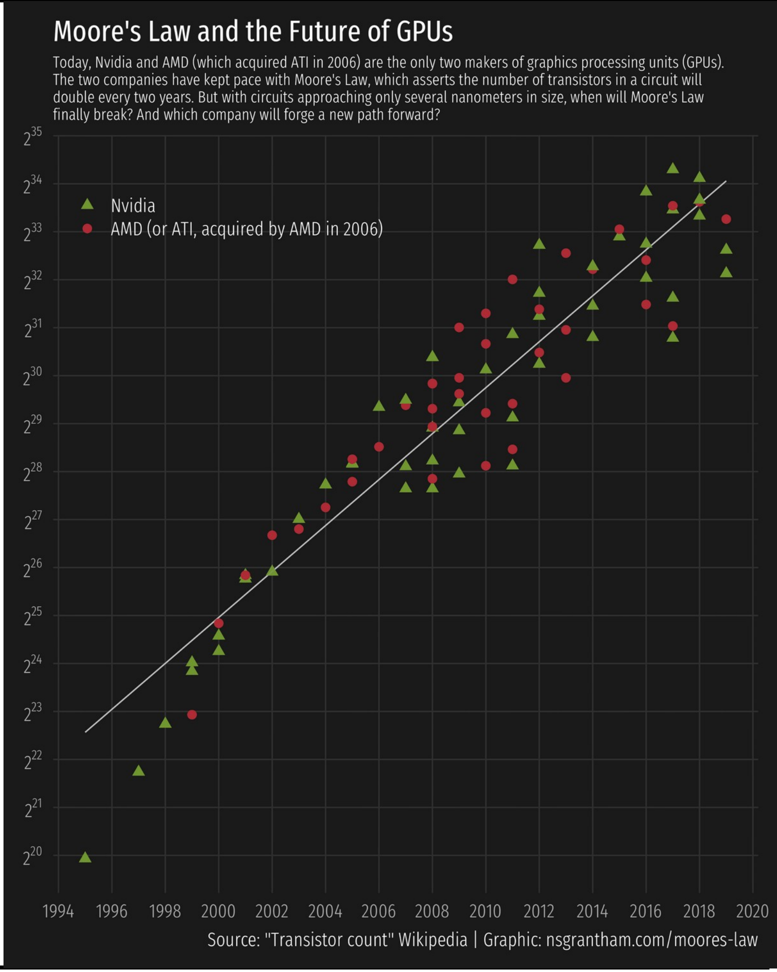






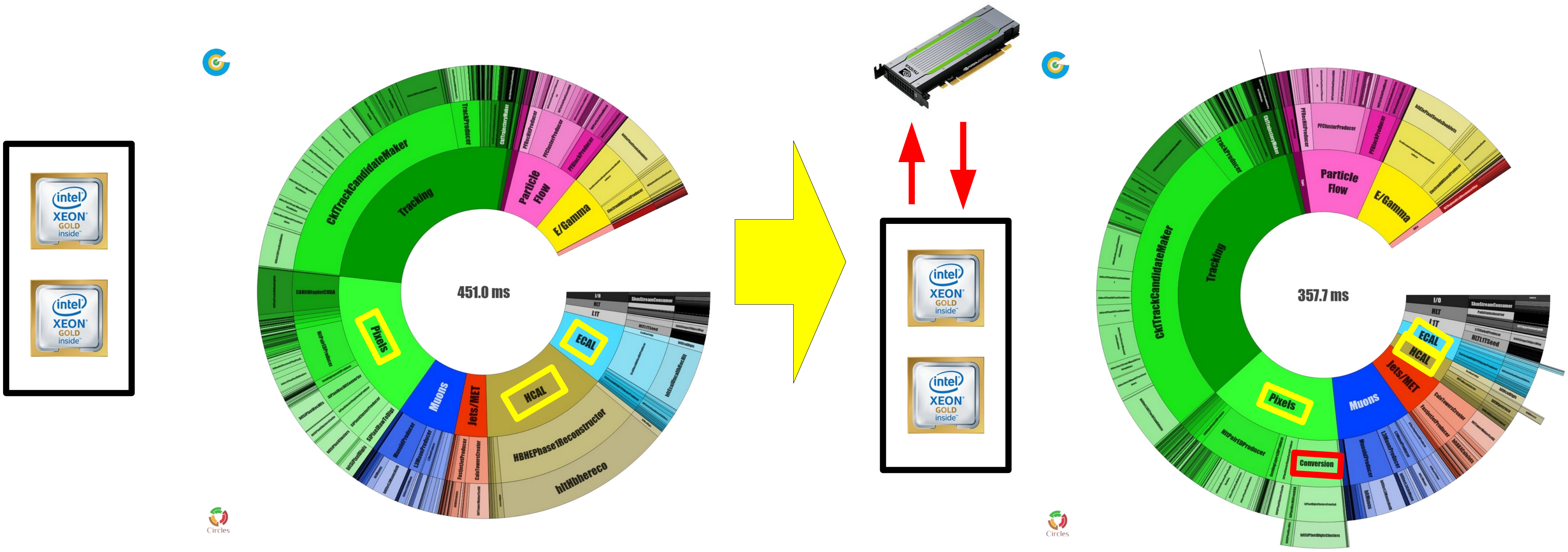
Graphics Processing Unit (GPU)

- **GPUs** very powerful in parallel computing,
  - exponential increase!
- Increasing usage in High Energy Physics
  - especially for Machine Learning.
- CMS will use GPUs in the trigger software starting from Run 3.
- Big effort in porting Pixel, HCAL, ECAL code on GPU (CUDA);
  - first step towards an **heterogeneous** era.



Software trigger and GPU

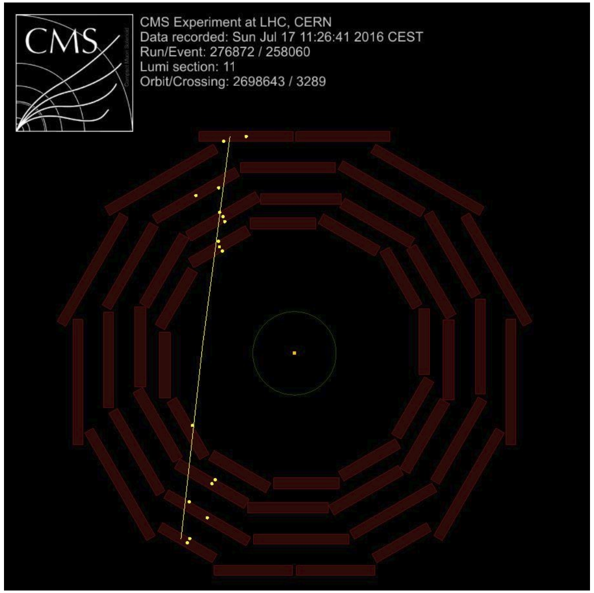
CPU only **CPU + GPU**



CPU: 2x Intel Skylake Gold 6130 with HT enabled (16 processes)
GPU: NVIDIA T4

Run-3 data taking

- The Run-3 luminosity will be similar to Run-2.
- The improvements (detectors, trigger, reconstruction, new ideas …) will allow to look for new physics in new ways.
  - Brainstorming ongoing (eg. GPU+scouting, new parking, ...)
- Search for new signatures:
  - Example: long-lived particles.



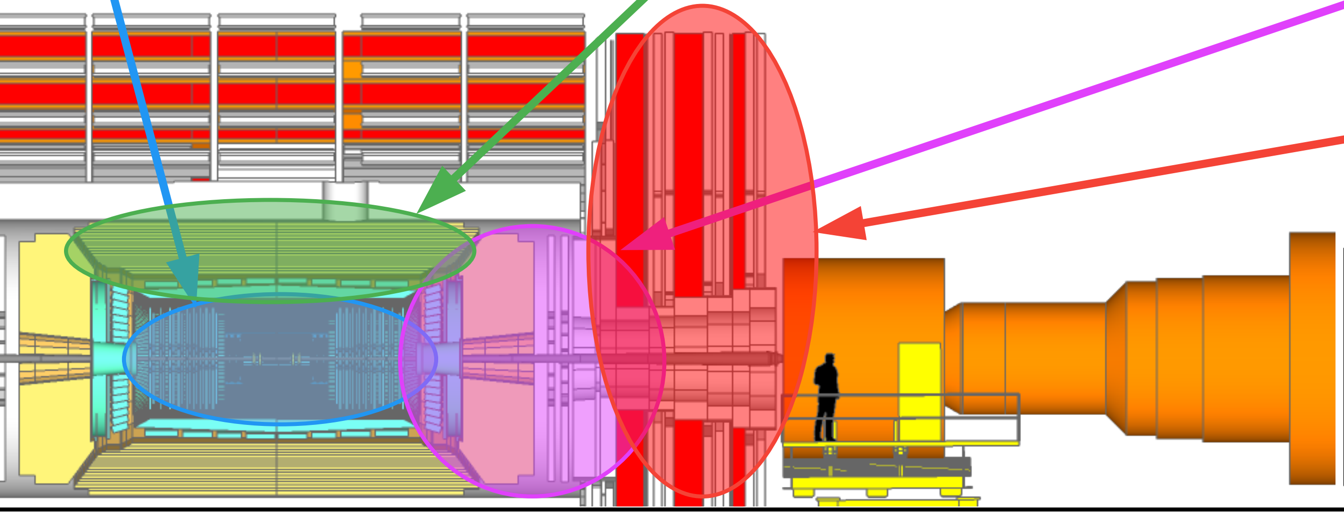
Upgrade for
High Luminosity LHC

Upgrade for HL LHC

New silicon tracker
Extended coverage |η|<3.8.
Track trigger at 40 MHz.
Reduced material budget.
Increased granularity.

Barrel calorimeter
ECAL crystal granularity readout at 40 MHz.
Precision timing for e/γ at 30 GeV for vertex localization ($H \rightarrow \gamma\gamma$).
ECAL and HCAL new Back-End boards.

New endcap calorimeter
(high-granularity calorimeter)
3D showers imaging for pattern recognition
Precision timing for PU mitigation
Si, Scint+SiPM in Pb/W-SS

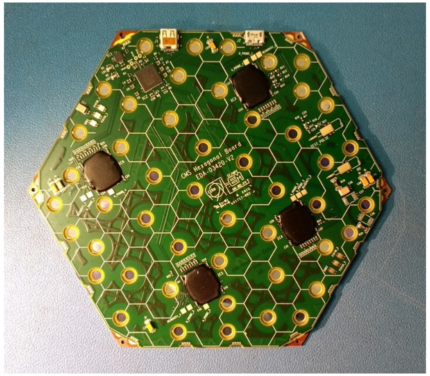


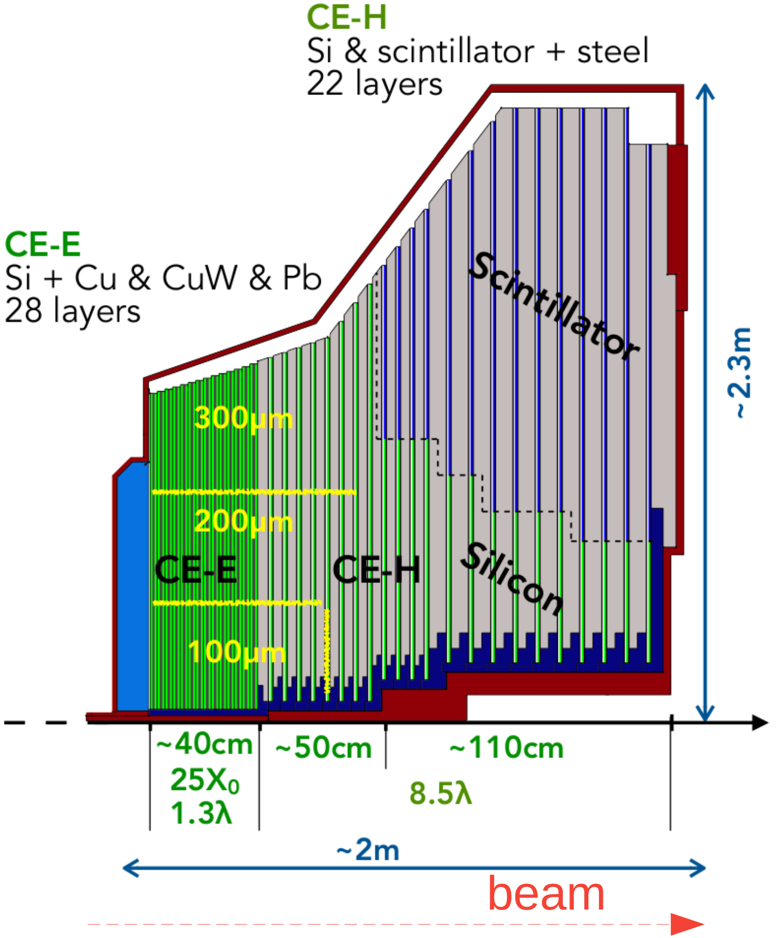
Muon chambers
Extended coverage to |η|<3
New readout
New detectors (GEM)

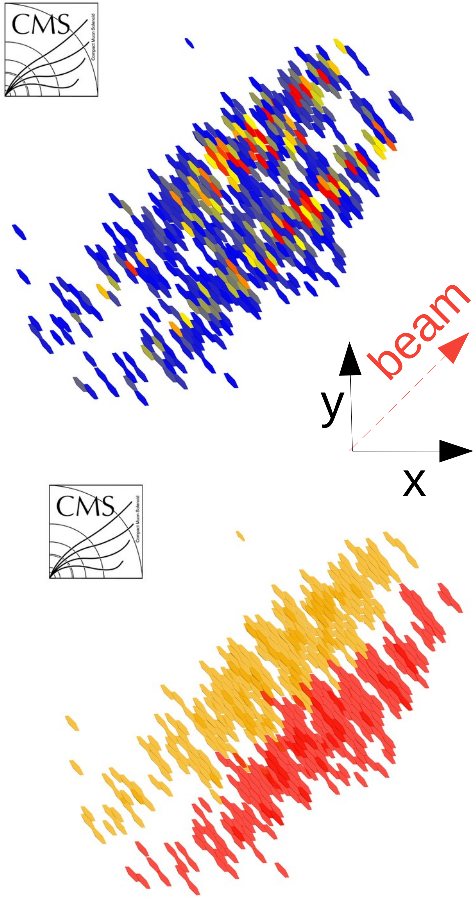
New MIP Timing Detector
Precision timing for PU mitigation
Barrel: LYSO crystals + SiPMs
Endcap : Low Gain Aval. Diodes

Endcap calorimeter

- **Acceptance:**
  $1.5<|\eta|<3.0$.
- **Sensors:**
  620 m² silicon + 400 m² scint.
- **Channels:**
  6M silicon + 400k scintillator.





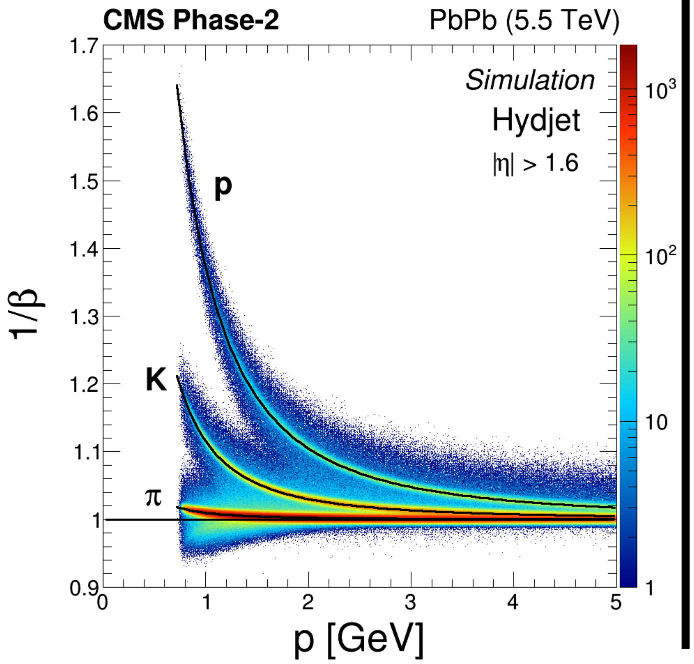


MIP Timing Detector

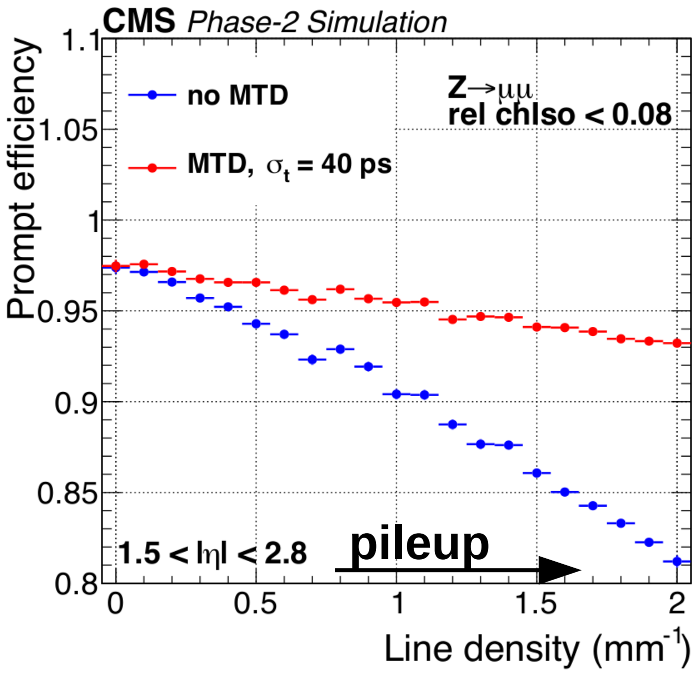
Particle identification:
pion vs kaon up to ~3 GeV

4D tracking: better performance, better vertexing, search for new physics signature

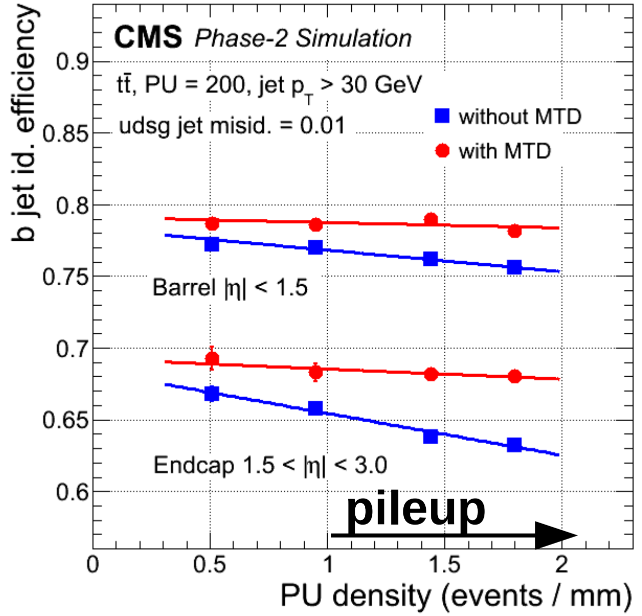
Arrival time vs momentum



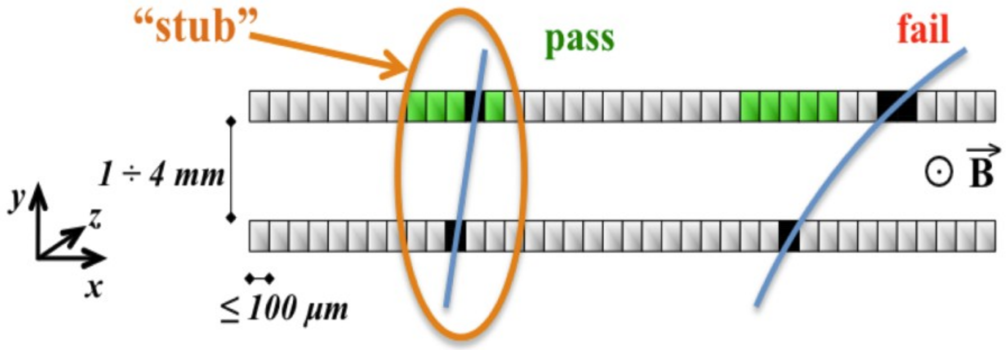
Muon iso efficiency vs pileup

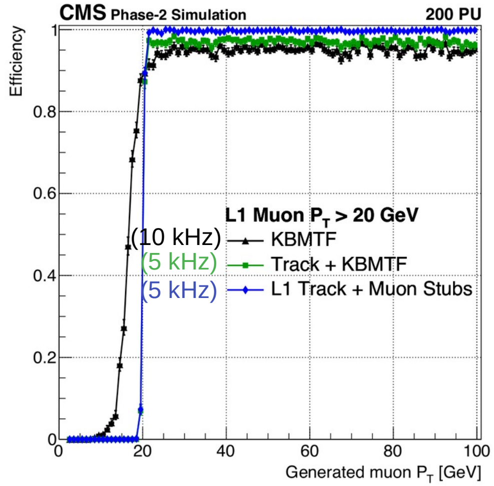


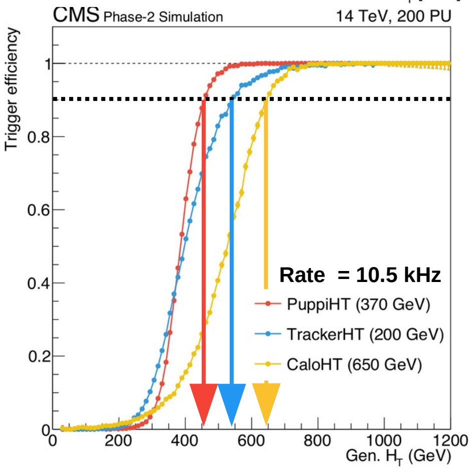
B-tag efficiency vs pileup



Trigger

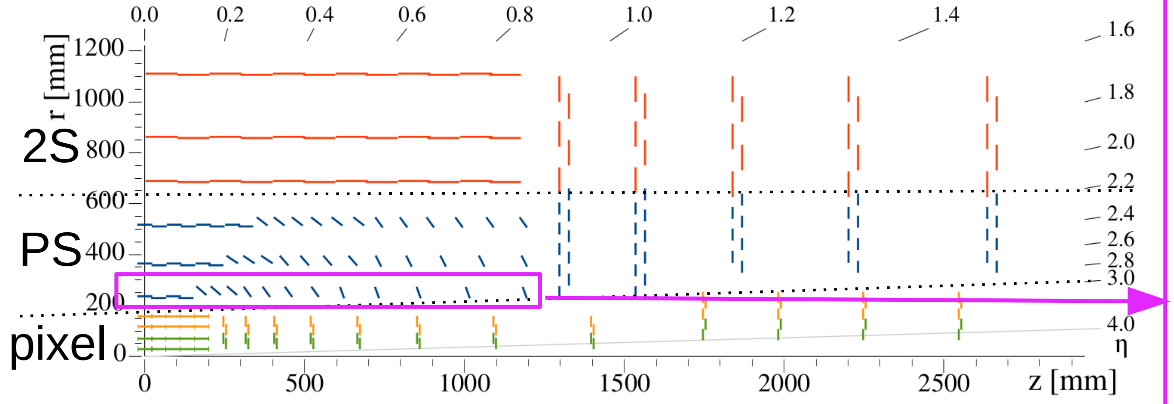


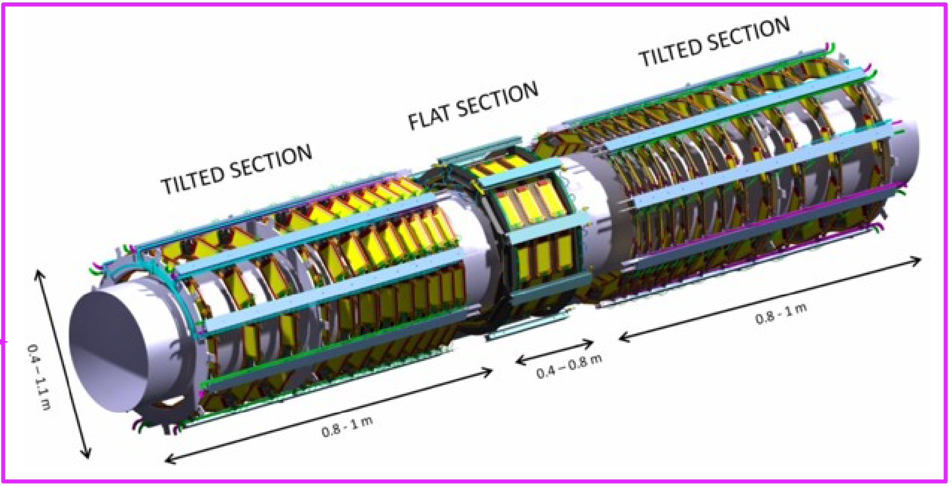




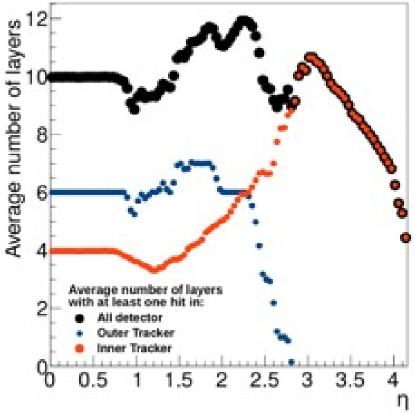
- Hardware trigger rate: **750 kHz**
  - Tracks from the outer tracker,
  - Particle Flow and PUPPI,
  - Scouting at 40 MHz!
- Software trigger rate: **7.5 kHz**

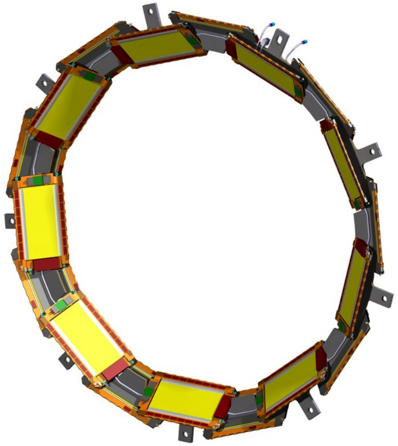
Tracker





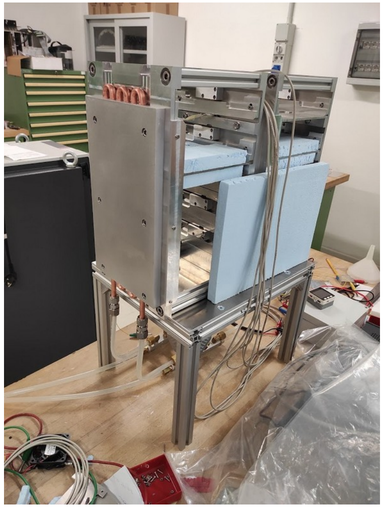
- Three modules:
  - Pixel (25×100 μm² or 50×50 μm²)
  - Pixel-Strip (PS, 1.5 mm × 100 μm)
  - Strip-Strip (2S, 5 cm × 90 μm)
- $C0_2$ cooling system: −35C.

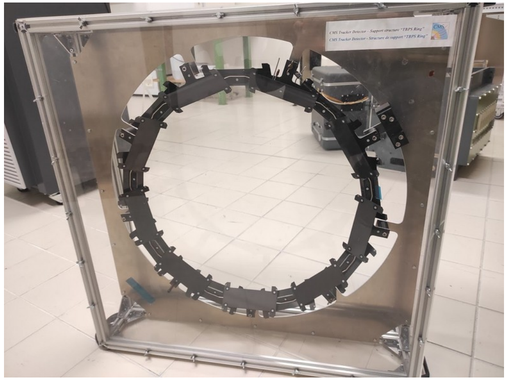


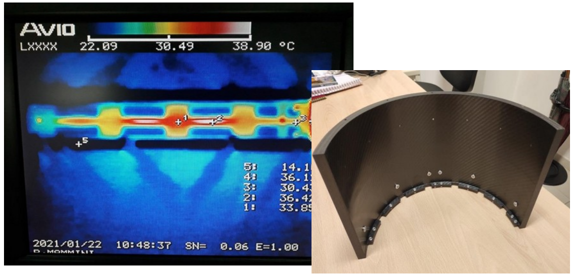


Tracker activities in Pisa

- Outer tracker (PS modules):
  - Study about thermal contact between modules and CO_2.
  - Module burn-in at -35C.
  - Integration of the PS modules in the wheels.
  - Production and test the boards for DAQ & trigger.
- Inner tracker:
  - Mechanical design.
  - 3D sensor studies.







Conclusions

- Many physics results based on **Run-2** data are in progress (eg. using B parking dataset).
- Important improvements are expected in **Run 3** (upgrades, PPS, GPU, new ideas…)
  - on top of the larger integrated luminosity ($190fb^{-1} \rightarrow 350fb^{-1}$).
- Many big upgrades are expected for **HighLumi-LHC**:
  - New detectors, new reconstruction (eg. timing detector)
  - Big jump in integrated luminosity ($350b^{-1} \rightarrow \sim 4000fb^{-1}$).
- Important contribution of **Pisa** to the Tracker upgrade.