The upgrades and future plans of the CMS experiment at the Large Hadron Collider

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for the CMS Collaboration
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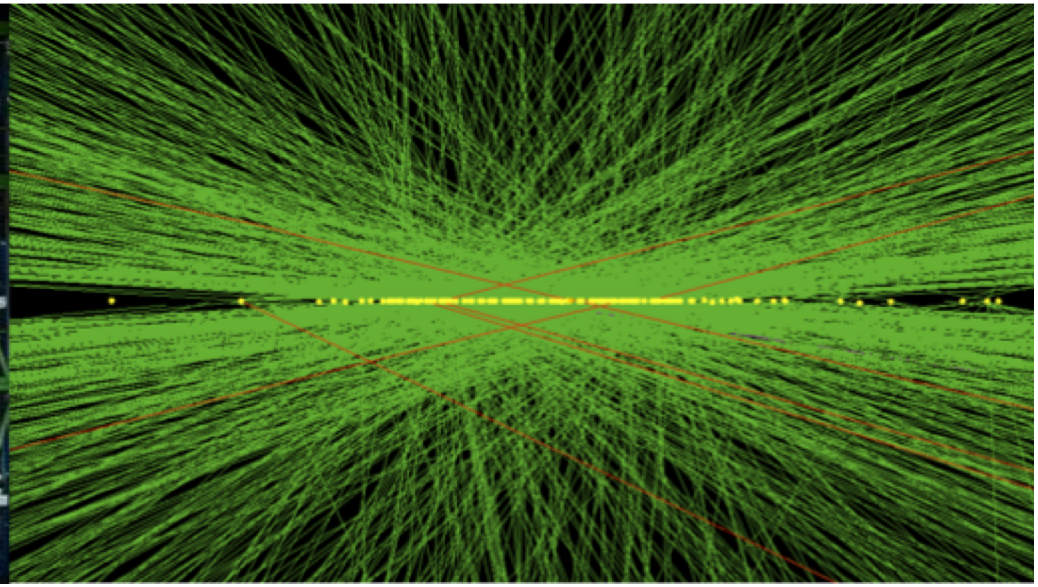
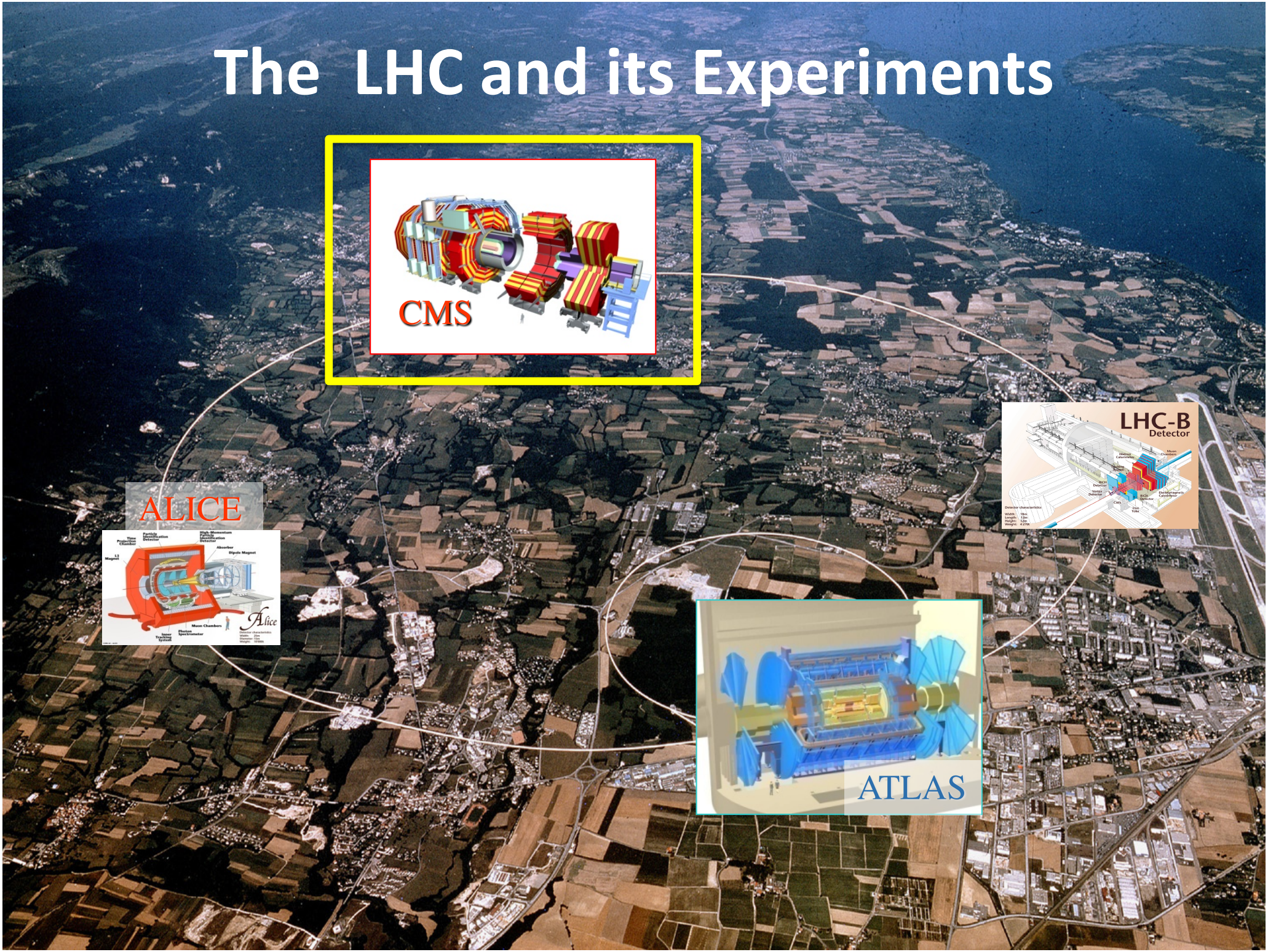


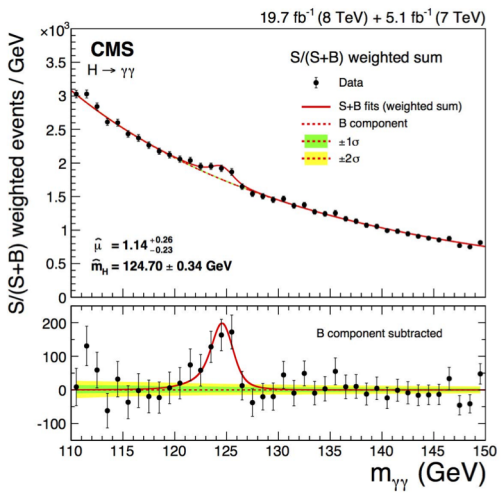
The LHC and its Experiments



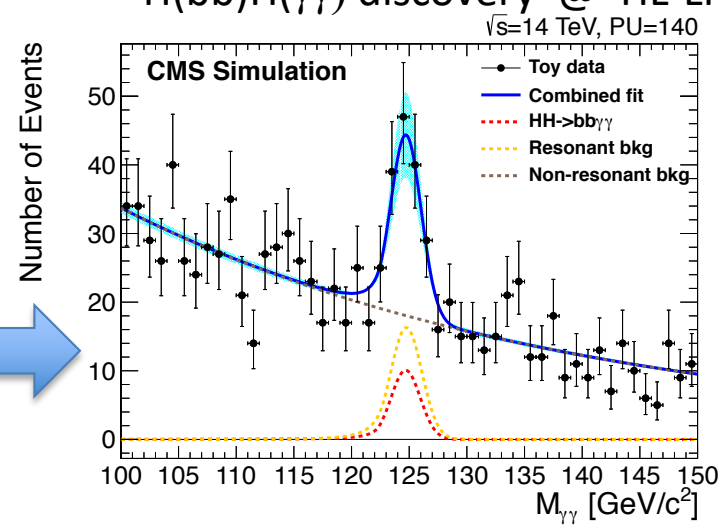
Motivations for a higher Luminosity LHC

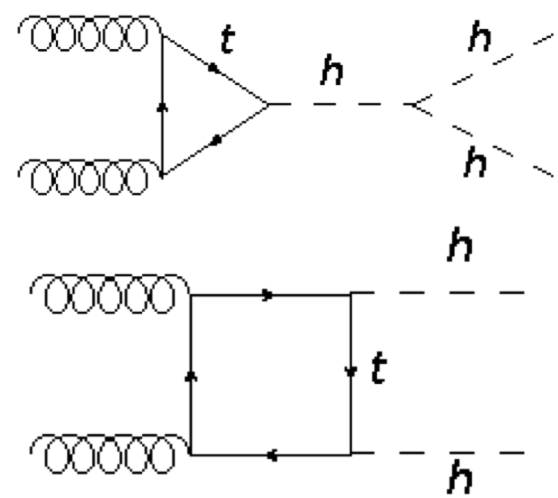
- O(1%) precision on SM Higgs couplings
- Extending reach of BSM searches (e.g Dark Matter candidates)
- Rare Higgs Decays (e.g H→μμ) and production (e.g. HH)

H→γγ discovery in Run1



H(bb)H(γγ) discovery @ HL-LHC





The High-Luminosity (or phase 2) LHC is an approved project

The Higher Luminosity LHC

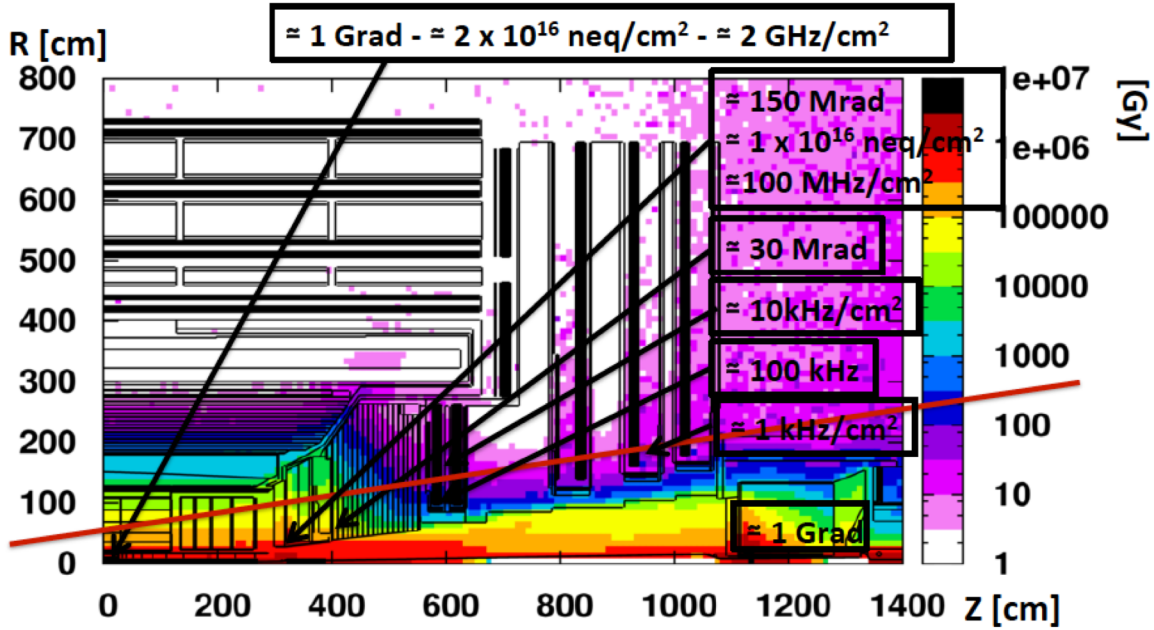
- Improved injection system
- Improved focusing in interaction region

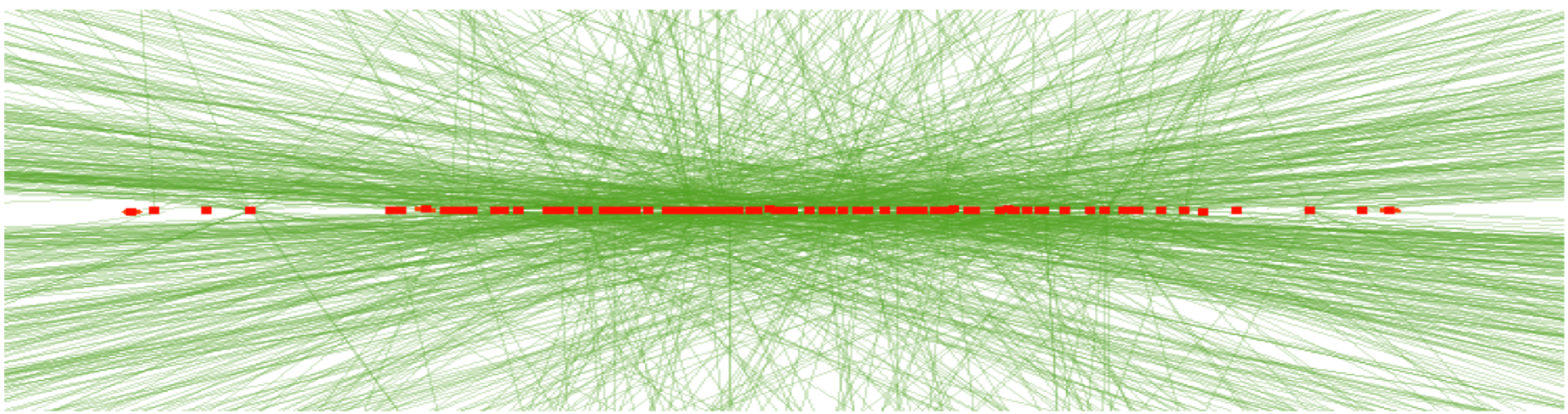
The HL-LHC will produce as many Higgs Bosons in one year as the LHC in 10 years

	Instantaneous Luminosity ($cm^{-2} s^{-1}$	Integrated luminosity fb^{-1}
LHC (2010-2023)	0 to 2 x 10^{34}	300
HL-LHC (2036-2036)	5 to 7.5 x 10^{34}	3000 to 4000

Challenges of the CMS Upgrade

- High Luminosity means
  - Many collisions (Pileup) (140 to 200 per event)
  - High irradiation (up to 1 GigaRad in forward region or close to collision point)

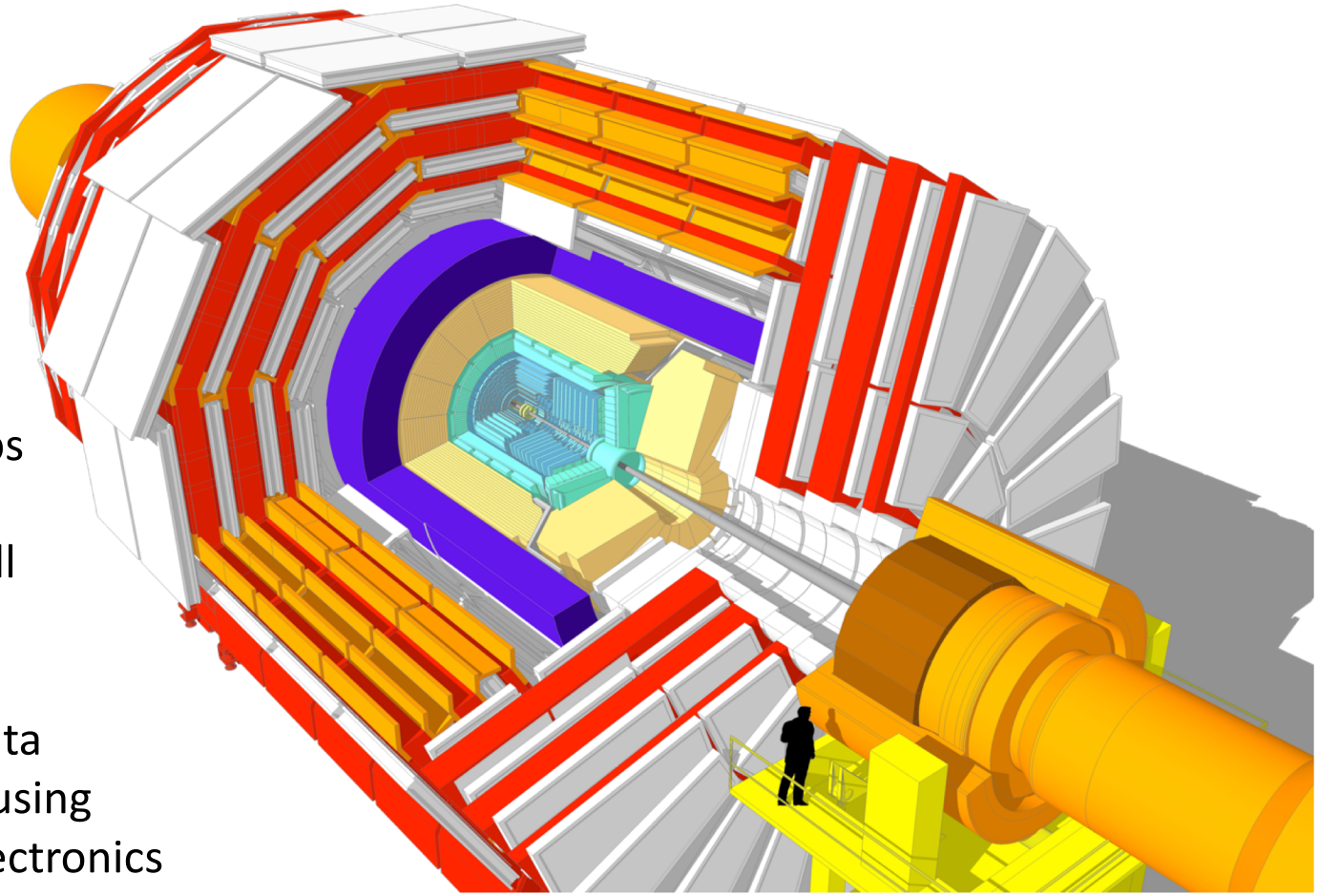




A top pair event with 140 collisions

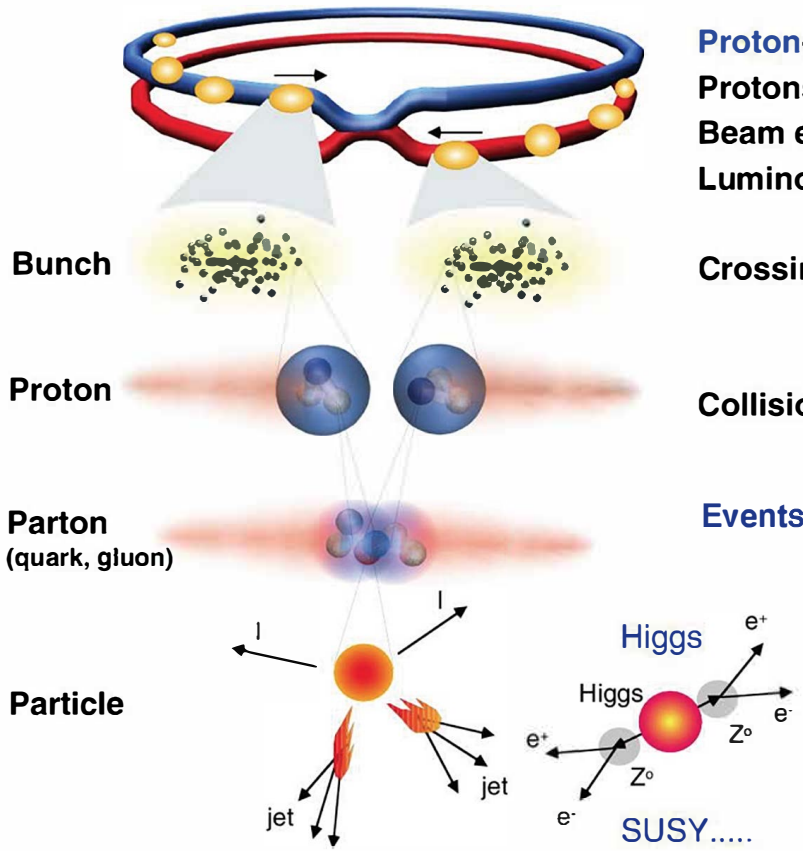
Strategies to Deal with the Challenges

- **Increased use of silicon sensors** (high radiation tolerance)
- **More granularity in the silicon** to deal with the high pileup
- **Precision timing** (< 50ps resolution) to separate collisions in time as well as space
- **Faster processing** of data in real time for trigger using modern high speed electronics



Essentially try to maintain or improve the legacy LHC performance in HL-LHC conditions

Triggering



Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	$5 \times 10^{34} cm^{-2} s^{-1}$
Crossing rate	40 MHz
Collisions ≈	10^{8} - 10^{10} Hz

Events written to disk at 7500Hz

Selection of 1 in 10,000,000,000,000

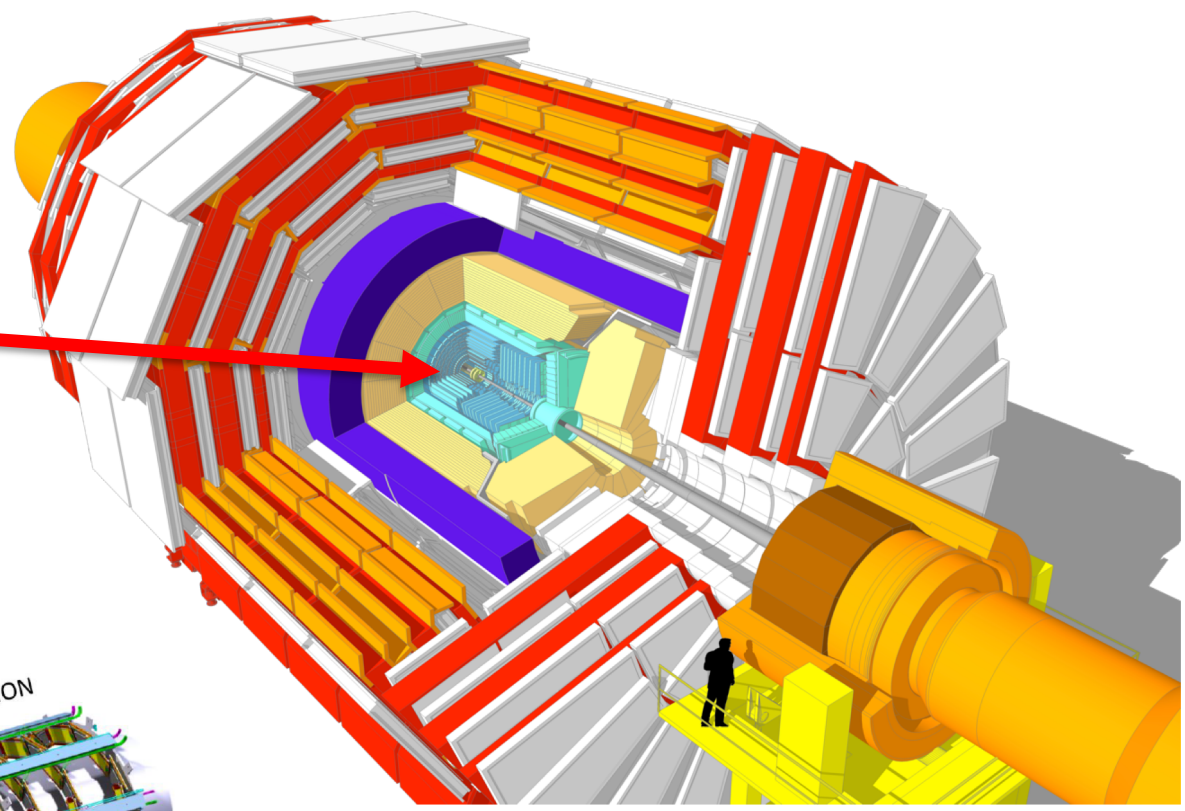
More that 99.99 % of events are discarded in real time by the level1 hardware trigger

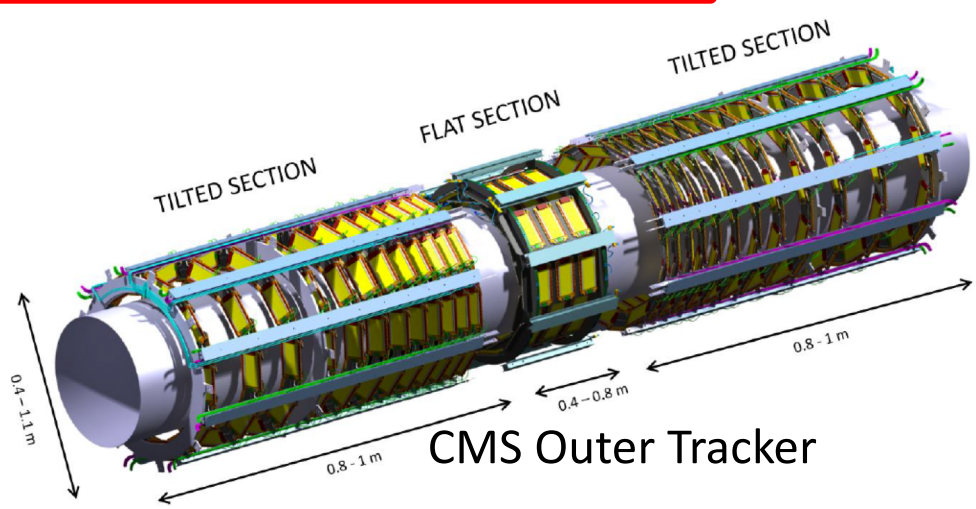
Processing must be done in 12.5µS and reduce rate from 10 GHz to 1 MHz

Silicon Tracker Upgrade

All New Silicon Tracker

- More granular
- Lighter (less material)
- Extended coverage to η=3.8
- Tracking included in L1 Trigger for the first time





CMS Outer Tracker

Inner plus Outer Tracker

Hermetic Silicon Coverage to $\eta = 3.8$

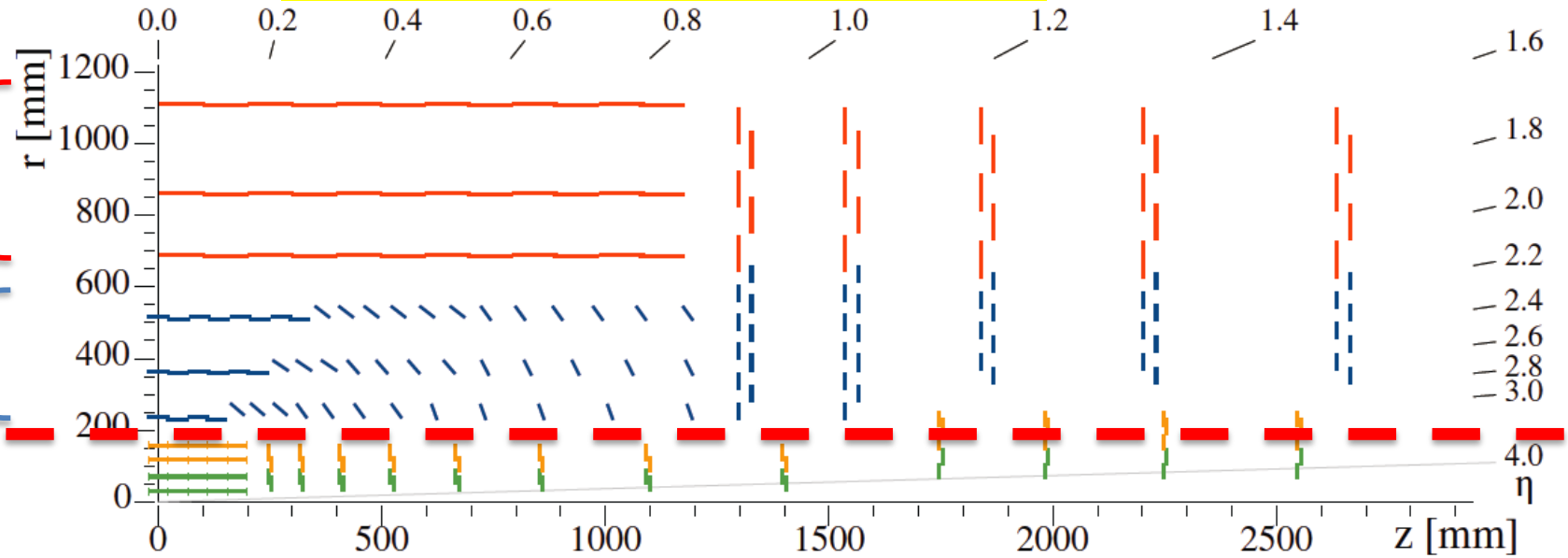
Outer Tracker

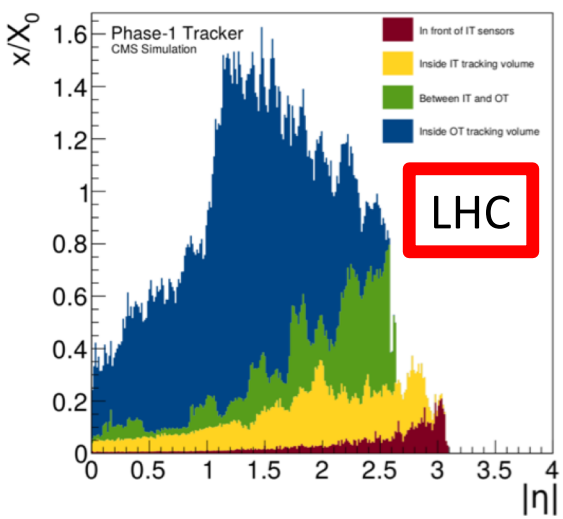
strip-strip (2S)

pixel-strip (PS)

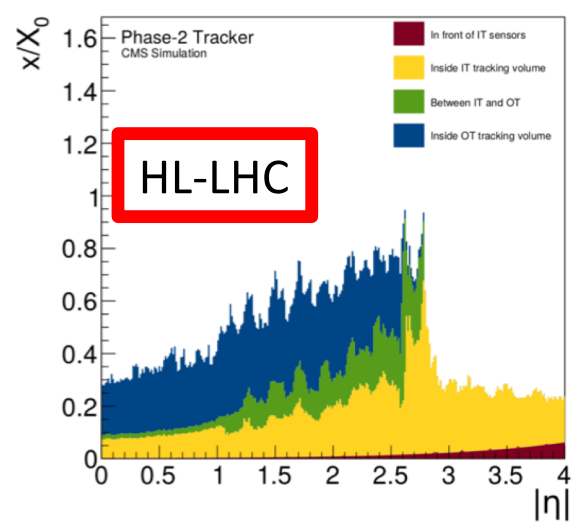
Inner Tracker

All Pixel



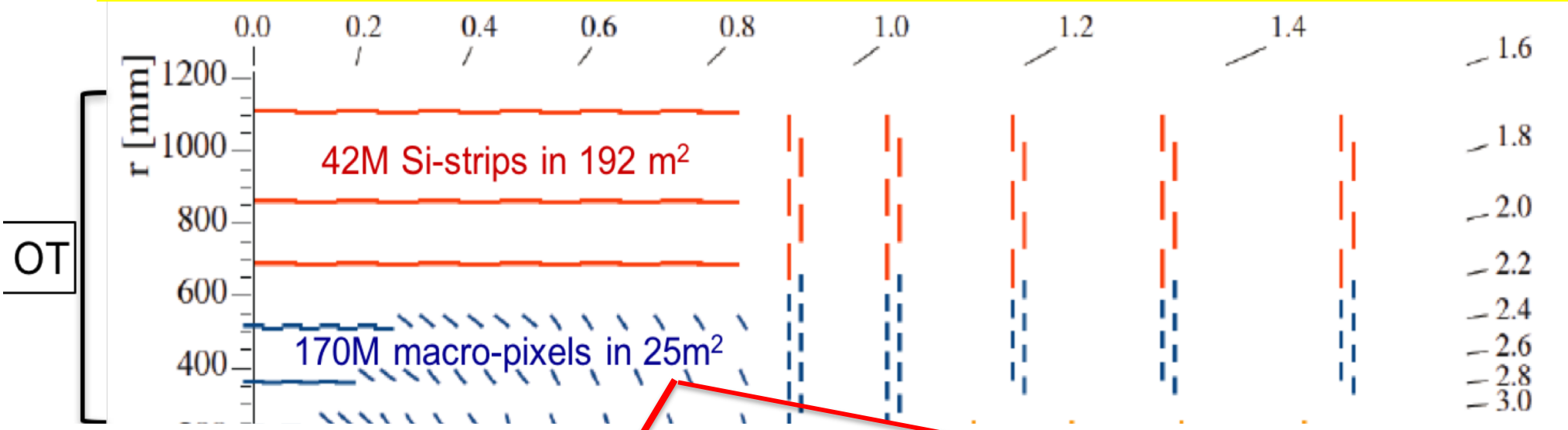


Significant reduction in tracker Material improves performance of tracker and calorimeters



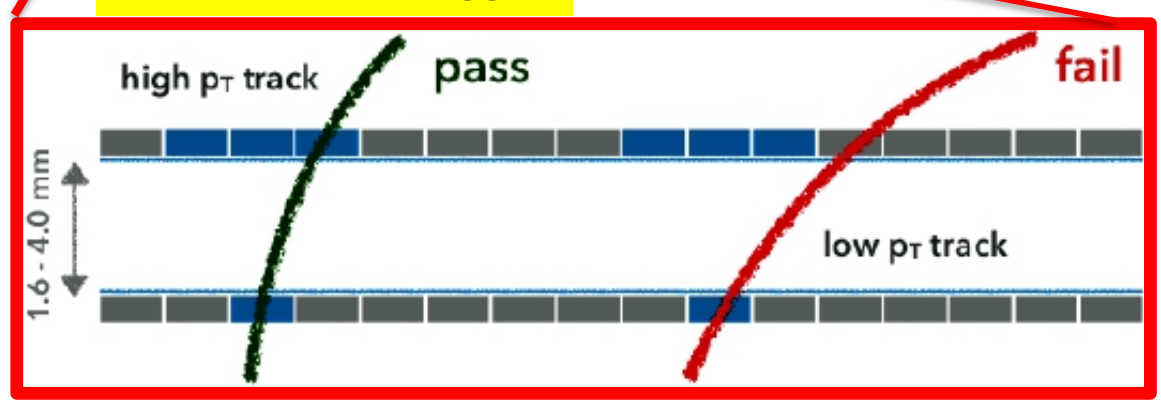
Outer Tracker – Track Trigger

OT Si-sensors ≃ 200µm thick - 90/100µm pitch - 2.5/5cm strips - 1.5 mm macro-pixels in inner layers



- Two layer track stubs remove low P_T tracks in trigger (<2GeV)
- Tilted modules to maintain geometric acceptance for stubs
- Track trigger reduces data rate by x 10

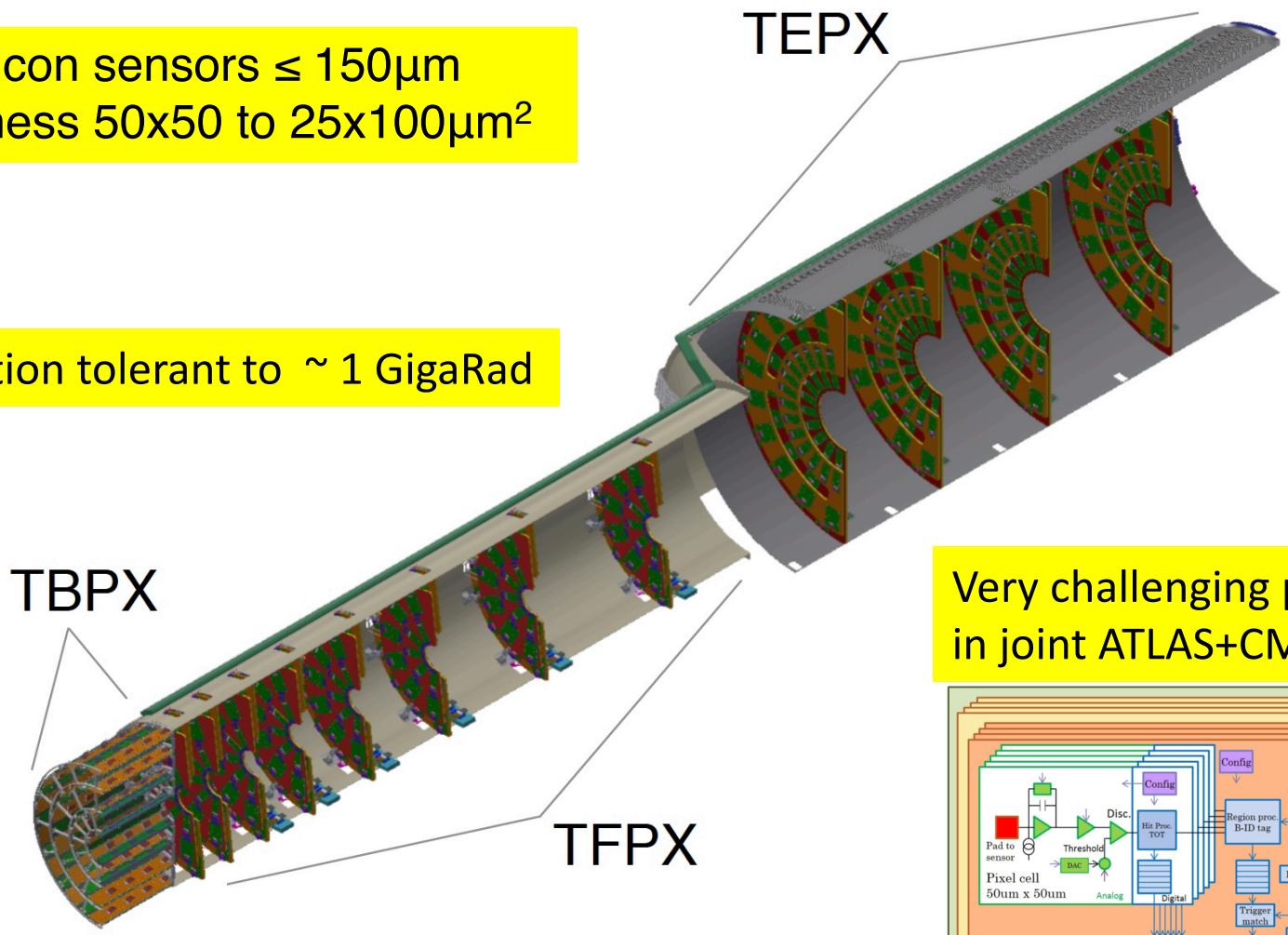
Track stubs in trigger



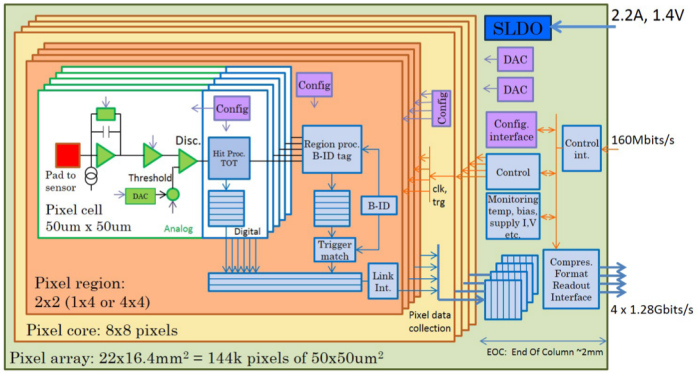
Inner Tracker (Pixels)

Si-Silicon sensors ≤ 150µm thickness 50x50 to 25x100µm^2

Radiation tolerant to ~ 1 GigaRad

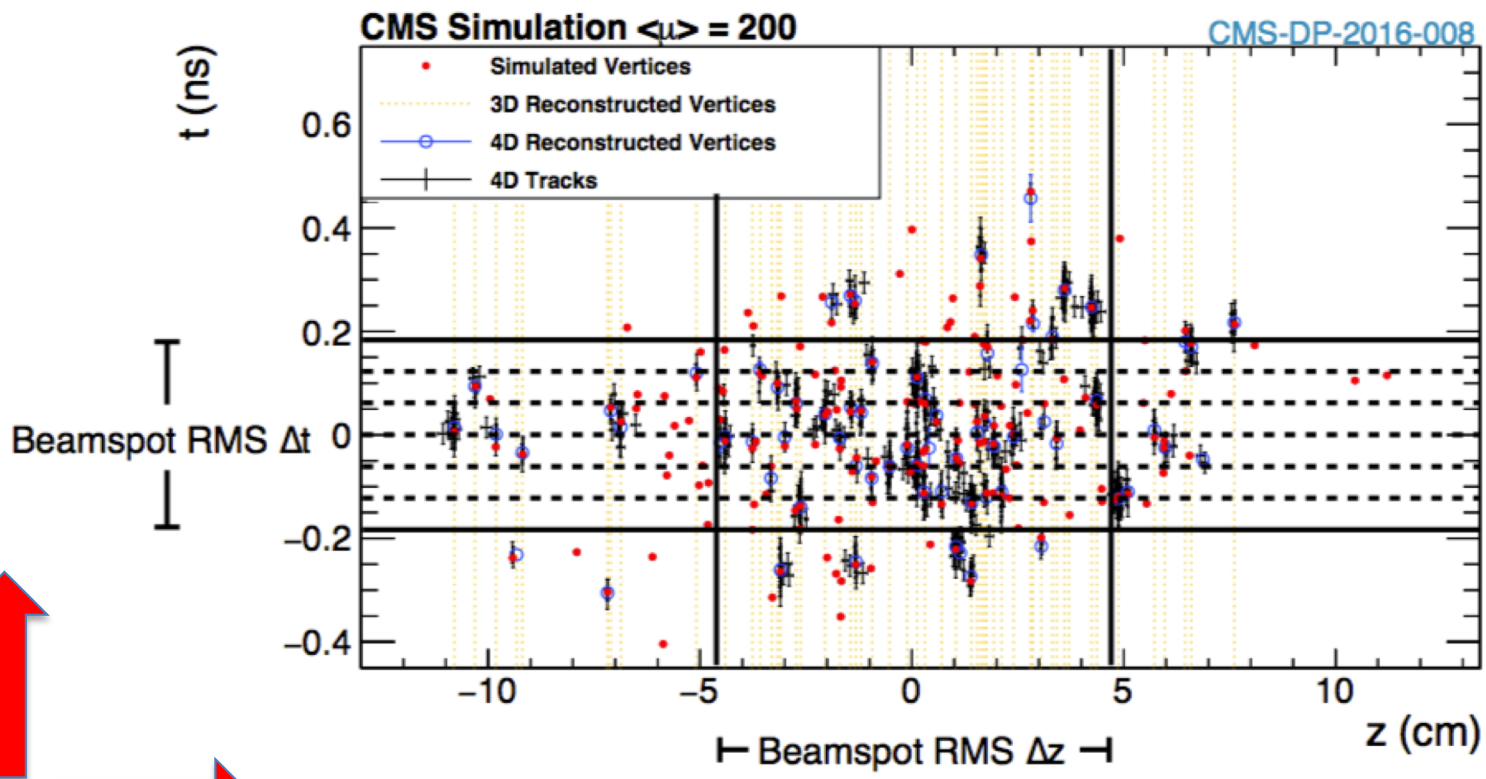


Very challenging pixel readout chip in joint ATLAS+CMS development



Precision Timing

Collision Vertices in the CMS interaction region with 200 Pileup



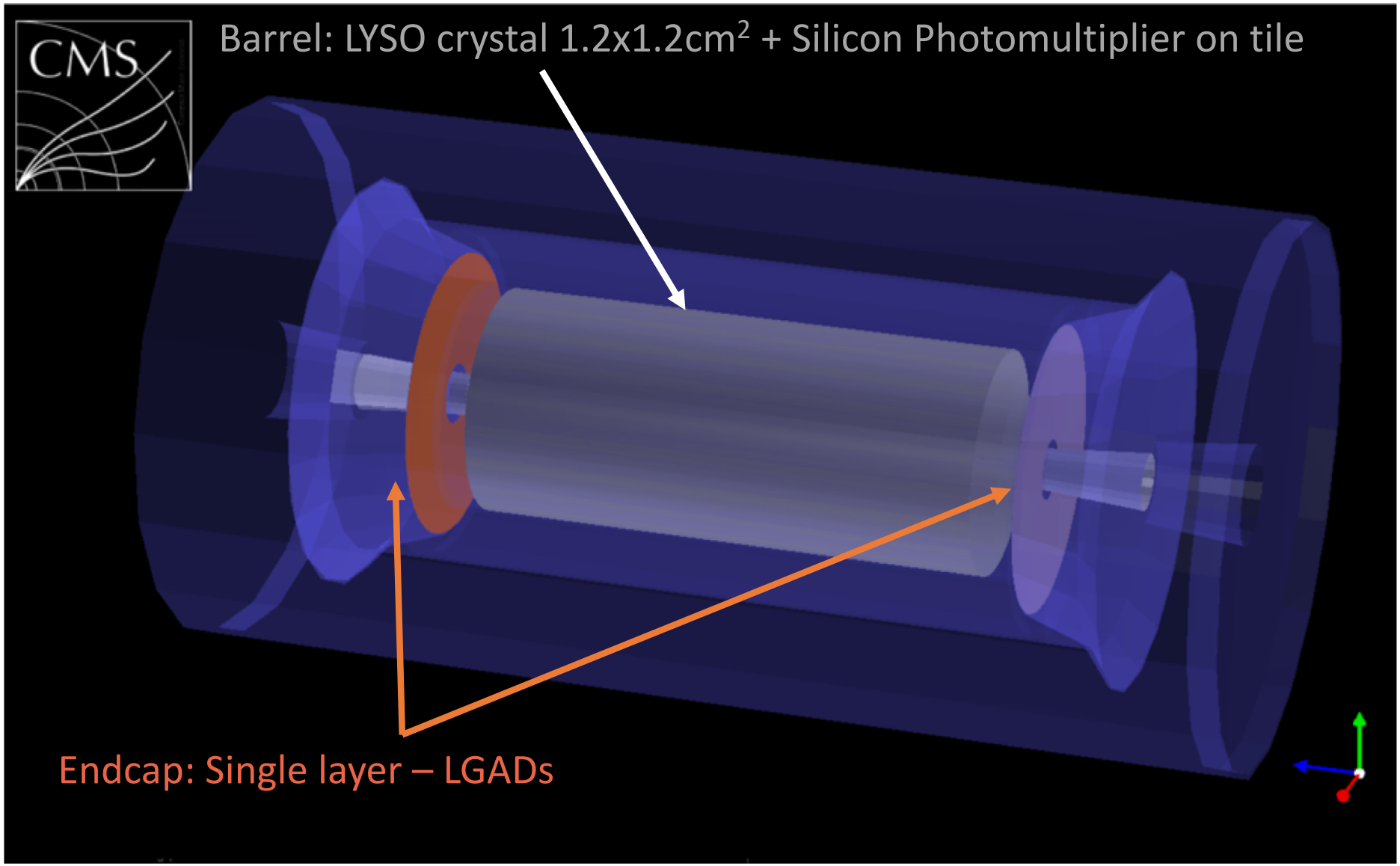
Time

Space

Precision timing with 30-50ps resolution allows separation of pileup

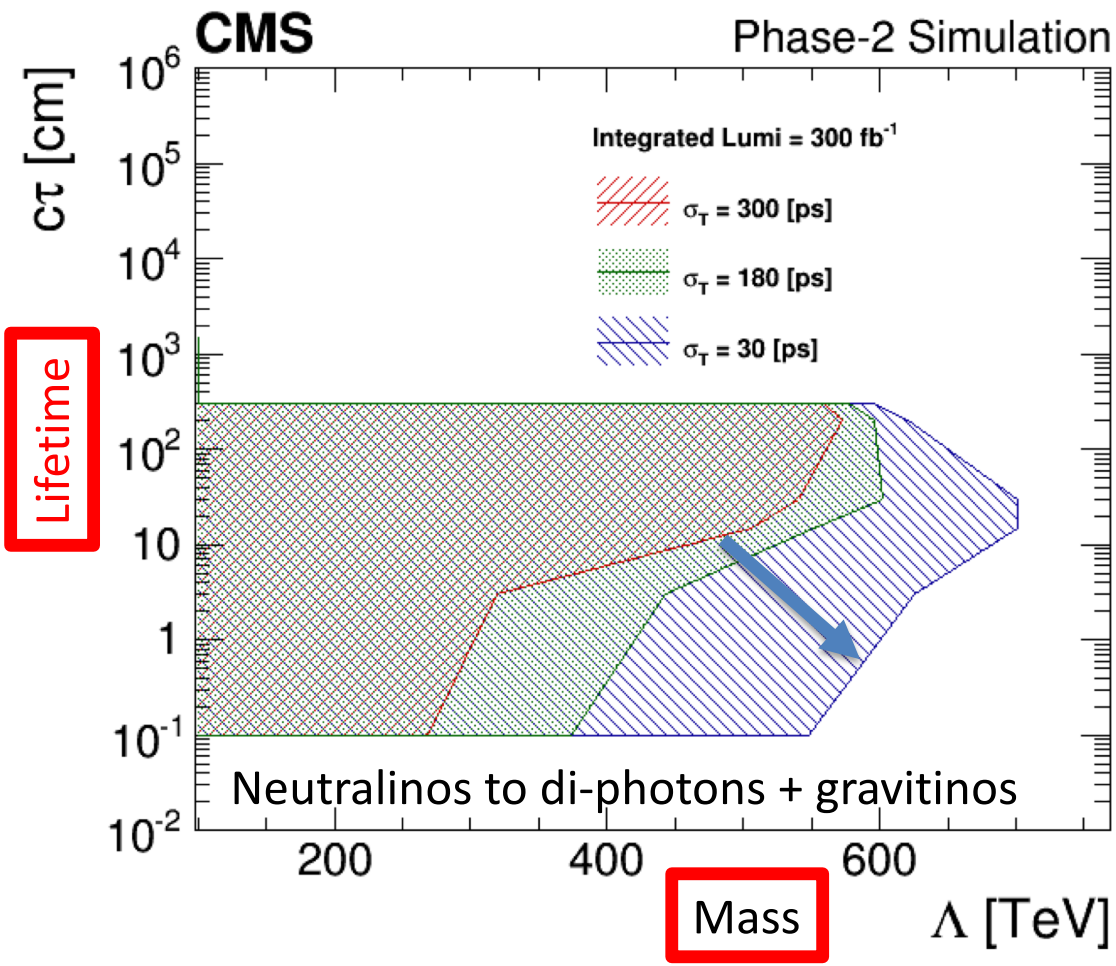
Requires dedicated timing layer for tracks and modification of readout for Barrel Calorimeter

Precision Timing Layer



Precision Timing Benefits

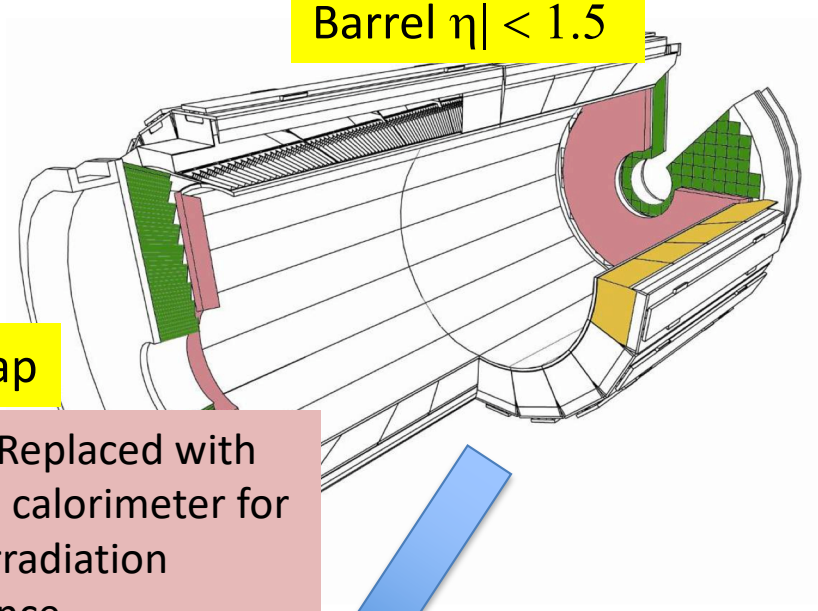
Long lived particle search sensitivity



- Pileup Mitigation
- Effective luminosity gain of O(20%) for some Higgs measurements
- Significantly enhances discovery potential for massive long lived particles (measure decay time)

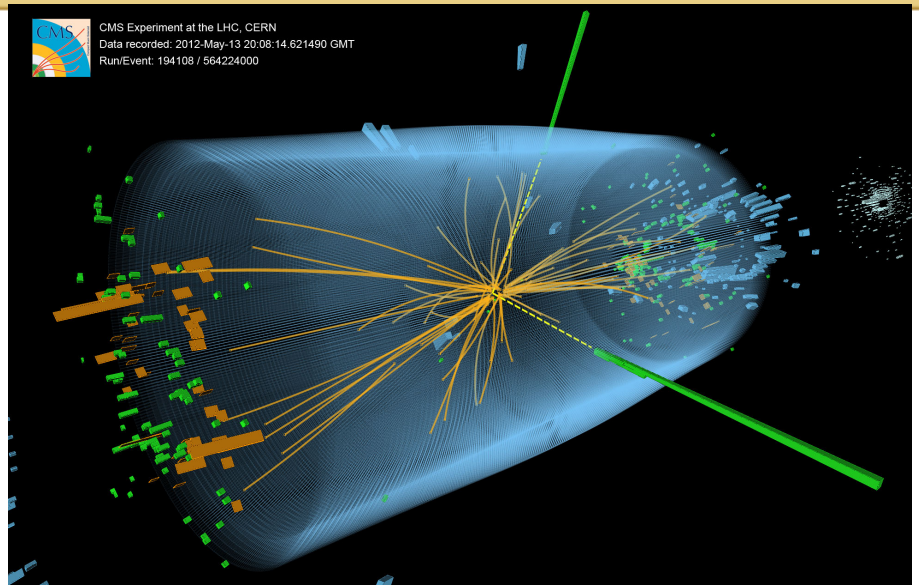
The CMS Calorimeter: Electromagnetic + Hadronic

Barrel $\eta| < 1.5$



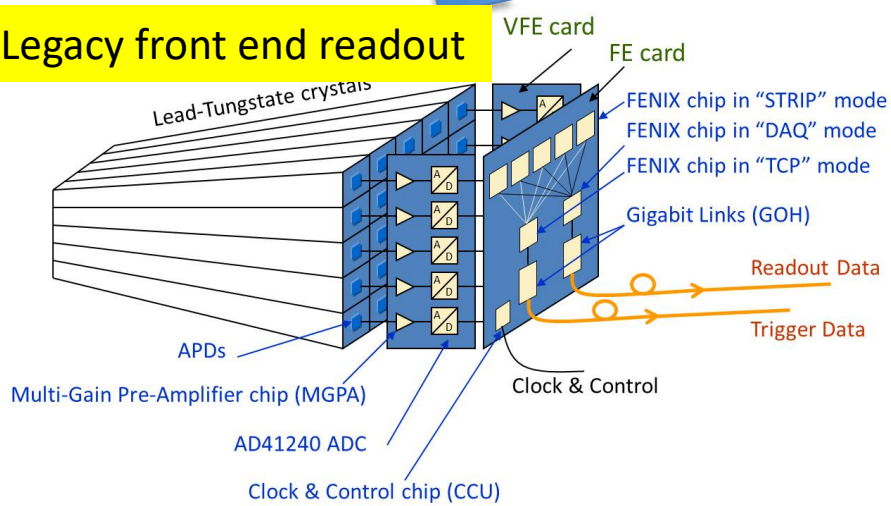
Endcap

To be Replaced with silicon calorimeter for high irradiation tolerance



A $H \rightarrow \gamma\gamma$ candidate event observed in the ECAL

Legacy front end readout

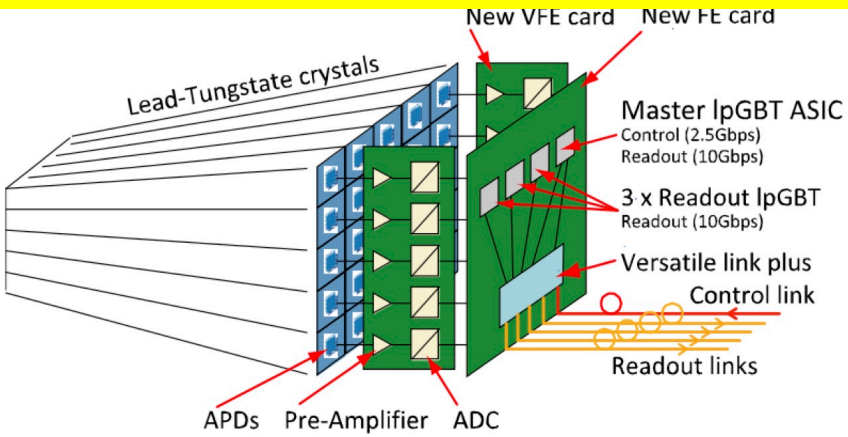


Barrel Electromagnetic Calorimeter electronics replaced for precision timing and better trigger granularity

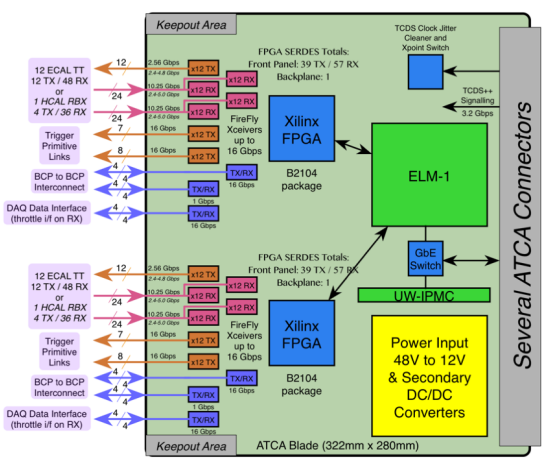
Hadron Calorimeter electronics replaced for better signal strength and higher trigger rates

Barrel Calorimeter Electronics Upgrade

Electromagnetic Calorimeter on detector



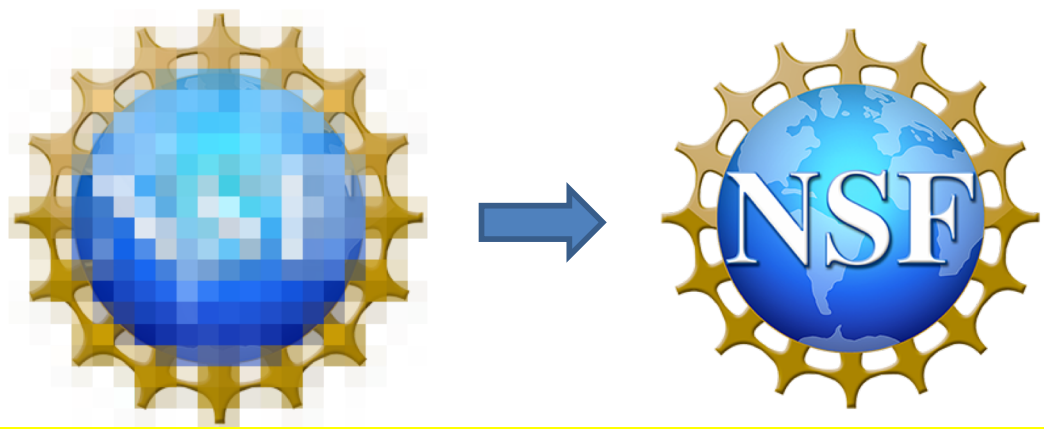
Electromagnetic + hadronic Calorimeter off detector



Faster response pre-amplifier to give 30ps timing for EM showers at 50 GeV

Higher bandwidth transmission off detector to provide more granularity to trigger

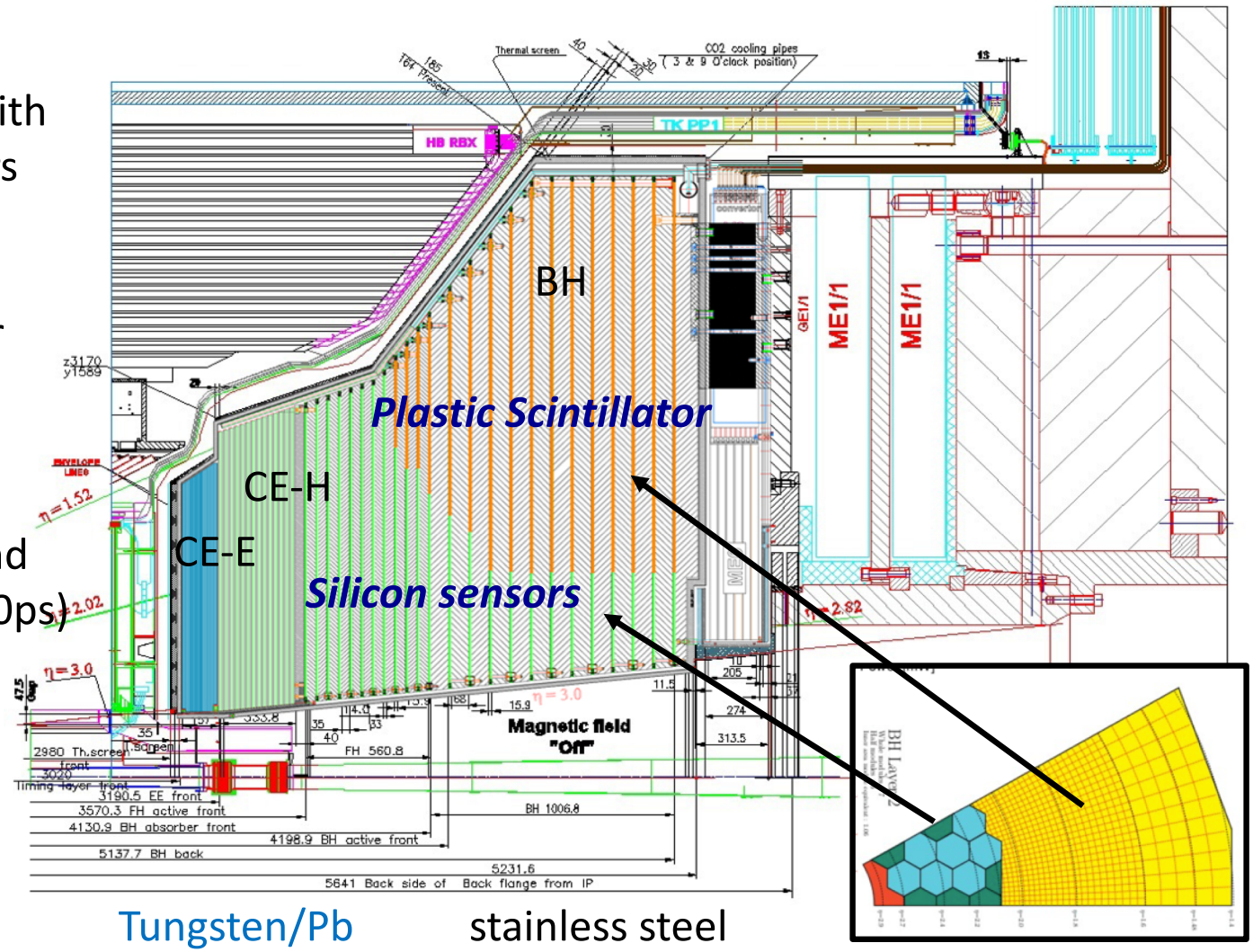
High speed processor board to deal with Greater spatial and time granularity



Like turning a 1M pixel camera to 25M pixel camera

Silicon+Scintillator Calorimeter Endcap

- Sampling calorimeter with 28 layers for EM showers 24 layers for Hadrons
- Silicon in front and inner regions for radiation tolerance
- High granularity in 3d and good time resolution (50ps) for pileup mitigation.
- Scintillator tiles + SiPM's in lower radiation regions



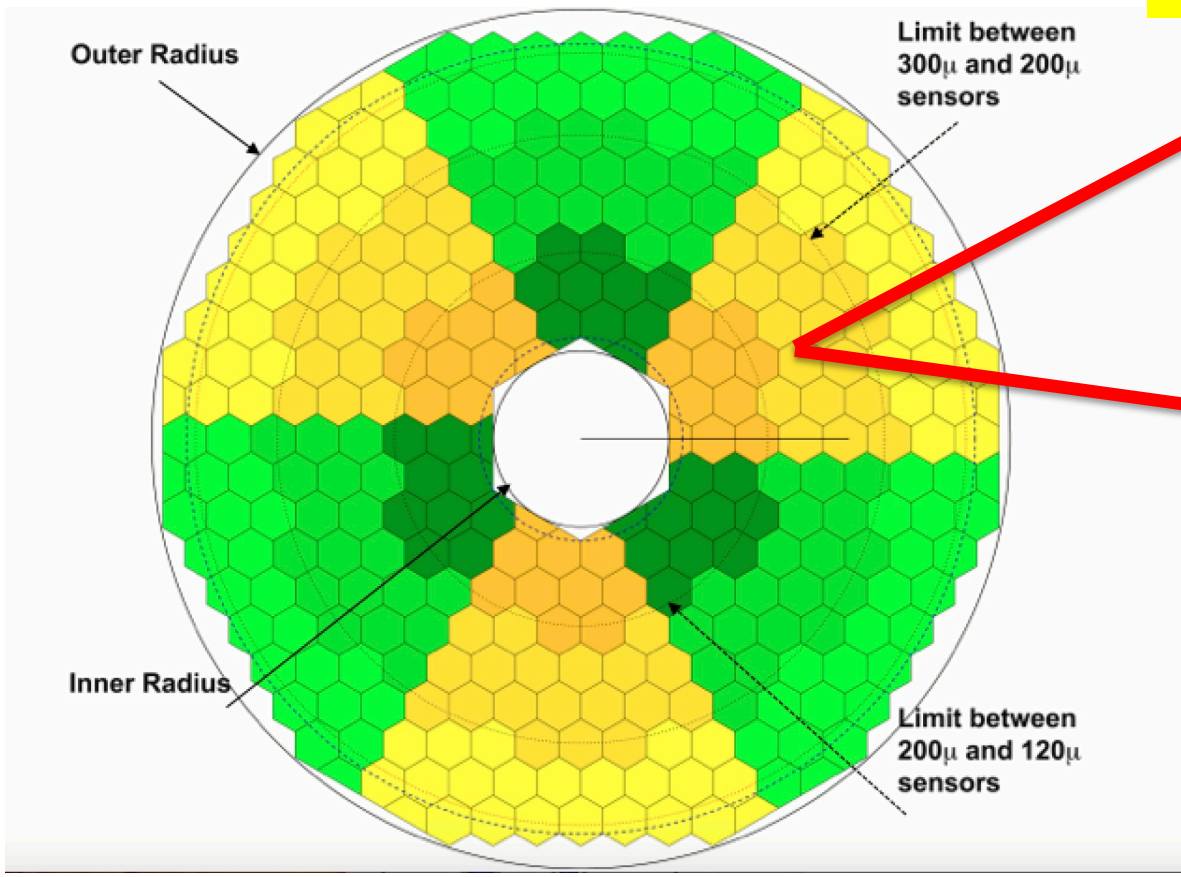
Tungsten/Pb stainless steel

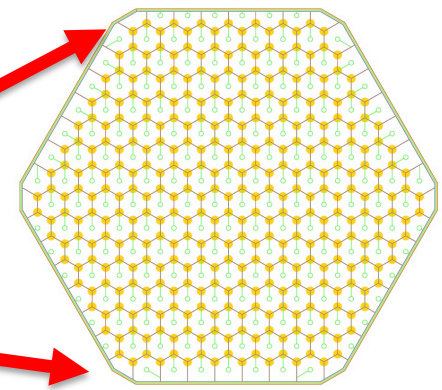
*CE-E: **28** sampling layers – 25 X_o + ~1.3 λ* ***24** sampling layers – 9 λ*

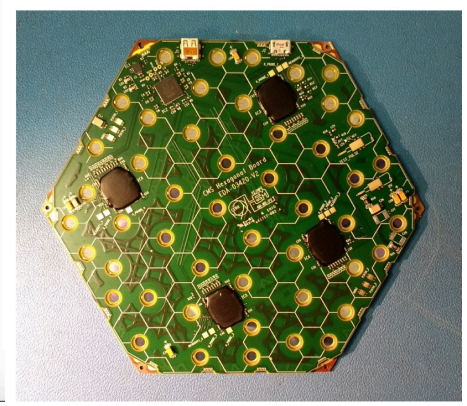
Calorimeter Endcap All Silicon layer

A cross-sectional layer of the EM endcap

Each Module subdivided into 0.5 -1.2 cm^2 hexagonal cells

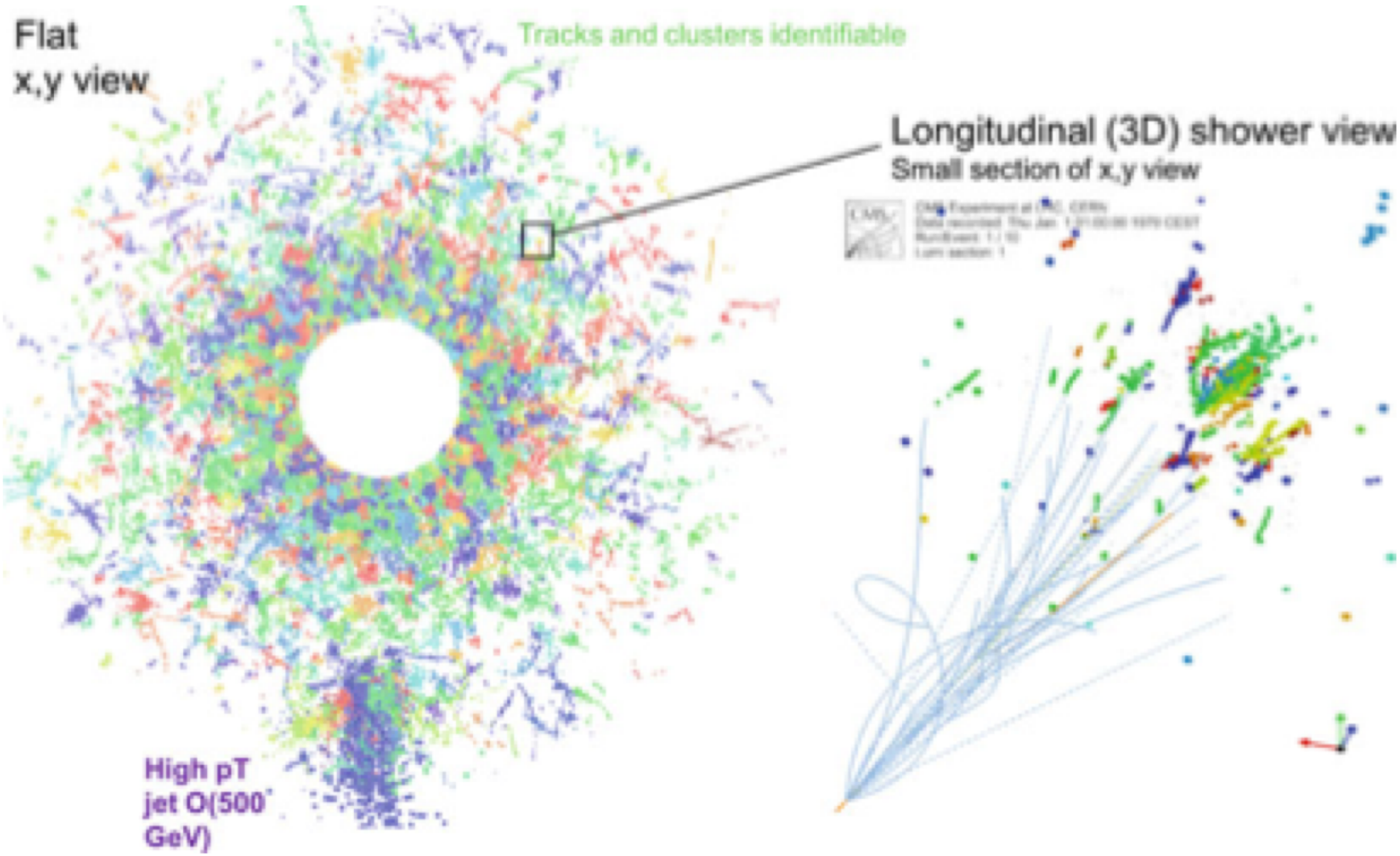






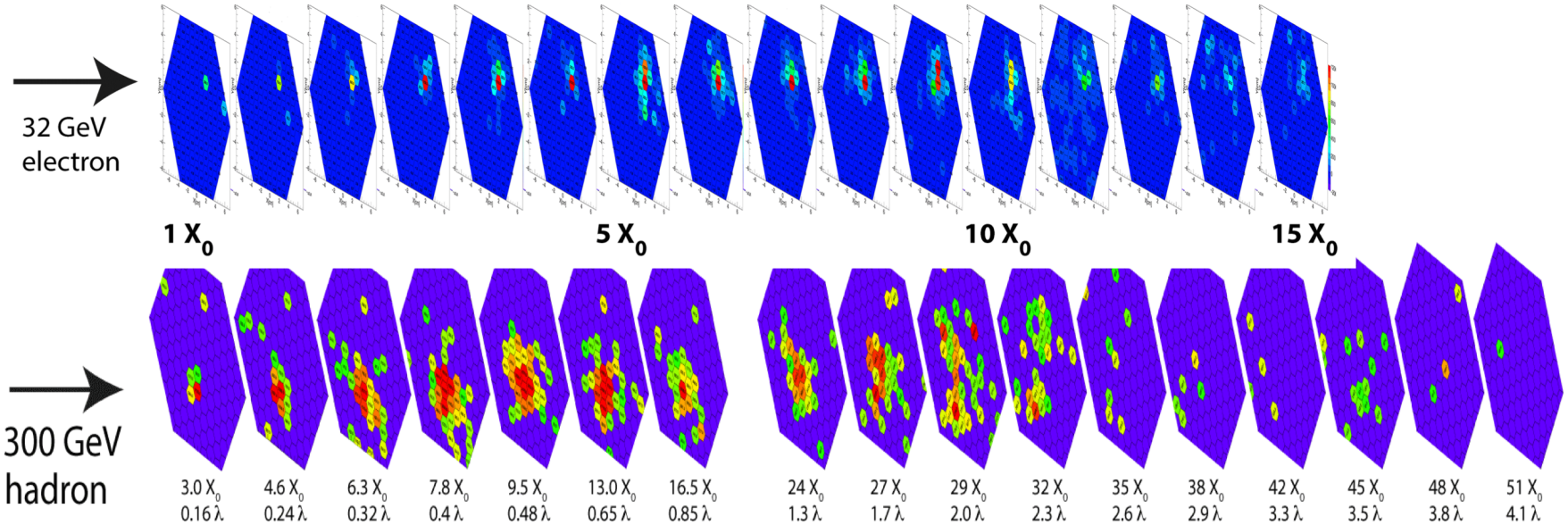
Module prior to wirebonding

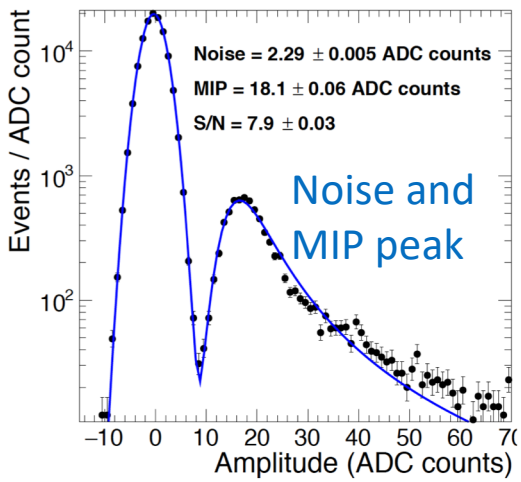
Calorimeter Endcap – A 4d imaging calorimeter

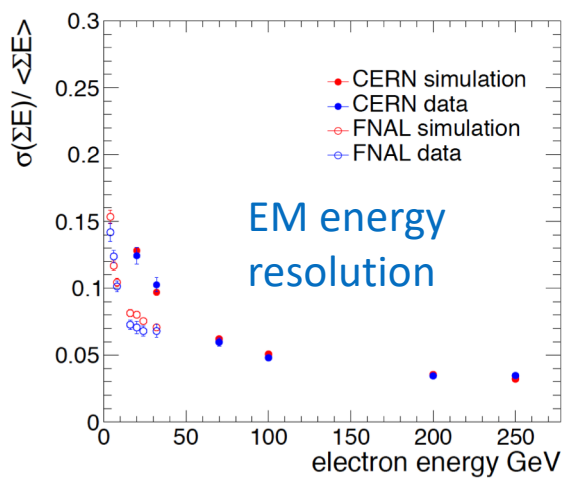


A simulated high P_T jet in 200 pileup showing the lateral and longtitudal granularity

Calorimeter Endcap Prototype tests







Proof of principal test successful

Expected prototype performance achieved

20

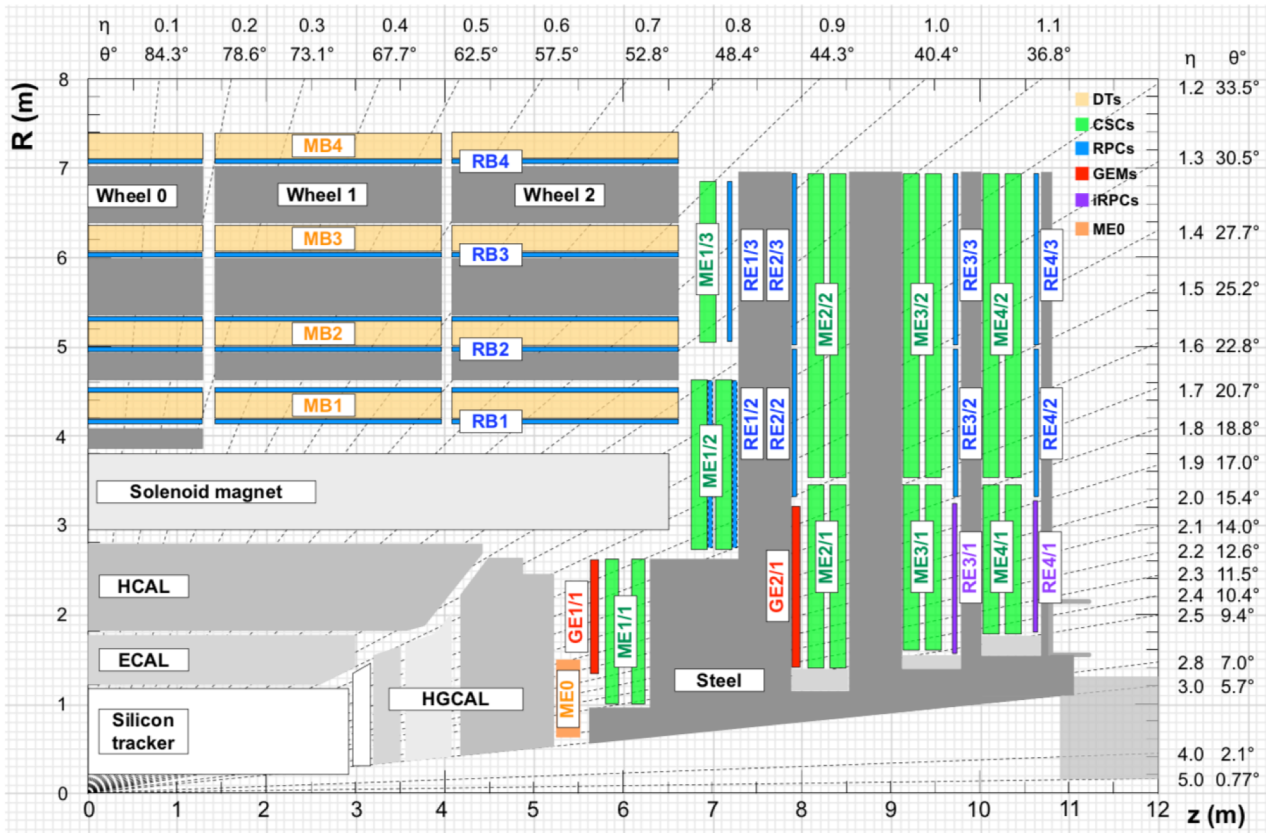
Muon Detector Upgrade

Muon detection is an essential element of the Compact Muon Solenoid (CMS)

Existing muon chambers most unchanged as they will be performant in HL-LHC

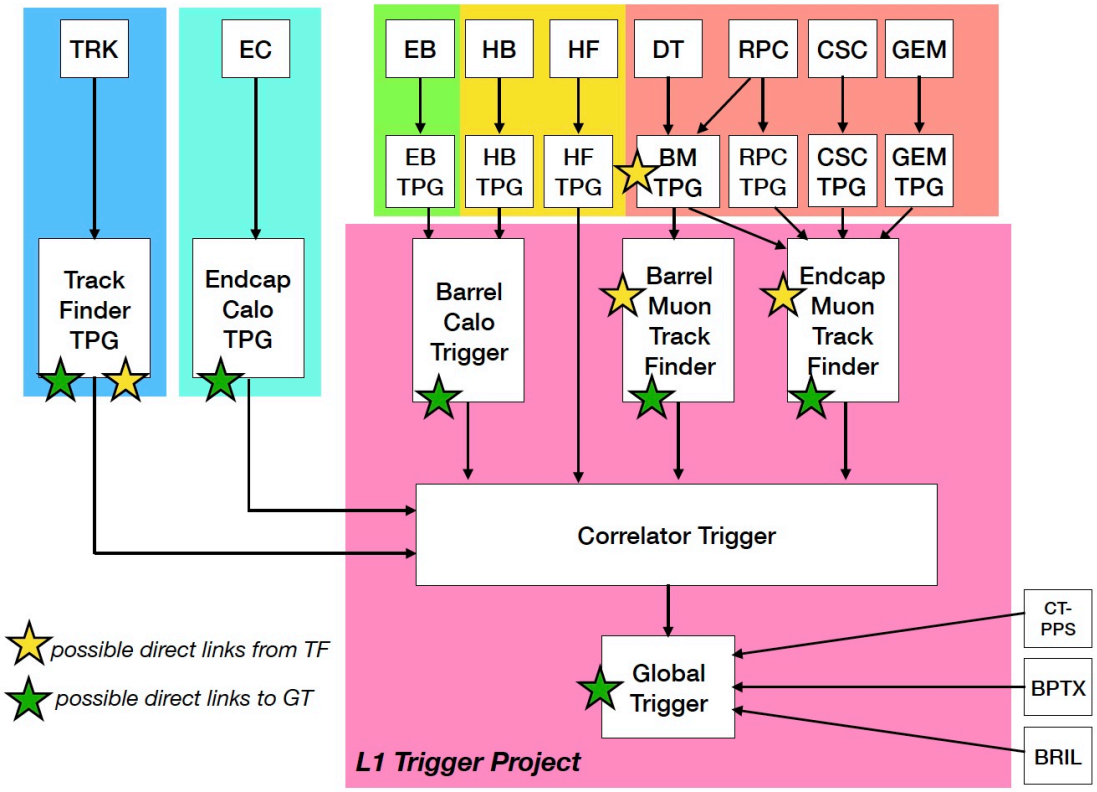
Replace electronics to improve trigger performance (lower P_T thresholds)

Extend coverage to n=3.0 in forward region with GEM's



Upgrades are relatively modest

Trigger/Data Acquisition Upgrade



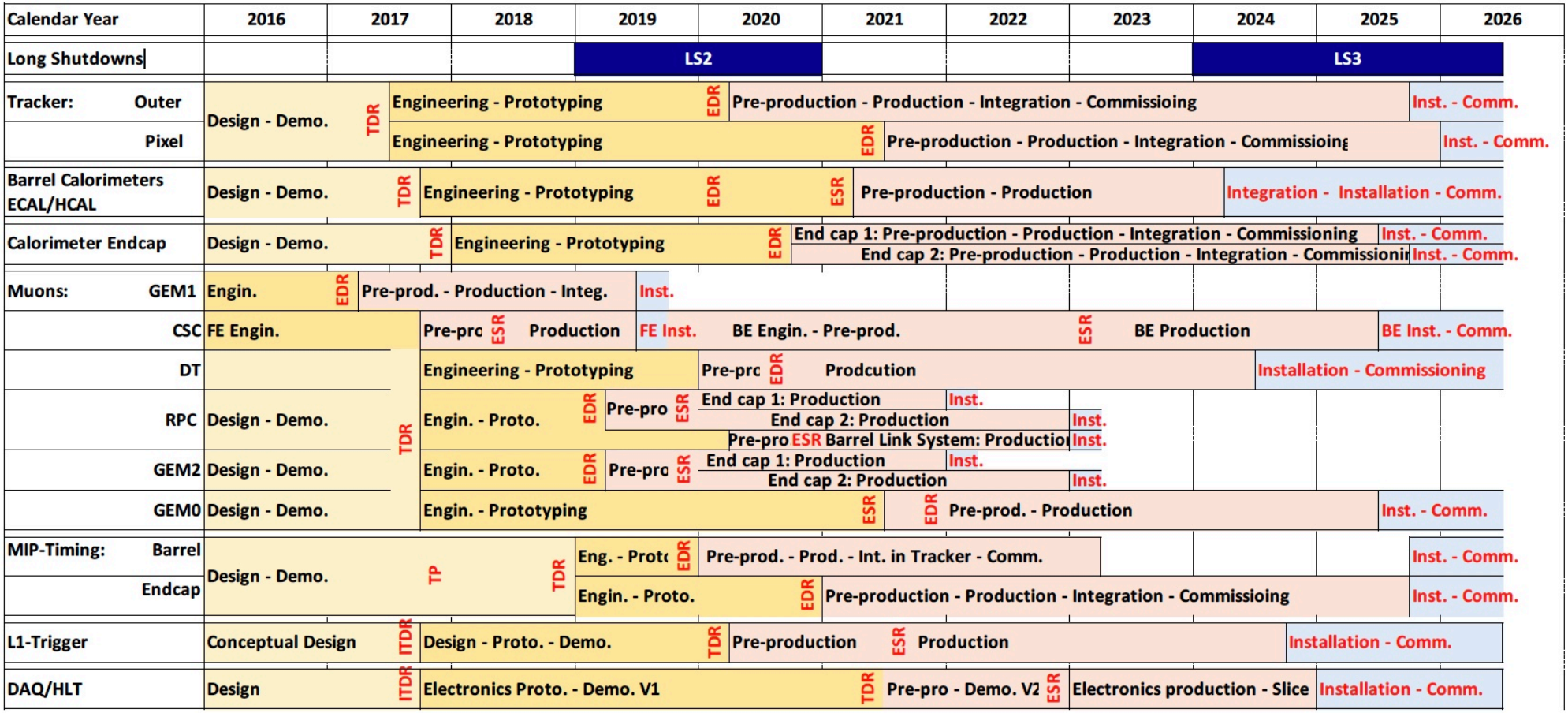
Adding tracking to the hardware trigger is critical

More sophisticated algorithms for pattern recognition in general

The ability to process the increased information from the more segmented detector in a more sophisticated way makes possible the entire upgrade program

It is due to advances in high speed optical links (10 Gb/s) and GHz FPGA's

Upgrade Status



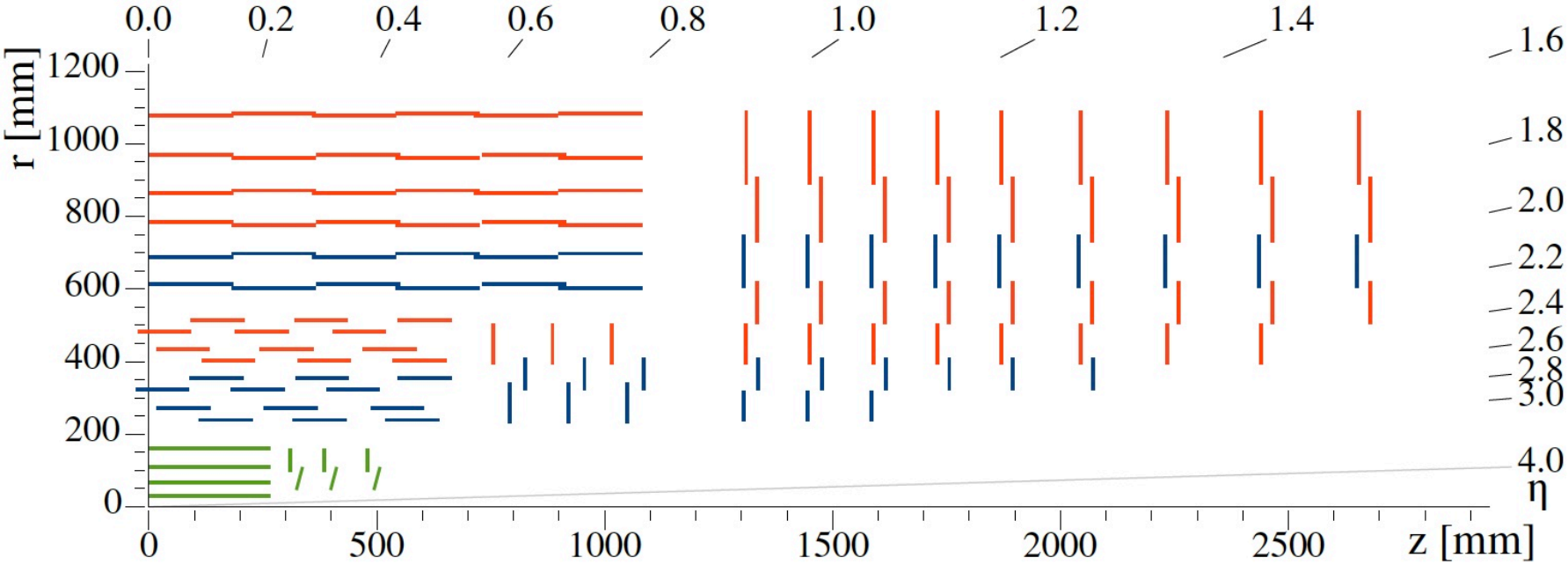
Now finishing the design phase and moving to prototyping (2018-2021). Production is 2021-2023 and installation 2024-2026

Summary

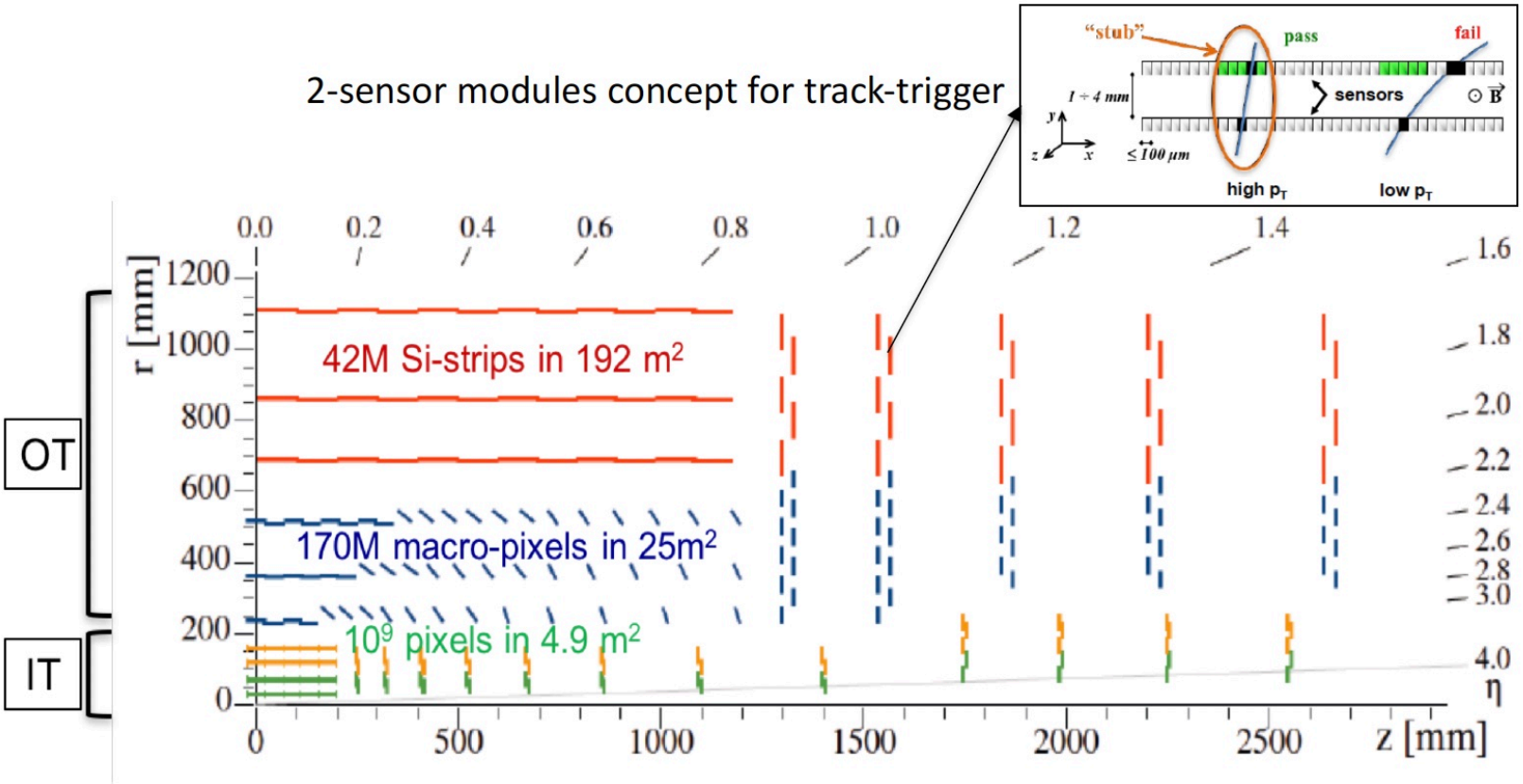
- The High Luminosity LHC is an approved project planned to operate 2026+
- The high radiation and multiple collisions make the detector upgrades very challenging
- CMS is harnessing new technology to significantly upgrade the detector and its discovery potential for a new era

ADDITIONAL MATERIAL

LHC era CMS tracker



HL-LHC Tracker



- OT Si-sensors ≃ 200µm thick - 90/100µm pitch - 2.5/5cm strips - 1.5 mm macro-pixels in inner layers
- IT Si-silicon sensors ≤ 150µm thickness - 50x50 to 25x100µm² - large pixels in outer layers?