New trends in detector R&D

The phase2 upgrades of the ATLAS and CMS detectors at the LHC

ANDREA PERROTTA – INFN BOLOGNA

ON BEHALF OF THE

CMS AND ATLAS COLLABORATIONS

The LHC accelerator upgrade: HL-LHC

High Lumi LHC will provide an almost 10-fold increase in the integrated luminosity, with pp collisions up to E_{cms} = 14 TeV

It will allow impressive improvements in physics capabilities:

- Precision measurement of Higgs boson properties: mass, width, coupling, self-coupling
- Precision measurements of the dominant Higgs production and decay modes, and possibility of observing rare modes
- Precision electroweak measurements: vector boson scattering, triboson couplings, rare processes
- Searches for Beyond Standard Model physics: SUSY, dark matter, leptoquarks, new resonances, long-lived particles
- Flavor physics studies: rare bottom and top decays, constraints on CKM and on flavor conservation

How can we achieve it?

The Collider

The Detector

The Nature

The Physics Reach

$$N = \varepsilon \cdot L \cdot \sigma$$

If we are able to maintain, or even improve, the detector performance that we have now in Run2, we will fully profit of the increased integrated luminosity

The challenges of the High Lumi LHC

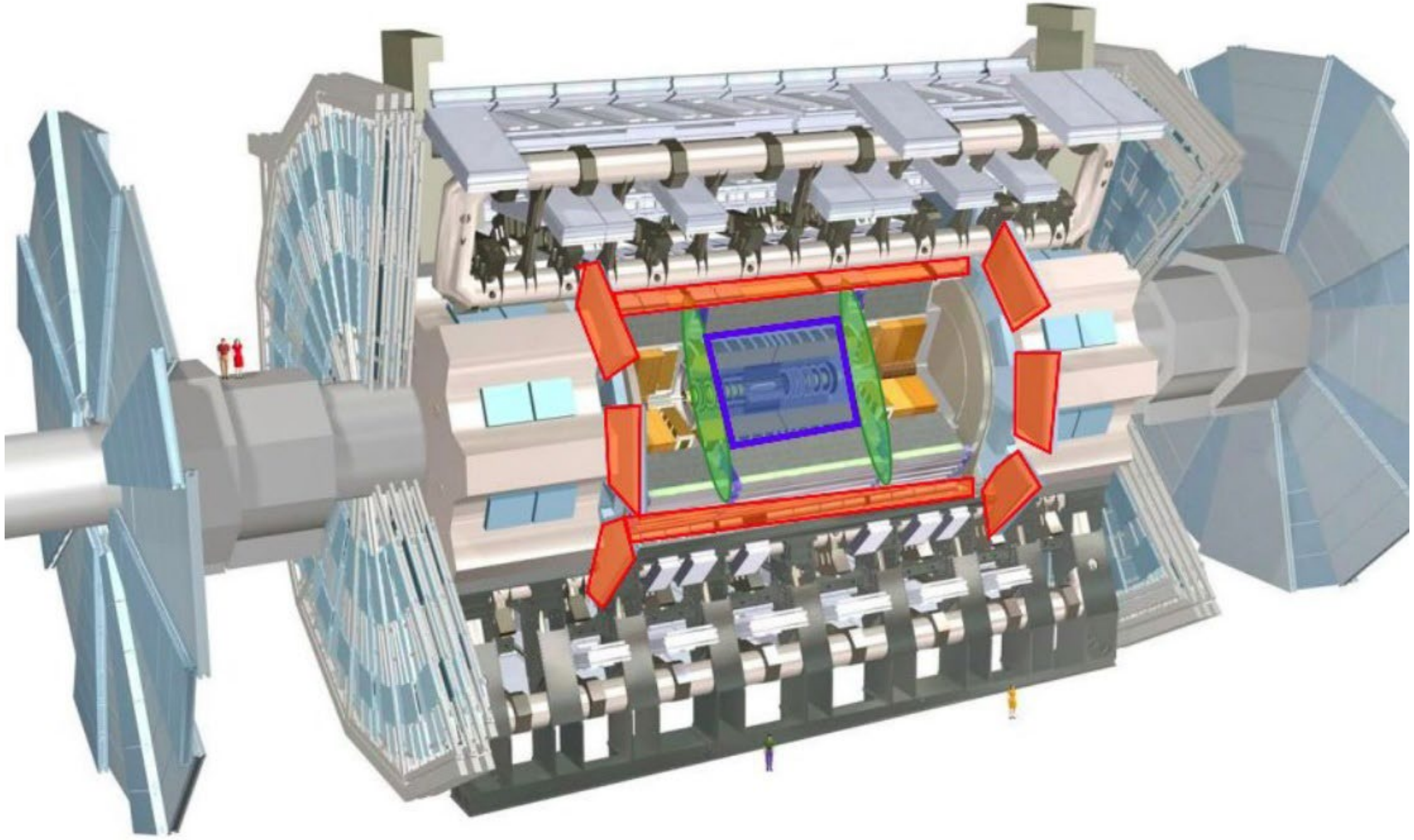
Instantaneous luminosity to increase from 2.0 to 7.5 $\times 10^{34}\ s^{-1}cm^{-2}$

Pile-up to increase from current ≈55 to 200

Higher radiation dose overall in the cavern

Major detector upgrades are needed to cope with the HL-LHC conditions

Overview of the upgrades for the ATLAS detector

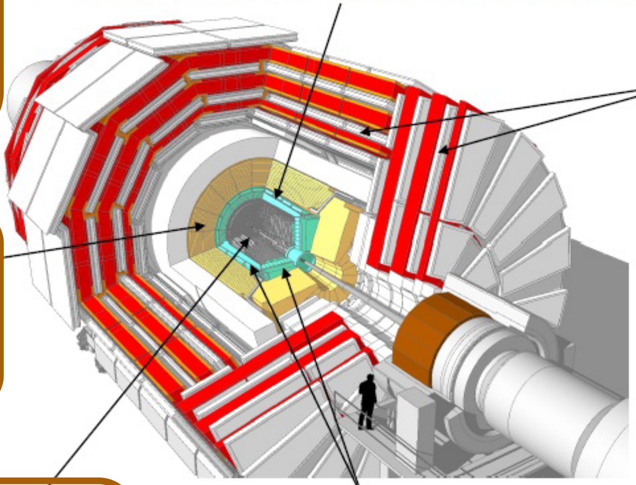


- **New muon chambers**
  Improved trigger efficiency, momentum and IP resolution; reduced fake rate
- **New inner tracker (ITk)**
  Less material & finer segmentation
- **High Granularity Timing Detector (HGTD)**
  Improved pile-up separation and bunch-by-bunch luminosity
- **EM calorimeter (LAr), hadronic calorimeter (Tile), and Muon detectors**
  On- and off-detector electronics upgrade
- **Upgraded TDAQ system**
  Single Level Trigger with 1 MHz output
- **Upgraded luminosity detectors**
  1% precision

Overview of the upgrades for the CMS detector

L1T and HLT/DAQ
- Tracker Tracks in L1T at 40 MHz
- PFlow selection at 750 kHz
- HLT output at 7.5 kHz
- 40 MHz Scouting: Real time analysis
- L1T latency: 4 → 12.5 μs

Barrel Calorimeters
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-end boards



Muon Systems
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$

Calorimeter Endcap
- High Granularity Calorimeter (HGCAL)
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

Beam Radiation Instr. and Luminosity
- Bunch-by-bunch luminosity measurement:
- 1% offline, 2% online

Tracker
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

MIP Timing Detector
- Precision timing with:
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

Towards HL-LHC

LHC schedule was shifted by 12 months this year: possible re-baseling of all upgrade projects in the two experiments

Trackers at HL-LHC

Being the closest detectors to the interaction point, the current systems cannot withstand the harsh HL-LHC running conditions: Trackers in ATLAS and CMS will be fully replaced, both for their inner and outer components

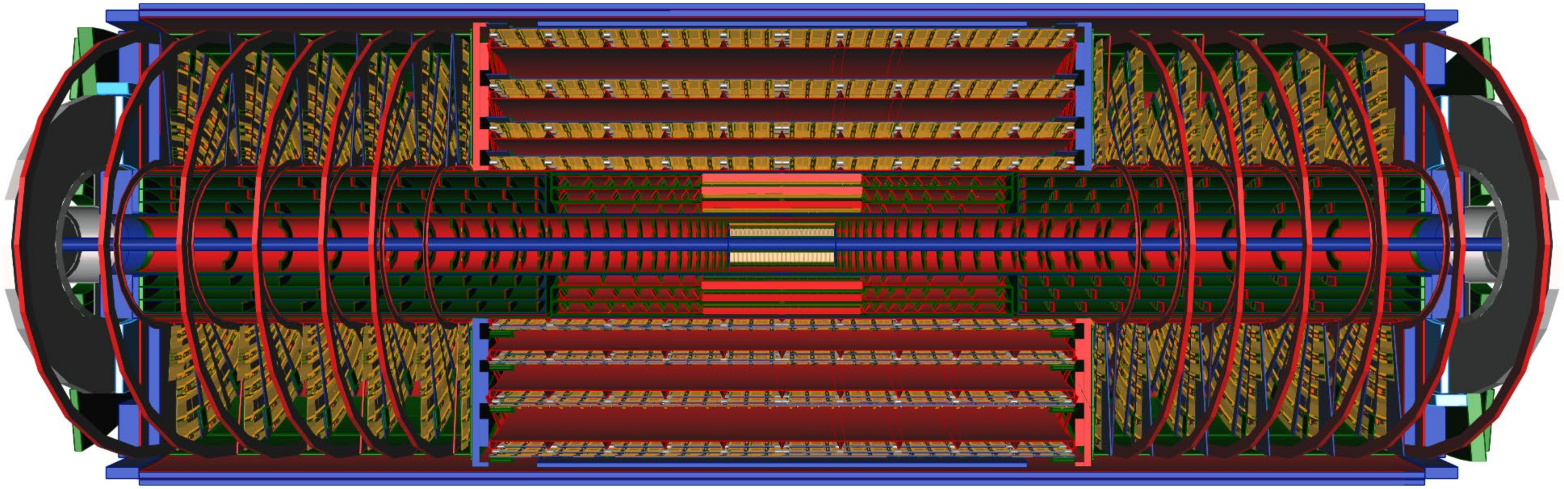
A few **common features** of the new trackers in ATLAS and CMS:

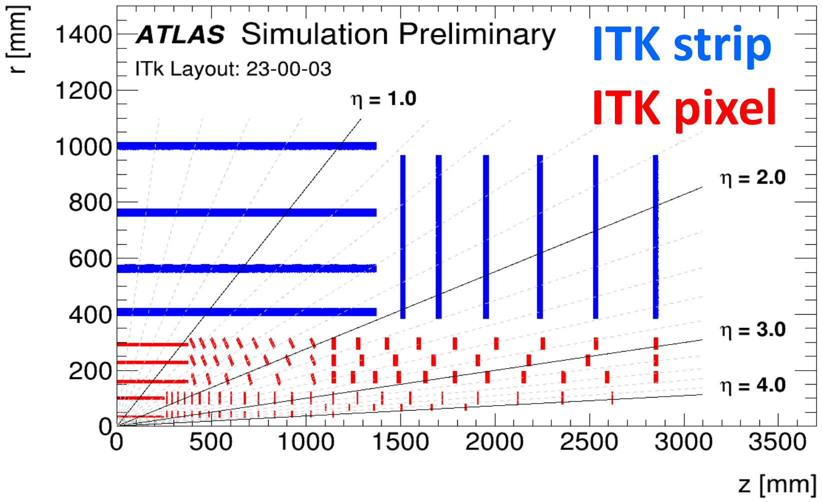
- Angular acceptance extended towards lower pseudorapidities
- Finer detector granularity to cope with the increased occupancy and improve impact parameter and vertex resolution
- Improved radiation hardness
- Increased transparency, in terms of material
- Similar pixel readout chips, based on those developed inside the RD53 collaboration (ATLAS+CMS)

ATLAS Inner Tracker (ITK) upgrade

New Inner Tracker made by all Silicon detectors:

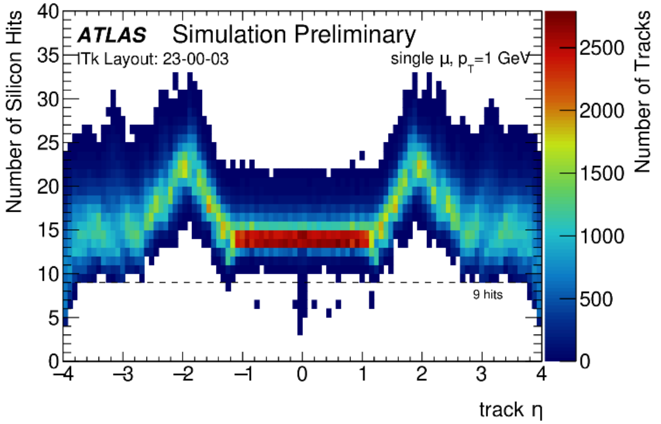
- Increased acceptance from $|\eta| < 2.5$ (current ID) to $|\eta| < 4$ (Phase2 ITK)
- Increased transparency (1/2 in terms of X_0): $L < 2.4\ X_0$





Outer strip detector:

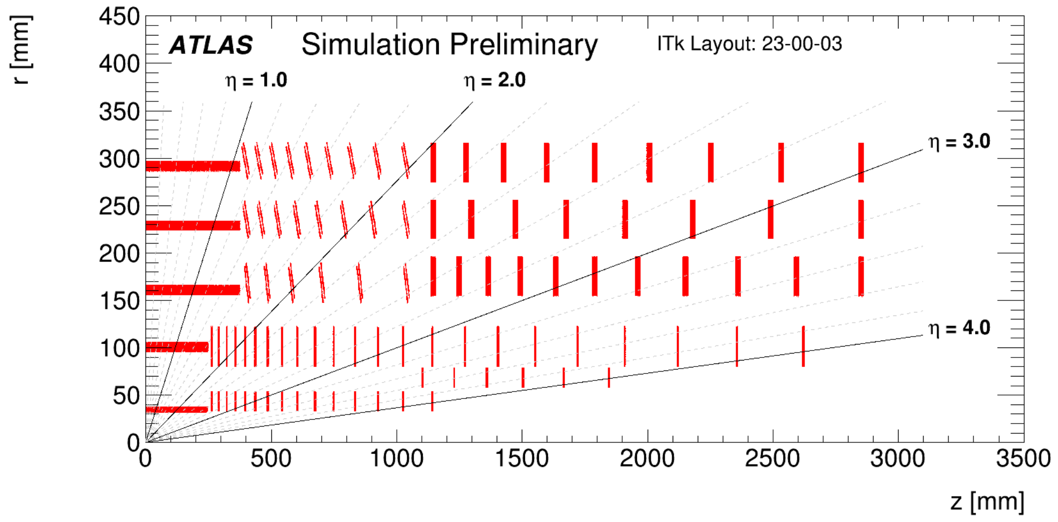
- 4 barrel layers
- 6 end-cap disks (double-sided)



ATLAS Inner Tracker (ITK) upgrade

Inner pixel detector:

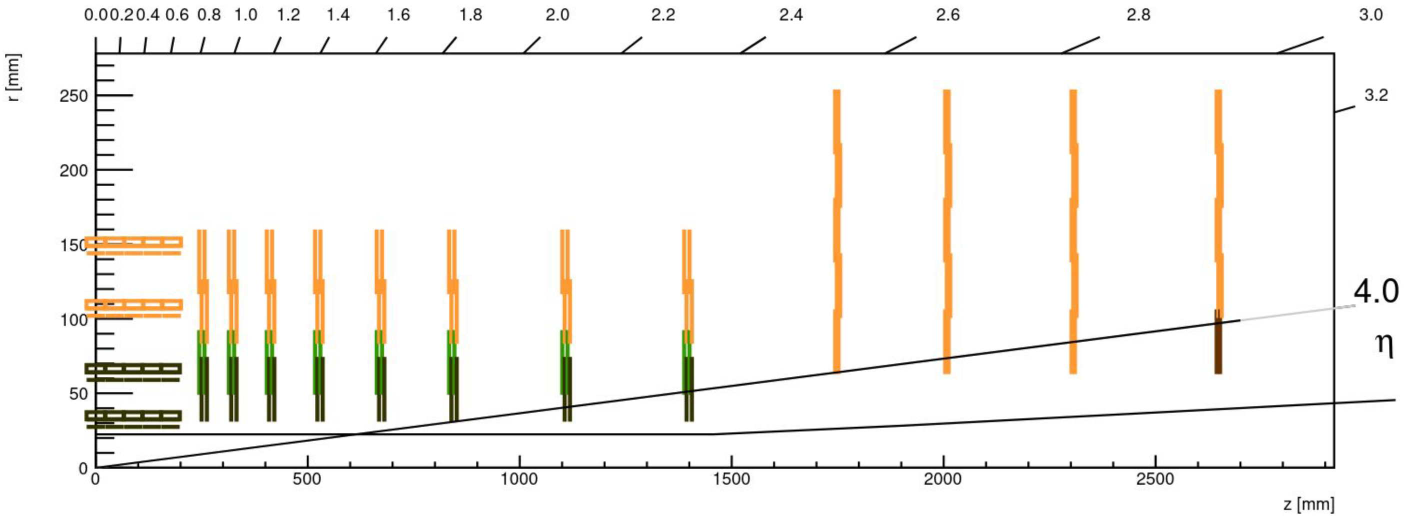
- 5 barrel layers + inclined and vertical rings
- innermost layer (L0) at radius ~34 mm [IBL 33.25mm]
- 9164 modules, covering surface of 12.8 m^2
- 12.8 million channels
- 1 MHz readout rate
- Sensors:
  - Pixel sizes 25 $\times$ 100 μm^2 in the L0 barrel. 50 $\times$ 100 μm^2 everywhere else.
  - 3D sensors in innermost barrel & disks, planar sensors everywhere else

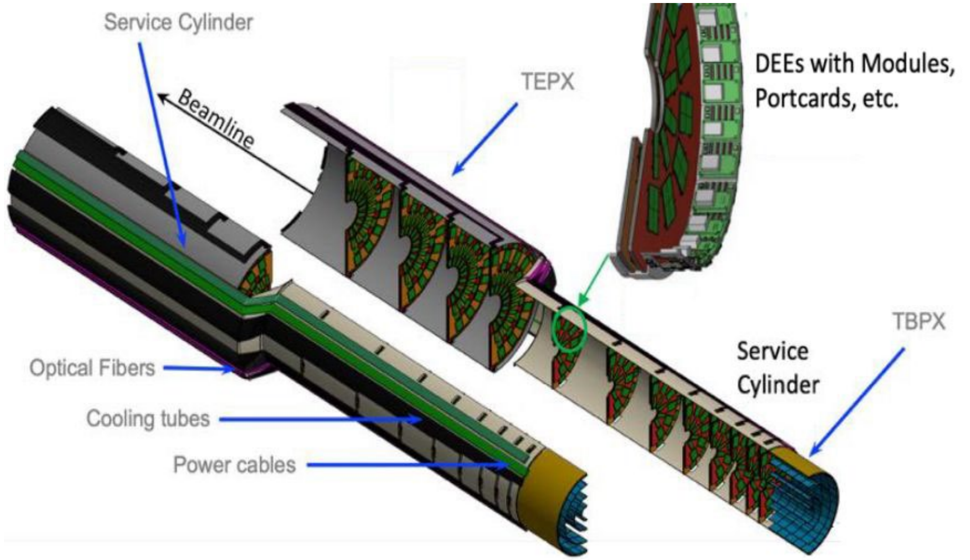


CMS Tracker upgrade

Acceptance increased to |eta| < 4, with at least 4 layers with at least one hit in all the acceptance

Simple and light (carbon fiber) mechanics, allowing easy removal for maintenance



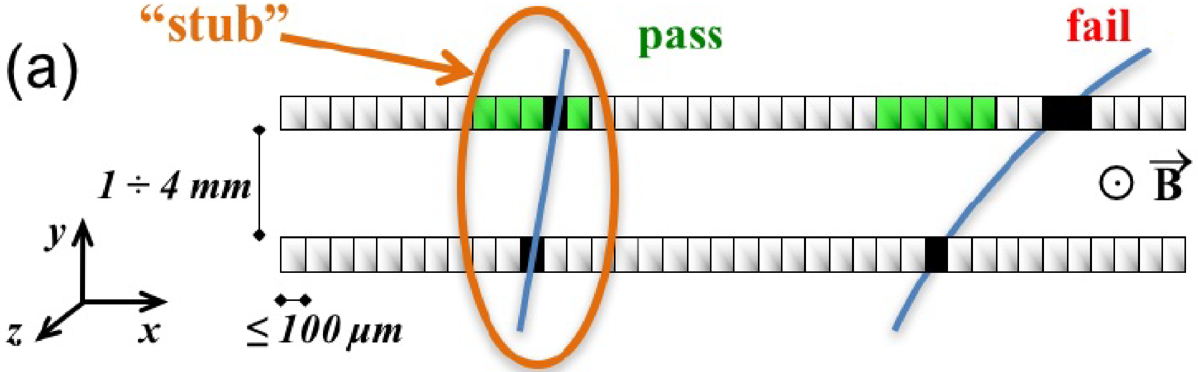


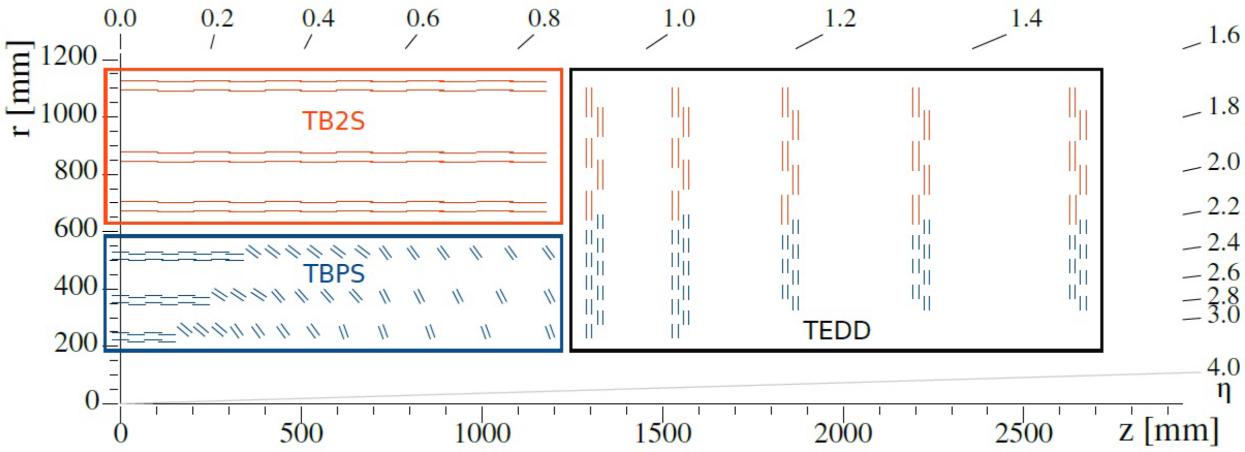
- 100 µm x 25 µm pixels
- Detector occupancy at the permille level
- 4.9 m^2 active detector → 5 times wrt Phase-1
- Similar material budget wrt Phase-1 detector
- n-in-p silicon hybrid sensors
- Planar or 3D sensors, depending on the layer

CMS Tracker upgrade

Providing tracking information to the L1 trigger is a main driver for the design of the **Outer Tracker**

pT modules realized with two strip sensors (**2S**) or with a strip and a macro-pixel sensor (**PS**): both top and bottom silicon sensors of a module must be connected to the readout electronics that performs **stub finding**





Six cylindrical "barrel" layers in the central region, complemented on each side by **five** "endcap" double-discs, in the region of 1200 < |z| < 2700mm:

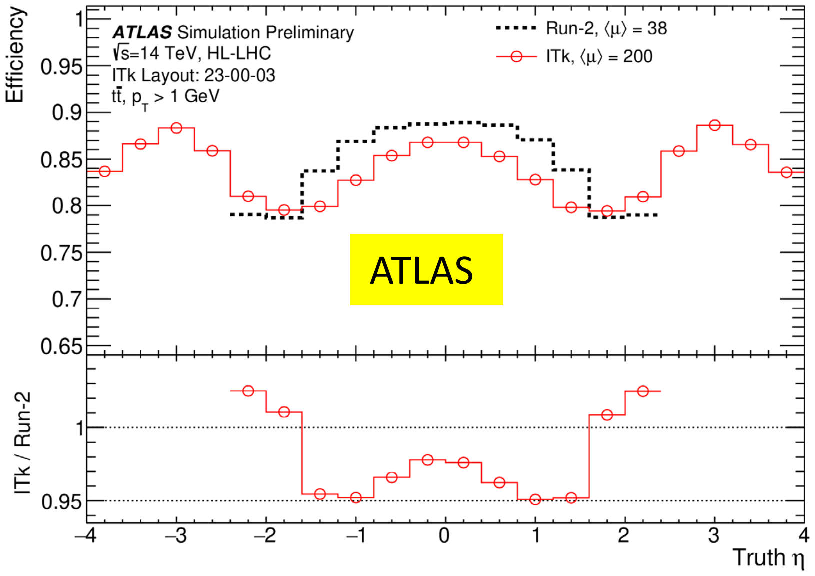
TBPS: Tracker Barrel with macro-Pixel + Strip modules,

TB2S: Tracker Barrel with 2 Strip modules

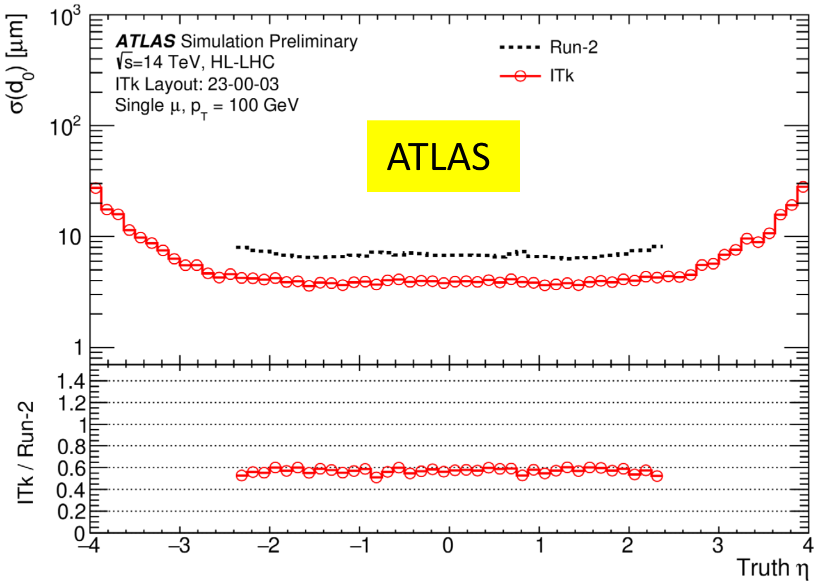
TEDD: Tracker Endcap Double-Discs

Expected performance for the Tracker upgrades in ATLAS and CMS

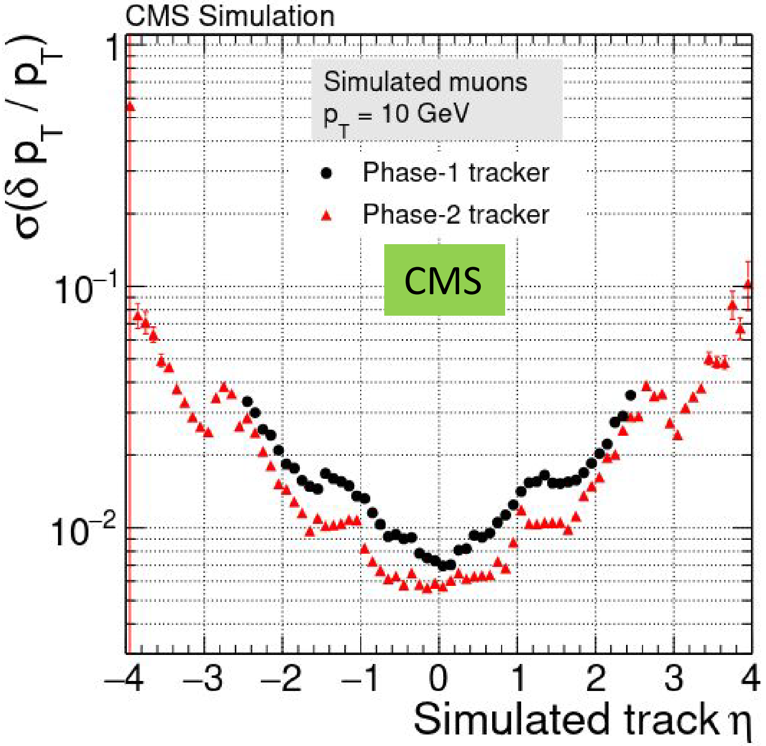
Efficiency for t-tbar events, <PU> = 200



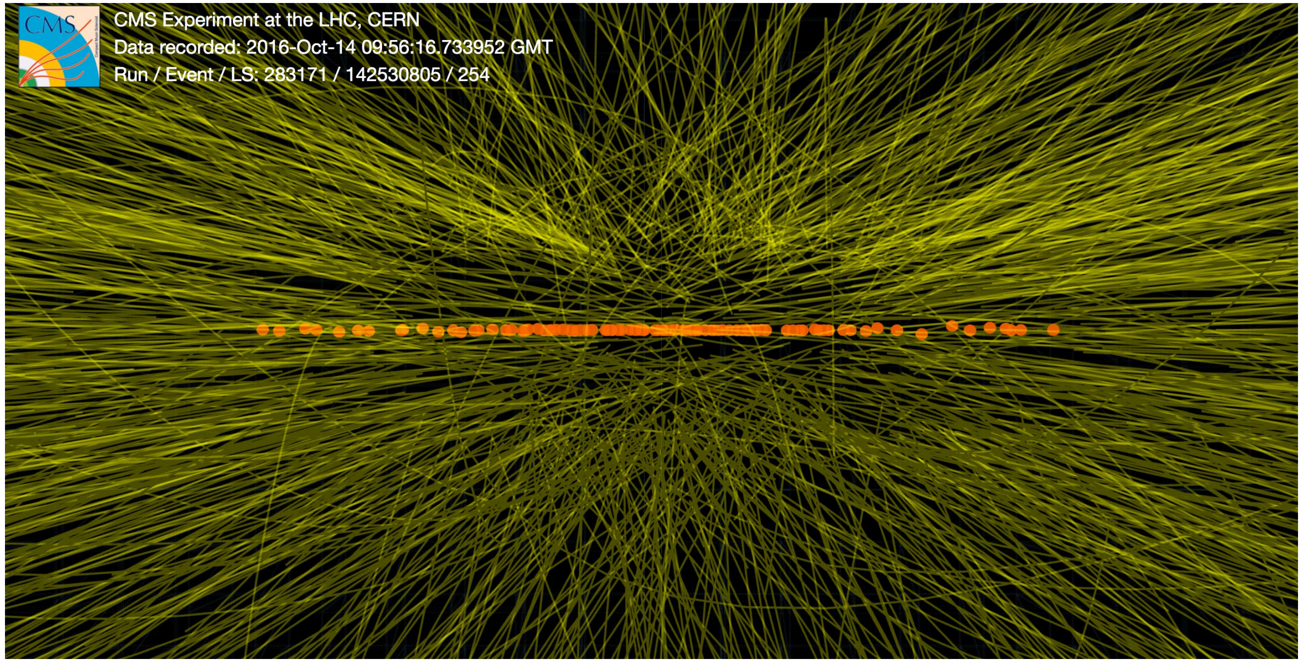
Transverse impact parameter resolution



Momentum resolution

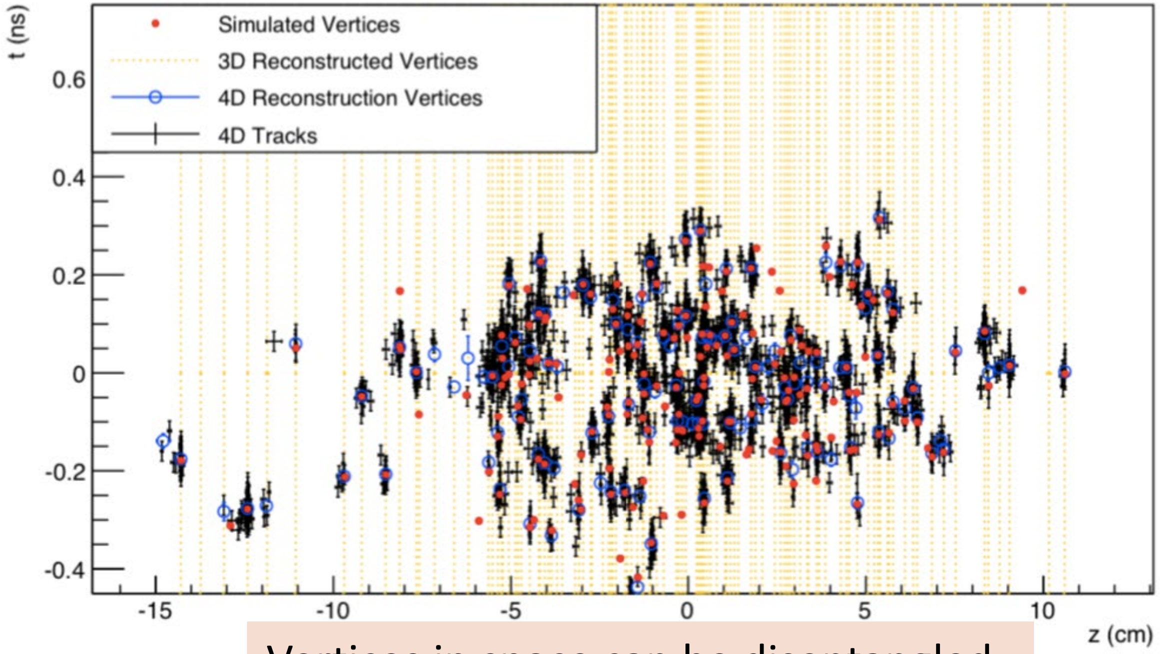


Timing Detectors at HL-LHC



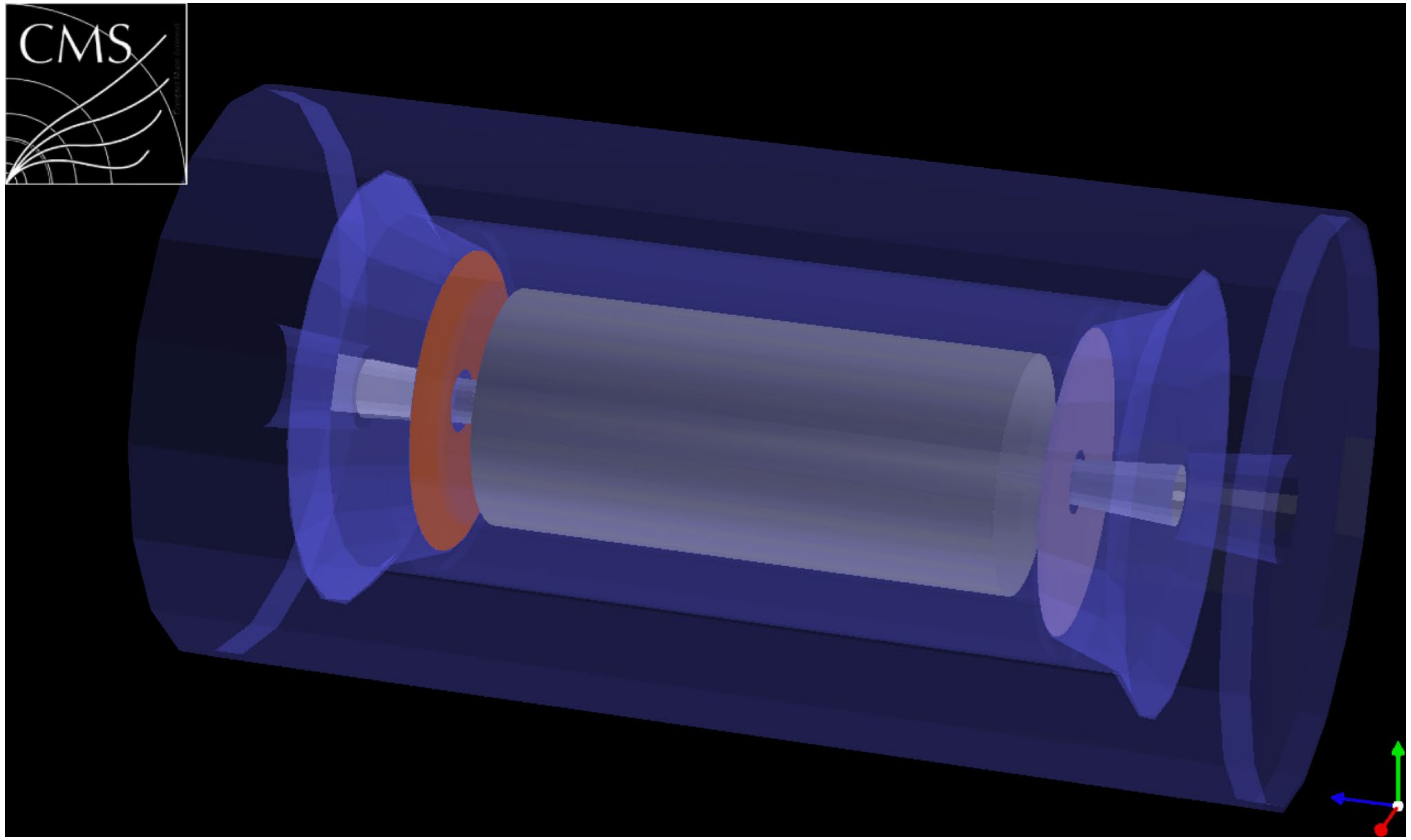
HL-LHC: 140-200 interactions per bunch crossing

The luminous region will have an estimated Gaussian spread of 30 to 60 mm along the beam axis; the width in time could range from 175 to 260 ps



Vertices in space can be disentangled if a fourth dimension is added: **time**

CMS MIP Timing Detector



Barrel Timing Layer (BTL):
LYSO:Ce crystals read-out by **SiPMs**
Total surface 38 m^2
Hermetic coverage for $|\eta|$ < **1.45**

Endcap Timing Layer (ETL)
Low Gain Avalanche Diodes with ASIC readout
Total surface 14 m^2
Hermetic coverage for **1.6** < $|\eta|$ < **3.0**

Collect timing information on charged particles and **combine it in tracking**

Provide a **timing resolution of 30-40 ps** at the start of HL-LHC, expected to degrade to 50-60 ps at end of HL-LHC

ATLAS High Granularity Timing Detector

HGTD aims to reduce pileup contribution at HL-LHC by augmenting the ITk in the forward region: $2.4 < |\eta| < 4.0$

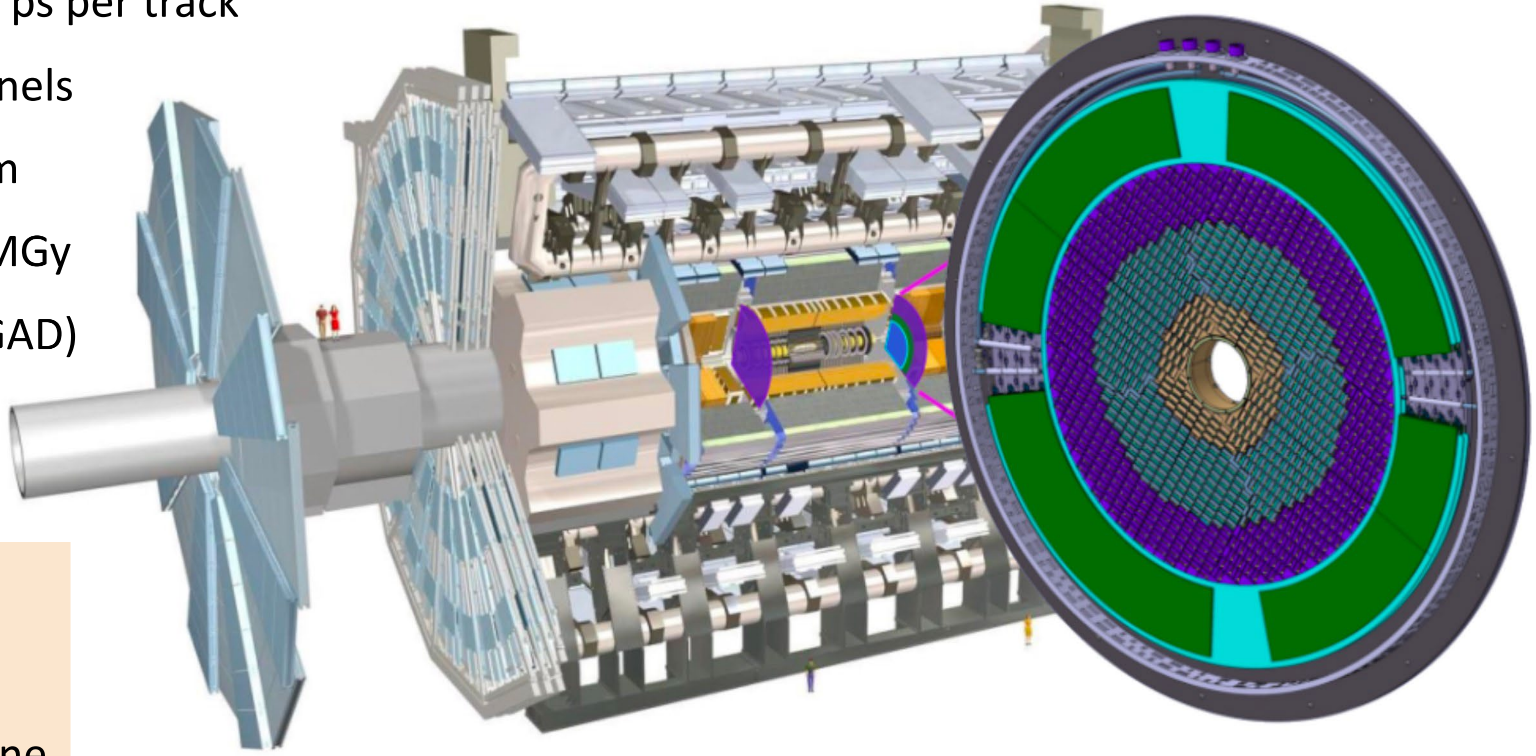
Timing resolution required to be better than 50 ps per track

6.4 m^2 area silicon detector and ~ $3.6 \cdot 10^6$ channels

High Granularity: pixel pad size: 1.3mm x 1.3mm

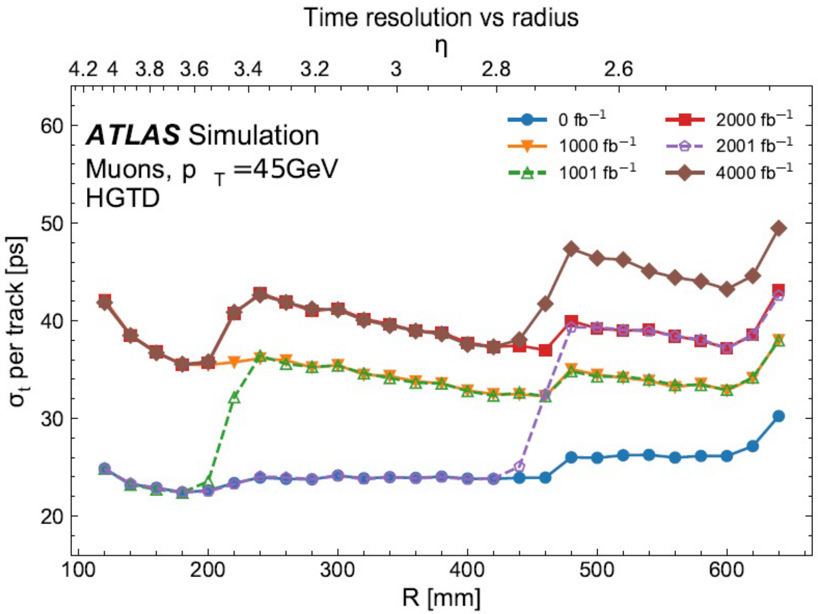
Radiation hardness : 2.5×10^{15} N_{eq} /cm^2 and 2 MGy

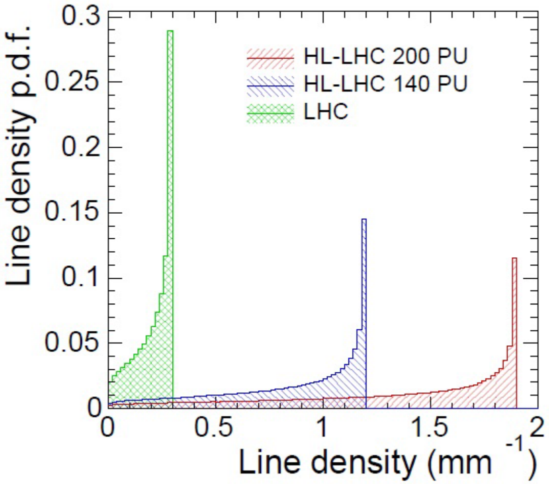
Silicon based Low Gain Avalanche Detectors (LGAD)

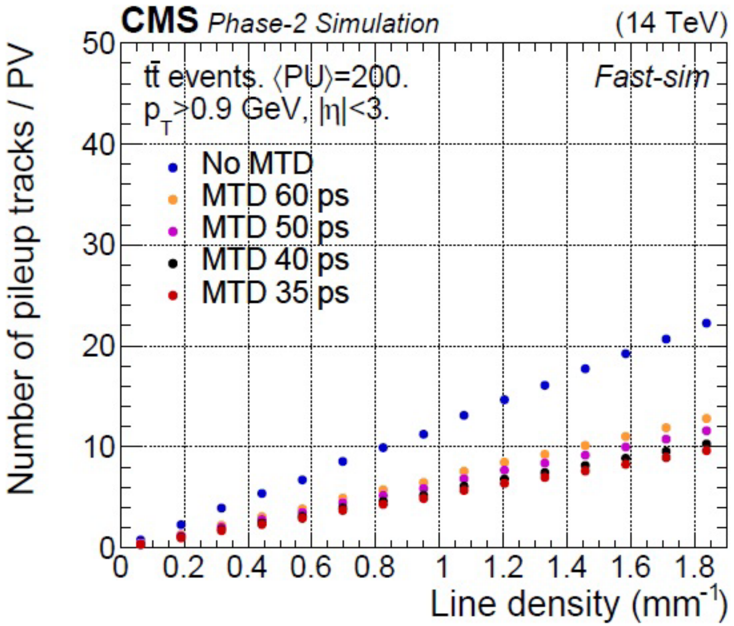


HGTD uniquely positioned to measure both the online luminosity on a bunch-by-bunch basis during HL-LHC running, and the high-precision determination of the integrated luminosity offline

Expected performance with the Timing detectors at HL-LHC







Timing Detectors are also adding new capabilities:

- Potential for direct measurement of LLP mass by reconstruction of the time of displaced vertices

- PID of low Pt charged hadrons through TOF measurement (High impact for heavy ions physics)

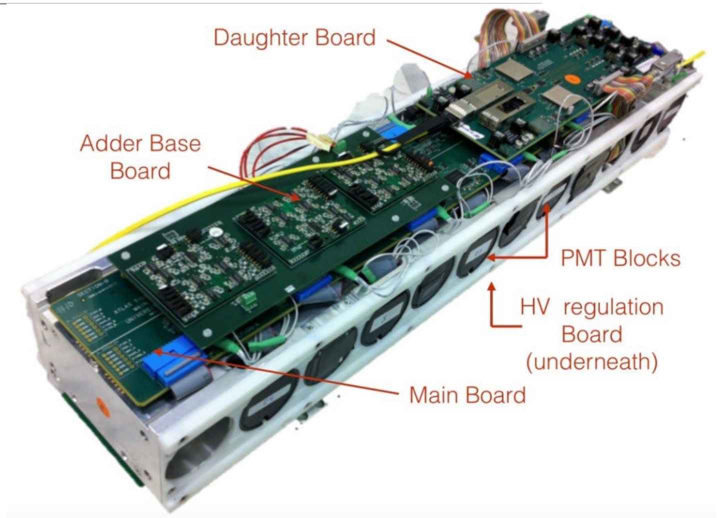
Calorimeters at HL-LHC

ATLAS electromagnetic calorimeter upgrade:

- New on-detector and off-detector electronics with 40 MHz continuous readout, increased granularity, and improved radiation hardness

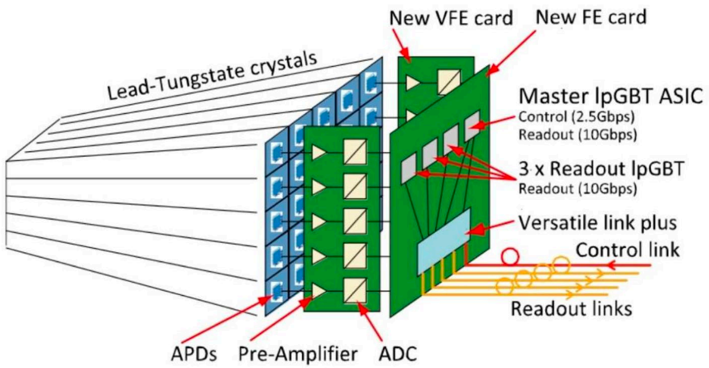
ATLAS hadronic calorimeter upgrade:

- Full replacement of front-end and back-end electronics, with modified mechanics for easier access and maintainability, and fully digital readout data and input to trigger system



CMS ECAL barrel upgrade:

- Faster FE electronics to improve timing performance and primary vertex identification: continuous stream of data (digitized analog waveform) sent to the backend, where all the trigger and readout intelligence is implemented using powerful FPGAs
- New off-detector L1 trigger and readout electronics, to cope with CMS-wide L1 trigger latency increase (from 3.5 to 12.5 us) and L1 trigger rates (from 100 kHz to 750 kHz)



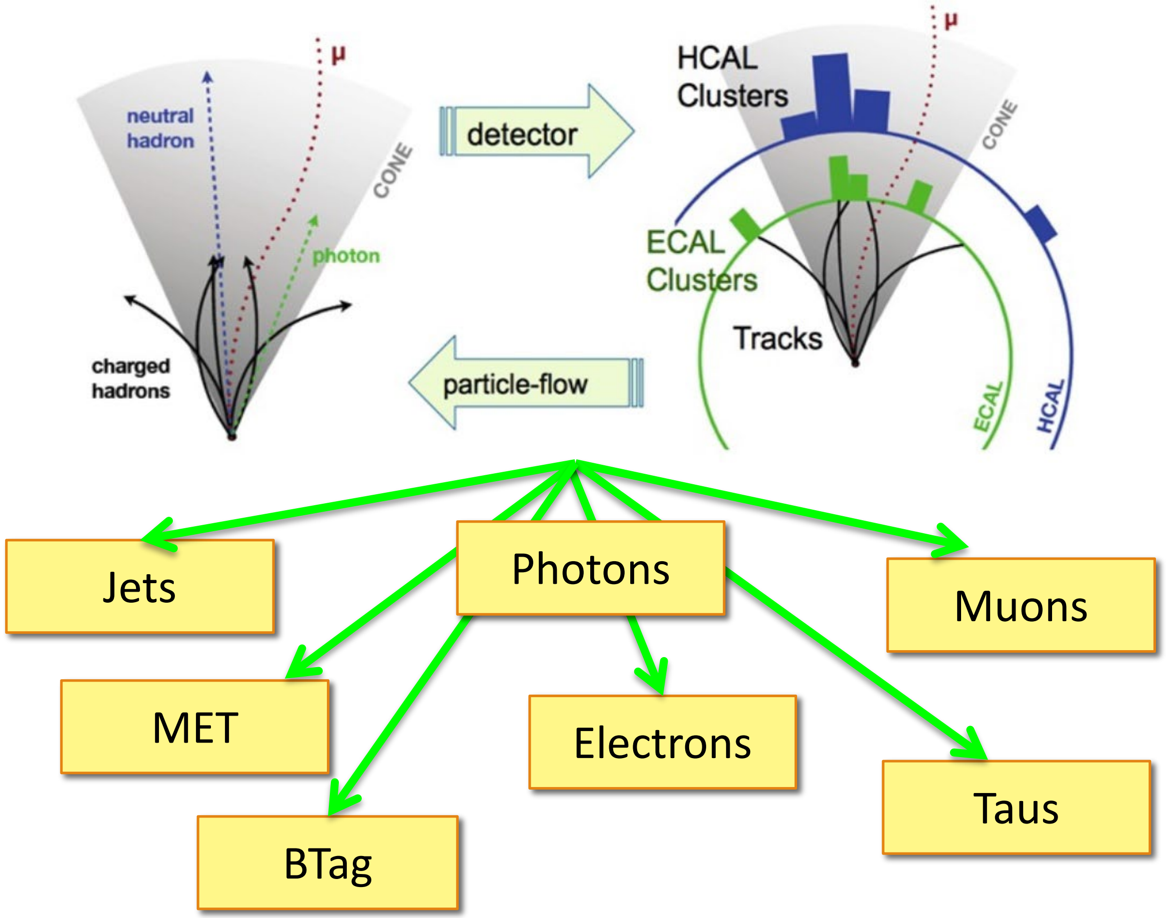
Particle Flow

Particle Flow techniques heavily used already in LHC Phase1: global event description using comprehensively all informations from the different subdetectors

Inputs from subdetectors must be linked and correlated among them: high granularity calorimeters instrumental in improving overal event description

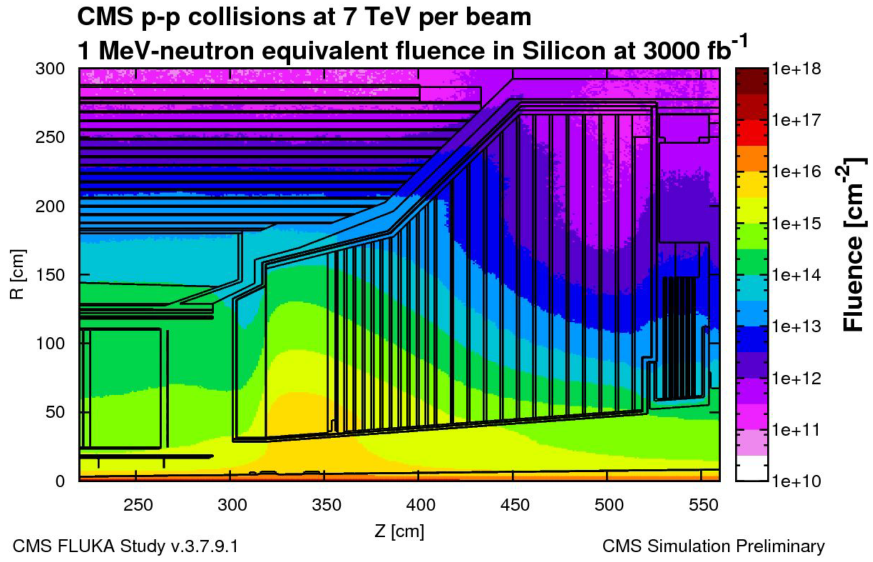
ML techniques will help

Future detectors must be thinked as a whole, aiming at the best performance for the overall event reconstruction



CMS High Granularity Calorimeter

Electromagnetic and hadronic endcap calorimeters will be **replaced** in CMS with a new combined electromagnetic and hadronic sampling calorimeter based primarily on **silicon pad sensors**. **Plastic scintillator tiles** will be used at large distances from the beam line in the hadronic section



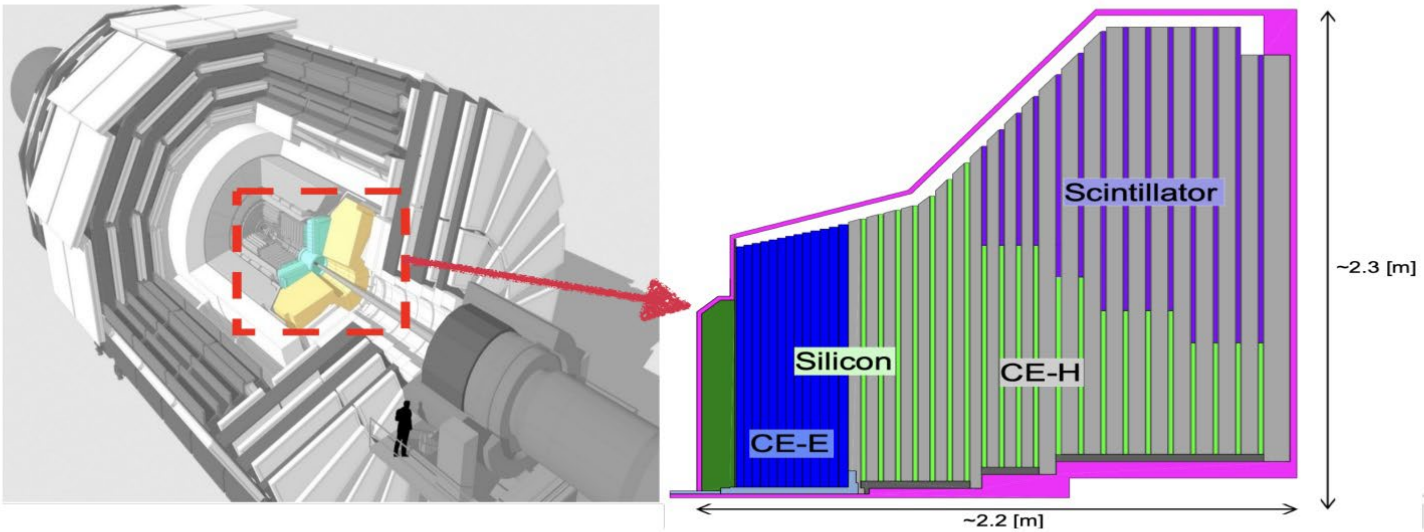
Harsh radiation environment:
full volume operated at -30C

Electromagnetic calorimeter (CE-E):

Si, Cu & CuW & Pb absorbers, 26 layers, 27.7 X_0 & 1.5 λ

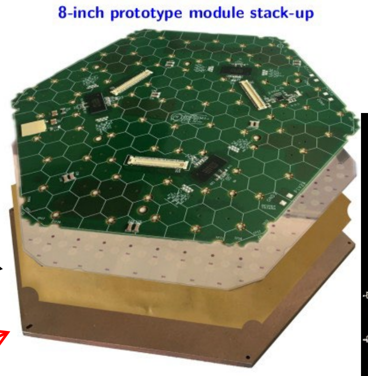
Hadronic calorimeter (CE-H):

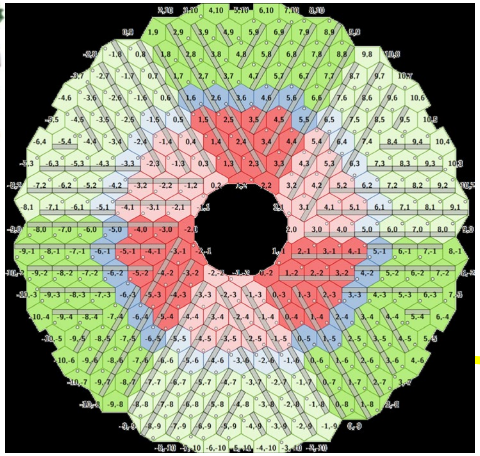
Si & scintillator, steel absorbers, 21 layers, ~8.5 λ

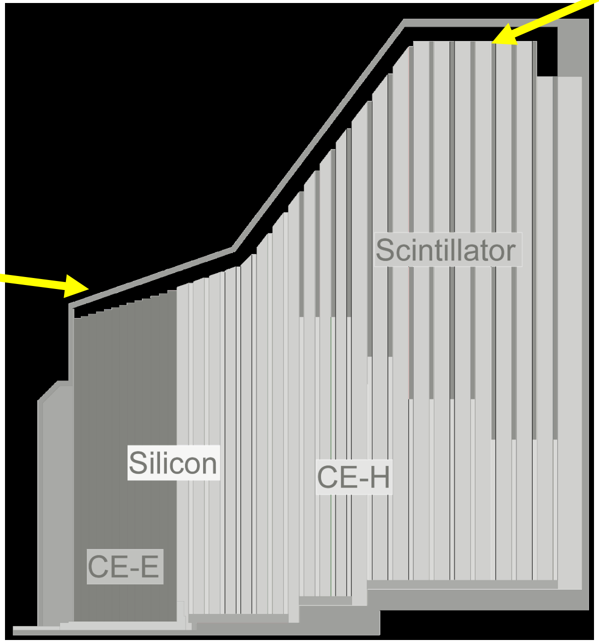


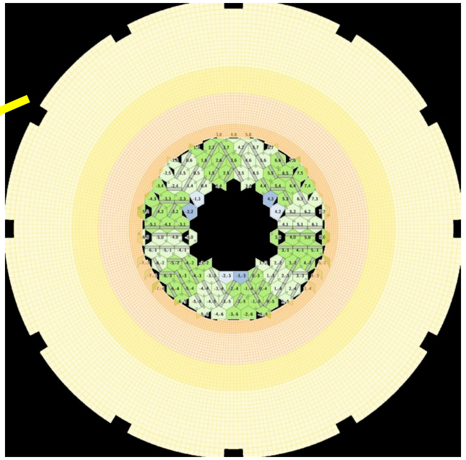
CMS High Granularity Calorimeter

Hexaboard
Si Sensor
Kapton layer
Cu/W baseplate









6M **silicon pads** (620 m^2)

- Cell size 0.6 or 1.2 cm^2
- Hexagonal silicon sensors, 120/200/300-µm thick, 8" wafer process
- 26k modules

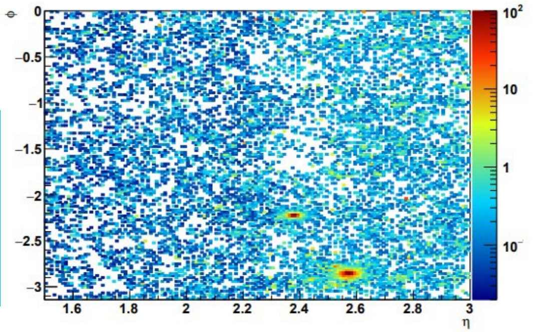
240k **plastic scintillator tiles** (370 m^2)

- Cell sizes from 4 to 30 cm^2
- SiPM- on-tile readout
- 3.7 k modules

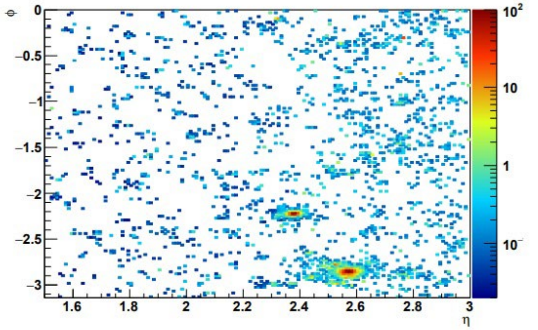
CMS High Granularity Calorimeter: 5D calorimetry

Calorimetric energy measurement with ≈ 50k dinamic range, calibrated on single MIP

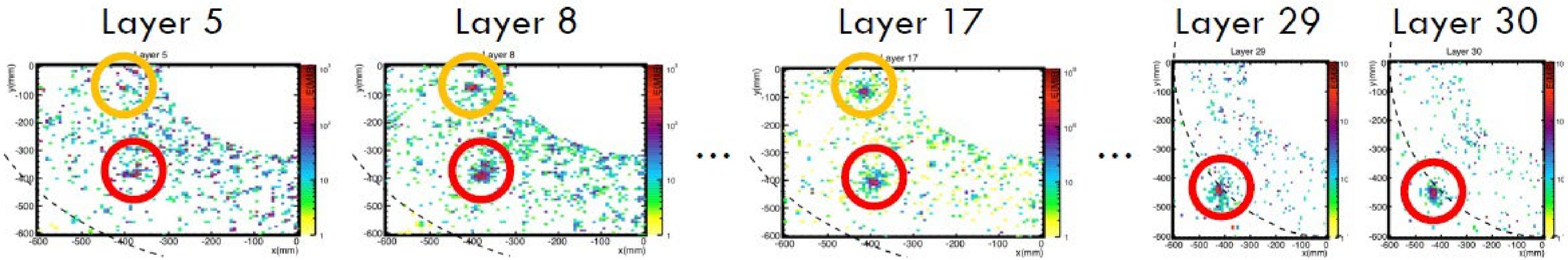
Precise timing for showers with 25 ns precision per channel energy above a few MIPs



3D imaging of the particle trajectory with tracking-like algorithms, based on 6M channels in about 40 m^3



removal of hits with |Δt| > 90 ps

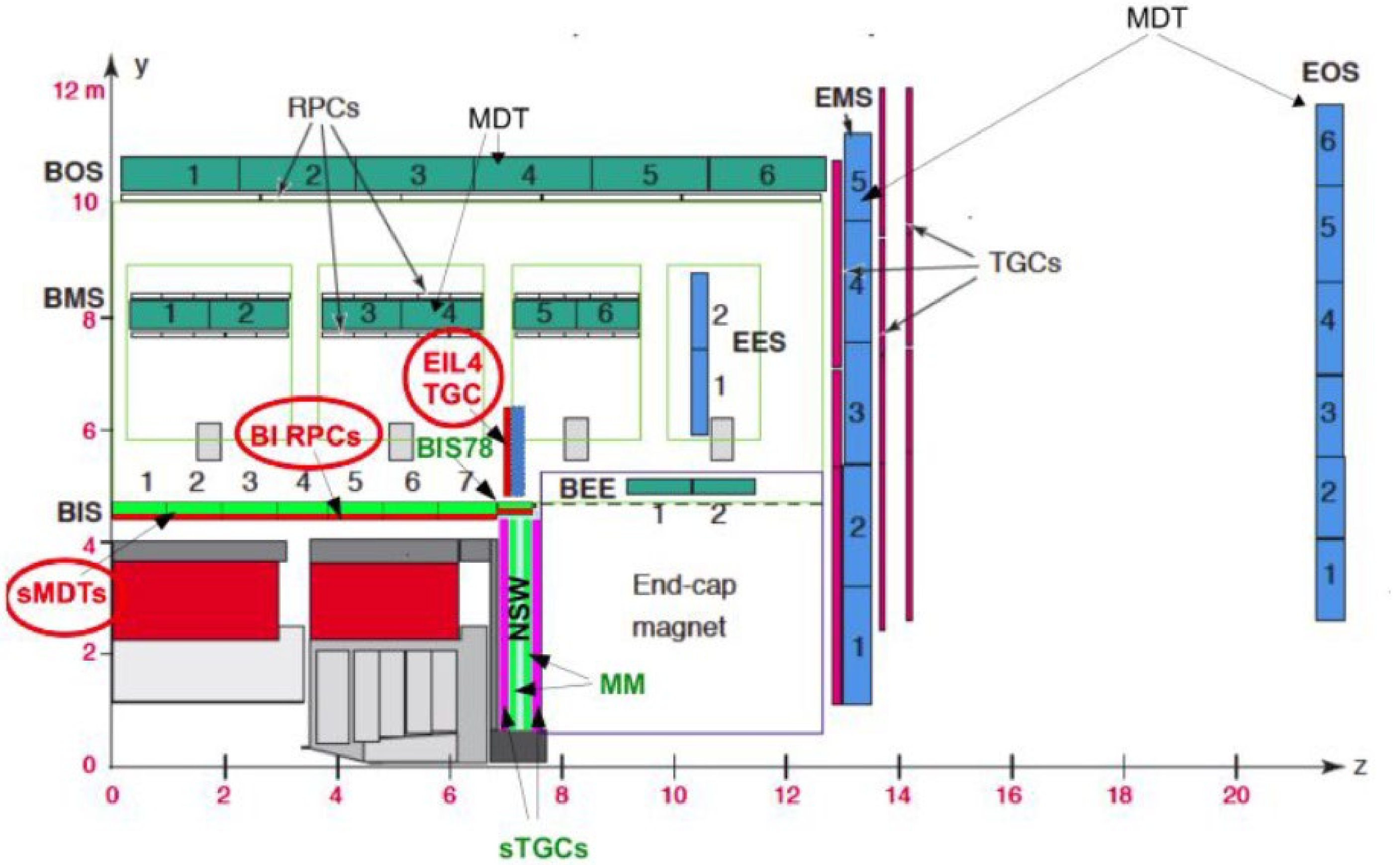


Upgrades of the Muon Detectors: ATLAS

Additional layers of muon detectors added to improve coverage, trigger uniformity & momentum resolution, fake rates:

- small-Diameter Monitored drift Tubes (sMDT)
- New generation of RPC detectors
- Thin Gap Chambers (TGC) in the endcaps

Updated readout and trigger electronics to 40 MHz



Upgrades of the Muon Detectors: CMS

Current muon chambers expected to cope with the increased particle rates

FE electronics to be replaced with improved versions to increase radiation tolerance, readout speed, and performance

Forward muon system enhanced with improved RPCs and new chambers based on the GEM technique

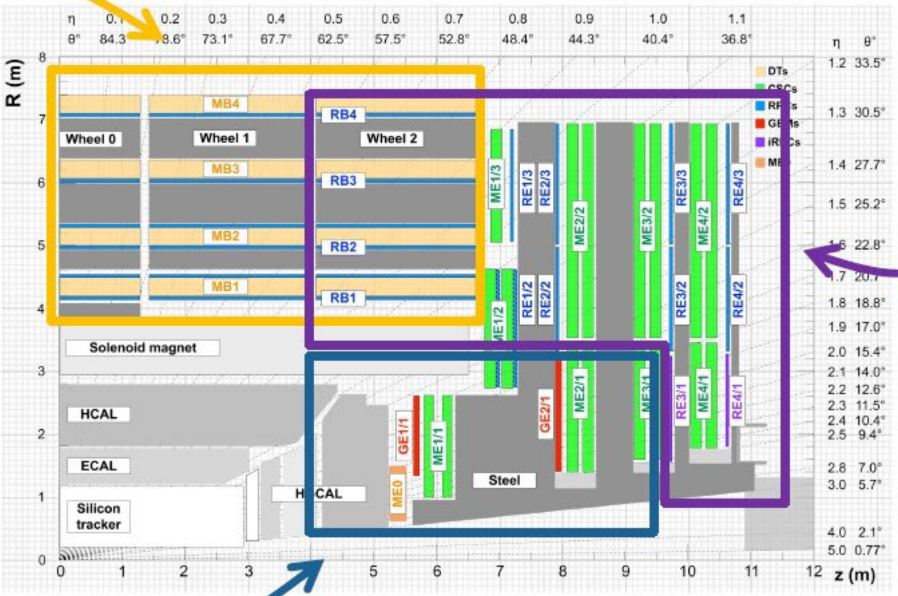
The new chambers add redundancy, improve the triggering and reconstruction performance, and increase the acceptance in the forward detector region

DT upgrade

- OBDT development and production
- YB+2 slice test

GEM upgrade

- GE2/1 production and demonstrator
- ME0 design finalization



RPC upgrade

- New link system
- iRPC installation and demonstrator

Irradiation and R&D:

- Longevity
- High-rate

Trigger and DAQ at HL-LHC

ATLAS DAQ architecture based on the FELIX card: hard- and firm-ware upgrade ongoing for HL-LHC

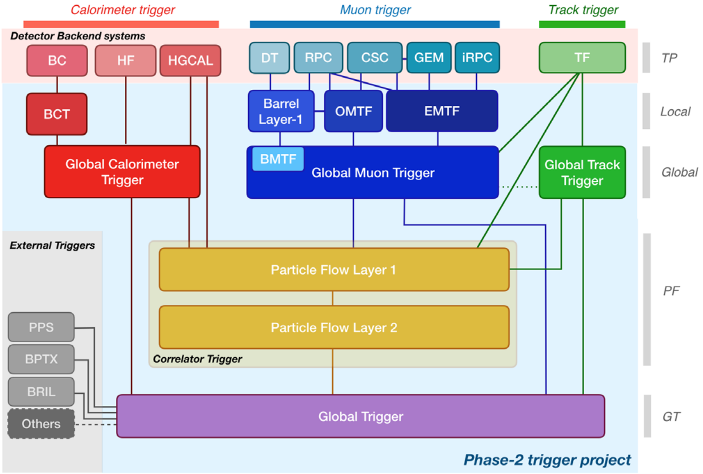
FE electronics linked via FELIX readout to DAQ

Expected HW and SW trigger performance:
- Level 0: 1 MHz, ~5.2 TB/s, 10 µs latency
- Event Farm: 10 kHz, ~52 GB/s

Exploit full detector granularity and extended tracking range, improve muon trigger efficiency

CMS: Latency of the L1 trigger increased to 12.5 µs L1 bandwith to 750 kHz, reduced at 7.5 kHz by HLT

Tracker and HGCal available at L1: higher input granularity exploited by sophisticated object reconstruction algorithms (PF, NN, implemented on FPGAs)



Possibility of trigger **scouting** at 40 MHz explored

Conclusions

- HL-LHC will allow a much deeper understanding of the processes we already know, and it will be a powerful instrument to enlarge the scope of our exploration of the unknown. At the same time it will present **unprecedent challenges** for the detector technologies and data acquisition systems
- All current ATLAS and CMS sub detectors must be either verified to be able to sustain the **high radiation doses** at HL-LHC, or updated to allow so, and in several cases even fully replaced by new more radiation resistent ones
- **4D tracking**, with timing information, and **improved granularity of the calorimeters** will allow separating the interesting events from the overlapping pile-up ones and improving the performance of the particle flow reconstruction algorithms
- Trigger and DAQ systems designed to achieve **much higher acquisition rates** than at Phase 1, **higher trigger latencies**, and **more sophisticated algorithms** applied already in the hardware trigger

Backups