



The CMS Outer Tracker Upgrade for the High Luminosity LHC

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August 8, 2023



Overview

- Motivation
Current CMS tracker, the HL-LHC accelerator upgrade

- The CMS Outer Tracker upgrade

Priorities:



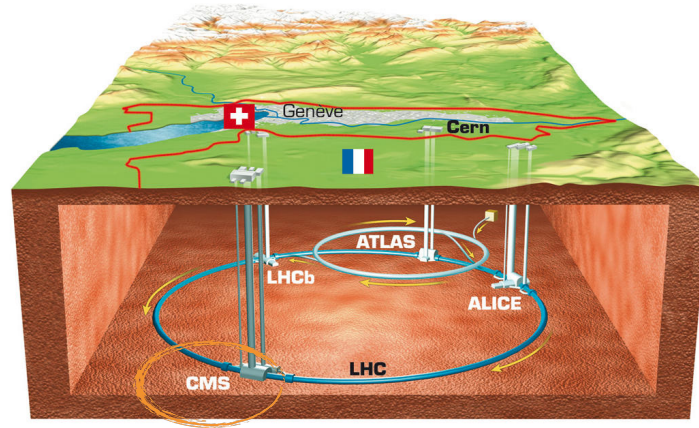
Trigger, layout, module design

- Spotlight on the MaPSA program
Prototype testing, plans for production



The Large Hadron Collider (LHC)

- Proton-proton collider at CERN, on the French-Swiss Border
- Collision energies are the highest ever reached
- Four experiments are located at points where the proton beams intersect



The Large Hadron Collider (LHC)



The Late Show: April 7, 2022

The CMS experiment



CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel (100x150 μm^2) ~1.9 m² ~124M channels
Microstrips (80-180 μm) ~200 m² ~9.6M channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000 A

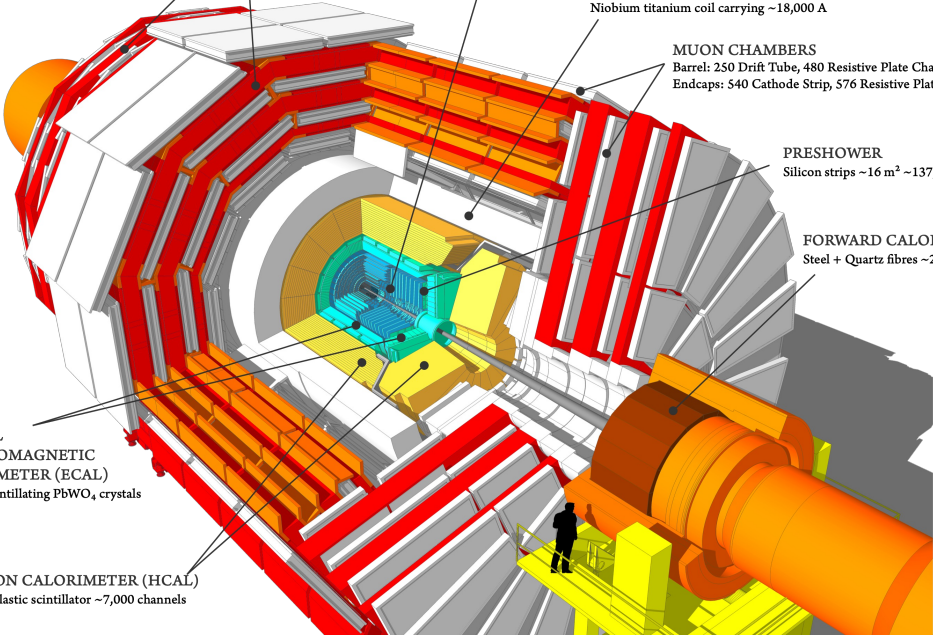
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers

PRESHOWER
Silicon strips ~16 m² ~137,000 channels

FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels

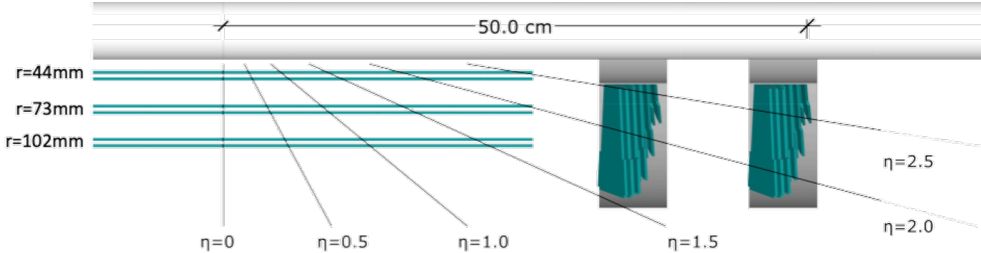
CRYSTAL
ELECTROMAGNETIC
CALORIMETER (ECAL)
~76,000 scintillating PbWO₄ crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels



The CMS pixel detector

- Original (2011): 3 barrel layers + 2 endcap disks
Pixel area $100 \times 150 \mu\text{m}^2$, thickness $320 \mu\text{m}$



The CMS pixel detector

- Original (2011): 3 barrel layers + 2 endcap disks

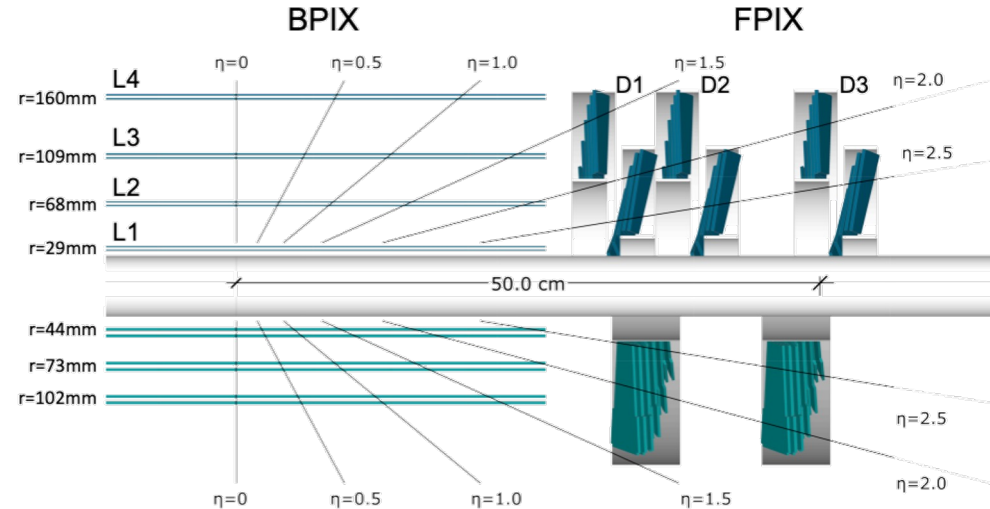
Pixel area $100 \times 150 \mu\text{m}^2$, thickness $320 \mu\text{m}$

- Phase 1 upgrade (2017): 4 barrel layers + 3 endcap disks

Innermost layer closer to collision

Pixel area same, thickness $285\text{-}300 \mu\text{m}$

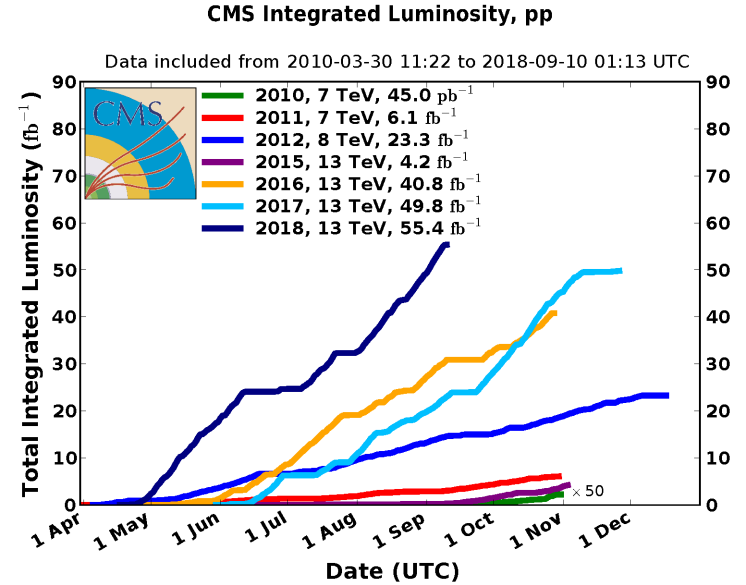
Less material in the forward region
(carbon-fiber mechanics, CO_2 cooling)



Why the Phase 1 upgrade?

- Every year, CMS collects MORE integrated luminosity in THE SAME amount of time

How?

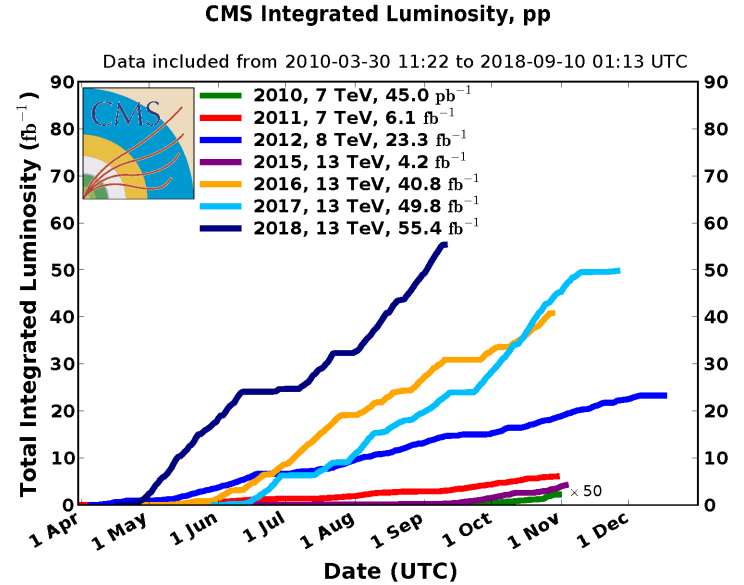


Why the Phase 1 upgrade?

- Every year, CMS collects MORE integrated luminosity in THE SAME amount of time
- Upgrades to the LHC accelerator give higher **instantaneous luminosity** \mathcal{L}

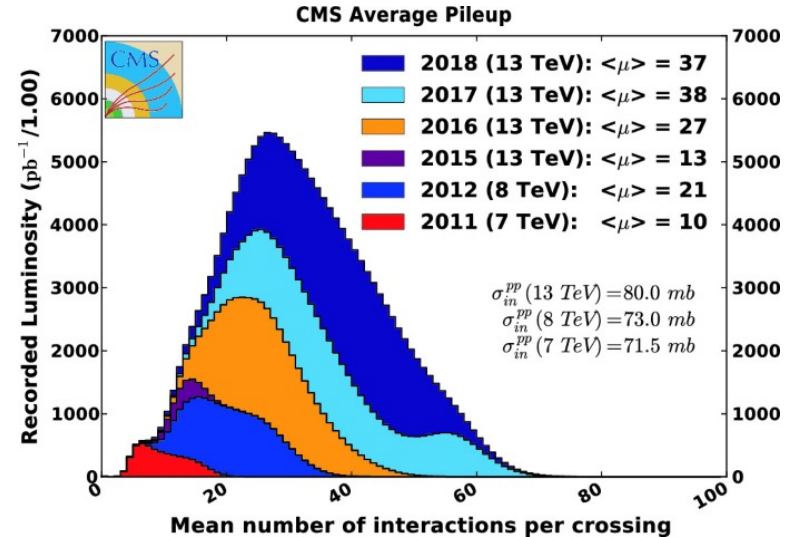
More collisions at the same time (**pileup**)

$$\mathcal{L} = \frac{n_p^2 n_b f}{4\pi\sigma_x\sigma_y}$$



Why the Phase 1 upgrade?

- Every year, CMS collects MORE integrated luminosity in THE SAME amount of time
- Upgrades to the LHC accelerator give higher **instantaneous luminosity** \mathcal{L}
More collisions at the same time (**pileup**)
- Levels of \mathcal{L} exceeded design expectations
Original pixel detector electronics could not cope!
Upgrade gave higher data output, larger buffers for data storage, etc.



The CMS strip tracker

- Two types of modules: **single-sided** and **double-sided** divided into four regions:

Tracker inner barrel (TIB)

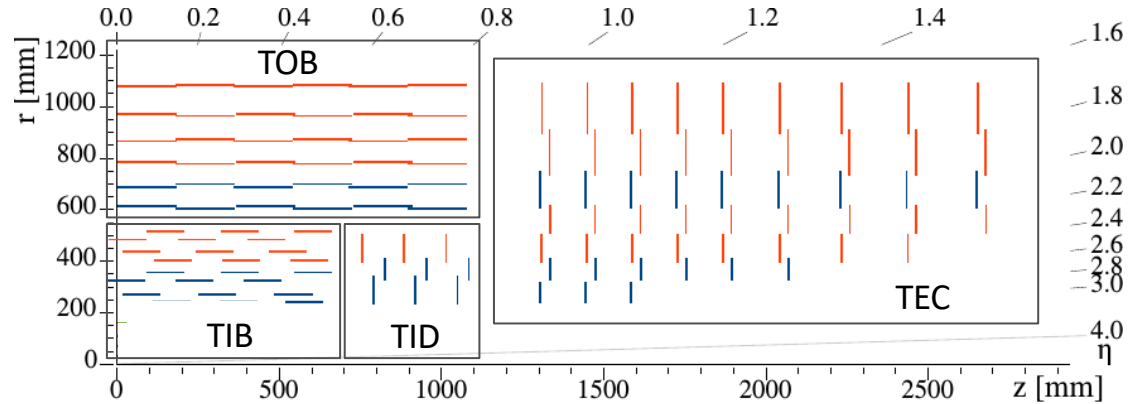
Tracker outer barrel (TOB)

Tracker inner disks (TID)

Tracker end-caps (TEC)

- 80-120 μm pitch
- Length 8.5-20 cm
- 320-500 μm sensor thickness
- This sub-detector is still the original!

Farther from the interaction point \rightarrow effects of pileup are less extreme



The HL-LHC

- By Run 3, we will have collected $\sim 450 \text{ fb}^{-1}$ in 11 years
- The **High Luminosity LHC (HL-LHC)** collider upgrade will provide 3000 fb^{-1} to CMS in 11 years

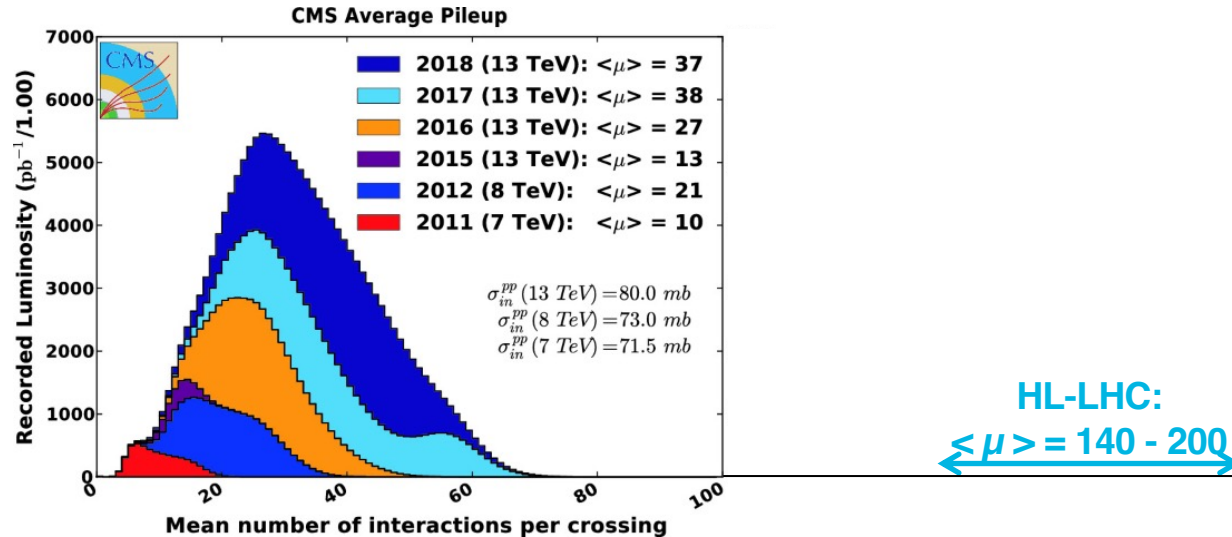
Up to 20x more integrated luminosity than we have now

100x more than we had at the time of the Higgs discovery

How?

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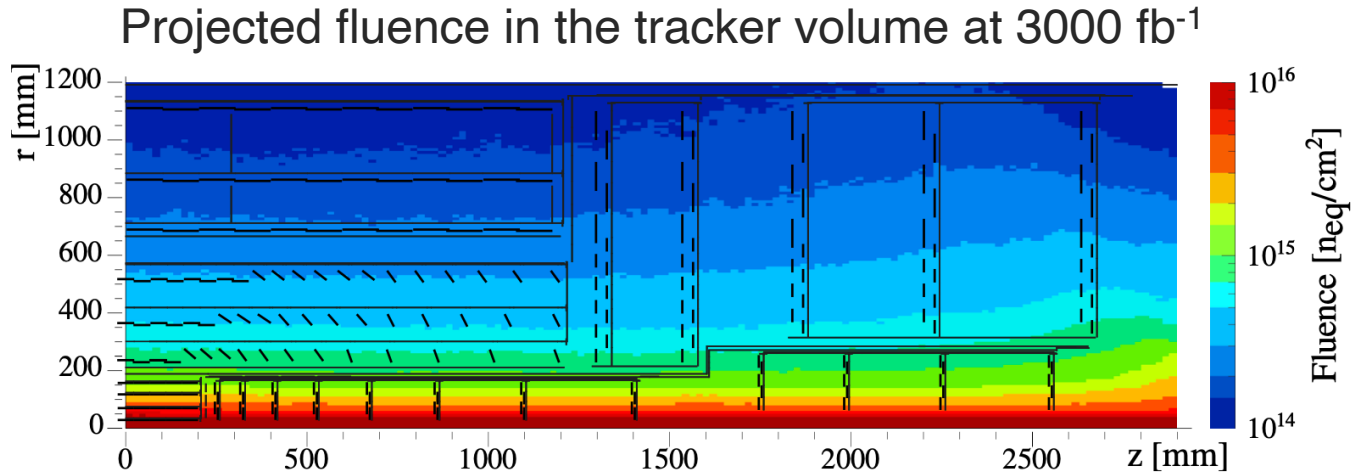


Running conditions at the HL-LHC



- Large doses of non-ionizing radiation, or **fluence**, cause damage to silicon sensors by disrupting the lattice
- **Fluence \propto integrated luminosity**

If we want more data, we have to deal with more damage.



Signs of wear in the tracker

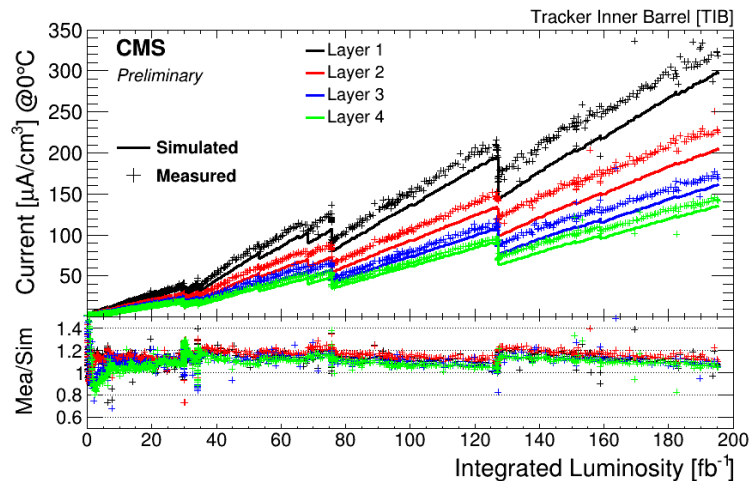


- Increasing **leakage current** due to damage to the silicon lattice

Periods of **annealing** when the detector is at room temperature

- Shown here for strip modules at different layers

Closer to the interaction point → more radiation damage → higher leakage current



Signs of wear in the tracker

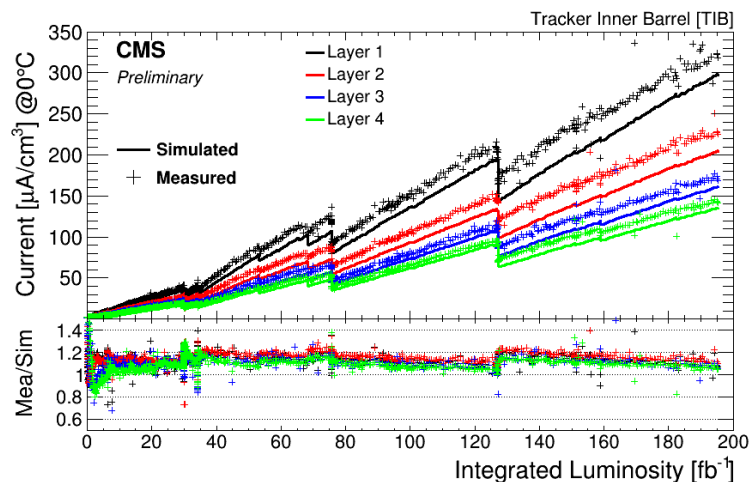


- Increasing **leakage current** due to damage to the silicon lattice

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Closer to the interaction point \rightarrow more radiation damage \rightarrow higher leakage current



- Without sufficient cooling, will experience **thermal runaway**

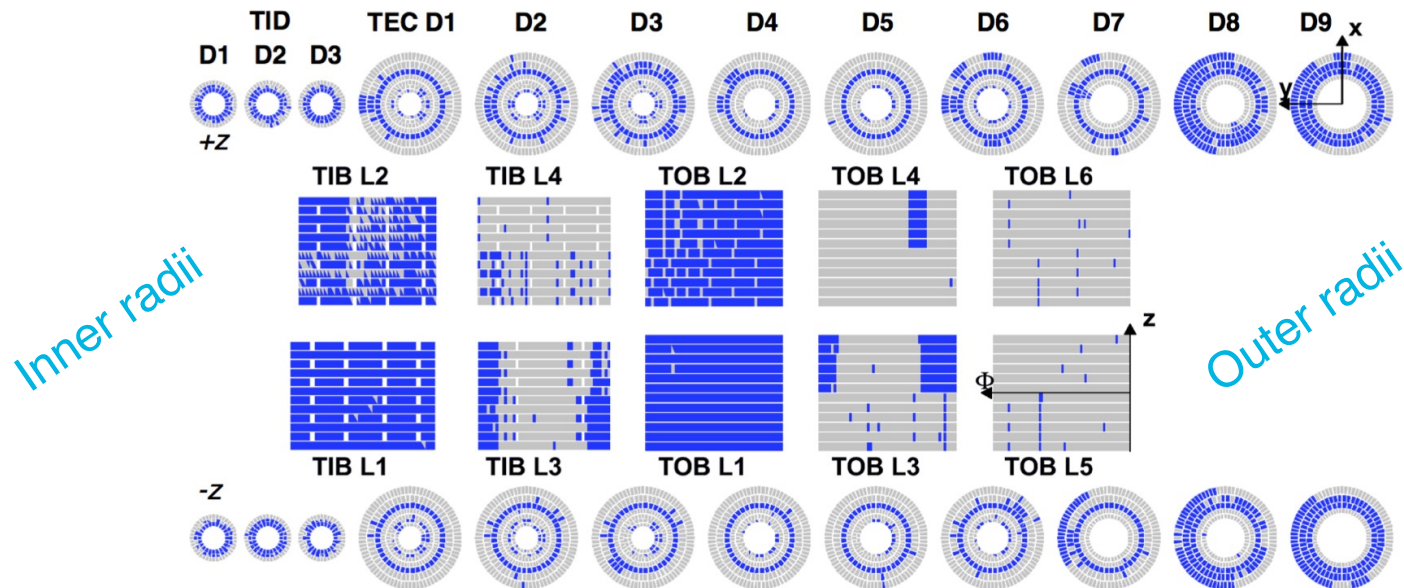
Higher I_{leak} increases temperature, which increases I_{leak} , etc.

Current tracker cooling system is limited to -20°C

What will the HL-LHC do to our tracker?

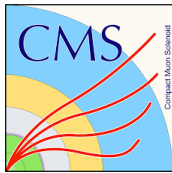


- After collecting only 1000 fb^{-1} , the blue modules in the current tracker become completely **in-operable**!



Phase 2 upgrade of the CMS tracker

Upgrading CMS for the HL-LHC



CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
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SILICON TRACKERS
Totally replaced

Trigger system:
all new

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000 A

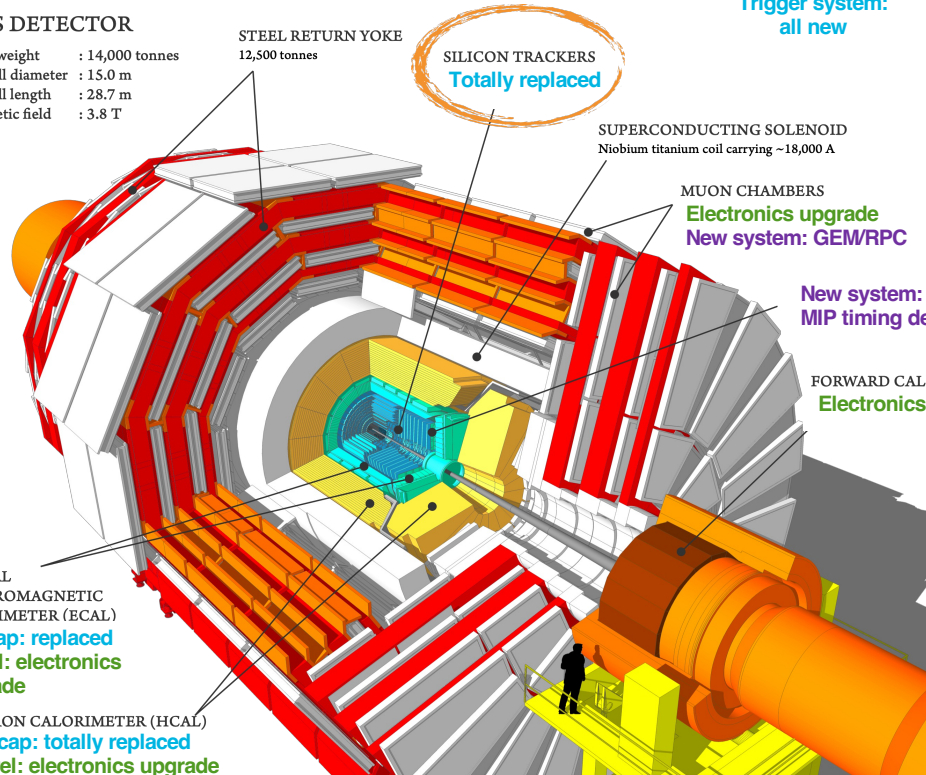
MUON CHAMBERS
Electronics upgrade
New system: GEM/RPC

New system:
MIP timing detector

FORWARD CALORIMETER
Electronics upgrade

CRYSTAL
ELECTROMAGNETIC
CALORIMETER (ECAL)
Endcap: replaced
Barrel: electronics
upgrade

HADRON CALORIMETER (HCAL)
Endcap: totally replaced
Barrel: electronics upgrade



Priorities of the tracker upgrade

 Robust **tracking** in high pile-up conditions

Fine granularity, less material

 **Built to last** for a decade or more

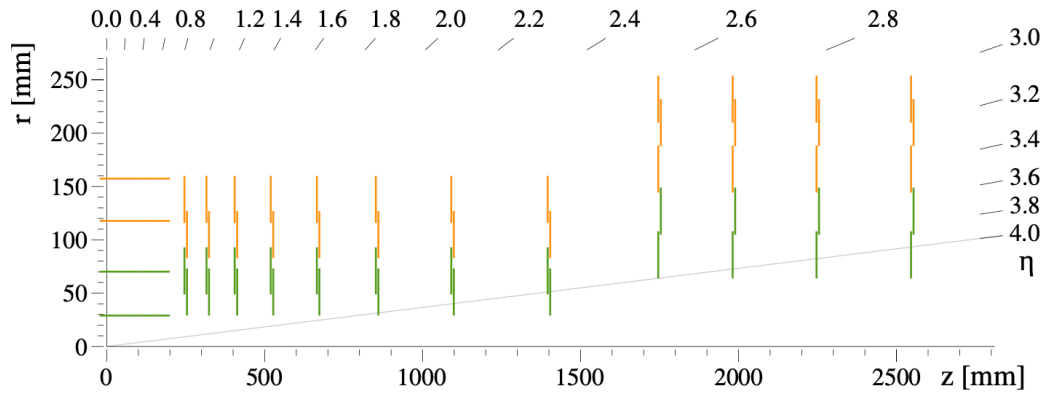
Radiation tolerance is critical

 Pass track info to the **hardware-level trigger** (L1) – Outer Tracker only

Using tracks to decide whether to read out data

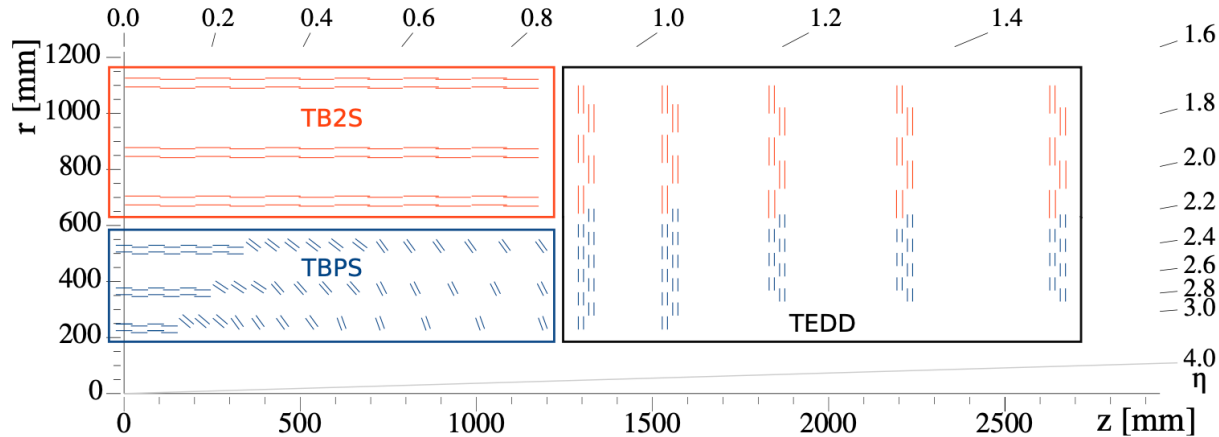
Phase 2 inner tracker (pixel)

- Consists of 4 barrel layers (TBPX) + 8 small and 4 large double-disks (TFPX)
 - 👩 Thinner sensors: 100-150 μm (compared to 285-300 μm)
 - 🐾 Smaller pixel size: 25 x 100 μm^2 or 50 x 50 μm^2
 - 🐾 Coverage up to $|\eta| < 4.0$ (compared to 2.5)



Phase 2 outer tracker

- Tracker Barrel (TB) region:
 - TBPS: 3 double-sided layers of **PS modules** (flat and tilted)
 - TB2S: 3 double-sided layers of **2S modules** (flat)
- Tracker Endcap Double Disks (TEDD): 5 double-sided disks



Tracker material budget



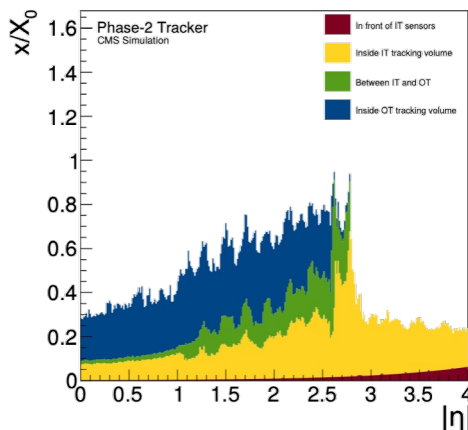
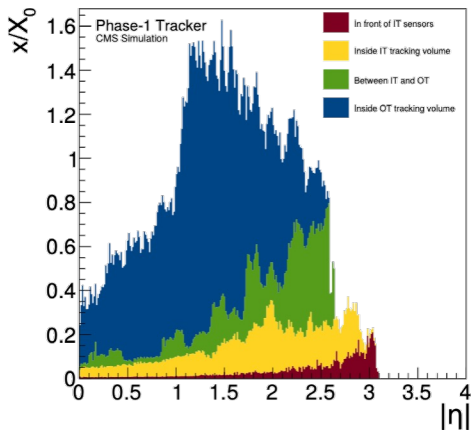
- Dramatic reduction in total material budget compared to current tracker!

Mechanical structures primarily made of **carbon fiber** and **carbon foam**

Dual-phase CO₂ cooling system uses far less material than current cooling system

Some **services** are moved outside of the detector volume

Tilted section uses fewer modules than flat



The upgraded level 1 trigger



- Can select more data to save: 100 kHz \rightarrow 750 kHz
If we make no other changes... would need a rate **~ 4 MHz** for pileup $\langle \mu \rangle = 200$
- **Receives info from the tracker**
Not possible in current detector, but critical for HL-LHC!
- Has more time to decide what to save: latency of 4 μ s \rightarrow 12.5 μ s
Use this time to perform some fast tracking

Example: single muon trigger



Efficiency

Do we save most of the target process above $p_T > 20$ GeV?

Rate

Does the amount of data that we save fit within the limitations?

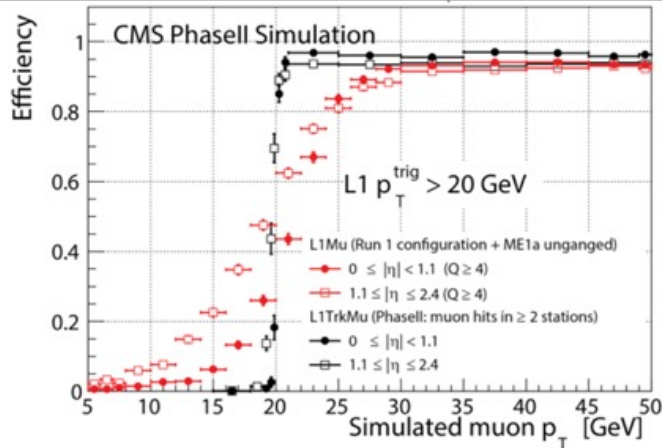
Example: single muon trigger



Efficiency

Do we save most of the target process above $p_T > 20$ GeV?

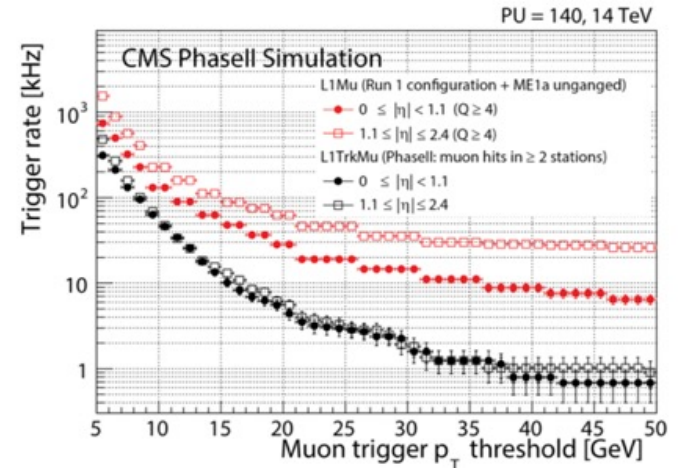
- With tracks: yes
- No tracks: not near the threshold



Rate

Does the amount of data that we save fit within the limitations?

- With tracks: yes
- No tracks: not for low thresholds



What do we gain from using tracks at L1?



- **Charged particle candidates**

Electrons and muons, hadronic taus, jets

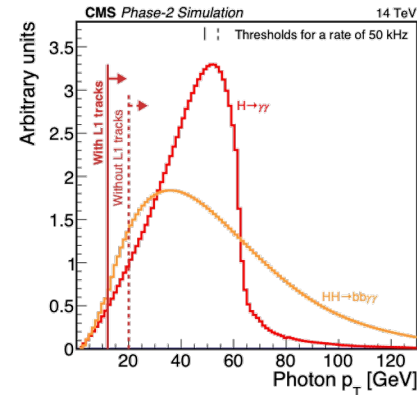
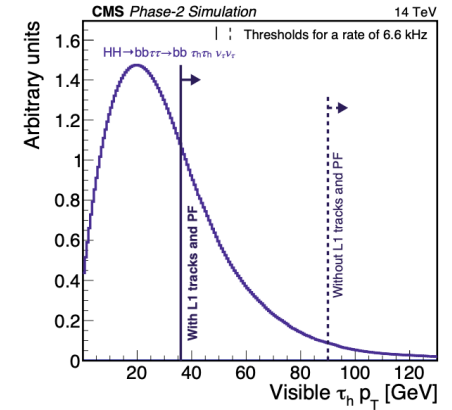
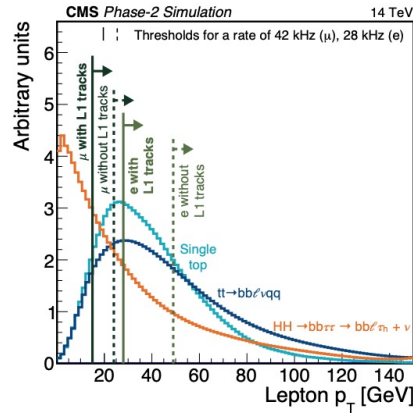
- Information about **isolation**

Are there a lot of tracks near a particle candidate?

- **A collision vertex!**

Gives photons and missing energy something to point back to

Rejection of pileup, which corresponds to the wrong vertex



Trigger: design of p_T modules



- Each module consists of two **closely spaced sensors**
- Given a hit in the inner sensor, the position of the hit in the outer depends on:

The particle's momentum (p_T)

The separation Δr between the sensors

Where the module is in the detector (r)

$$\Delta x = r \Delta r \frac{qB}{2p_T}$$

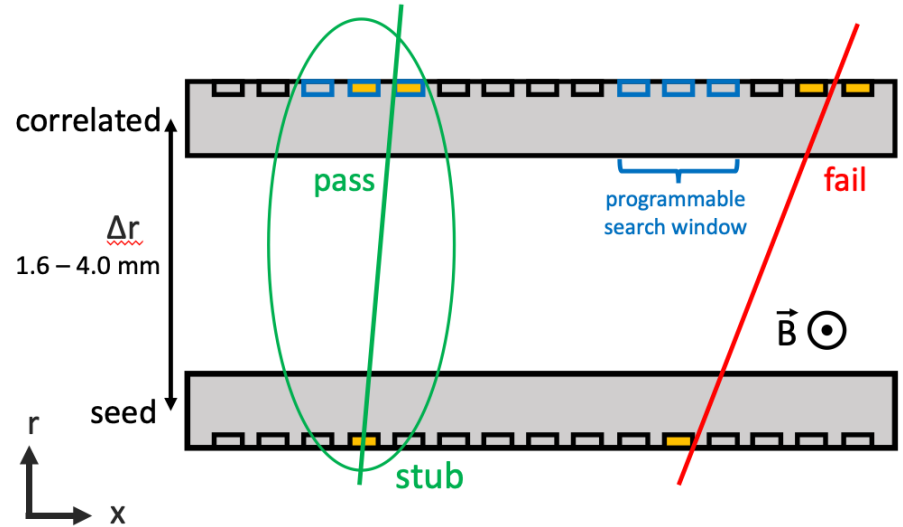
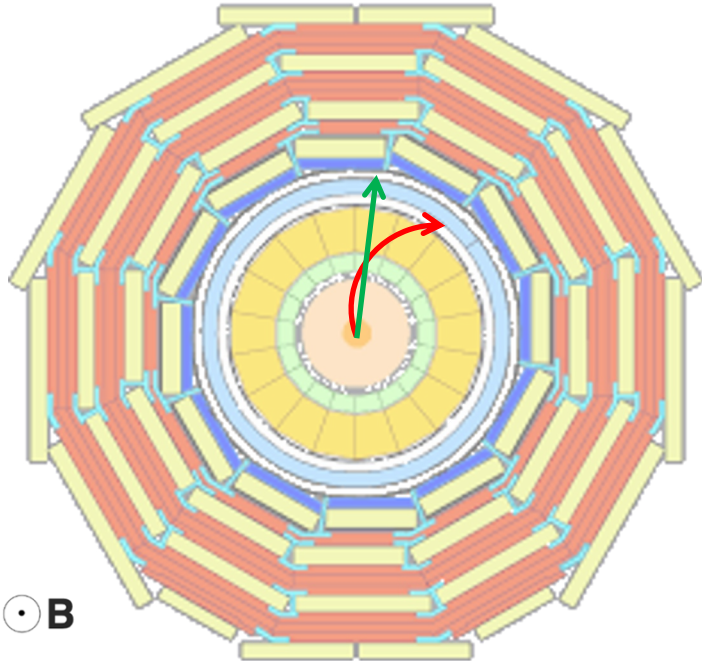
- For a given Δr , can define a search window where the second hit will be for all tracks with **$p_T > 2 \text{ GeV}$**

Position and width of stub window depend on where the module is in the detector (programmable)

Trigger: design of p_T modules



- Patterns of hits consistent with high p_T tracks (**stubs**) are passed to L1 trigger



2S module: design

- Two silicon strip sensors

Area $10 \times 10 \text{ cm}^2$

👤 Thickness of **$300 \mu\text{m}$**

🐾 2 rows of **$90 \mu\text{m} \times 5 \text{ cm}$** strips

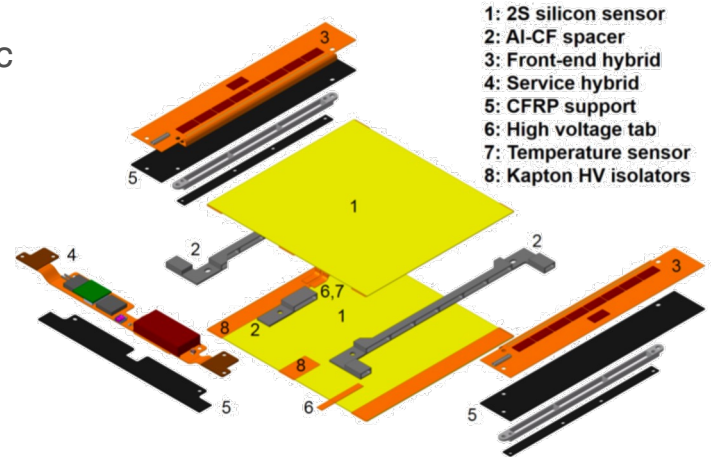
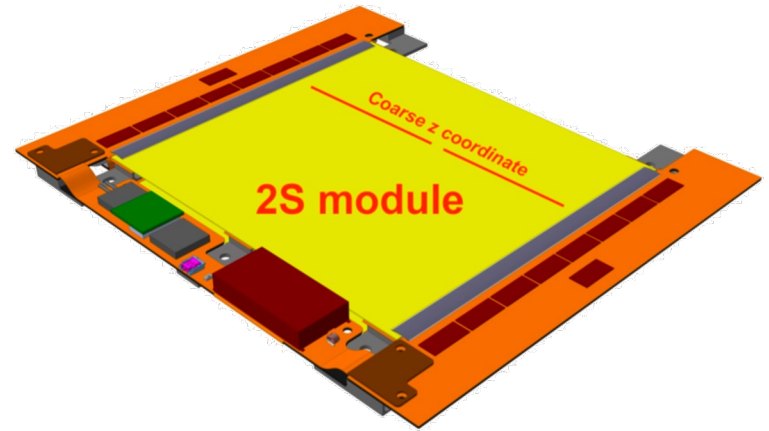
- Two front end hybrids, each with

8x CMS Binary Chips (CBC) for sensor readout, stub logic

1x Concentrator Integrated Circuit (CIC) for data aggregation, clustering, etc.

- Service hybrid

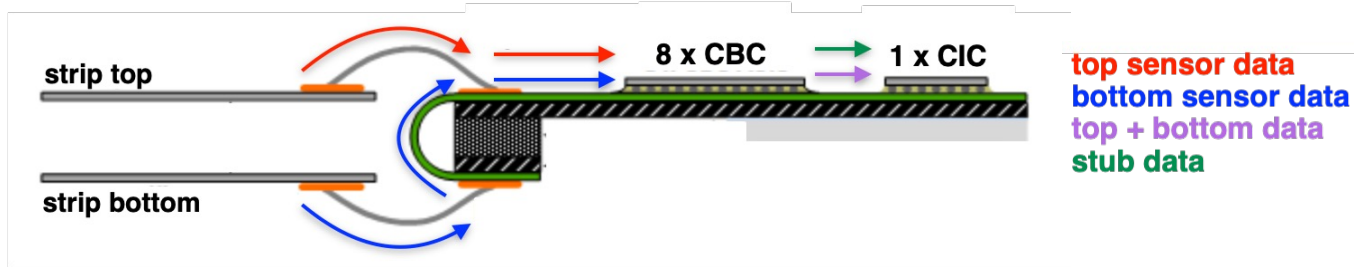
Provides power, electrical-optical conversion, etc.



2S module: design & fabrication

- Sensors are wire-bonded to front end hybrids

Top and bottom connected to same CBC for stub correlation



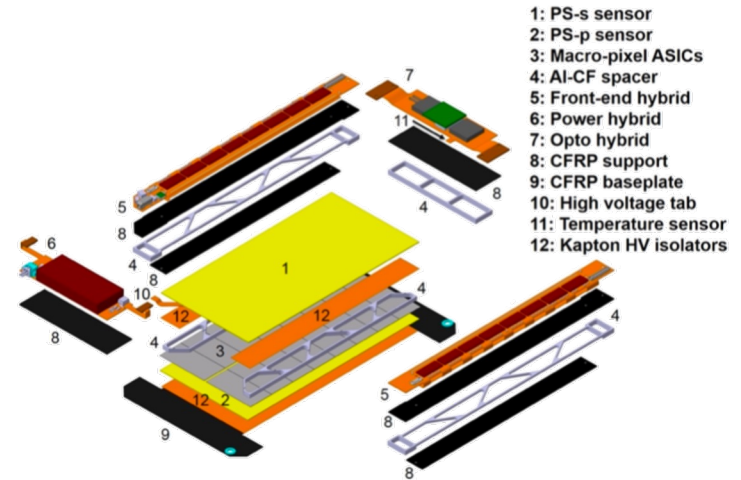
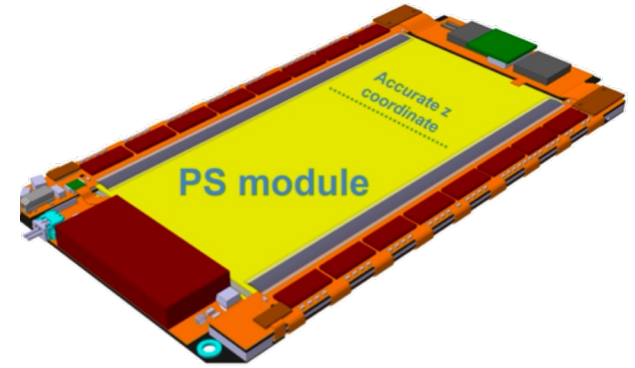
- Prototype assembly and testing underway

Assembly planned in Germany, Belgium, US, India, & Pakistan

- Small prototypes have been irradiated and tested in magnetic field, test beam 🧑🏻

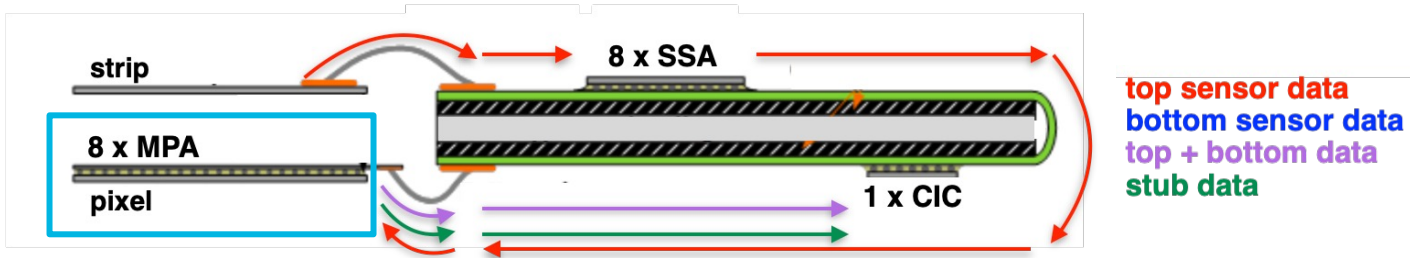
PS module: design

- Two silicon sensors
 - Area $5 \times 10 \text{ cm}^2$
 - 👤 Thickness of **$300 \mu\text{m}$**
- Top: strip sensor (PS-s)
 - 🐾 Two rows of strips, **$100 \mu\text{m} \times 2.4 \text{ cm}$**
- Bottom: Macro-Pixel Sub-Assembly (**MaPSA**)
- Two front-end hybrids, each with
 - 8x Short Strip ASICs (SSA) for readout of strip sensor
 - 1x CIC for data aggregation, clustering, etc.
- Separate optical & power hybrids



PS module: design & fabrication

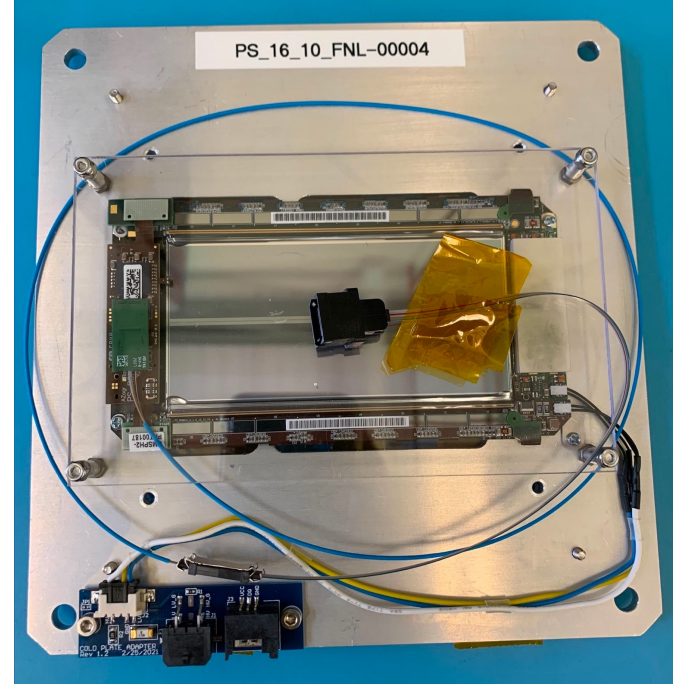
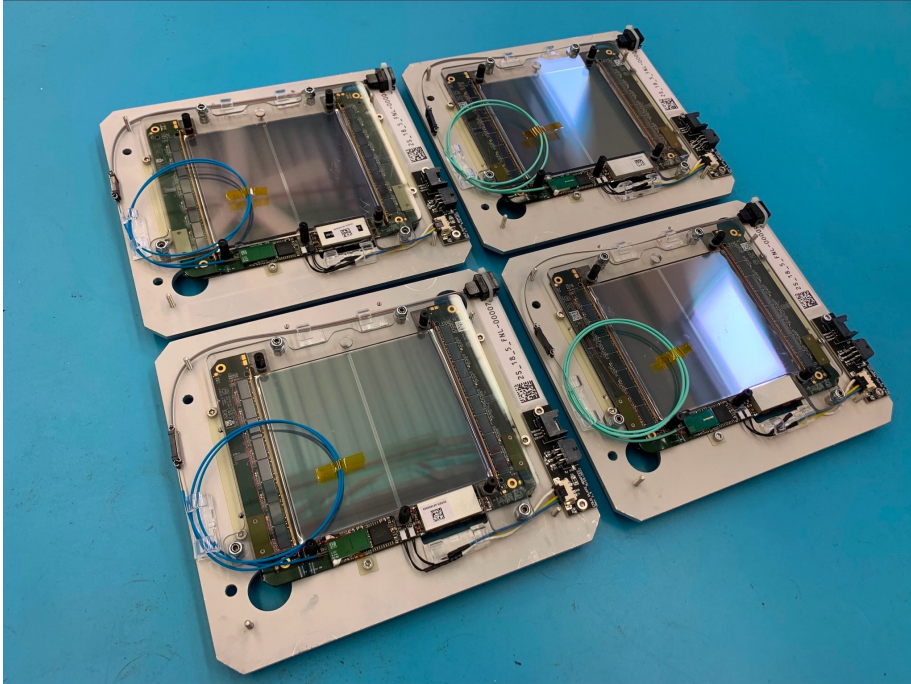
- **MaPSA** assembled at bump-bonding vendors
- Top sensor and MaPSA are wire-bonded to front-end hybrids



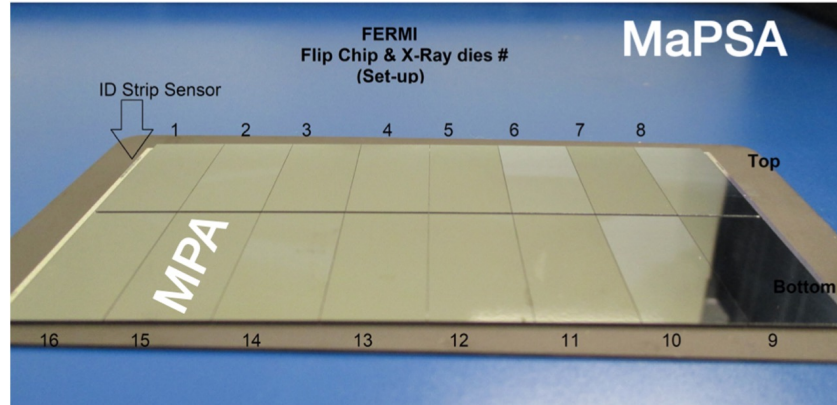
- Prototype assembly and testing underway
Assembly planned in Germany, Italy, & US
- Prototype recently irradiated and tested in test beam 🧑🏻

Prototype modules

- 9 2S and 4 PS built at Fermilab so far

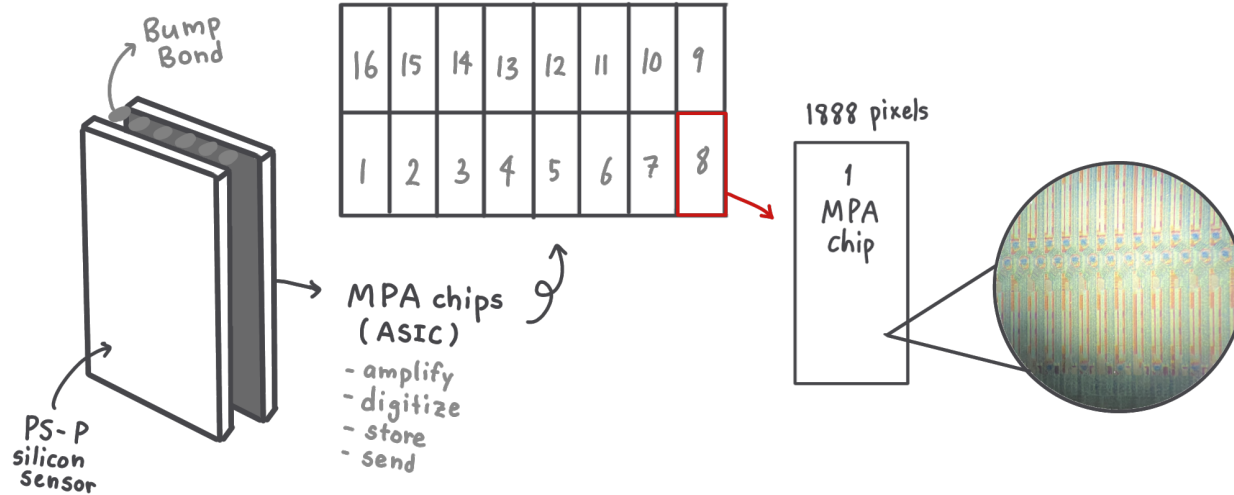


The MaPSA program



Macro-Pixel Sub-Assembly

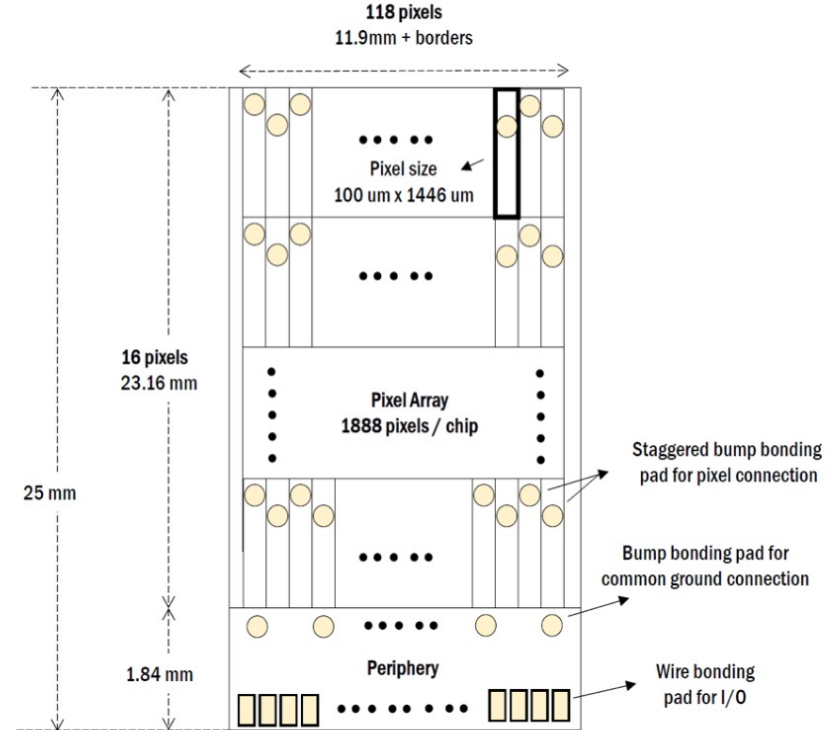
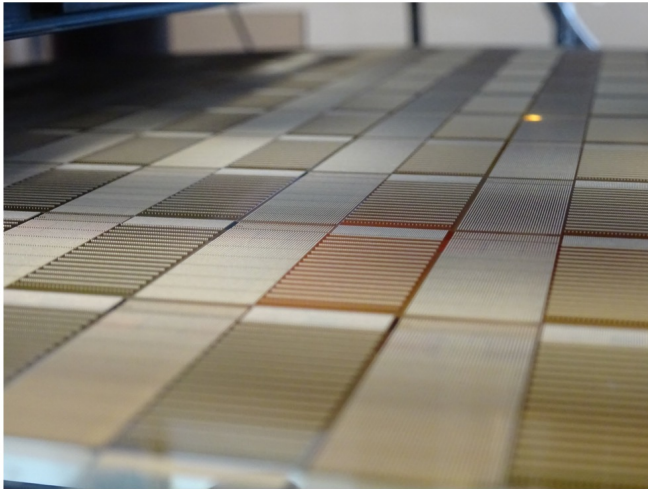
- 1x PS-p sensor
 - Macro-pixels with size **100 μm x 1.5 mm** 🐾
- 16x Macro-Pixel ASICs (MPA), 8 per side



Macro-Pixel ASIC

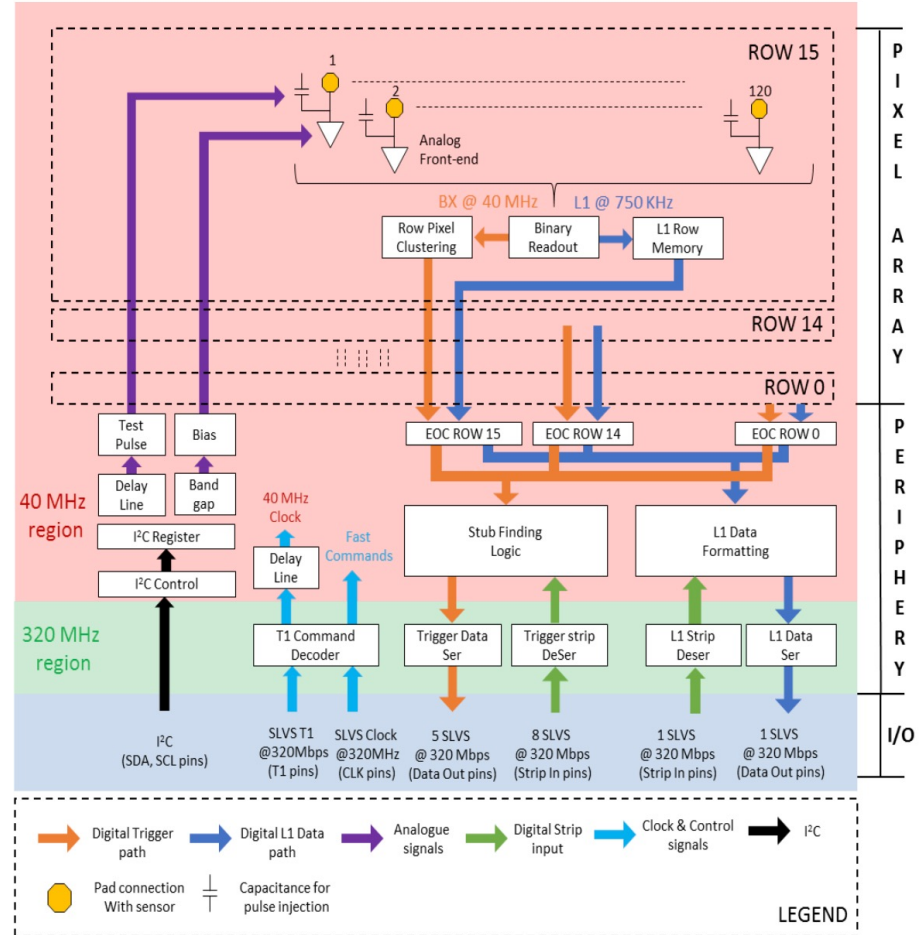
- Implemented in 65 nm CMOS technology
- 16 rows x 118 columns of pixels per ASIC
- Radiation tolerant design 🧓

Bumps Applied to MPA



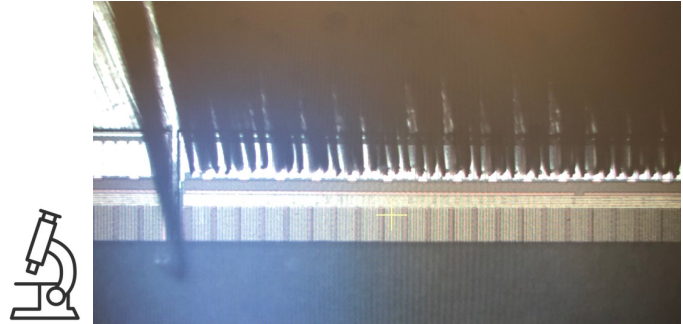
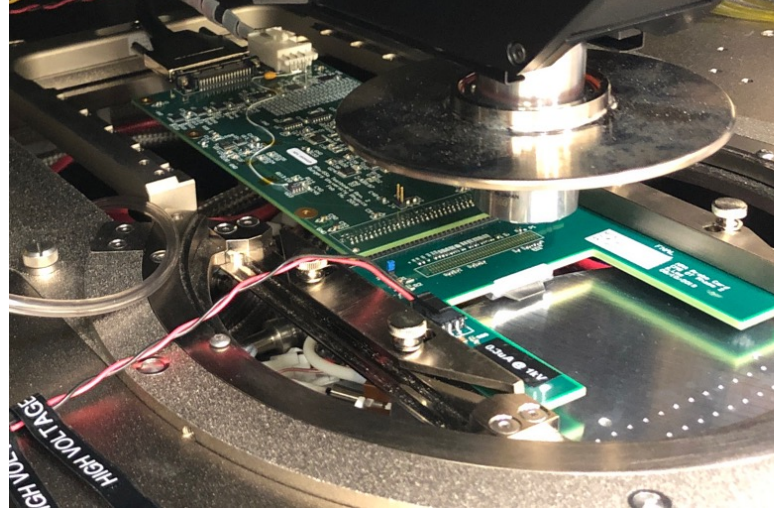
Macro-Pixel ASIC functionality

- Receive test commands
- Propagate them to pixels
- Receive strip hit info from SSA
- Perform stub logic, send to trigger
- Send full data out once triggered



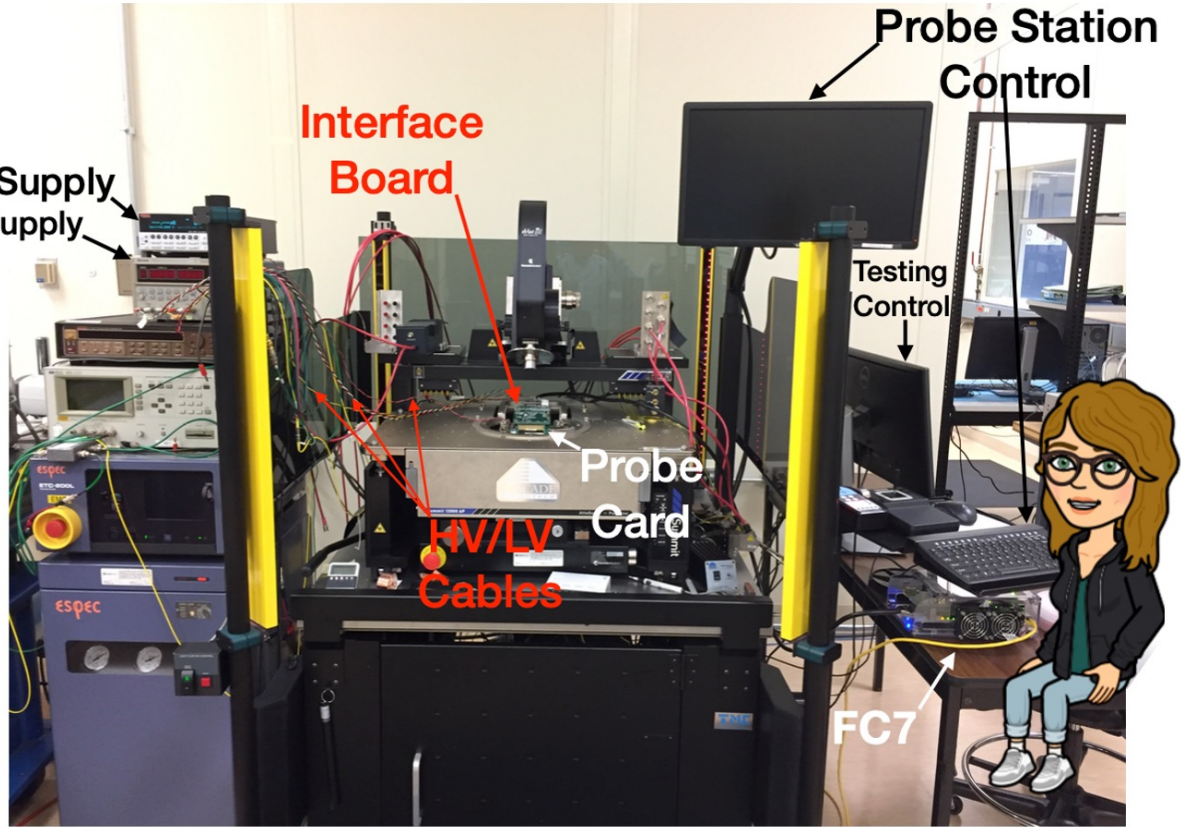
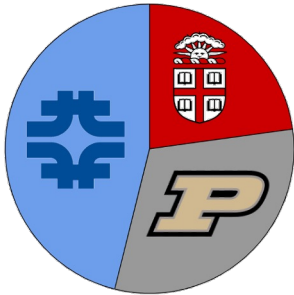
MaPSA probe testing

- Test the functionality of the **MPAs**
Do all pixels function? Must have $> 95\%$ operable to be installed in CMS
What is the noise in each pixel? $\sim 350e$
- Test the quality of the **bump bonds**
Are they all connected?
- Test the sensor **leakage current** (IV)
At what bias voltage does the current become too high?
- Prototypes perform very well
The MaPSA works!






MaPSA probe testing

- 150 prototypes already tested at Fermilab
 - 3 vendors
 - 3 prototype rounds
- 6500 production MaPSAs to take place in the U.S.
 - Test time: **1 hour / MaPSA**



In summary,

- Upgrading the CMS tracker is necessary to ensure good physics performance at the HL-LHC
- The upgraded Outer Tracker design ensures that it will
 -  Contribute to the L1 trigger (critical at high pile-up!)
 -  Provide robust tracking capabilities in high-pileup events
 -  Perform well through the end of HL-LHC data-taking
- The Macro-Pixel Sub-Assembly project is entering the production phase
Large scale plans for probe testing are in place!

Backup Material

Map of sensor spacing in the OT

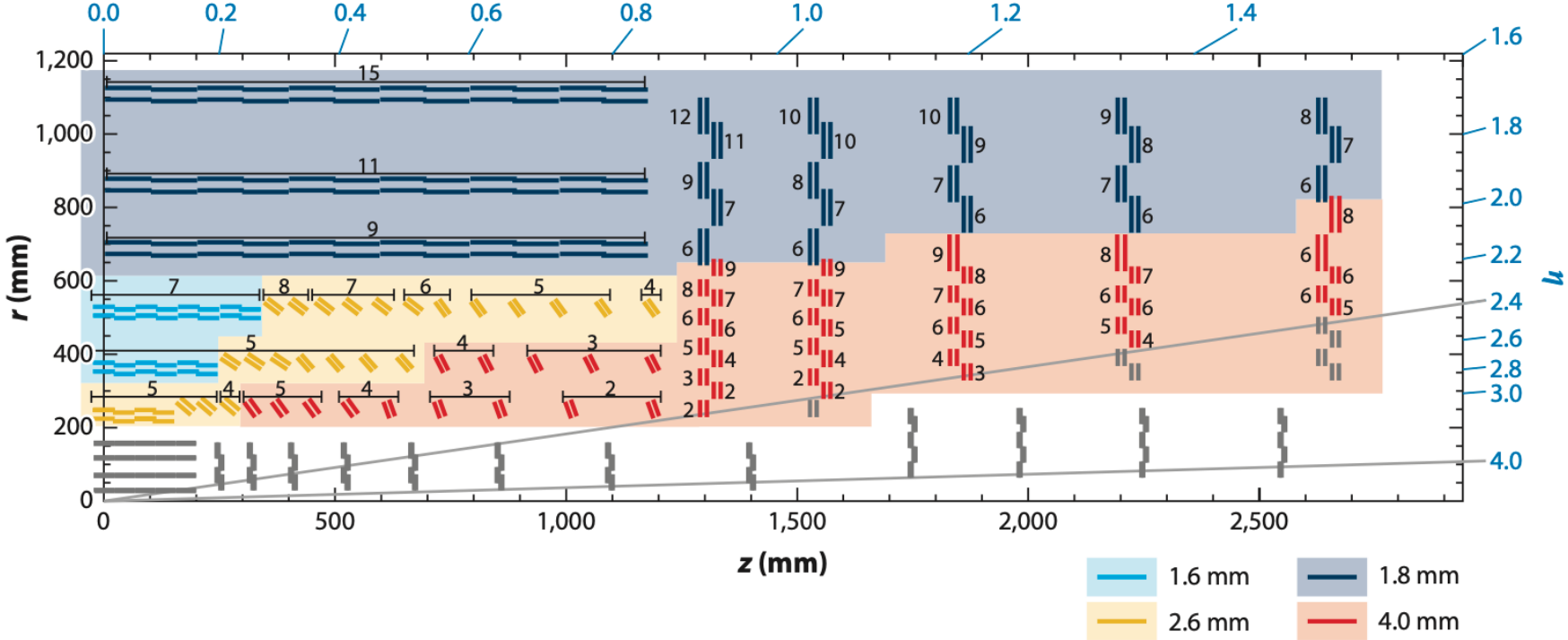
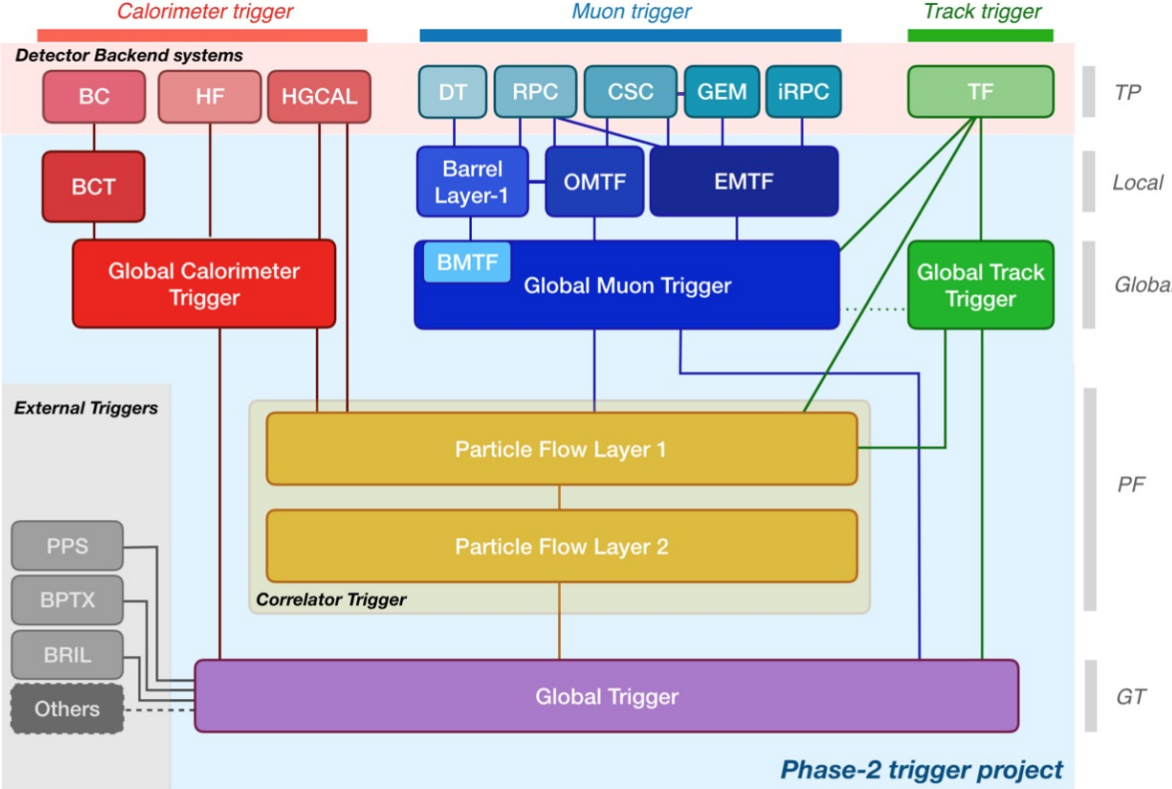


Diagram of the Phase 2 trigger system



Outer tracker layout

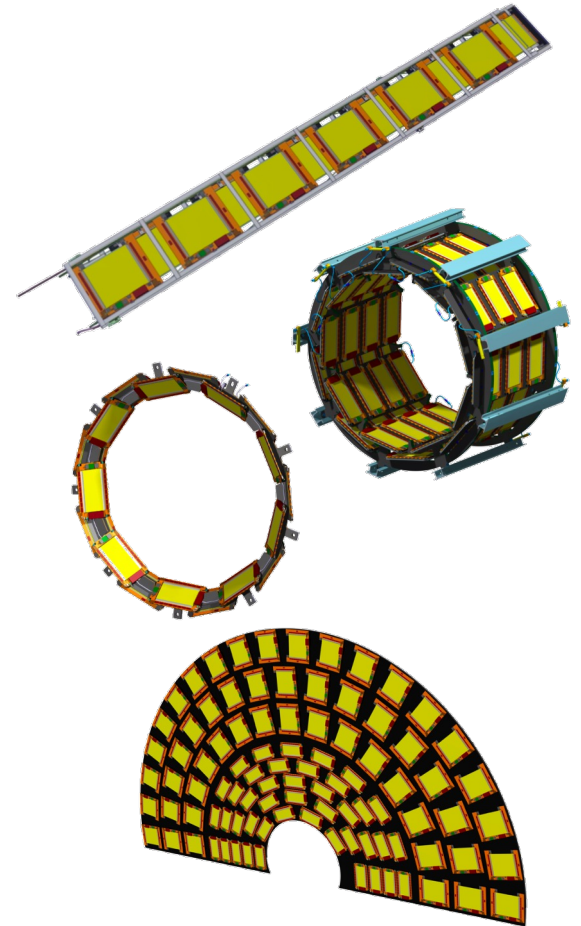
- In the barrel, modules overlap in z , ϕ to ensure hermiticity 🐾

2S modules are mounted on **ladders**

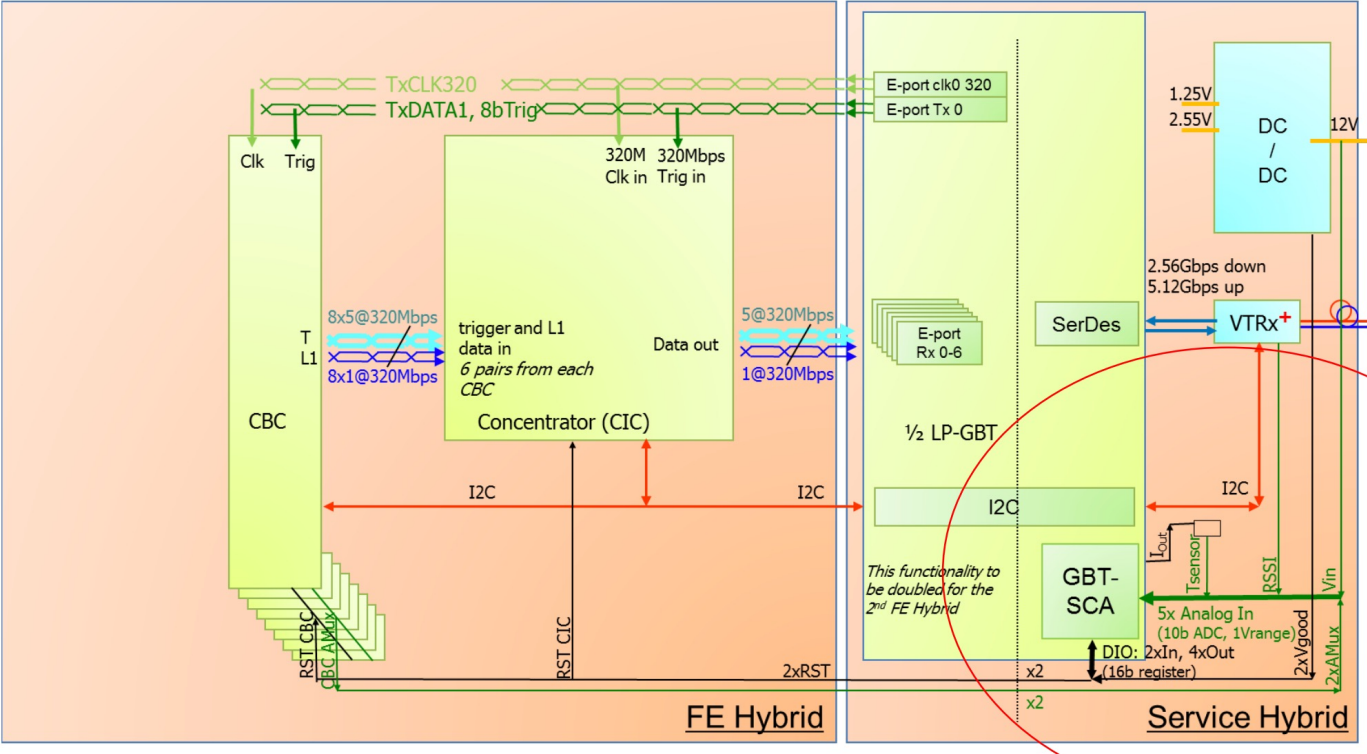
PS modules are mounted on **planks** (flat) and **rings** (tilted)

- In the endcap, modules overlap in r , ϕ 🐾

Both types of modules are mounted on **dees**



2S module: data flow



PS module: data flow

