The CMS Pixel Detector for the High Luminosity LHC

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on behalf of the CMS Tracker Group

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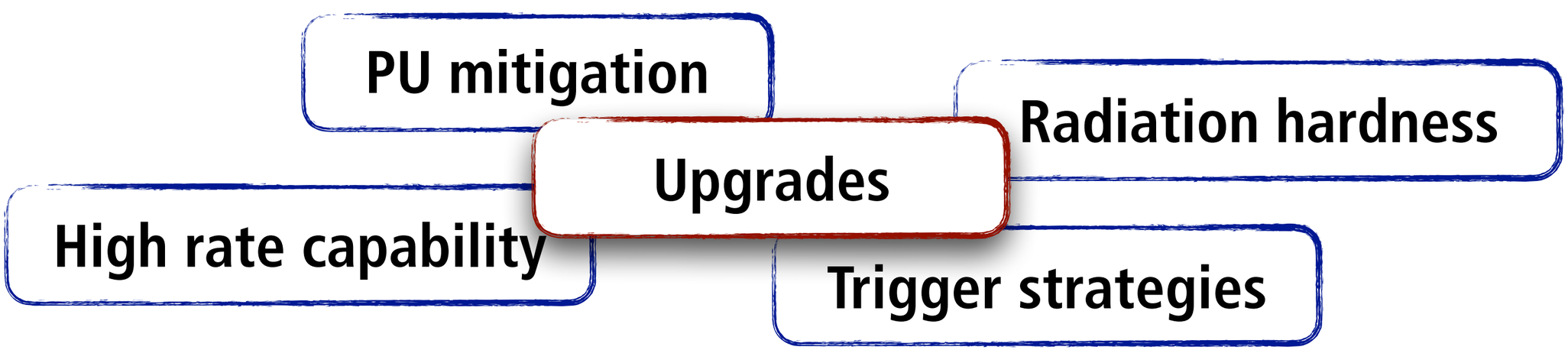
The High Luminosity phase of LHC

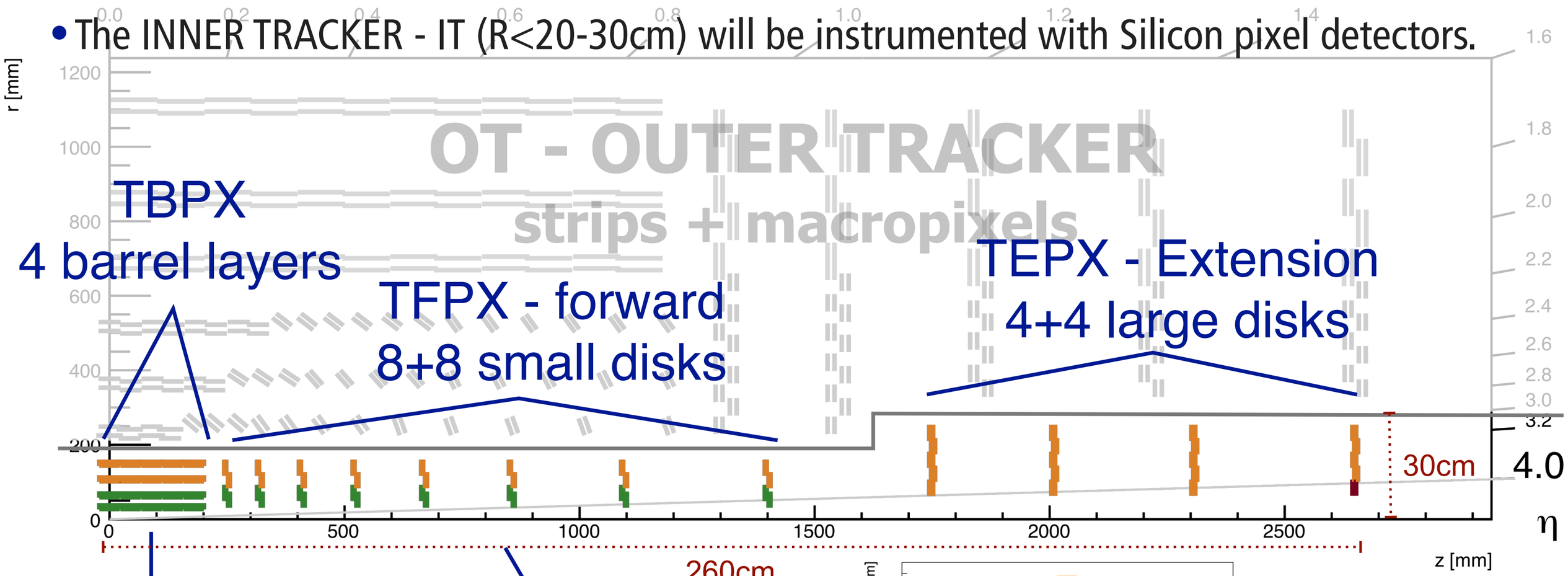
LHC 2010-2024	**HL-LHC** 2026-2039
7-14TeV	14 TeV
L_{IST}=**2 · 10^{34}cm^{-2}s^{-1}**	L_{IST}=**5-7.5 · 10^{34}cm^{-2}s^{-1}**
PU<**50-60**	PU=**140-200**
L_{INT}=**300fb^{-1}**	L_{INT}=**3000-4500fb^{-1}**

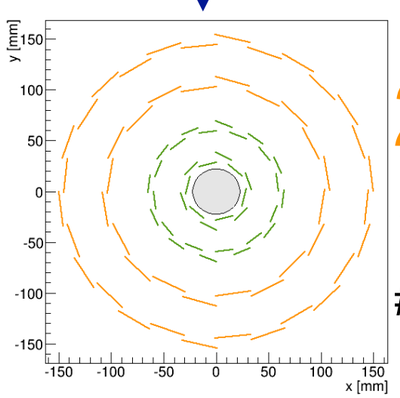
LHC experiments will undergo substantial upgrades to be ready for phase-2 in 2026; the current CMS tracker needs to be completely replaced because it will underperform in the harsh HL-LHC conditions and will no long survive radiation…



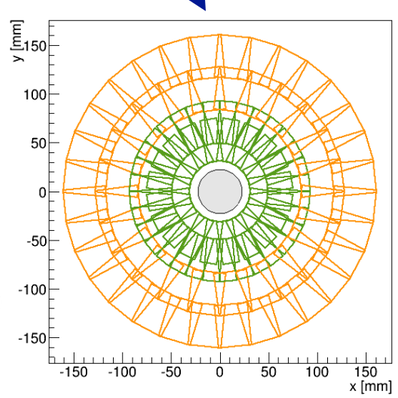
The CMS tracker upgrade for HL-LHC

- The INNER TRACKER - IT (R<20-30cm) will be instrumented with Silicon pixel detectors.





2x2
1x2
#chip/module



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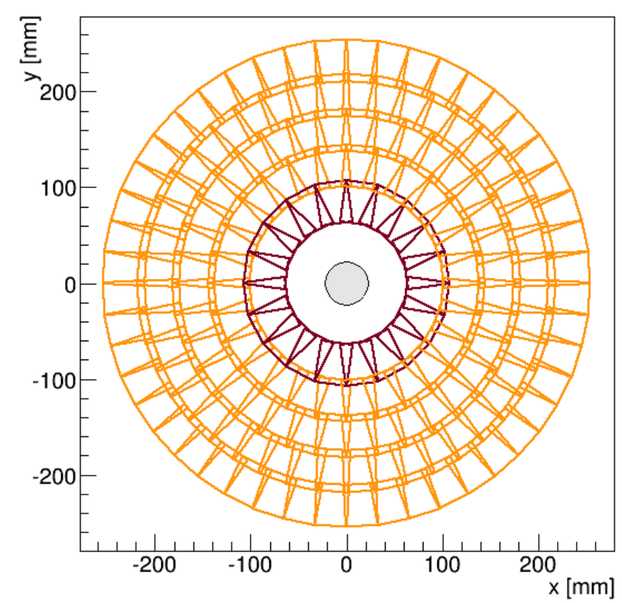


2x2
#chip/module

1156 1x2 mod.
2736 2x2 mod.
3892 in tot,
4.9m² of Si

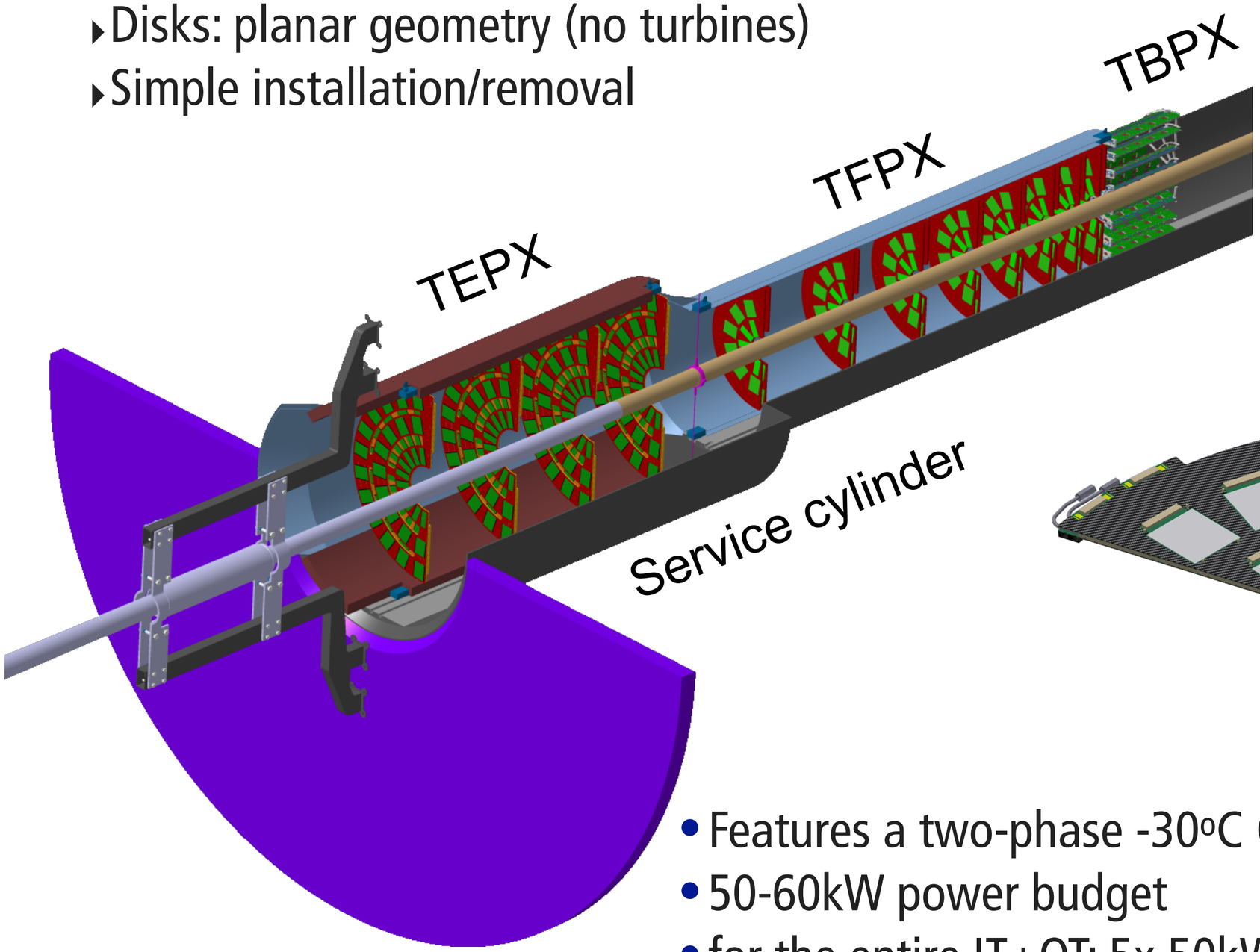
CMS Tracker upgrade requirements

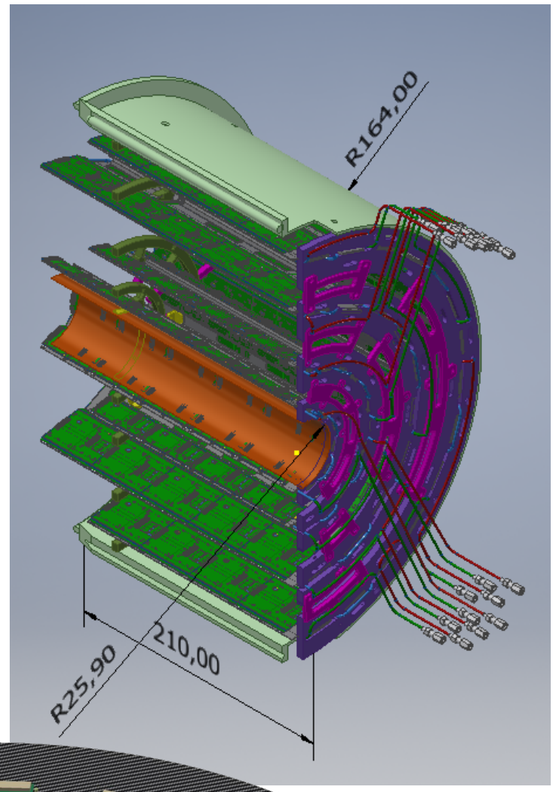
The Outer Tracker and the Inner Tracker are part of the same project. Some requirements do apply only on the IT and viceversa

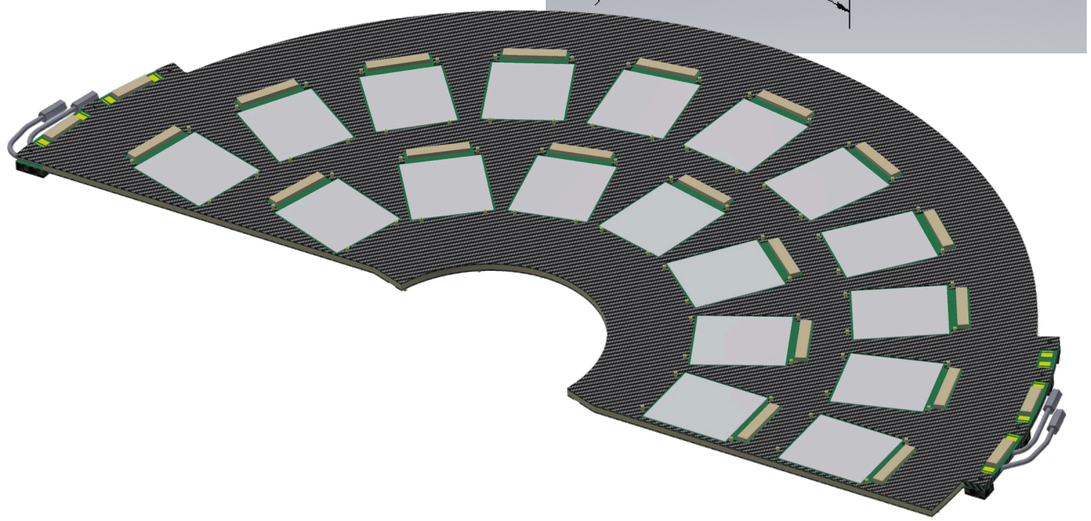
- **Radiation tolerance and cold (–20°C) operation to be functional up to 3ab^{-1} (with margins to comply with the best performance scenario)**
- **Optimized layout and granularity for robust pattern recognition in 140-200PU environment** (occupancy <O(1%) for the OT and **<O(0.1%) for the IT**)
- **Reduced passive material with respect to phase-1 tracker**
- Track Trigger capabilities to contribute to L1 (only the OT)
- **Large readout bandwidth and deep front-end buffers compliant with the rate (750kHz) and the long latency (12.5μs) of the upgraded L1 trigger system**
- **Coverage up to |η|~4 for efficient PU mitigation and better physics objects reconstruction in the forward region**
- **Very forward part of IT usable as a luminosity monitor**
- **IT fully accessible for maintenance and part replacement**

IT mechanical structure

- Simple mechanics:
  - Barrel: inspired to the current Phase-1 design, splits in half at z~0
  - Disks: planar geometry (no turbines)
  - Simple installation/removal



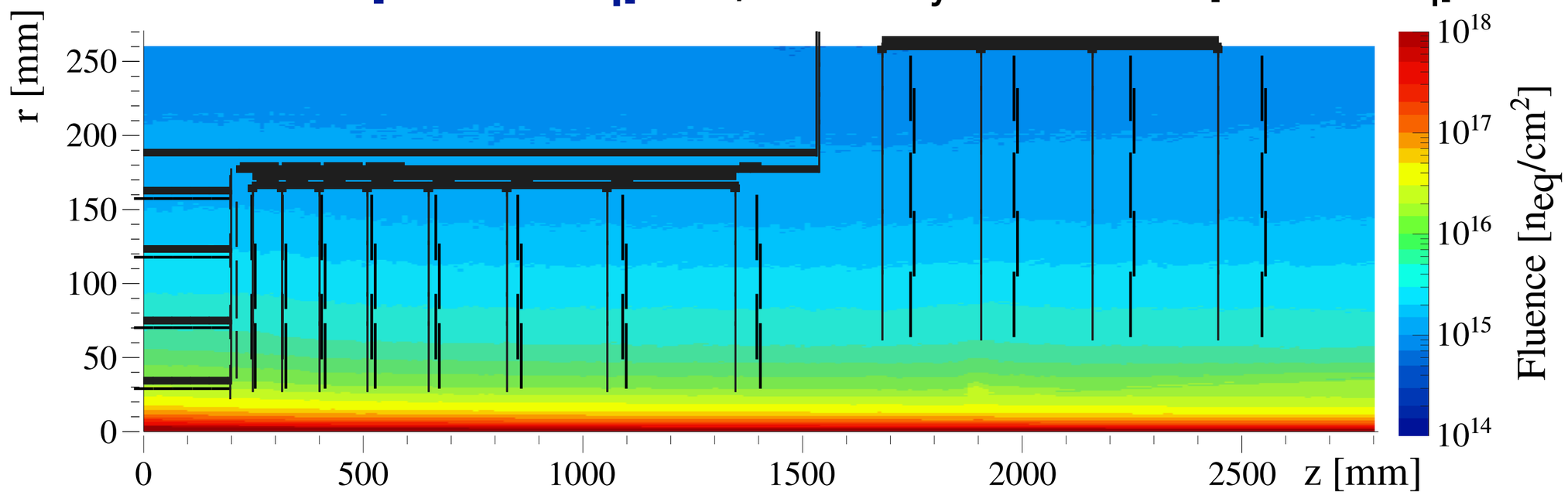




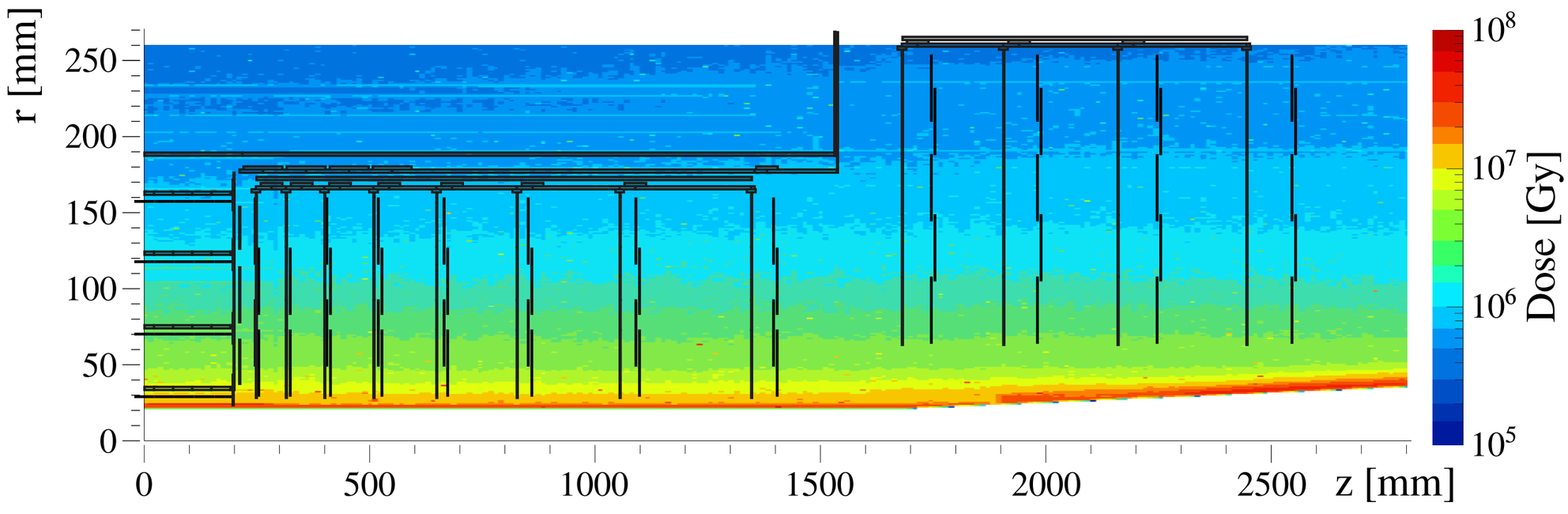
- Features a two-phase -30°C CO_2 cooling system;
- 50-60kW power budget
- for the entire IT+OT: 5x 50kW cooling plants for redundancy, one always in stand-by

The radiation environment

Fluence: **max 2.3x10^{16} [1 MeV neq]/cm^2**; service cylinder ~10^{15} [1 MeV neq]/cm^2

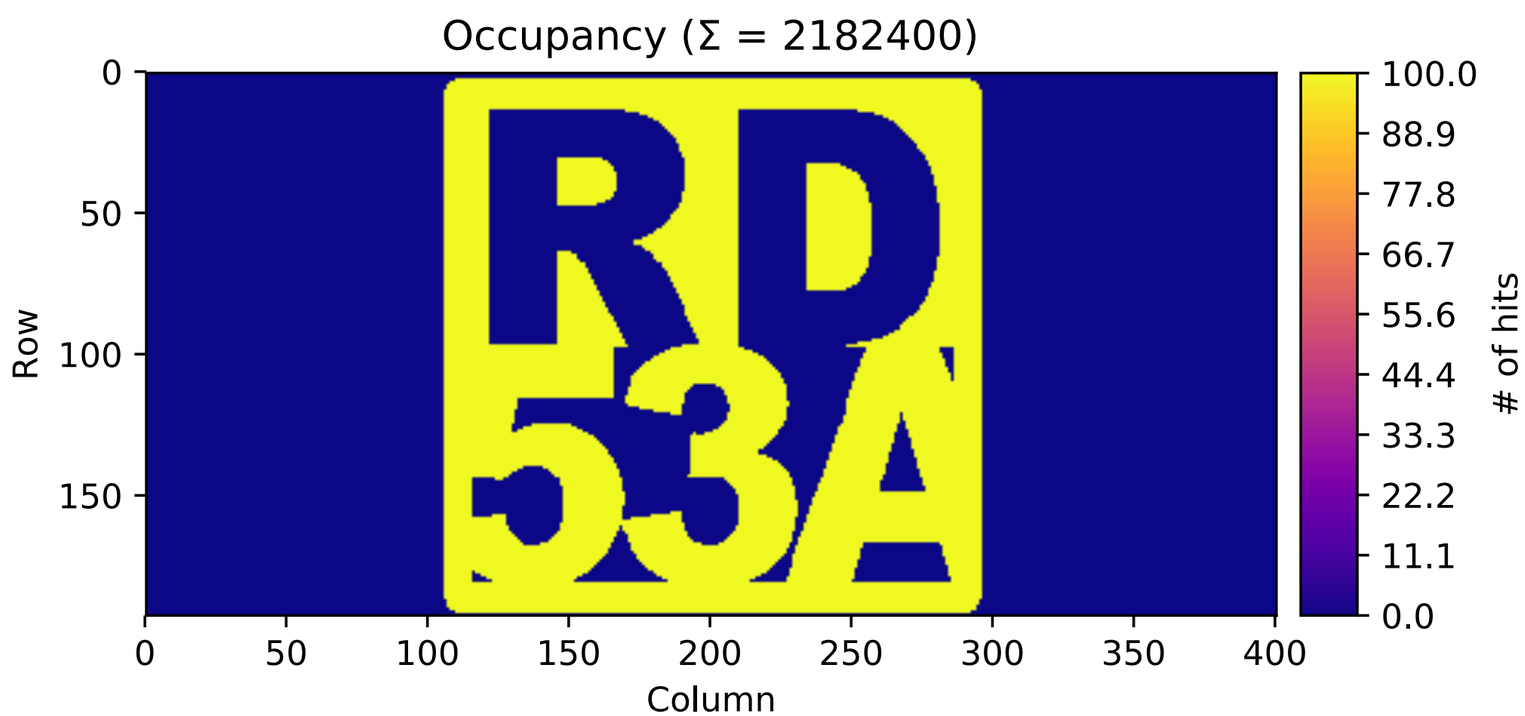


Dose: **max 1.2Grad**; service cylinder ~100Mrad



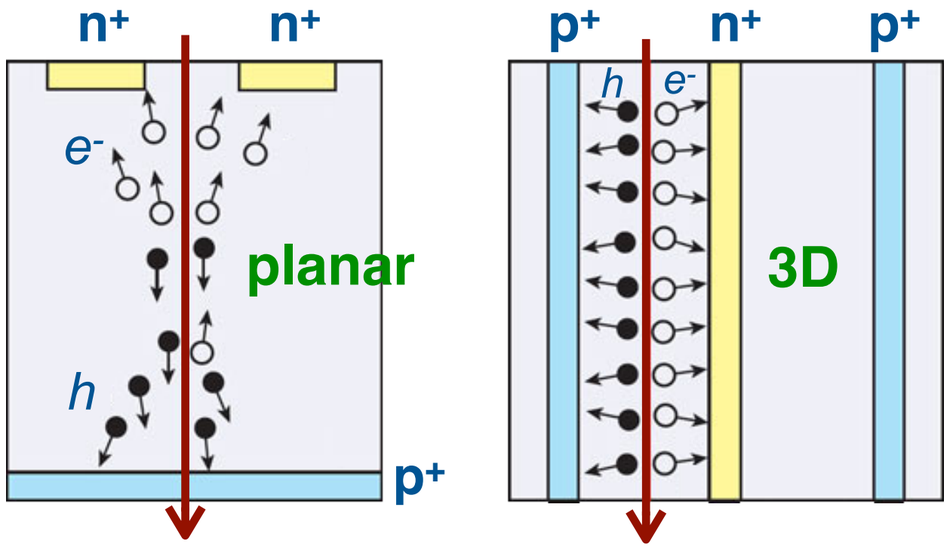
Frontier ROC for 1.2Grad and 3.2GHz/cm^2

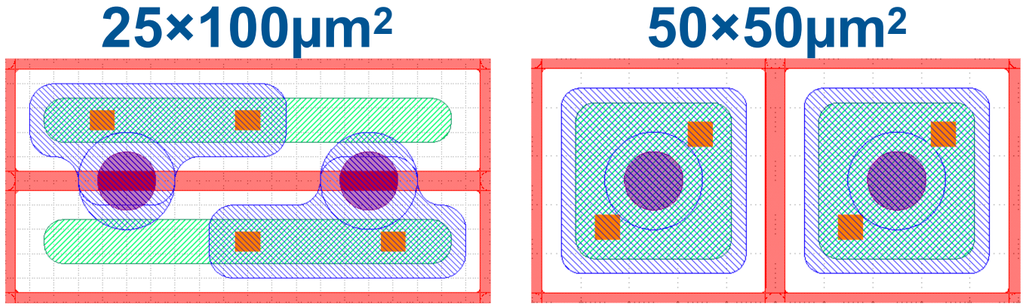
- It is being developed by the RD53 collaboration in 65nm, features 50x50μm^2 cell, low threshold (≲1000e-), high hit and trigger rate (up to 4x 1.28Gb/s output links), radiation resistance and serial powering capabilities. CMS chip size: 16.8x21.6 mm^2 (336x432cells). First CMS chip prototype submitted in 2020.
- **RD53A is the first prototype** (~1/2 size) used for the R&D. Specs goals have been matched and currently RD53A is the workhorse for sensor and detector R&D in general.
  - Radiation hard (up to 5 MGy) / Low thresholds / High hit and trigger rate capabilities / 65 nm technology / 50x50 μm^2 cell size / 160 Mbps input and 1.28 Gbps output links
  - Three analog front-ends to play with: Synchronous / Linear / Differential
    - Good performance of all front-ends, with low threshold and noise



Silicon Pixels sensors to go >10^{16}neq/cm^2

- **Thin planar n-in-p sensors**: 100-150μm in thickness, to have stable charge collection with radiation. Need higher bias (up to 0.8-1kV) and spark protection between ROC and sensor.
- **3D sensors**: potentially more rad-hard, an option for inner modules but more complex fabrication and larger cell capacitance.
- Small pitch pixel cells (a factor 6 smaller than current pixel phase-1) with two possible aspect ratios (the bump bonding pad pattern stays the same): 25x100μm^2 (baseline); 50x50μm^2. Cross talk issues are being investigated.

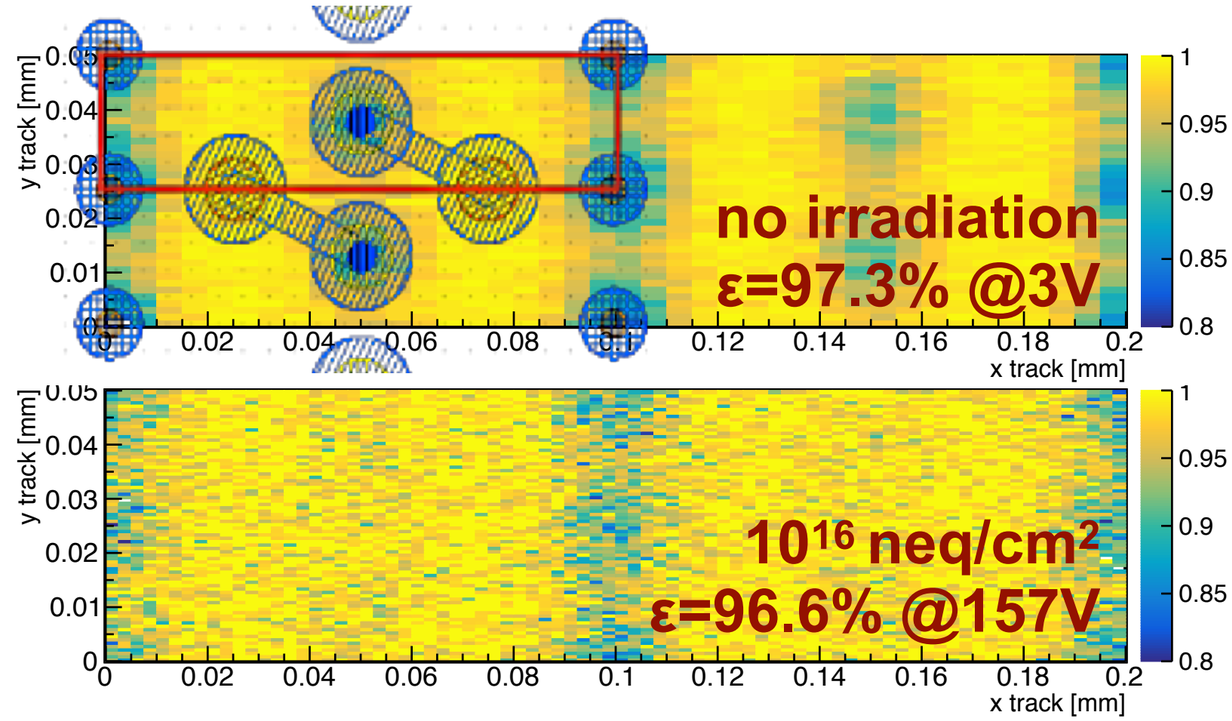




- Extensive irradiation plus test beams (CERN, Desy, FNAL) campaign on-going to establish radiation hardness of the **sensor+ROC assembly**!
- Extensive simulation campaign: FEA to optimize thickness choice (affects heat removal properties); analytical estimation of resolution (tkLayout tool) and full simulation (CMSSW) cell aspect ratio (could depend on the instrumented region)

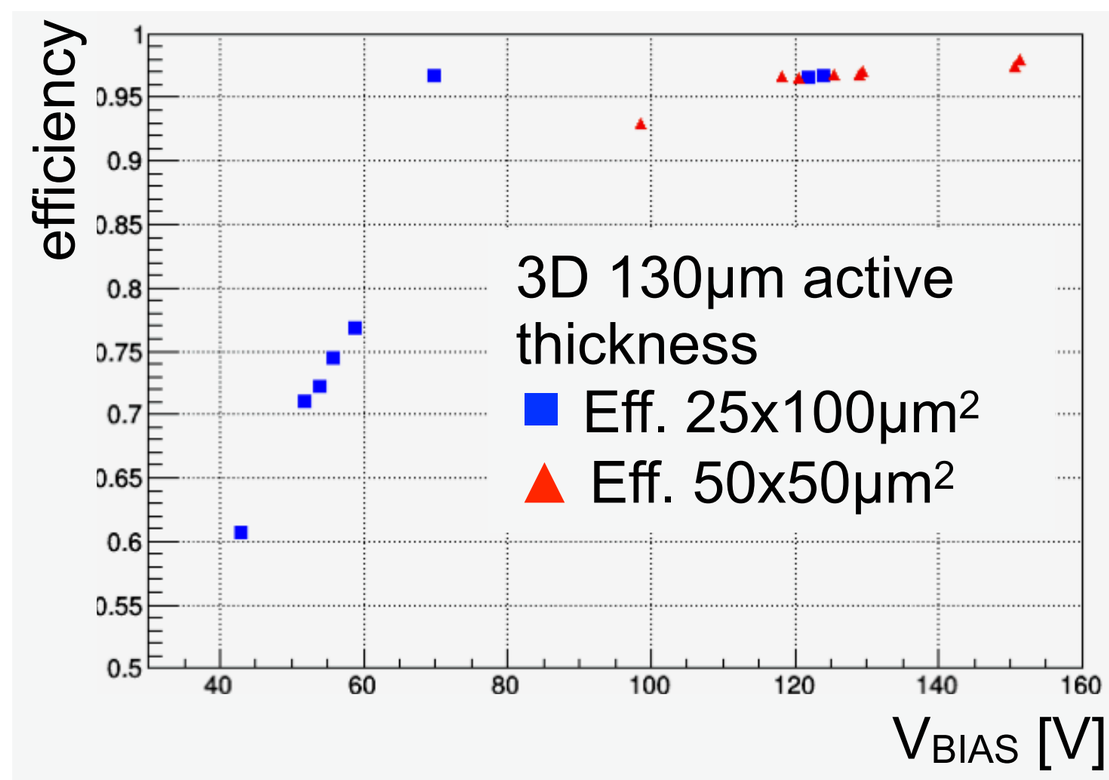
An example of sensor R&D results

- Example results:
  - FBK 3D sensors + RD53A
  - Si-Si wafer bonded, 130 μm active thickness, 200 μm total
  - No biasing structure, temporary metal for testing
  - 25x100μm² and 50x50μm² pixel cells, for RD53A chip
- CERN TB H6B
  - High efficiency measured for ½ layer 1 lifetime fluence
  - Normal incidence



NB normal incidence and different color scale

3D Pixel-RD53A Linear FE	$25 \times 100\ \mu m^2$	$50 \times 50\ \mu m^2$
Before irradiation	97.3%	98.6%
After irradiation	96.6%	97.5%



Hit Efficiency vs. Effective Bias
V_{BIAS} = HV_set - Vdrop (on HV limiting resistors, 0.2MOhm total)

The IT powering vs. material challenge

- **High Granularity**
- **CMOS @65nm** ASICs (radiation resistant but low operating voltage)
- **Large area**
- **Large Bandwidth**
- **Small collected charge (thin sensors)**

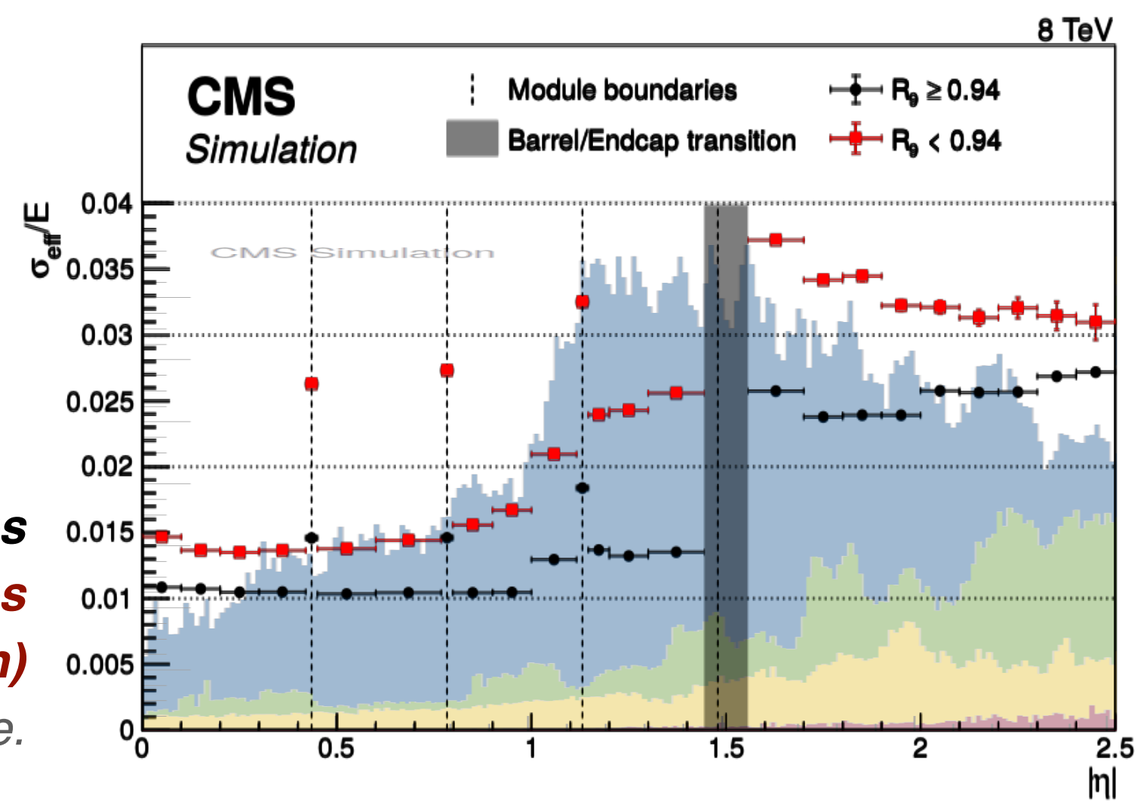
design choices

- Large consumption of digital circuitry (bandwidth)
- Large consumption of analog circuitry (low threshold and low noise)
- 2 billions channels
- **Enormous power budget 50-60 kW (40-50kA @~1.2V)**

Passive material is dangerous for tracking and for downstream detectors.

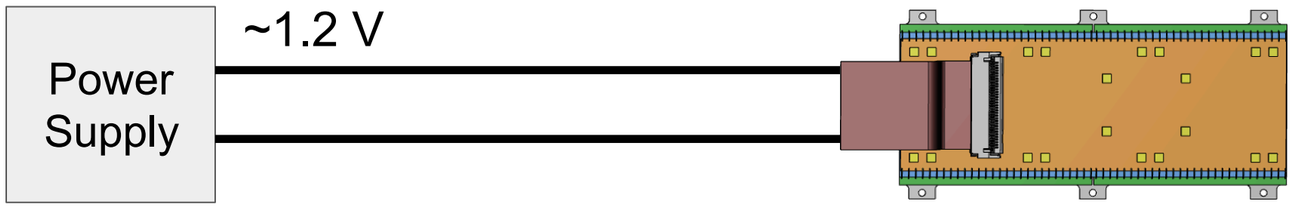
Degradation in tracking (vertexing, impact parameter, momentum resolution, pattern recognition) and in electromagnetic calorimeter performance

Passive material is a limitation. The Tracker Upgrade project is committed to minimize it!



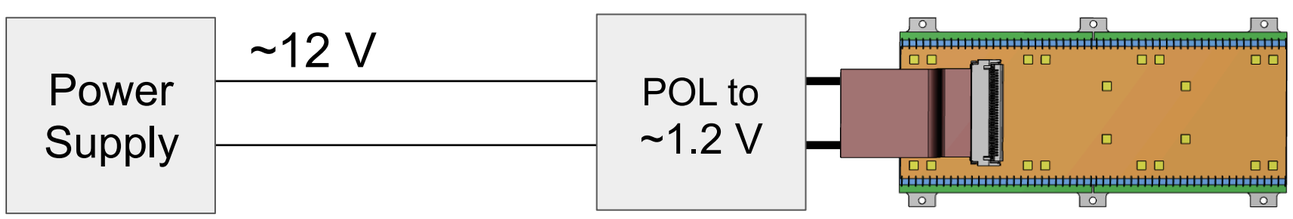
*Photon energy resolution vs. |η| in H→γγ for **photons not interacting in the tracker** and **photons interacting in the tracker (photon conversion)** superimposed to the tracker material profile.*

The choice of serial powering



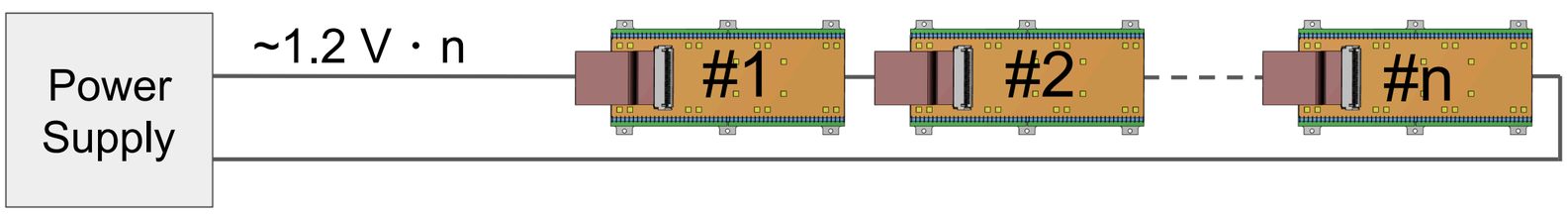
Direct powering

50kW/1.2V ~ 40kA
(20kg or 10%X_0 of Copper)



Local (POL) conversion

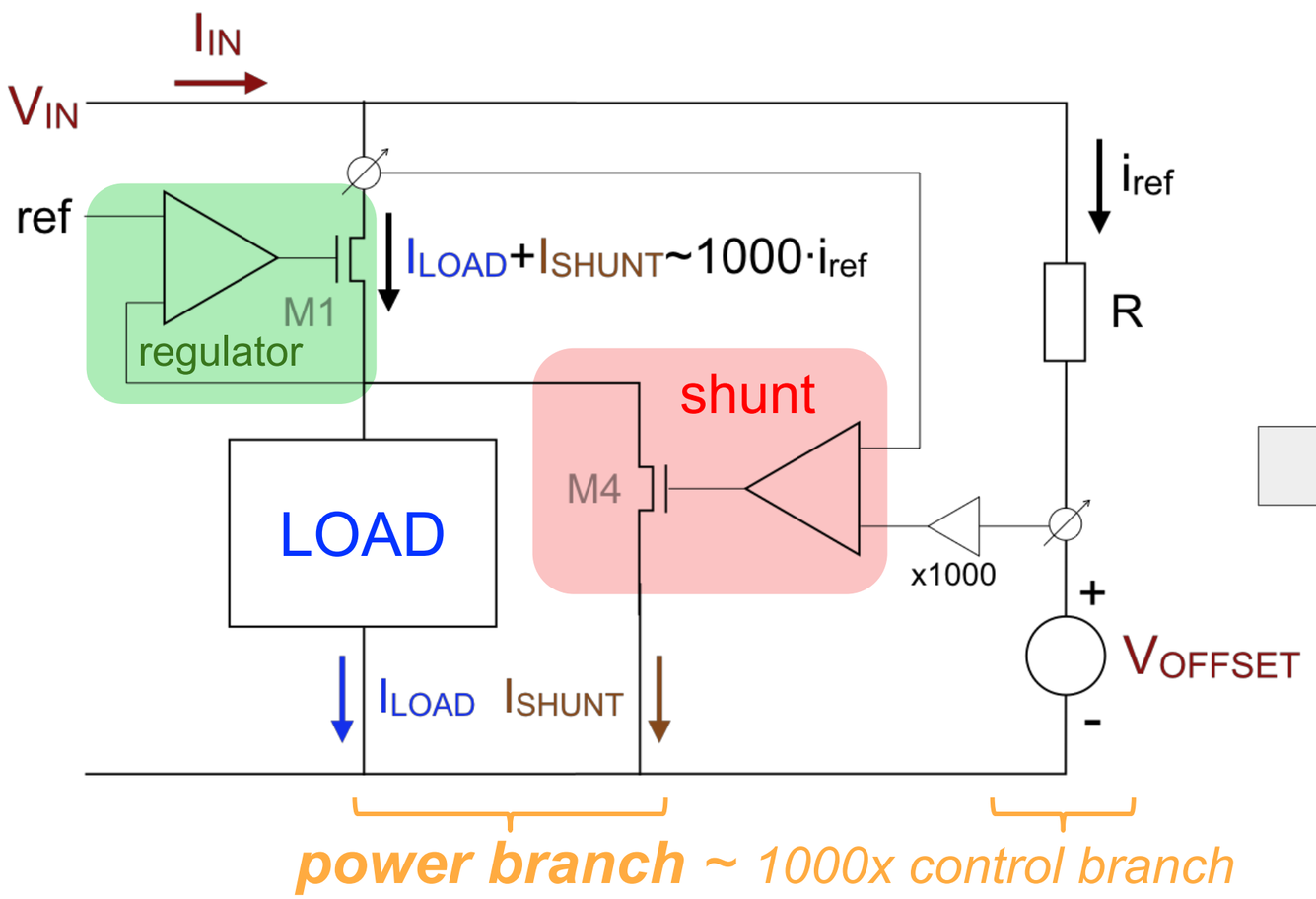
DCDC converters not enough radiation hard, heavy and bulky (no space)

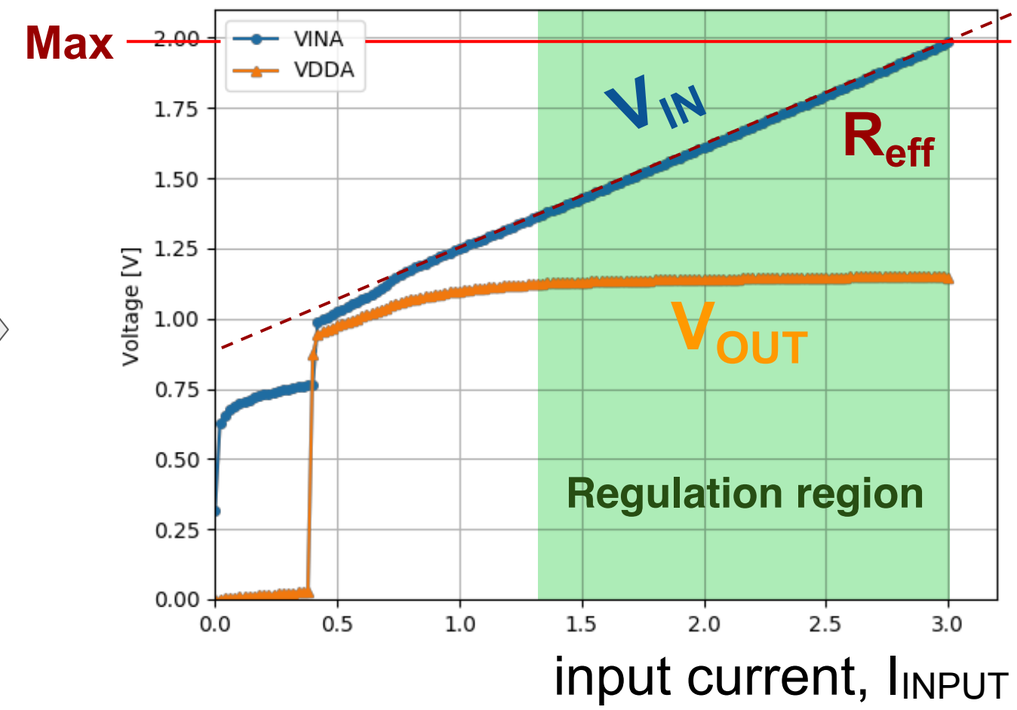


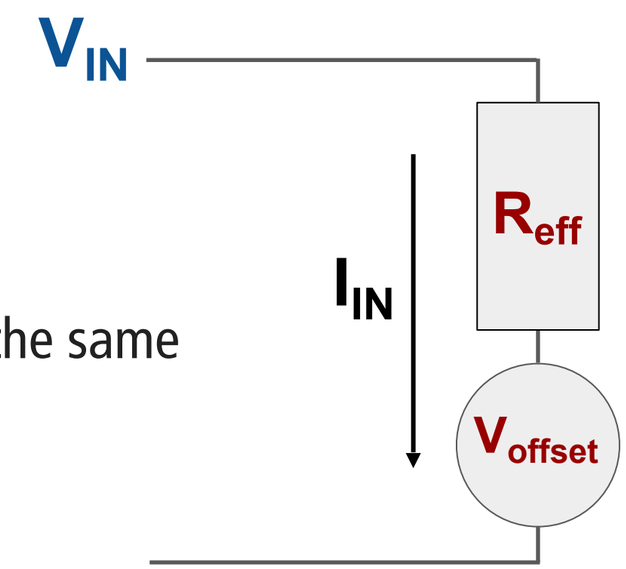
Serial powering!
40kA/(n~8-10)

- The serial powering is the unique scheme compatible with HL-LHC physics. It is a major technological challenge since it has never been used on large scale.
- In a serial powering scheme all chain elements see the same current (by construction); voltage is equally shared if all elements represent **the very same and constant load**…
- This is the task of the ShuntLDO, an IP block of the ROC and no additional ancillary components are needed…

Serial powering with the ShuntLDO



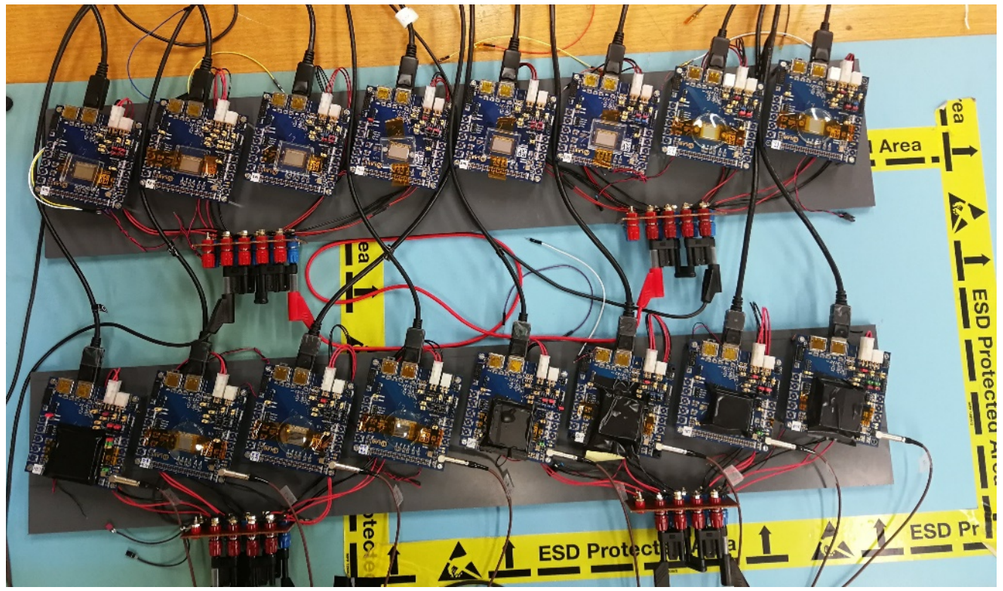




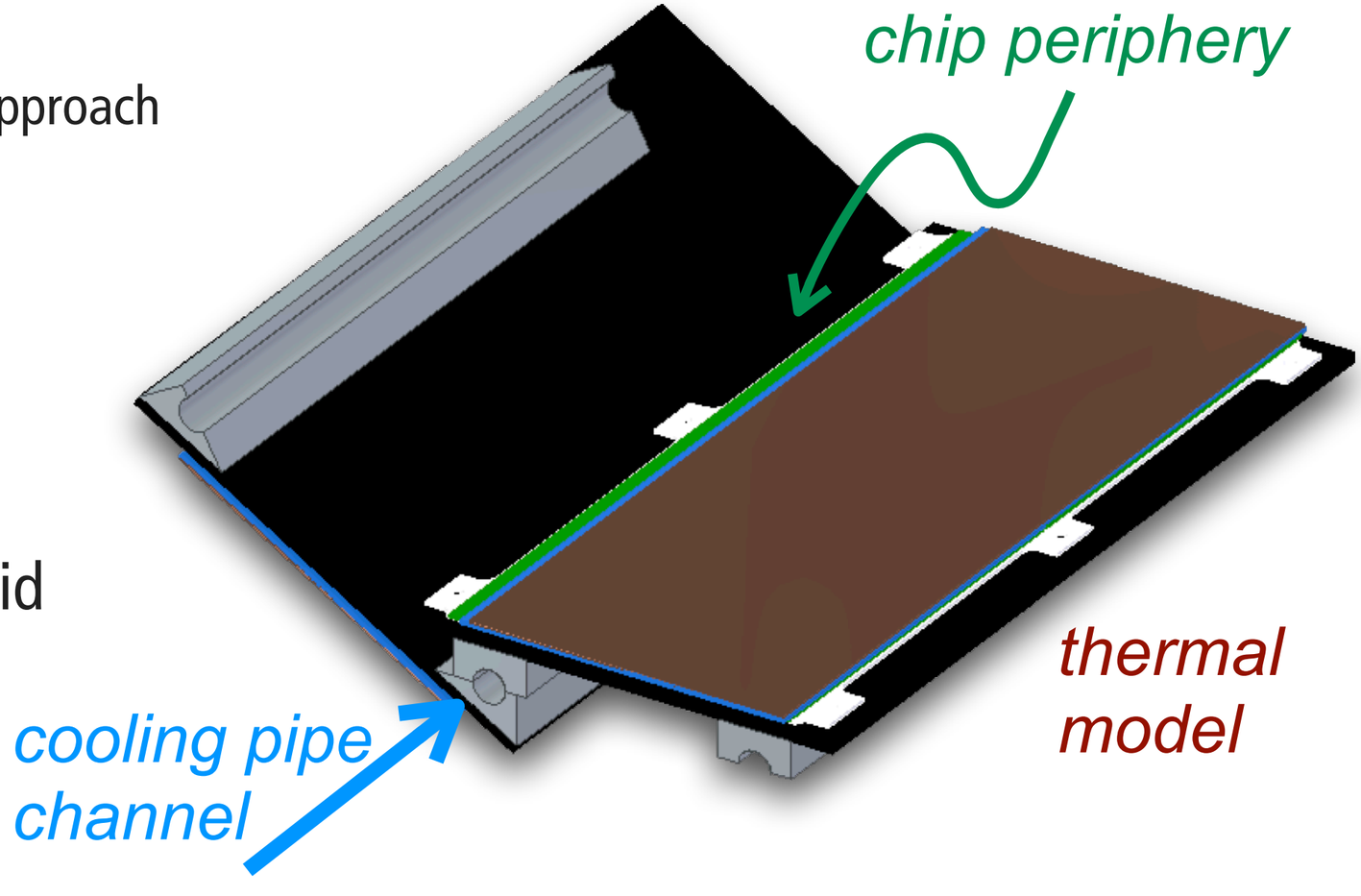
- Integrated **on-chip solution**
  - Low mass, Radiation hard, no extra ASICs
- Equivalent to **a resistor in series with a voltage source**
  - Healthy behavior in parallel applications (Digital and Analog domains in the same chip and on chips on the same modules)
- Each module has **its own local ground**
  - I/O in AC and not trivial bias distribution to sensors
- A brand new world of **failure modes** and intrinsically **not efficient**

System aspects of serial powering

- First failure mitigation: the IT can be accessed and any part replaced by design
  - optimization of power grouping layout
- No other failure modes identified so far (shunt failure, regulator failure…)
- CMS confident that there is no need of any ancillary safety circuitry

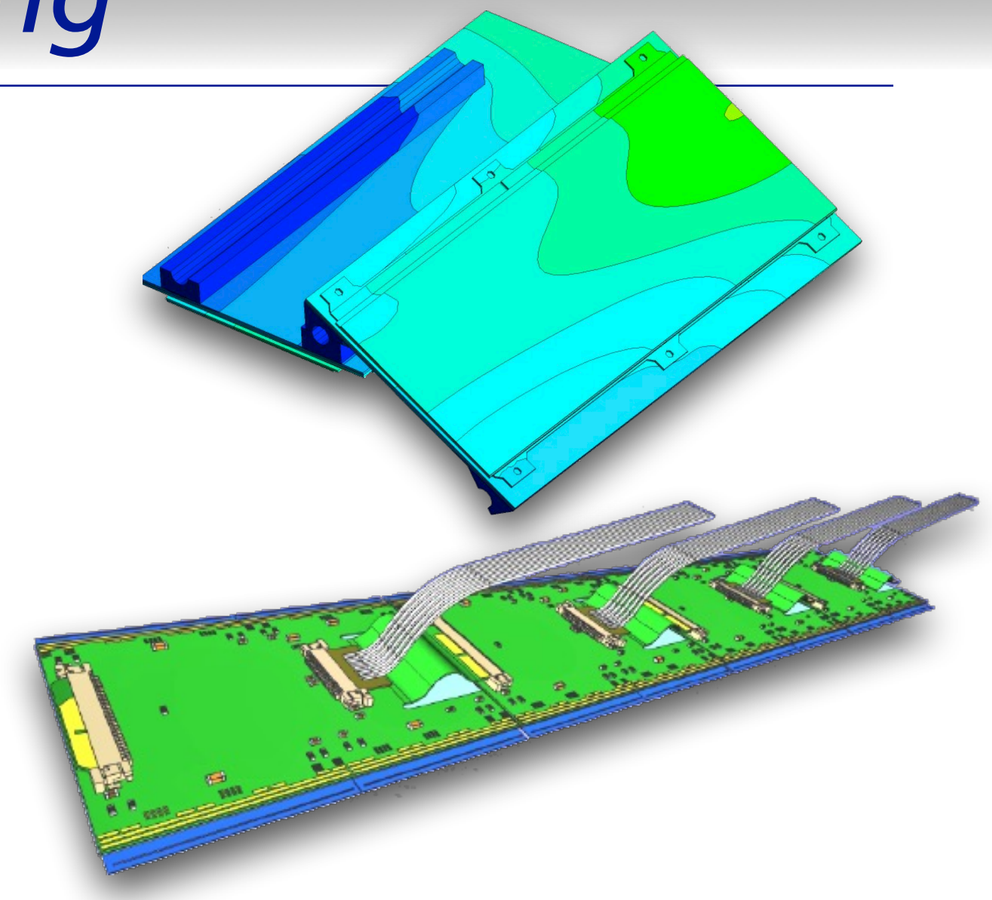


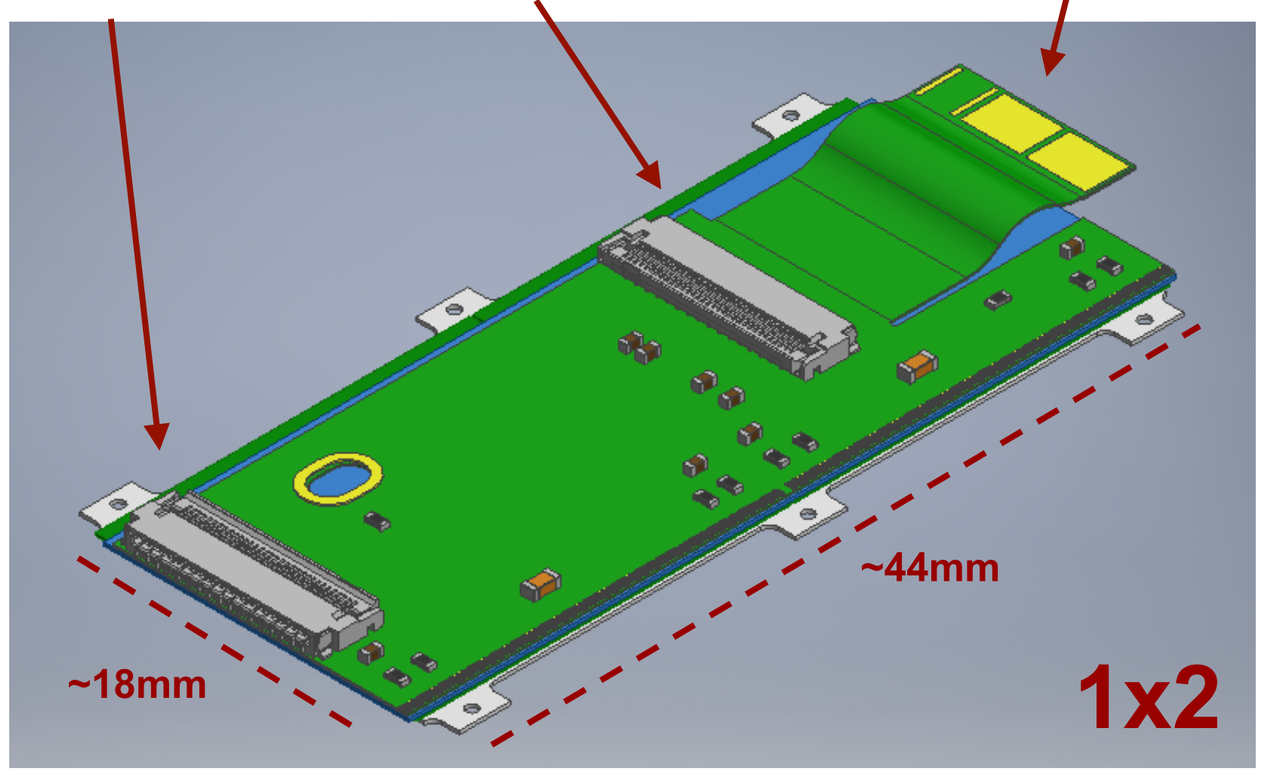
- Extensive system test
  - evaluate weaknesses fo the serial powering approach
  - optimize HV distribution scheme
- Improved SLDO versions coming with undercurrent and overvoltage protections
- SLDO power transistors are distributed in the chip periphery of the chip to avoid dangerous hotspots; in the mechanics design cooling pipes runs close-by

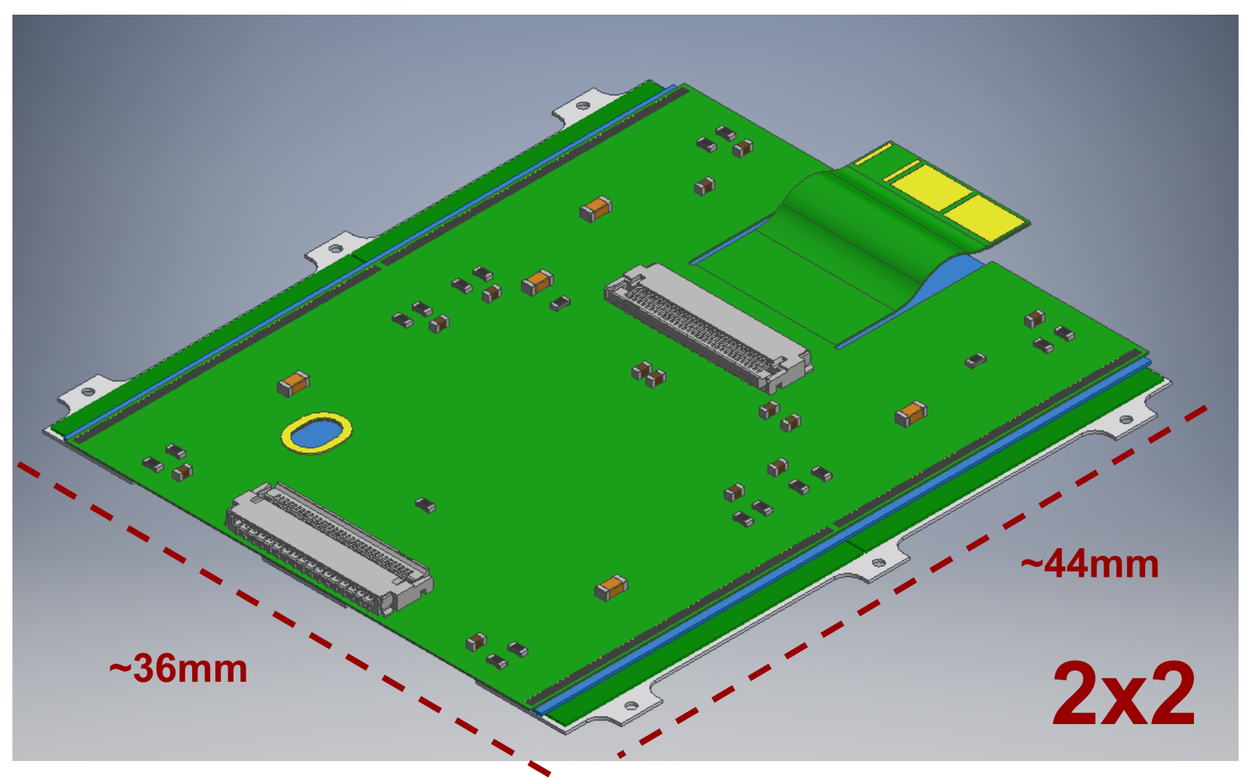


IT Modules for serial powering

- Simple design, the pixel ROC is the only active electronics; two versions: 1x2 (1156x) and 2x2 (2736x) chips versions
- HDI hosts decoupling capacitors, connectors and connect to chips via wire bondings
- The design is optimized to be adapted to mechanical and cooling constraints

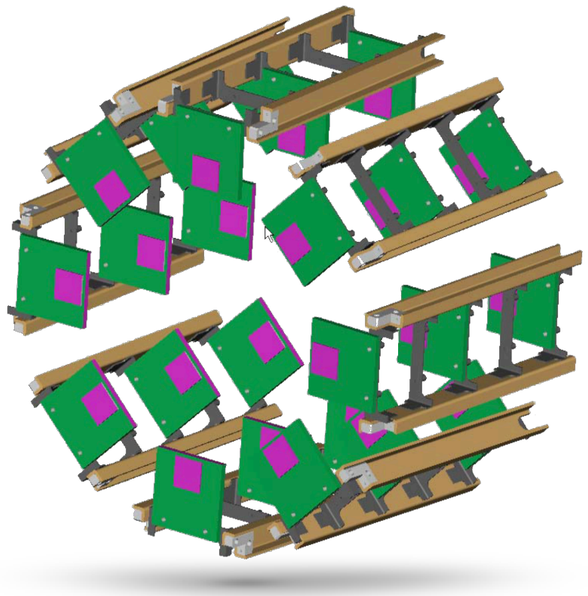


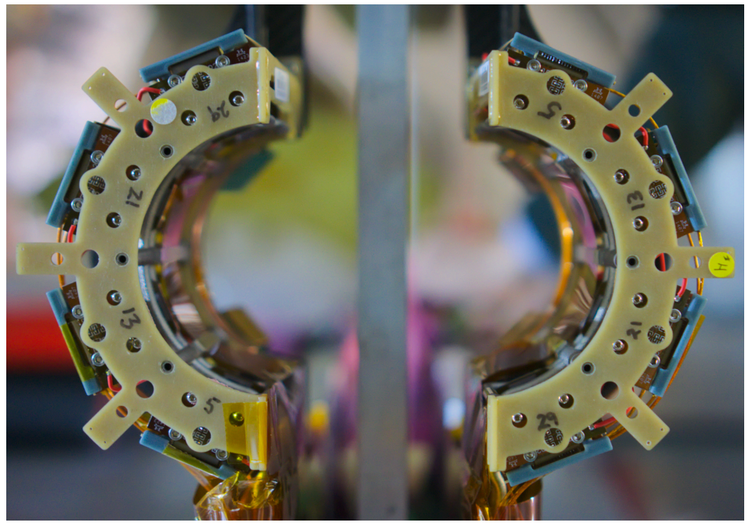




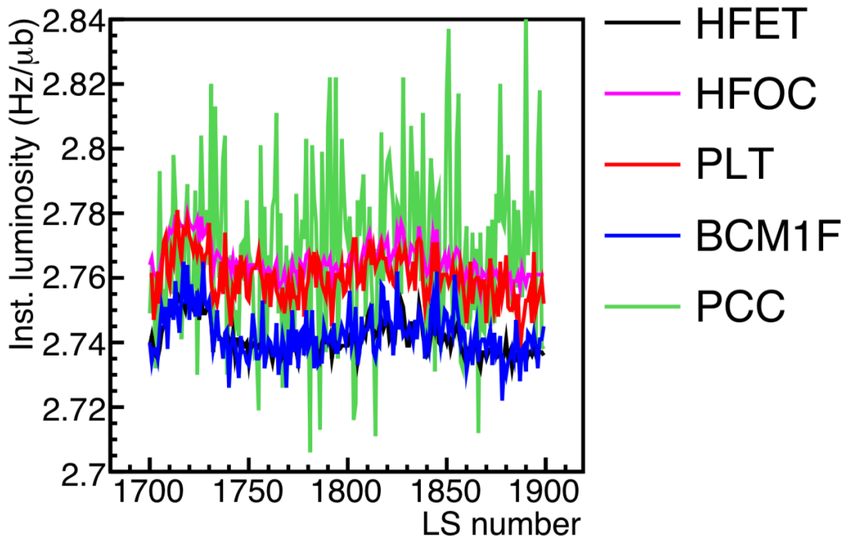
Luminosity measurement in Run-I and Run-II

- Several methods have been deployed in CMS to measure beam conditions and luminosity. Among these…
- **PLT - Pixel Luminosity Telescope**
  - device dedicated to luminosity measurement
  - 8+8 3x single-die **pixel telescopes**
  - @|z|=1.8m
  - operates in any beam condition
  - **triple coincidence** (but no 'track' reconstruction) and offline correction for accidentals (beam halo)



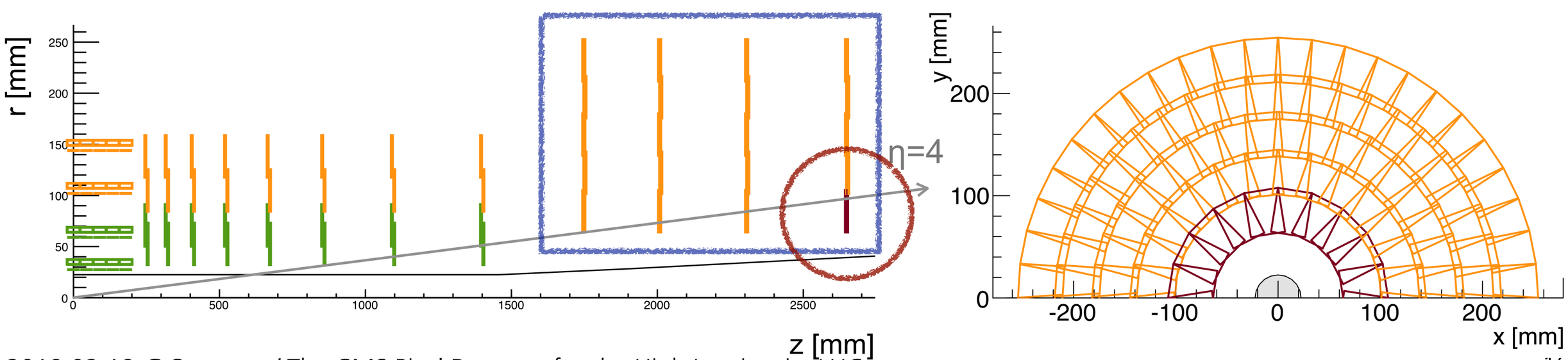


- **PCC - Pixel Cluster Counting**
  - use of pixel detector
  - operates only in stable beams
  - Excellent linearity (thanks to low occupancy) and time stability
  - Excellent agreement with other luminometers
  - Measurement integrated over a Lumi Section (23s)



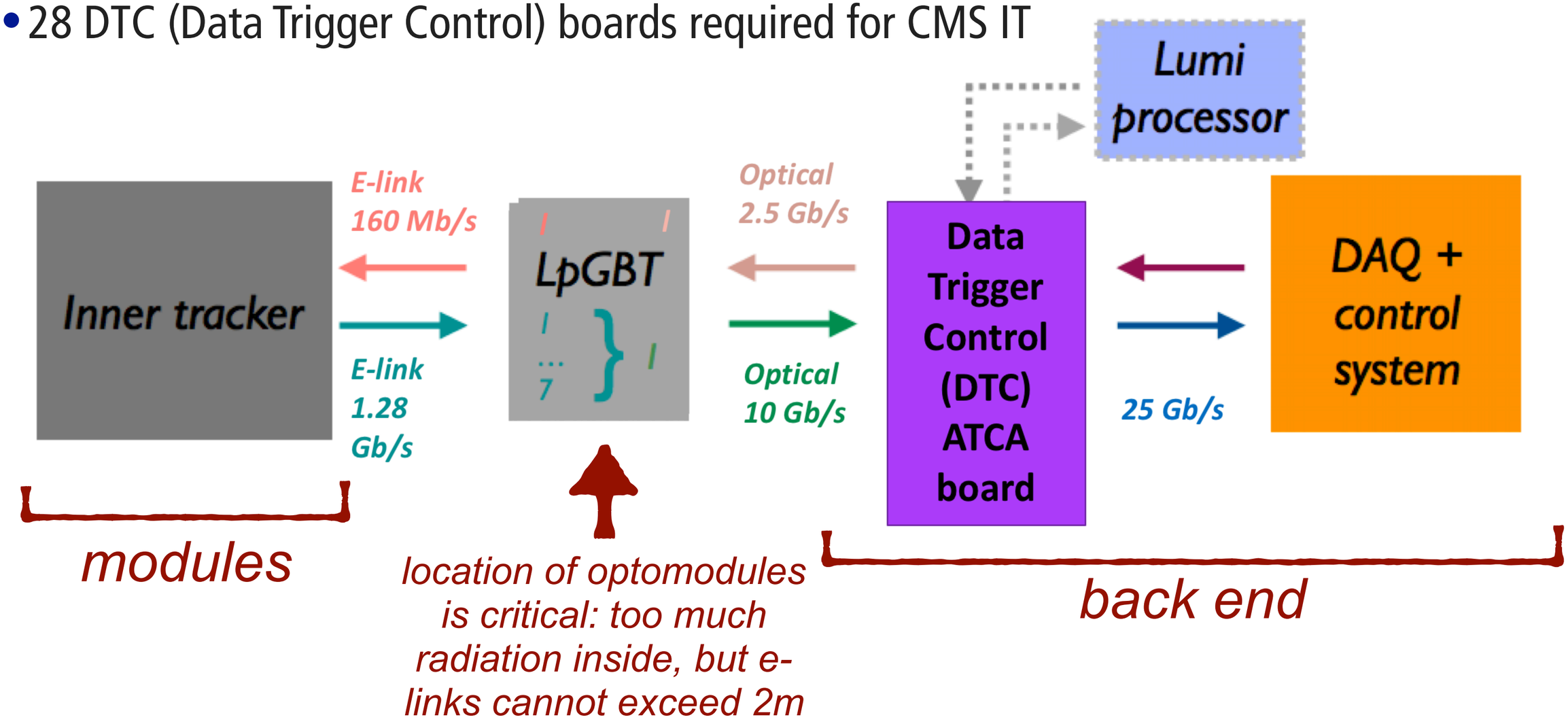
TEPX as main luminometer in Phase2

- **TEPX** operated during VDM scans and in all conditions where beams are safe (ADJUST, STABLE BEAMS); **no data taking**: all bandwidth available for lumi triggers (up to ~10MHz); **during data taking**: special triggers (+10%, 75kHz) added to physics.
- **TEPX D4R1**, the first ring of the last TEPX disk (outside Tracking acceptance) is **fully dedicated to BRIL (Beam Radiation Instrumentation and Luminosity) functionalities**: beam background, luminosity during Machine Development and Unsafe Beam Conditions. Hermetic coverage not required, failures tolerable.
- Several methods under study for the luminosity measurement:
  - cluster counting (high statistics, large fake rate)
  - multi-hit stub counting using overlaps (still fairly large statistics, reduced fake rate)
  - track counting (needs back-end processing)

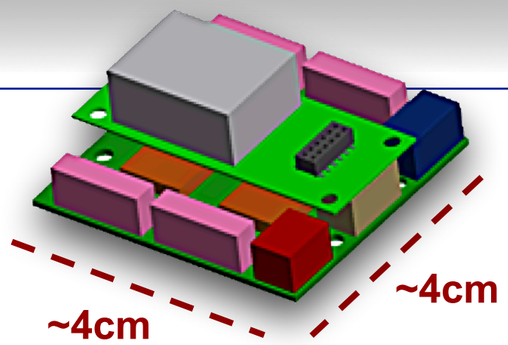


LpGBT based readout chain

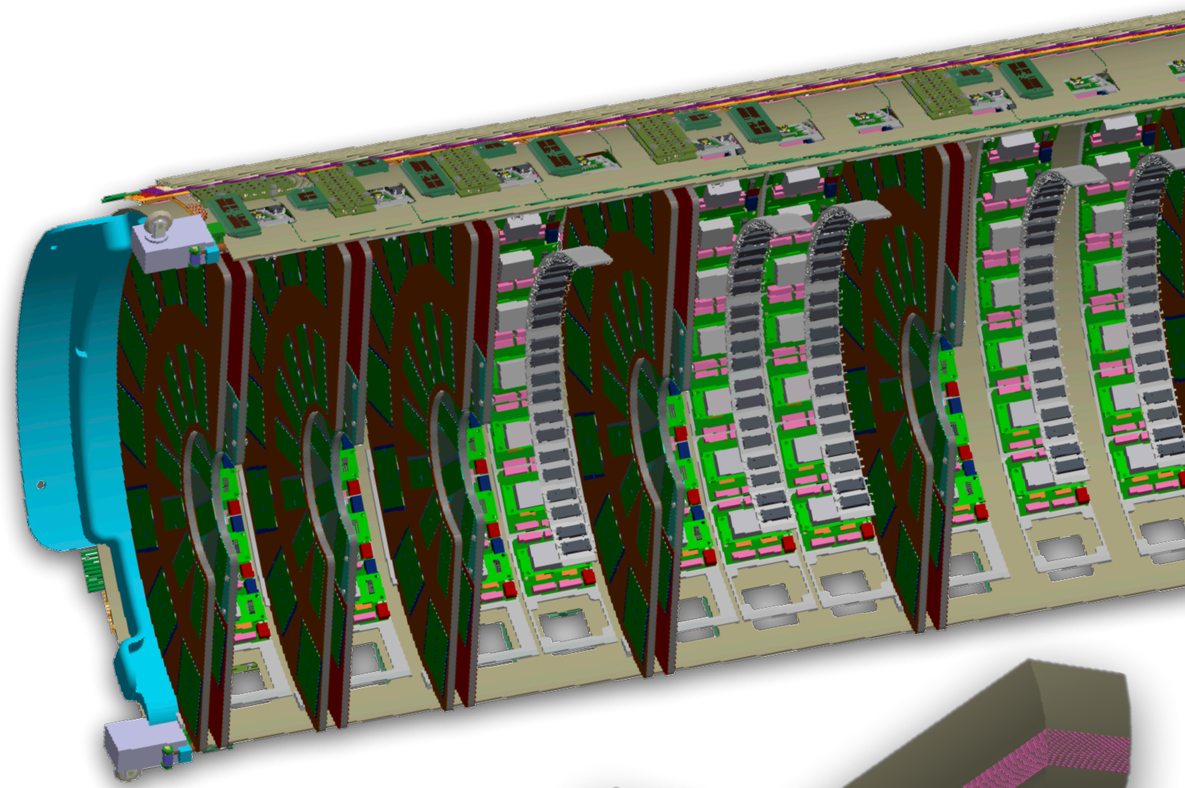
- **Up-links**: data from L1 accept, monitoring info to DAQ and control system
  - Up to 6 electrical up-links @1.28 Gb/s per module to LpGBT
  - Modularity depends on hit rate (location)
  - Efficient data formatting to reduce data rates (factor ~2) / 25% bandwidth headroom on e-link occupancy
- **Down-links**: clock, trigger, commands, configuration data to modules
  - One electrical down-link @160 Mb/s per module from LpGBT
- 28 DTC (Data Trigger Control) boards required for CMS IT

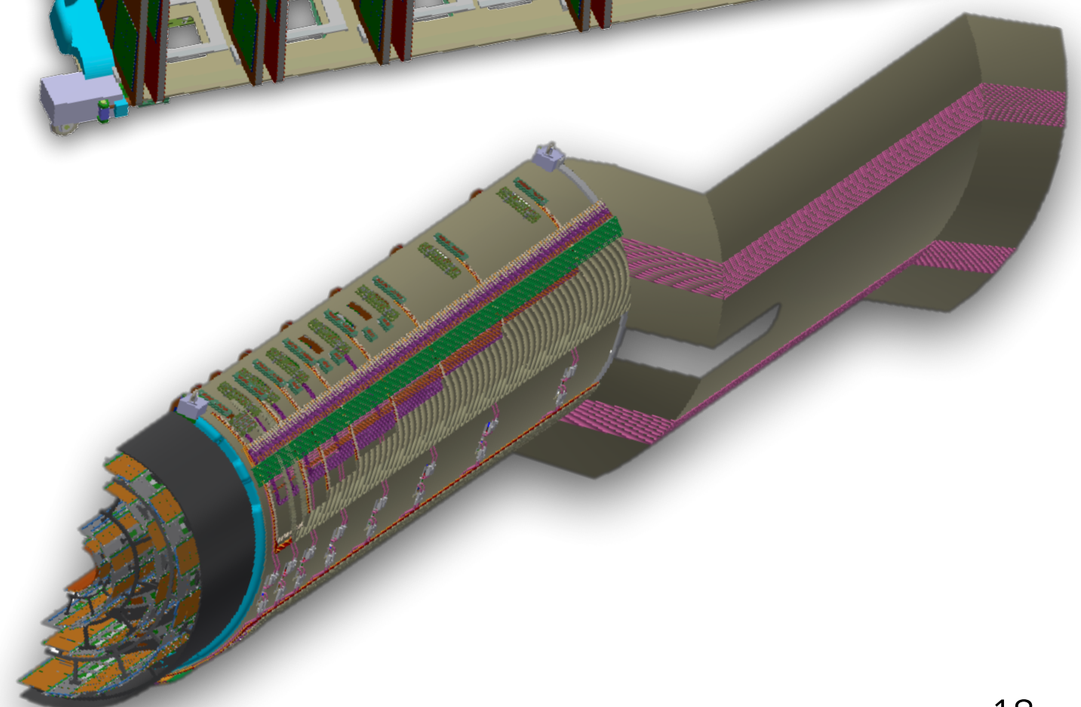


Elinks / Optomodules / Integration



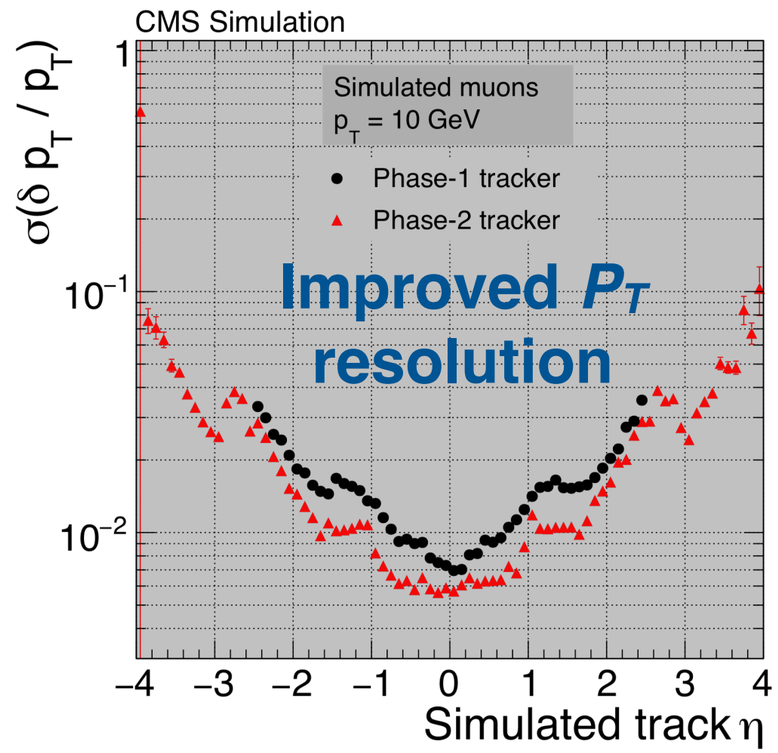
- Optomodule (aka portcard) designed in 2018:
  - 2 Low-power Gigabit Transceiver (LpGBT)
  - 2 Versatile Link+ (VL+)
  - powered by a pair of DC-DC converters
  - ~750 optomodules to readout/control CMS IT
  - they sit on the Service Cylinder where radiation is compatible with LpGBT and VL+
- ~7k readout + 4k control differential electrical links (e-links)
  - brings the module I/O to the optomodule that sits on
  - AC- coupled e-links due to serial powered modules
- Various e-link options investigated with simulations and tests:
  - Flex and twisted pair: 0.1 – 1m
  - Objective: Minimize mass for acceptable cable losses
  - Studying: Pre-emphasis, Cross coupling, Eye-diagrams
- Cables and other services are routed on the SC

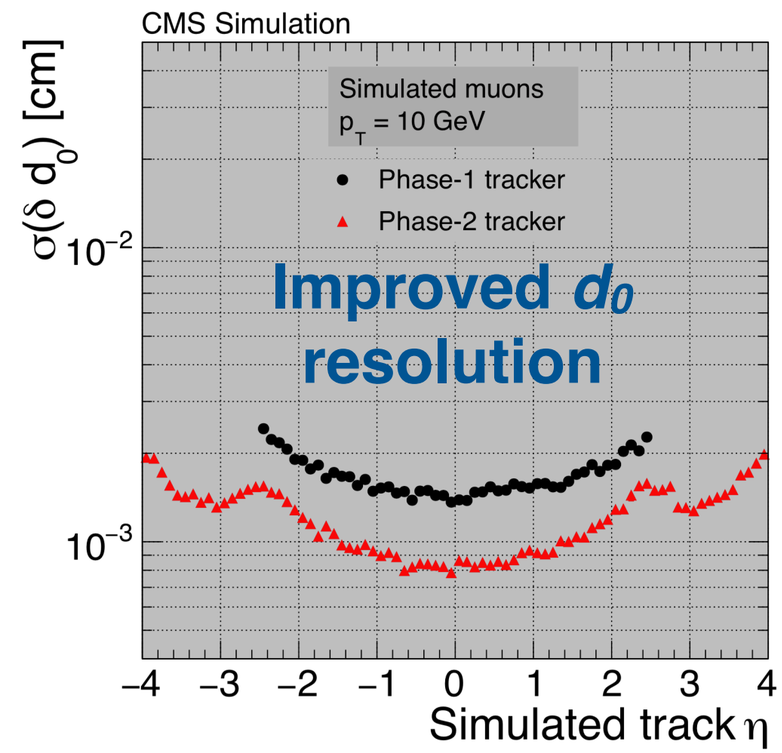


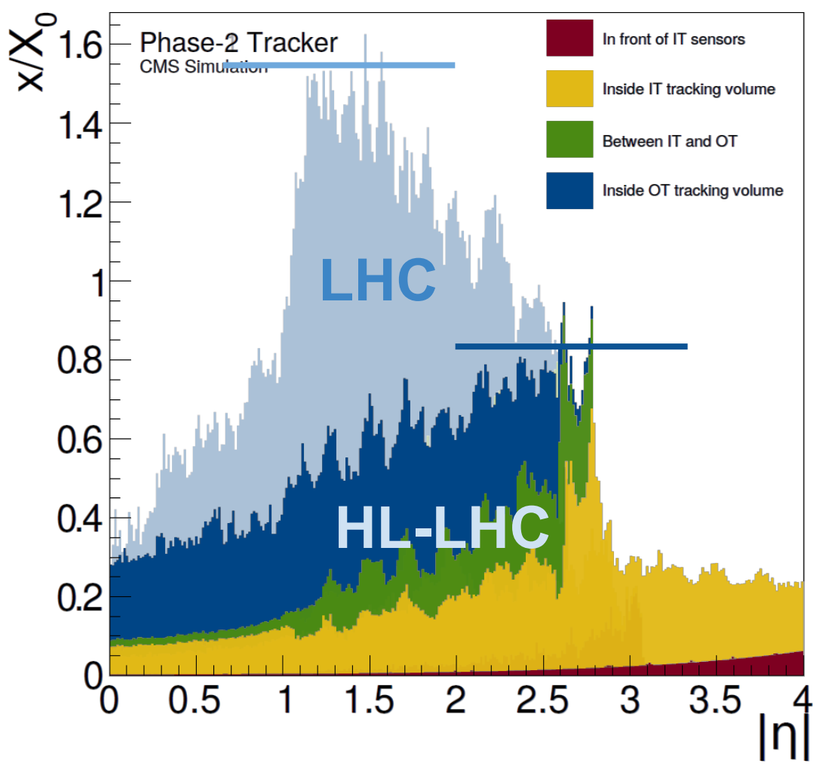


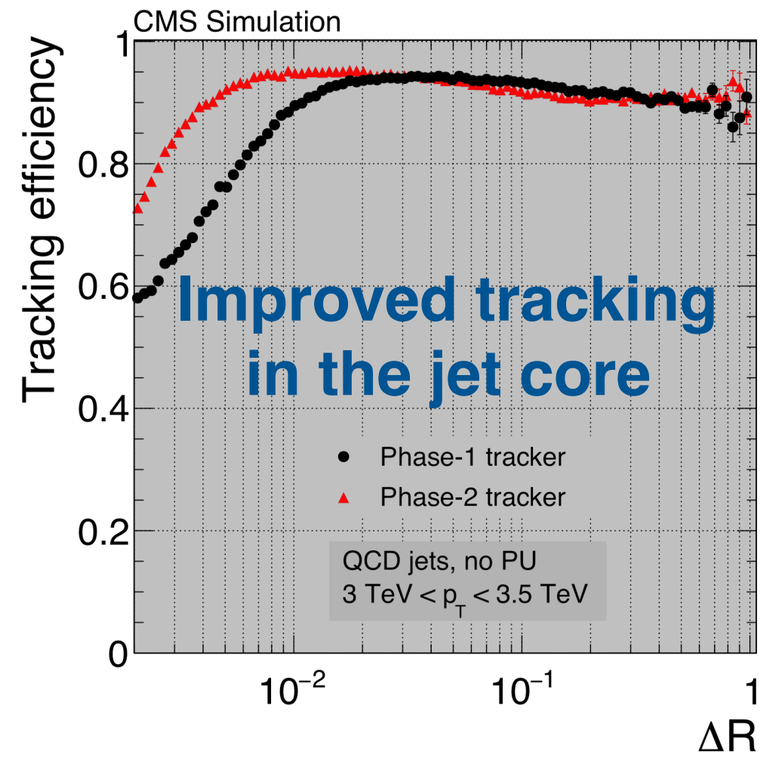
Performance

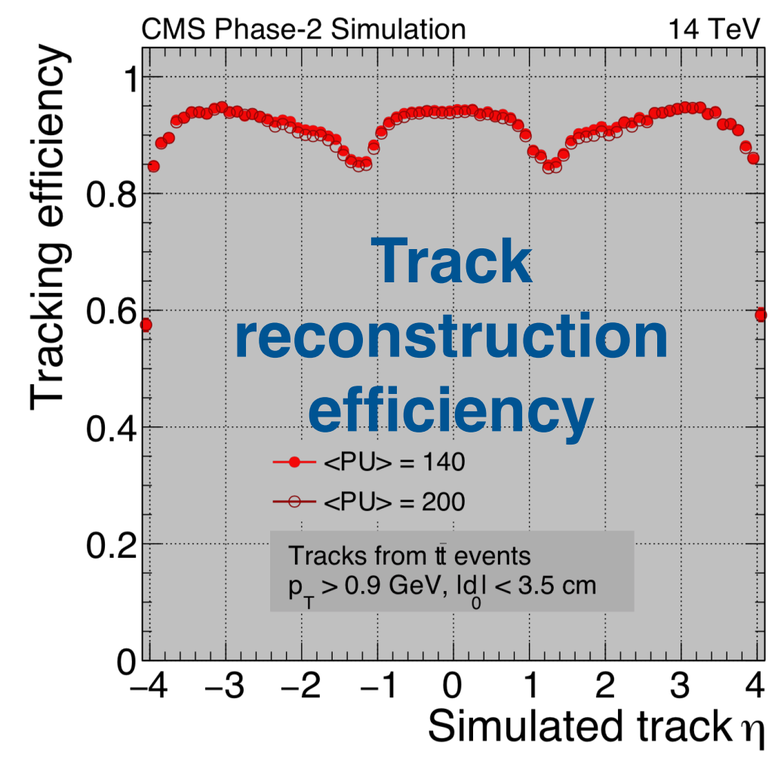
Thanks to the better granularity and the reduced material, the upgraded tracker improves on all physics observables even with 200 PU. **IT is crucial for seeding, the first reconstruction step.**











Summary and conclusions

Current Phase-1 pixel detector
~1.8m² Silicon Sensors
123M 100x150μm² pixels
1856 Modules
100kHz max readout rate
15kW power budget

Upgraded Pixel Detector (Inner Tracker)
~4.9m² Pixel Silicon Sensors
1'924M 25x100μm² or 50x50μm² pixels
~4'000 Modules
750kHz readout rate (on L1 accept)
50-60kW power budget

- The CMS Upgrade Inner Tracker is an extremely challenging project
- The design is advanced in all the main areas (modules, electronics, mechanics, cooling)
- Radiation hard ROC+sensors are at hand
- Many challenges ahead of us: system level validation and verification of Serial Powering, mechanics, cooling…
- … and then industry-like module production and detector integration

Thank you!

Backup

Other related VCI2019 contributions

The CMS Outer Tracker for the High Luminosity LHC - Erik Butz
https://indico.cern.ch/event/716539/contributions/3246645/

Operational Experience of the Phase-1 CMS Pixel Detector - Benedikt Vormwald
https://indico.cern.ch/event/716539/contributions/3246025/

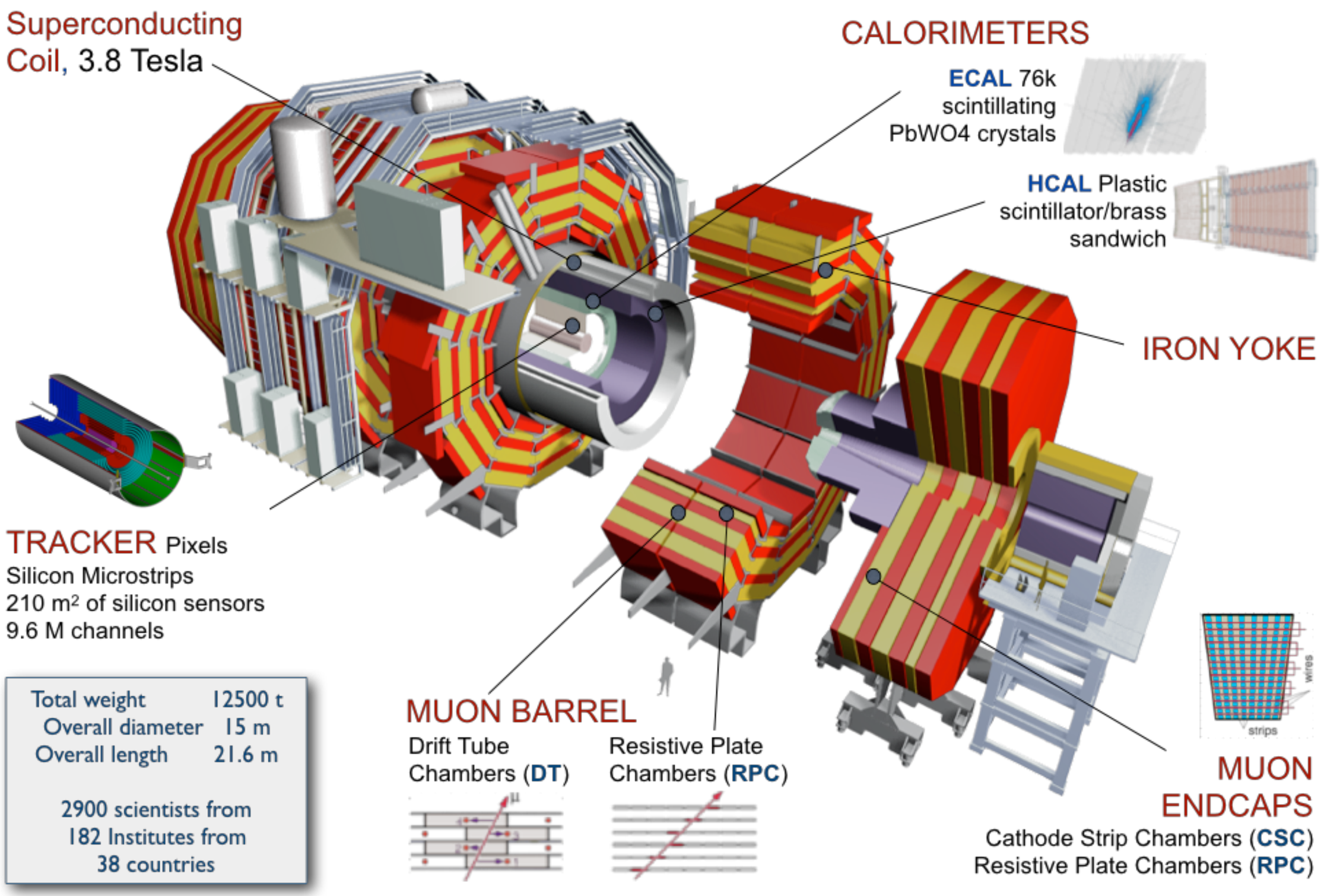
Level-1 track finding with an all-FPGA system at CMS for the HL-LHC - Kristian Hahn
https://indico.cern.ch/event/716539/contributions/3246163/

RD53A: a large-scale prototype chip for the phase II upgrade in the serially powered HL-LHC pixel detectors - Aleksandra Dimitrievska
https://indico.cern.ch/event/716539/contributions/3246032/

First results on 3D pixel sensors interconnected to RD53A readout chip after high energy proton irradiation - Jordi Duarte Campderros
https://indico.cern.ch/event/716539/contributions/3246092/

HL-LHC Schedule

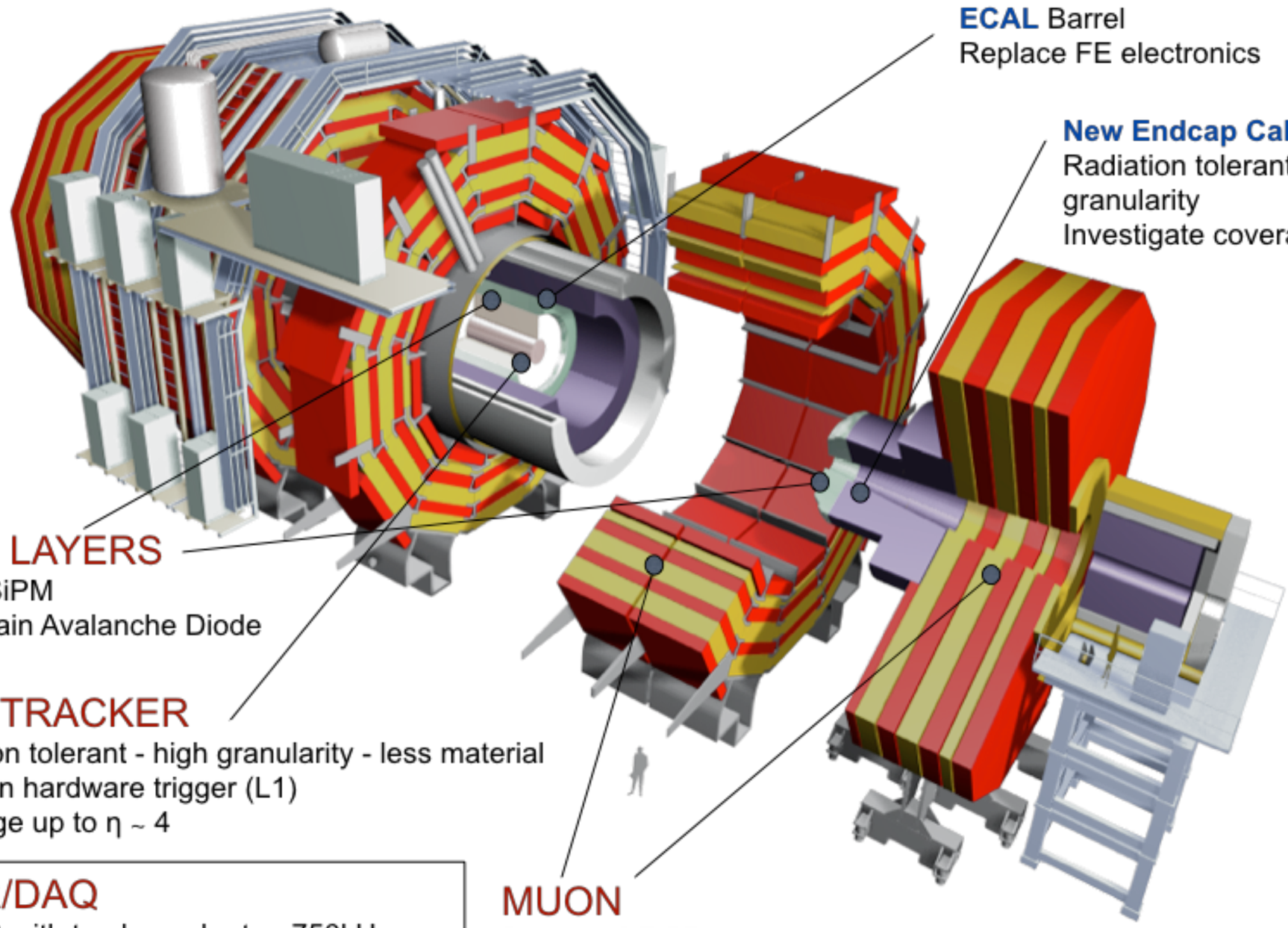
The CMS detector



Total weight	12500 t
Overall diameter	15 m
Overall length	21.6 m

2900 scientists from
182 Institutes from
38 countries

The CMS detector upgrades



CALORIMETERS

ECAL Barrel
Replace FE electronics

New Endcap Calorimeters
Radiation tolerant - high granularity
Investigate coverage up to η ~ 4

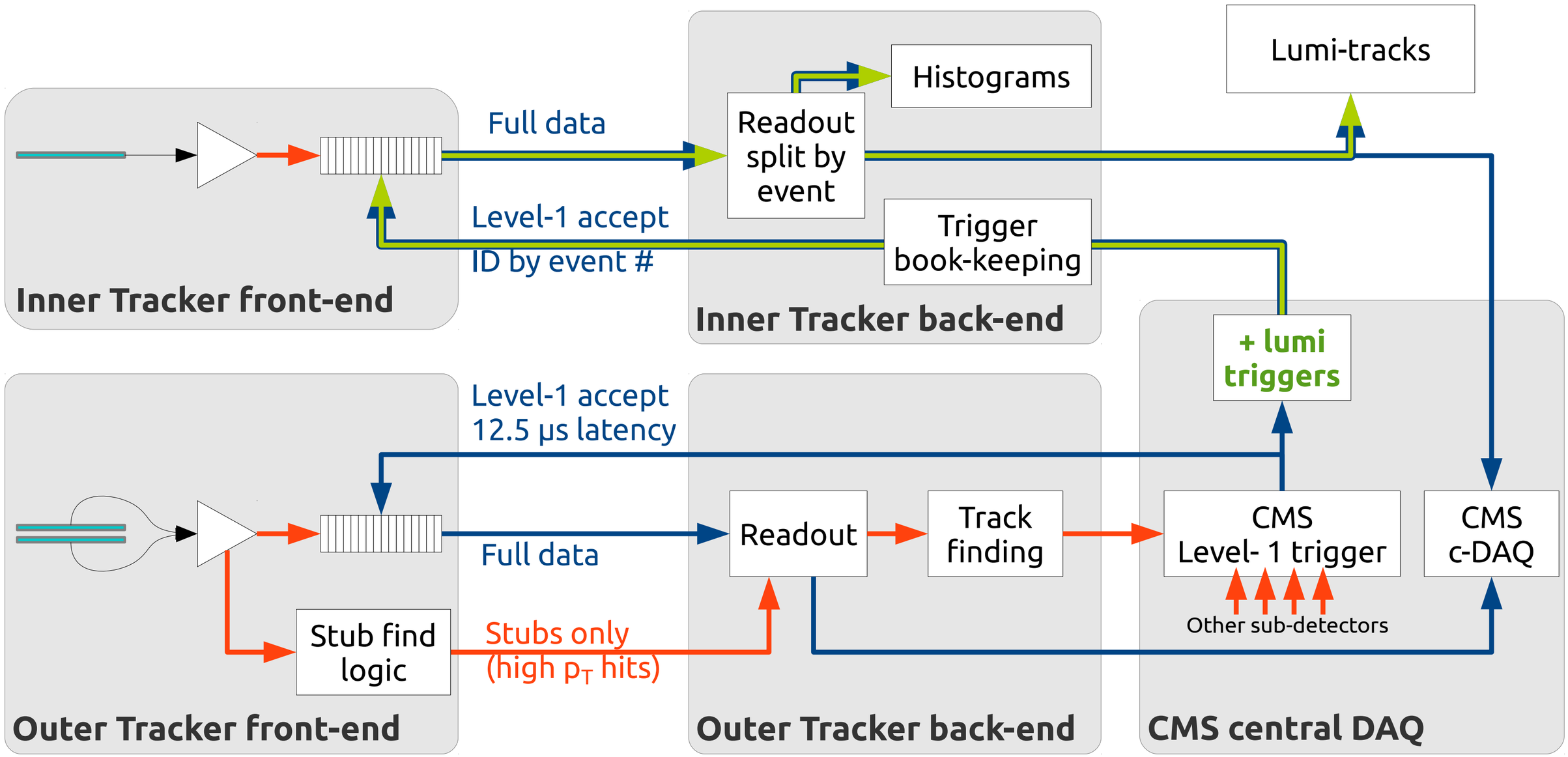
MIP TIMING LAYERS
Barrel: LYSO + SiPM
Endcaps: Low Gain Avalanche Diode

NEW TRACKER
Radiation tolerant - high granularity - less material
Tracks in hardware trigger (L1)
Coverage up to η ~ 4

TRIGGER/DAQ
L1 (hardware) with tracks and rate ~750kHz
Latency ≥ 10 μs
HLT output up to 10 kHz

MUON
Replace DT FE electronics
Complete RPC coverage in forward region (new GEM/RPC technology)
Investigate Muon-tagging up to η ~ 4

The Tracker Upgrade trigger and readout



40 MHz – Real time **750 kHz** – CMS Level-1 trigger **~75 kHz** – Lumi-specific trigger