The Phase 2 upgrade of CMS Outer Tracker

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on behalf of the CMS Collaboration

17.12.2019

HSTD12 Hiroshima, Japan

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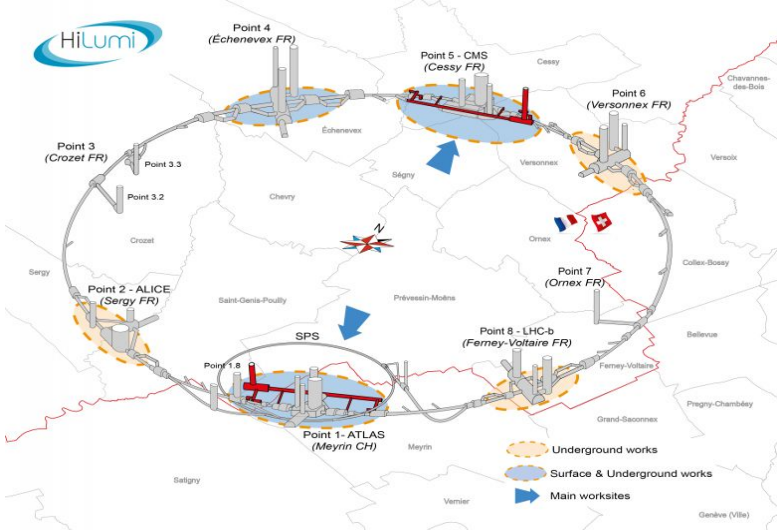
SCUOLA NORMALE SUPERIORE

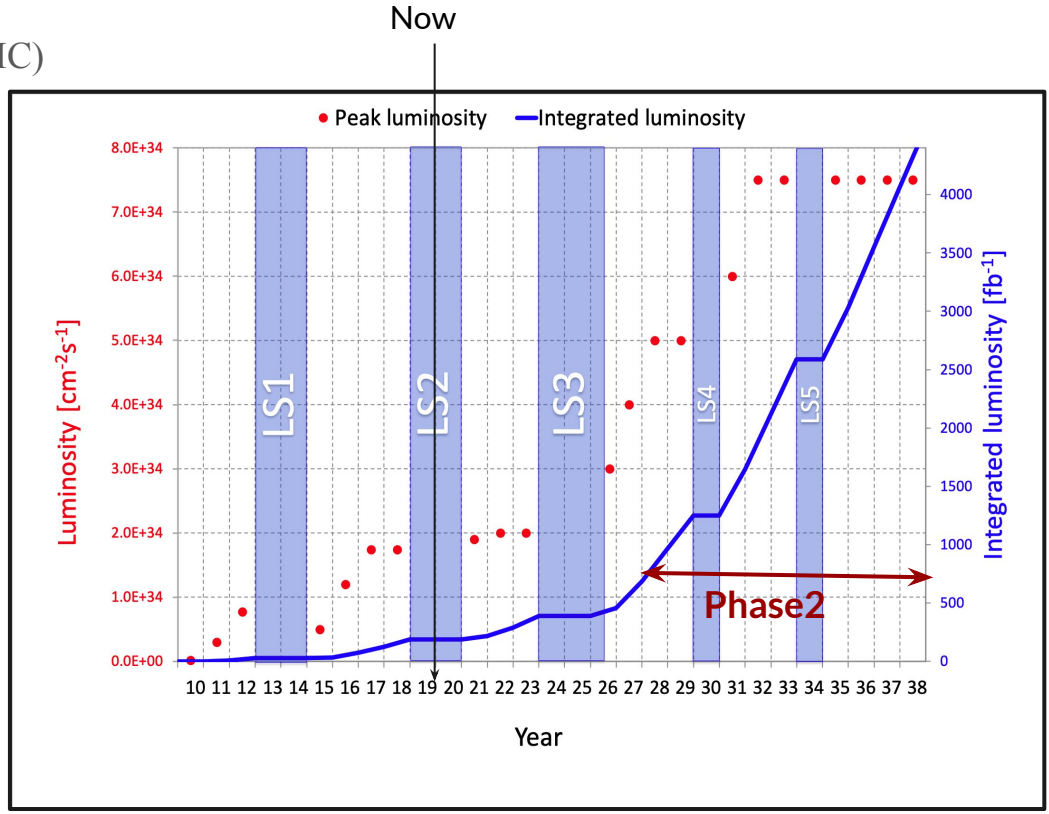
Outline

- High Lumi LHC(HL-LHC)
- Tracker layout.
- Tracker input to L1 trigger
  - Concept of pT module.
- Outer tracker modules
  - Module design
  - Readout
  - Sensors
- Performance
  - Prototype modules in test beams
  - Offline tracking from simulation studies
- Conclusions

The High-Luminosity LHC

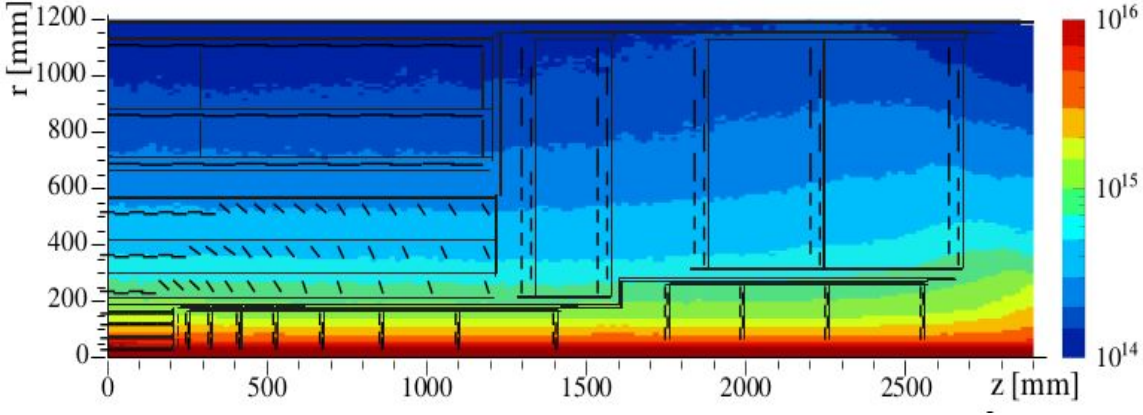
- High Luminosity upgrade after LS3(HL-LHC)
- Expected instantaneous luminosity of $7X10^{34}$ cm^{-2} s^{-1} (* ultimate scenario).
- Expected pileup ~ 200 per bunch crossing.
- Civil engineering is ongoing.
- Expected installation : 2024–2026





CMS Phase2 tracker requirements

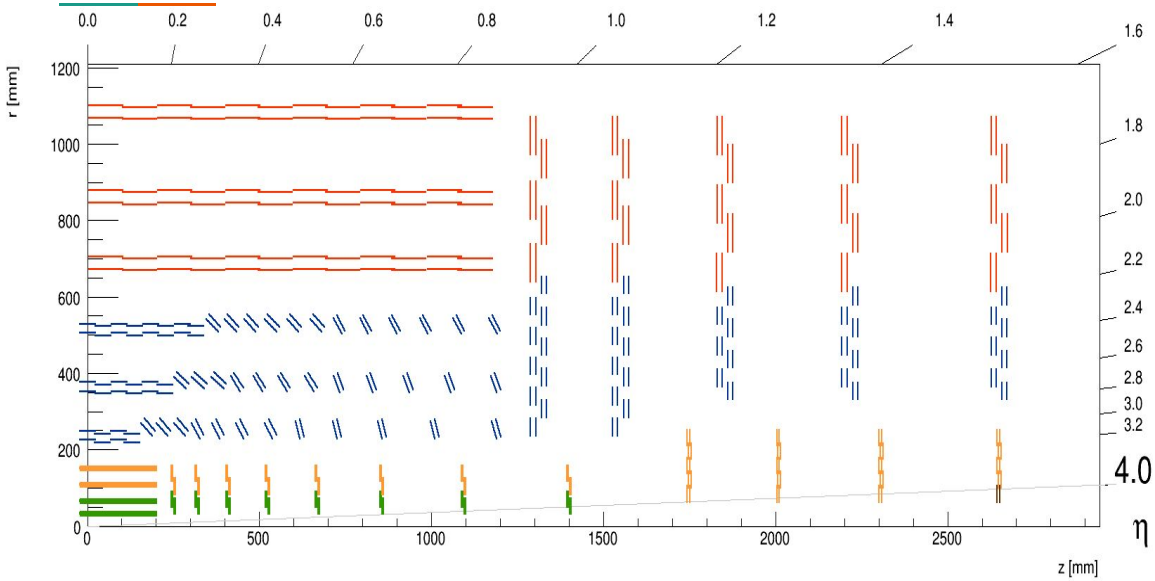
- The current CMS tracker was designed to operate upto an integrated luminosity of 500 fb^{-1}, and an average PU of < 50. Thus, to have an efficient tracking system for the HL-LHC period, a new silicon tracker is being designed.
- The requirements of the upgraded tracker:
  - Radiation tolerance: The upgraded tracker must be fully efficient up to a target integrated luminosity of 3000 fb^{-1}.
  - Granularity: The tracker must be granular to allow tracking even in high pileup.
  - Reduced material budget in the tracking volume.
  - **Contribution to the Level-1 trigger decision**
  - Extended tracking acceptance(forward pixel detectors).

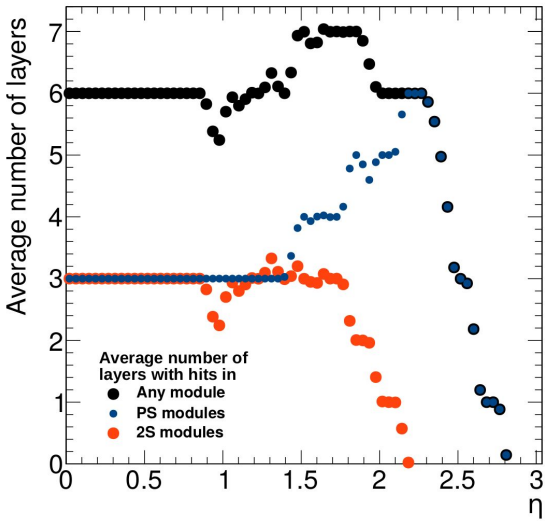


Region or component	Max. fluence [n_{eq}/cm^2]	r [mm]	z [mm]
OT PS modules	9.6×10^{14}	218	129
OT 2S modules	3.0×10^{14}	676	2 644

Maximum expected fluence for selected detector regions or components for 3000 fb^{-1} (CMS-TDR-014) using FLUKA simulation.

Phase2 tracker layout

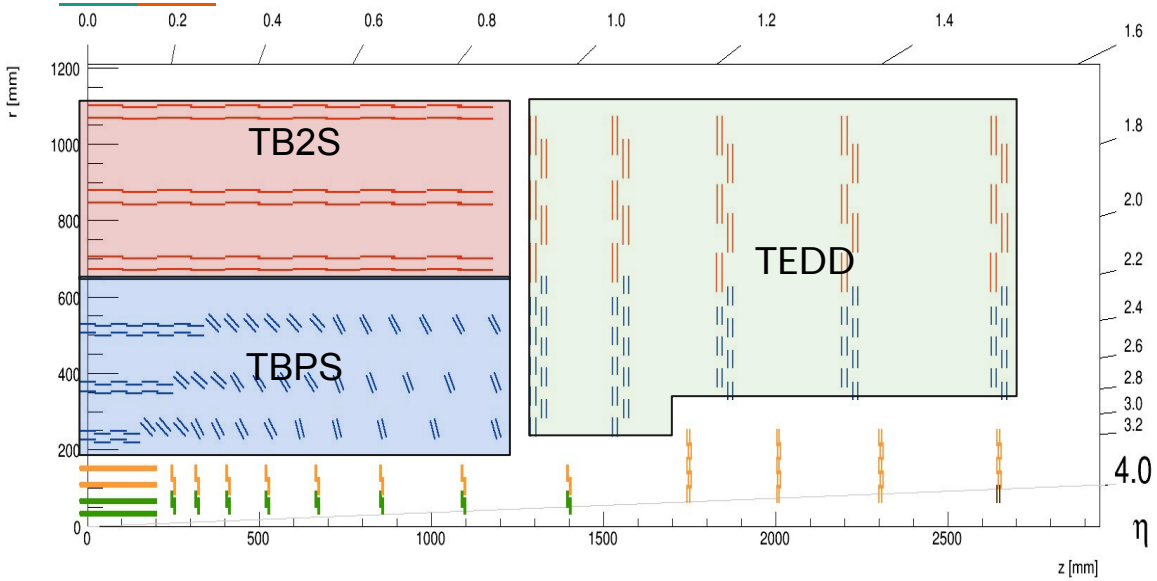


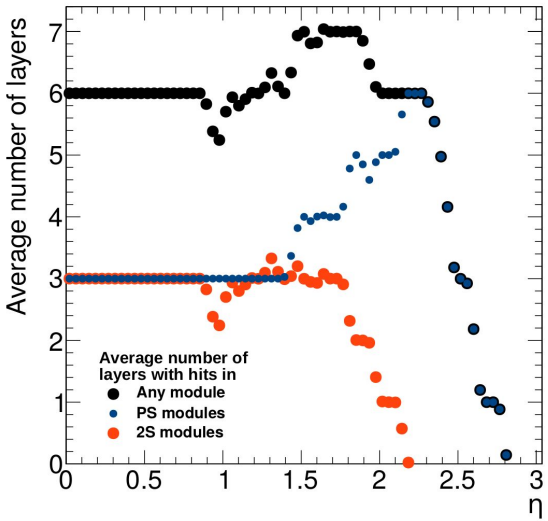


- Acceptance up to |η| ~ 4 including the Inner Tracker (IT).
- Outer Tracker (OT) is made up of 6 cylindrical layers in the barrel and 5 discs in the endcap.
- 2 module types: **Strip - Strip (2S)** and **Macro-Pixel-Strip (PS)**
- Innovative tilted geometry in inner barrel.
- 13'296 modules, 192 m^2, 42M strips, 170M macro-pixels (~25 m^2).
- Module choices in layers determined by expected occupancy.

Talk: The Phase 2 upgrade of CMS Inner Tracker by S. Orfanelli.

Phase2 tracker layout





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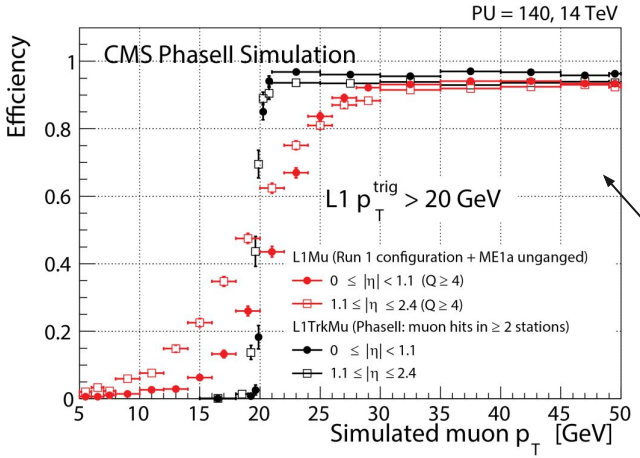
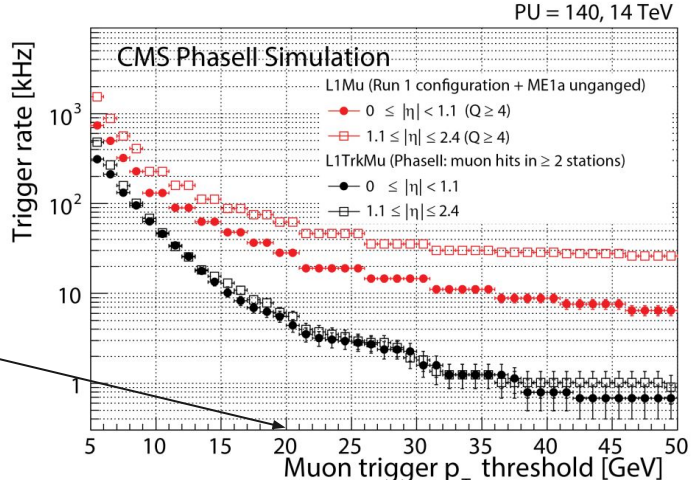
- **TBPS**: Tracker Barrel with PS modules
- **TB2S**: Tracker Barrel with 2S modules
- **TEDD** : Tracker Endcap Double Disks
- Outer tracker coverage ~ |η| ~ 2.5

Tracker input to L1 trigger

- The target L1 rate ~ **750 kHz** with a trigger latency of **12.5 µs**.
- Tracker information at L1 highly beneficial for L1 trigger performance
  - Better discriminating power.
  - Improvement in L1 object using tracker information - better p_T resolution, ability to use tracker isolation(to mitigate effects of pileup.) , vertex identification.



Using tracks in L1
Rate reduction with a threshold of 20 GeV without loss of efficiency



LHCC-P-008

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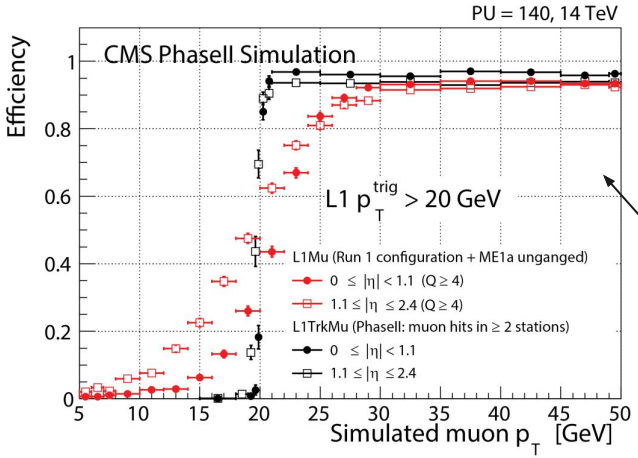
  - Better discriminating power.
  - Improvement in L1 object using tracker information - better p_T resolution, ability to use tracker isolation(to mitigate effects of pileup.) , vertex identification.
- To be part of the L1 trigger, the OT has to be read out at every bunch crossing.
- But all tracker data cannot be read out at bunch crossing frequency.
- Requirement for data reduction on the module itself : **concept of pT modules!**



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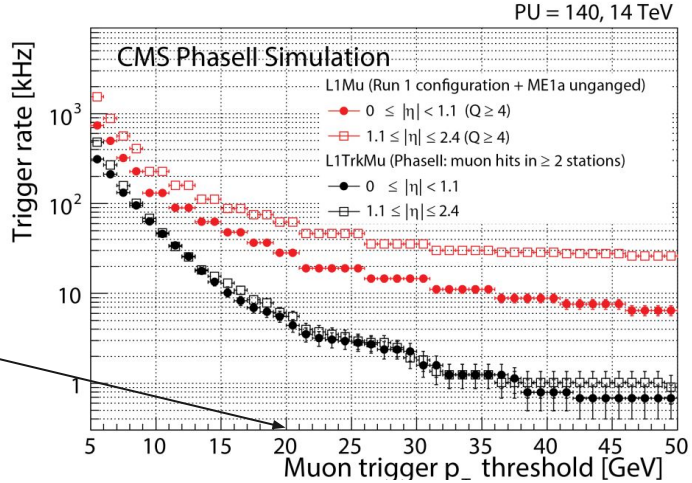
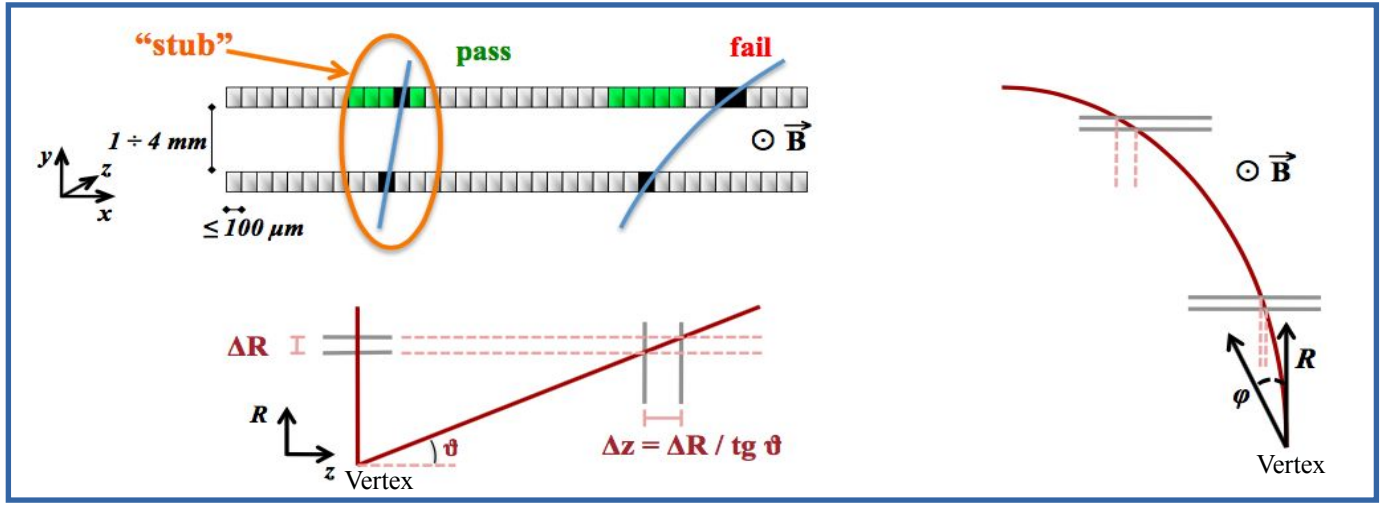


LHCC-P-008

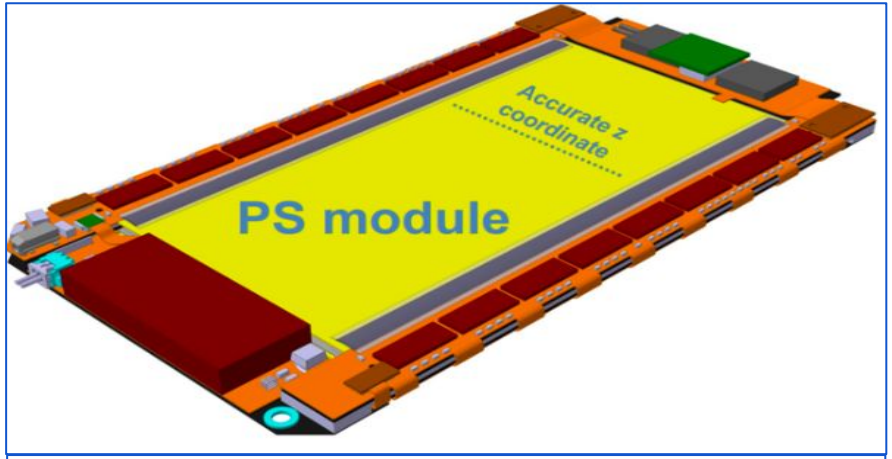
Concept of pT modules

- The outer tracker will be made up of modules with 2 stacked sensors readout by a common FE.
- A hit in the bottom sensor is matched to one in the top sensor if they are within a predefined window,in number of strips(programmable on the FE chip).
- This correlated hit pair forms a short track segment - **”stub”**
  - **This hit matching is done by the front-end electronics.**
- Stubs used in Level-1 tracking and combination of L1 tracks + muon system + calorimeters leads to the L1 decision.
- With a 2GeV threshold, a data reduction by an order of magnitude is achieved enabling stub readout at 40MHz.

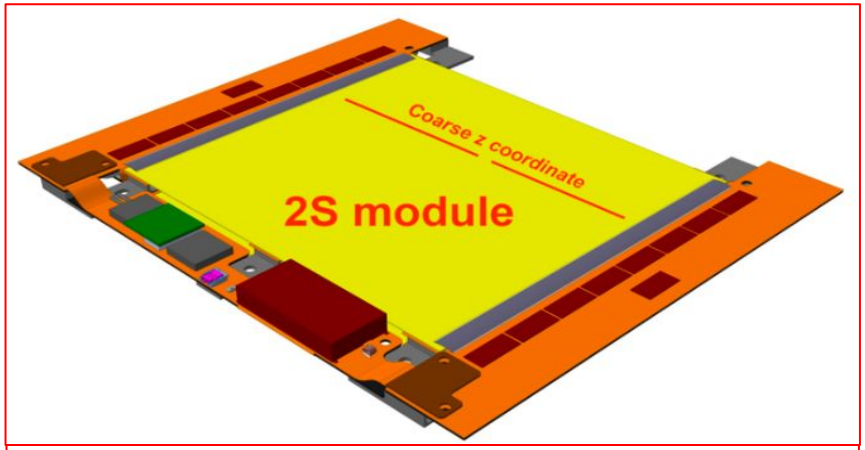


- In the presence of a magnetic field(3.8 Tesla), tracks will bend in a plane transverse to the direction of the beam.
- Particles passing through the module creates hits in two closely spaced top and bottom sensors.
- Radius of curvature of the tracks proportional to p_T.

OT modules

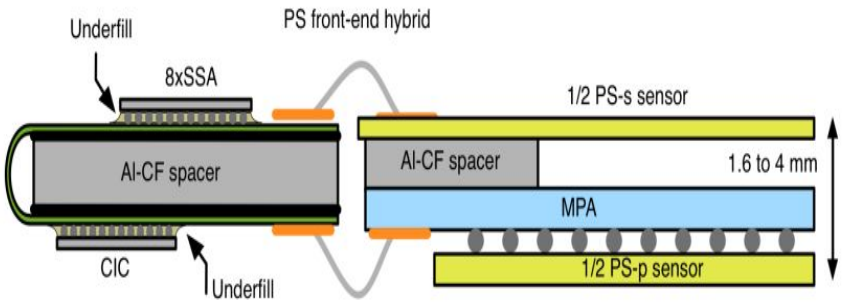


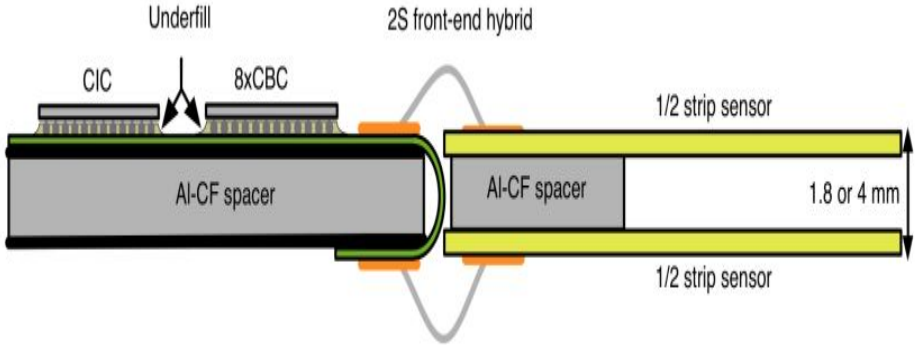
- PS Modules
  - 3 different spacing : 1.6mm & 2.6mm &4mm
- 2 × 960 strips: ~ 2.4 cm × 100 µm
- 32 × 960 macro-pixels: ~ 1.5 mm × 100 µm
  - Accurate Z coordinate.
- Sensor dimension 5cm x 10 cm
- First 3 layers of barrel
- 10 inner rings in TEDD 1 , 2 and 7 inner rings of TEDD 3-5



- 2S Modules
  - 2 different spacing : 1.8mm & 4mm
- 2 micro strip sensors with 5cm x 90µm strips
- Sensor dimension are 10cm x 10cm
- Two column of 1016 strips
- 3 outermost layers of barrel.
- 5 outer rings of TEDD

OT module: readout





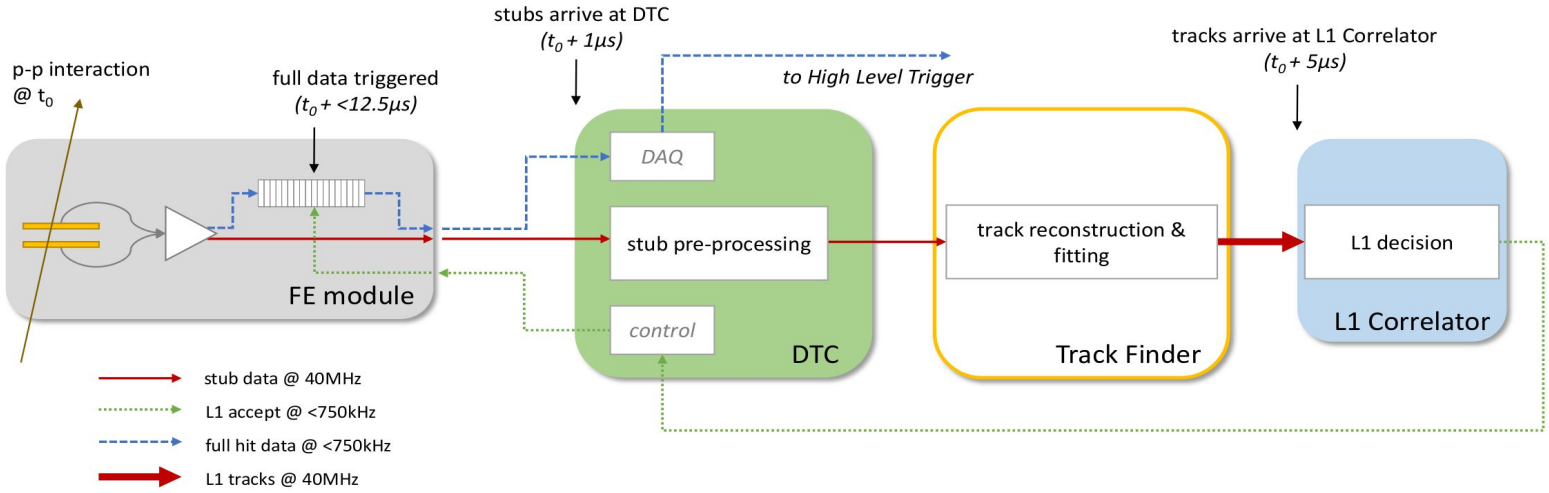
- PS modules are readout by MPA and SSA chips
- Short Strip ASIC(SSA)
  - Reads strip data
- Macro-pixel ASIC (MPA)
  - Reads macro-pixel data
- MPA receives the clusters from SSA and forms stubs.

- 2S modules are readout by CMS Binary Chip(CBC)
- Possibility to read out in unsparsified(channel data) or sparsified mode(clusters).
- 254 strips per chip - half connecting to top sensor and other half connecting to the bottom.

The hybrid is bent to allow connection to the two sensors.

OT module: readout

- Data from the CBC/MPA are formatted by Concentrator Integrated Circuit(CIC) chips.
- 2CIC chips per module
- Packs data for 8 bunch crossings.
- Priority to Trigger data.



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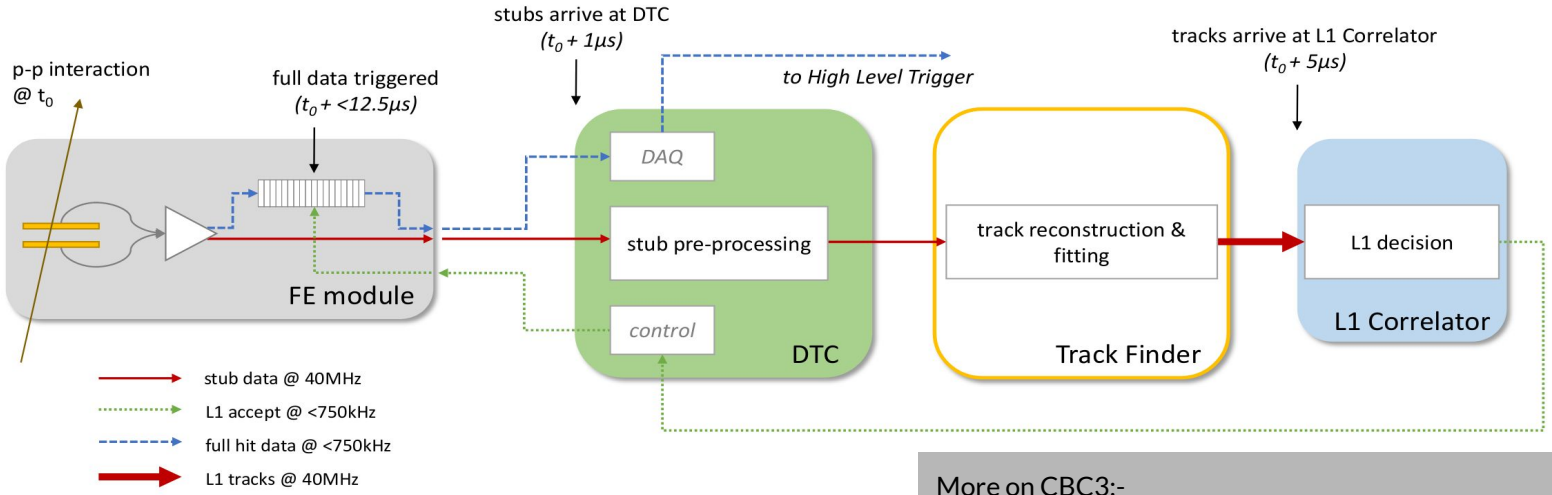
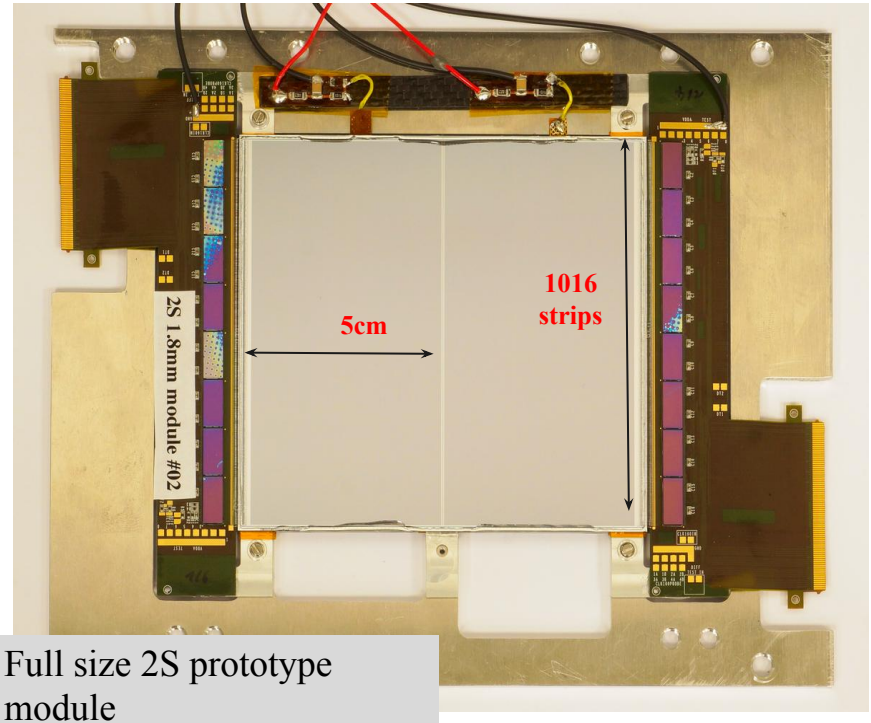


- Design for CBC 3.1 is finalized.
- Prototypes of MPA, SSA, CIC, have been produced.

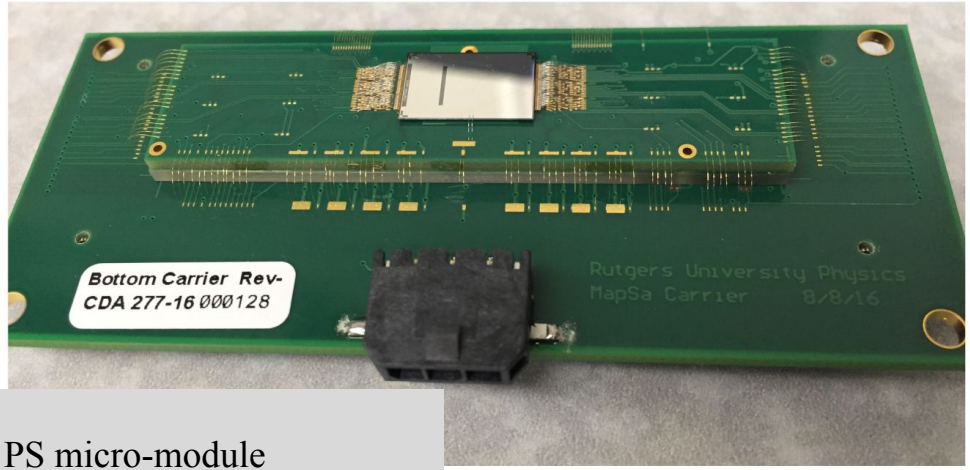
More on CBC3:-
Talk: "Single Event Upset evaluations of CBC readout chips" by G. Hall, today.

Poster: "Results from the CBC3.1 readout ASIC for CMS 2S-modules" by K. Uchida.

OT prototype modules



Full size 2S prototype module



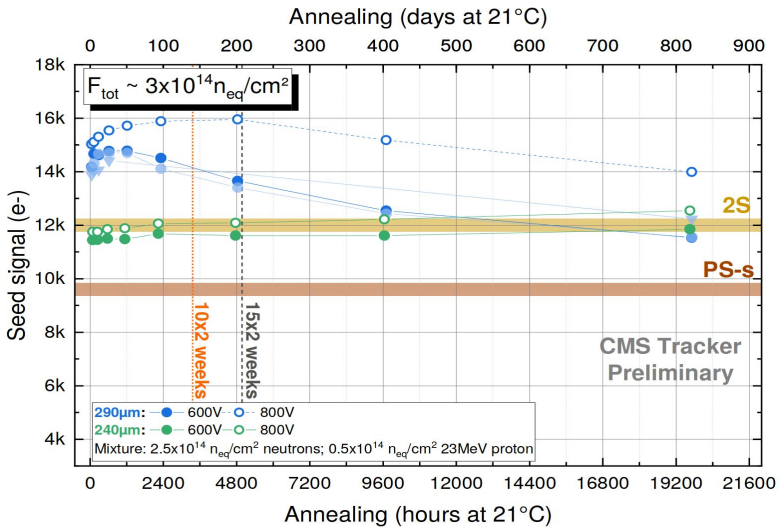
PS micro-module

- Fully functional 2S module prototypes produced
  - mini-modules with 2 X CBC2 and CBC3 readout.
  - full size module with 16 CBC readout(both CBC2 and 3 readout).
  - irradiated mini module with CBC2 readout.
  - Studies at beam tests with both mini and full sized modules

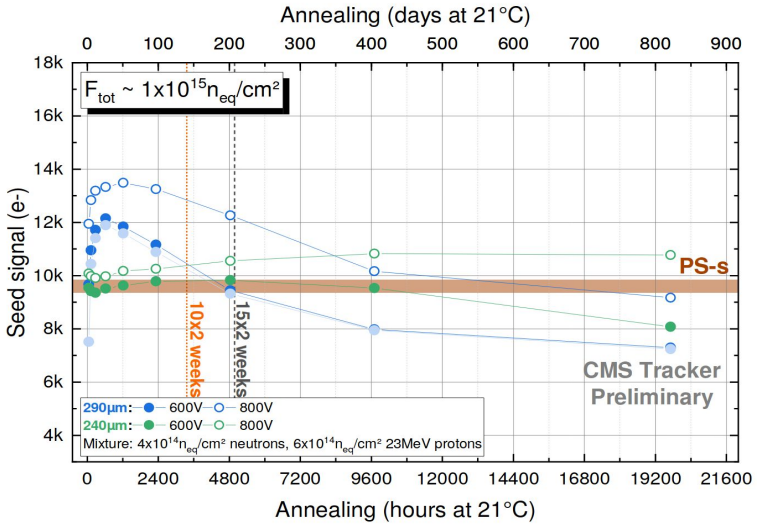
- Fully functional PS module prototypes produced
  - MaPSA-light module : 6 MPA chips bump bonded to PSp sensors with 48 channel readout channels each
  - PS micro module: two MaPSA-light module stacked.
  - MPA and SSA communication being checked on a test bench.
  - Functional hybrid expected by 2020.
  - Single MaPSA module - beam test studies performed.

OT sensors

1. All results in TDR were based on deep diffused float zone(ddFZ) sensors with 240micron active thickness. However, they are not available anymore.
2. Extensive irradiation and characterization campaign was undertaken to study the different sensor choices
   a. FZ290 : 290 micron active thickness(Same material as current tracker in terms of thickness and backside doping.)
   b. Th240 : 240 micron active thickness.
3. Choice of sensor is FZ290
   a. Better performance after irradiation. Sensor performance studied after irradiation to the maximum expected fluence.
   b. thFZ240 sensors have shown to be more sensitive to mechanical damage due to handling.
   c. thFZ240 has 15% higher costs.



Results for max expected fluence of 2S layers



Results for max expected fluence of PS layers

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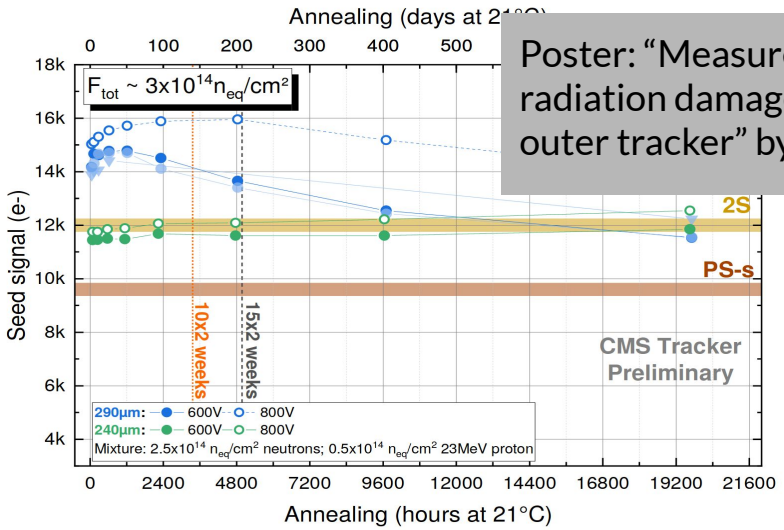
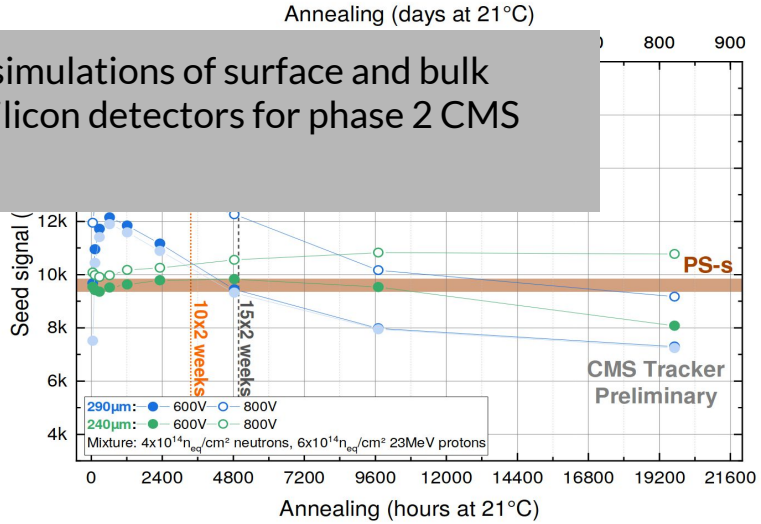
Poster: “Measurements and simulations of surface and bulk radiation damage effects in silicon detectors for phase 2 CMS outer tracker” by V. Mariani.



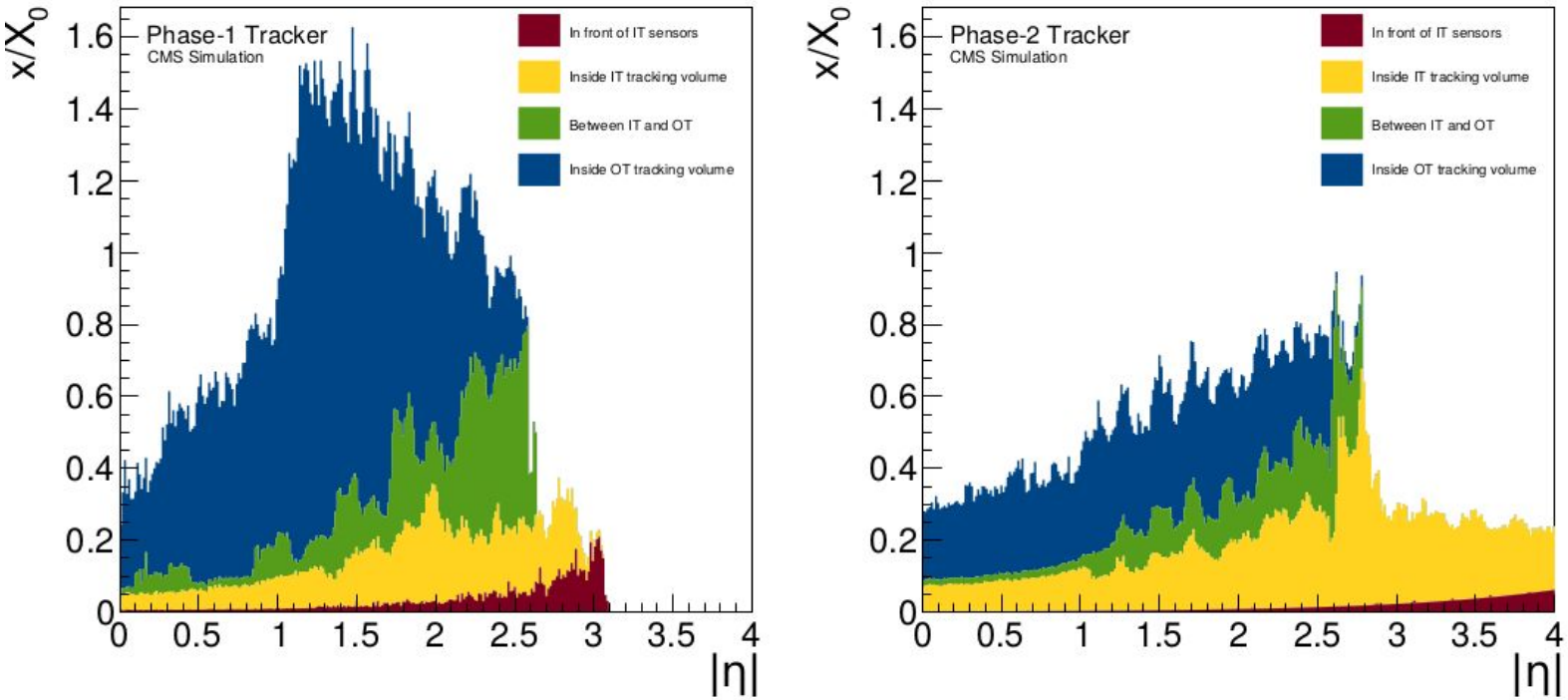
Results for max expected fluence of 2S layers



Results for max expected fluence of PS layers

CMS Phase2 tracker: Material budget

(CMS-TDR-014)



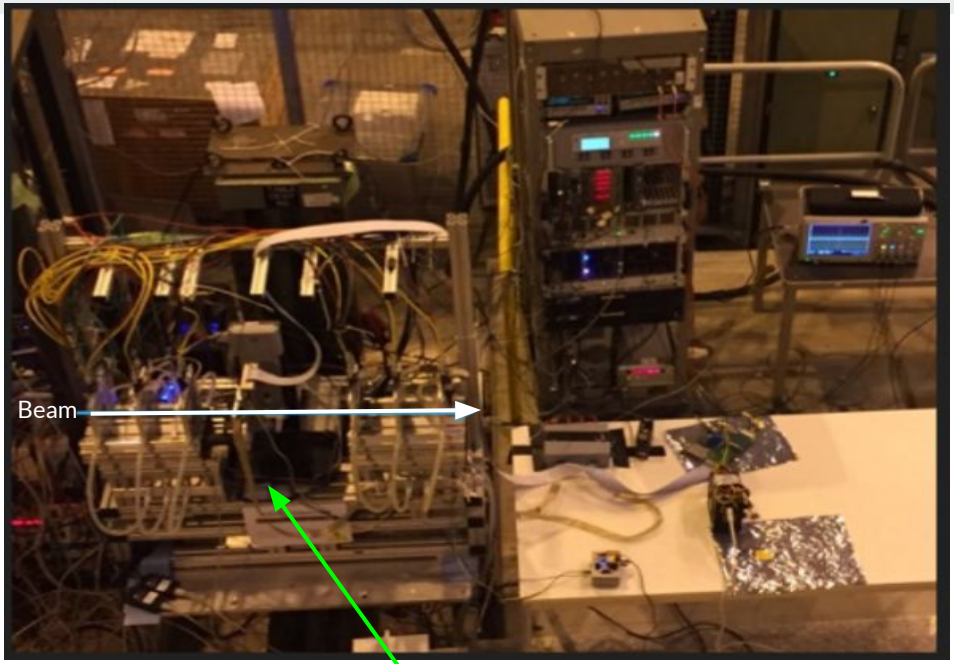
Phase1 → Phase2

- The amount of material in the tracking volume is less compared to the Phase1 tracker(Phase1 pixels + Phase 0 strips).

Performance of prototype modules in beam tests

- Different prototype modules have been put to test in particle beams.

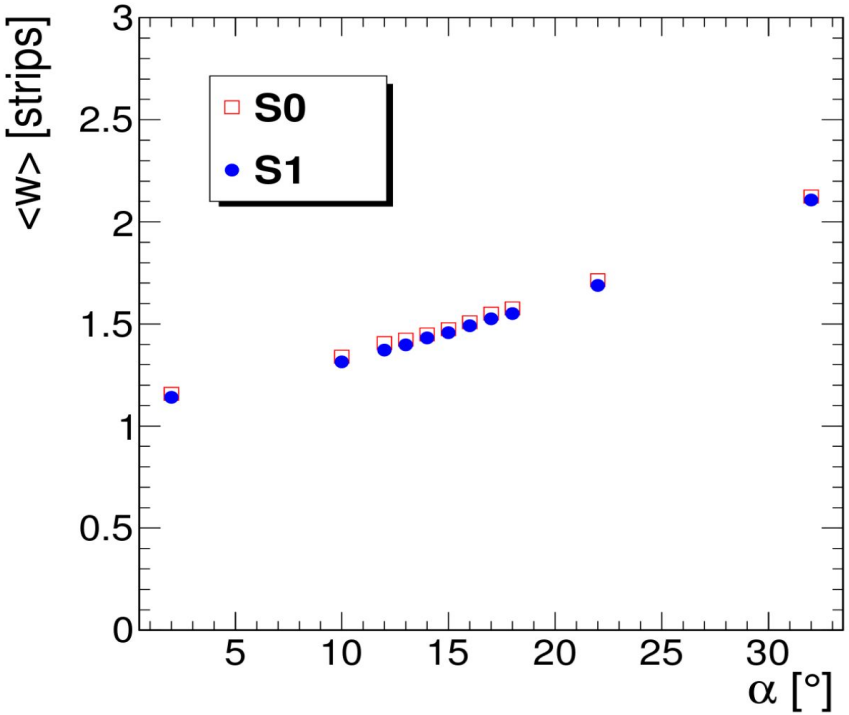
Module type	CHIP	BT Facility
2S mini-module	CBC2 (2 chips on mini-sensor)	DESY, CERN, Fermilab
2S mini-module(irradiated)	CBC2	CERN
2S full-size module	CBC2 (16 chips on full sensor)	CERN, Fermilab
2S mini-module	CBC3	Fermilab
PS micro-module	MPA	Fermilab
Single MaPSA	MPA	DESY

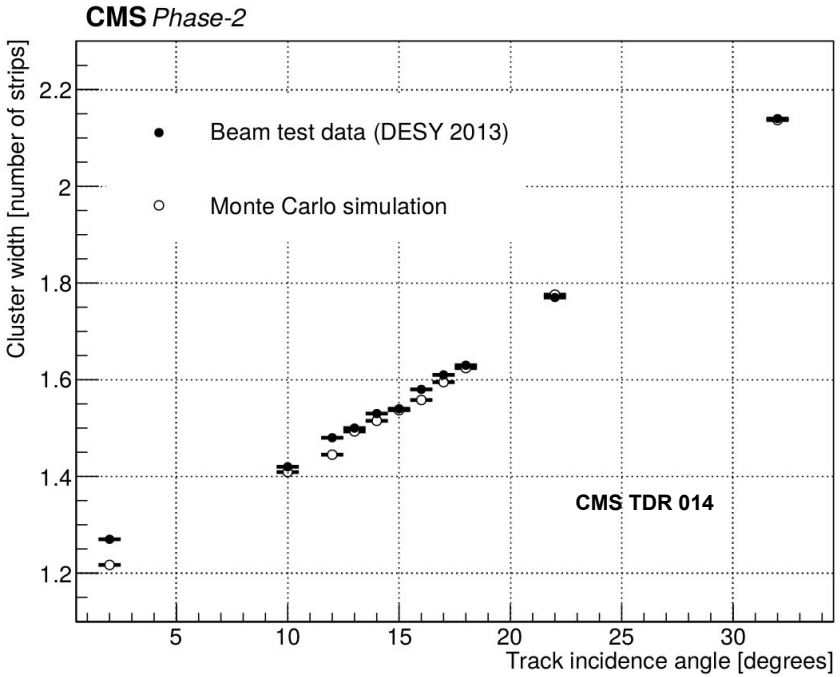


@CERN BT

Detector under test

Performance of prototype modules in beam tests

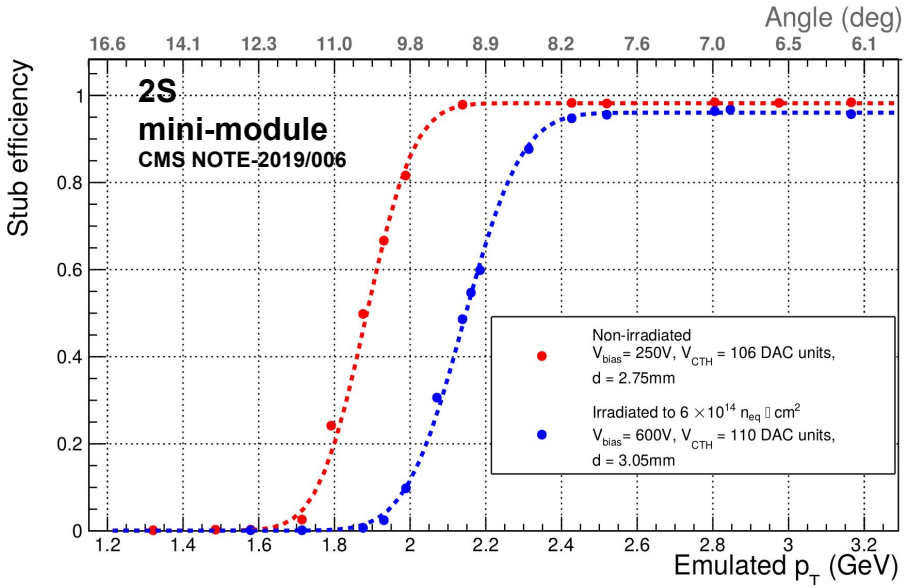




- Cluster width as a function of beam incident angle is an important quantity to study.
- Used to tune the parameters of the “Digitizer” in CMS software.

Performance of prototype modules in beam tests

Bending of charged particles inside the magnetic field emulated by rotating the modules w.r.t beam direction.



- Stub efficiency measured as a function of emulated pT.
- The modules demonstrate the power to discriminate tracks with p_T <~ 2 GeV.
- The difference in the turn-on threshold for the irradiated module compared to non-irradiated one is due to different sensor spacing.
- No significant loss of efficiency even after irradiation.

x

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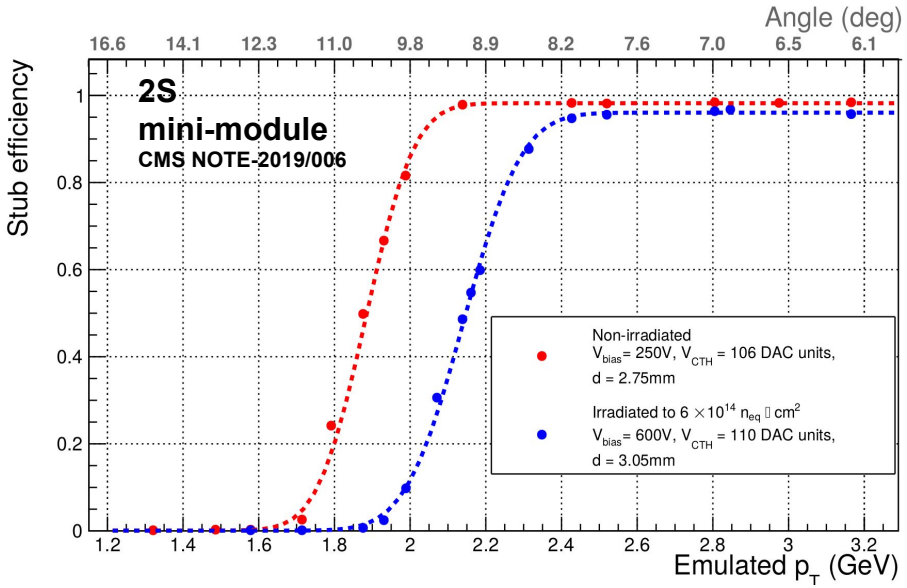

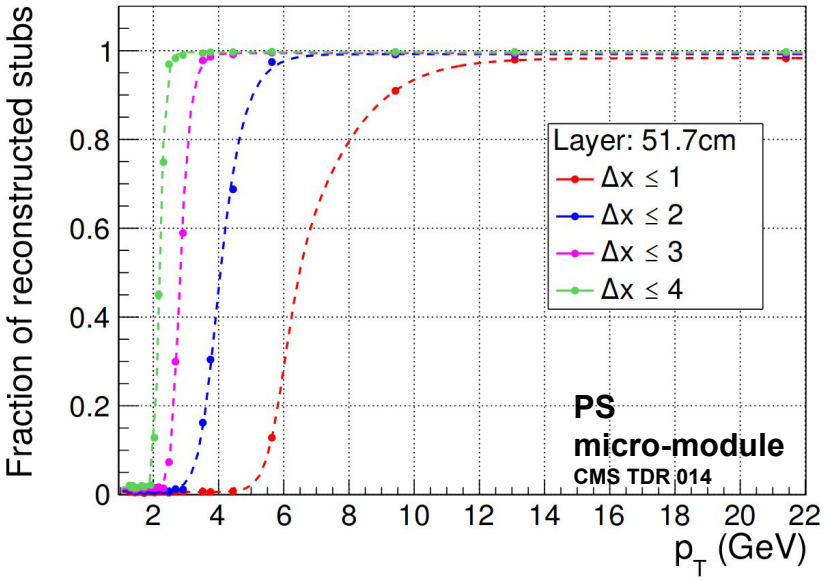

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- Stub efficiency measured as a function of emulated pT for different correlation window(Δx in units of macro-pixel).
- Discriminating power for tracks with p_T ~ 2 GeV.

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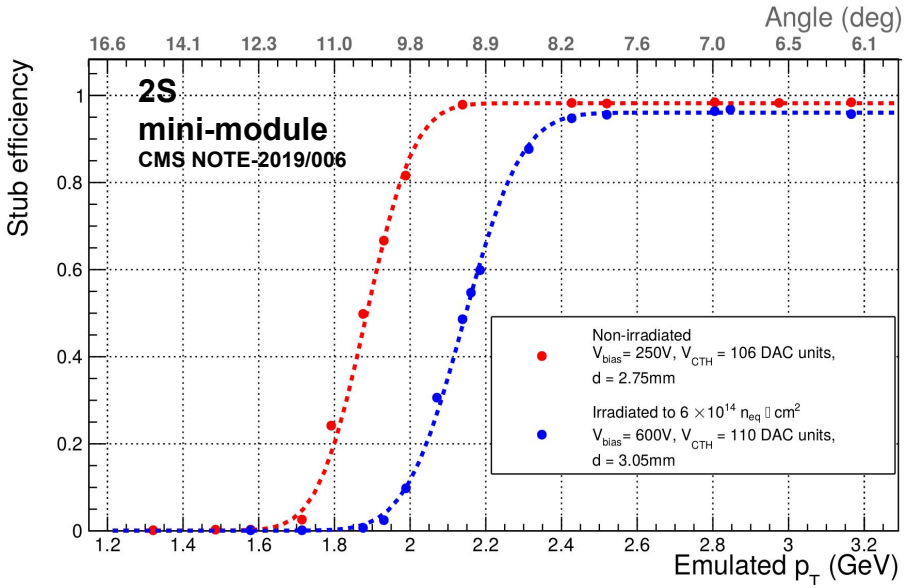

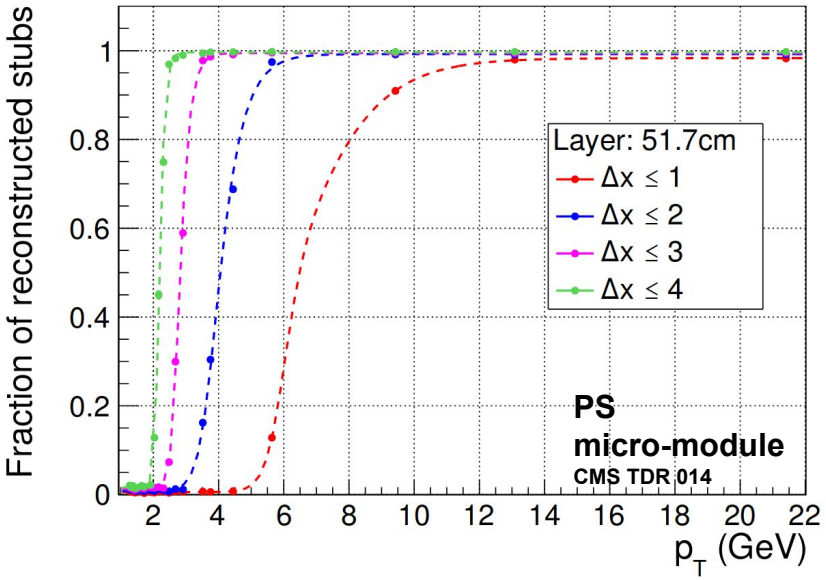

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- The modules demonstrate the power to discriminate tracks with p_T <~ 2 GeV.
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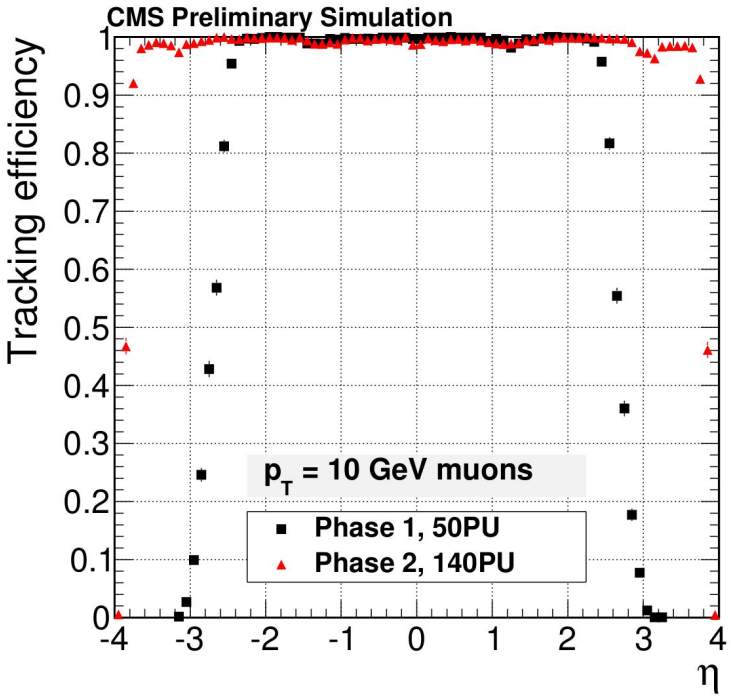
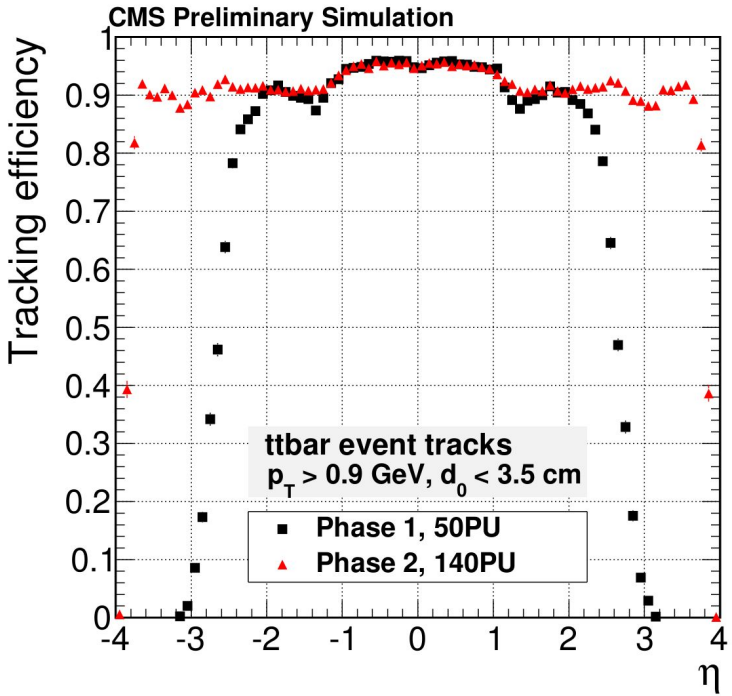
- Stub efficiency measured as a function of emulated pT for different correlation window(Δx in units of macro-pixel).
- Discriminating power for tracks below p_T <~ 2 GeV.

Concept of p_T discrimination working!!!

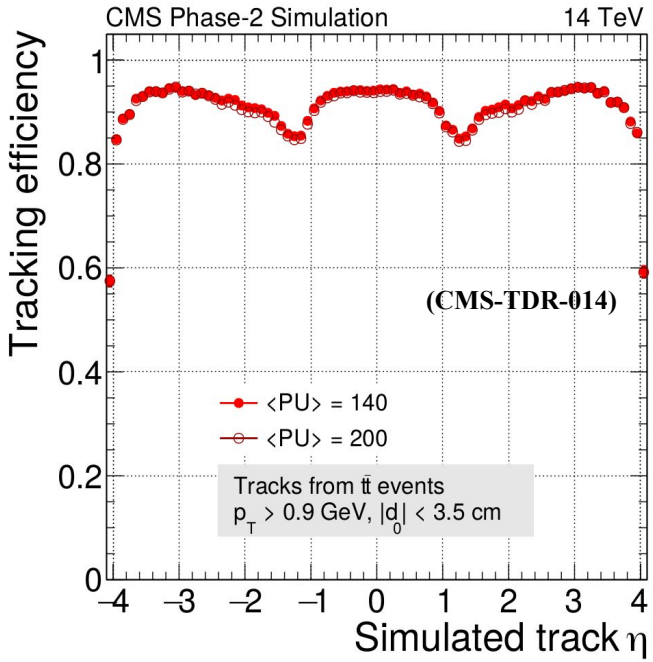
Performance : Offline tracking Phase 1 vs Phase 2

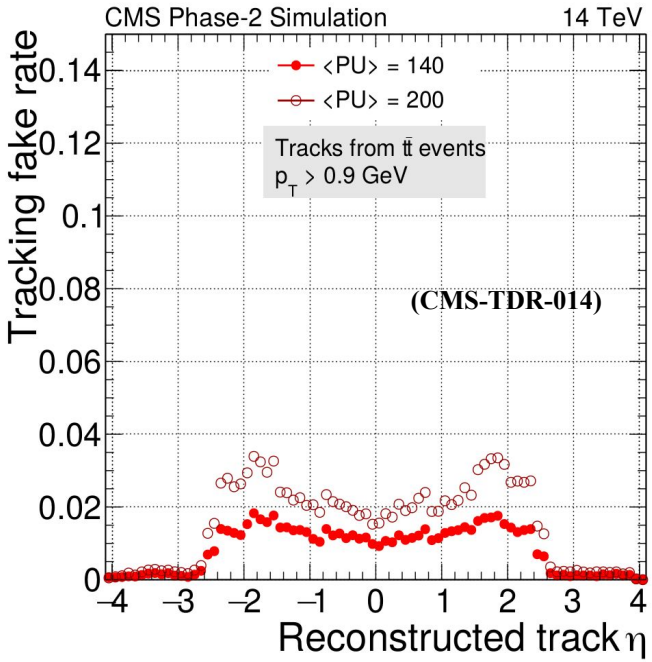




- Excellent performance in offline tracking.
- Extended coverage η.

Performance : Offline tracking efficiency





- High tracking efficiency (~90%) also at 200PU.
- Fake rate below 2(4)% at 140(200)PU.

- ttbar events + pileup used for the studies
- A reconstructed track is associated to a simulated particle if at least 75% of its hits originate from this simulated particle(otherwise fake).
- Tracking efficiency = frac. of charged particles associated to at least one reconstructed track.
- Fake rate = frac. of fake tracks among all reconstructed tracks.

Conclusion

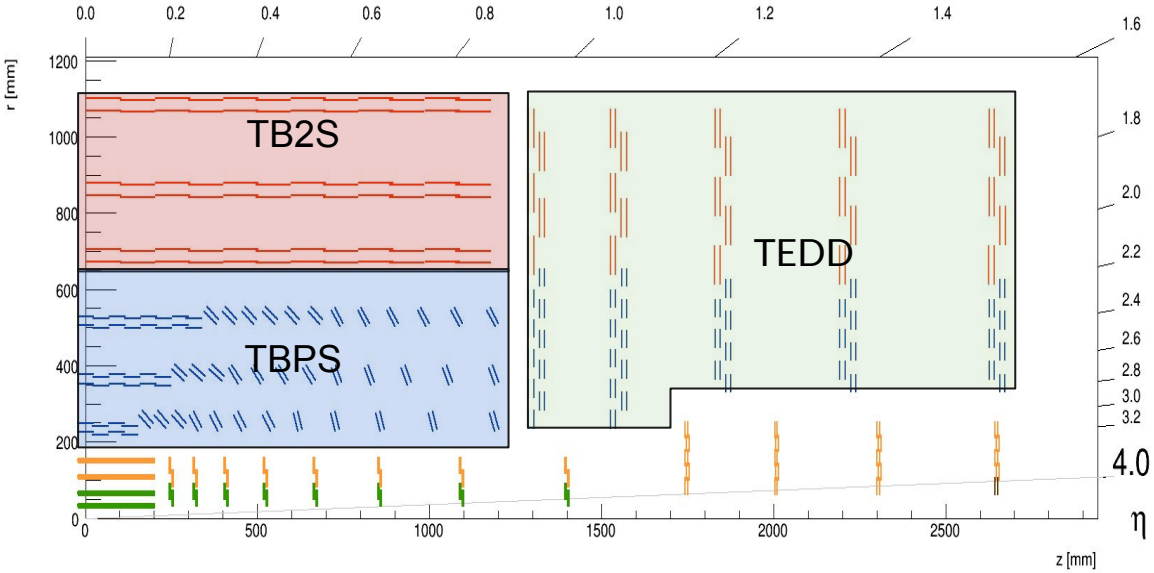
- The Phase2 upgrade of the CMS tracker is an important project to ensure efficient performance of the CMS detector in the HL-LHC era.
- Designed to operate even at high pileup environment ~200.
- Participate in L1 trigger decisions.
- Data reduction on the module itself by the FE-chips
- Layout of the tracker is quite advanced.
- Prototype modules are being studied under test beams.
  - Encouraging performance demonstrating the power of p_T discrimination.
  - Still several tests planned in the next year to understand the properties better.
- Developments also ongoing in CMS software- tracking, electronics emulation etc.
- Choice of sensors finalized.
- CMS working towards HLT technical design report, more results from L1 track trigger expected.
- A tight schedule ahead of CMS before the final installation of the system - sensor production, qualification, module assembly, building of support structures etc...

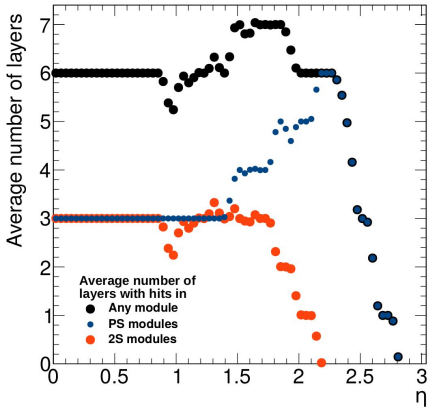
Pre-production: 2020-2021
Production: 2021-2023/24
OT installation: 2025

Thank You

Backup

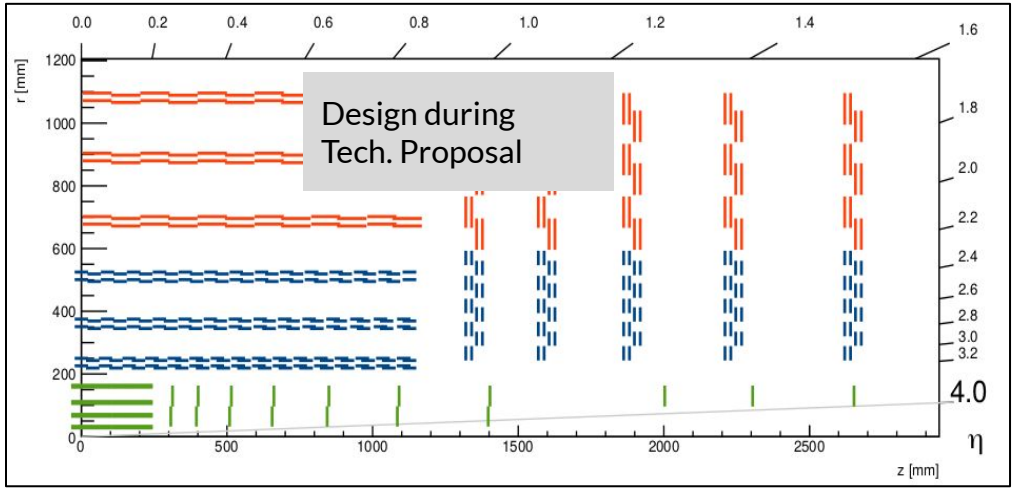
Phase2 tracker: OT regions



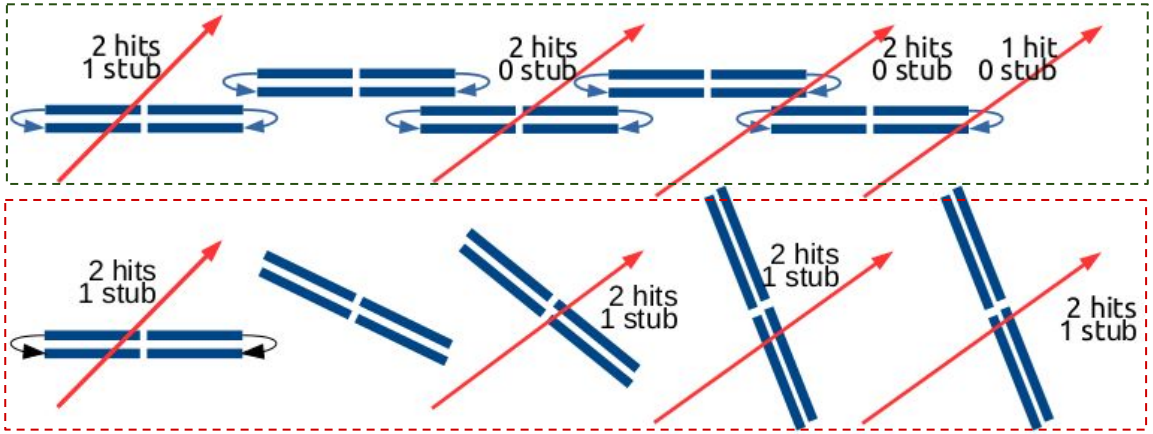


- **TBPS**: Tracker Barrel with PS modules
- **TB2S**: Tracker Barrel with 2S modules
- **TEDD** : Tracker Endcap Double Disks
- Outer tracker coverage ~ $|\eta|$ ~ 2.5

Tilted barrel geometry



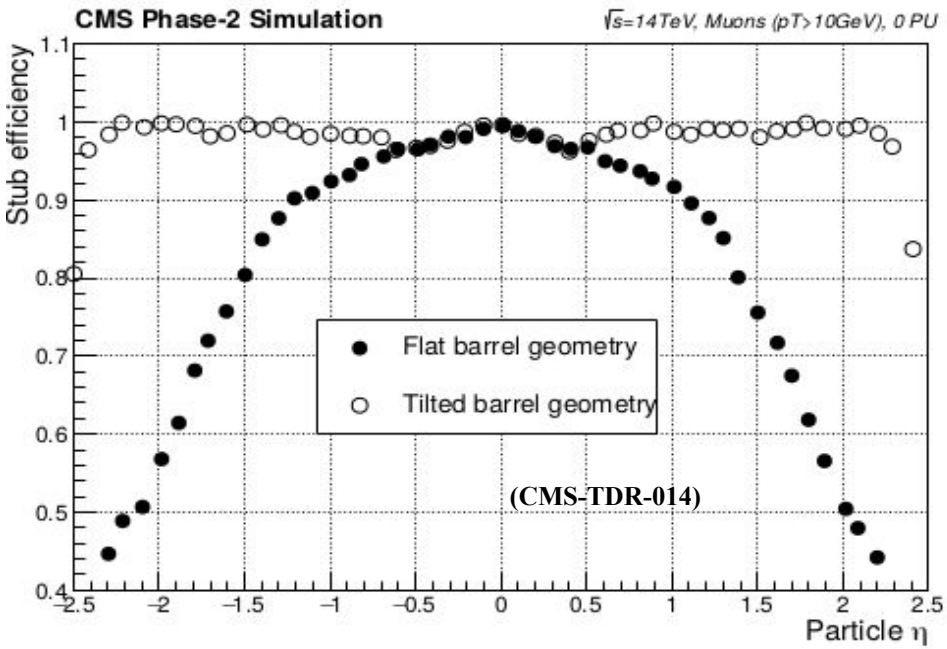
- Stub formation will take place if the incident particle hits the same side of a pT module(or hits readout by chips on the same side of the module).
- In the flat geometry, as η increases, this may not be the case.
- Progressively tilt the barrel PS modules



Flat

Tilted

Tilted barrel geometry

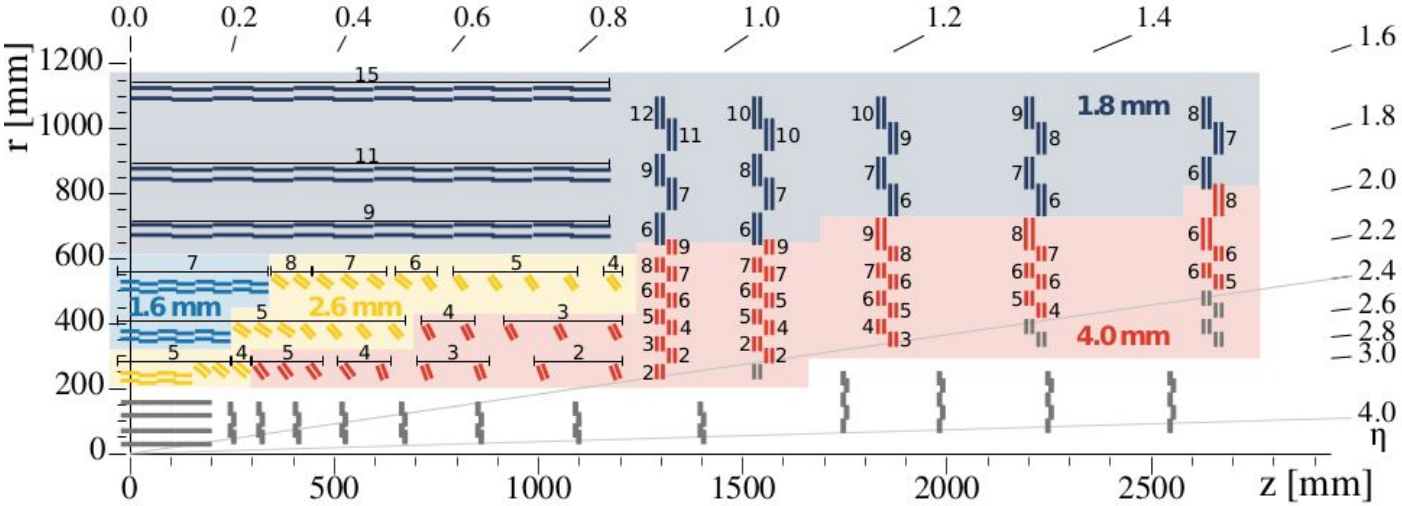


- Stub formation will take place if the incident particle hits the same side of a pT module(or hits readout by chips on the same side of the module).
- In the flat geometry, as η increases, this may not be the case.
- Progressively tilt the barrel PS modules
  - Reduced no. of modules from ~15K (flat) to ~13K (tilted).
  - Lesser material traversed in larger η

Outer tracker modules

- p_T discrimination depends on the acceptance window & sens separation
- Acceptance window is programmable (both width and position)
  - Large spacing → good p_T resolution
  - Large spacing ↔ large window needed
  - Large window → more fakes
- Choice of spacing for inner layers is a compromise between the above.

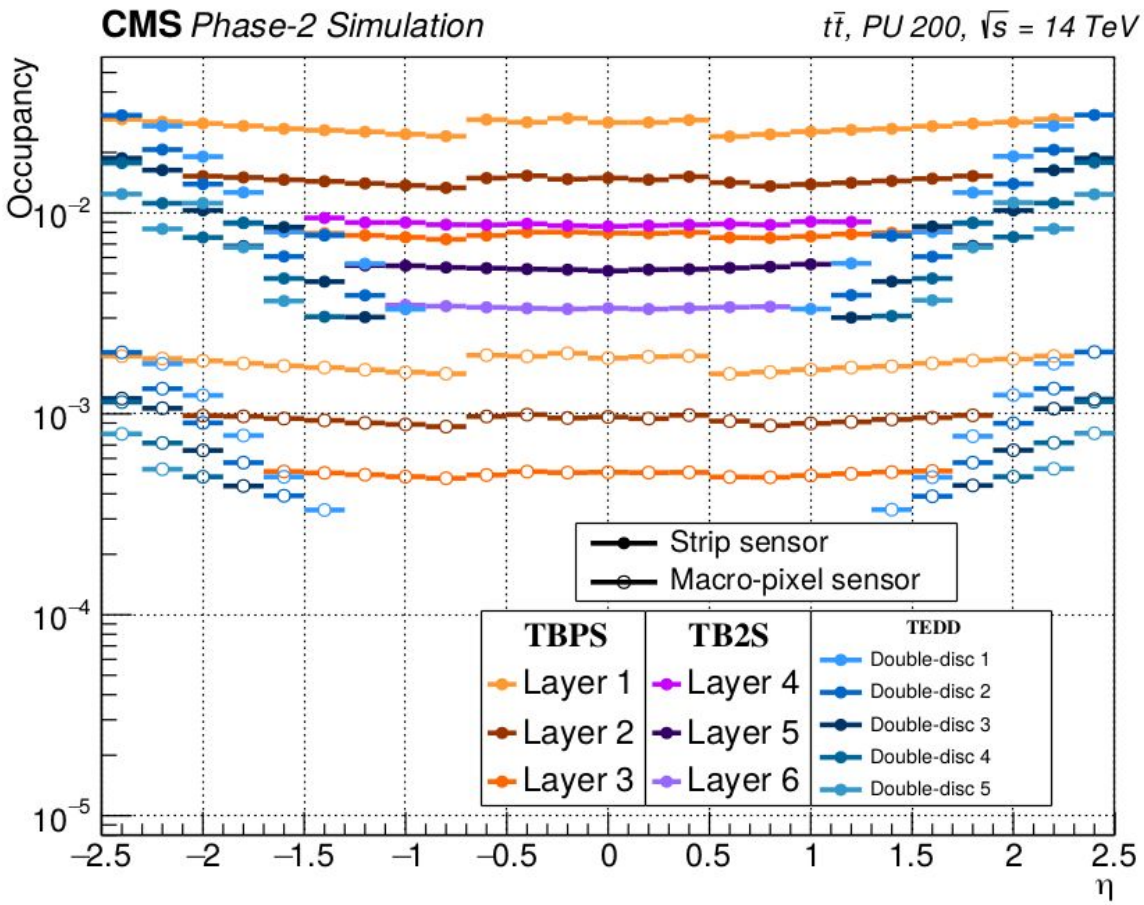
Module type and variant		TBPS	TB2S	TEDD	Total per variant	Total per type
2S	1.8 mm	0	4464	2792	7256	7680
	4.0 mm	0	0	424	424	
PS	1.6 mm	826	0	0	826	5616
	2.6 mm	1462	0	0	1462	
	4.0 mm	584	0	2744	3328	
Total		2872	4464	5960	13296	



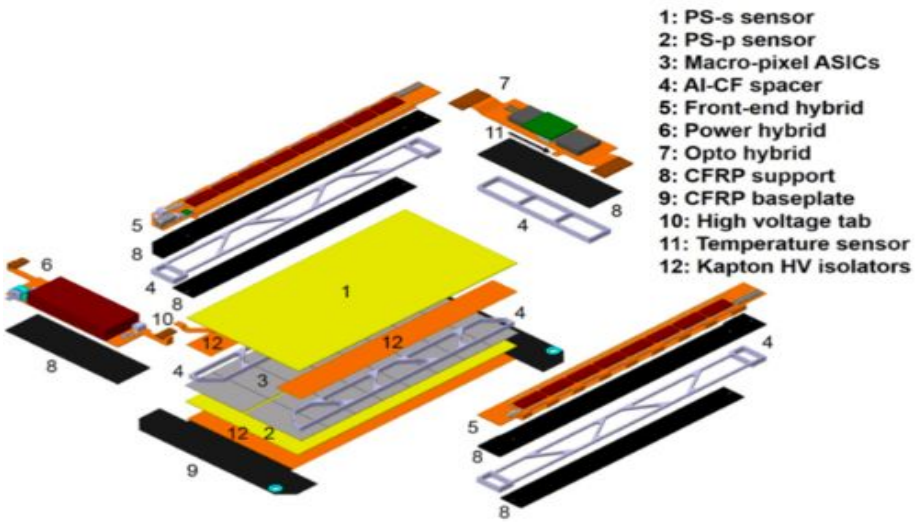
Colours=sensor spacing
Numbers= acceptance window

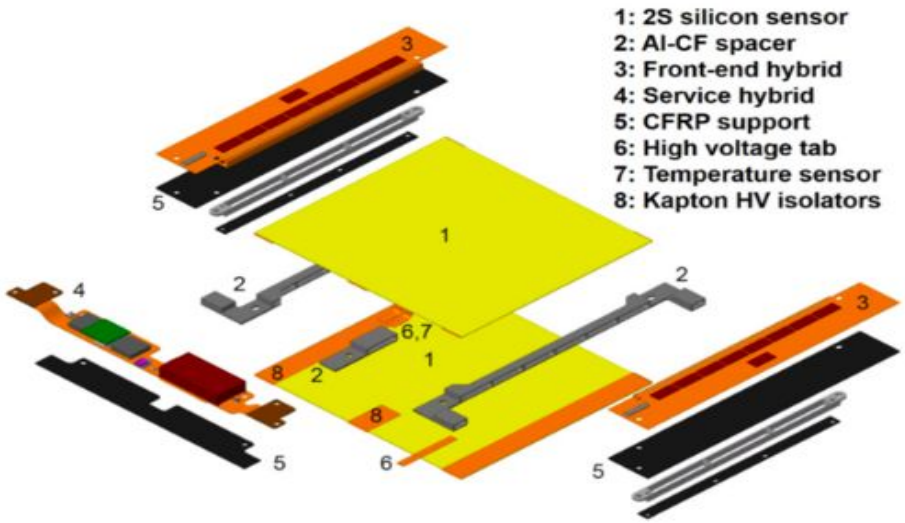
Window setting assuming threshold of 2GeV

OT Hit occupancy



Outer tracker modules

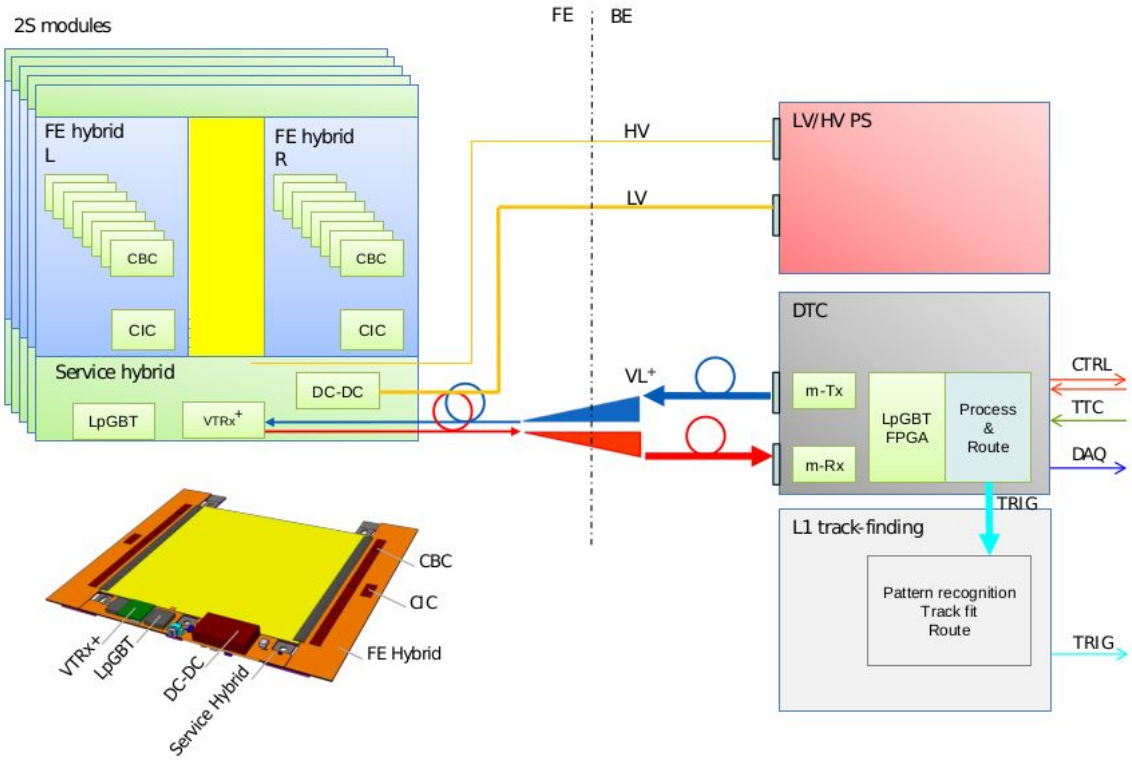




- PS Modules
  - 3 different spacing : 1.6mm & 2.6mm &4mm
- 2 × 960 strips: ~ 2.4 cm × 100 µm
- 32 × 960 macro-pixels: ~ 1.5 mm × 100 µm
  - Accurate Z coordinate.
- Sensor dimension 5cm x 10 cm
- First 3 layers of barrel
- 10 inner rings in TEDD 1 , 2 and 7 inner rings of TEDD 3-5

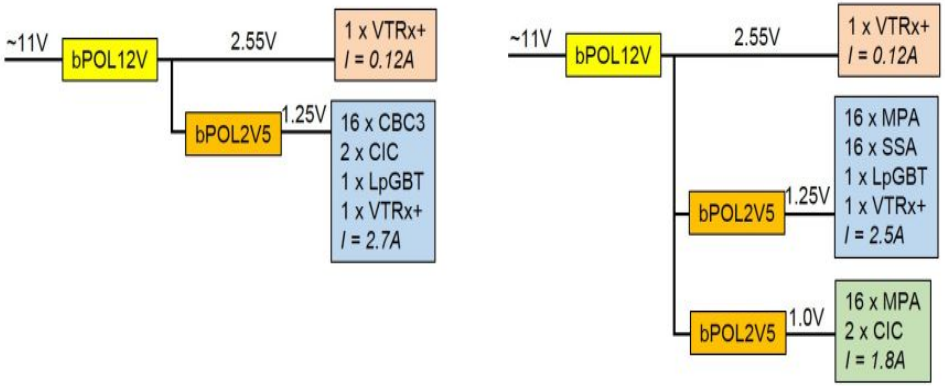
- 2S Modules
  - 2 different spacing : 1.8mm & 4mm
- 2 micro strip sensors with 5cm x 90µm strips
- Sensor dimension are 10cm x 10cm
- Two column of 1016 strips
- 3 outermost layers of barrel.
- 5 outer rings of TEDD

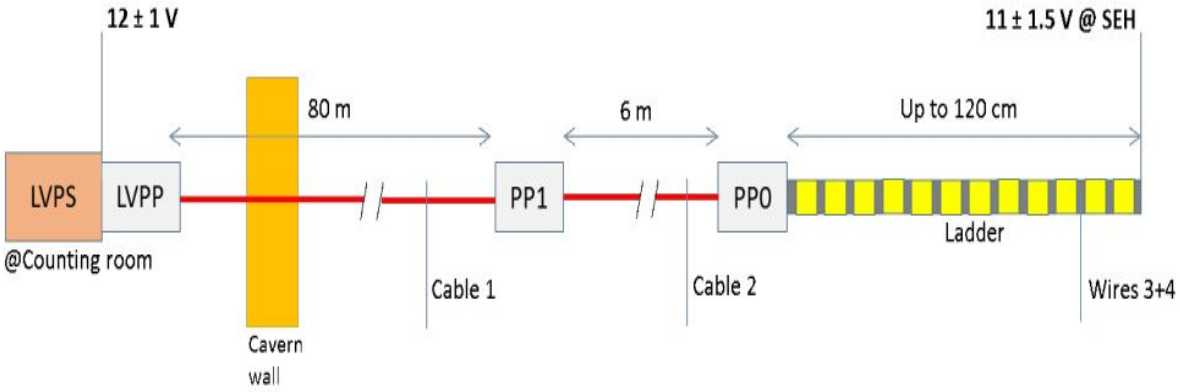
Back end electronics



- Data, Trigger & Control Board
- 72 input fibres(max)
- ACTA standard
- Bi-directional optical links

Outer tracker powering

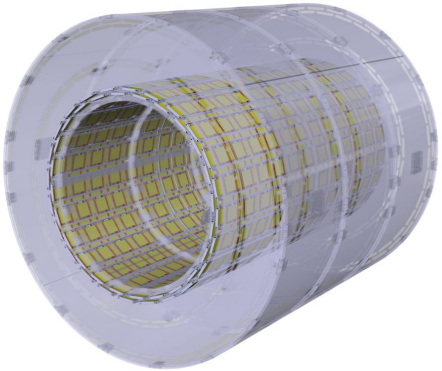


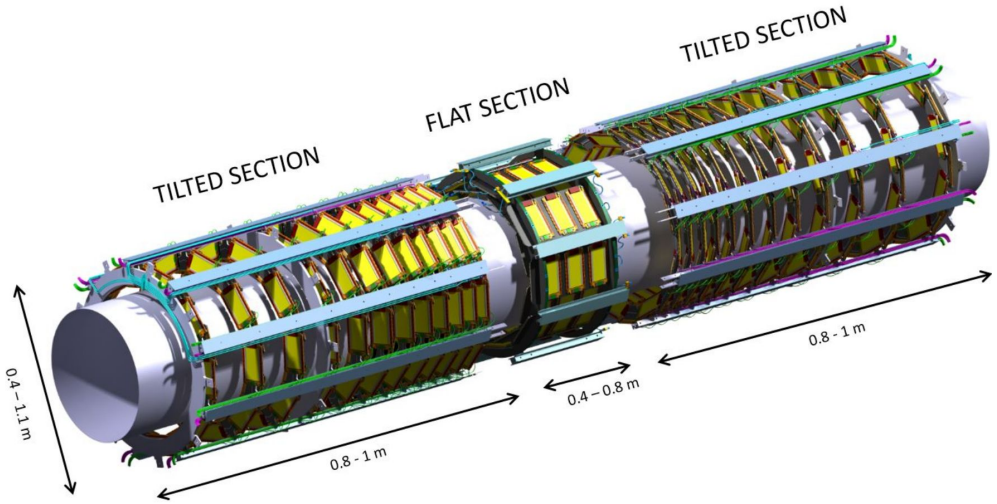


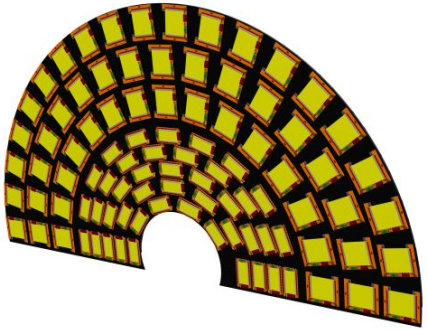
- High Power Budget : Outer Tracker ~100kW
- A cascaded DC-DC conversion scheme is foreseen to produce the required supply voltages from the ~11 V supply.
- The HV system will need to generate up to – 800 V of sensor bias voltage, with close to 2 mA of leakage current per module at end of life in the most exposed areas of the tracker.
- Both HV and LV upto module level granularity.

OT Mechanics

- TBPS: Flat part planks while tilted part rings
- TB2S: Ladders
- TEDD: Half dee

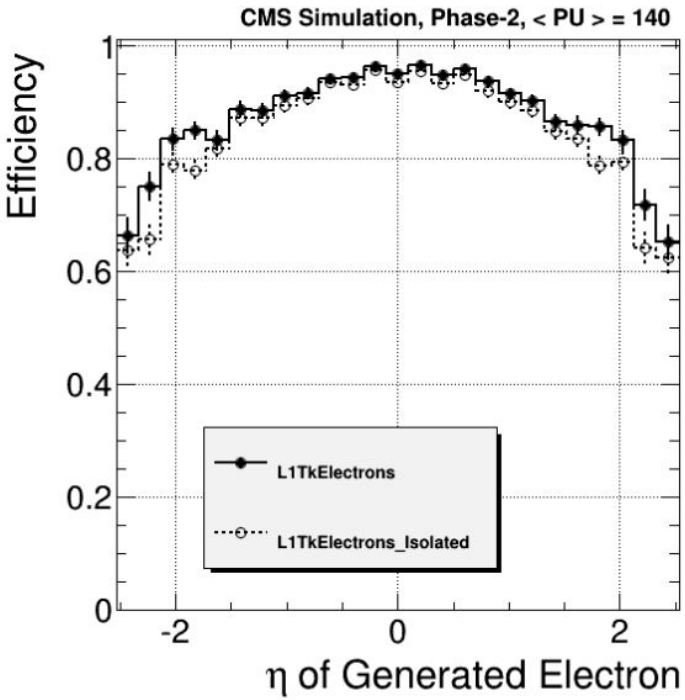


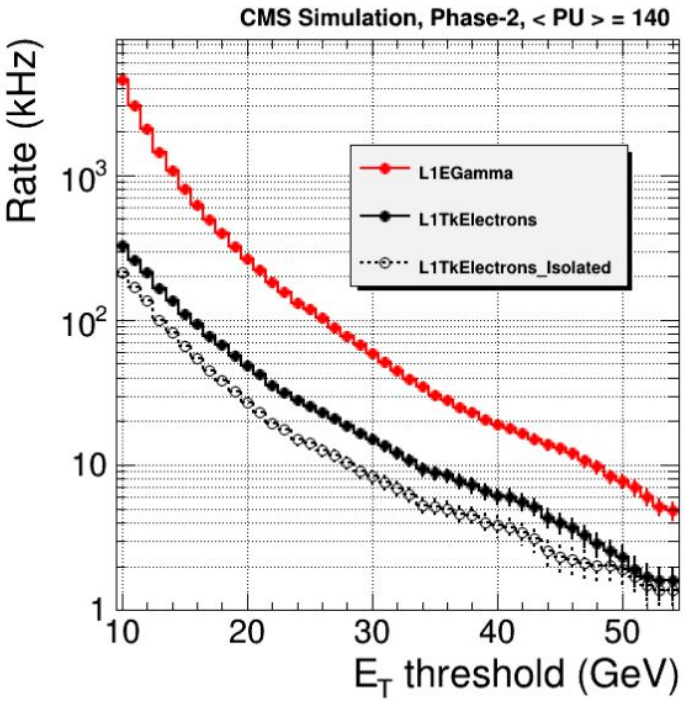




L1 Track trigger

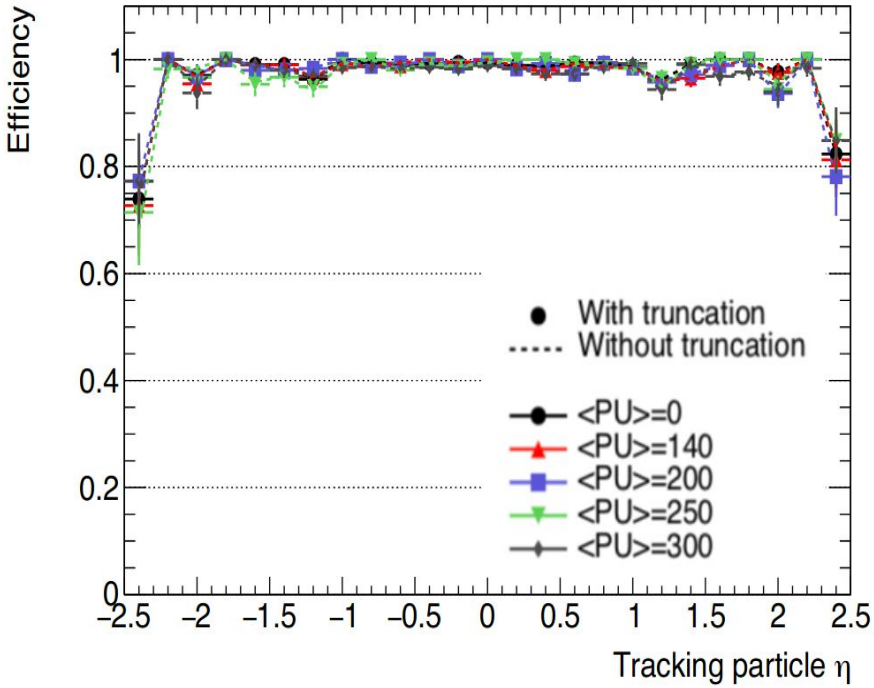
LHCC-P-008

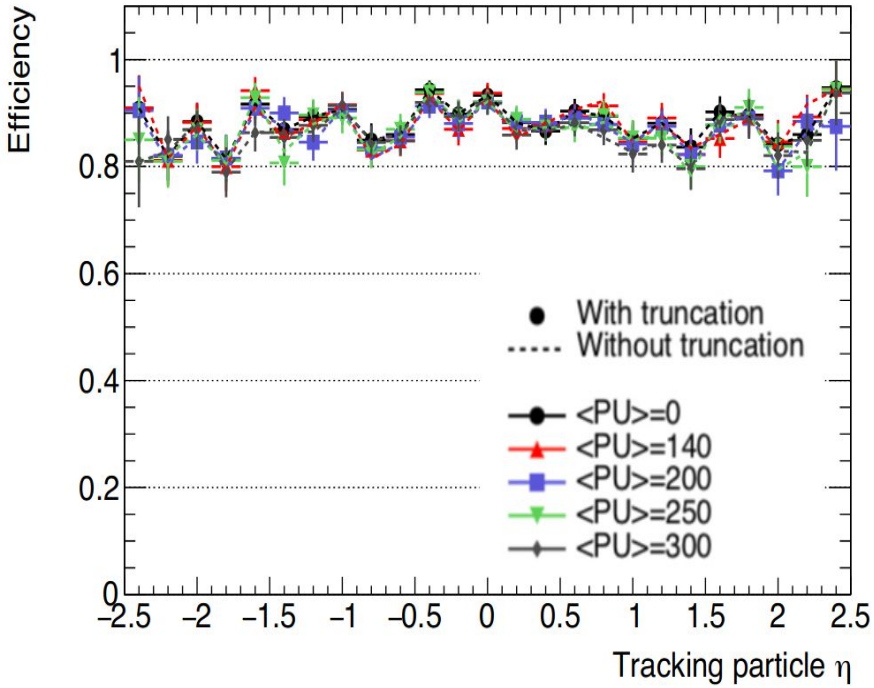




- Left: Efficiency vs. η of the track-matching selection optimised for high E_T electrons(>20 GeV)
- Right: Rate of a single electron trigger as a function of the threshold

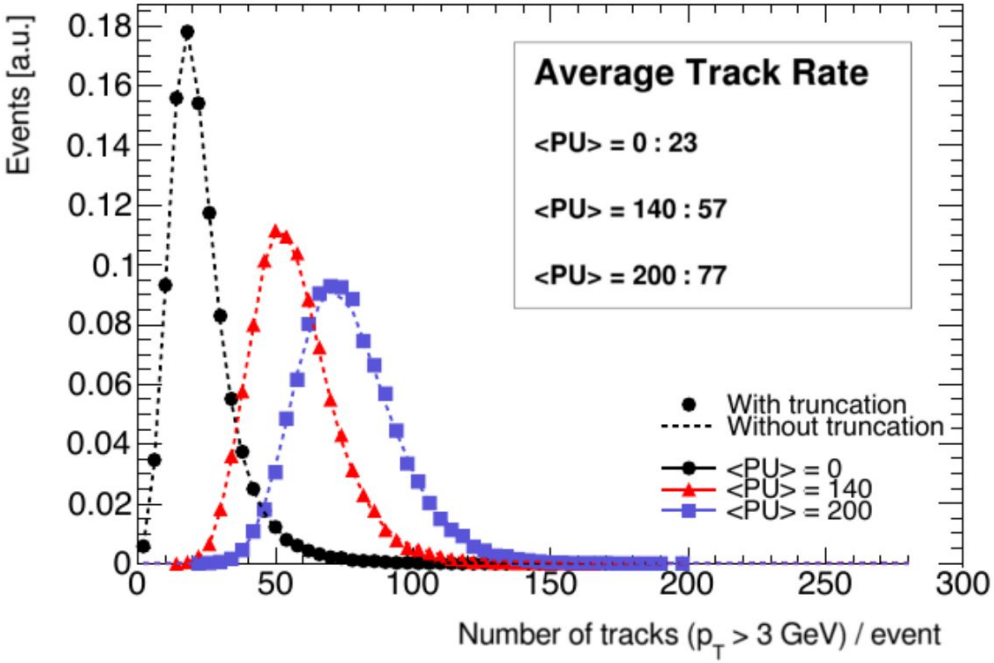
L1 Track finding



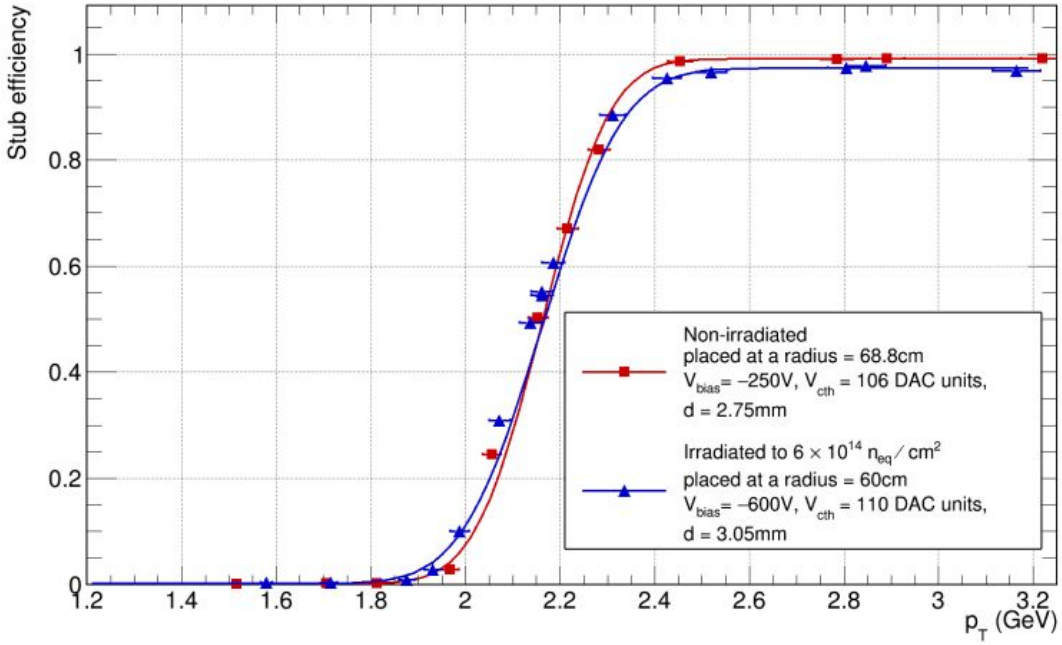


- Track finding efficiency against particle η for muons (left), and electrons (right) (p_T > 2GeV).

L1 Track finding



2S mini module

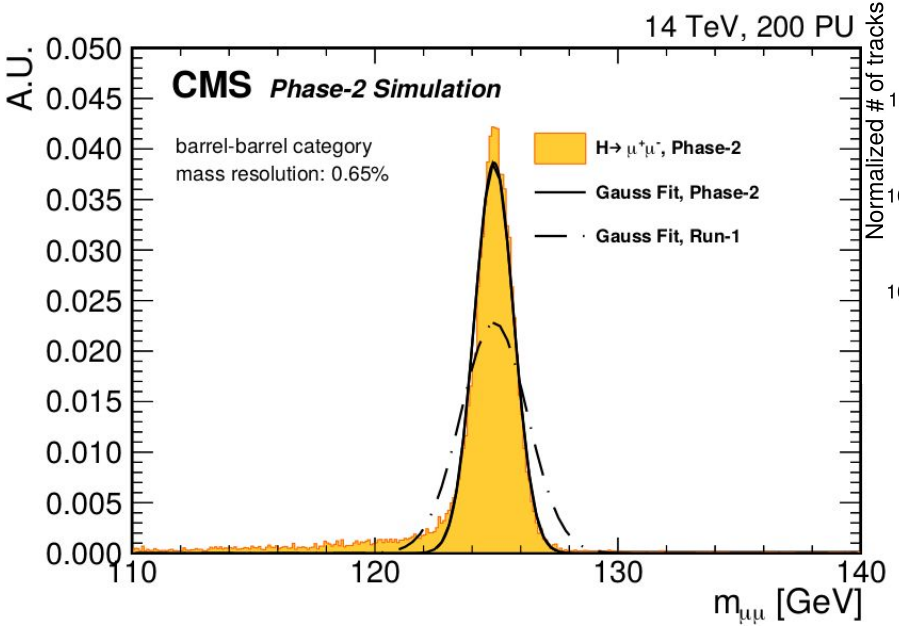


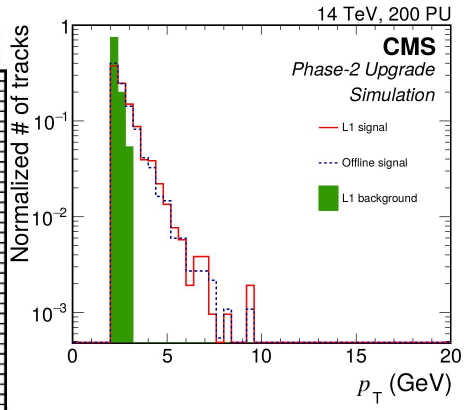
L1 Trigger rates

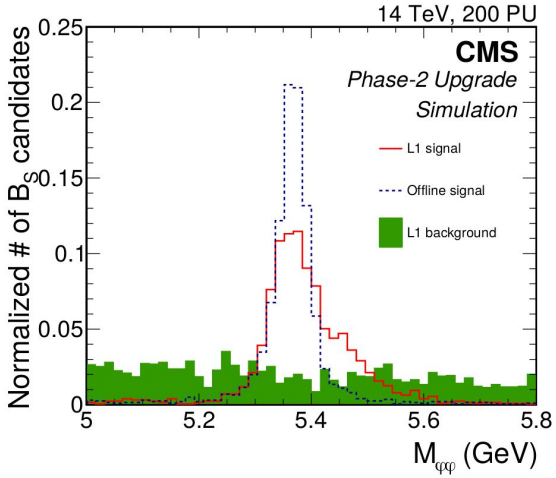
$L = 5.6 \times 10^{34}$ cm^{-2}s^{-1} $\langle PU \rangle = 140$	Level-1 Trigger with L1 Tracks	
Trigger Algorithm	Rate [kHz]	Offline Threshold(s) [GeV]
Single Mu (tk)	14	18
Double Mu (tk)	1.1	14 10
ele (iso tk) + Mu (tk)	0.7	19 10.5
Single Ele (tk)	16	31
Single iso Ele (tk)	13	27
Single γ (tk isol)	31	31
ele (iso tk) + e/γ	11	22 16
Double γ (tk isol)	17	22 16
Single Tau (tk)	13	88
Tau (tk) + Tau	32	56 56
ele (iso tk) + Tau	7.4	19 50
Tau (tk) + Mu (tk)	5.4	45 14
Single Jet	42	173
Double Jet (tk)	26	2@136
Quad Jet (tk)	12	4@72
Single ele (tk) + Jet (tk)	15	23 66
Single Mu (tk) + Jet (tk)	8.8	16 66
Single ele (tk) + $H_{\mathrm{T}}^{\mathrm{miss}}$ (tk)	10	23 95
Single Mu (tk) + $H_{\mathrm{T}}^{\mathrm{miss}}$ (tk)	2.7	16 95
H_{T} (tk)	13	350
Rate for above Triggers	180	
Est. Total Level-1 Menu Rate	**260**	

Impact on physics

- HL-LHC period is a great opportunity to perform precision measurements of the Standard Model parameters as well as new physics beyond the standard model.
- The tracker upgrade will play a crucial role in improving the physics sensitivity of the CMS experiment in HL-LHC







- Lower material budget : better di-muon mass resolution
- Higgs coupling to muons can be measured with an uncertainty of 5%.

- $B_{0s} \rightarrow \varphi\varphi \rightarrow 4K$: FCNC process. Forbidden at the tree level in SM.
- Sensitive to CP violating phase in CKM matrix.
- Challenge : low pT final states.
- B_{0s} candidates can be formed at L1 level.
- Requires low L1 trigger thresholds.
- For signal eff. 30% can be achieved at L1