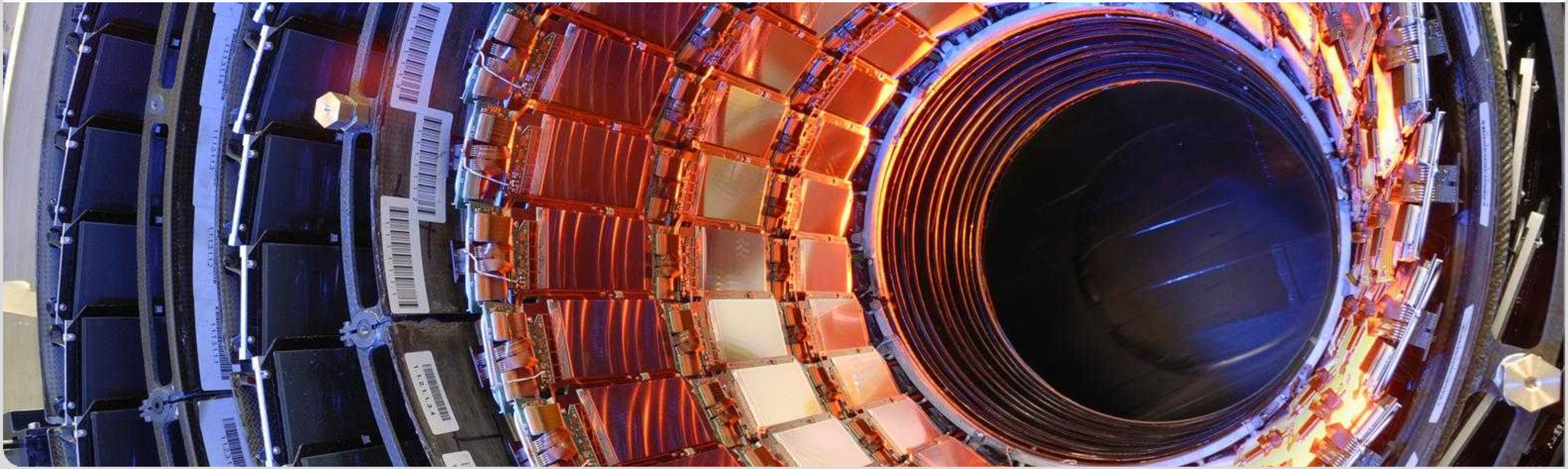
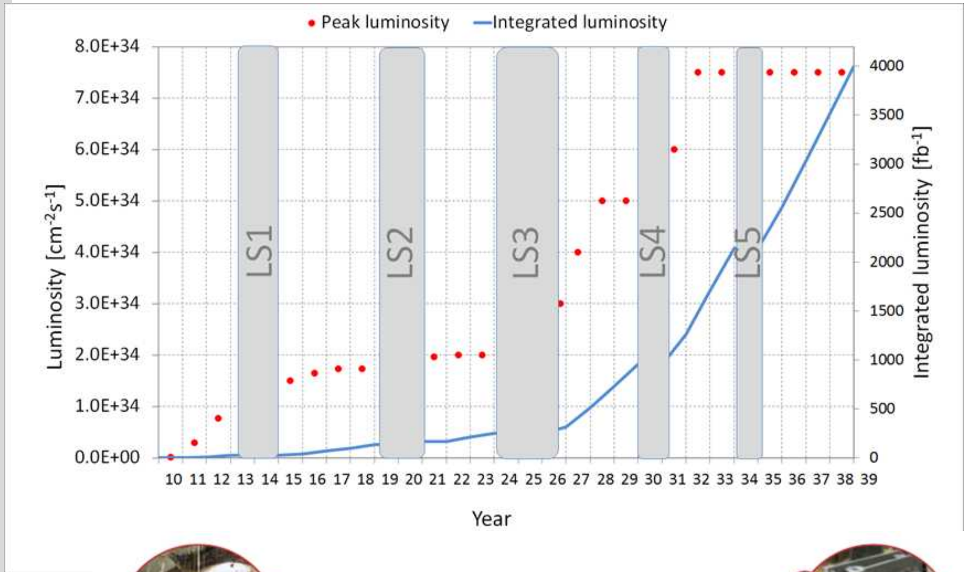
$200\ m^2$ Silicon Detectors Today and Tomorrow

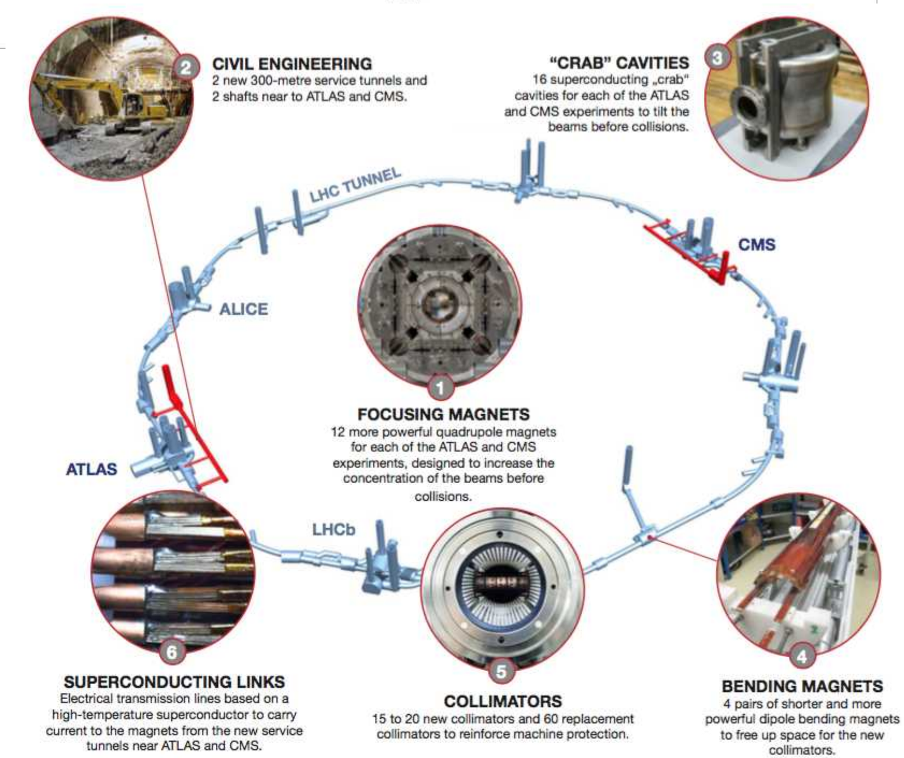
The ATLAS and CMS upgrades with a backdrop from the current CMS tracker

Institute of Experimental Particle Physics (ETP)



High Luminosity LHC

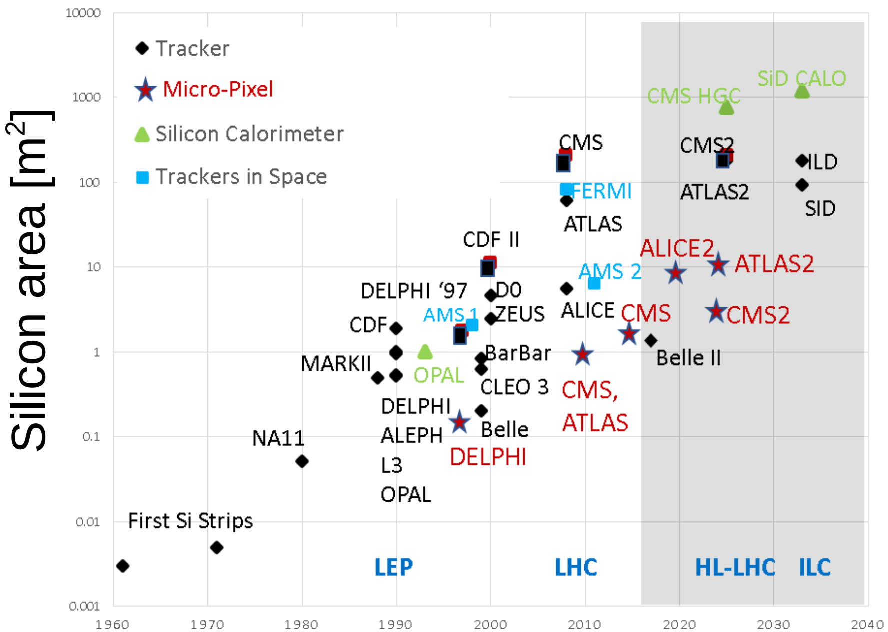




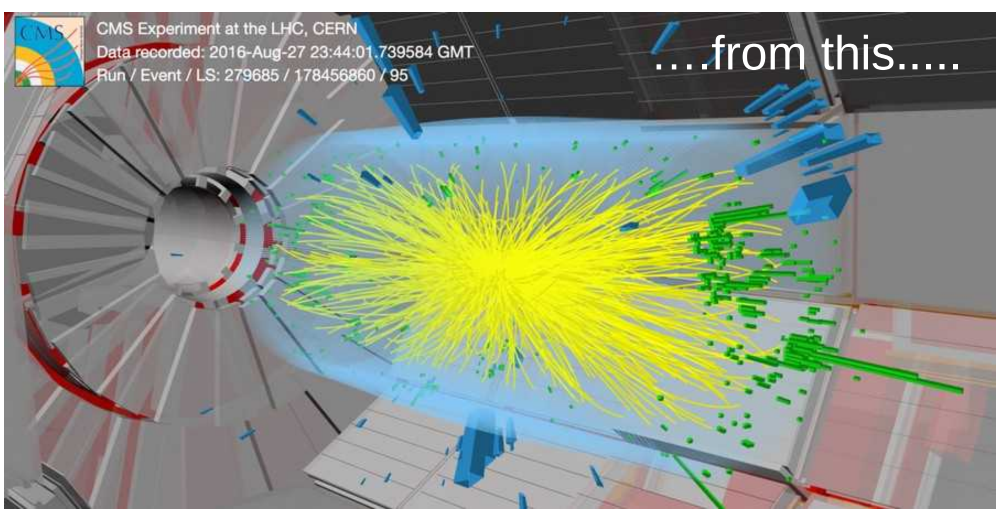
- Luminosity upgrade for post-LS3 running
- Peak luminosity ~7.5x10^{34} cm^{-1}s^{-1}
- Pile-up of up to 200
- Hit rates up to 3 GHz/cm^2

- Civil engineering for new access shafts and service tunnels
- New Nb_3Sn magnets (11 T)
- Crab cavities
- ...

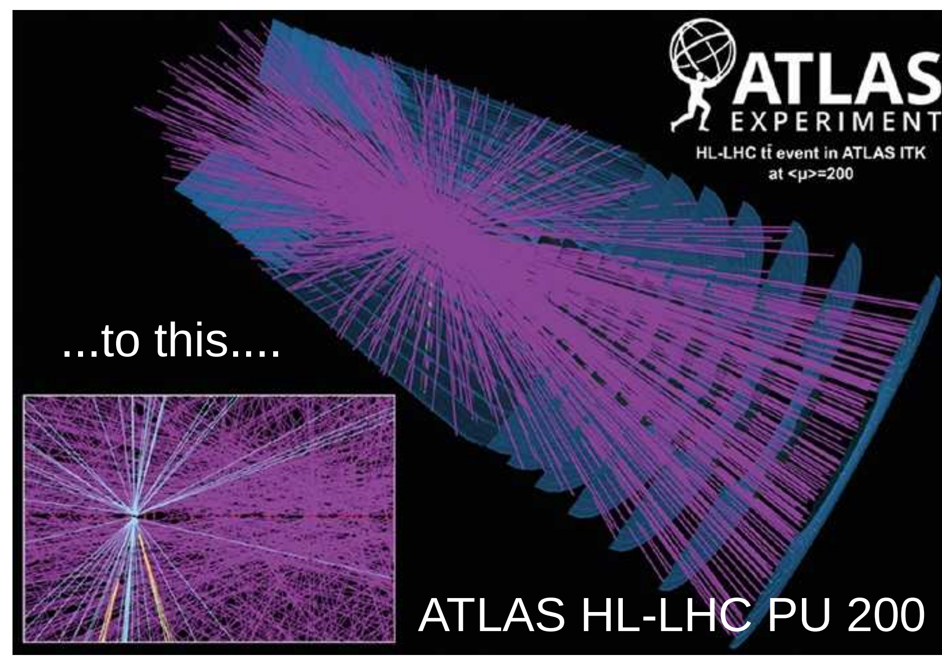
200 m^2 of silicon over time



- First time with 200 m^2 of silicon for CMS phase 0 strip detector
- Inner tracking detectors will be replaced for both ATLAS and CMS during LS3
  - Both upgraded detectors will have about 200 m^2 of silicon area
- Events to be reconstructed go

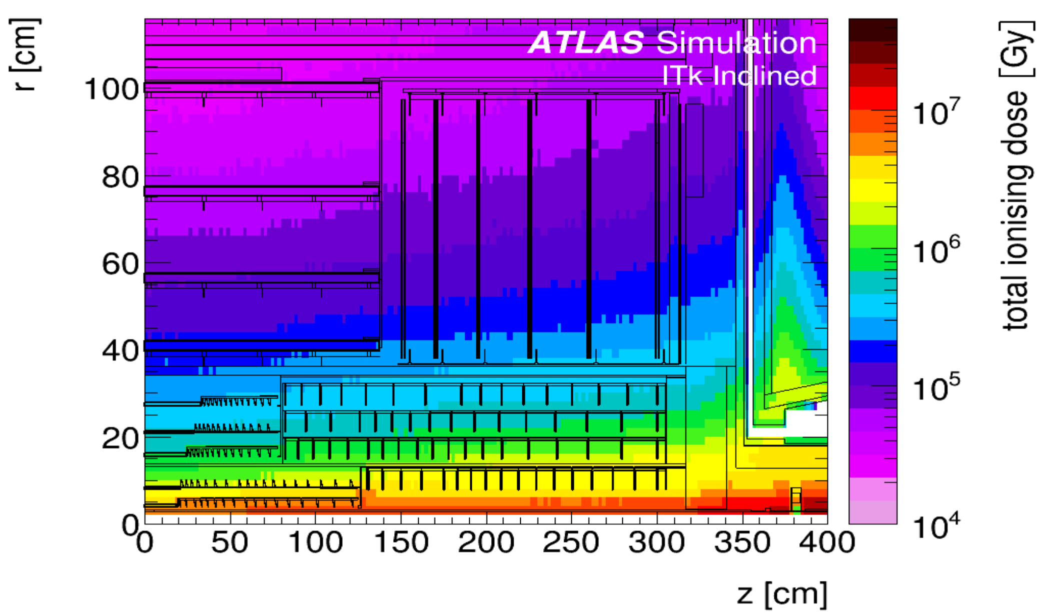


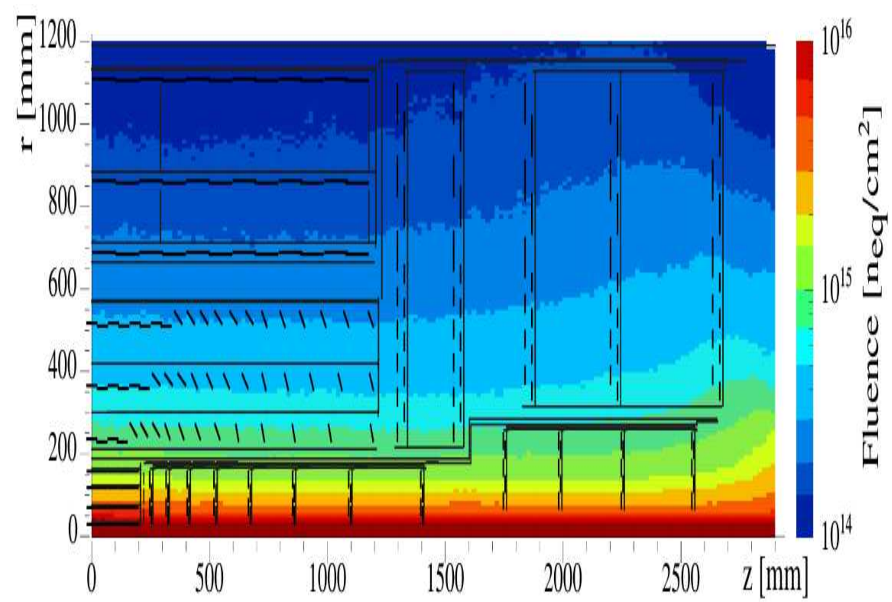
CMS run 2 ~25 pile-up



Radiation envionment

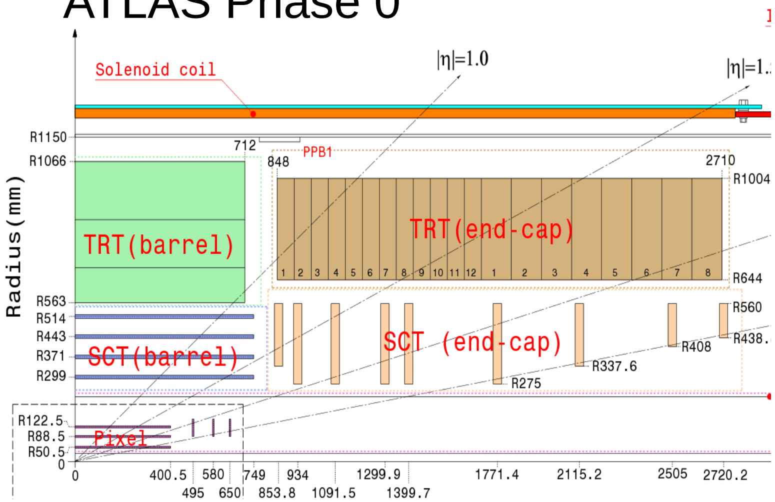
- Radiation environment at HL-LHC will become increasingly hostile
- Inner layers of pixel detectors at few cm in radius will need to stand fluences in excess of 10^{16} MeV neutron equivalent
- Even outer layers “far away” from interaction point will see $>10^{14}$ MeV neutron equivalent
  - similar or more than innermost strip tracker layers at 20 cm for today's trackers after 10 years of LHC running





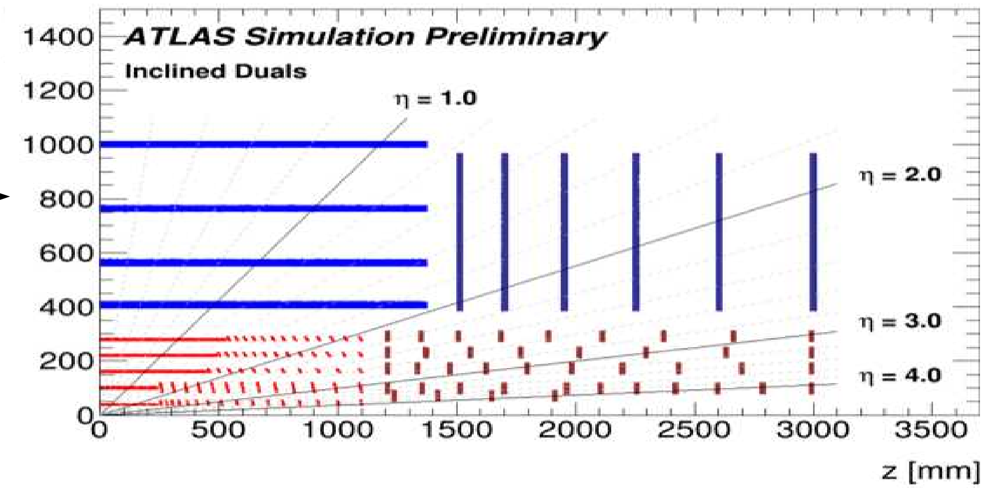
ATLAS and CMS Trackers – post LS3

ATLAS Phase 0

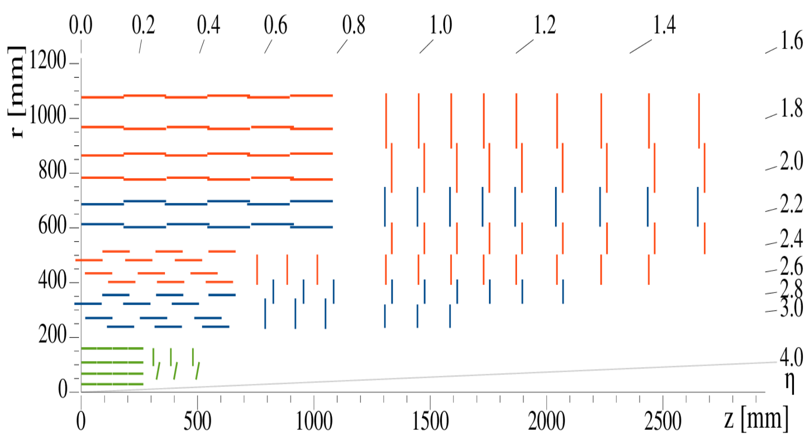


ATLAS Phase 2

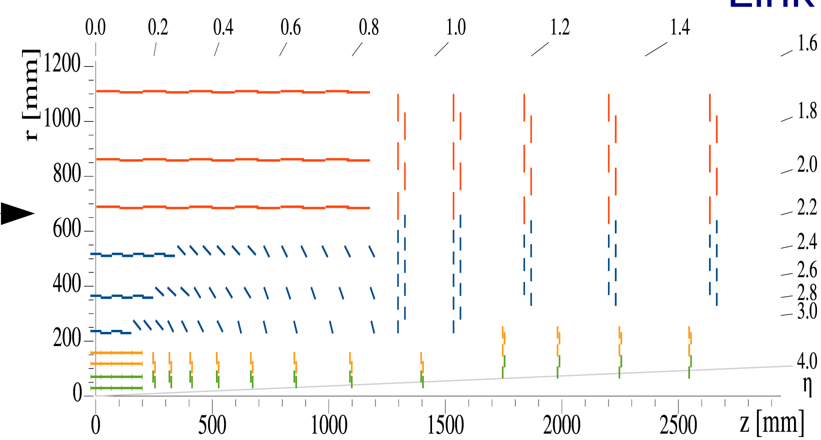
Link to TDR



Link to TDR



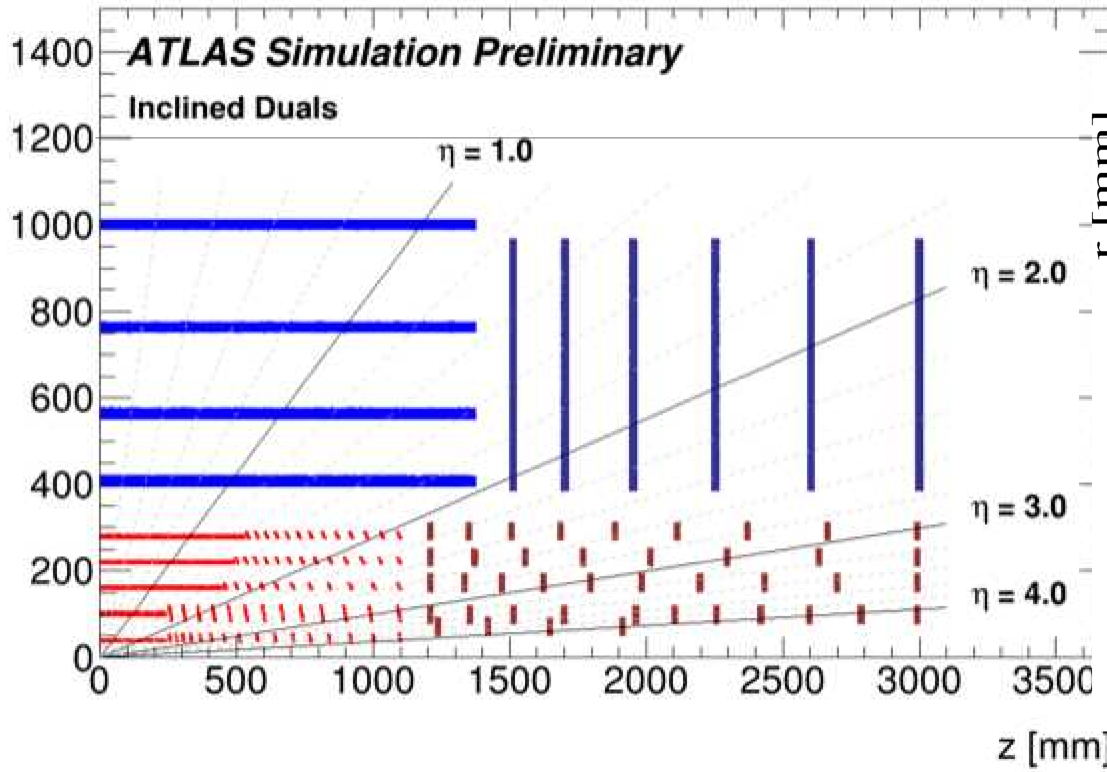
CMS Phase 0

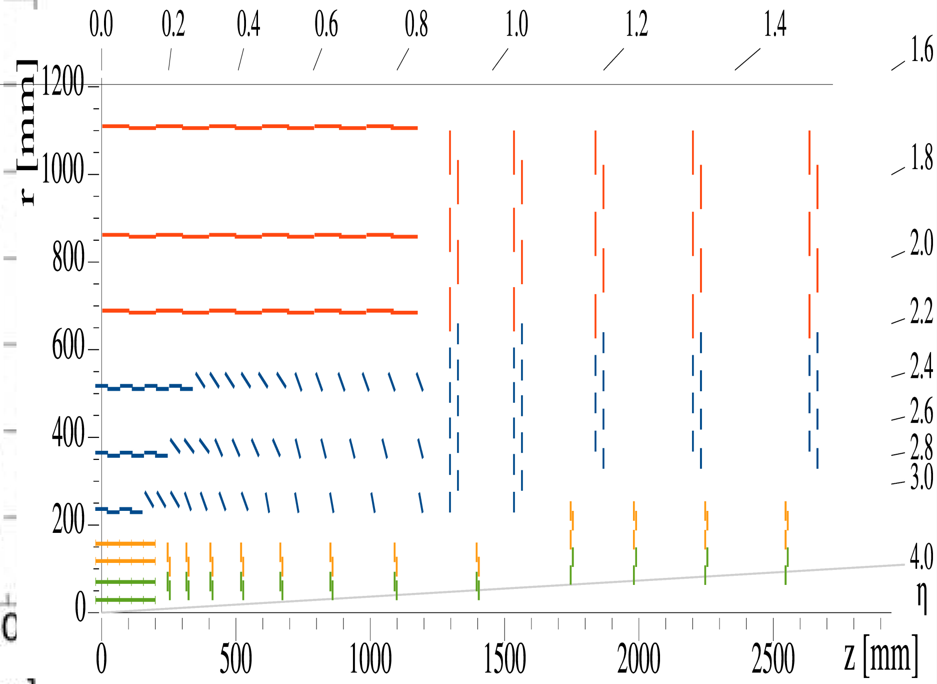


CMS Phase 2

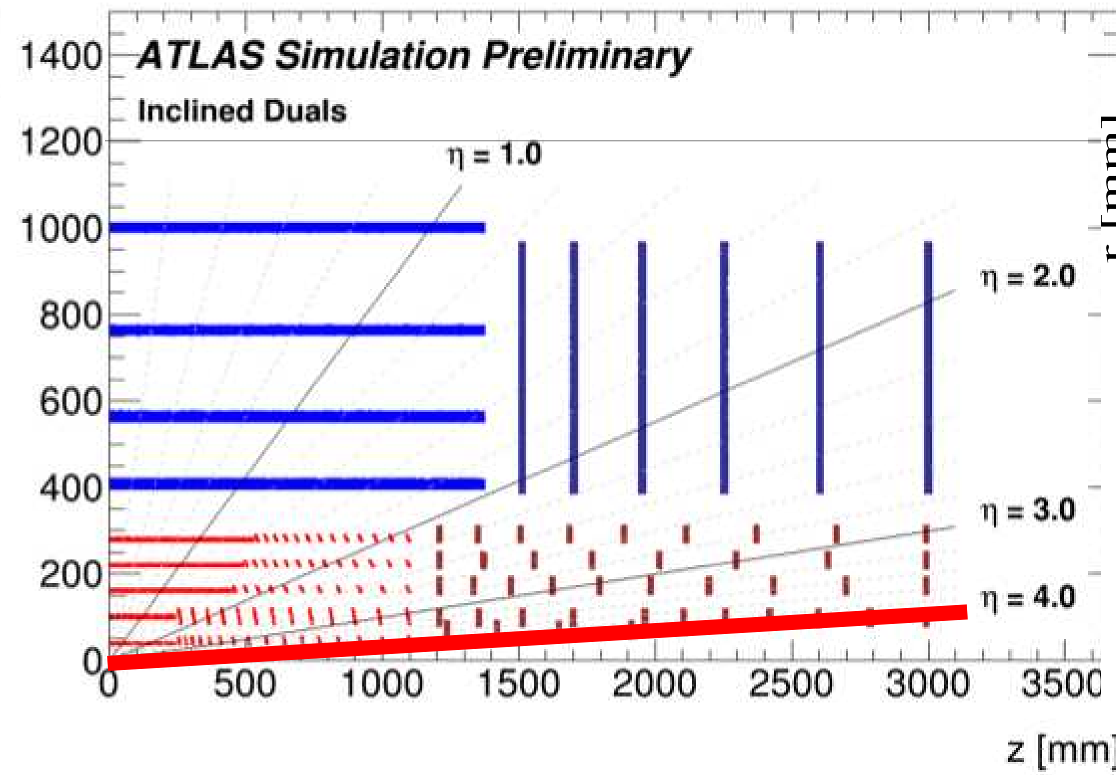
What's old, what's new, what's....

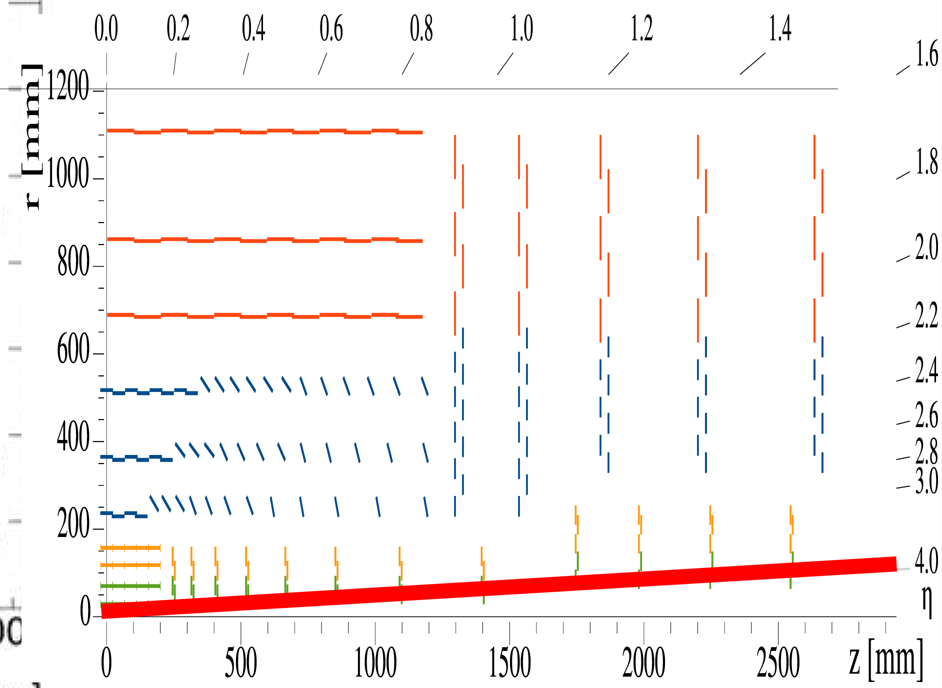
ATLAS and CMS Trackers for HL-LHC





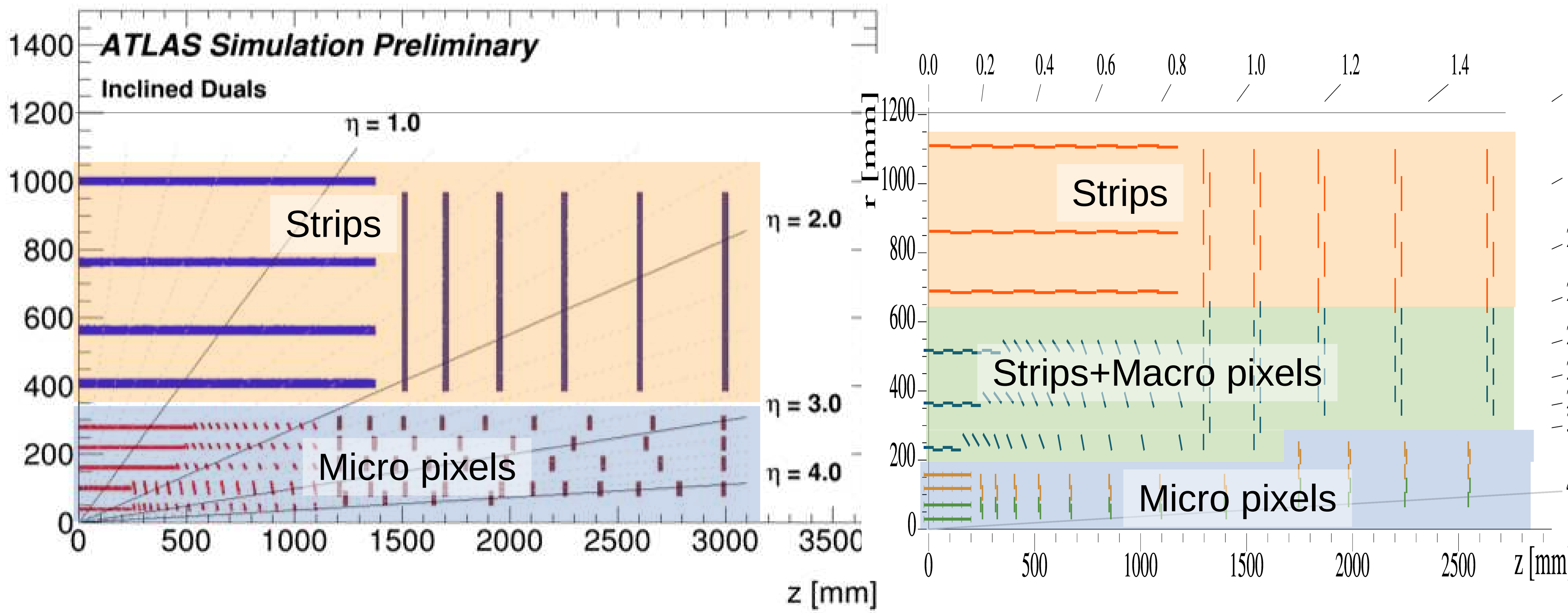
ATLAS and CMS Trackers for HL-LHC





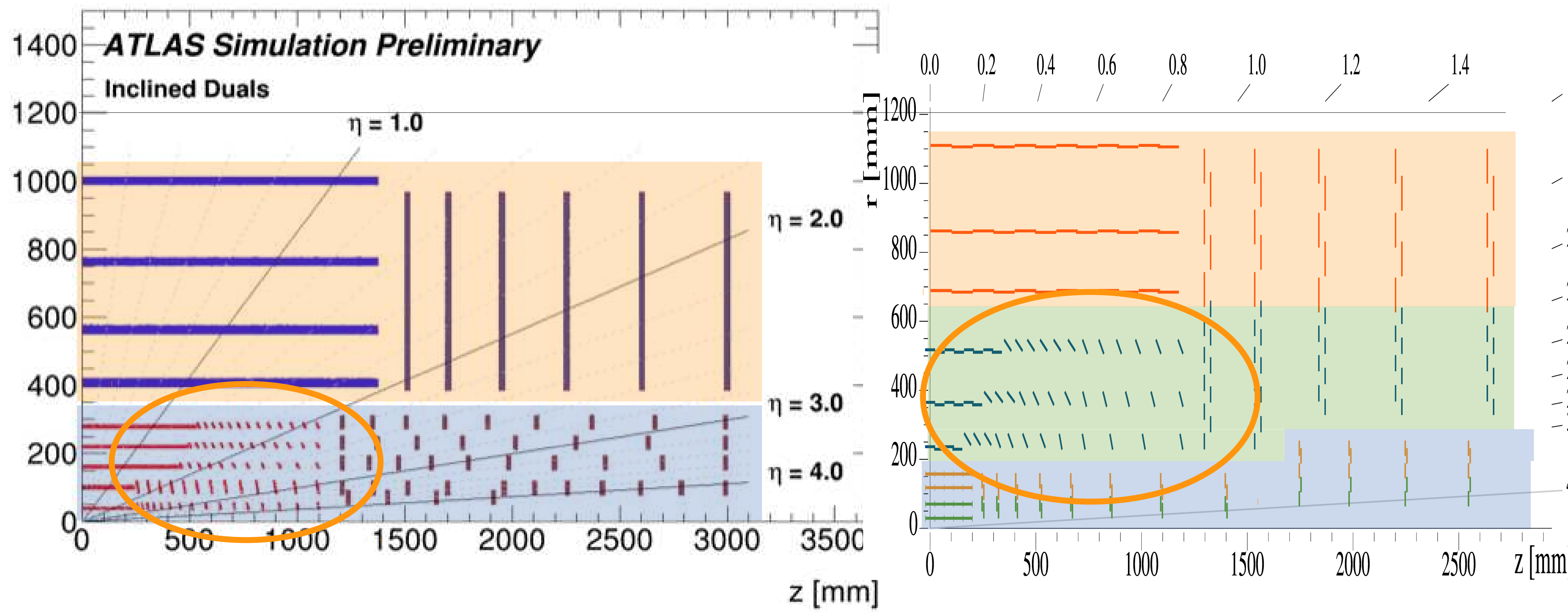
- Both trackers cover |η| < 4.0 instead of |η| < 2.5

ATLAS and CMS Trackers for HL-LHC



- Both trackers cover $|\eta| < 4.0$ instead of $|\eta| < 2.5$
- ATLAS: Micro pixel inner tracker, strip tracker in outer region
- CMS: Micro pixel inner tracker, strips+macro pixel medium radii, strip tracker in outer part

ATLAS and CMS Trackers for HL-LHC



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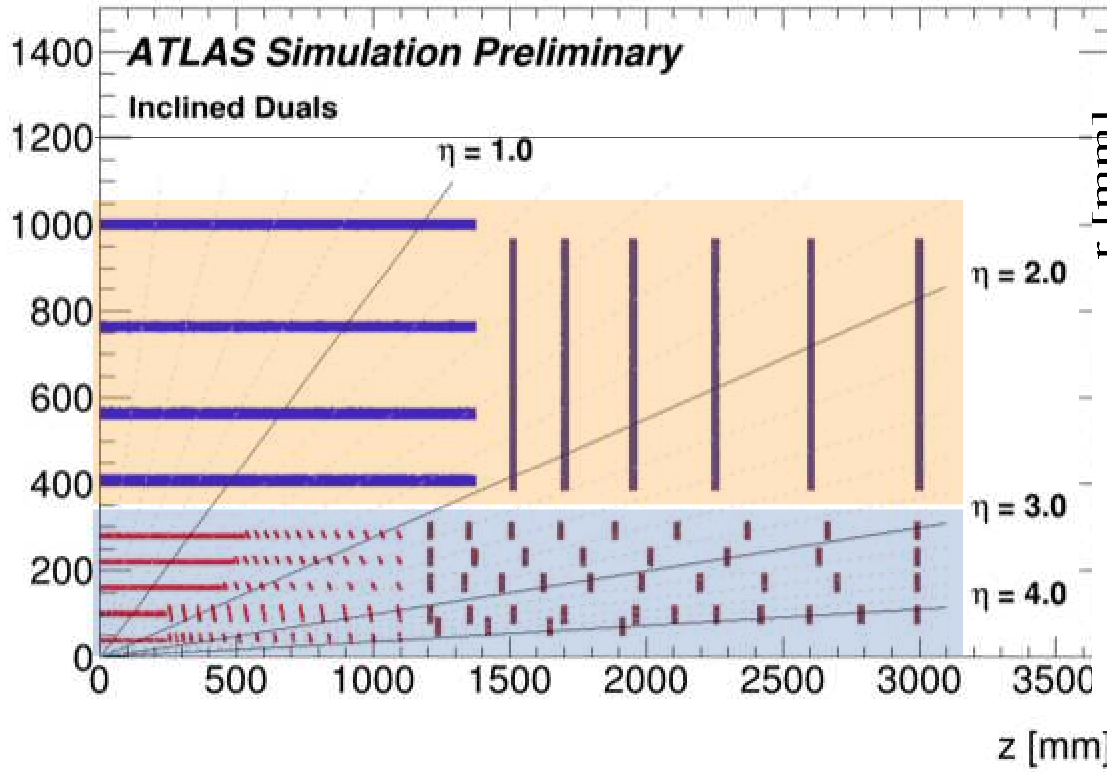
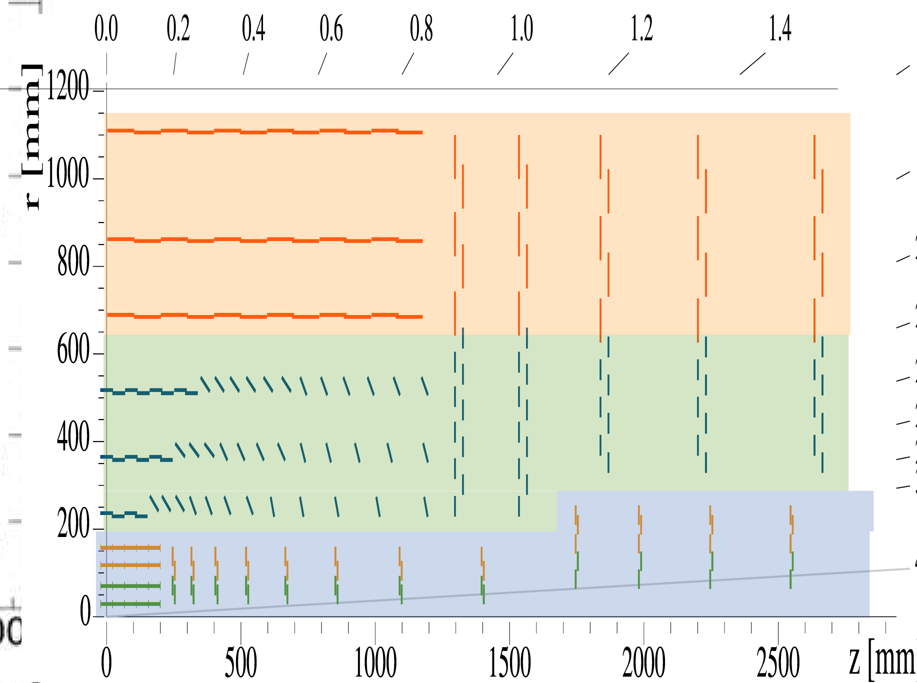
ATLAS and CMS Trackers for HL-LHC





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- ATLAS: Micro pixel inner tracker, strip tracker in outer region
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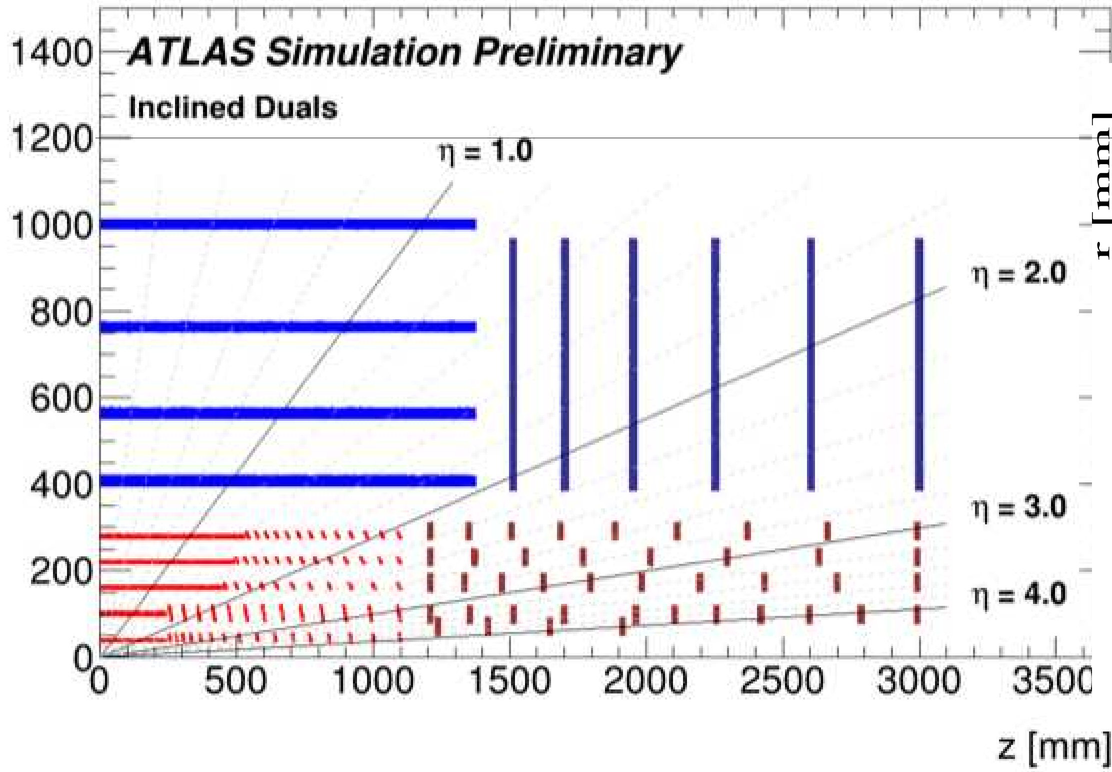
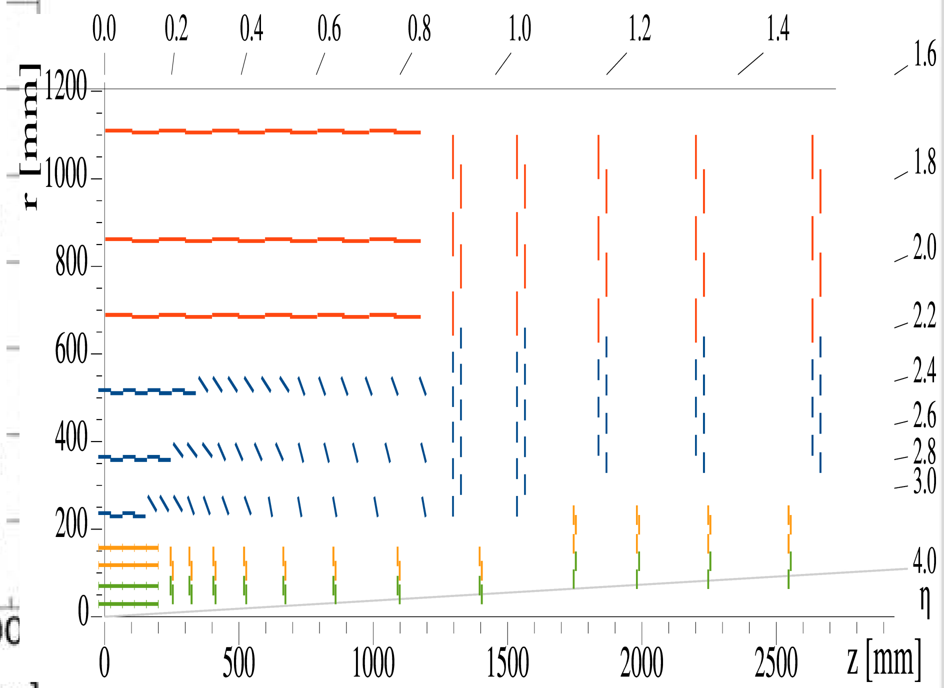
- Both use inclined geometries (ATLAS pixel, CMS TBPS)
- CMS: L1 trigger capability

Number of channels

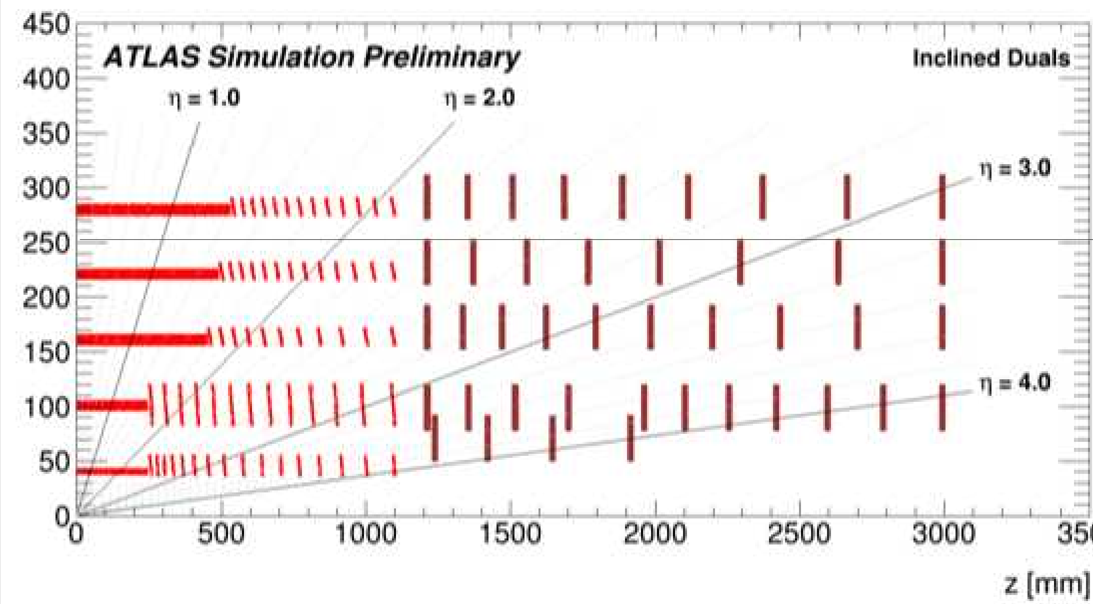




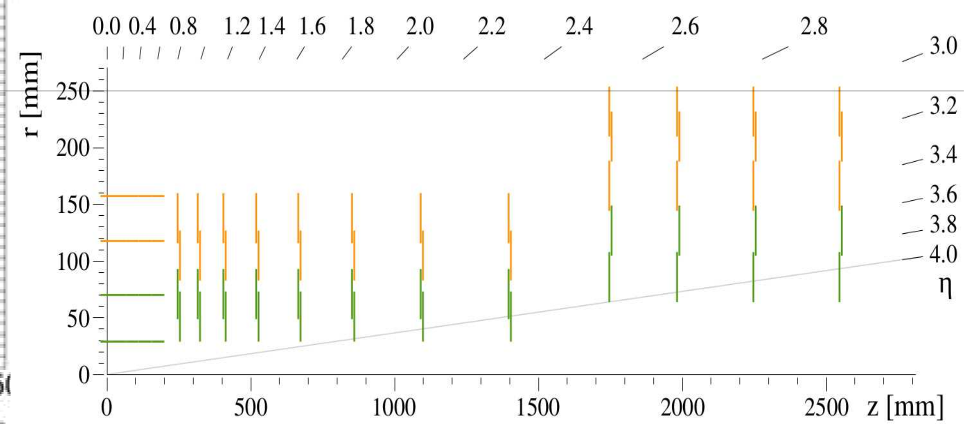
Number of channels increases by orders of magnitude

	Channels Today		Channels Upgrade
ATLAS Strips	6.3M	→ x10 →	60M
ATLAS Pixels	92M	→ **x54** →	5000M
CMS Strips	9.8M	→ x17 →	42M + 127M
CMS Pixels	127M	→ x15 →	2000M

ATLAS and CMS – post-LS3 Pixels

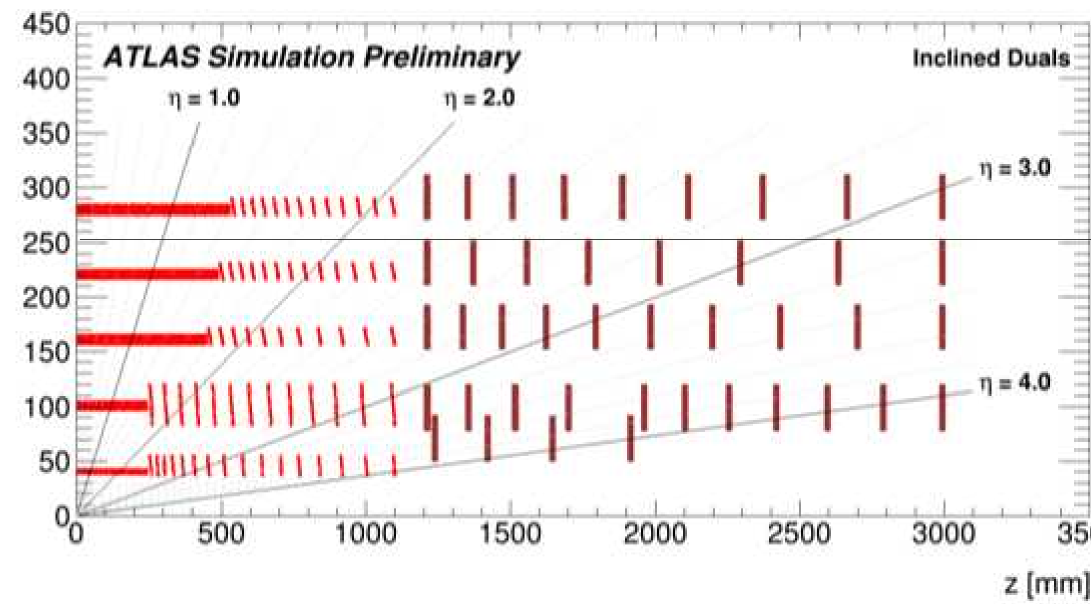


CMS Phase 2 pixel

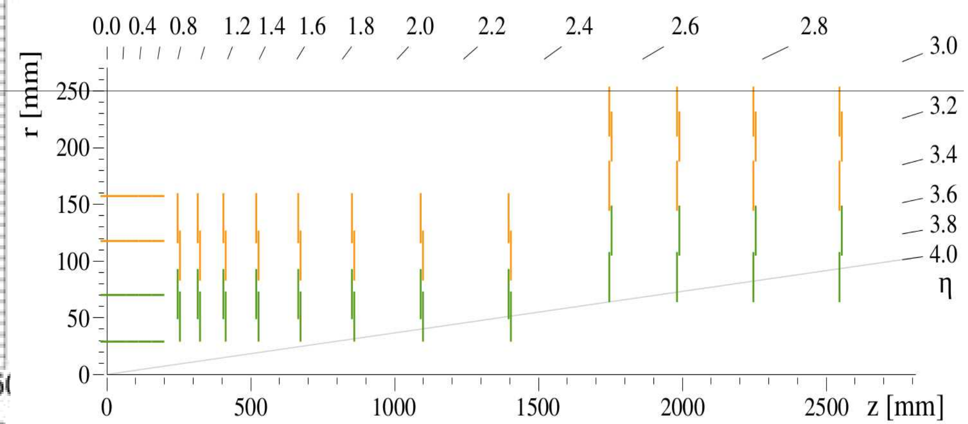


- ATLAS system much bigger
  - R: last layer at 27 cm (CMS 15.6 cm)
  - Z: last disk at 3 m (CMS ~2.5 m)
  - Area: **~13** m^2 (CMS: 4.87 m^2)
  - 5 barrel layers
- CMS innermost layer closer to IP
  - R = 2.9 cm (ATLAS: 3.9 cm)

ATLAS and CMS – post-LS3 Pixels

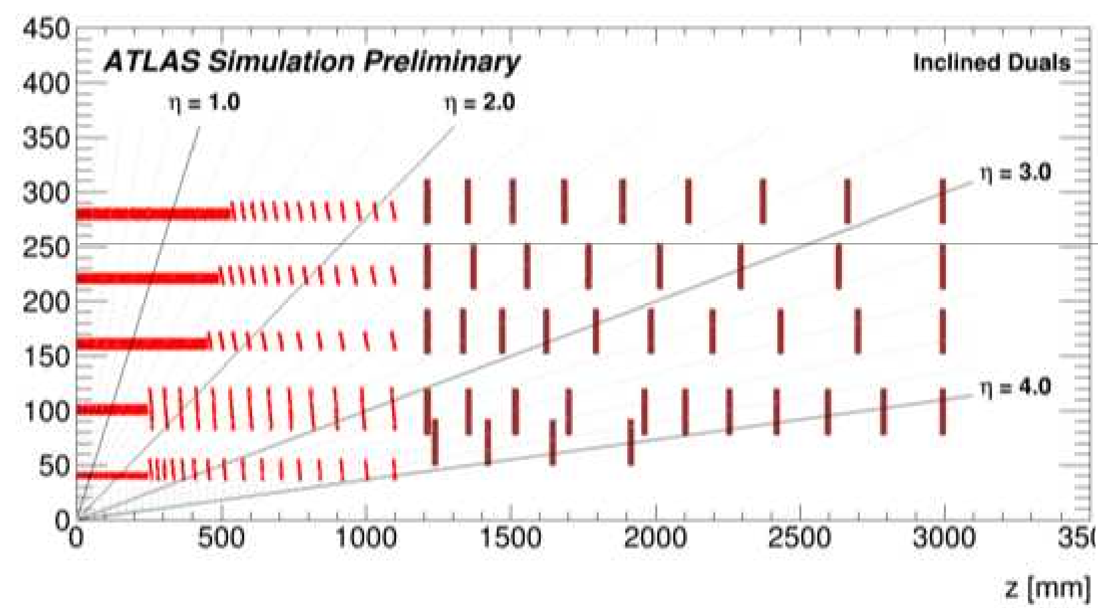


CMS Phase 2 pixel

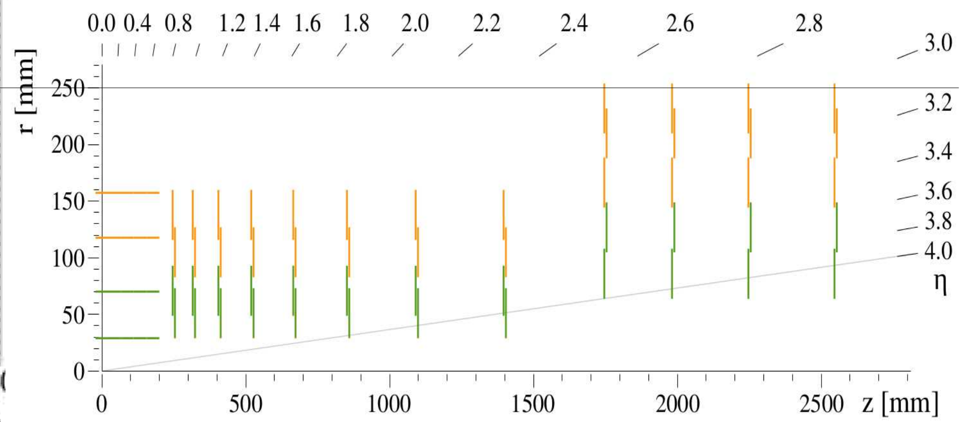


- Technologies:
  - Thin planar n-on-p detectors (maybe/probably 3D for first layer for both, ATLAS maybe CMOS for last layer?)
  - Common R&D for readout chip (RD53)
    + customizations for each experiment?
  - 1x1 (ATLAS only), 2x1 or 2x2 readout chips per module

ATLAS and CMS – post-LS3 Pixels



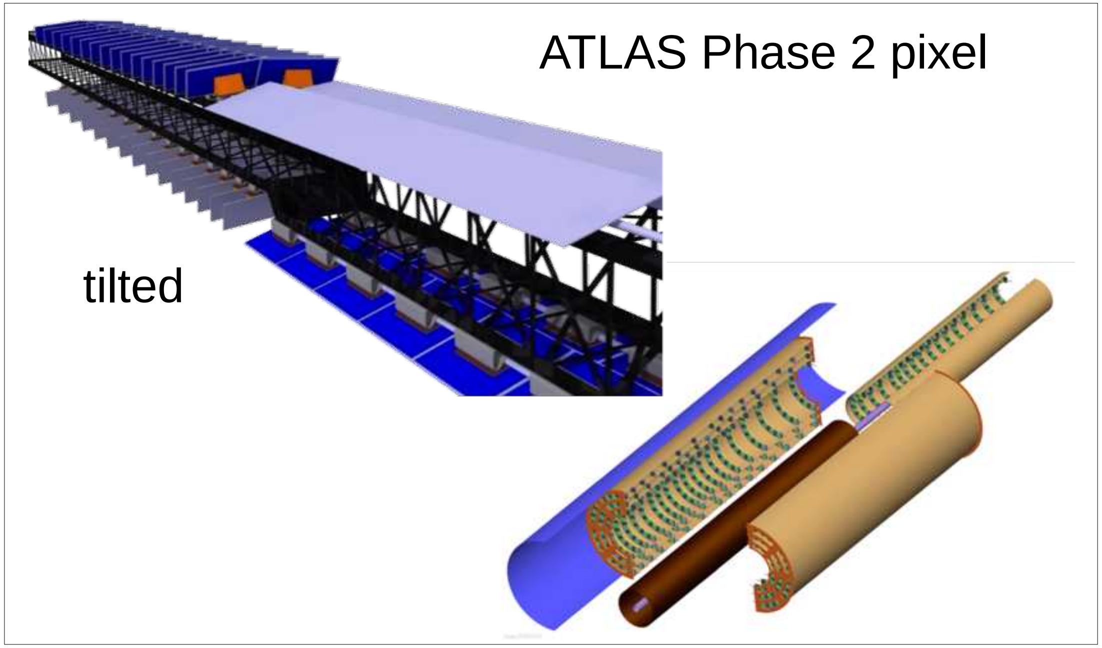
CMS Phase 2 pixel

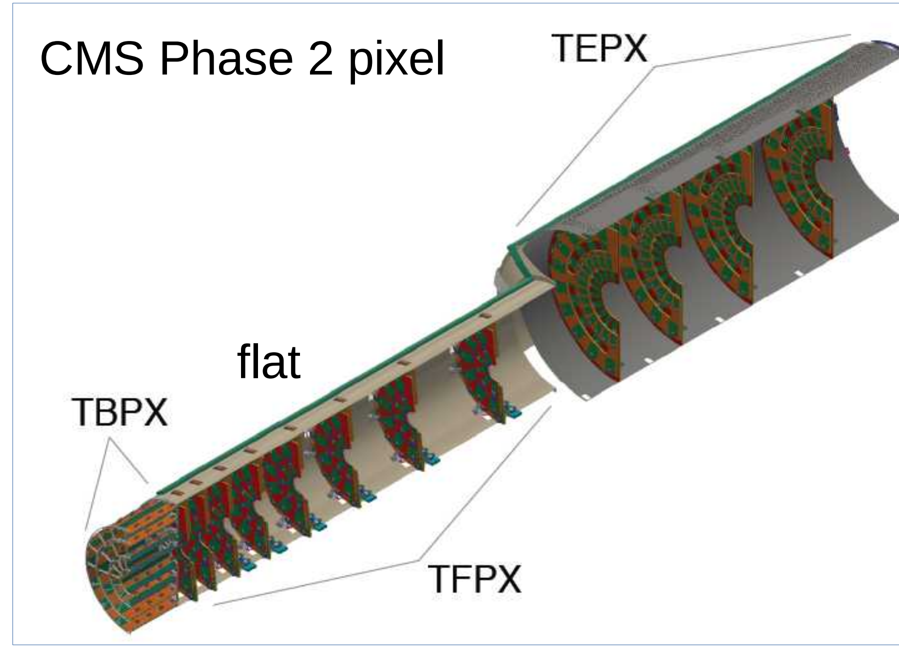


- Cell size:
  - 50x50 μm² or 25x100 μm² under discussion for both collaborations
  - Recall currently:
    - ATLAS 50x400 μm² (IBL: 50x250 μm²)
    - CMS: 100x150 μm²

  → Factor 5-8 reduction in pixel area
- Serial powering

ATLAS and CMS – post-LS3 Pixels





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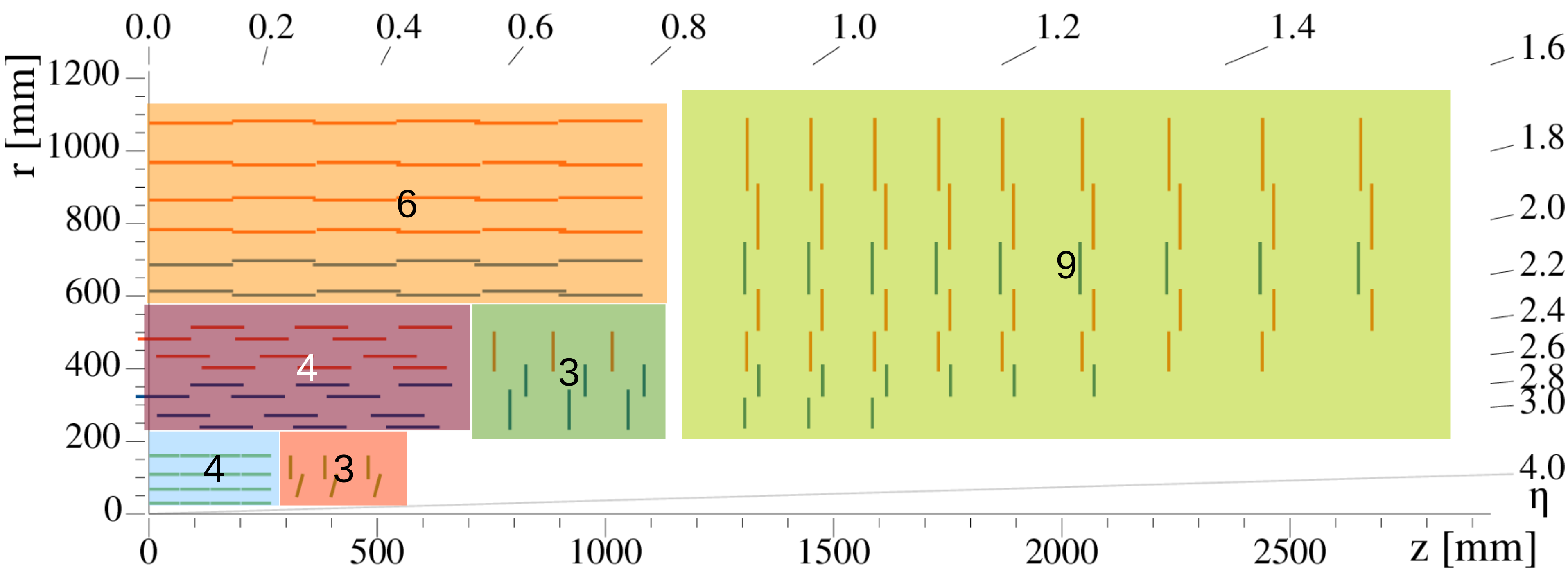
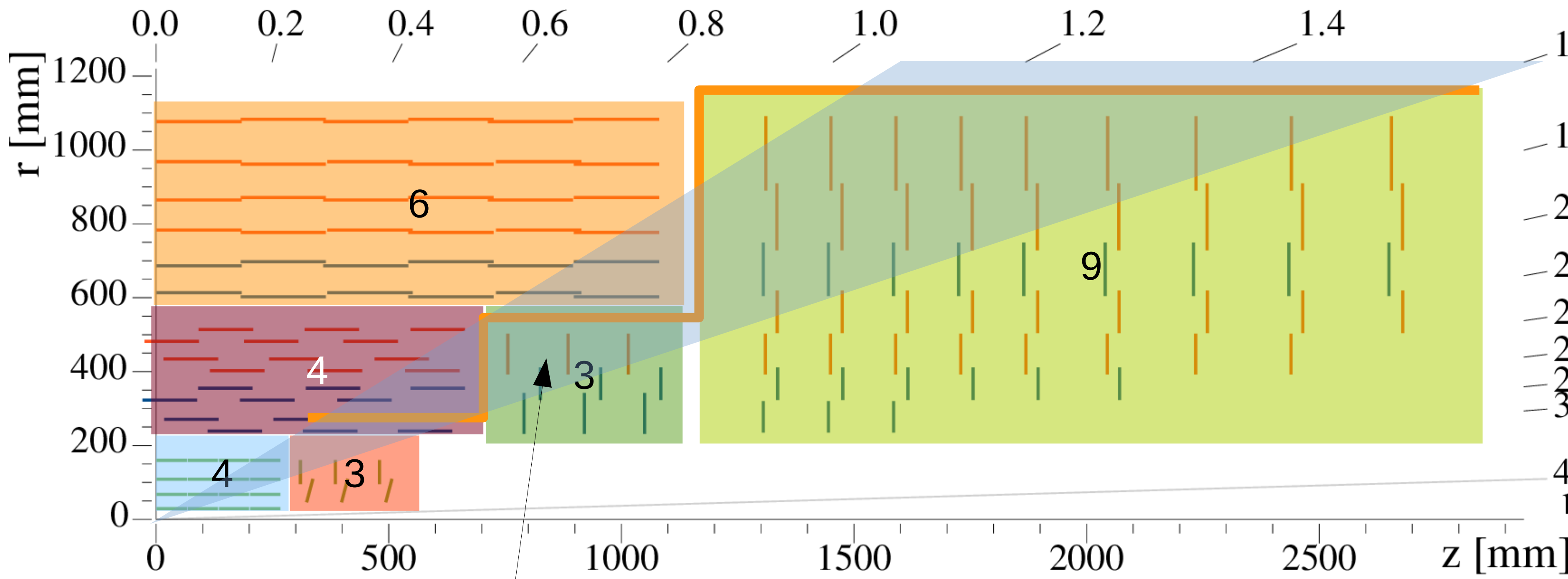
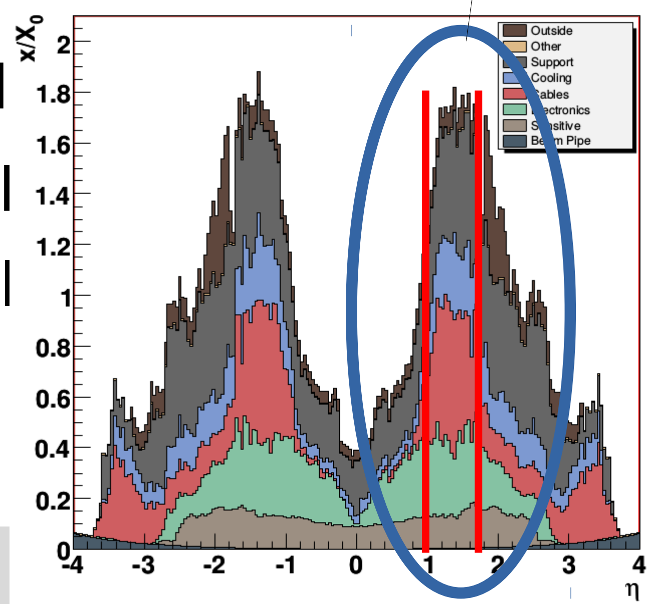
Number of layers



- CMS Phase 0 tracker has LOTS of layers
  - Lots of redundancy for tracking
  - In return lots of services needed

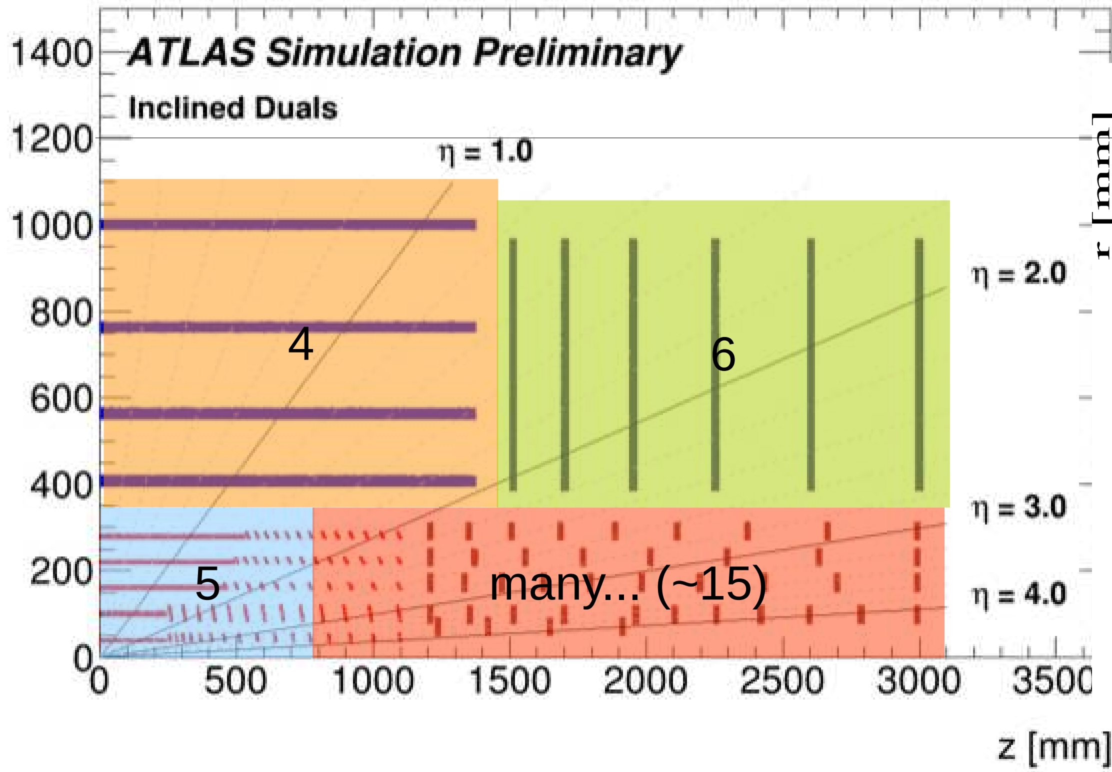
Number of layers

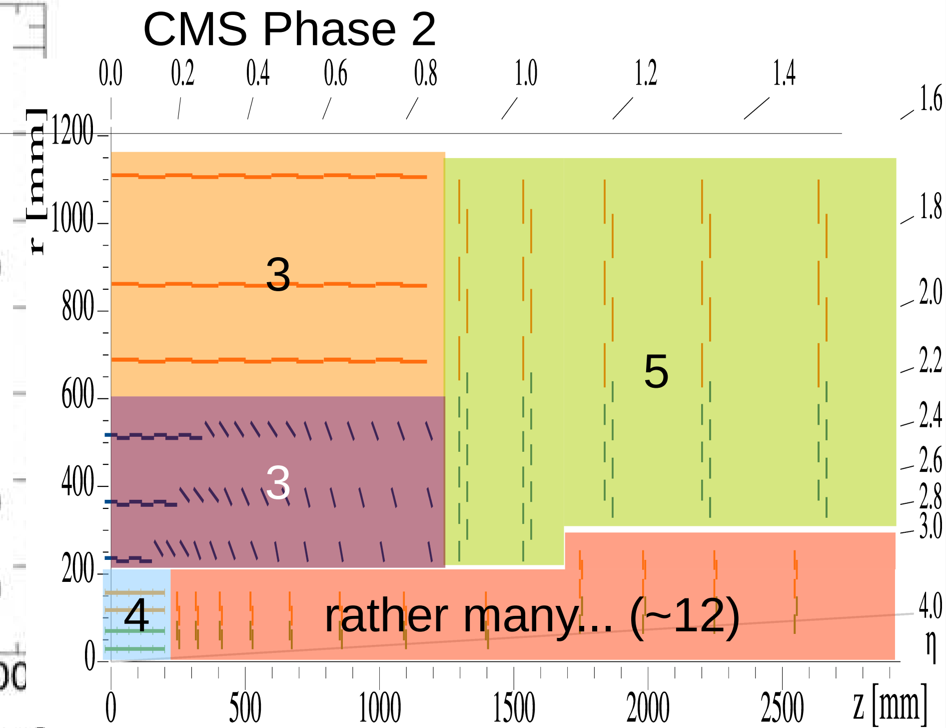




- CM ... LOTS of layers
  - I ... tracking
  - I ... s needed

Number of layers



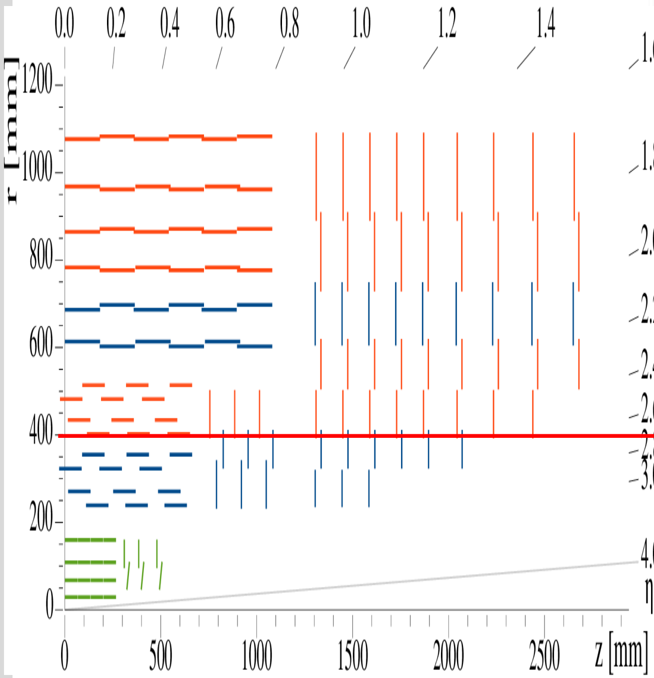


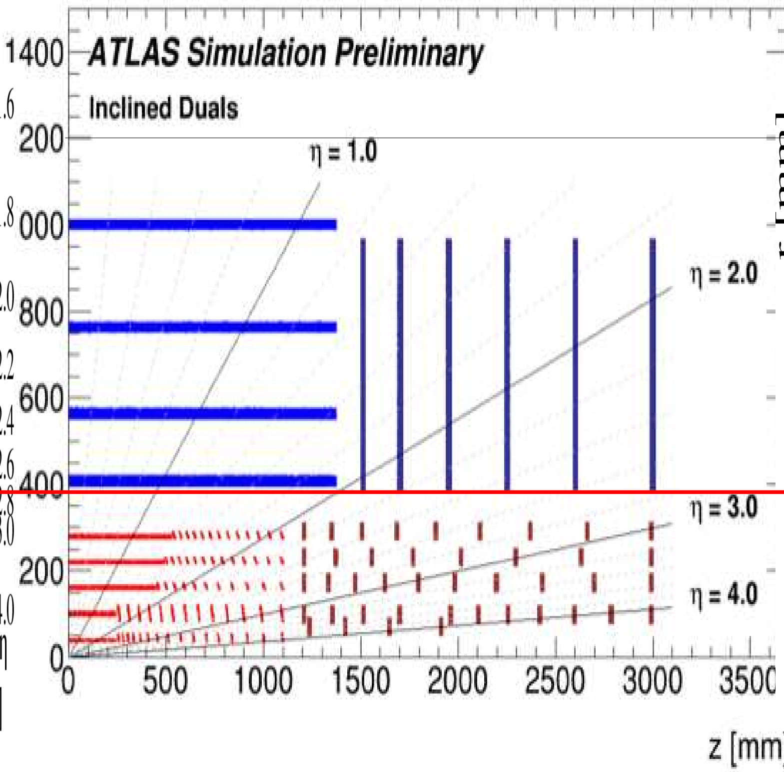
- Number of Barrel layers decreased in both case
  - CMS Phase 0: 14 Layers
  - ATLAS Phase 2: 9 Layers
  - CMS Phase 2: 10 Layers

} Strips + Pixels

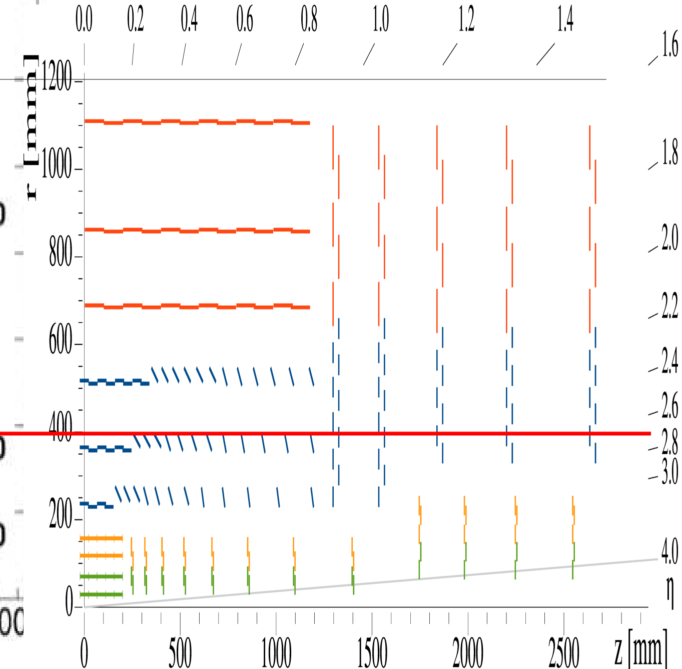
Number of layers

CMS Phase 0





CMS Phase 2

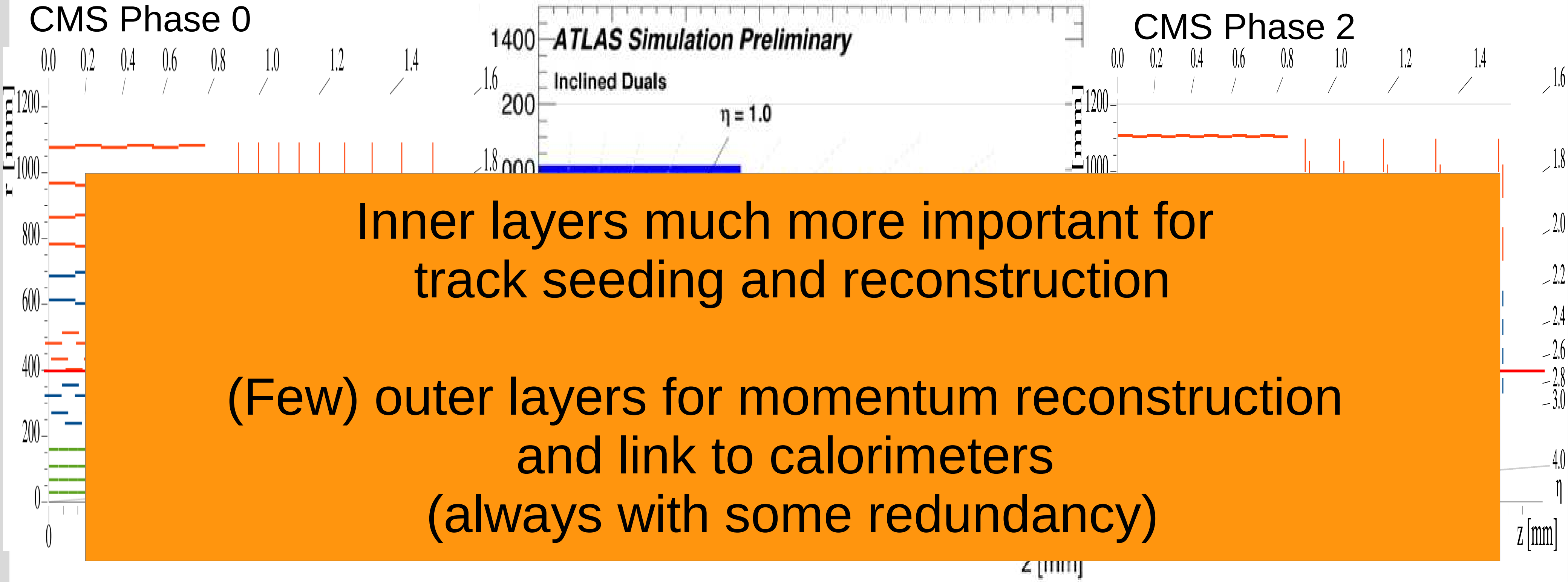


- Even more striking:
  - At R > 40 cm
    - CMS Phase-0: 8 layers
    - ATLAS Phase-2: 4 layers
    - CMS Phase-2: 4 layers

Number of layers

CMS Phase 0

CMS Phase 2

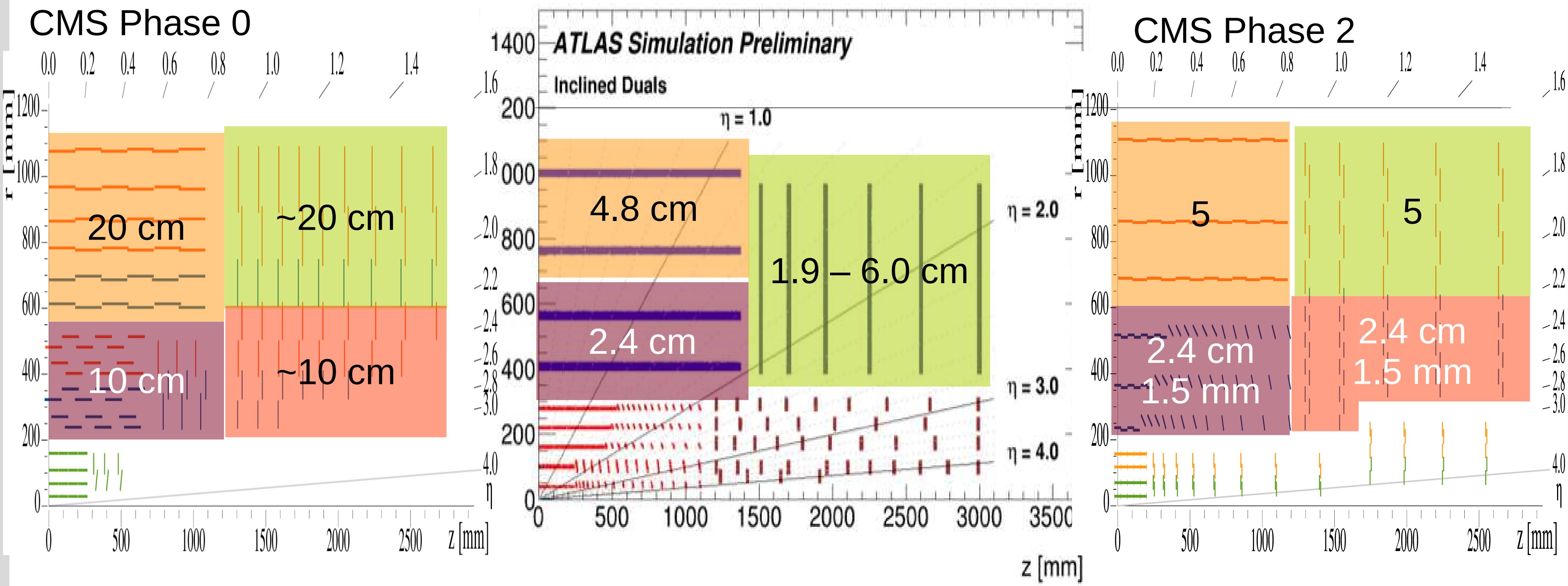


Inner layers much more important for track seeding and reconstruction

(Few) outer layers for momentum reconstruction and link to calorimeters (always with some redundancy)

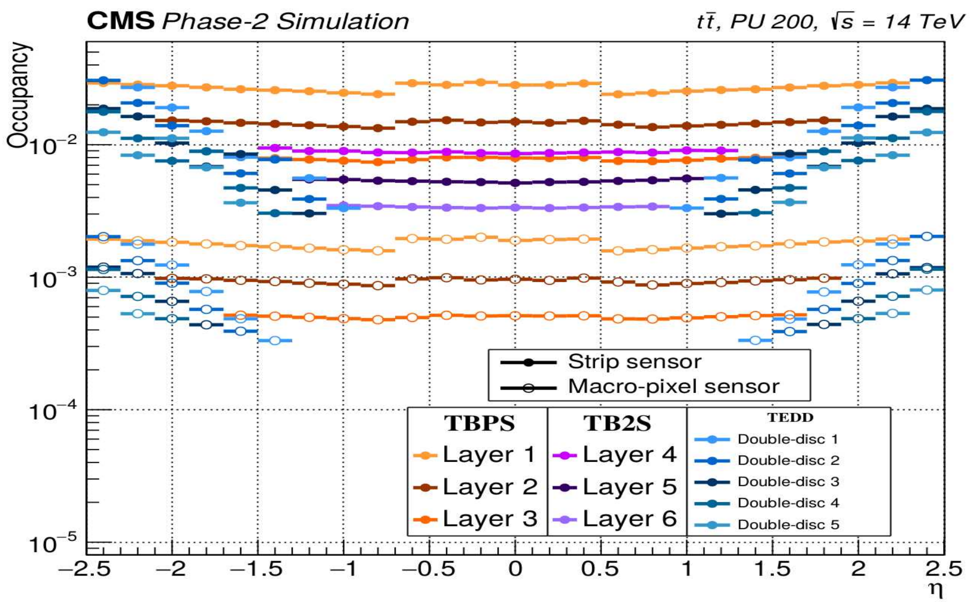
- Even more striking:
  - At R > 40 cm
    - CMS Phase-0: 8 layers
    - ATLAS Phase-2: 4 layers
    - CMS Phase-2: 4 layers

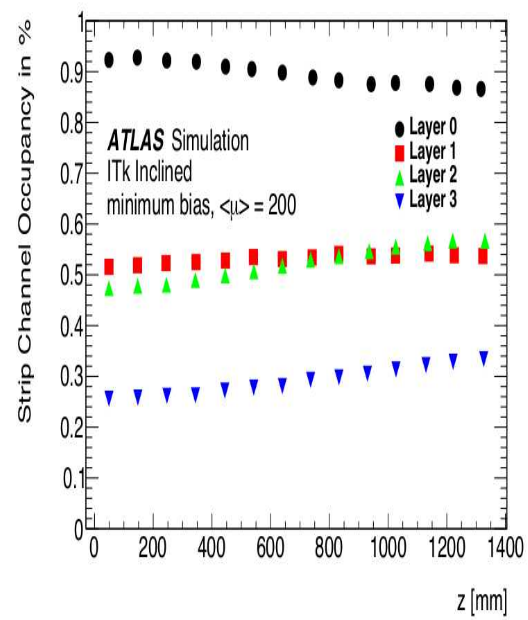
Scaling of strip cell sizes

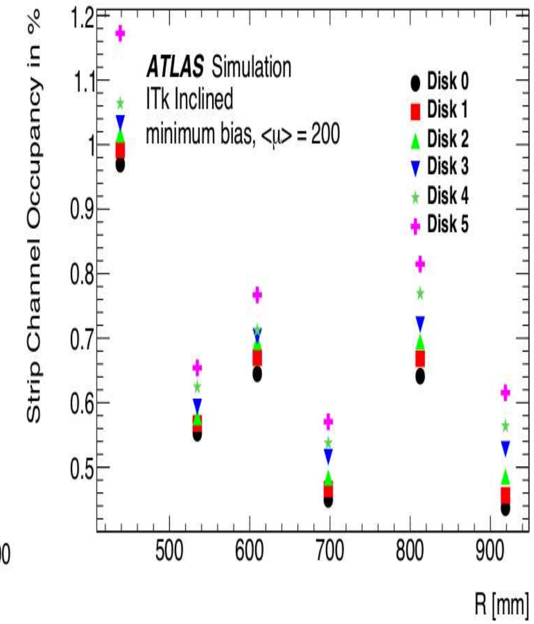


- Cell sizes decrease by factor ~4 (special case: CMS macro pixels)

Scaling of strip cell sizes

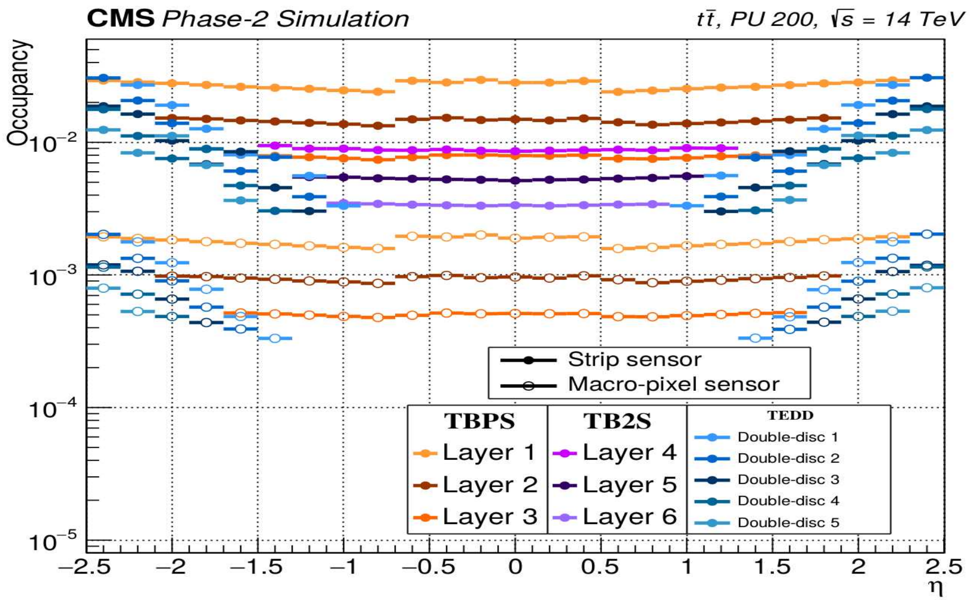


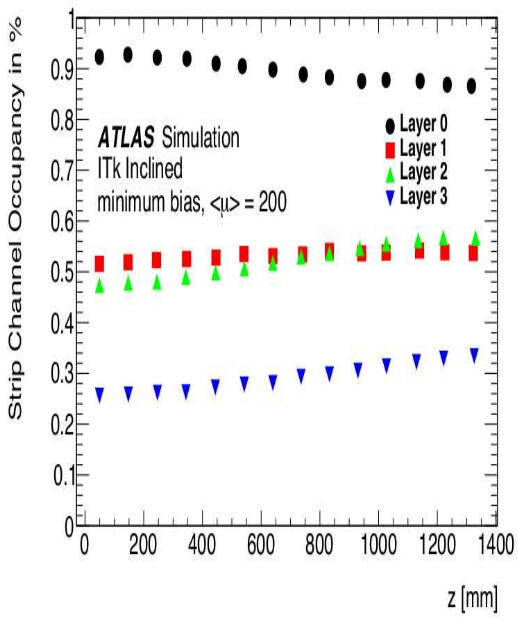


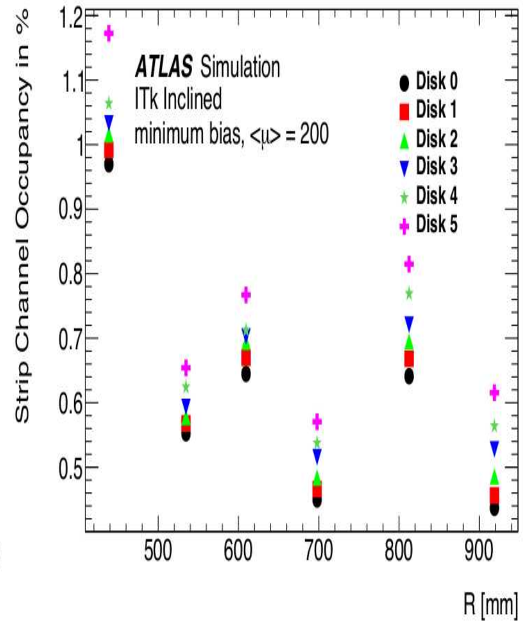


- Cell sizes decrease by factor ~4 (special case: CMS macro pixels)
- Cell occupancy kept low even at pile-up ~200

Scaling of strip cell sizes

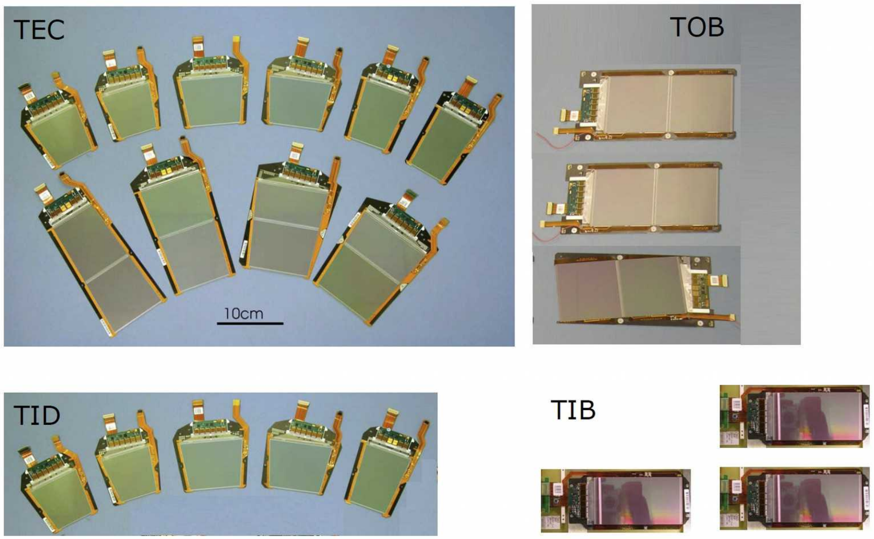




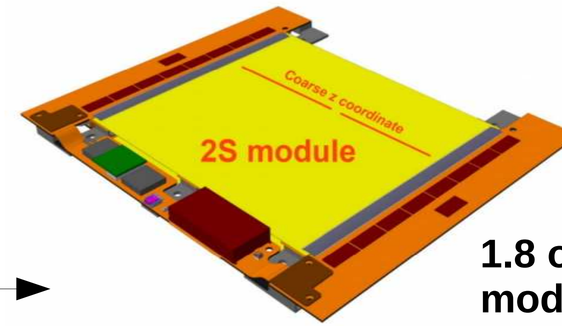


- Cell sizes decrease by factor ~4 (special case: CMS macro pixels)
- Cell occupancy kept low even at pile-up ~200
- What does this mean for the modules we are using?

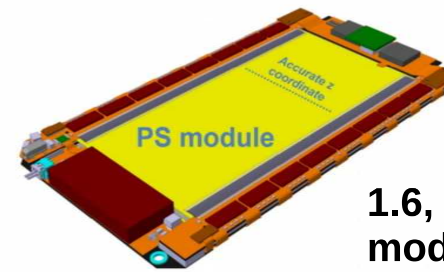
More complicated or more simple?



Fewer module type but modules have trigger capability

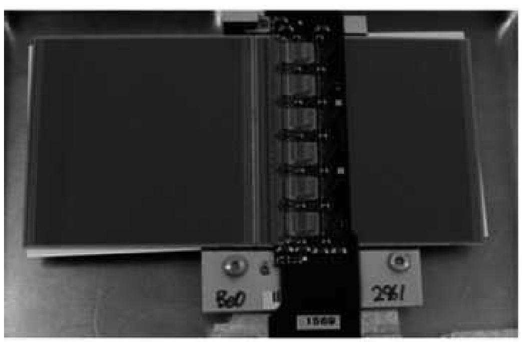


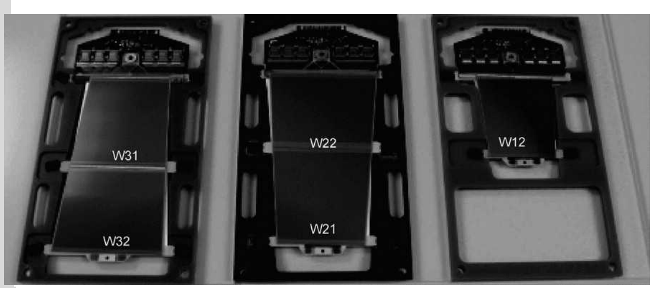
1.8 or 4.0 mm module spacing



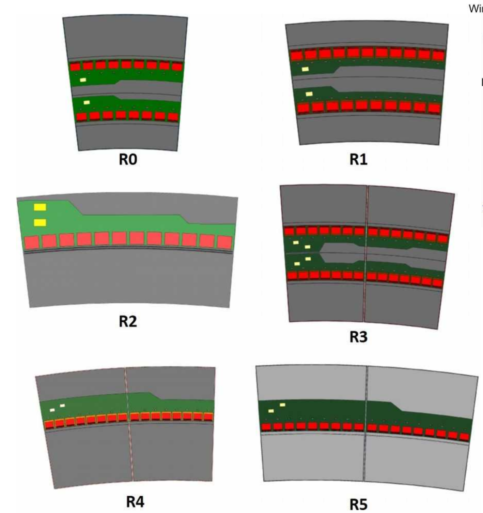
1.6, 2.6 or 4.0 mm module spacing

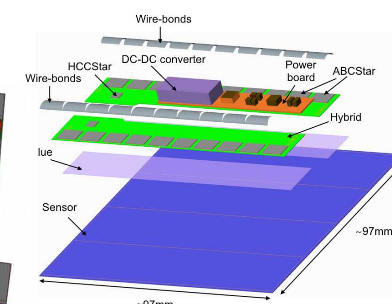
Both: n-on-p silicon sensors, different thicknesses





More endcap module types for hermetic coverage

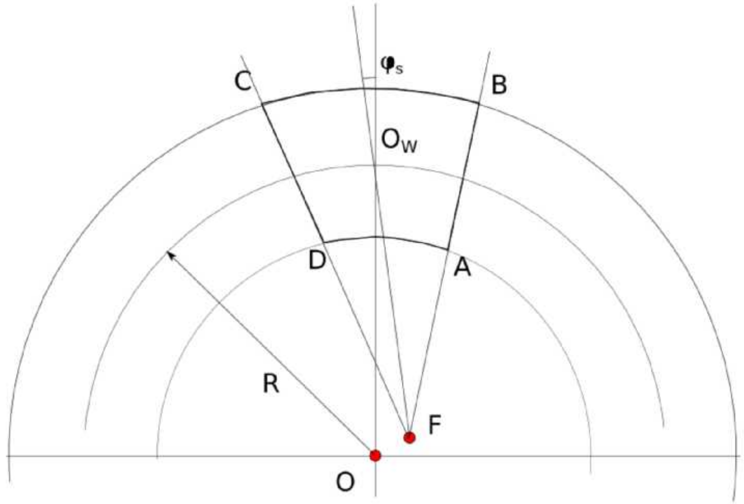




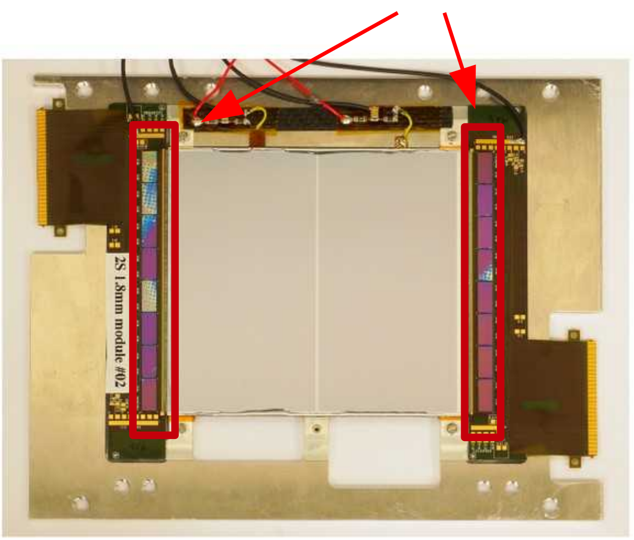
Two versions:
short strip
long strip

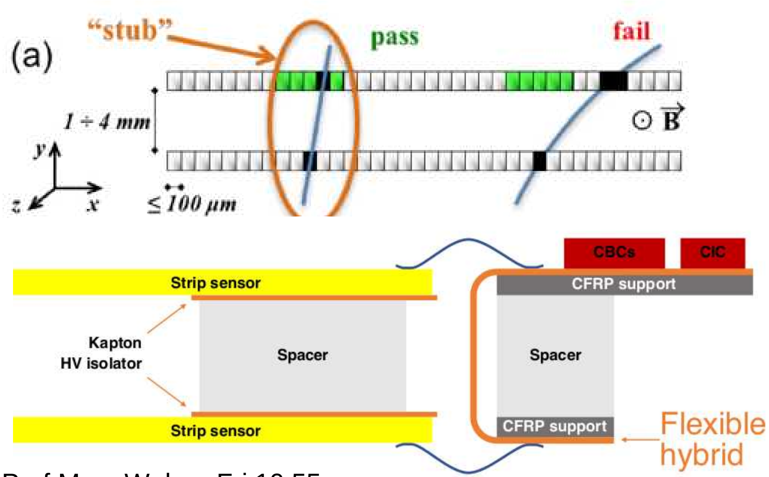
New Modules

- ATLAS: stereo angle in wafer for endcaps, readout chips on module for more flexible granularity



CMS: p_T modules for L1 trigger information, no stereo angle possible, readout chips at the edges, tight tolerances on sensor tilt

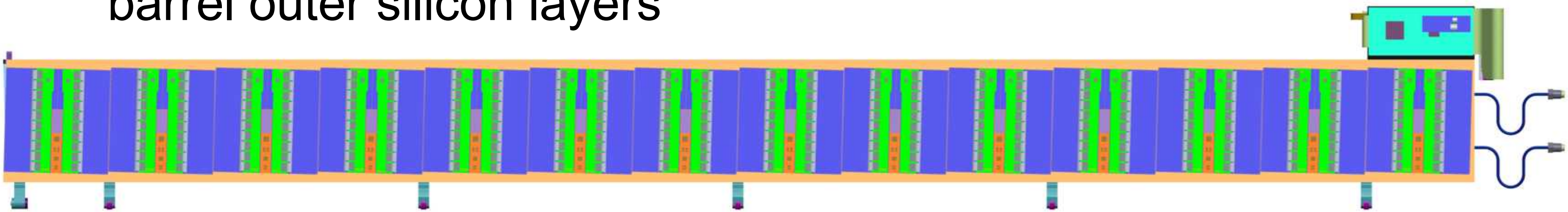




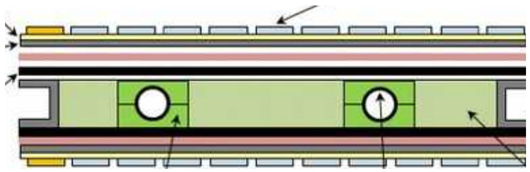
The CMS Track Trigger, Prof Marc Weber, Fri 10:55

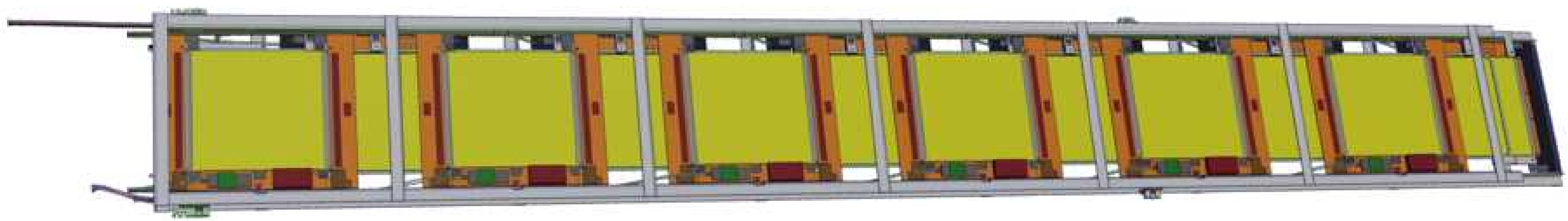
Mechanics – Outer Barrel

- Both collaborations will use ladders/staves in the barrel outer silicon layers



ATLAS stave: seemless module placing, 20 mrad stereo angle,
double-sided with sensors mounted on
front and back of support structure,
end of stave card for power and communication

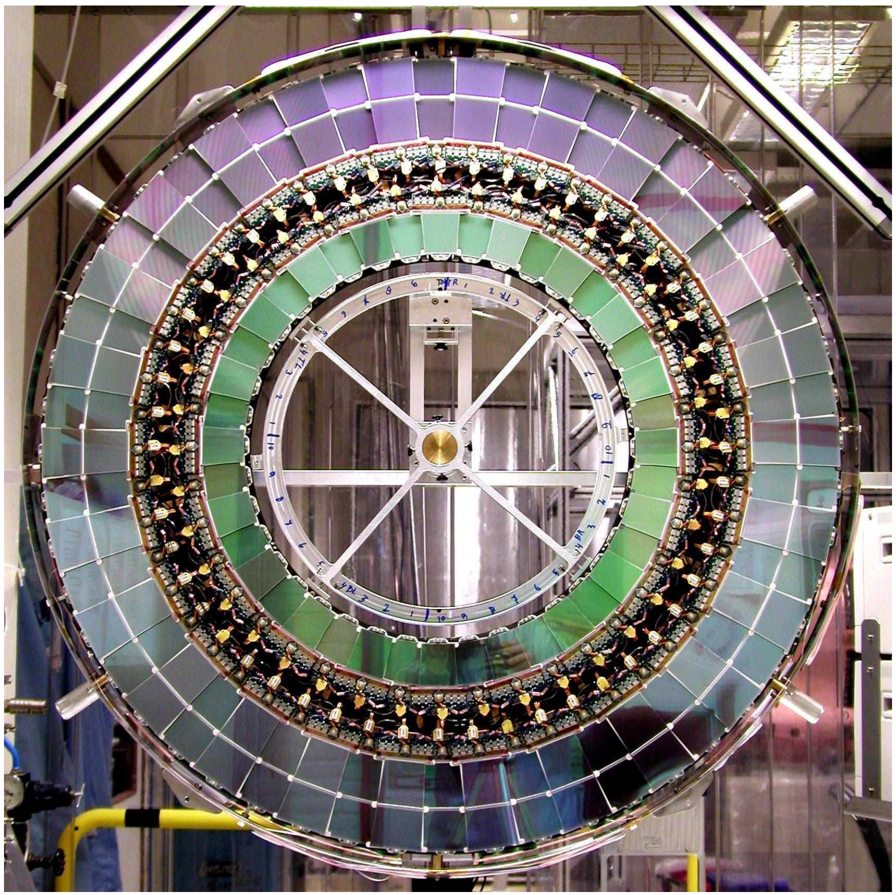




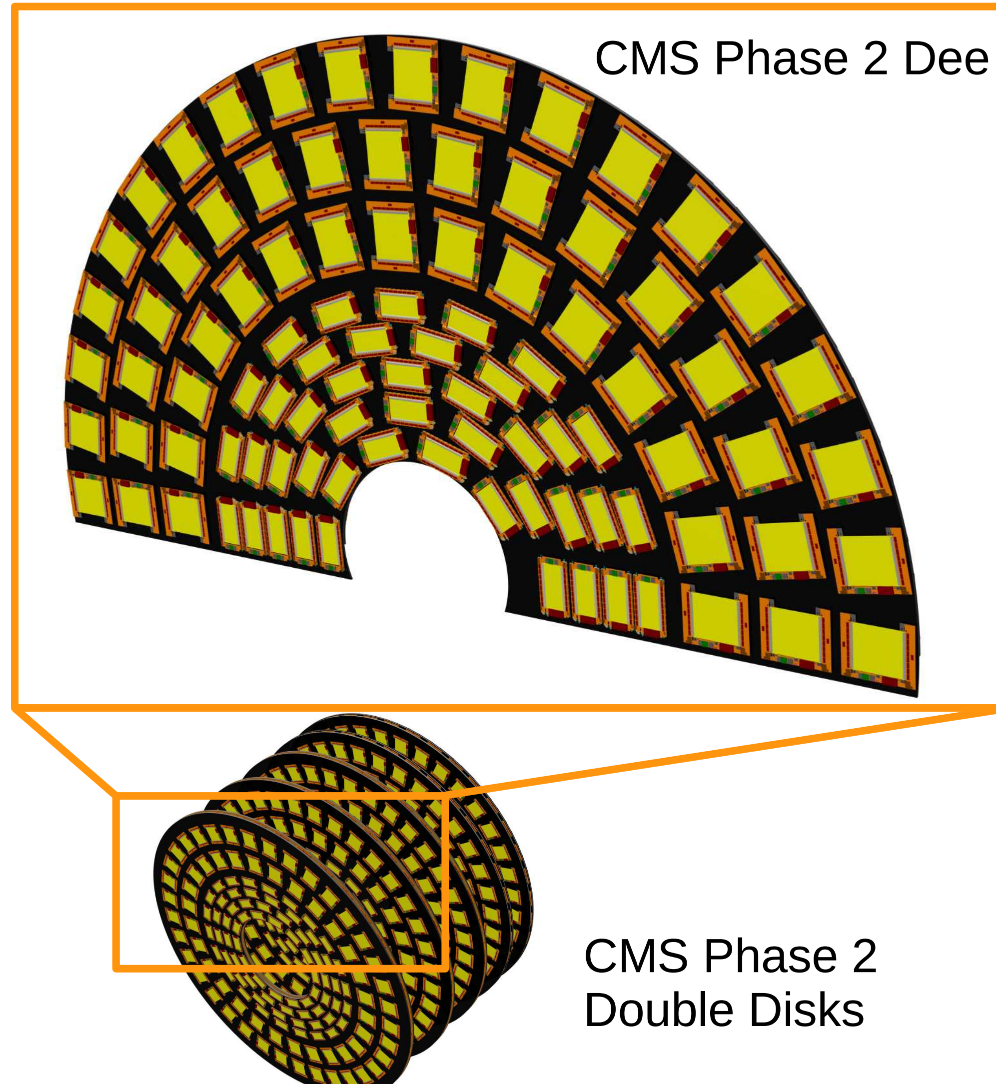
CMS TB2S ladder: modules place alternating r for overlap,
p_T modules for triggering (*module* is the system, no other card)

Mechanics – Endcap

- ATLAS successfully employed the concept of full disks in phase 0, now CMS is going to build the phase 2 endcaps using (half-)disks



ATLAS SCT Phase 0 disks



CMS Phase 2 Dee

CMS Phase 2 Double Disks

Mechanics – Endcap

- CMS successfully employed the concept of petals in phase 0, now ATLAS is going to build the phase 2 encaps using petals

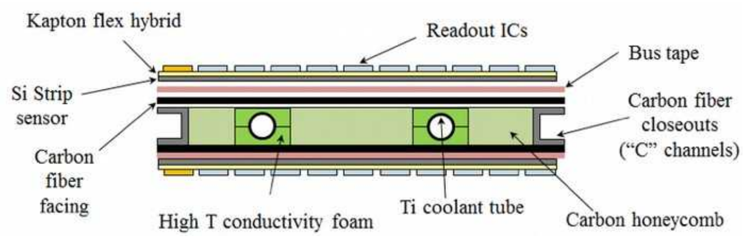
CMS Phase 0 Petal

ATLAS Phase 2 Petal
Thermomechnical Prototype

So what is the “right” solution to build an endcap?

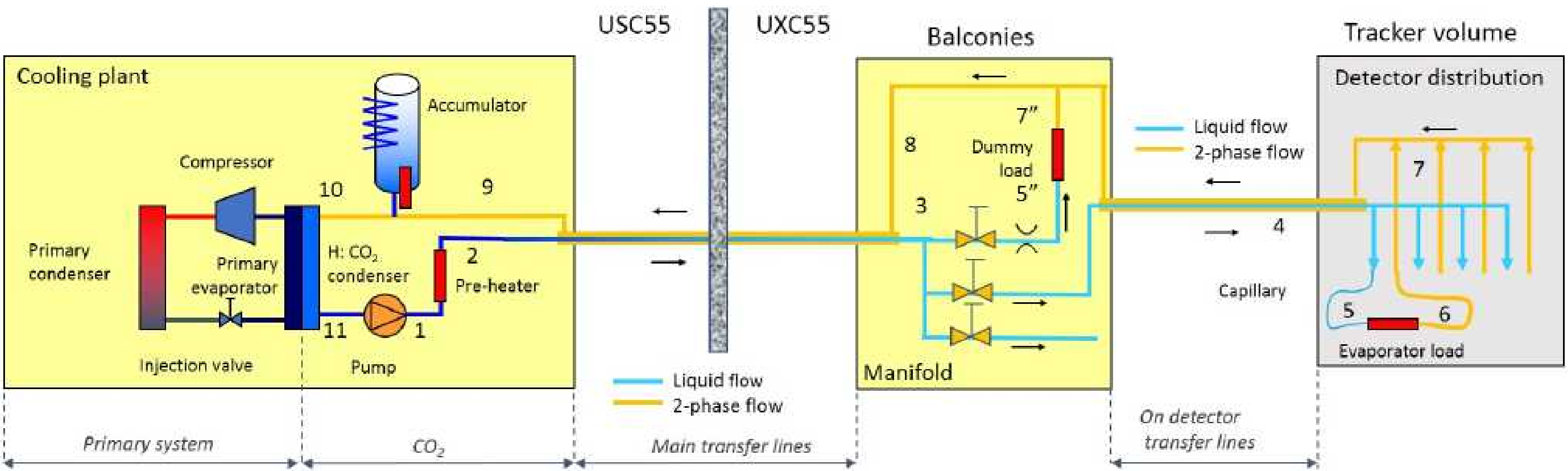
- CMS:
  - very few module types (rectangular, same as barrel)
  - Mechnically simple and lightweight
  - Modules “on disk”
  - Service routing not always easy
  - More overlap due to rectangular modules

- ATLAS:
  - Rather complex module geometry
  - In return: common service concept for barrel and endcap
    - Modules on carbon fiber planks
    - Services co-cured onto carbon fiber skins
  - High parallelism during construction
  - System-like testing possible early on
  - Easy replacements of non-functioning components (full petals)



Cooling

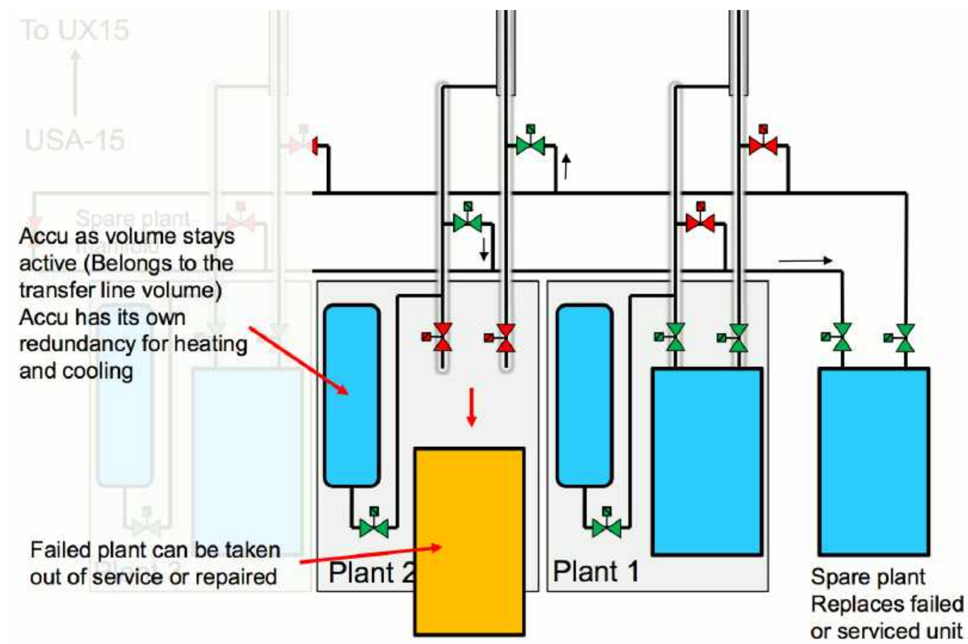
- Both collaborations use evaporative CO2 cooling
  - Low mass pipe work
  - Lighter liquid
  - High heat transfer
  - Environmentally friendly
- Successfully used in LHCb, ATLAS IBL, CMS Phase-1 Pixel
- Downside
  - High operating pressure BUT
  - Stored energy (pressure X volume) comparable to other refrigerants



CMS Phase 1 pixel cooling layout, very similar schematics for e.g. ATLAS IBL

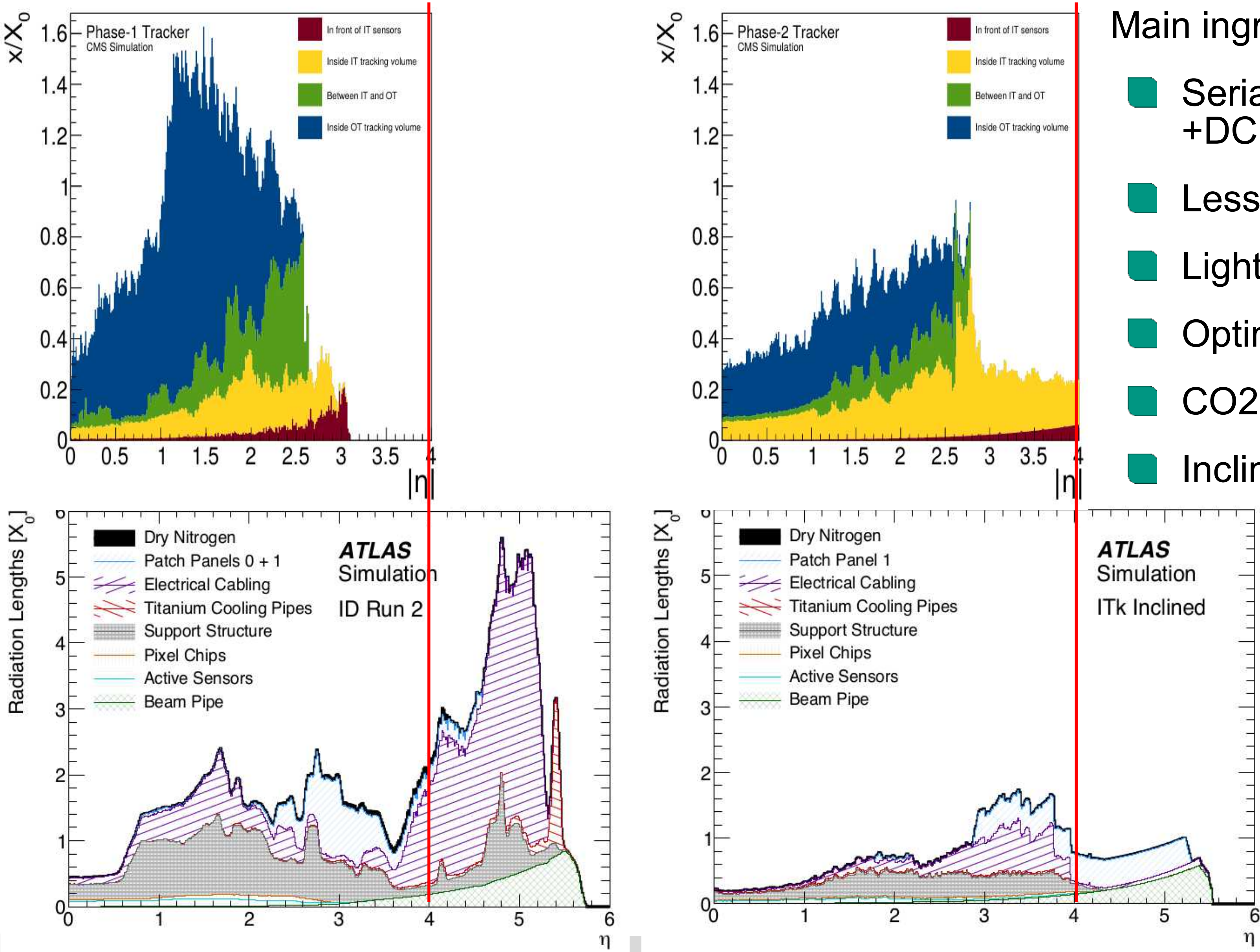
Cooling

- Power requirements
  - CMS Phase 0: 60 kW (strips) + 3.6 kW (pixels), **198** cooling loops (180 strips, 18 pixels)
  - ATLAS: 89 kW (Strips) + 100 kW (pixels), 100 cooling loops (72 strips, 38 pixels)
  - CMS: 100 kW (OT) + 50 kW IT (IT), 66 cooling loops (46 strips, 20 pixels)
- Several identical cooling units in service caverns foreseen for both collaborations
  - Redundancy foreseen to allow single cooling plants to be under maintenance or repair without loss of operations time
  - Assumed cooling plant power 30-50 kW
- Distribution
  - Transfer lines to experimental cavern
  - First manifolds in accessible locations
    - Muon system (ATLAS)
    - Experimental Cavern balconies (CMS)
  - Further splitting to capillaries inside detector volume



Material Budget

Material budget MUCH reduced for both concepts compared to phase 0 detectors



Main ingredients

- Serial powering +DCDC converters
- Less layers
- Lighter materials
- Optimized service routing
- CO_2 cooling
- Inclined geometry

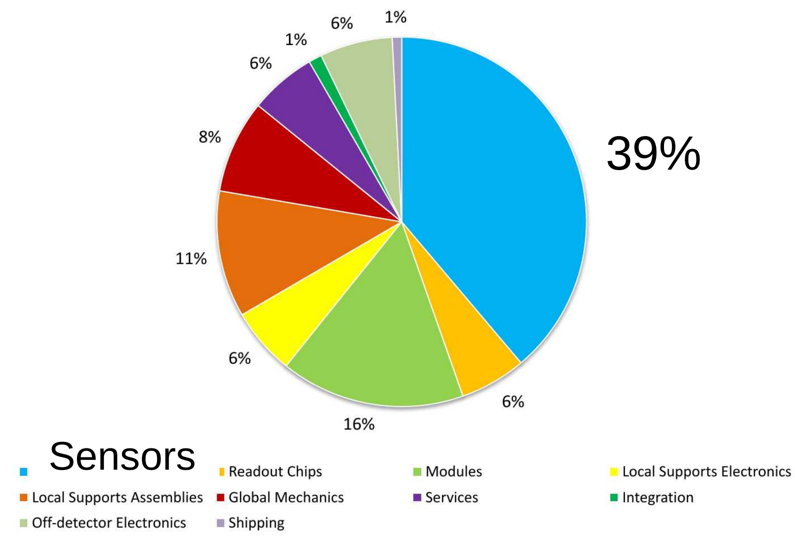
Module Cost – Strip Detectors

- CMS Phase 2
  - 2S modules: 10 CHF/cm^2
  - PS modules: 15 CHF/cm^2
- ATLAS Phase 2
  - Strip Modules: 14.3 CHF/cm^2
- CMS Phase 0
  - sensor fabrication on 6 inch instead of 4 inch wafers reduced the sensor cost to 5–10 CHF/cm^2
- Both collaborations use 6” as baseline for phase-2

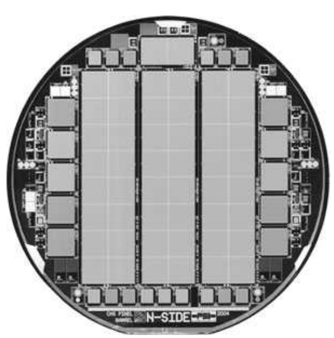
→ can't we gain by going to 8” technology instead?

8” Technology

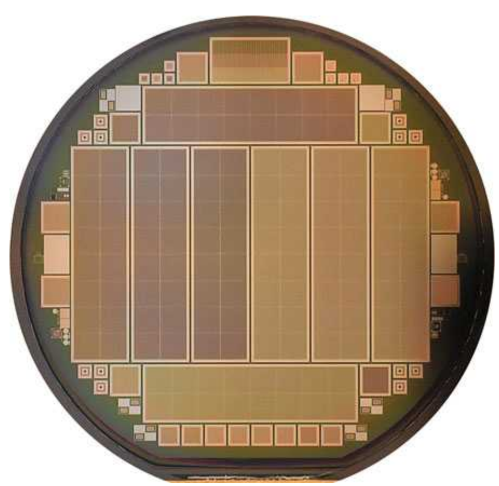
- Sensors clearly contribute a large fraction to the overall cost
- 8” clearly cheaper in terms of CHF/cm^2 but can we use this gain?
- Examples of good use of going to larger wafer sizes



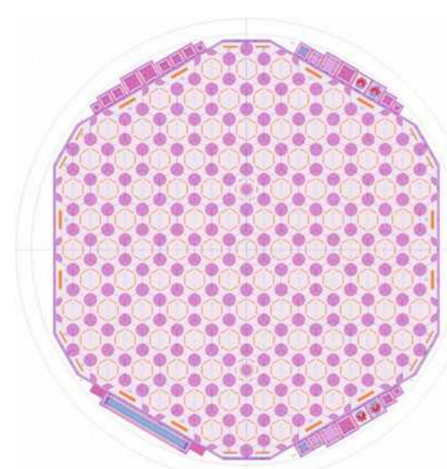
CMS Phase 1 pixel sensors

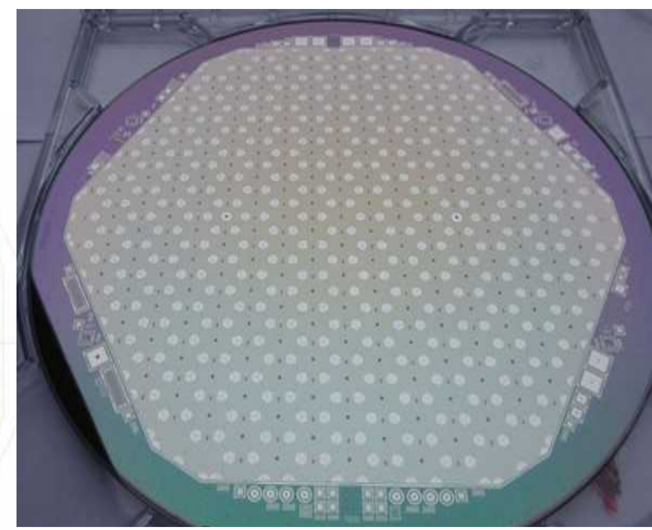


3 sensors on 4” wafer



8 sensors on 6” wafer



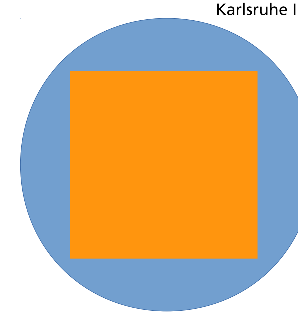


CMS HGCAL wafer 6” (left) or 8” (right)
All the details on this from K.Gill

8” Technology

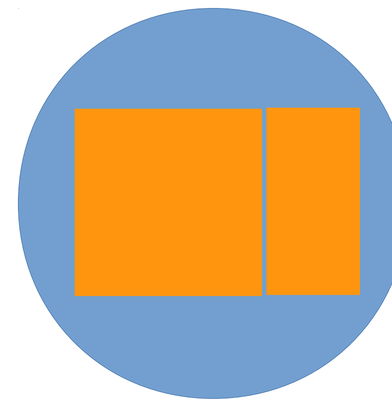
- Do you change the layout of the detector (e.g. strip length) to better match the new wafer size?
  - More tiling probably increases number of modules
  - Or: better use of area might couple production of different module types
- Other question marks:
  - Number of available production lines?
  - Yield?

→ For phase-2 both collaborations do not adopt 8” as baseline



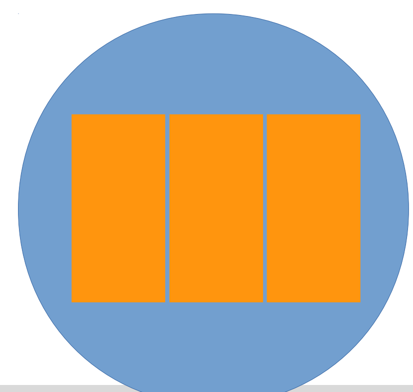
52% coverage

10x10 cm^2 on 6”



44% coverage

Hypothetical layout on 8”



Hypothetical layout on 8”

44% coverage

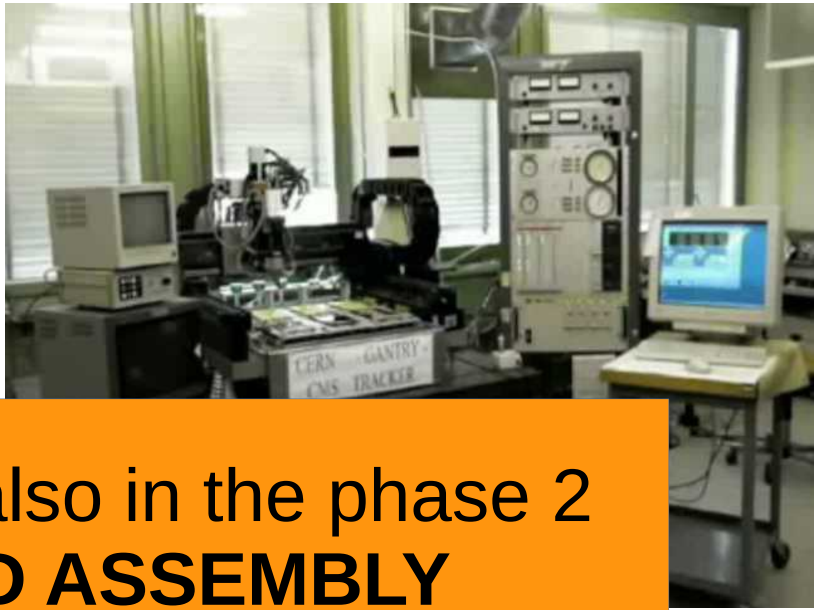
Module assembly

- CMS Phase 0 Strip Tracker
  - Automated assembly with gantry robot
  - Identical hardware at different assembly centers
  - 6 assembly centers doing module production
    - 15 geometries means customization for several components like trays to hold modules and pickup tools
- Total of 17000 modules produced
- Achievable throughput:

  15-20 modules per day

Module assembly

- CMS Phase 0 Strip Tracker
  - Automated assembly with gantry robot
  - Identical hardware at different as
  - 6 m
    - nents



With high module counts also in the phase 2 trackers **AUTOMATED ASSEMBLY** clearly the right solution?

- Total of 17000 modules produced
- Achievable throughput:

  15-20 modules per day

Assumed production rates – Outer Tracker Modules

- ATLAS:
  - 12688 Barrel Modules, 8 production centers, 550 working days* → **2.9 modules/day**
  - 7976 End-cap Modules, 7 production centers, 550 working days* → **2.1 modules/day**

  *)3.5 years total time assumed but production centers at 50% efficiency during first year, estimates include yield estimates for all parts in the chain

- CMS:
  - 7680 2S modules, 5 production centers, 400 working days** → **5 modules/day**
  - 5616 PS modules, 3 production centers, 400 working days** → **5 modules/day**

  **) sites dimensioned to complete module production in two years while three years are available in the schedule

→ Answer: NO automated production for both collaborations

Conclusions

- Two very interesting and challenging tracker designs with some 200 m^2 of silicon are under development for the HL-LHC running
- Many lessons have been learned and applied from the previous construction round
- Collaborations reached different (almost complementary?) conclusions how to build the trackers
  - In both cases choices are well motivated and justified
  - Solutions adopted do not agressively try to max out available technology for size and throughput
    - 8” wafers
    - Automated module assembly

Conclusions

- Two very interesting and challenging tracker designs with some 200 m^2 of silicon are under development for the HL-LHC running
- Many lessons have been learned and applied from the previous construction round
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  - In both cases choices are well motivated and justified
  - Solutions adopted do not agressively try to max out available technology for size and throughput
    - 8” wafers
    - Automated module assembly

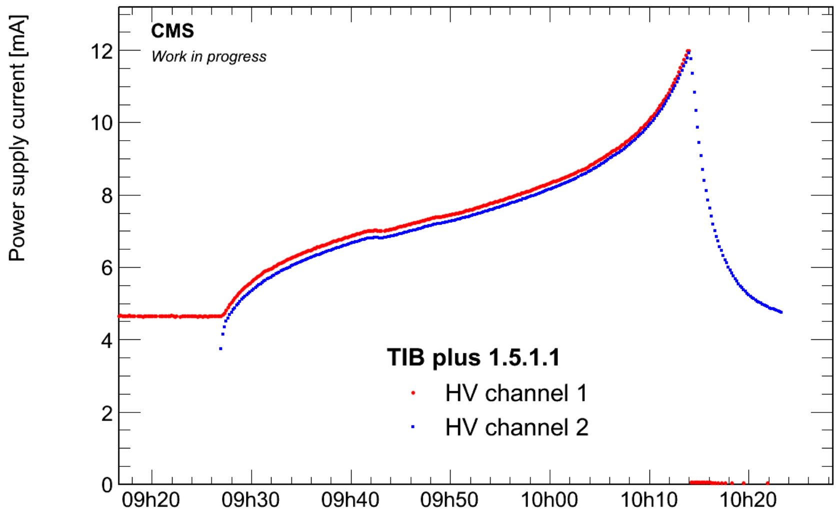
Let's take 10x10 cm^2 silicon wafers, the ATLAS phase-2 number of assembly sites, paired with the CMS phase-0 production rate, work for the 400 days that CMS phase-2 assumes in their planning and have a

1000 m^2 silicon detector!

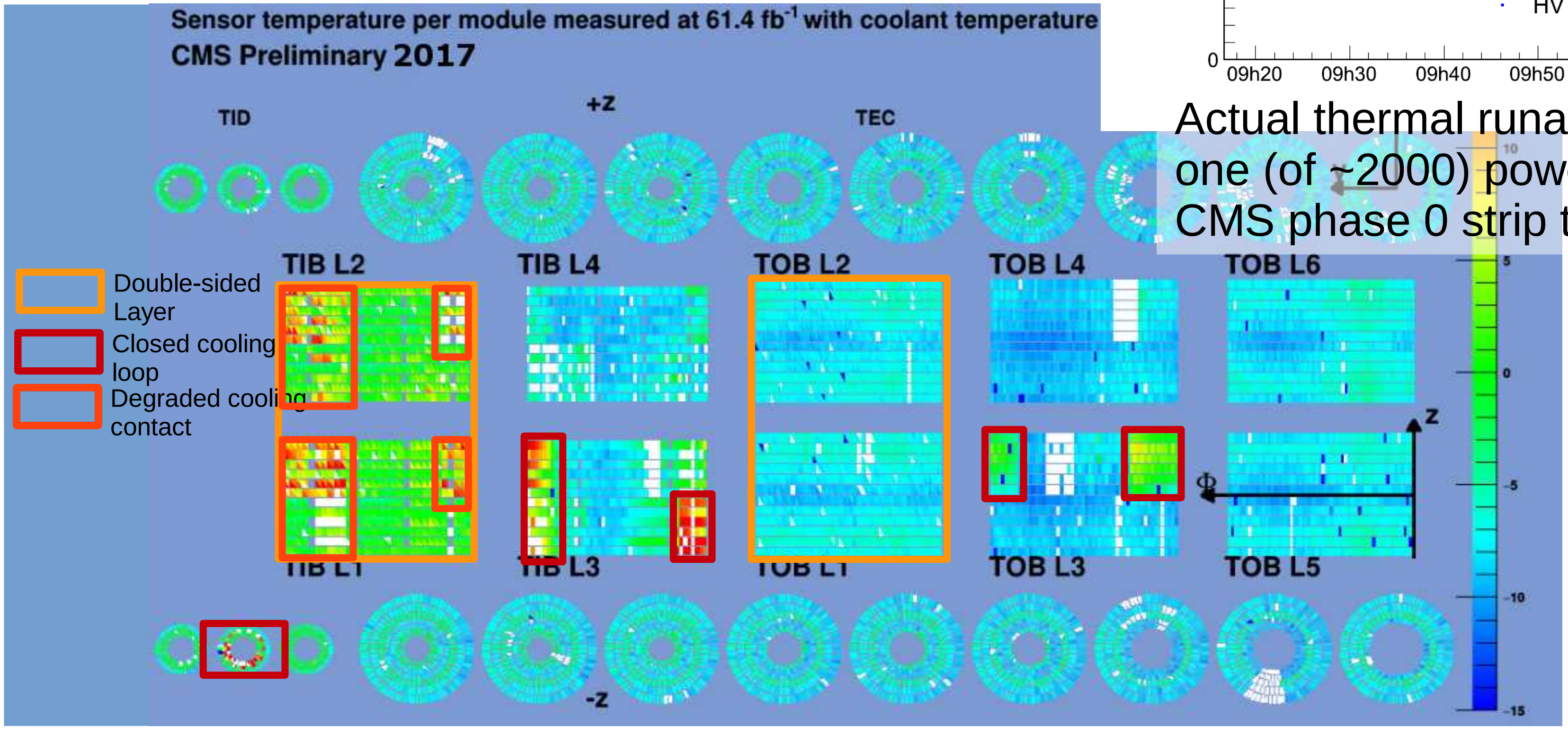
BACKUP

Result of cooling problems in real life

- Increased temperature in some parts of the system
- In turn leads to higher leakage current
- In turn leads to reduced lifetime (PSU limits, thermal runaway)

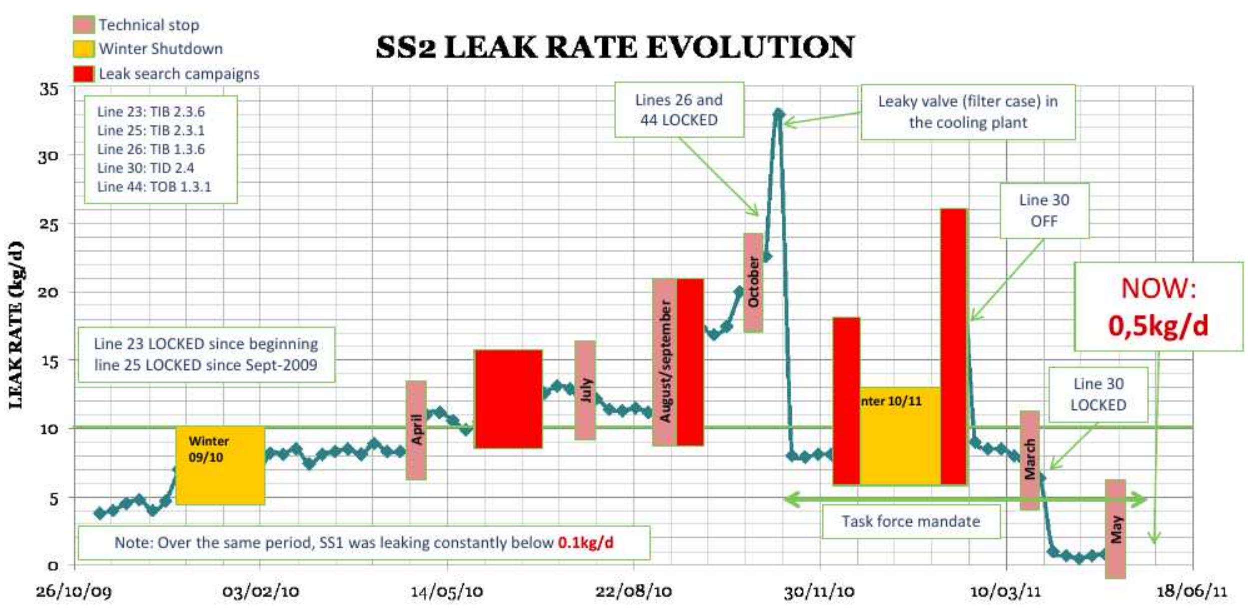


Actual thermal runaway observed in one (of ~2000) power groups in the CMS phase 0 strip tracker



CMS Phase 0 Tracker Cooling

- 3 non-redundant C6F14 cooling plants with about 90 kW total power
  - 2 strips + 1 pixels (phase-0), all located in experimental cavern
  - 198 loops from cooling plants to detector
- In one strip tracker cooling plant problems with leaks
  - Overpressure accident in 2009
  - Several detector loops developed leaks
    - short periods at >30 kg/d of C6F14!
  - 5 detector loops had to be closed to reach low sustainable leak rate



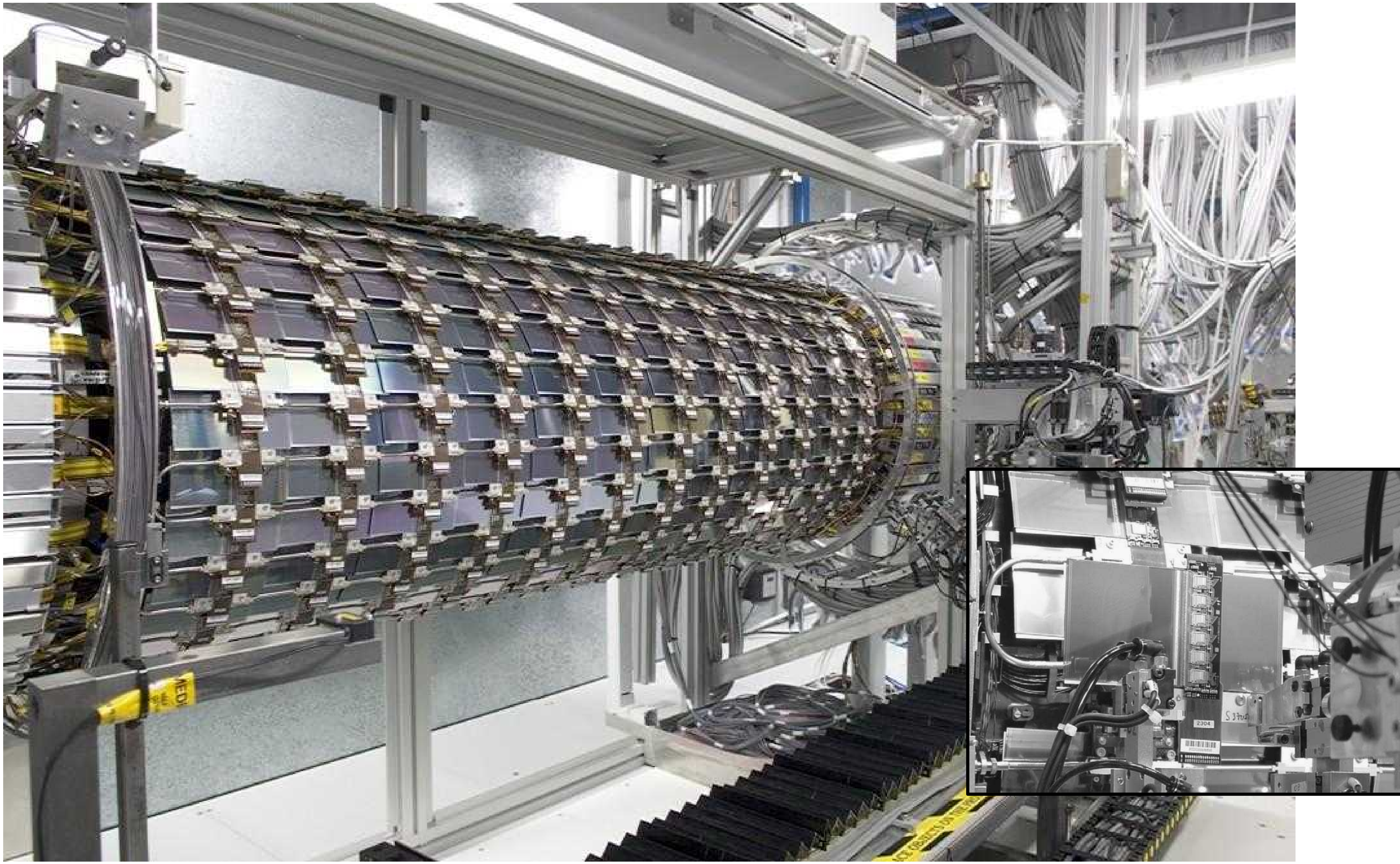
Automated module assembly for CMS phase-0 Tracker

- Time needed to reach “proof of principle”: about 1.5 years
- Additional time to reach steady full production rate: 1-1.5 years
- Cost for 6 assembly robots: ~1 MCHF
- large variety of module types (15) implied many different component and module trays as well as different types of pick-up tools. Strong engineering and machining support groups at each assembly centre were essential for achieving reliable results
- Simplified threshold calculation as to when automated production can become viable: >~ 5000 modules needed in short time (< 2 years)
- However many other factors contribute
  - In house competence, existing laboratory resources, available funding

A.Honma, Industrialization of Silicon Detector Module Production, Vertex 2010

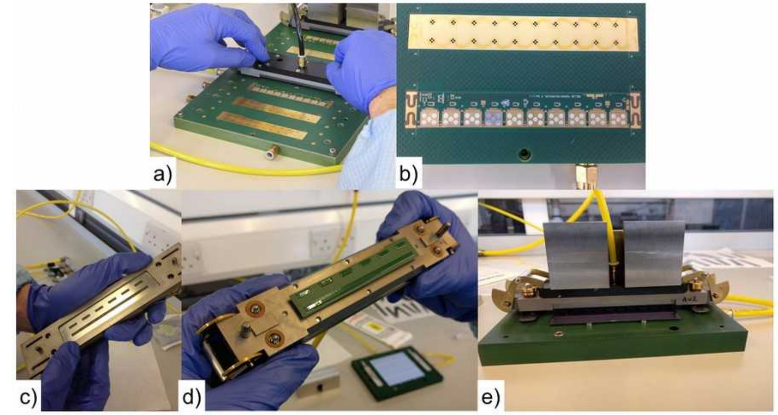
Automated module placement for ATLAS SCT

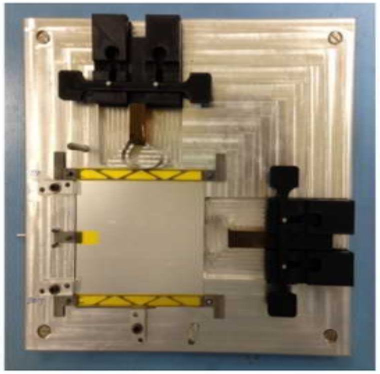
assembly of modules onto the cylinder structure



Module assembly

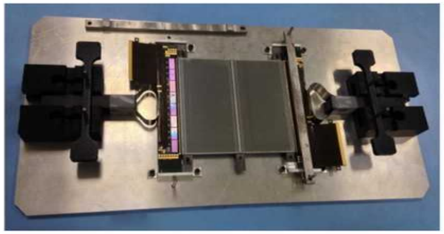
- ATLAS
  - Pre-tested ASICs are glued onto hybrids and wire bonded
  - Hybrids are tested electrically
  - Hybrids and power boards are glued to the sensors.
  - ASICs are wire bonded onto sensors
  - Full module is tested
- CMS Phase 2
  - Dedicated jigs for (largely identical for 2S and PS modules)
    - Gluing HV circuitry to sensor backplane
    - Gluing 2 sensors to AL-CF bridges
    - FEH and Service hybrid to sensor assembly
    - Wire-bonding



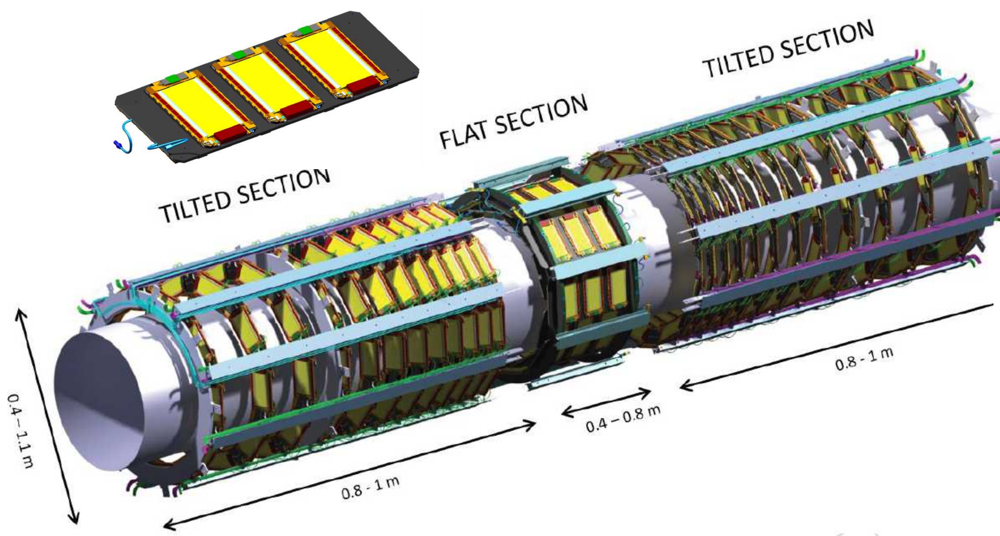


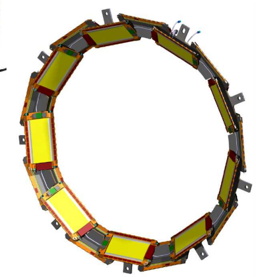
Sensor to AL-CF bridge gluing

Front-end and Service hybrid gluing

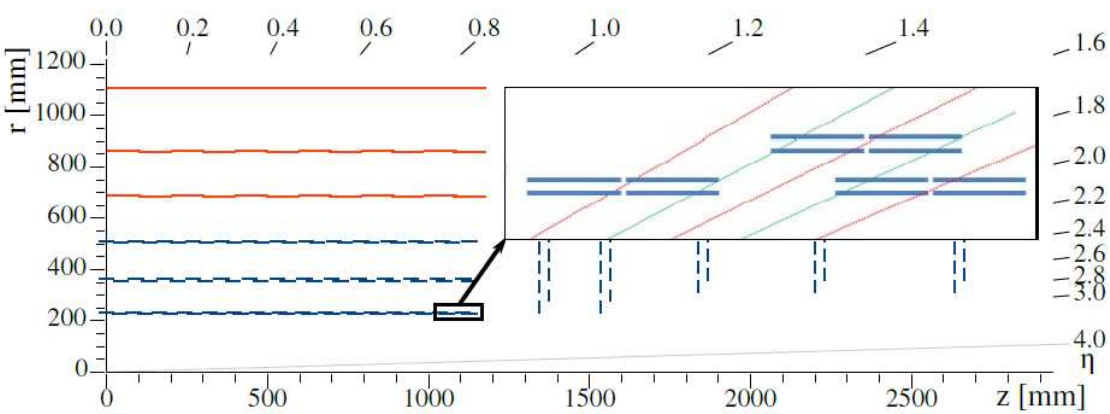


CMS Barrel Mechanics – TBPS Section





- TBPS barrel composed of planks and rings
- Tilted geometry to increase coverage for L1 trigger



Track stubs that cross different modules in lower and upper sensor are **lost**