CMS Tracker Upgrade:
Requirements and Layout

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On behalf of the CMS Collaboration
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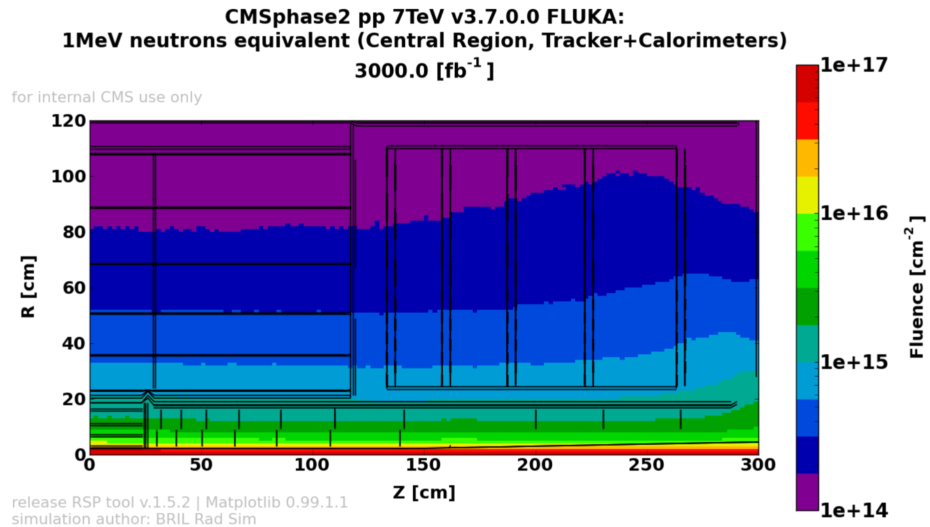
Requirements from HL-LHC

Pile up to **200**
Occupancy **~ %**

Operate up to 200 <PU>
Maintain occupancy at the ~1% level
higher granularity in the strip detectors

Radiation tolerance
up to **∫L.dt = 3000 fb^{-1}**

Radiation tolerance up to 3000 fb^{-1}
Maybe the inner parts of the pixel detector could be replaced if needed



- Radiation levels depend essentially on R, not much on z
  - Target is ~ 10× present trackers:
    i.e. about ~10^{15} for the Outer Tracker & 2×10^{16} for the innermost pixel layer
- Challenging for silicon sensors and electronics (notably in the pixel region)

Requirements from experiment

Hi-Lumi: **improve trigger**

The Trigger is much more challenging at HL-LHC
selection algorithms become less effective in high pileup!

Solution:

- **Higher first-level trigger rate**
- More effective event selection: **higher latency**
- **the Outer Tracker contributes to the first trigger decision**

100 kHz → 750 kHz
3.2 ms → 12.8 μs

(**ATLAS:** 100 kHz → 1000 kHz
2.5 ms → 6.0 μs)

Additional improvements

Extend tracking acceptance

- **Extended tracking acceptance**
  - Up to η~4 (concerns mostly the pixel detectors)
  - Main goal: **assign jets to primary vertices** in forward
  - Helps for Vector Boson Fusion and Vector Boson Scattering physics

Improve resolution
Reduce **secondaries**

- **Reduce the amount of material** in the tracking volume
  - The tracker material is a major limitation for the overall performance today:
    - Multiple scattering limits pT resolution
    - Secondary interactions

Requirements & solutions

Requirement	Solution
Radiation tolerance up to **$\int L.dt$ = 3000 fb^{-1}**	**Radiation hardness** **Operating cold** (-20°C) **Pixel replacement possible**
Pile up to **200** Occupancy **~ %**	**Increase granularity**
Hi-Lumi: **improve trigger**	**Longer latency → 12.5 μs** **Higher L1A rate → 750 kHz** **Tracking @40MHz for trigger**
Improve resolution Reduce **secondary interactions**	**Increase granularity** **Reduce material**
Extend tracking acceptance	Mostly through **pixel layout**

Material vs. data rate

Material amount is limiting current tracker's performance: reduce material

LESS power/material ← → **MORE power/material**

New technologies

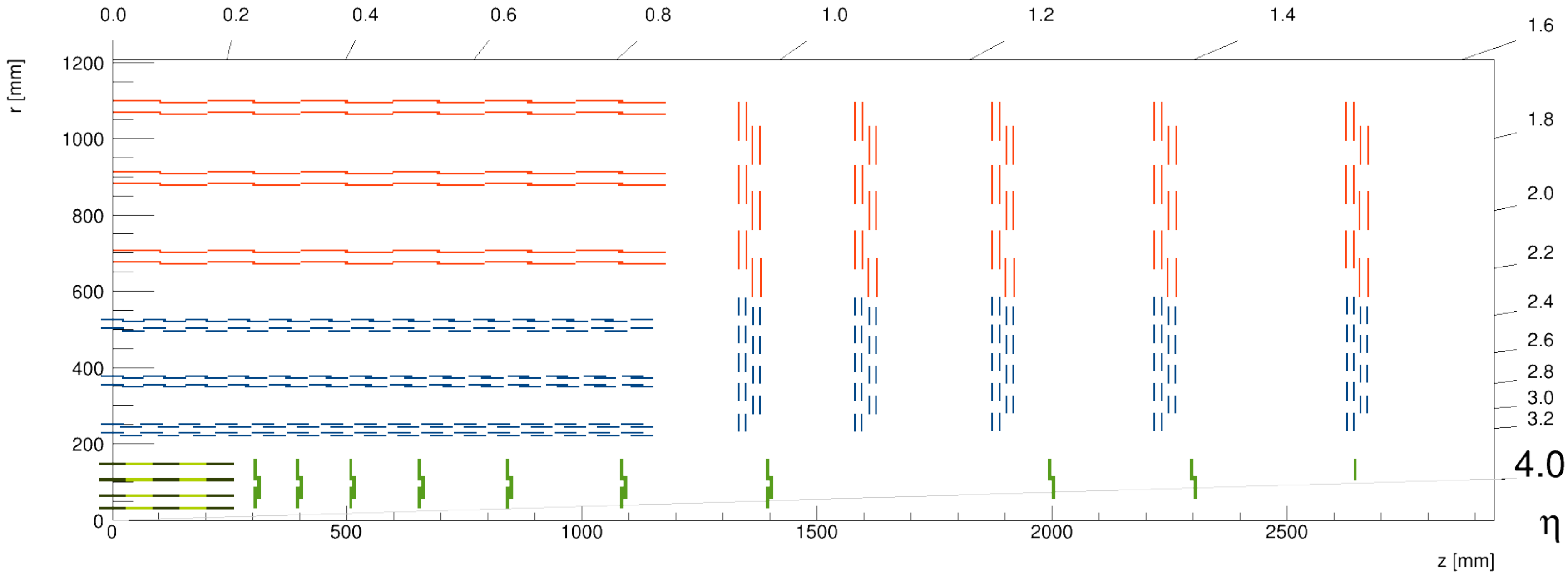
- DC-DC converters
- CO_2 cooling
- lp-GBT
- Front-ends

Less layers in outer tracker

Higher

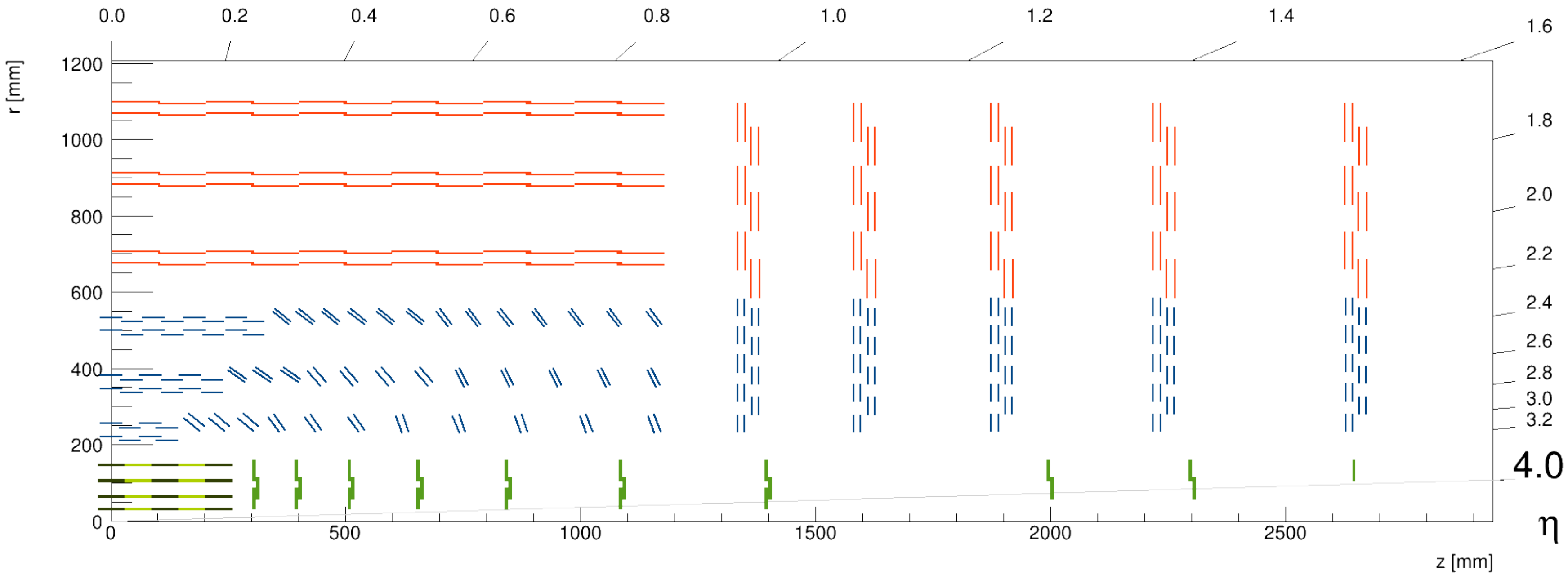
- granularity
- radiation tolerance
- **bandwidth**

Layout overview



Layout not final, and not the only option under study, notably for the **Pixel**

Layout overview

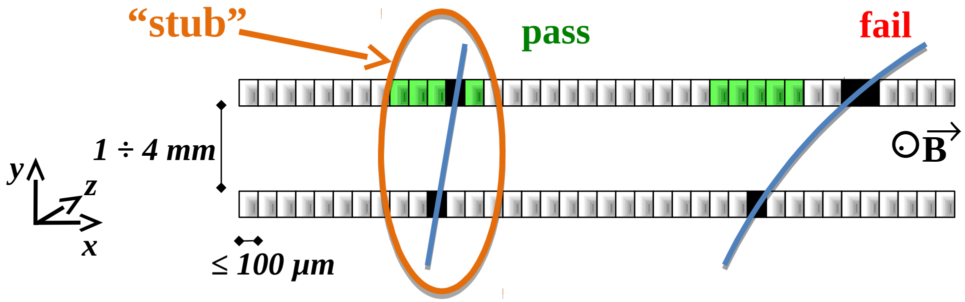


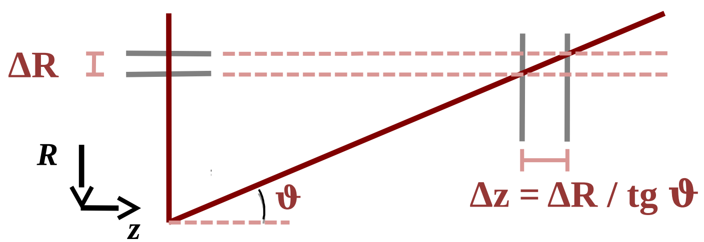
Also a ***tilted*** layout under study for the inner layers of the Outer Tracker Barrel

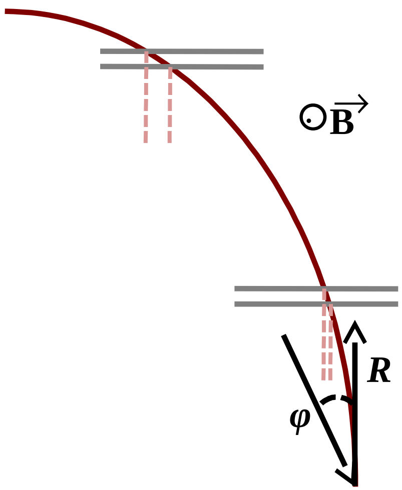
Tracker input to Level-1 trigger

- Silicon modules provide at the same time "Level-1 data" (@ 40 MHZ), and "DAQ data" (upon Level-1 trigger)
  - The whole tracker sends out data at each BX
- Level-1 data require local rejection of low-pT tracks
  - To reduce the data volume, and simplify track finding @ Level-1
  - Threshold of ~ 2 GeV/c ⇒ data reduction of ~ one order of magnitude
- Design modules with pT discrimination ("pT modules")
  - Correlate signals in two closely-spaced sensors
    exploiting the strong magnetic field of CMS
  - Provide (relatively) precise information also on the z (R) coordinate
    to identify the origin along the beam axis with 1÷2 mm precision, to enable some vertex discrimination
- Level-1 "stubs" are processed in the back-end
  - Form Level-1 tracks, pT above ~2 GeV
    to be used to improve different trigger channels

pT modules

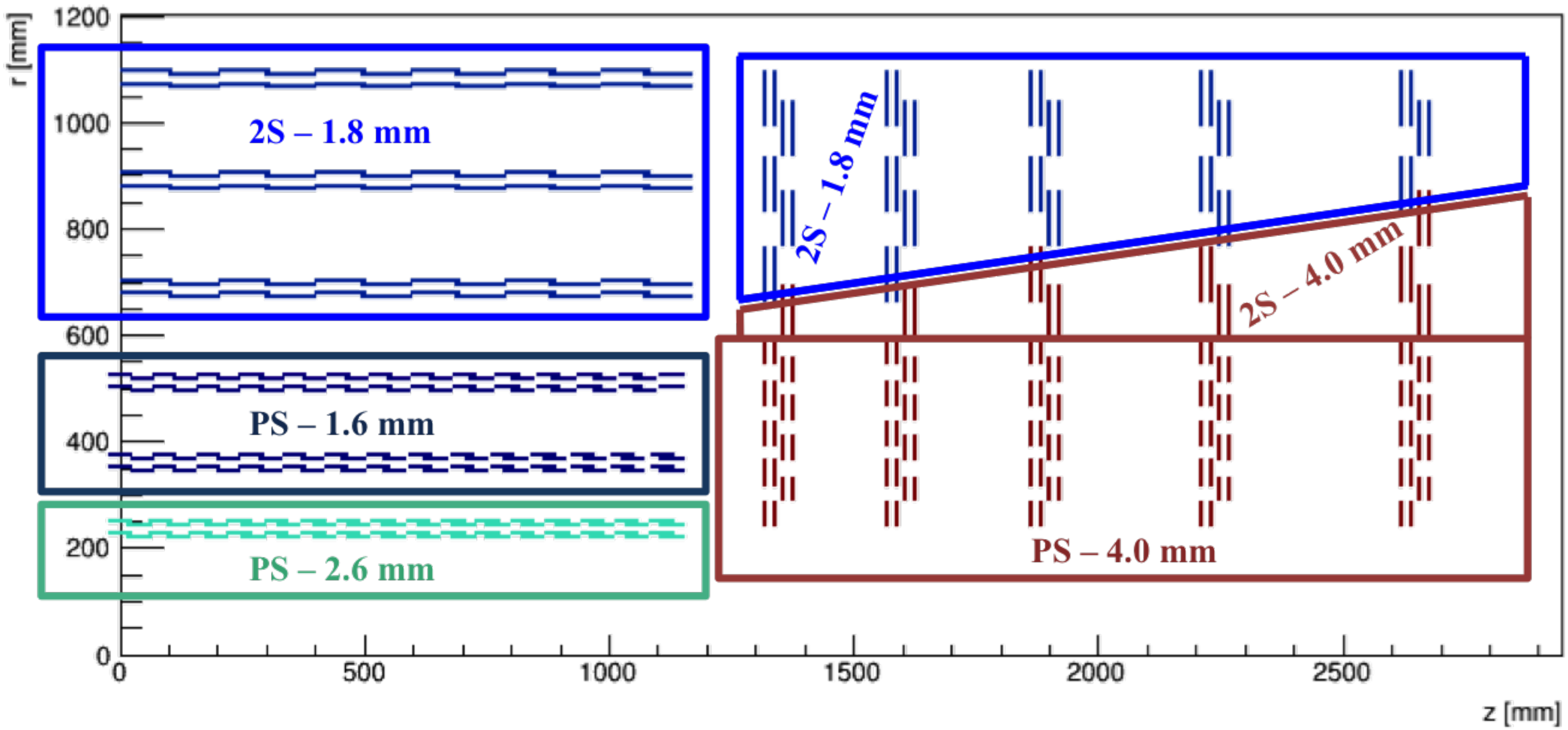






- Sensitivity to pT from measurement of Δ(Rφ) over a given ΔR
  - For a given p_T, Δ(Rφ) increases with R
  - In the barrel, ΔR is given directly by the sensors spacing
  - In the end-cap, it depends on the location of the detector (tgϑ)
    (end-cap configuration typically requires wider spacing, and yields worse discrimination)
- Optimize selection window and/or sensors spacing
  - To obtain, as much as possible, consistent pT selection through the tracking volume
- The concept works down to a certain radius
  - 20÷25 cm with the CMS magnetic field and a realistic ~ 100 μm pitch
- **No room for stereo strips**

Tracker Layout



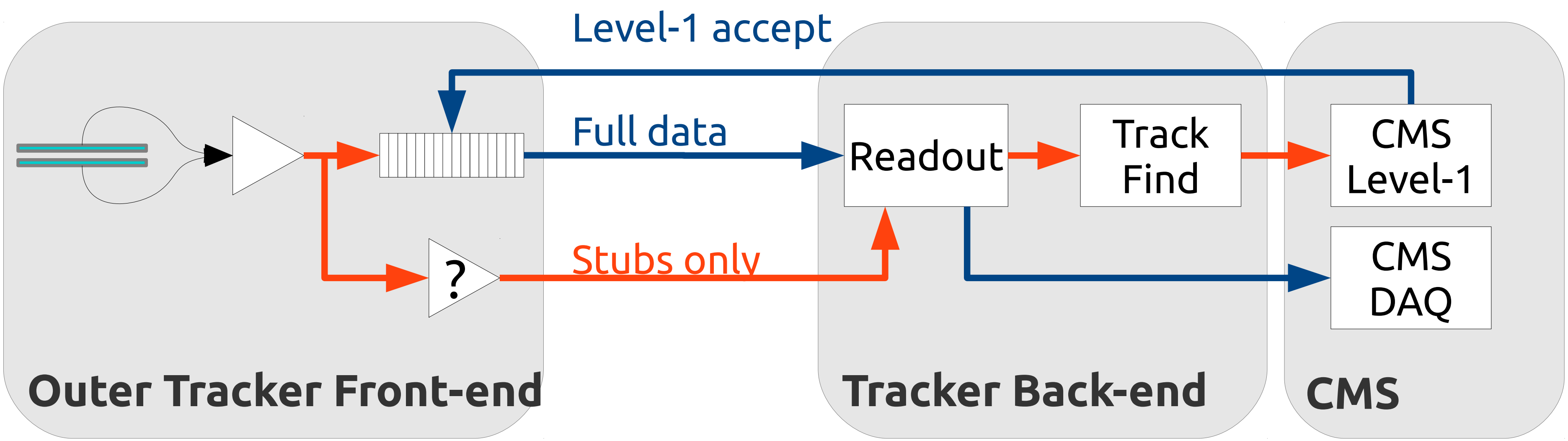
Sensor spacing in the Outer Tracker was tuned to have as much as possible a uniform pT cut (around 2 GeV/c).

Further tuning is performed by adjusting the hit-matching windows

Providing tracks for trigger

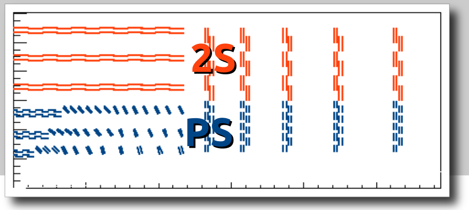
Level-1 “stubs” are processed in the back-end

Form Level-1 tracks, pT above ~ 2 GeV,
contributing to CMS Level-1 trigger

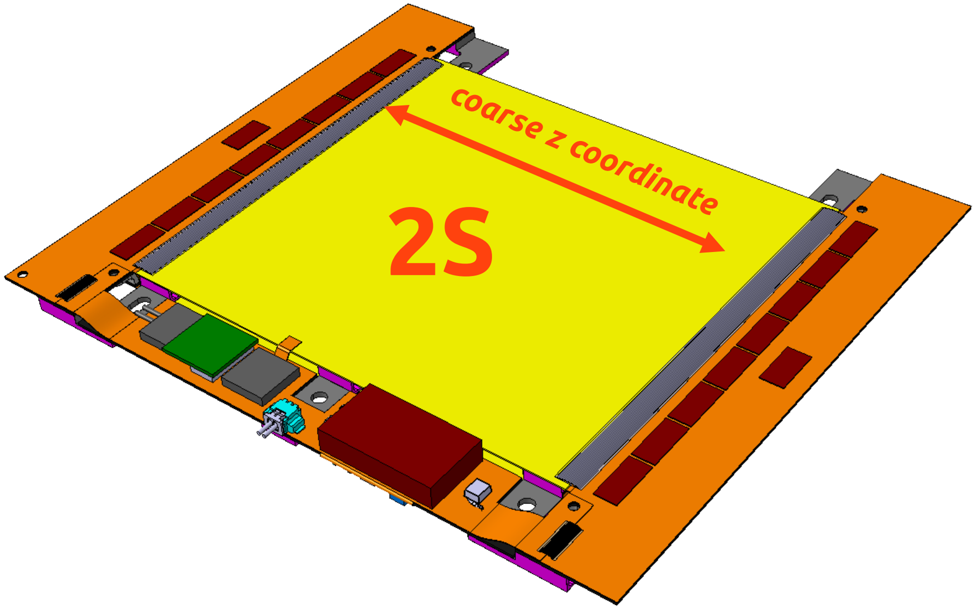


@ 40 MHz – Bunch crossing
@ 750 kHz – CMS Level-1 trigger

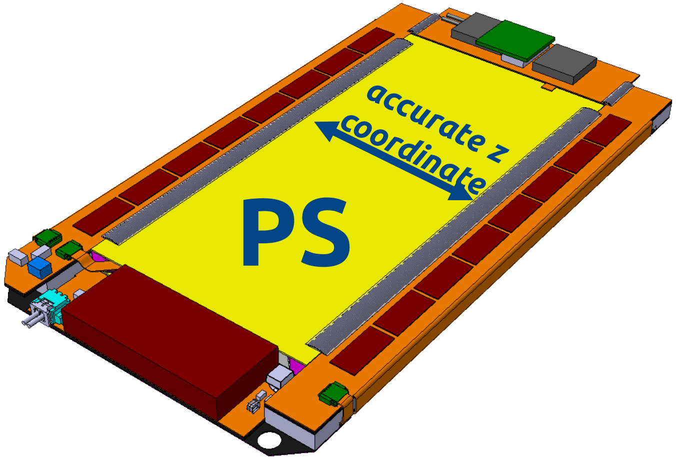
P_T modules



2 Strip sensors
2×1016 Strips: ~ 5 cm × 90 μm
2×1016 Strips: ~ 5 cm × 90 μm
P ~ 5 W
~ 2× 90 cm^2 active area
For r > 60 cm
Spacing 1.8 mm and 4.0 mm

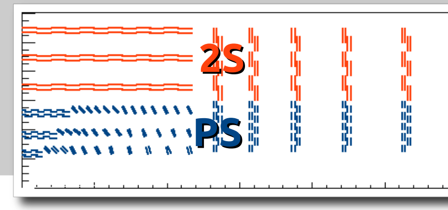


Pixel + Strip sensors
2×960 Strips: ~ 2.5 cm × 100 μm
32×960 Pixels: ~ 1.4 mm × 100 μm
P ~ 7 W
~ 2× 45 cm^2 active area
For r > 20 cm
Spacing 1.6 mm, 2.6 mm and 4.0 mm

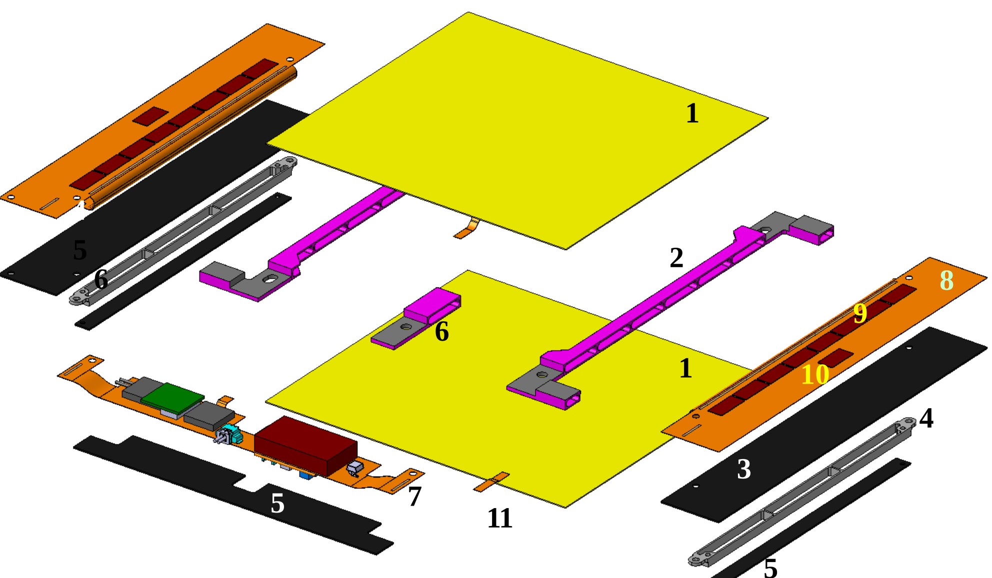


Operate sensors at about -20°C with cooling set point at -30°C

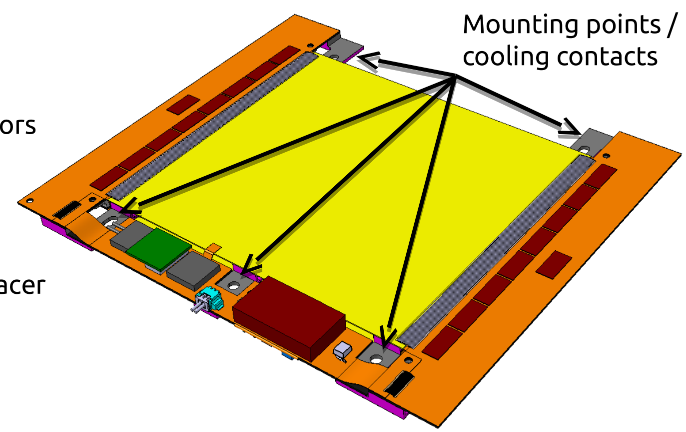
2S module

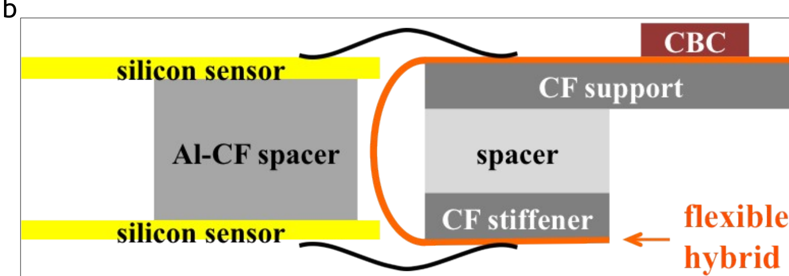


- Read out from the edges, to avoid difficult / expensive TSV technologies
- Flex hybrid circuit collects signals from both sensors
  - Supports wire-bonding to sensors and bump-bonding of readout ASICs
  - Complex routing and high-density of lines
  - 8 CBC, 1016 channels per sensor per end
- The sensors has **90 µm pitch** – at the **limit** of the hybrid technology

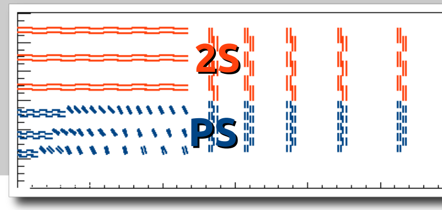


1. 2S silicon sensors
2. Al-CF spacer
3. CF support
4. Al-CF spacer
5. CF stiffener
6. Al-CF short spacer
7. Service Hybrid
8. FE Hybrid
9. CBC
10. CIC
11. HV tab

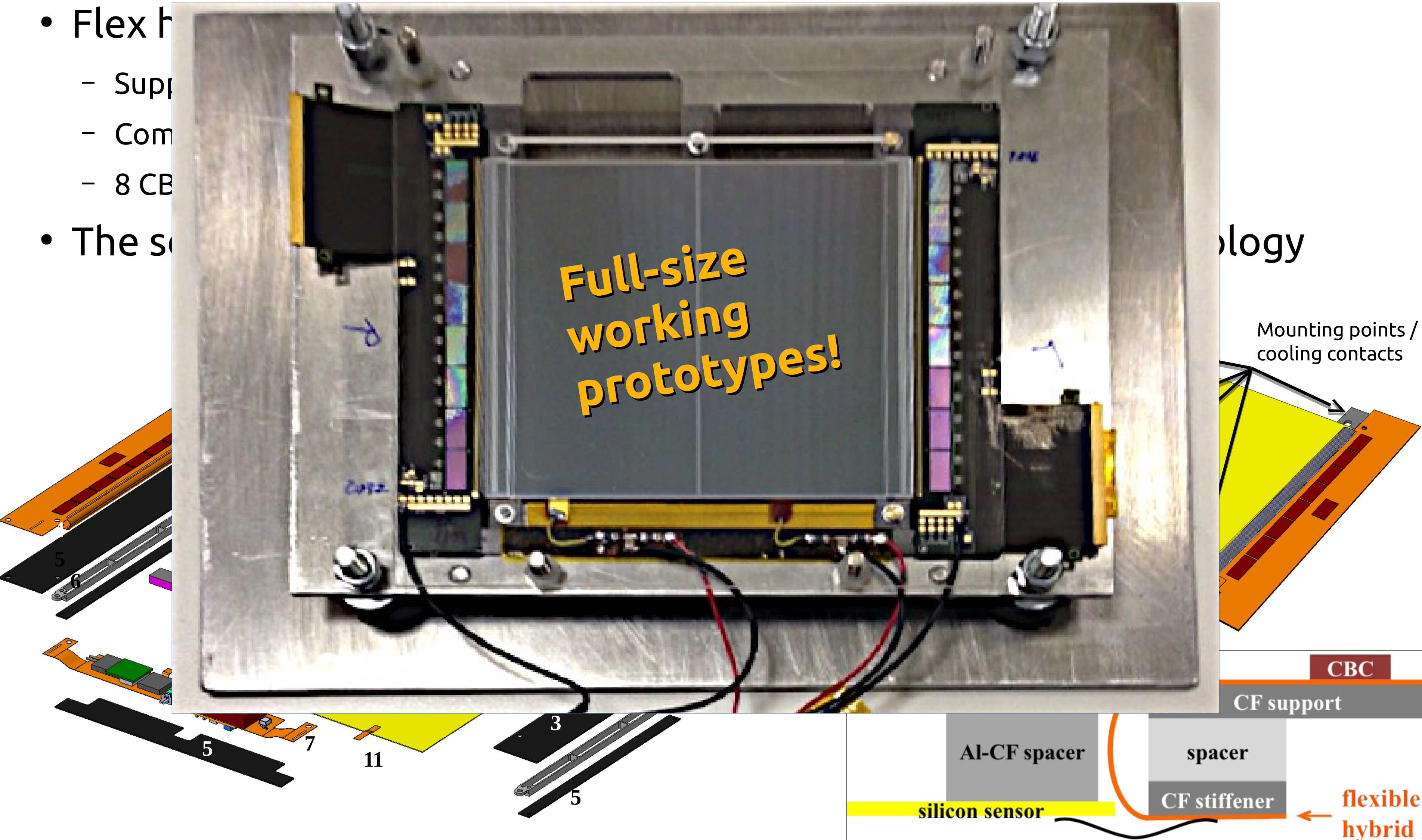




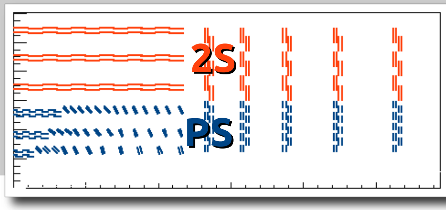
2S module



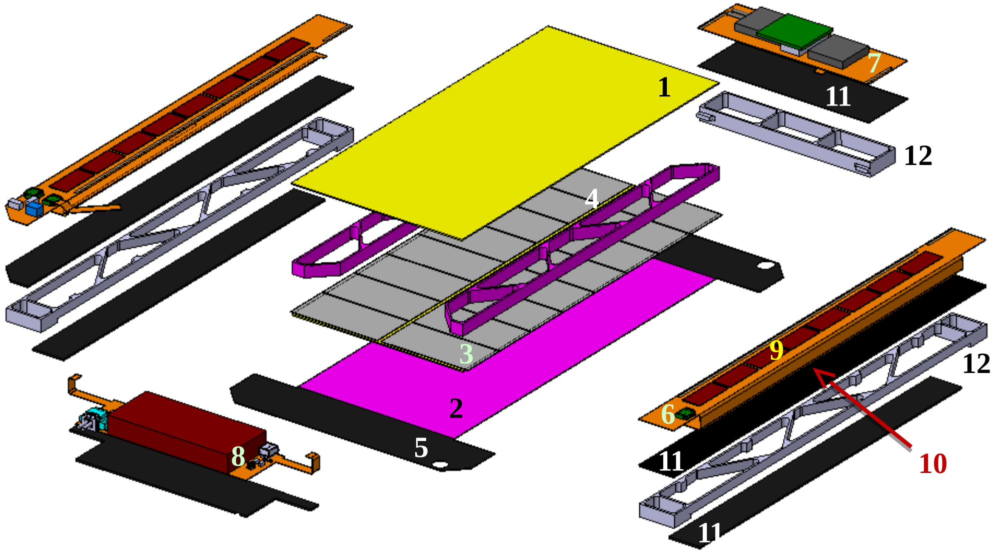
- Read out from the edges, to avoid difficult / expensive TSV technologies
- Flex h
  - Supp
  - Com
  - 8 CB
- The s   ology



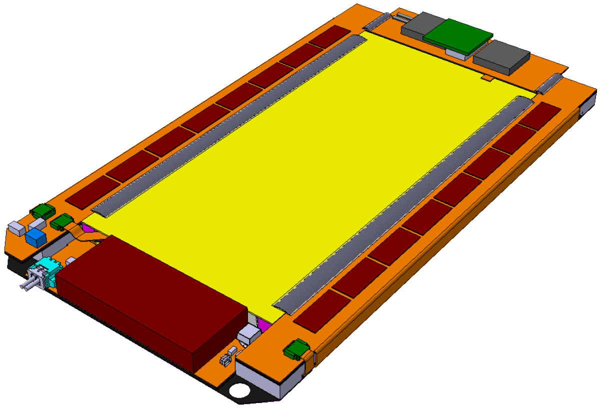
PS module

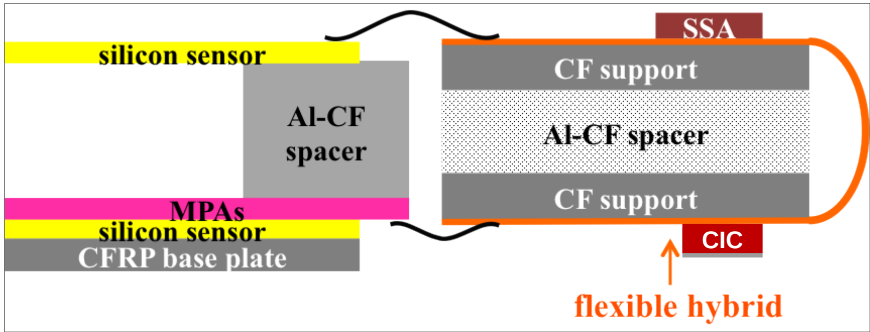


- Size limited to ½ 6” wafer
  - Cover the length with 2 chips – connect from the sides
  - 25 mm long strips required at low radii anyway
- **Hard limit at 100 μm pitch** in order to use (inexpensive) C4 bump-bonding
  - N.B. 30 m² of Macro-Pixel Sensors
- Segmentation in z is a compromise between z_0 resolution and power dissipation
- Deploy down to ~20 cm to achieve desired z_0 resolution in L1 tracking
  - Also much less expensive and power-hungry than pixel modules!

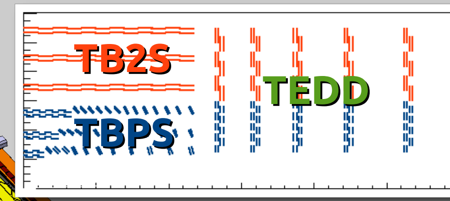


1. PS-s silicon sensor
2. PS-p silicon sensor
3. MPAs
4. Al-CF sensor spacer
5. CFRP base plate
6. FE Hybrid
7. Opto-Link Hybrid
8. Power Hybrid
9. SSA
10. CIC
11. Hybrid CF support
12. Al-CF Hybrid spacer

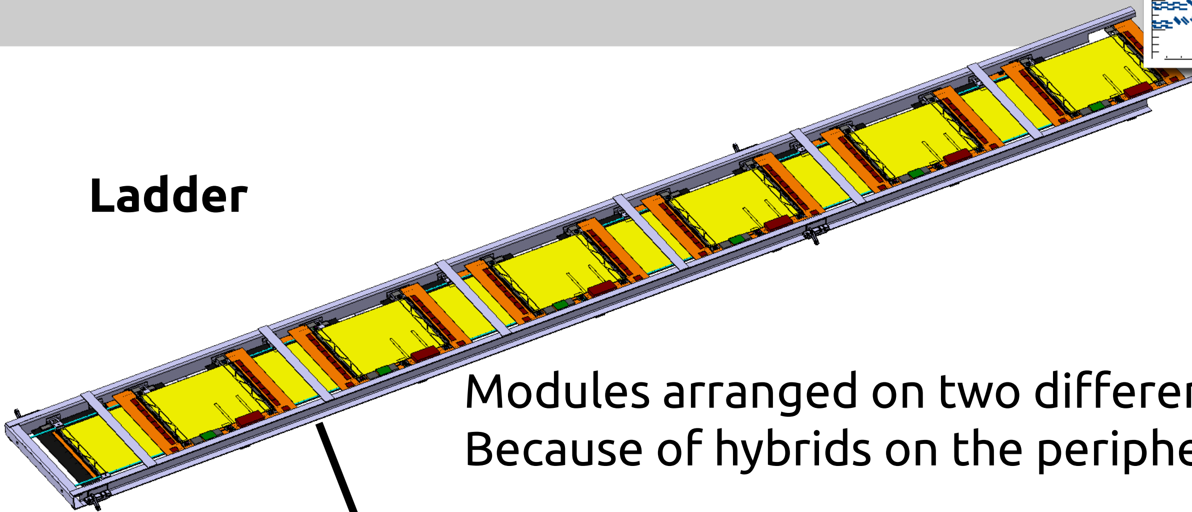




Tracker Barrel 2S



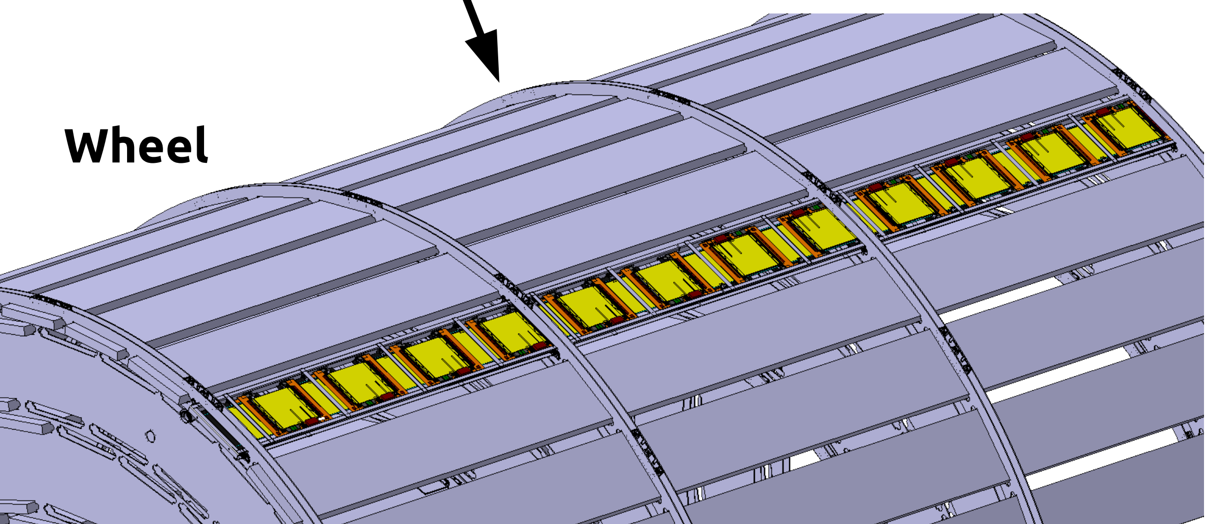
Ladder

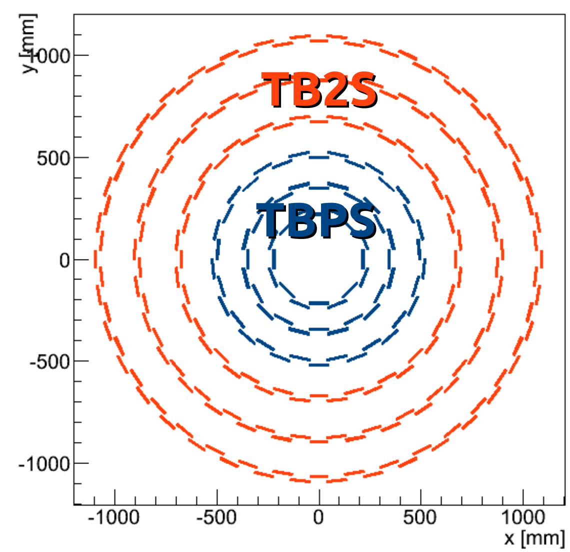


Modules arranged on two different surfaces
Because of hybrids on the periphery!

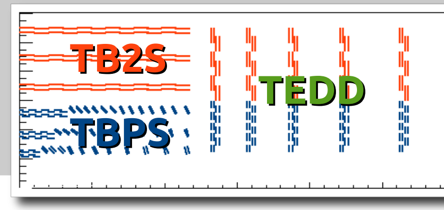
Four surfaces to form one layer

Wheel



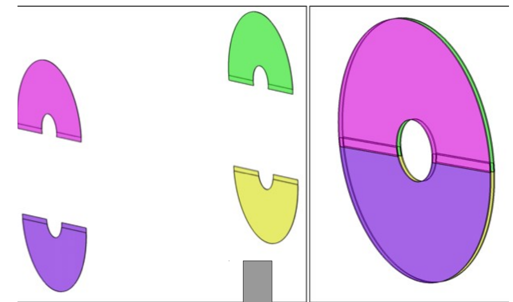


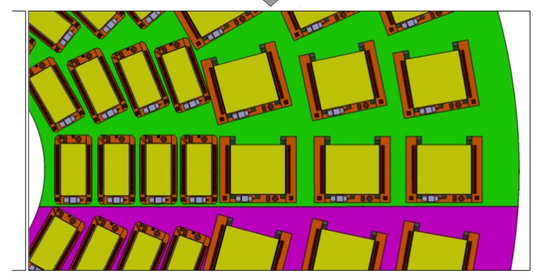
End-cap Double Disks

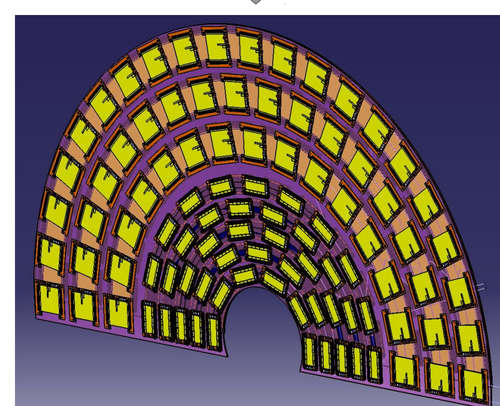


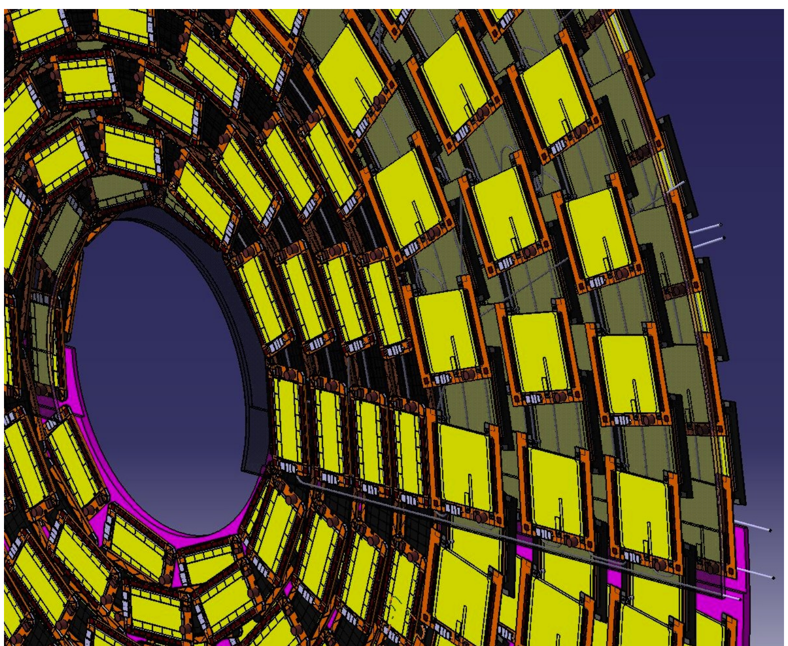
- Modules mounted on four surfaces on two disks, each made of two D's
- φ overlap within disk, R overlap with next disk
- Same **rectangular** modules as in the barrels

  Not wedge-shaped modules:
  - 15 rings would imply 30 different hybrid circuits – not feasible
  - resolution ~same with rectangular modules

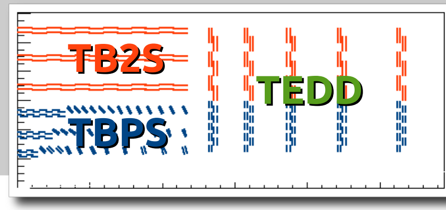


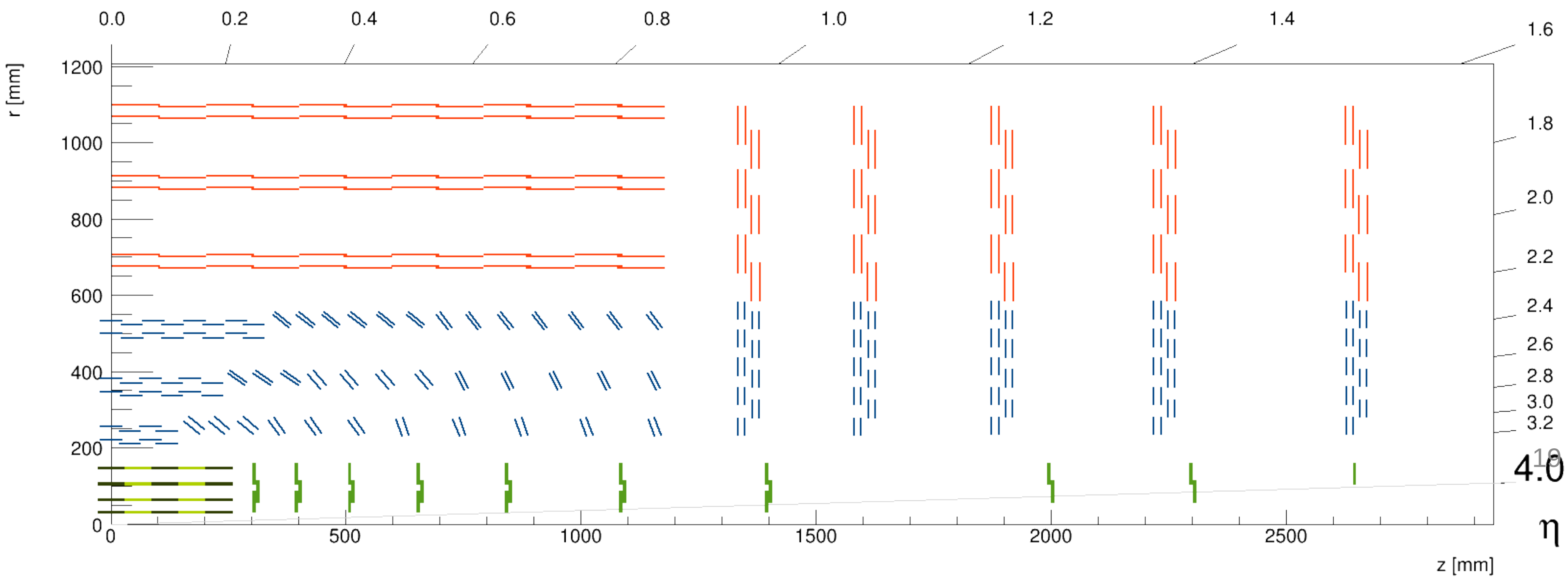






Tilted TBPS motivation





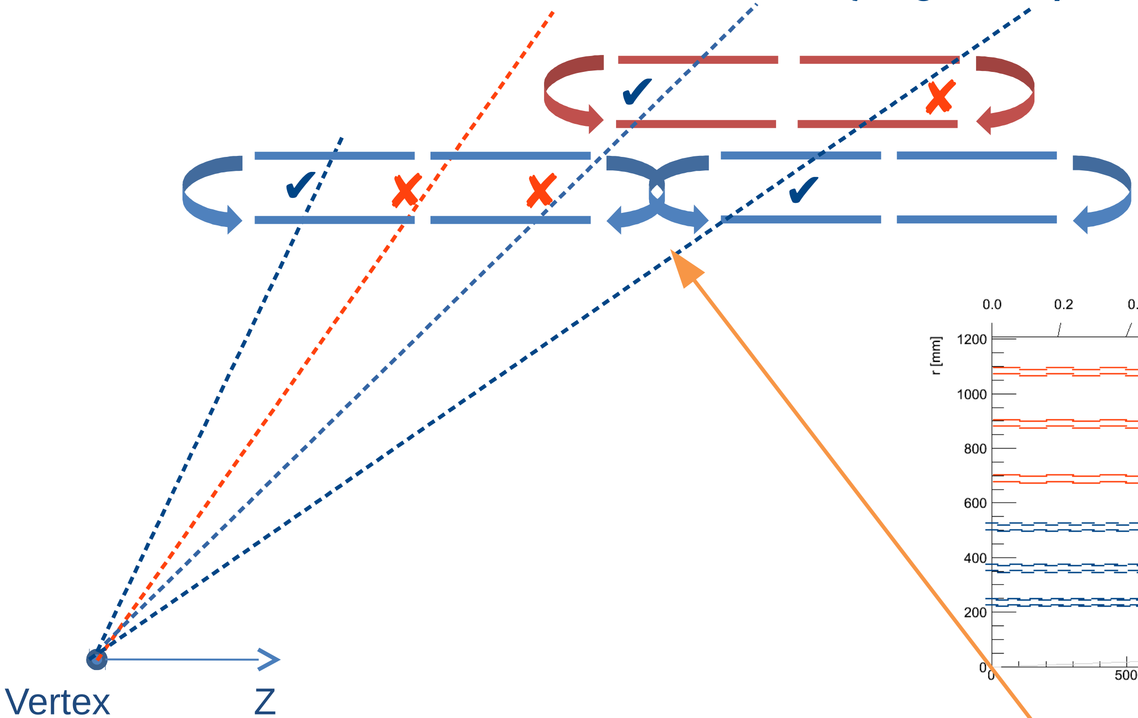
- Variant of **TBPS** geometry with progressively tilted modules
- Short central section followed by groups of rings with same tilt
- Same coverage and ~ same tracking performance with a smaller number of modules

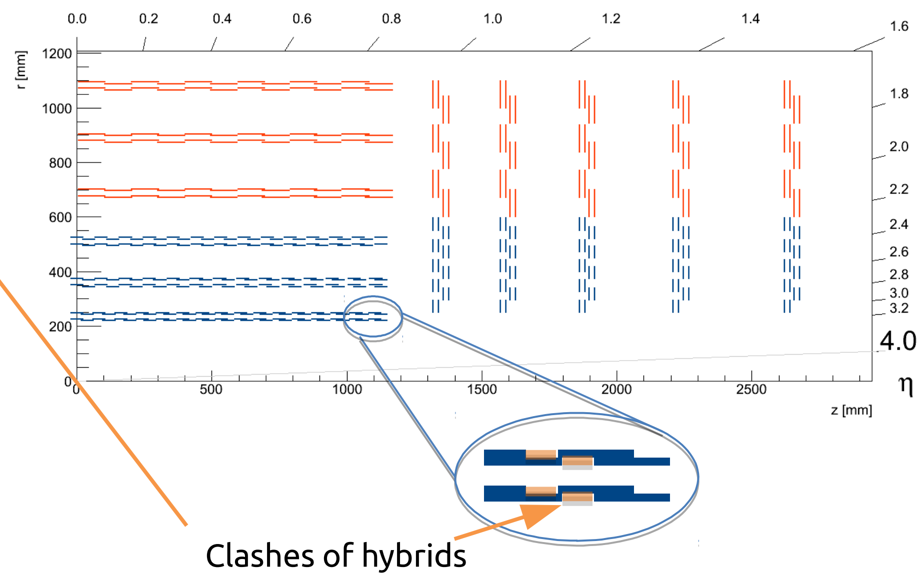
Stub finding efficiency

Stub finding efficiency drops at the edge of the “flat” TBPS without an interconnect technology (ex: TSV) between the two halves of the module, tracks crossing the middle will not generate a stub

Inefficiency in the centre is irrecoverable

Inefficiency at the edges can be recovered… at the cost of large overlaps

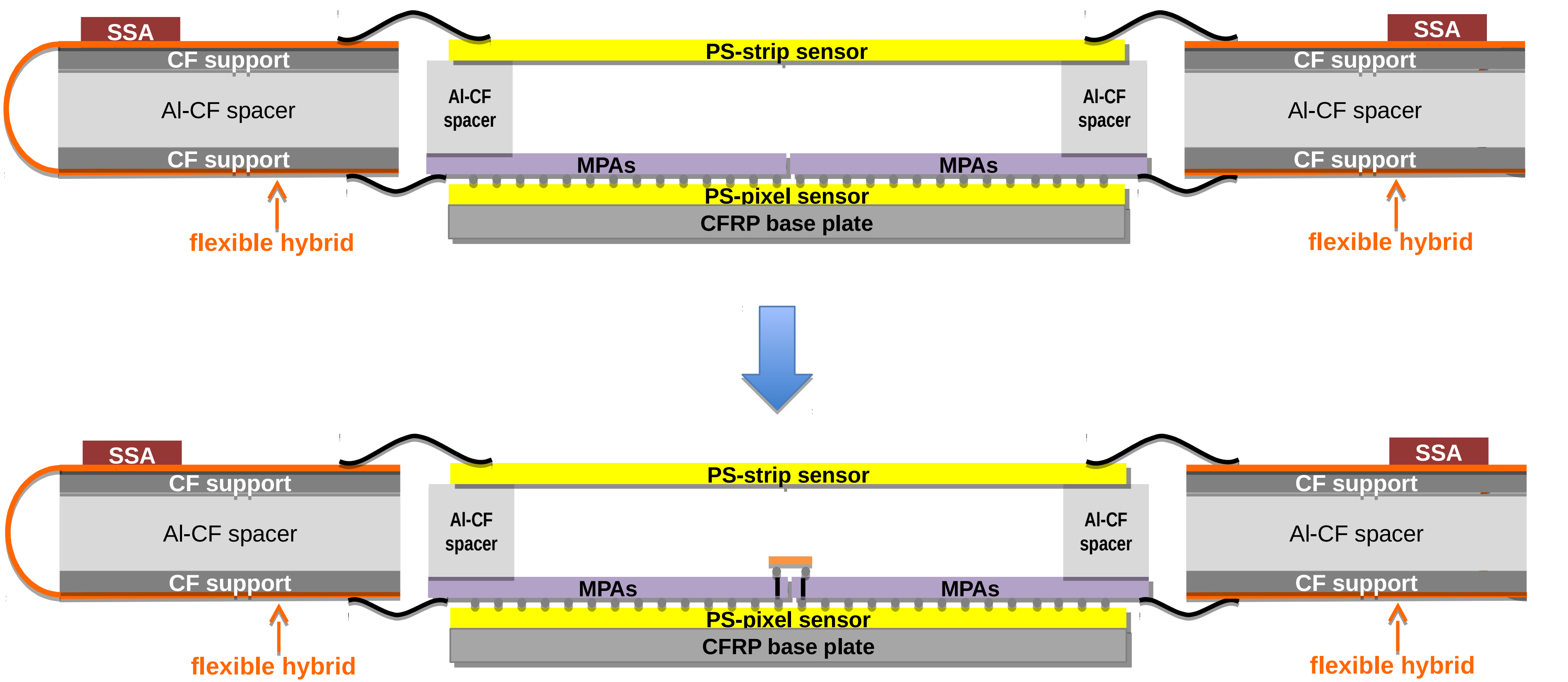




Even with large overlaps, the stub acceptance at the edge of the layer would drop below 70%!

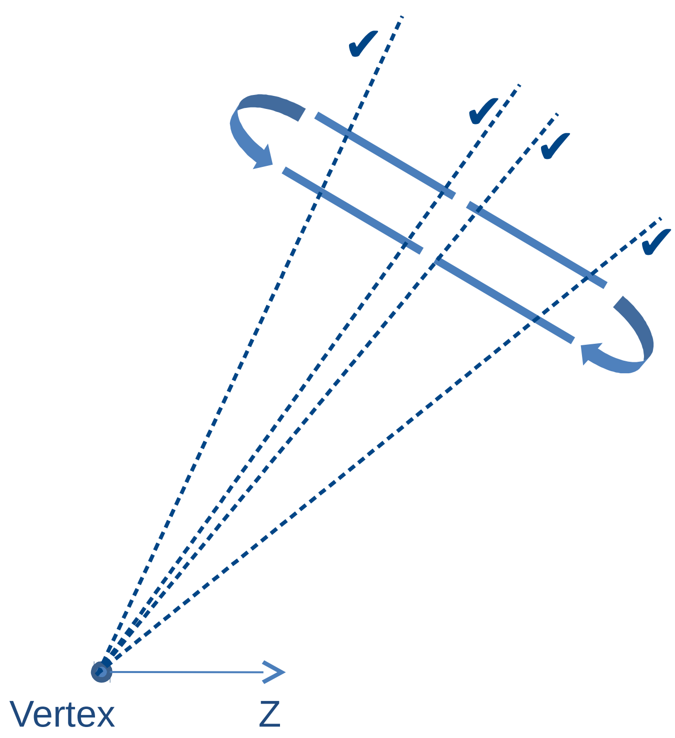
Stub finding efficiency

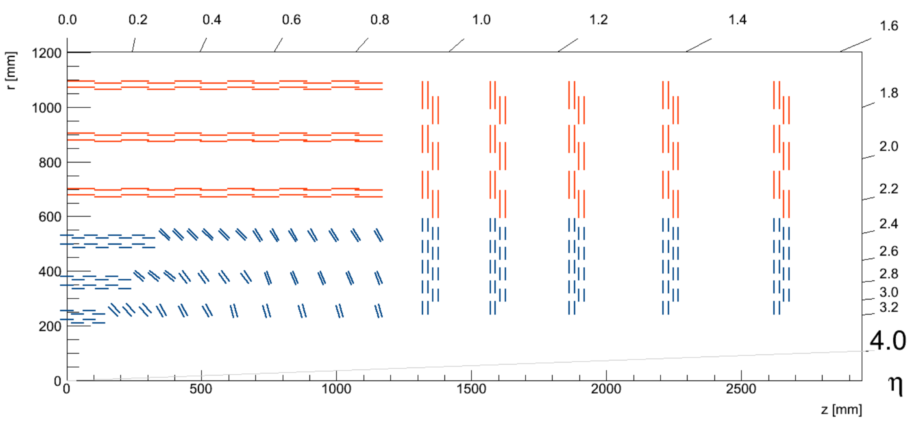
Through-Silicon Vias would be required to achieve acceptable efficiency in the “flat” layout



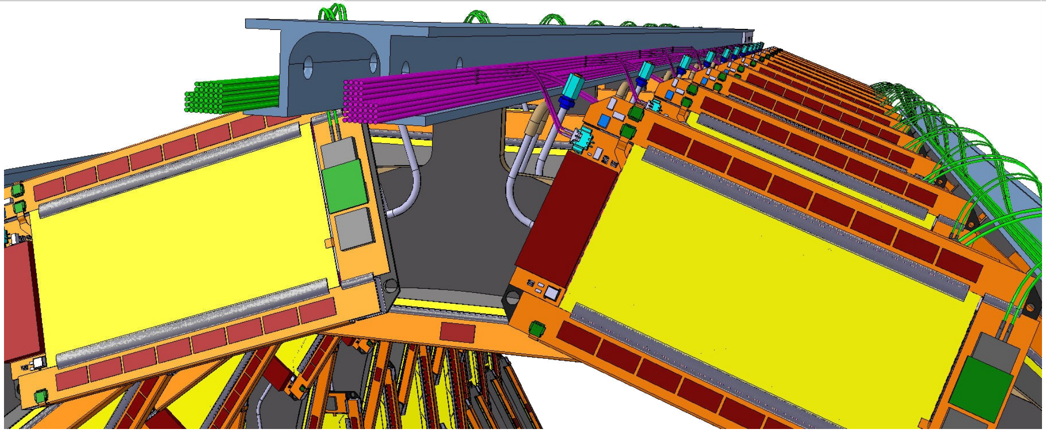
Stub finding efficiency

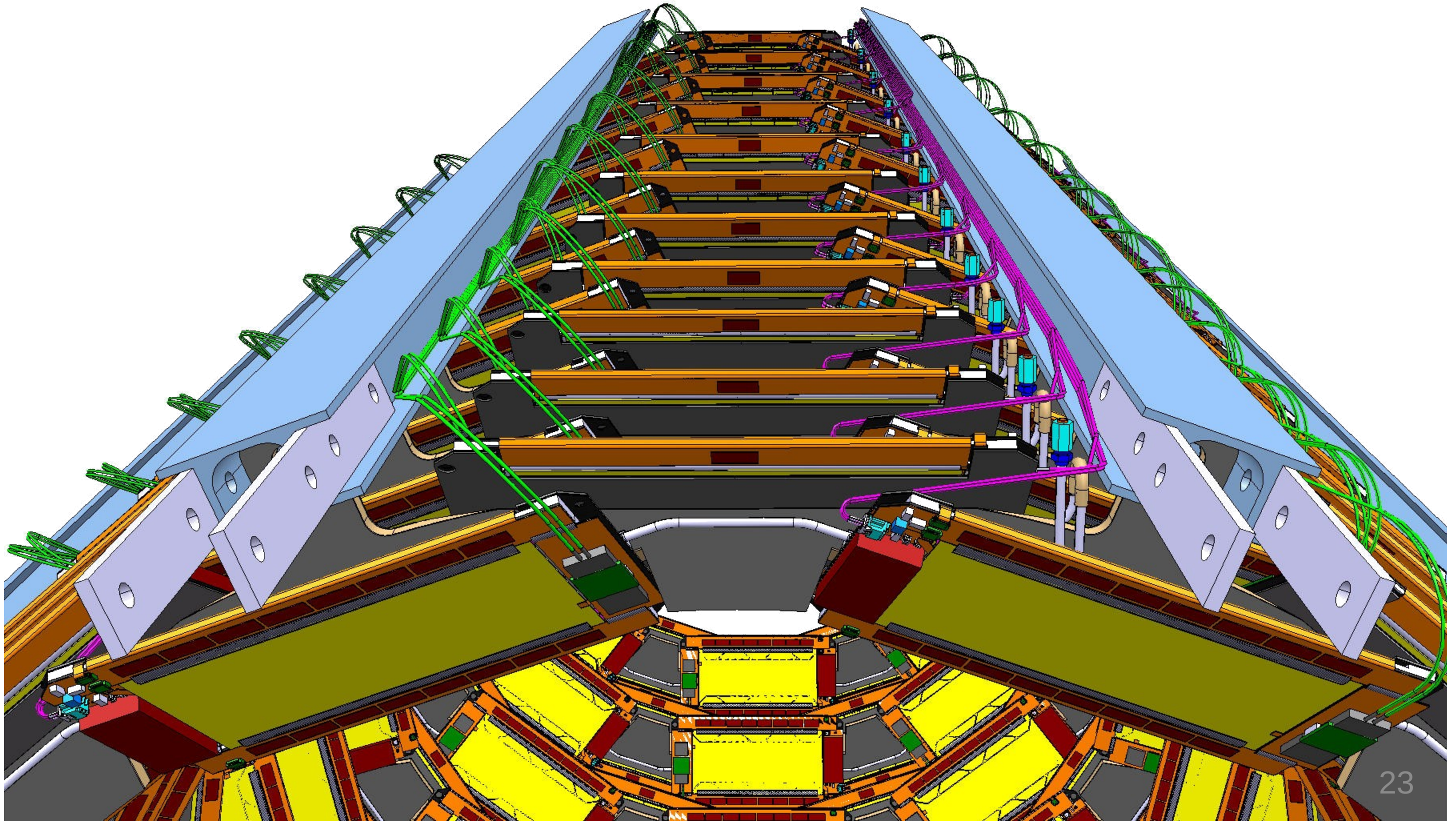
Stub Finding efficiency recovered in the tilted TBPS with a smaller number of modules needed!
(for an ideal tilt, and very small inefficiency for a near-ideal tilt)



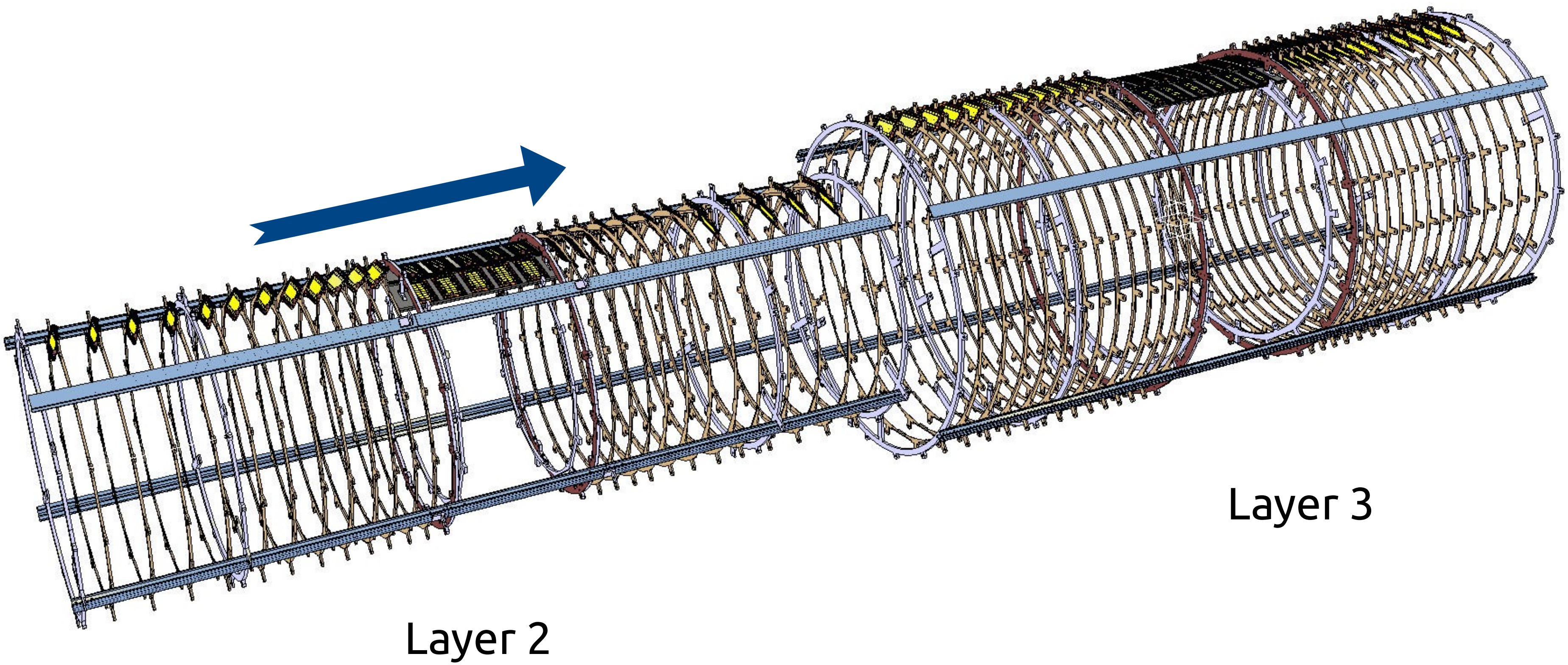


Tilted barrel rings





Joining layers



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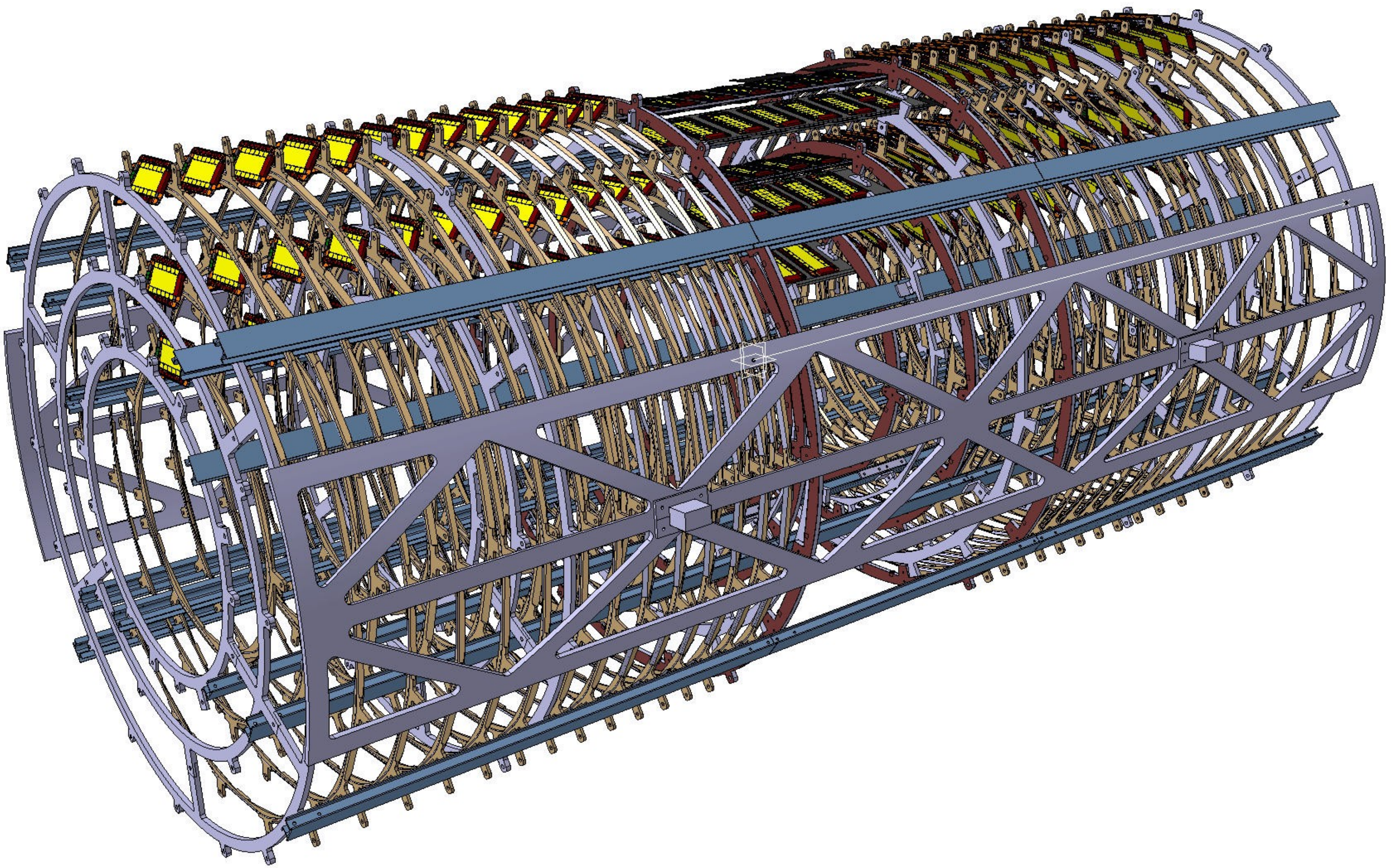


Pixel detector

(possibly 3D sensors in the inner regions)

Enhanced **radiation** tolerance → **Thinner silicon** sensors → **Less charge** available → Readout chip with **small cell-size** & **low threshold** for hit detection

Improved **two-track separation** for high-energy jets → Readout chip with **small cell-size** & **low threshold** for hit detection

Common ATLAS & CMS development in RD53, 2500 μm² cell size

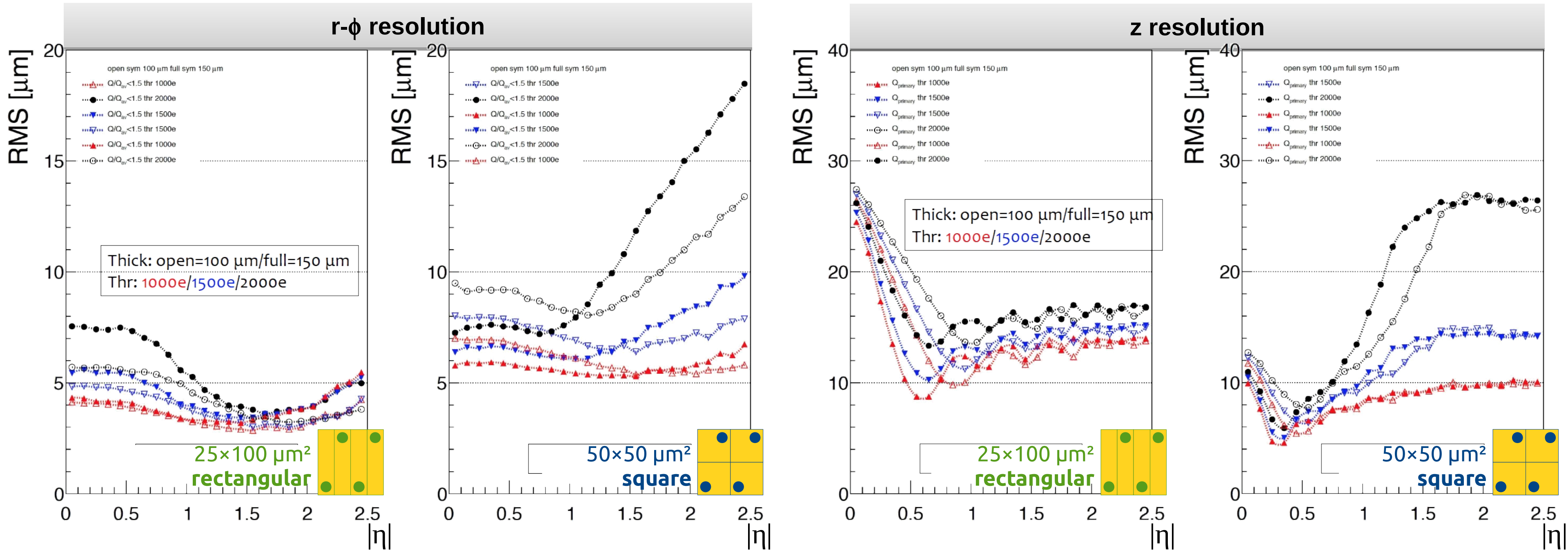
Final detectors will probably look quite different, though…

- Ability can to extract/install the pixel detector with the beam pipe in place is required
- Module placement limited by mechanical tolerance
- Radial boundary assigned: 29 mm → 200 mm

Hit resolution study

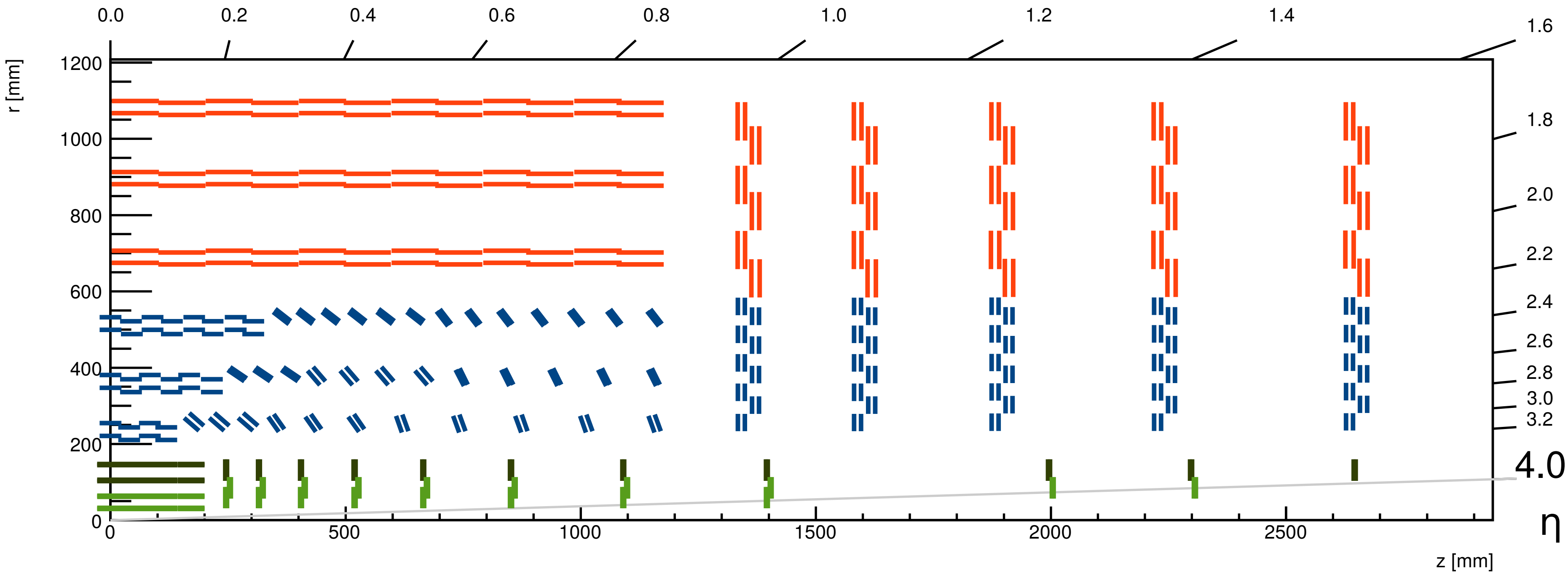
Hit resolution study on barrel layer 1 to explore a wider range of incident angles

Full simulation, different sensor thickness and detection thresholds, **no radiation damage**



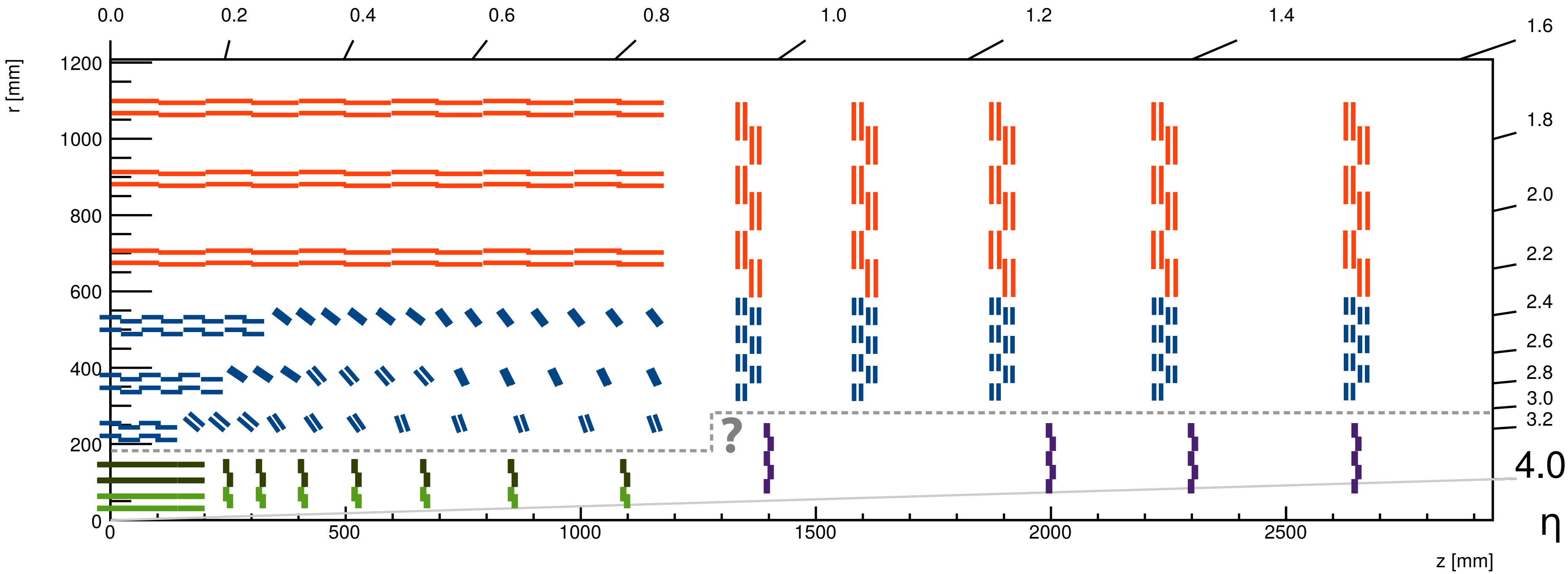
- **Square pixels** are better for z resolution in the central region
  - also require lower detection threshold: will get even worse with rad damage – study ongoing
  - also aggravate substantially the bandwidth requirement
- **Rectangular pixels** are better in all other cases
  - needed in a barrel flat geometry

Pixel detector layout



- Initial design based on phase-1 detector
- Extension of η coverage obtained by increasing number of disks
- End-cap geometry inspired by Outer Tracker Double-Disks
  - Different options for module size under consideration
  - Large pixels (×4 surface) could be used in the outermost layers/rings, to save power

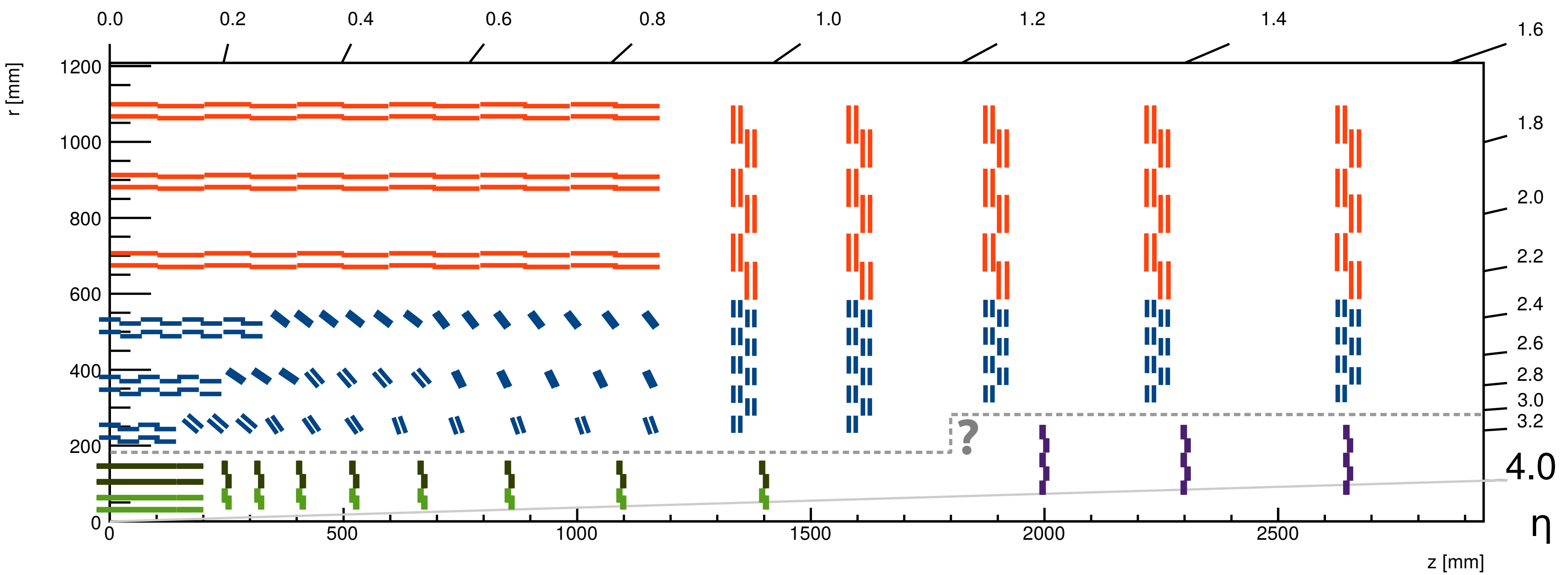
Pixel detector layout



- **Complication**: installation of central section around the beam pipe requires a larger opening in the forward
  - The detector slides in with an inclined angle
- The OT/Pixel boundary must be at larger radius in the forward part
  - A **step**? Where? How large?
  - A **conical boundary**?

Studies just started

Pixel detector layout



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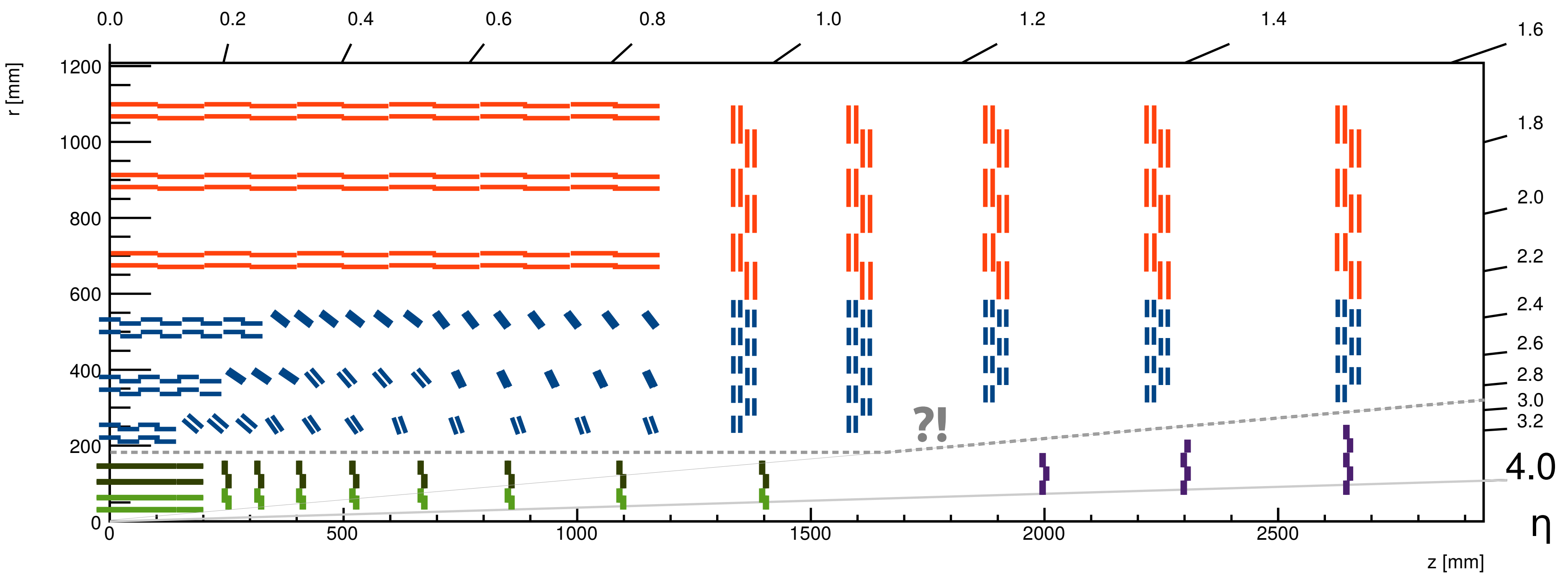

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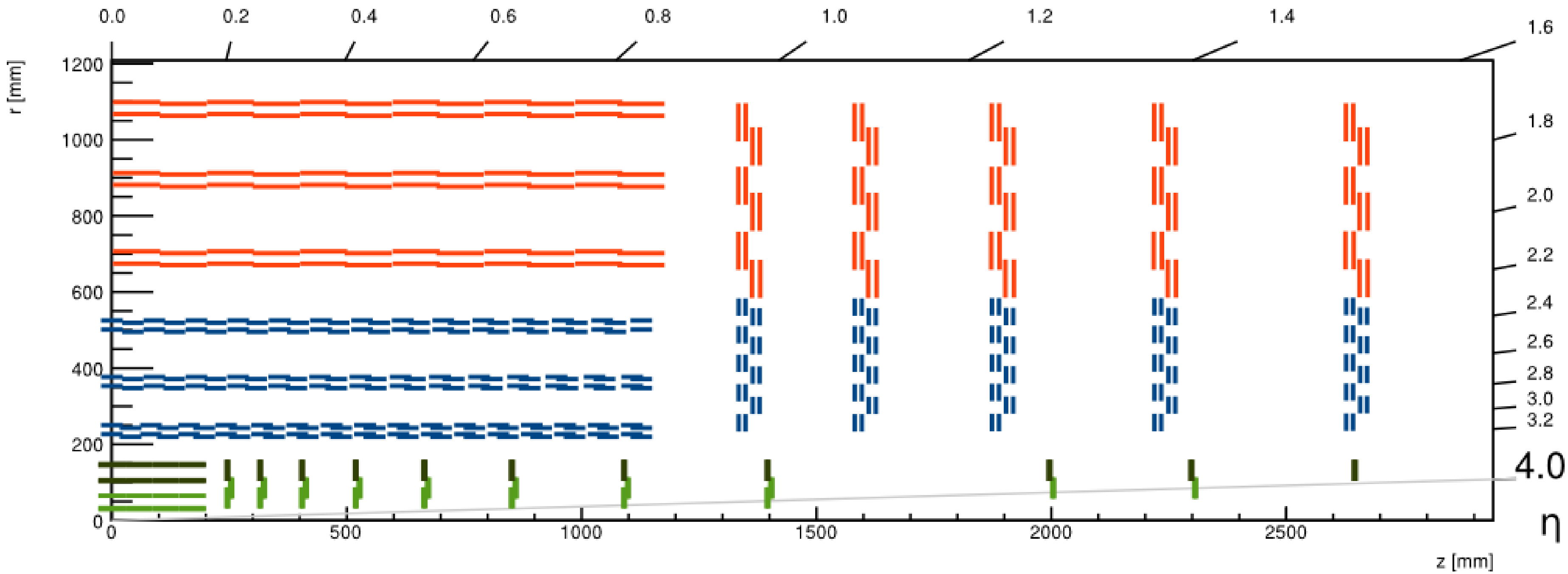
Tracker layout



Lower density
2S modules outside
(8224 modules)

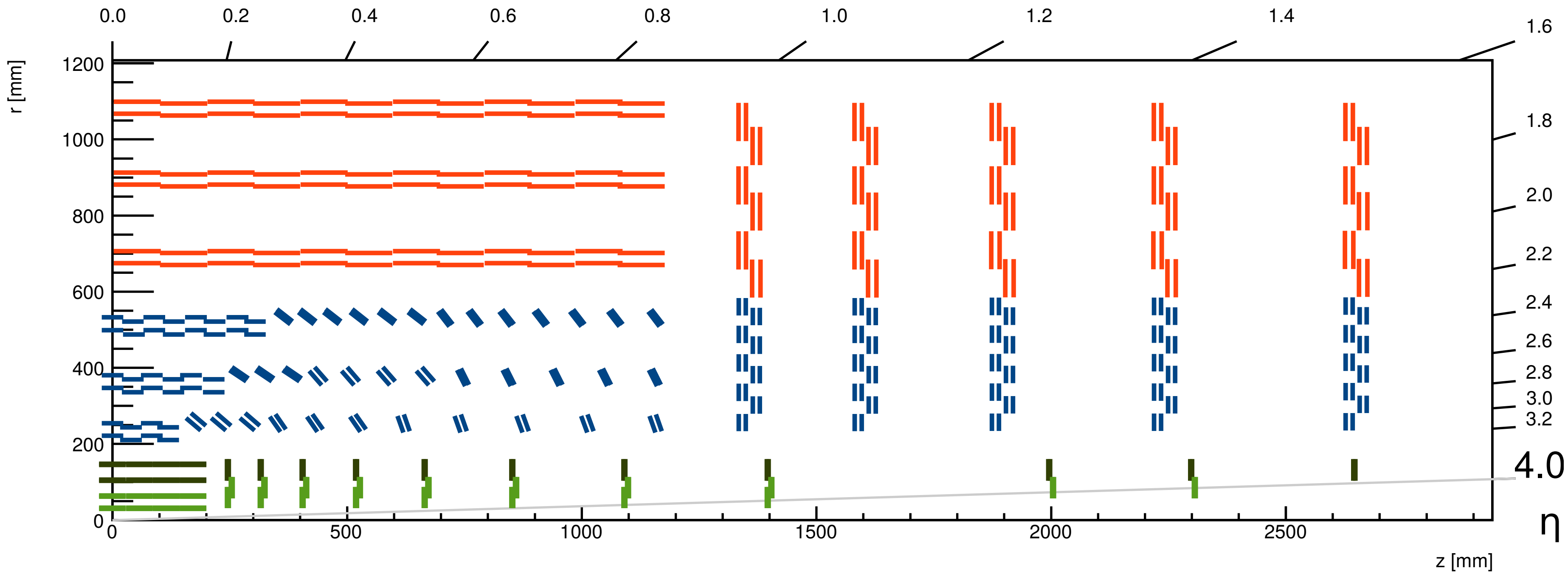
PS modules middle
z info in trigger
θ info in trigger
(6890 modules)

Pixel modules inside
accurate impact parameter resolution & forward coverage

Detailed material model

First material model
"Small version" 3284 modules
(Insertion issue to be solved)

Tracker layout



Lower density
2S modules outside
(8224 modules)

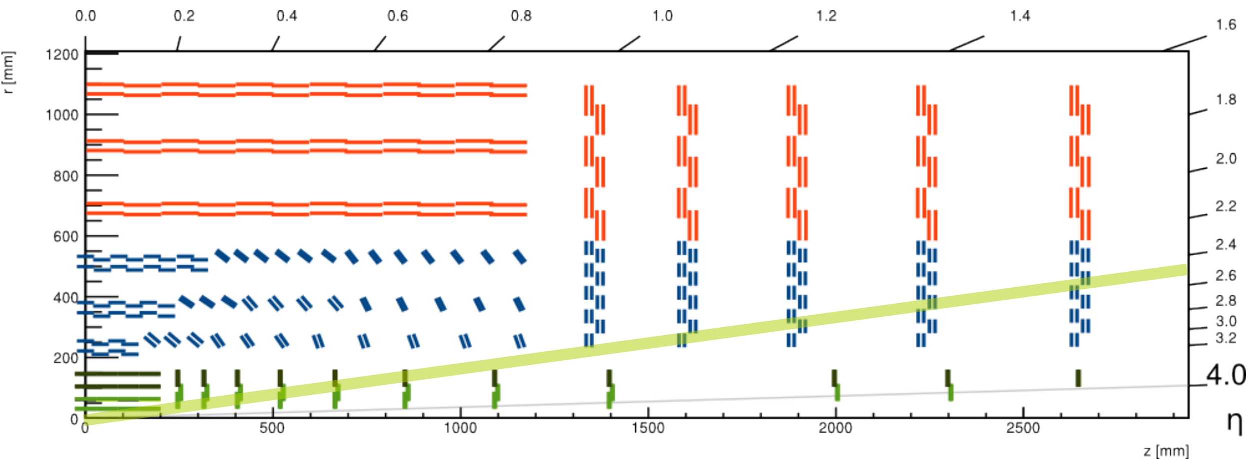
PS modules middle
z info in trigger
θ info in trigger
(5668 modules)
-1222 modules discount!

Pixel modules inside
accurate impact parameter resolution & forward coverage

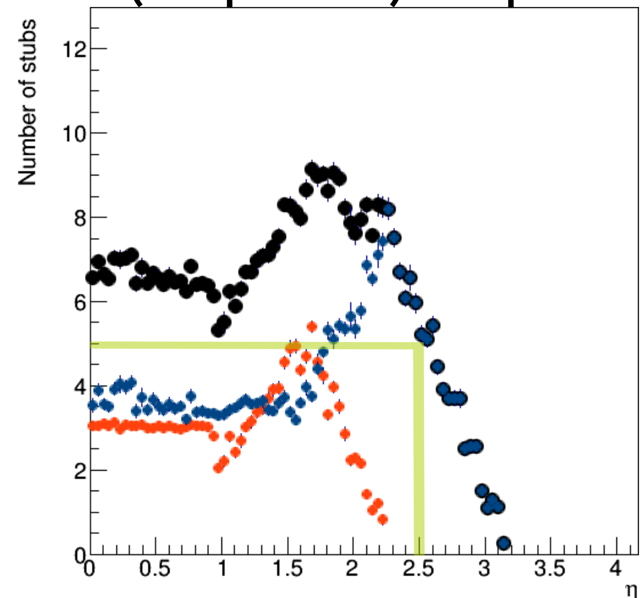
Detailed material model

First material model
"Small version" 3284 modules
(Insertion issue to be solved)

Layout of current baseline



5 trigger stubs
(10 points) → η=2.5



- **×4 granularity** in strip sensors
- +3 layers of **MacroPixel sensors**
  - Unambiguous **3D coordinates** helps track finding in high pile-up
- Up to **10 points** available for track-trigger up to η=2.5
  - Comparable to current tracker's coverage, **but at L1**

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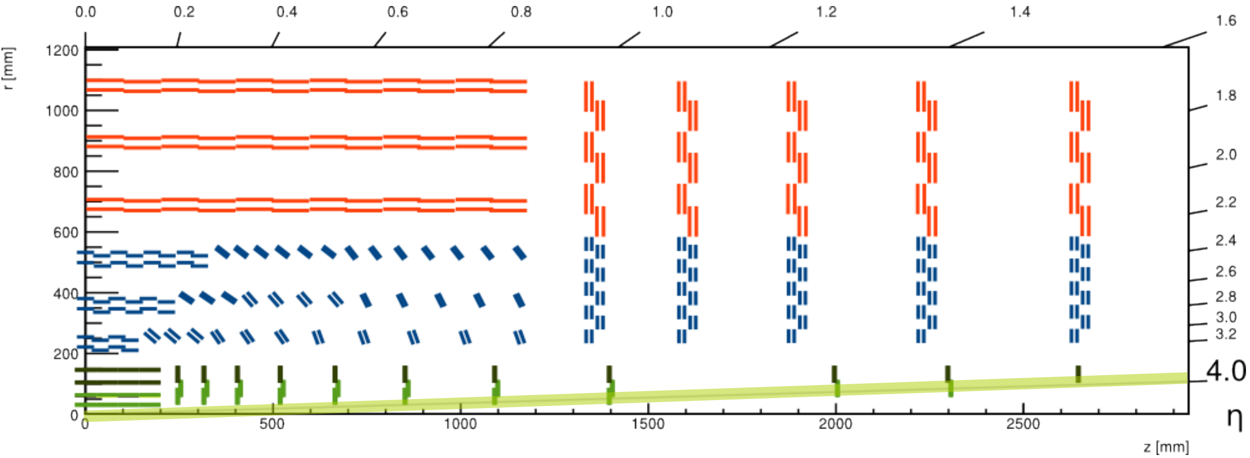
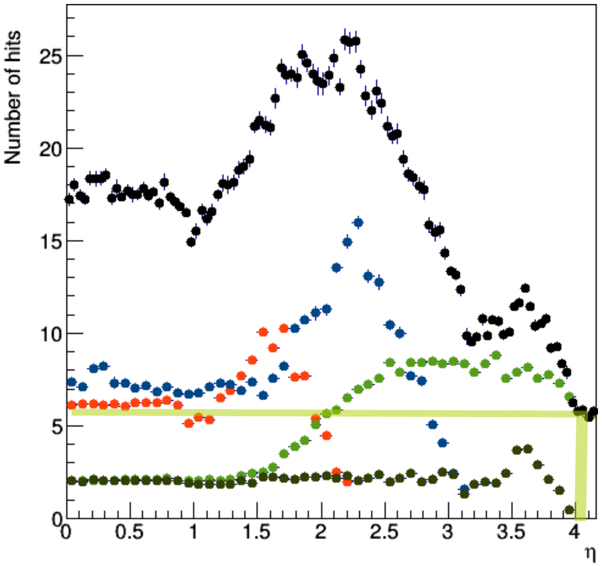


Hit coverage → η≈4



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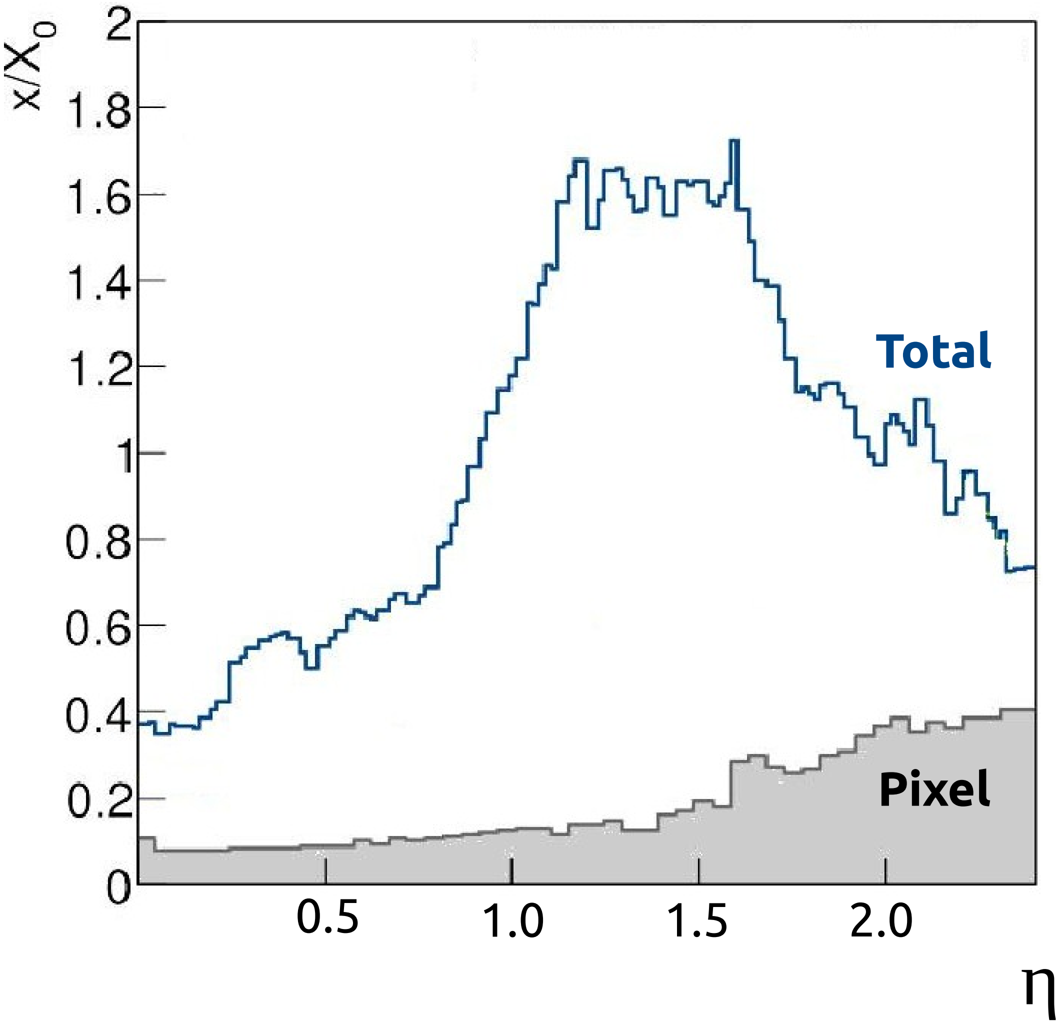
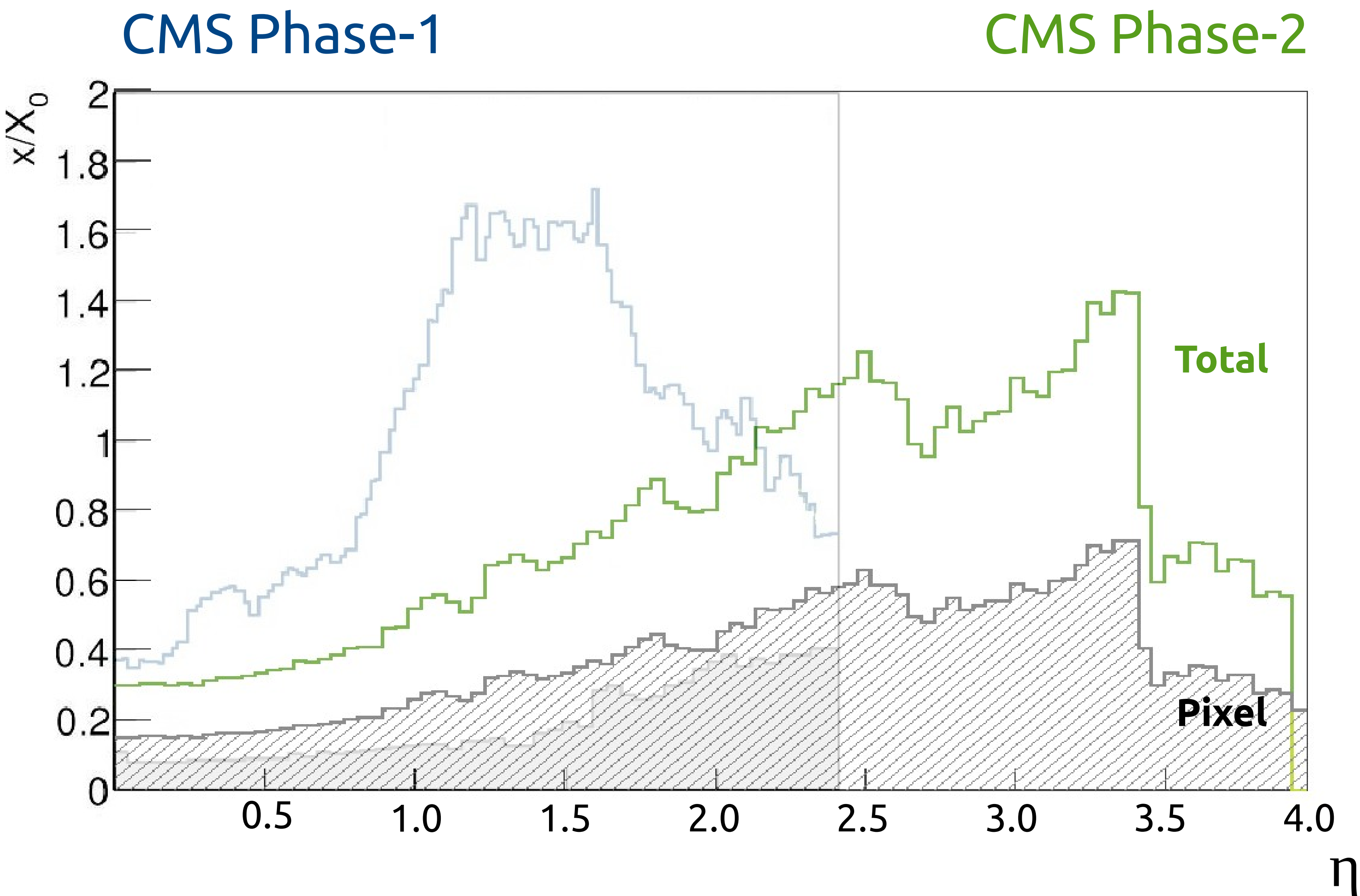
- Up to **10 points** available for track-trigger up to η=2.5
  - Comparable to current tracker's coverage, **but at L1**
- Hit coverage up to **η≈4** in full readout (after L1 Accept)

Tracker material budget

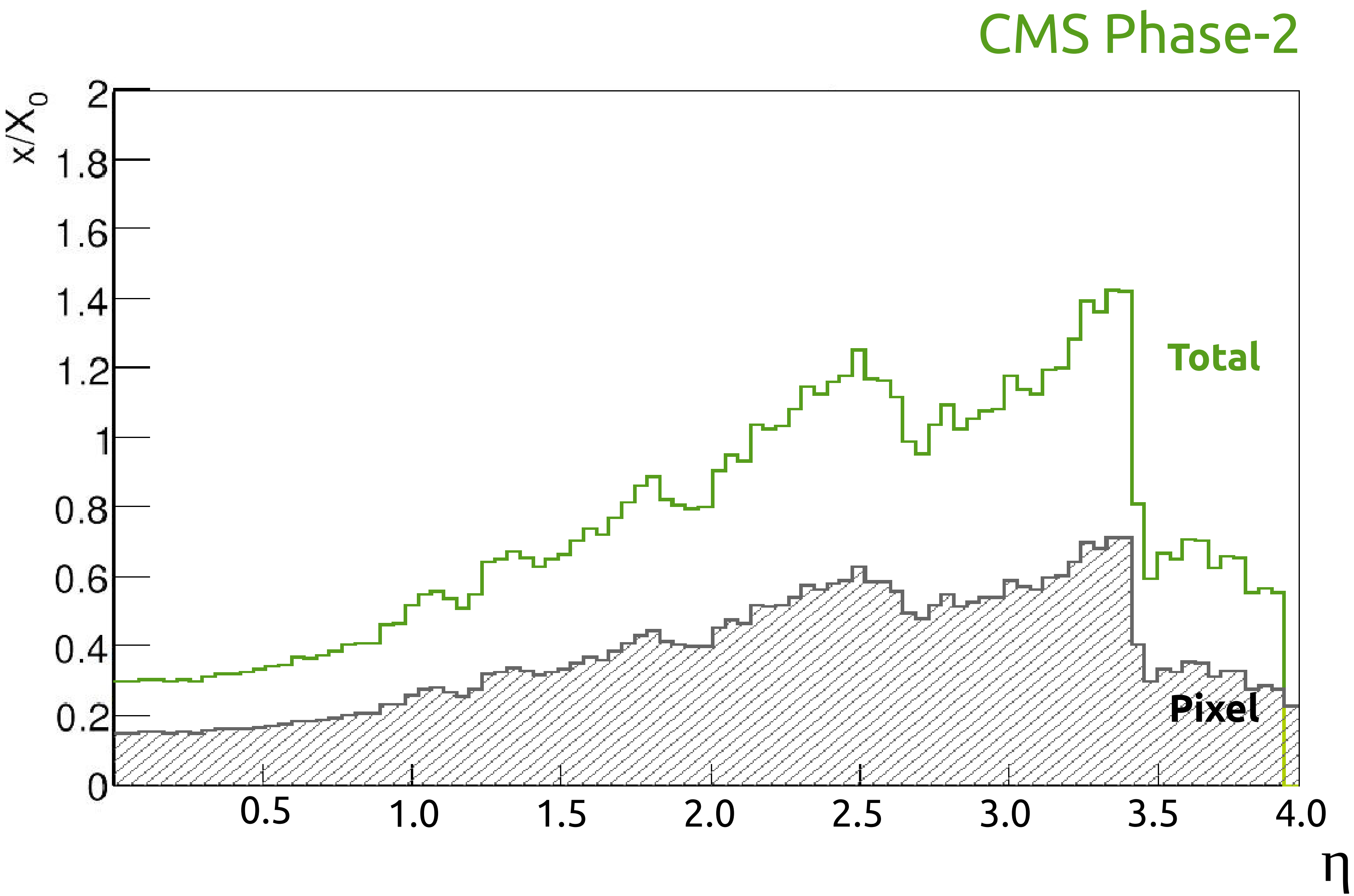
CMS Phase-1



Tracker material budget



Tracker material budget



Upgrade overview

	Current		Upgrade	
(tilted) Outer	~200 m^2	Silicon	~202 m^2	Silicon
	9.3 M	Strips	44.3 M	Strips
	0	MacroPixels	174 M	MacroPixels
	15'148	Modules	13'892	Modules
	100 kHz	readout rate	40 MHz	readout rate*
(small) Pixel	~1 m^2	Silicon	3.2 m^2	Silicon
	66 M	Pixels	700 M	Pixels
	1440	Modules	3284	Modules
	100 kHz	readout rate	750 kHz	readout rate

* only high-pt hits read-out

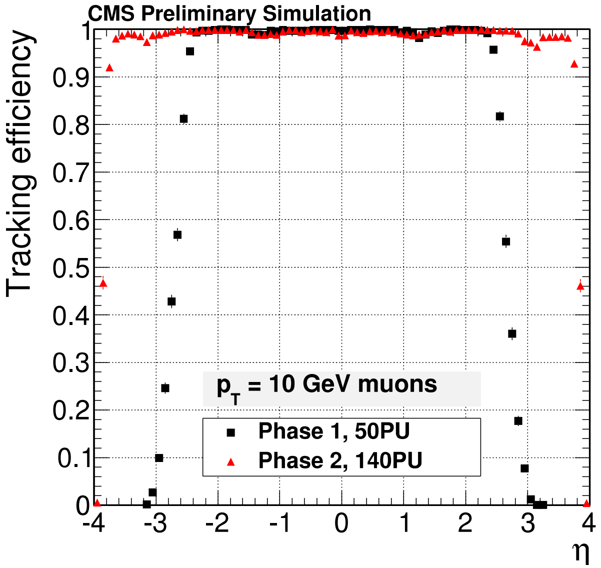
Conclusions

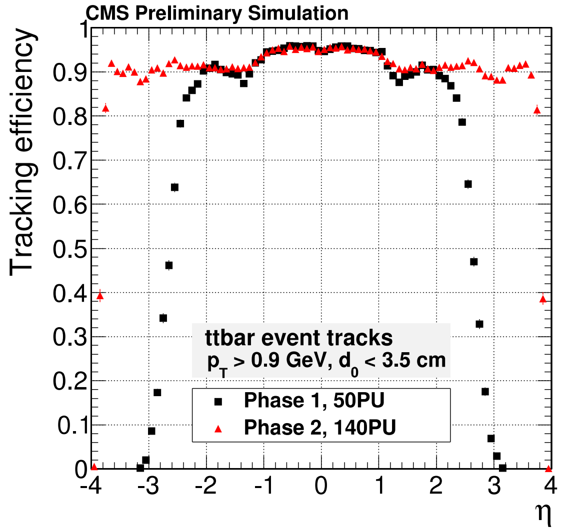
- Full tracker:
  - Higher granularity to enable efficient tracking in high-pileup
  - Also offers improved tracking resolution
  - Material budget challenge (especially for pixels)
- Outer Tracker:
  - Implementation of tracking in the first level of the trigger has driven several design choices
  - 6-barrel-layers + 5-disks configuration was selected
  - Tilted PS barrel is the favored option
  - End-cap inner boundary to be defined (depends on pixel)
- Pixel:
  - Material models and single-hit resolution studies are becoming available to optimize the detector layout for tracking
  - Several layout options are still under study

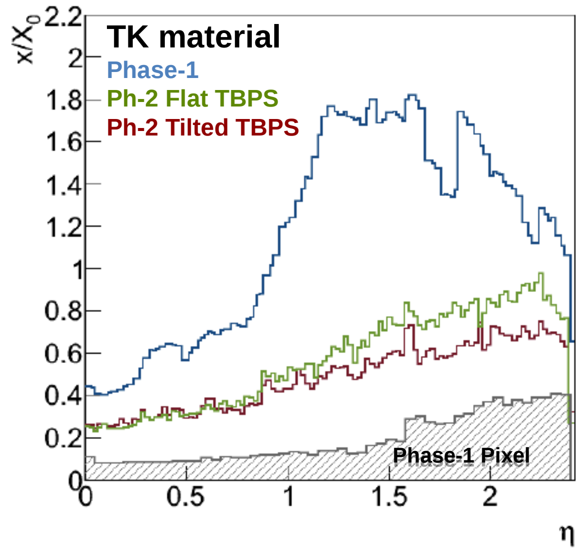
Back-up

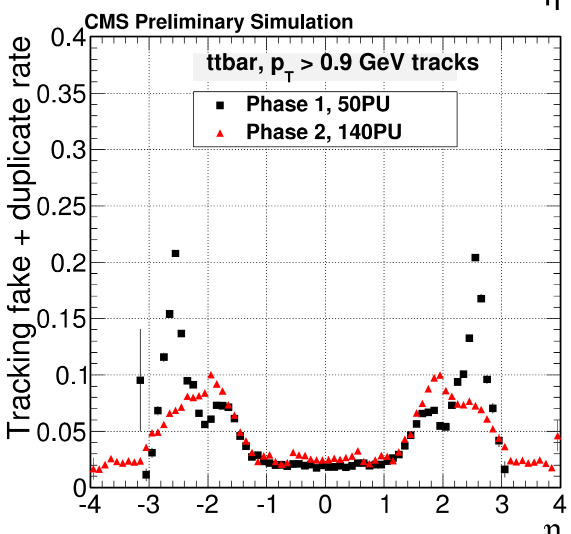
Detector performance

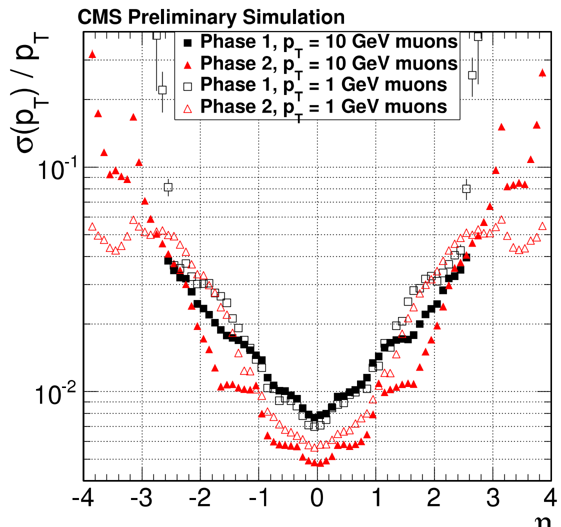
Phase-1 @ 50 PU vs. Phase-2 @ 140 PU











Expect substantial improvement also in z_0 resolution and b-tagging

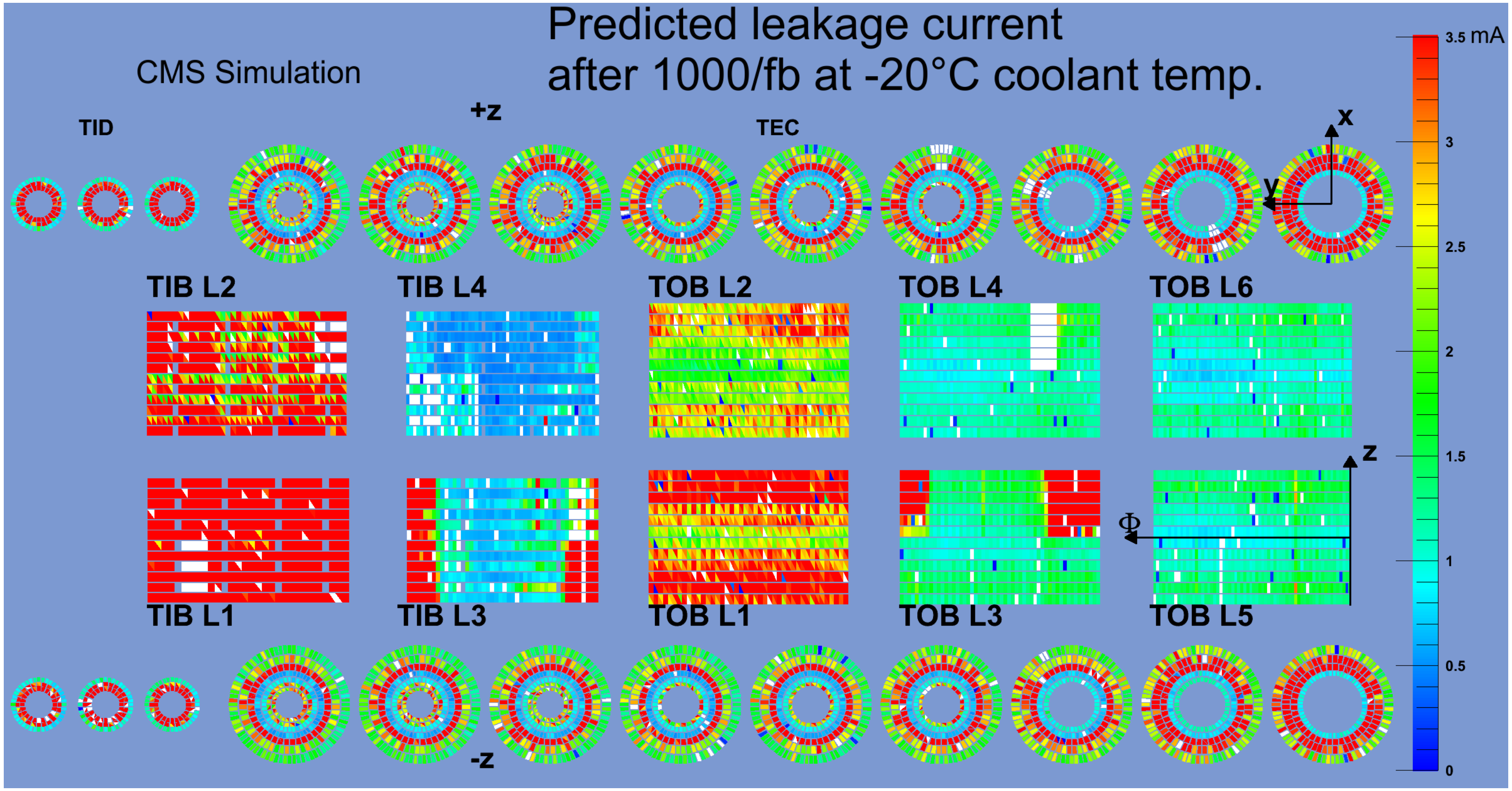
Too early to give quantitative estimates

Limitations of current tracker

Cannot push the detector (much) beyond design lifetime of 500 fb^{-1} and specifications PU ≈ 20

Pixel:
Pile-up!
- 2-track resolution
- efficiency

Outer tracker:
Radiation damage
- **leakage current**
- double-sided not cooled
- Huge impact on tracking performance



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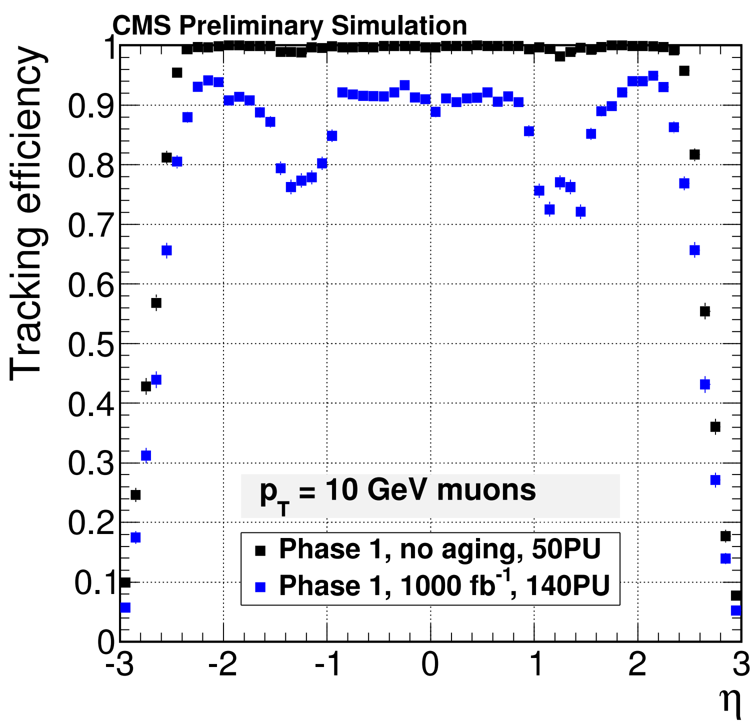
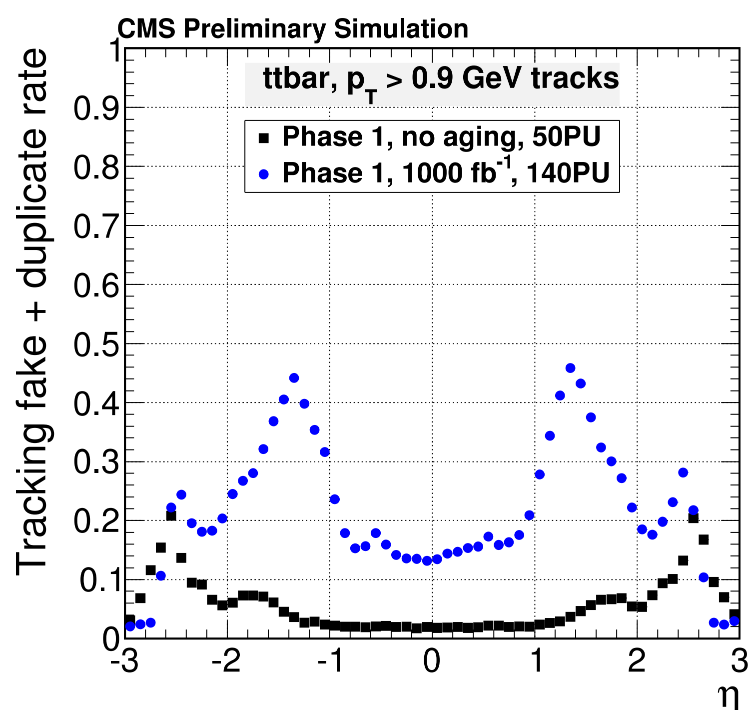
After installation
At **1000 fb^{-1}** & **PU=140**





Summary of Outer Tracker