CMS Tracker Upgrade: Requirements and Layout

Stefano Mersi
On behalf of the CMS Collaboration
19 March 2014
ACES 2014

Total tracker replacement

Pixel & strip replacement: aim at LS3

- Survive **$\int L.dt$ = 3000 fb^{-1}**
- Higher L1A rate → **> 500 kHz**
- Resolve **<μ>=140** → 200
- Latency → **> 10 μs**
- Ensure **experiment lifetime**
- **Improve tracking** at high pT
- **Improve tracking** at low pT
  Reduce **secondary interactions**
- **Increase forward acceptance**
- **Improve CMS trigger**

New outer tracker & new pixel

Total tracker replacement

Pixel & strip replacement: aim at LS3

Survive **∫L.dt = 3000 fb^{-1}**	**Radiation hardness** **Operating cold** (-20°C)
Higher L1A rate → **> 500 kHz**	**Bandwidth!**
Resolve **<μ>=140** → 200	**Higher granularity**
Latency → **> 10 μs**	Larger front-end **buffers**
Ensure **experiment lifetime**	**Redundancy** for Outer Tracker Possible **extraction** for Pixels
Improve tracking at high pT	**Increase granularity**
Improve tracking at low pT Reduce **secondary interactions**	**Reduce material**
Increase forward acceptance	Mostly through **pixel layout**
Improve CMS trigger	**Provide tracking to Level-1** 40 MHz output for L1

The challenge

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

LESS power/material

MORE power/material

New technologies
- DC-DC converters
- CO_2 cooling
- Low-power GBT
- Front-ends

Less layers

Higher granularity

Bandwidth!

Outer Tracker

Challenging requirements:

- Trigger readout (40 MHz)
- Power (=material!)
- Track finding @L1
- ...

pT modules

Providing "stubs" for tracking trigger

Need to ship hits off detector

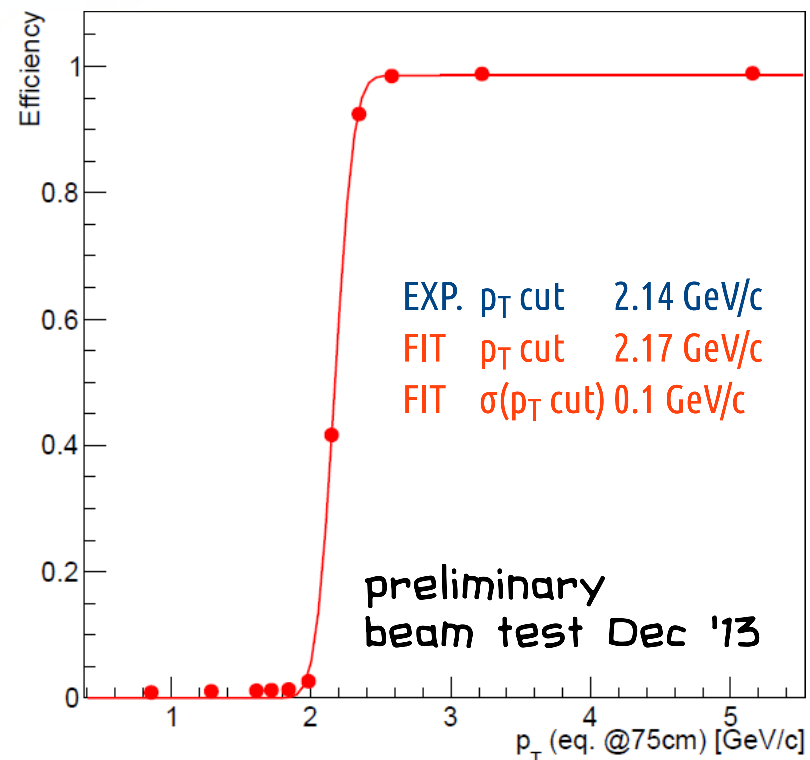
Ship all hits @ 40 MHz? No

- Bandwidth needed: off by 1 order of magnitude (order of 10 Gbps per module)
- Track reconstruction ~ impossible

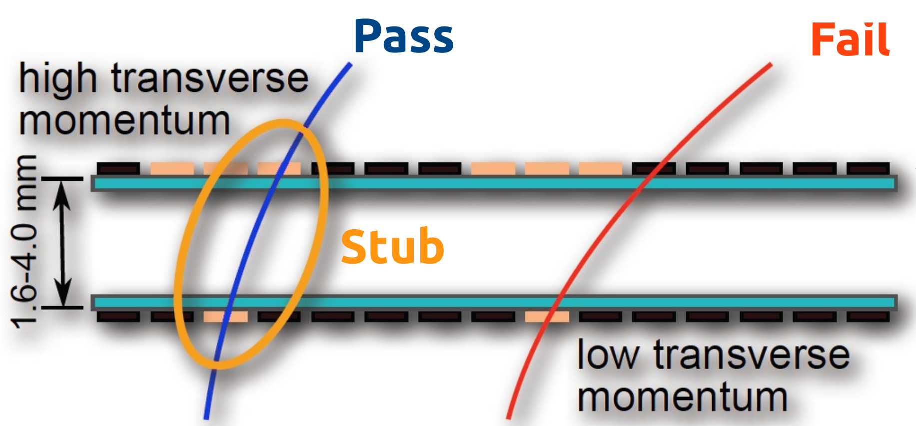
Solution: ship only high-pT hits (stubs)

- Threshold of ~ 2 GeV
- Data reduction of one order of magnitude or more

Modules with pT discrimination ("pT modules")



Thanks to CMS 3.8 T magnetic field!



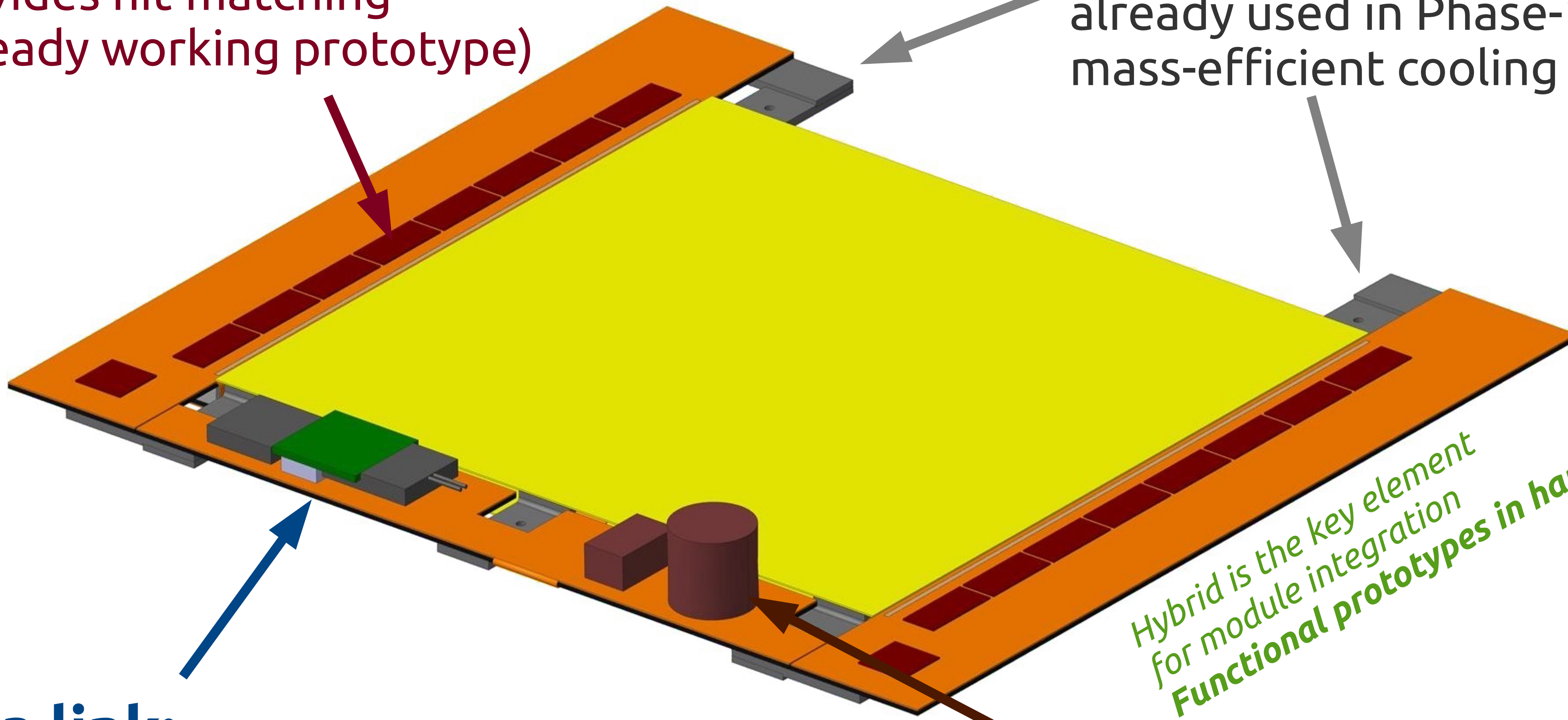
Same electronics reads two sensors

Module design

Concept: integration at the module level

Binary readout: CBC
provides hit-matching
(already working prototype)

CO_2 cooling
already used in Phase-1
mass-efficient cooling



Hybrid is the key element
for module integration
Functional prototypes in hand!

Data link:
Low-power GigaBit Transceiver
lpGBT currently under development
integrated at module level

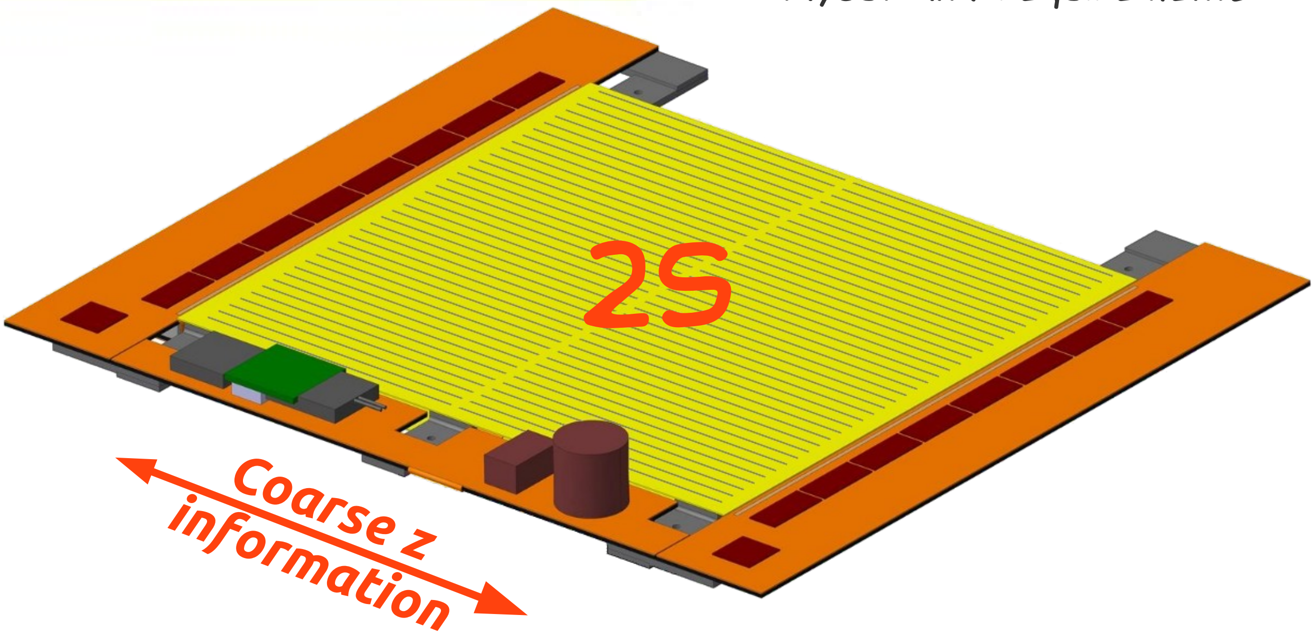
DC/DC converter
already used in Phase-1
10 V lines: lower current, lower material

Module design

Only two module types

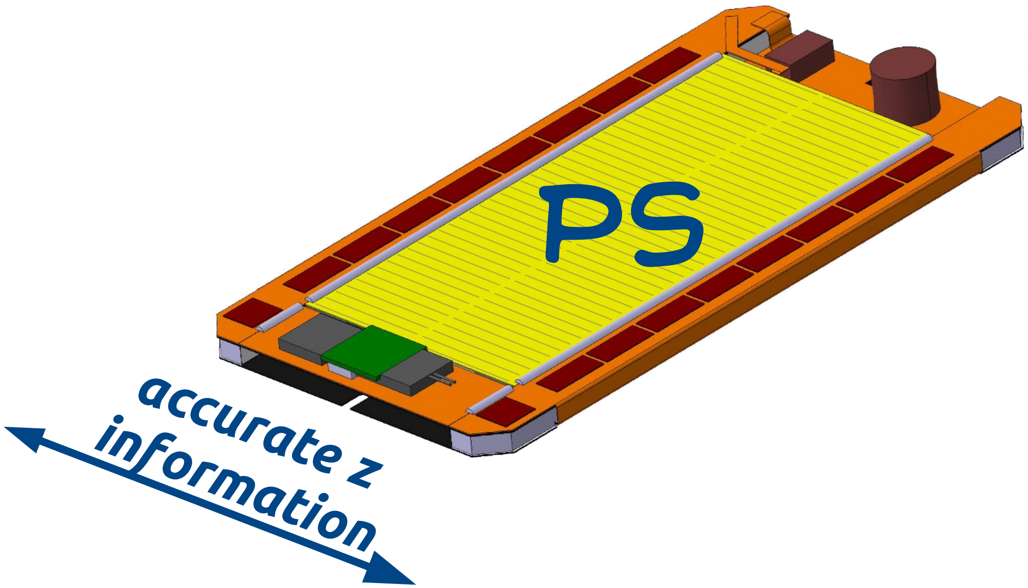
2 Strip sensors

Strips: 5 cm × 90 μm
Strips: 5 cm × 90 μm
P = 2.7 W
~ 92 cm² active area
For r > 40 cm



Pixel + Strip sensors

Strips: 2.5 cm × 100 μm
Pixels: 1.5 mm × 100 μm
P = 5.0 W
~ 44 cm² active area
For r > 20 cm



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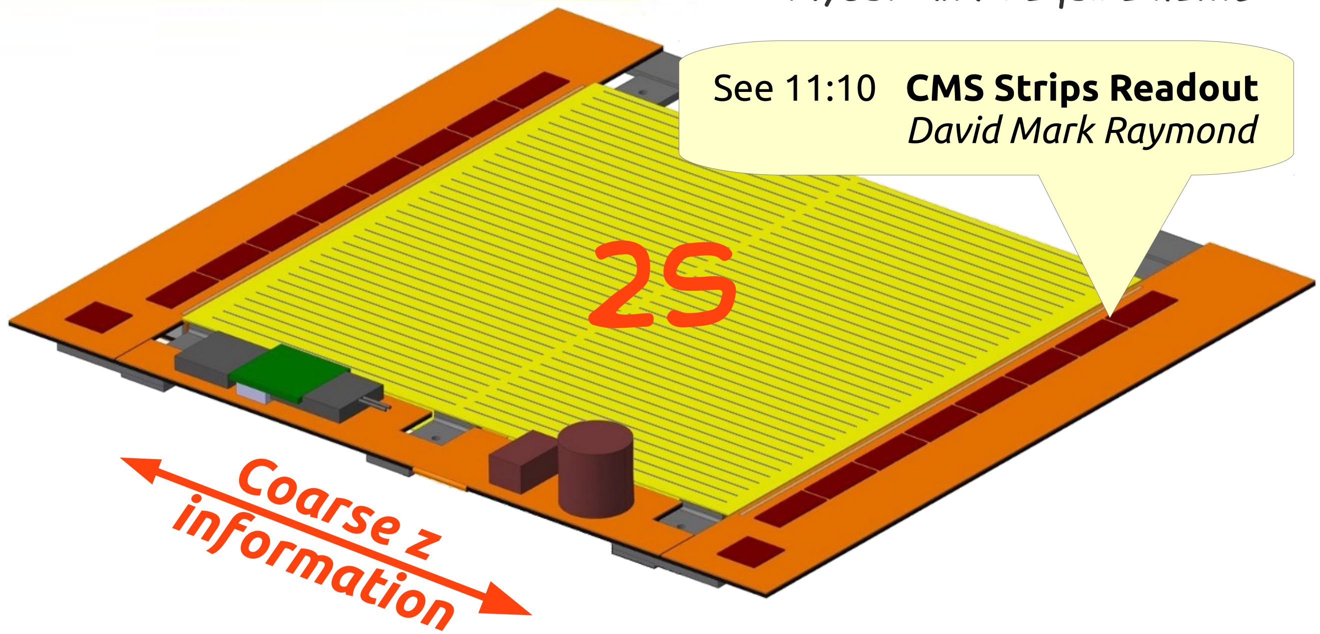

See 11:10 **CMS Strips Readout** *David Mark Raymond*

Pixel + **S**trip sensors

Strips: 2.5 cm × 100 μm

Pixels: 1.5 mm × 100 μm

P = 5.0 W

~ 44 cm^2 active area

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Module design

Only two module types

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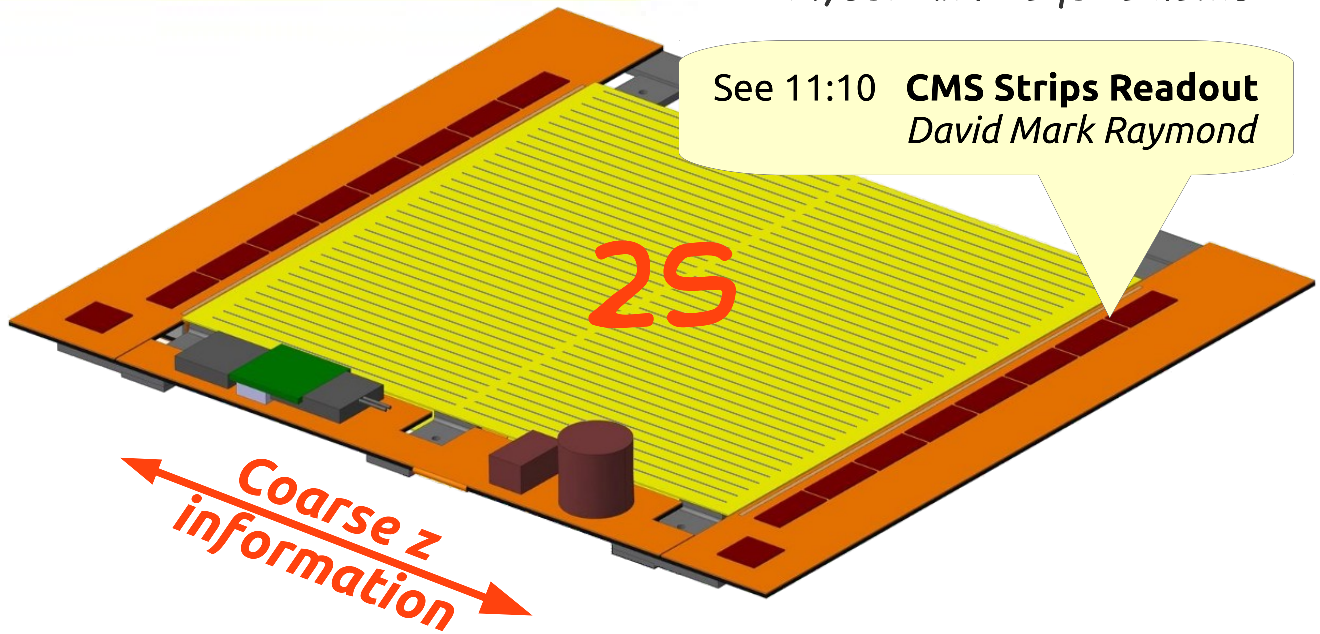


See 11:10 **CMS Strips Readout**
David Mark Raymond

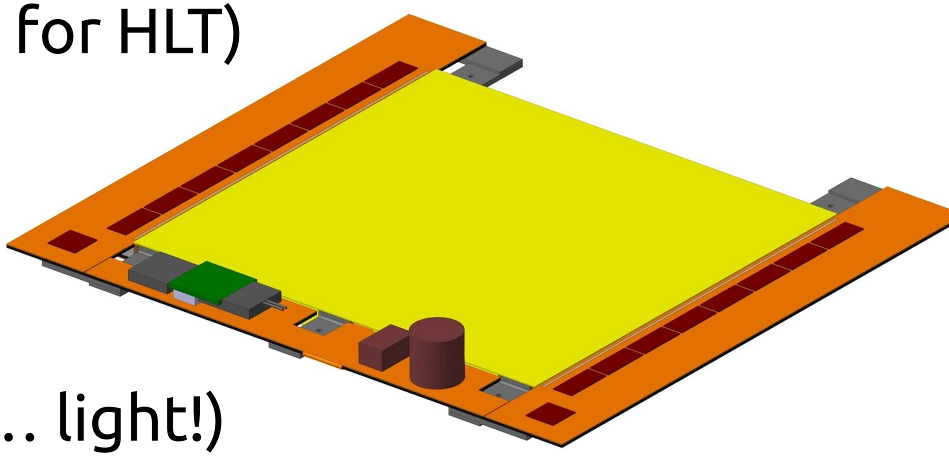
Pixel + **S**trip sensors
Strips: 2.5 cm × 100 µm
Pixels: 1.5 mm × 100 µm
P = 5.0 W
~ 44 cm² active area
For r > 20 cm

See 11:30 **CMS Pixel-Strip Project**
Kostas Kloukinas

Module design

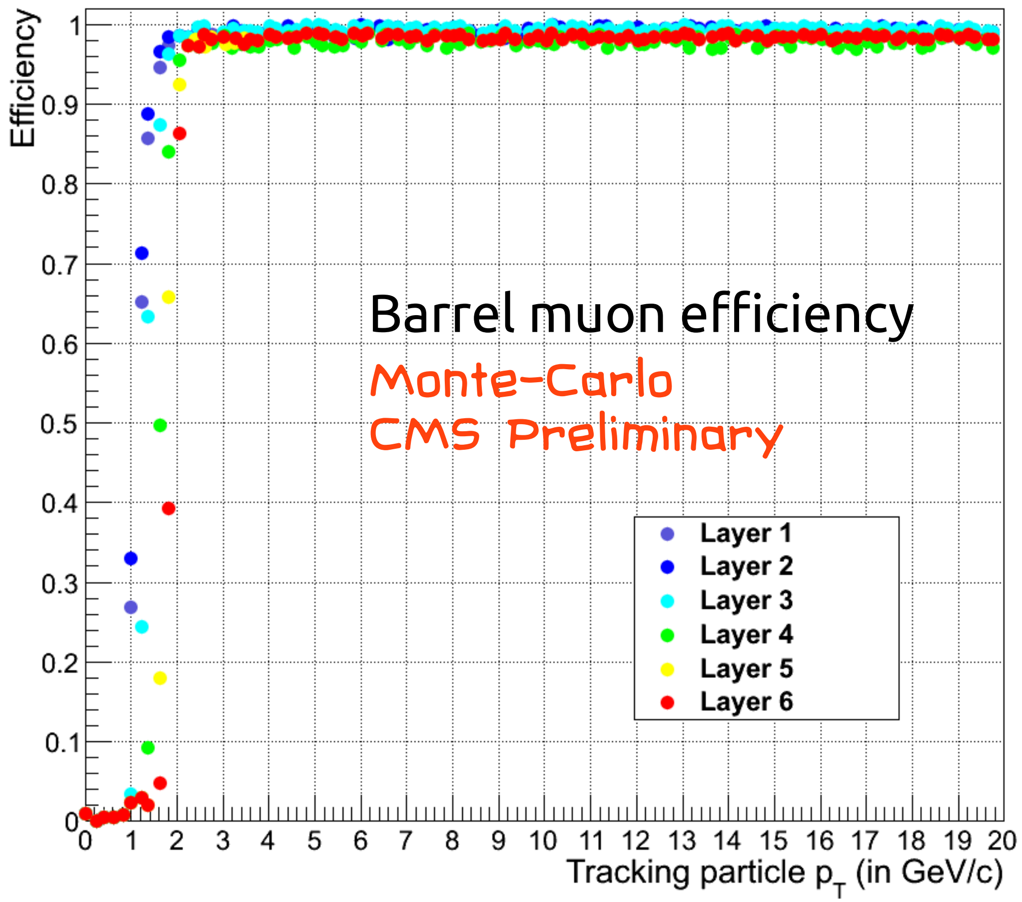
Concept: integration at the module level

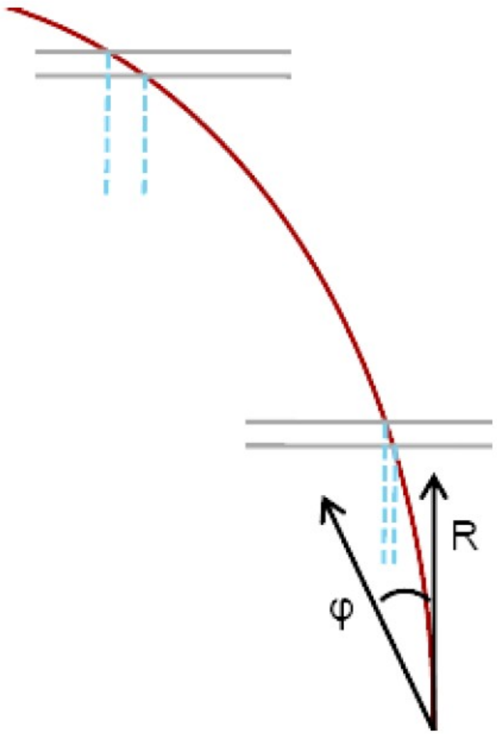
- **Two sensors per module**
  - Mass-effective way of collecting two coordinates
  - Help for pattern recognition (also for HLT)
- Large bandwidth needed =>
  one link per module
  - Contribution to power: moderate
  - System very simple and elegant (… light!)
    - Almost no electrical connectivity in the tracking volume
    - The module is a self-contained system



The chosen implementation brings many
more advantages than drawbacks

Uniform cut
Possible, with tuning

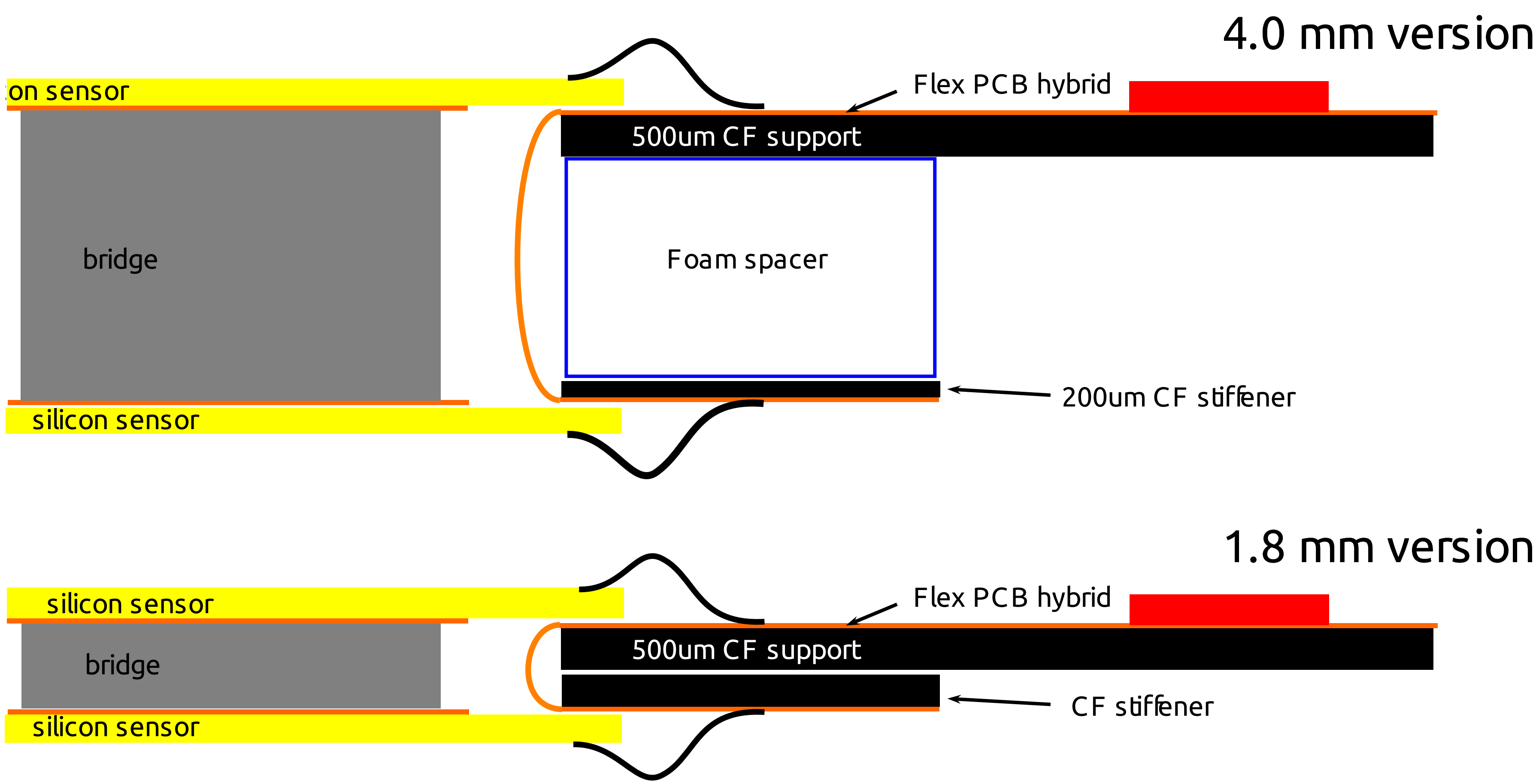




(@construction) (@front-ends)

Need to tune **sensor spacings** and **hit matching windows** are required to maintain uniform p_T cut

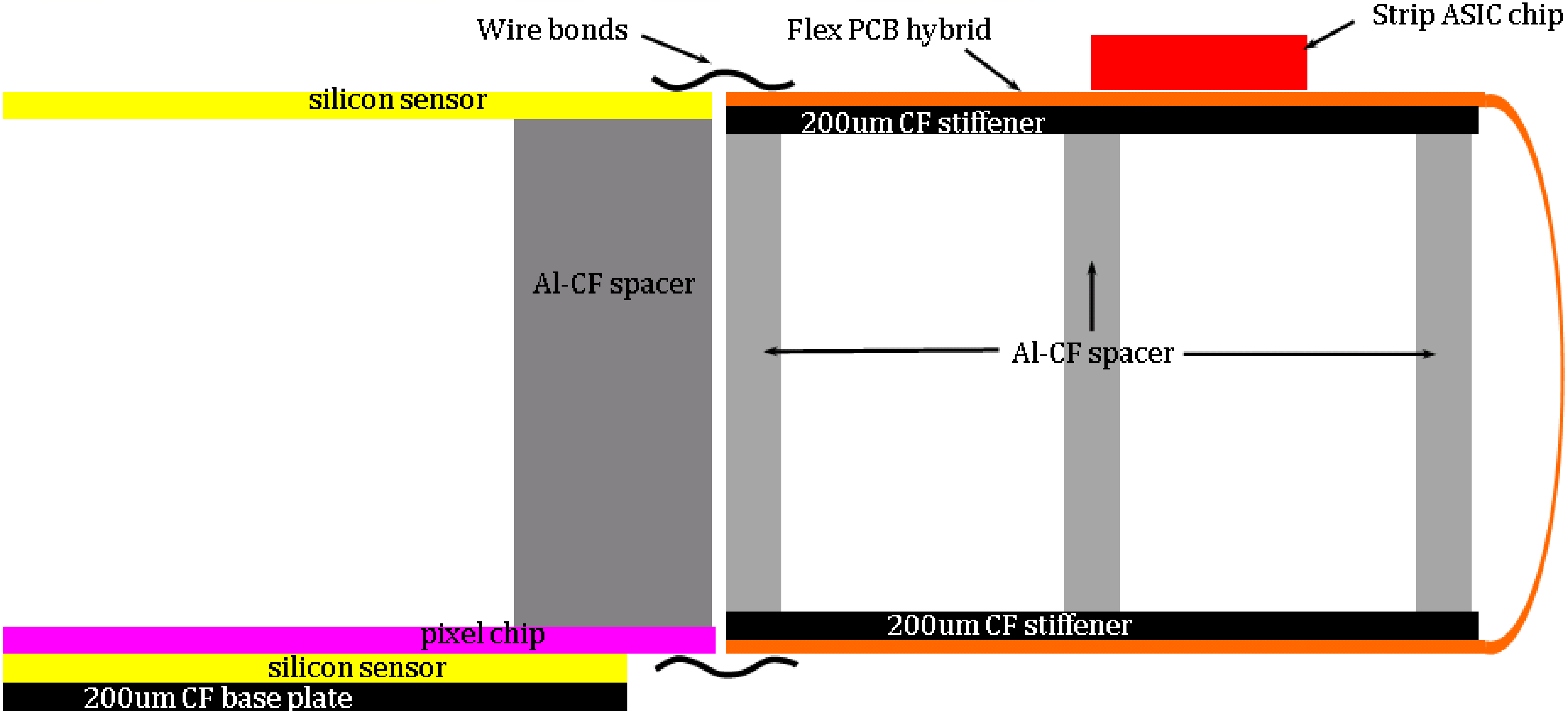
2S modules



Flex hybrid:

- Technology leap
- Key element for 2-sensor design

PS modules



Flex hybrid:

- Technology leap
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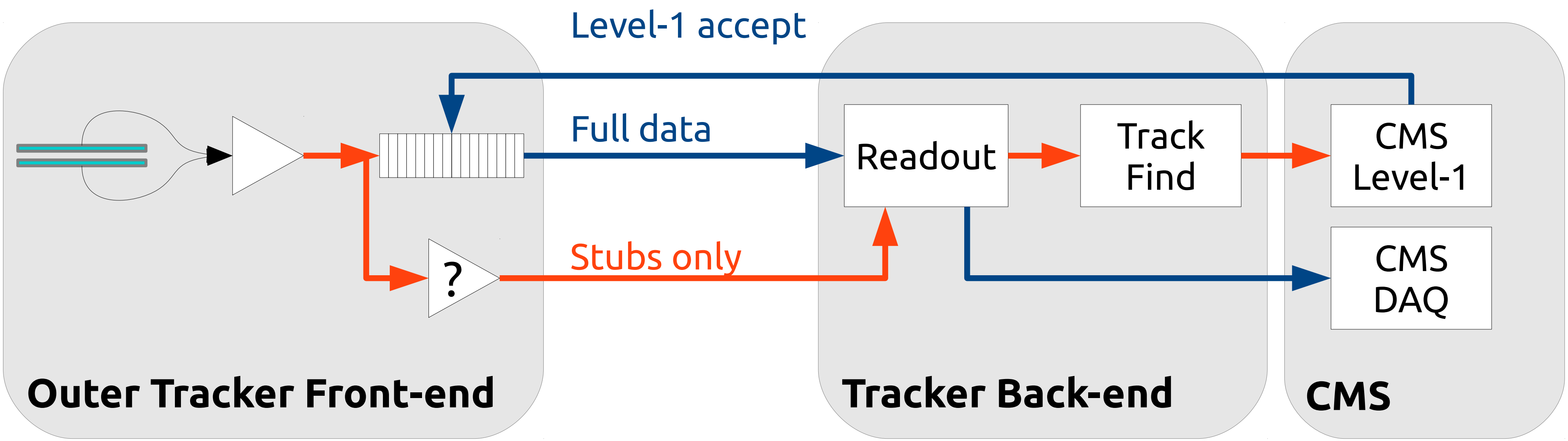
Providing tracks for trigger

Readout architecture

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

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



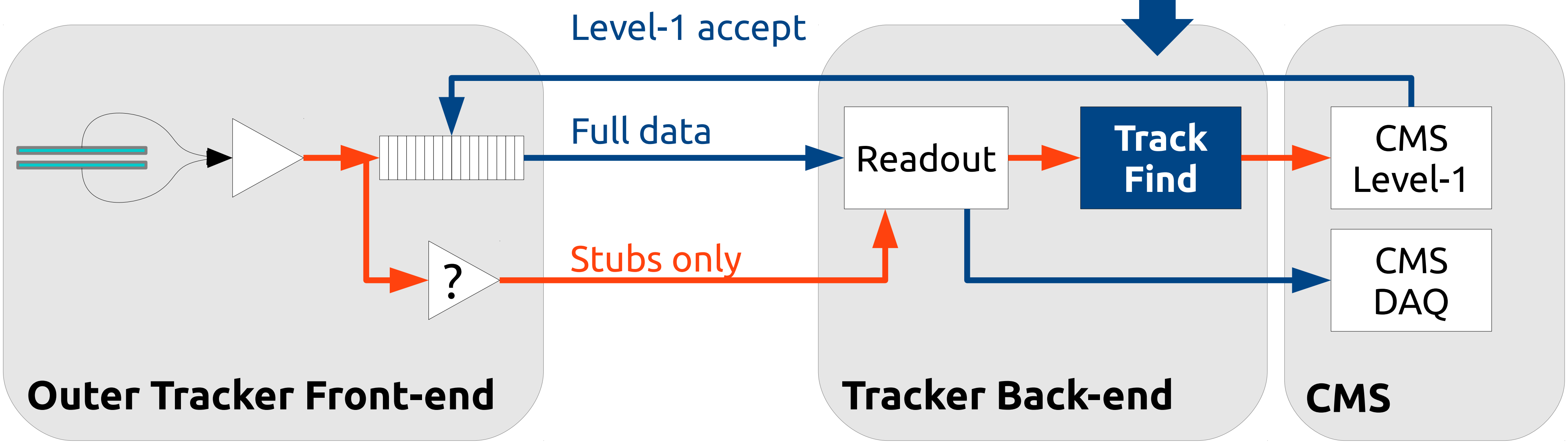
@ 40 MHz – Bunch crossing

@ ~ 500 kHz – CMS Level-1 trigger

Providing tracks for trigger
Readout architecture

See 14:20 **CMS Views for the Off-Detector Track Trigger Electronics**
Ted Liu

Completely new system component
new sub-project



@ 40 MHz – Bunch crossing
@ ~ 500 kHz – CMS Level-1 trigger

Pixel detector

Challenging requirements:

- Radiation hardness
- Readout bandwidth
- Power (=material!)
- Contribution to trigger ?

Pixels: radiation hardness

Sensors and front-ends

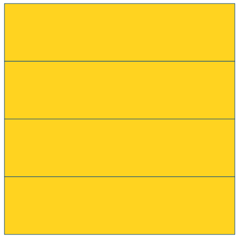
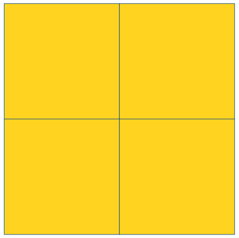
- Sensors: Φ up to 2×10^{16} neq cm^{-2} @ r=5 cm

With current CMS pixel @600V
CCE = 50% at 10^{16} neq cm^{-2}

Pixels: radiation hardness

Sensors and front-ends

- Sensors: Φ up to 2×10^{16} neq cm^{-2} @ r=5 cm
  - Thin planar
  - 3D
  - Resolution? Smaller pixels:
    - $100 \times 25\ \mu m^2$
    - $50 \times 50\ \mu m^2$

Pixels: radiation hardness
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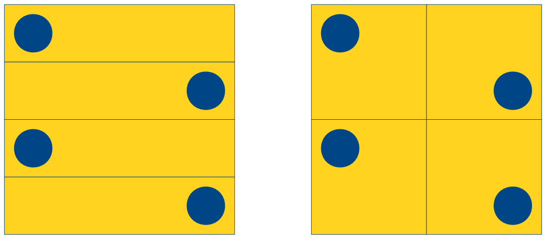

- Front-end: up to 10 MGy
  - ROC Chip 65 nm CMOS
    - One chip, footprint compatible with both pixel geometries

Pixels: radiation hardness

Sensors and front-ends

- Sensors: Φ up to 2×10^{16} neq cm^{-2} @ r=5 cm
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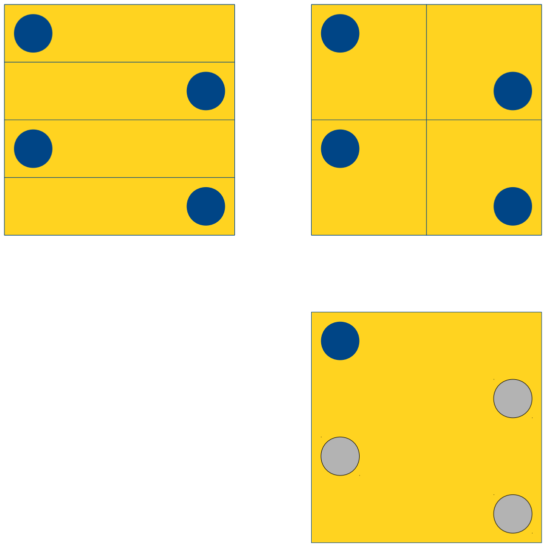

- Front-end: up to 10 MGy
  - ROC Chip 65 nm CMOS
    - One chip, footprint compatible with both pixel geometries
    - Same chip compatible also with $100 \times 100\ \mu m^2$ pixels
  - Radiation hardness? Other electronics?

Pixels: radiation hardness

Sensors and front-ends

- Sensors: Φ up to 2×10^{16} neq cm^{-2} @ r=5 cm
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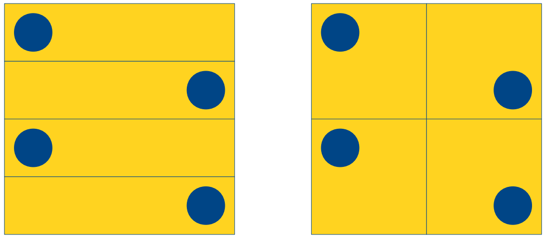
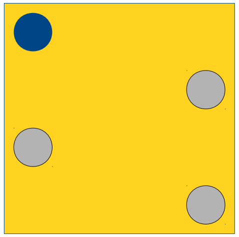
  - 3D
  - Resolution? Smaller pixels:
    - 100 × 25 μm^2
    - 50 × 50 μm^2





- Front-end: up to 10 MGy
  - ROC Chip 65 nm CMOS
    - One chip, footprint compatible with both pixel geometries
    - Same chip compatible also with 200x200 μm^2 pixels
  - Radiation hardness? Other electronics?

See 11:50 **RD53** *Jorgen Christiansen*

Pixels: readout bandwidth

Huge increase w.r.t. present system

- Present system
  - Rate → **200 MHz/cm²**
  - L1 rate **100 kHz**

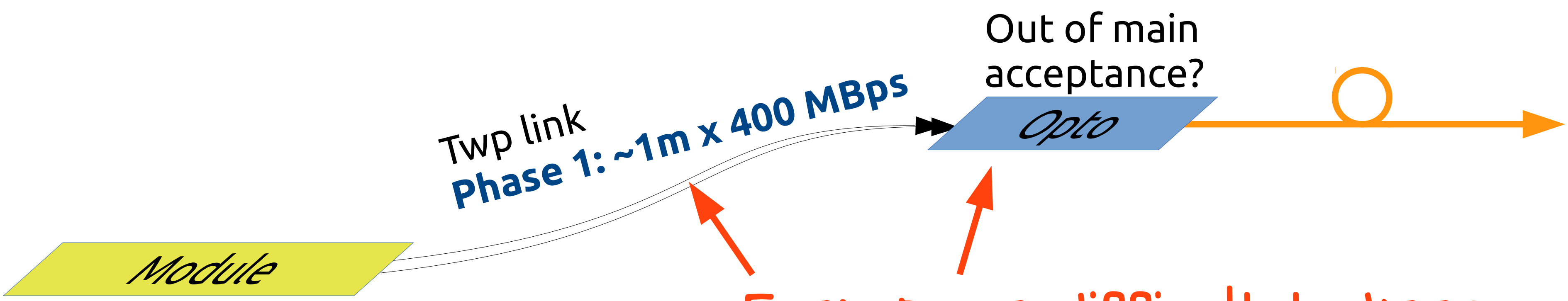
× 10

× 5~10

- HL-LHC
  - Rate → **2 GHz/cm²**
  - L1 rate **500 kHz (1 MHz)**

× 50~100

- Optical on-board readout not possible:
  - Rad-hardness
  - Material/space
- **Electrical links to opto links**



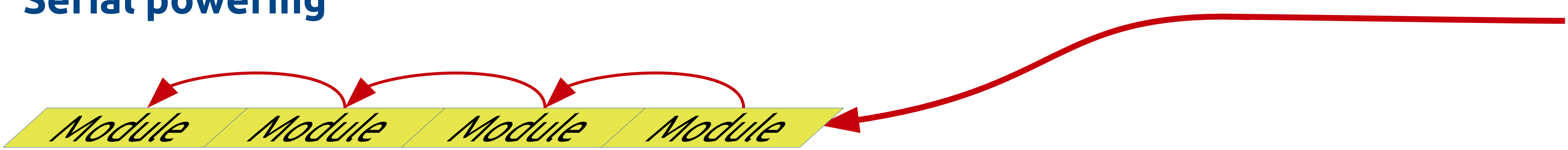
Even more difficult to keep material budget under control

Pixel: powering

Mantra: power => material

- Target: O(0.5) W/cm^2
- Traditional inductor-based on-board DC/DC not possible:
  - Rad-hardness
  - Material/space
- Possible options:

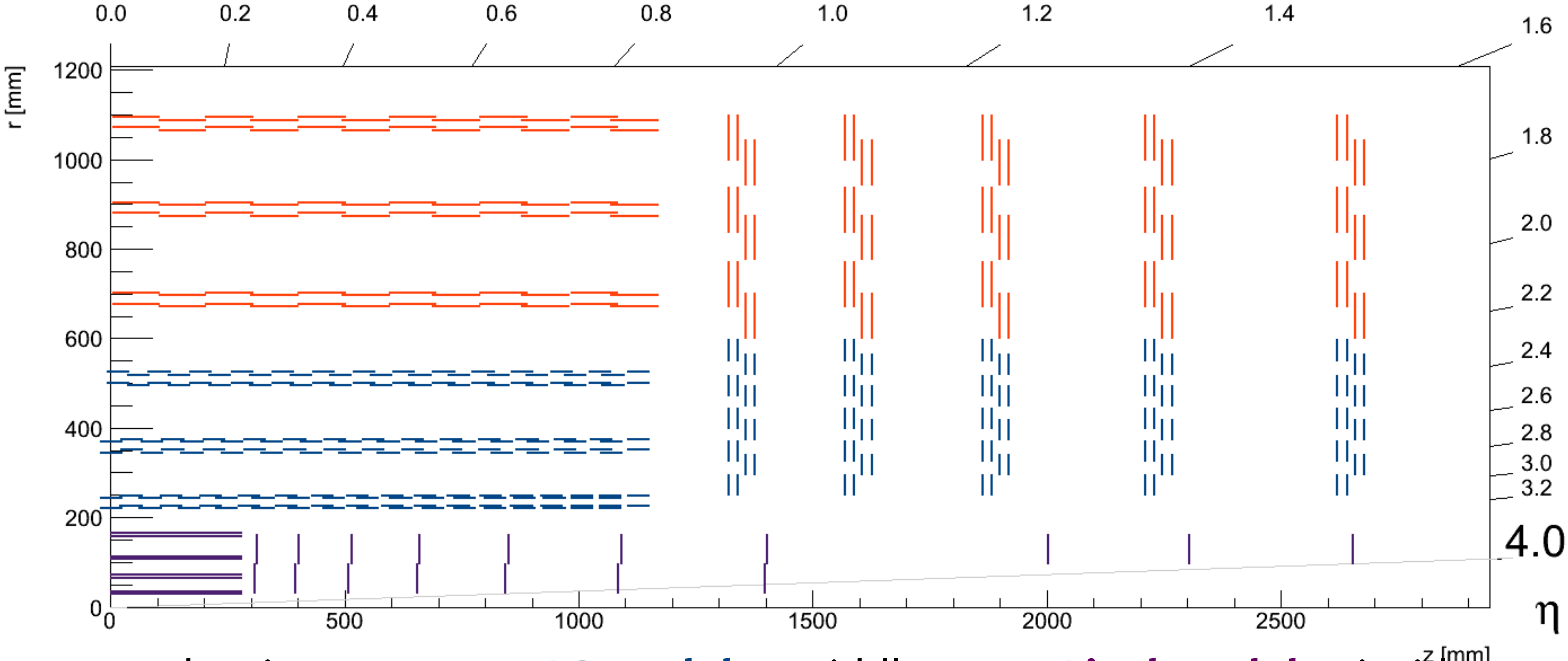
Serial powering



More complex schemes

Layout and expected performance

Tracker Layout



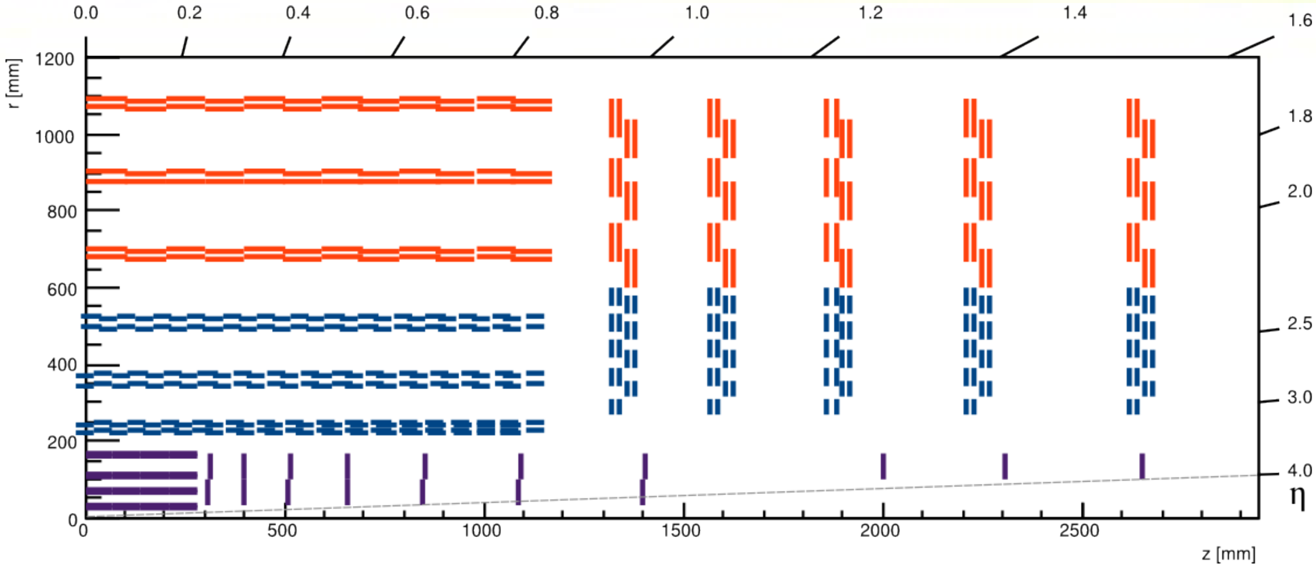
Lower density
2S modules outside
(~8400 modules)

PS modules middle
z info in trigger
θ info in trigger
(~7100 modules)

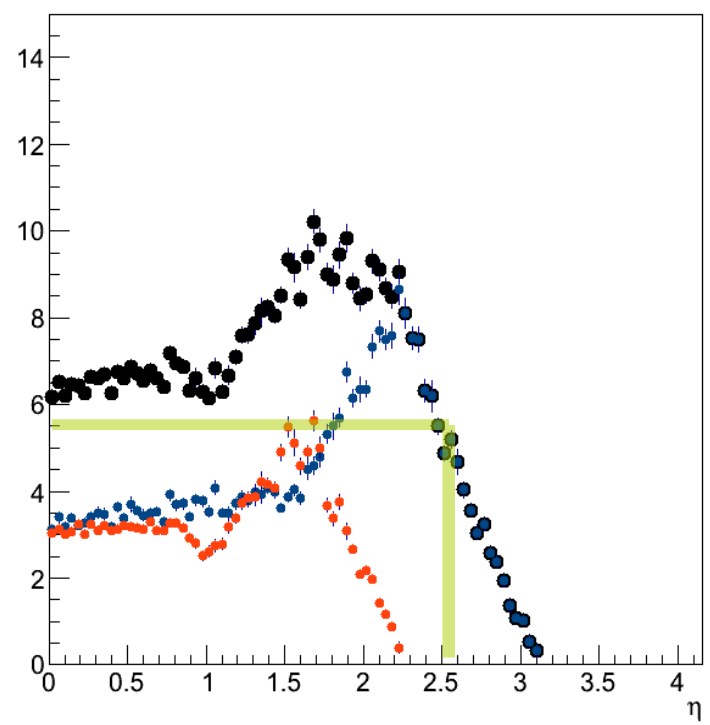
More detailed model

Pixel modules inside
accurate impact parameter resolution & forward coverage
No detailed model: using Phase-I detector layout w/ more disks in the forward

Layout
Current baseline

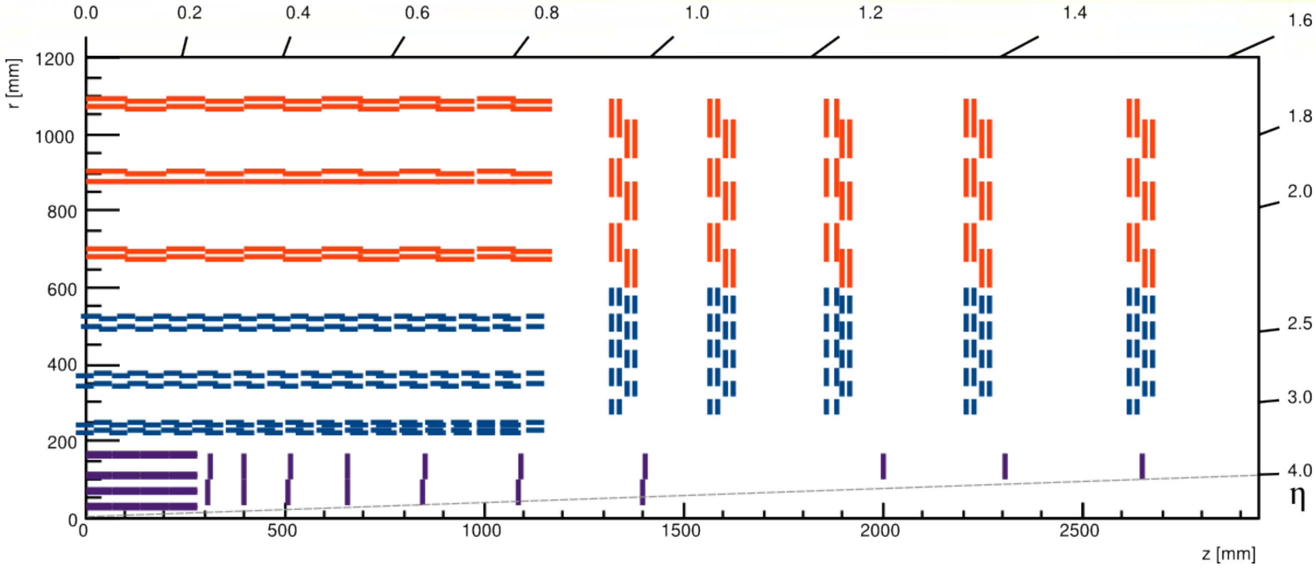


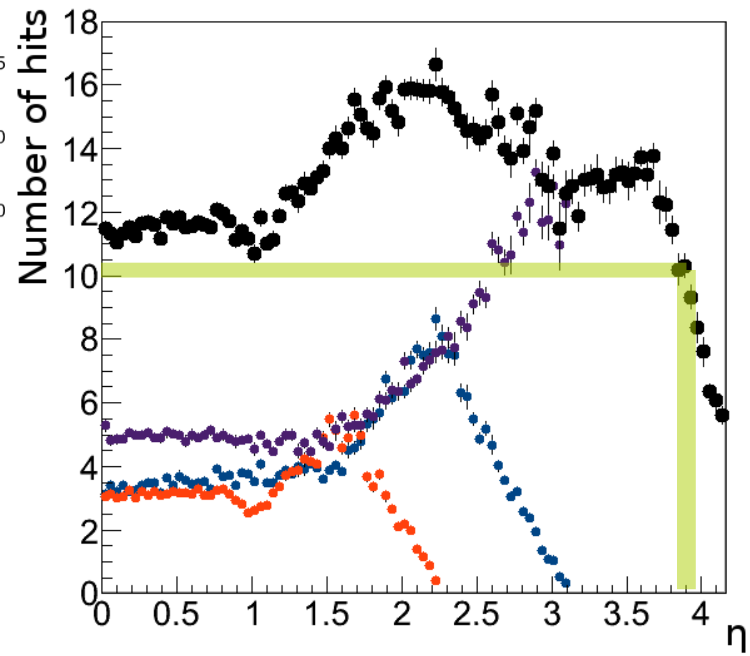
10 trigger hits → η=2.5



- **×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**

Layout
Current baseline





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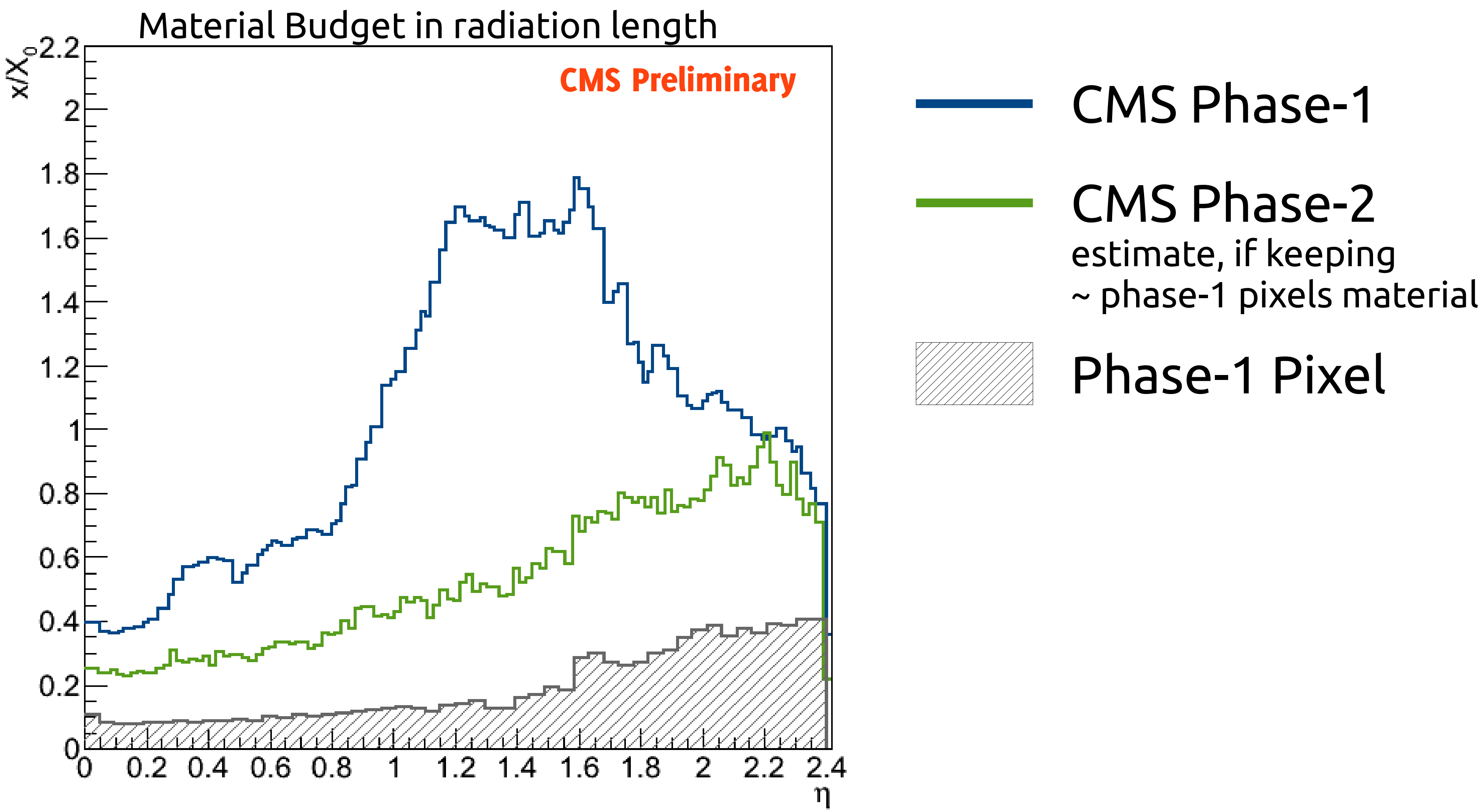
- Up to **10 points** available for track-trigger up to η=2.5
  - Comparable to current tracker's coverage, **but at L1**
- Hit coverage up to **η≈4** at L1A

Upgrade overview

	Current		Upgrade	
Outer	~200 m^2	Silicon	~220 m^2	Silicon
	9.3 M	Strips	47.8 M	Strips
	0	MacroPixels	217 M	MacroPixels
	15'148	Modules	15'508	Modules
	100 kHz	readout rate	40 MHz	readout rate*
Pixel	~1 m^2	Silicon	4.6 m^2	Silicon
	66 M	Pixels	O(1) G?	Pixels
	1440	Modules	??	??
	100 kHz	readout rate	>500 kHz	readout rate

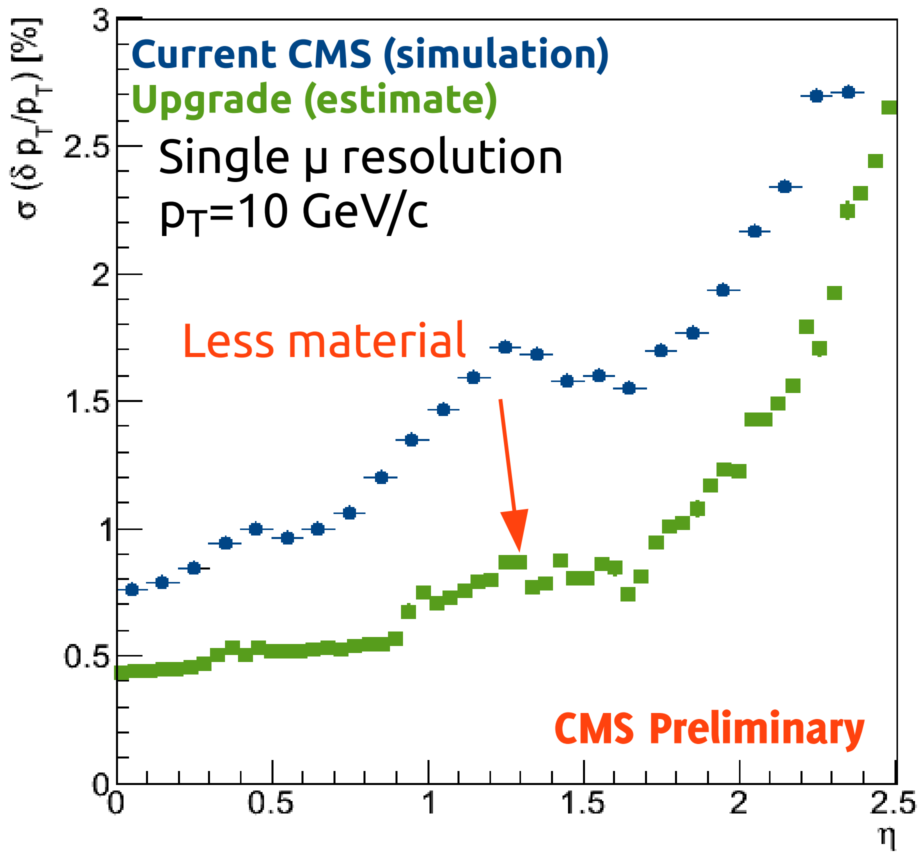
* only high-pt hits read-out

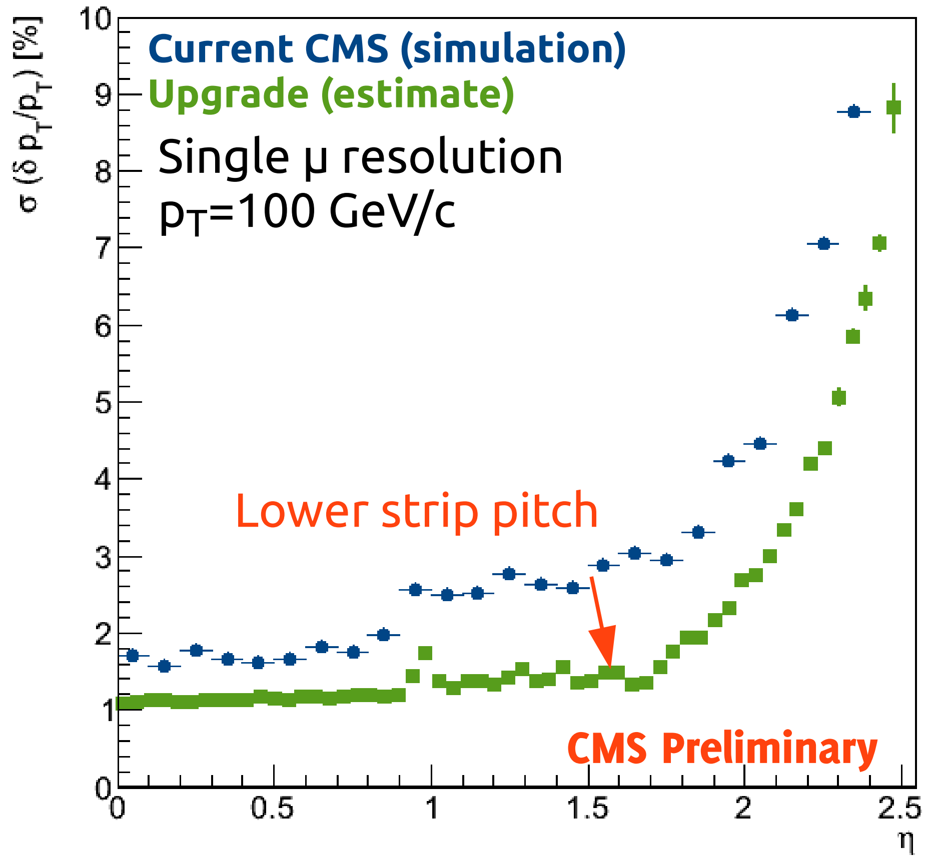
Tracker material budget



Tracking resolution

pT resolution of single muons

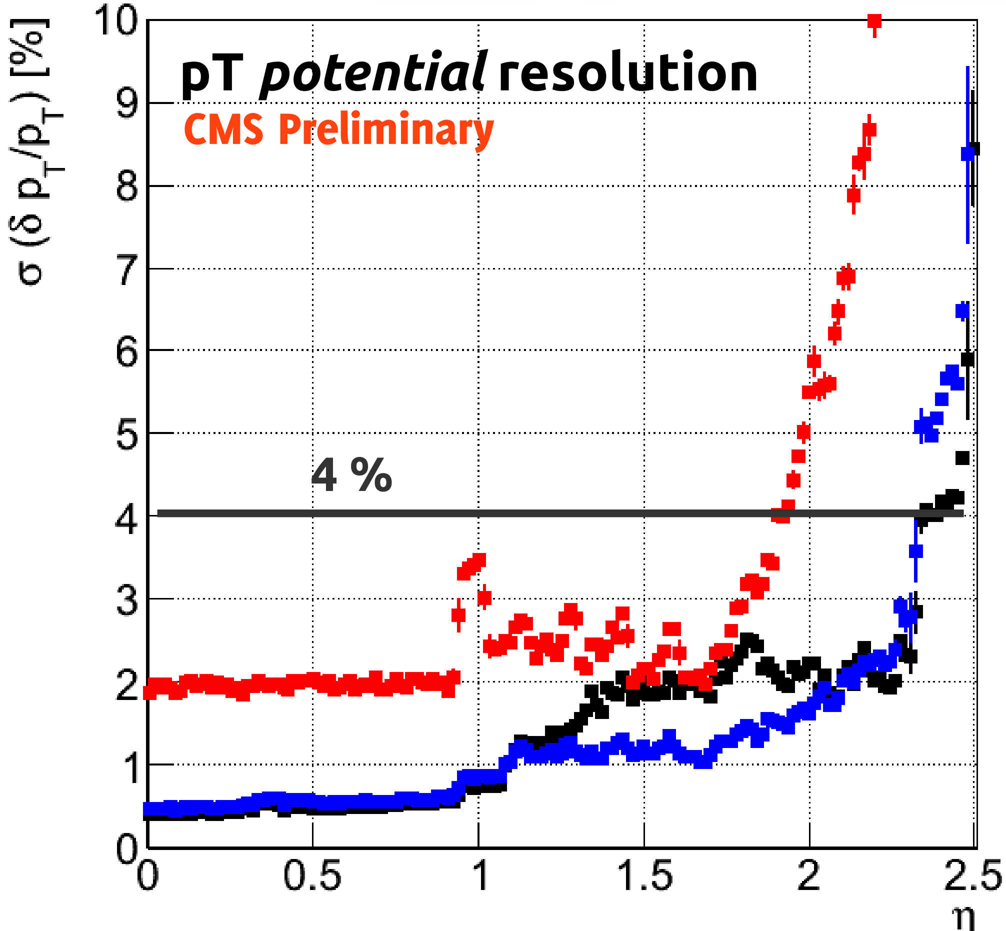


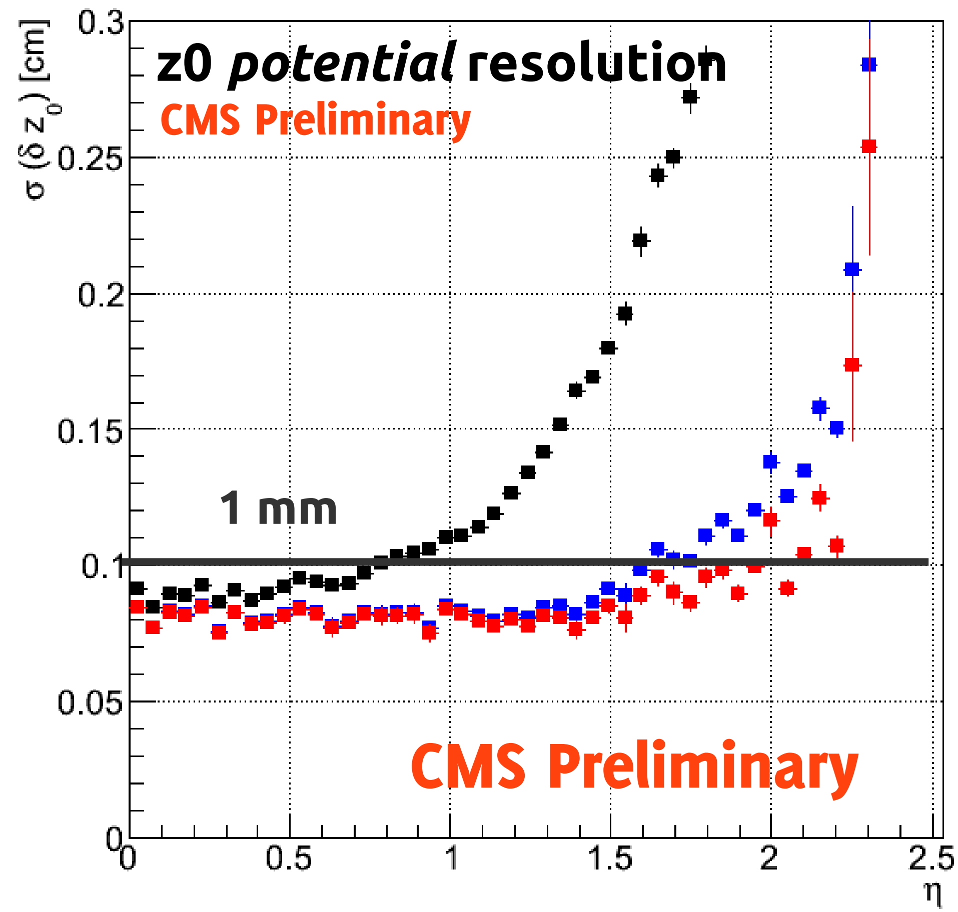


Clear improvement expected in the whole pT range

Track-trigger resolution

Potential pT resolution using all stub info





Challenge for L1-track finding:
finding precise tracking information

Single μ p_T=2 GeV/c
Single μ p_T=10 GeV/c
Single μ p_T=100 GeV/c

See 14:20 **CMS Views for the Off-Detector Track Trigger Electronics**
Ted Liu

Thank you!

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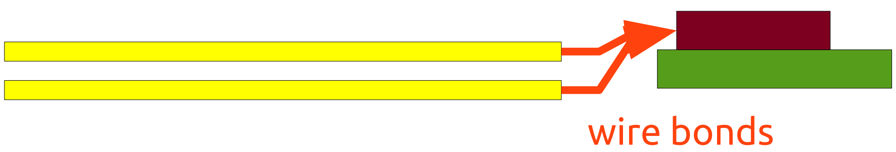
Higher L1A rate → **> 500 kHz**	**Bandwidth!**
Resolve **<μ>=140** → 200	**Higher granularity**
Latency → **> 10 μs**	Larger front-end **buffers**
Ensure **experiment lifetime**	**Redundancy** for Outer Tracker Possible **extraction** for Pixels
Improve tracking at high pT	**Increase granularity**
Improve tracking at low pT Reduce **secondary interactions**	**Reduce material**
Increase forward acceptance	Mostly through **pixel layout**
Improve CMS trigger	**Provide tracking to Level-1** 40 MHz output for L1

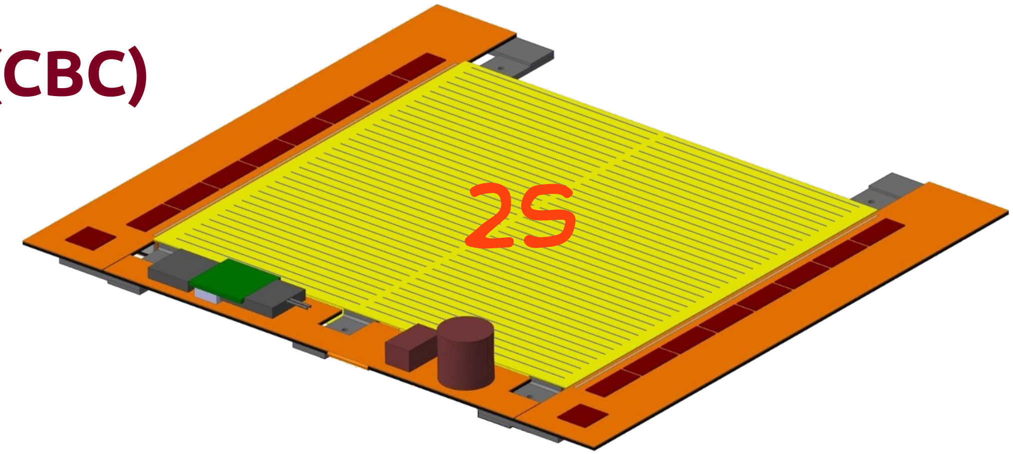
Module design

Only two module types

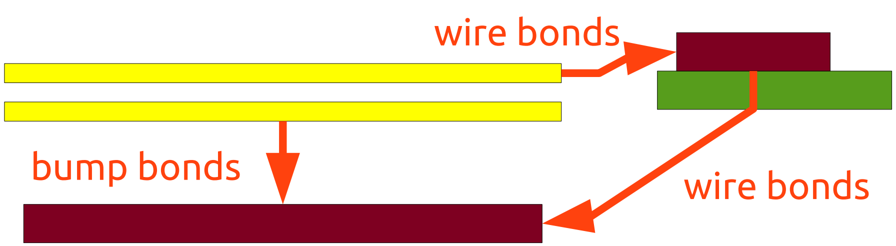
Hit correlation in different chips

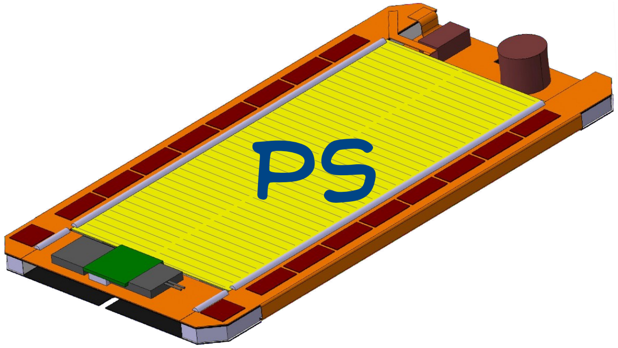
Cms Binary Chip (CBC)
strip readout
+ correlation





Readout only

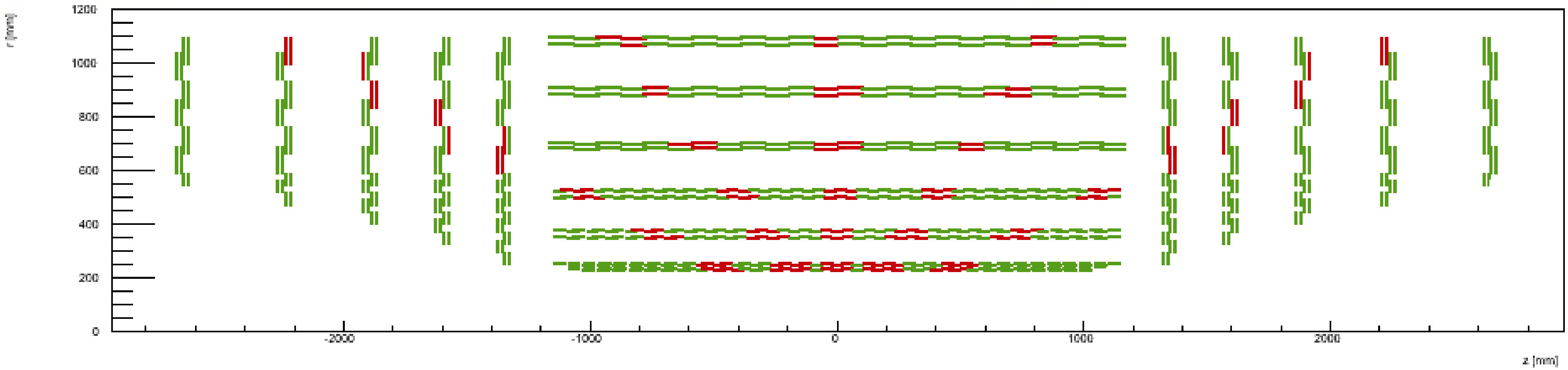




MacroPixel ASIC (MPA):
pixel readout
+ correlation

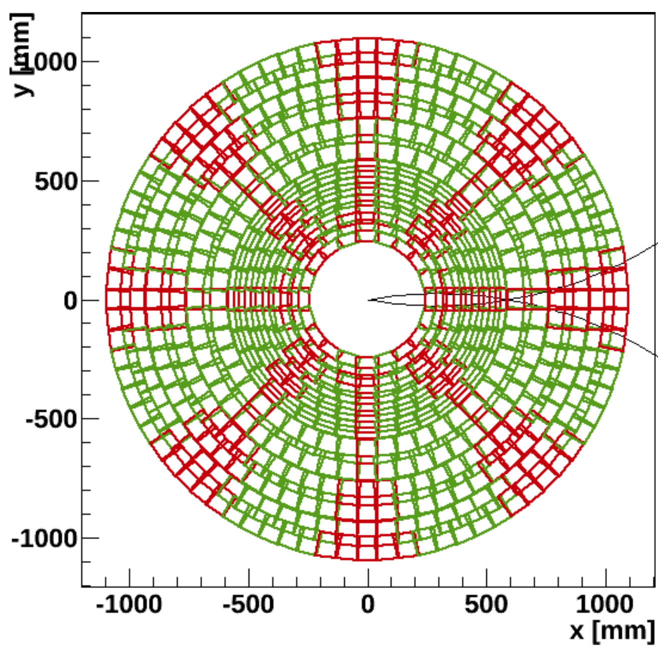
Track finding at Level-1

Divide & impera!

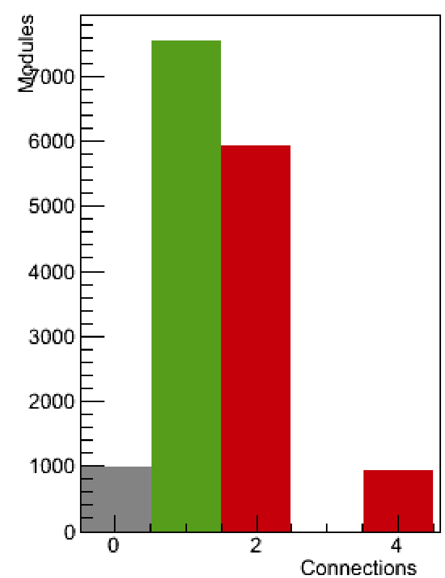


Working hypothesis:

- Each sector independent
- Overlap regions function of
  - Luminous region Δz
  - Minimum pT cut

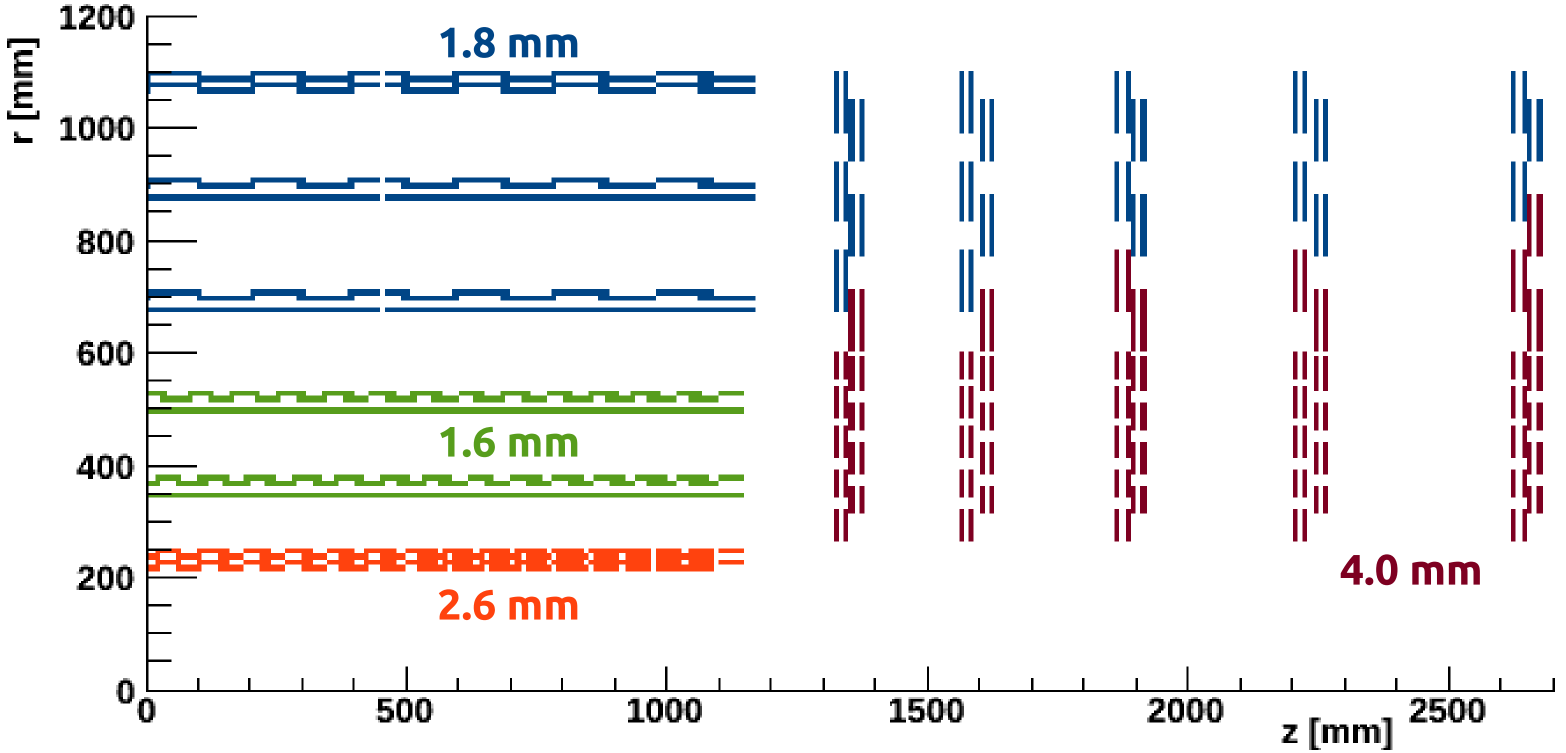


Number of sectors connected to a module

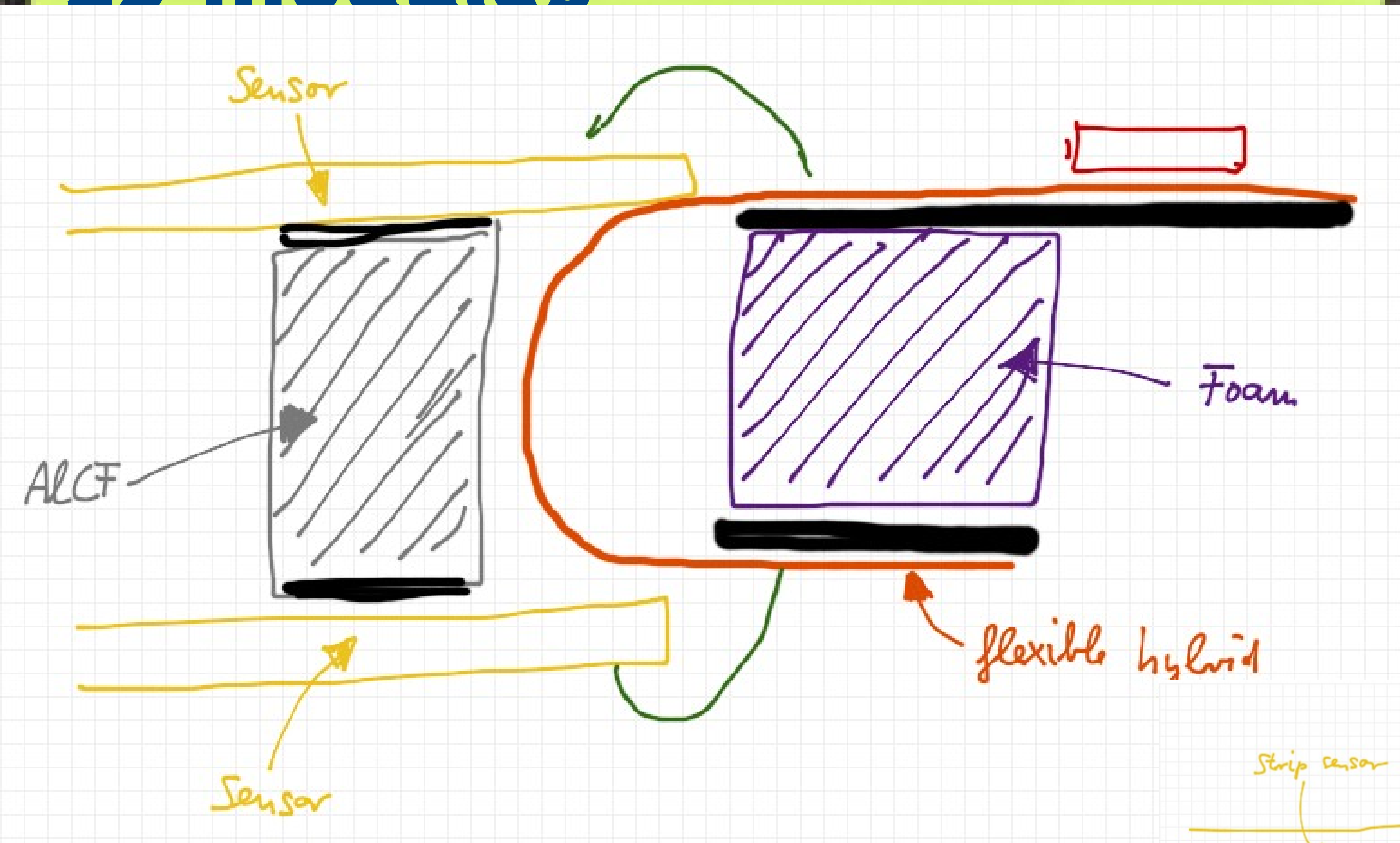


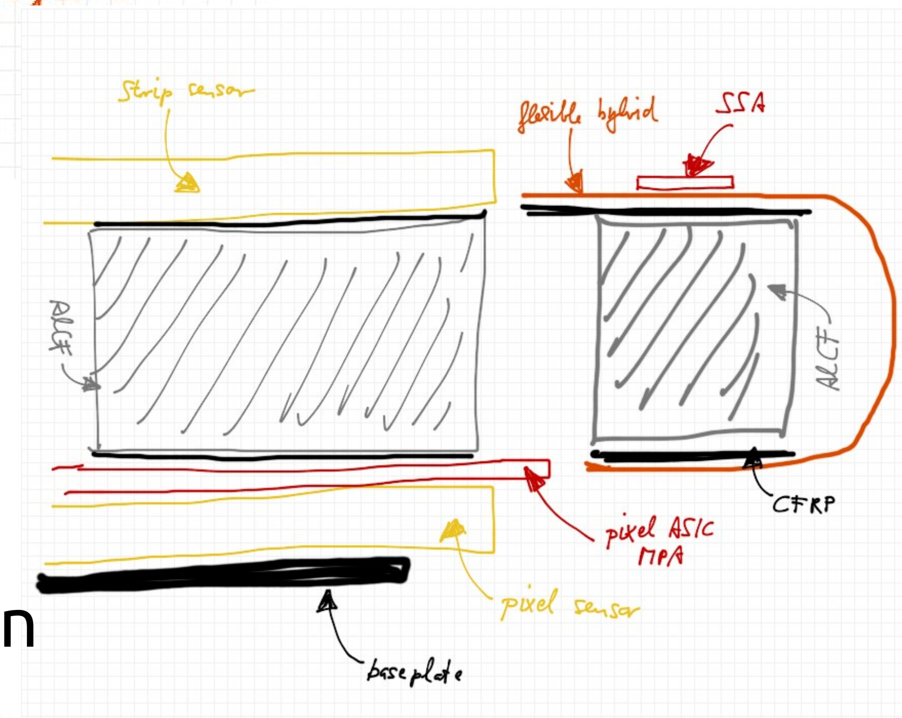
sensor spacing

must be tuned along with search windows



2S modules





Flex hybrid:

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- Key element for 2-sensor design

Radiation map