Upgrade of the CMS tracker for the HL-LHC

Design, status and prospects

Martin Delcourt

7 December 2016

Upgrade of the CMS tracker for the HL-LHC
What ? Why?



> The goal of the CMS experiment at the Large Hadron Collider (LHC) is to answer fundamental questions in particle physics.

CERN-LHCC-2015-19

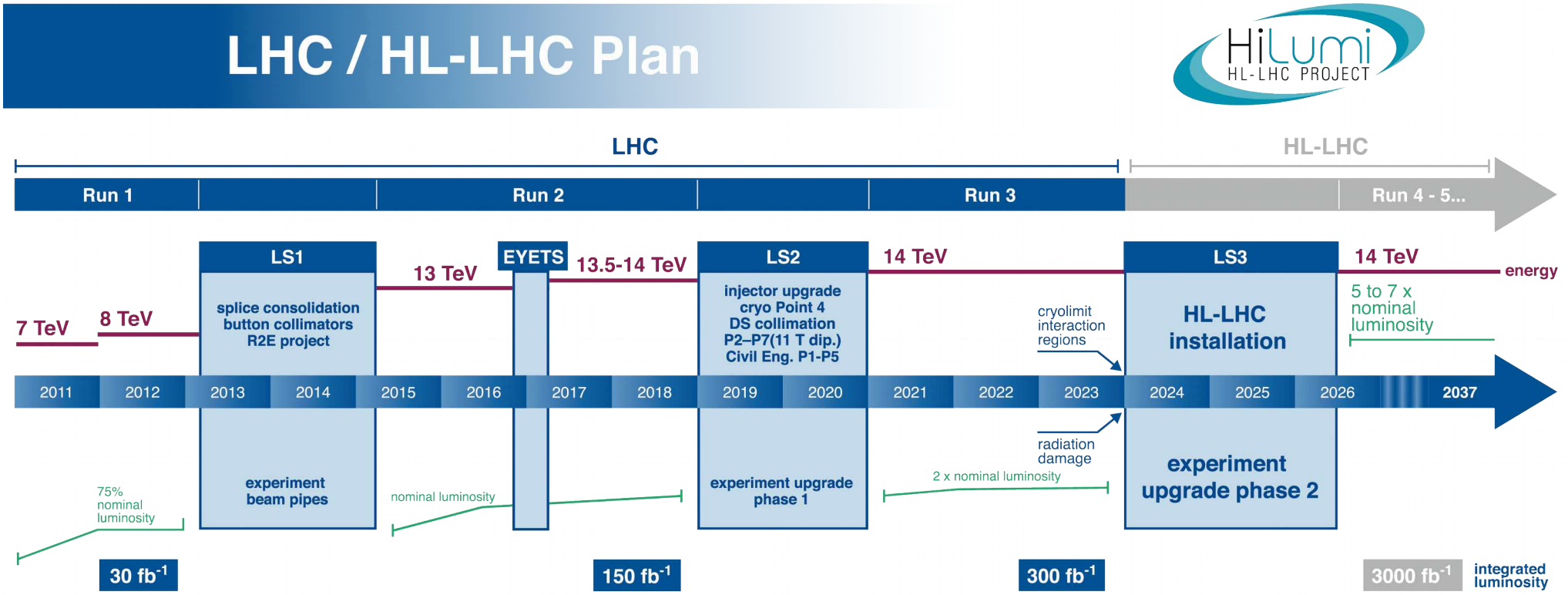
- How does the Higgs boson behave?
  - Coupling to other particles? Rare decays?
- Super-symmetry?
  - Very weakly interacting particles? Stealth SUSY?
- Precision measurements.
  - Is BSM hiding in highly suppressed, well-predicted processes?
- Higher mass particles? Dark matter candidates?
- …

More statistics are needed to try to answer these questions!

Upgrade of the CMS tracker for the HL-LHC

More statistics? More luminosity!

- Major upgrade project to the LHC and injection complex
  - Goal : deliver 5-7 times the nominal luminosity and multiply by 10 the total integrated luminosity
    - 300fb^{-1} by 2023 → 3000fb^{-1} by 2037

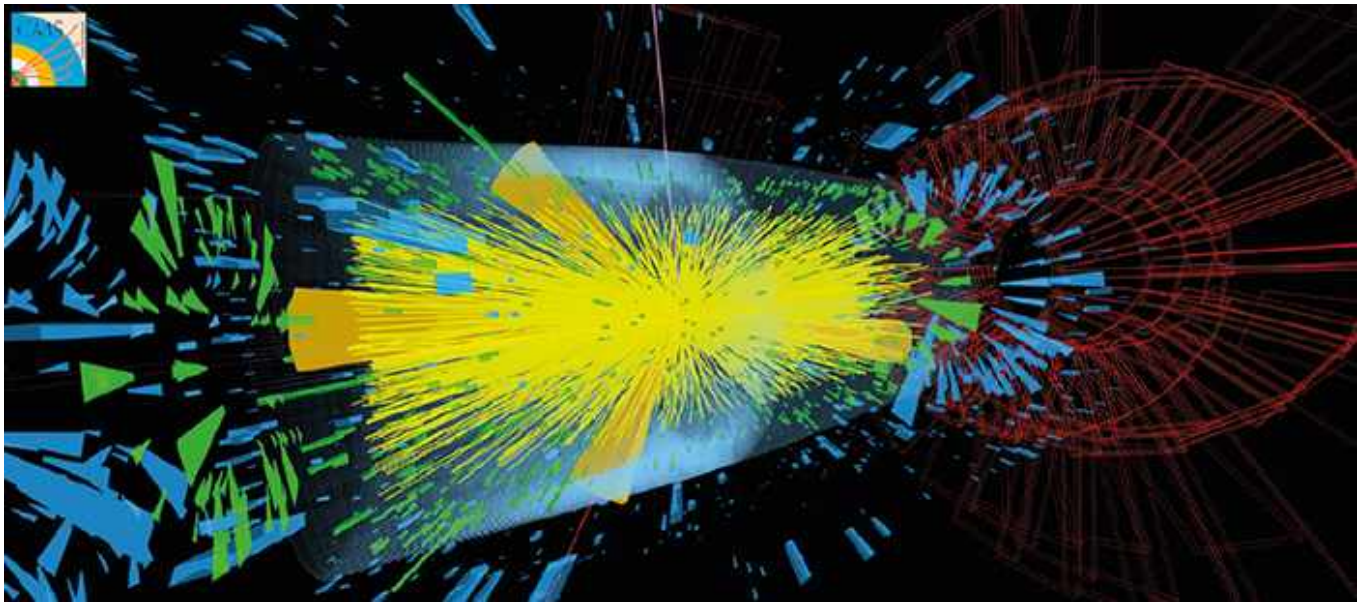


Upgrade of the CMS tracker for the HL-LHC
Why would we upgrade CMS ?

- Luminosity is no good if we can't record it!
- Two main challenges are facing us
  - $\mathcal{L}_{inst}$ → Pile-up of 140-200

    Complexity, fakes, energy resolution, confuses the trigger,...
  - $\int \mathcal{L}_{inst}$ → Ageing of the detector.

    Radiation damages would blind us



Upgrade of the CMS tracker for the HL-LHC



265.000.000 CHF question:

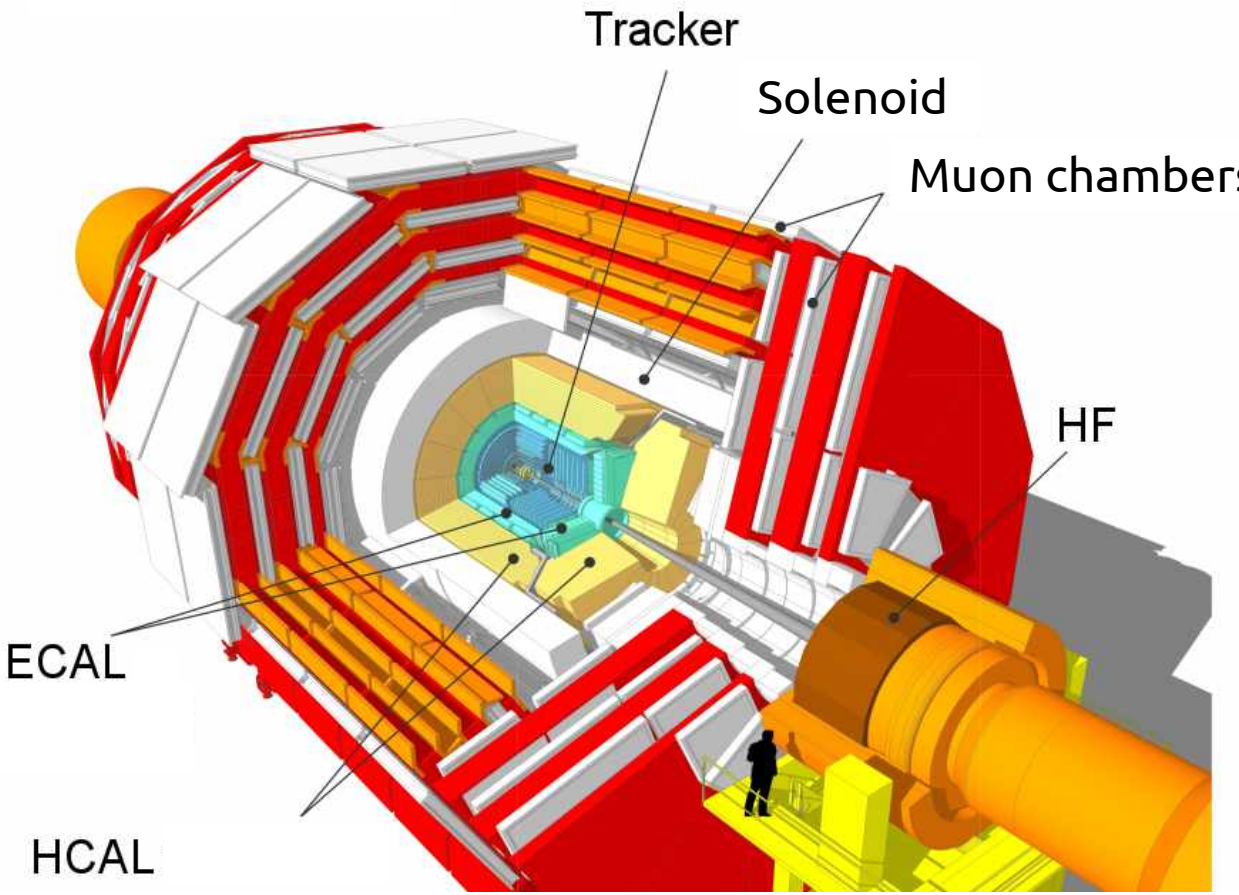
How can we maintain the performance of the detector through run 3?

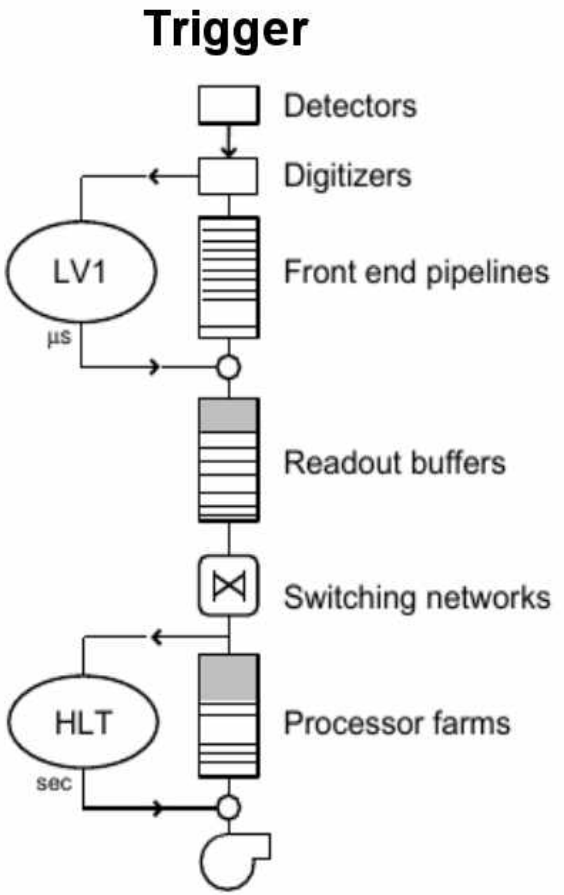
Upgrade of the CMS tracker for the HL-LHC
Outline of the talk



- CMS upgrade
- Tracker upgrade
  - Goals and current design
- Current status – prototype testing
  - MAPSA
  - CBC2
- Prospects – construction
  - Belgian / UCL involvement ?

CMS upgrade
Mandatory CMS picture

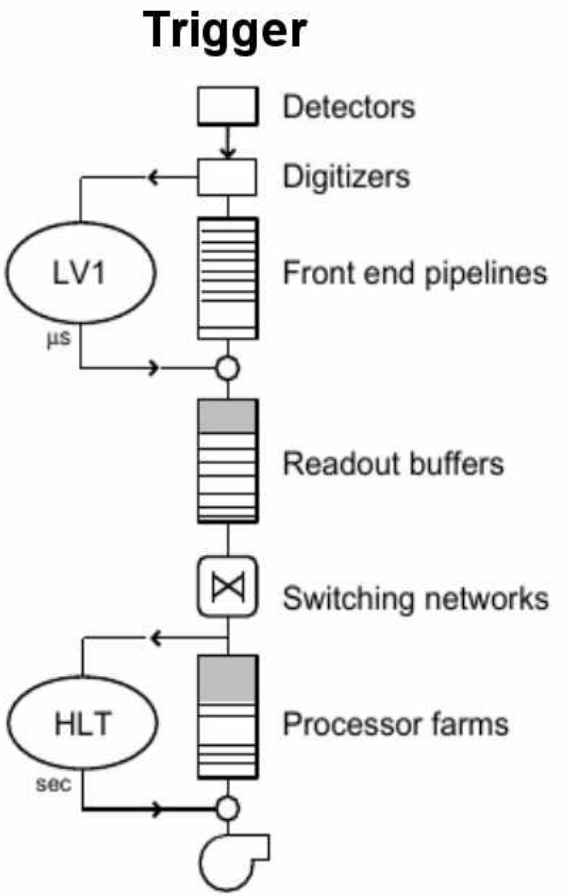




CMS upgrade
Trigger upgrade

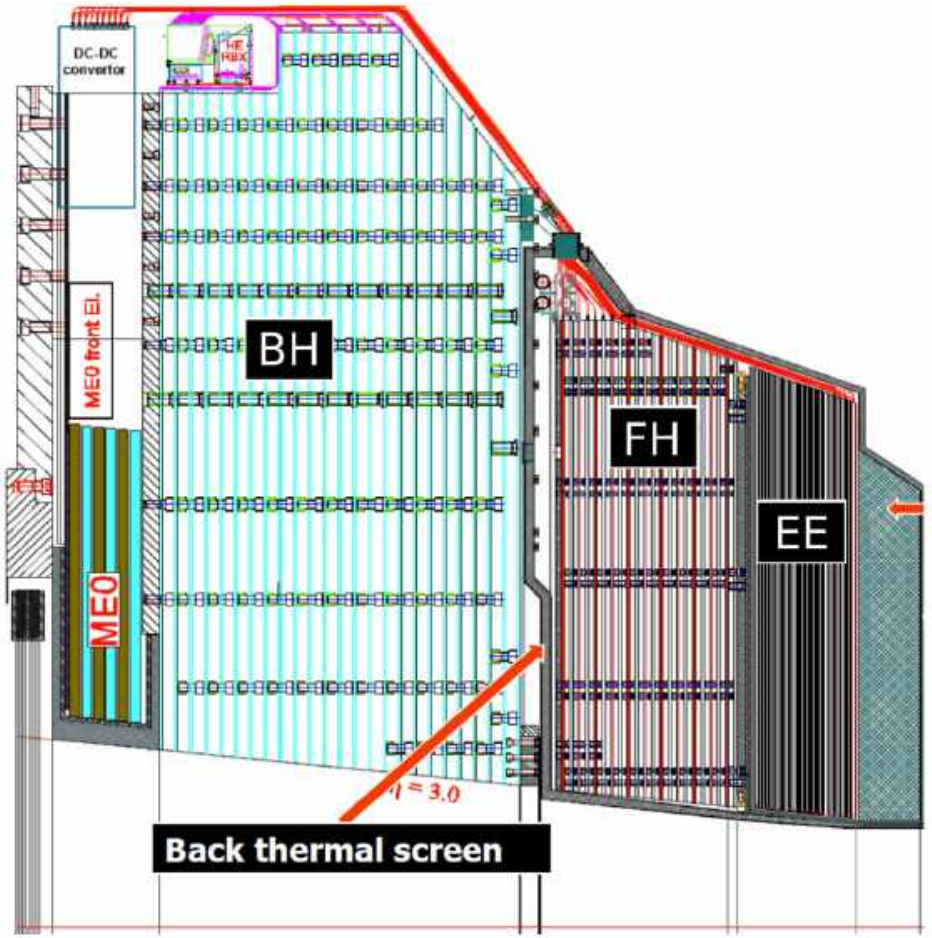
- We need a good trigger more than ever!

- Increased trigger rate
- Smarter (but slower) L1 trigger
  - Include tracker information
  - Match tracks to muon and calorimeter information
  - topological trigger combining objects of different nature
  - 12.5μs latency (vs 6.4μs)



CMS upgrade
Calorimeters

- Very few changes to barrel.



- End-caps will be fully replaced
  - High granularity, 3D shower information
    - EE : Silicon + Tungsten
    - FH : Silicon + Brass
    - BH : Scint. + Brass
  - Precise timing information

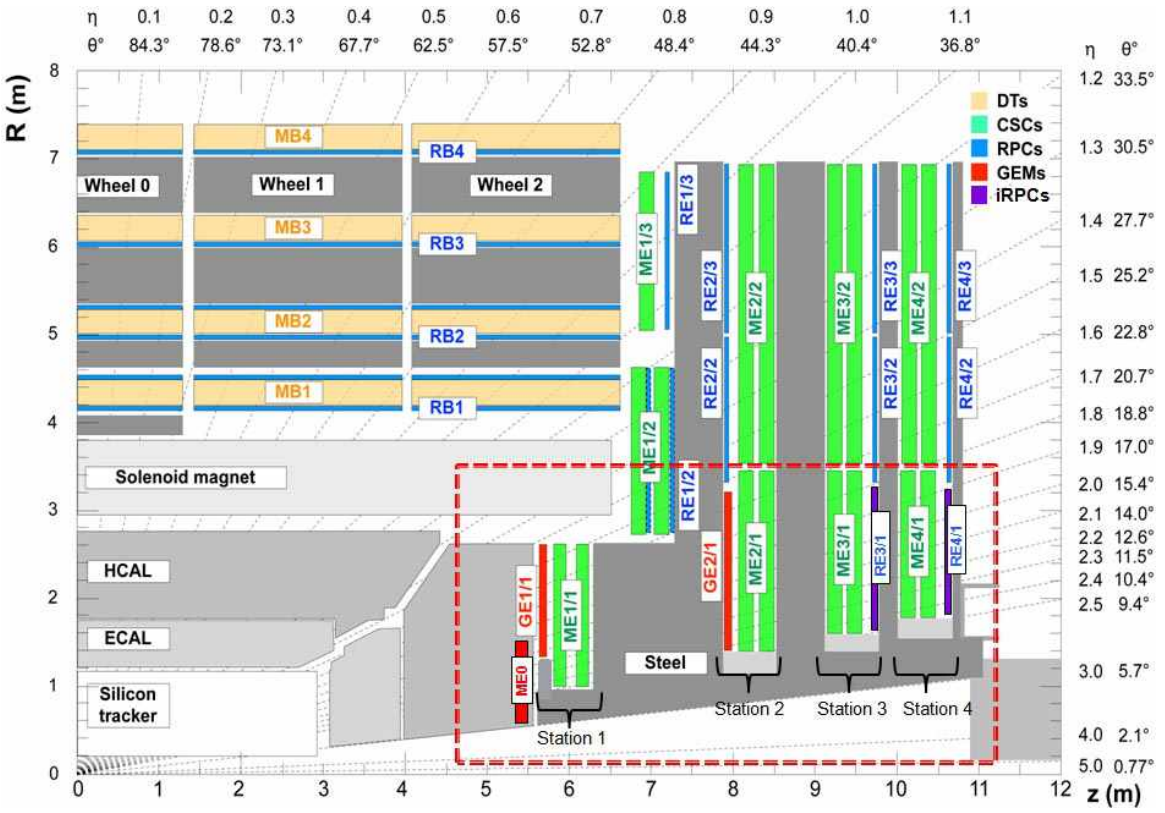
→ Improves pile-up rejection

CMS upgrade
Muon system

- Changes to readout electronics

- Adding redundancy in high eta region

- Adding muon tag station in space gained from calo upgrade.
  - Extends eta coverage up to 3



Upgrade of the CMS tracker for the HL-LHC
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  - **Goals and current design**
- Current status – prototype testing
  - MAPSA
  - CBC2
- Prospects – construction
  - Belgian / UCL involvement ?

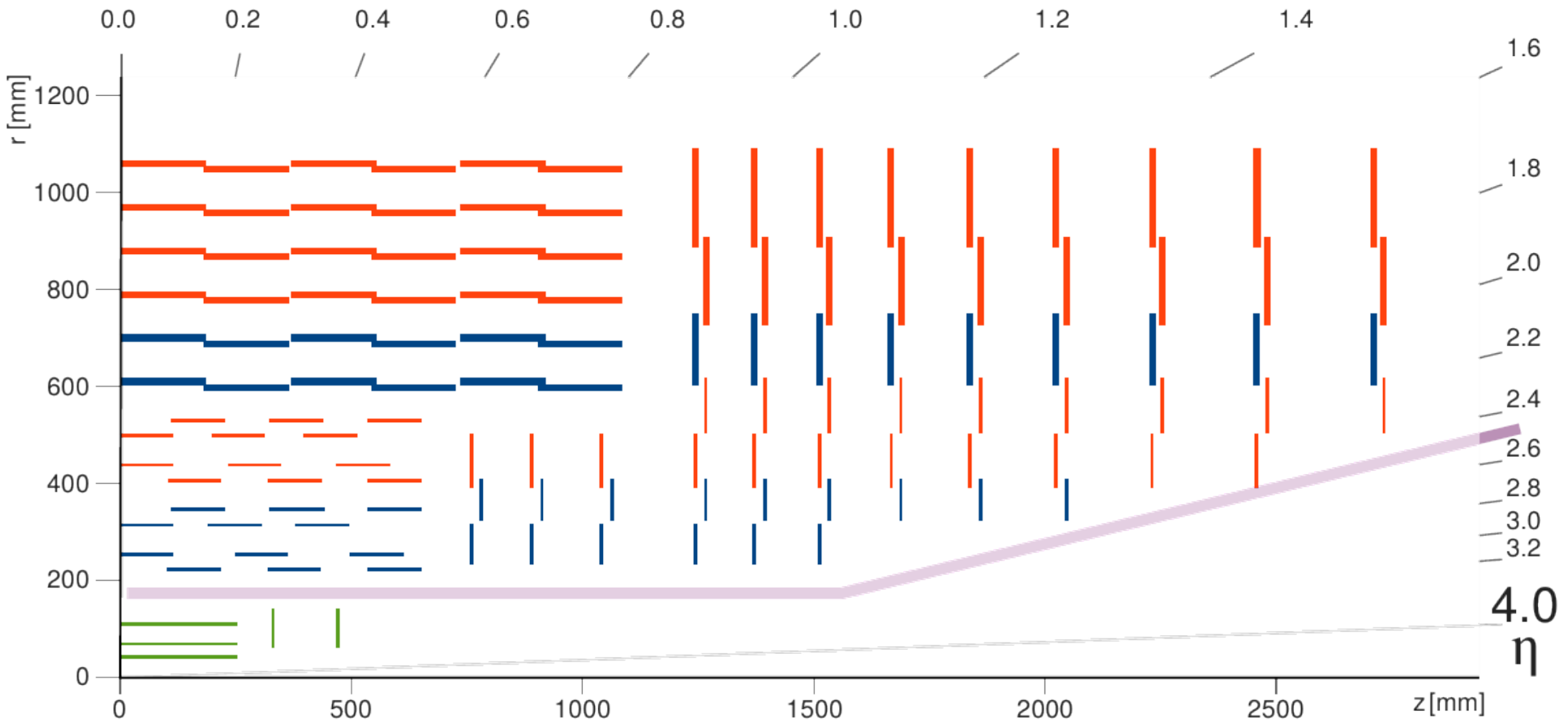
CMS tracker upgrade

Goals



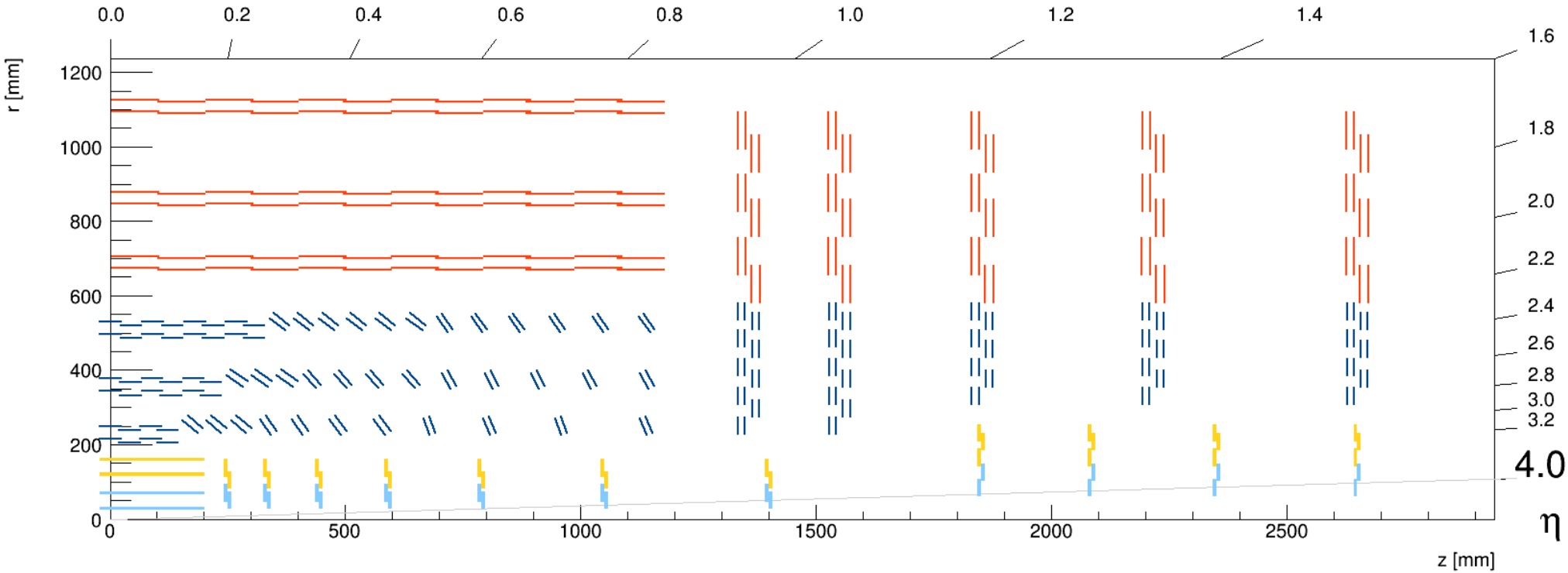
- Tolerate the radiation associated with 3000fb^{-1}
- Improve 2-tracks separation, improve resolution at high pT
- Cope with increased trigger rate
- Participate to the trigger decisions
- Improve low pT resolution
- Extend tracking acceptance

CMS tracker upgrade
Geometric design



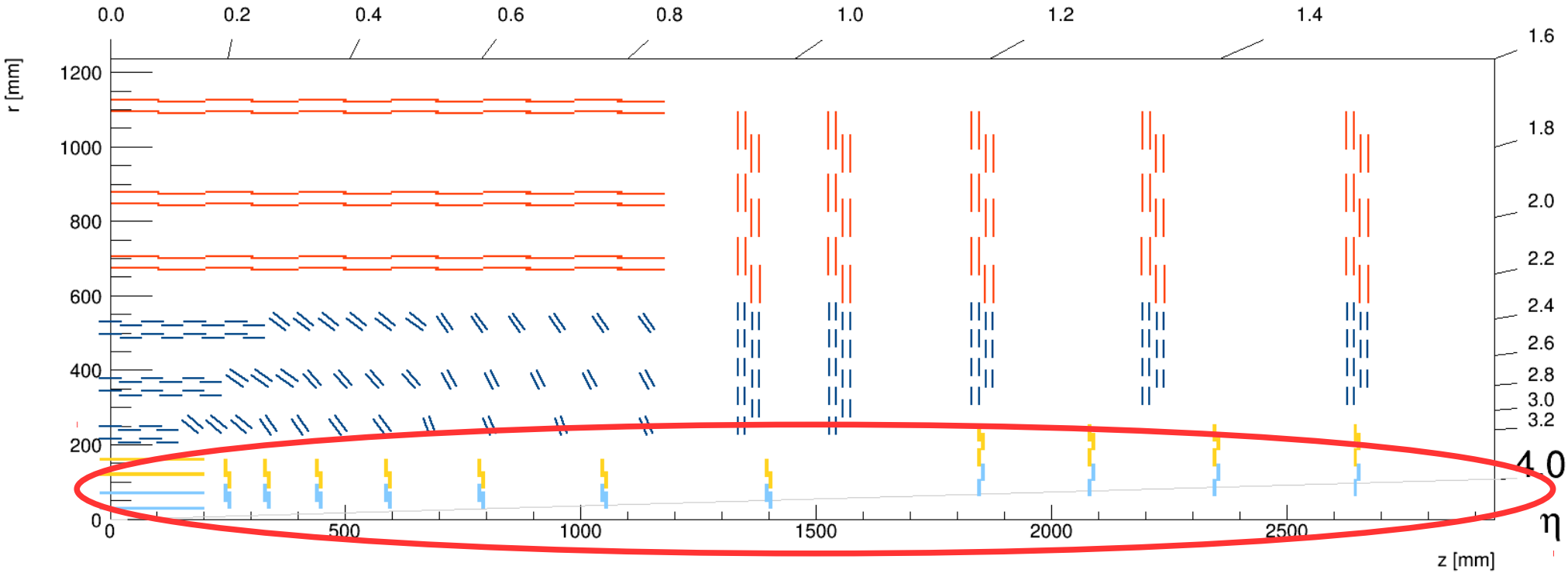
Current tracker

CMS tracker upgrade
Geometric design



Phase-2 tracker (current design)

CMS tracker upgrade
Geometric design



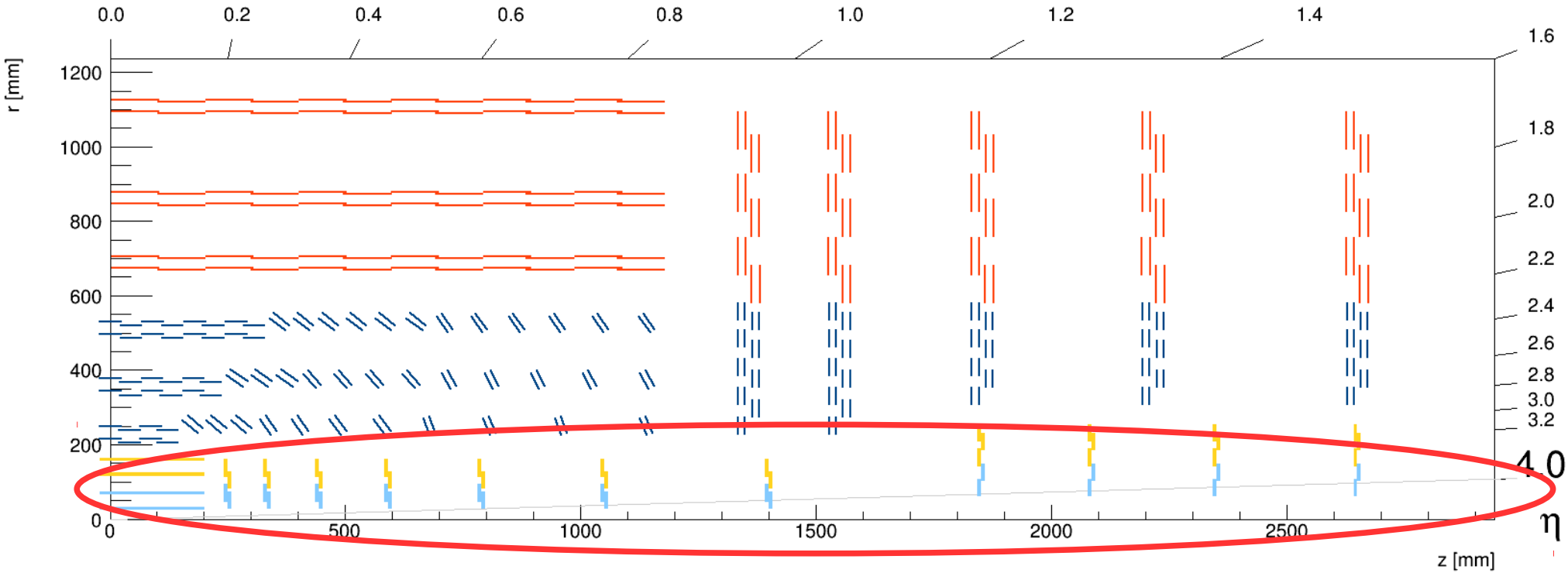
Pixel detector

Phase-2 tracker (current design)

CMS tracker upgrade

Geometric design

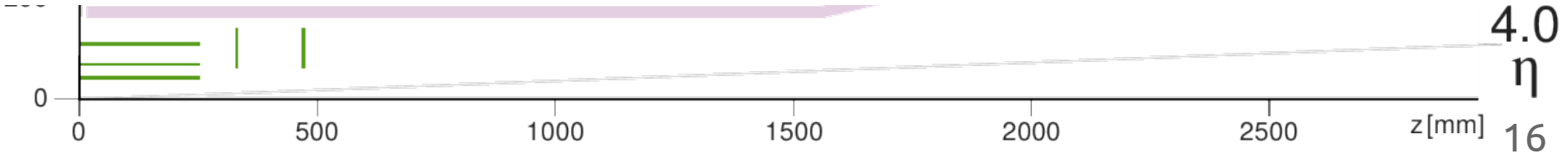
Phase-2 tracker (current design)



Pixel detector

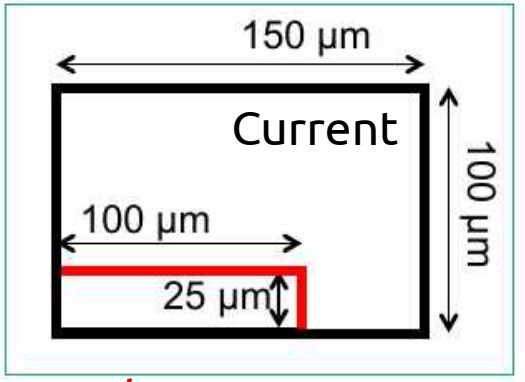
Current pixel

Huge increase in number of wheels → better eta coverage



CMS tracker upgrade
Pixel detector upgrade

- Number of pixels : 66 M → 1870M
- Silicon surface : ~1m² → ~4.7m²
- Reduced size of pixels
  - 6 times smaller
    - → better 2-track separation
    - → helps with radiation tolerance

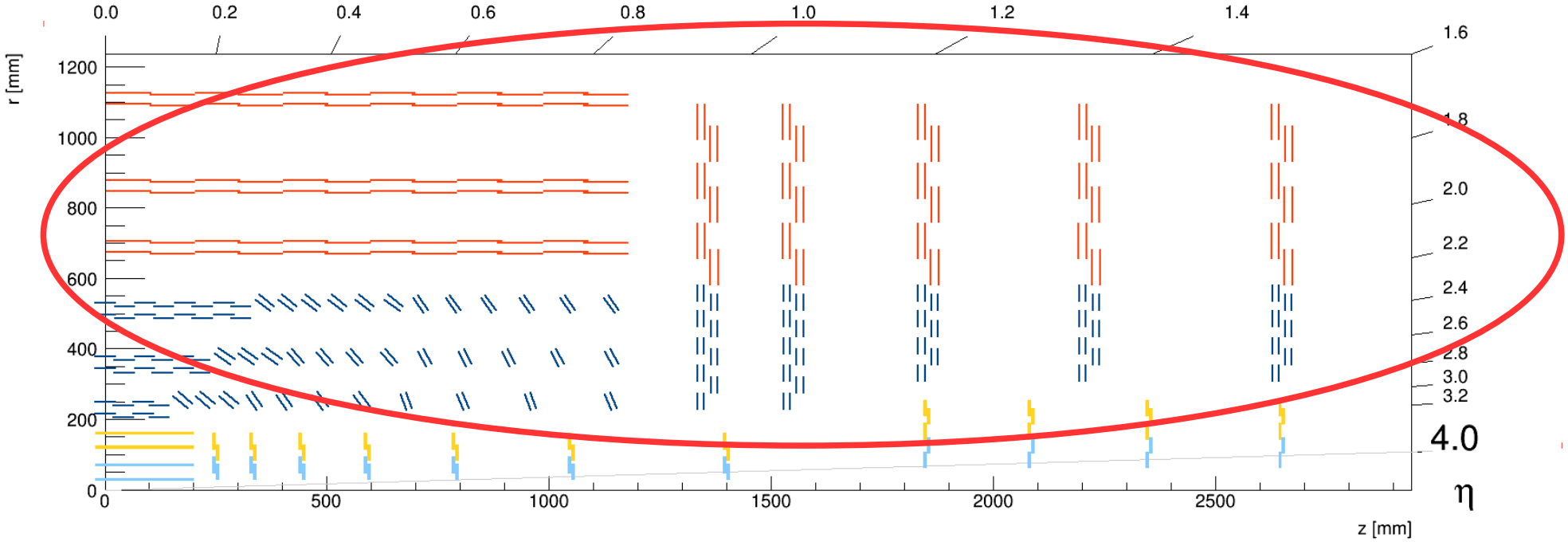


Phase 2

- Highly challenging conditions for Read-Out Chips
  - 5 times the hit rate
  - 5-10 times the trigger rate

CMS tracker upgrade
Geometric design

Outer tracker



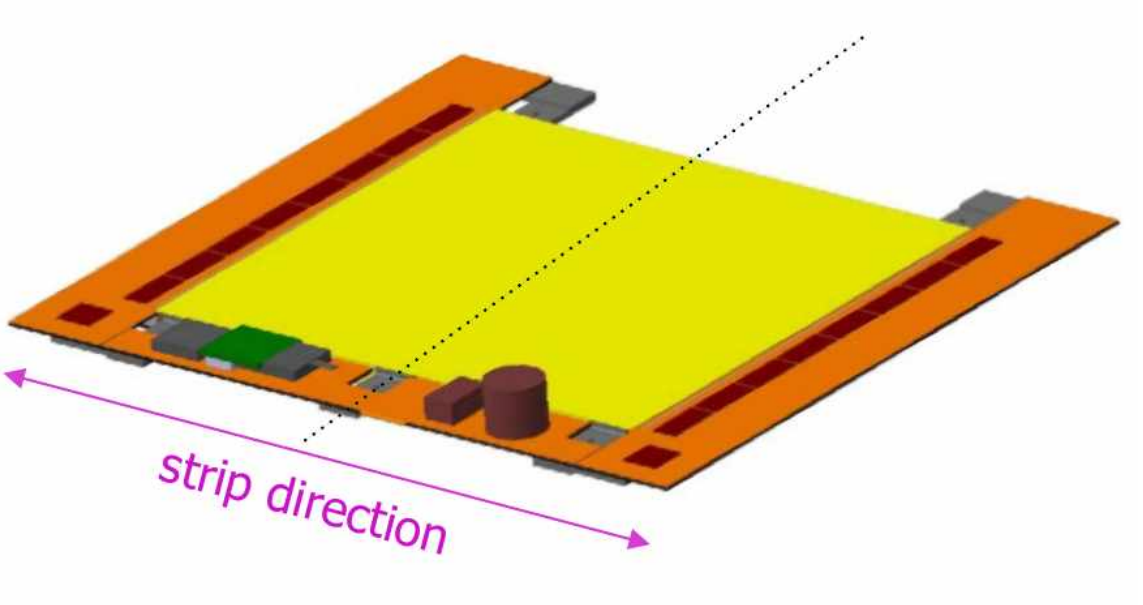
Recent design (October 2016)

6 Barrel layers vs 10 now? 5 disks vs 9?
How can we not loose redundancy ?

CMS tracker upgrade
New modules

- There is a huge conceptual difference for the new tracker

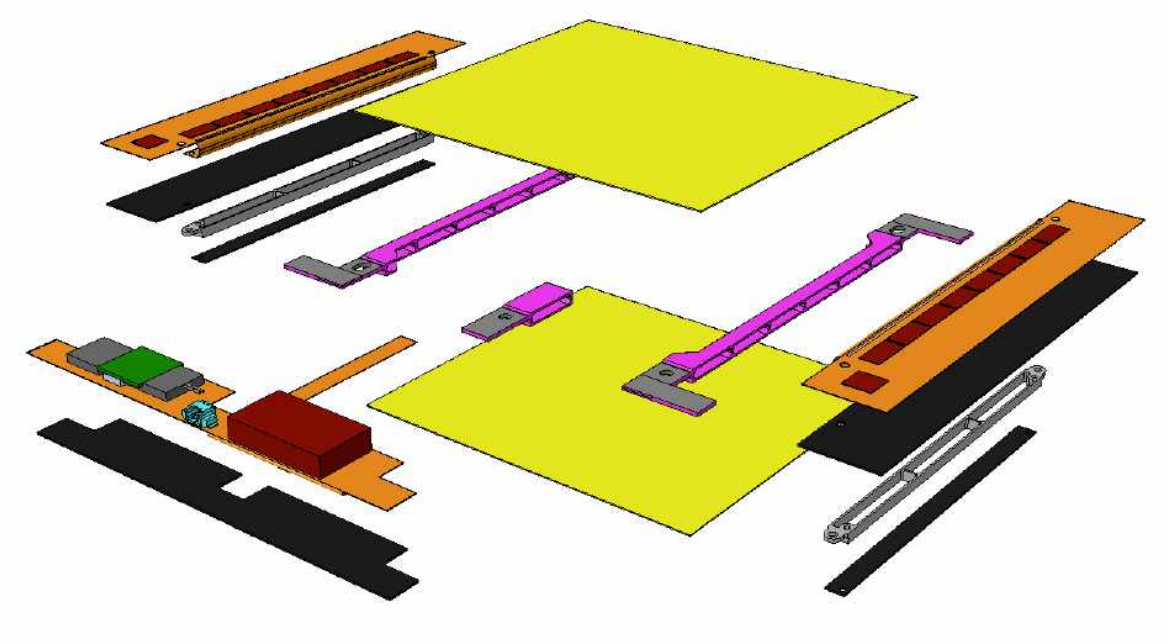
Design of an outer tracker module type



CMS tracker upgrade
New modules

- There is a huge conceptual difference for the new tracker

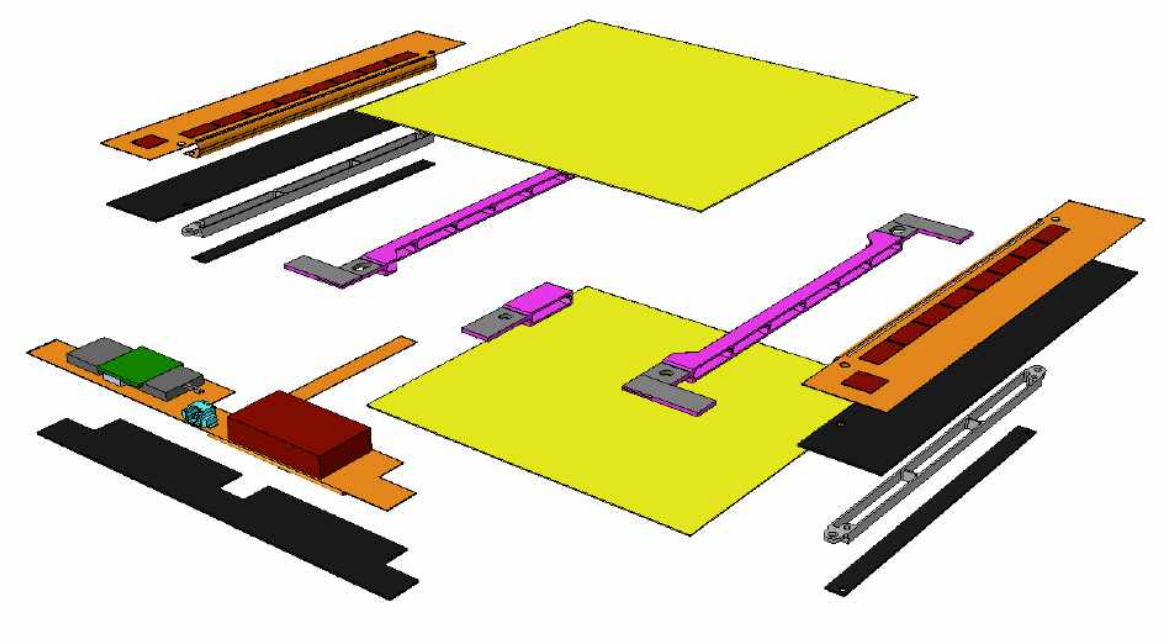
Design of an outer tracker module type



CMS tracker upgrade
New modules

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Design of an outer tracker module type

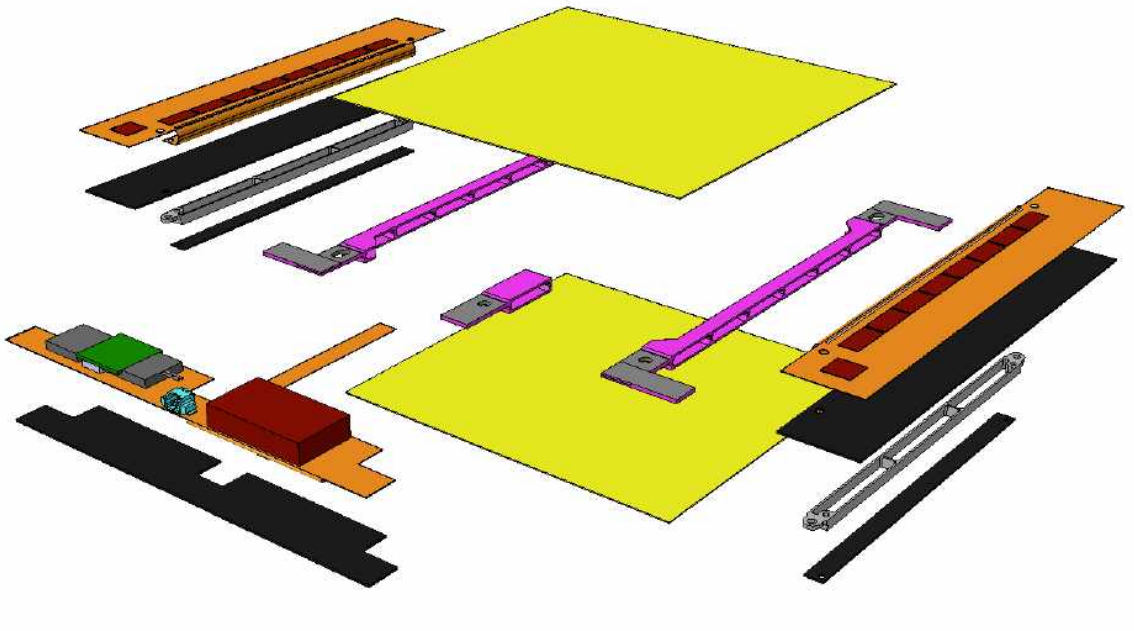


- Double sensors

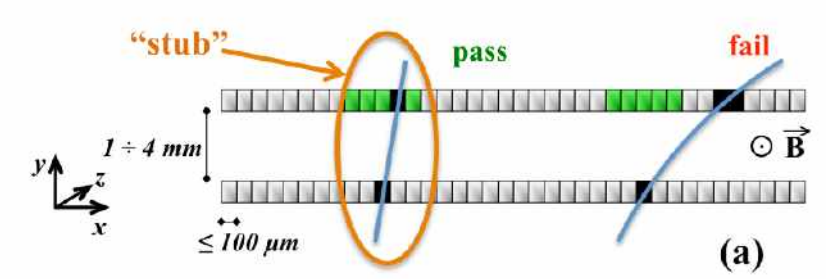
CMS tracker upgrade
New modules

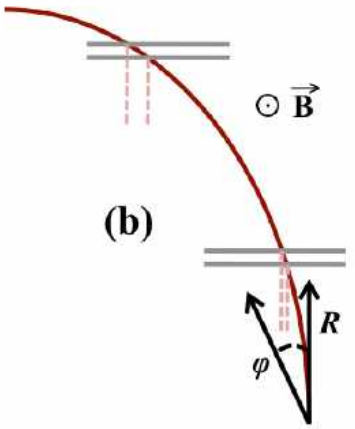
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Design of an outer tracker module type



- Double sensors



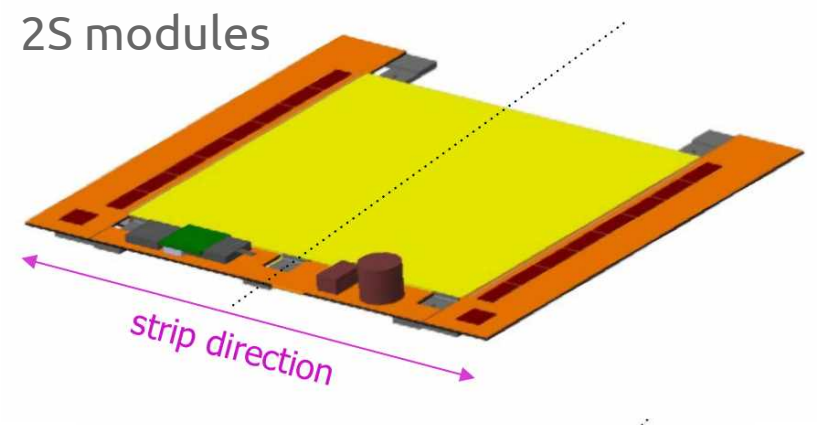


➞ A module can discriminate on pT

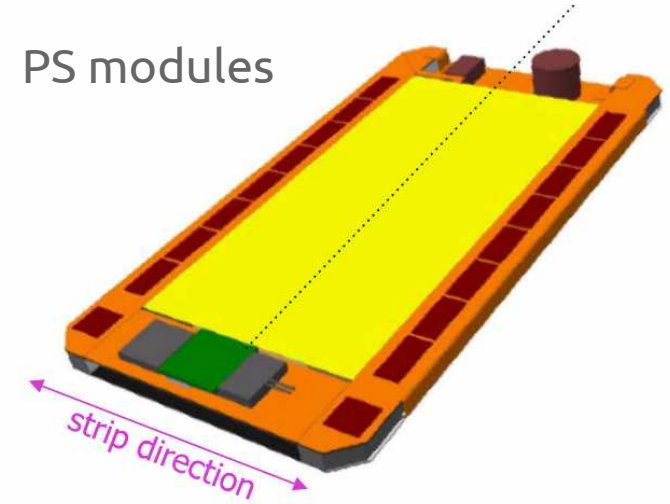
➞ "stubs" (mini-tracks) of particles with pT > 2GeV/c can be sent to L1

CMS tracker upgrade
New modules

- Two types of modules



- 2 Strip sensors :
  - 5cm x90µm big strips
- ~8200 modules



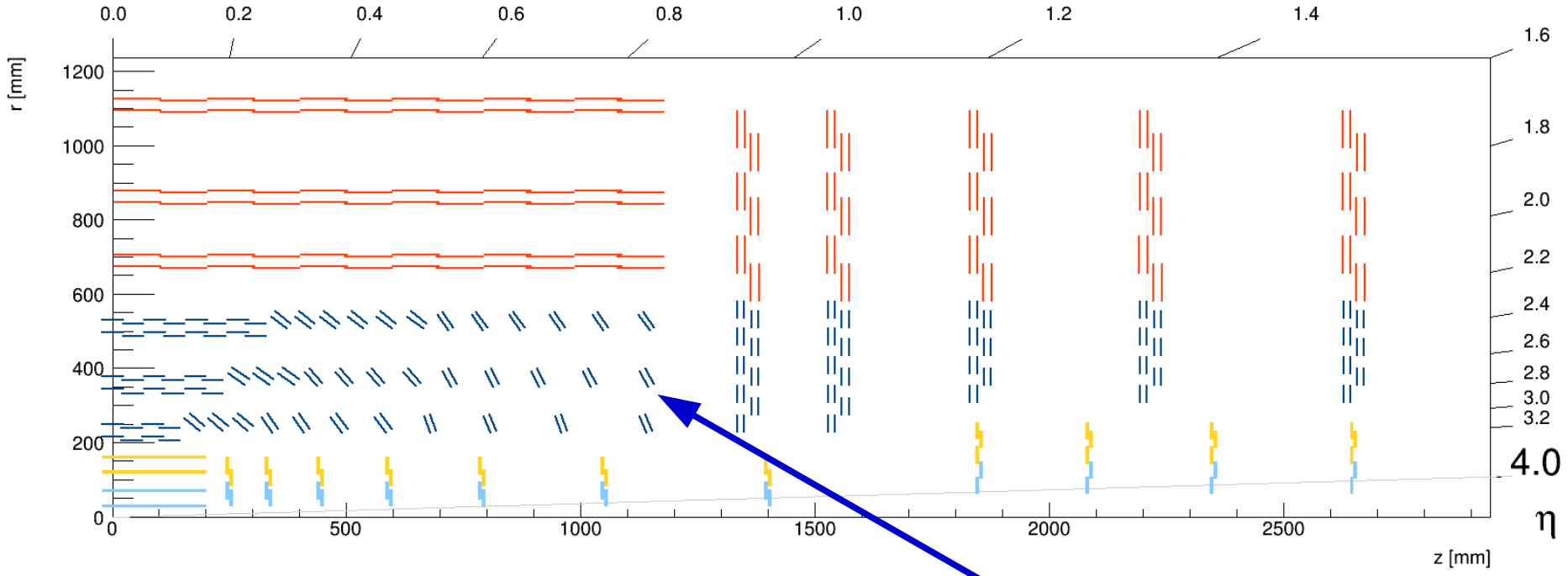
- 1 Strip sensor :
  - 100µm x 2.5 cm
- 1 Pixel sensor
  - 100µm x 1.5mm
- ~5300 modules

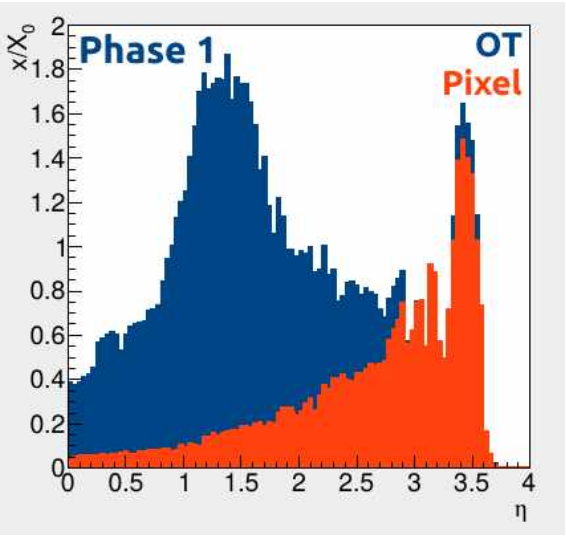
- For both, stubs sent at 40MHz, full data if L1A (750kHz)

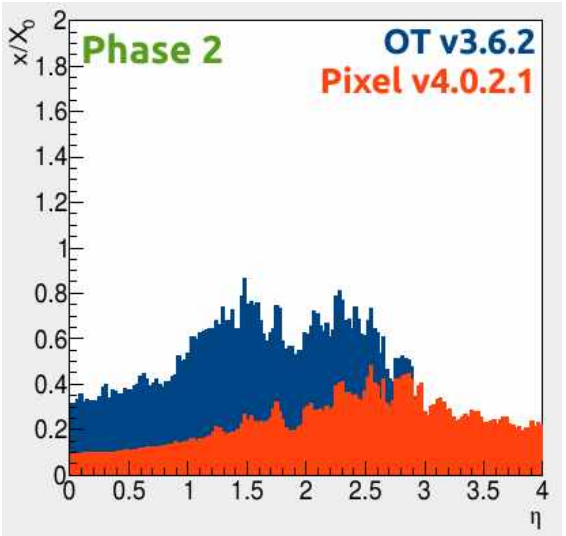
CMS tracker upgrade
Geometric design

2S modules

PS modules







Tilted modules in the barrel
→ Less material
(→ better resolution and lower cost)
→ Better stub efficiency
(particles go through the sensors of the same module)

CMS tracker upgrade

Goals

- Tolerate the radiation associated with 3000fb^{-1}
- Improve 2-tracks separation, improve resolution at high pT
- Cope with increased trigger rate
- Participate to the trigger decisions
- Improve low pT resolution
- Extend tracking acceptance

CMS tracker upgrade

Goals



- Tolerate the radiation associated with 3000fb^{-1}
  - New rad-hard design. Pixel will be replaceable
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- Improve 2-tracks separation, improve resolution at high pT
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  - New read-out chip design, high bandwidth
- Participate to the trigger decisions

- Improve low pT resolution

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CMS tracker upgrade

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- Improve 2-tracks separation, improve resolution at high pT
  - Increased granularity
- Cope with increased trigger rate
  - New read-out chip design, high bandwidth
- Participate to the trigger decisions
  - Stubs read-out at 40MHz
- Improve low pT resolution

- Extend tracking acceptance

CMS tracker upgrade

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  - New read-out chip design, high bandwidth
- Participate to the trigger decisions
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- Improve low pT resolution
  - Material budget decreased
- Extend tracking acceptance

CMS tracker upgrade
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- Extend tracking acceptance
  - Pixel layout extended

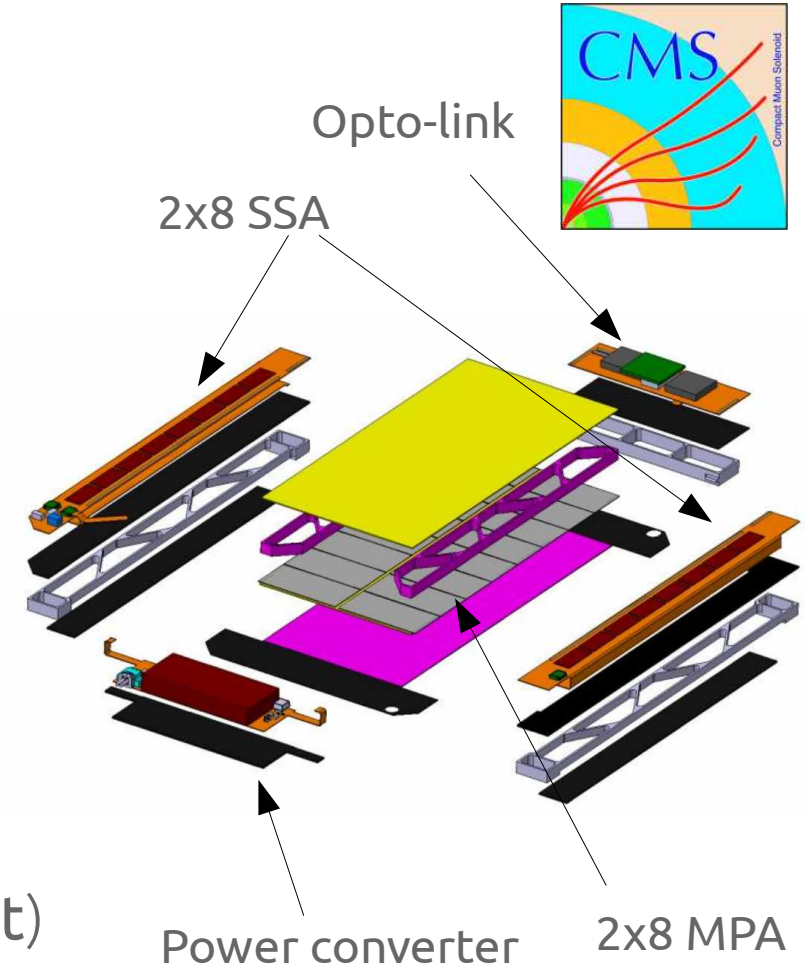
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Outline of the talk



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  - **CBC2**
- Prospects – construction
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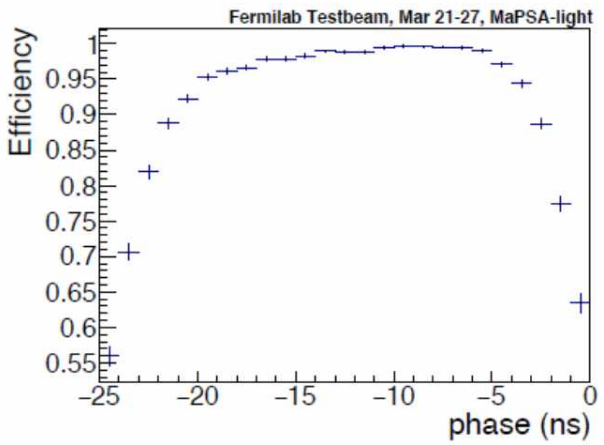
Current status – prototype testing
PS modules

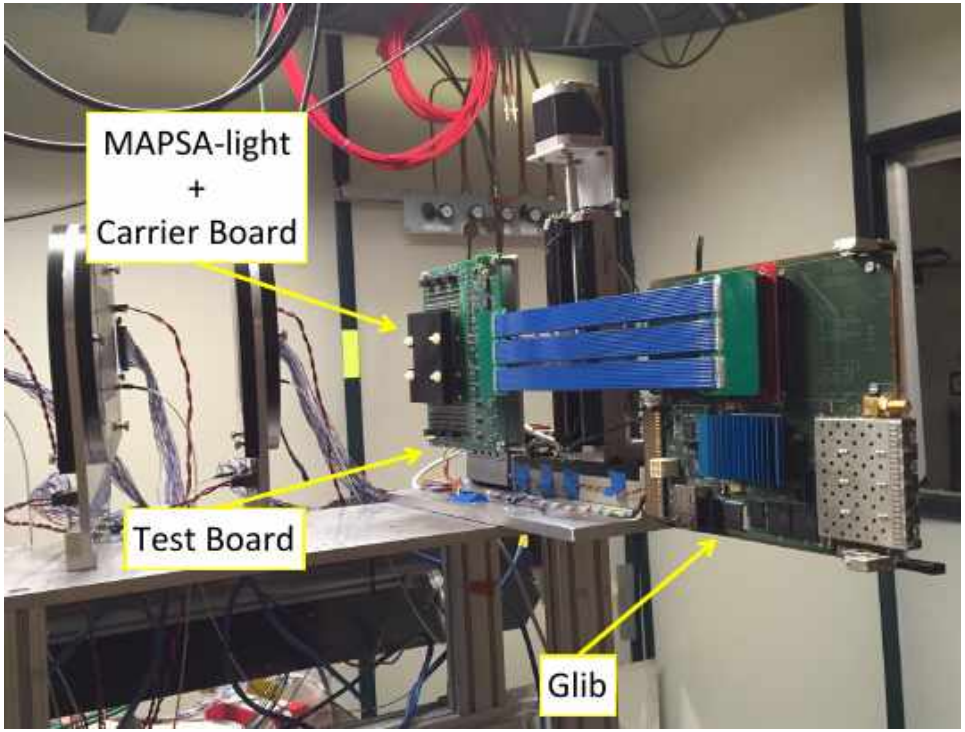
- Parts of a PS module
  - Strip Sensor ASIC (SSA)
    - Reads out strips
    - Prototype to be submitted in 2017
  - Macro Pixel ASIC (MPA)
    - Reads out pixels
    - Provide stubs
    - Small prototype available (MPA-light)
    - Full size to be submitted in 2017
  - Service hybrids
    - Power converter
    - Optical link



Current status – prototype testing
PS modules

- A **MPA-light** assembly was tested at Fermilab end of last year
  - 6MPA-light on a sensor
    - → No stub information yet...
    - → Efficiency, cluster size, ...

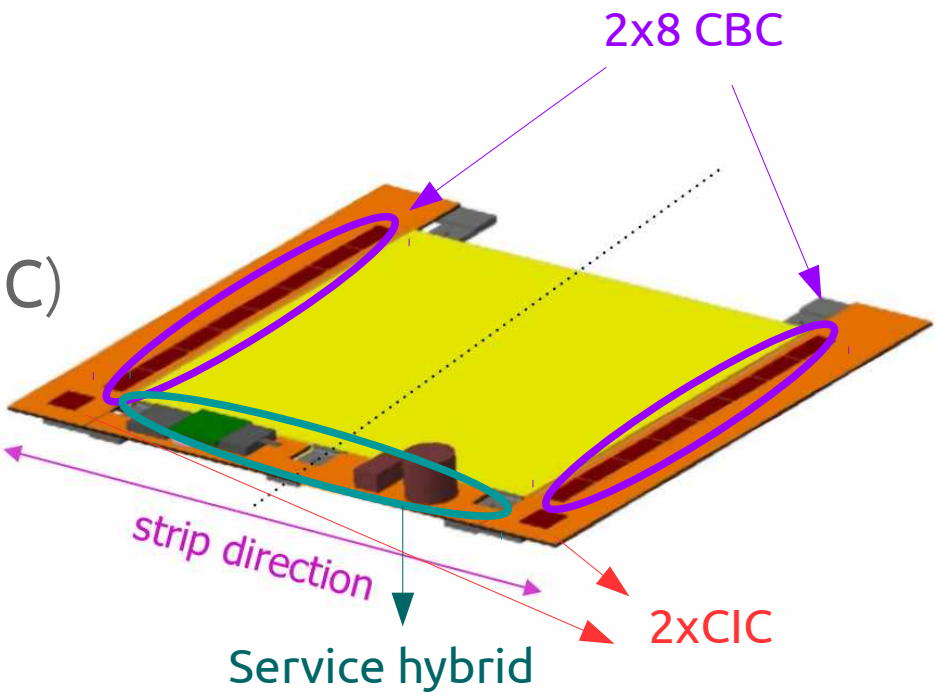




Beam test on a double sensor MPA-light micro-module currently ongoing!

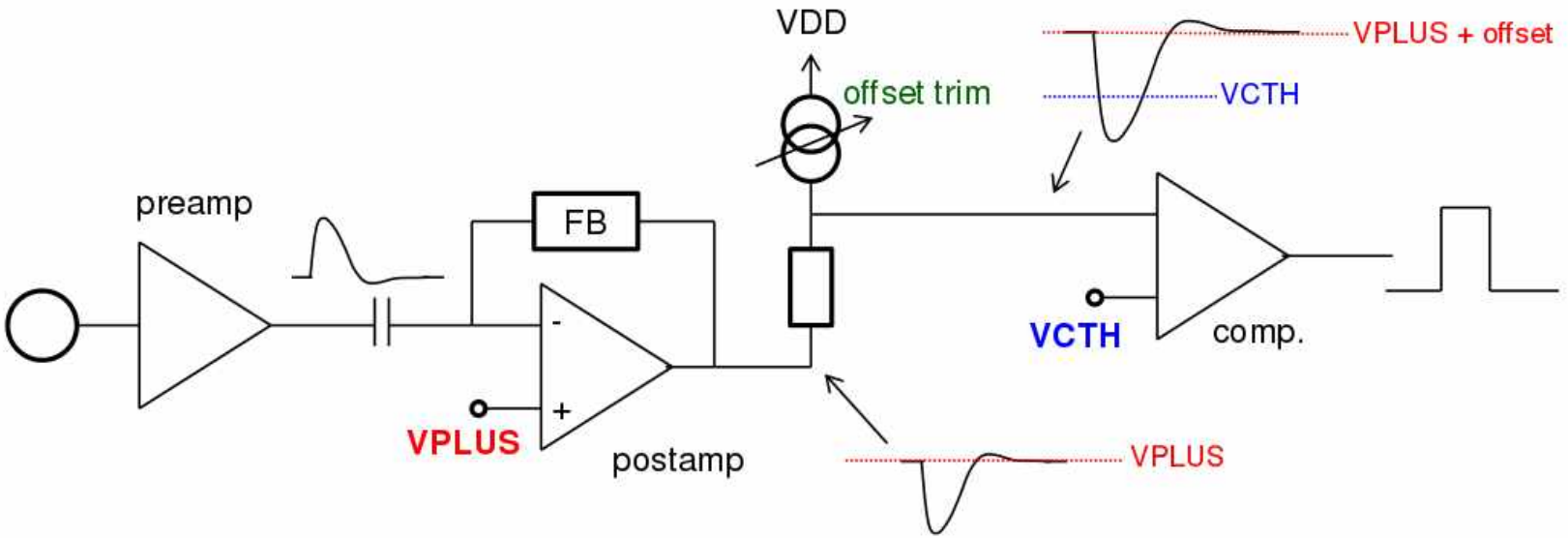
Current status – prototype testing
2S modules

- A 2S module will need the following ingredients :
  - Read-out chip: **C**ms **B**inary **C**hip
    - Version 2 available (**CBC2**)
    - Version 3 planned for end of 2016
  - **C**oncentrator **I**ntegrated **C**ircuit (**CIC**)
    - Aggregates data and stubs
    - Optimises use of bandwidth
    - Prototype to be submitted in 2017
  - Service hybrid
    - Power converter
    - Optical link
    - Prototypes submitted/expected before end of 2017



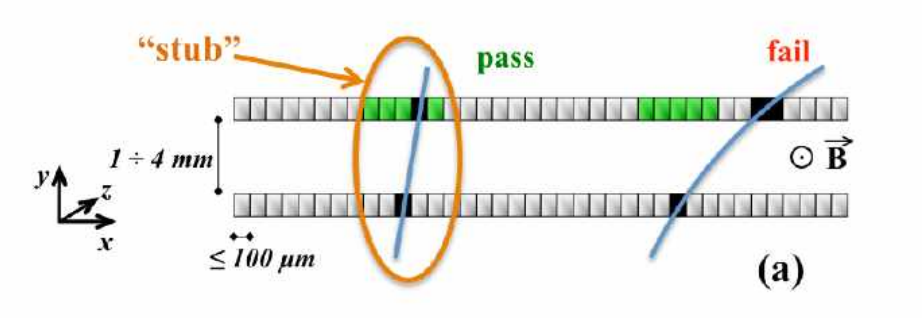
Current status – prototype testing
CBC2 – tasks

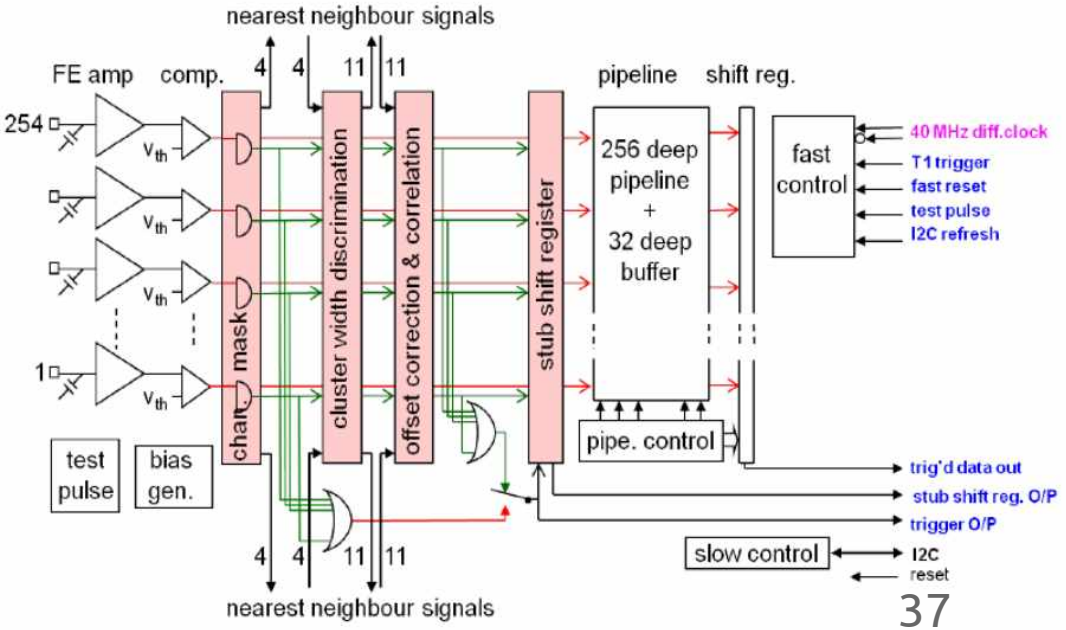
- What are the tasks of the CBCs?
- Analogue side:
  - Collect, shape and amplify the charge
  - Provide hit detect logic
    - To simplify : if charge > threshold, hit!



Current status – prototype testing
CBC2 – tasks

- Digital side:
  - Produce clusters
    - CBCv2: **clusters not read-out, only hits**
  - Correlate sensors and produce stubs
    - CBCv2: **stubs not read-out,** stub bit sent if a stub was produced
  - Send stubs continuously
  - Send data if L1A received





Current status – prototype testing
CBC2 – Beam tests!



- How do we proceed from here?

BEAM TESTS

- Two objectives:
  - Testing:
    - Test prototype, measure performances, check for anything unexpected
    - Test DAQ, readout softwares, reconstruction
  - Integration:
    - Check that all developments work together

Current status – prototype testing
CBC2 – Beam tests!



- Numerous beam tests were organised
  - DESY 11-2013 First stub logic validation
  - Louvain 09-2014 “SEU tests” → ~CBC radiation tolerance tests
  - CERN 06-2015 Irradiated sensor test
  - CERN 11-2015 Full-size module test
  - CERN 05-2016 Irradiated sensor test
  - CERN 10-2016 Precise measurement
  - Louvain 11-2016 Heavy ionising particles test

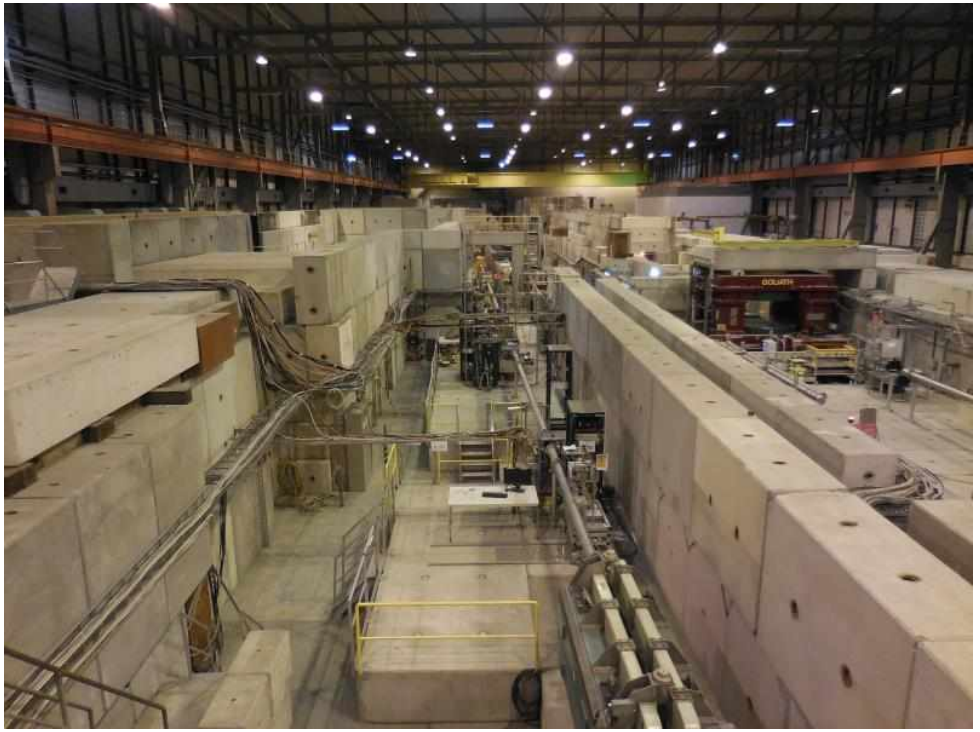
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CBC2 – Beam tests!

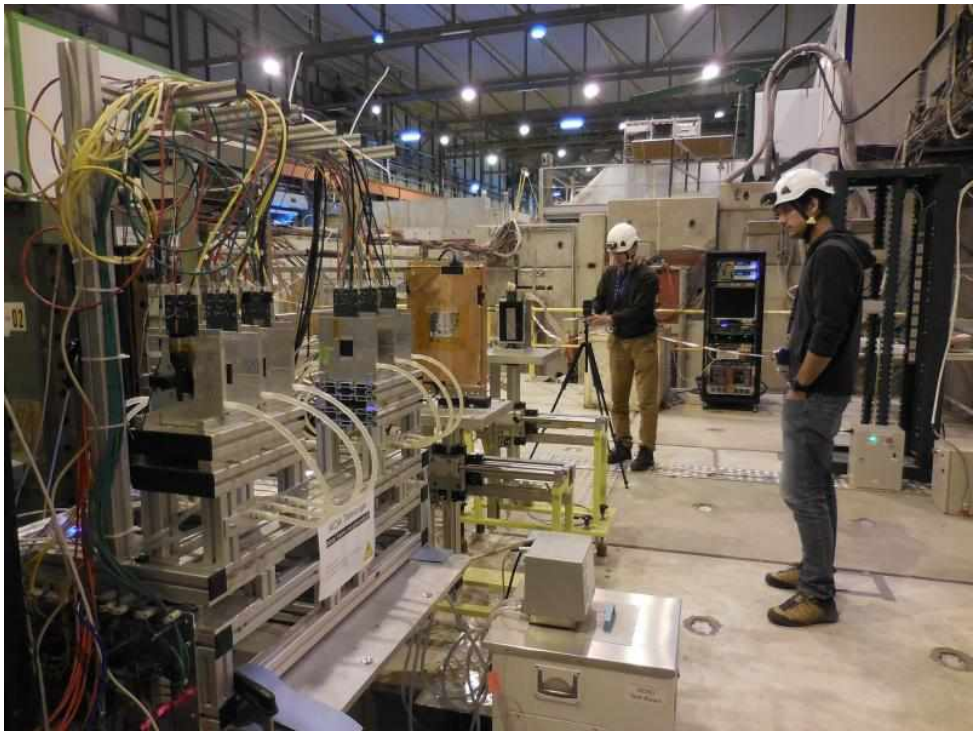


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Current status – prototype testing
SPS Beam tests

- CERN Beam tests
  - Four beam tests were organised at CERN during the “CBC2-era”
  - One week each time at a secondary beam of the SPS
    - A few GeV pion or muon beam → MIP



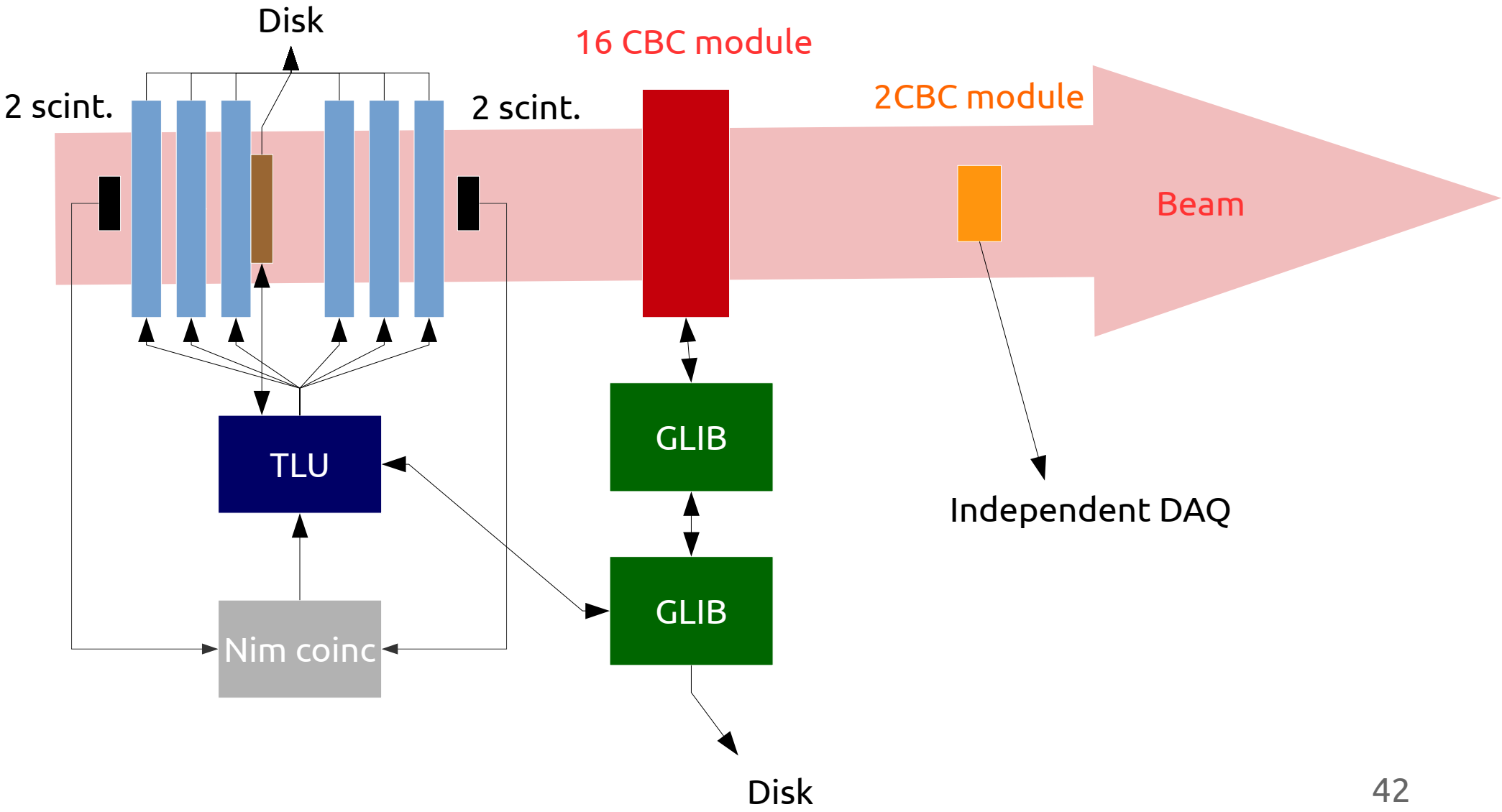


Current status – prototype testing

SPS Beam tests – Example setup, simplified view

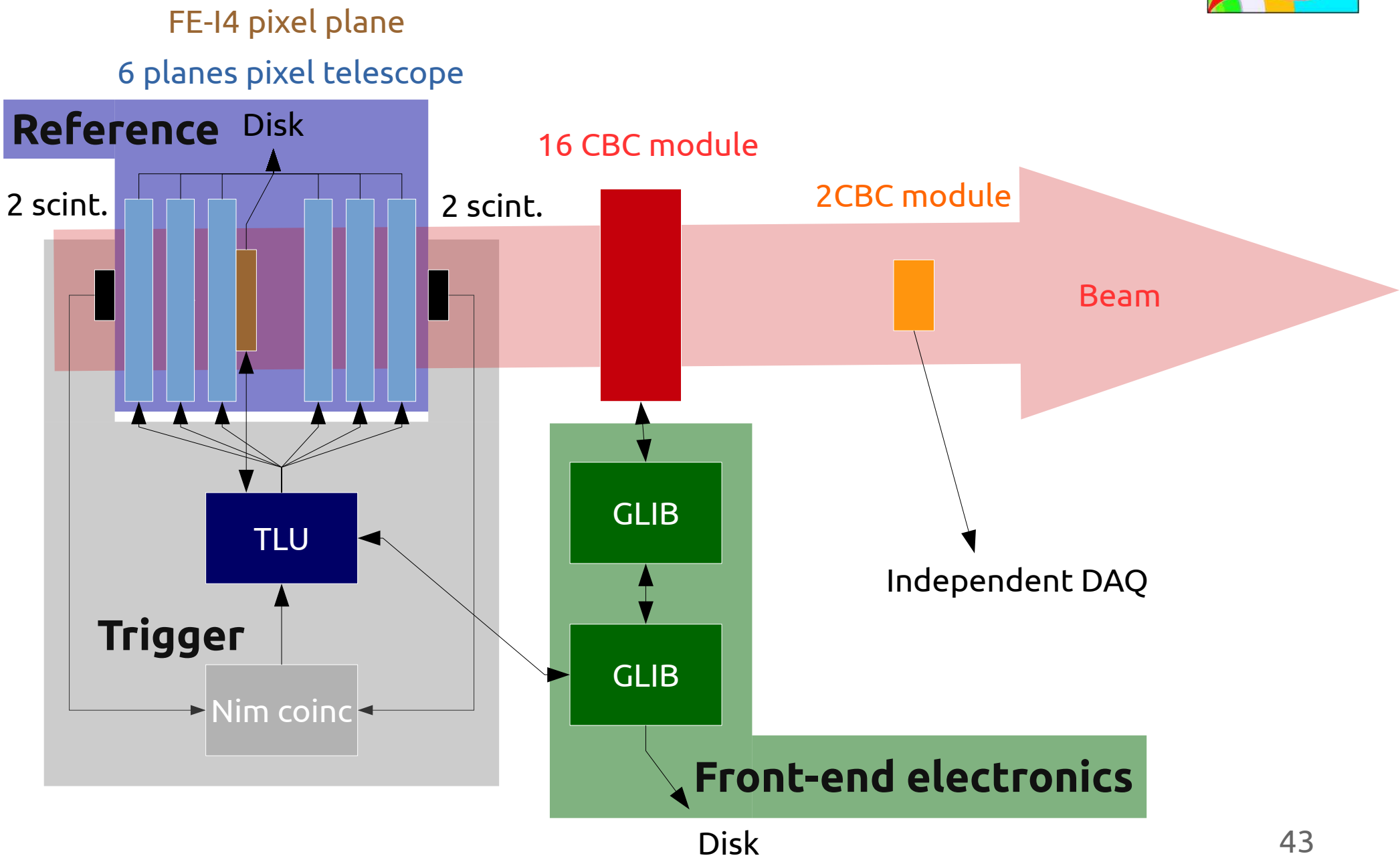
FE-I4 pixel plane

6 planes pixel telescope



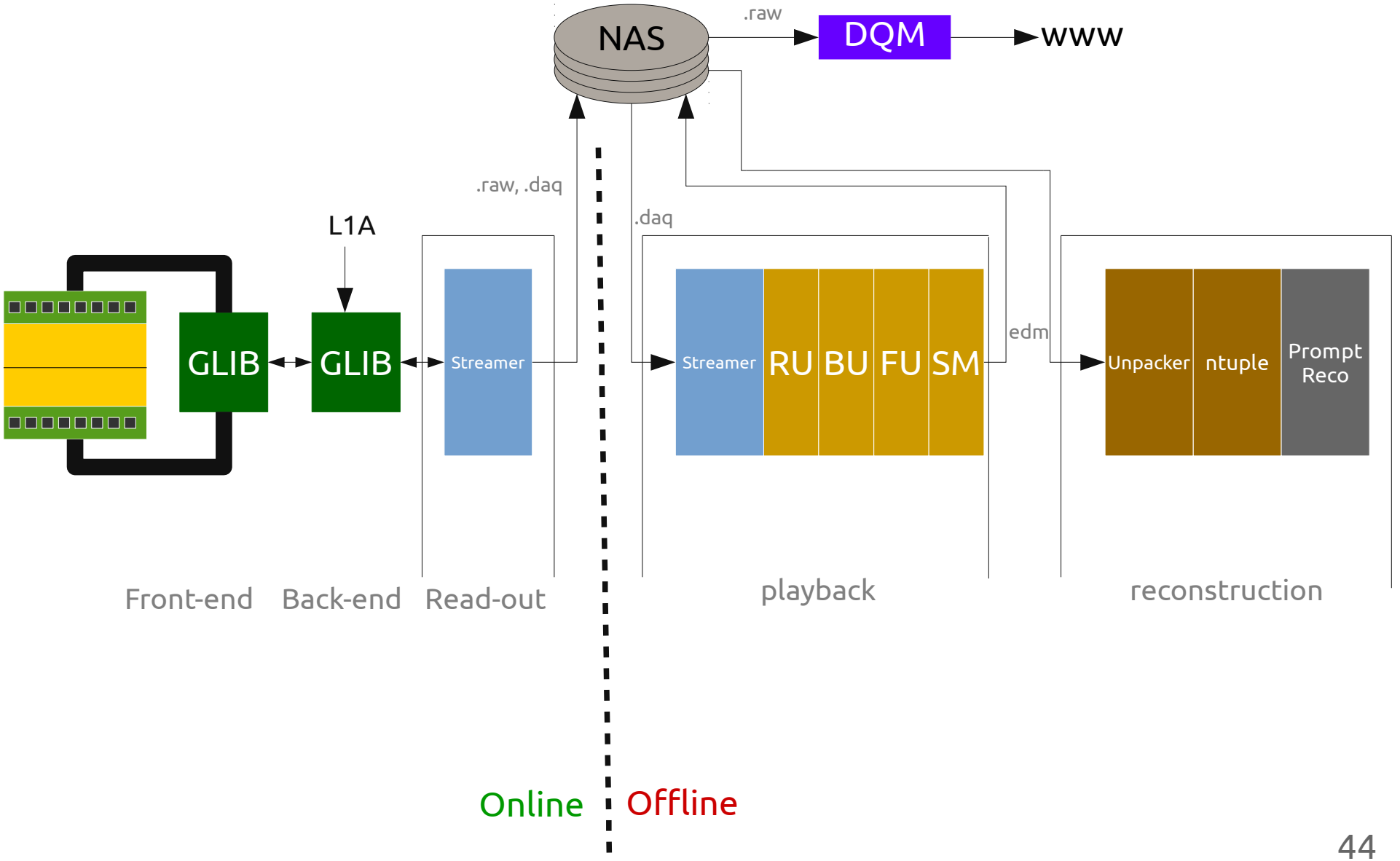
Current status – prototype testing

SPS Beam tests – Example setup, simplified view



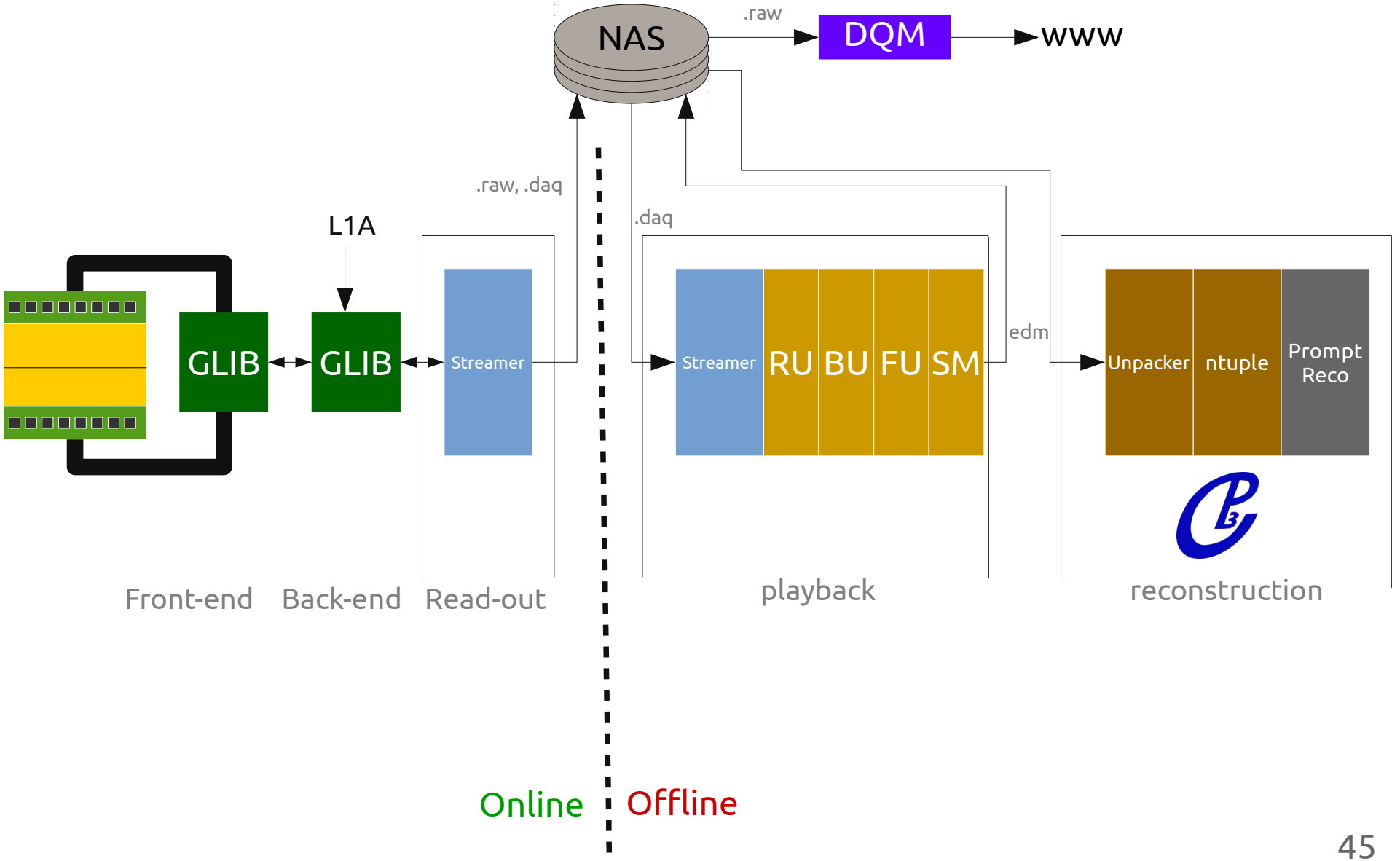
Current status – prototype testing

SPS Beam tests – Example setup, simplified view



Current status – prototype testing

SPS Beam tests – Example setup, simplified view



Current status – prototype testing
SPS Beam tests – Results?



- What was the outcome of the beam tests?

- Huge step forward in the development of the front-end electronics firmware and downstream software.
  - The whole system is now remarkably stable and automated.

- Loads of data to analyse

  → And loads of interesting results!

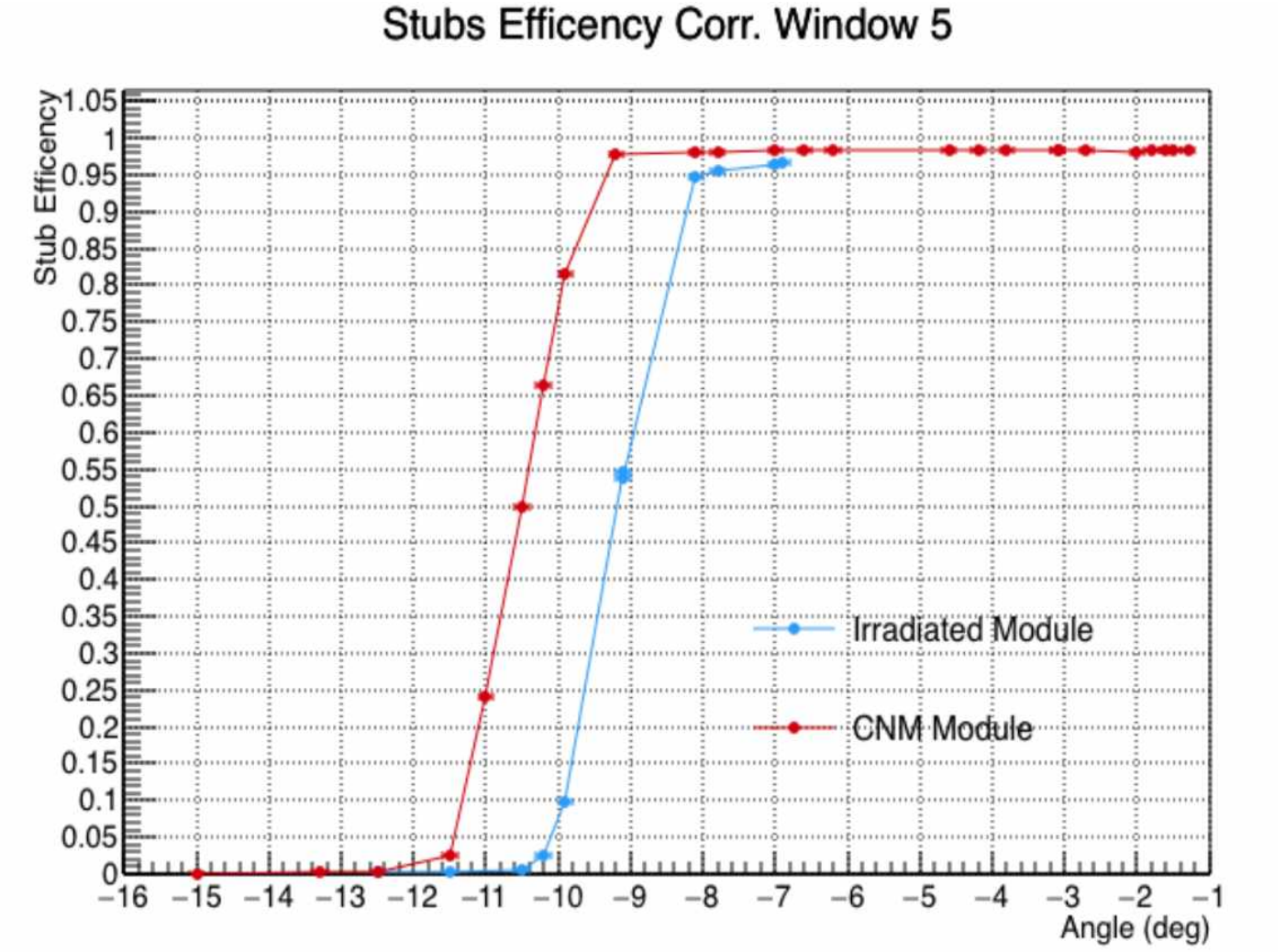
  - Very good efficiencies, >98% (99%) for (un-)irradiated module
  - Stub logic working as expected

Data still being analysed.
Full results will be in the Technical Design Report

Current status – prototype testing

SPS Beam tests – Efficiency

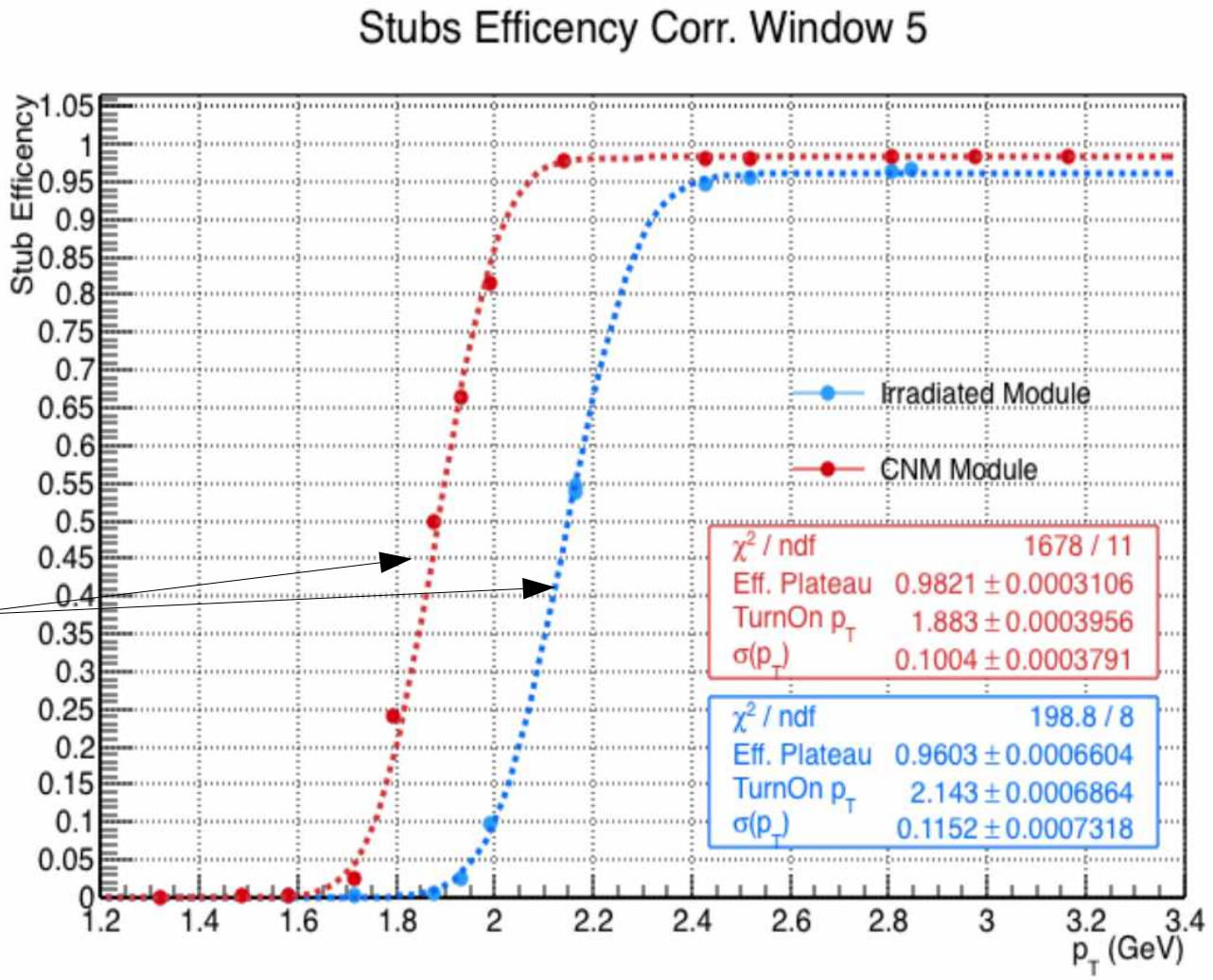
- Conclusion of these beam tests in two plots (1/2)
  - By turning the module, we can emulate the pT of particles



Current status – prototype testing

SPS Beam tests – Efficiency

- Conclusion of these beam tests in two plots (2/2)
  - Assuming a radius of 60cm, we can convert angle to pT :



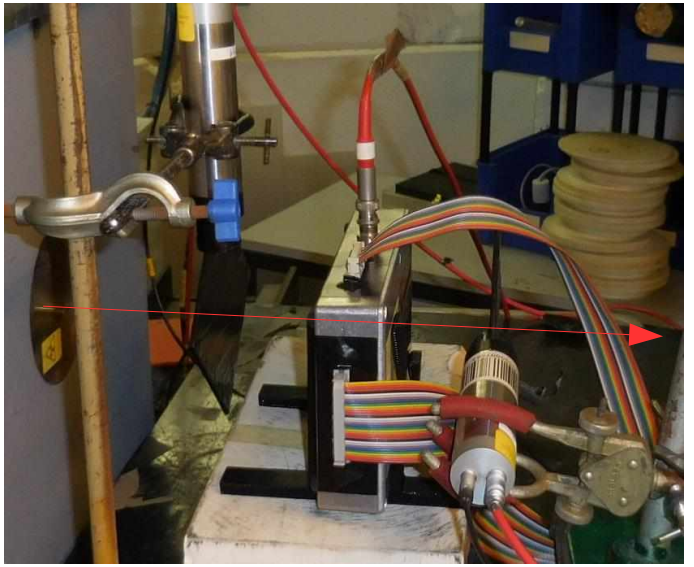
Difference from spacing between sensors

Current status – prototype testing
Louvain Beam test

- Louvain Beam test
  - One month ago (8-9/11)
  - 65 MeV protons
    - Could reduce energy
  - High intensity
    - ~2E3 → 2E8 Hz/cm²

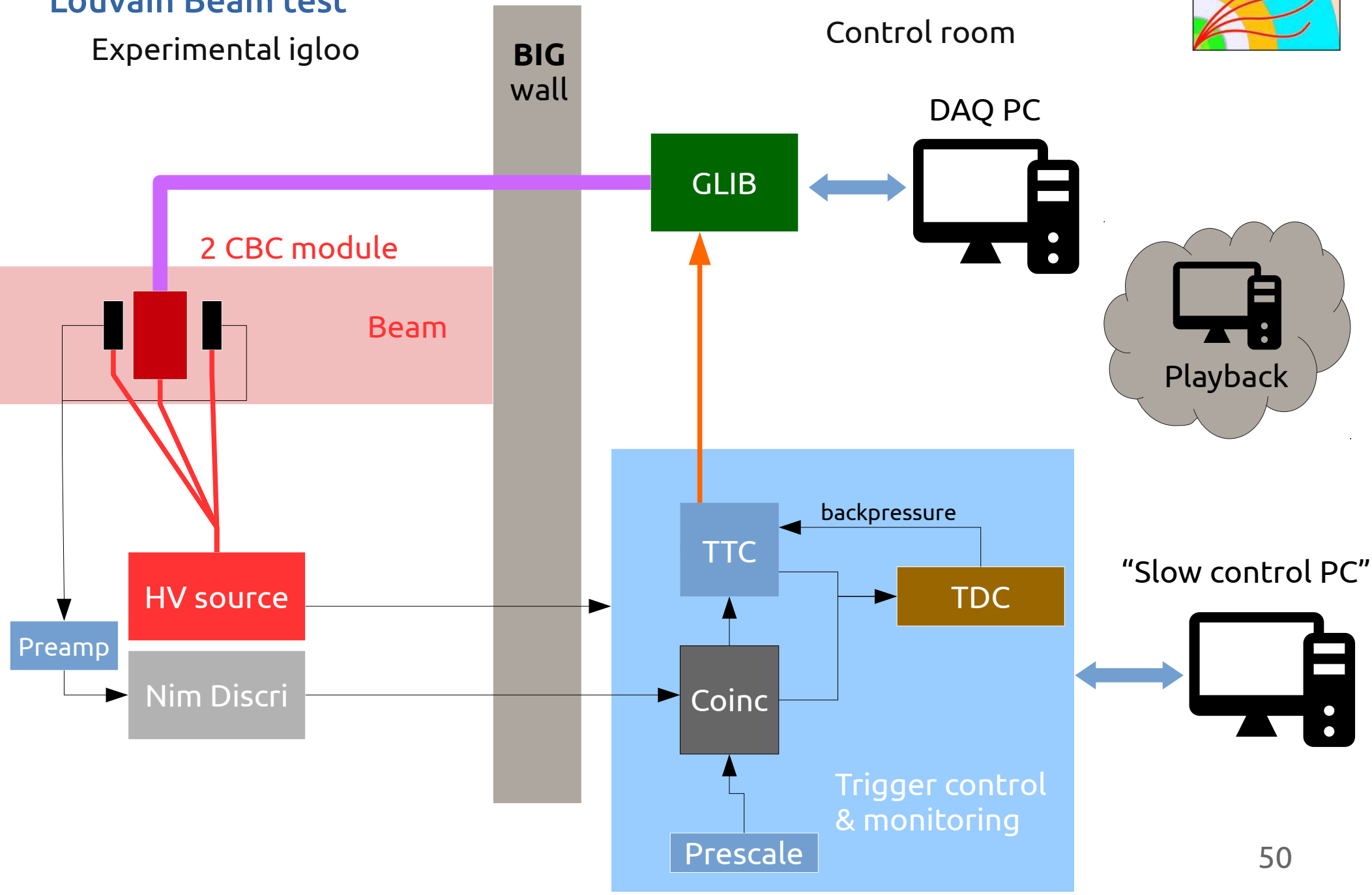






Current status – prototype testing

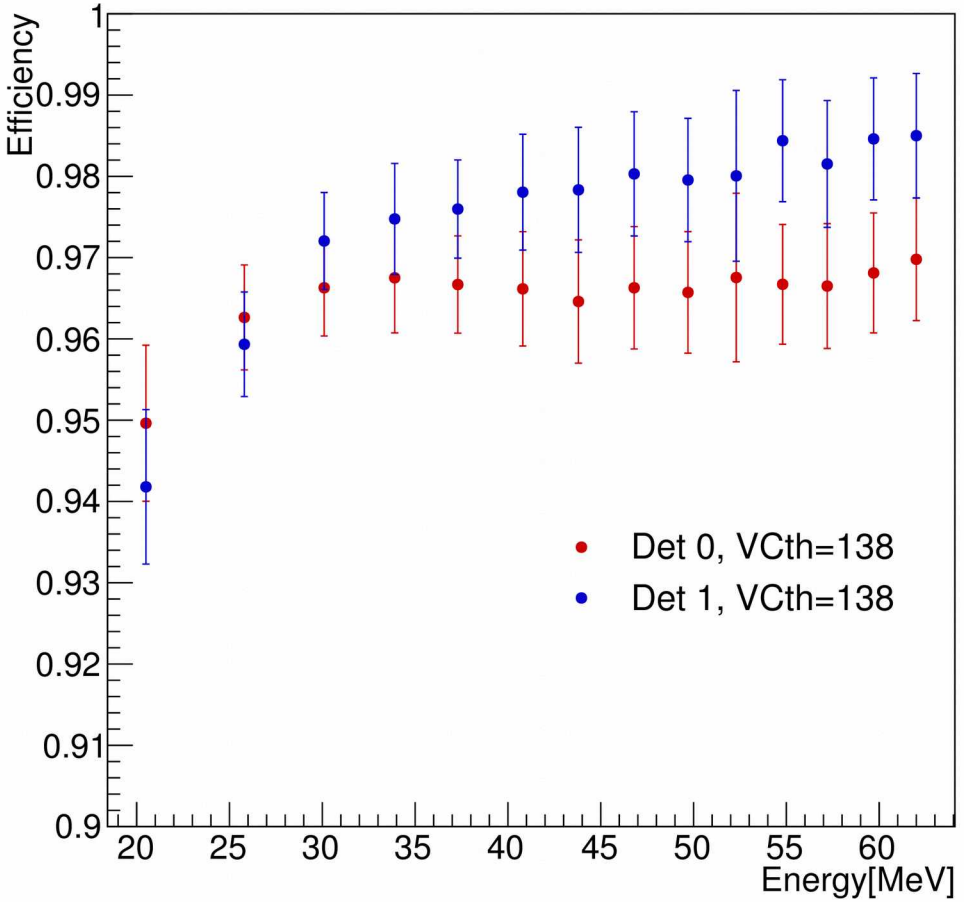
Louvain Beam test



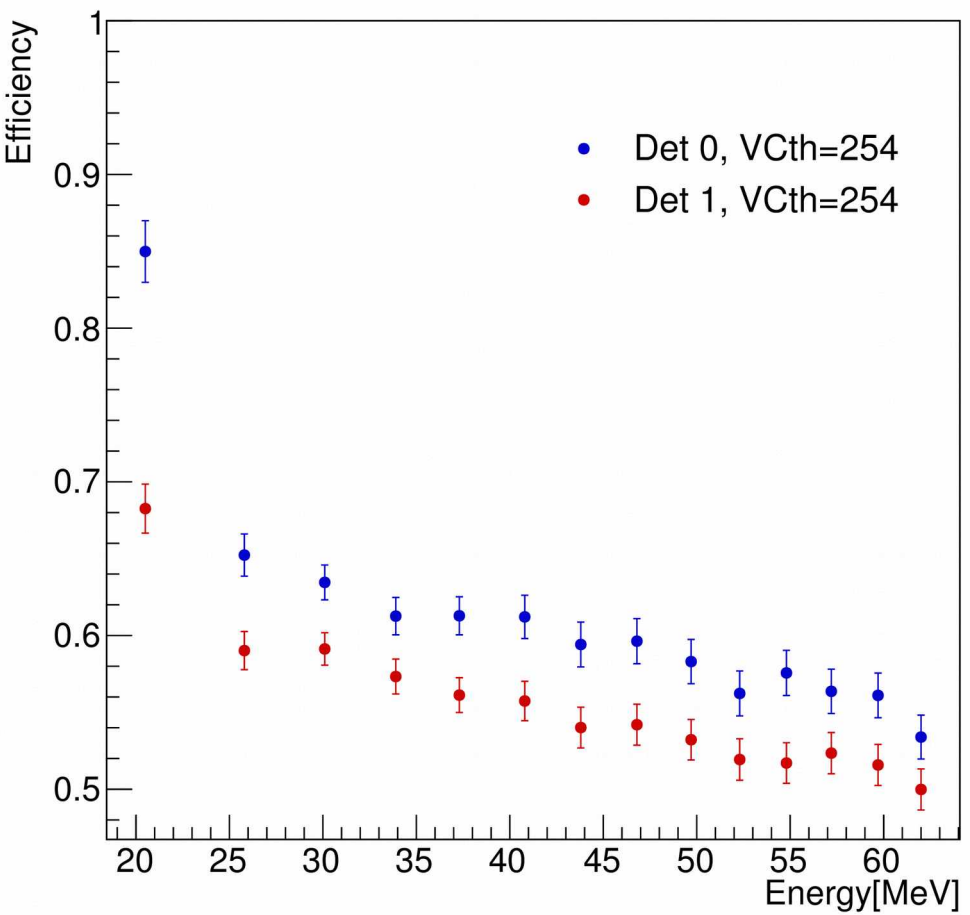
Current status – prototype testing

Louvain Beam test

- Efficiency estimate :
  - If first sensor hit, probability of finding a close hit in the second.
- VCTH = threshold to detect a hit



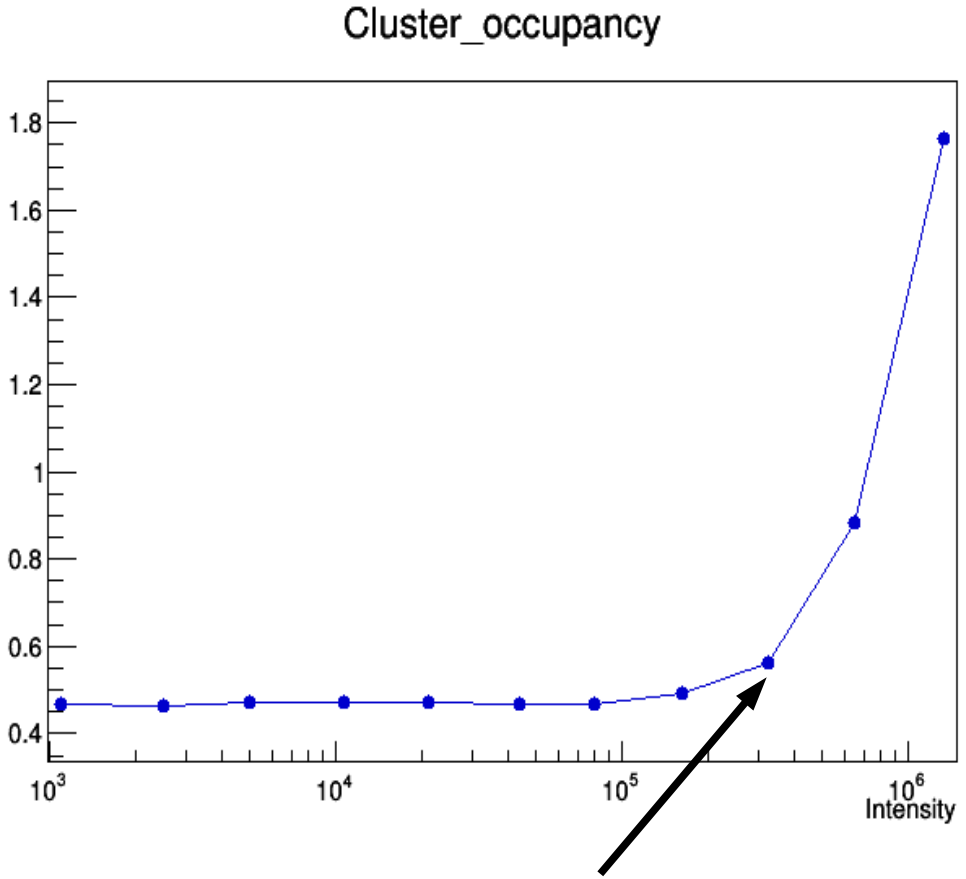
Nominal VCTH



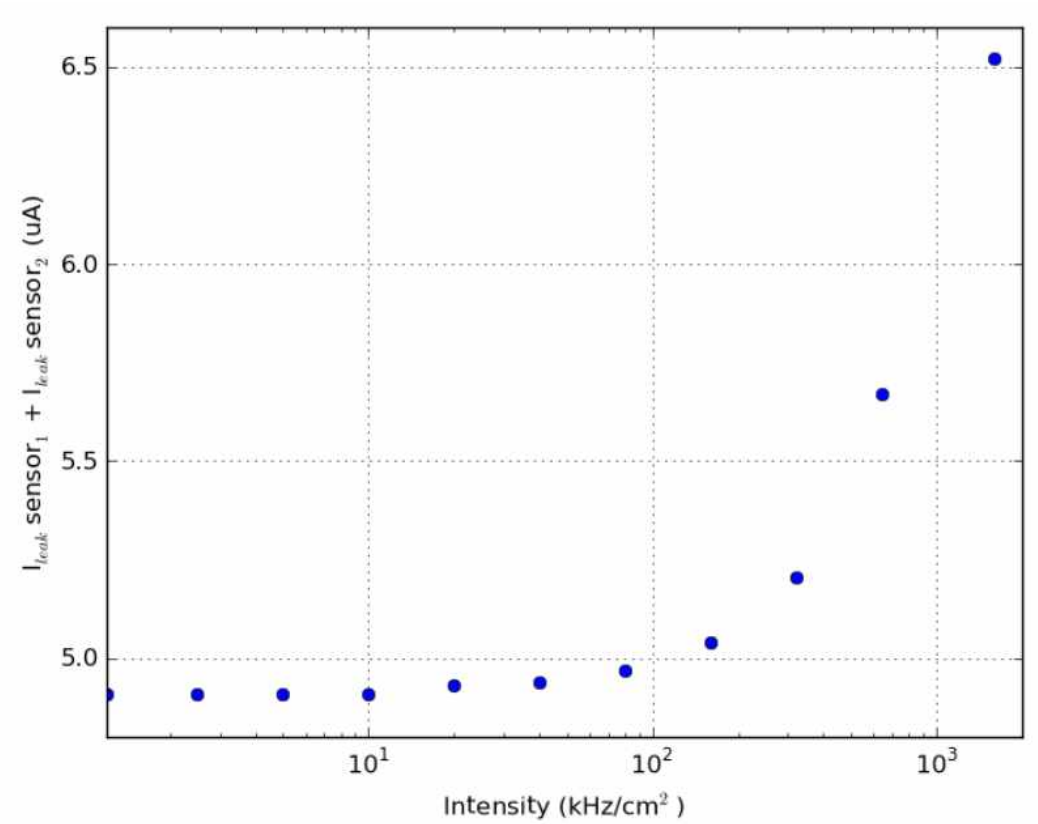
Very high VCTH

Current status – prototype testing
Louvain Beam test

- Intensity scan :
  - Efficiency estimate and leakage current



Apparition of out of time pile-up



Total leakage current nicely increasing with rate

Upgrade of the CMS tracker for the HL-LHC
Outline of the talk



- CMS upgrade
- Tracker upgrade
  - Goals and current design
- Current status – prototype testing
  - MAPSA
  - CBC2
- Prospects – construction
  - Belgian / UCL involvement?

Upgrade of the CMS tracker for the HL-LHC

Prospects – construction



- We are slowly but surely arriving towards the end of the prototyping phase

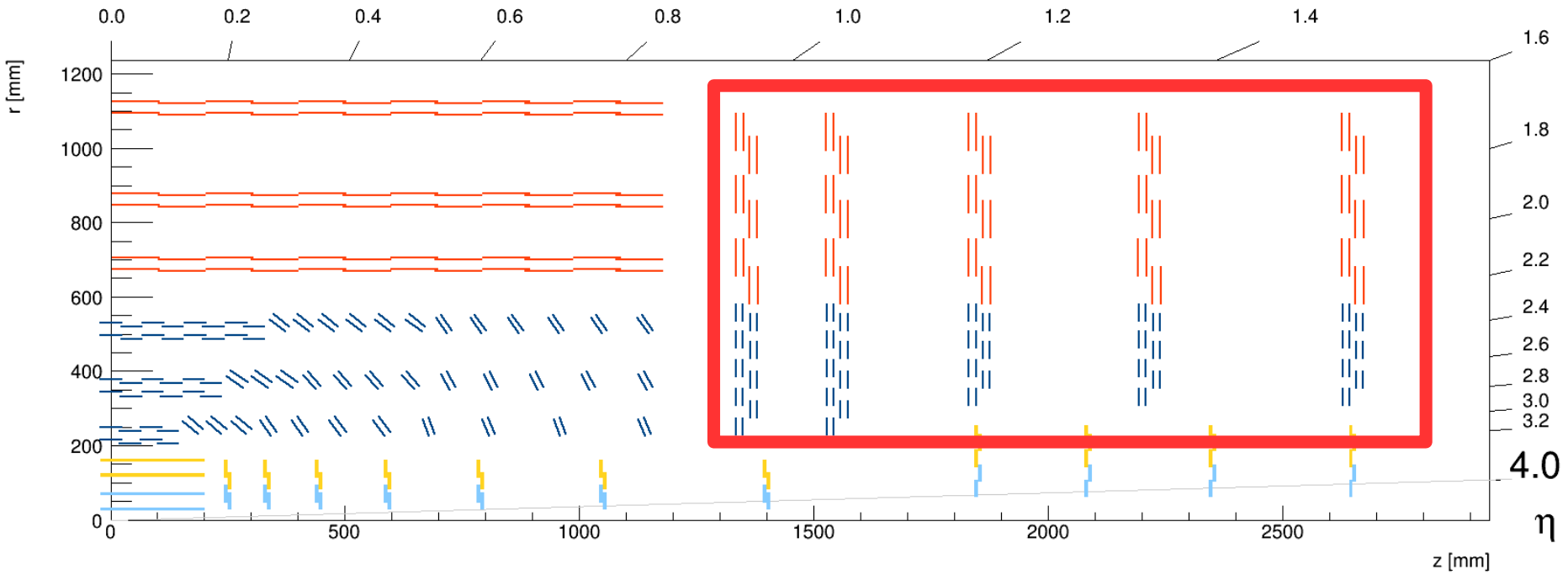
  → We have to think about production now!

Upgrade of the CMS tracker for the HL-LHC
Prospects – construction

- We are slowly but surely arriving towards the end of the prototyping phase

  → We have to think about production now!

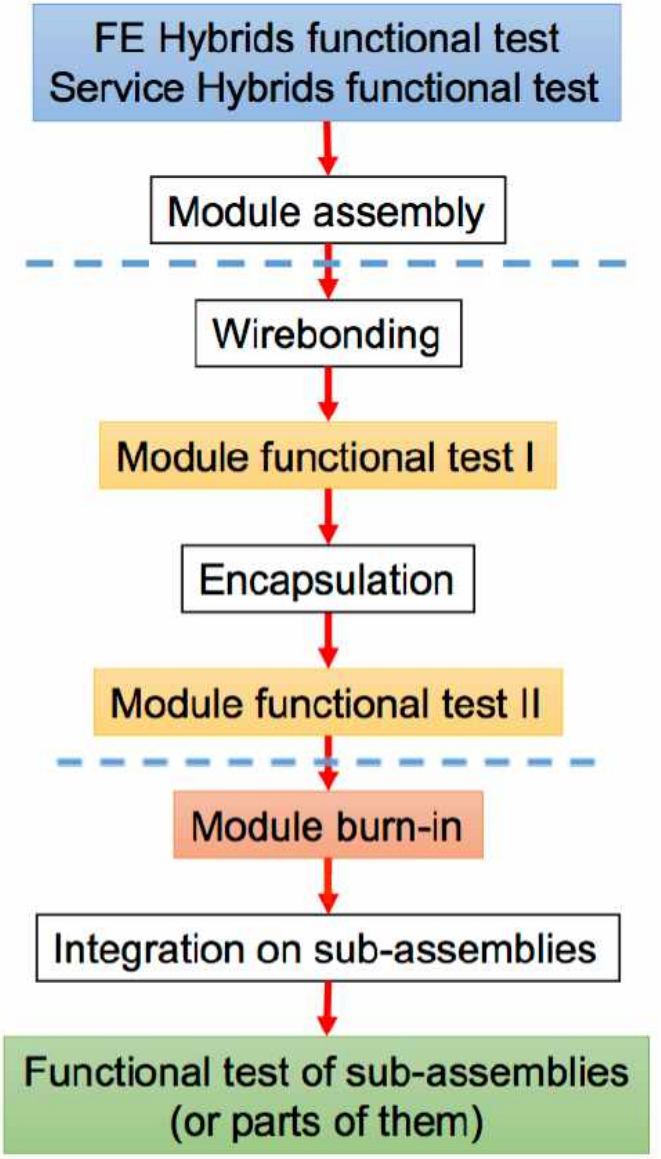
Our ambition, in Belgium, is to build an end-cap



Upgrade of the CMS tracker for the HL-LHC

Prospects – construction

- How do we go from the raw components to an end-cap ?

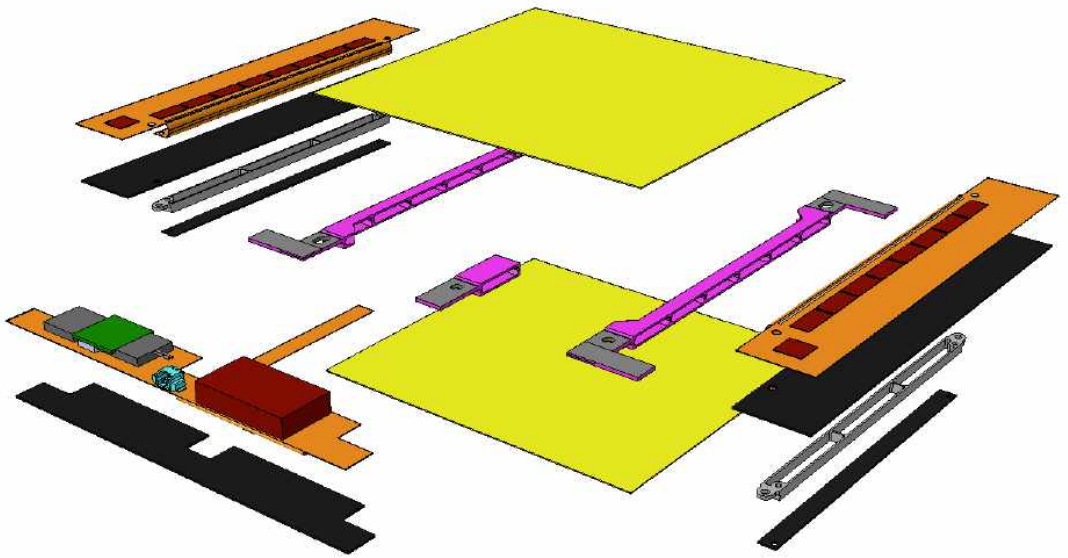


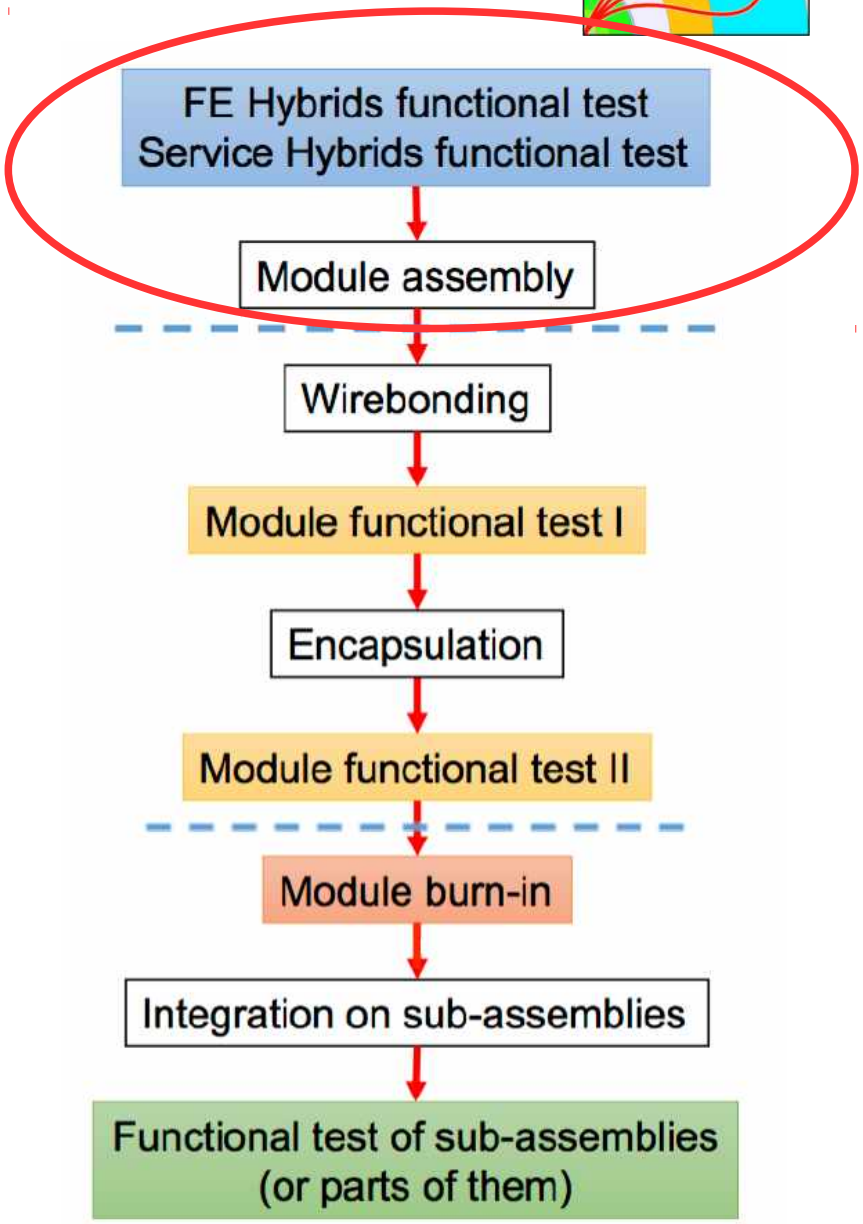
Upgrade of the CMS tracker for the HL-LHC

Prospects – construction

- First step : assemble modules
  - Test components from industry
    - Under cold and room temperature
  - Assemble them into a module

~2000 modules will have to be built

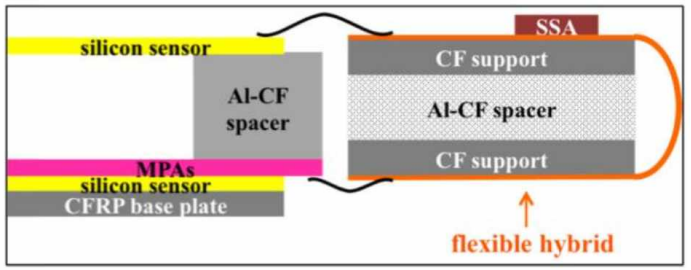


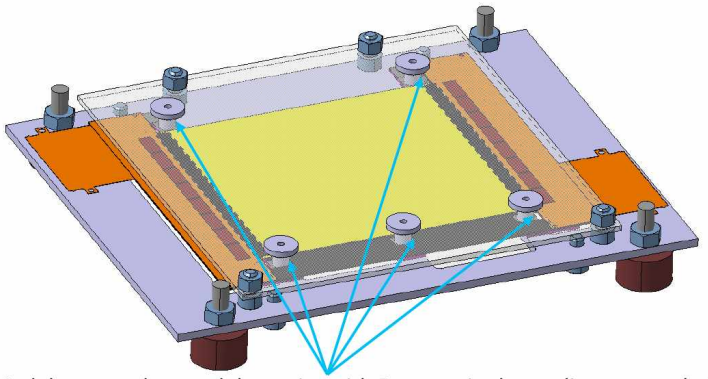


Upgrade of the CMS tracker for the HL-LHC

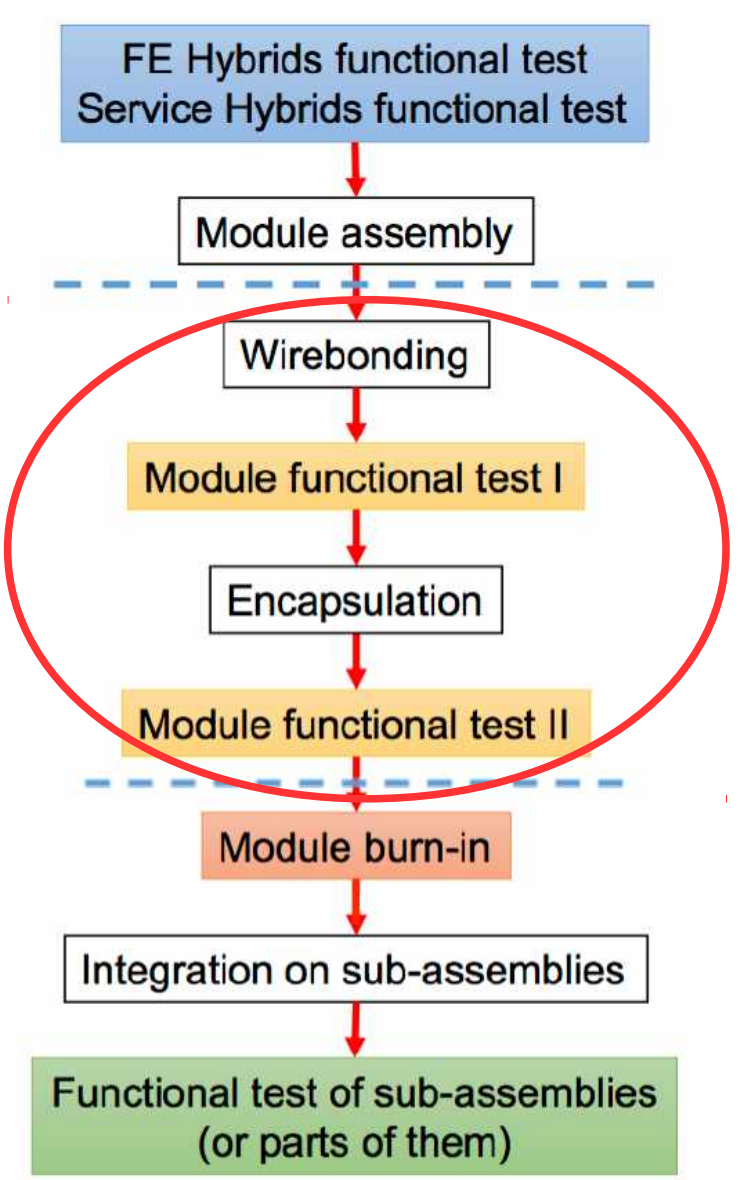
Prospects – construction

- Second step : wirebonding and encapsulation
  - Connect strips to CBCs
  - Encapsulate the bonds
  - Add mechanical and cooling support
  - Test the correct behaviour





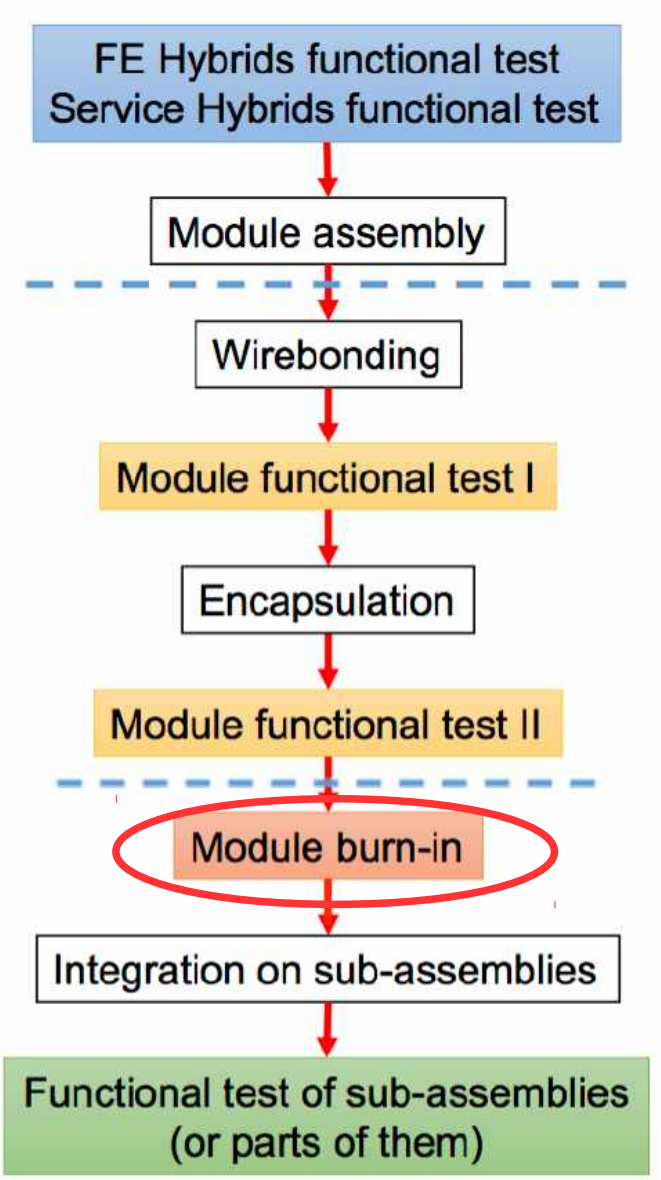
Module secured to module carrier with 5 screws in the cooling contact holes



Upgrade of the CMS tracker for the HL-LHC

Prospects – construction

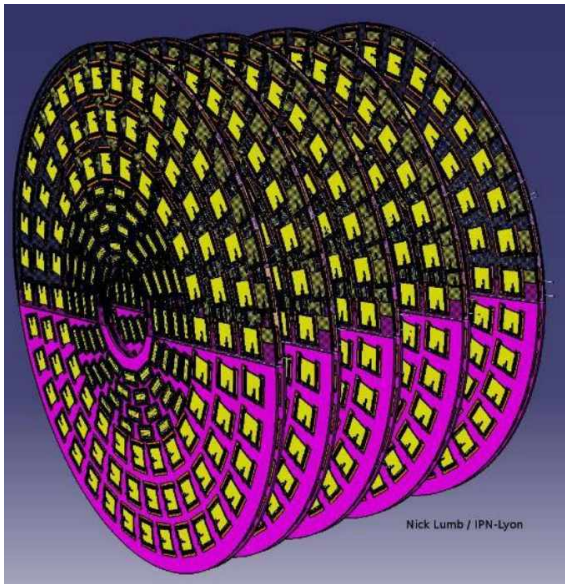
- Step 2.5 : Module burn-in
  - Thermal cycle module between -30°C and room temperature

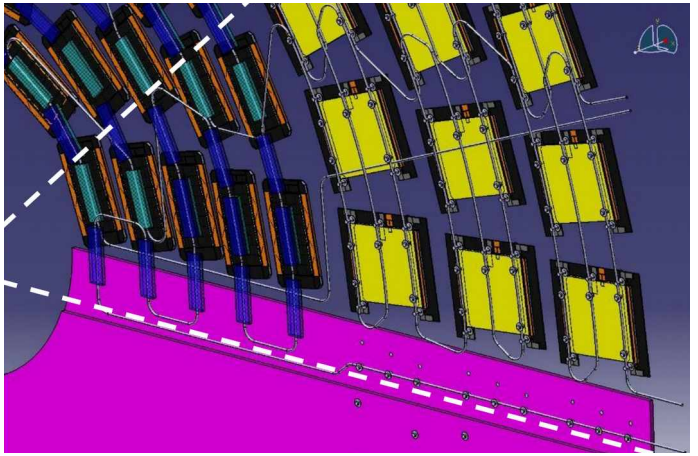


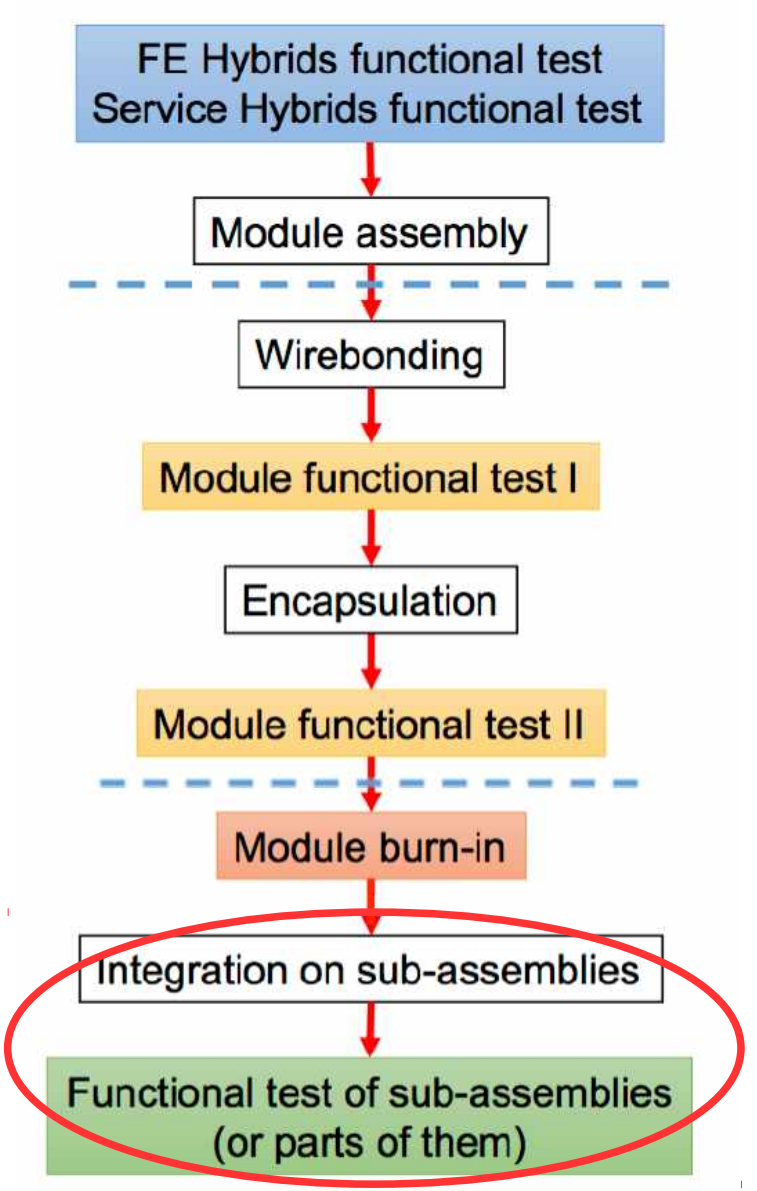
Upgrade of the CMS tracker for the HL-LHC

Prospects – construction

- Step 3 : Integration
  - Assemble module into “Dees”
  - Assemble “Dees” into disks
  - Assemble disks into an end-cap
- Complex geometry with cooling embedded in the support structure



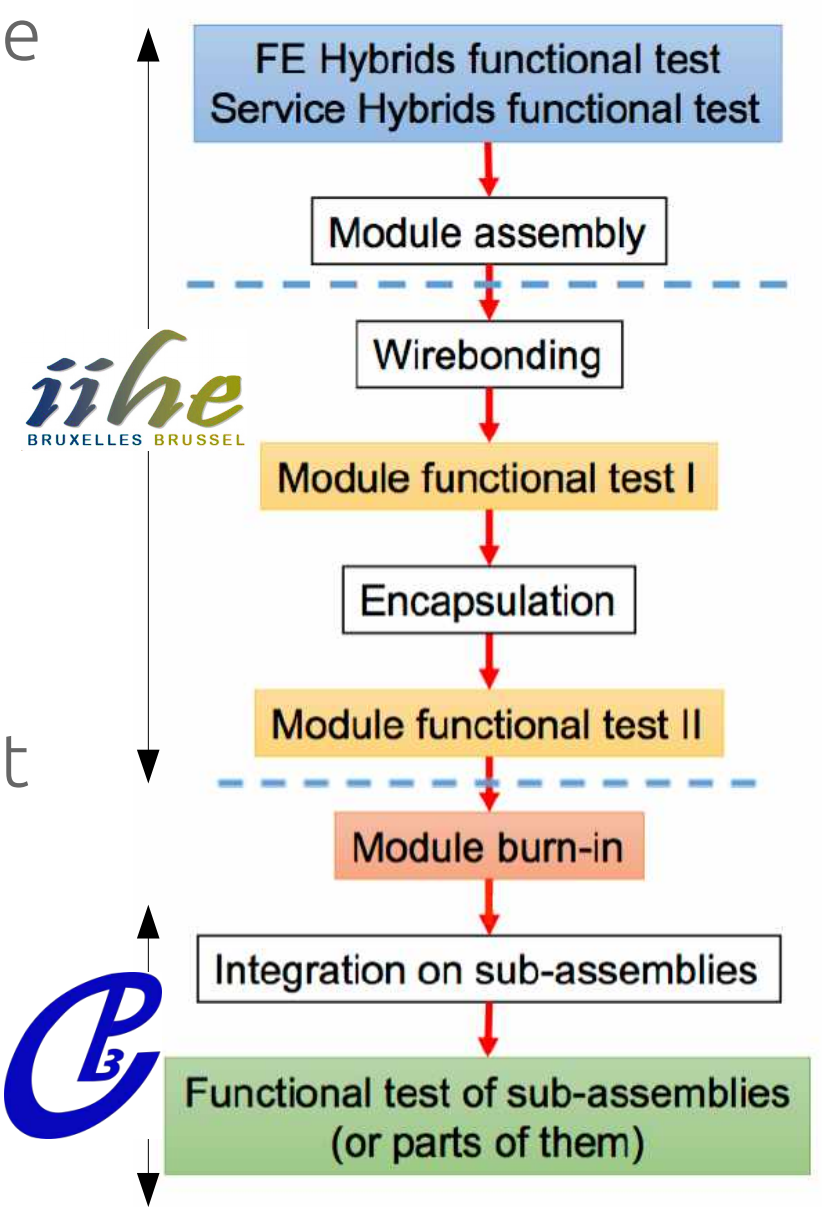




Upgrade of the CMS tracker for the HL-LHC

Prospects – construction

- Belgian's ambition is to produce one of the 2 tracker end-caps
- Production would be split in two lines
  - Brussels
  - Louvain
- Budget could soon be secured
- Decision from CMS will fall next year



Upgrade of the CMS tracker for the HL-LHC
Conclusion



- CMS is getting ready for the HL-LHC

- One key part will be the tracker
  - Design well on the way
  - Prototypes have been tested successfully

    ➞ The new design seems to meet the phase-2 challenges

- Belgium (and CP3) is highly involved in the project

    ➞ There is a big chance that we could be building a part of the new tracker

UCL Université catholique de Louvain

CMS Compact Muon Solenoid

Thank you for your attention

Upgrade of the CMS tracker for the HL-LHC
A few links



- Technical proposal

- ECFA talks
  - CMS overview
  - Tracker design
  - Pixel status
  - Outer tracker status