# The Phase1 CMS Pixel detector upgrade

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*8th International Workshop on Semiconductor Pixel Detectors for Particles and Imaging, 5 September 2016, Sestri Levante, Italy*

ETH Zürich

ETH Institute for Particle Physics

# Outline

- Present CMS Pixel detector
- Reasons and concept of detector upgrade
- Elements of upgrade
- Detector module production
- Structure, services and final system

# Present CMS Pixel Detector

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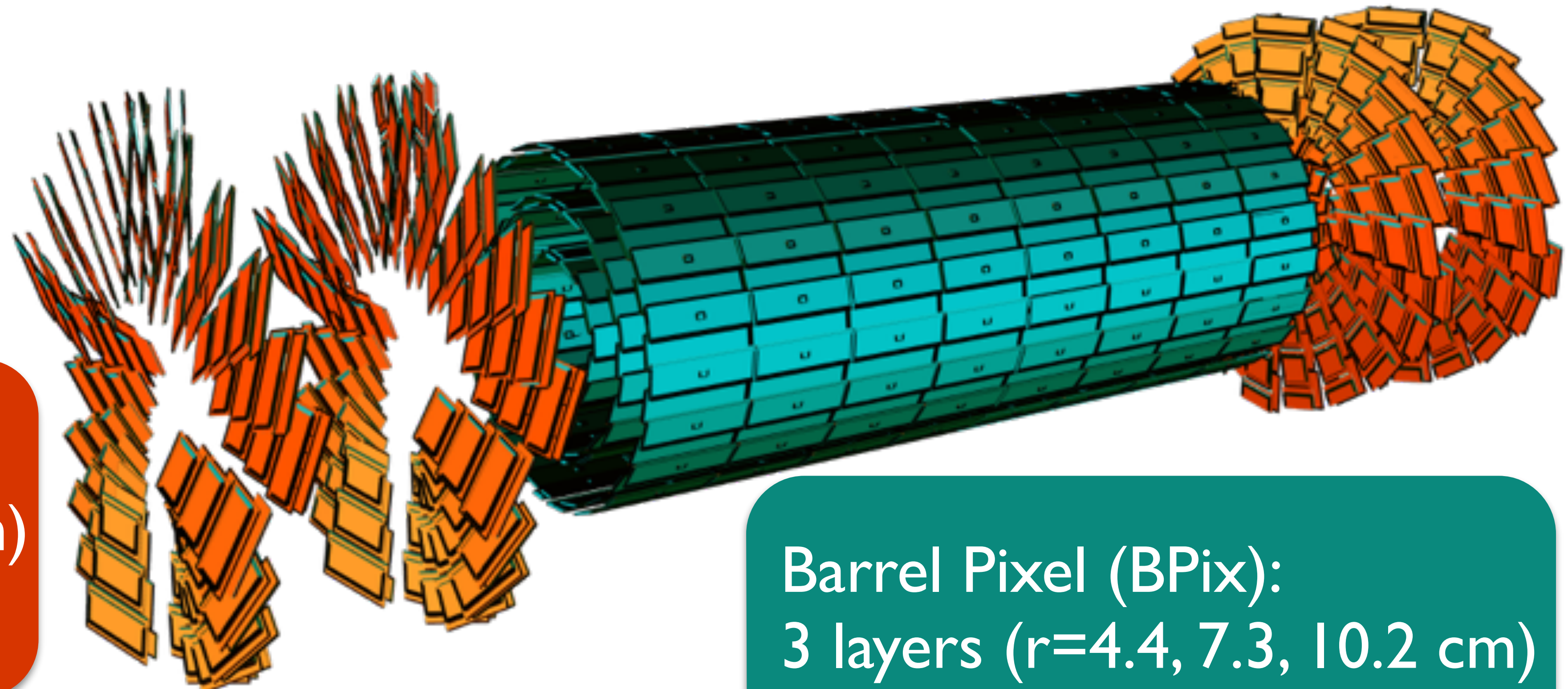


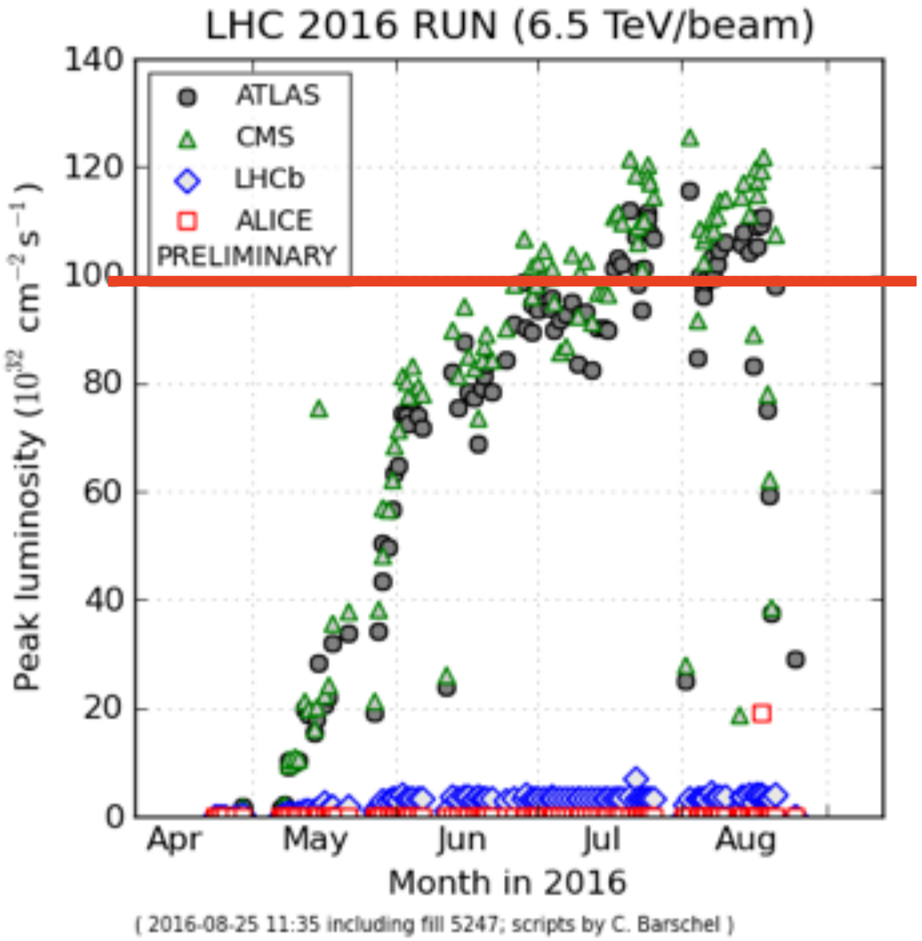
Forward Pixel (FPix):
2+2 disks (z=34.5, 46.5 cm)
18M channels

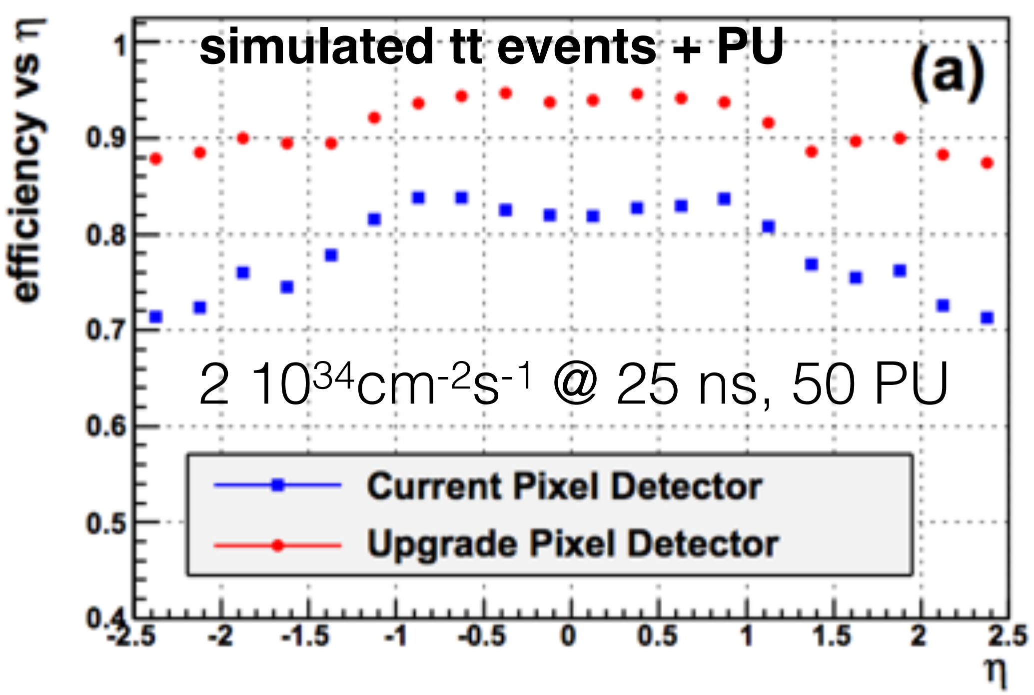
Barrel Pixel (BPix):
3 layers (r=4.4, 7.3, 10.2 cm)
48M channels

- **$n^+$-in-n** sensors with pixel size of 100x150 $\mu m^2$ (rϕ-z)
- Present detector performed very well in **Runs I and II** of the LHC
  - **Excellent resolution**: 10μm (r-ϕ), 20-40μm (z)
  - **High efficiency** (>99%)
  - Pivotal role in **tracking, vertexing**

# Reasons for upgrade

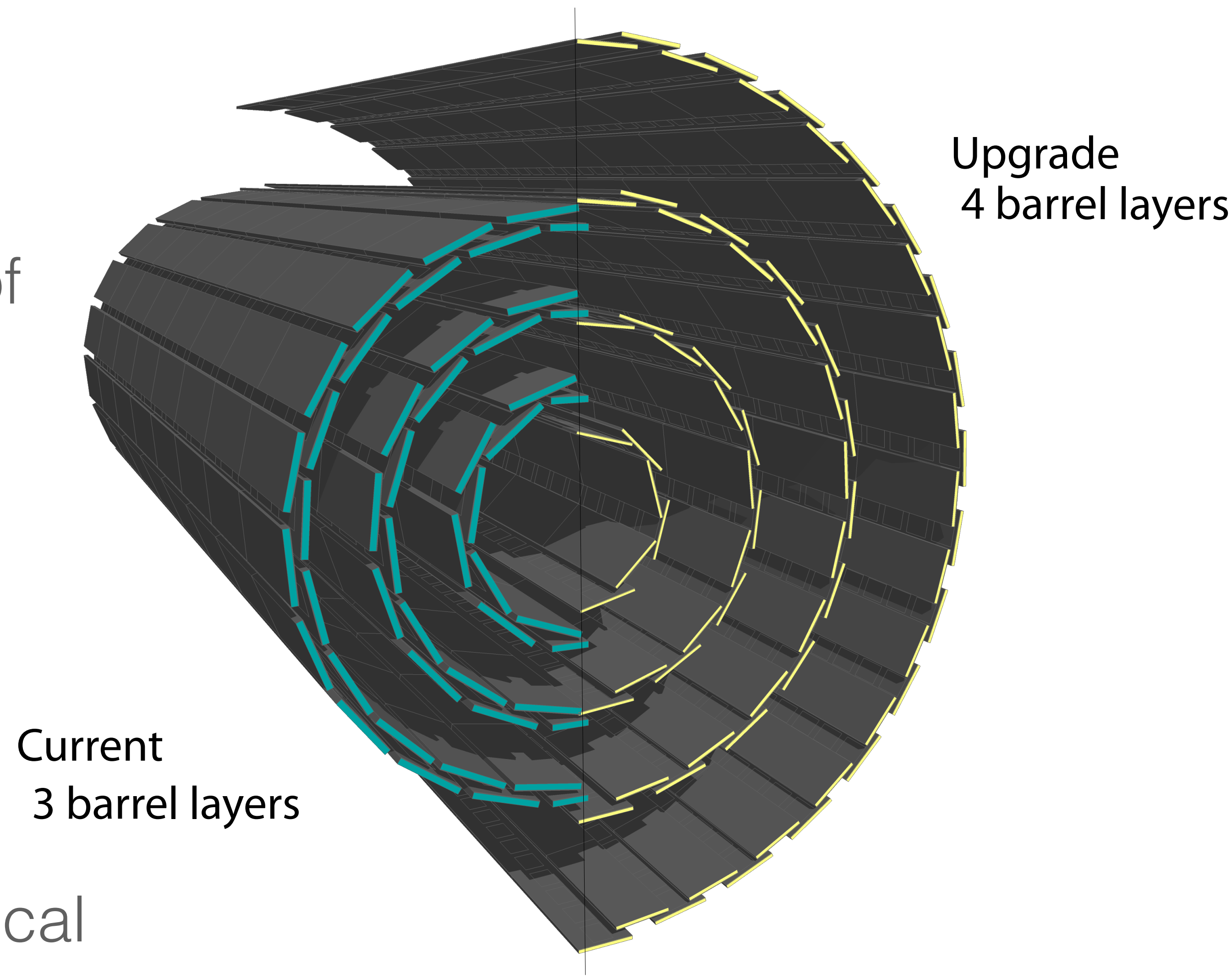
- Present system designed for
  - **Integrated** luminosity 500 $fb^{-1}$ (radiation tolerance of Layer1)
  - **Instantaneous** luminosity $10^{34} cm^{-2} s^{-1}$ @ 25ns bunch spacing
- Expect **2** $10^{34} cm^{-2} s^{-1}$ and 500 $fb^{-1}$ before LS3 (~2024)
  - Exceeds capability of present **ReadOut Chip (ROC)** and data links
    - **Large hit inefficiency** due to data/hit buffer overflow
- Sensitive tracking volume containing **significant material budget**



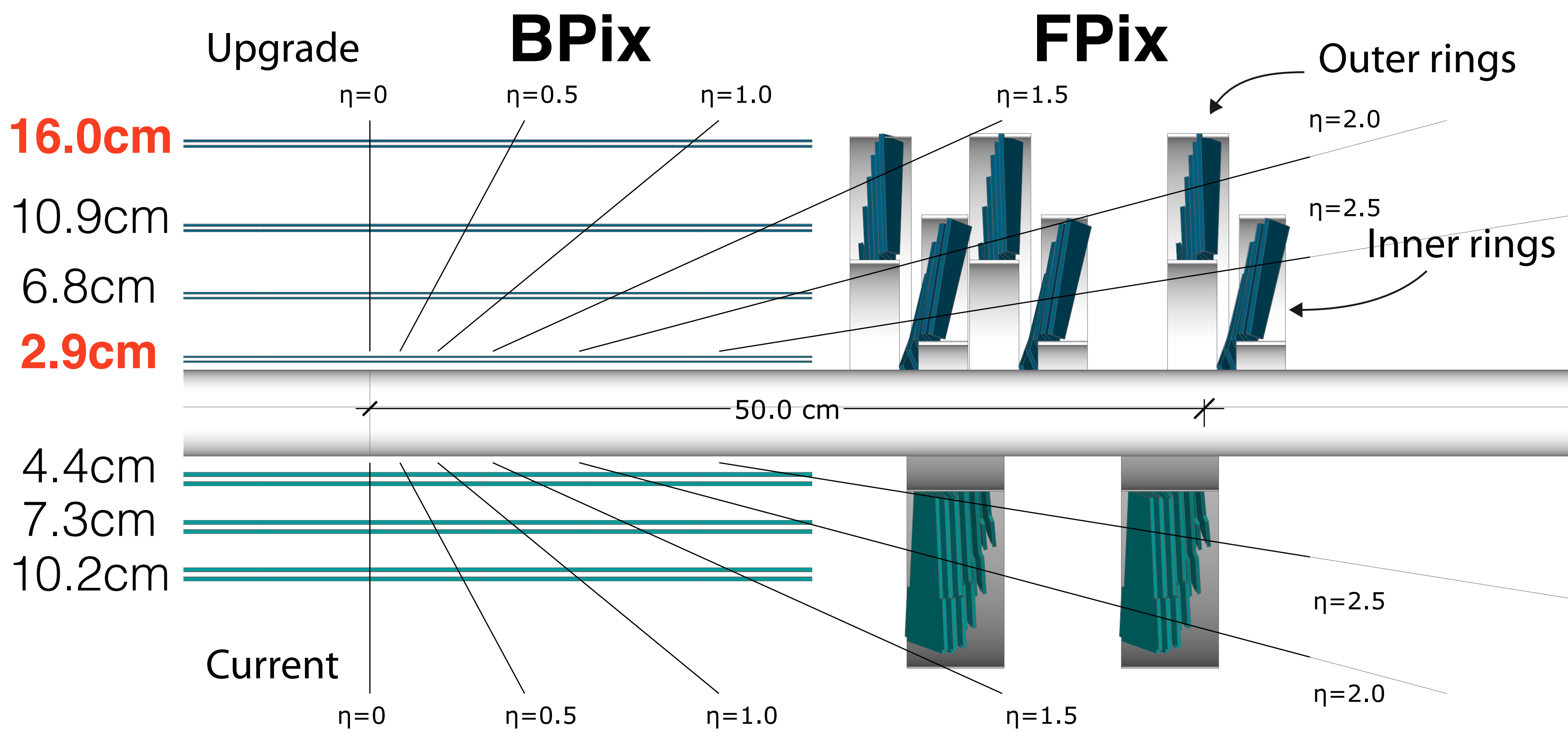
# Phase I upgrade concept

- **Evolutionary upgrade:** present detector baseline with major improvements and novelties
- **Goal**: maintain or improve performance of present detector at higher instantaneous luminosity
- **Detector core unchanged**:
  - Pixel size, sensor technology, module concept
- Insertion during **2016-17** Year-End Technical Shutdown, with **minimal impact** on data taking

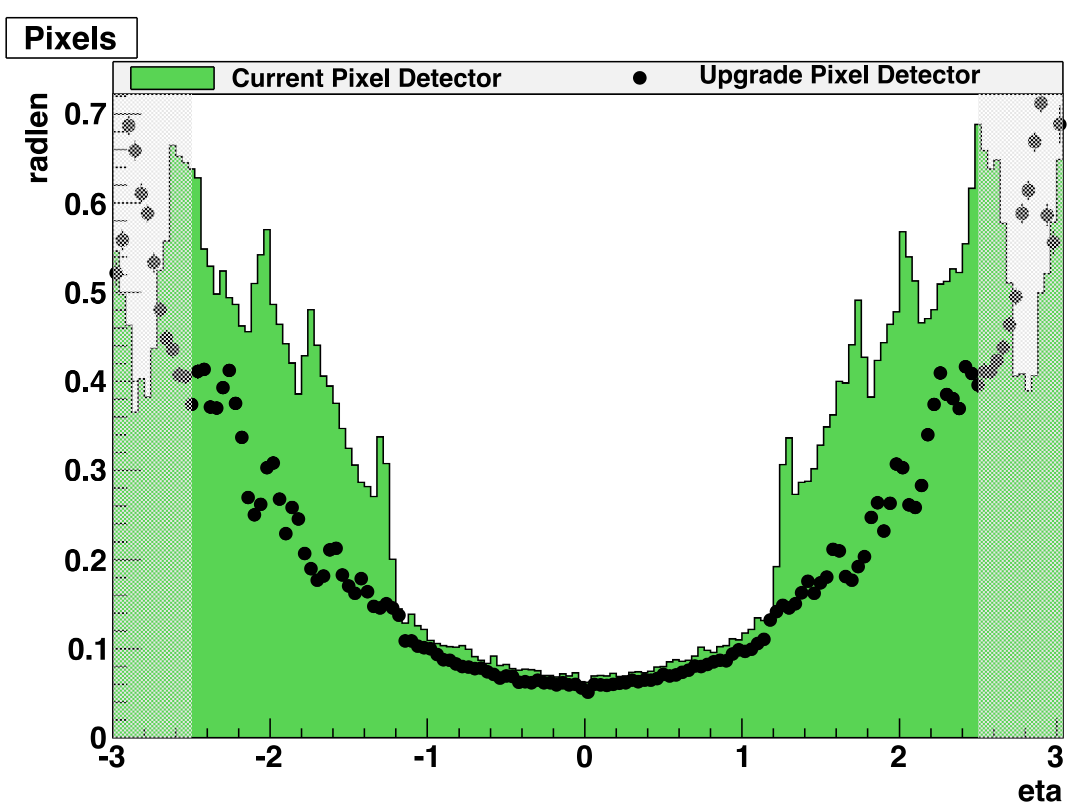


# Detector layout and material budget

- **Performance improvements:**
  - **Additional layer (disk)** in barrel (endcap region) → reduced combinatorics thanks to a layer closer to the innermost layer of the Strip Tracker
  - New, improved **digital** ROC

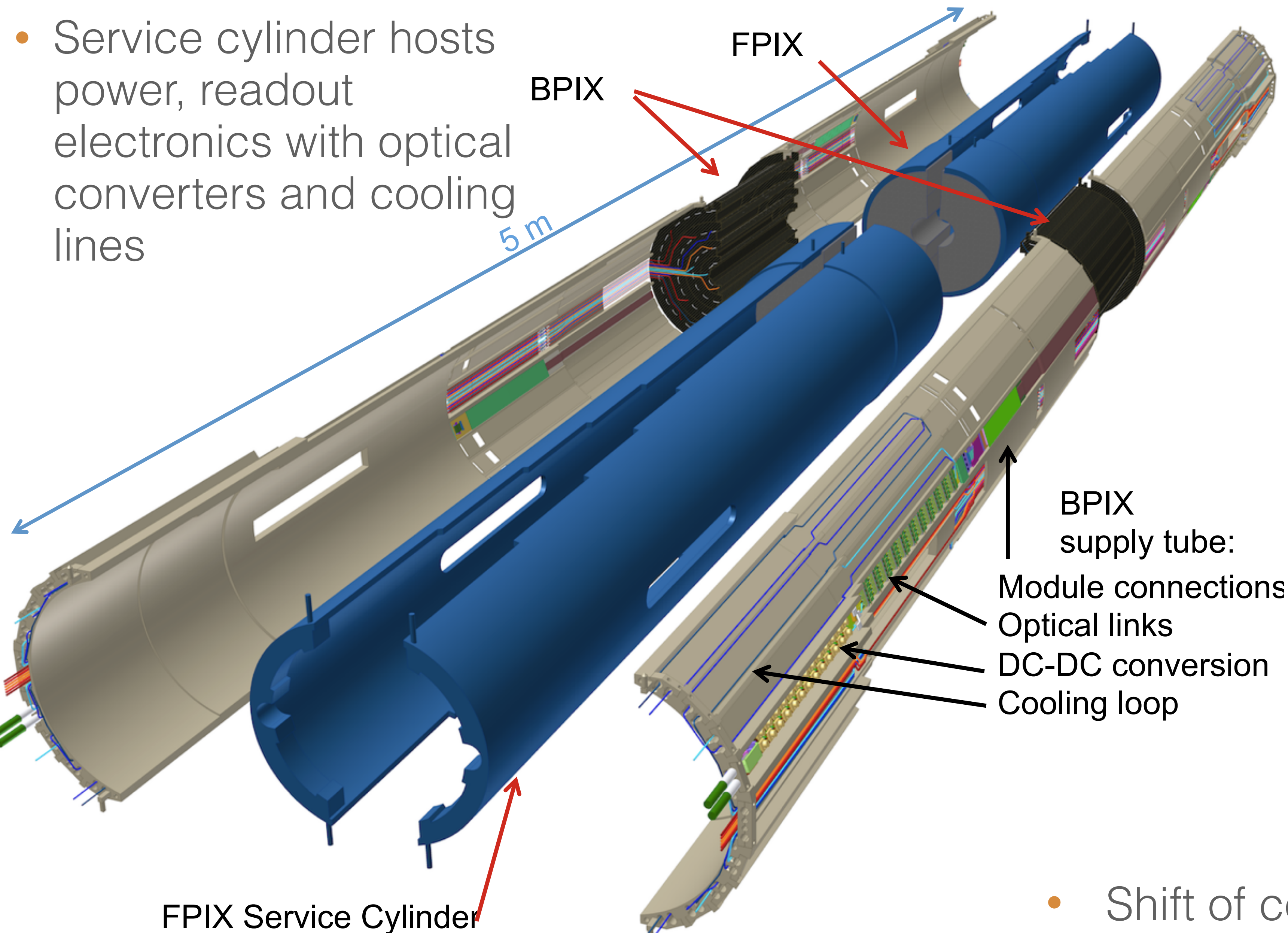


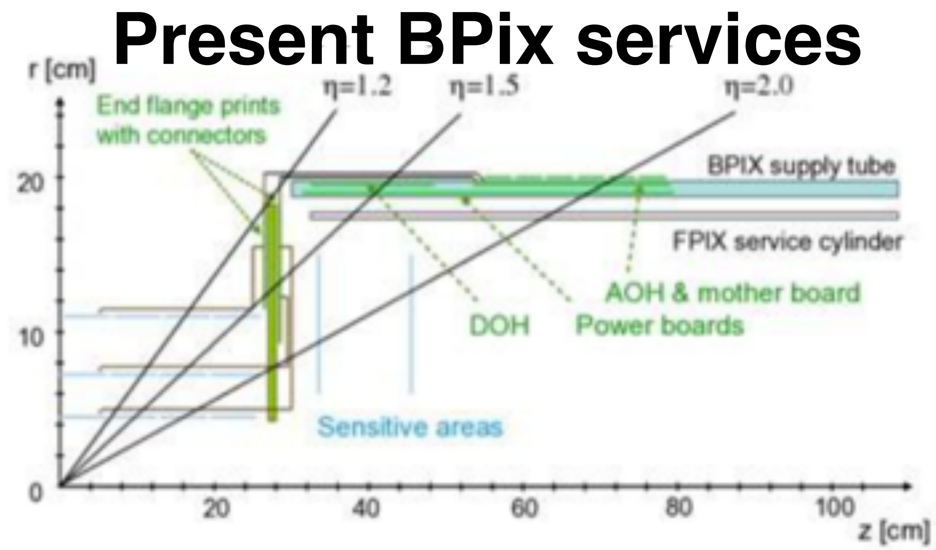

- First layer **closer to interaction point**; New beampipe with smaller radius **(30 → 22.5 mm)** → better vertex resolution and b-tag efficiency
- New $CO_2$ cooling system, relocation of electronics boards → **optimised material budget**, despite x1.9 number of channels
  - BPix: 48M → 79M ; FPix: 18M → 45M
  - in the central region, same material but one extra layer!

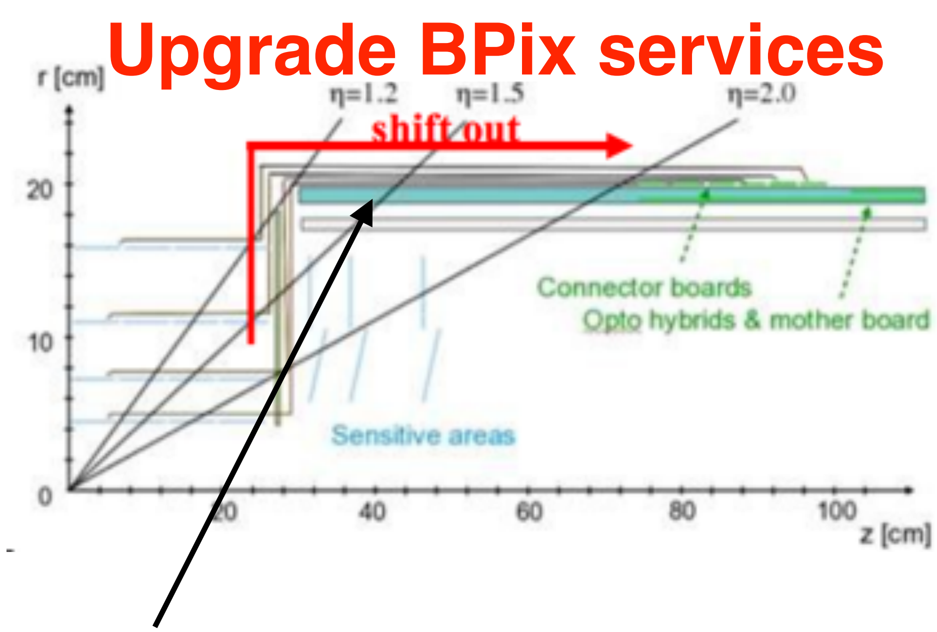


# CMS Pixel System

- Service cylinder hosts power, readout electronics with optical converters and cooling lines



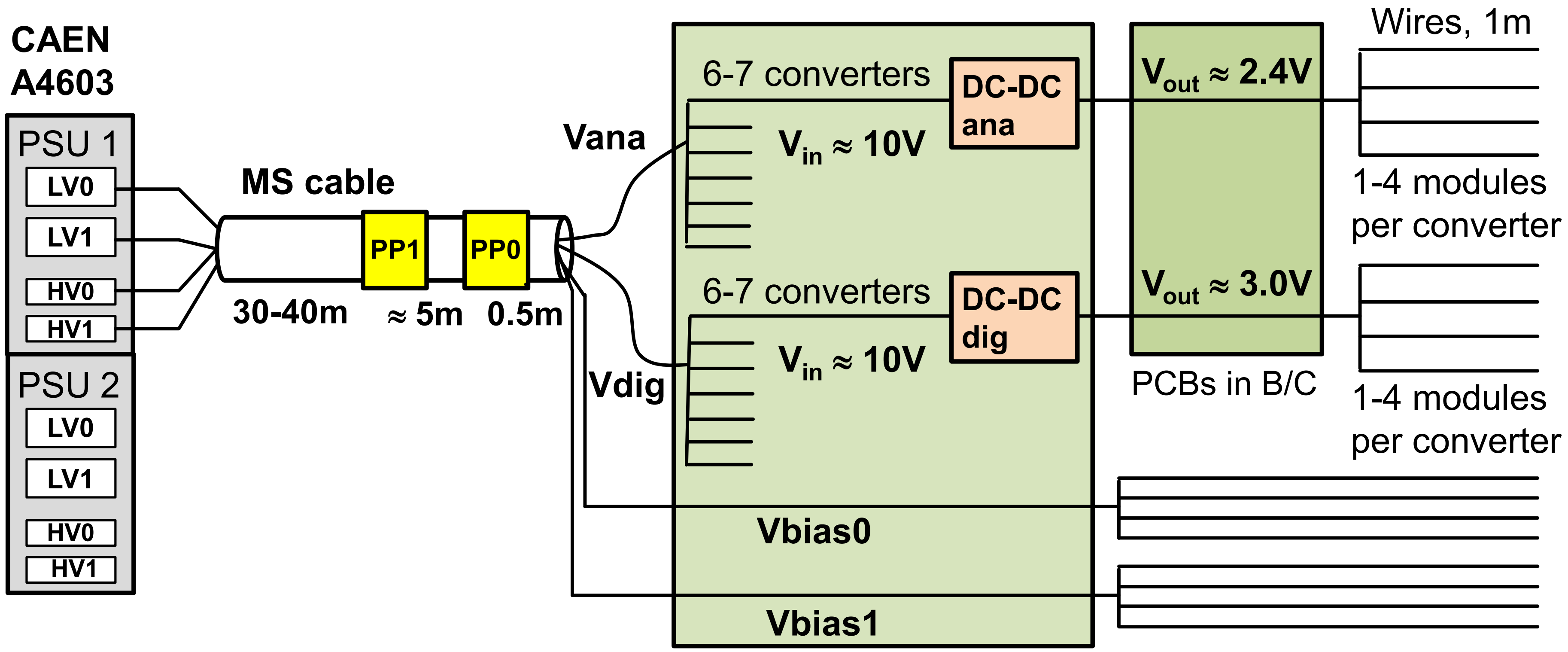



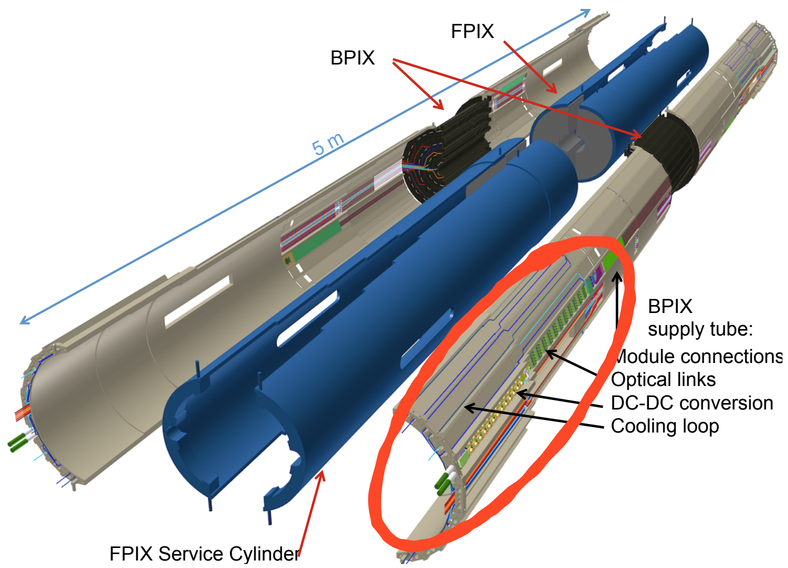




- Shift of connectors and electronics boards to higher eta
- Long (~1m) module cables

- **Same set of power services** has to power x1.9 readout channels
- Solution: **DC-DC conversion** powering (higher power transmission with same current in cable), **close to the detector**
  10V → 3.0V / 2.4V, 80% efficiency
- 1200 converters in total, outside tracking volume

DC-DC converter, AMIS5 ASIC



# Phase1 Pixel digital ROC

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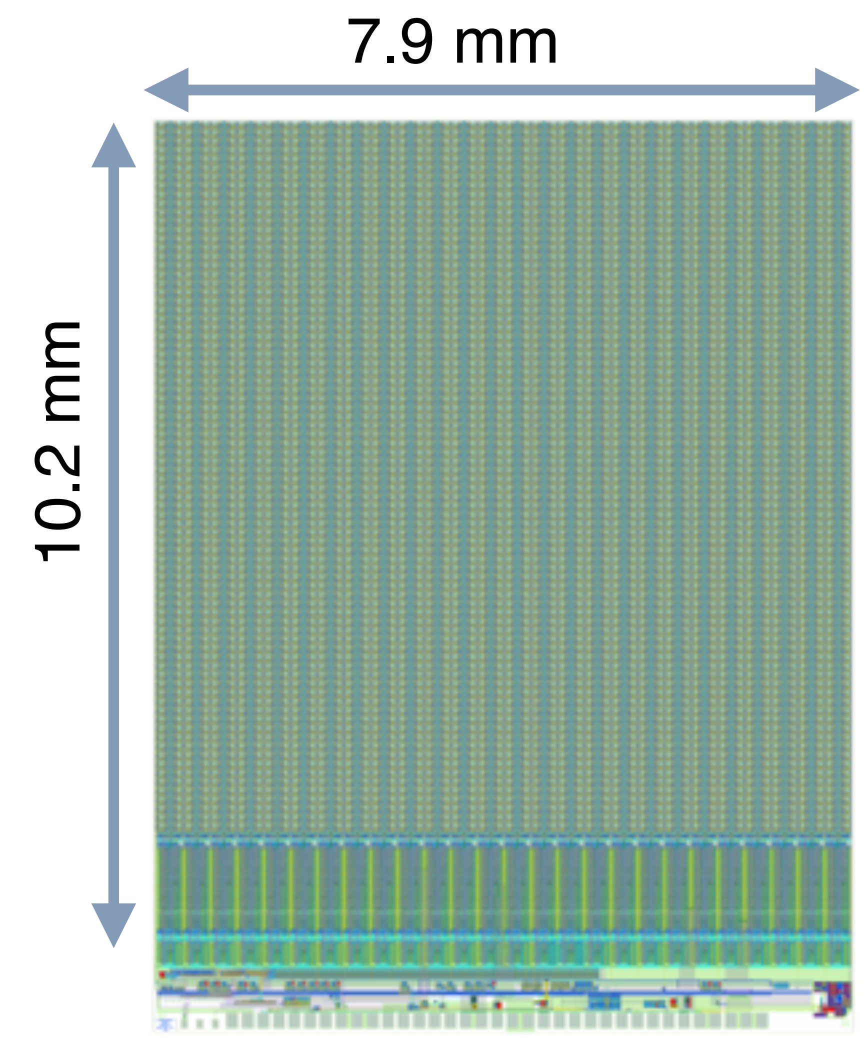
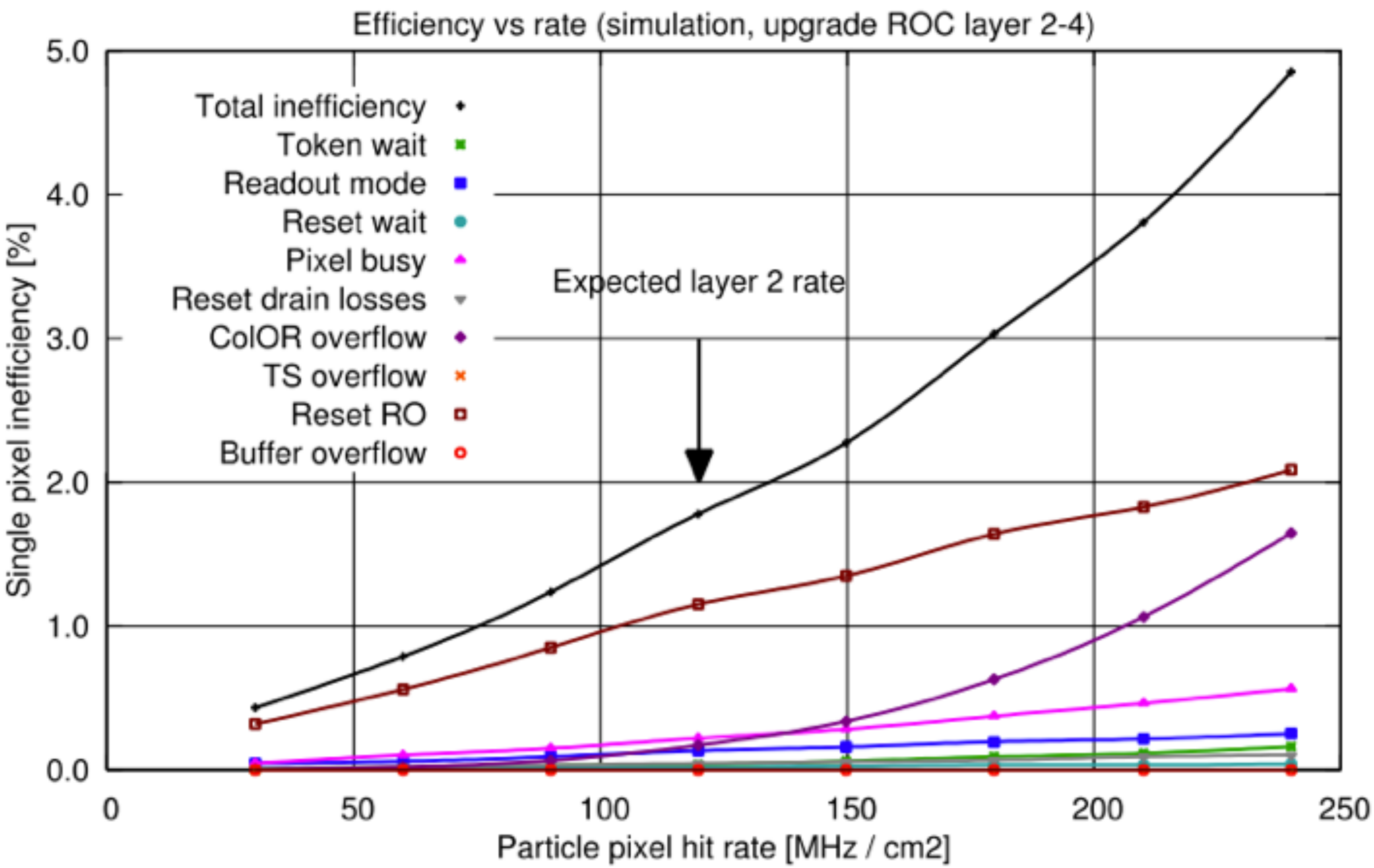
- New readout chip based on present psi46
- Same architecture and technology (250nm CMOS), with **important improvements**:
  - 40 MHz analog readout → 160 Mbit/s **digital** readout
  - **Increase** of hit (32 → 80) and timestamp (12 → 24) **buffers**
  - **Less sensitive to radiation**-induced effects (enlarged DAC ranges, choice of transistor types)
  - **Reduced threshold** (**3500 e → 1800 e**) thanks to smaller cross-talk and improved comparator → improved efficiency, resolution and longevity
- Dedicated **Layer 1 ROC** able to stand higher rates (600 MHz/cm$^2$)
  - see Andrei Starodumov's talk on Thursday *"High rate capability and radiation tolerance of the new CMS pixel detector readout chip PROC600"*

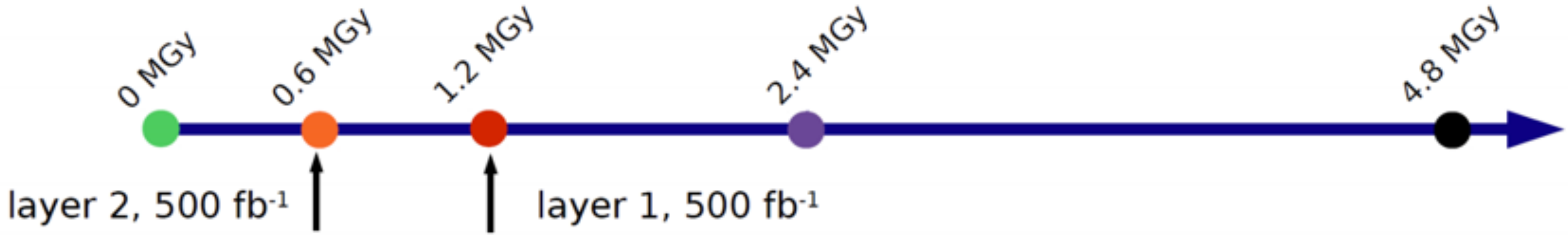



- *100x150 μm$^2$ pixels*
- *52x80 cells*
- *26 double columns with buffers periphery (column drain)*

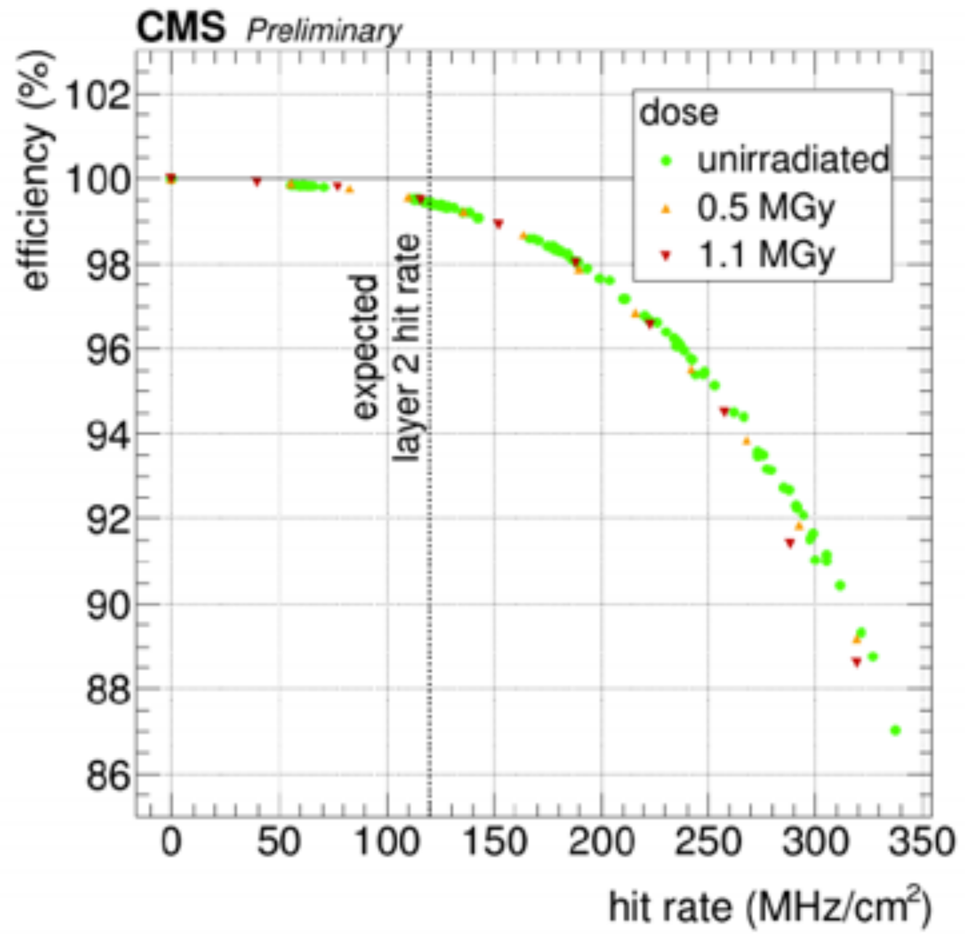
# Readout efficiency

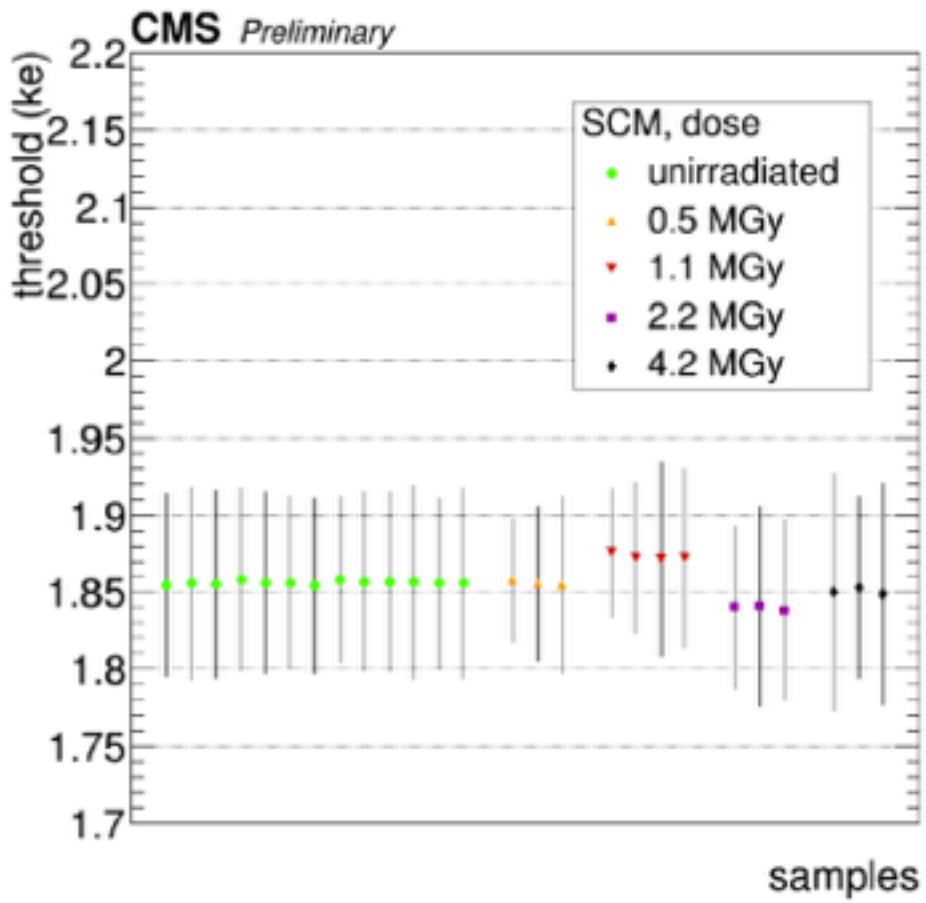
- Extracting test hits in presence of **high rate background**
- Simulations validated with X-ray single-hit events
- LHC-like conditions (**2.3 hits/time-stamp**)
- **Tolerable losses** for L2-4 and FPix





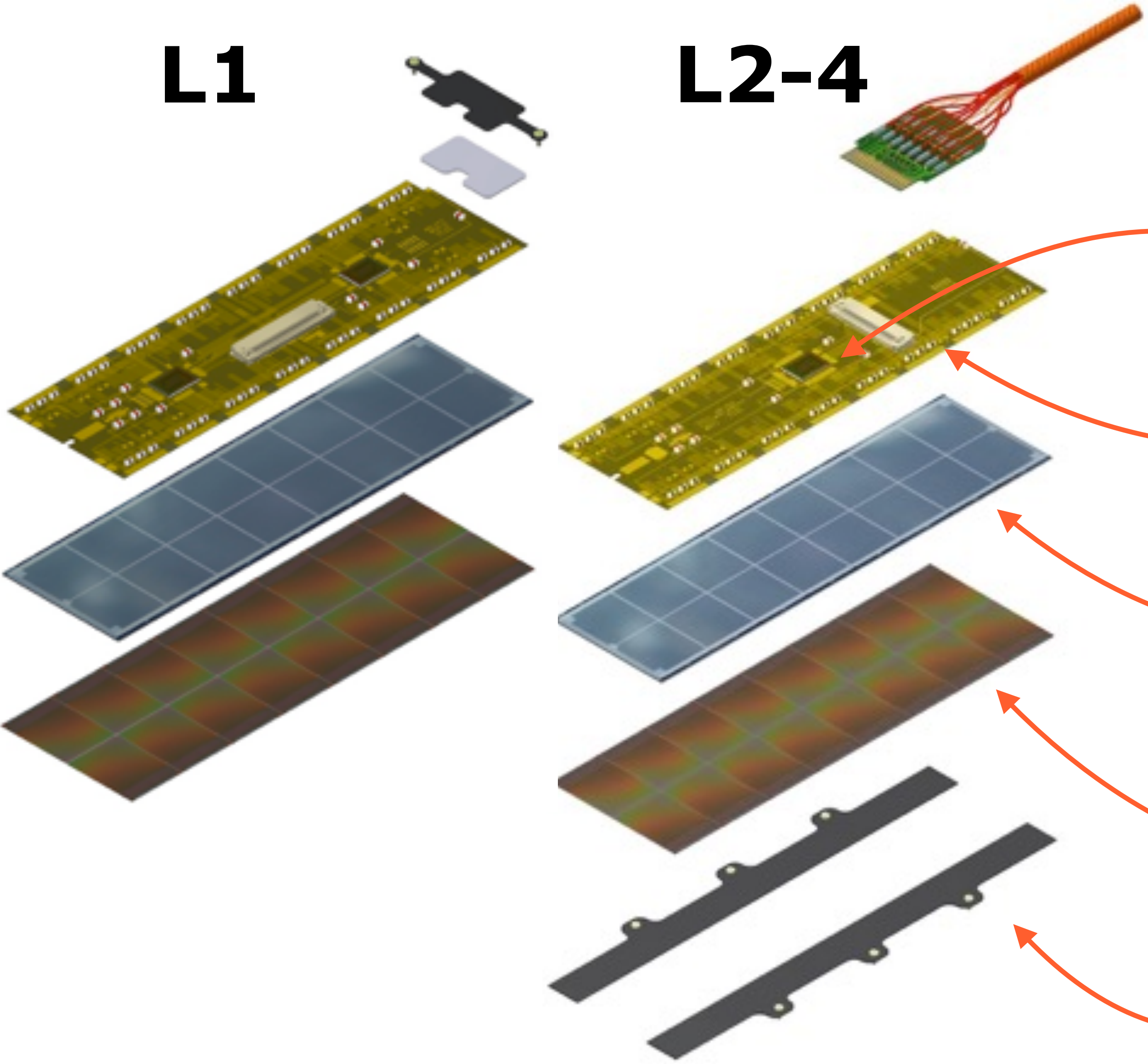

- L1 expected dose after 500fb$^{-1}$ is ~1.2 MGy, quickly decreasing with radius




- psi46dig behaves very well after nominal L2 dose and beyond

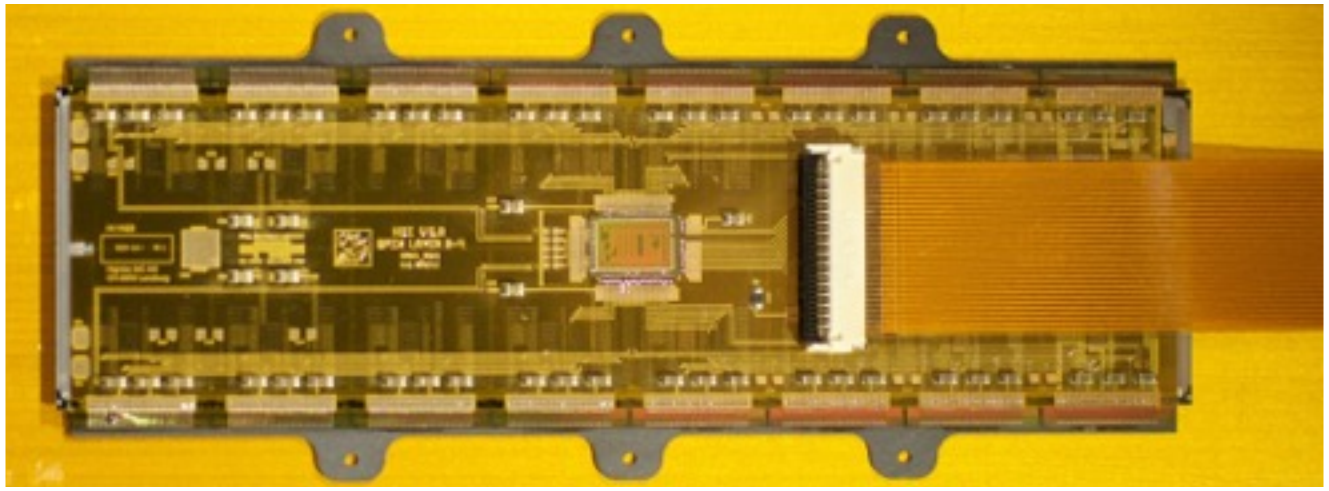
# PhaseI detector modules



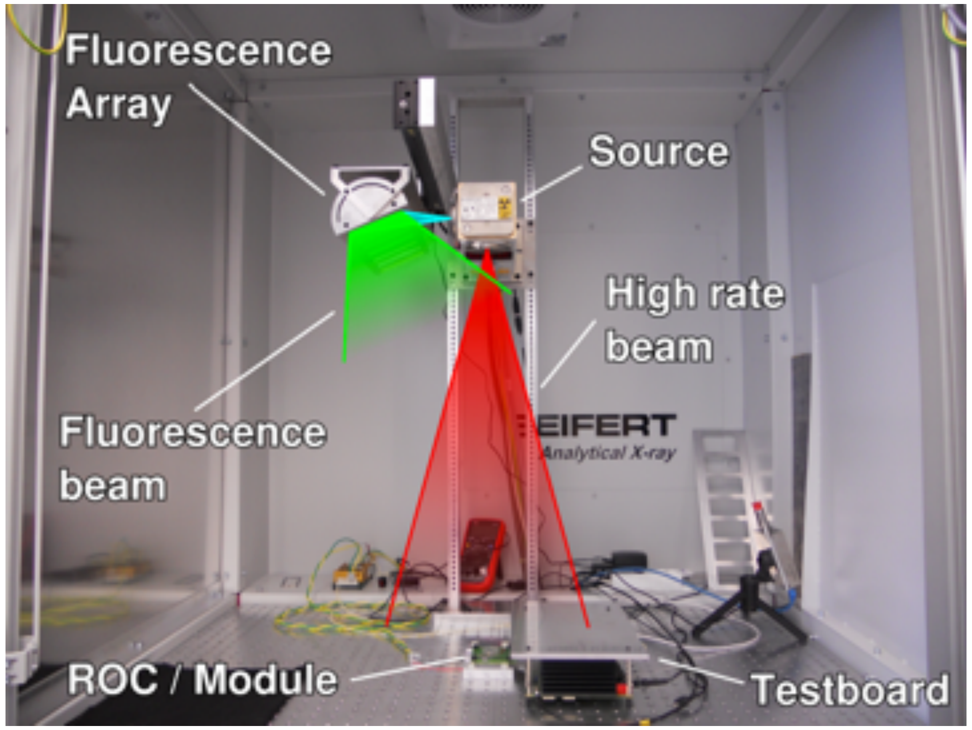

- Module cable for signal transmission and powering
- Token Bit Manager (TBM) distributes power and organises chips' readout data stream (2x for L1)
- High Density Interconnect provides support and connection to all chips
- 285 μm hybrid-pixel technology $n^{+}$-in-n silicon sensor, active area 16.2 x 64.8 $mm^2$
- 2x8 array of (ROCs) bump bonded to the sensor
- Base strips for mounting and mechanical stability, carbon fiber clip for L1

- *Same geometry for FPix, different in details*
- *1856 modules in total*

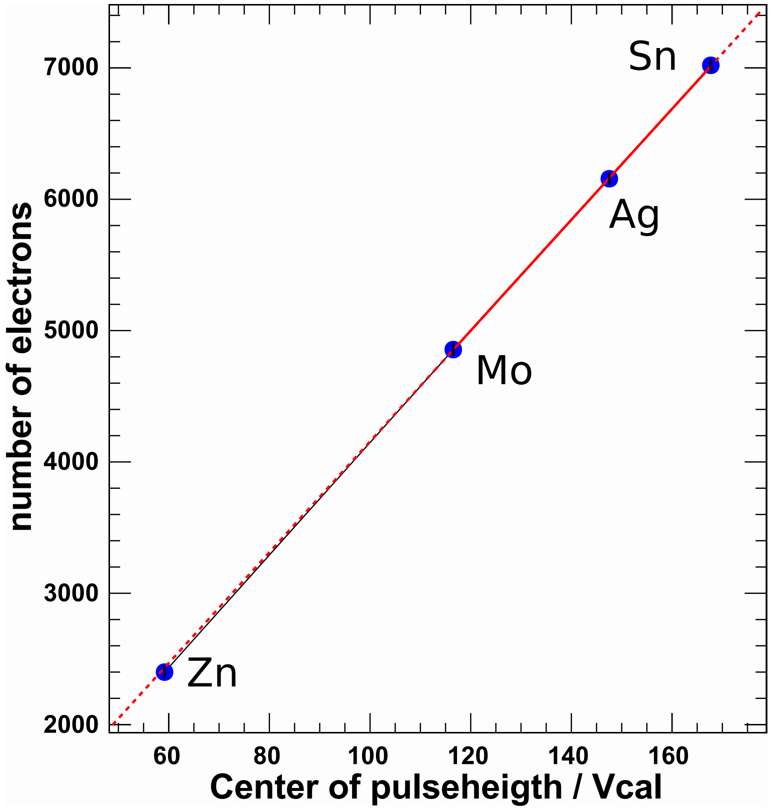
L1+L2: Switzerland
L3: CERN/Finland/Taiwan/Italy
L4: Germany
FPix: USA



- **Electrical qualification**
  - Temperature and RH controlled environment studied to reproduce **conditions of final system**
  - 10 thermal cycles between +17C and -25C
  - **"Electrical" test**: qualification and calibration of electrical functionality of the module and sensor
  - Test performed before and after cycles at -20C and after cycles at +17C
  - **Grading** based on sensor leakage current, defective pixels, result of calibrations

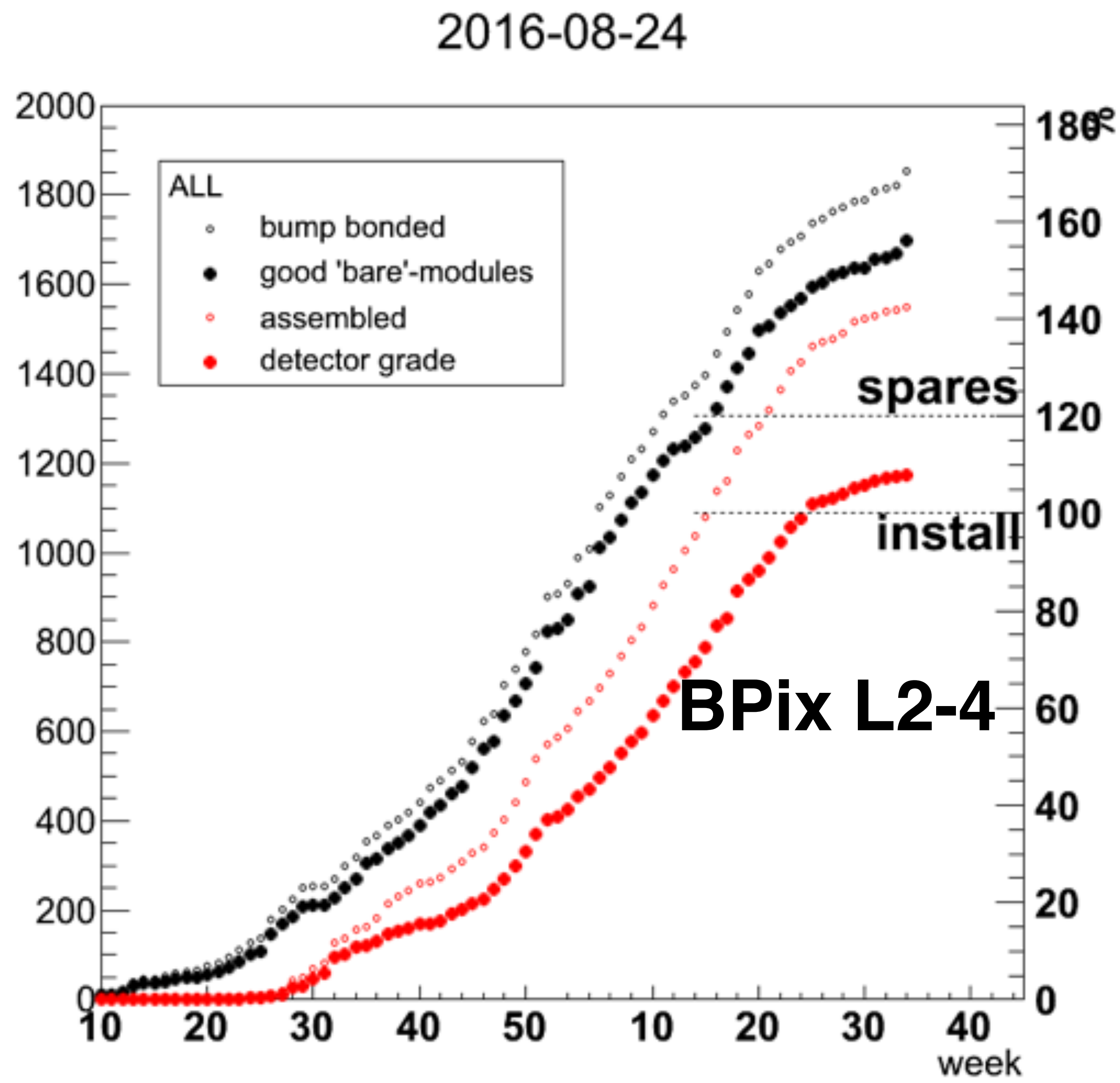



- **X-ray test**
  - **Efficiency** measurement under **high X-ray rates** (internal calibration pulses injected through X-ray background)
  - **Energy calibration** to fluorescence lines



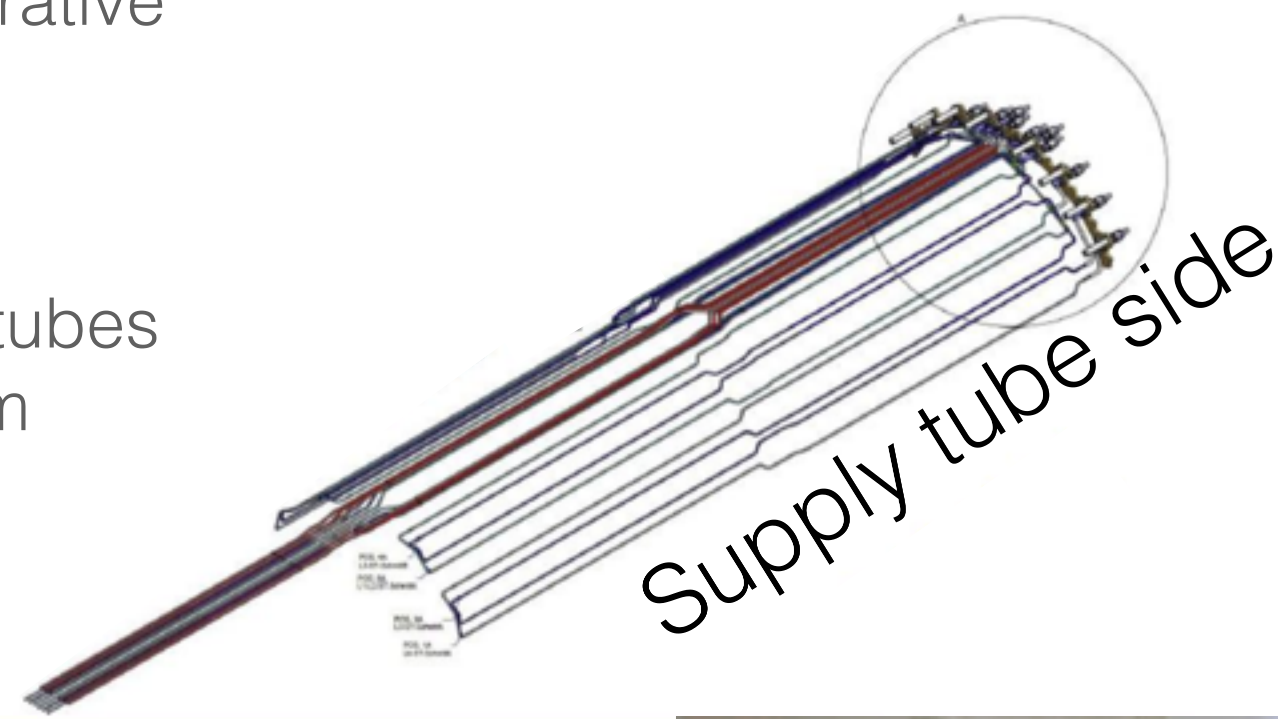
# Module production status

- Number of modules needed for **installation reached** for BPix Layers 2-4!
- Production still going on to reach foreseen amount of **spares**
- **L1 module** production ongoing (8% of total production)
- **FPix** module production close to completion
- Detector-grade module **production yield** ~80% at all production centers



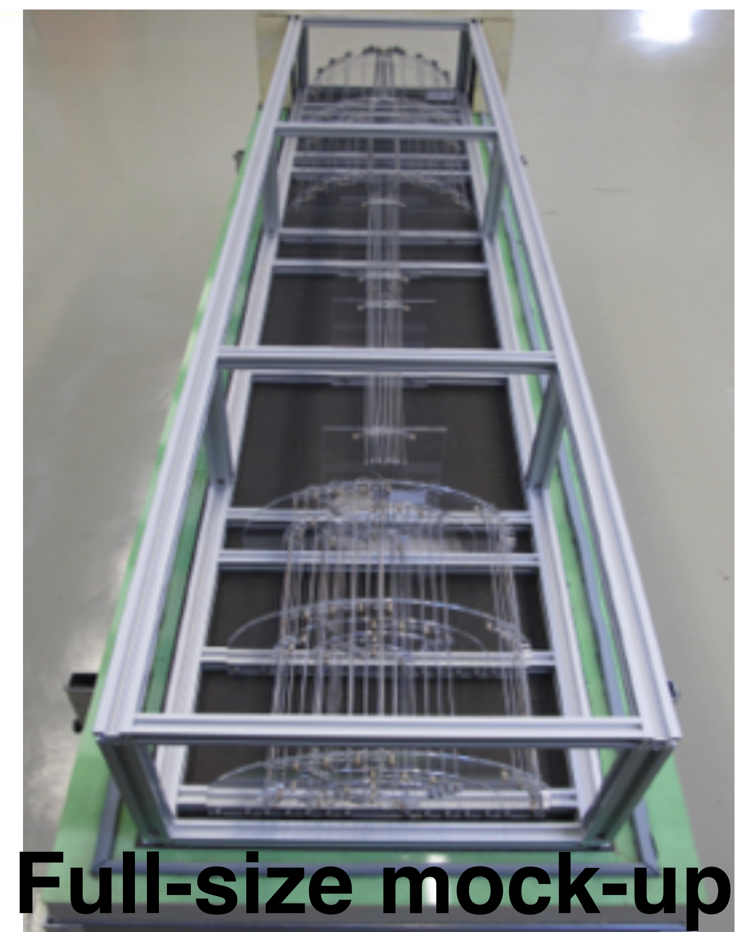
# Cooling

- Mono-phase $C_6F_{14}$ → **bi-phase** evaporative $CO_2$
  - heat removed through **latent heat**
  - high pressure (20 bar), small steel tubes (1.6mm internal diameter, 50-100μm thickness)
- BPix cooling tubes run along service cylinder and detector



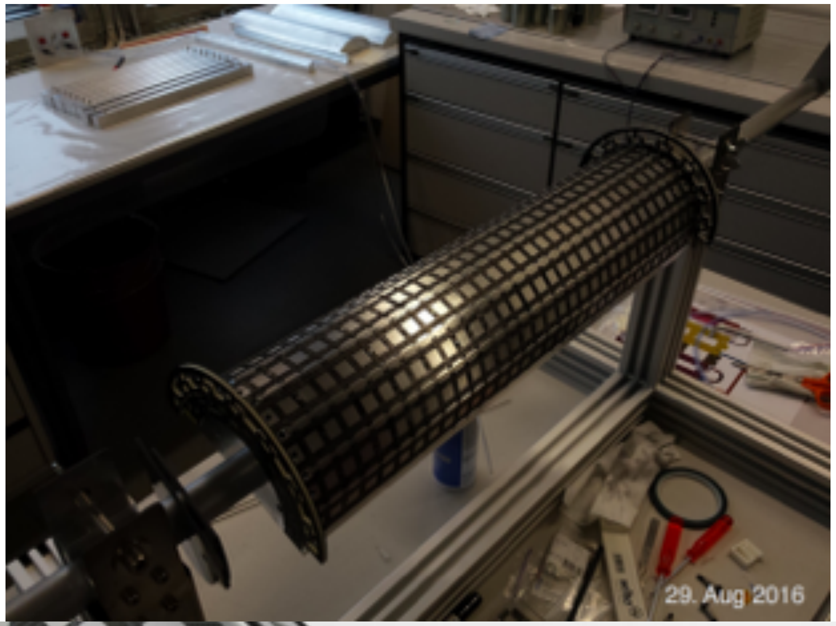


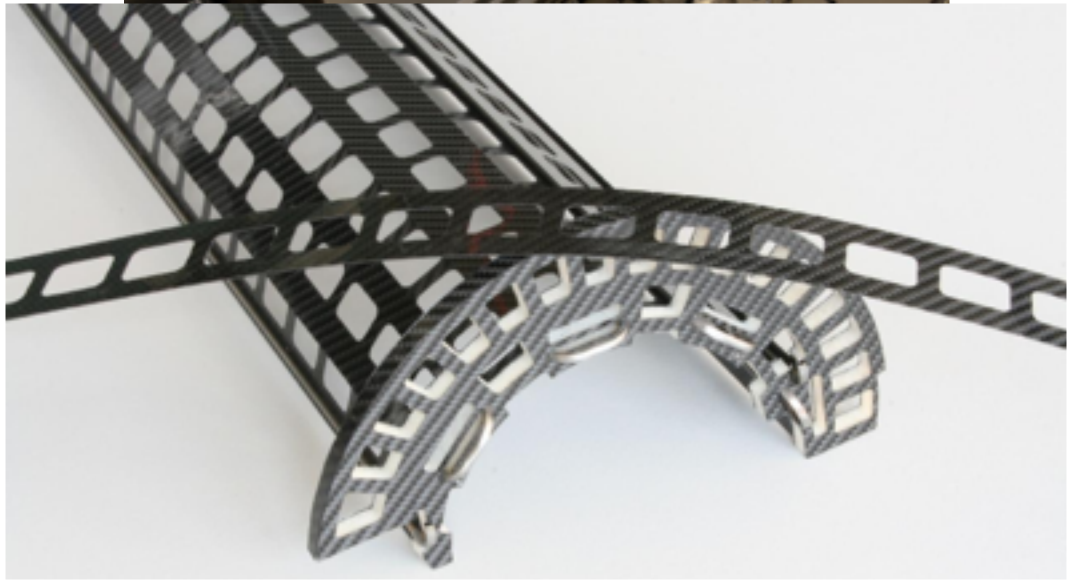
- $CO_2$ plant **installed** at CMS experimental area during LS1
- All loops cut and bent, laser welding ongoing

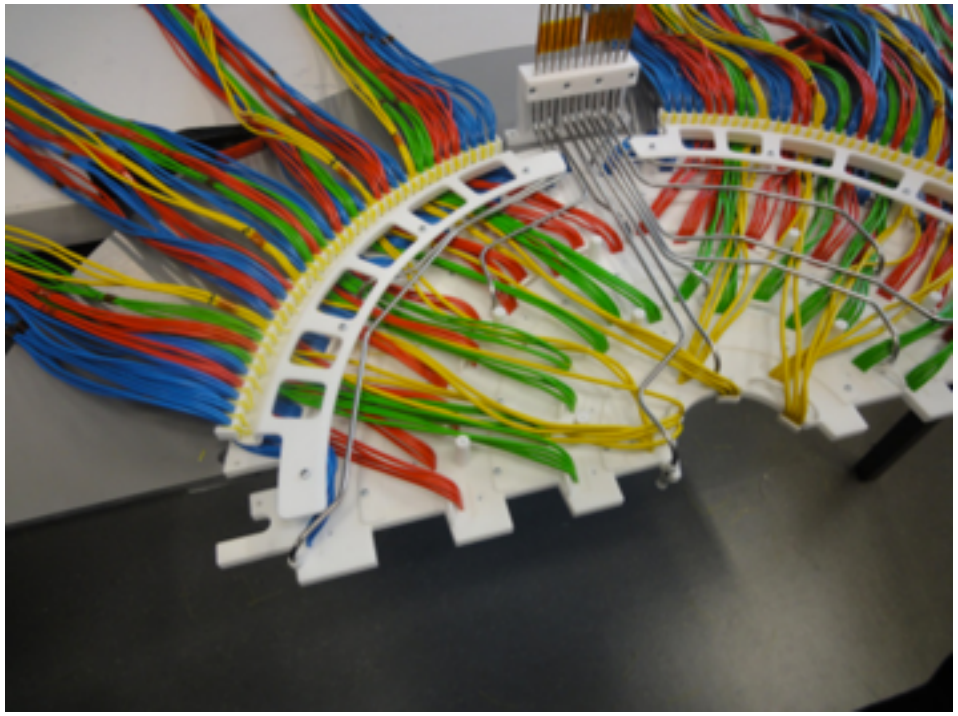


# Pixel Barrel structure

- **Lightweight** mechanics made from CFRP/Airex compound
- **Cooling** tubes are the **backbone** of the structure
- L1-2 half shells with cooling pipes ready, L3-4 in preparation
- Module mounting and BPix assembly happening in the next weeks



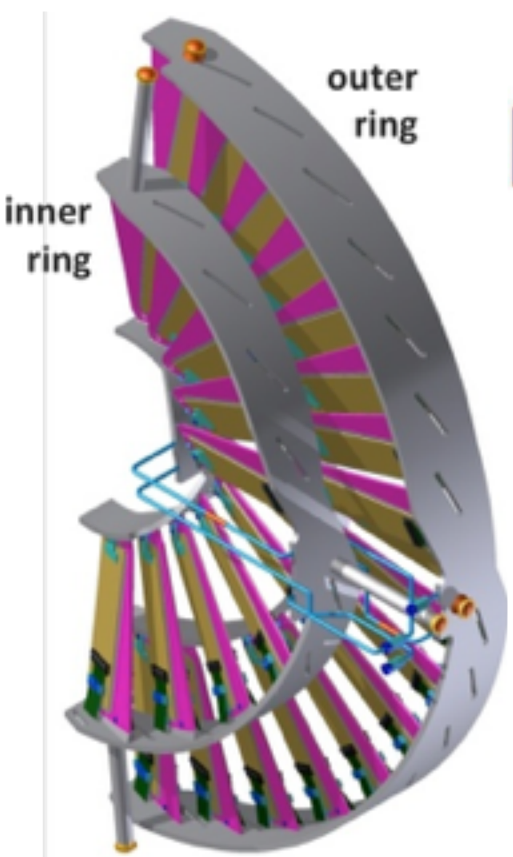


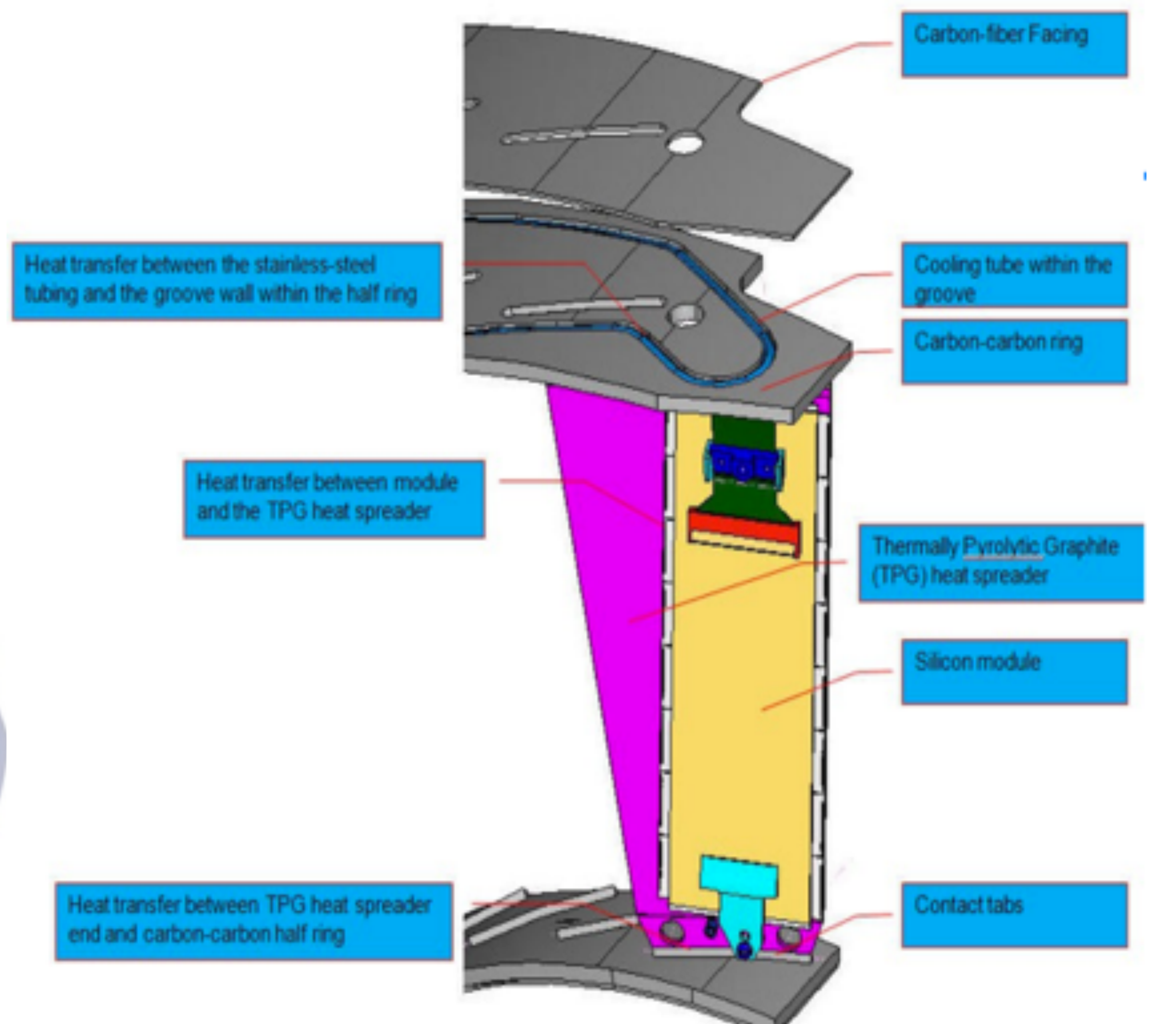
- Non-trivial routing of **~1m long** module cables
- First radial routing of L2-4, then L1
- 3D printed mock-up to develop cabling procedure

# Pixel Endcaps structure



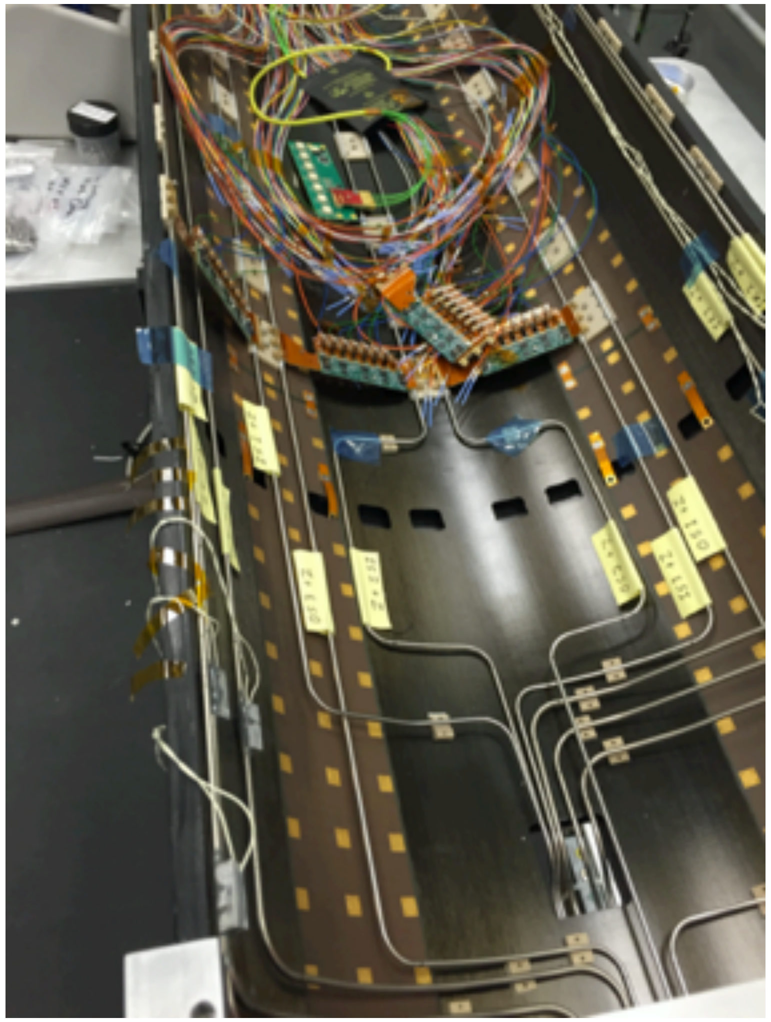
- Each **half-disk** assembled from inner and outer blade, inserted in service half-cylinder
- Cooling loops are embedded in **graphite rings**
- Thermal Pyrolytic Graphite (TPG) transfer heat to rings

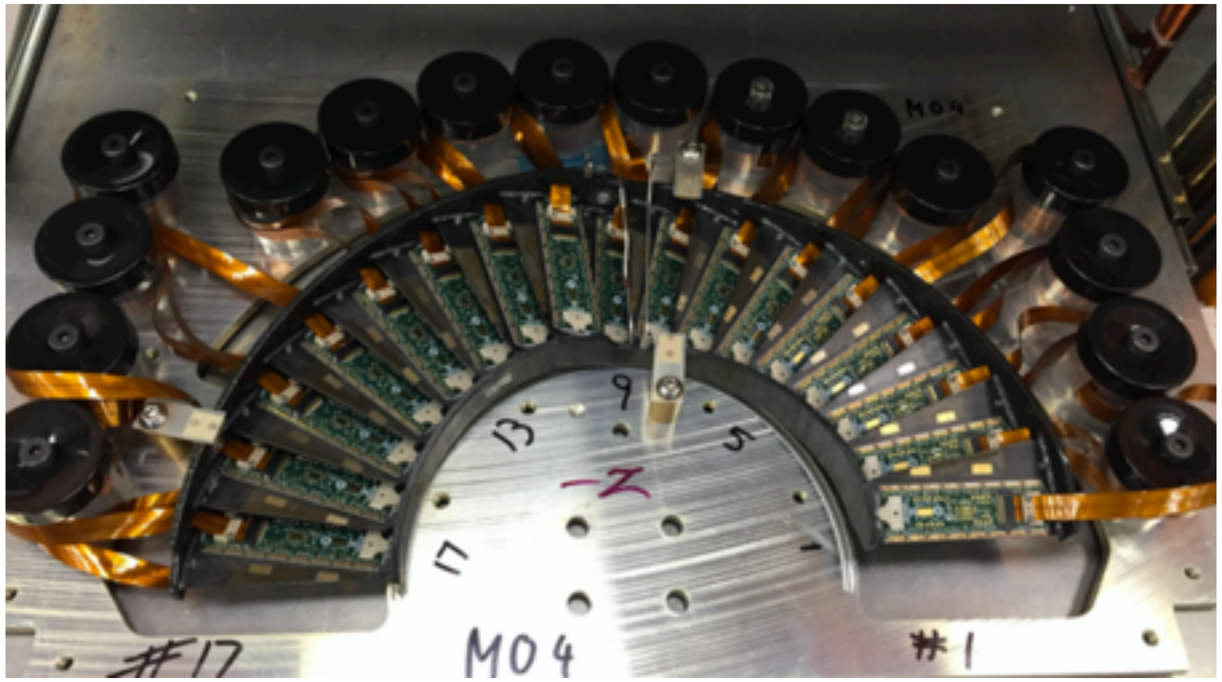


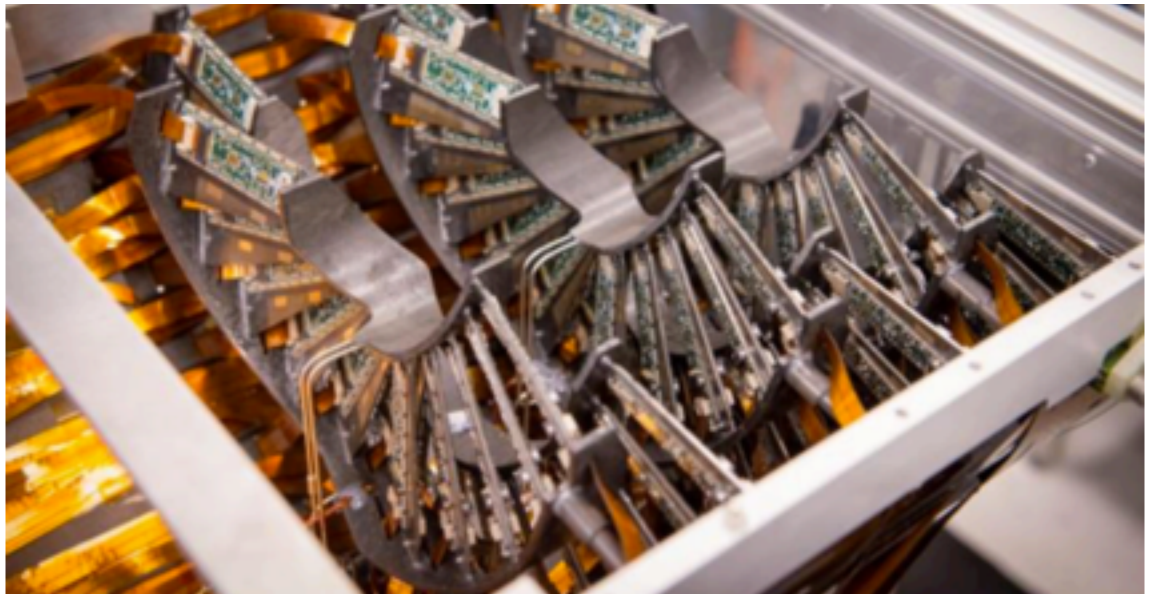




# Pixel Endcaps assembly

- First two half cylinders **fully assembled!**
- Readout with µTCA DAQ tested (**>99.98%** responsive channels); integrated tests with $CO_2$ cooling
- First half cylinder arrived at CERN **Aug 31**, half disks expected this week
- **50% of FPix detector** assembled and ready for testing at **CERN** by the end of September
- 3rd and 4th half-cylinders in preparation

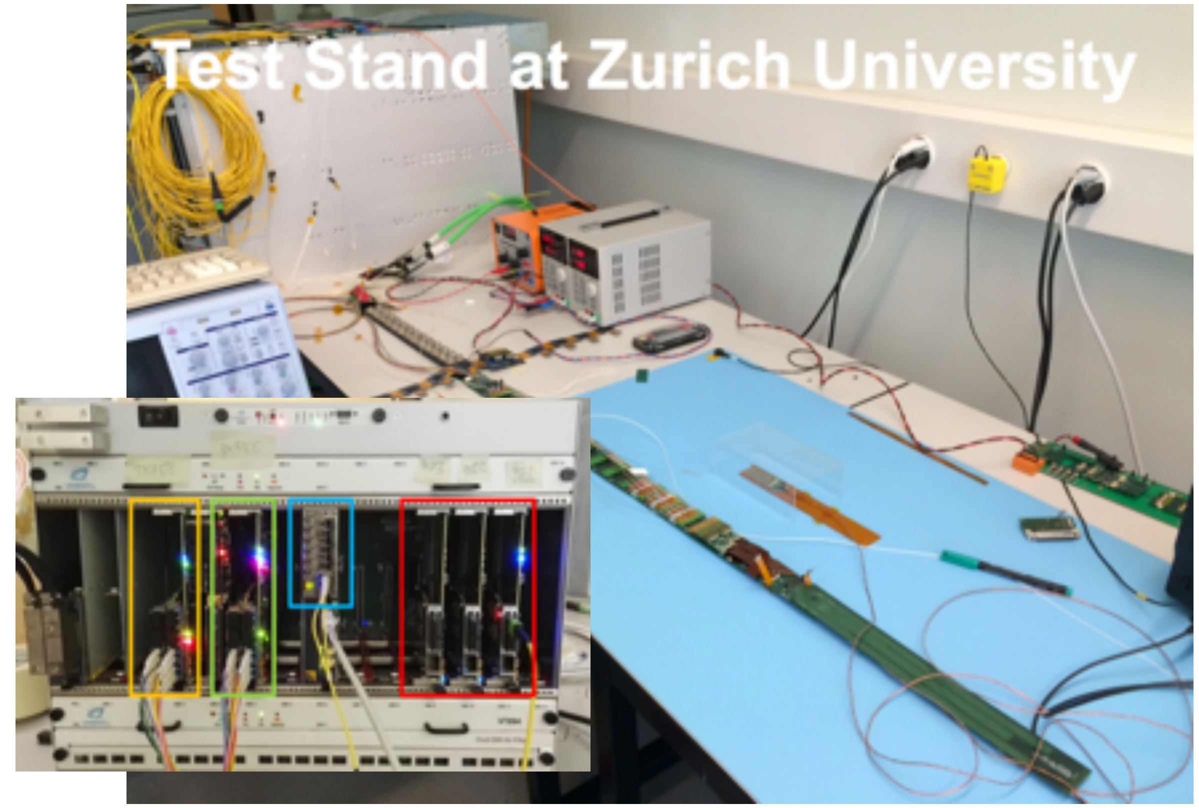


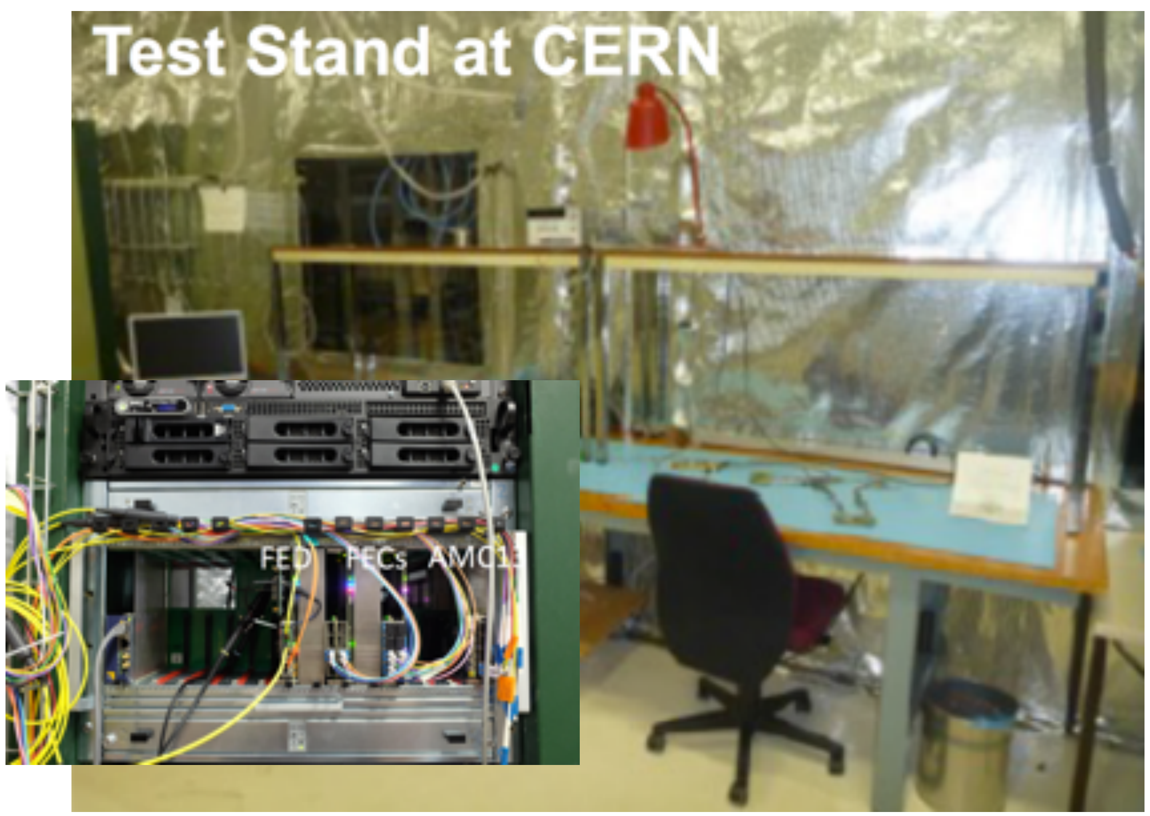


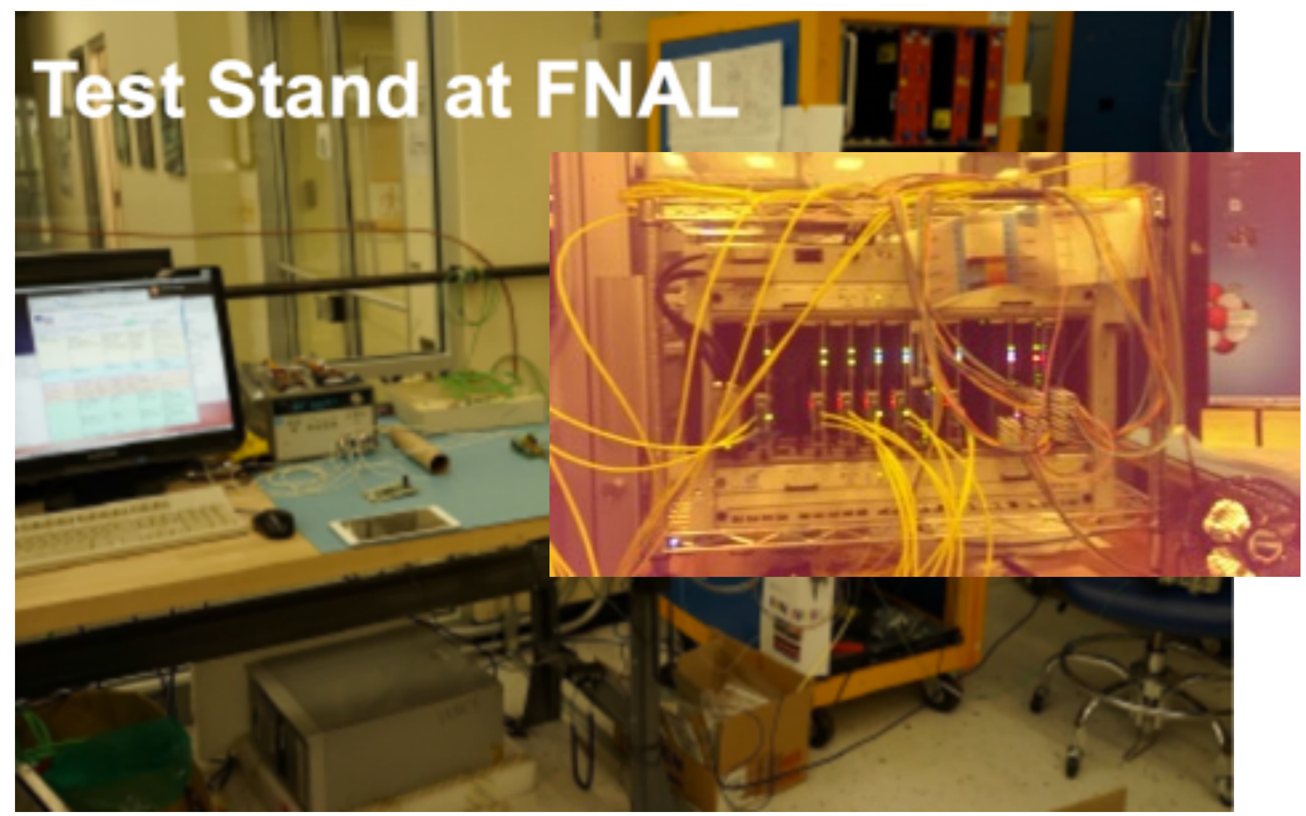



# System tests

- BPix and FPix system tests to gain experience in **operating new system**
- Test final-like system and all components before installation
- Establish and exercise calibration procedures
- Exercise with VME to **μTCA** transition



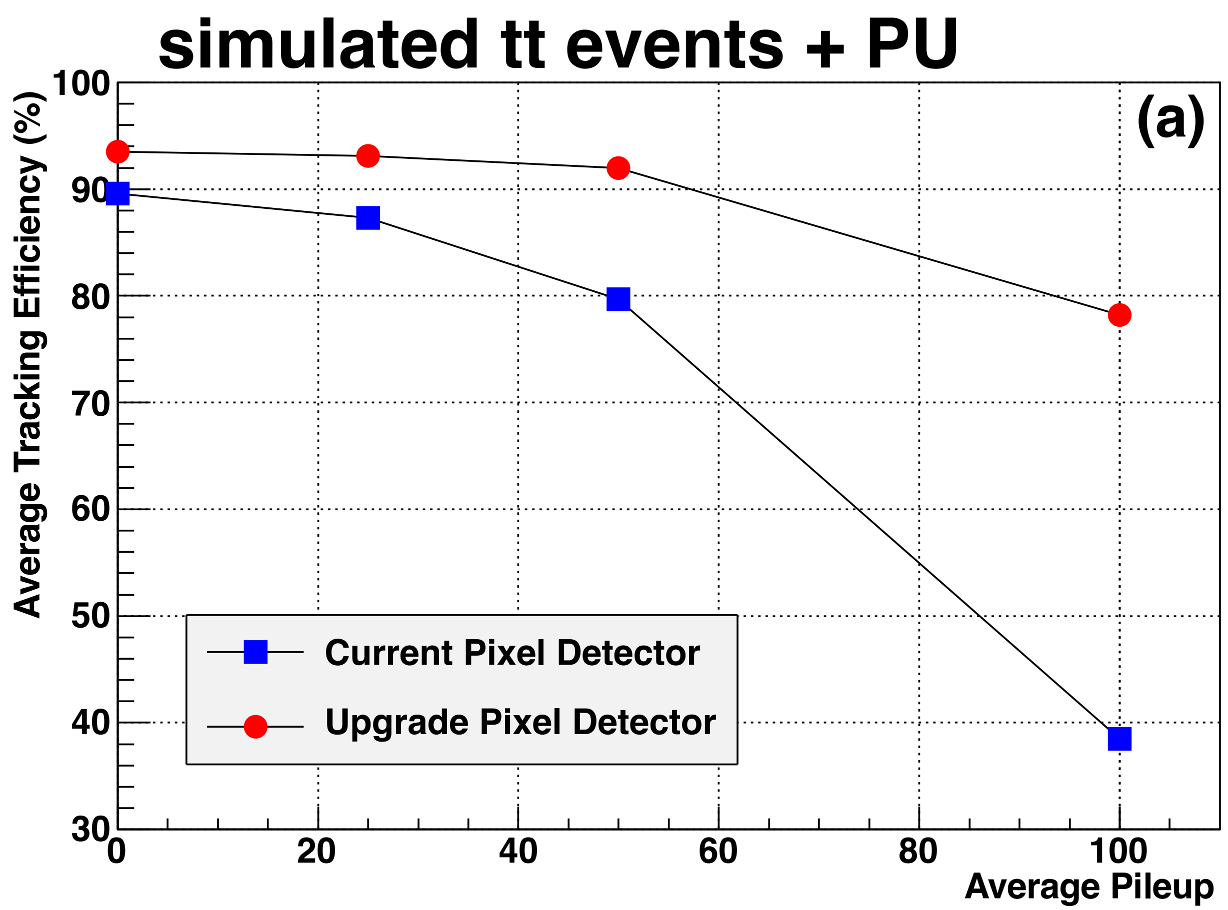
# Status and outlook

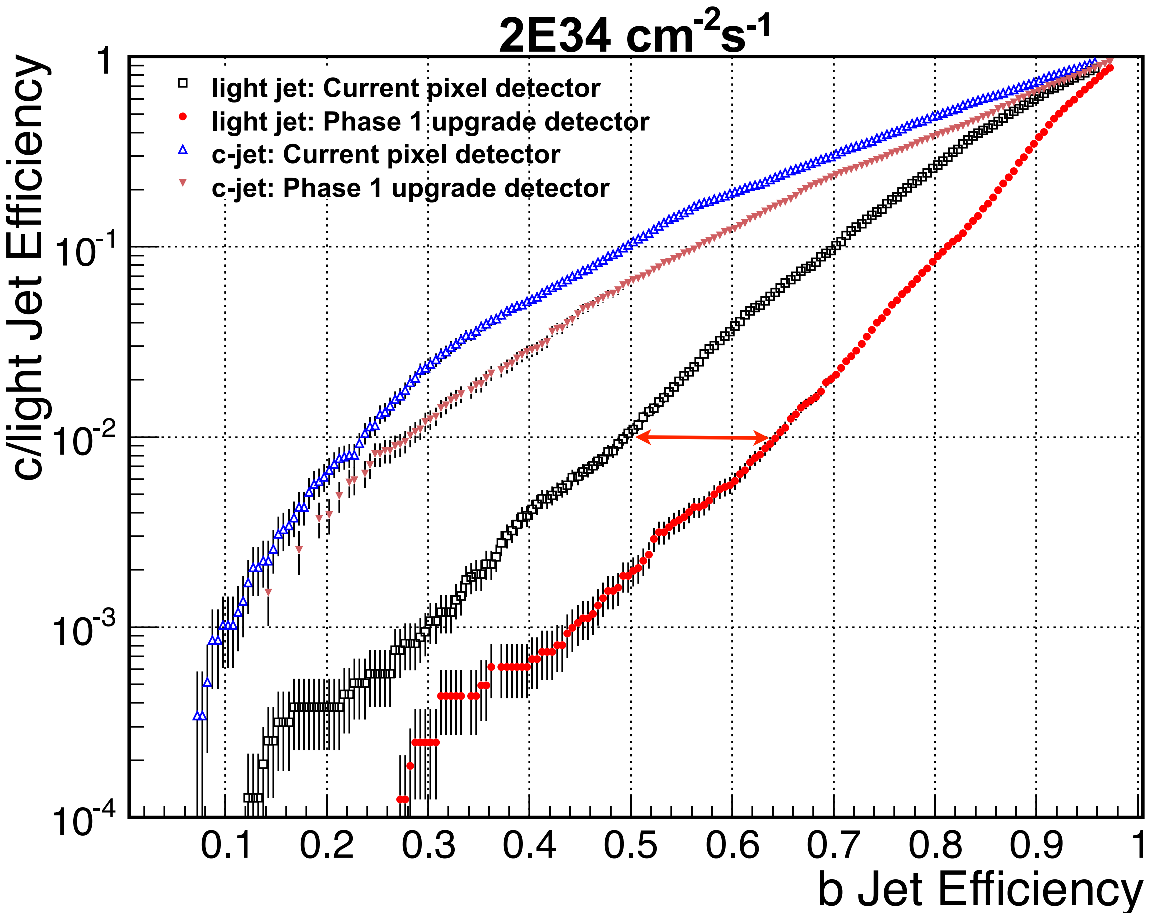
- CMS will replace its present pixel detector during the Extended Year-End Technical Stop in winter 2016-17
- New detector features additional tracking barrel layer and endcap disk, higher-rate capability, reduced material budget and lower operational threshold
- Module production is reaching completion
- Assembly of mechanical structure, cooling system and services is progressing towards final detector assembly
- Looking forward to an exciting end of the year!

BACKUP

# Expected tracking performance

- Tracking efficiency and performance more robust against harsher PU conditions thanks to:
  - improved single hit efficiency
  - additional tracking layer

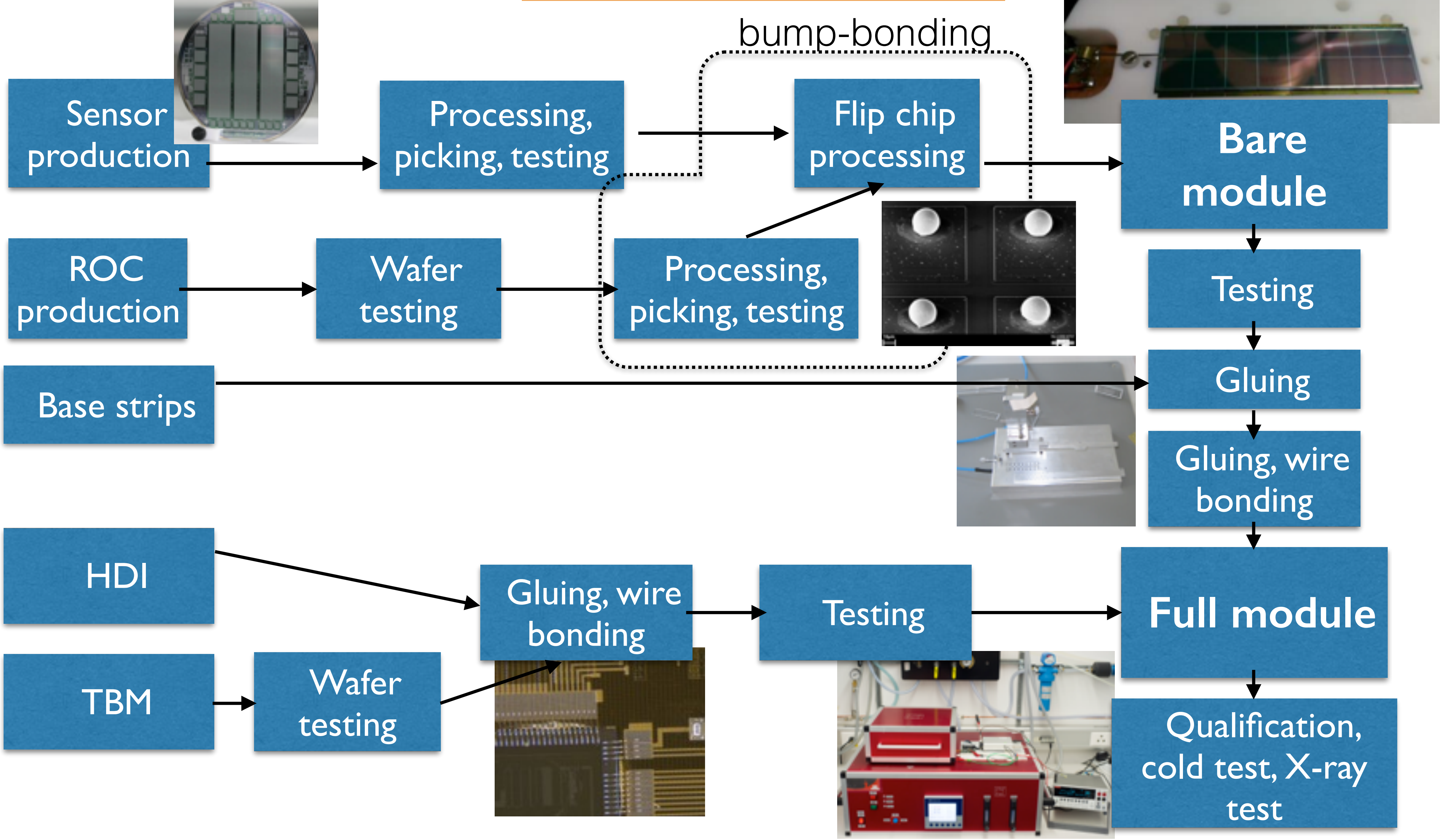


# Module production

- Production distributed among several centres

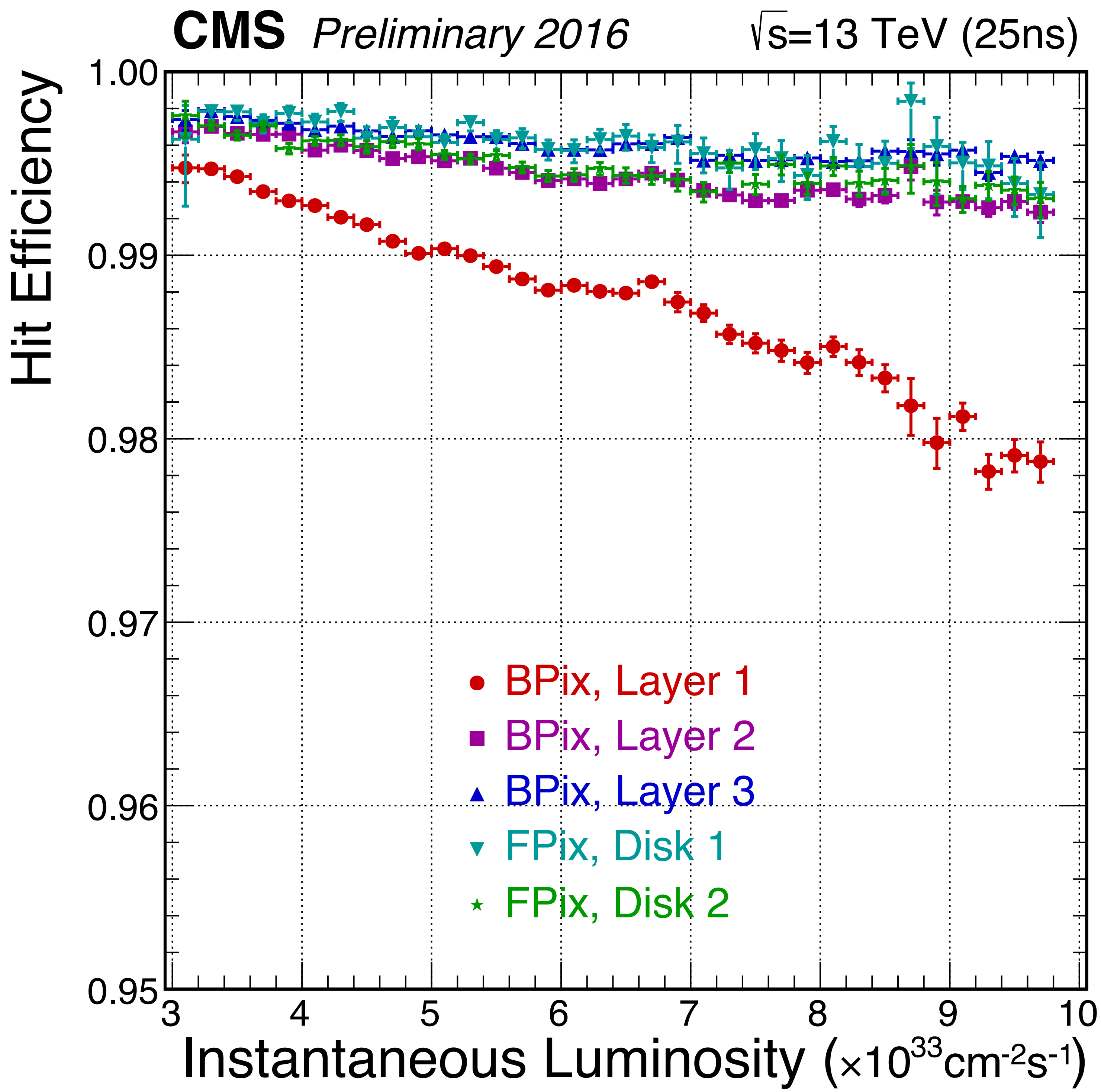
**L1+L2: Switzerland**
**L3: CERN/Finland/Taiwan/Italy**
**L4: Germany**
**FPix: USA**



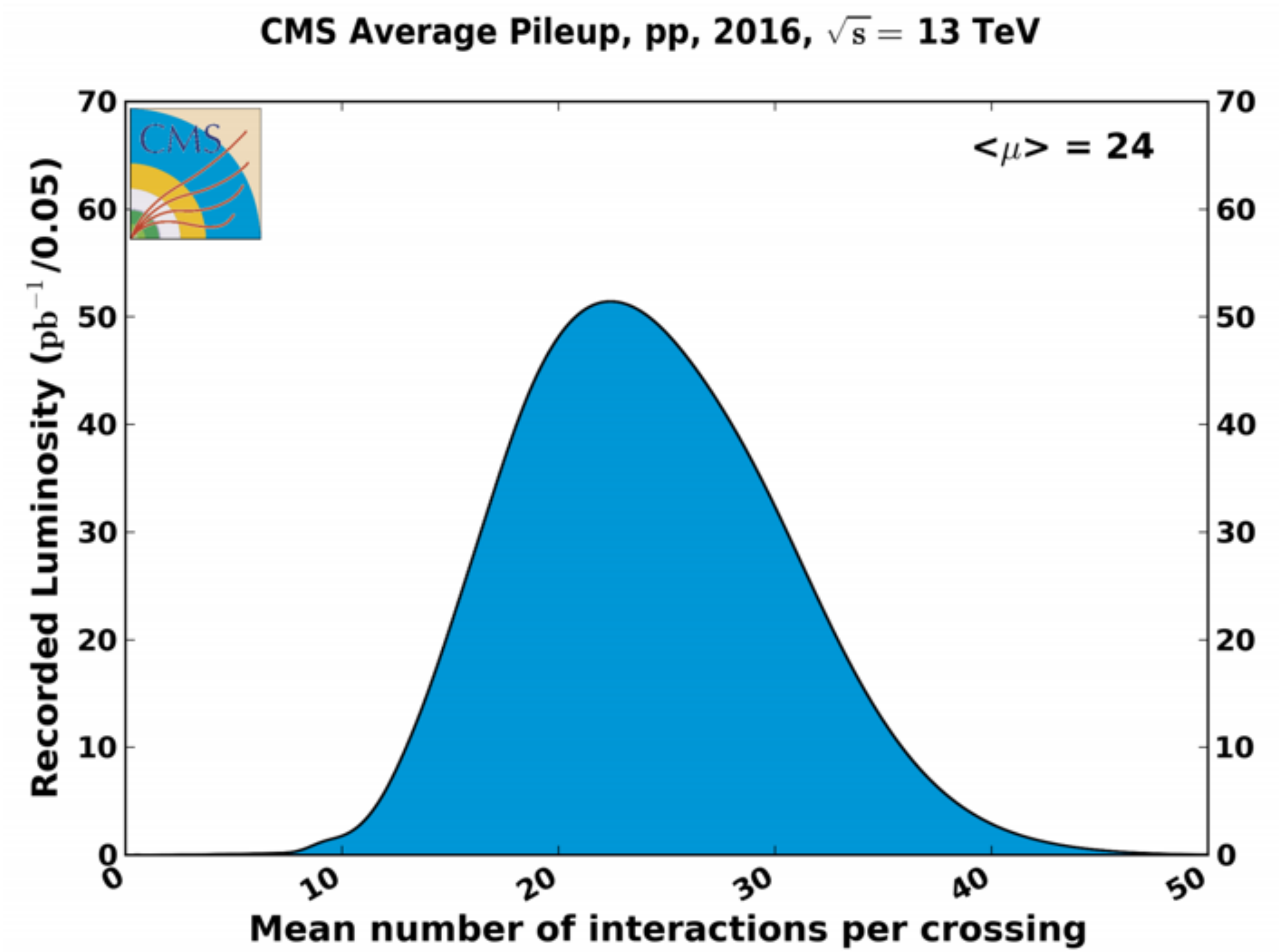
# Bump bonding

| | Bumps place, size material | Flip-chip | Sensor UBM | ROC wafer UBM | ROC wafer thinning/ dicing/ picking | Sensor opening, passivation, metalisation |
|---|---|---|---|---|---|---|
| **Desy/ UniHH** | In-house, 40um, SnAgCu | In-house | PacTech | PacTech | external | 30um, SiO2+Si3N4, AlSiCu |
| **KIT** | RTI, 20um, SnAg | In-house | PacTech | RTI | RTI | 30um, SiO2+Si3N4, AlSiCu |
| **INFN** | IZM, 25um, SnAg | IZM | IZM | IZM | IZM | 30um, Si3N4, AlSi |
| **CERN/ TW/HIP** | Advacam, 30 um, SnPb | Advacam | Advacam | Advacam | Advacam | 30um, Si3N4, AlSi |
| **CH** | Dectris, 25um, Indium | Dectris | CiS | Dectris | external | 10um, Si3N4, AlSi |

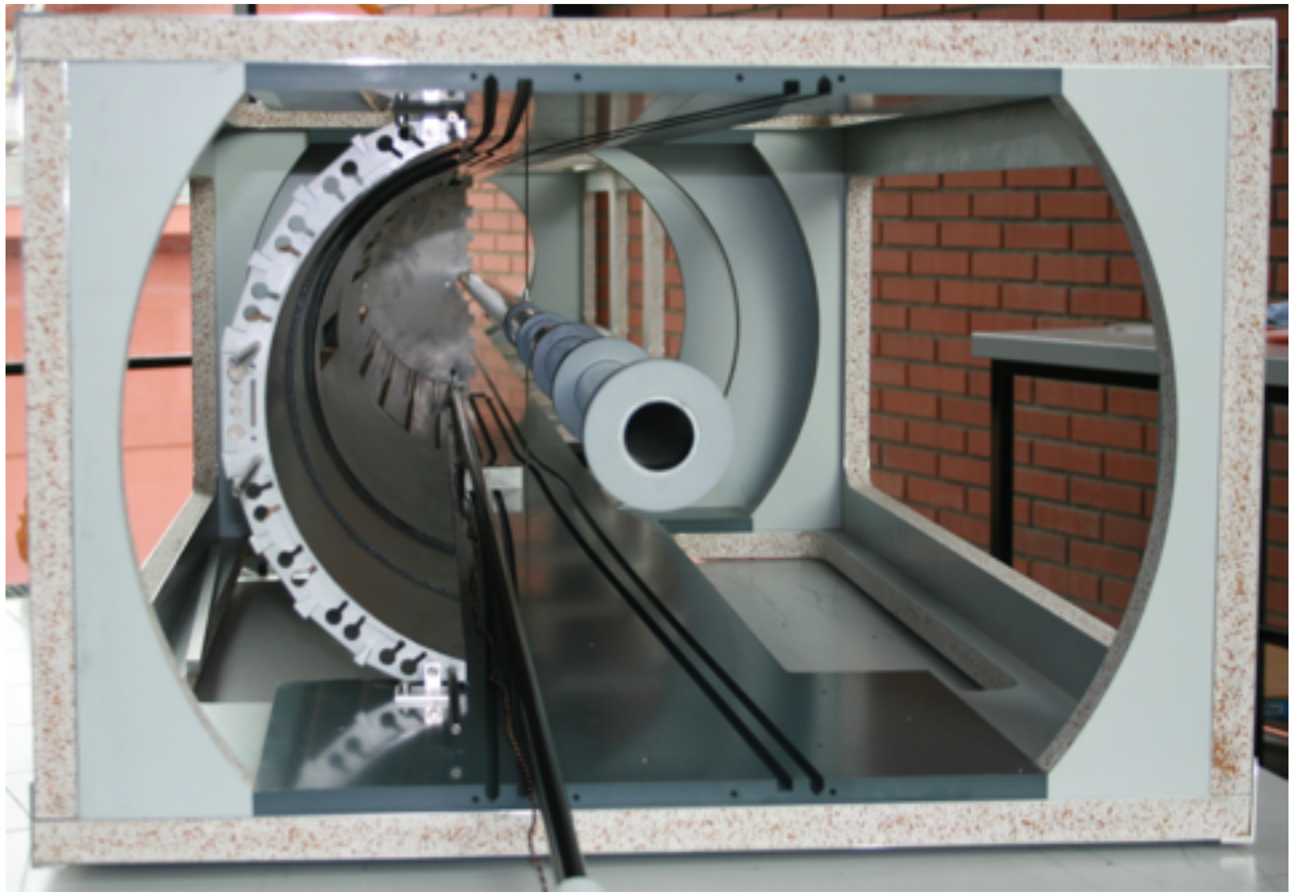
# Hit efficiency in 2016

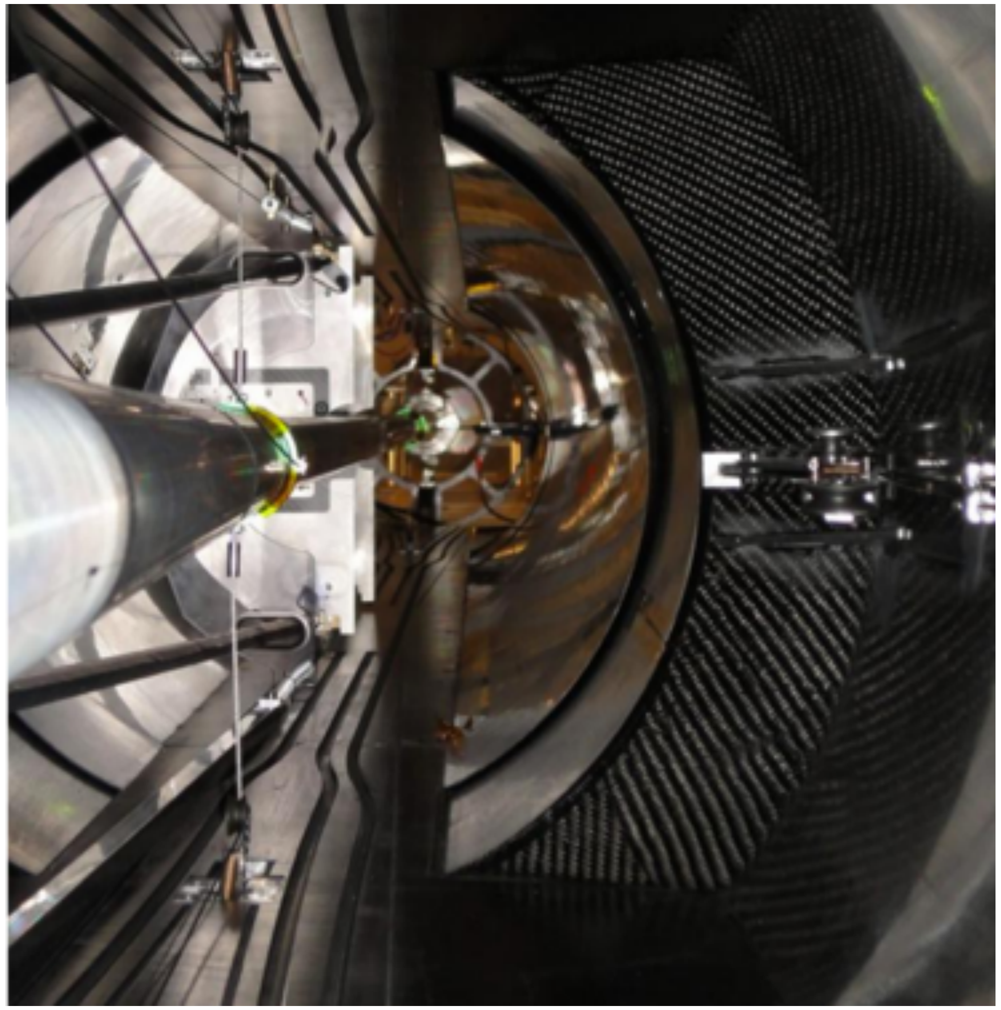


# Pile-up in 2016



- **Insertion** of detector around new smaller beampipe on curved rails
- **New** in Phase 1:
  - Adjustable wheels (BPix) both vertically and horizontally
  - Insertion of half shells distant from beampipe
  - Horizontal closing when in final position

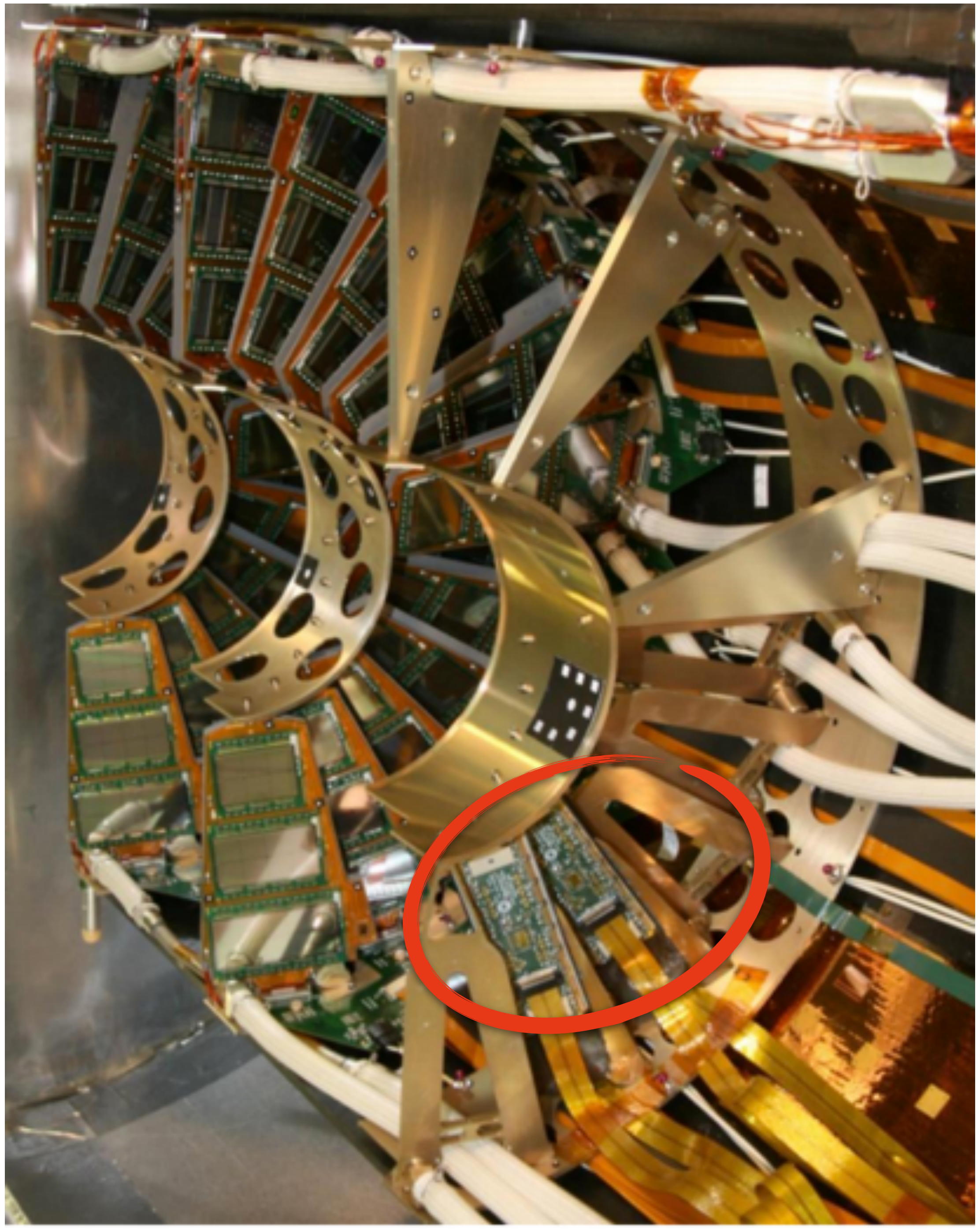




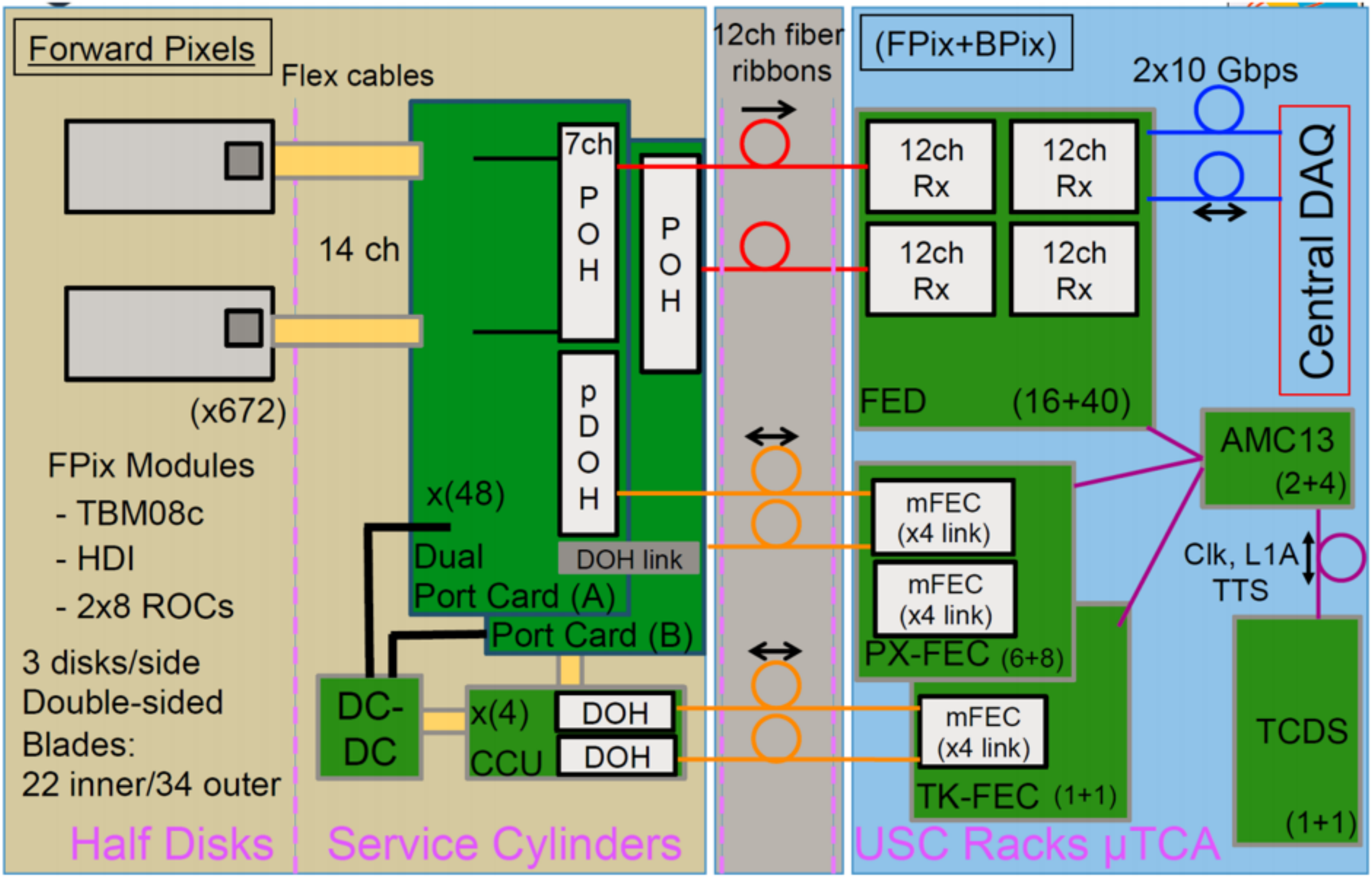
# Pilot system



- 8 phase1-modules installed on present detector during Long Shutdown 1
- Hosted in the third, unpopulated endcap disk
- Exercise readout control, DAQ and integration under realistic conditions



- Helped identify in advance possible issues:
  - Required modifications of backend readout board (FED)
- Crucial for transition after upgrade
- Now taking data in **CMS**


Forward Pixels
Flex cables
14 ch
(x672)
FPix Modules
- TBM08c
- HDI
- 2x8 ROCs
3 disks/side
Double-sided
Blades:
22 inner/34 outer
7ch
POH
POH
pDOH
x(48)
Dual
Port Card (A)
DOH link
Port Card (B)
DC-DC
x(4)
CCU
DOH
DOH
12ch fiber ribbons
(FPix+BPix)
2x10 Gbps
12ch Rx
12ch Rx
12ch Rx
12ch Rx
FED
(16+40)
Central DAQ
AMC13
(2+4)
mFEC
(x4 link)
mFEC
(x4 link)
PX-FEC (6+8)
Clk, L1A
TTS
mFEC
(x4 link)
TK-FEC (1+1)
TCDS
(1+1)
Half Disks
Service Cylinders
USC Racks µTCA

# Performance