Pixels@LHC

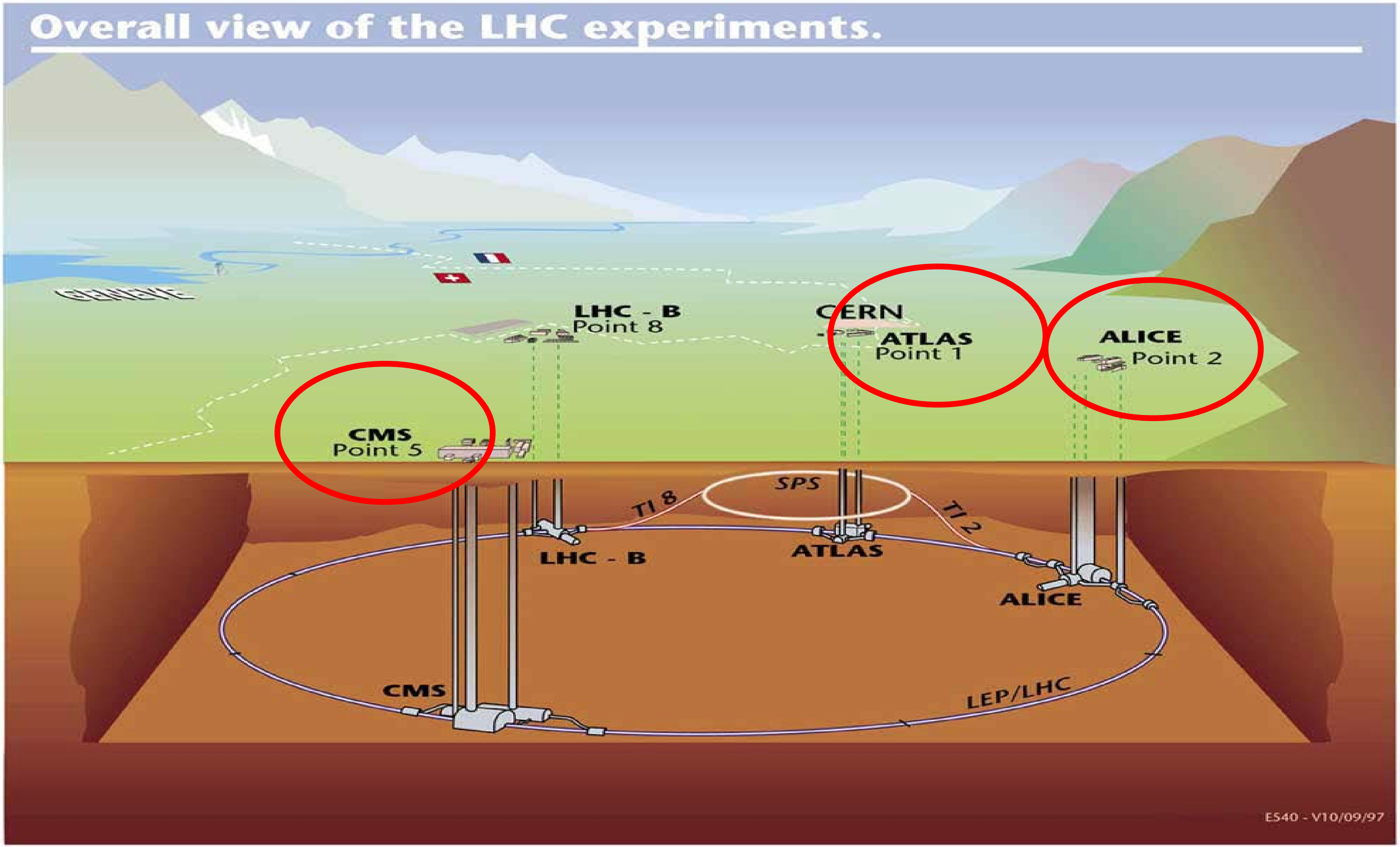
Danek Kotlinski/PSI
PSI, 6/7/11

LHC Experiments
Why pixels?
Design choices
Performance
Radiation Effects

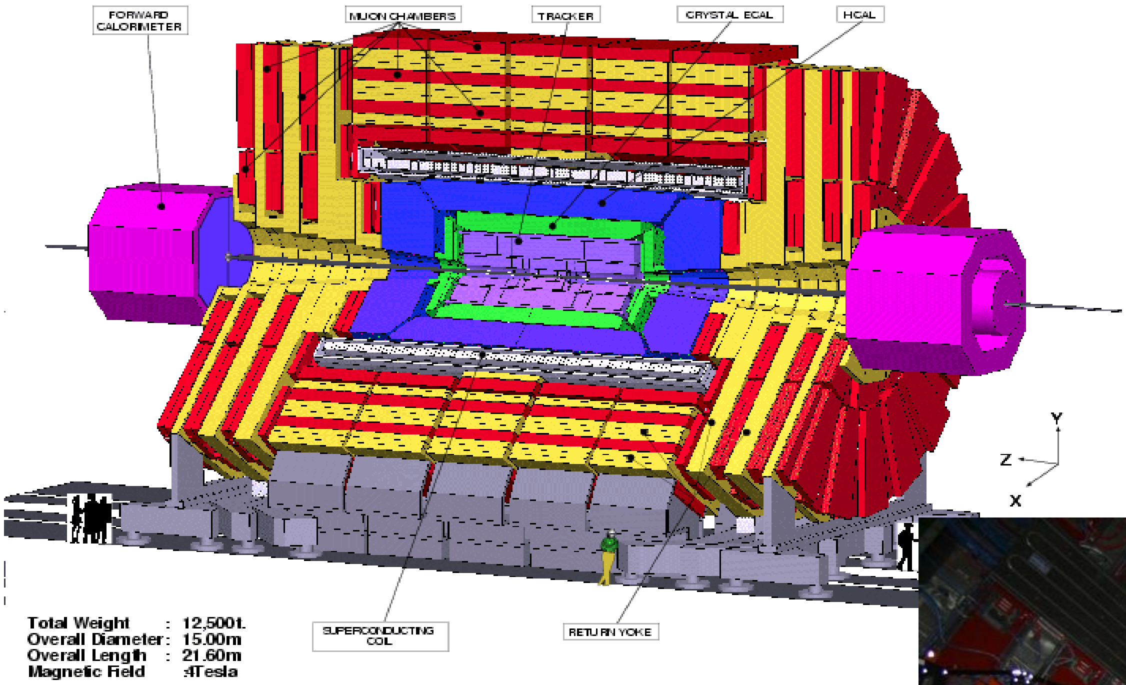
I will give many details about the **CMS** pixel detector,
some information about the **Atlas** pixels,
and less about the **Alice** detector.
Sorry for that.

LHC/CERN - Experiments

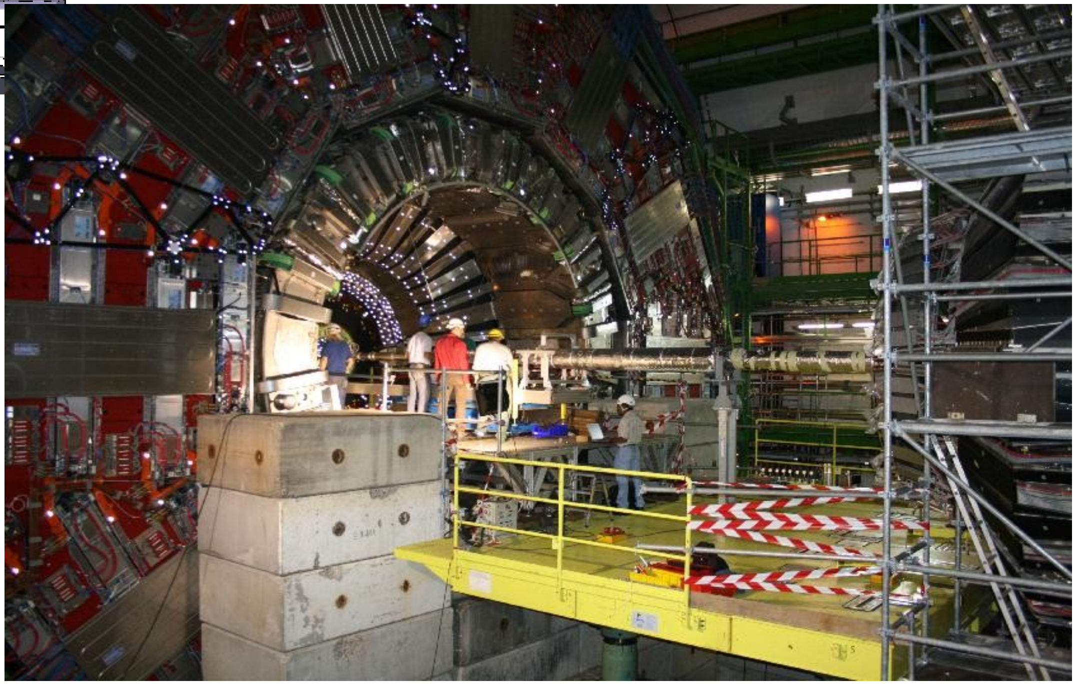
Pixels are used in Alice, Atlas & CMS



LHC Detectors (CMS as an example)



A sketch

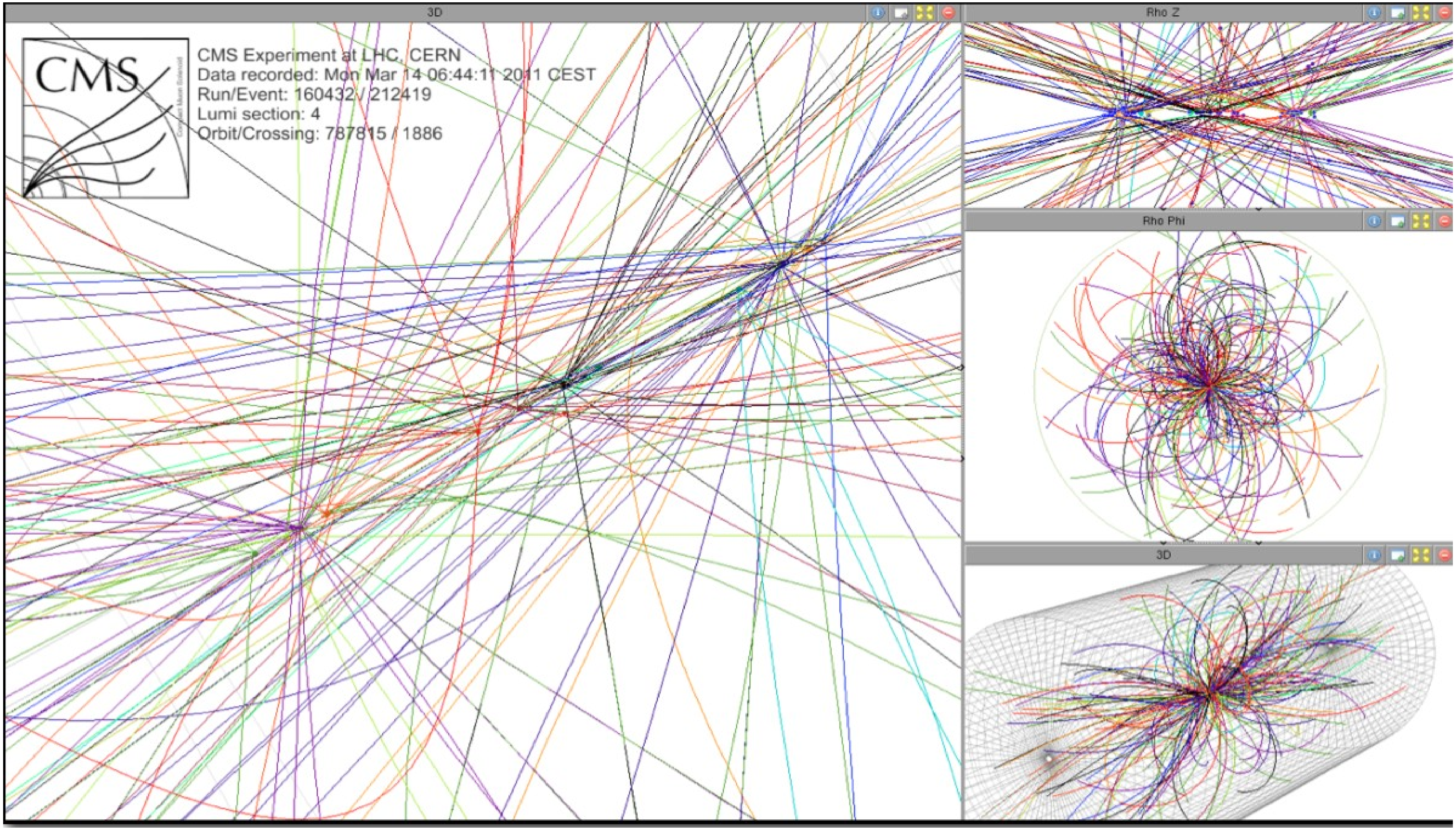


The real thing

These are big detectors,
pixels are a very small
part in volume/weight but a large
part in the number of channels.

Why pixels?

Example event from CMS. March 14th., several simultaneous collisions



How can we reconstruct all these tracks?

Why pixels?

At the LHC we have

- Every 25 nsec (40 MHz) there are several proton-proton collisions (6 -> 25).
- Each collision on the average produces 0.75 tracks/cm2
- This results in a very high hit rate of 30 M hits/cm^2/sec
- BUT these tracks are not uniformly spread of the detector.
  There are areas where the track density is much larger (jets).
- Therefore one needs a highly granular detector with a good spacial resolution.
- A pixel detector, in principle, fulfills this need.

Detector Requirements

- High granularity – small pixel size
- Very good position resolution (10-20μm).
- Fast - High Readout Speed
  Each collision on the average produces
  Hits – 4000 per event, 30 M hits/cm^2/sec
  Pixels – 16500 per event, 150 M pixels/cm^2/sec
- Large data volume - for one event 66 kbytes
  at 40MHz interaction rate – 2.6 Tbytes/sec (internal rate)
  at 100kHz trigger rate - 6.6 Gbytes/sec (readout rate)
- Radiation:
  instant particle fluences up to 3*10^7 particles/cm^2/sec
  integrated fluence up to – 10^{15} particles/cm^2, dose 50 Mrad (500 kGy)
- Has to run cold (< 0deg) – needs active cooling (remove a few kW)
- Low mass (light mechanics) – not to disturb the rest of the experiment

Some of these requirements are contradictory!

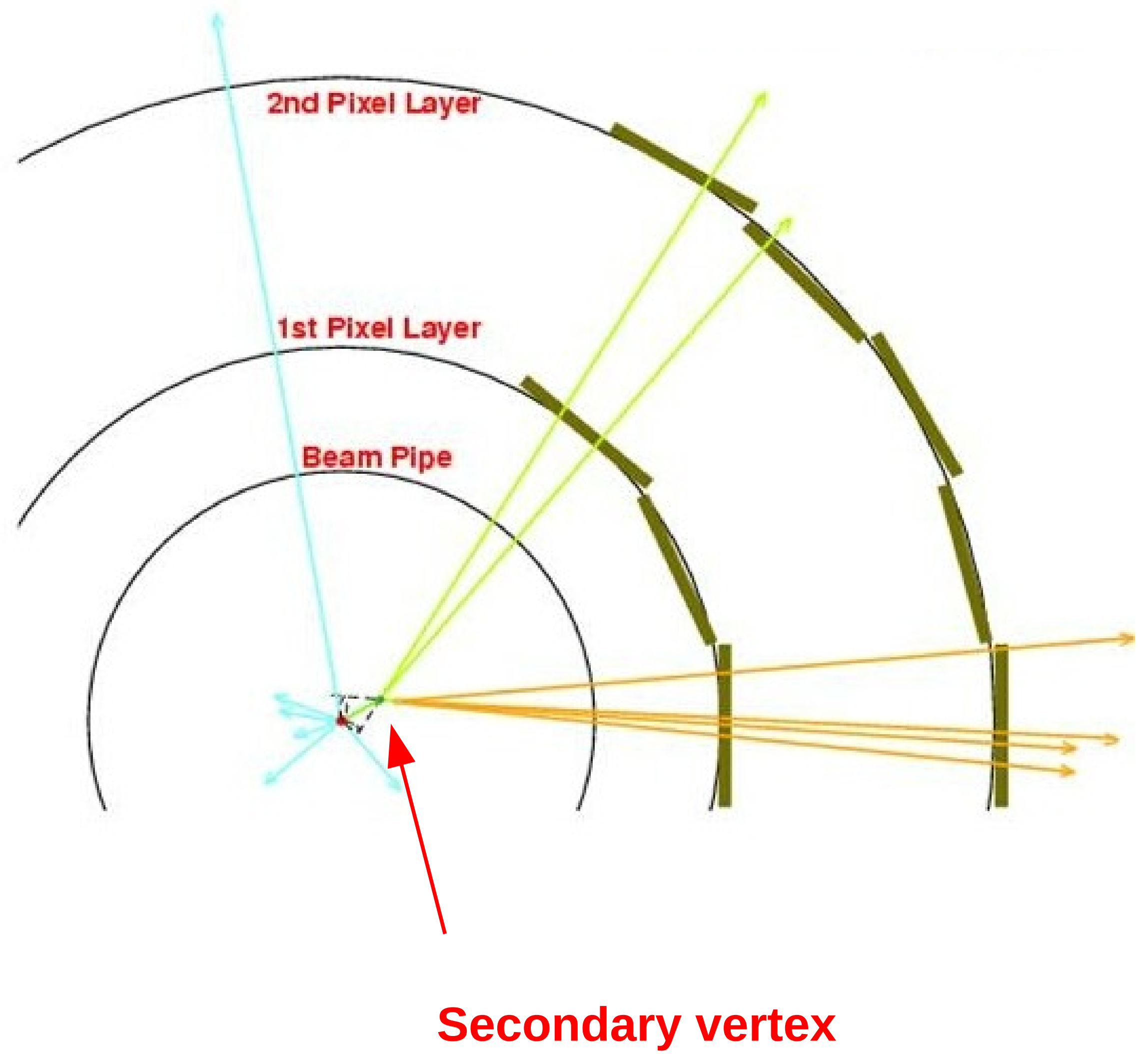
What are pixels useful for?

Pattern recognition

High granularity allows to build tracks out of 2 pixel hits.

Vertexing

Very good position resolution allows to find precise track impact parameter (displacement from the origin) and the track vertex (origin of the track)



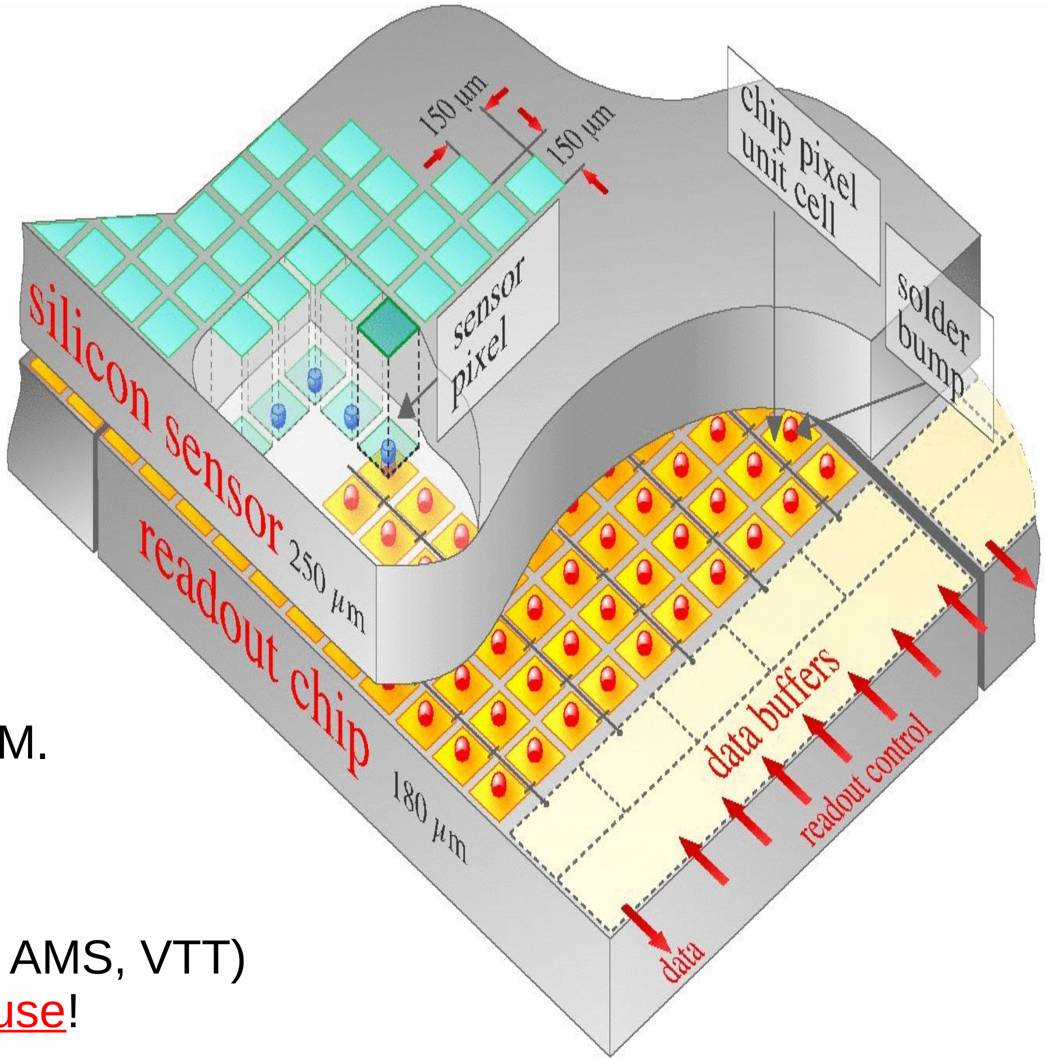
Design – Hybrid Pixels

The main design parameters
had to be fixed in **mid 90-ties**.

The only realistic choice at that time
was a **hybrid detector** with a
silicon senor bump bonded to
a silicon **CMOS readout chip**.

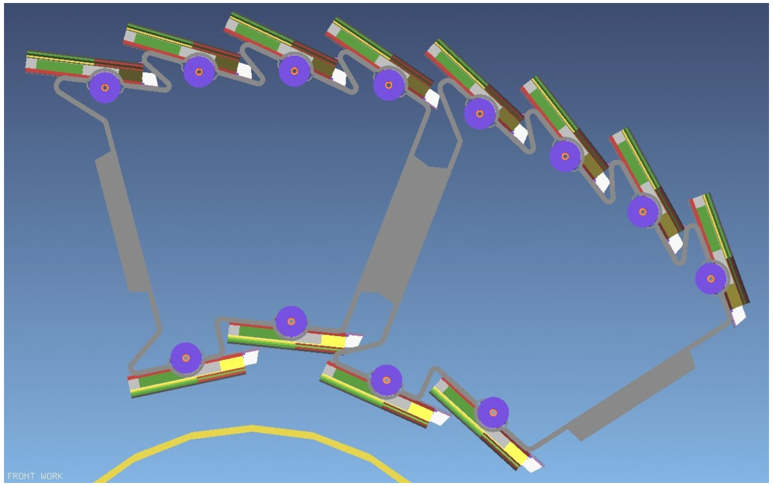
Sensor:
Both Diamond and GaAs sensor were
considered. Silicon won by far!

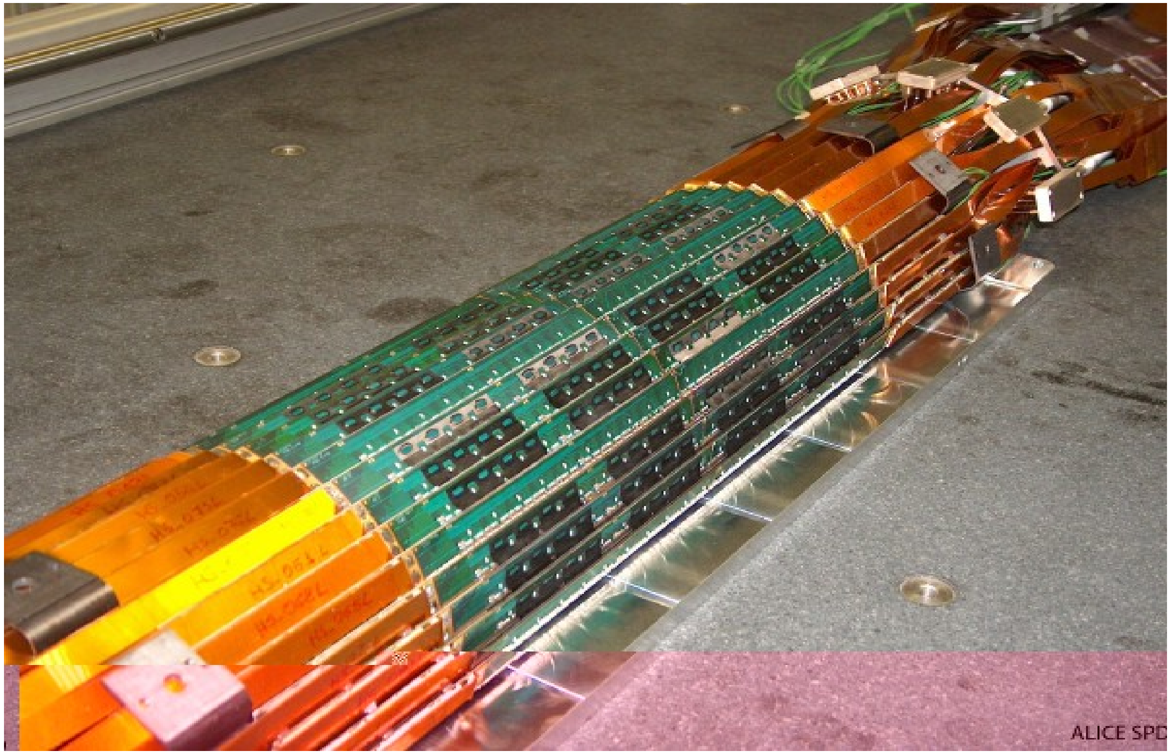
Readout chips:
Several technologies were considered.
For a while it looked like the DMILL
process was the winner.
Finally we all went to 0.25 micron CMOS IBM.



Bump bonding:
Very new technology.
Several companies learnt how to do it (IZM, AMS, VTT)
PSI developed its own bump-bonding in-house!

Alice Pixel Detector





Optimized for Heavy Ion (Pb-Pb) collisions.
This means very large occupancy (many hits per event) but low event rate.

Very low mass, 1.1% per layer!

Non hermetic coverage.

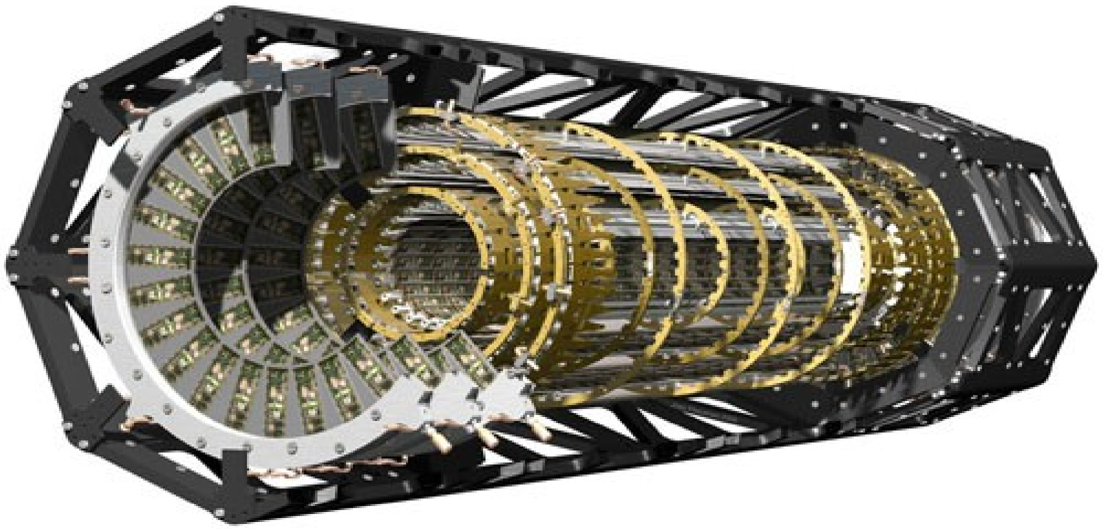
C4F10 cooling at 29degC.

Lower clock rate (10MHz).

Atlas Pixel Detector

The largest among the LHC pixel detectors:

3 barrel layers + 2*3 disks
80M pixels, 1744 modules.
1.7 m2. area.



Digital readout.
Includes Time-Over-Threshold mechanism to measure the analog signal (like an ADC), so it has charge signal information.

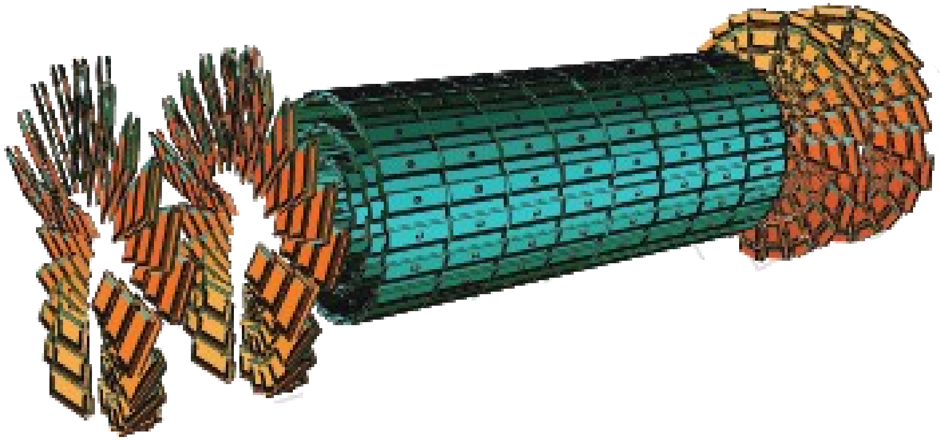
High granularity of the services:
one power supply per module,
one clock/control fiber per module.

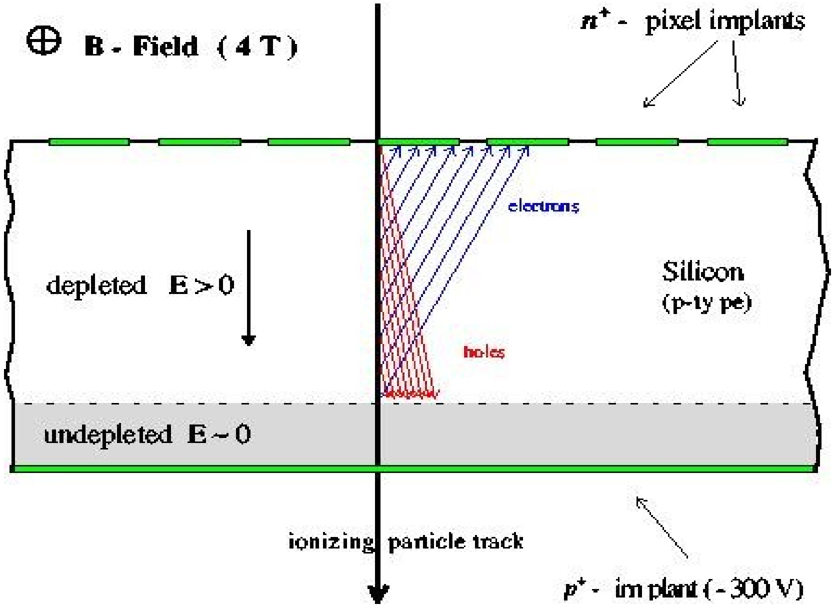
C3F8 cooling. Temperature -13 to -5 degC.

CMS Pixel Detector

The only detector with **analog readout,** and almost square pixels.
Smaller than Atlas but still fully hermetic.

Build to allow quick extraction and insertion.
It needs about **1 week** to take it out and put back in (Atlas needs a few months).
There is a catch, CMS needs 3 weeks to open the detector to allow pixel access.
C6F14 cooling, presently running at 7degC.

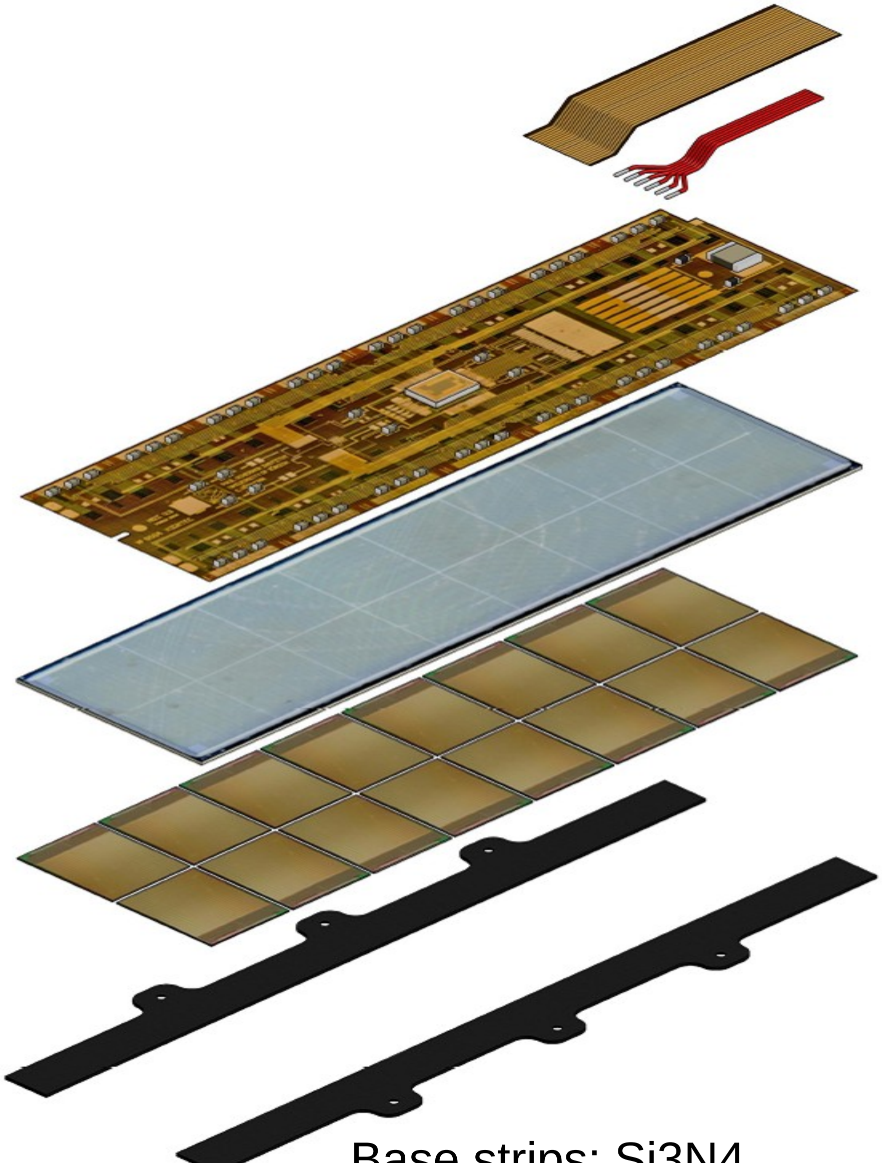




Make use of the large charge drift in Magnetic field (Lorenz angle) to enhance the charge sharing and therefore the position resolution.

Therefore CMS can use almost square pixels 100 * 150 μm^2

CMS Module Design



Cables: signals & power

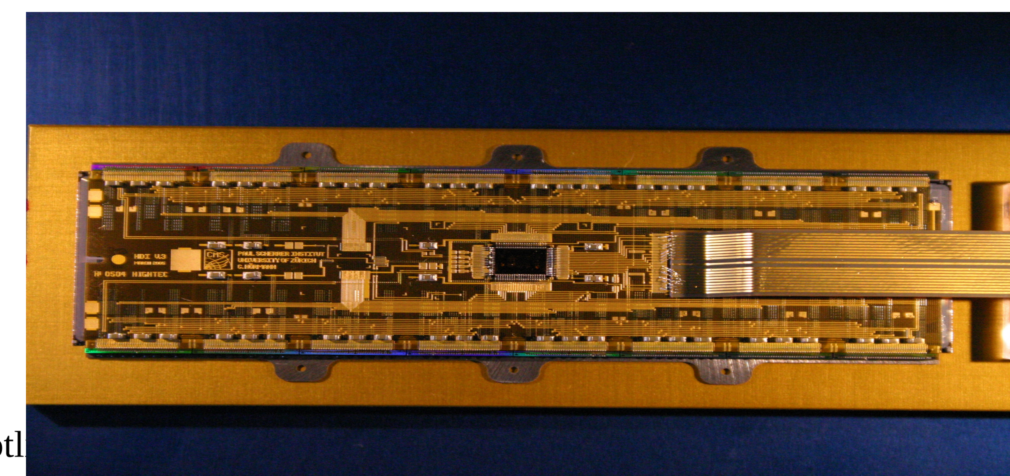
HDI print with the TBM chip

Si sensor (280um)

16 ROCs (180um)

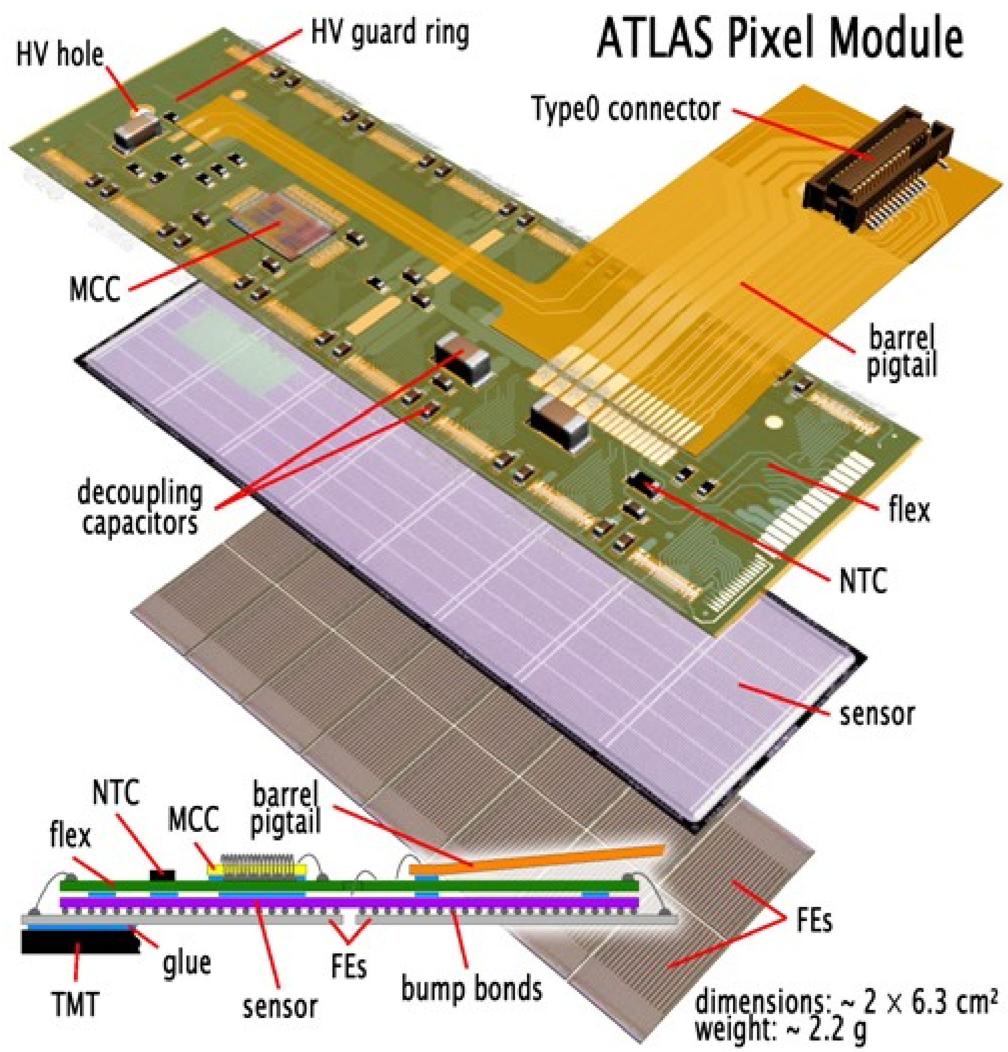
Base strips: Si3N4

Ready module (1200 produced @PSI)

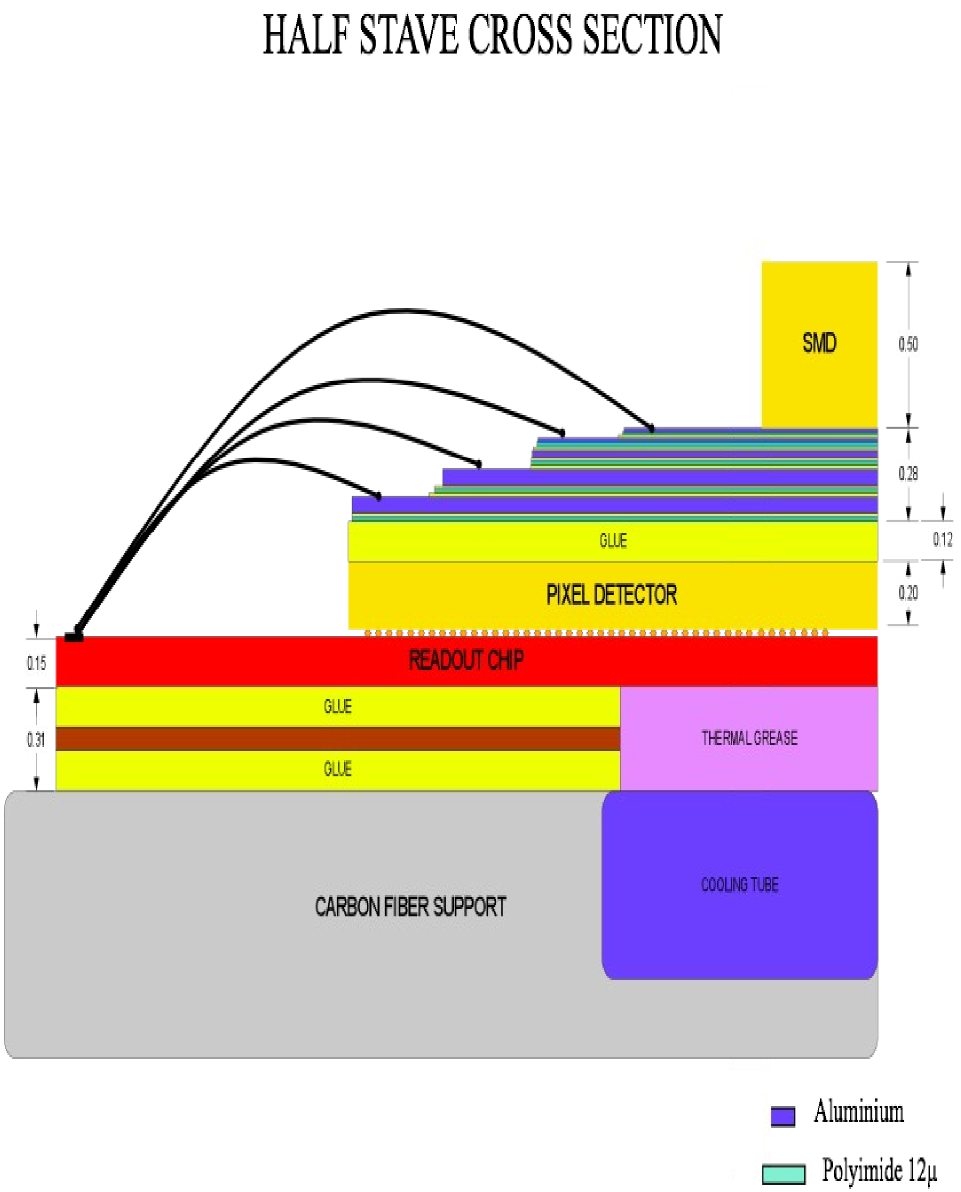


Atlas Module Design

- Sensor:
  - 250 µm thick n-on-n sensor
  - 47232 (328 x 144) pixels
  - Typical pixel size 50 x 400 µm²
    (50 x 600 µm² pixels in gaps between FE chips)
  - Bias voltage 150 – 600 V
- Readout:
  - 16 FE chips, 2880 pixels each
  - Zero suppression in the FE chip, MCC builds module event
  - Pulse height measured by means of Time over Threshold
  - Data transfer 40 – 160 MHz depending on layer



ALICE Silicon Pixel Detector



Optimize material budget:

~1.1% X0 per layer

- Carbon fibre: 200 µm
- Cooling tube (Phynox): 40 µm wall thickness
- Grounding foil (Al-Kapton): 75 µm
- Pixel chip (Silicon): 150 µm
- Bump bonds (Pb-Sn): diameter ~15-20 µm
- Silicon sensor: 200 µm
- Pixel bus (Al+Kapton): 280 µm
- SMD components
- Glue (Eccobond 45) and thermal grease

Design - Summary

	Alice	Atlas	CMS
Pixel size (in μm)	50*425	50*400	100*150
Num of pixels	10M	80M	66M
Area (m2)	0.24	1.7	1.2
Barrel layers	2	3	3
Disks	0	6	4
Minimum Radius (cm)	3.9	5.0	4.2
Clock (MHz)	10	40	40
Readout	Digital	Digital (+ ToT)	Analog

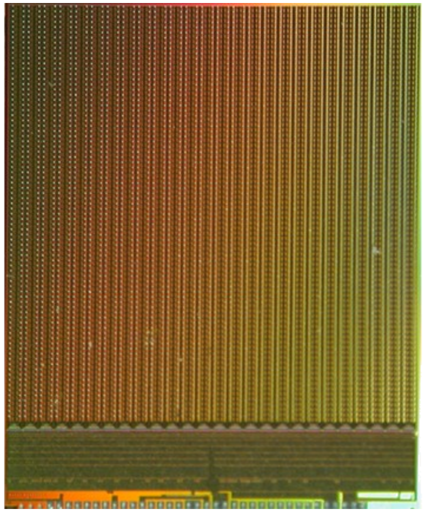
Readout chips

All: CMOS 250nm, zero suppressed readout, only triggered data are read out.

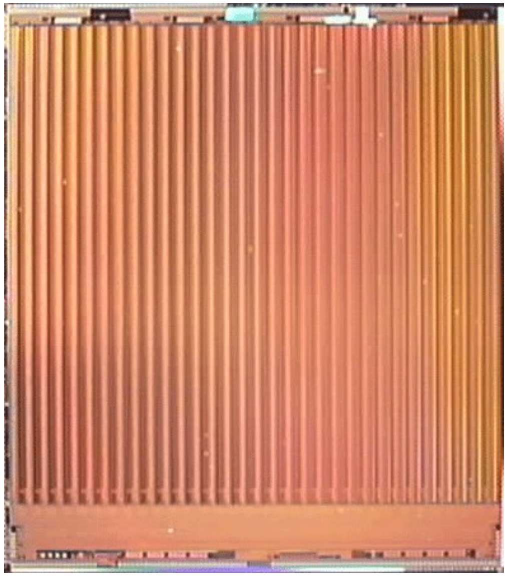
	PSI46 (CMS)	FEI3(Atlas)	CMOS6(Alice)
Size (mm)	7.9*9.9	7.6*10.8	12.8*13.6
Num of transistors	1.3M	3.5M	13M
Array	80*52 (4160)	18*160(2880)	32*256(8192)
Wafer yield	74%	80%	-
Power per pixel (μW)	11/17	42/34	~100

Atlas

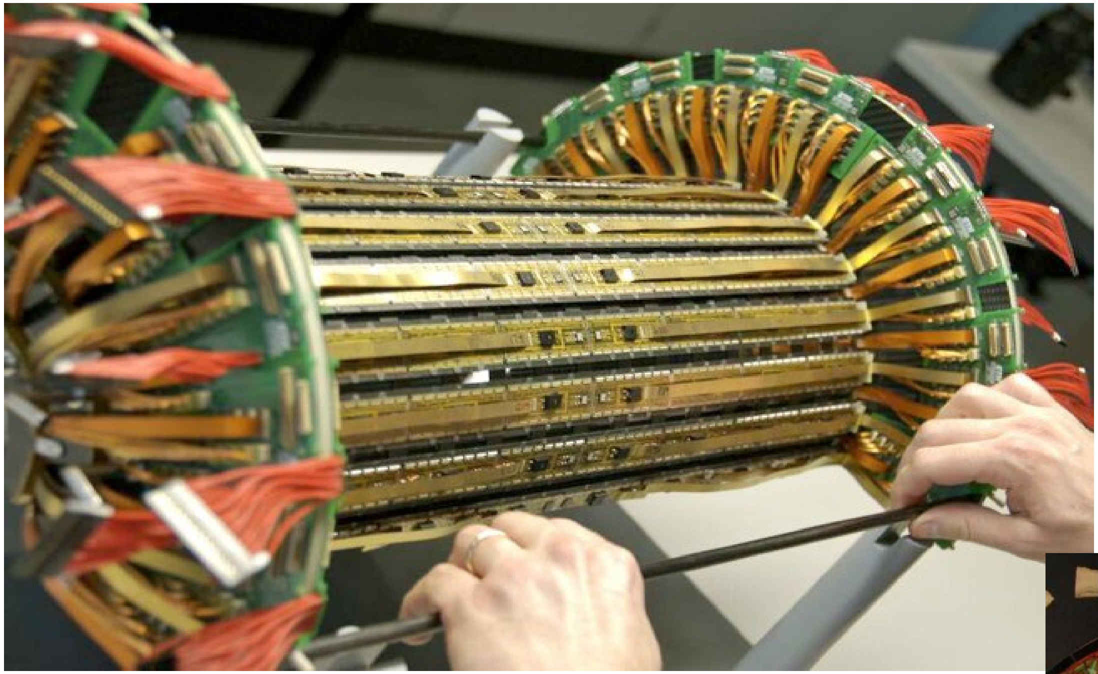
CMS



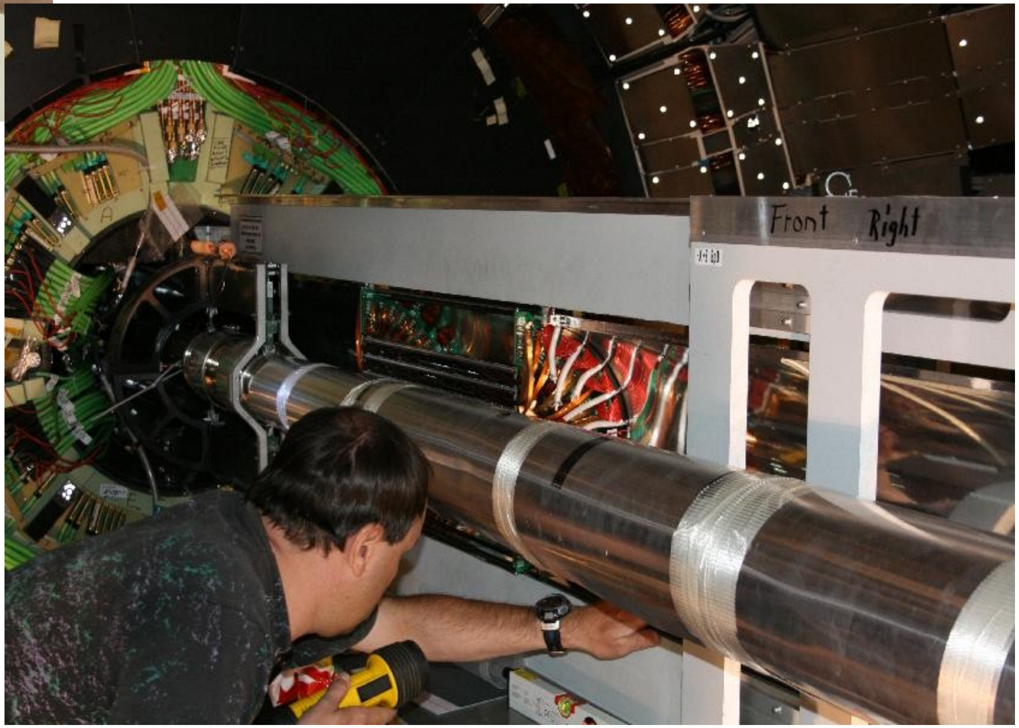
Alice



Integration, Insertion, Commissioning/Testing



Barrel Integration, testing



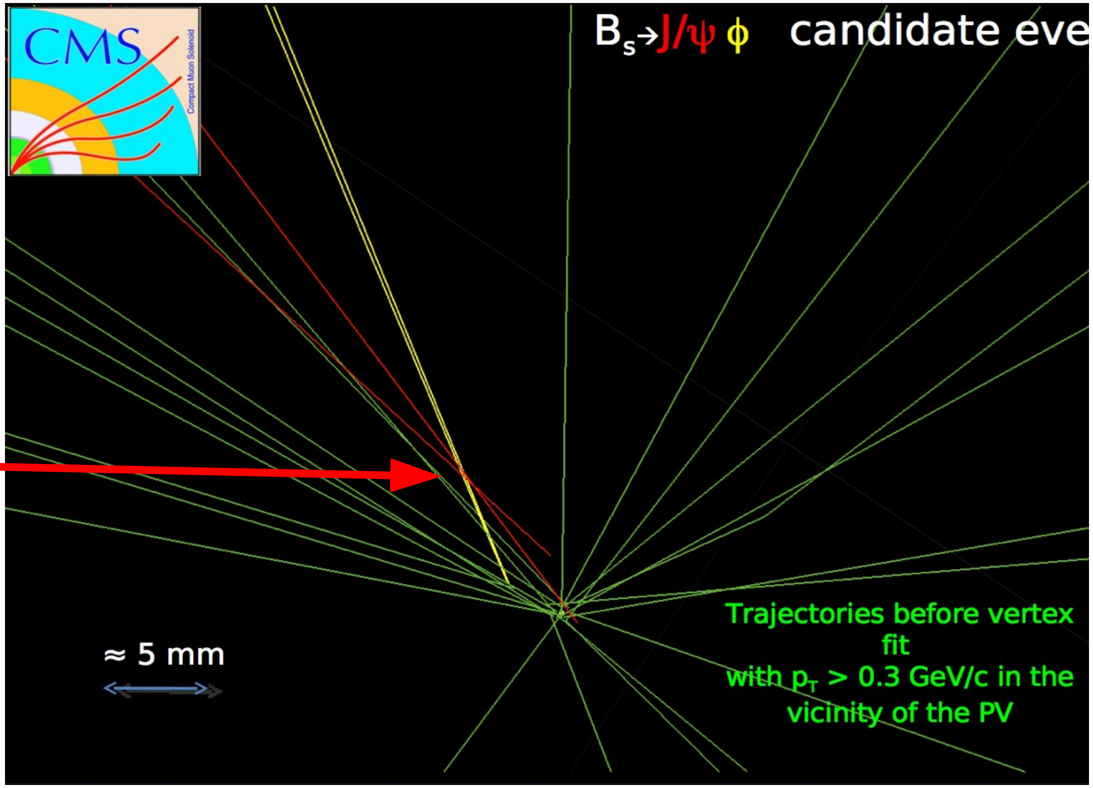
Detector insertion

Pixel were the last detector to be installed.

Be careful with the vacuum beam pipe!

Detector Performance

Is the detector performance good enough to measure things like this?



See the secondary vertex

B_s Meson

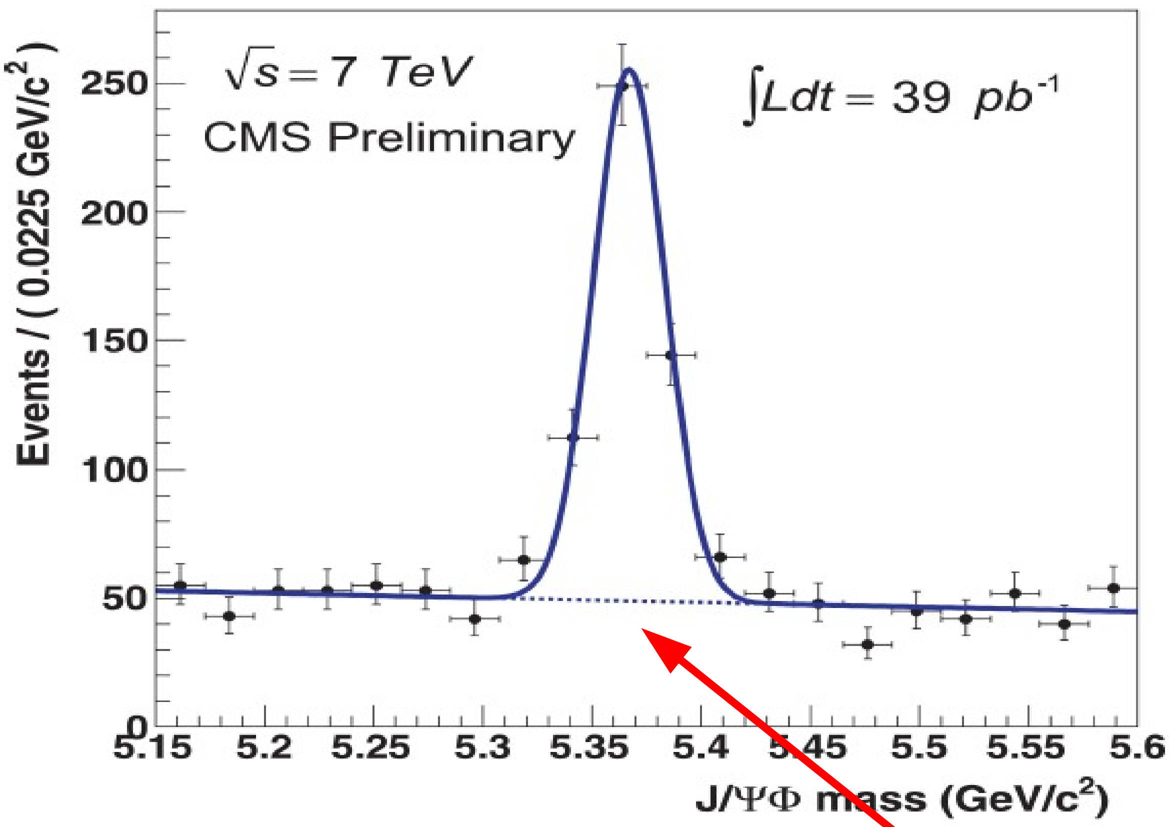
$B_s \rightarrow J/\Psi\ \Phi$

$J/\Psi \rightarrow \mu\mu$

$\Phi \rightarrow KK$

Detector Performance

Yes it is!



B_s Meson

$B_s \rightarrow J/\Psi\ \Phi$

$J/\Psi \rightarrow \mu\mu$

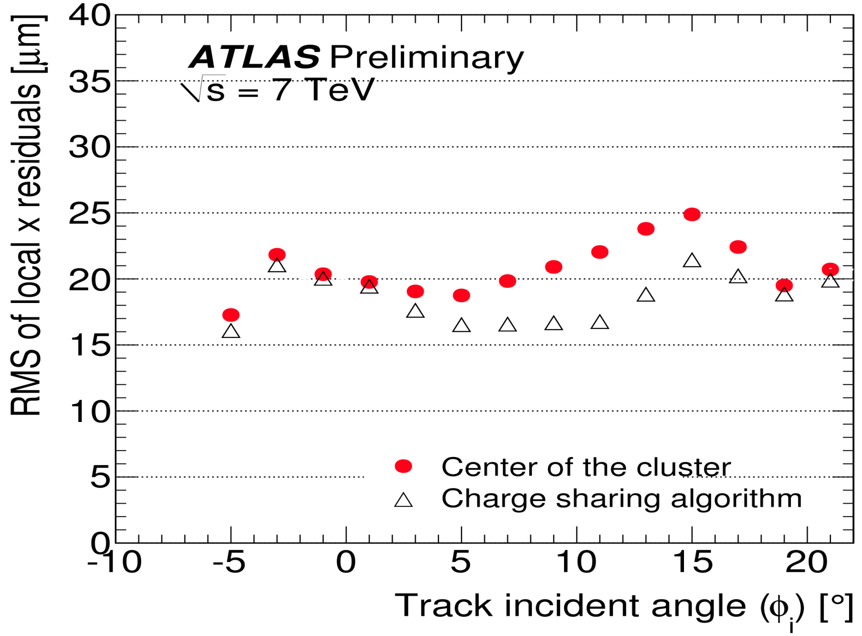
$\Phi \rightarrow KK$

The Bs meson mass peak is in the correct place and is narrow. GOOD!

Position Resolution

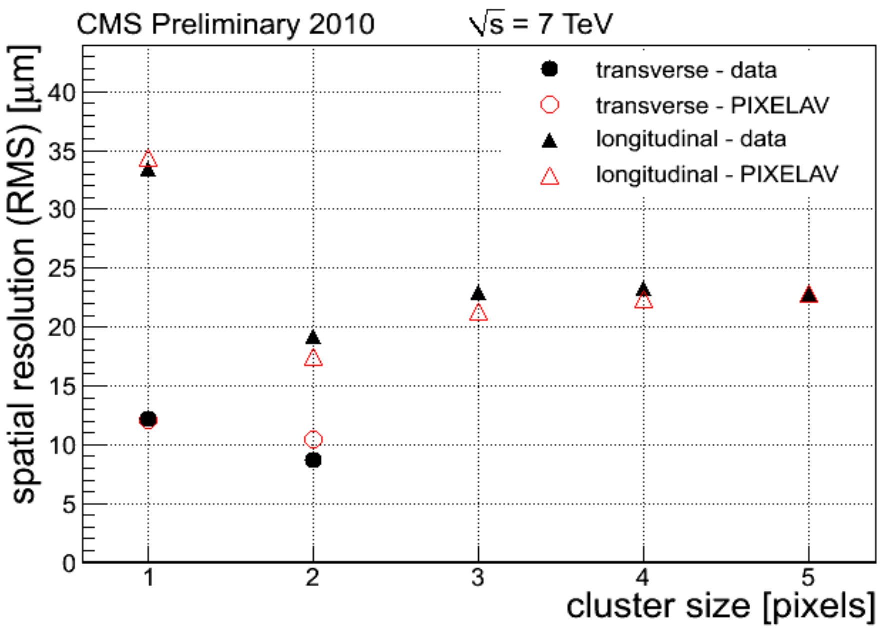
One of the two main performance parameters.

ATLAS



The pixel shape
(non-square/almost-square)
and the readout (digital/analog)
are quite different for Atlas & CMS.
Atlas analog information is through ToT.

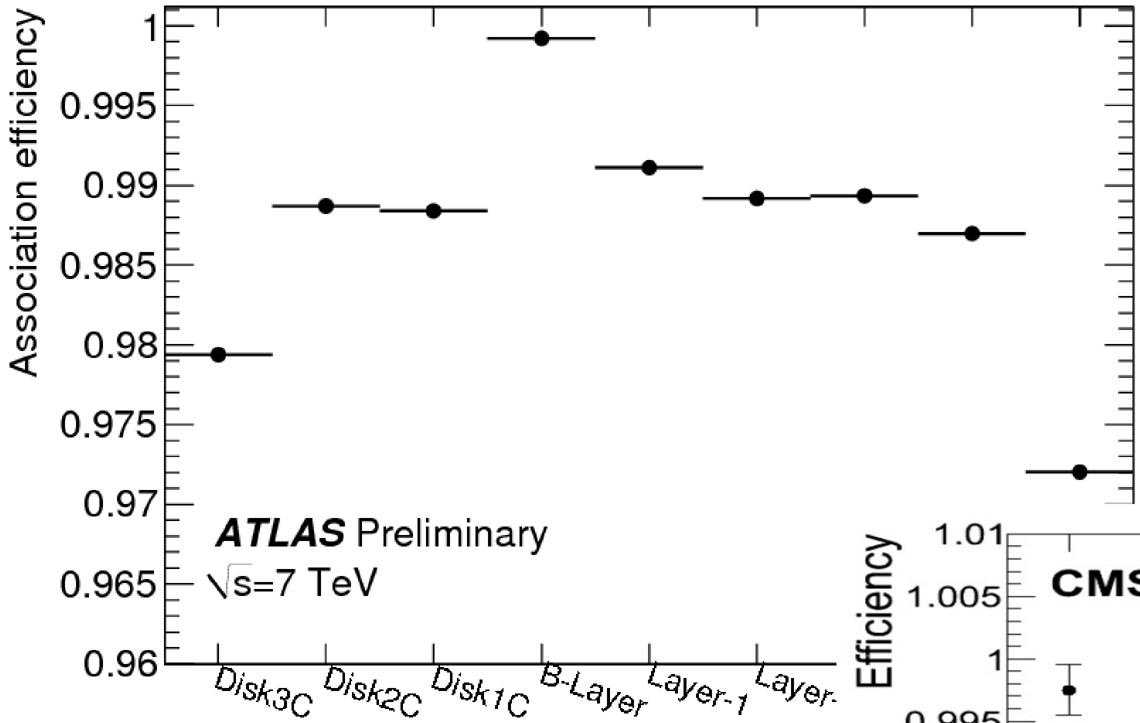
CMS



Nevertheless in both cases a good position resolution of 20um has been achieved!

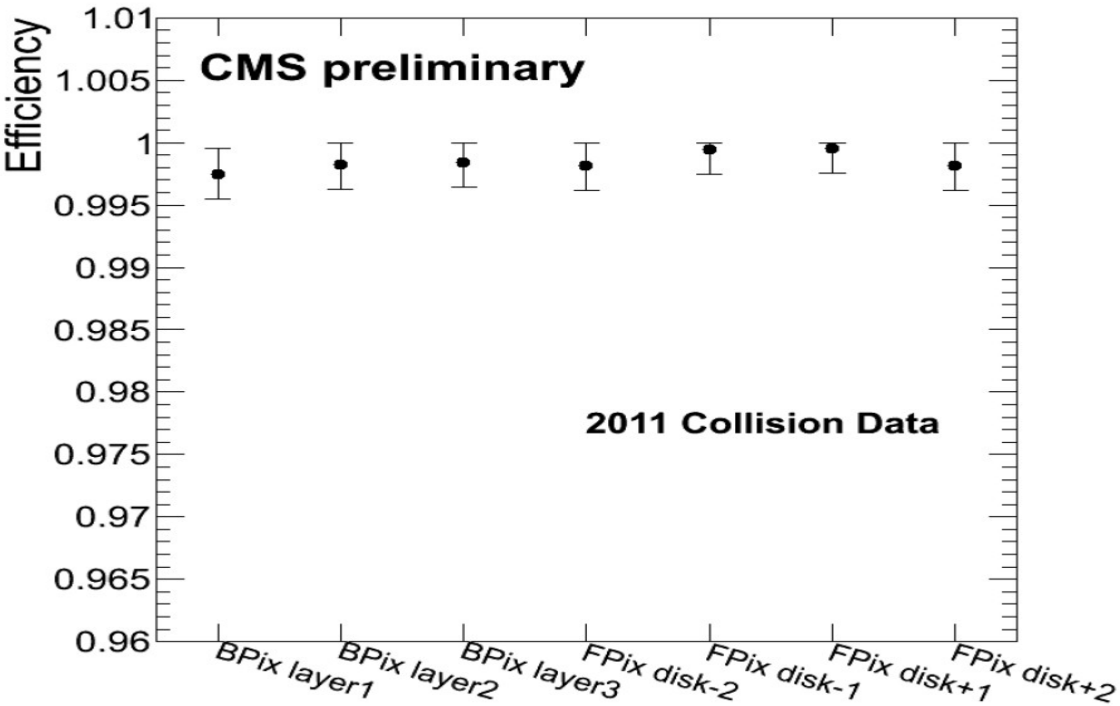
Hit efficiency

The 2nd important parameter



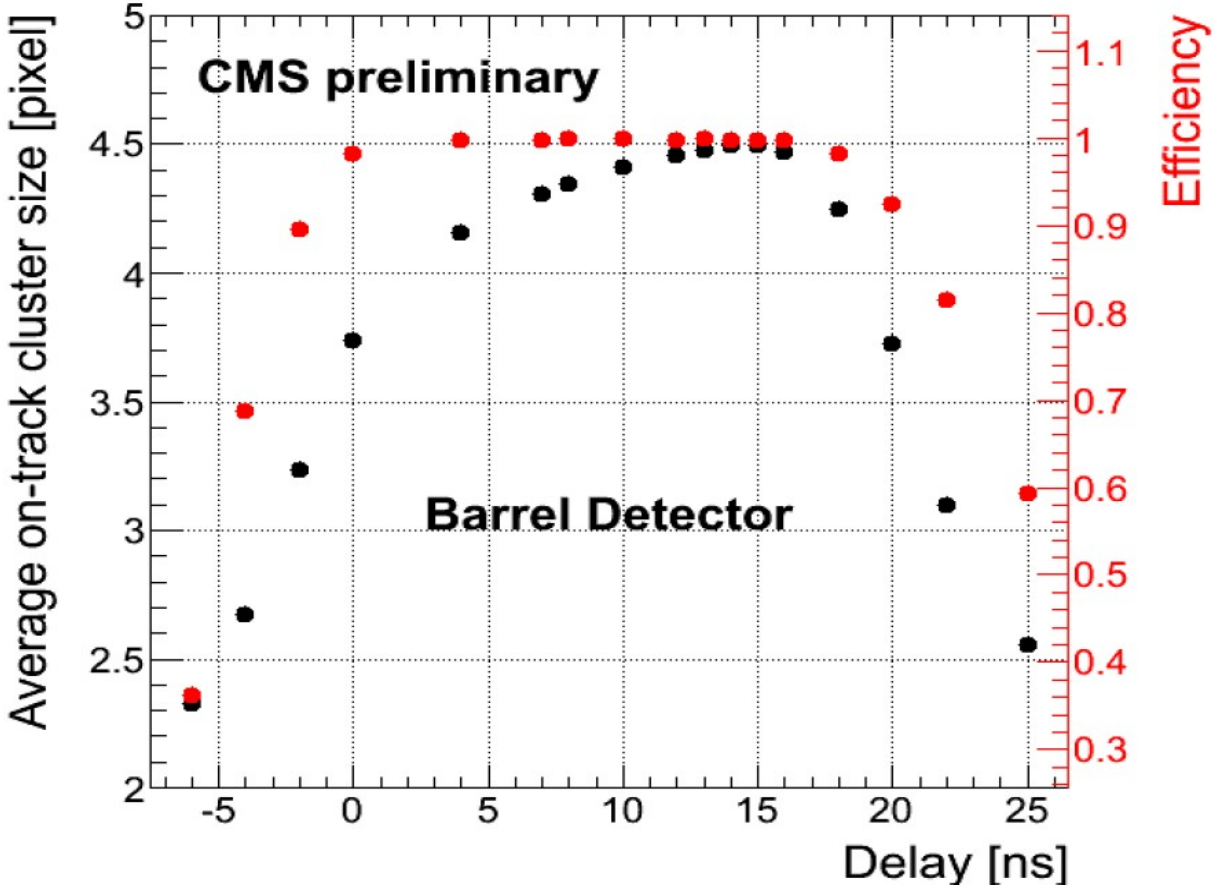
Disabled modules are excluded.

Edge hits are excluded, “large pixels” excluded.



In both cases the efficiency is excellent and the small inefficiency does not compromise physics performance.

Timing calibration



40MHz clock phase

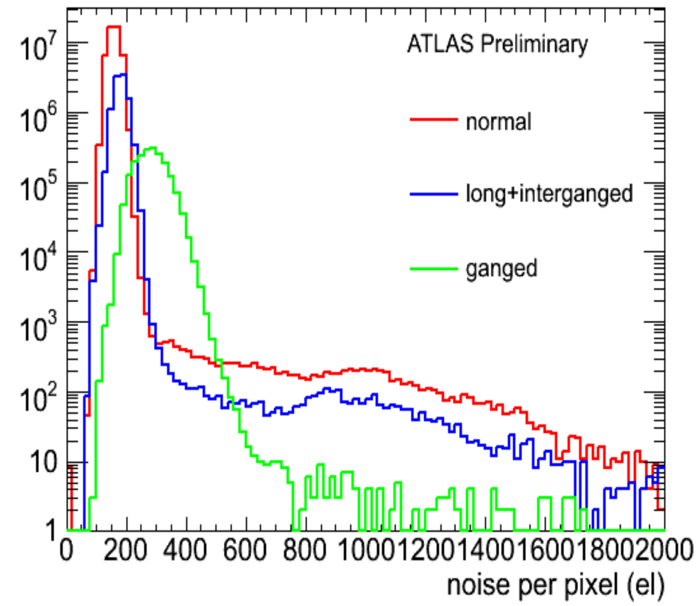
The detector can read particle hits within out 25ns (this is out time-frame).

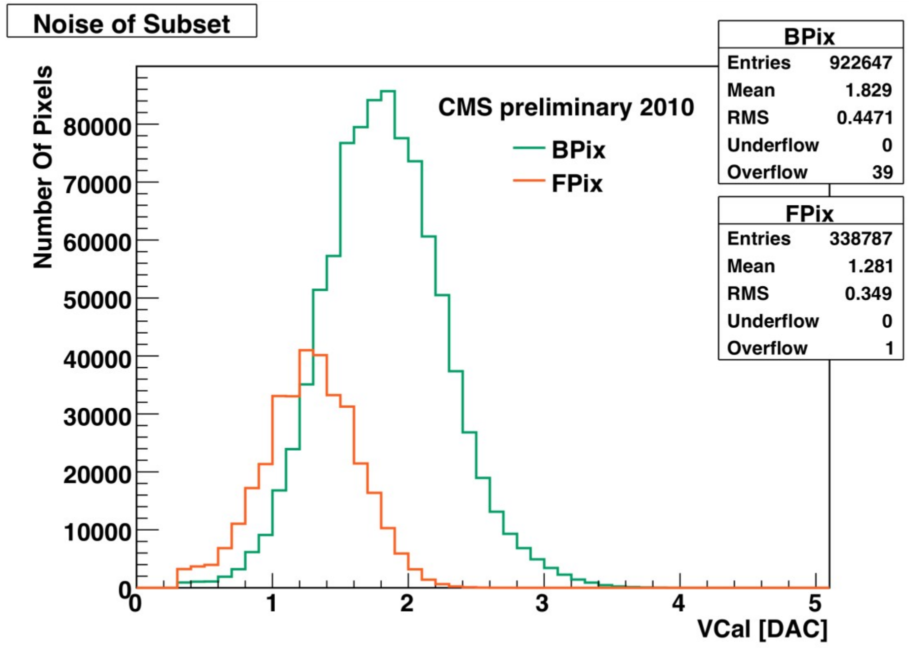
The clock phase has to be adjusted to be in-time with the particles coming from collisions to select the right event.

Noise Measurements

Electronic noise measured in a pixel.

Atlas: noise ~170 electrons



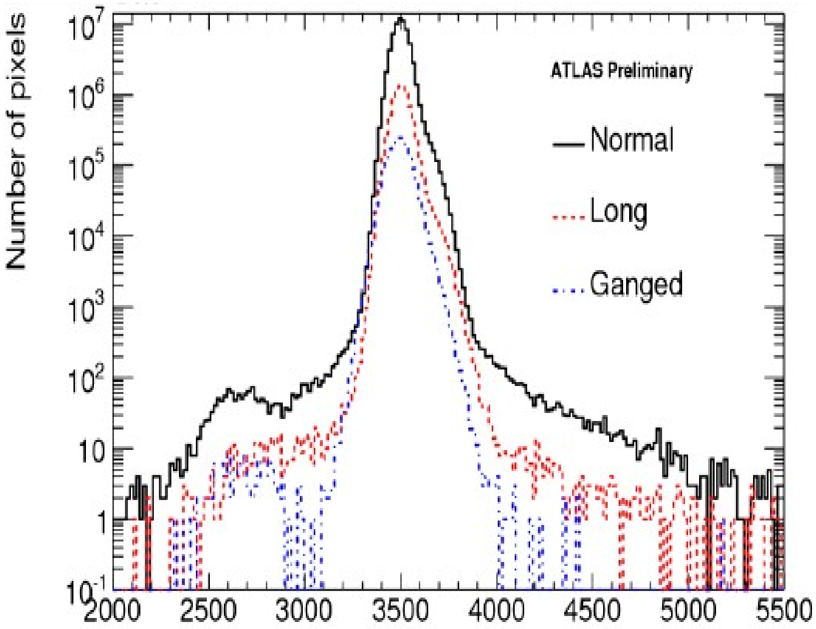


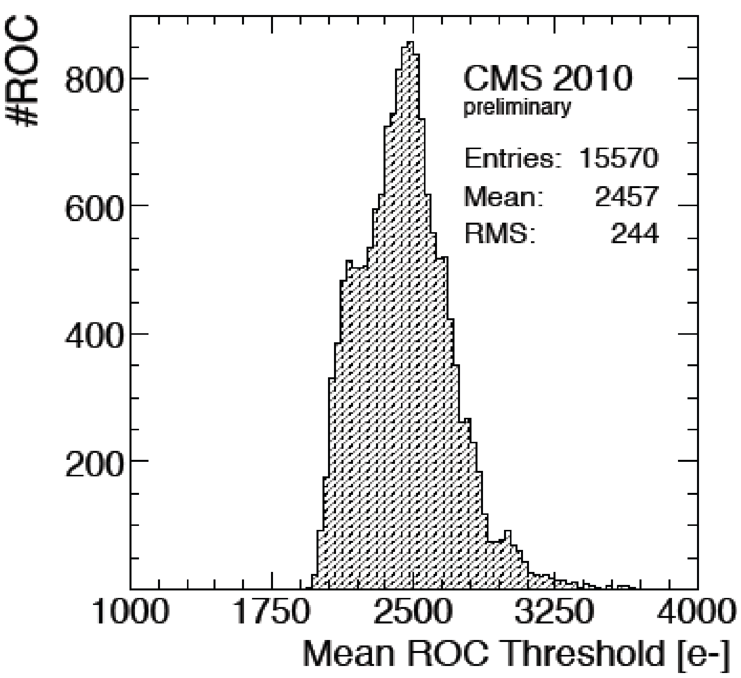
These values should be compared with the expected signal of 22 kelectrons.

The pixel detectors are almost noiseless!

CMS: noise = 1.8 * 65 = 120 electrons

Pixel Readout Threshold





The threshold is very important.
Position resolution depends on charge sharing which in turn depends on thresholds.
The lower the threshold the better the position resolution.

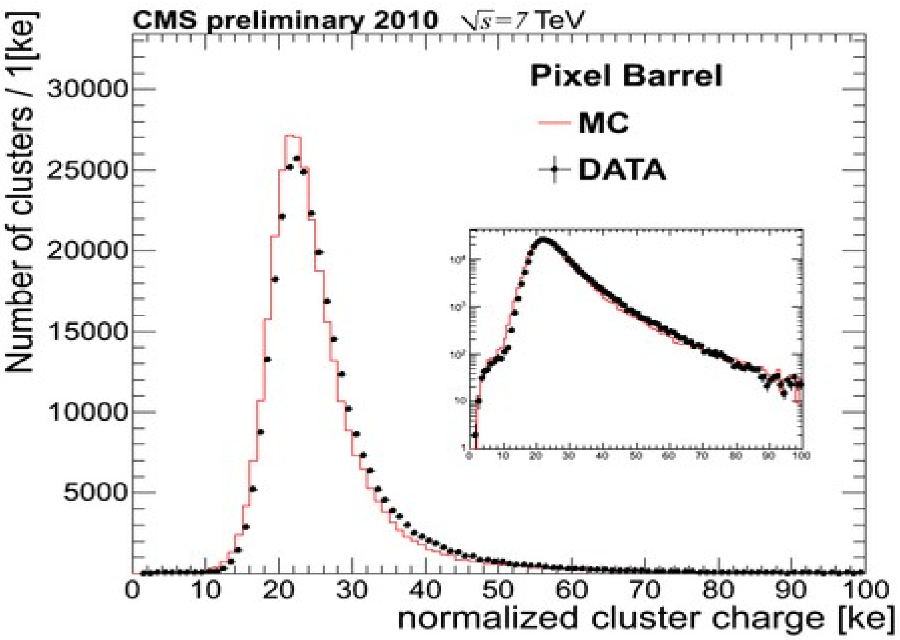
Threshold:
Atlas – 3500 electrons
CMS – 2500 electrons

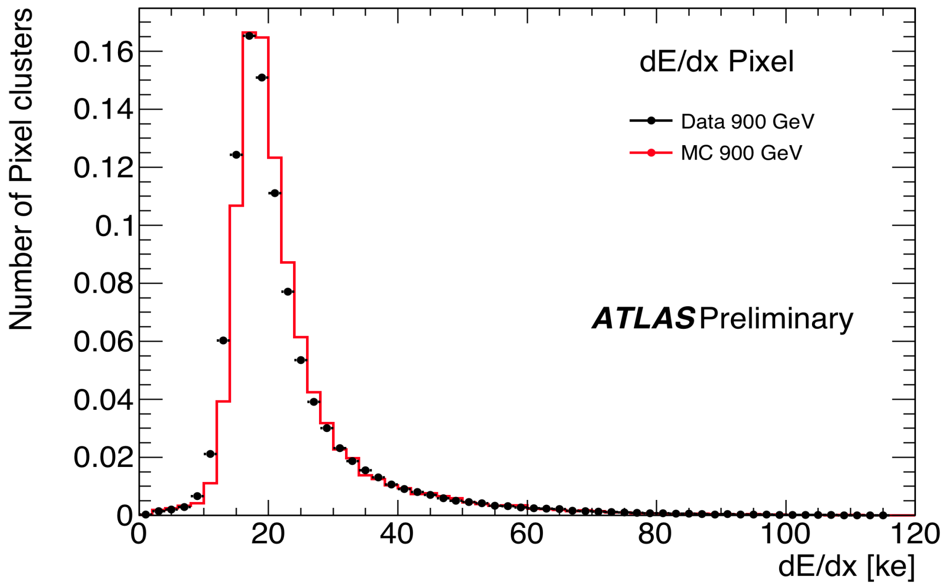
These thresholds are much above the pixel noise.
The threshold is determined by the internal cross-talk and NOT by the electronic noise.

These very low thresholds guarantee a very good position resolution for both detectors.

Cluster charge (Landau) – comparison with simulations

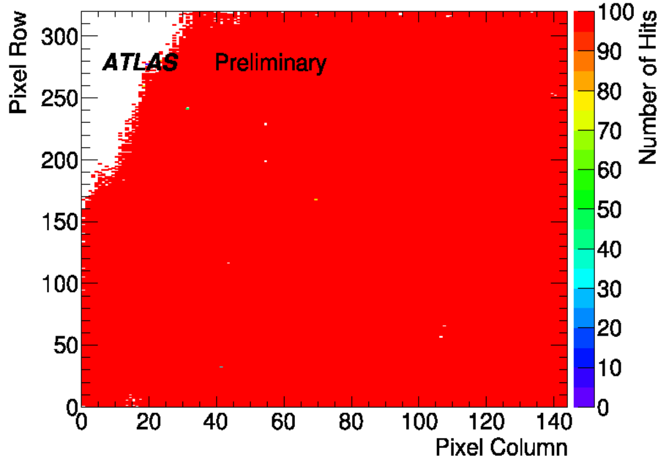
Measured cluster charge distribution compare with MC simulations.





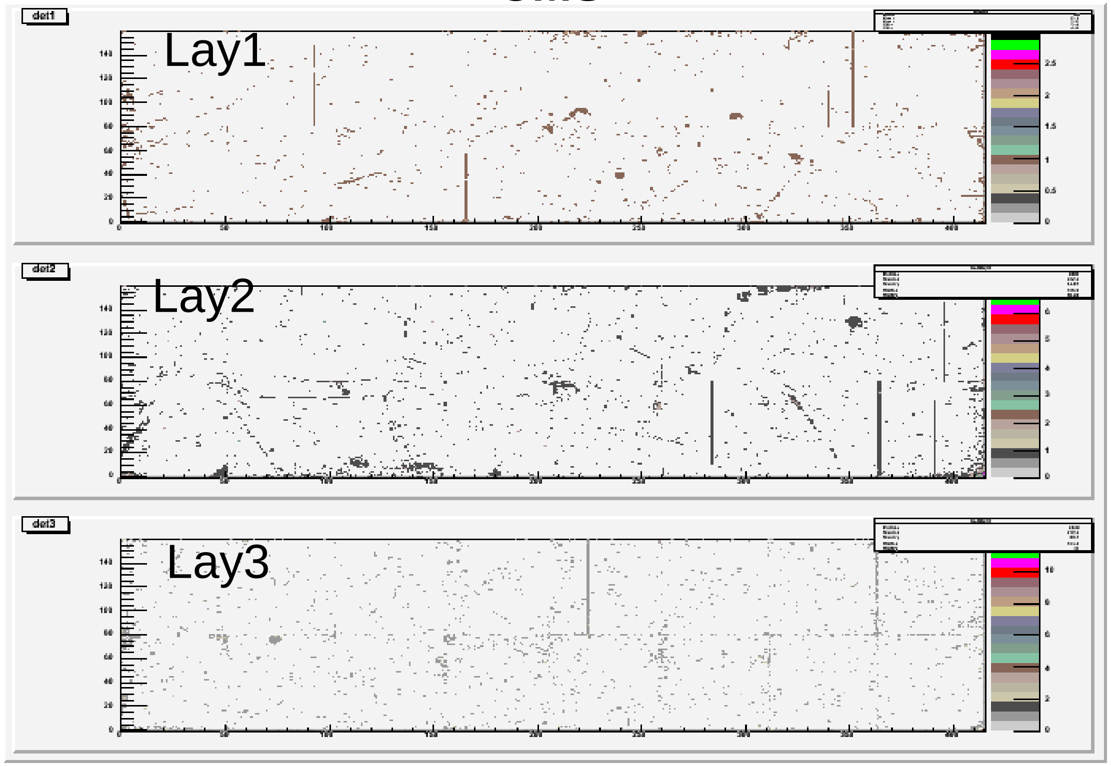
The good quality of the data-MC comparison shows that we understand our detectors very well.

Not Everything Is Perfect



An Atlas module with bad (non-connected) bump bonds.

CMS



An overlay of all modules (CMS) showing the bad bump-bonds.
7300 bad pixels in 48M
1.5E-4 (**CMS**)
Negligible inefficiency.

Number of masked pixels
600 -> **1.2E-5 CMS**

Atlas 0.1% masked, resulting in
no noise contribution 0.1 pixel/80M.

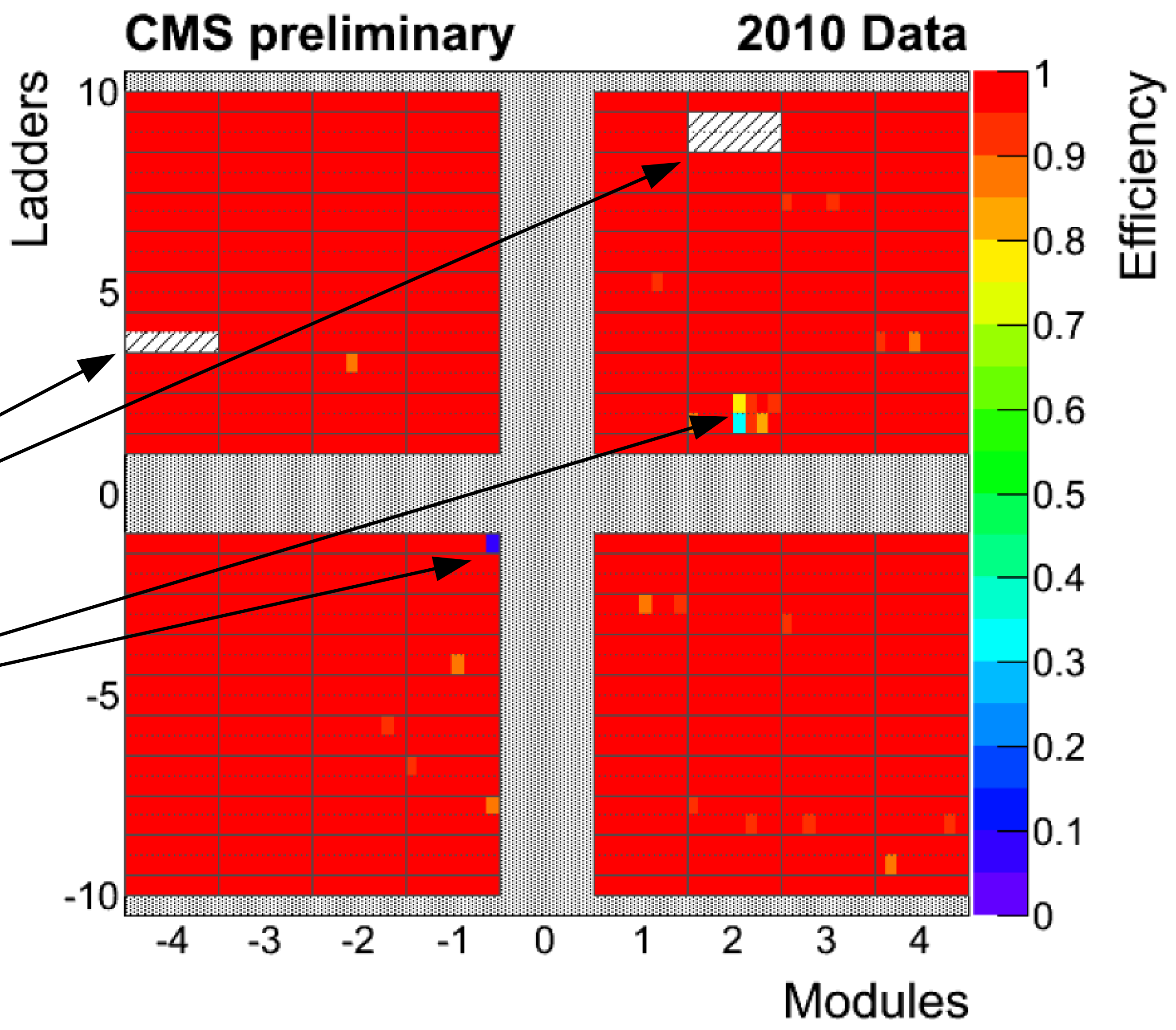
Alice – masked **1E-4**, but rather larger number of dead pixels **1.2%** (broken bumps).

Inefficiency

CMS barrel layer 1.
Most readout chips have almost 100% efficiency.

Bad modules

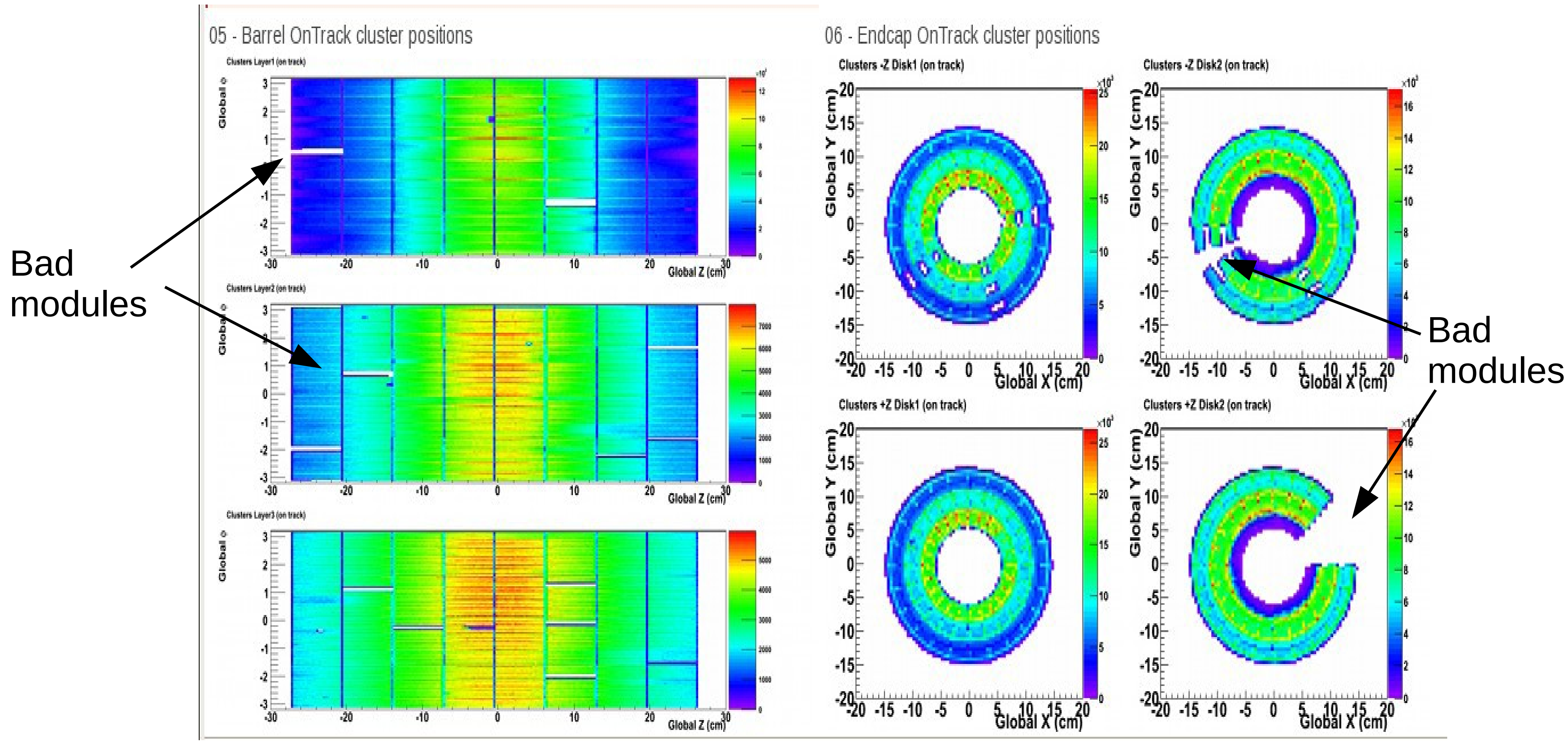
Bad ROCs



Broken modules

CMS: barrel layers

Endcaps

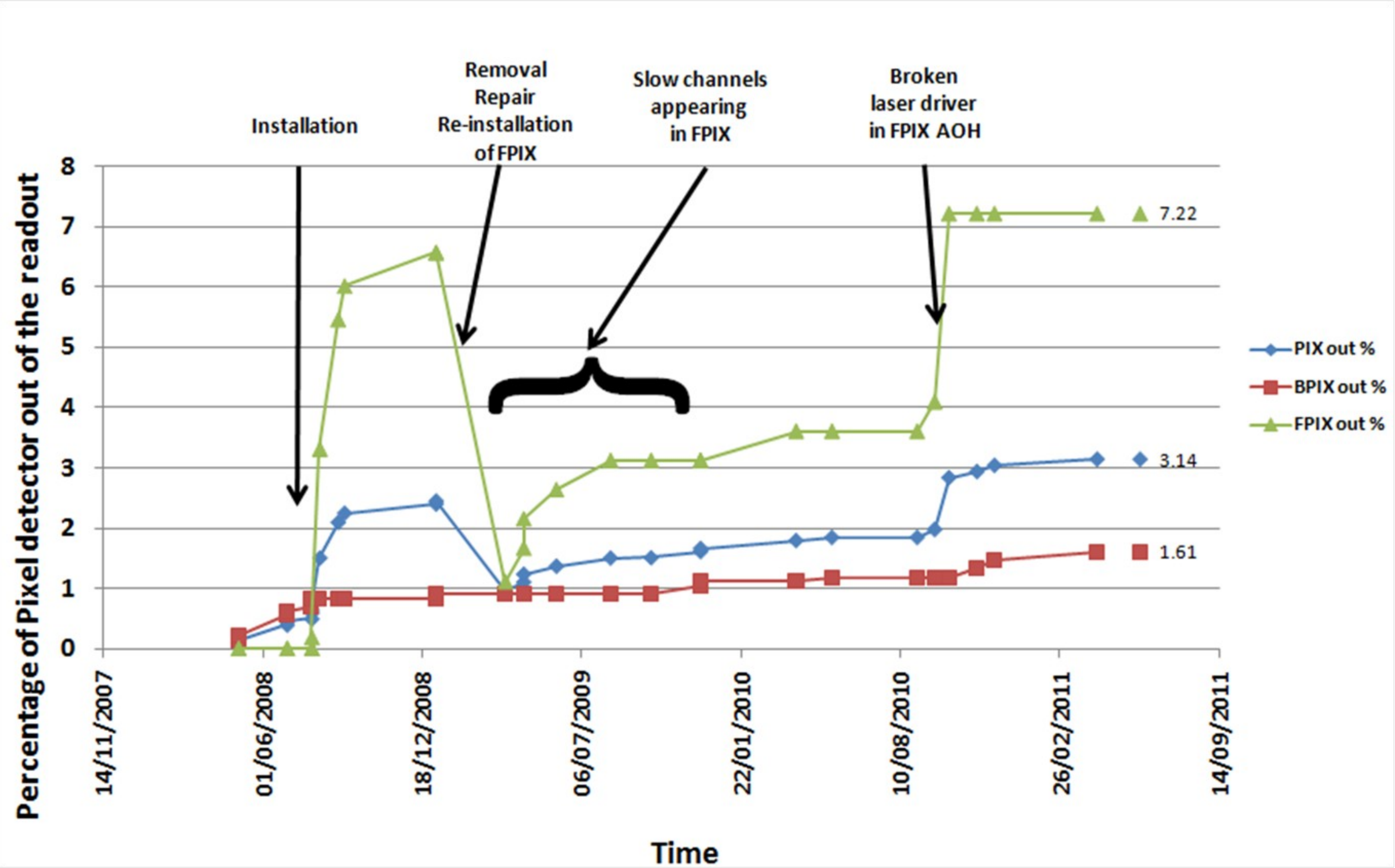


CMS: Bpix – 98.4% Fpix – 92.8%

Atlas: 96.7% (55 bad modules 3.1%, 45 bad ROCs 0.2%)

Alice: 92% (mostly due to problems with some cooling circuits).

Failure history - CMS

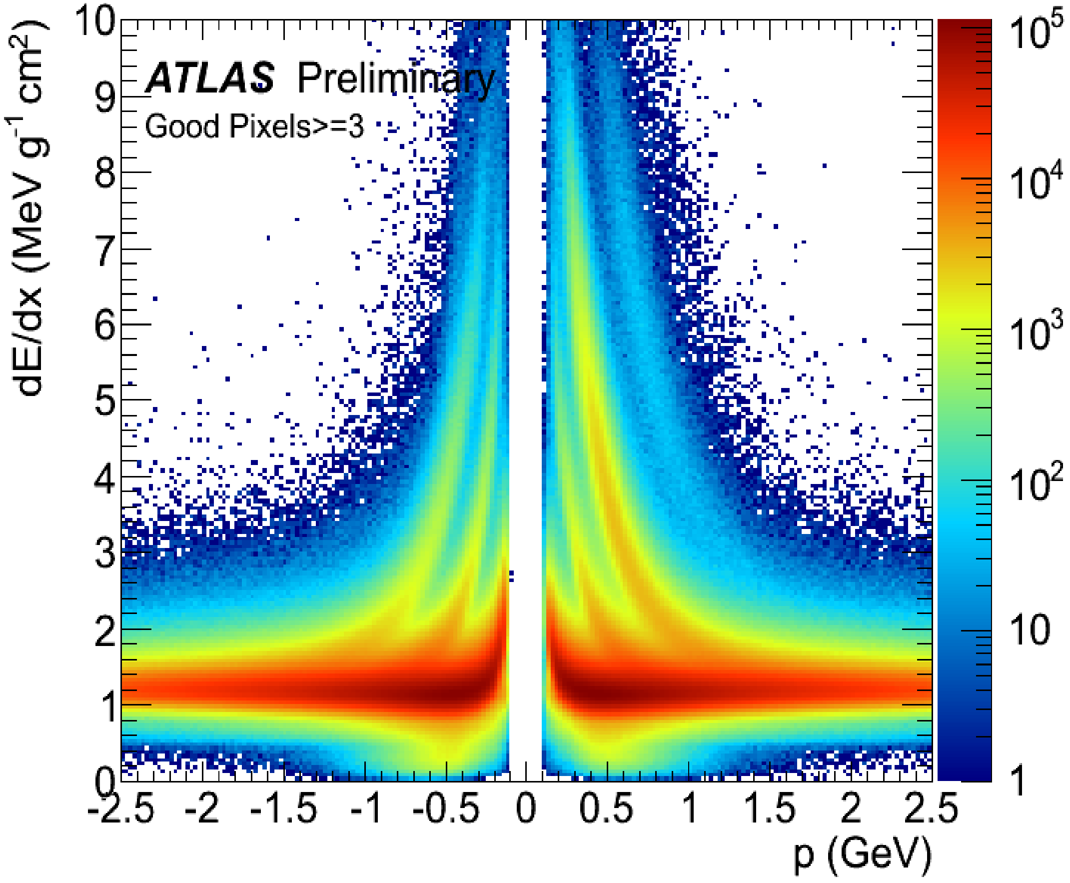


FPix – dominated a few big failures, BPix – single module failures (wire bonds?)

Detector Performance – Example I, Atlas

Charge measured in the Atlas pixel detector used for DeDx type of measurement, to distinguish different particle types: μ/π, K, p, d.

Proves that the charge resolution is very good and that the analog signal calibration is (almost) perfect.



Detector Performance - Example II, CMS

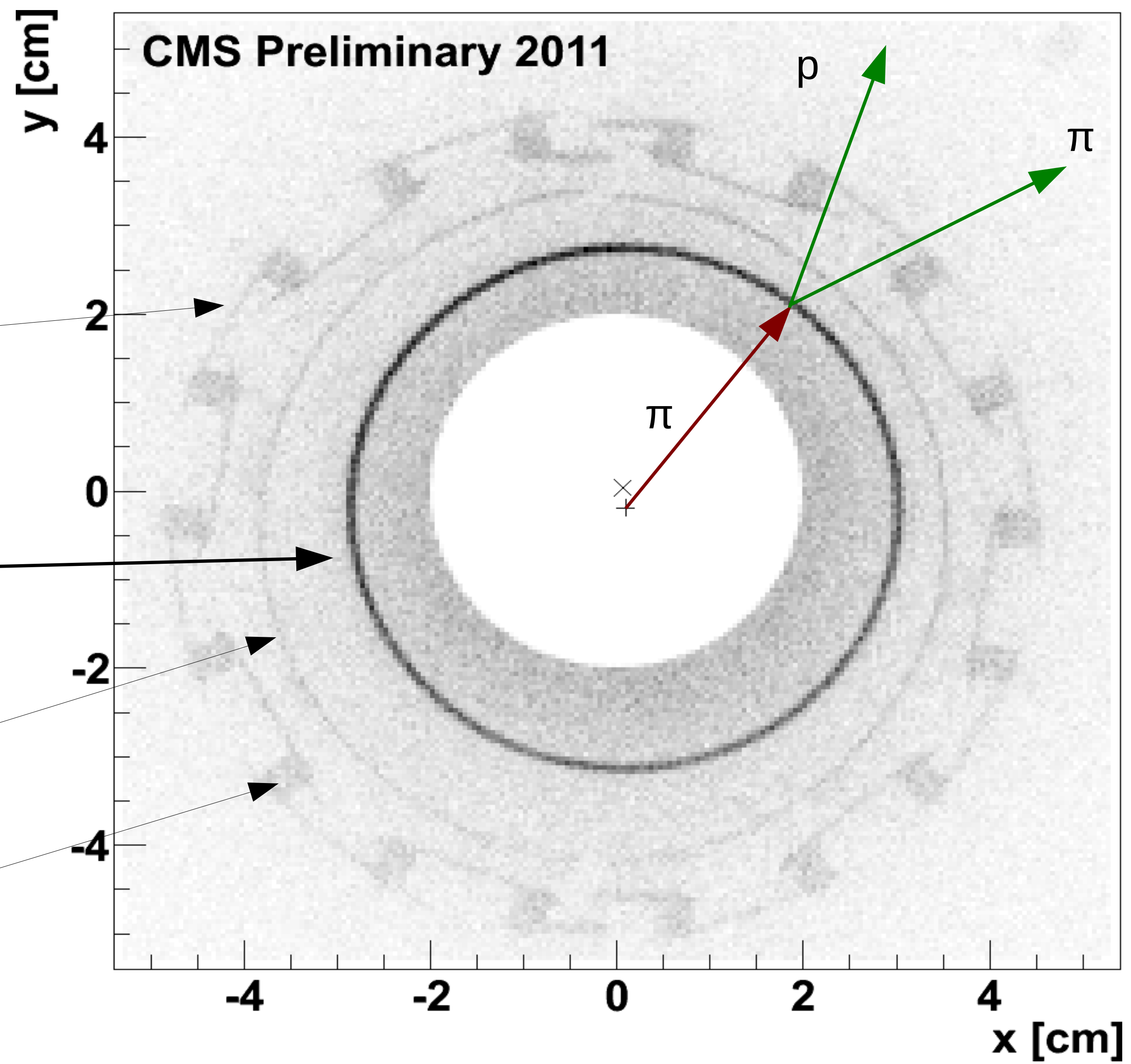
Material close to the proton beam measured through secondary interactions (vertexes of nuclear/hadronic interactions).

Pixel module

Beam pipe

Kapton-Al shield

Cooling pipe



Radiation Effects

At the accumulated luminosity of 1 1/fb the total charge particle fluence until now is about **2.5*10^{12} particles/cm^{2}.**
This is still low when compared to the total expected fluences of about 5*10^{14} particle/cm^{2}.

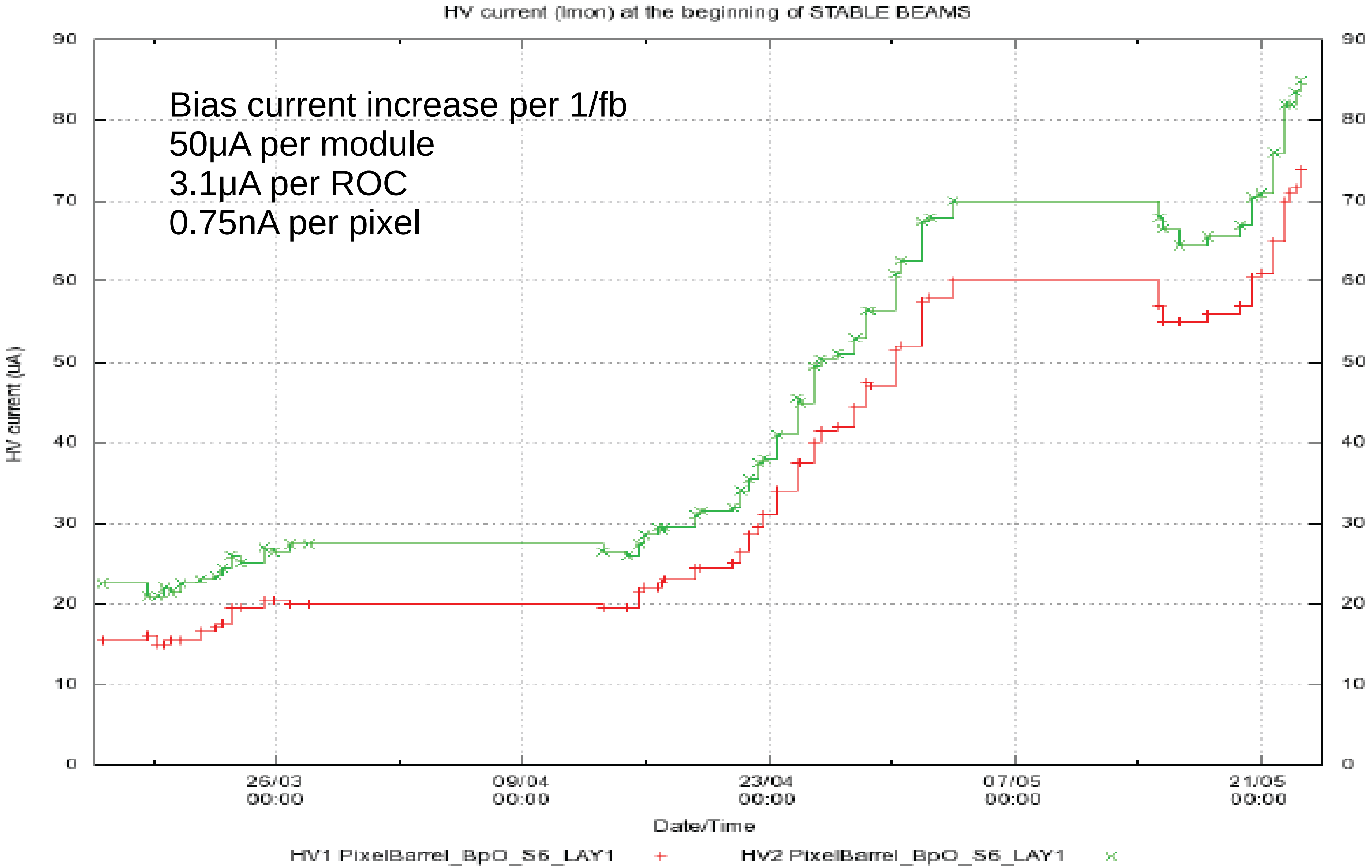
1) **Sensor damage** – increased leakage currents
Seen from the beginning (see next slide).

2) **Sensor damage** – partial depletion, charge trapping,
need to increase the bias voltage.
Not yet observed.

3) **Single Event Upsets (SEUs)** – change of state 0<->1 in flip-flops due to
the passage of a heavy ionizing particle.
First observations at instant luminosities of 10^{33} (2.5*10^{6} particles/cm^{2}/sec).
Needs confirmation.
The effect manifests itself by a sudden change in some readout parameter.
Detector reconfiguration brings it back to normal.

4) **ROC (Readout chip) damage** – change of the internal voltages due to .
Not yet observed.

Leakage current – CMS pixels (Layer 1 modules)

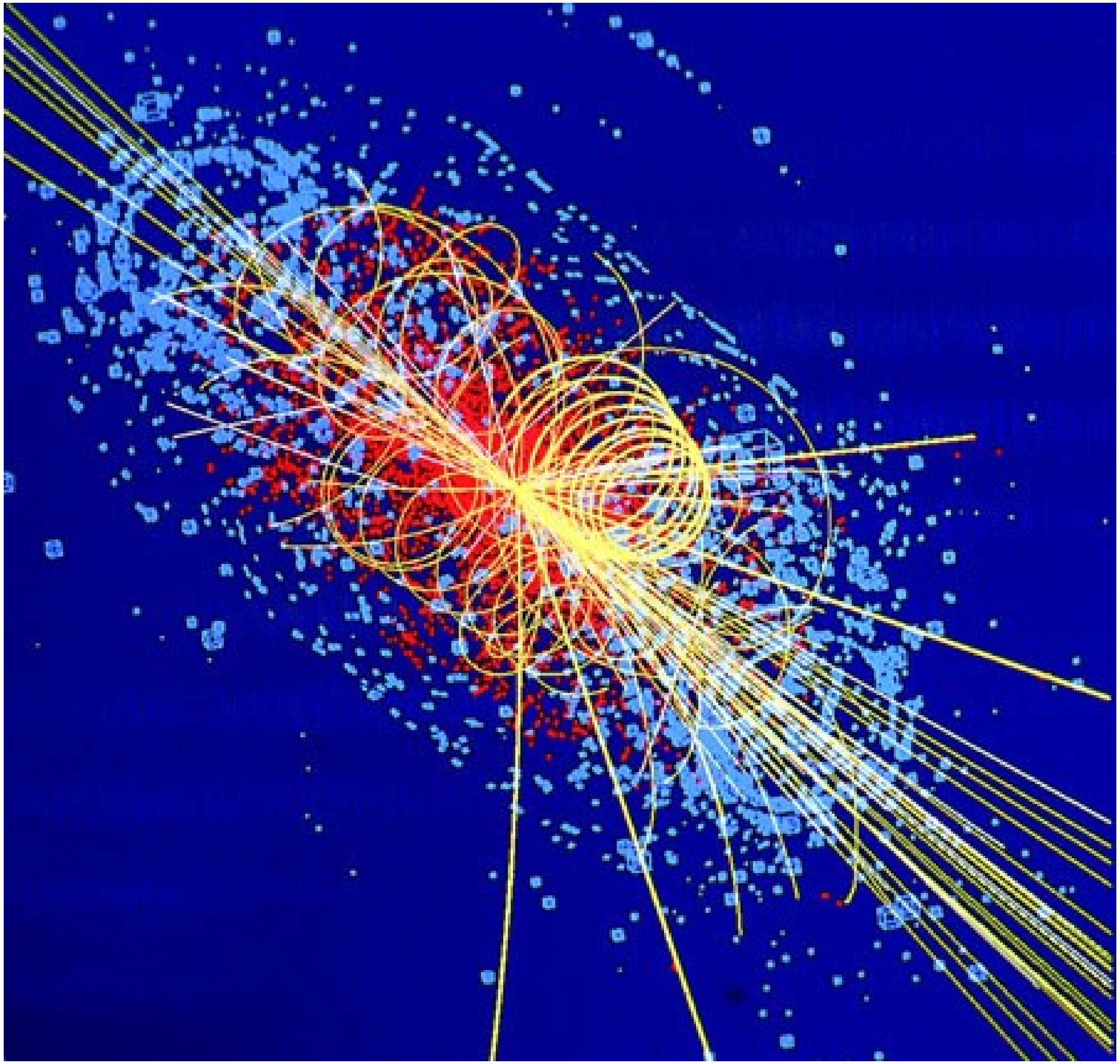


Thank You For Your Attention

Spare Slides

Much More Details - Problems

Much More Details - Problems



Much More Details - Problems