The CMS pixel detector: ready for the future?

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Many thanks to Benedikt Vormwald

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Photo courtesy of Erik Butz

The Large Hadron Collider at CERN

Large Hadron Collider

Hadron: composite particle made of quarks held together by the strong force

6.5 tera-electron volt (**TeV**) per proton beam

2x2800 bunches of protons 25 ns apart

protons

LHCb

ATLAS

CERN

CERN Prévessin

SPS 7 km

SUISSE

FRANCE

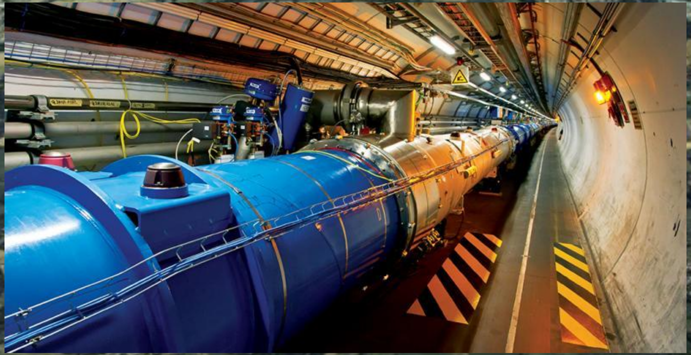
CMS

Two beampipes!

p

p

LHC 27 km



https://www.youtube.com/watch?v=NhXMXiXOWAA

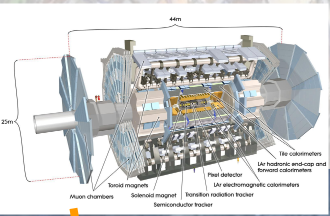
https://cdn.zmescience.com/wp-content/uploads/2015/05/cern-lhc-aerial.jpg

H t tp://s ites.uci.edu/energyobserver/files/2012/11/lhc-aerial.jpg

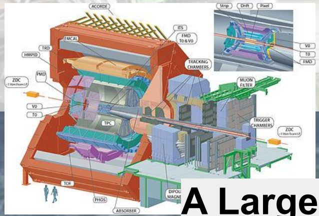
https://home.cern/sites/home.web.cern.ch/files/image/inline-images/old/lhc_long_1.jpg

https://upload.wikimedia.org/wikipedia/commons/6/62/CERN_LHC_Proton_Source.JPG

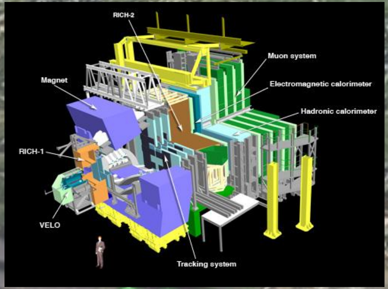
Detectors at the LHC



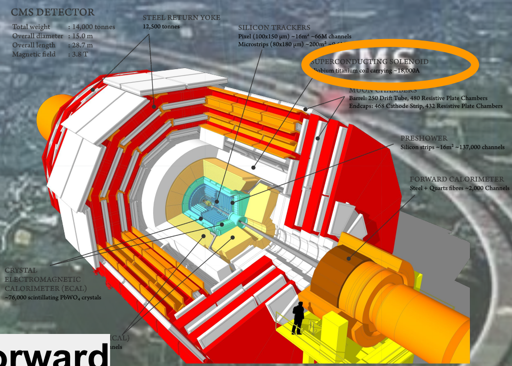
A Toroidal LHC ApparatuS:
25 m x 25 m x 46m
The largest volume detector ever constructed for a particle collider!
Multipurpose detector.



A Large Ion Collider Experiment: specialized in **heavy ion** collisions and quark-gluon plasma: fraction of second after big bang!



Compact Muon Solenoid
14000 tons: 1.5* Eiffel tower weight, half the size of ATLAS: 15 m x 15 m x 21 m very compact!
Largest superconducting solenoid magnet ever made

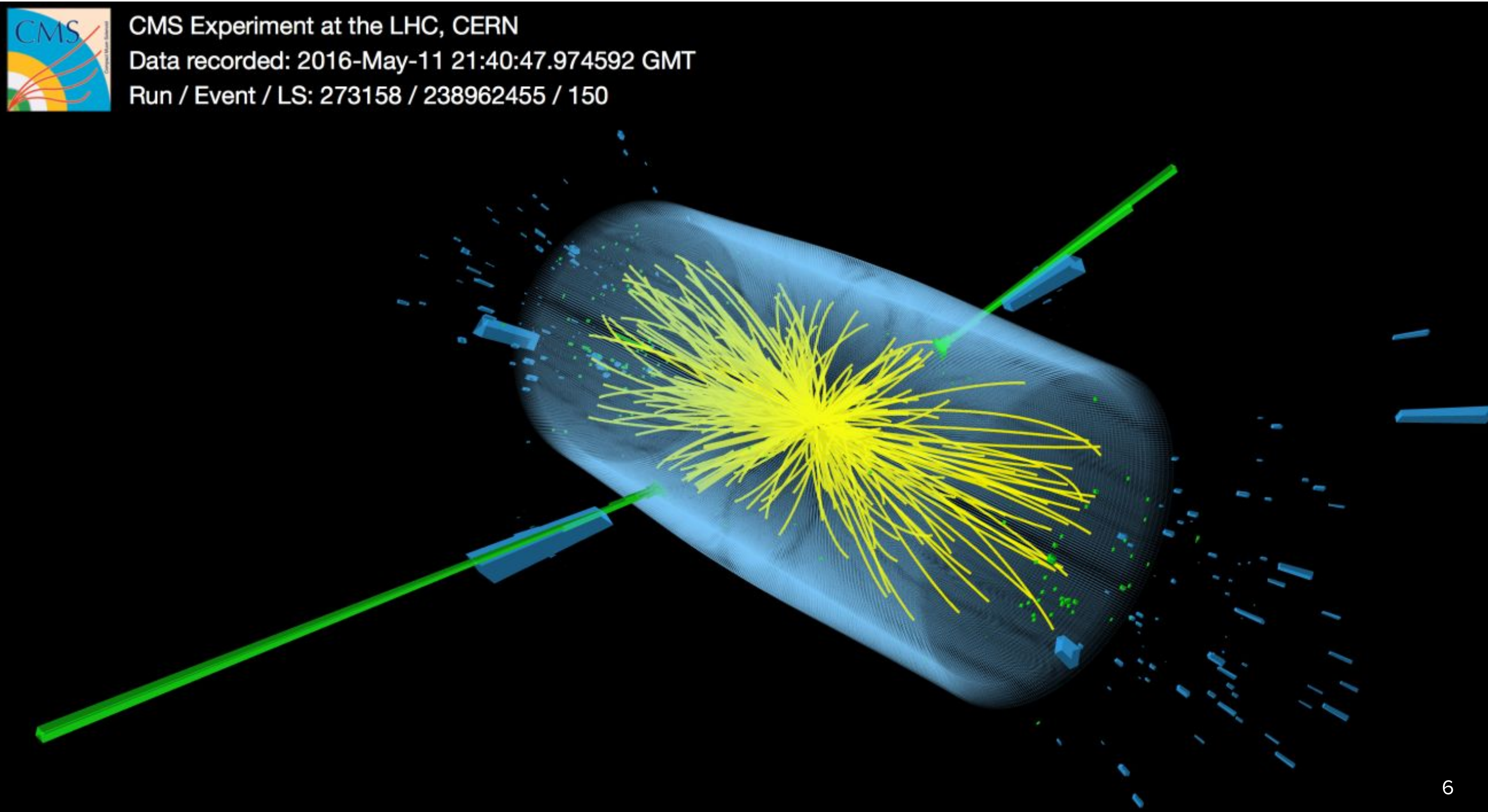


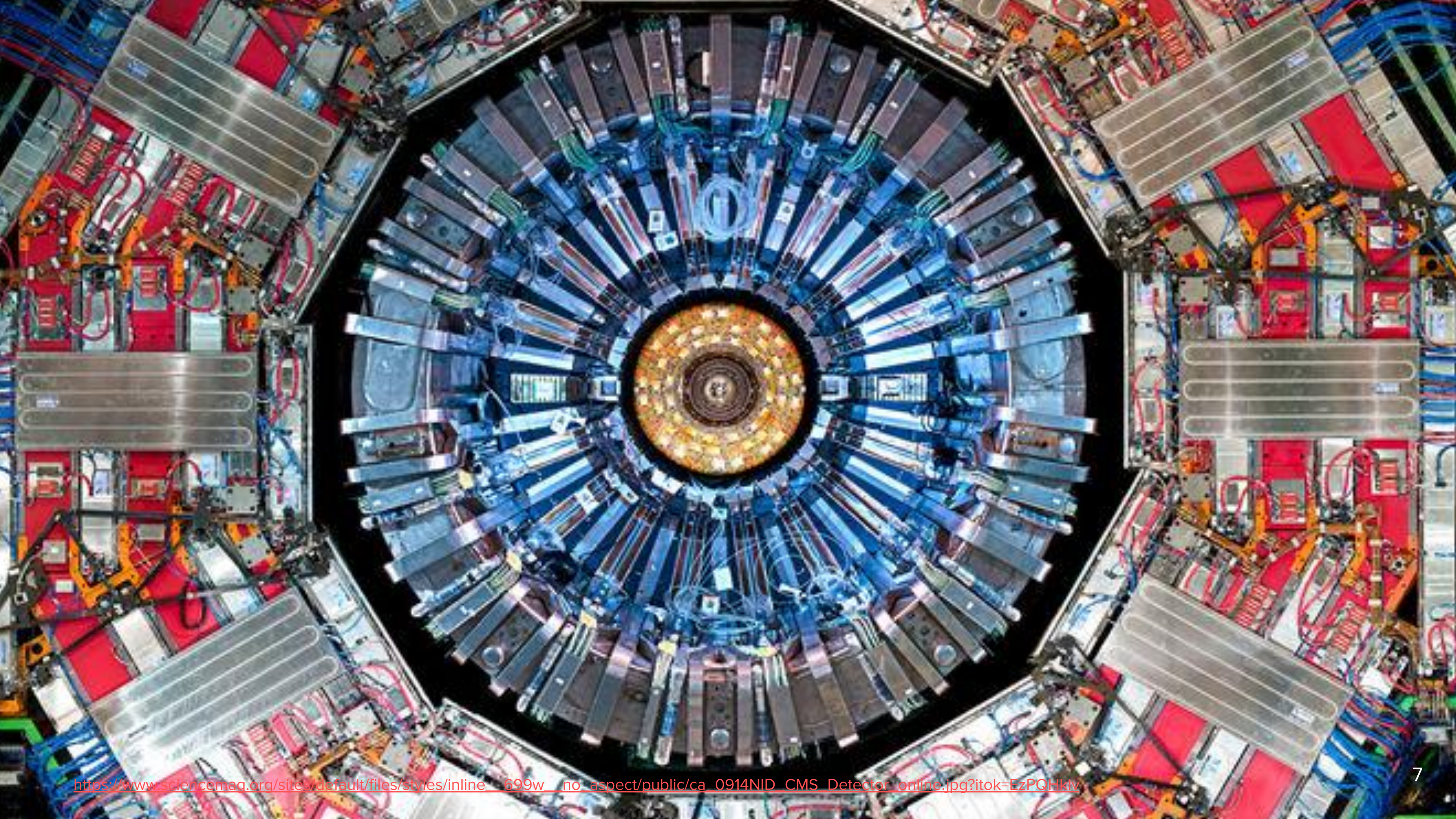
LHC beauty:
A single-arm **forward** detector designed for the study of particles containing **b or c quarks**.

Other detectors: MoEDAL, TOTEM, LHCforward

https://cms-docdb.cern.ch/cgi-bin/PublicDocDB/RetrieveFile?docid=11514&version=1&filename=cms_120918_03.png

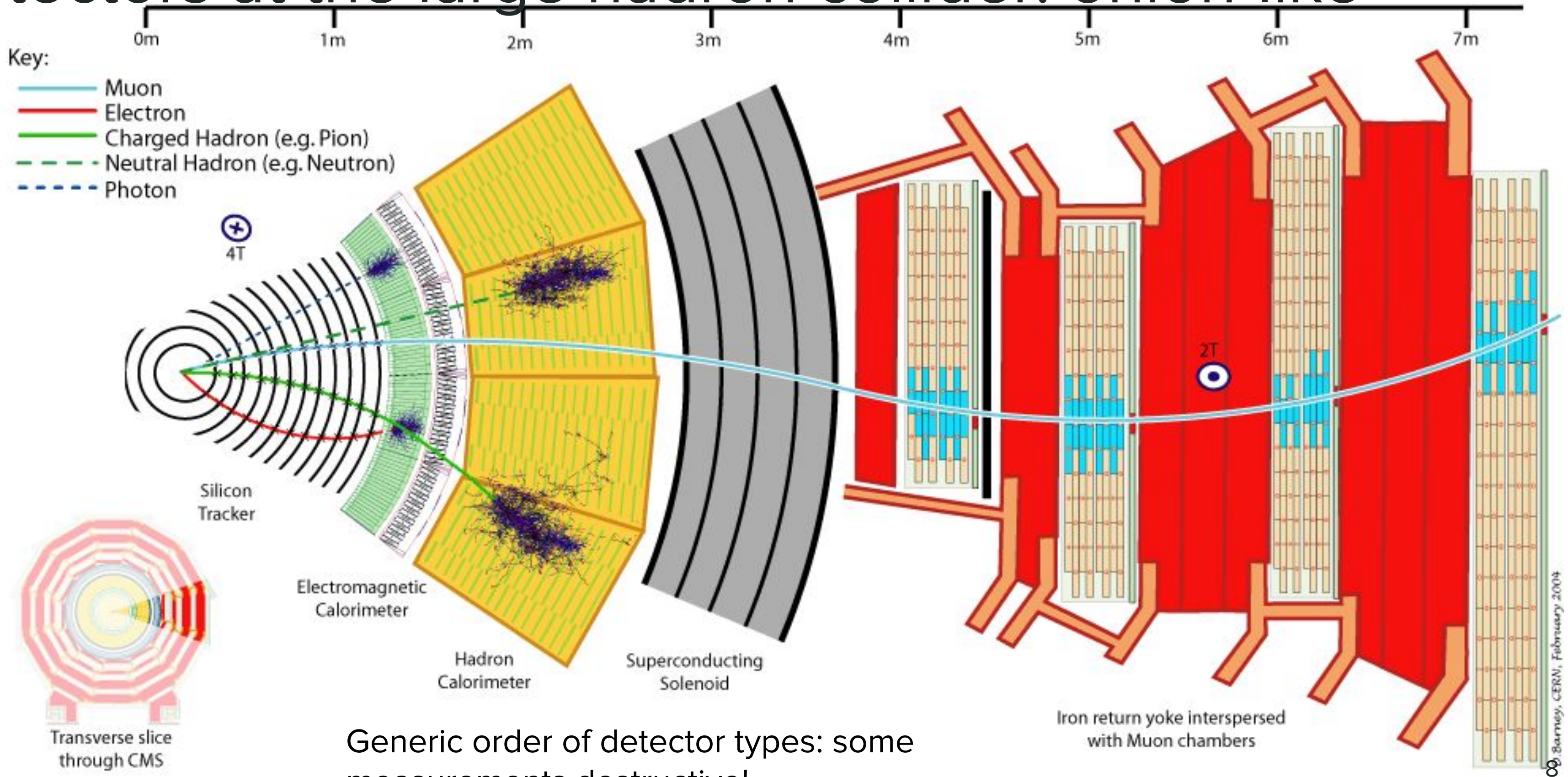
100 meters underground in the CMS cavern


CMS
CMS Experiment at the LHC, CERN
Data recorded: 2016-May-11 21:40:47.974592 GMT
Run / Event / LS: 273158 / 238962455 / 150



https://www.sciencemag.org/sites/default/files/styles/inline__699w__no_aspect/public/ca_0914NID_CMS_Detector_online.jpg?itok=EzPQHklv

Detectors at the large hadron collider: onion-like

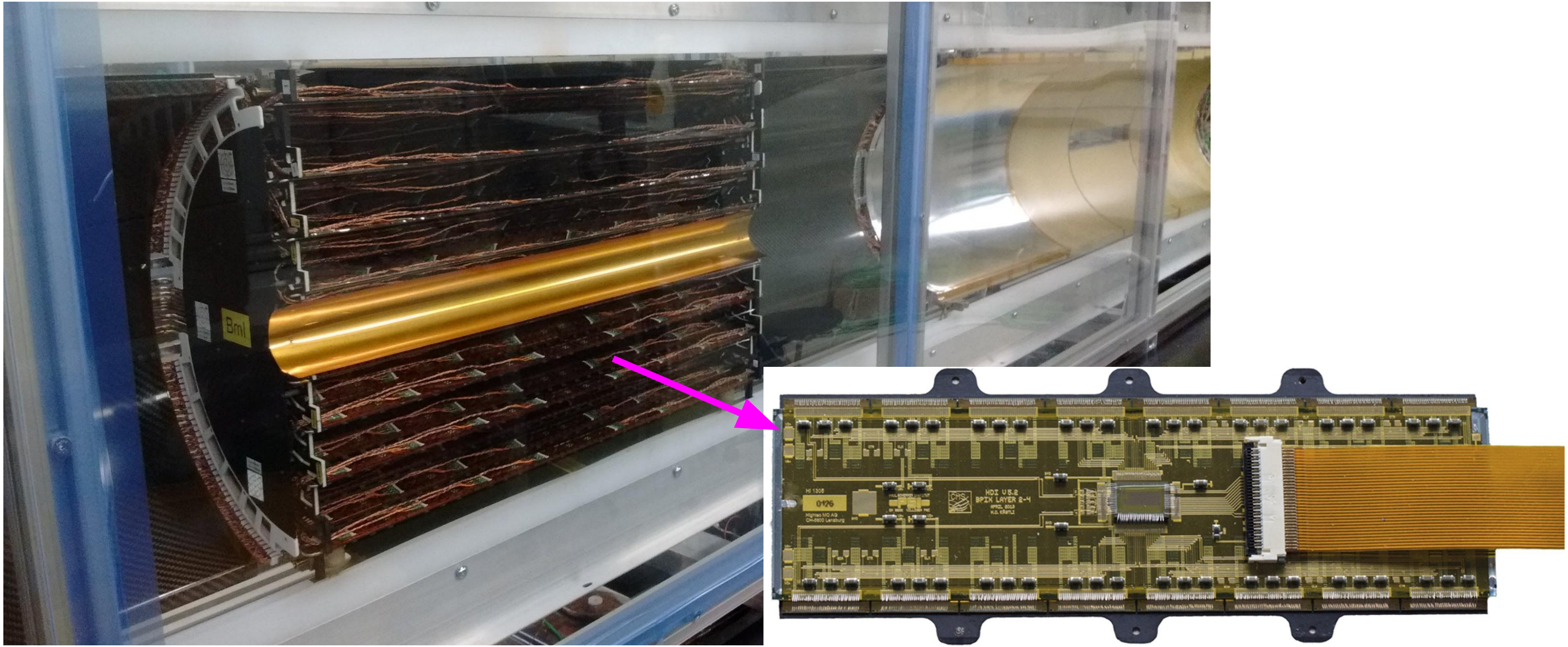


http://inspirehep.net/record/826852/files/EPS_CMS_Slice.png

Generic order of detector types: some measurements destructive!

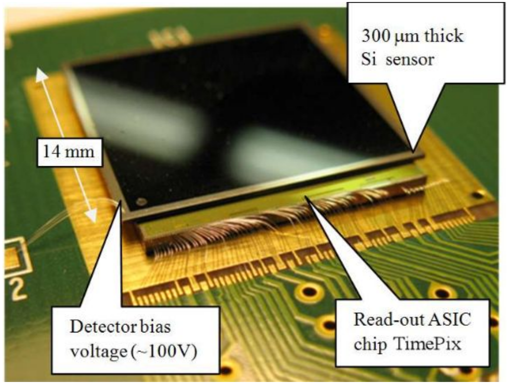
https://www.sciencemag.org/sites/default/files/styles/inline__699w__no_aspect/public/ca_0914NID_CMS_Detector_online.jpg?itok=EzPQHklv

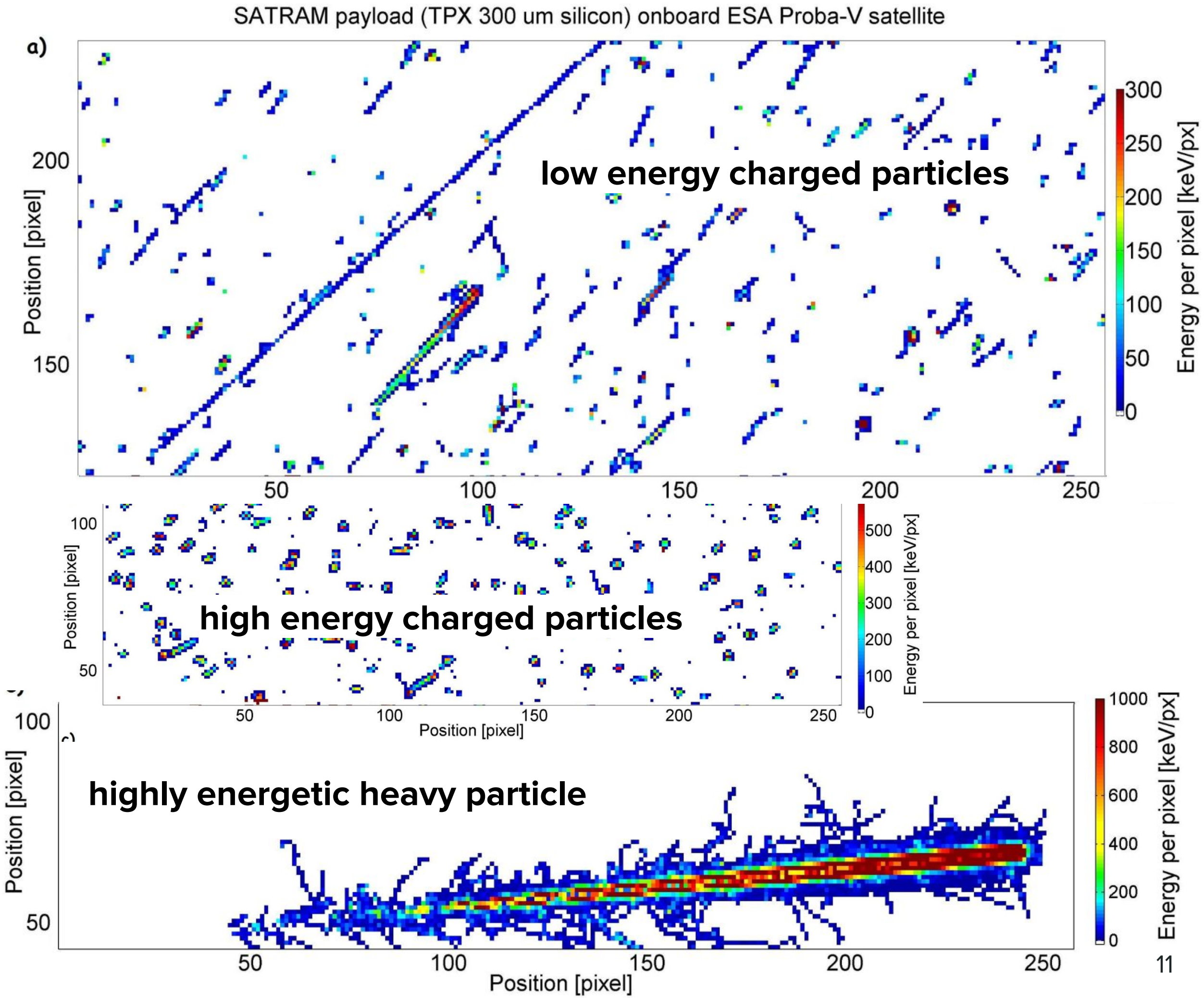
One pixel detector



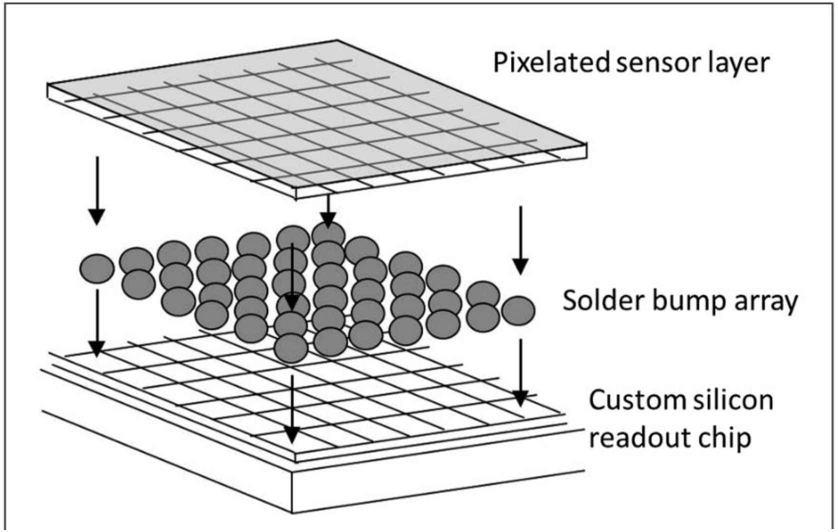
Particle detection

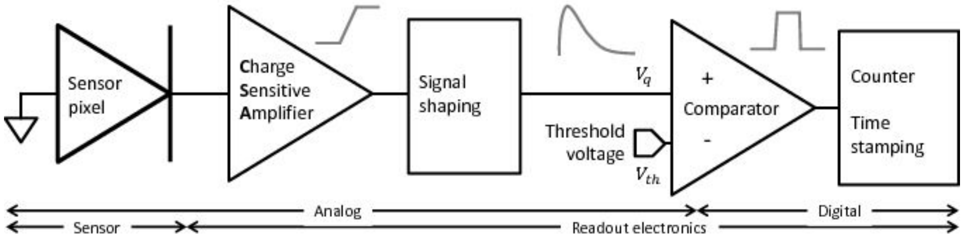
Space radiation in keV per pixel in x-y plane on a Timepix chip with a 300 µm thick silicon pixel sensor.

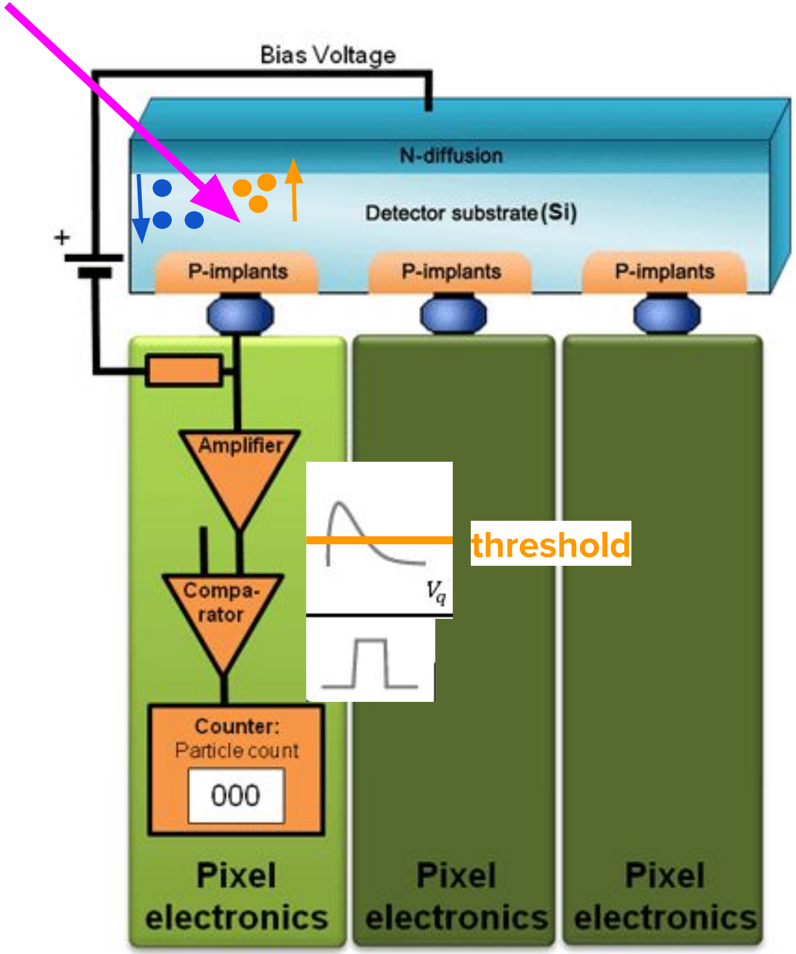




Hybrid pixel detector

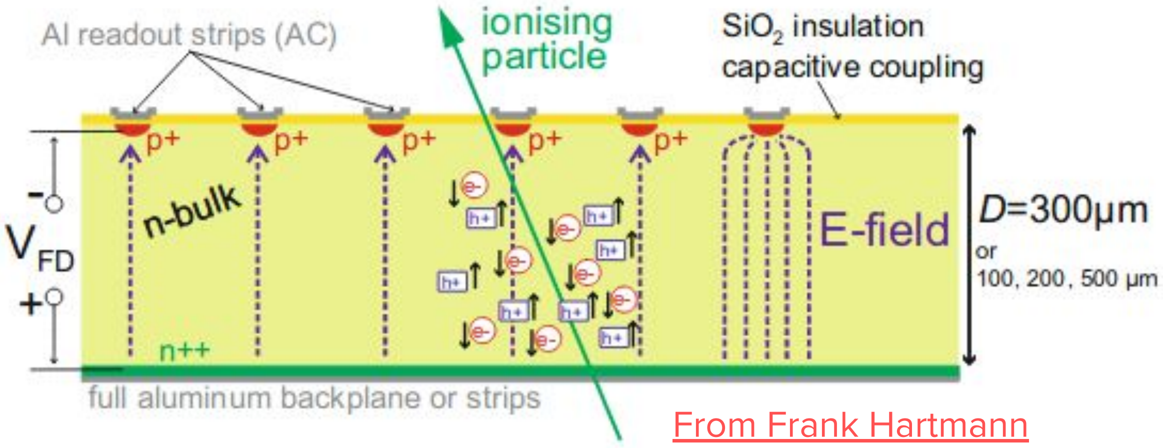






Ideal signal detection with silicon sensors

- A *minimum ionizing particle* (MIP) traveling through a *fully depleted* region (V_{FD}) creates electron hole pairs
- The charges drift to opposite directions under the electric field
- Within nanoseconds, a signal is induced at the readout



From Frank Hartmann

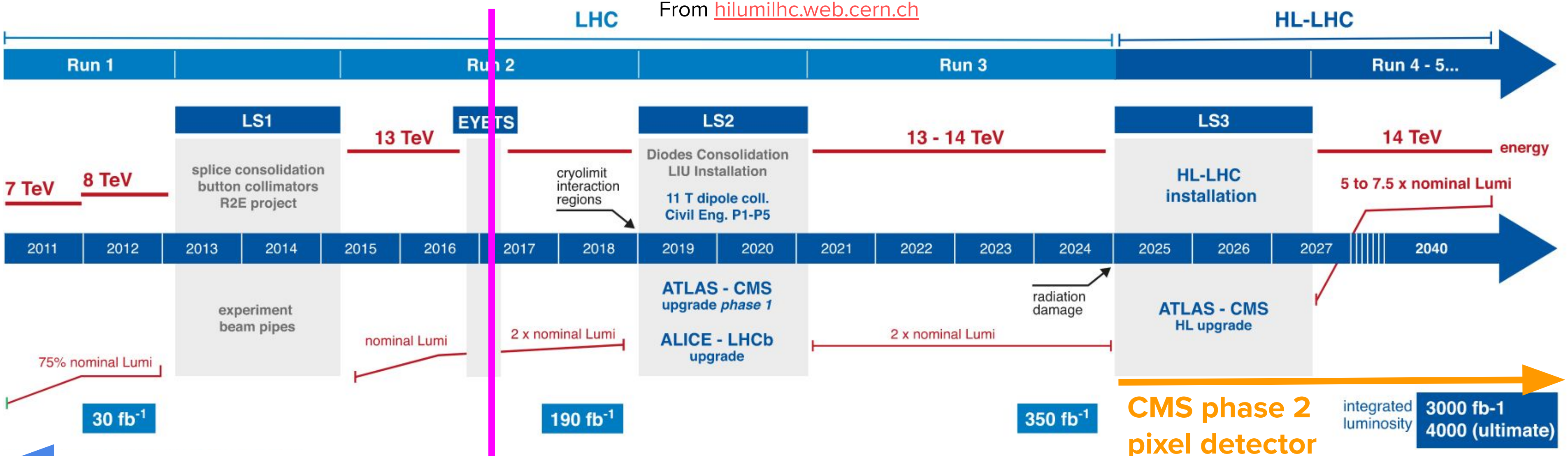
p-in-n silicon sensor

One can measure V_{FD} by **scanning the *bias voltage*** during data taking so that the V_{FD} yielding optimal signal can be applied.

The CMS phase 1 detector

Plan for the LHC and CMS pixel

From hilumilhc.web.cern.ch

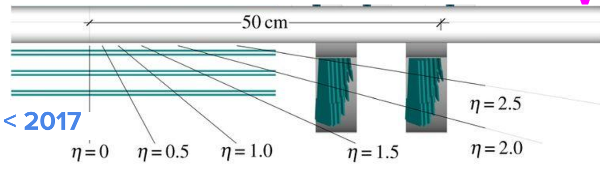


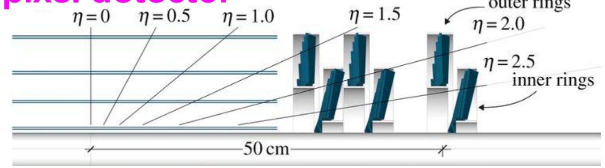
CMS phase 2
pixel detector

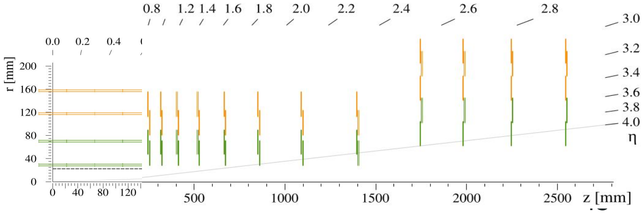
CMS phase 0 pixel detector

Installation of phase 1
pixel detector

< 2017

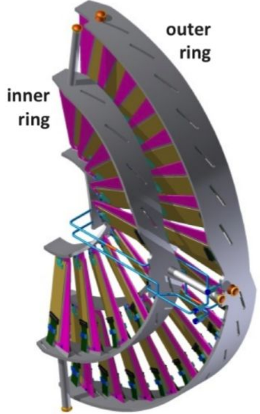


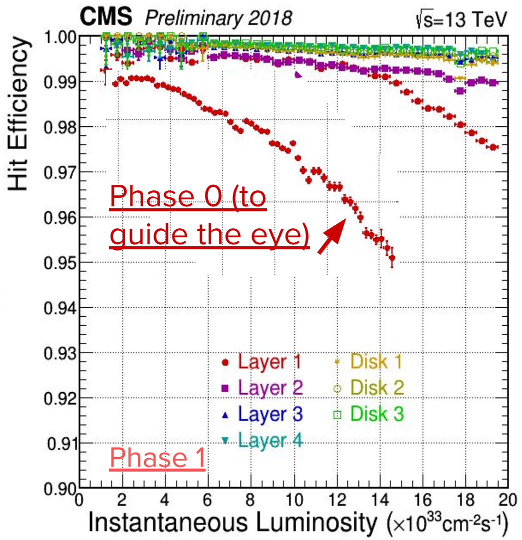




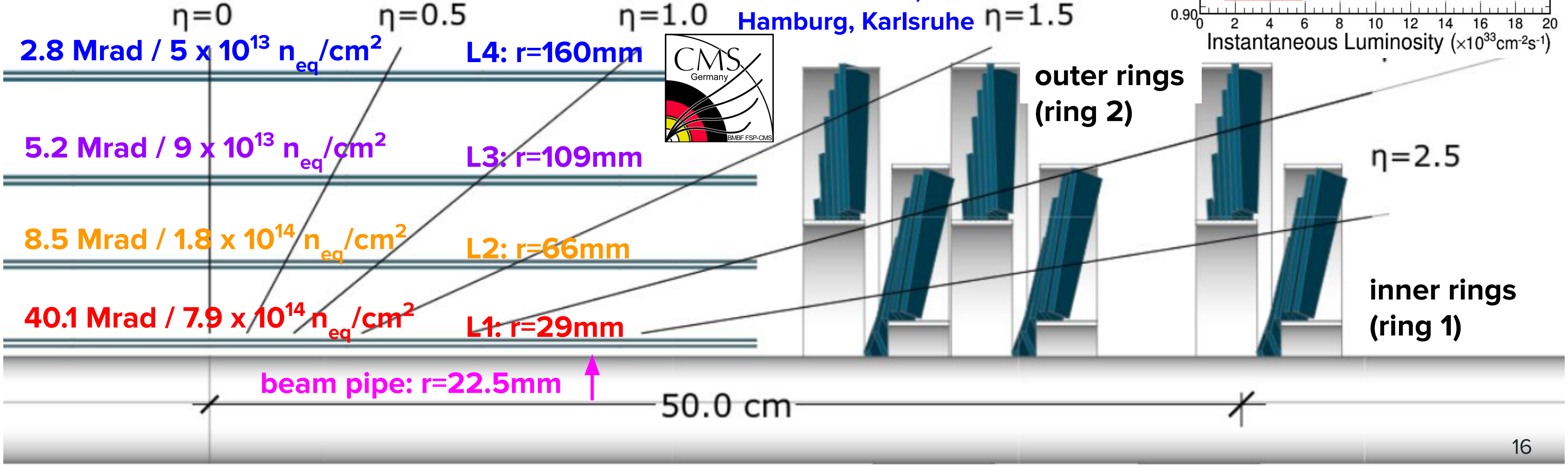
CMS phase 1 pixel detector

- 4 hit coverage and high-rate capability as opposed to 3 before
- Turbine-like structure for endcap disks for optimal resolution
- CO_2 cooling and DCDC conversion for reduced material
- Digital readout (as opposed to analog before)
- Excellent performance 2018-2017





All 512 L4 modules built in Aachen, Hamburg, Karlsruhe



Fluences as of today, from FLUKA 3.23.1.0

DCDC power conversion in the pixel detector

- 1.9*amount of channels compared to previous detector ➔ more current
- Same cables: no space!
- Power loss ∝ current^2
- Solution: keep current low over longer distance
  ➔ keep voltage high until close to endpoint

$$P_{\text{cable loss}} = I^2R$$

230 kV

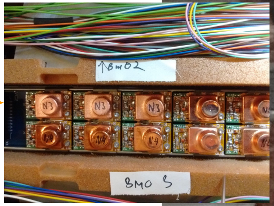
\> 100 km

220 V

< 1 km

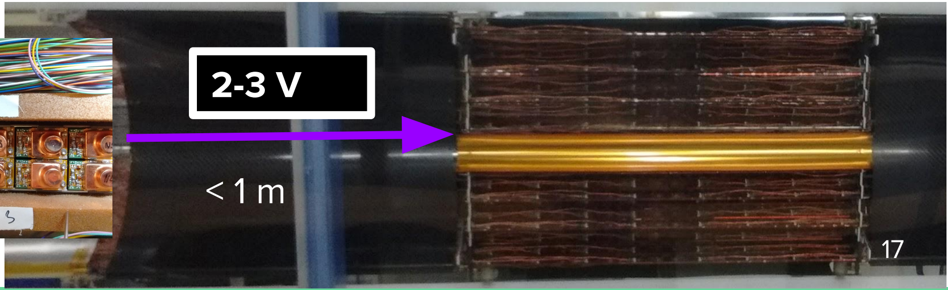
9 V

\> 50 m



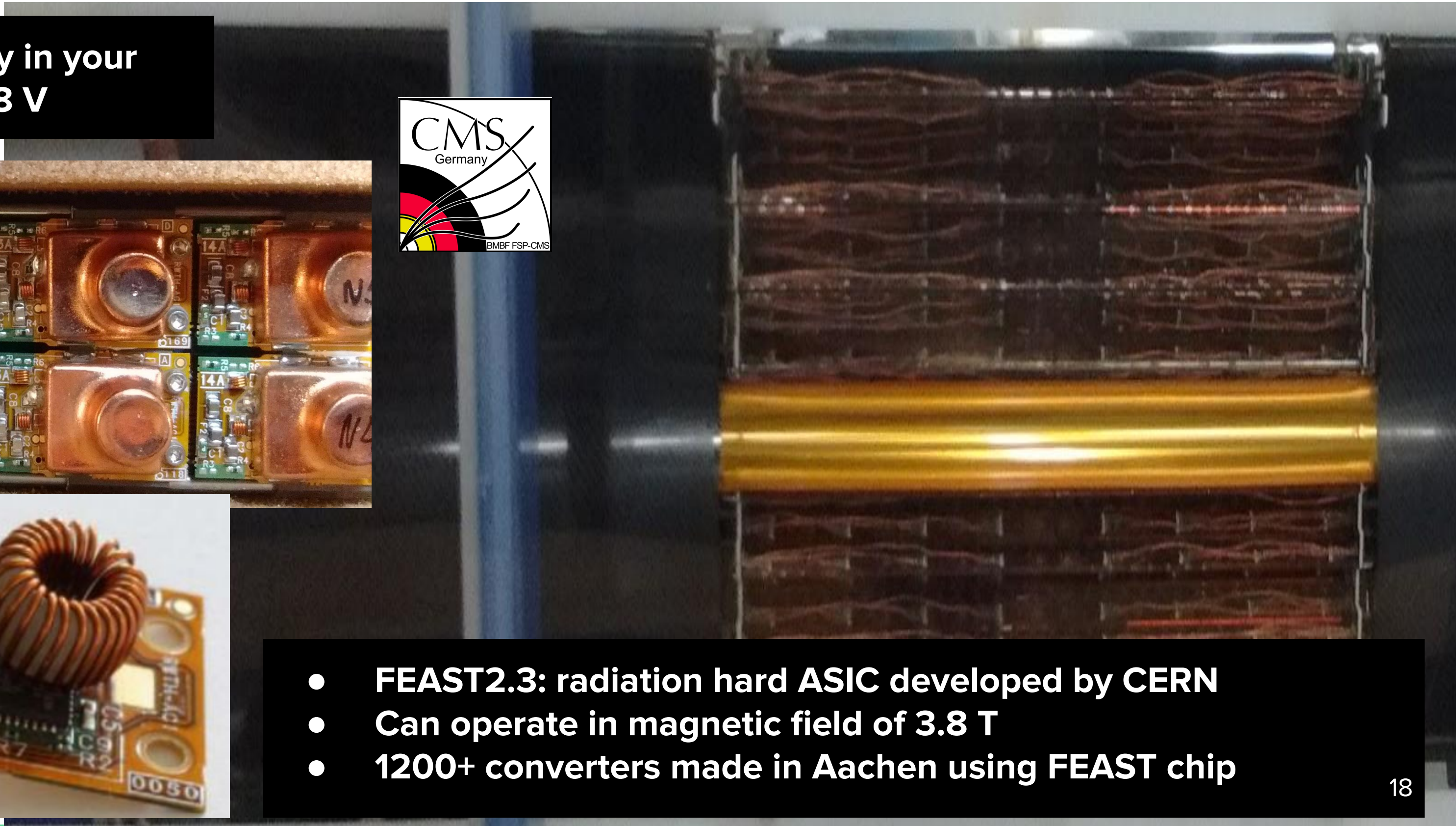
2-3 V

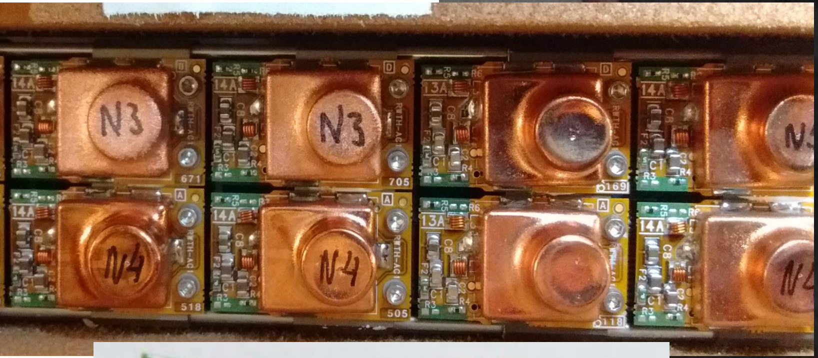
< 1 m

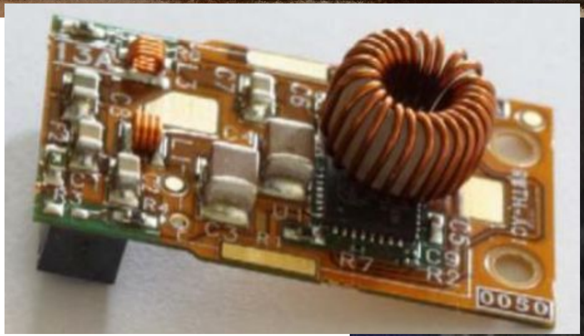


DCDC power conversion in the pixel detector

buck converter: probably in your laptop! 12 V in, CPU < 1.8 V

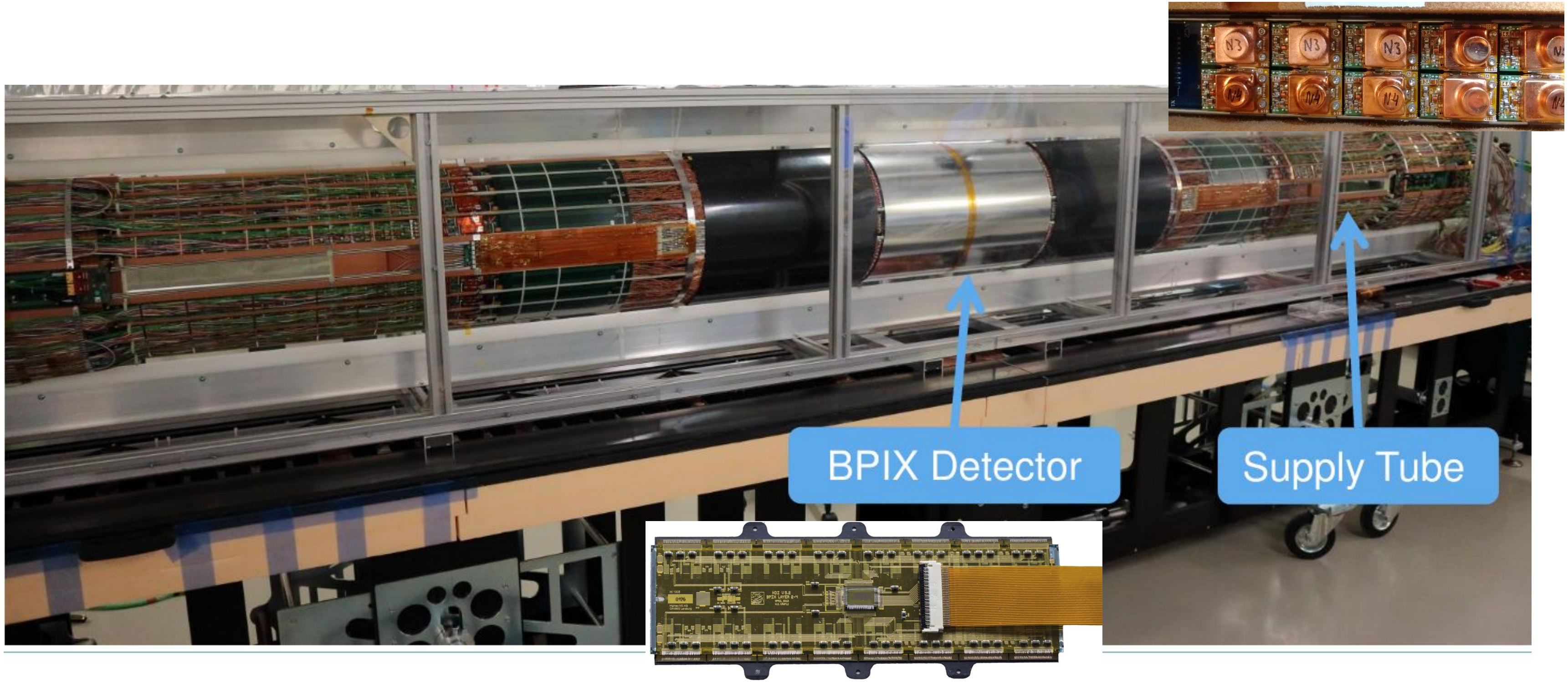






- **FEAST2.3: radiation hard ASIC developed by CERN**
- **Can operate in magnetic field of 3.8 T**
- **1200+ converters made in Aachen using FEAST chip**

One half of the pixel barrel detector



Module and signal

Flex print

wire bonded

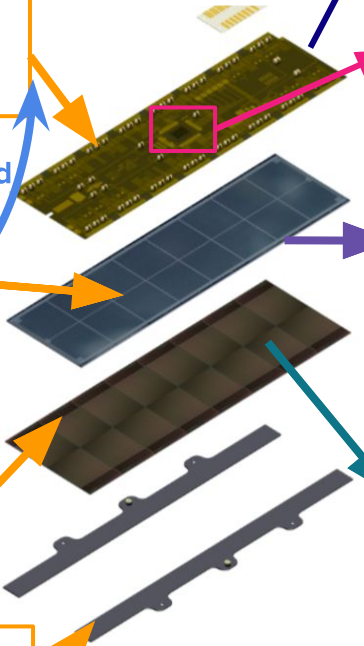
glued

sensor

bump bonded

ROCs

Mechanical support

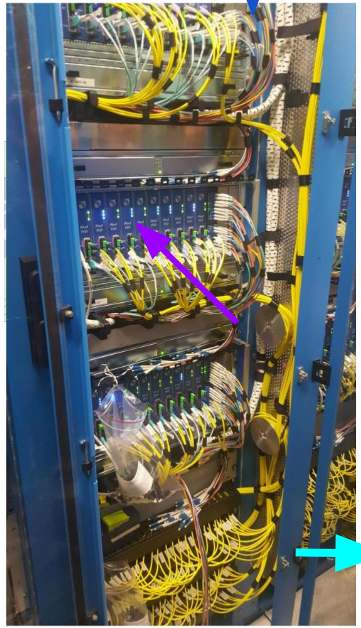


High density interconnect (HDI): power, TBM

Token bit manager: TBM
Clock and trigger distribution, ROC readout

Sensor: 285 μm^2 n^+ in n with 150 x 100 μm^2 pixels

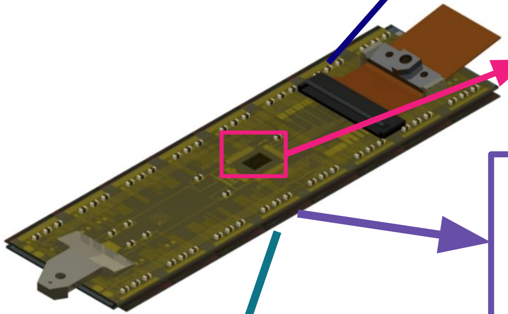
Readout chip (ROC):
250 nm CMOS PSI46digv2 and PROC600.
8 bit digitization of signal above threshold.
PROC600 for up to 600 MHz especially for innermost layer.



Counting room: next to CMS cavern

To upstairs at up to 10Gb/s

Signal path



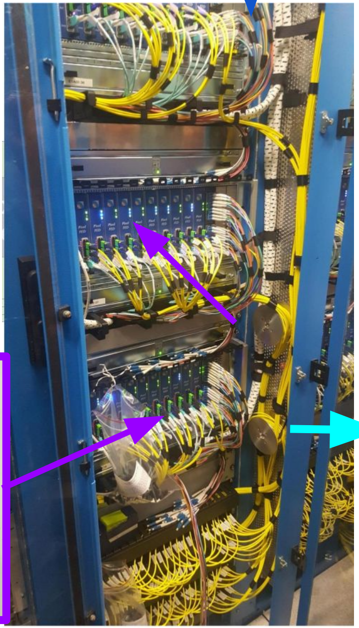
High density interconnect (HDI): power, TBM

400 Mbit/s

400 Mbit/s

Token bit manager: TBM
Clock and trigger distribution, ROC readout

Sensor: 285 μm^2 n$^+$ in n with 150 x 100 μm^2 pixels



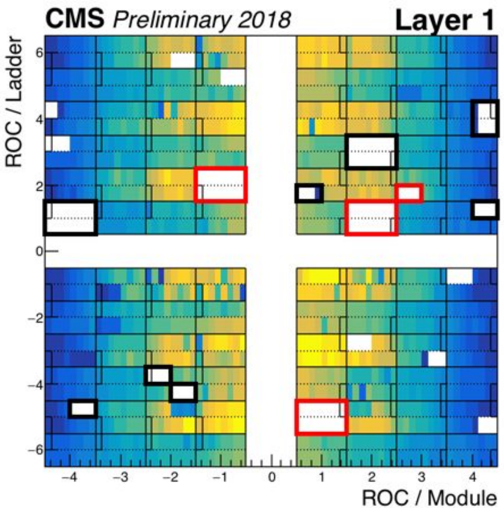
Data acquisition (DAQ) in CMS crate standard: μTCA

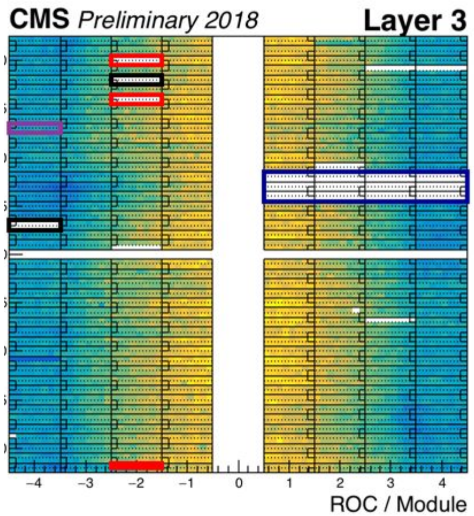
To HLT upstairs at up to 10Gb/s

Readout chip (ROC):
PSI46digv2 and PROC600.
8 bit digitization of signal above threshold

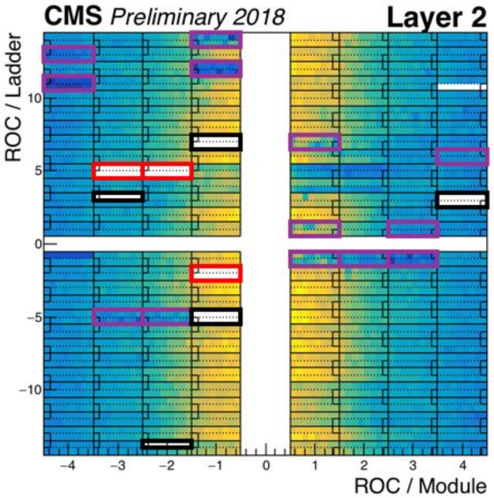
127 Xilinx **Kintex 7 FPGAs** with 4 GB DDR3 RAM on **FC7** **advanced mezzanine cards**

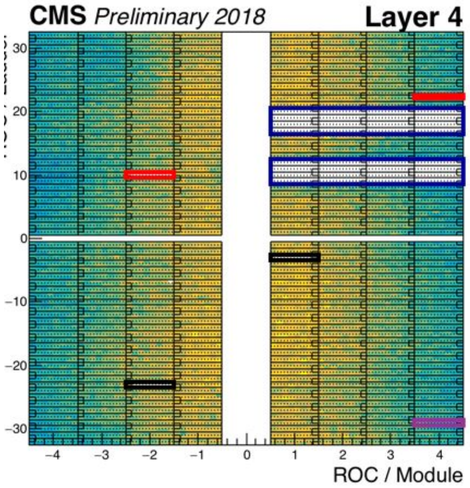
Operating the CMS pixel detector





Pixel barrel detector 93.5 % efficient



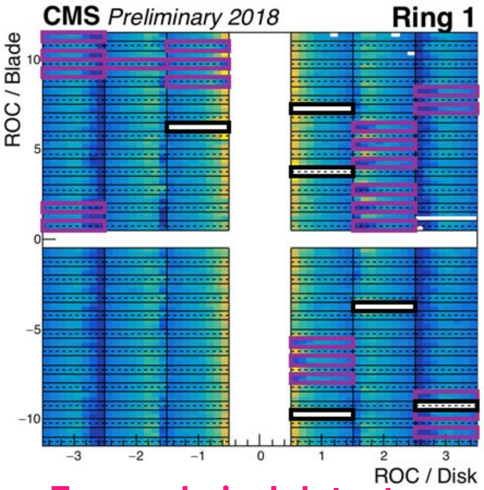


Malfunction since 2018

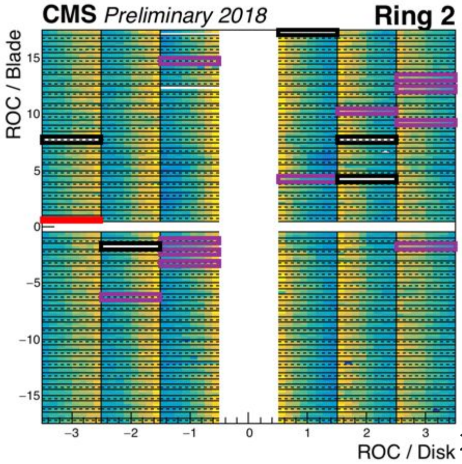
Malfunction since 2017

Behind 2017 broken DCDC converters (see later)

Connection problem → bias voltage switched off (see later)

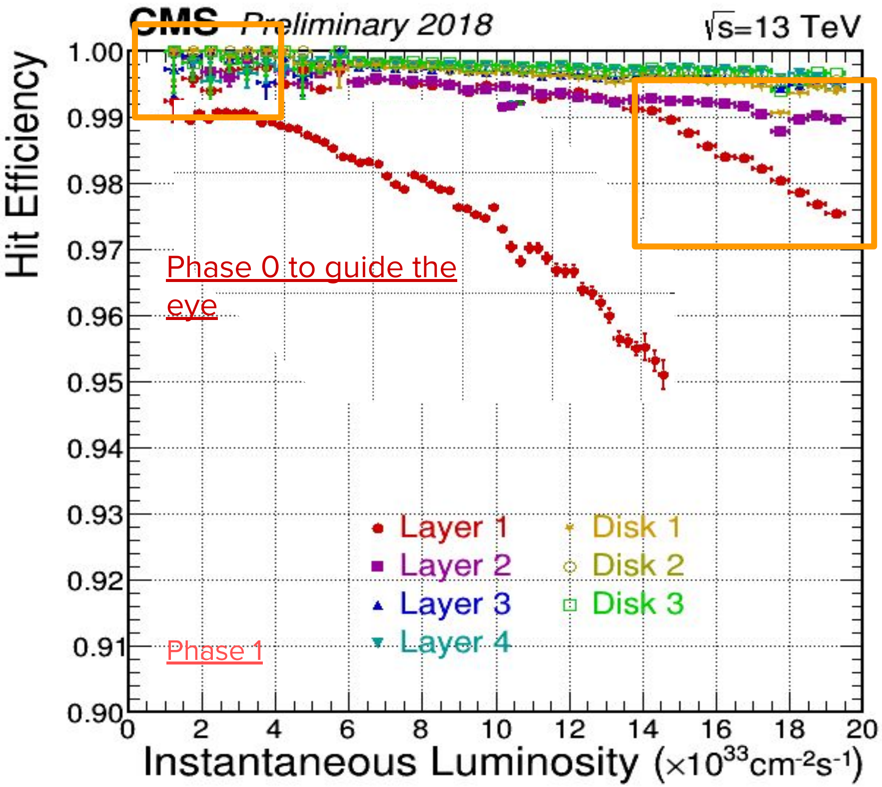


Forward pixel detector 96.7% efficient



94.3% efficient

Detector performance



Data and time stamp are buffered until a trigger or reset arrives.

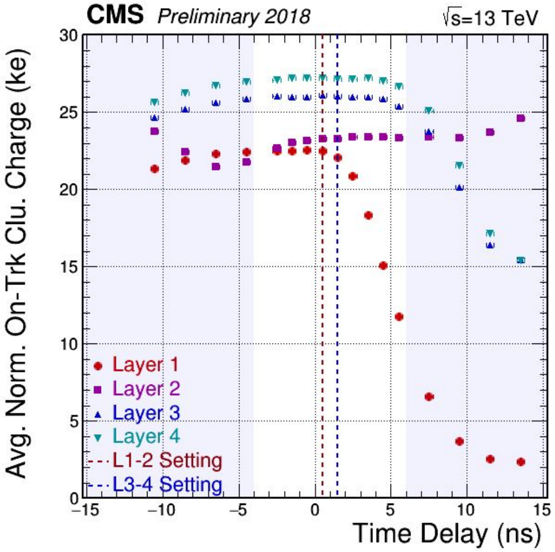
Overall a high efficiency: good performance!

Inefficiency from synchronization loss between data and time stamp buffer at high and low rates:

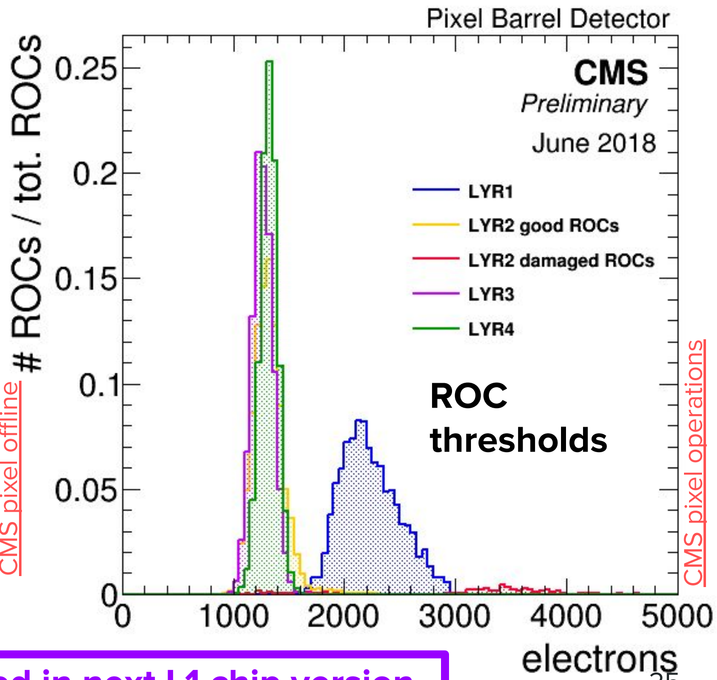
- low L ~ 1E33/cm^2/s^2
- high L > 1.4E34/cm^2/s^2
- solved by 70 Hz CMS reset rate

Layer 1 chip PROC600: timing, crosstalk, inefficiency

- Layer 1 readout **chip speed ½ clock faster than** layer 2 ROC ➔ **not enough delay setting granularity**: L1, L2 on same clock
- **High thresholds** resulting from crosstalk ➔ "noise" hits
  solved with software



CMS pixel offline

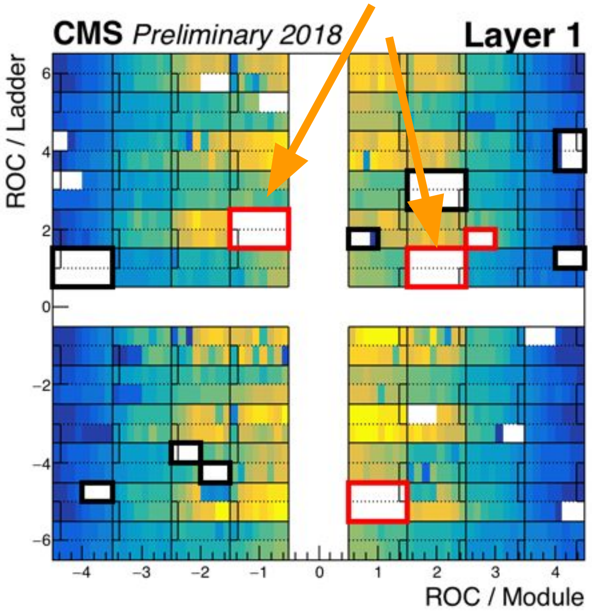


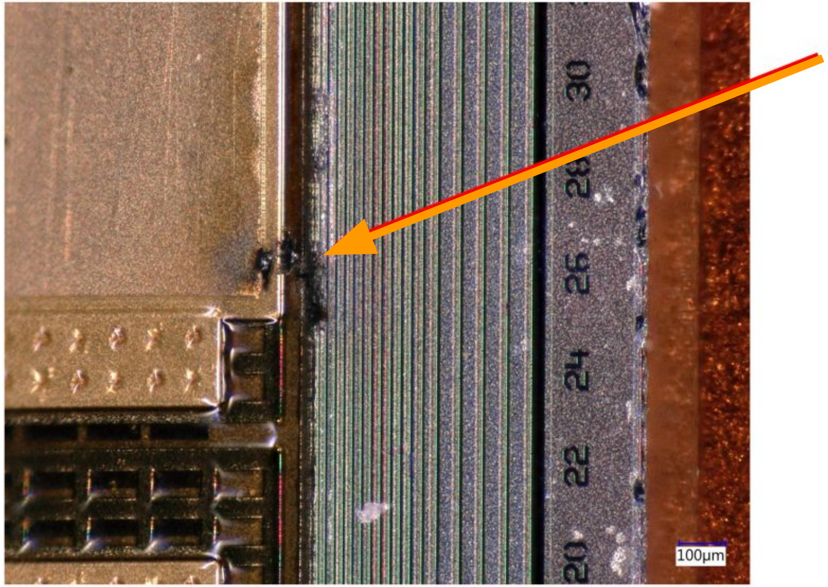
CMS pixel operations

All solved or addressed in next L1 chip version.

More problems with layer 1

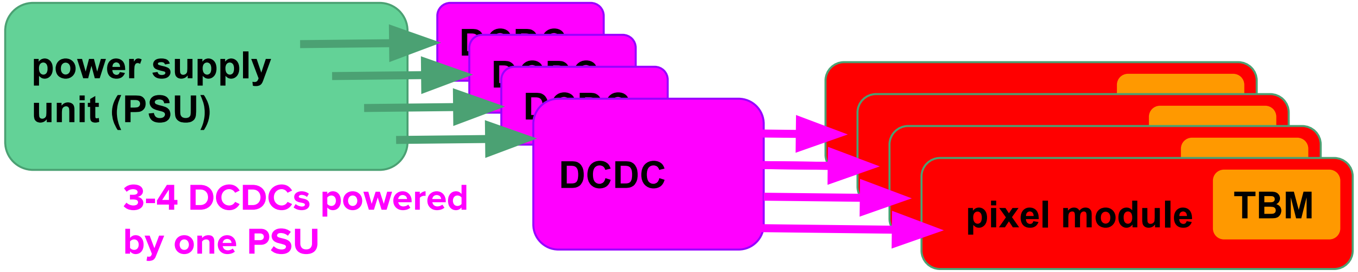
- HV problem on the High Density Interconnect (HDI), the flex on the module: shorts in June 2018
- Stayed at 450 V in 2018





From Danek Kotlinski

Stuck TBMs and malfunctioning DCDC converters



3-4 DCDCs powered by one PSU

1-4 modules powered by 1 DCDC

1: token bit manager (TBM)

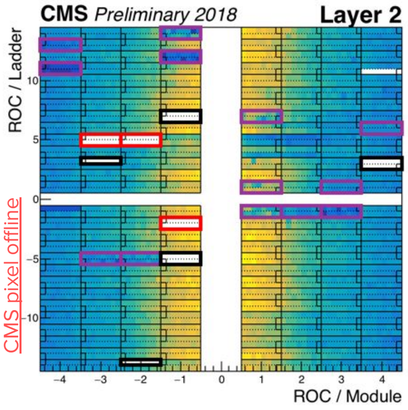
- 30 single event upsets (SEUs)/fb^{-1} in L1 transistor in TBM latch sets TBM to 'no readout' mode: "**stuck TBMs**"
- recovery only with **power cycle**. Lowest granularity: one **DCDC converter**.

2: irradiated DCDCs stopped functioning in disabled state

- Increased leakage current as a result of one transistor
- 63/1216 at end of 2017 stopped functioning, another 333 had high current

2018: powercycling with PSU. No DCDC broke.

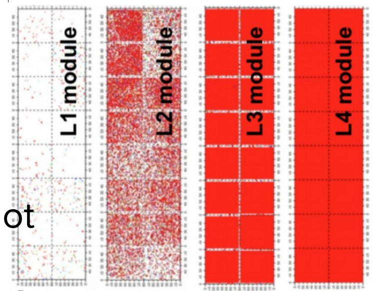
2020+: new DCDCs, new L1 TBMs.



Layer 2 damaged chips

3: readout chips

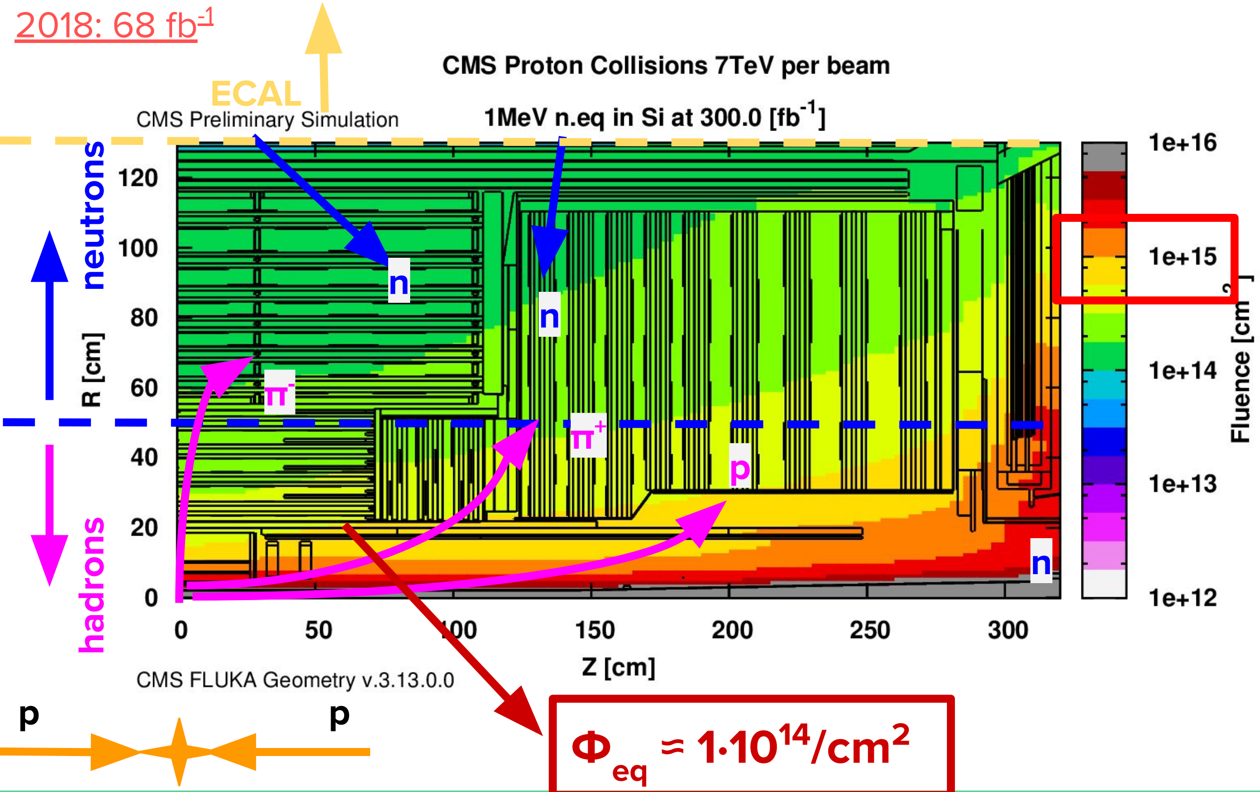
- module power and bias voltage grouping not the same
- **HV on, LV off caused chip damage** from sensor leakage current: 8/96 L1 modules lost in 2017



Radiation effects

LHC: a challenging environment

2017+2018: 118 fb^{-1}
2018: 68 fb^{-1}



Radiation effects are challenging for operations and performance:

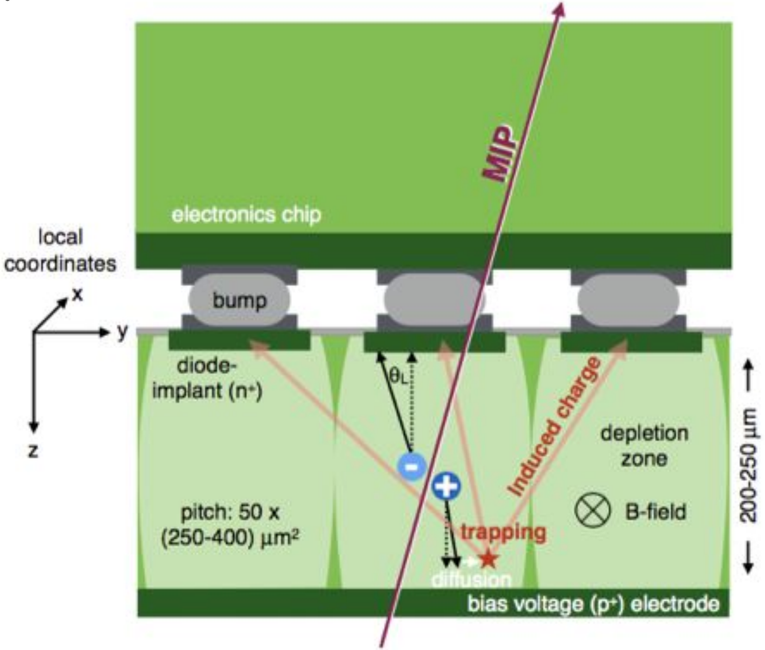
- Damage and single event upsets (SEUs) in electronics
  ➜ false signals, chip damage
- Bulk defects cause change of space charge distribution
  ➜ bias voltage increase
- Increasing leakage currents and heat dissipation
- Charge trapping in sensor:
  ➜ decreasing charge collection efficiency

Φ_{eq} neutron equivalent number of particles per unit area

Not so ideal signal detection: radiation damage

Charges induced by an incident particle are collected with reduced efficiency as a result of radiation damage that causes:

- **Deformation** of the electric field
- **Trapping** induces screening of charge
- Diffusion or annealing deflects the path: **Annealing**
- Magnetic field, which changes with operational bias voltage and changing electric field, deflects the path: **Lorentz angle**

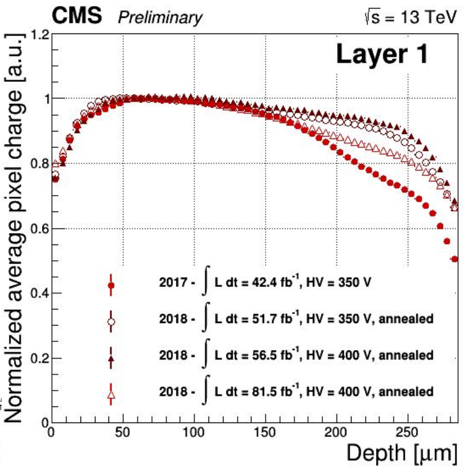


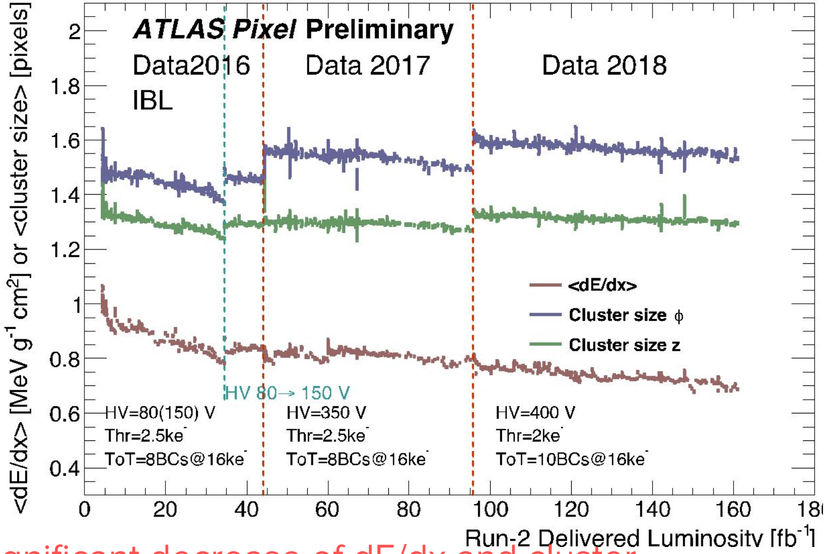
[From Ben Nachman]

Impact on data

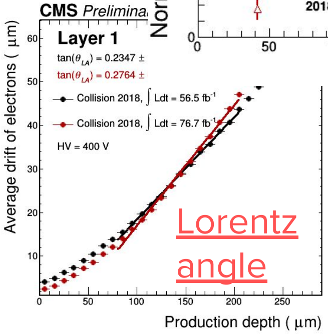
Modeling radiation damage is important for performance (➔ operational voltage) but also for physics

Average pixel charge

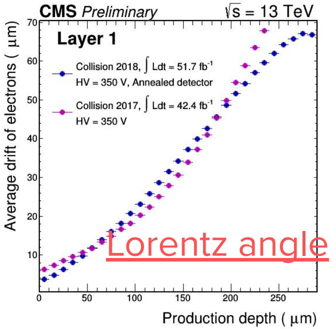




Significant decrease of dE/dx and cluster size for IBL

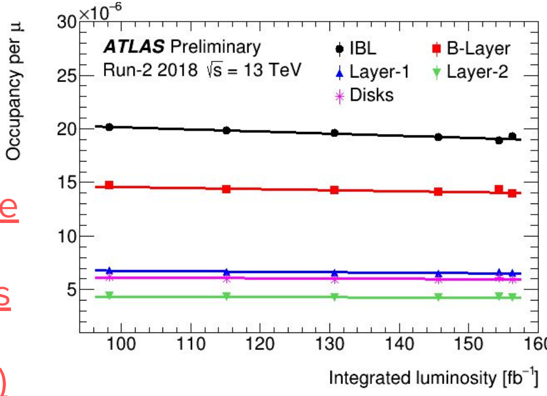


Lorentz angle

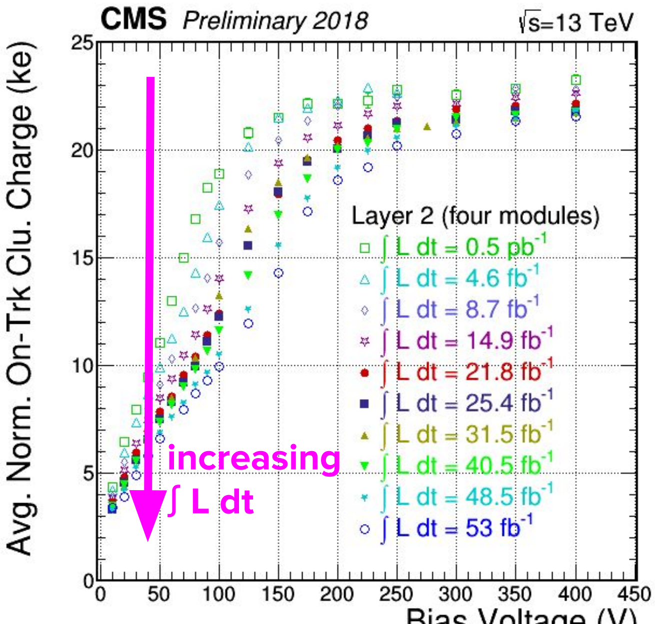


Lorentz angle

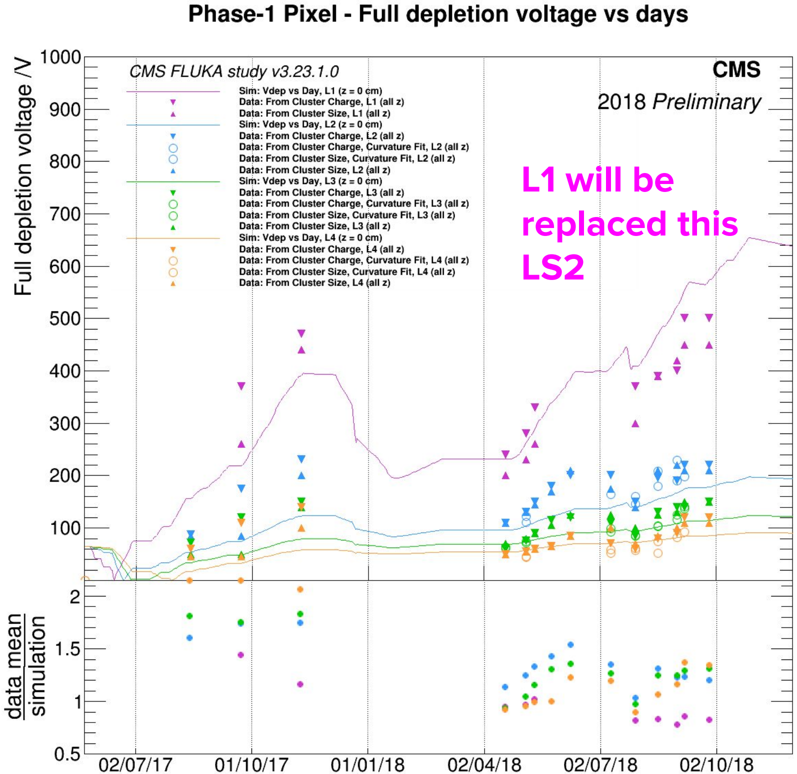
Pixel occupancy per average number of interactions per bunch crossing (μ)



Radiation effects on depletion voltage



CMS pixel offline



Run 3 depletion voltages expected to be within power supply limit of 800V.

Operational voltages at end of run 2:
L1: 450V
L2: 300V
L3-L4: 250V
Ring 1: 350V
Ring 2: 300V

Regular sensor bias voltage scans on subset of representative modules

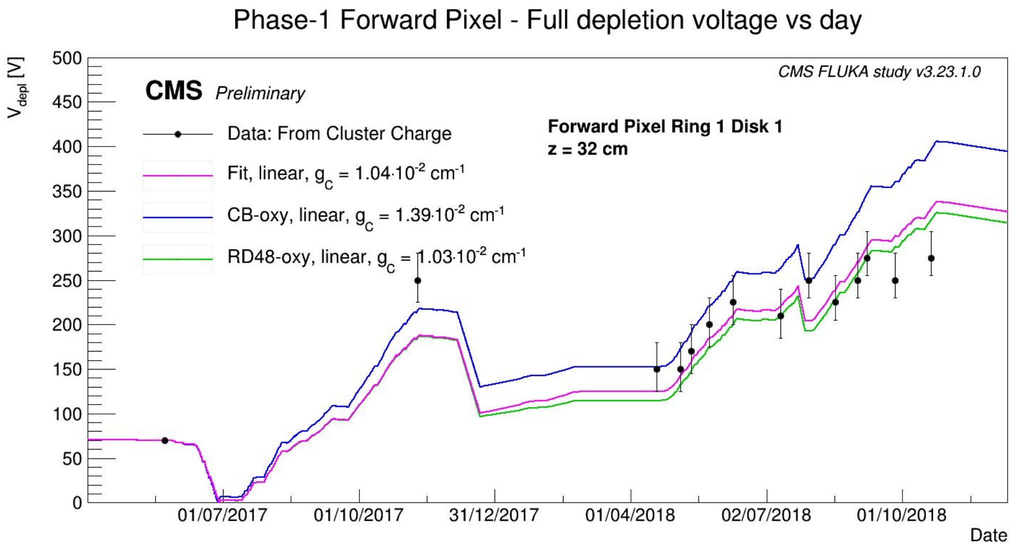
Simulation with effective space charge Hamburg model (E_{eff}=1.21 eV), fluence from DPMJet + FLUKA 3.23.1.0

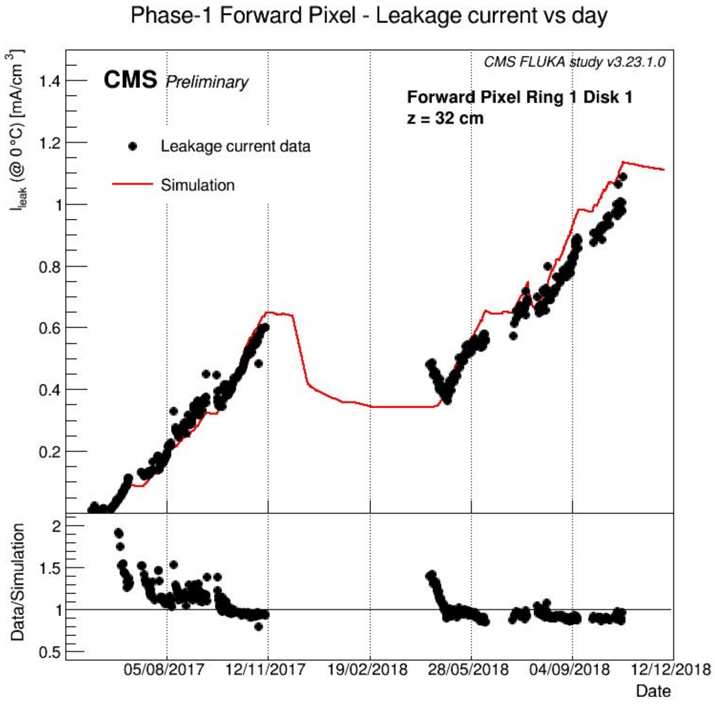
Hamburg model parameters from Michael Moll

CMS pixel operations

Radiation effects in the forward pixel detector

- On-module temperatures better understood than in barrel detector





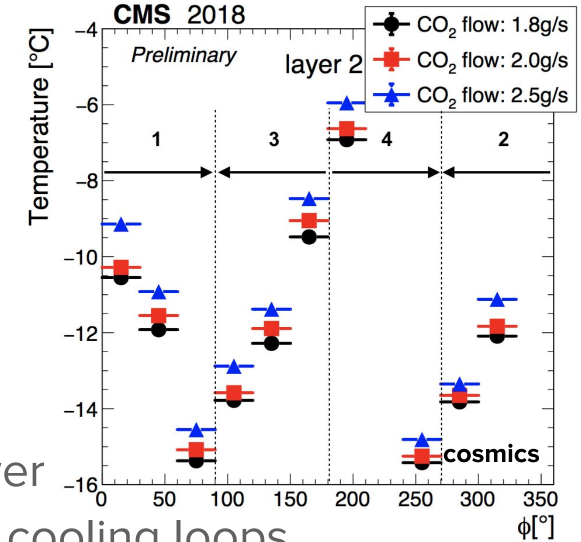
Leakage current depends on fluence and temperature

Cooling and temperatures

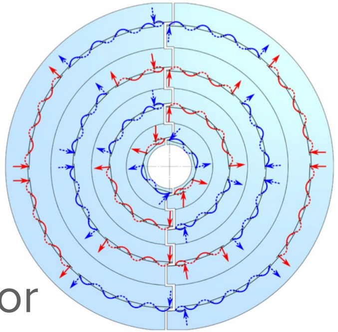
CO_2 cooling

Important to understand detector temperatures for radiation effects:

- ✓ -22°C, option to go lower
- ✓ 1.7mm ø stainless steel cooling loops
- ✓ wall thickness 50µm
- ✓ very lightweight
- ❌ gradient of 4-5K along cooling loop
- ❌ efficient cooling but **no efficient heating** which can be problematic for targeted **annealing or safety**

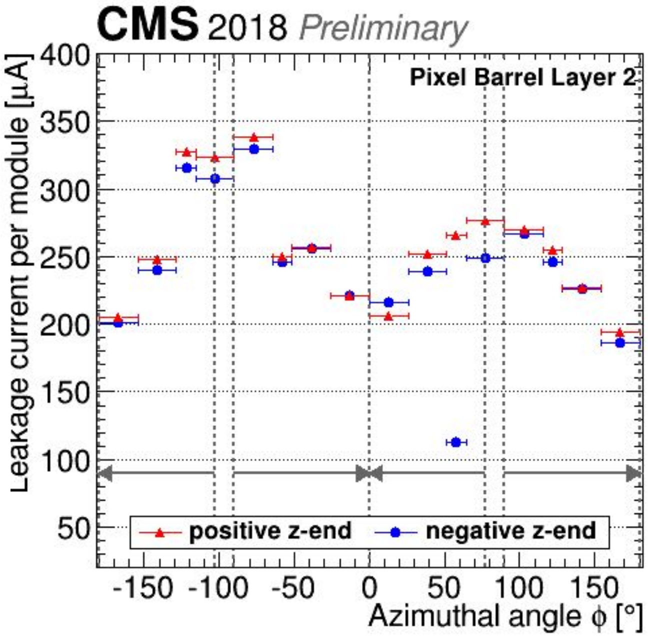


Increasing the flow did decrease some gradient but still a **non-negligible pressure drop** along cooling loop



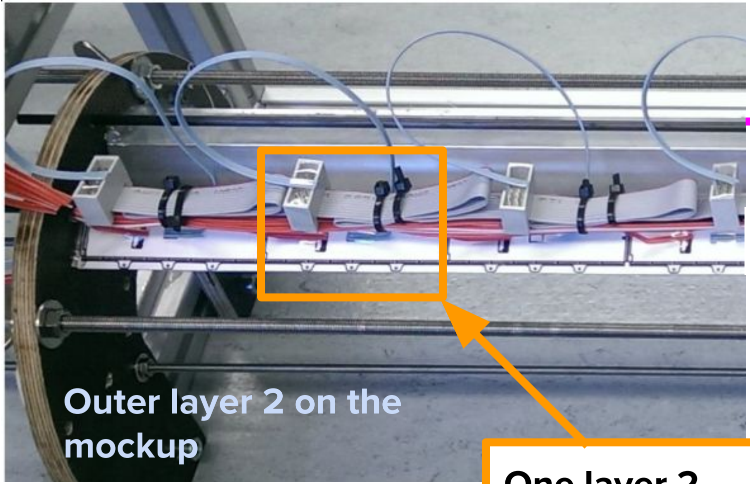
CMS-TDR-011

Leakage currents are affected by temperature



CMS pixel operations

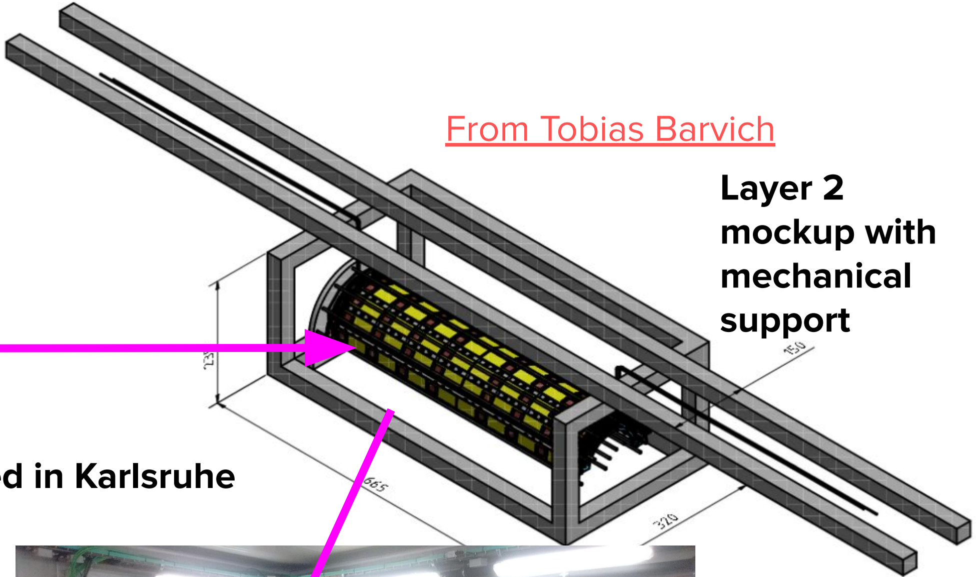
Test setup: CO_2 cooling



From Johanna Renner

One layer 2 pseudomodule with adjustable heat load

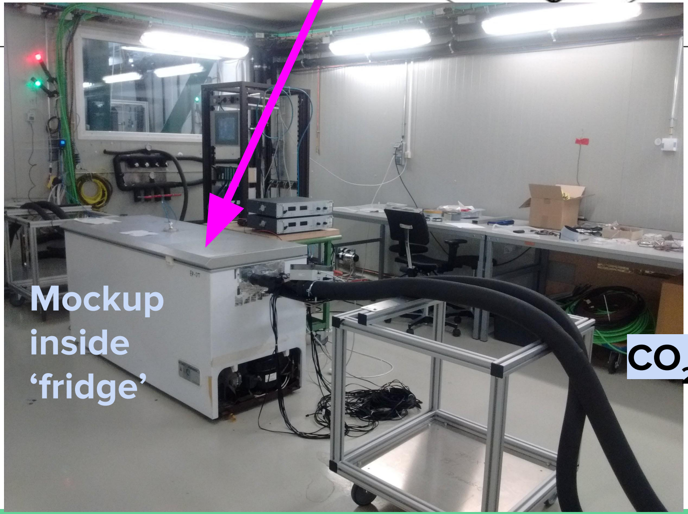
Realistic layer 2 mockup with **adjustable preheating and heat load on pseudo-modules** used to study CO_2 cooling and temperatures.
Flow on CO_2 is adjustable.



From Tobias Barvich

Layer 2 mockup with mechanical support

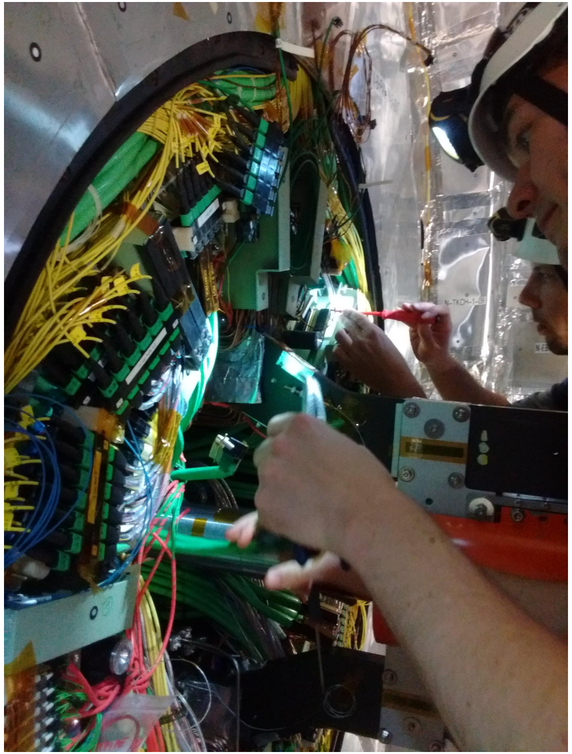
Designed in Karlsruhe



CO_2 cooling lines

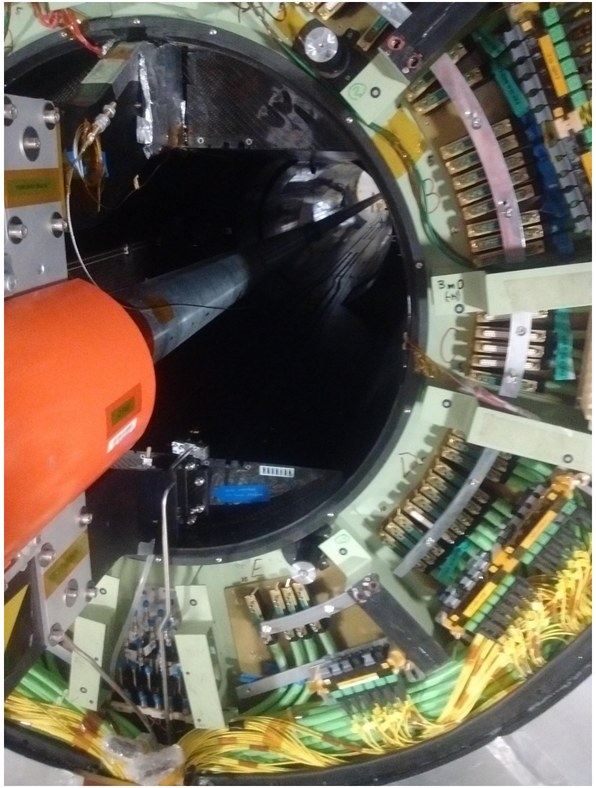
Work this long shutdown

Pixel extraction



The CMS pixel detector was installed in 2017

Detector on the surface



One can now see through CMS!

Now cold in clean room. Cold is important! To prevent **reverse annealing** that worsens radiation damage.

The long shutdown 2 (LS2) has started after two years of operation of this CMS phase 1 pixel detector. **Currently there are no collisions at the LHC.**

Maintenance in LS2

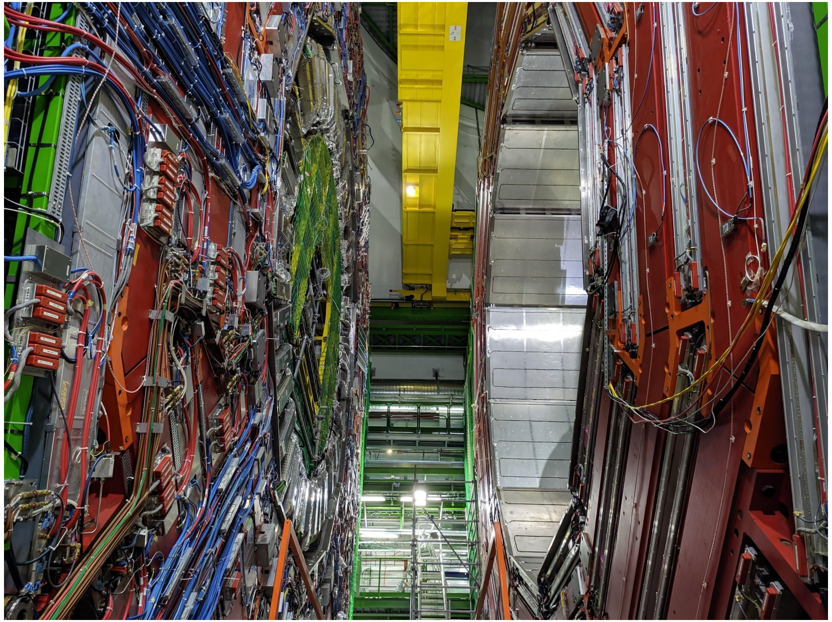
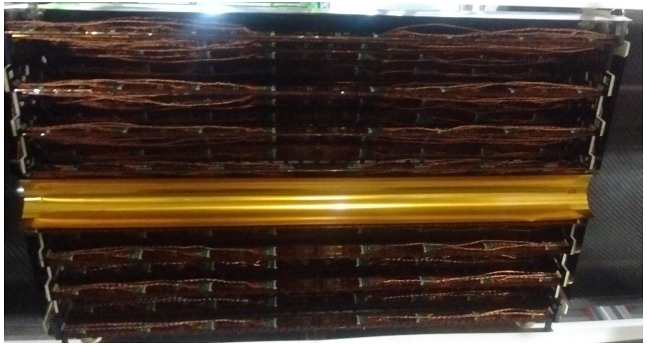
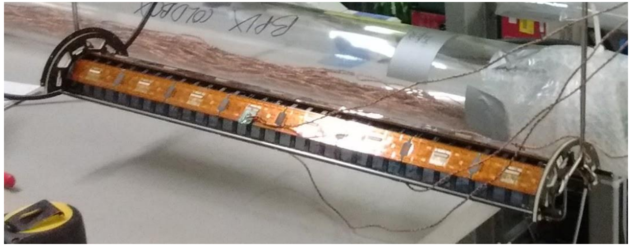


Photo courtesy of Mădălina Wittel



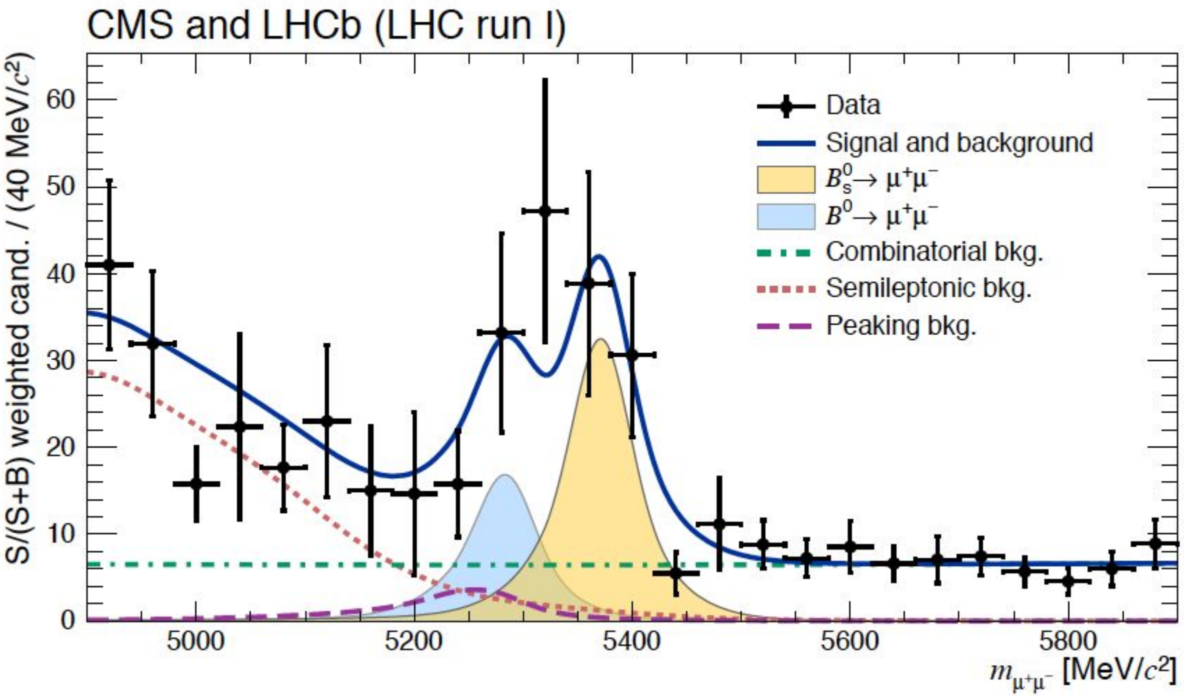


Upgrade of the innermost layer including new chips with improved TBMs

… and more prepare to make the most out of run 3!

High luminosity LHC

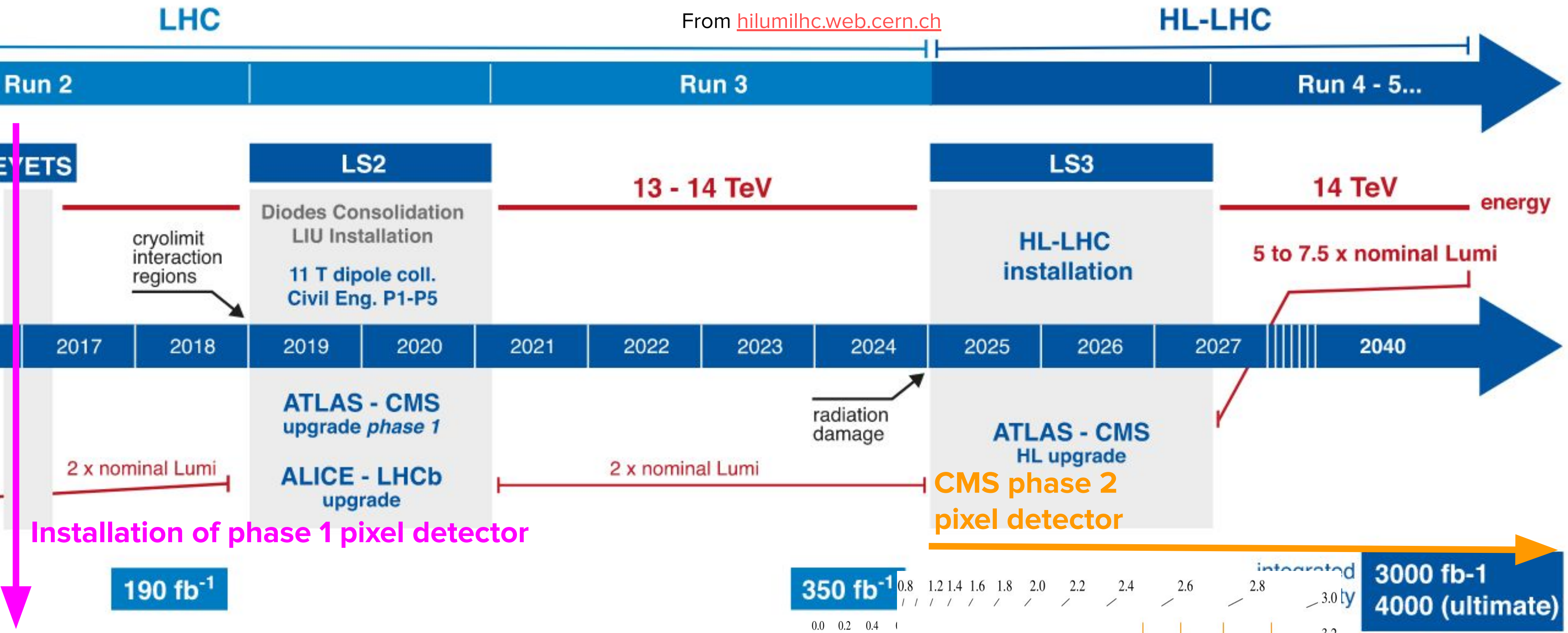
High luminosity ➜ high precision

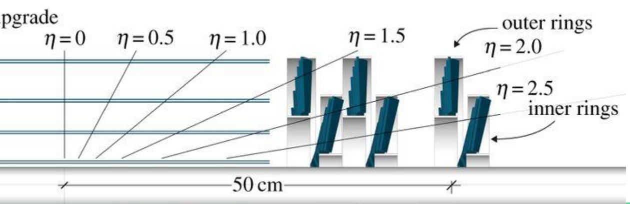


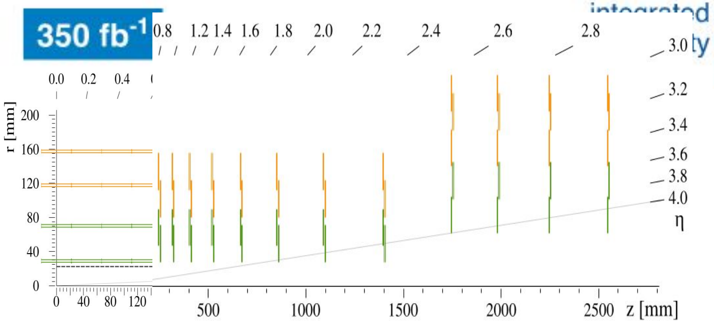
Much better precision for Higgs coupling strengths and measurements like $B_s^0 \to \mu^+\mu^-$

$B \to \mu\mu$ measurements are expected to achieve 6.8σ precision

From hilumilhc.web.cern.ch



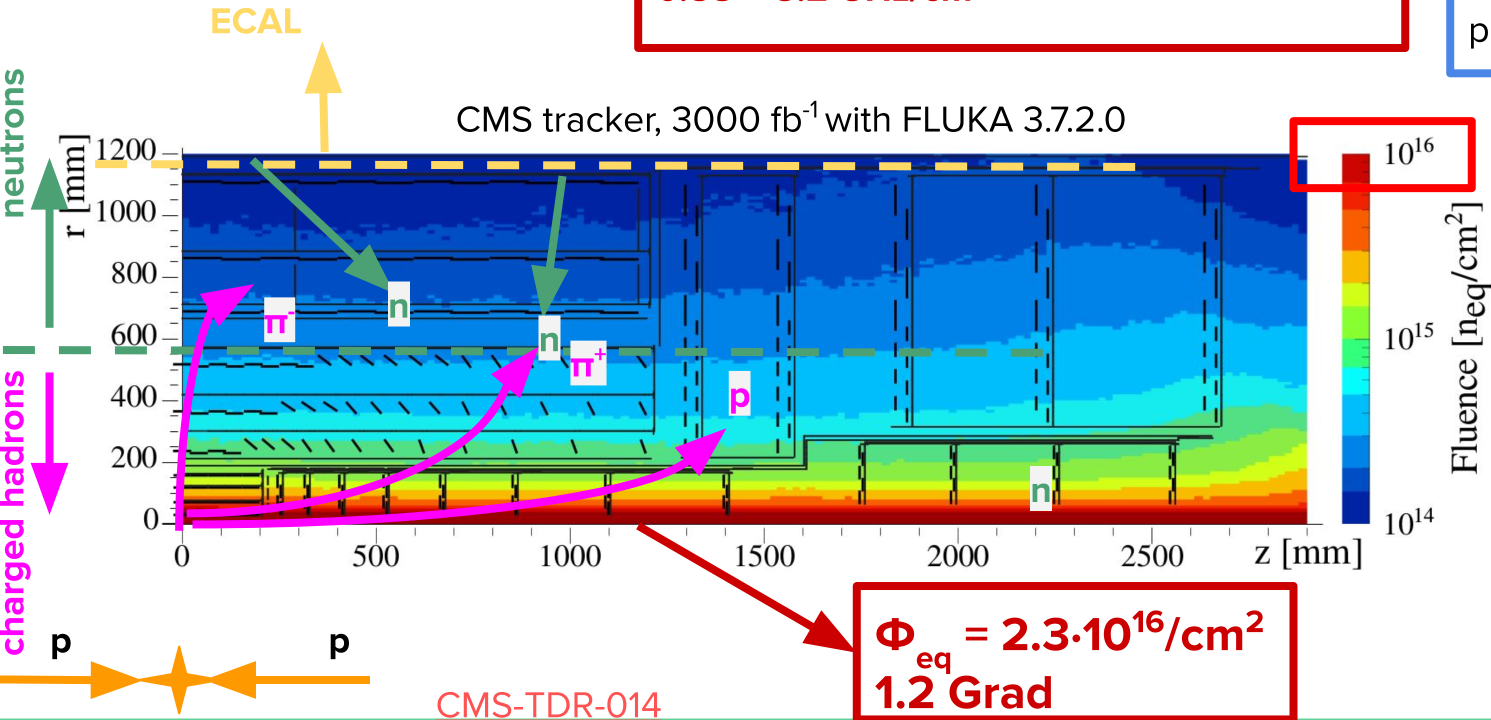




High luminosity LHC: a very challenging environment

5 × higher hit rate than in current detector: 0.58 → 3.2 GHz/cm²

Φ$_{eq}$ neutron equivalent number of particles per unit area



Φ_{eq} = 2.3·10^{16}/cm^2
1.2 Grad

Pileup up to 200 events per bunch crossing at HL-LHC
Peak lumi up to 7.5e34/cm^2/s

What is needed to cope with these fluences and rates?

CMS-TDR-014

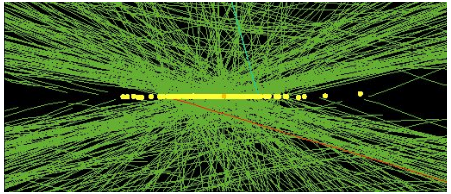
Requirements for the CMS tracker for high-lumi LHC

Must-haves:

- **More radiation hard** ➔ thinner or 3D sensors
- **Deal with high rates** ➔ smaller pixels
- Low enough leakage current ➔ **no thermal runaway**

Wishlist for good physics:

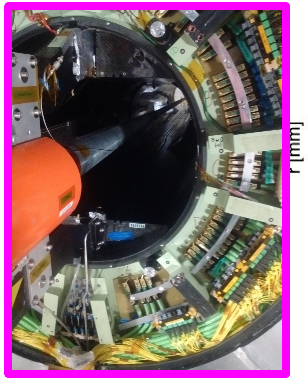
- High spatial **resolution**
- Good **signal/noise**
- **High single pixel hit efficiency**



Event with pileup of 78 in CMS in 2012

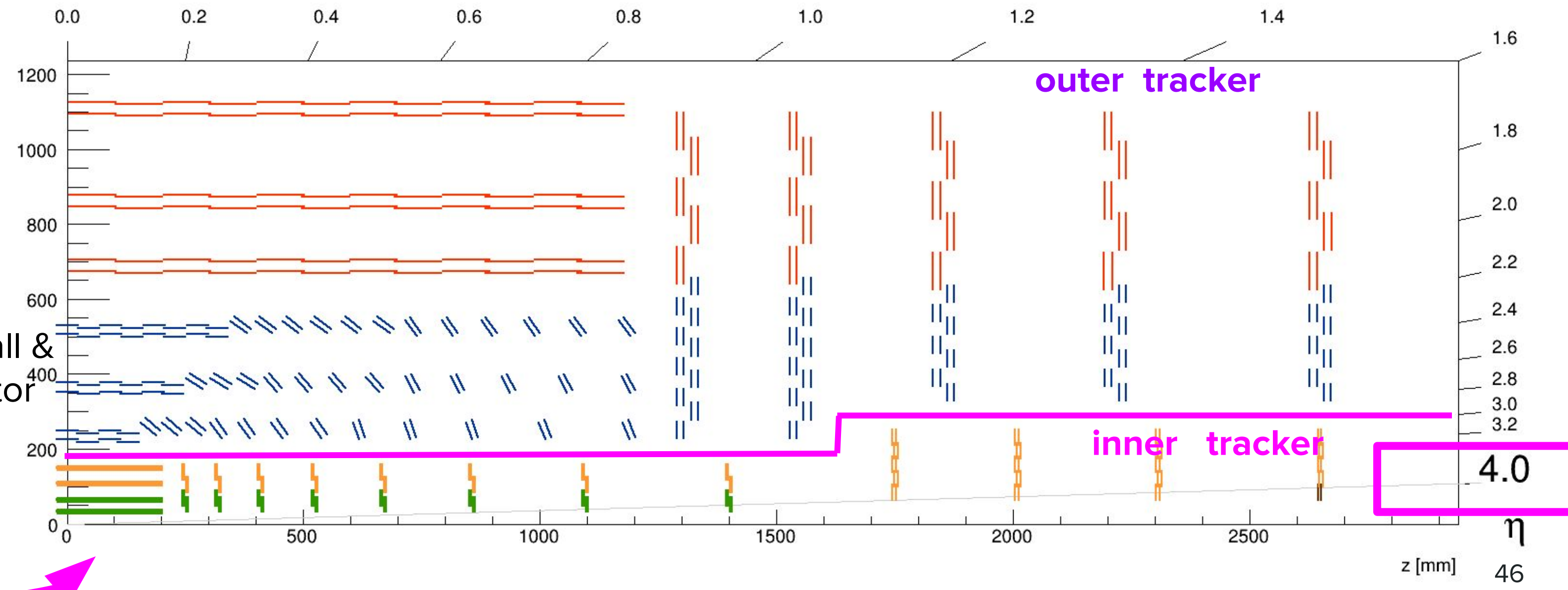
CMS tracker for the high luminosity LHC

In long shutdown 3, the entire CMS tracker will be replaced with one that fulfills the requirements for the high luminosity LHC.



Like now, easy install & remove pixel detector

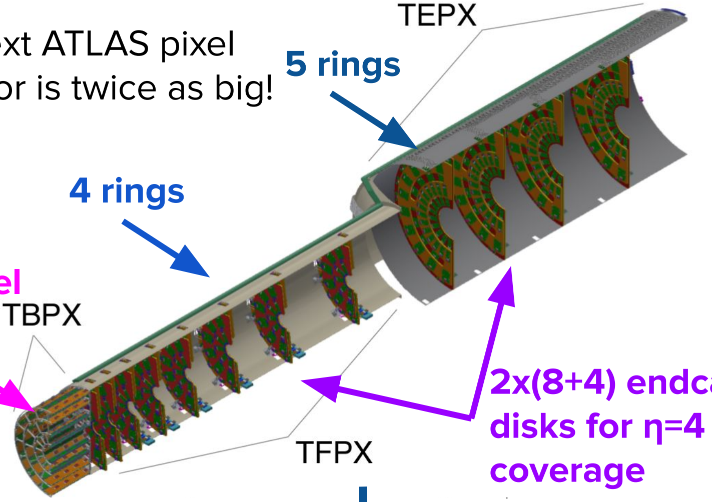
CMS inner tracker upgrade

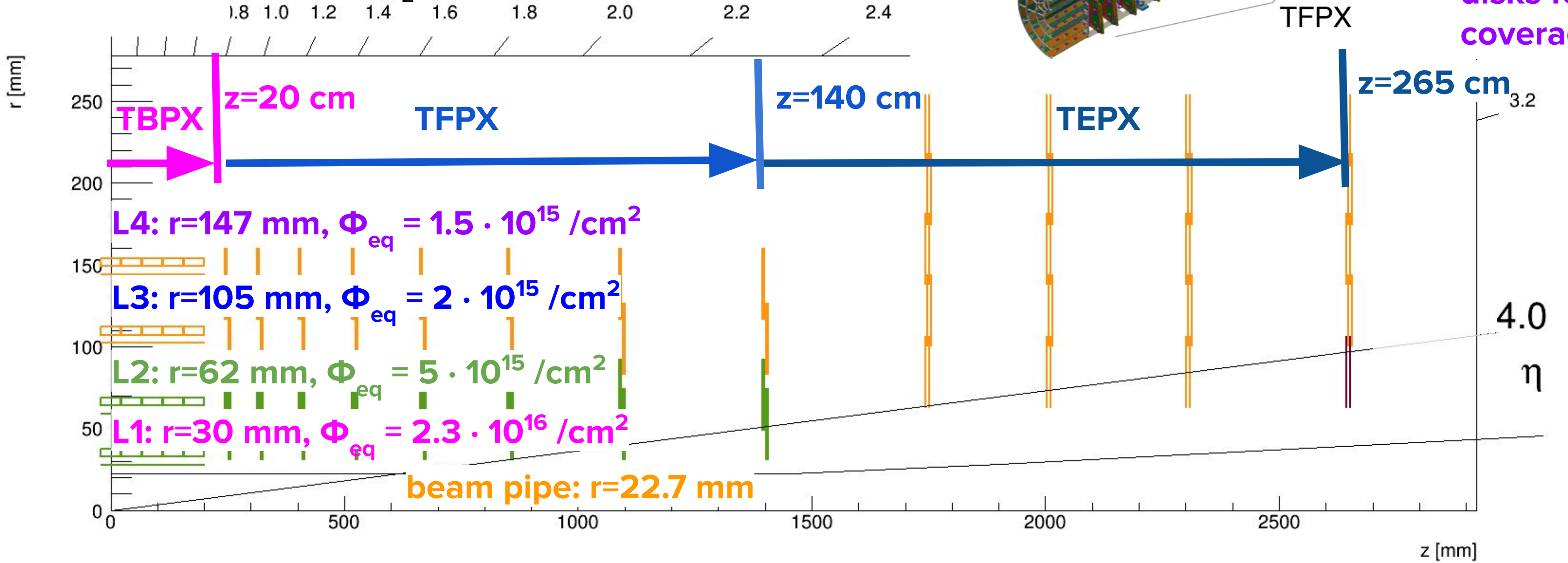


CMS phase 2 pixel detector

- Coverage up to η=4 (from η=2.5) and high-rate capability
- Smaller pixels of **25x100** or **50x50** μm^2
- 3D sensors option for innermost layer
- RD53 65nm CMOS ASIC for CMS and ATLAS
- Serial powering and CO_2 cooling for low material budget

The next ATLAS pixel detector is twice as big!





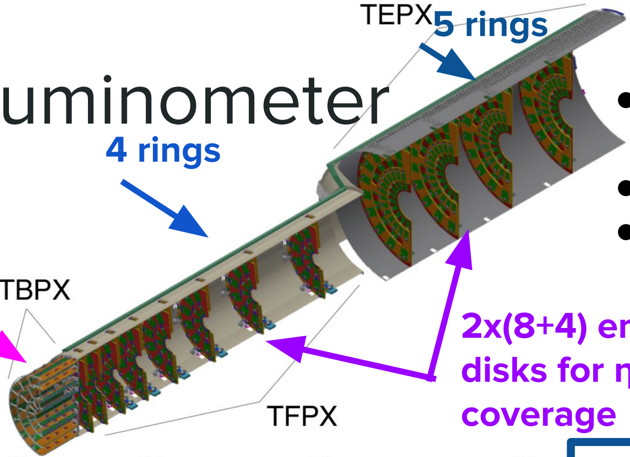
CMS-TDR-014

CMS pixel phase 2 layout

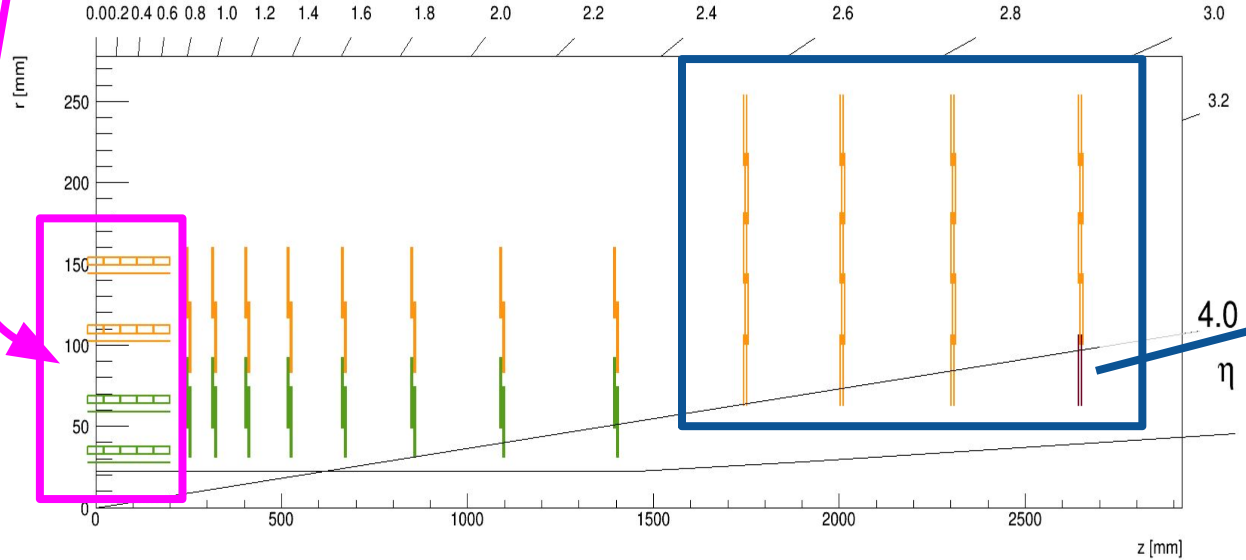
η=0 coverage and luminometer

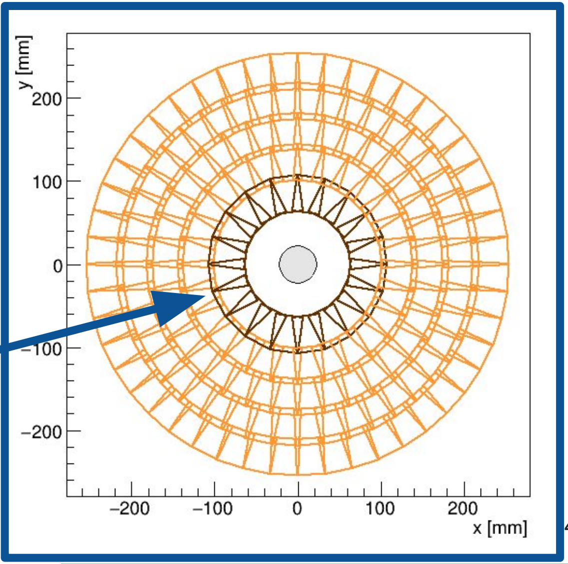
TEPX:

- Extra triggers for **luminosity measurement**
- Large, powerful luminometer
- First ring in last disk:
    - lumi and background monitoring
    - independent readout and control



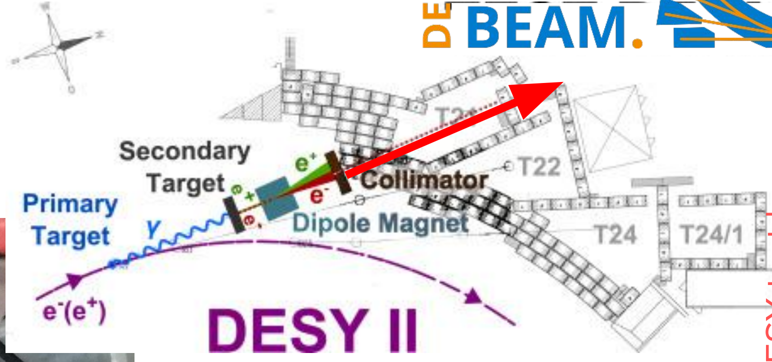
4 and 5 modules resp. on each barrel half: **no gap at η=0**





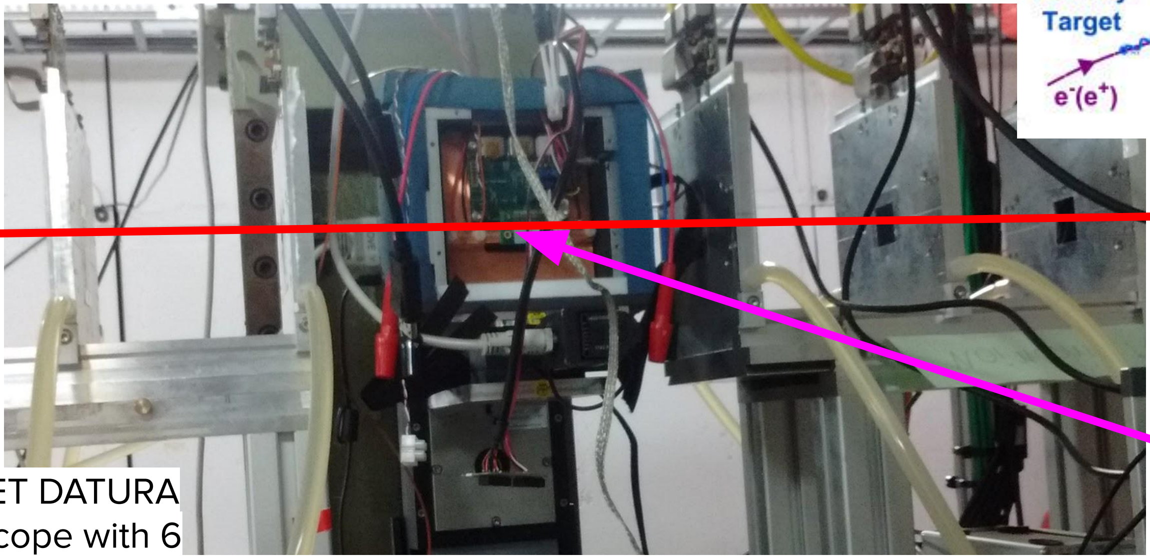
Sensor characterization at test beam

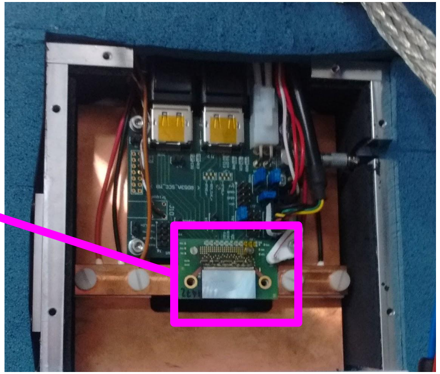
Tests of CMS phase 2 planar and 3D sensors on RD53A or ROC4SENS (R&D) chip



DESY test beam

1-6 GeV e^-e^+ up to 10kHz

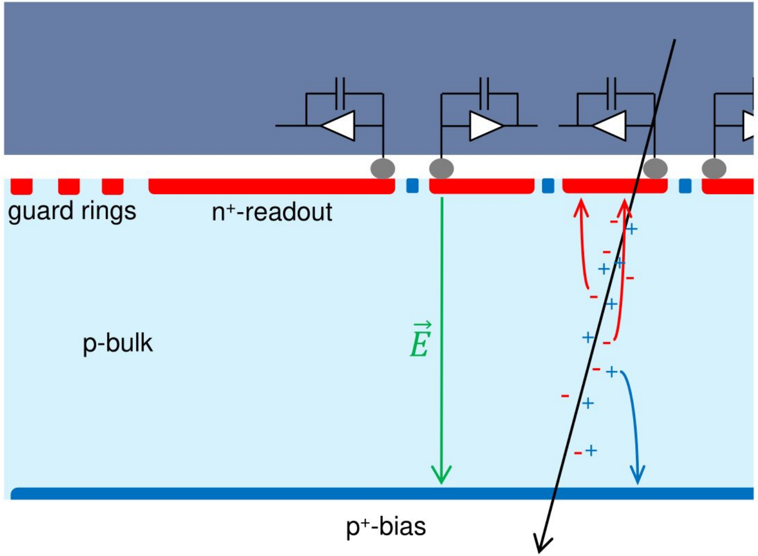




EUDET DATURA telescope with 6 MIMOSA26 (MAPS for ILC, 50 µm thick, 18.4 µm^2) planes with resolution of 5.7 µm

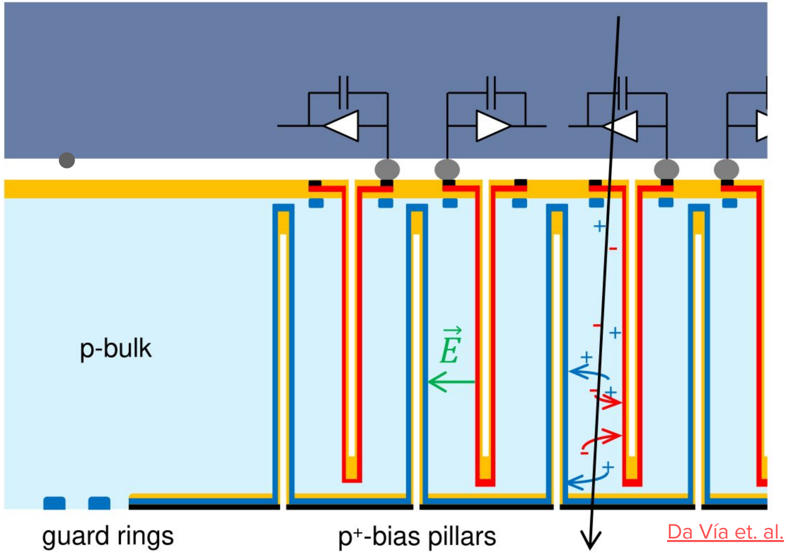
Planar sensors

- Used in present pixel detectors
- High production yield
- Large area sensors



3D sensors

- Collection and drift distance decoupled
- Lower chance of trapping
- Reduced depletion voltage: O(10) V
- Fast charge collection
- Option for innermost layer of CMS



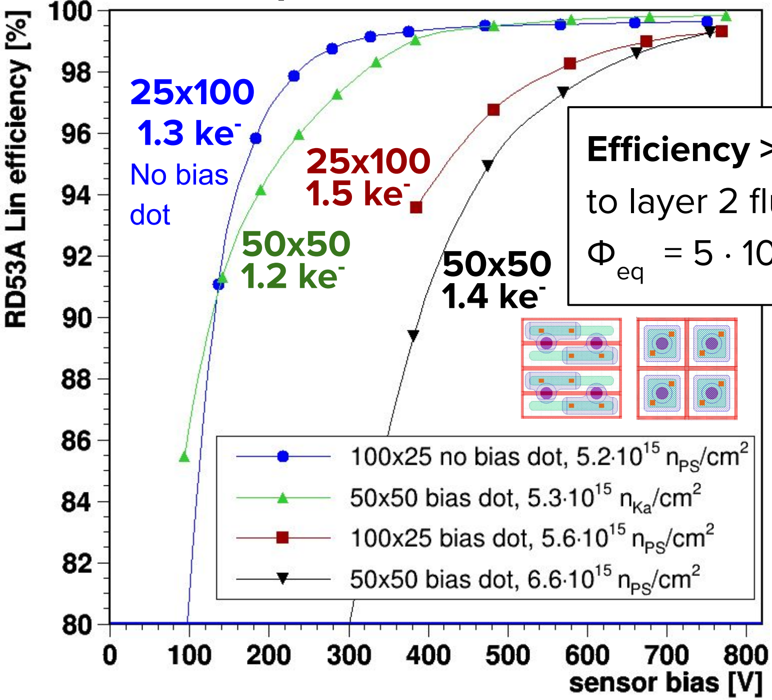
Da Vía et. al.

Planar sensors

150 μm n^+ in p

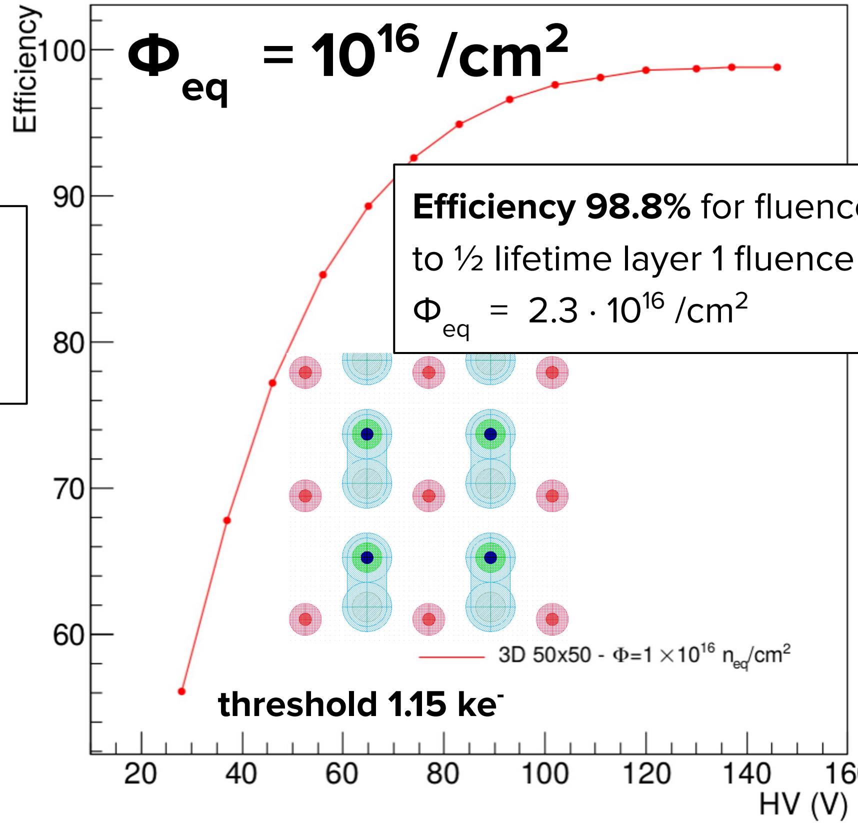
3D sensors

$\Phi_{eq} > 5 \cdot 10^{15}$ /cm^2



Efficiency > 99% up to layer 2 fluence of $\Phi_{eq} = 5 \cdot 10^{15}$ /cm^2

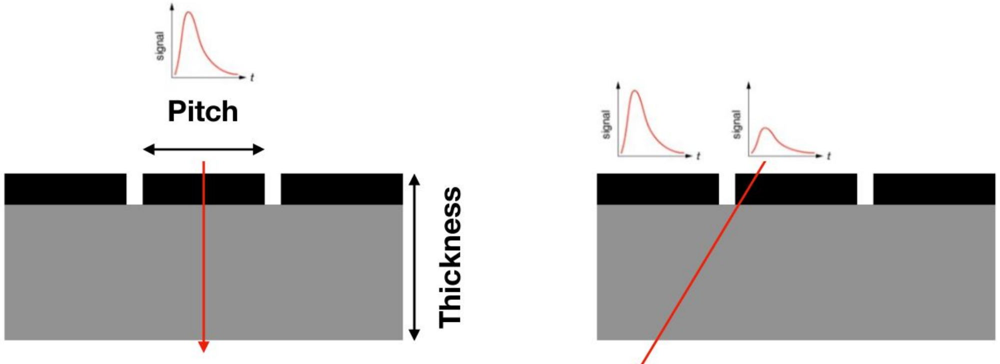
$\Phi_{eq} = 10^{16}$ /cm^2



Efficiency 98.8% for fluences up to ½ lifetime layer 1 fluence of $\Phi_{eq} = 2.3 \cdot 10^{16}$ /cm^2

Charge sharing improves resolution

For physics results the resolution obtained with new pixel module is important:

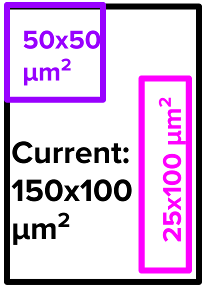


Position = center of the pixel
Resolution = pitch / √12 *
= 25 µm / √12 ~ 7.2 µm

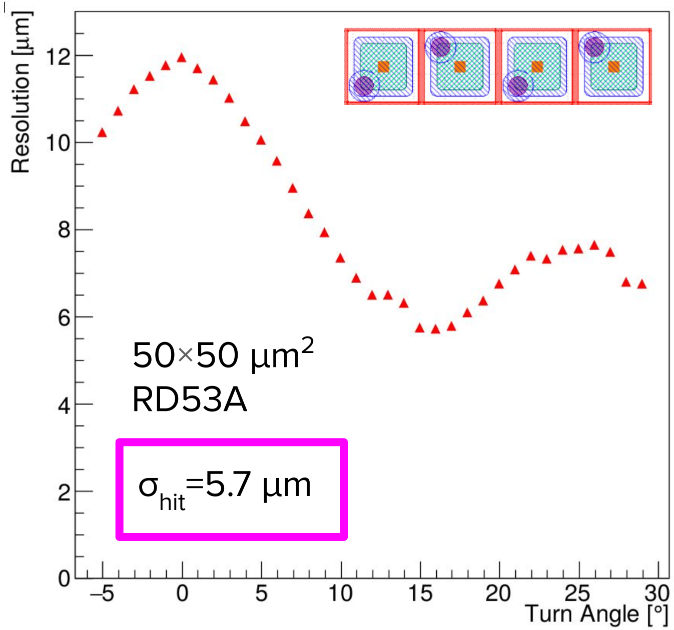
Position = weighted average
Resolution < pitch / √12

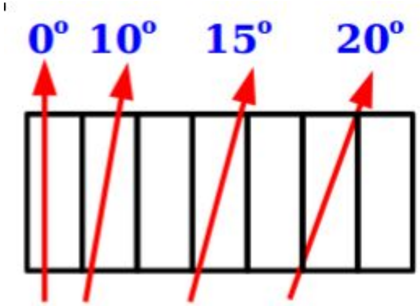
Resolution improves with angle: charge sharing gives a weighted average
➜ better resolution

Pixel cell dimensions and resolution

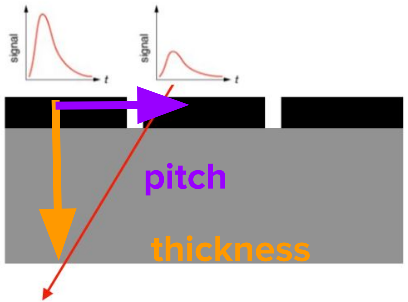


- 25×100 µm^2 or 50×50 µm^2: charge sharing different
- **Best resolution: cluster size of 2**





2 pixel charge sharing for 18°



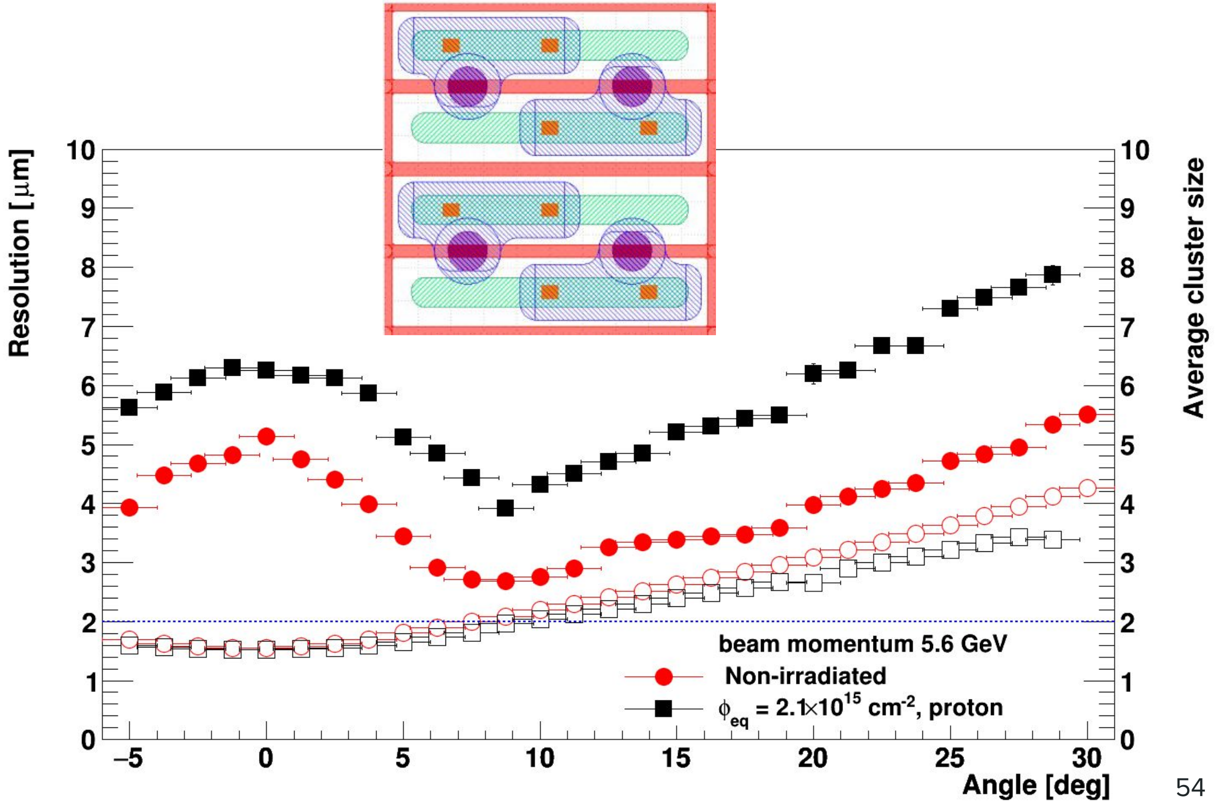
Position = weighted average
Resolution < pitch / √12

Optimal charge sharing at an angle atan(pitch/depth):

- **50×50 µm^2:** atan(50/150) = 18.4°
- **25×100 µm^2:** atan(25/150) = 9.5°
  - ➔ increase E-field with higher bias

Resolution for 25x100 μm^2 pixels

- Optimal charge sharing is for 9.5°
- Best hit resolution 2.68 µm before irradiation
- Best hit resolution 3.92 µm for proton-irradiated sensor at $\Phi_{eq} = 2{\cdot}10^{15}/cm^2$



The CMS pixel detector: ready for the future!

- The CMS pixel phase 1 detector has delivered excellent data throughout 2017 and 2018 despite the challenges
- Test setups and temperature mockup have proven very valuable
- The phase 1 pixel detector will get a new innermost layer
- R&D is ongoing to make the decision for the phase 2 sensor type and pixel size: first results very promising!

	Fluence (order of magnitude)	**Energy**	**Integrated lumi**
LHC	$\Phi_{eq} = 10^{15}/cm^2$	13-14 TeV	300/fb
HL-LHC	$\Phi_{eq} = 10^{16}/cm^2$	14 TeV	3000/fb
FCC	$\Phi_{eq} = 10^{18}/cm^2$	100 TeV	30000/fb

More to come!

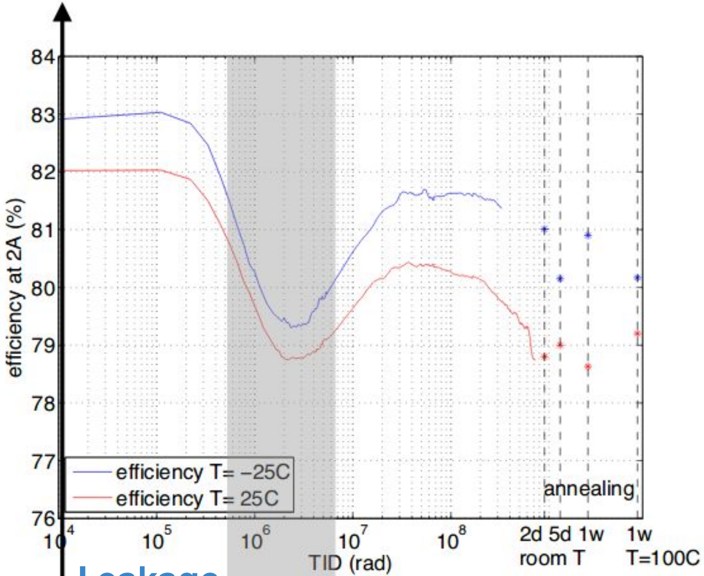
R&D continues for detectors beyond HL-LHC!

https://www.sciencemag.org/sites/default/files/styles/inline__699w__no_aspect/public/ca_0914NID_CMS_Detector_online.jpg?itok=EzPQHklv

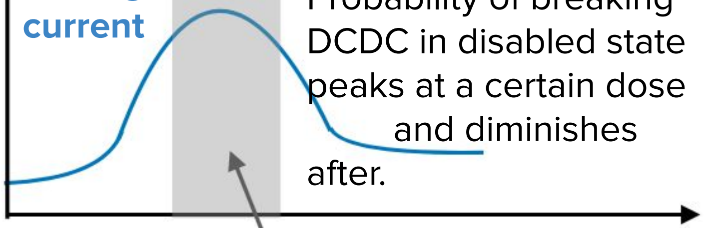
Additional material

DCDC converter story

DCDC malfunctioning

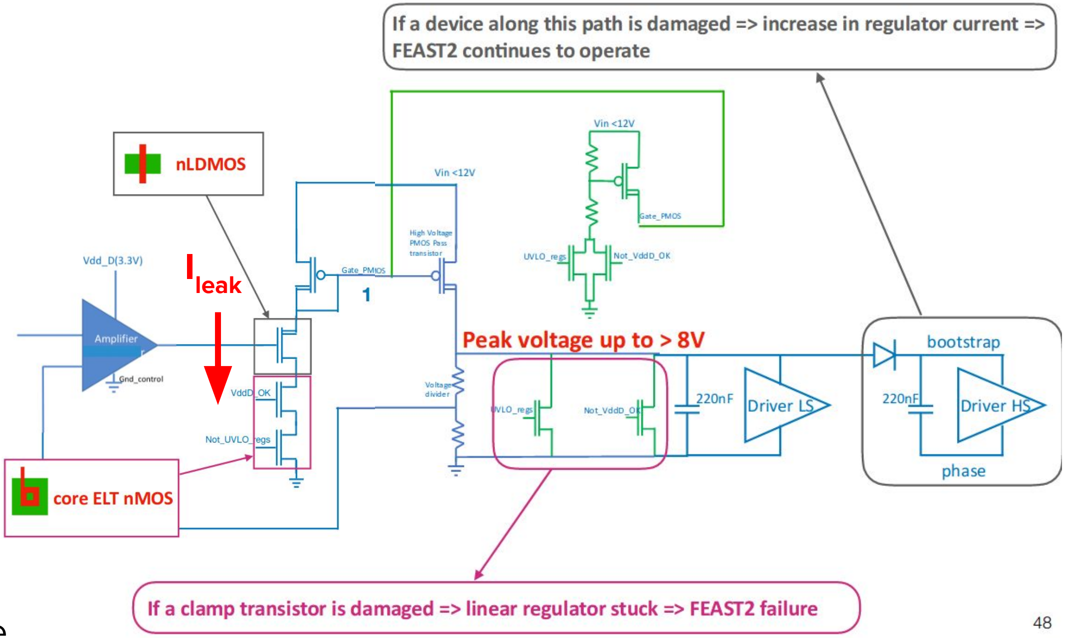


Leakage current



Probability of breaking DCDC in disabled state peaks at a certain dose and diminishes after.

Enclosed layout (ELT) vs linear transistors ➔ can 'cut' leakage current path by adding ELT in series

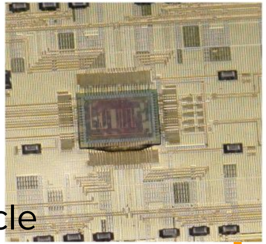


Capacitor charges up in disabled state and causes spikes beyond 3.3V

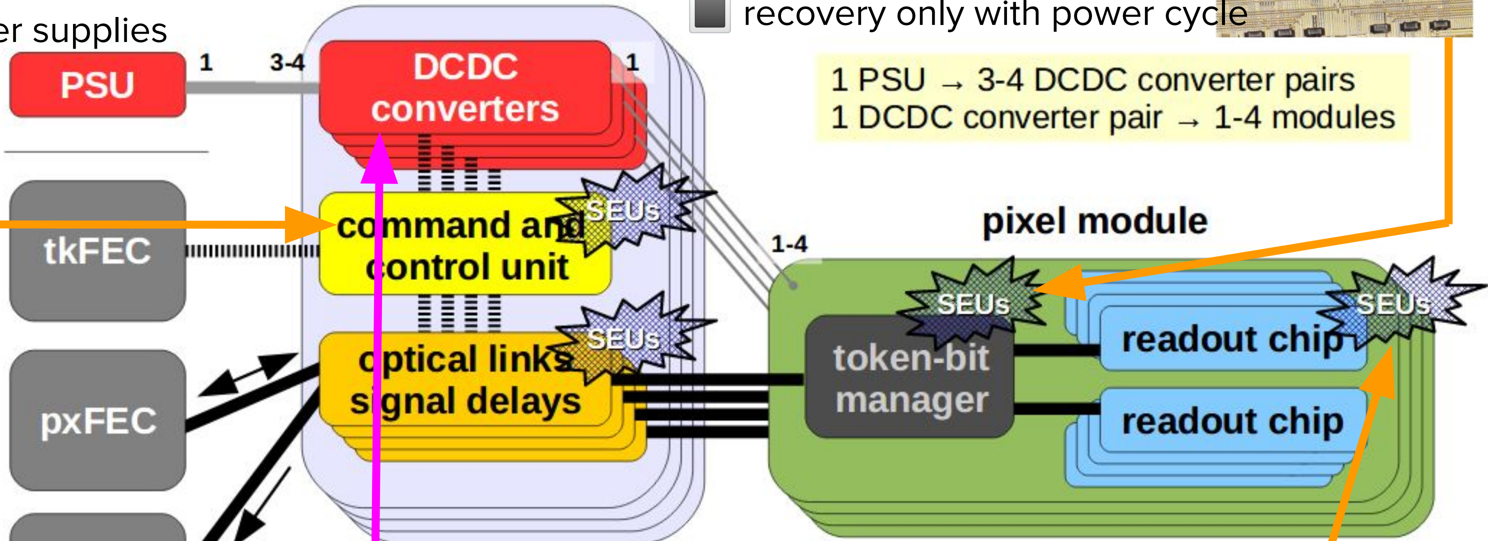
From Federico Faccio

Radiation effects in electronics

TBM
- $30/fb^{-1}$ in L1 transistor in TBM flipflop sets TBM to 'no readout' mode: "**stuck TBMs**"
- recovery only with power cycle



Power supplies



CCU misbehavior:
- $1/300pb^{-1}$ reset portcard ➔ reprogram
- 1/month reset DCDCs

From Klaas Padeken

Front end controllers/drivers

From Benedikt Vormwald

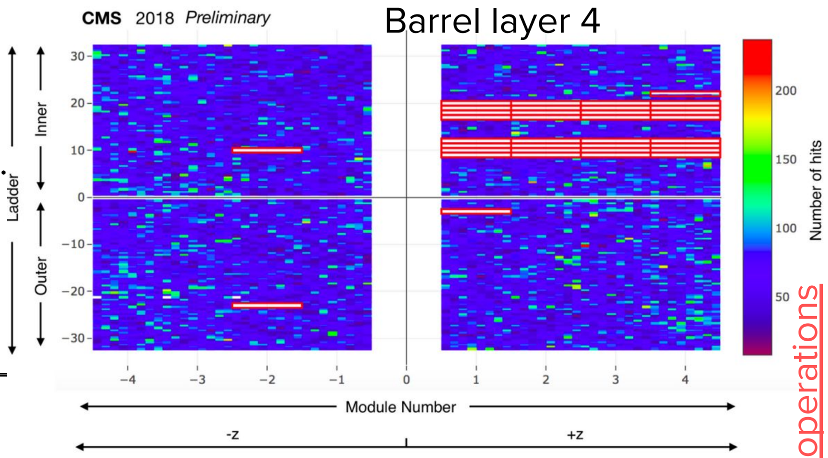
Irradiated DCDCs stop functioning in disabled state (not an SEU)
- 63/1216 at end of 2017 stopped functioning
- 333/1216 in 2017 found to have high current

ROC: solved by reprogramming

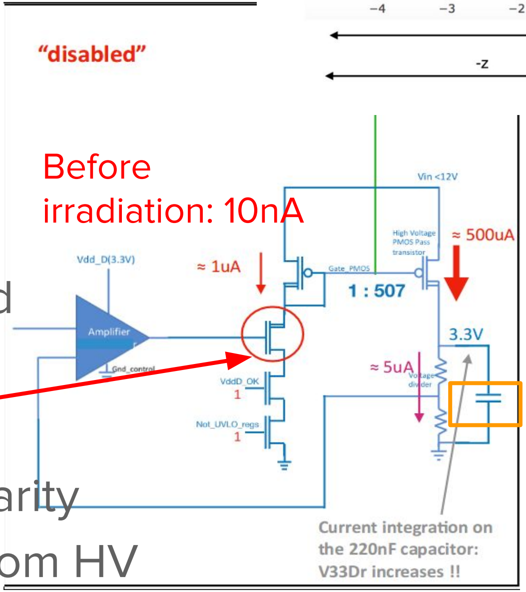
Compensation for chip radiation effects in offline reconstruction

DCDCs

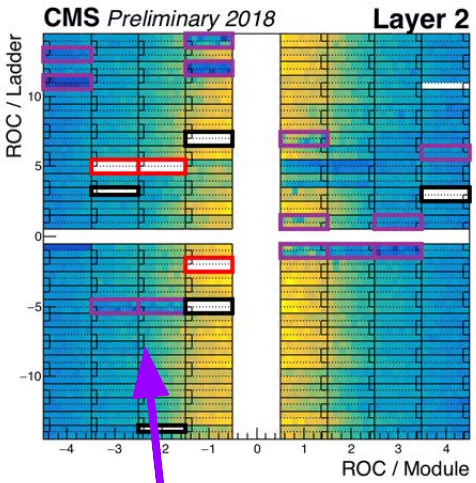
Disconnected DCDCs: for safety switched off entire power supply (LV and HV).
No DCDC broke in 2018!



- SEU in transistor in TBM flipflop sets TBM to ‘no readout’ mode ➔ powercycle TBM
- Powercycled with DCDCs (lowest amount of modules) in 2017
- Increased leakage current in DCDCs after irradiation causes charging up of capacitor in disabled state ← design mistake in layout around one transistor:
- High and low voltage group granularity not the same: damaged modules from HV on where DCDCs were broken ➔ LV off.



From Federico Faccio

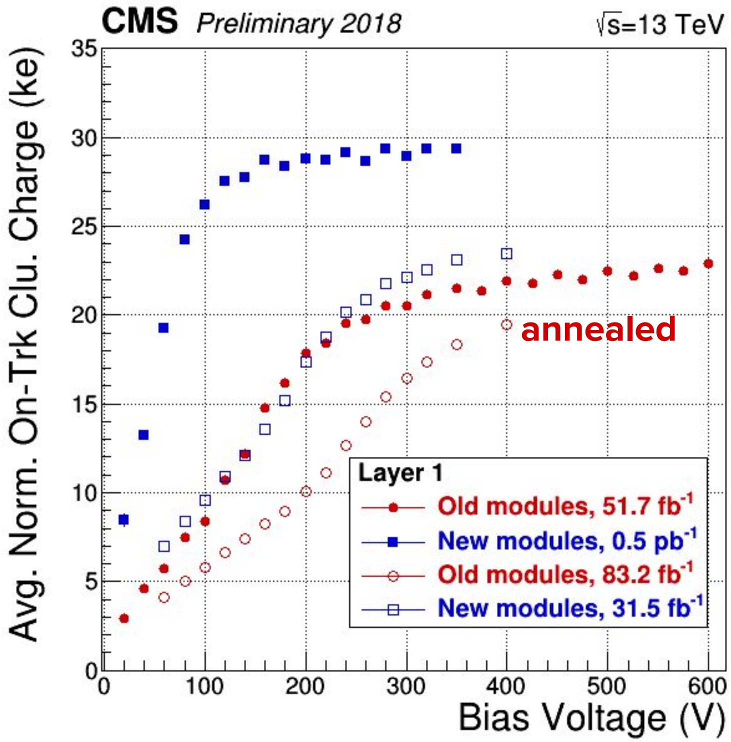


CMS pixel operations

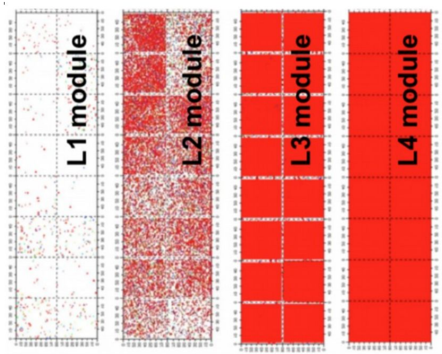
CMS pixel offline

Damaged modules behind failed DCDCs in 2017

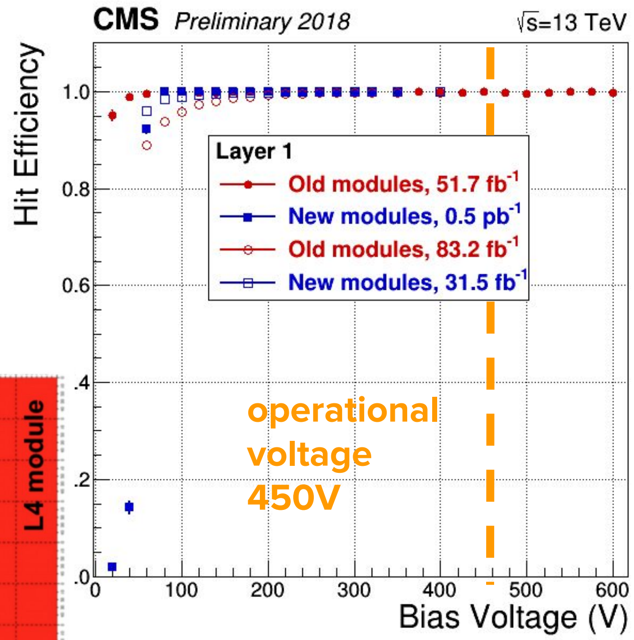
Radiation effects: on-track cluster charge



In long shutdown 2017-2018: replaced 6 of 8 layer 1 modules damaged by high voltage leakage current



No impact on hit efficiency!

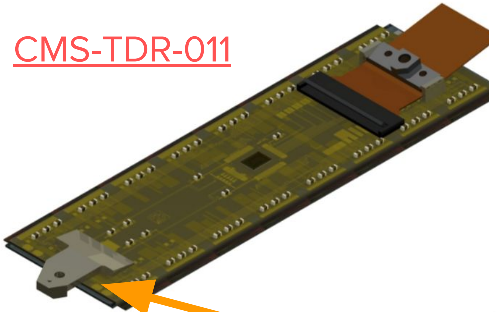


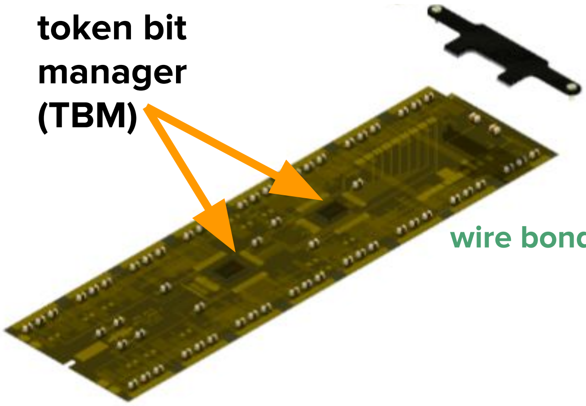
[CMS pixel offline]

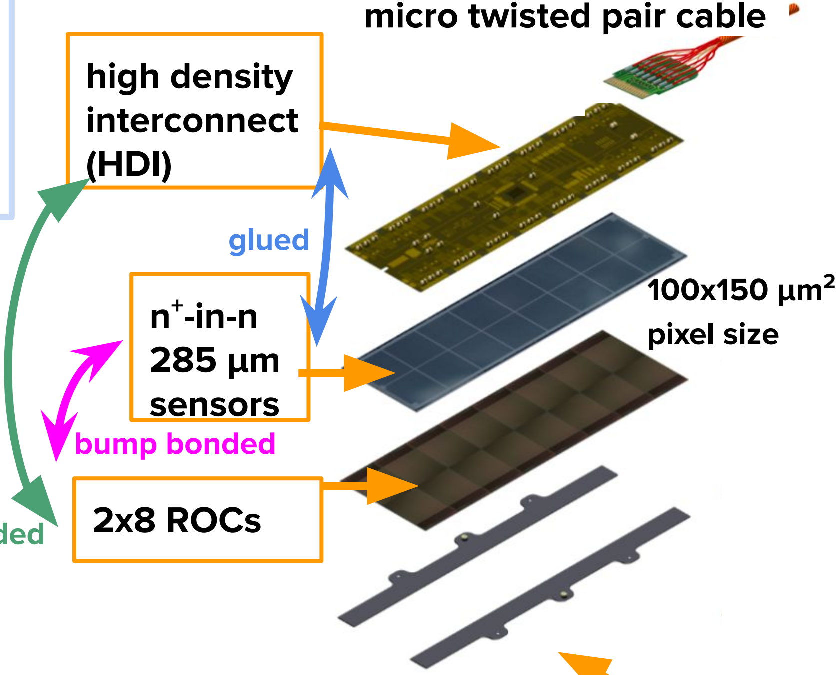
Module design

Readout chips (ROCs):
80x52pixels, 250nm CMOS ASIC, pulse height **digital** readout

CMS-TDR-011







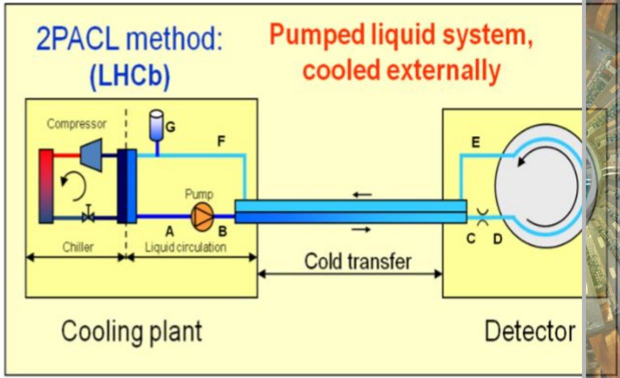
base strips for fixation

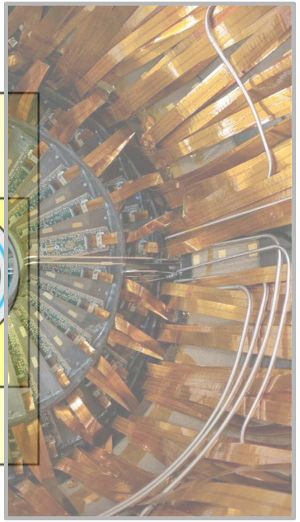
Endcap disks 1-3
- 672 modules
- 40-100 MHz/cm^2
- PSI46dig: column drain
- 2 TBM readout channels
- Functions up to 150 Mrad

Barrel layer 1
- 96 modules
- 580 MHz/cm^2
- PROC600: dynamic cluster column drain
- 8 TBM readout channels
- Functions up to 480 Mrad

Barrel layer 2-4
- 1088 modules
- 40-100 MHz/cm^2
- PSI46dig: column drain
- 2 TBM readout channels (L3,L4) / 4 TBM readout channels (L2)
- Functions up to 150 Mrad

CO_2 cooling

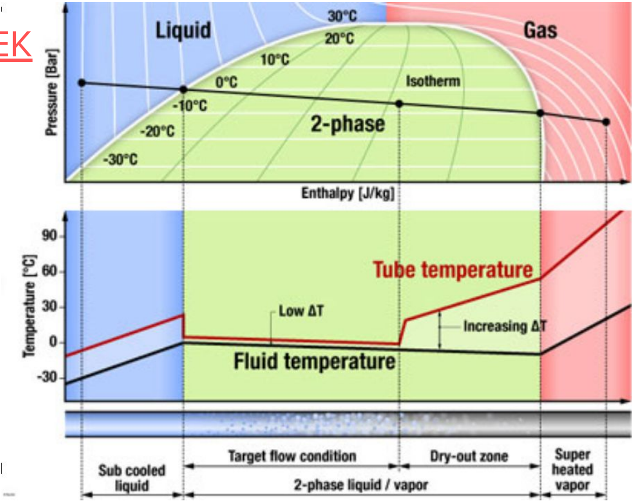


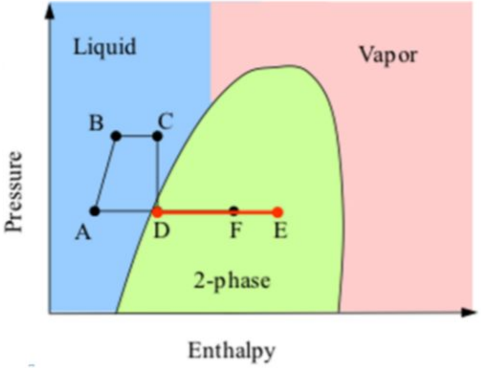


[CMS-TDR-011]

Temperature at end of cooling loop is higher than at start!

[From KEK]





A→B: CO_2 pressure is increased for transfer to the experiment
B→C: temperature increases from heat exchange with returning CO_2
C→D: pressure inside the detector is reduced to reach onset of evaporation
D→E: heat from the detector is absorbed
E→F: CO_2 liquid/vapor mixture condensates on incoming colder CO_2 pipe
F→G: CO_2 is cooled with main chiller
G: temperature in detector is regulated with pressure in accumulator:
D-G low impedance system with ~constant pressure back to D

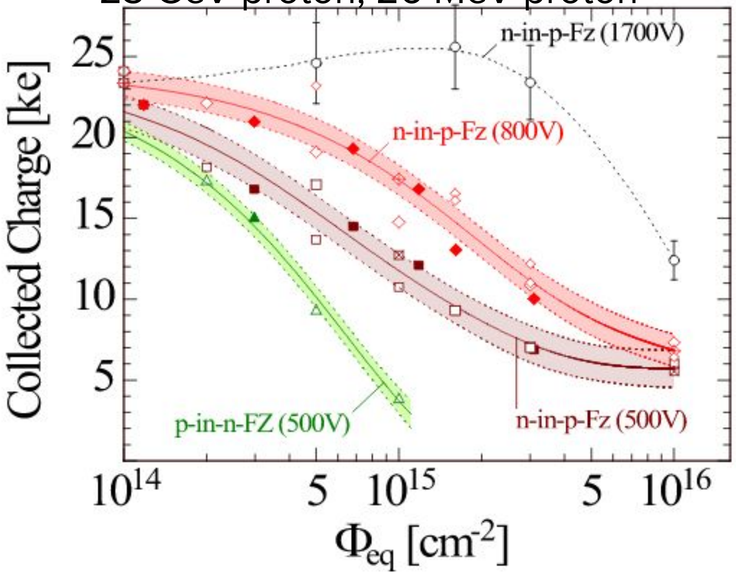
Radiation damage in silicon

Effects from radiation damage

Effects from radiation damage can be challenging in operation of detectors as well as for physics:

- Increasing leakage currents
- Charge accumulation in silicon oxide layers
- Single event upsets, in readout only ➔ see electronics session
- Decreasing signal-to-noise ratios
- Changing depletion voltages
- Radiation induced activation of components

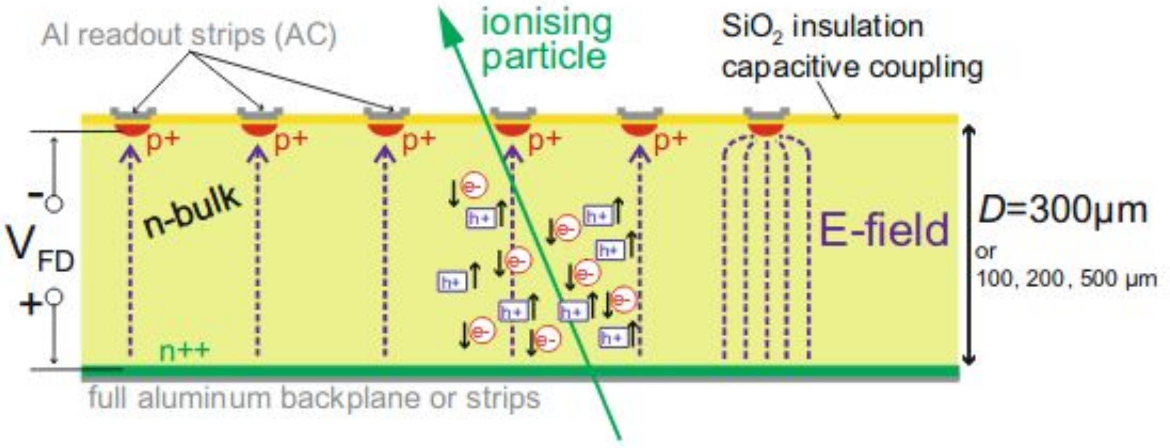
23 GeV proton, 26 MeV proton



From Michael Moll

Ideal signal detection with silicon sensors

- A minimum ionizing particle (MIP) traveling through a fully depleted region (V_{FD}) creates electron hole pairs
- The charges drift to opposite directions under the electric field
- Within nanoseconds, charges are collected at the readout

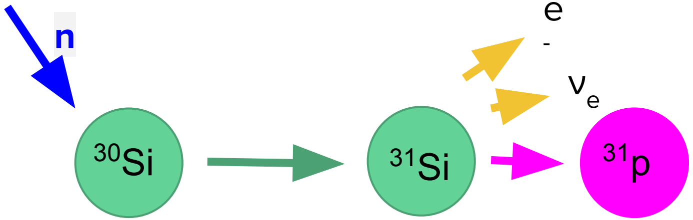


p-in-n silicon sensor

From Frank Hartmann

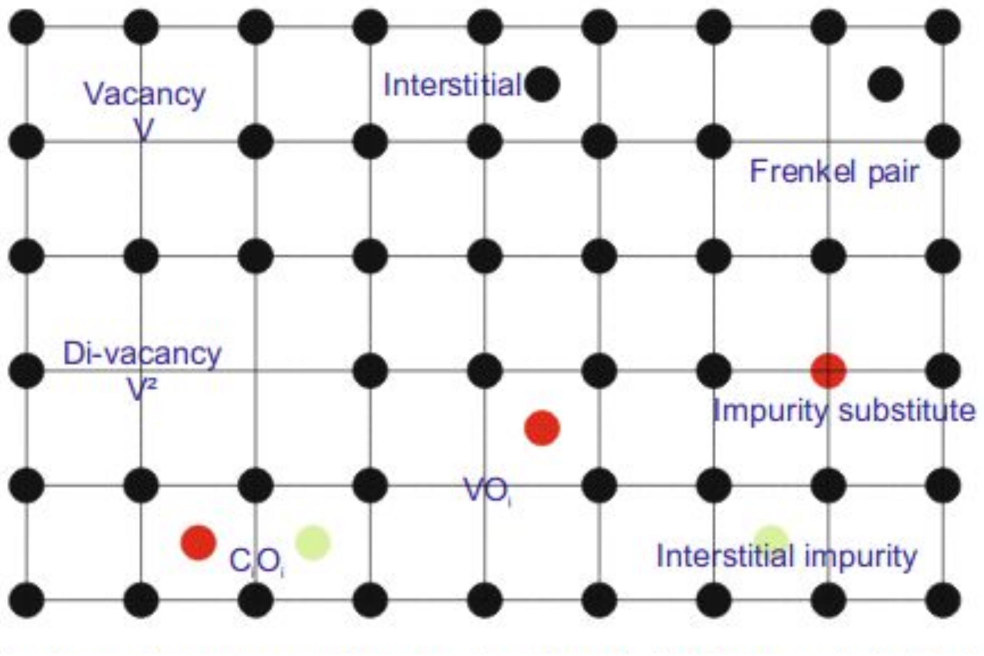
Microsocopic defects

- **Bulk damage**: non-ionizing energy loss (NIEL), e.g.:



  - Frenkel pair: vacancy + interstitial

- **Surface damage**, or ionizing energy loss: not considered for silicon but important in silicon oxide



Modeling radiation damage: the depletion voltage Hamburg model

Assumptions:

$$V_{\mathrm{dep.}} = |N_{\mathrm{eff}}| \cdot \frac{ed^2}{2\epsilon\epsilon_0}$$

- Little trapping
- No double junction
- 1 MeV neutron equivalence

$$\Delta N_{eff}(t) = N_{\text{beneficial a.}}(t) + N_{\text{stable damage}} + N_{\text{reverse a.}}(t)$$

Input:

$$dN_A^{\mathtt{stable}}/dt \propto \Phi(t)$$

- Fluence
- Temperature over time (in order to include annealing effects)
- Sensor thickness d, sensor material

Output: effective space charge N_{eff} ➔ depletion voltage V_{dep}

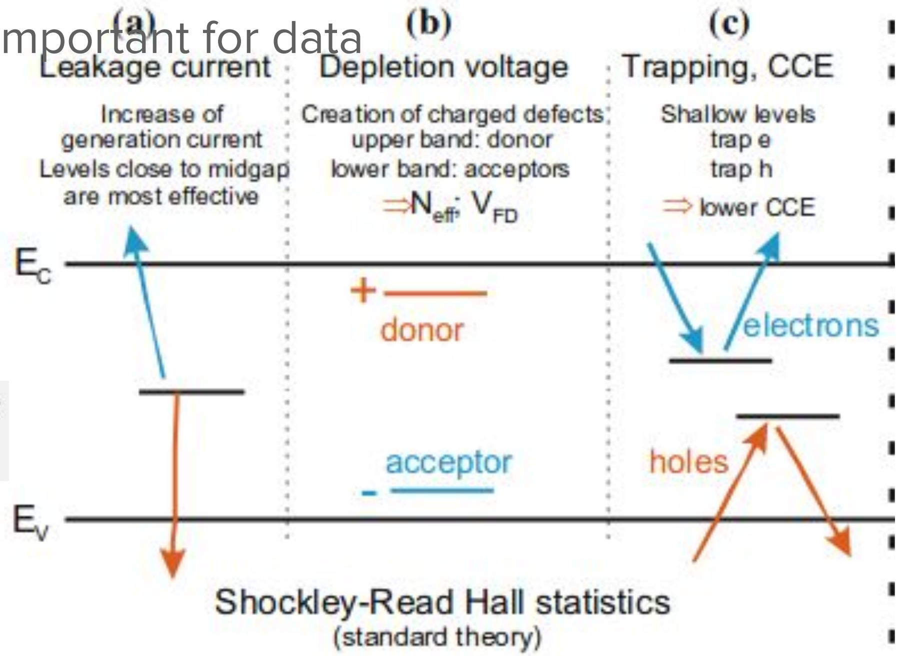
Modeling radiation damage

Modeling of radiation damage is very important for data quality

- Hamburg model can serve to model leakage currents and depletion voltages

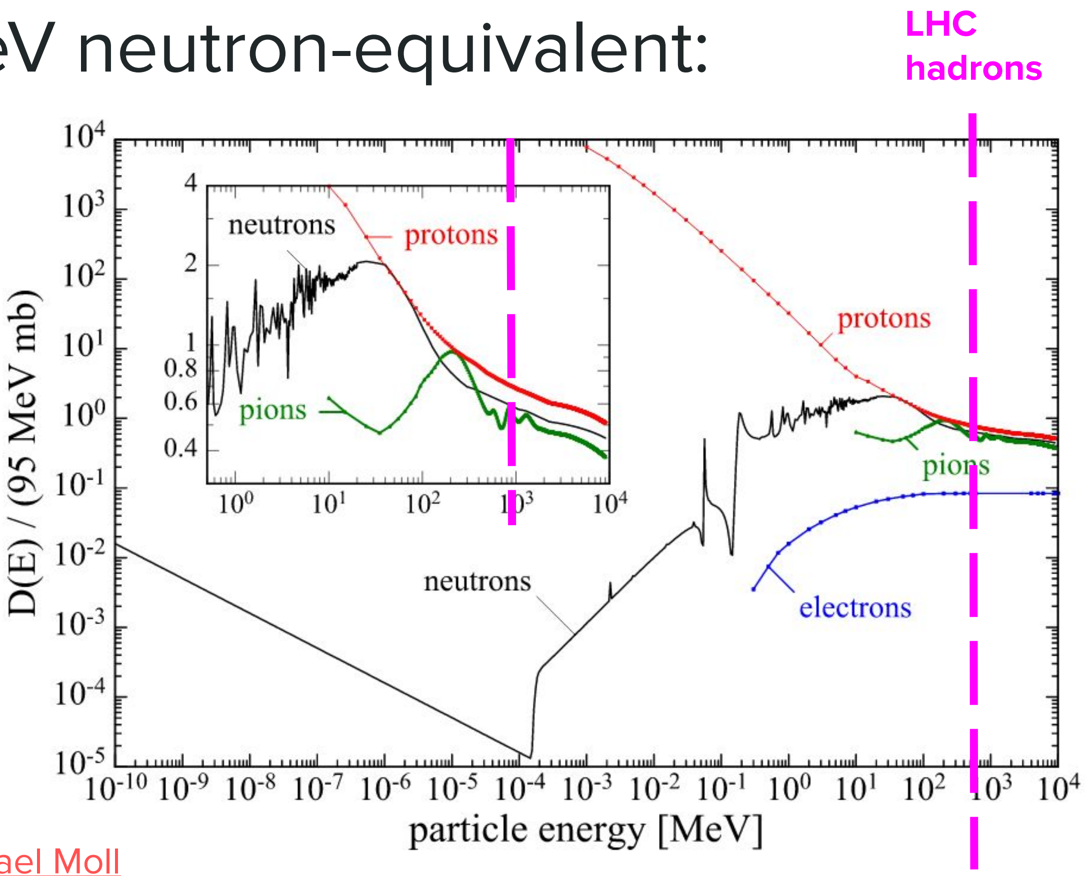
$$\Delta I_{leak}(t,T;\Phi_{eq}) = \alpha(t,T)\,\Phi_{eq}(r,z)\,V$$

- To model **signal**: need to include defect parameters from trapping in Poisson and transport equations like in technology computer-aided design (TCAD).



From Michael Moll

1 MeV neutron-equivalent:

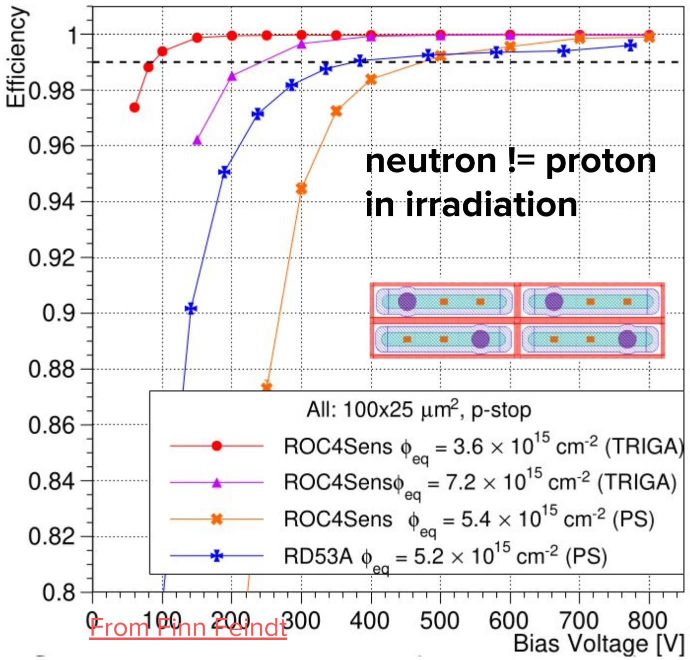


Michael Moll

D(E): displacement damage function in

- 1 MeV neutron-equivalent, or
- NIEL cross section MeV mb
- Reference: 1 MeV neutron-equivalent at 95MeV mb

Performance of CMS phase 2 sensor candidates



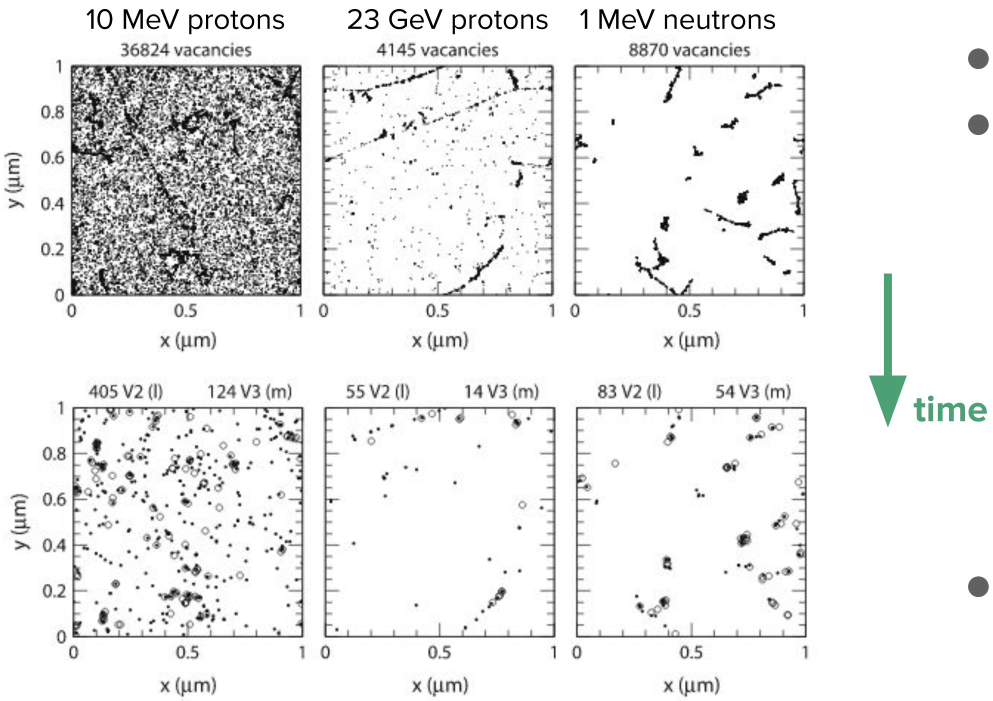
From Finn Feindt

- For higher irradiation, more bias voltage is needed to reach the same efficiency
- Need 400V more bias for proton irradiated than for neutron irradiated sensors to achieve an efficiency of 99%

Φ_{eq} **neutron equivalent (?)** number of particles per unit area

Radiation damage

Annealing: recombination



Effects from radiation damage:

- Leakage current increase
- Space charge distribution: bulk doping in undamaged sensors but contribution from defects after irradiation ➔ change in operational voltage
  Material dependent (oxygen-content) and particle-type-dependent
- Trapping ➔ decreased charge collection efficiency

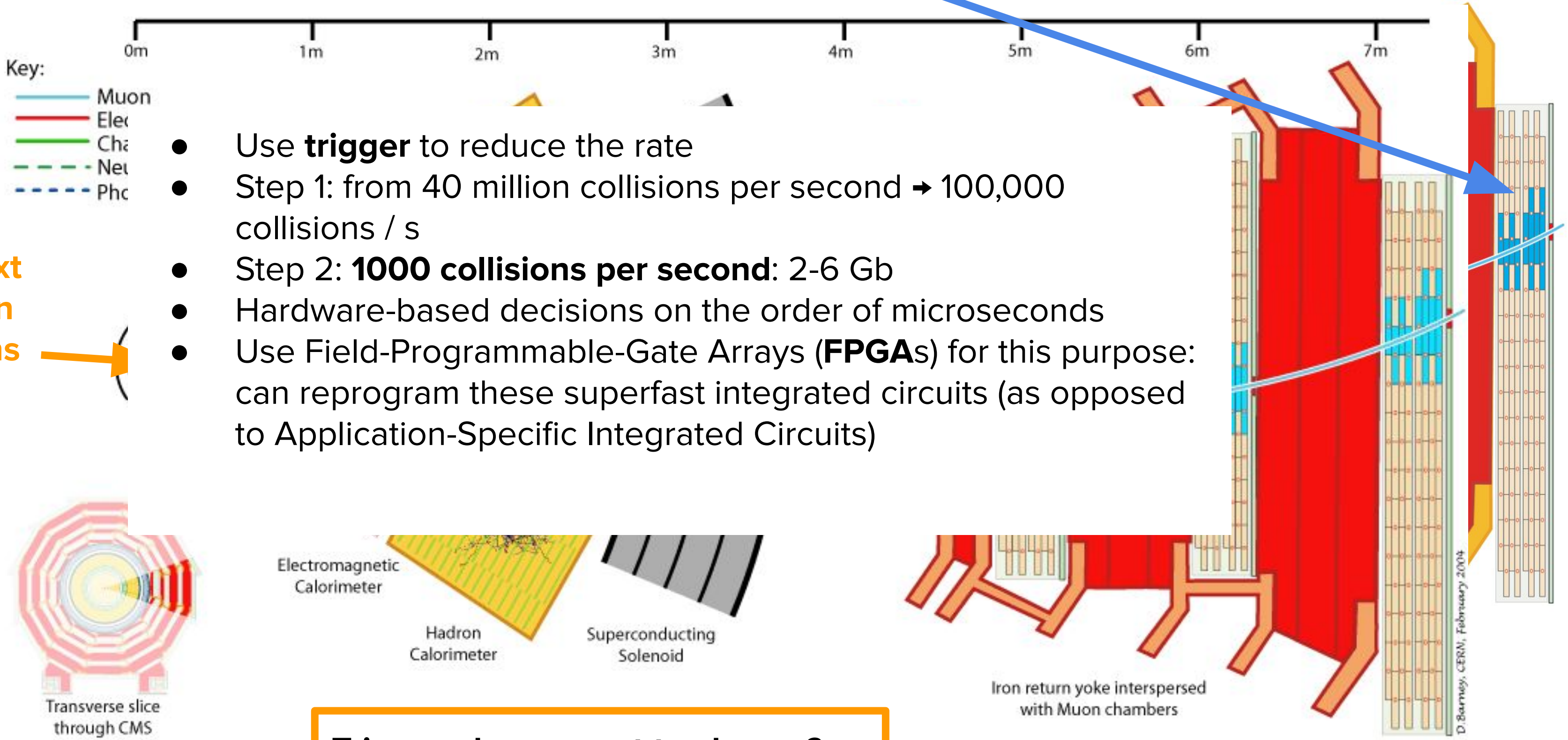
From Michael Moll

https://rd.springer.com/book/10.1007/978-3-319-64436-3

How to detect a particle?

Note when the muon arrives here

http://inspirehep.net/record/826852/files/EPS_CMS_Slice.png



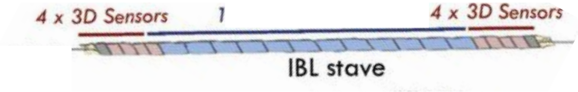
- Use **trigger** to reduce the rate
- Step 1: from 40 million collisions per second ➔ 100,000 collisions / s
- Step 2: **1000 collisions per second**: 2-6 Gb
- Hardware-based decisions on the order of microseconds
- Use Field-Programmable-Gate Arrays (**FPGA**s) for this purpose: can reprogram these superfast integrated circuits (as opposed to Application-Specific Integrated Circuits)

The next collision happens here:

Trigger: do *we* want to choose?

CMS and ATLAS pixel detectors in LS2

Now: 118 /fb Run 3 **2023 (2024)**: 220 (320) /fb
Fluences could triple!



2.8 Mrad / Φ_{eq}=$5\cdot10^{13}$/cm^2 L4: r=160 mm

5.2 Mrad / Φ_{eq}=$9\cdot10^{13}$/cm^2 L3: r=109 mm

8.5 Mrad / Φ_{eq}=$1.8\cdot10^{14}$/cm^2 L2: r=66 mm

40.1 Mrad / Φ_{eq}=$7.9\cdot10^{14}$/cm^2 L1: r=29 mm

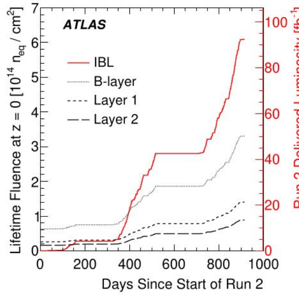
beam pipe: r=22.5mm

Layer-2: r=122.5 mm Φ_{eq}=~$6\cdot10^{13}$/cm^2

Layer-1: r=88.5 mm Φ_{eq}=~$1.4\cdot10^{14}$/cm^2

B-Layer: r=50.5 mm Φ_{eq}=~$3\cdot10^{14}$/cm^2

IBL: r=33.5 mm Φ_{eq}=~$6\cdot10^{14}$/cm^2



50.0 cm

From ATLAS-IDET-2017-10

Fluences as of today, from FLUKA 3.23.1.0

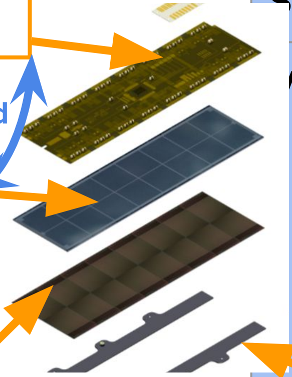
Phase 1 → 2

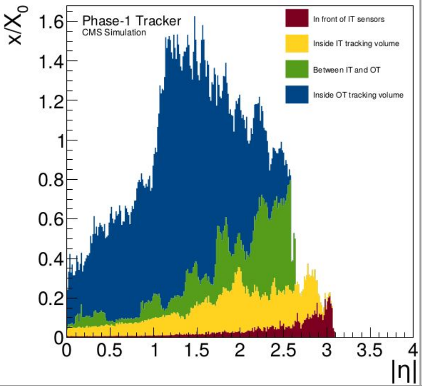
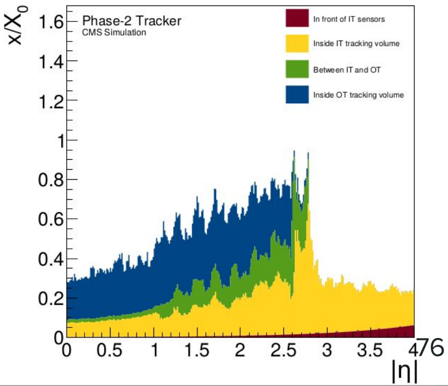
CMS pixel layout

CMS-TDR-011

CMS-TDR-014

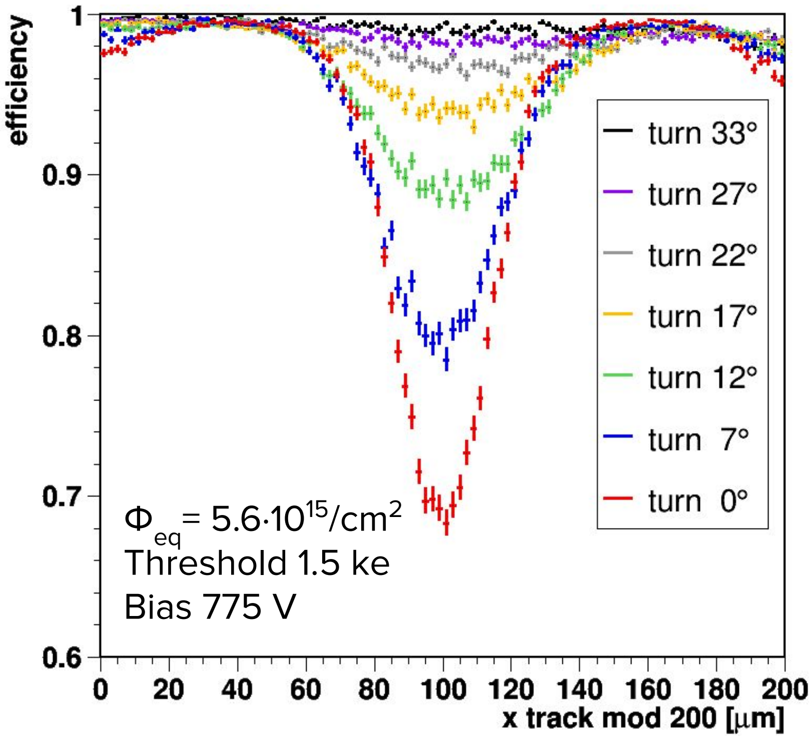
Module stacking for both phase 1 and phase 2:

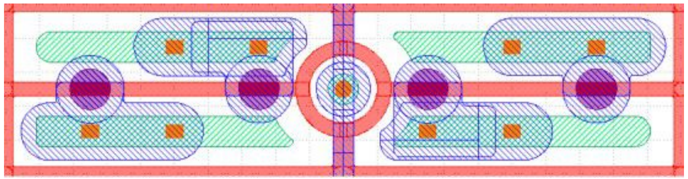


	phase 1 < 2024	phase 2 >= 2024
Disks, layers, reach	4 layers, 3 disks to $\eta=2.5$	4 layers, 12 disks to $\eta=3.8$
Number of pixels	$124 \cdot 10^6$	$1949 \cdot 10^6$
Pixel size	$100\times150\ \mu m^2$	$100\times25\ \mu m^2$, $50\times50\ \mu m^2$
Active silicon area	$1.85\ m^2$	$4.9\ m^2$
Readout chips	PSI46dig/PROC600 250 nm	RD53B = CROC 65 nm
Number of ROCs	$1856 \cdot 16$ ROCs	$1156 \cdot 2 + 2736 \cdot 4$ ROCs
Sensor type	n^+-n planar 285 μm	n^+-p planar/3D 100-150 μm
Material budget		

With or without bias dot

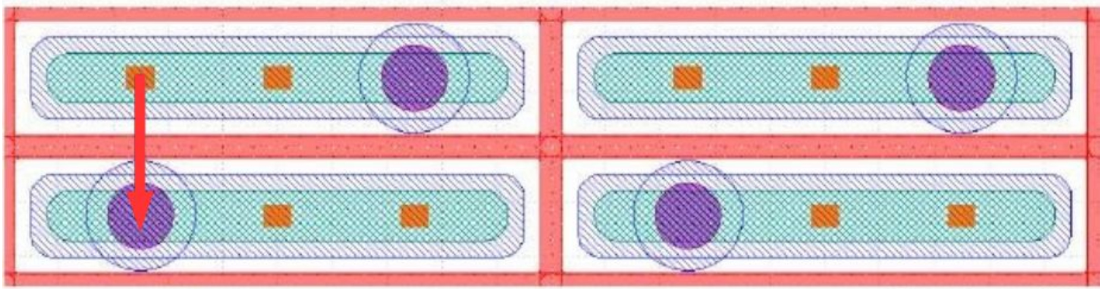
- Efficiency 97% at vertical incidence
- Efficiency 99.7% at 34°
- Efficiency loss at bias dot
- disappears only at large angles (27°)
- Almost vertical incidence in forward pixel detector (TFPX)
- Without bias dot no test of sensors before bump bonding
- Possible to use small test sensors with bias dot for wafer acceptance



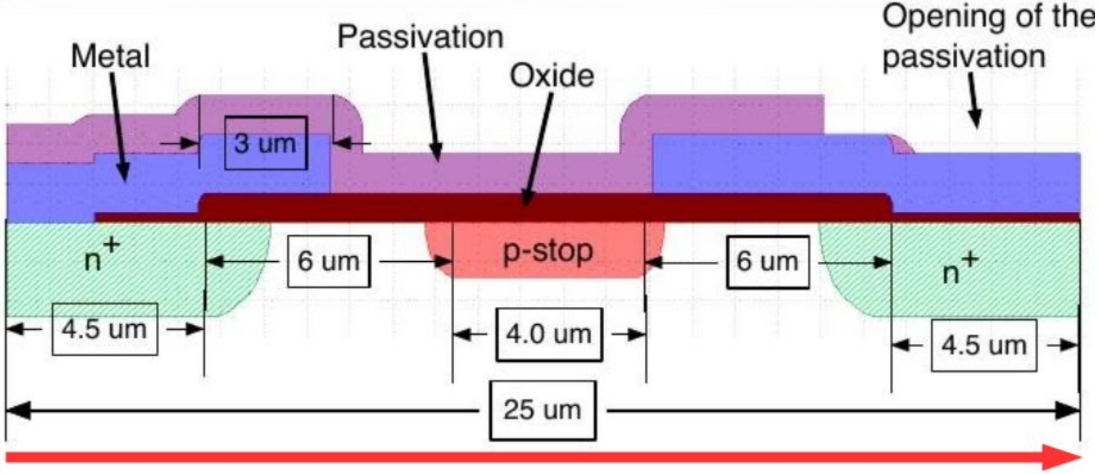


Sensor design

Top view of 25x100 μm^2 n^+p (n^+ ➔ collecting electrons) sensor:



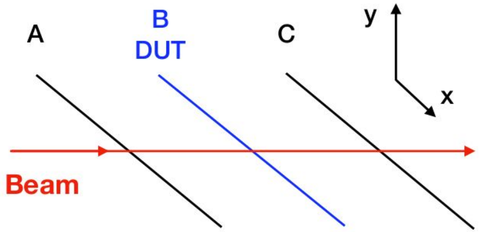
Cut image along red arrow:

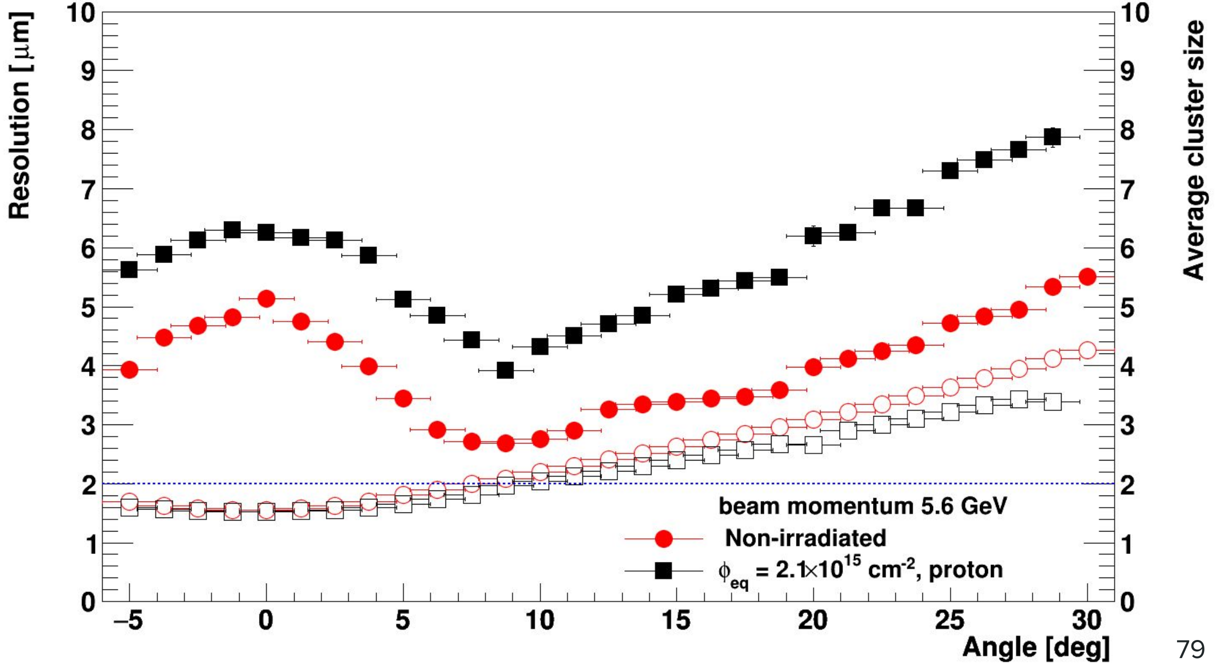


Resolution vs incidence angle

- Optimal charge sharing is for 9.5°
- Best hit resolution 2.68 μm before irradiation
- Best hit resolution 3.92 μm for proton-irradiated sensor at $\Phi_{eq} = 2{\cdot}10^{15}/cm^2$

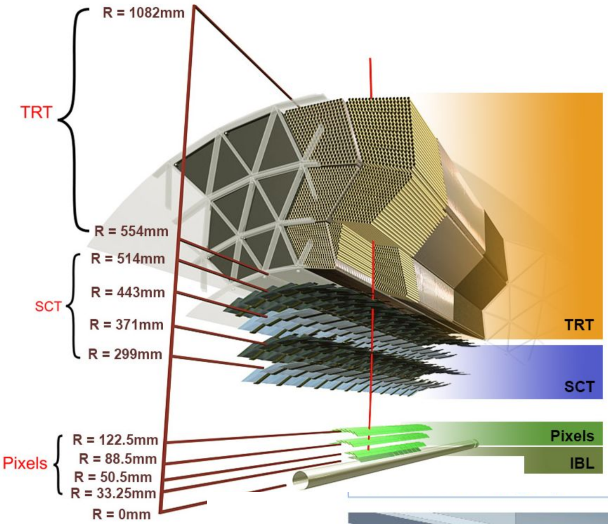
Resolution obtained using triplet residuals



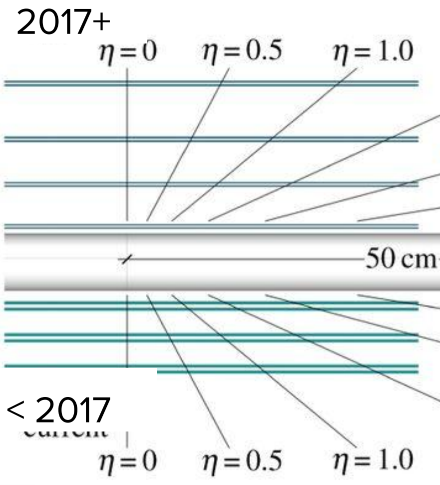


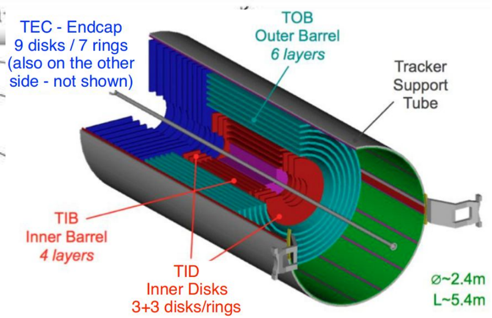
Future LHC detectors

LHC Run 2: inner detector systems December 2018

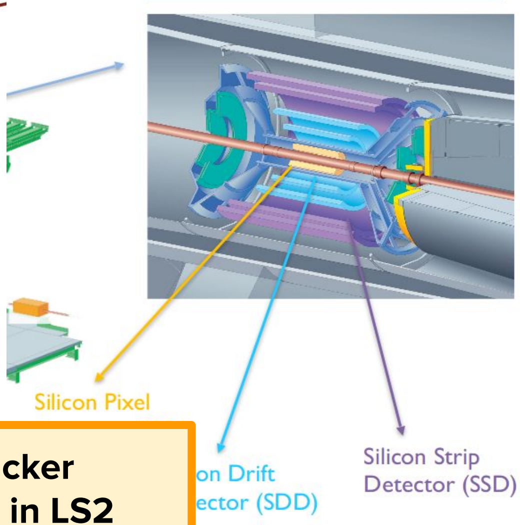


ATLAS: 3.325 cm from beam line



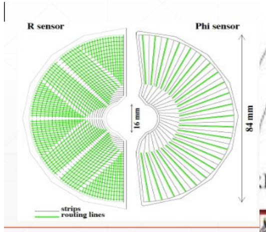


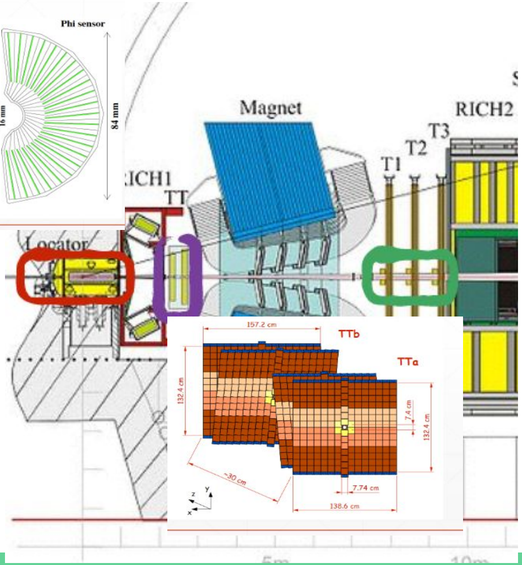
CMS: 2.9 cm from beam line

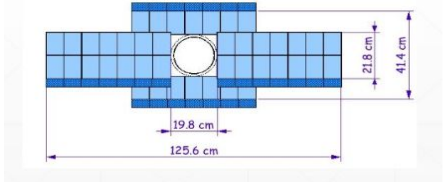


ALICE: 3.3 cm from beam line

Inner tracker upgrade in LS2

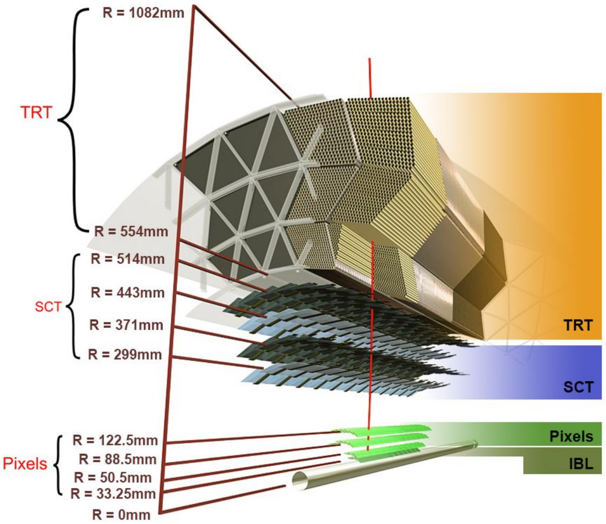






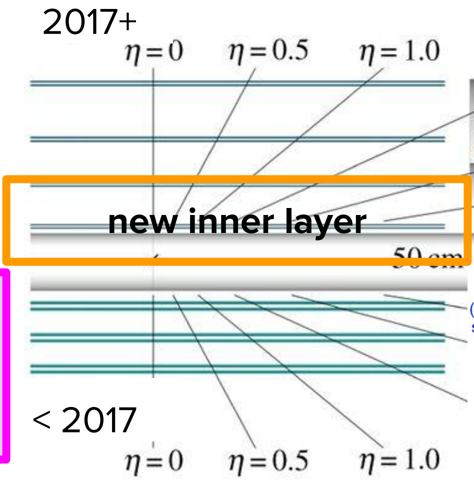
LHCb: 0.7 cm from beam line

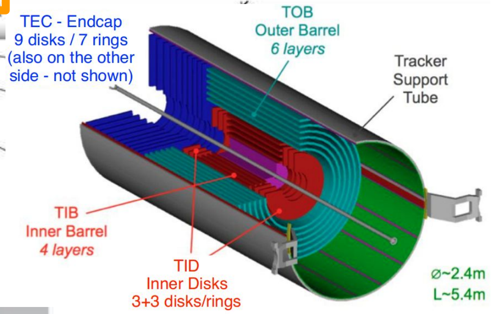
Velo upgrade in LS2



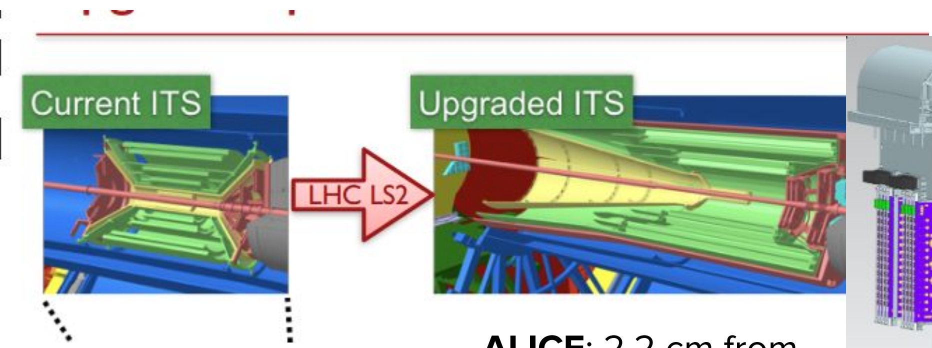
ATLAS: 3.325cm from beam line

LHC Run 2: inner detector systems early 2021



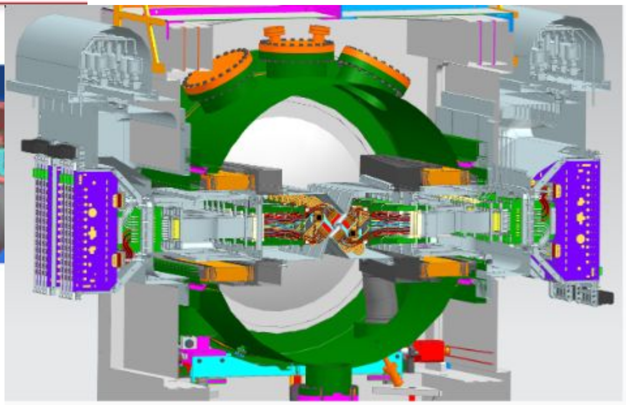


CMS: 2.9 cm from beam line



Inner tracker upgrade in LS2

ALICE: 2.2 cm from beam line, monolithic active pixel sensors 33 µm x 33 µm



LHCb: 0.51 cm from beam line, pixel sensors 55 µm x 55 µm in VELO

VELO and trackers upgrade in LS2


KG7400