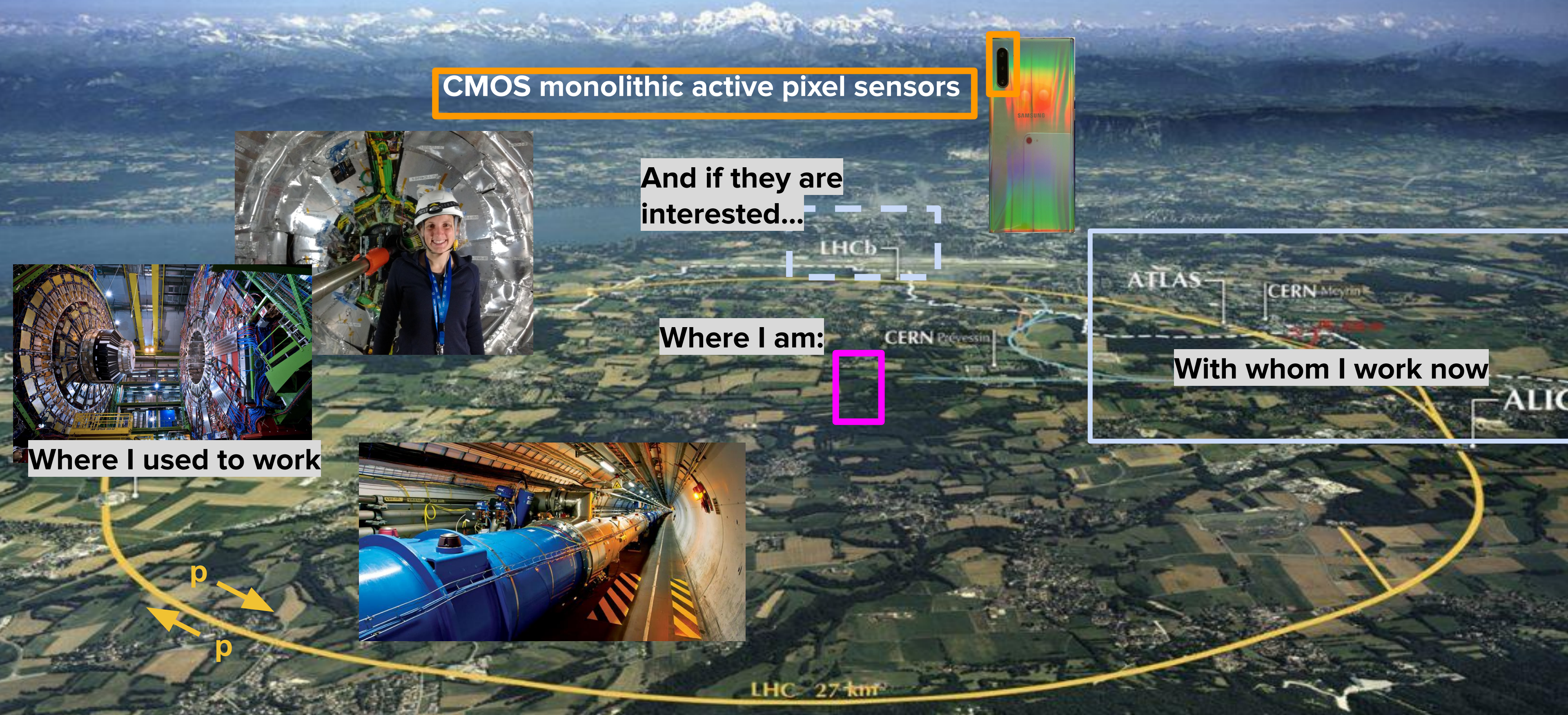
Pixel detectors and fast timing with MAPS

Jory Sonneveld

Jory Sonneveld -- Nikhef detector R&D



jory.sonneveld@nikhef.nl

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

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

https://...15/05/cern-lhc-aerial.jpg

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

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

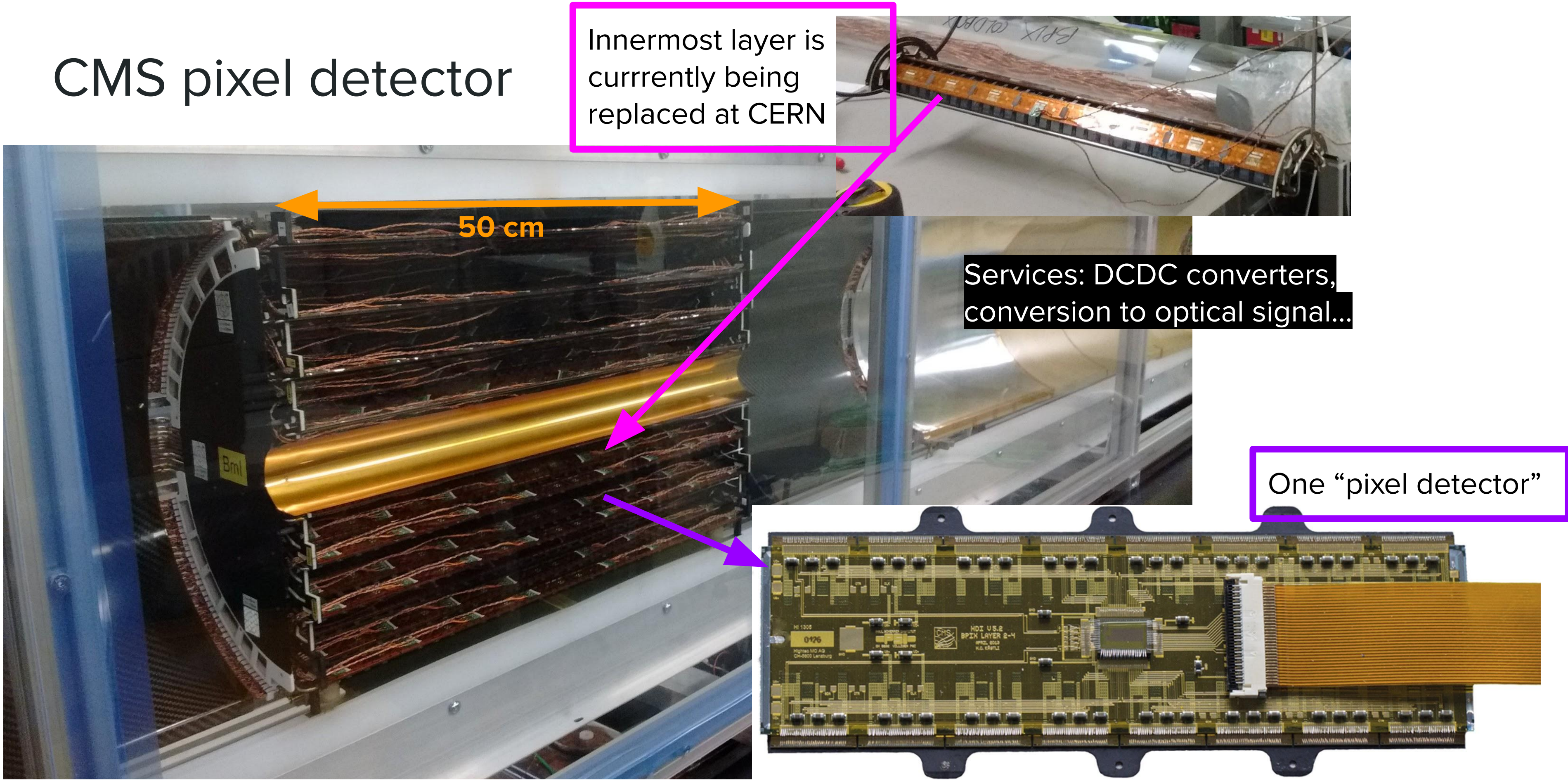
CMS pixel detector operations

I worked in pixel operations to ensure this subdetector worked without problems with smooth data taking for good physics results

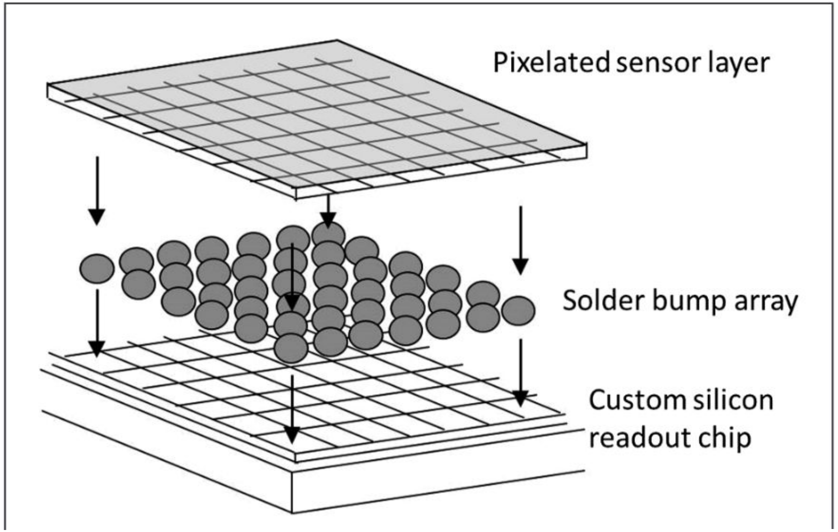
I did my master (at Nikhef) and PhD (in Aachen) in theoretical particle physics.

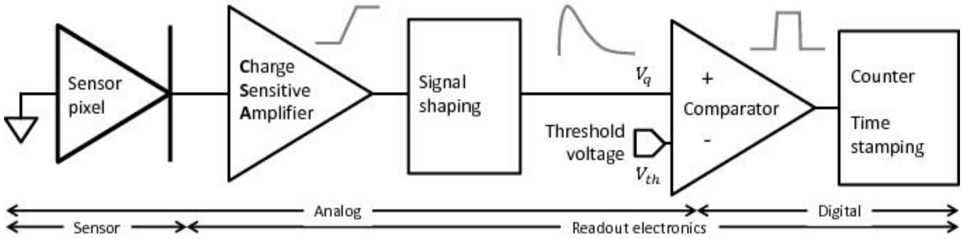
https://www.sciencemag.org/sites/default/files/styles/inline__699w__no_aspect/public/ca_0914NID_CMS_Detector_online.jpg?itok=EzPQHklv

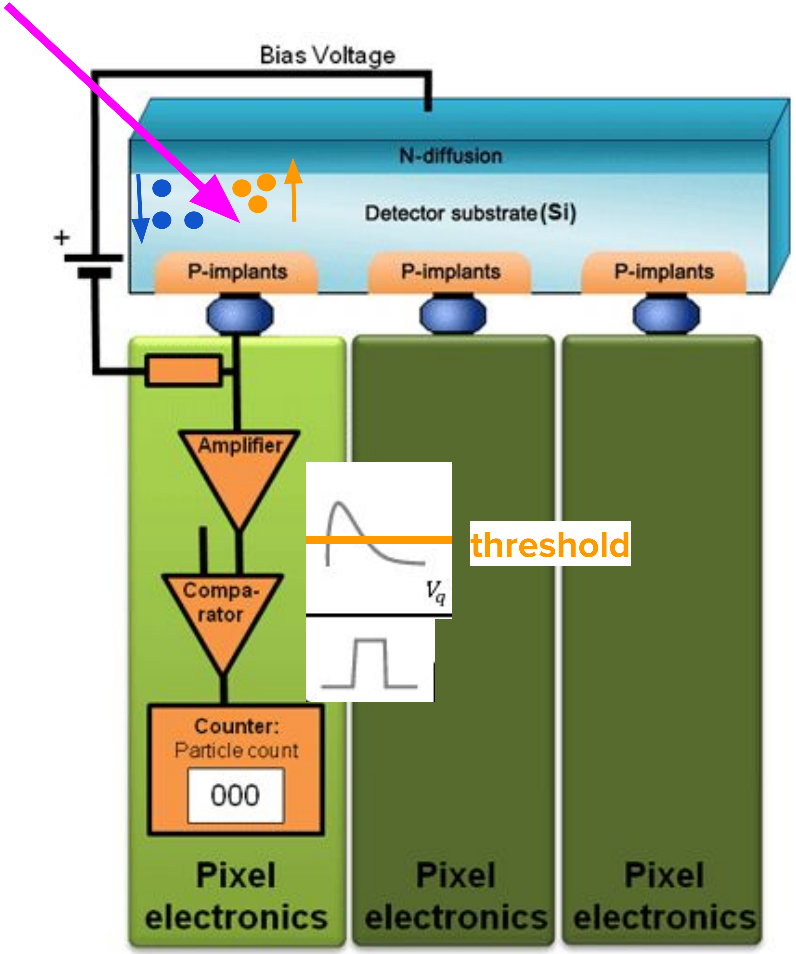
CMS pixel detector



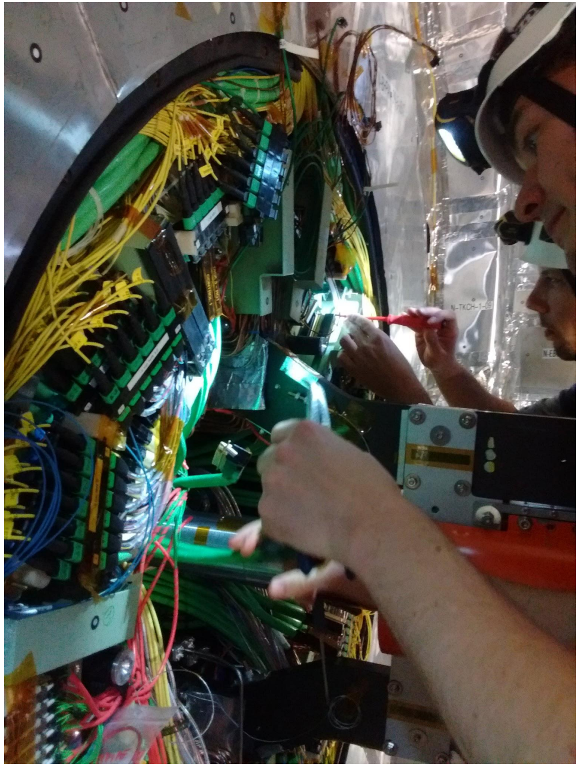
A hybrid pixel detector

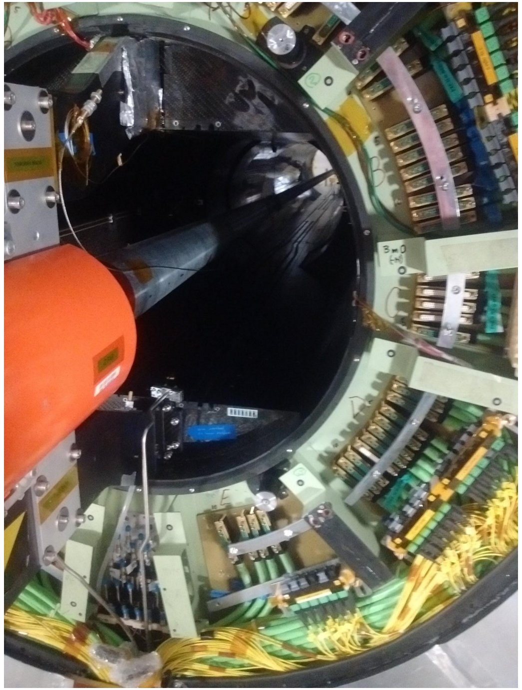






Pixel extraction January 2019

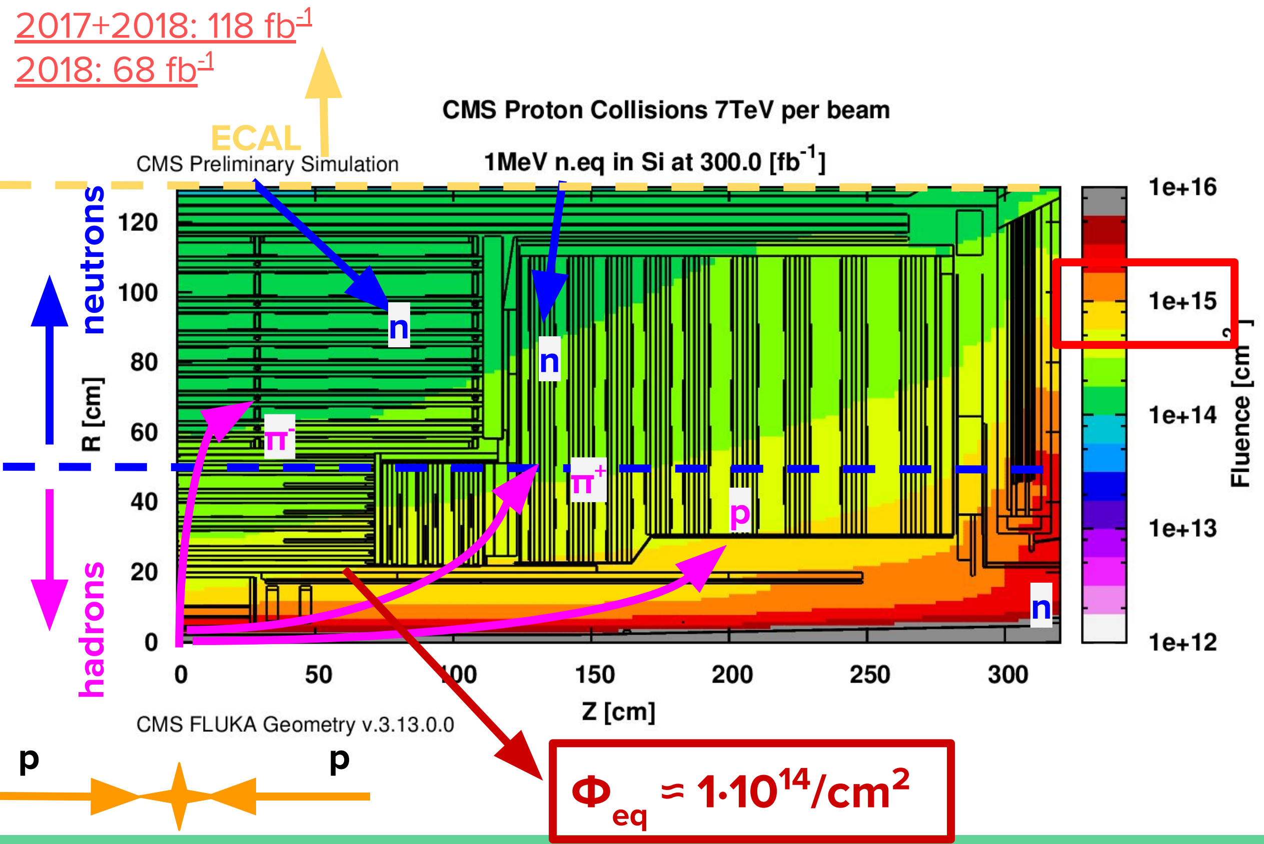




The CMS pixel detector was installed in 2017

Radiation damage modeling

LHC: a challenging environment



Radiation effects are challenging for operations and performance:

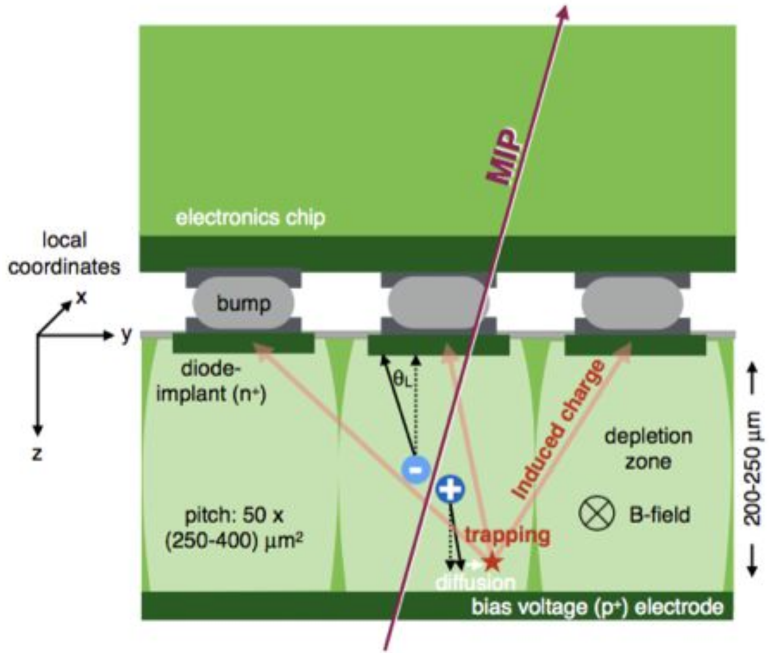
- Damage and single event upsets (SEUs) in electronics
  ➔ false signals, chip damage
- Bulk defects cause change of space charge distribution
  ➔ bias voltage increase
- Increasing leakage currents and heat dissipation
- Charge trapping in sensor:
  ➔ decreasing charge collection efficiency

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**

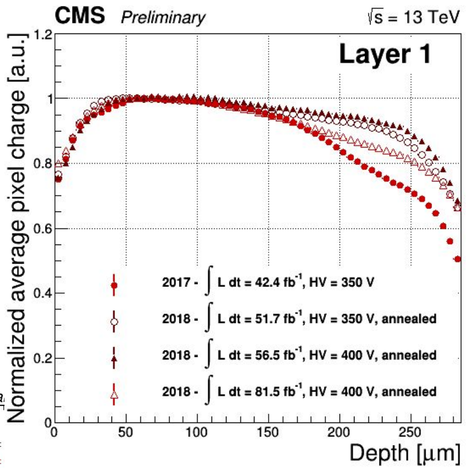


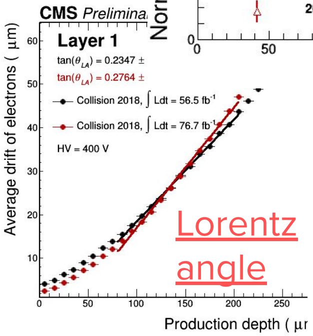
From Ben Nachman

Impact on data

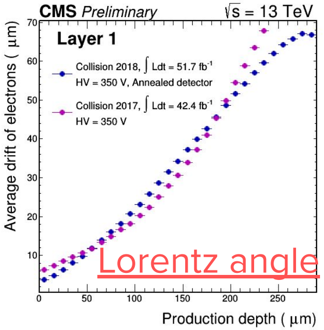
Modeling radiation damage is important for performance (➔ operational voltage) but also for physics

Average pixel charge



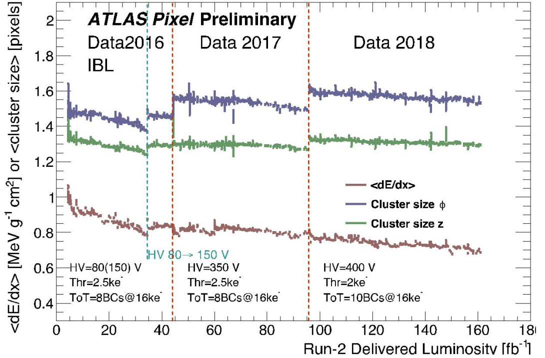


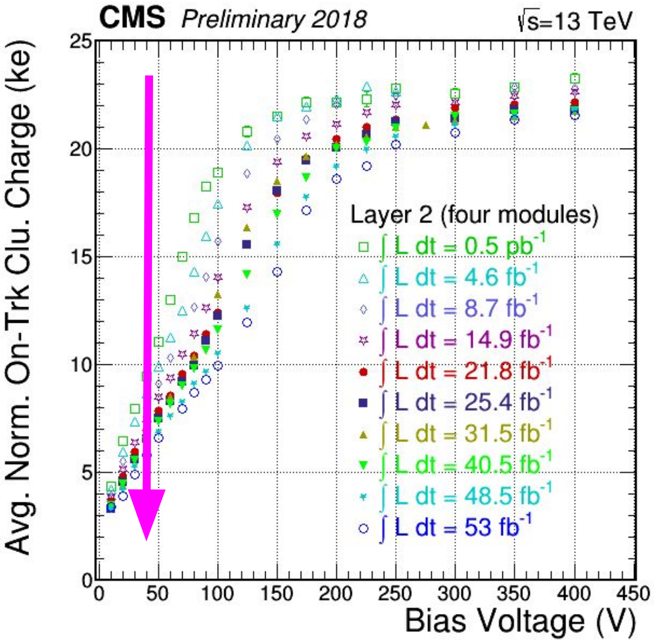
Lorentz angle



Lorentz angle

Significant decrease of dE/dx and cluster size for IBL

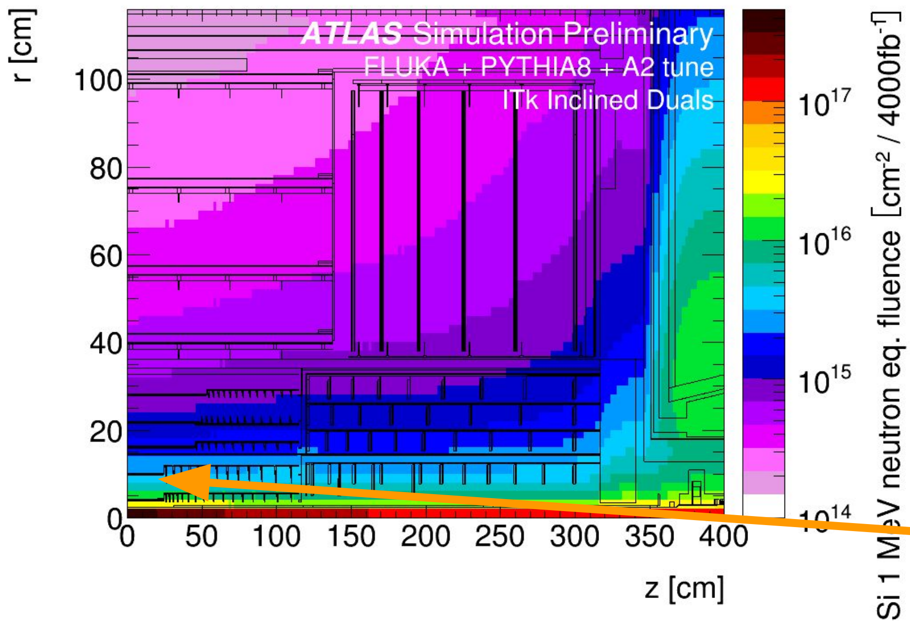


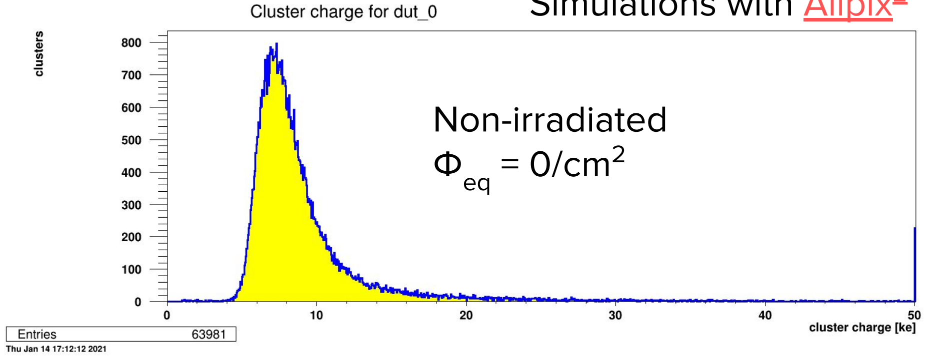


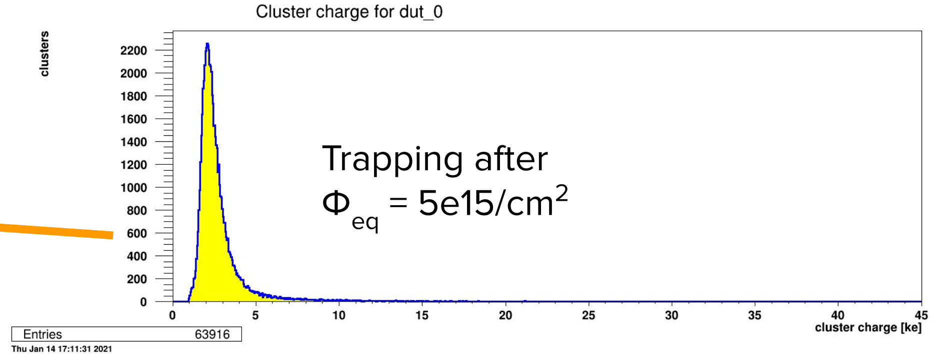
Radiation damage modeling for ATLAS ITk

ATLAS: modeling radiation damage

Simulations with Allpix^2

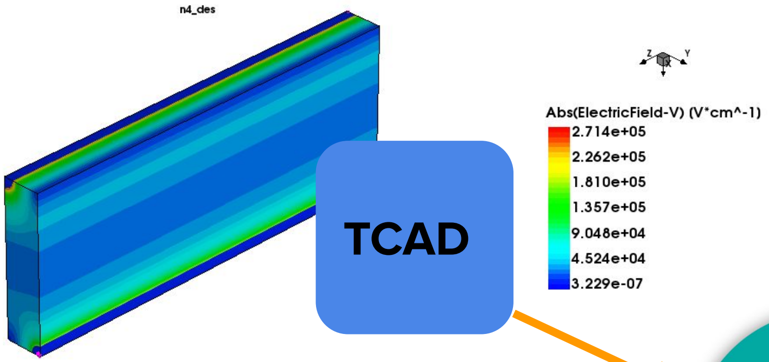






In the ATLAS group I work in the silicon radiation damage group on modeling trapping with Allpix^2

Validate models with testbeam data and TCAD



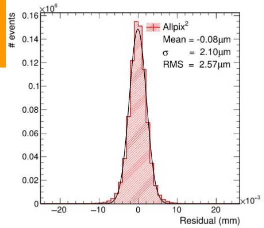
TCAD

Technology computer aided design
Output: Electric field maps
Input: drift time, Ramo potential

ap² allpix squared

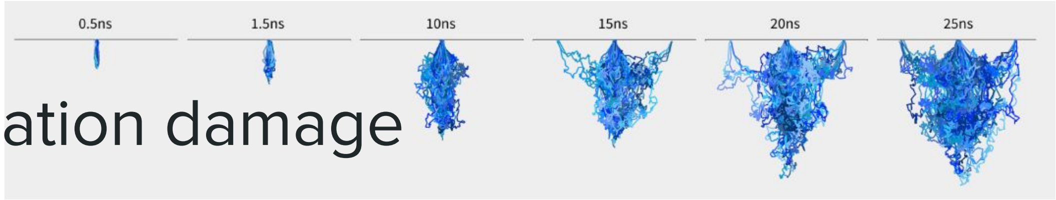
Test beam data

Residuals, cluster size, cluster charge...

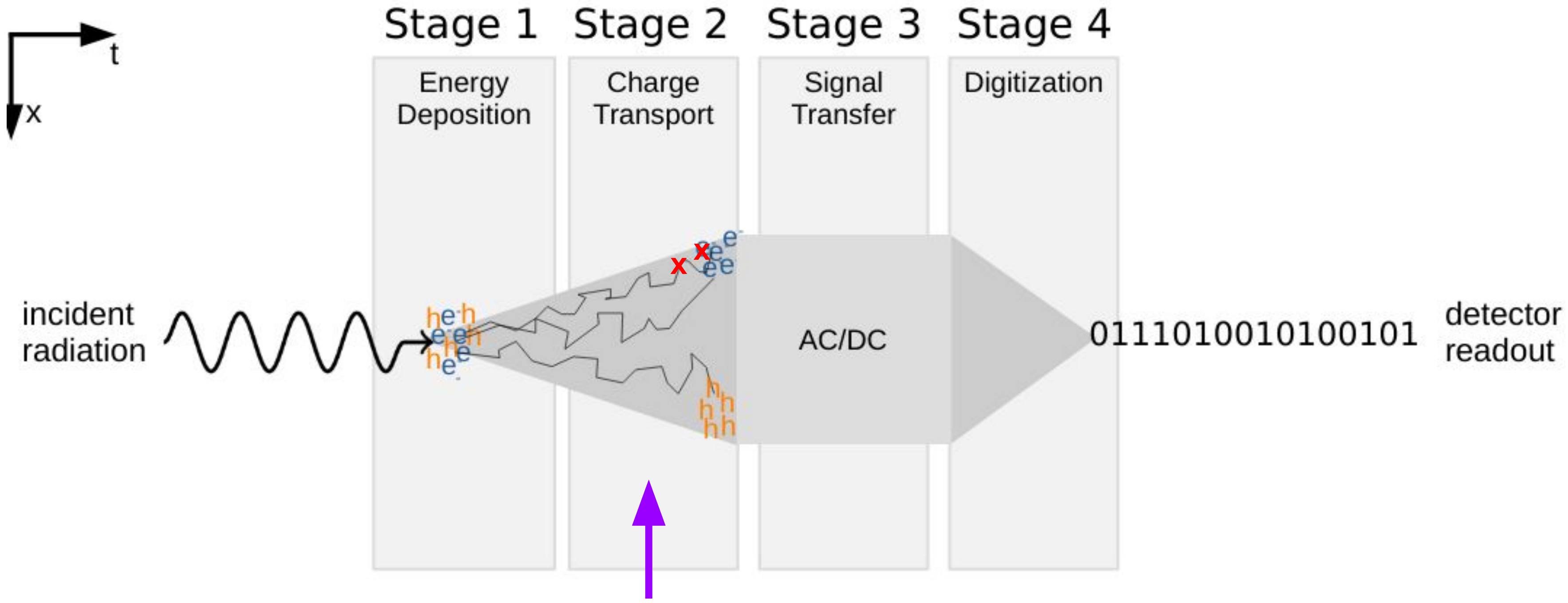


Allpix²: relies on ROOT, Geant4
Input: electric field, detector geometry
Output: corryvreckan, ROOT
Charge deposition, propagation, transfer, digitization
Implement trapping in charge propagation

Allpix^2 simulation with radiation damage



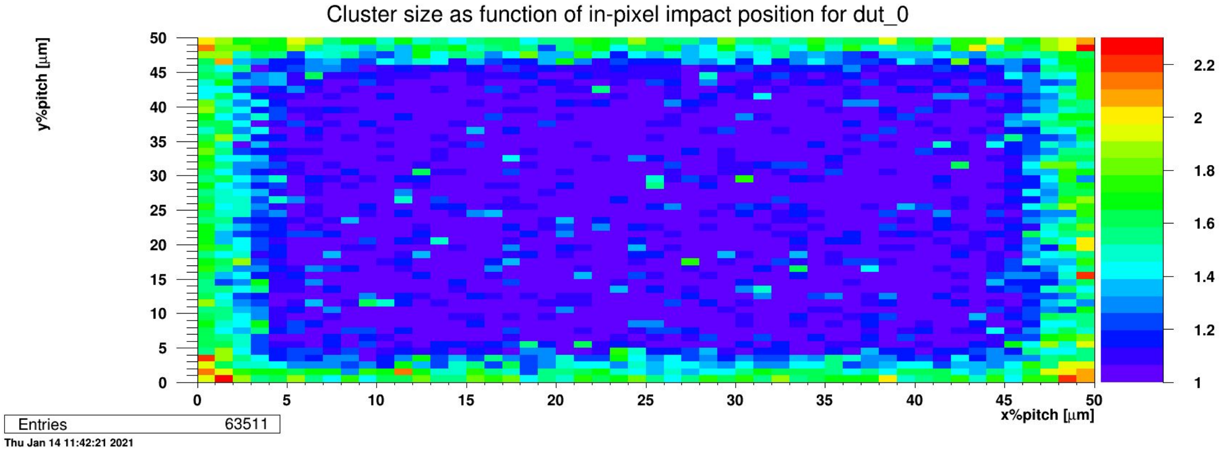
From Paul Schütze



Implement trapping here

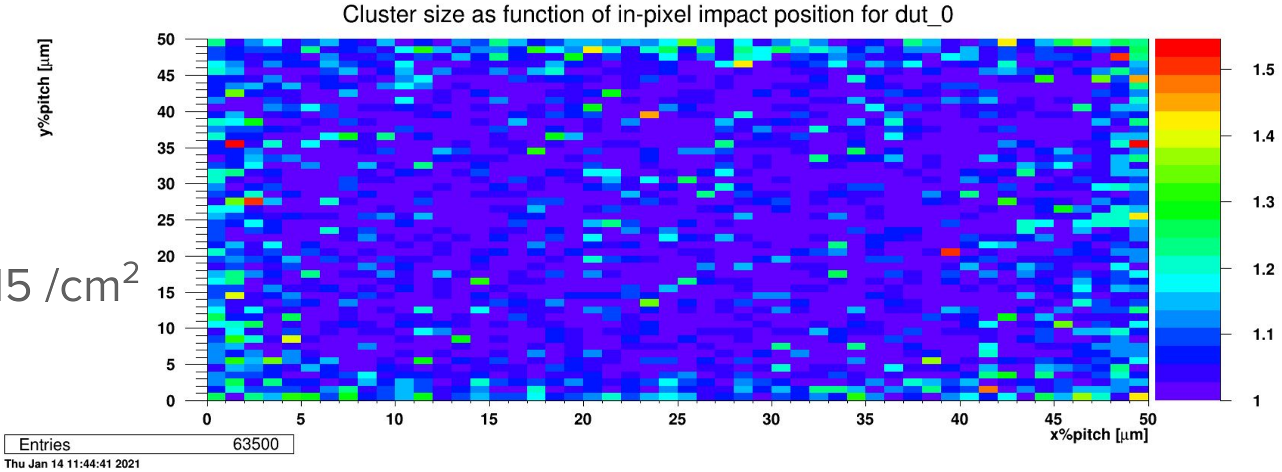
Cluster size

- Unirradiated



- 100k events
- DUT RD53
- Threshold 1000e$^-$

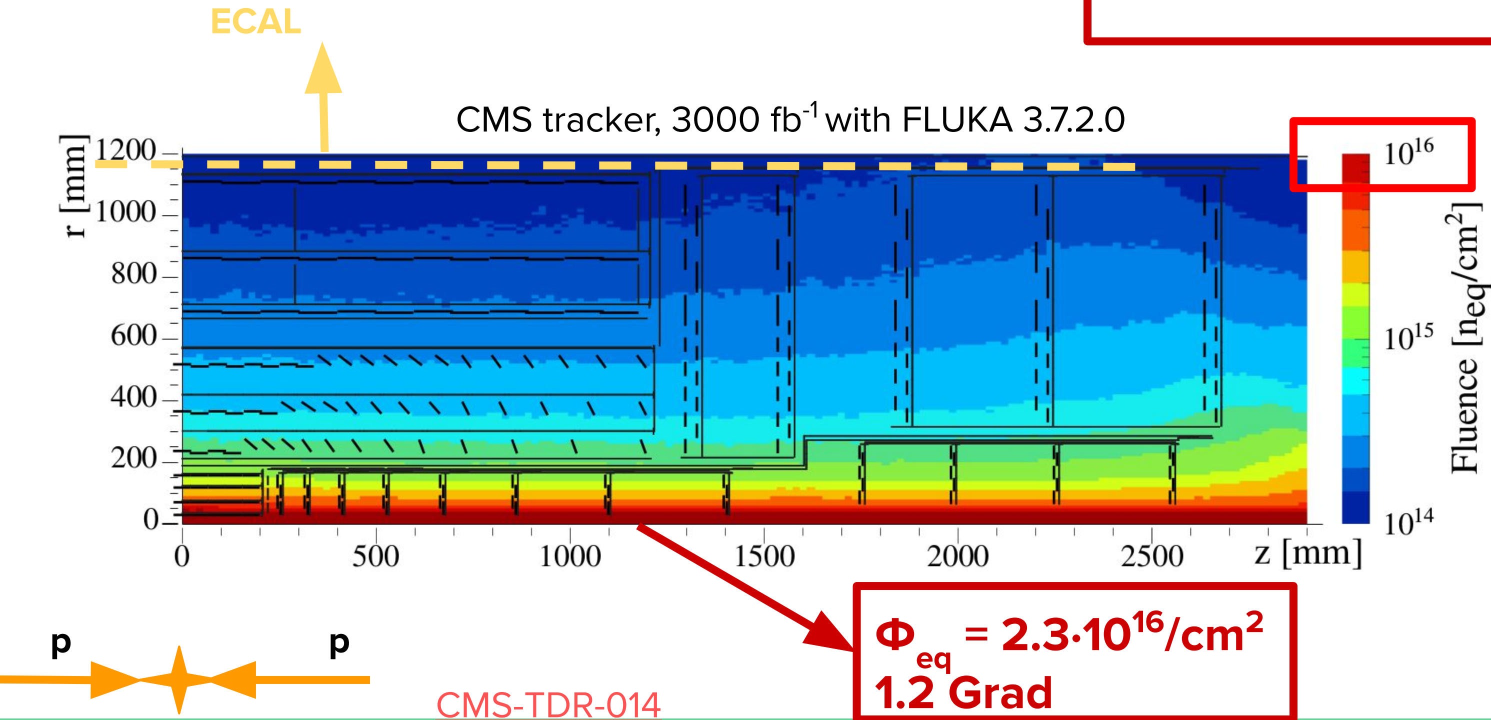
- Trapping Φ_{eq} = 5e15 /cm^2



Sensor characterization

High-luminosity-LHC: a challenging environment

5 × higher hit rate than in current detector: 0.58 → 3.2 GHz/cm^2



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

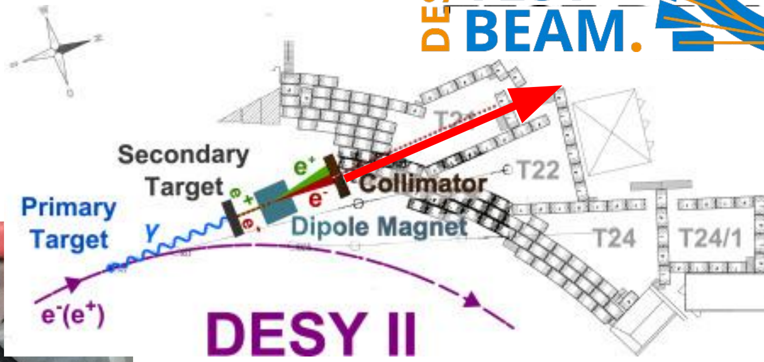
What is needed to cope with these fluences and rates?

Φ_{eq} = 2.3·10^{16}/cm^2
1.2 Grad

CMS-TDR-014

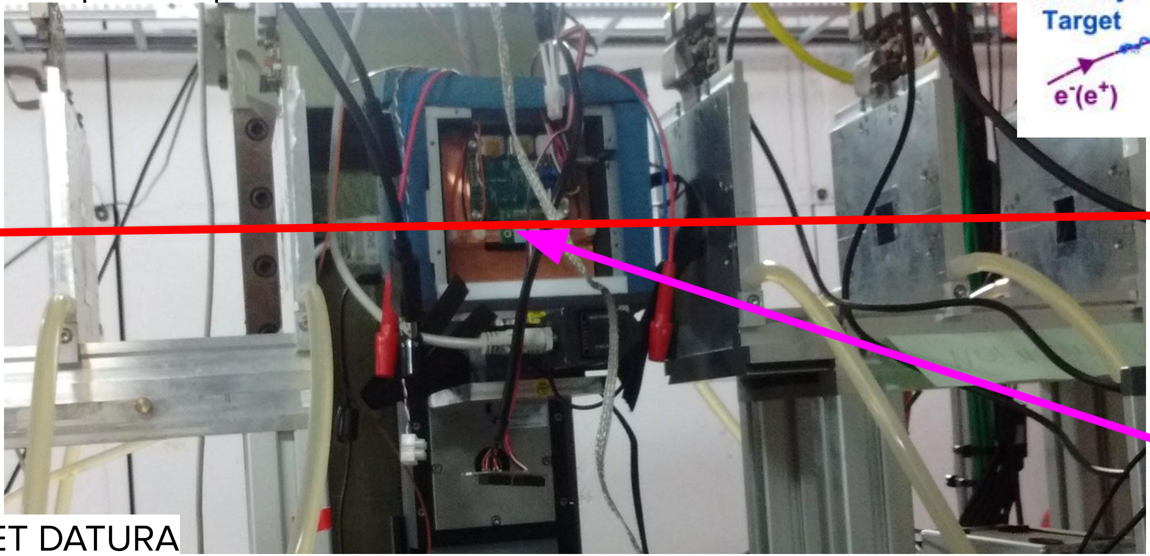
Sensor characterization at test beam

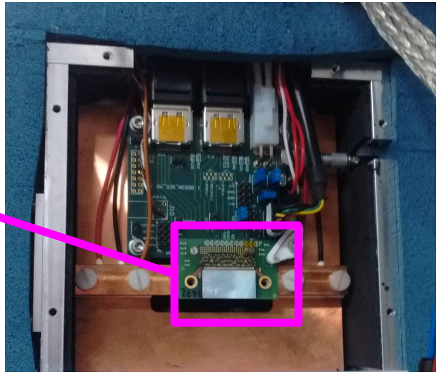
Tests of CMS phase 2 planar and 3D sensors on
RD53A or ROC4SENS (R&D) chip
as well as phase 1 pixel modules



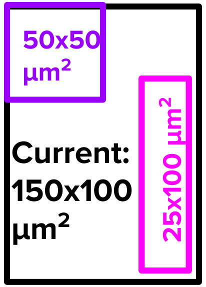
DESY test beam

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



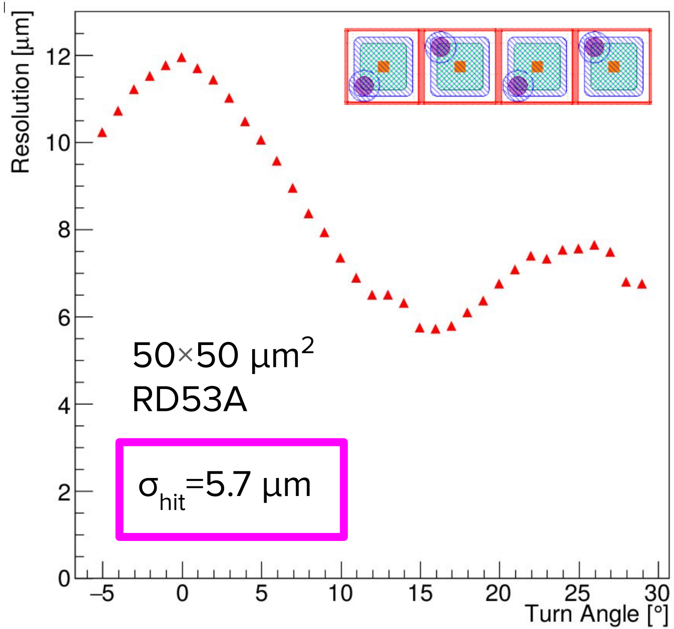


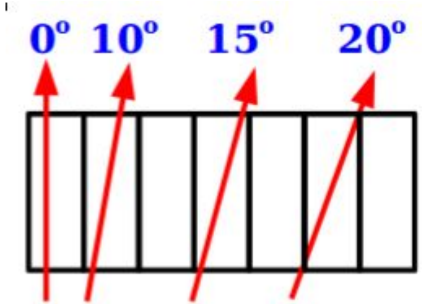
EUDET DATURA
telescope with 6
MIMOSA26 (MAPS for ILC, 50 µm thick, 18.4 µm^2) planes with resolution of 5.7 µm



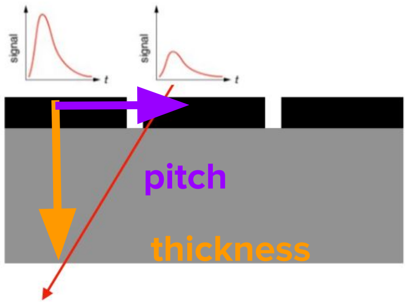
Pixel cell dimensions and resolution of RD53A

- 25×100 µm² or 50×50 µm²: charge sharing different
- **Best resolution: cluster size of 2**





2 pixel charge sharing for 18°



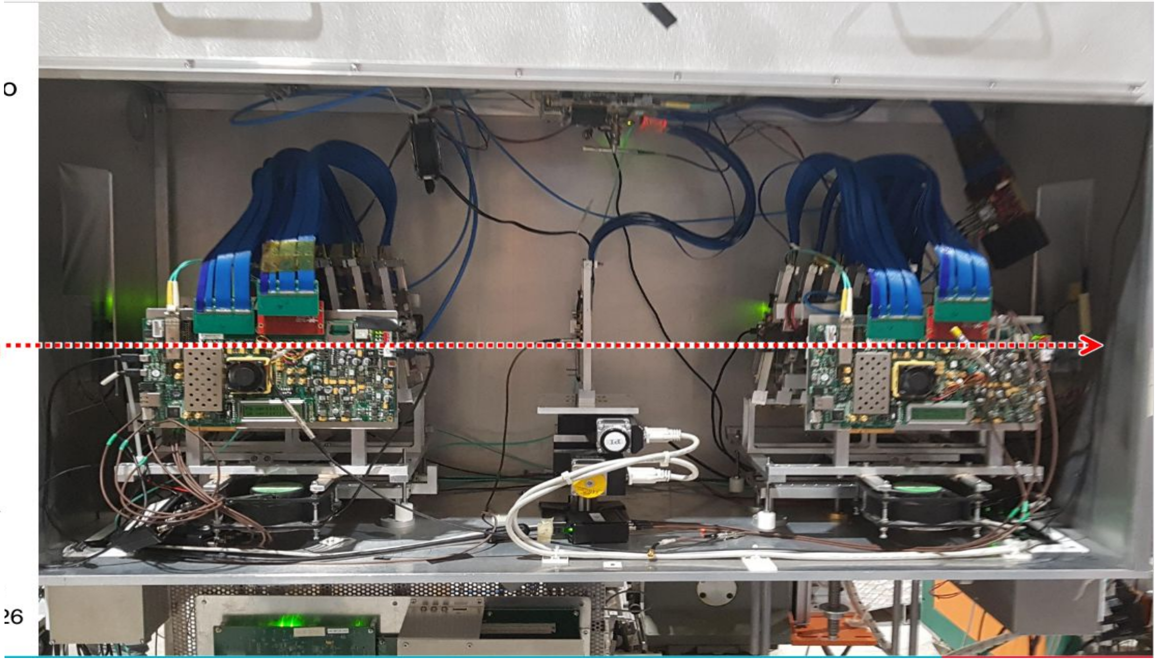
Position = weighted average
Resolution < pitch / √12

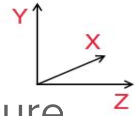
Optimal charge sharing at an angle atan(pitch/depth):

- **50×50 µm²:** atan(50/150) = 18.4°
- **25×100 µm²:** atan(25/150) = 9.5°
  ➔ increase E-field with higher bias

Nikhef detector R&D: Timepix telescope

- Previously Nikhef built a fast Timepix 3 telescope for sensor and ASIC characterization
- 1.6 µm spatial resolution
- Track time resolution of 236 ps
- **Now we will build a Timepix 4 telescope with picosecond time resolution for characterization of fast detectors**
- And much more infrastructure in the lab for (3D) sensor characterization including a **TPA-TCT setup**





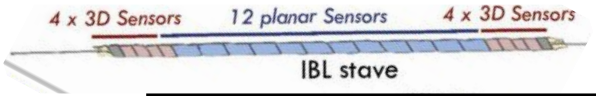
K. Akiba et al 2019 JINST 14 P05026
K. Heijhoff et al 2020 JINST 15 P09035

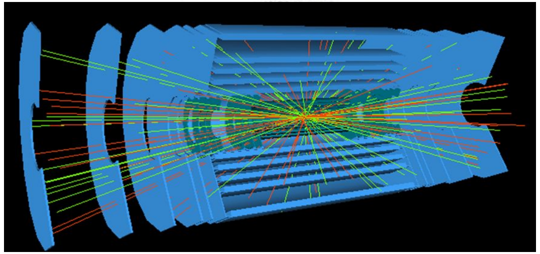
Fast timing in detector R&D group

LHC timeline

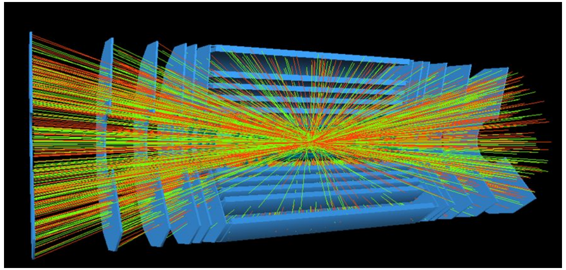
From the high lumi LHC project

From Kerstin Lantsch

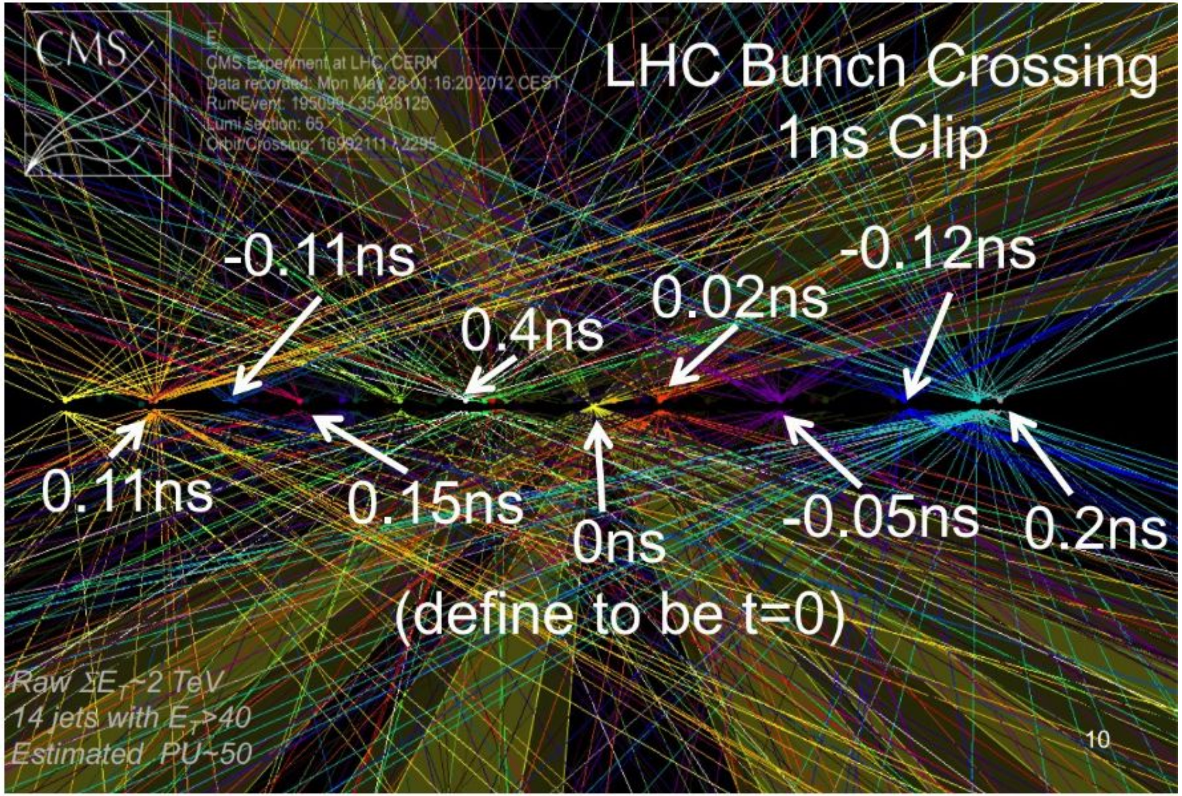




Pileup x 10

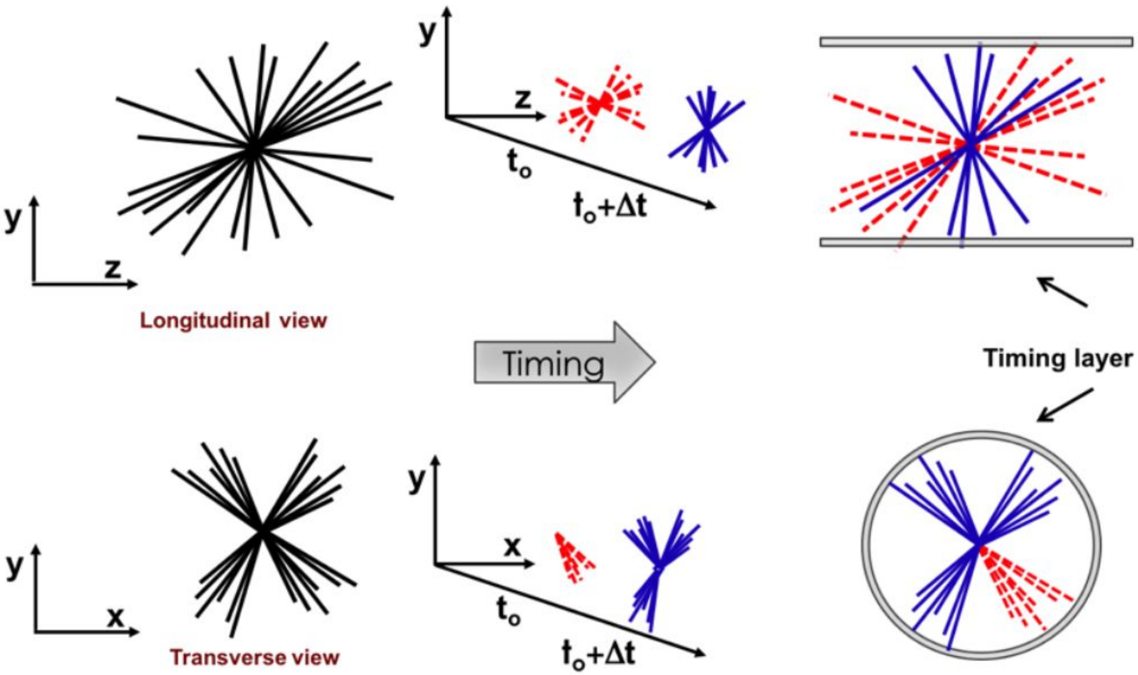


Why picosecond timing?



From Nicolo Cartiglia

Timing information from a timing layer



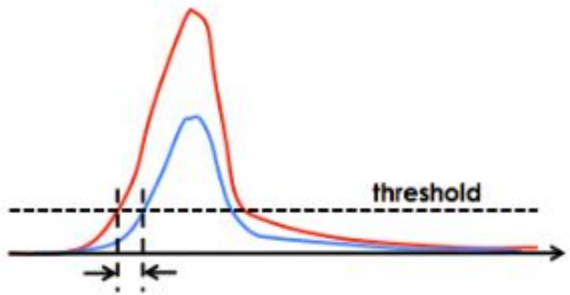
From Nicolo Cartiglia

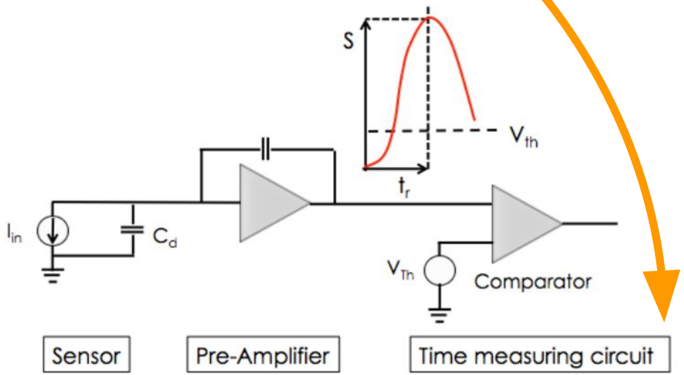
Time resolution

$\sigma_t^2 = \sigma_{timewalk}^2 + \sigma_{jitter}^2 + \sigma_{TDC}^2$

Time walk: smaller signals have a ‘time delay’

~ Noise / (dV/dt) inversely with steepness of signal





Time to digital converter

From arxiv:1312.1080 -- see also slides by Nicolo Cartiglia

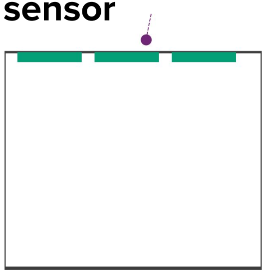
ATLAS High Granularity Timing Detector: a timing layer

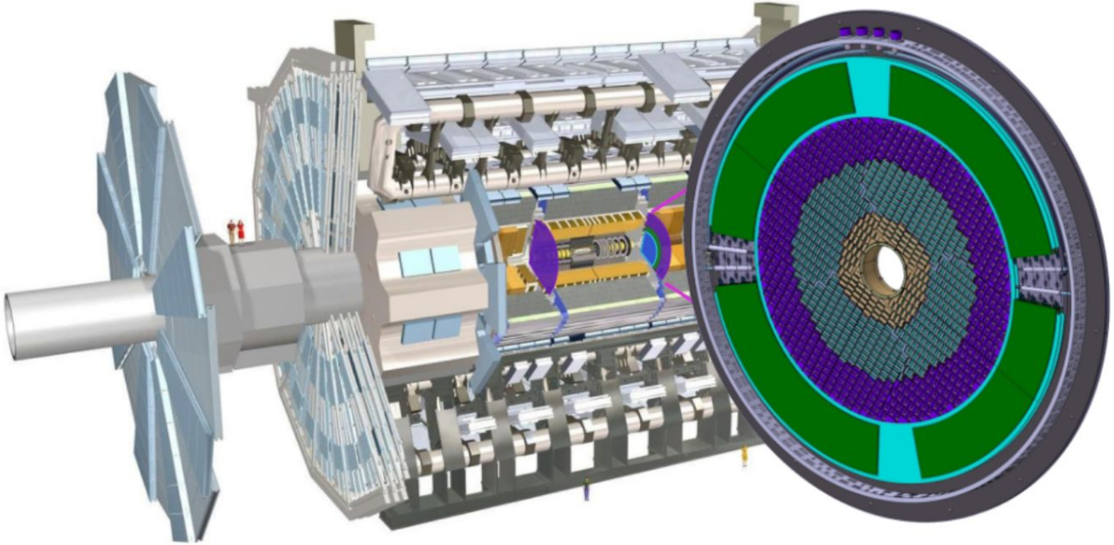
TDR

- **LGADs** with time resolution per track (per hit) 25 ps (35 ps) for r = 120 mm
- **Half will be replaced after 1000 fb^{-1}**: timing degrades with radiation damage

Low Gain Avalanche Diode signal: charge is multiplied in gain layer! Animation by Robbert Geertsema

Planar sensor signal:

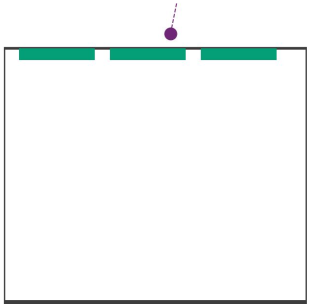




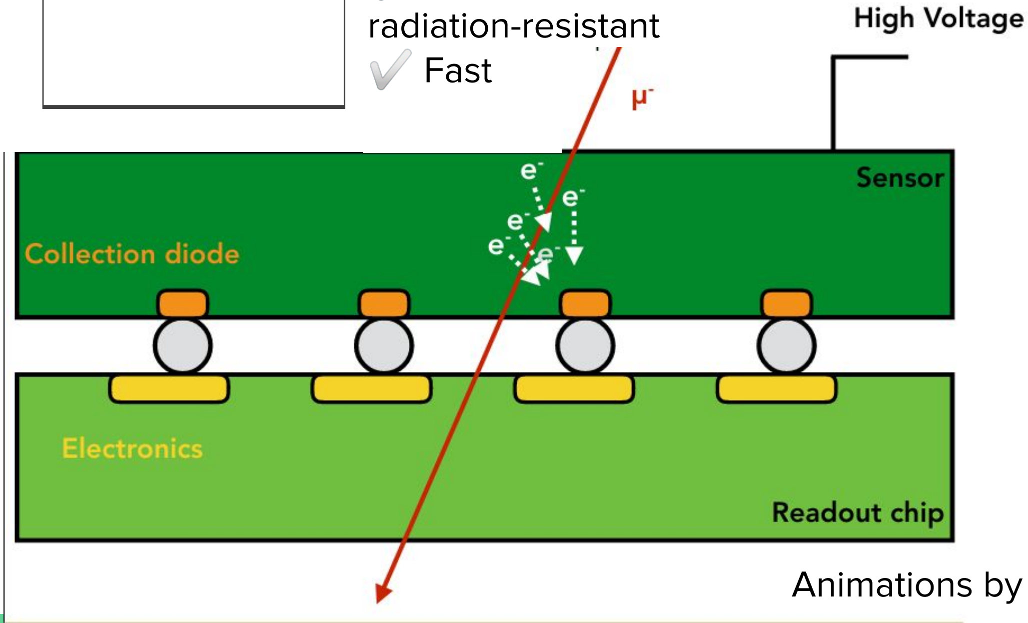
Animations courtesy of Robbert Geertsema

Figures from [Daniel Hynds]

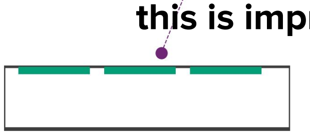
What are MAPS?

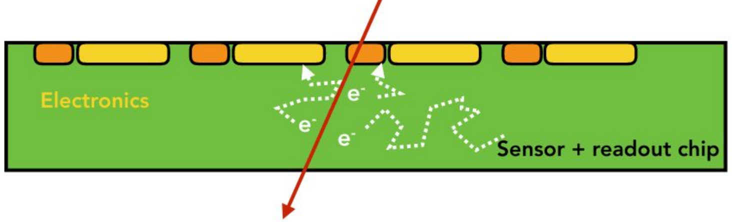


Planar hybrid sensor:
❌ Limited thickness for stability
❌ Limited pixel pitch
❌ Bump bonding costly
✔️ But widely used and reliably radiation-resistant
✔️ Fast



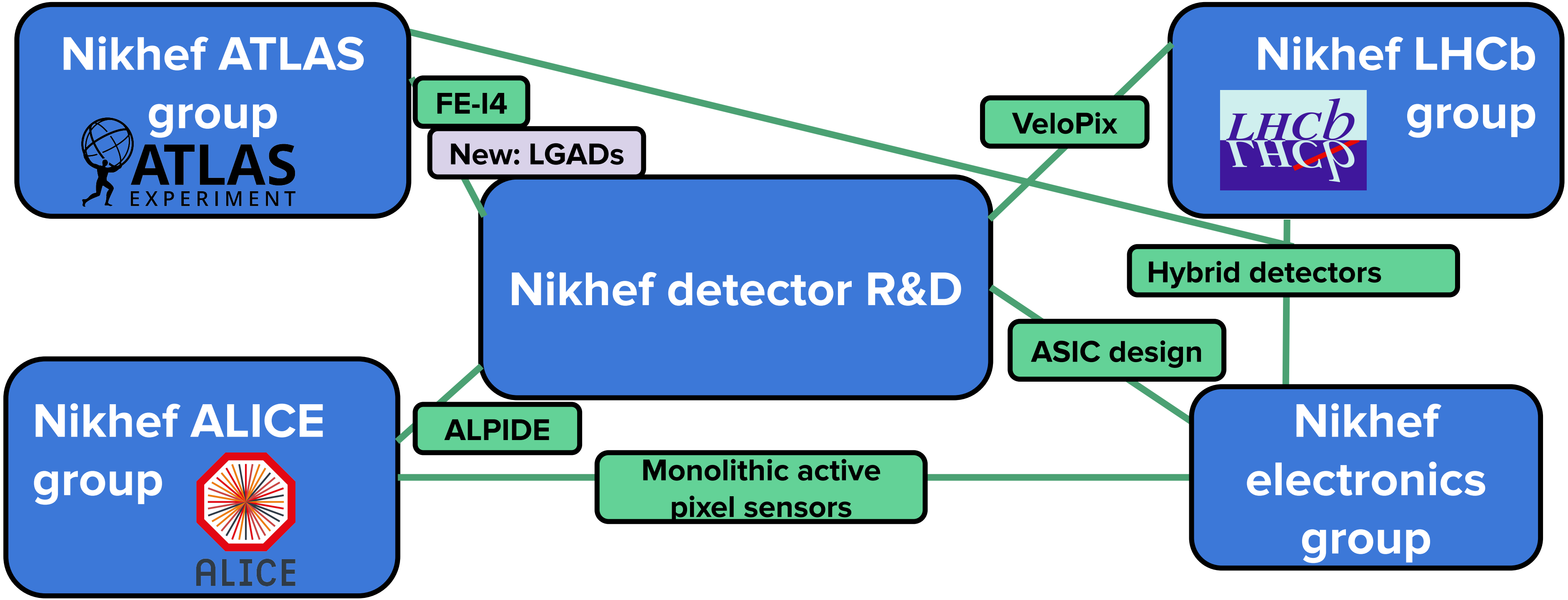
Monolithic sensor:
✔️ Very little material
✔️
❌ Limited depletion region: slow charge collection by diffusion **but this is improving**
❌ Not very radiation-hard **but this is improving**





Animations by Robbert Geertsema

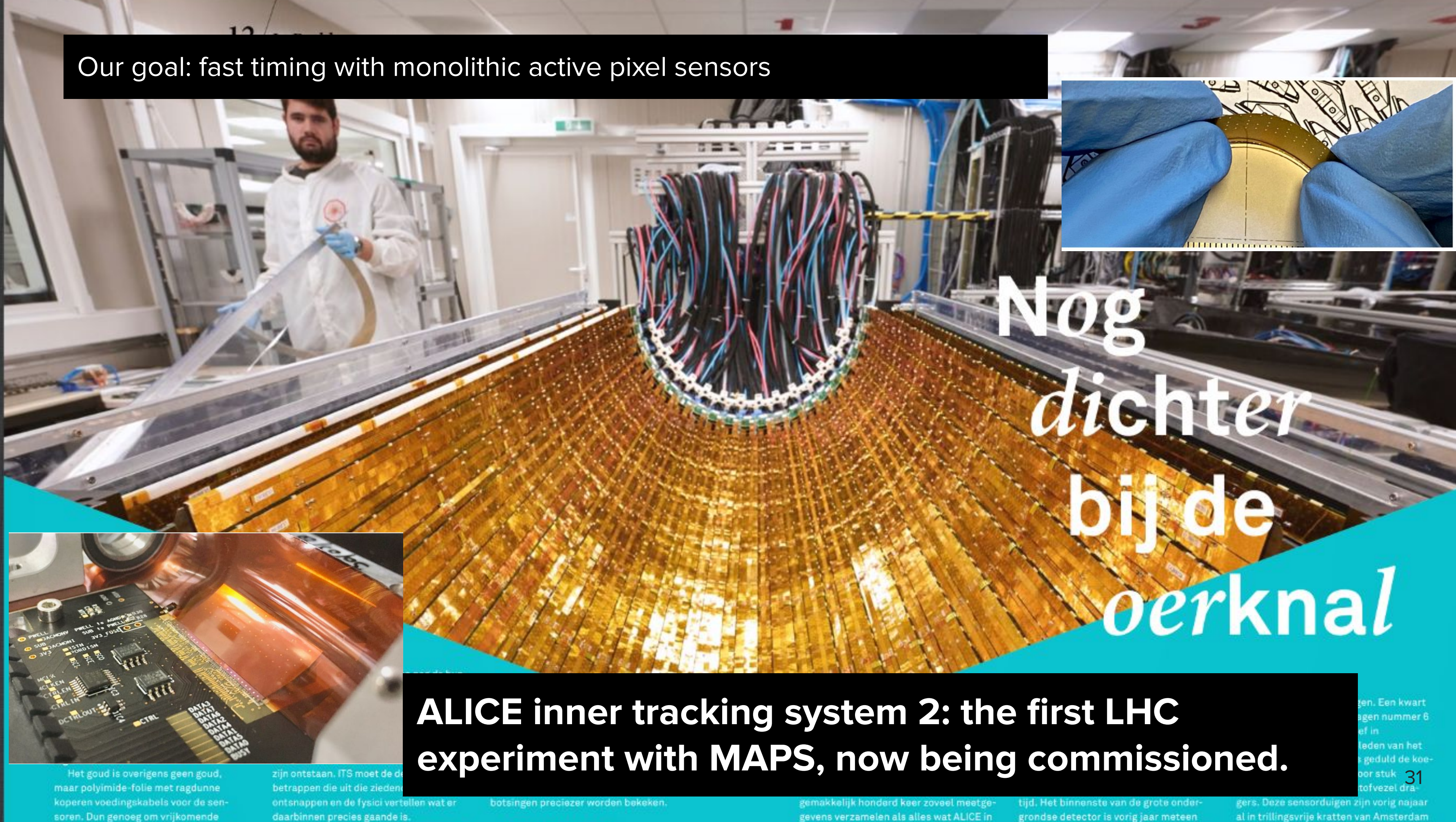
Nikhef detector R&D with Nikhef LHC groups



Work on fast timing in both MAPS and hybrid detectors

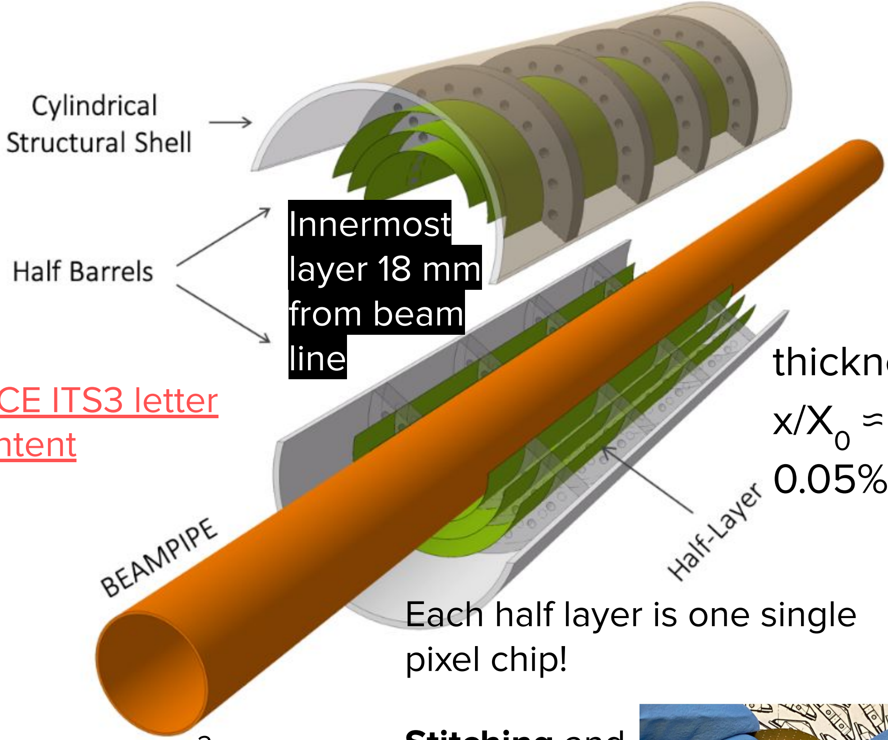
Fast timing and MAPS at the LHC

Our goal: fast timing with monolithic active pixel sensors



ALICE inner tracking system 2: the first LHC experiment with MAPS, now being commissioned.

ALICE ITS3: 2025



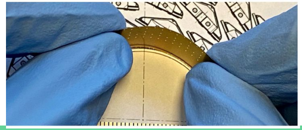
Innermost layer 18 mm from beam line

[ALICE ITS3 letter of intent]

thickness: $x/X_0 \approx 0.05\%$

Each half layer is one single pixel chip!

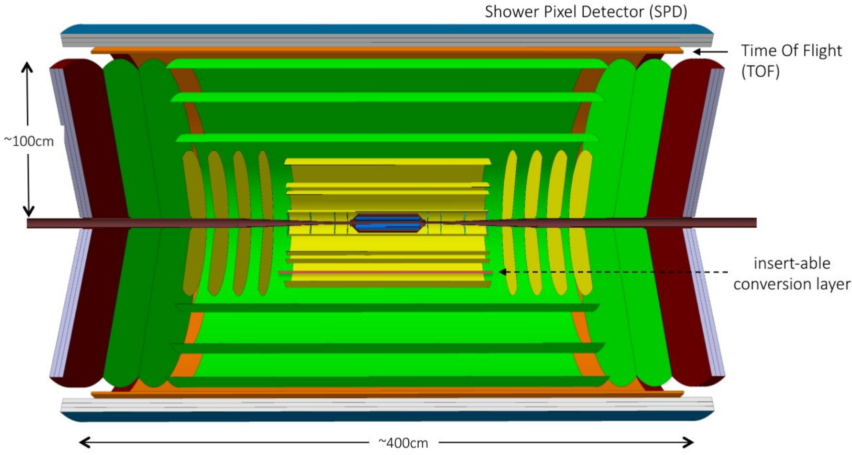
Stitching and **bending**



$\Phi_{eq} = 1e13\ cm^{-2}$, 10 kGy
Much less than ATLAS!

ALICE3: 2030

ALICE3 expression of interest
https://arxiv.org/pdf/1902.01211.pdf

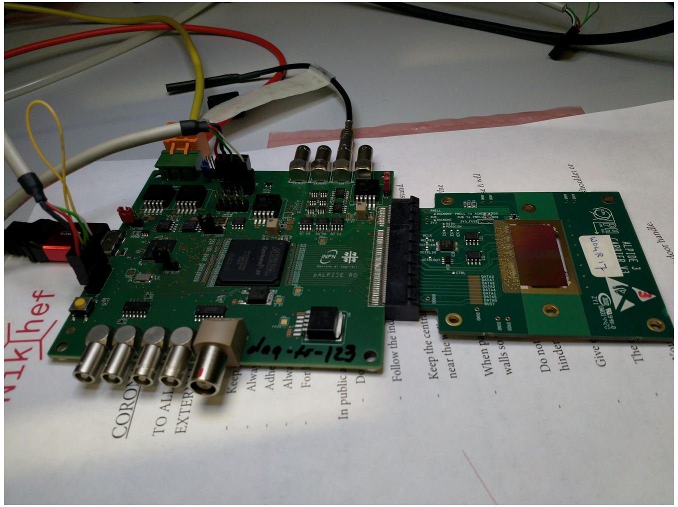


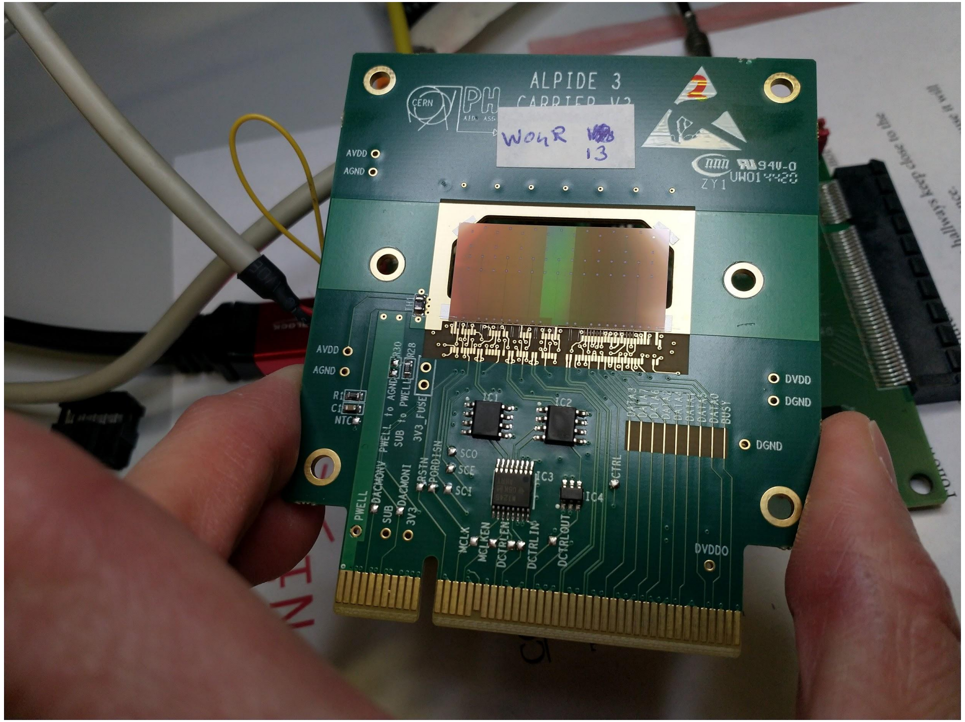
$0.05\%\ X_0$ per layer

Time of flight detector with 20 ps time resolution -- possibly depleted MAPS: $\Phi_{eq} = 1e12\ cm^{-2}$

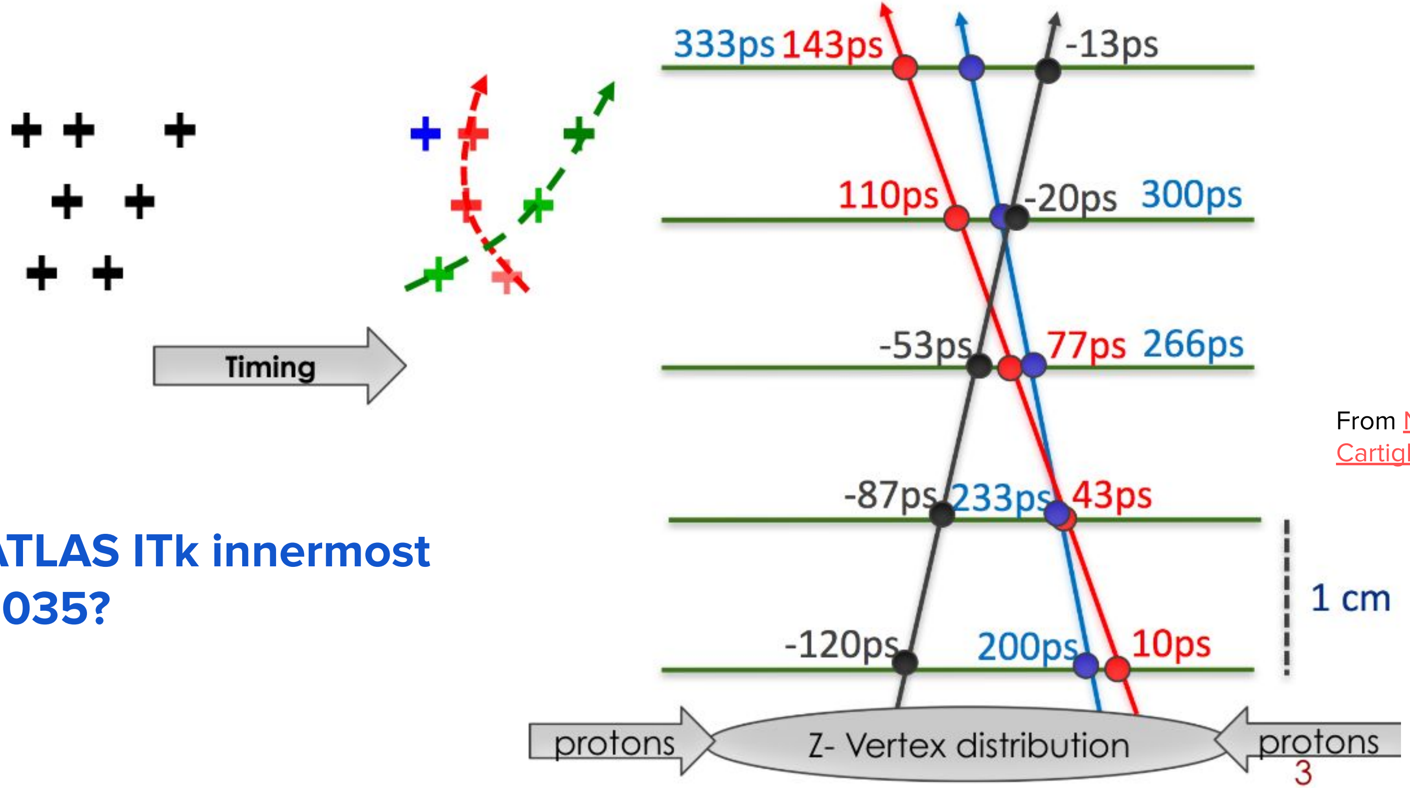
ALPIDE chips in the Nikhef R&D lab

With Roberto Russo:
measurement and simulation of
ALICE ALPIDE time resolution





Timing at points along the track



From [Nicolo Cartiglia](#)

MAPS in ATLAS ITk innermost layers in 2035?

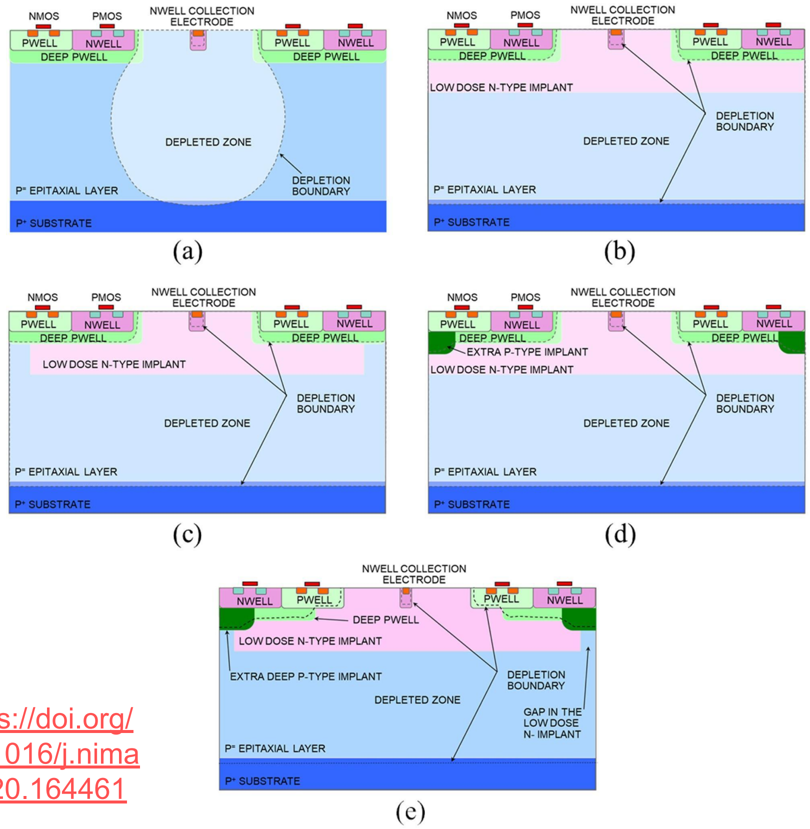
Fast MAPS example: FASTPIX

FASTPIX: coming soon

- tens of ps
- 20 uW power consumption

See also talk by Magdalena Munker **now at 11:00**: https://indico.cern.ch/event/997569/

Many groups looking into MAPS + fast timing.
Other examples: ARCADIA, MonPicoAD



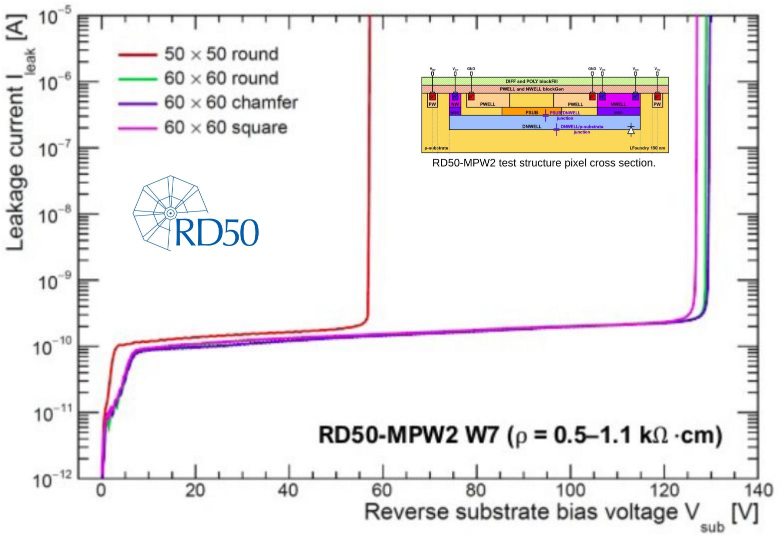
https://doi.org/10.1016/j.nima.2020.164461

HV CMOS MAPS

Radiation hard depleted MAPS

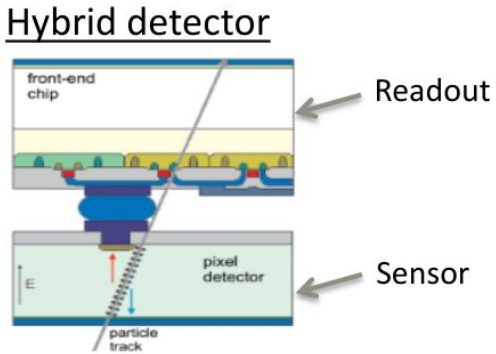
ALICE ALPIDE is a **low-resistivity CMOS** chip: back bias up to maximum 6 V. Small collection electrode.

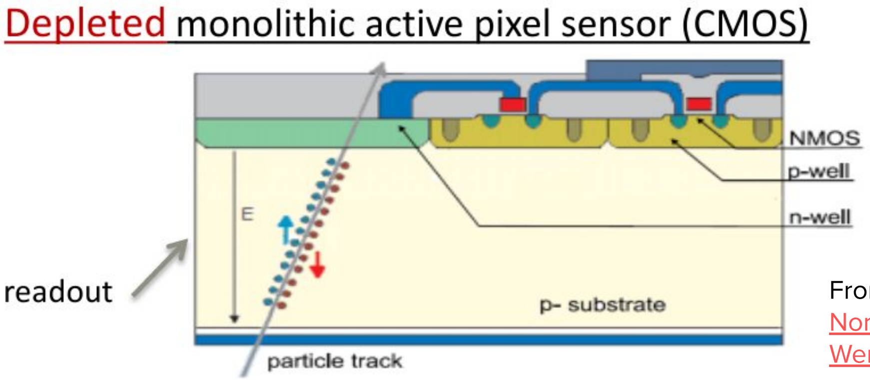
With Christina Tsolanta: measurement and simulation of time resolution for RD50 MPW2 HV CMOS test structure.



From Ricardo Marco Hernández

HV CMOS or depleted MAPS (DMAPS) can have a much higher bias voltage and larger collection electrode:
fast collection time and **radiation tolerant.**





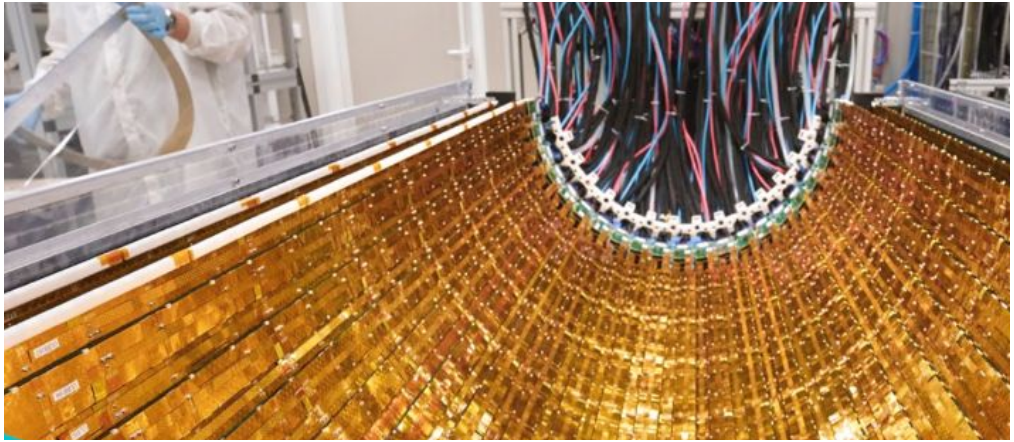
From Norbert Wermes

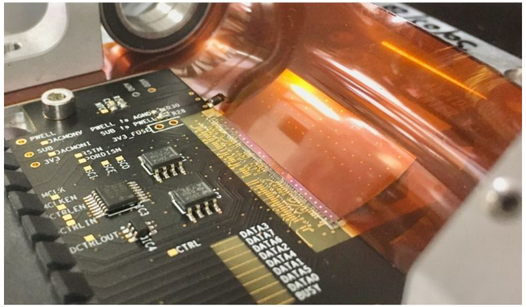
MAPS are the future

4D tracking is the future

One option is monolithic active pixel sensors: they are

- Thin
- Cheap
- Large collection electrode like RD50 depleted MAPS:
    - High breakdown voltage
    - Large signal
    - Radiation tolerant
- Small collection electrode like ALPIDE:
    - Low capacitance
    - Low noise
    - Low power
    - Radiation hardness in sight
    - We will contribute to time resolution measurements





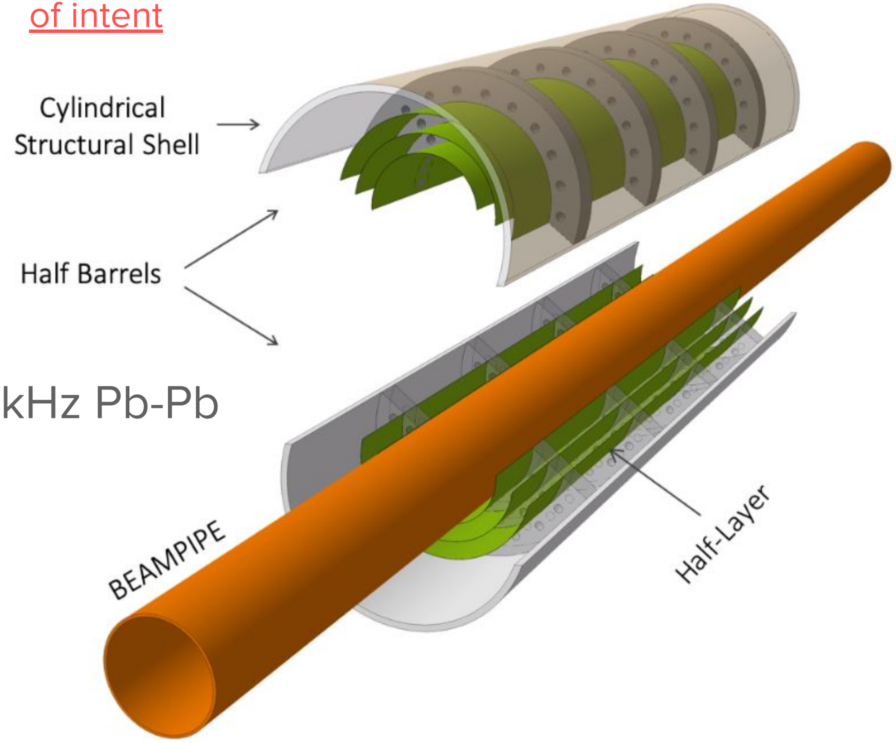
Additional material

ALICE ITS3

[ALICE ITS3 letter of intent]

Each half layer is one single pixel chip!

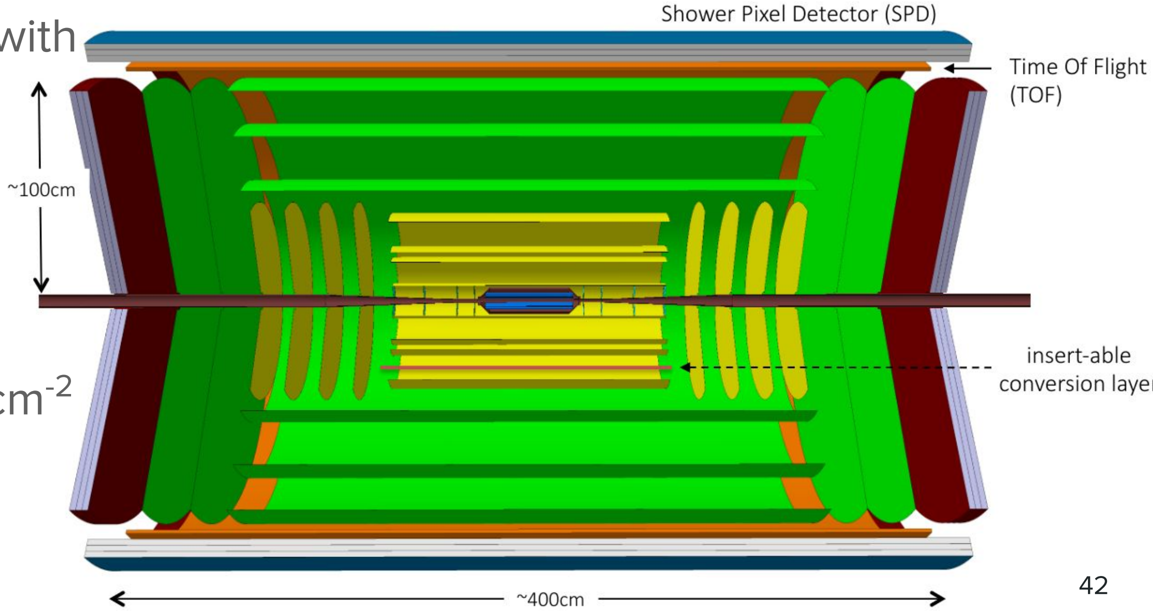
- Innermost layer 18 mm from beam line
- For 50 µm thickness: $x/X_0 \approxeq 0.05\%$
- Target thickness: 20-40 µm
- Occupancy 1e-3 → 2.2 MHz cm^{-2} for 50 kHz Pb-Pb
- 5 µm resolution
- 1 µs integration time
- Φ_{eq} = 1e13 cm^{-2}, 10 kGy
- Power requirement 20 mW cm^{-2}
- 7 mW cm^{-2} in pixel matrix
- 150 mW cm^{-2} digital periphery



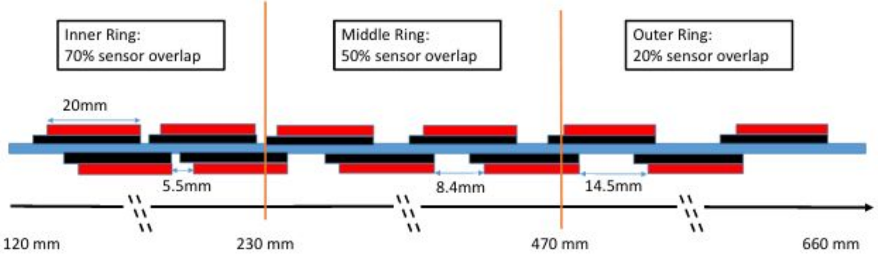
ALICE ITS4

ALICE expression of interest
https://arxiv.org/pdf/1902.01211.pdf

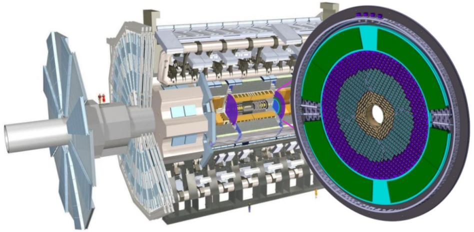
- 3 layers inside beam pipe up to 5-15 mm from beam line with 0.05% X_0 per layer
- 1e6 pixels cm^{-2} in innermost layers: 10 µm x 10 µm
- 3 µm resolution
- 7 layers outside beam pipe with 0.5 % X_0 per layer
- Time of flight detector with 20 ps time resolution depleted MAPS/SPADs: $\Phi_{eq} = 1e12\ cm^{-2}$
- Innermost layer $\Phi_{eq} = 3e14\ cm^{-2}$
  - 5e15

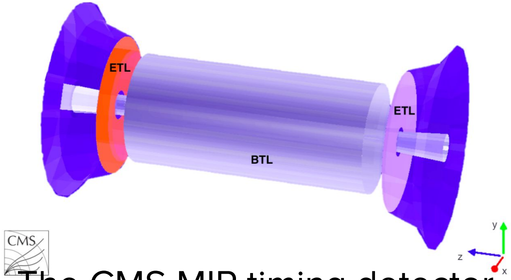


ATLAS High Granularity Timing Detector



- High lumi LHC: 4000 fb^{-1}
- $z = \pm 3.5$ m
- Outside ITk
- In front of endcap calorimeters
- r = 120-640 mm
- CO_2 cooling @ -30 °C
- Overlapping double modules
- Time resolution per track (per hit)
  25 ps (35 ps) for r = 120 mm
- After 4000 fb^{-1}: 42 ps (60 ps)
- Φ_{eq} = (5.5) 8.3e15 cm^{-2} , 7.5 (3.3) MGy
- **Half will be replaced**: < 230 mm after 1000 fb^{-1}, < 470 after 2000 fb^{-1}



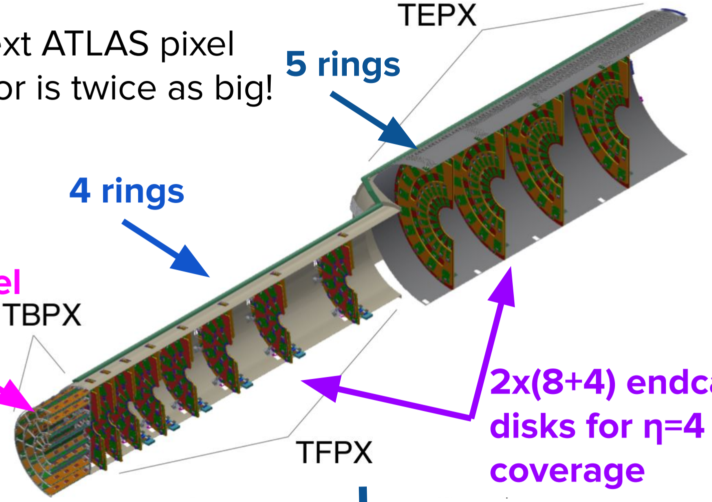


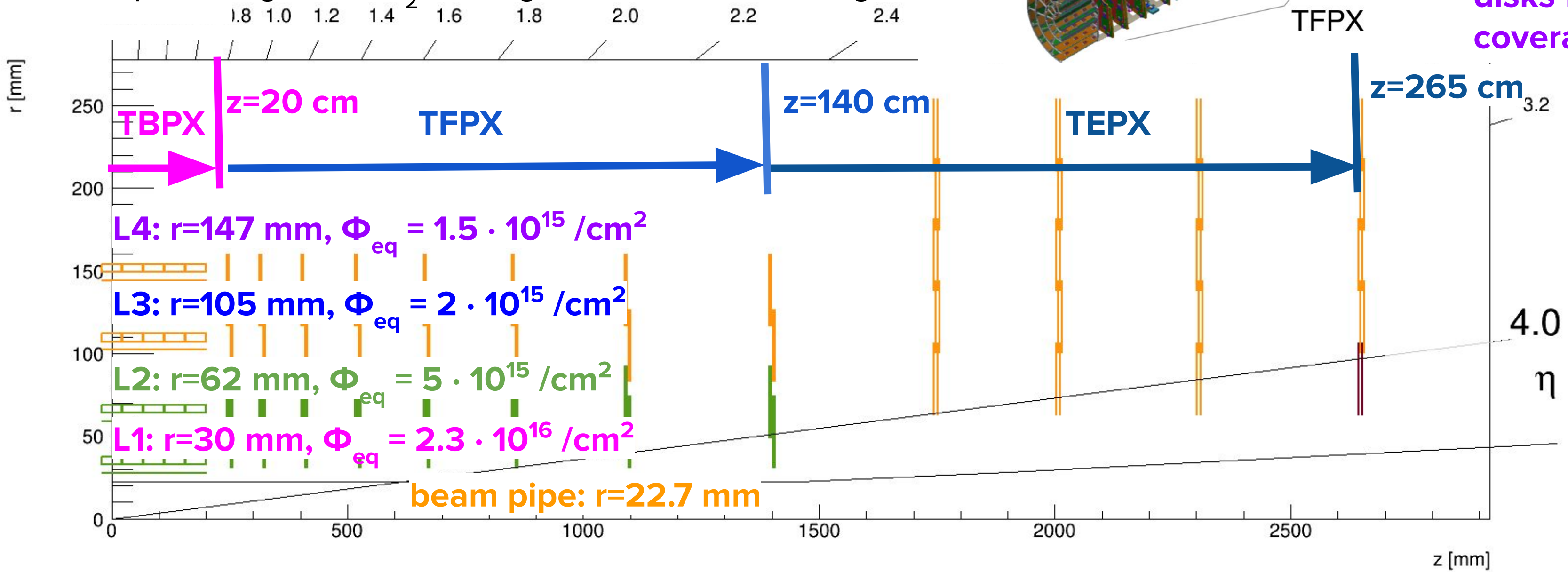
The CMS MIP timing detector also has a barrel layer with silicon photomultipliers

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

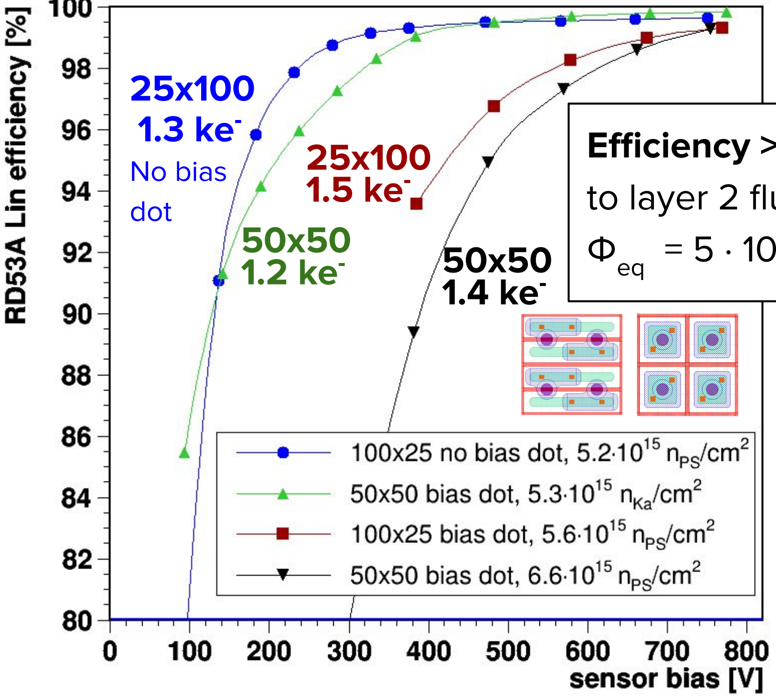
CMS pixel phase 2 layout

Planar sensors

150 μm n^+ in p

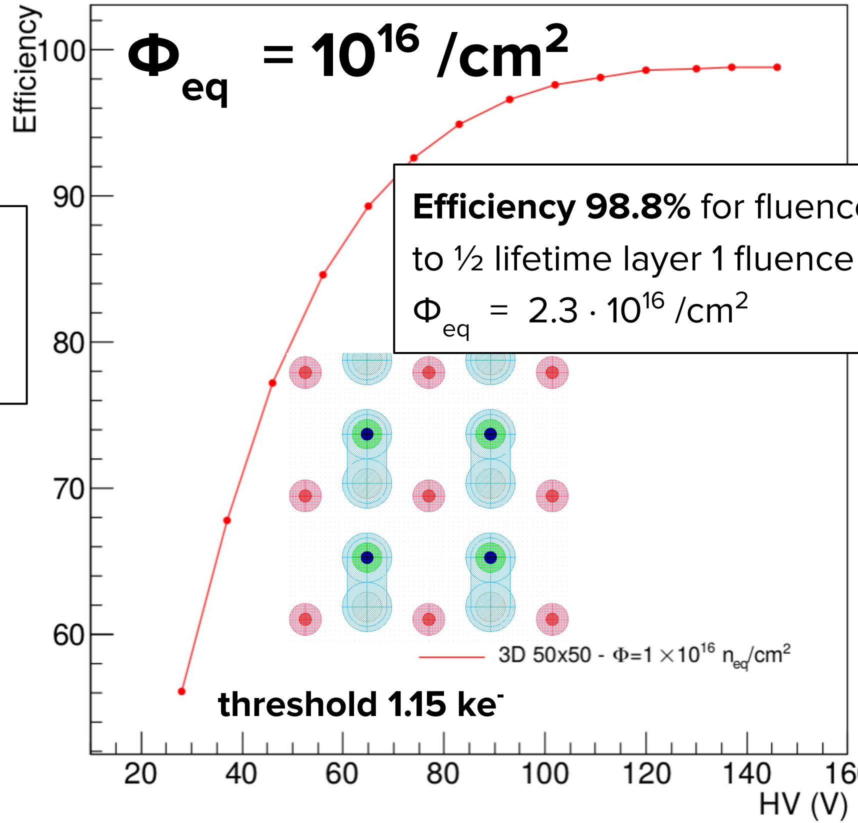
3D sensors

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



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

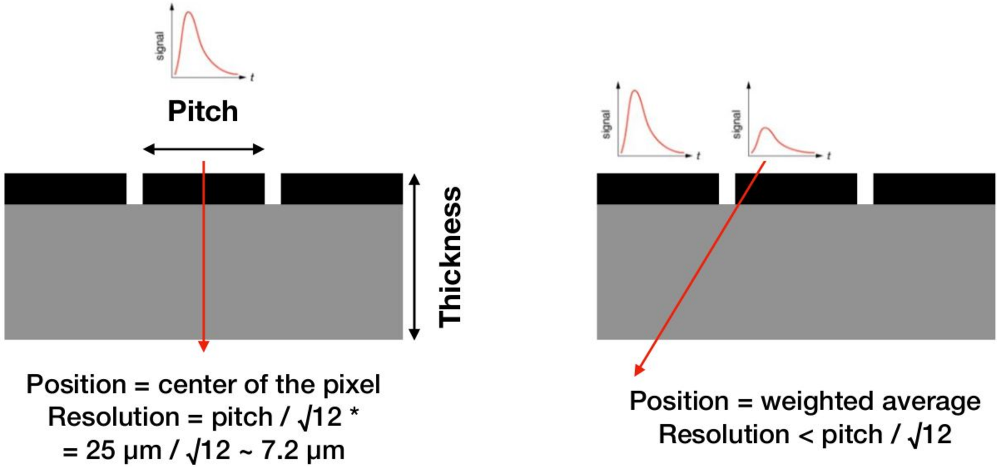
$\Phi_{eq} = 10^{16}$ /cm^2



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

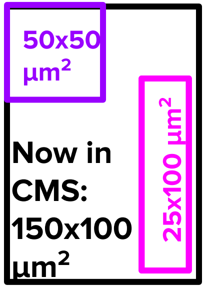
For physics results the resolution obtained with new pixel module is important:



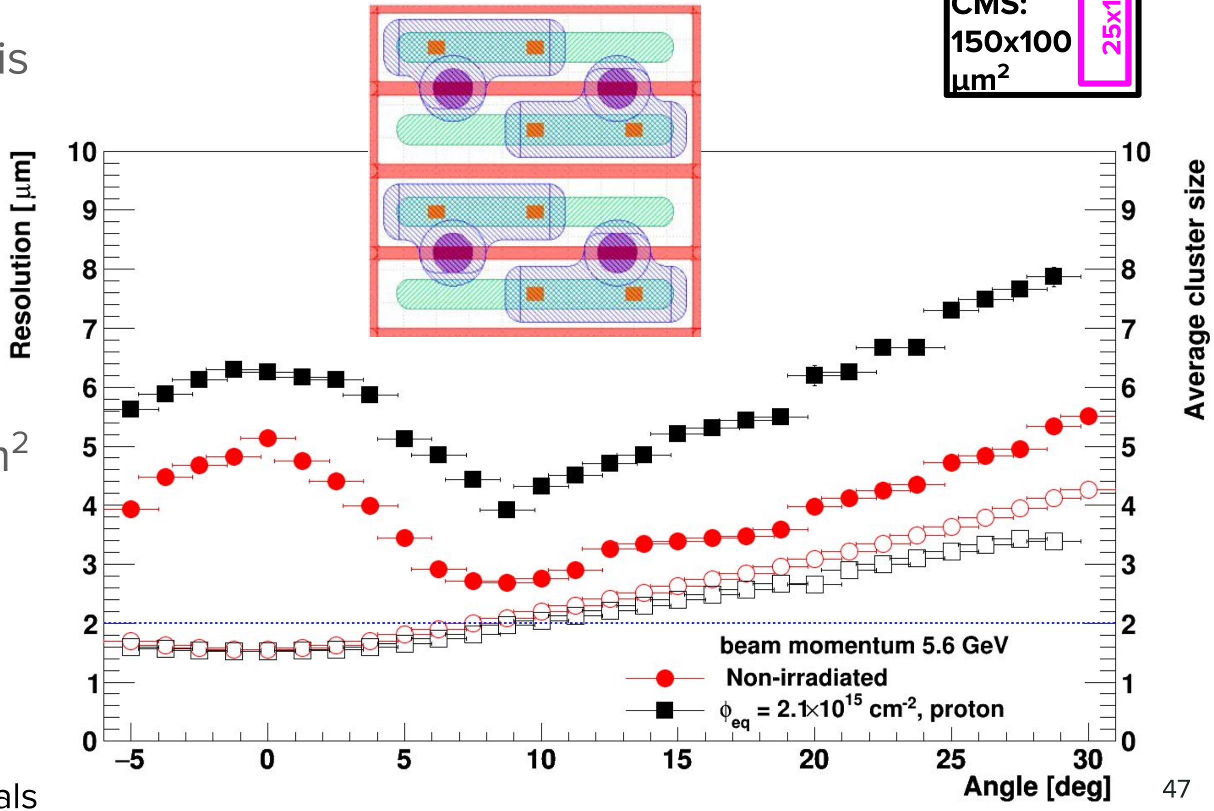
Resolution improves with angle: charge sharing gives a weighted average

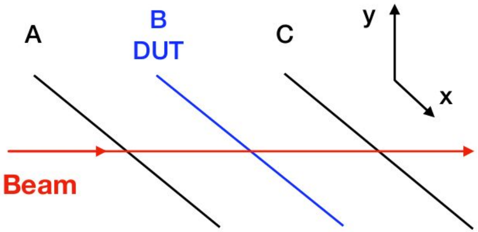
➡ better resolution

Resolution for 25x100 μm^2 pixels RD53A



- 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 $\Phi_{eq} = 2{\cdot}10^{15}/cm^2$

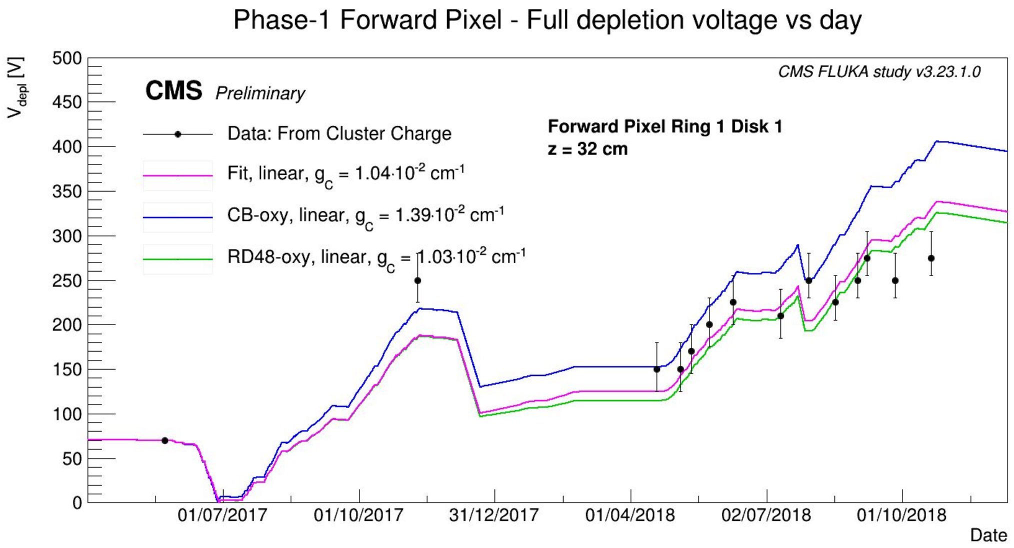


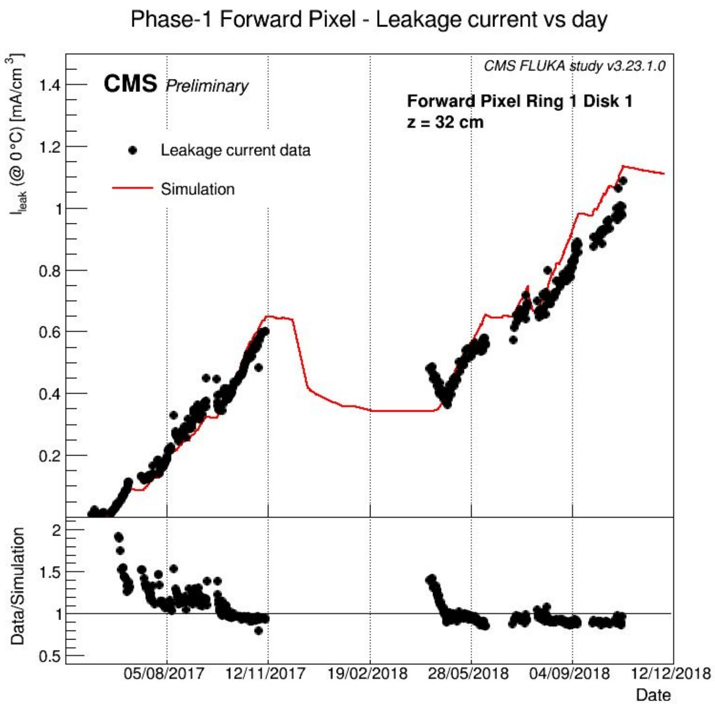


Resolution obtained with triplet residuals

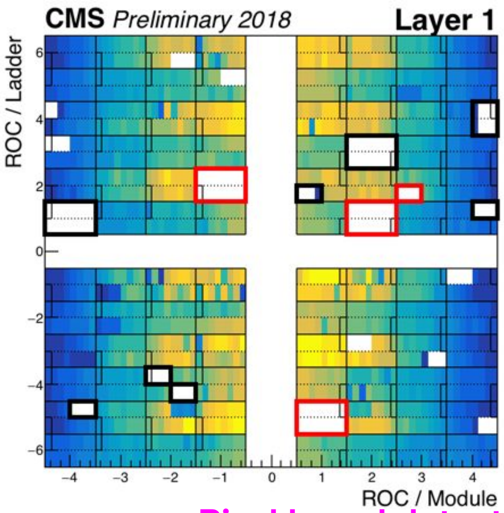
Radiation effects in the CMS forward pixel detector

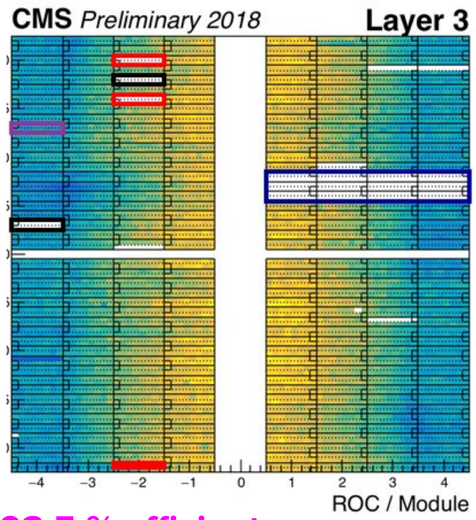
- On-module temperatures better understood than in barrel detector



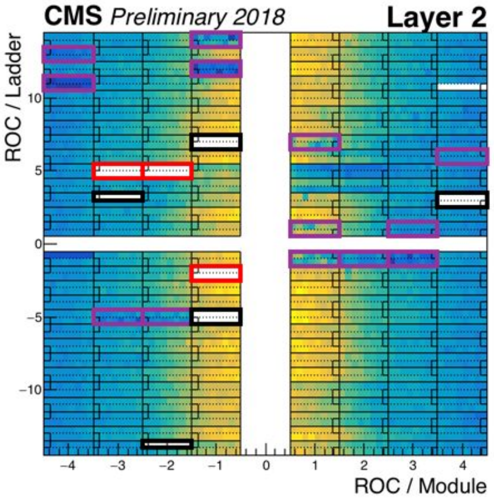


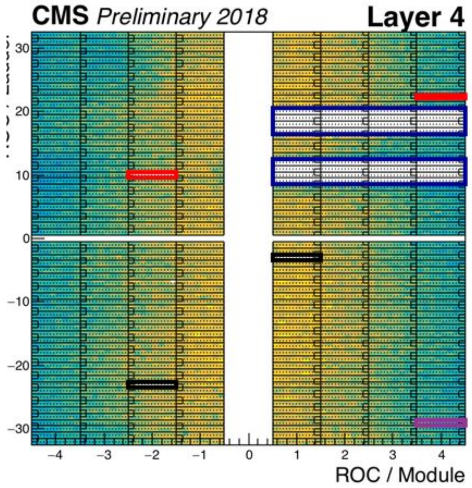
Leakage current depends on fluence and temperature





Pixel barrel detector 93.5 % efficient





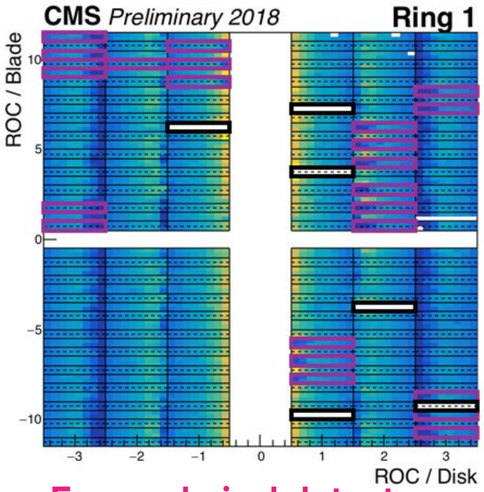
Malfunction since 2018

Malfunction since 2017

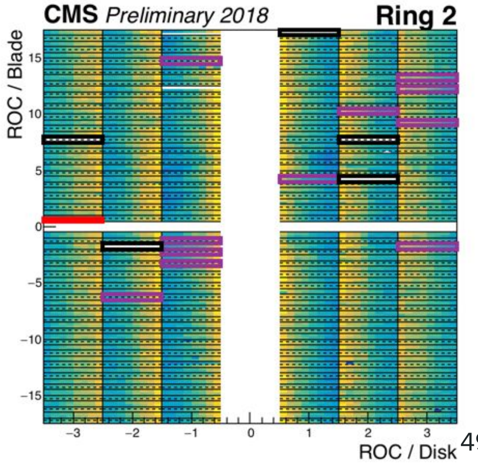
Behind 2017 broken DCDC converters (see later)

Connection problem → bias voltage switched off (see later)

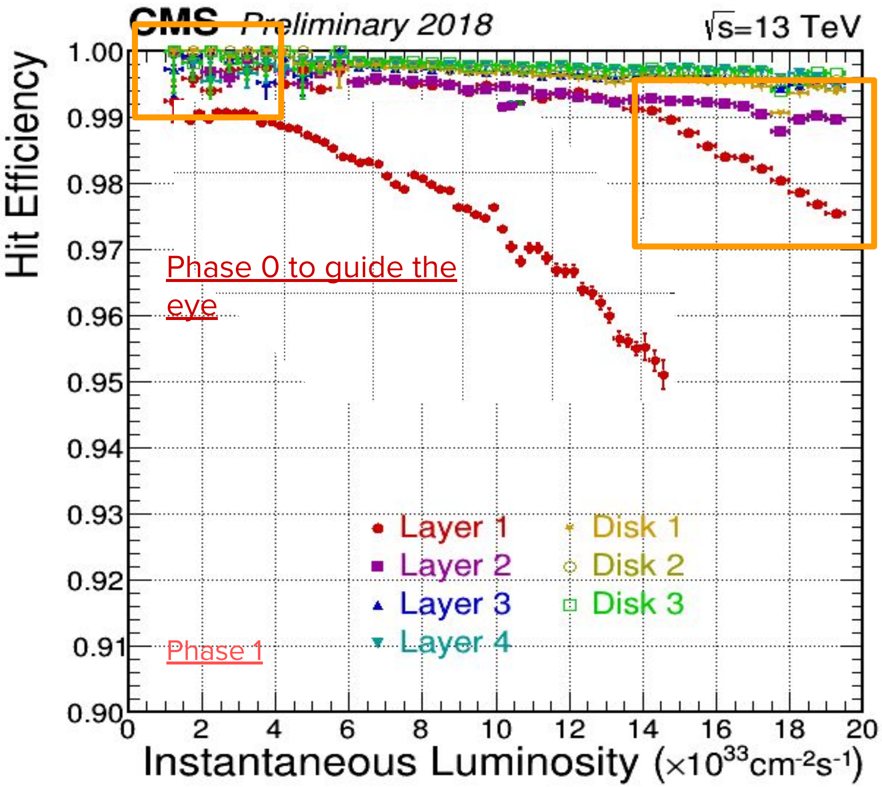
94.3% efficient



Forward pixel detector 96.7% efficient



Detector performance



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

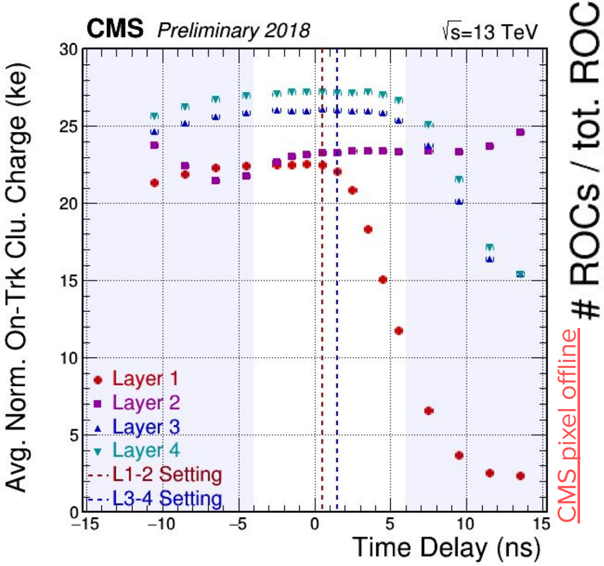
Overall a high efficiency: good performance!

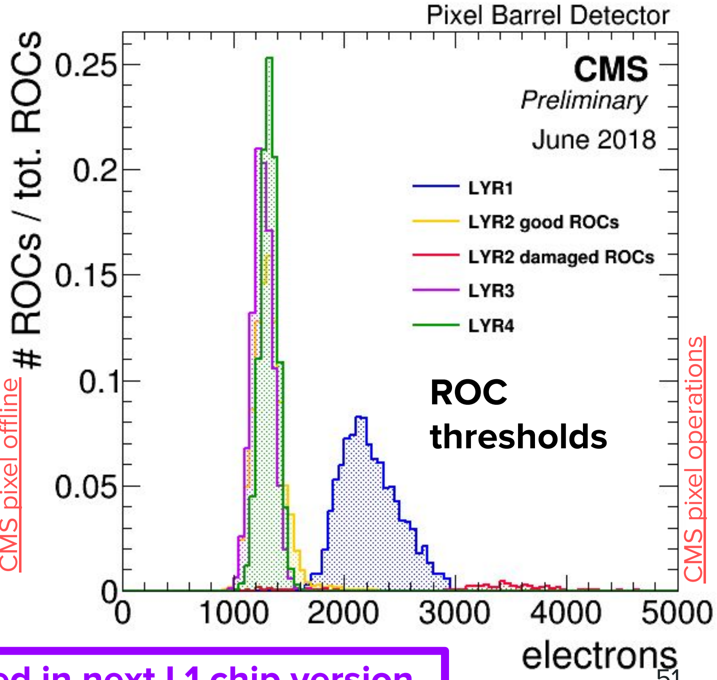
Inefficiency from synchronization loss between data and time stamp buffer at high and low rates:

- 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

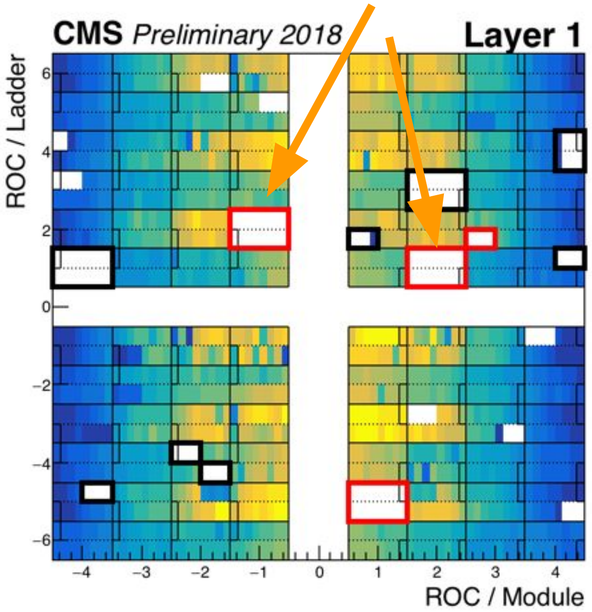


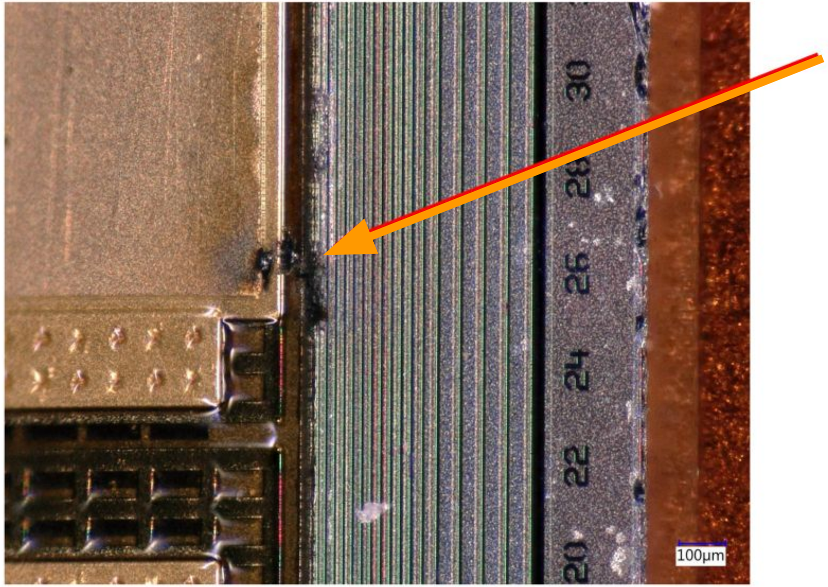


All solved or addressed in next L1 chip version.

More problems with layer 1

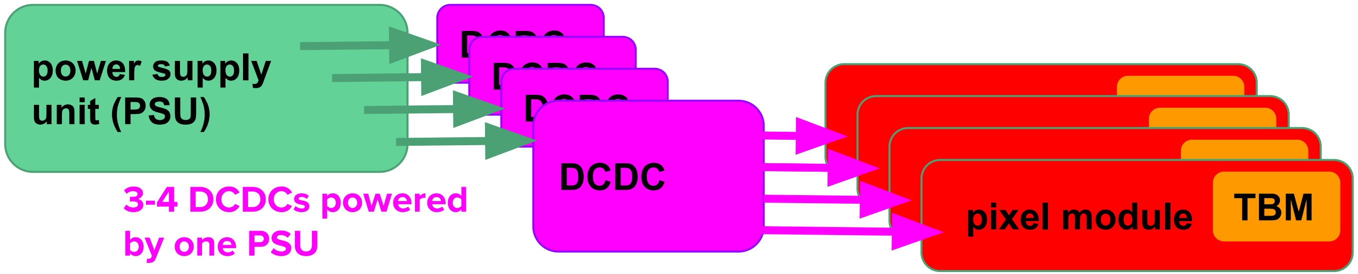
- HV problem on the High Density Interconnect (HDI), the flex on the module: shorts in June 2018
- Stayed at 450 V in 2018





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)

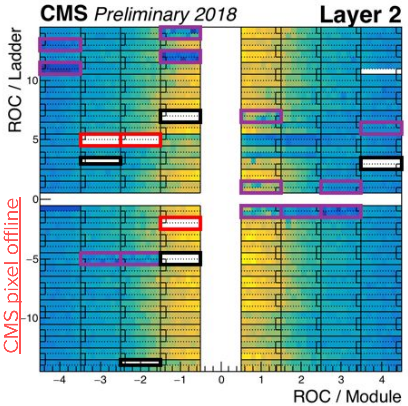
- 30 single event upsets (SEUs)/fb^{-1} in L1 transistor in TBM latch sets TBM to ‘no readout’ mode: “**stuck TBMs**”
- recovery only with **power cycle**. Lowest granularity: one **DCDC converter**.

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.

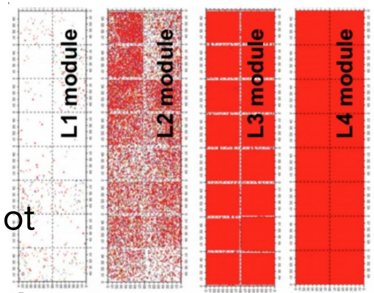
2020+: new DCDCs, new L1 TBMs.



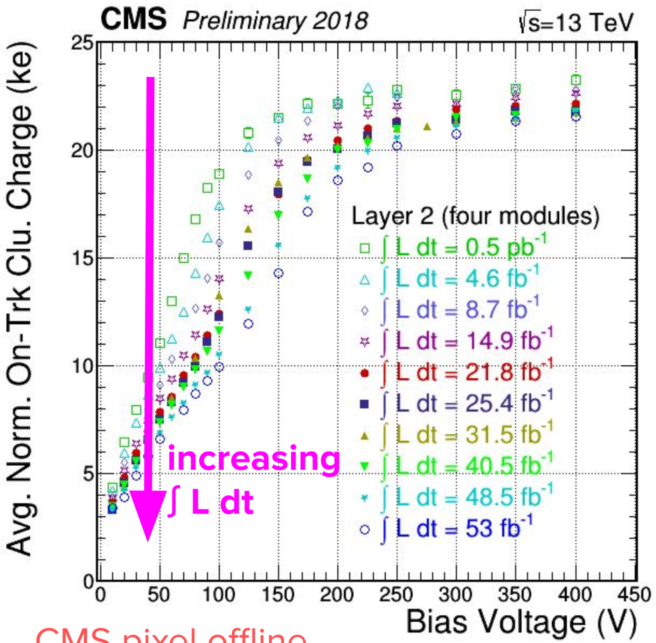
Layer 2 damaged chips

3: readout chips

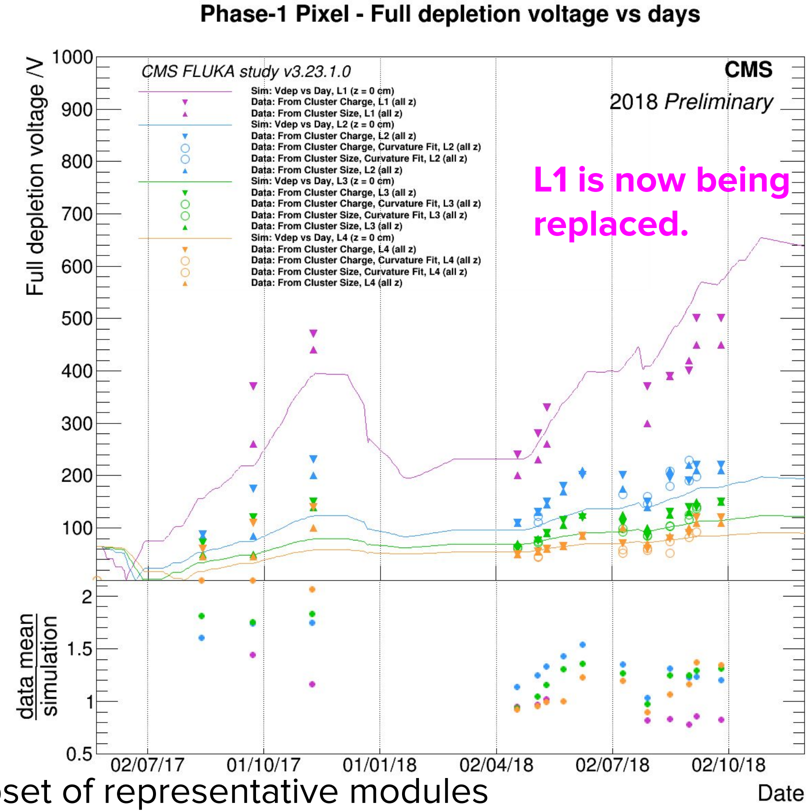
- module power and bias voltage grouping not the same
- **HV on, LV off caused chip damage** from sensor leakage current: 8/96 L1 modules lost in 2017



Radiation effects on depletion voltage in CMS



CMS pixel offline



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

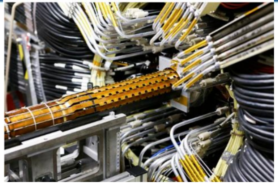
Simulation with effective space charge Hamburg model (E_{eff}=1.21 eV), fluence from DPMJet + FLUKA 3.23.1.0

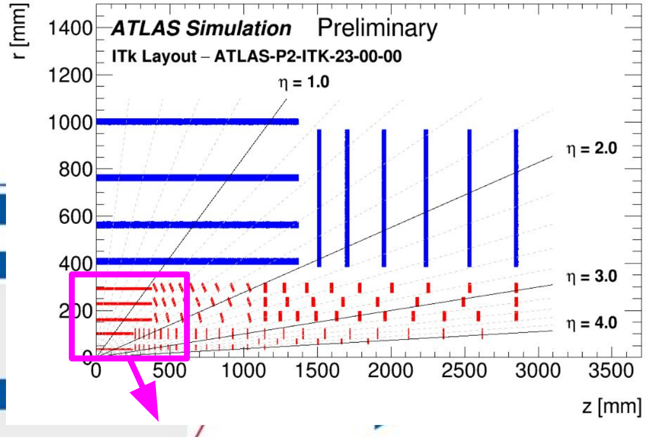
Hamburg model parameters from Michael Moll

CMS pixel operations

Fluences in the ATLAS pixel detector

From the high lumi LHC project





Current ATLAS pixel detector

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

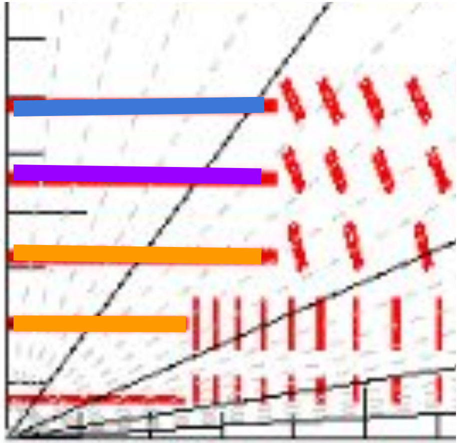
ITk predictions

Φ_{eq}=~$1\cdot10^{15}$/cm^2

Φ_{eq}=~$4\cdot10^{15}$/cm^2

Φ_{eq}=~$4\cdot10^{15}$/cm^2

3D: Φ_{eq}=~$8.1\cdot10^{16}$/cm^2



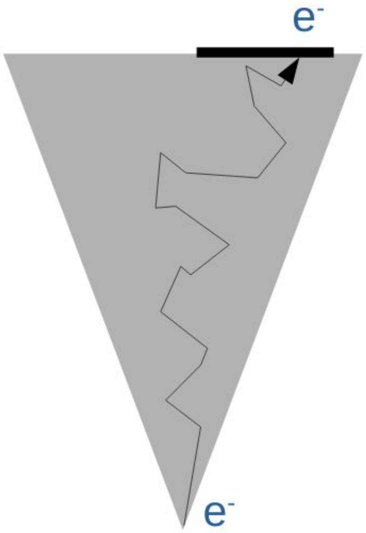
From ATLAS-IDET-2017-10

Allpix^2 charge propagation

Generic Propagation module:

- Mobility from E and B fields with Jacoboni, Canali et al.
- Make steps with each the drift velocity and diffusion offset
- Steps for groups of charge carriers
- Default number of carriers per group: 10
- Default propagated charge: electrons

From Paul Schütze



Generic propagation

Implementation of trapping

By Sinuo Zhang

Propagate only **part of the charges in a group** according to

$$Q(t) = Q(t = 0)\exp[-t/\tau]$$

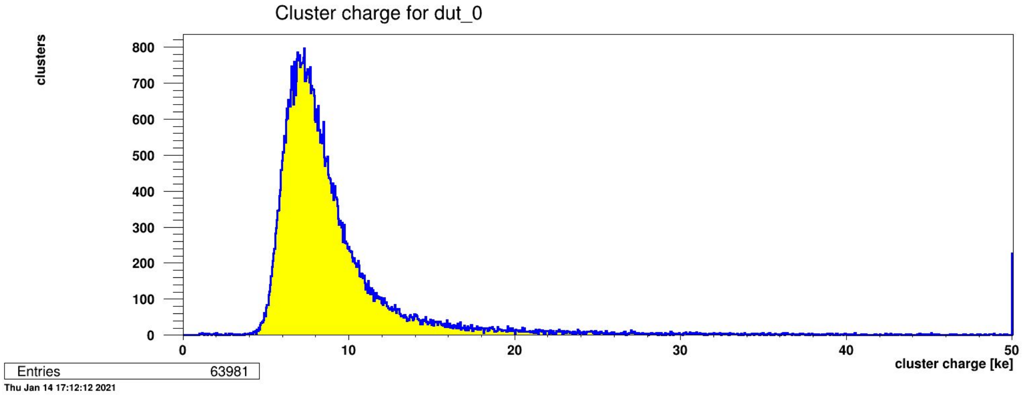
Effective trapping time by Kramberger et al

$$\frac{1}{\tau_{\mathrm{eff}_{e,h}}} = \beta_{e,h}\Phi_{eq}$$

$$\beta_h = (6.1 \pm 0.3) \times 10^{-16}\ \mathrm{cm^2/ns}. \quad \beta_e = (4.2 \pm 0.3) \times 10^{-16}\ \mathrm{cm^2/ns}$$

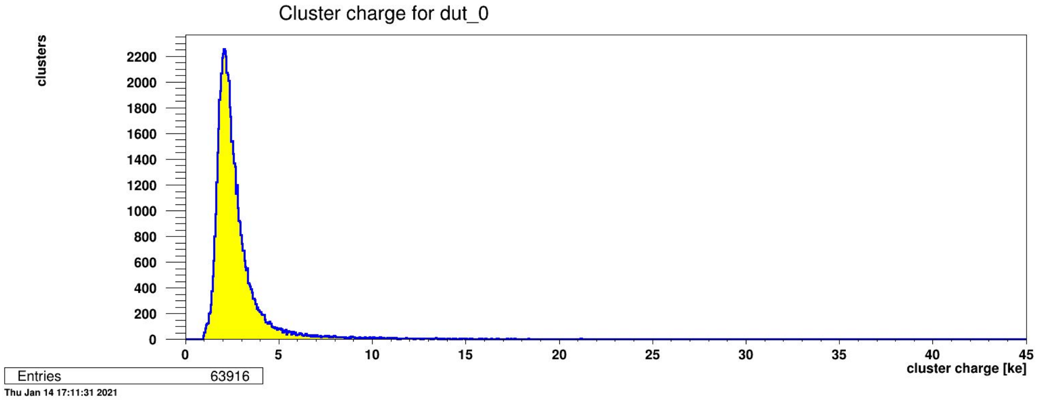
Cluster charge after trapping

- Unirradiated



- 100k events
- DUT RD53
- Threshold 1000e^-

- Trapping Φ_{eq} = 5e15 /cm^2



Further possibilities for trapping and simulation

- Temperature dependent trapping

$\kappa_e = -0.86 \pm 0.06 \qquad \kappa_h = -1.52 \pm 0.07$

$$\beta_{e,h}(T) = \beta_{e,h}(T_0)\left(\frac{T}{T_0}\right)^{\kappa_{e,h}}$$

From Kramberger et al

- Electric field dependent trapping

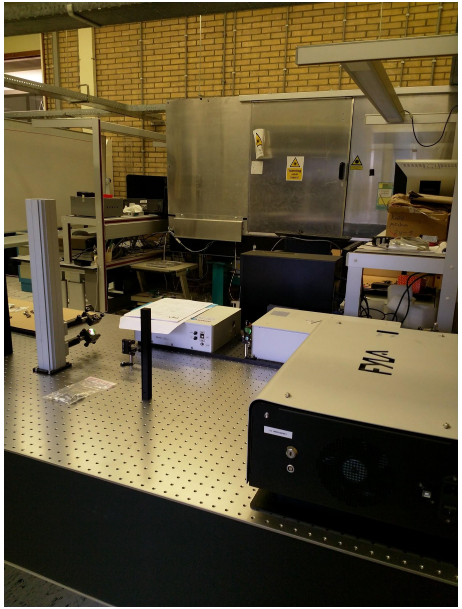
$$\tau(E) = \tau_0 + \tau_1 \cdot E$$

Thesis by Thomas Pöhlsen

- Error bars from errors on parameters: errors are not implemented / accounted for in Allpix^2
- Use corryvreckan for alignment procedure and analysis (see also this tutorial)

Lab infrastructure for sensor characterization

Laser diodes with 660, 980, 1060 nm



Commissioning a 200 fs pulse TPA-TCT setup

Laser setups used for

- Characterization of timing properties
- Characterization of sensor material
  - Can be used as input for TCAD studies
- Various other instruments:
  - X-ray tube 90 kV
  - Various radioactive sources
  - Oscilloscopes up to 33 GHz
  - Süss PA300 probe station
  - Keithley SCS4200 semiconductor characterisation station
  - Small scanning electron microscope
  - Wire bonder
- Experience with TCAD Sentaurus

Detector R&D lab infrastructure for sensor characterization

Laser diodes with 660, 980, 1060 nm

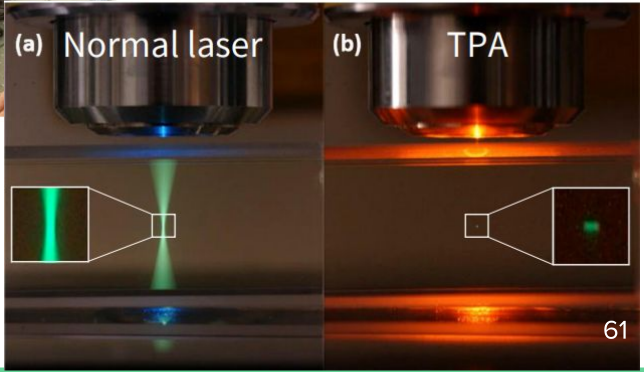
Commissioning a 380 femtosecond pulse “two-photon-absorption transient current technique” TPA-TCT setup

Laser setup already used to measure time resolution of Timepix chip.

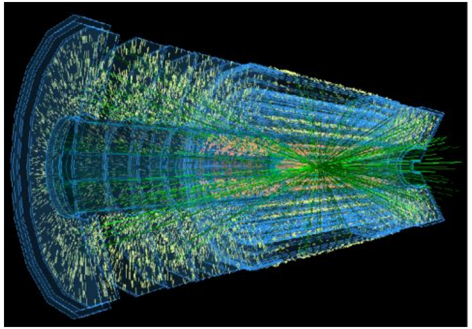
Will use TPA setup for precise 3D characterization of MAPS as well.

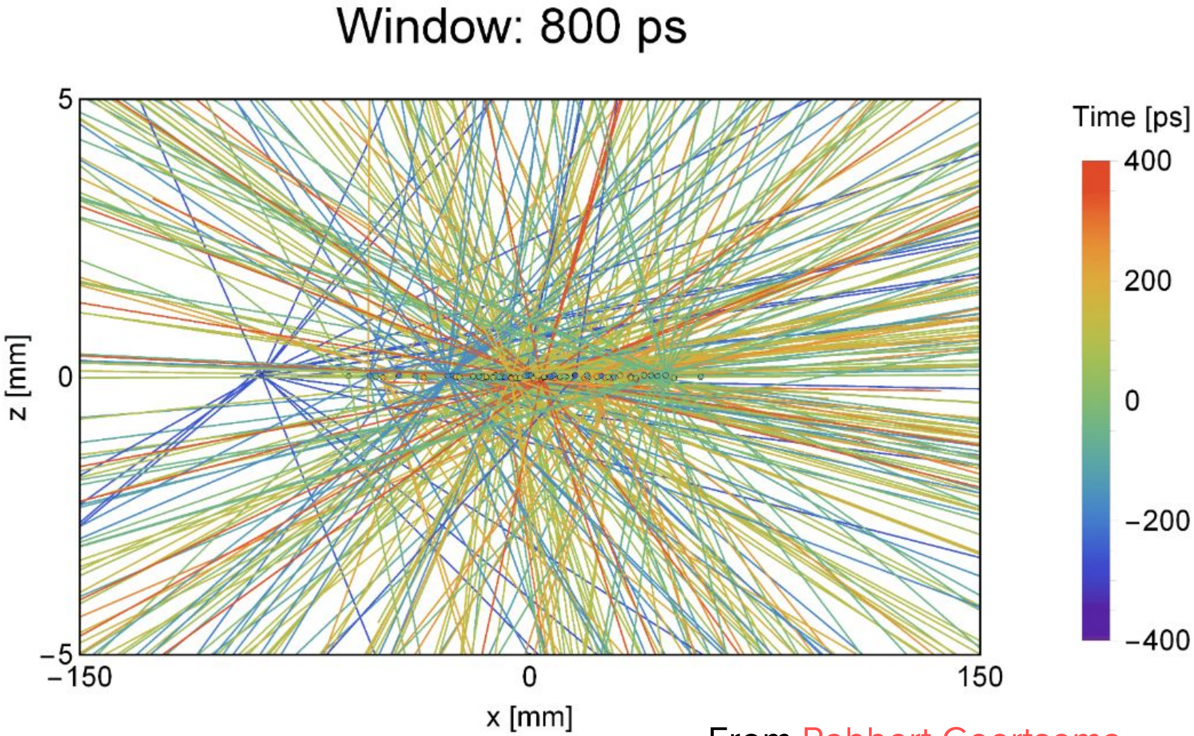
380 fs – 5.5 nJ – 1 μm wide spot

fast – powerful – precise



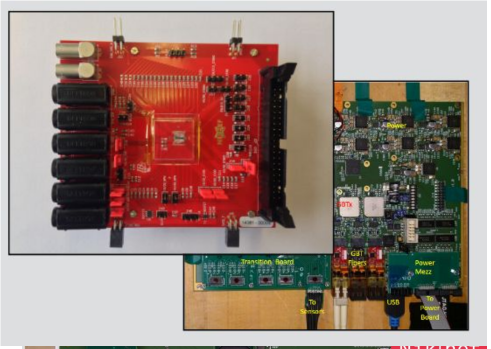
Distinguish vertices based on timing information





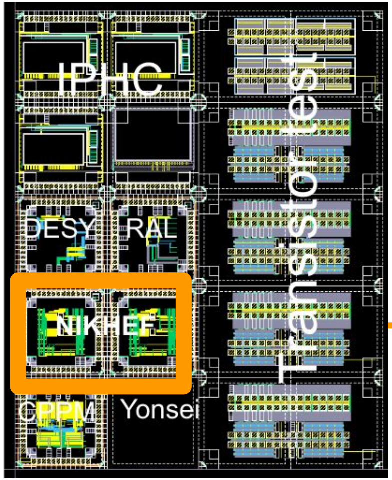
From [Robbert Geertsema]

Towards fast timing with MAPS



Nikhef was involved in ASIC design and readout of TowerJazz **180 nm ALPIDE** for the Alice ITS2 system

First MLR submission



Nikhef is involved in design of TowerJazz **65 nm ALPIDE** for the ALICE ITS3 system

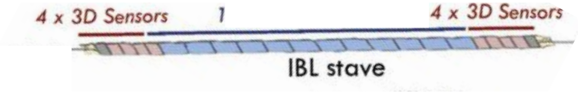
We currently defining our fast timing sensor and ASIC development program with Nikhef ET, ALICE and LHCb -- and eventually ATLAS? =)

Continue development of TJ 65 nm
Investigate timing with MAPS

CMS and ATLAS pixel detectors in LS2

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

[From Kerstin Lantsch](#)



2.8 Mrad / Φ_{eq}=5·10^{13}/cm^2 **L4: r=160 mm**

5.2 Mrad / Φ_{eq}=9·10^{13}/cm^2 **L3: r=109 mm**

8.5 Mrad / Φ_{eq}=1.8·10^{14}/cm^2 **L2: r=66 mm**

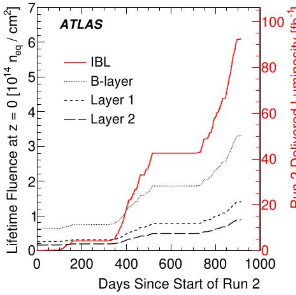
40.1 Mrad / Φ_{eq}=7.9·10^{14}/cm^2 **L1: r=29 mm**

Layer-2: r=122.5 mm **Φ_{eq}=~6·10^{13}/cm^2**

Layer-1: r=88.5 mm **Φ_{eq}=~1.4·10^{14}/cm^2**

B-Layer: r=50.5 mm **Φ_{eq}=~3·10^{14}/cm^2**

IBL: r=33.5 mm **Φ_{eq}=~6·10^{14}/cm^2**

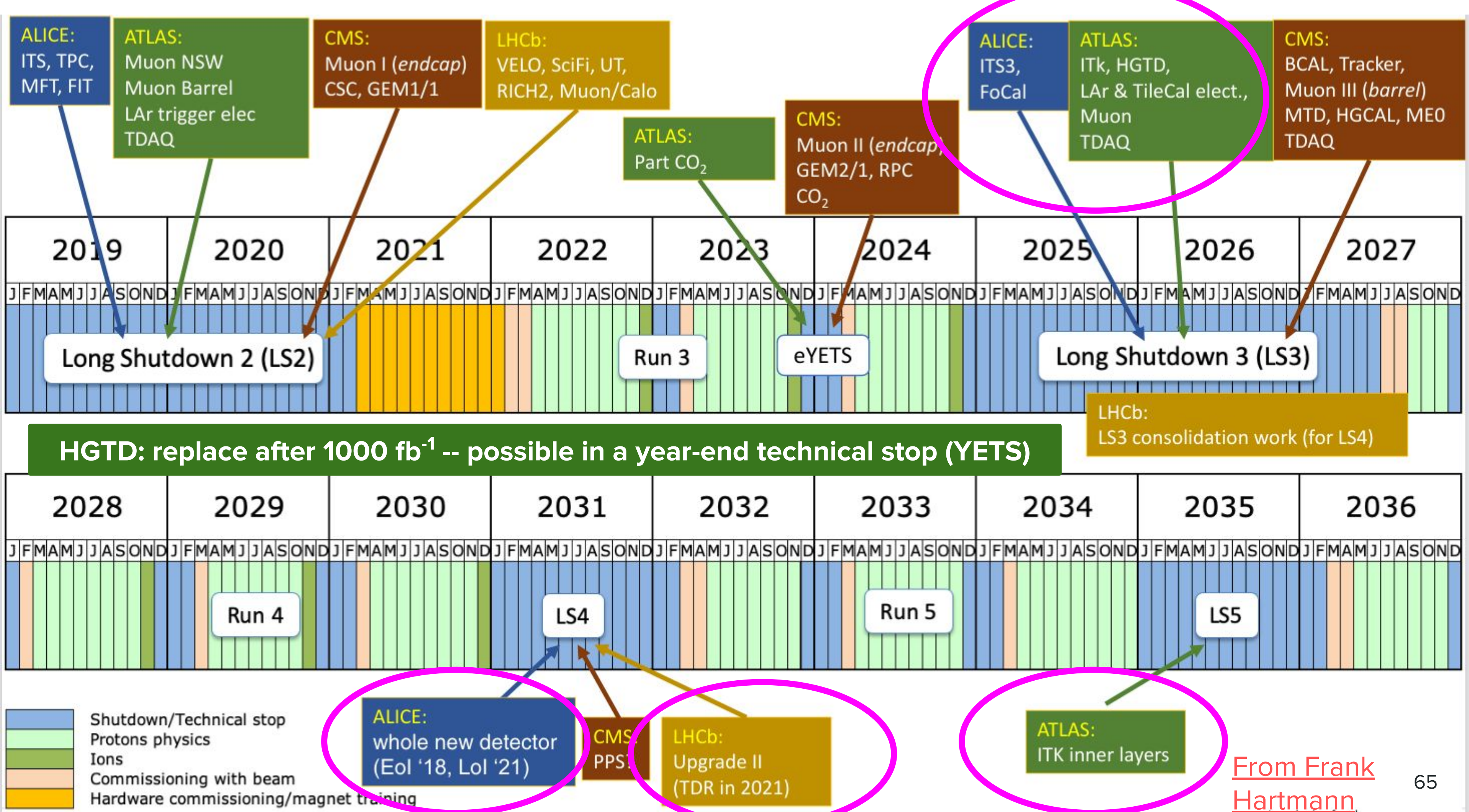


beam pipe: r=22.5mm

50.0 cm

[From ATLAS-IDET-2017-10](#)

Fluences as of today, from FLUKA 3.23.1.0



From Frank Hartmann