timo.peltola@helsinki.fi

Finnish Society for Natural Philosophy,
Helsinki, 17 February 2015

HELSINKI INSTITUTE OF PHYSICS

Silicon Sensors for CMS Tracker at High-Luminosity Environment

- Challenges in particle detection -

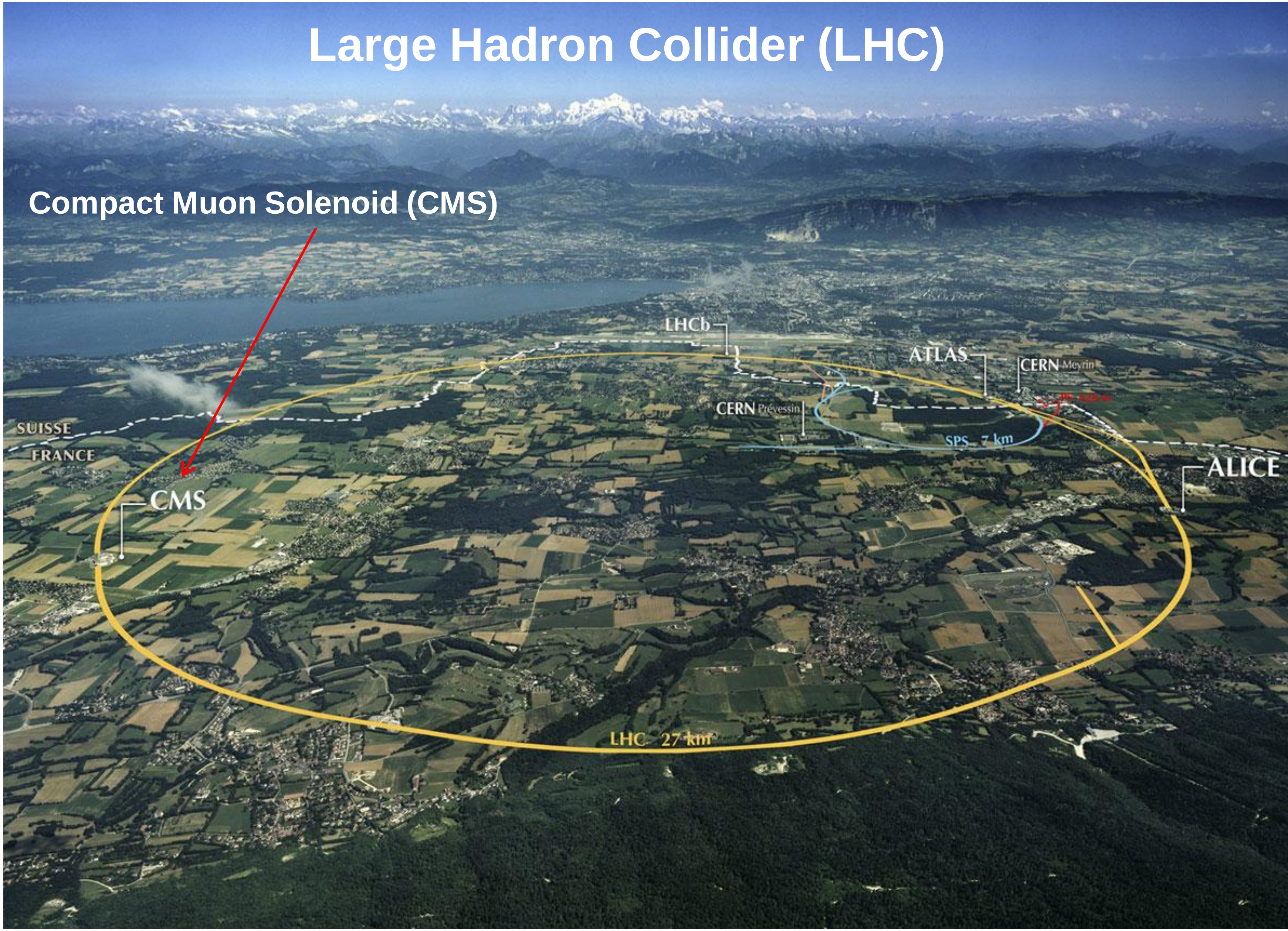
Timo Peltola

Helsinki Institute of Physics, P.O. Box 64 (Gustaf Hällströmin katu 2) FI-00014 University of Helsinki

Outline:

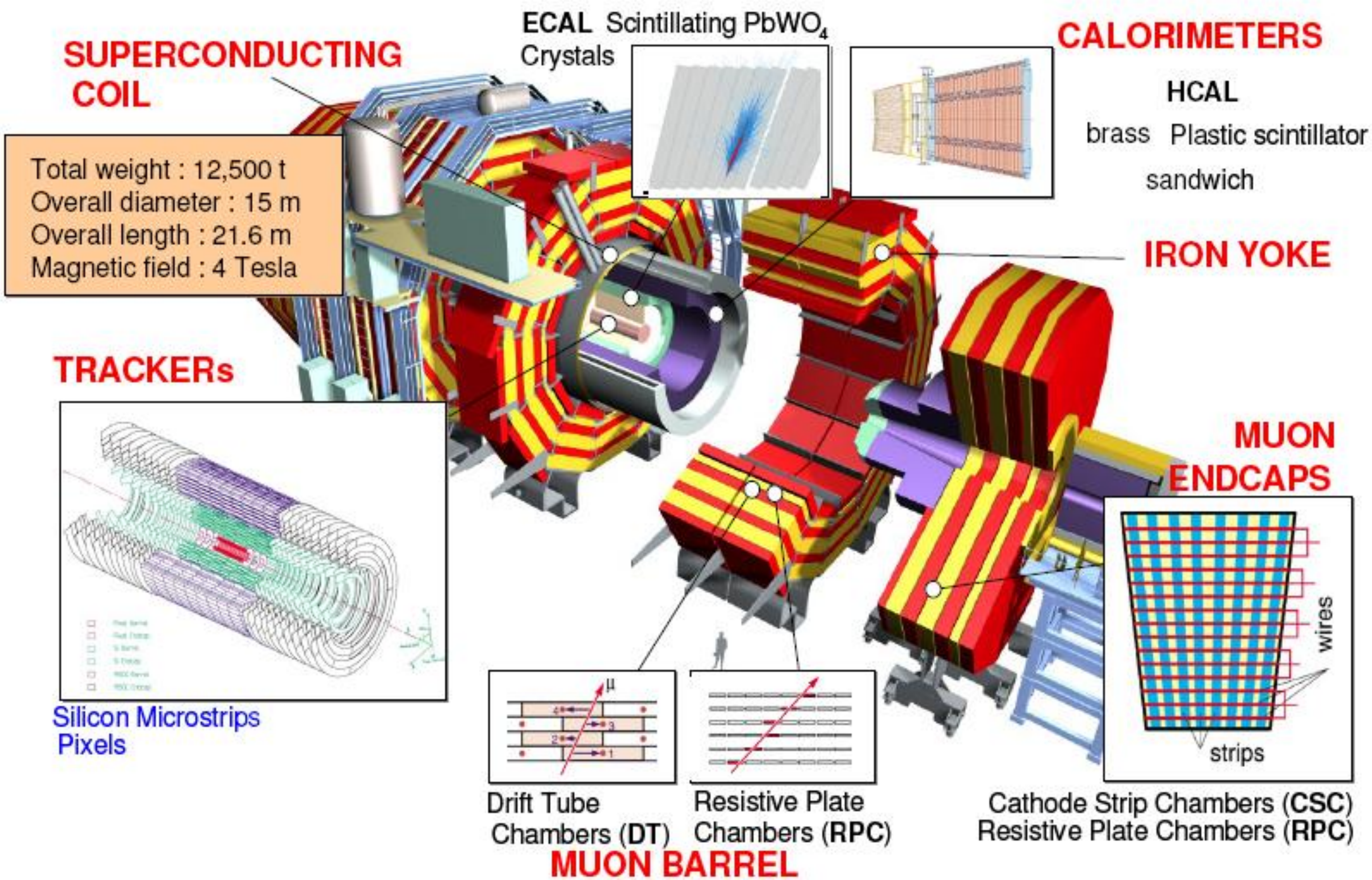
- **Introduction: LHC**
- **Compact Muon Solenoid**
  - Silicon detectors in CMS Tracker
  - Tracker upgrade to HL-LHC
- **R&D of silicon detectors for HL-LHC**
  - Defect Characterization
  - Numerical simulations
  - Sensor/material engineering: p-type, thinned ...
  - New structures: 3D, active edges, LGAD …
- **Summary**

Large Hadron Collider (LHC)



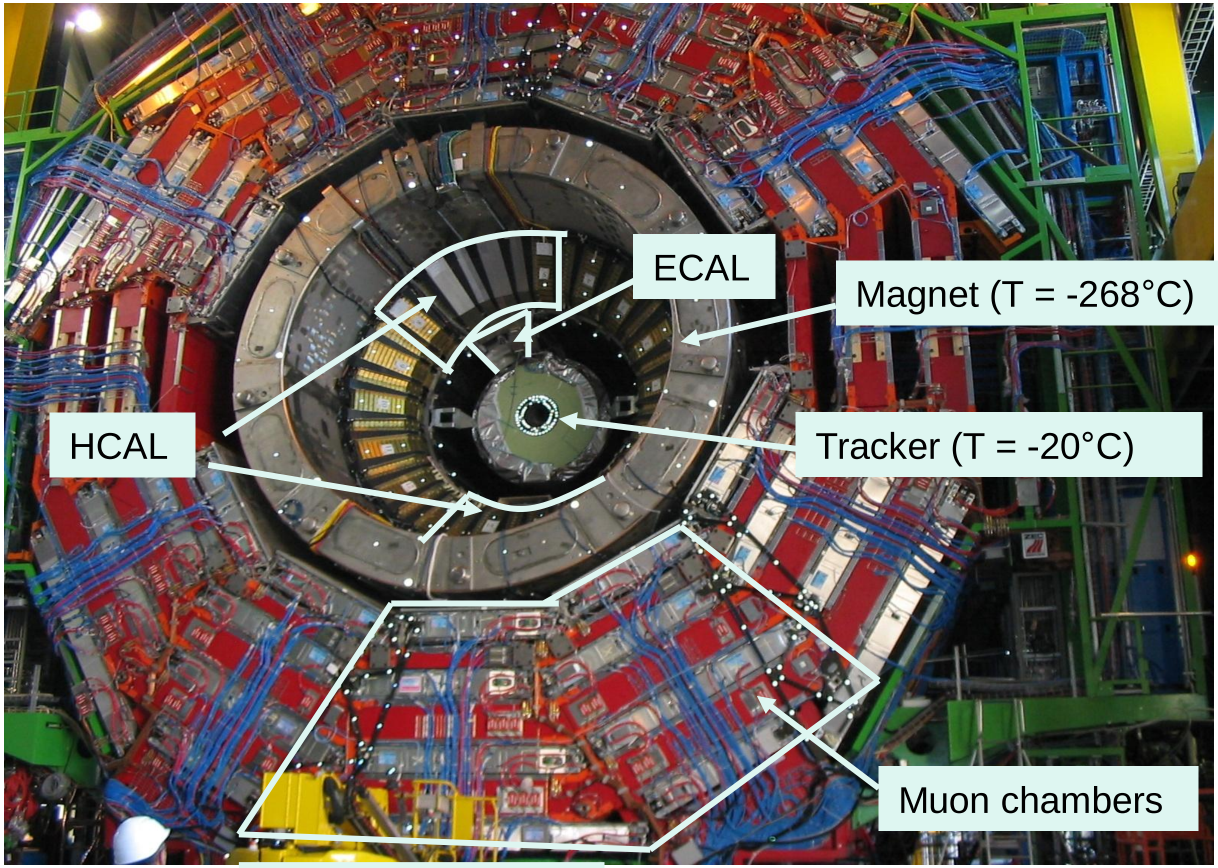
CMS detector: design I

- **CMS magnet**: T = 4.65 K doubles magnetic field ***B*** strength compared to STP
- **Iron return yoke**: 12-sided, 3-layered iron structure to contain and guide the ***B***



CMS detector: design II

Sub-detectors in Compact Muon Solenoid



HCAL: Hadron Calorimeter
ECAL: Electromagnetic Calorimeter

DETECTOR TYPES:

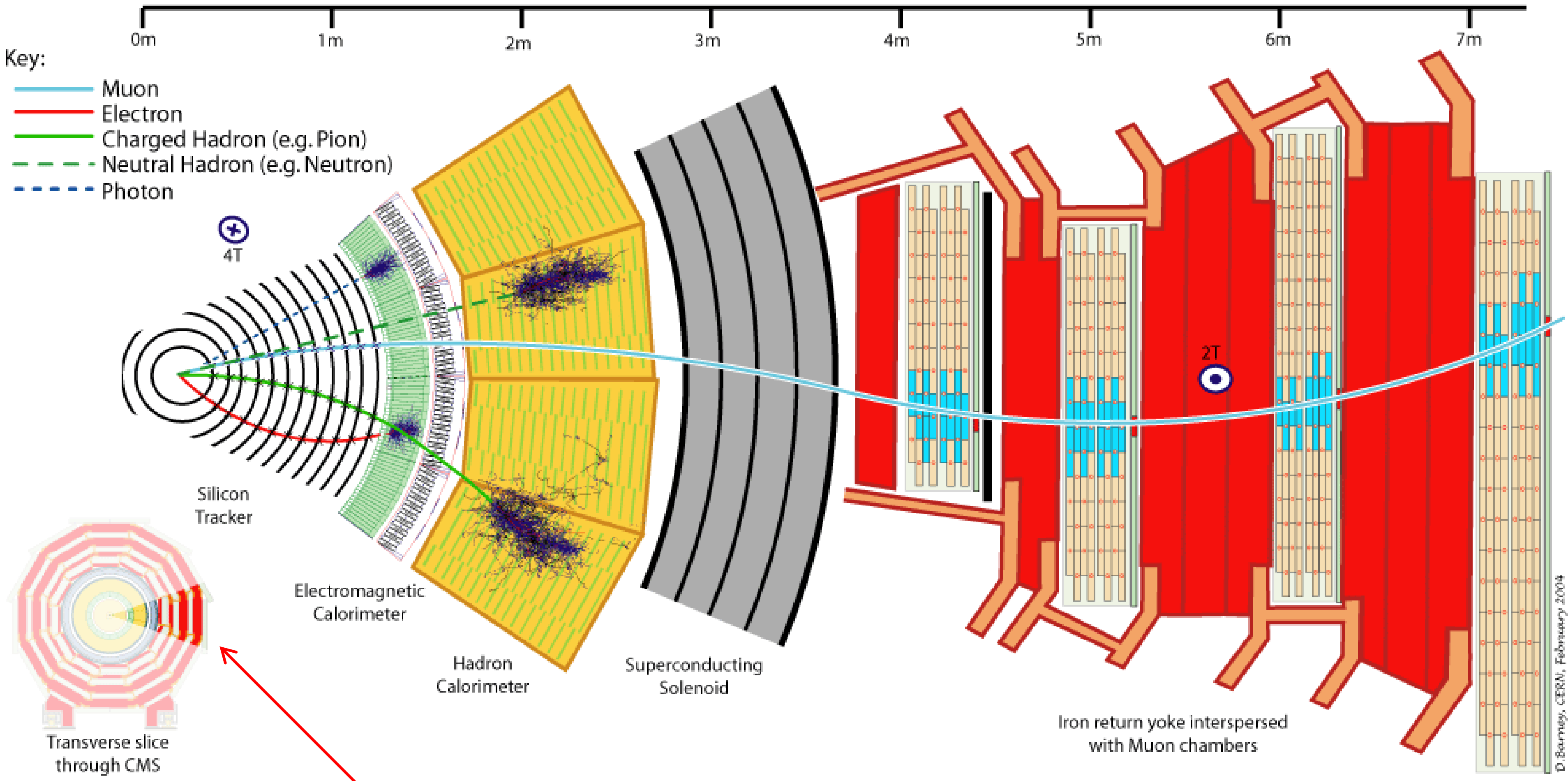
- ❑ **Tracking:** Semiconductor (Si) & gas detectors
- ❑ **Energy:** Scintillators

IN SEARCH OF:

- ✓ Higgs boson, found 2013
- ❑ Supersymmetric particles
- ❑ "Micro Quantum Black Holes"
- ❑ Gravitons
- ❑ Extra dimensions
- ❑ Dark matter, etc.

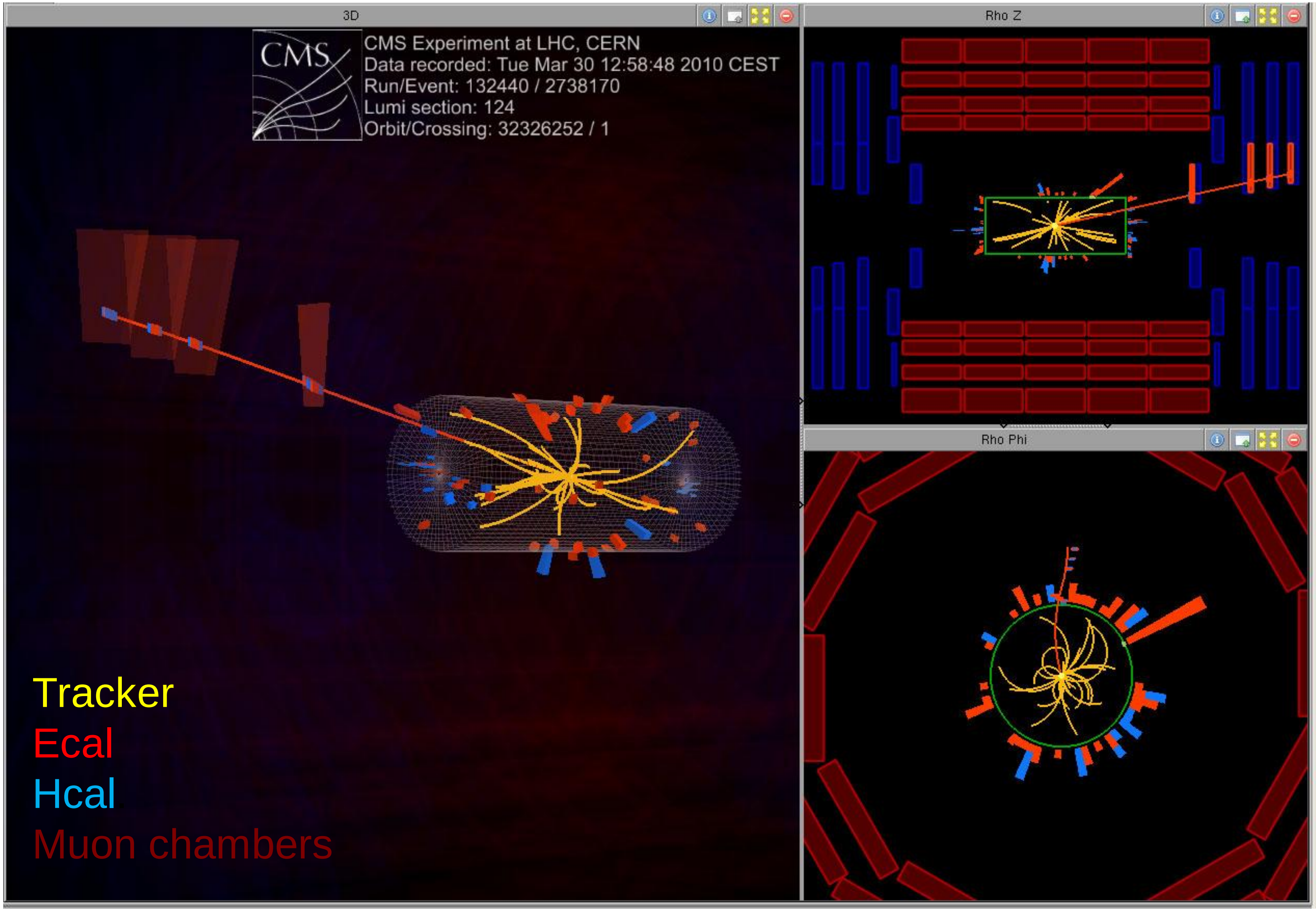
New particles produced at high energy: Likely to decay into particles that are known and detectable or inferred through the missing energy used up in making them

CMS detector: Particle detection I



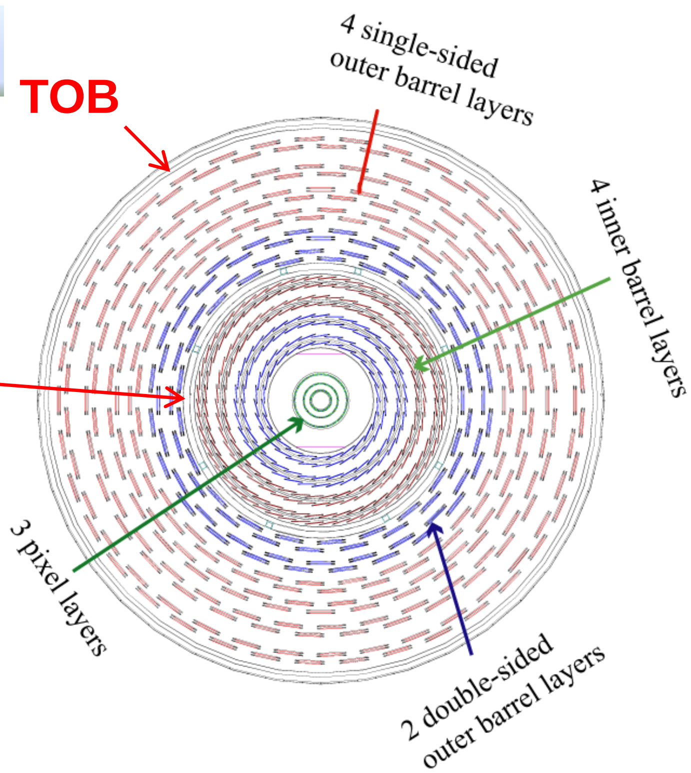
Transverse slice through CMS detector.

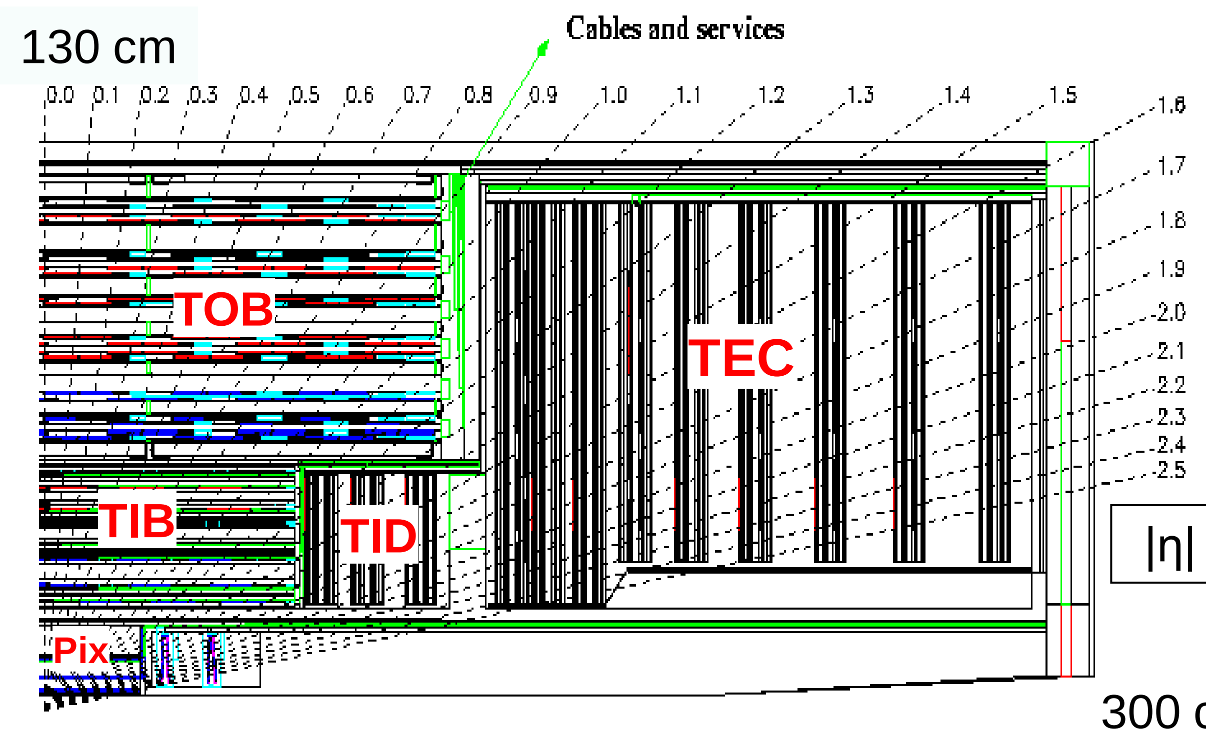
CMS detector: Particle detection II



CMS Tracker: structure I

- ❑ Paths of charged particles are recorded by finding their positions at key points
- ❑ Position accuracy ~10 μm
- ❑ **Design**: Silicon microstrip detectors surrounding the core of Si pixels → 225 m^2 of silicon

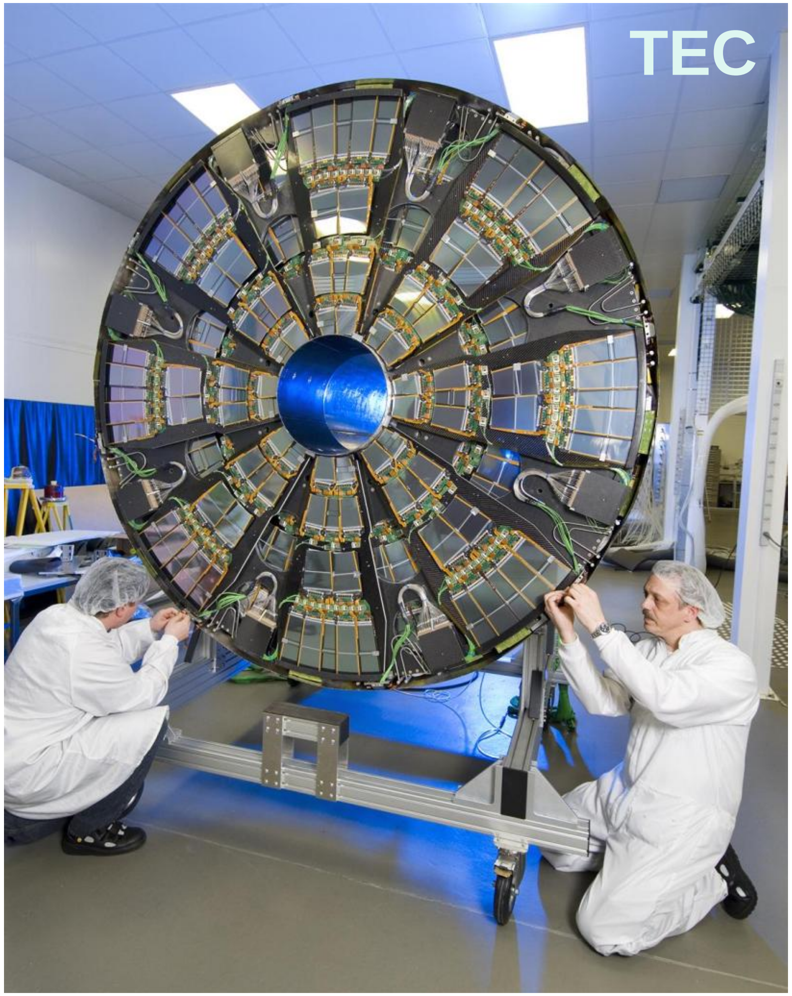




$|\eta| < 2.5$

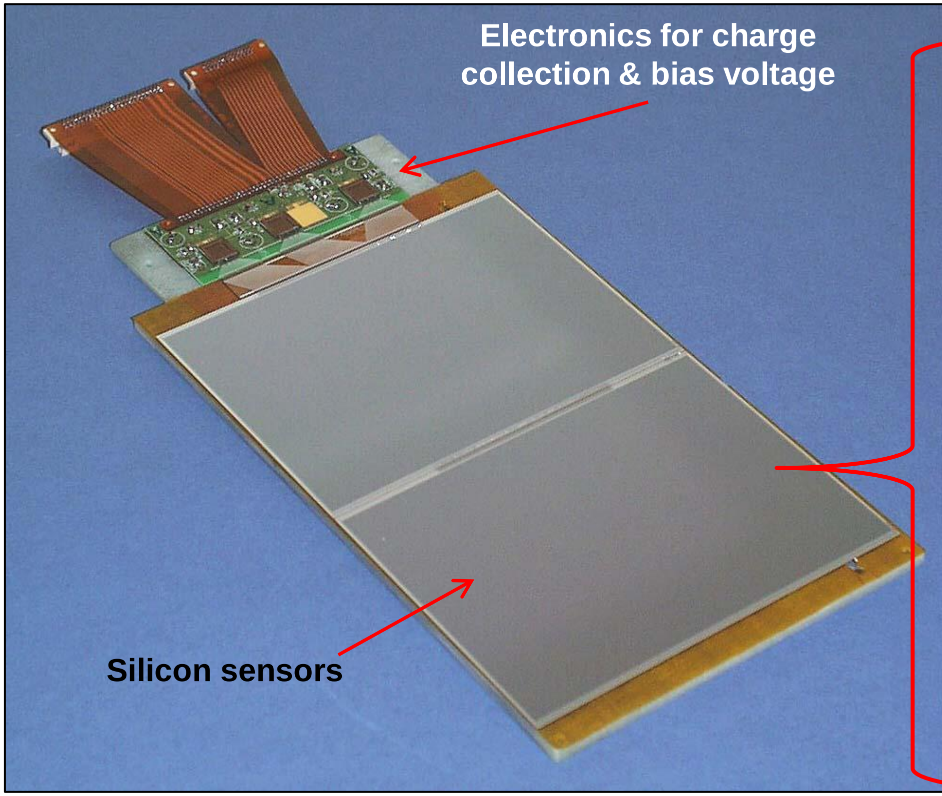
- 65M pixels
- 10M detector strips read by 80k microelectronic chips

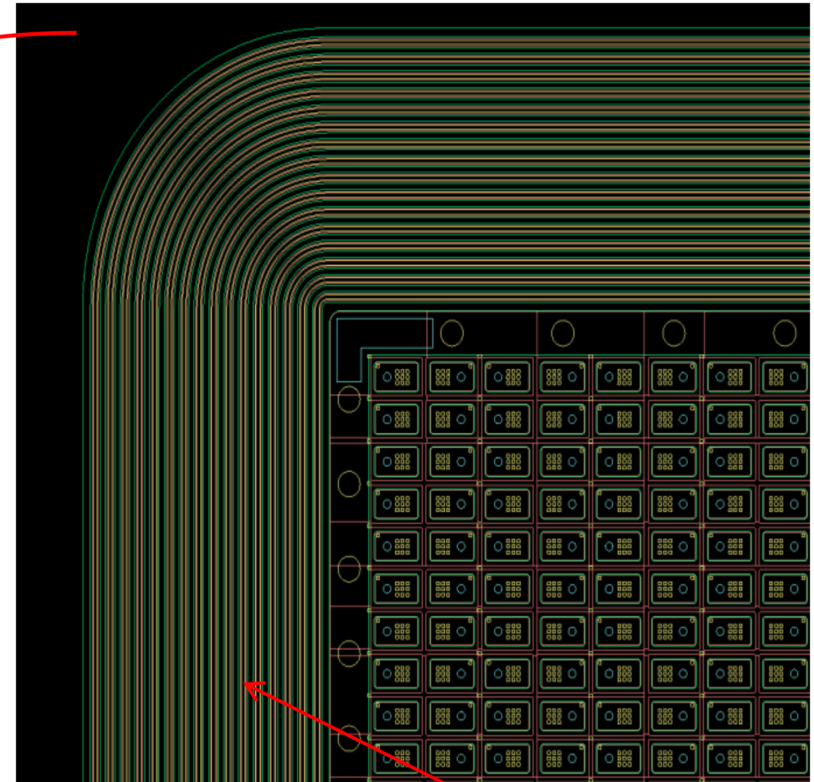
CMS Tracker: structure II



Tracker inner barrel (TIB) layer and endcap (TEC)

CMS Tracker: Silicon detectors





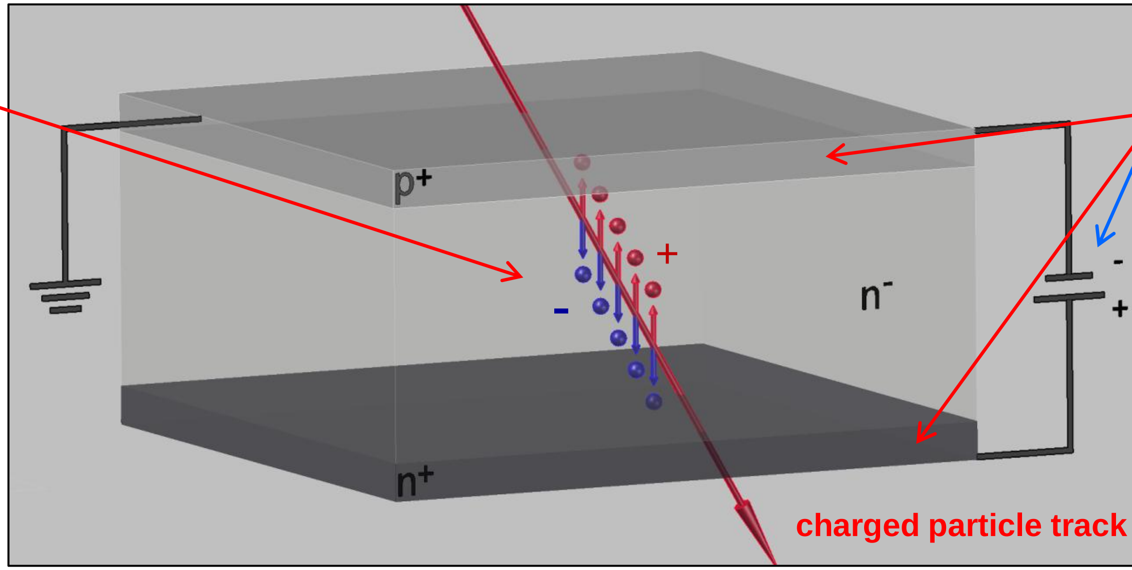
Silicon detector module made of APV25 and two 6" detectors

Pixel detector design with 18 guard rings

Operating principle of a silicon particle detector

2. Particle generates electron-hole pairs that are collected at electrodes opposite to their charge sign (+/-)

3. By segmenting the collecting electrodes (strips, pixels,…) position information is gained



1. Sensor volume is depleted of charge carriers by engineered doping concentrations & reverse biasing voltage

❑ **n^+/ n^-** : heavily/lightly doped silicon by donor atoms

PROS (in LHC):

❑ Charge is collected in nanoseconds

❑ Operation close to room temperature (Si: -20°C, Ge: -200°C)

❑ Cheap material, easy to process

CONS (in LHC):

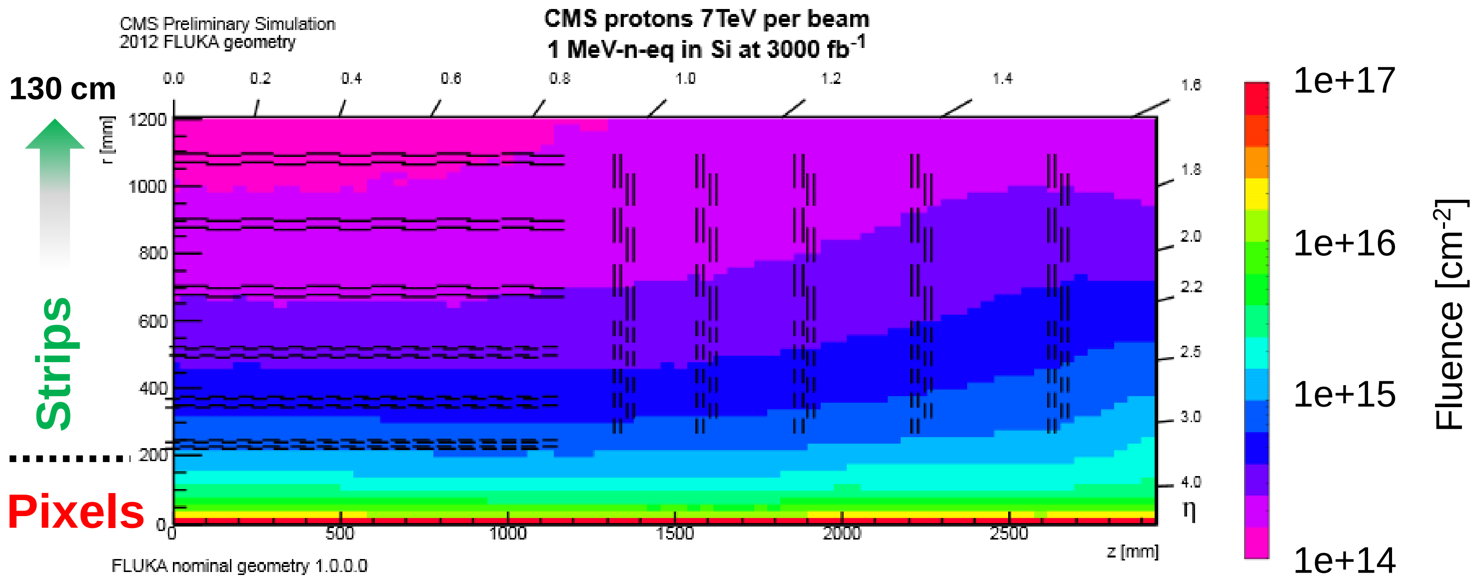
❑ High radiation fluences (>10^{13} cm^{-2}) produce defects to silicon crystal → eventually signal is lost to noise

CMS Tracker: upgrade to HL-LHC

- **Upgrade:** LHC → High Luminosity LHC (HL-LHC)
  - Expected $\int L = 3000\ \mathrm{fb}^{-1}$ after 10 years of operation
  - Pseudorapidity coverage from $\eta = 2.5 \rightarrow 4$

Challenges for tracker:
- Higher radiation hardness
- High occupancy → higher granularity
- Reduce material budget → thin sensors (~200 μm)

Estimated fluences in CMS Tracker at HL-LHC after 10 years of operation



Silicon detectors will be exposed to hadron fluences more than $10^{16}\ n_{eq}\ cm^{-2}$
→ beyond the performance level of detectors used currently at LHC

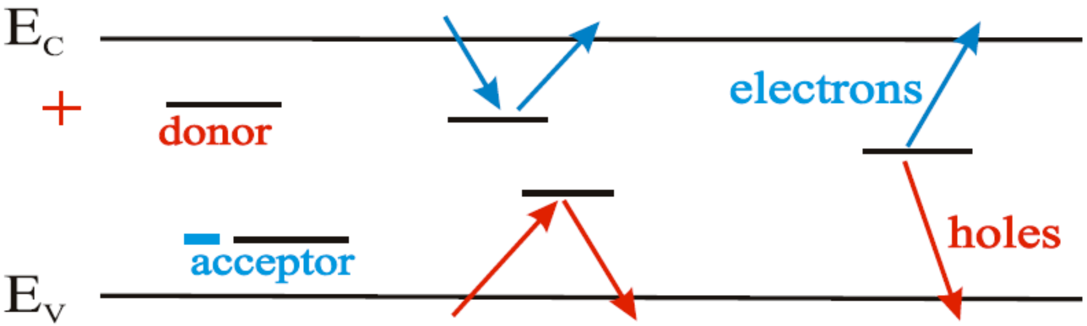
⇨ **R&D mission: development of silicon sensors for HL-LHC**

R&D: Defect Characterization

Motivation & Goal: New ways to develop radiation hard Si sensors → bridge the gap between the defect analyses and device performances

❑ Radiation induced degradation of the devices is caused by defects

❑ Electronic defect properties rule the impact on the device



Charged defects: N_{eff}, V_{dep}

Captured e, h: trapping → CCE

Generation e, h: I_{leak}

Measurement methods:

- C-DLTS (Capacitance Deep Level Transient Spectroscopy)
- I-DLTS (Current Deep Level Transient Spectroscopy)
- TCT (Transient Charge Technique)
- TSC (Thermally Stimulated Current)
- CV/IV (Capacity/Voltage vs. Current) ..

- Tests after irradiation with protons, neutrons, electrons and ^{60}Co-gammas

Defect parameters:

$\sigma_{n,p}$: cross sections
ΔE : ionization energy
N_t : concentration
type: acceptor, donor,…

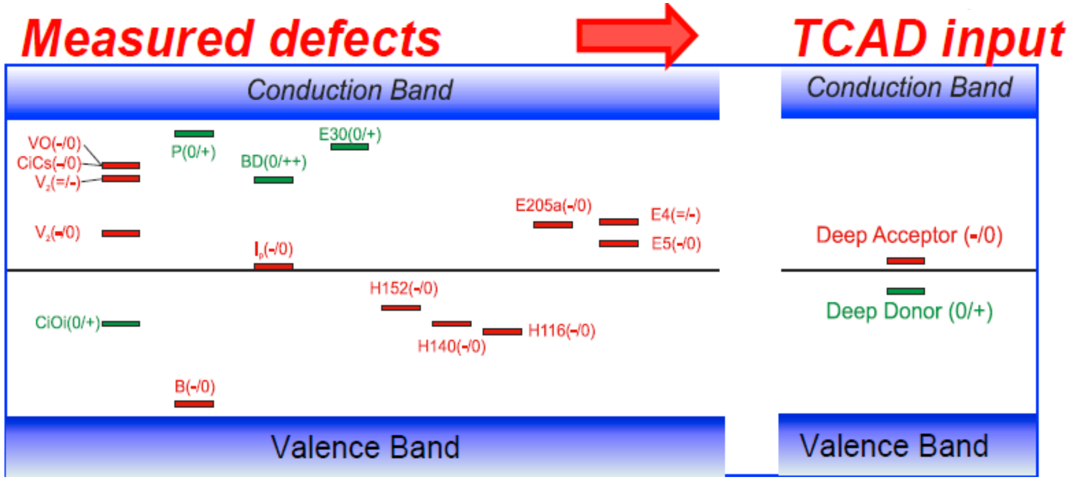
R&D: TCAD simulations

❑ **Why Technology Computer-Aided Design (TCAD) Simulations:**

- Electric fields not possible to measure directly
- Verify measurements → Find physical explanation to ‘weird’ results
- Make predictions from structures & conditions not yet measured → provide design parameters to new detectors

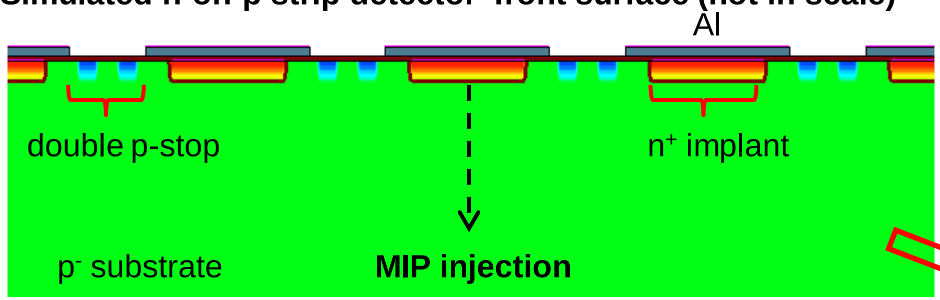
❑ **Working with ‘effective defect levels’ for simulation of irradiated devices**

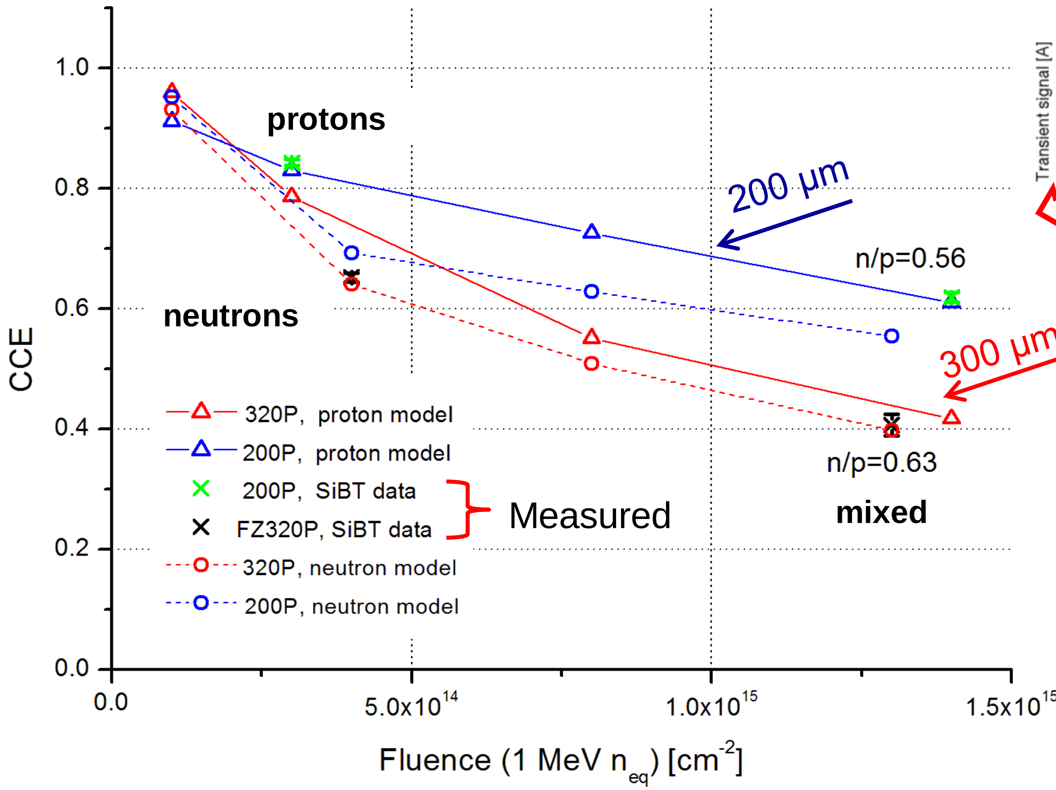
- Bulk damage approximated by ‘effective levels’ & surface damage by placing fixed charges Q_f at oxide/silicon interface
- Concentrations and cross sections of defects tuned to match experimental data



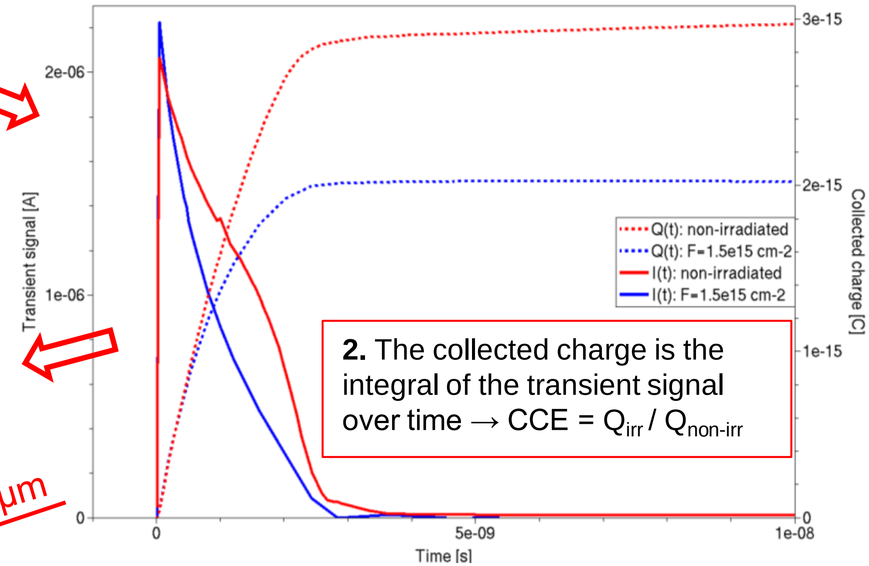
R&D: Simulated CCE

1. Simulated n-on-p strip detector front surface (not in scale)





- Charge Collection Efficiency (CCE) is the defining measure of the radiation hardness of a detector



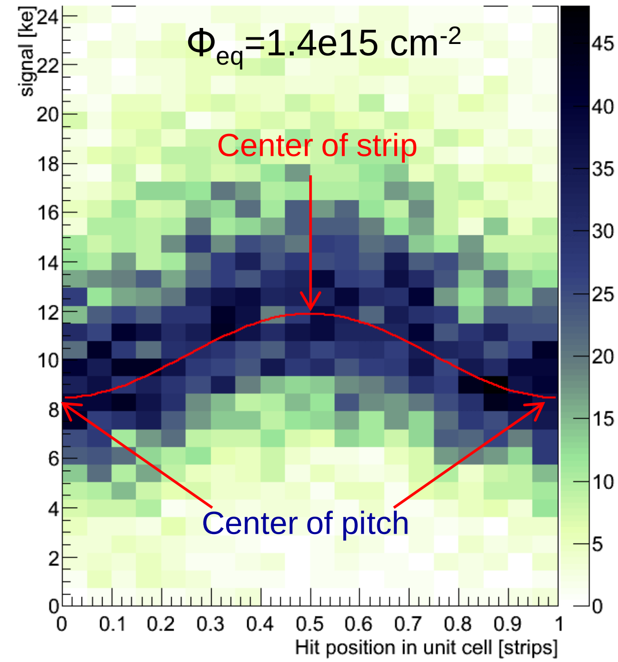
2. The collected charge is the integral of the transient signal over time → CCE = Q_{irr} / $Q_{non\text{-}irr}$

3. Simulated CCE of one detector type matches with measurement → **predictions for other detector types with equal irradiation type/dose possible**

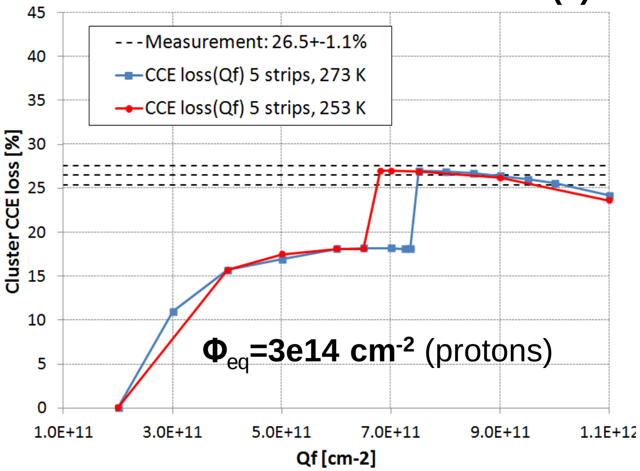
R&D: Measured & Simulated CCE(x)

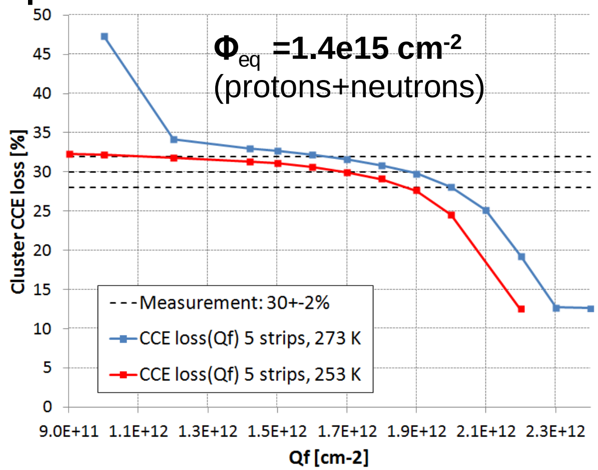
- **Observation:** **Heavily irradiated strip detectors demonstrate unexpected & significant position dependency of CCE (CCE(x))**
- **Simulation task:** **Find out why!**
- **Solution:** **Irradiation produces non-uniform distribution of shallow acceptor traps close to detector surface → greater drift distance, higher trapping of signal charge carriers**

Measured CCE(x):
CCE loss between strips ~30%



Simulated CCE(x) compared to measured:





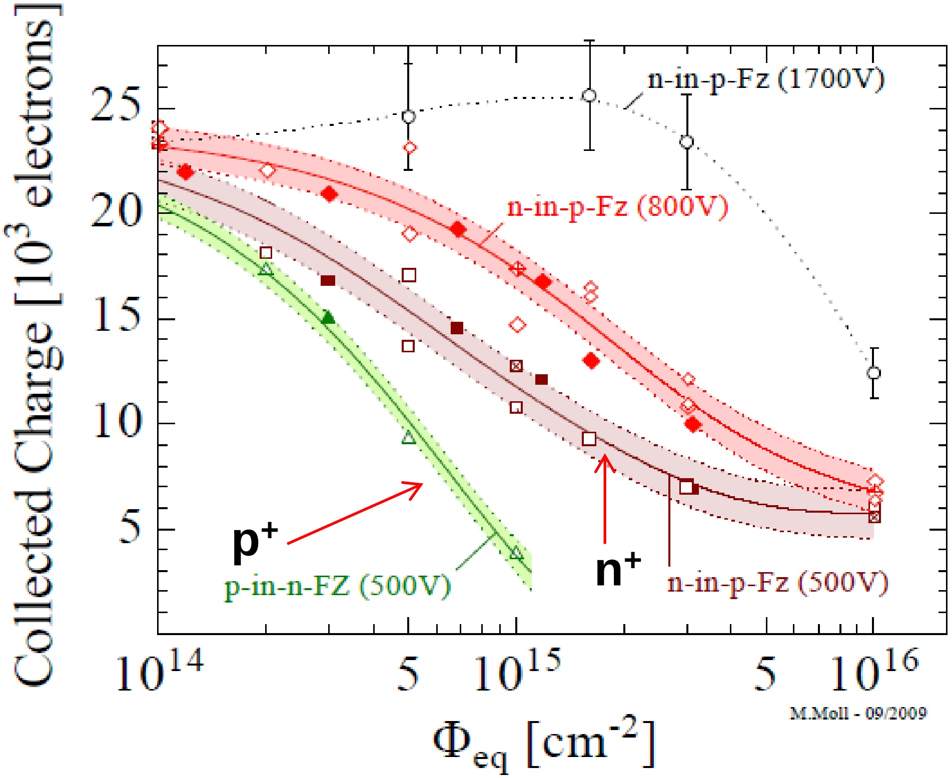
Interface charge $Q_f=(8.5\pm1.0)\times10^{11}$ cm^{-2} $Q_f=(1.6\pm0.2)\times10^{12}$ cm^{-2}

- Preliminary parametrization of the model for fluence range 3e14 – 1.5e15 cm^{-2}

3-level model within 2 µm of device surface

Type of defect	Level [eV]	σ_e [cm^2]	σ_h [cm^2]	Concentration [cm^{-3}]
Deep acceptor	E_C - 0.525	1e-14	1e-14	1.189*Φ + 6.454e13
Deep donor	E_V + 0.48	1e-14	1e-14	5.598*Φ - 3.959e14
Shallow acceptor	E_C - 0.40	8e-15	2e-14	14.417*Φ + 3.1675e16

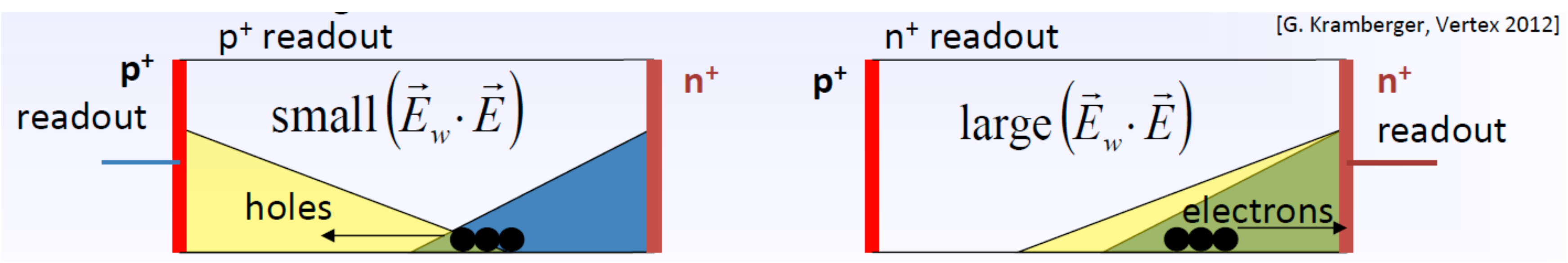
R&D: n^+ vs. p^+ readout



n^+-electrode readout (natural in p-type silicon):

- Electric field & weighting field maxima are at the same electrode ($E \cdot E_w$ maximum)
- Electron collection superior over hole collection:
  - 3 times higher mobility
  - Slightly lower trapping
  - Decrease of trapping probability with annealing for electrons
- **Drawback:** Additional isolation structures needed between n^+ electrodes

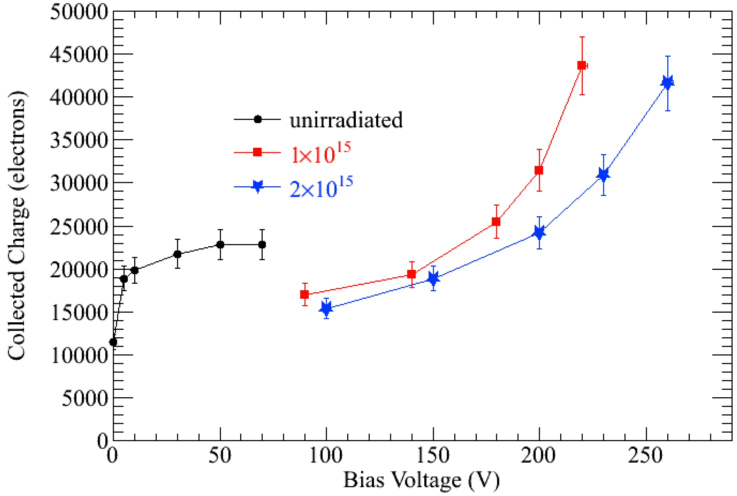
Situation after high level of irradiation:



R&D: Sensors with intrinsic gain - LGAD

❑ Charge Multiplication observed after high levels of irradiation

CM: 3D n-on-p sensors (Φ_{eq} =1-2x10^{15} cm^{-2})



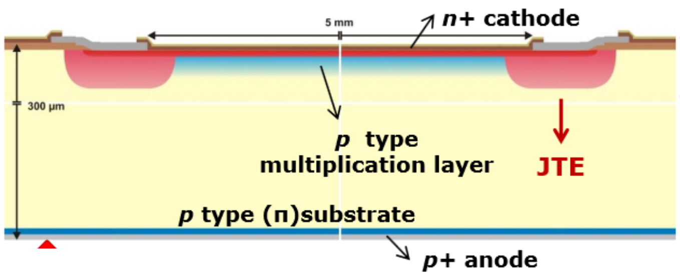
Origin: Irradiation leads to high negative space charge concentration in detector bulk
→ increase of the electric field close to n-type strips
→ impact ionization

Exploit charge multiplication by:

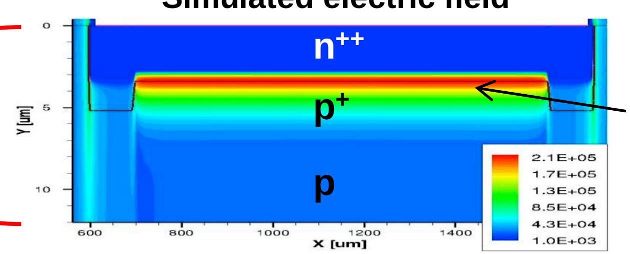
○ Junction engineering to study and control amplification in irradiated devices → Detectors with built in gain

❑ Low Gain Avalanche Detector (LGAD): detectors with implemented multiplication layer

LGAD structure



Simulated electric field



❑ Under reverse bias, a high E-field is created below n^{++} electrode → impact ionization leads to multiplication for electrons reaching the electrode

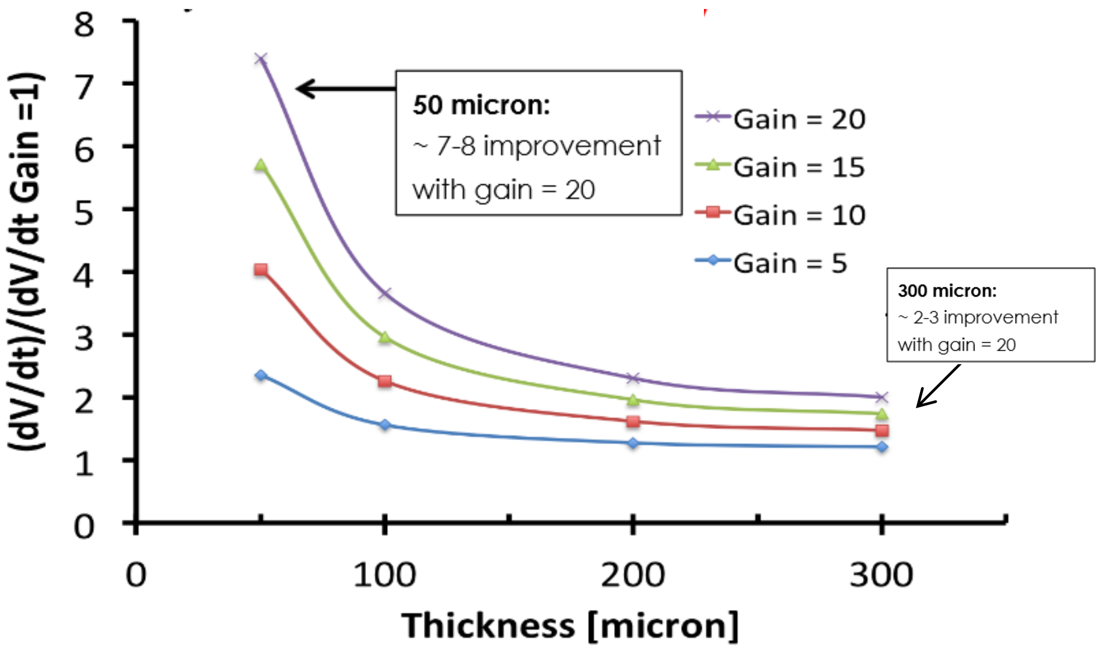
❑ **To be solved:** The gain of LGAD reduces significantly after irradiation

R&D: Thin detectors

- **Thin detector:**
  - Shorter collection distance → lower trapping probability → better charge collection
  - Reduced mass → reduced material budget
  - **Drawback:** Lower signal before very high fluences

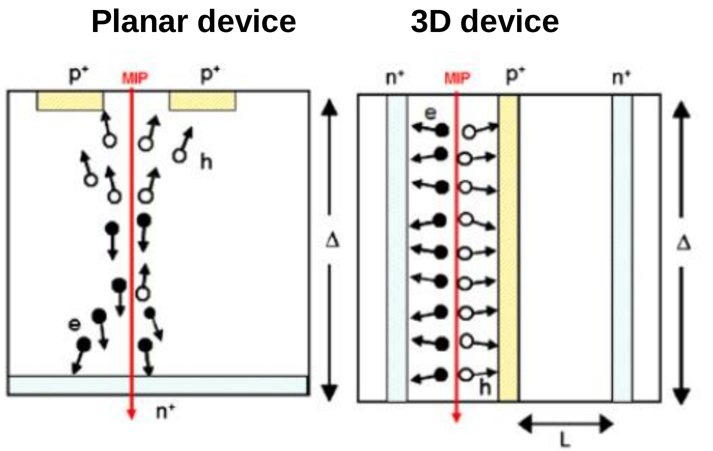
- **Combined with LGAD:** Thinner detectors can be produced to give the signal of thick ones

- **Significant improvements in time resolution require thin detectors:**



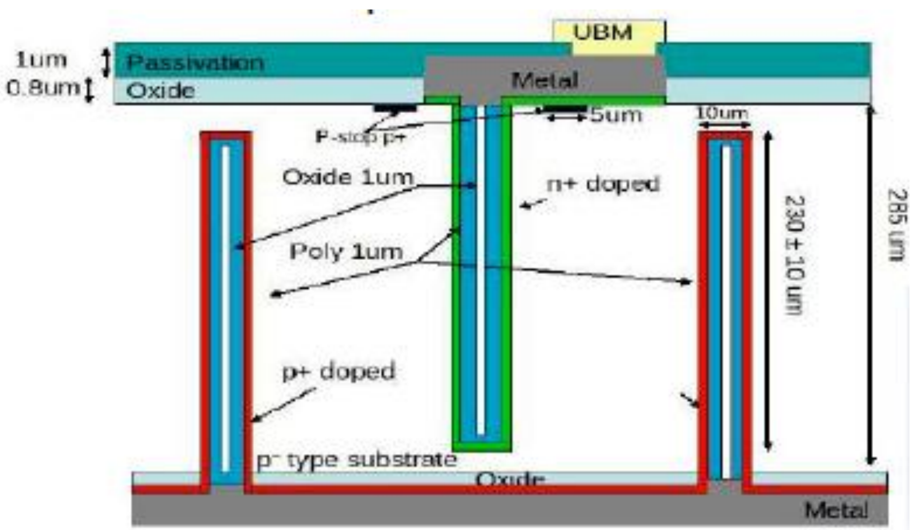
R&D: 3D columnar sensors

3D detector: columns etched into the silicon bulk vertically
→ geometry of 3D sensors decouples charge drift length from the ionization path
→ drift length = inter-column spacing, while signal is still proportional to the detector thickness
→ higher radiation tolerance

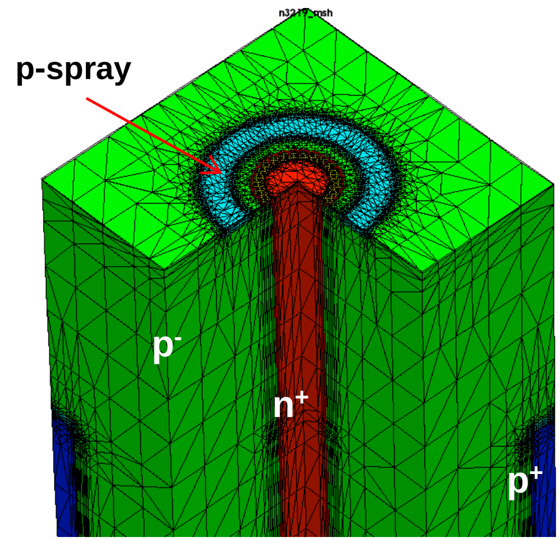


Drawbacks: Complex processing, higher electronics noise, hit position dependent signal size

Double column 3D detector design



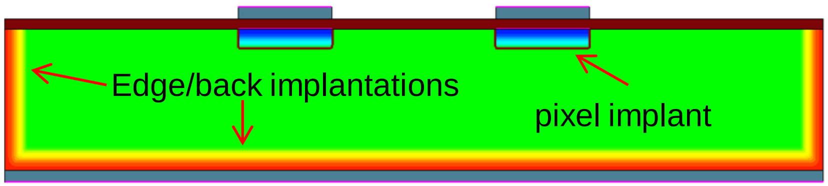
Sliced TCAD simulation structure of a 3D detector cell



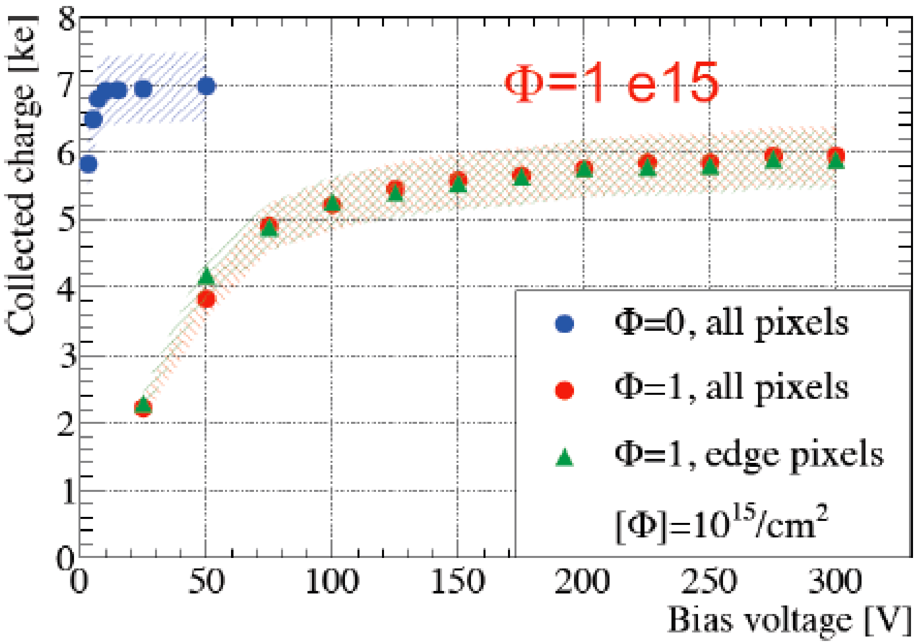
R&D: Active/slim edge sensors

- **Reduced edge width:** Method to maximize the sensitive region of the silicon sensors in tracking detectors
- Can be applied with any of previous detector designs
- Possible to reduce dead space around active area from 1 mm to ~50 µm

Principal design of a detector with active edges



Φ=10[15] p/cm[2],125 µm slim edge:
No difference between edge and other pixels



Summary

The CMS detector has **3 main components**

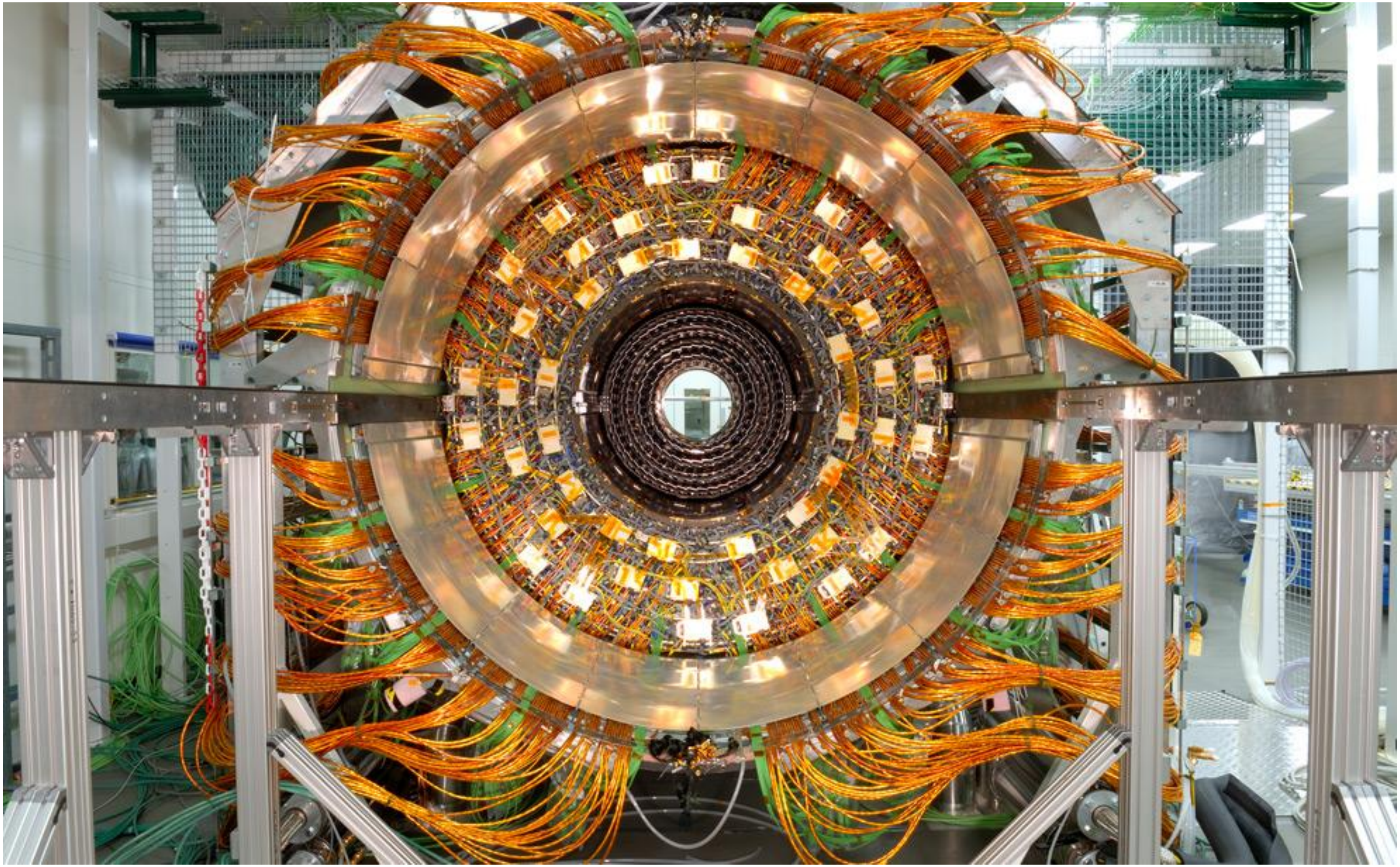
- ❑ **Silicon tracker** (Si pixels, Si microstrip detectors)
- ❑ **Calorimeters**
  - ○ ECAL (Scintillators, Pb/Si preshower detectors)
  - ○ HCAL (Scintillators)
- ❑ **Muon chambers** (Gaseous detectors)

❑ **Upgrade to HL-LHC:** fluences beyond the performance level of detectors used currently

❑ **Research & Development of silicon detectors:**

- **Defect characterization of Si**
  - ○ Consistent lists of defects covering several particles' damage (p, π, n, e, γ)
- **TCAD simulations**
  - ○ Simulations able to reproduce pulse shapes, depletion voltage, charge collection, leakage current and surface properties

- **Main properties of silicon sensors under investigation:**
  - ○ **Reduced trapping probability:** p-type silicon, thinned & 3D sensors
  - ○ **Enhanced charge carrier generation:** sensors with intrinsic gain
  - ○ **Maximized sensitive area:** active edge sensors



KIITOS!