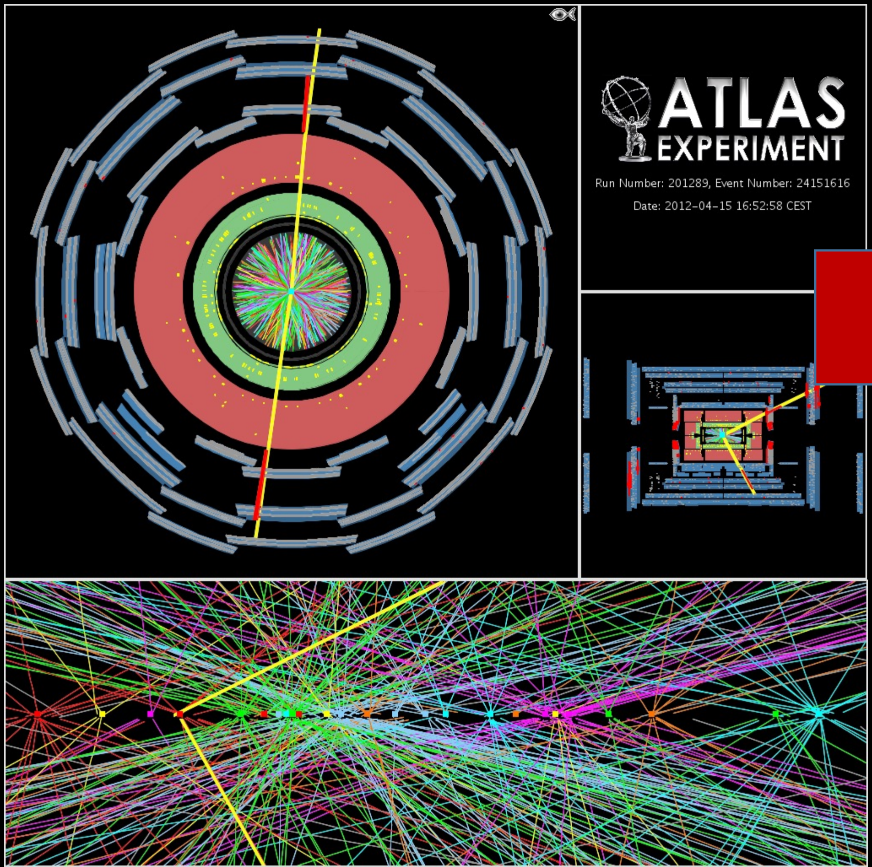
Innovative silicon detectors for HL-LHC

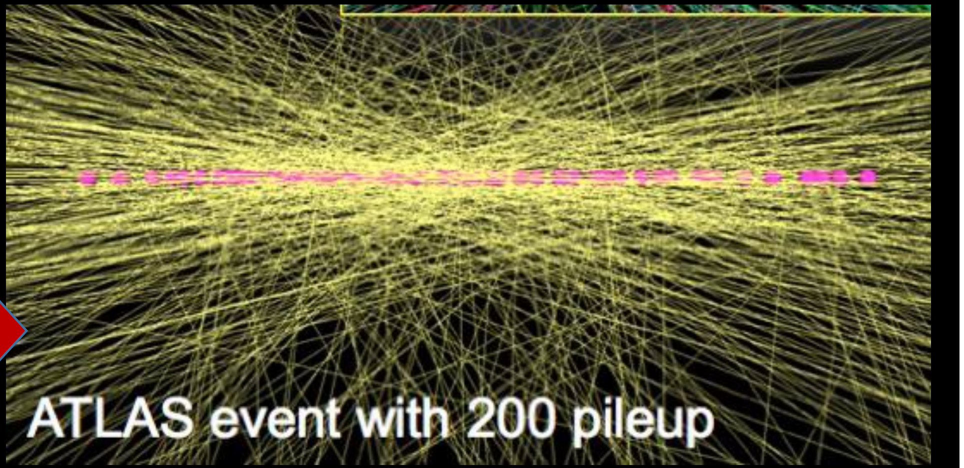
Daniela Bortoletto

The incredible challenge of HL-LHC

Run 2 LHC pileup $<\mu> =$ 37



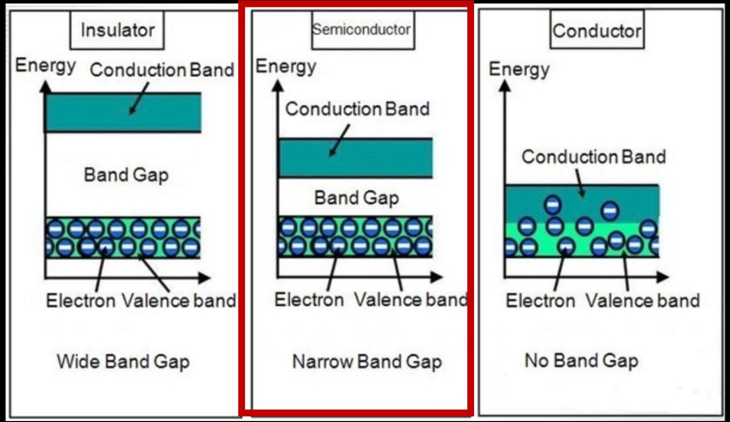
HL-LHC pileup $<\mu> =$ 200

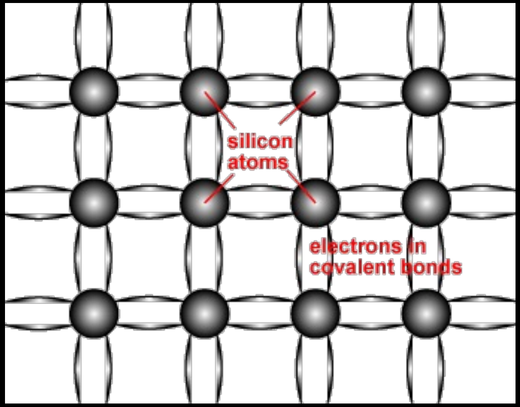


- Radiation levels up to:
  - fluence of $2\text{x}10^{16}$ 1 MeV n_{eq}/cm^2
  - Total Ionizing Dose (TID) ~ 1 Grad
  - Damage due to multitude of particles (charged particles, neutrons, etc…)

Silicon

- Second-most abundant element on the planet, after oxygen.

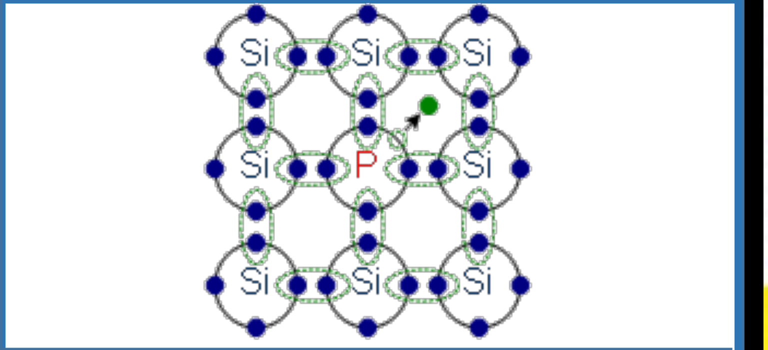




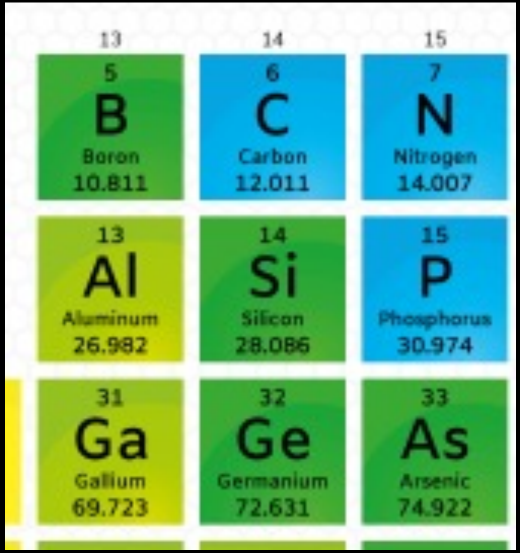
- At T>0 K electrons can move to the conduction band
- In a semiconductor the number of mobile charge carriers varies with temperature.

Si: $1s^2 2s^2 2p^6 3s^2 3p^2$

n-type silicon doped with P or As – contains excess electron (donor)

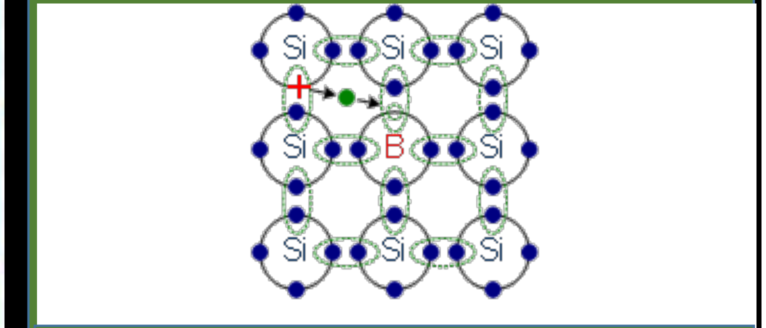


Electrons – Majority carriers



13	14	15
5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007
13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974
31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922

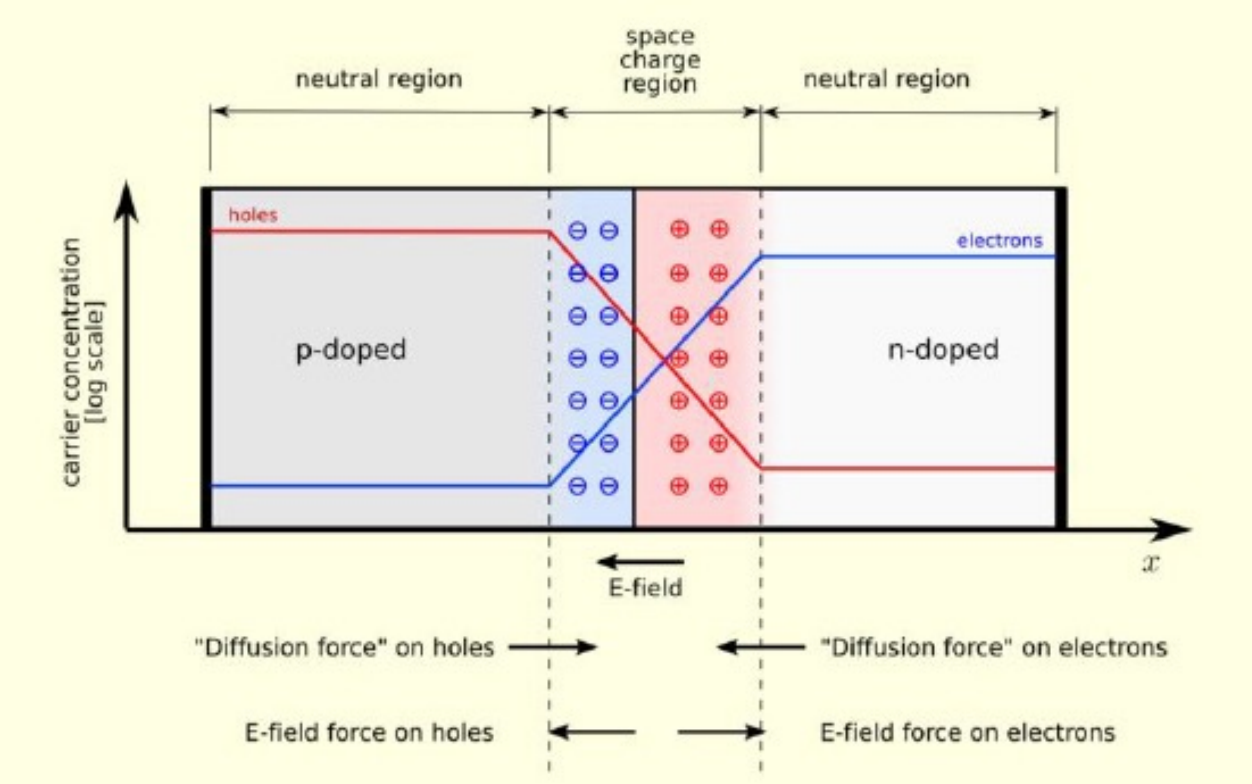
p-type silicon doped with B, or Ga – with one less electron (acceptor)

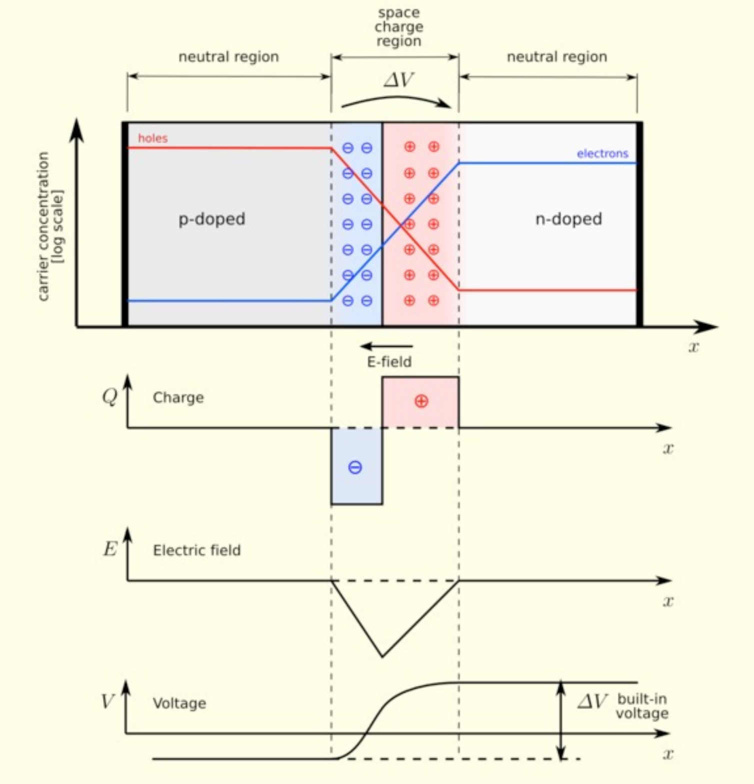


Holes – Majority carriers

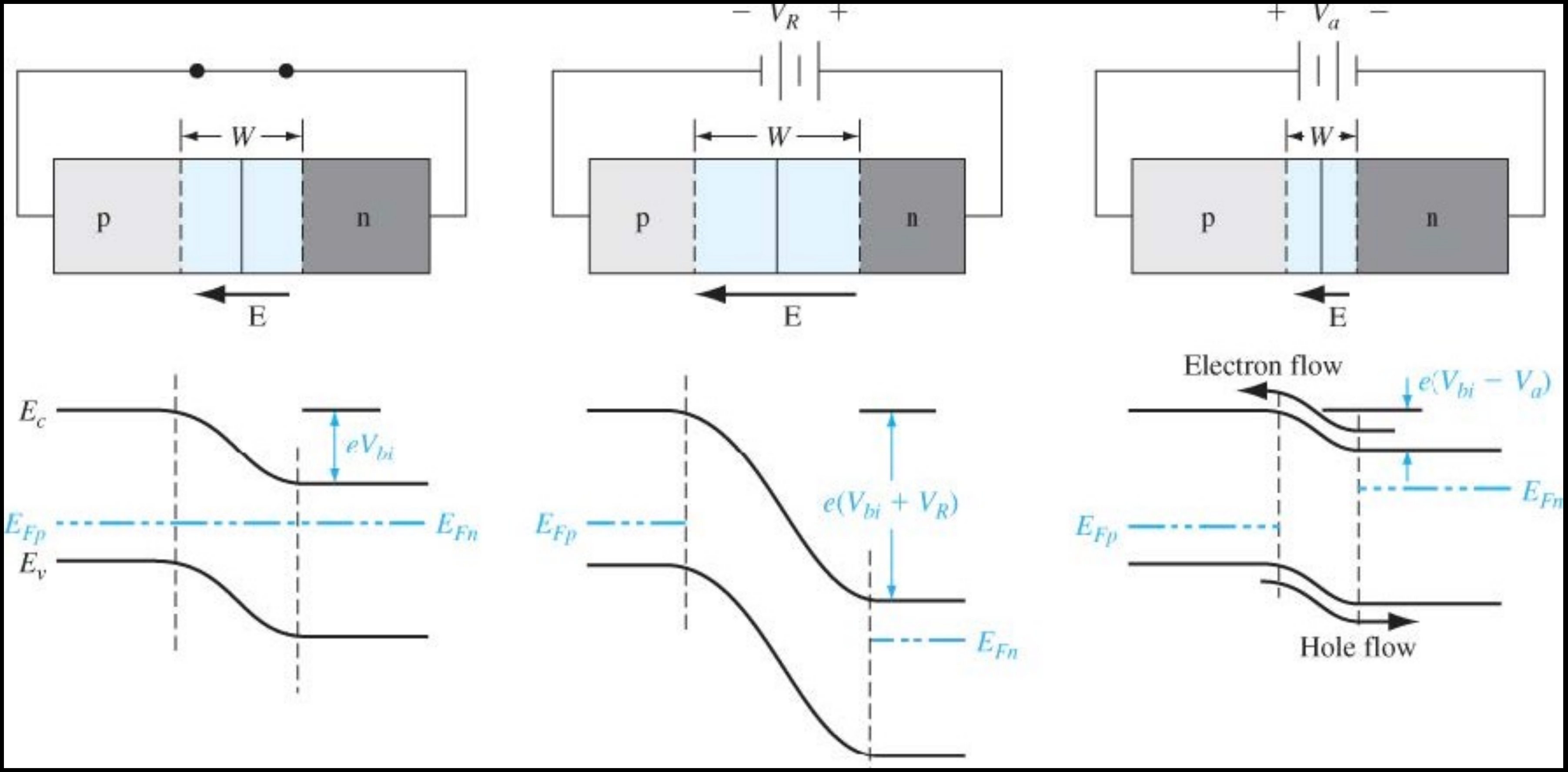
P-N junction

- In an unbiased p-n junction diode majority carriers migrate from one side to the opposite side, until the potential difference - ΔV – due to the charge distribution halts the process.





P-N Junction

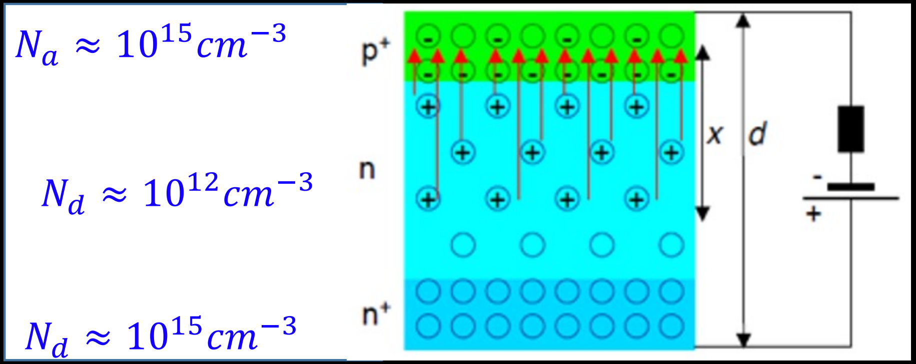

W
p
n
E
$-\ V_R\ +$
W
p
n
E
$+\ V_a\ -$
W
p
n
E
E_c
eV_{bi}
E_{Fp}
E_{Fn}
E_v
E_{Fp}
$e(V_{bi}+V_R)$
E_{Fn}
Electron flow
$e(V_{bi}-V_a)$
E_{Fn}
E_{Fp}
Hole flow

Principles of a semiconductor detector

- Voltage to deplete thickness d

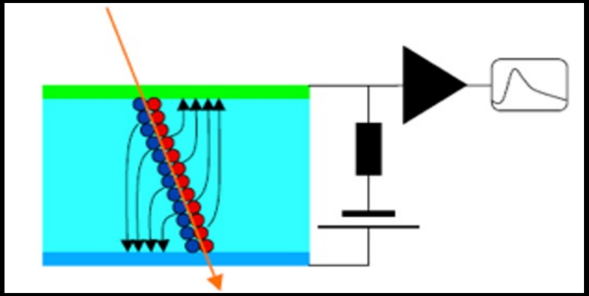
$$V_{dep} = d^2 N_{eff} \frac{e}{2\epsilon\epsilon_0}$$

$N_{eff} =$ $doping\ concentration =$ N_{donors}-$N_{acceptors}$



- Ionizing particles create e-h pairs that drift in the E field and induce signal on electrodes

E(e-h pair) = 3.62 eV (≈ 30 eV for e-ion in gas)
dE/dx (M.I.P.) ≈ 3.87 MeV/cm
N(e-h) ≈107/µm average value
N (e-h) ≈ 80/µm most probable value



e and h are different

$v_{e,h} = \mu_{e,h} E$ Drift velocity

$\mu_{e,h} = e\, \tau_{e,h} / m_{e,h}$ Mobility

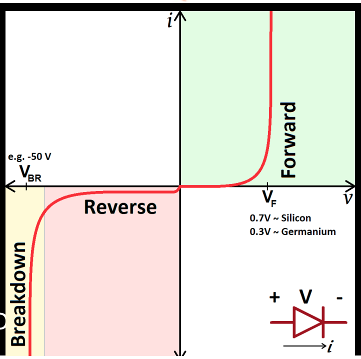
μ_e(Si, 300 K) ≈ 1450 cm²/Vs

μ_h(Si, 300 K) ≈ 450 cm²/Vs

electrons about 3 times faster then holes

- Keep leakage current low (approximately doubles for ≈ 8°C increase in temperature)

$$I \propto T^{3/2} \exp\left(-\frac{E_g}{2kT}\right) \text{ x Volume}$$

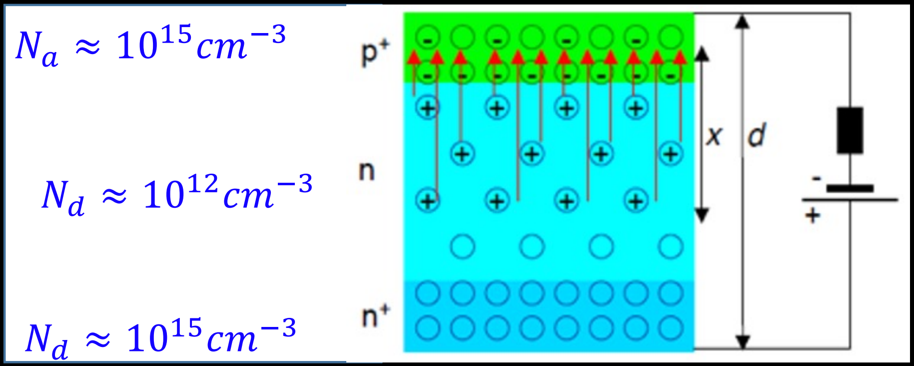


Principles of a semiconductor detector

- Voltage to deplete thickness d

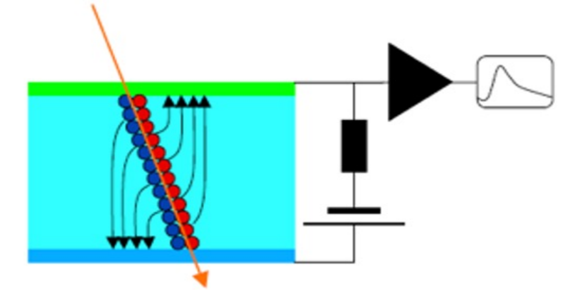
$$V_{dep} = d^2 N_{eff} \frac{e}{2\epsilon\epsilon_0}$$

N_{eff} = doping concentration = N_{donors}-$N_{acceptors}$



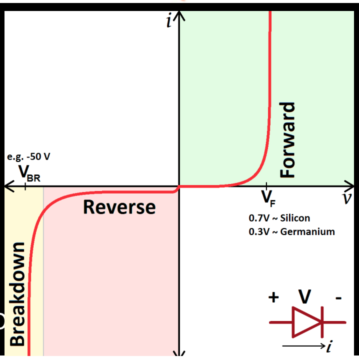
- Ionizing particles create e-h pairs that drift in the E field and induce signal on electrodes

E(e-h pair) = 3.62 eV (≈ 30 eV for e-ion in gas)
dE/dx (M.I.P.) ≈ 3.87 MeV/cm
N(e-h) ≈107/µm average value
N (e-h) ≈ 80/µm most probable value

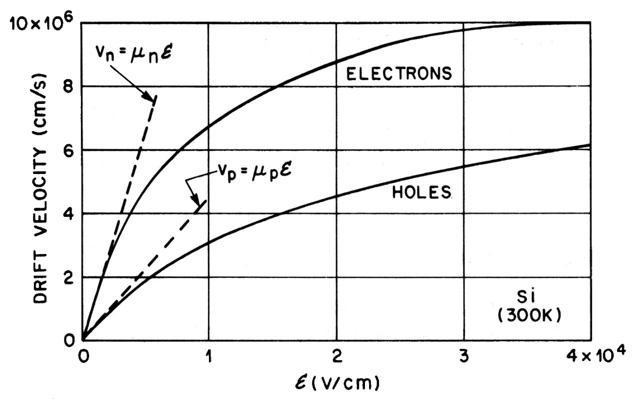


- Keep leakage current low (approximately doubles for ≈ 8°C increase in temperature)

$$I \propto T^{3/2} \exp\left(-\frac{E_g}{2kT}\right)$$ x Volume

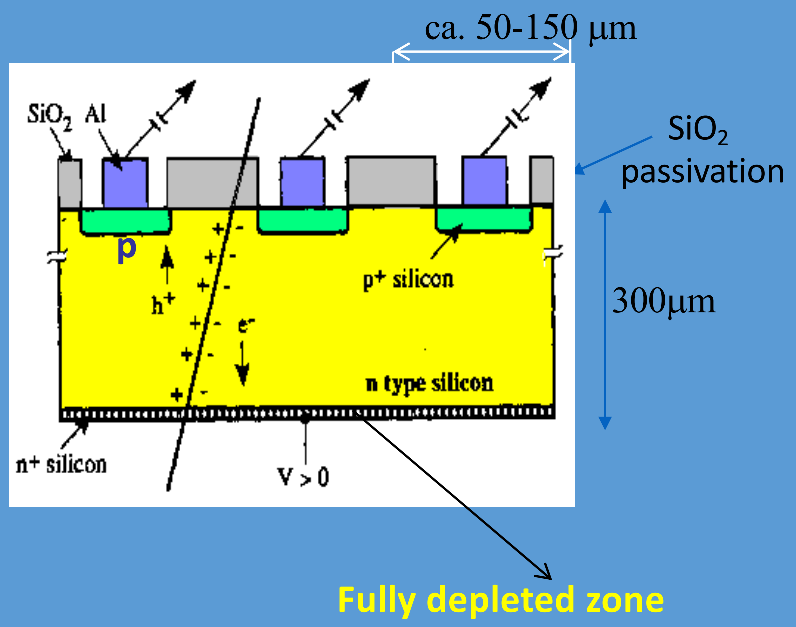


e and h are different



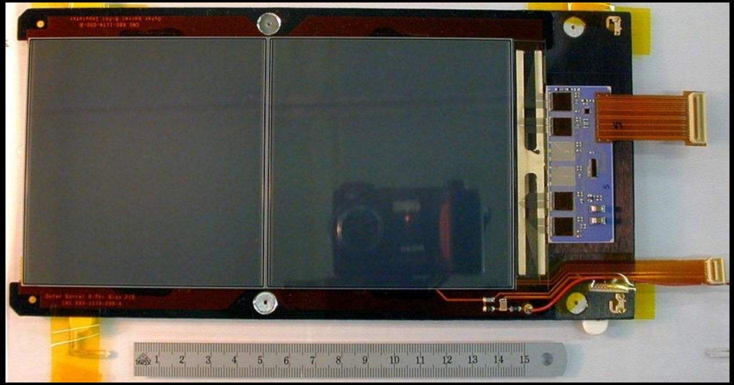
electrons about 3 times faster then holes

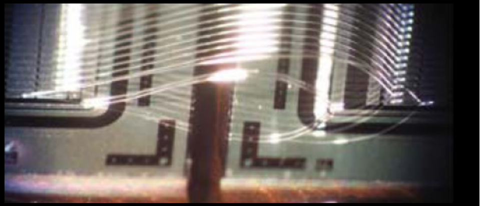
Silicon Sensors



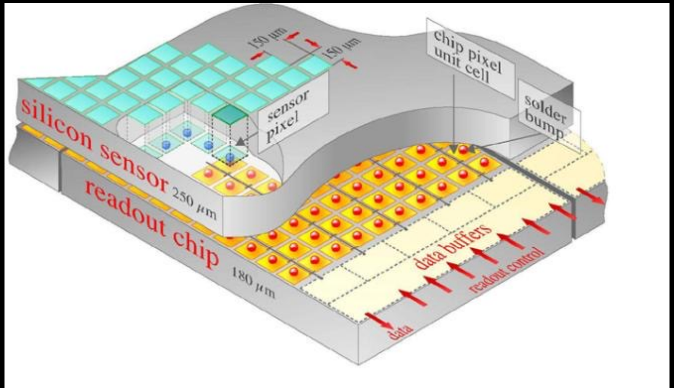
- Thickness 150 - 500 µm
- Strip separation (pitch) 20 - 150 µm
- Resolution 5 - 40 µm (pitch/√12)
- Most probable Energy loss ≈ 80 e-h pairs per µm
- 300 µm thickness ➛ 24000 pairs/MIP
- Output signal: $Q_{out} \sim 4$ fC
- Charge collection 20 ns

STRIPS

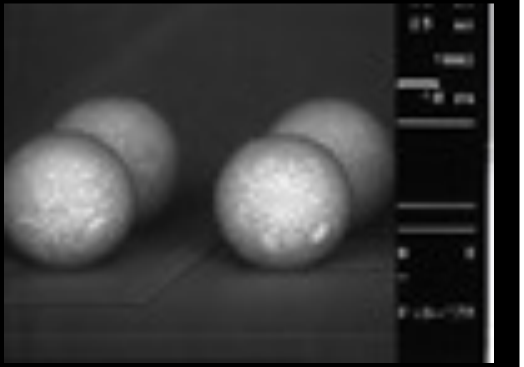




Pixel

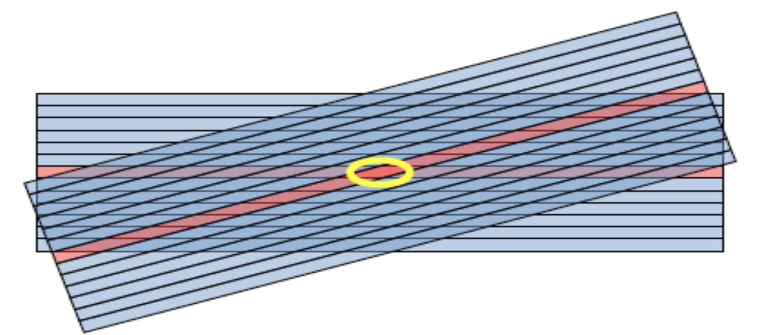


Solder bumps r ≈ 20$\approx\mu m$

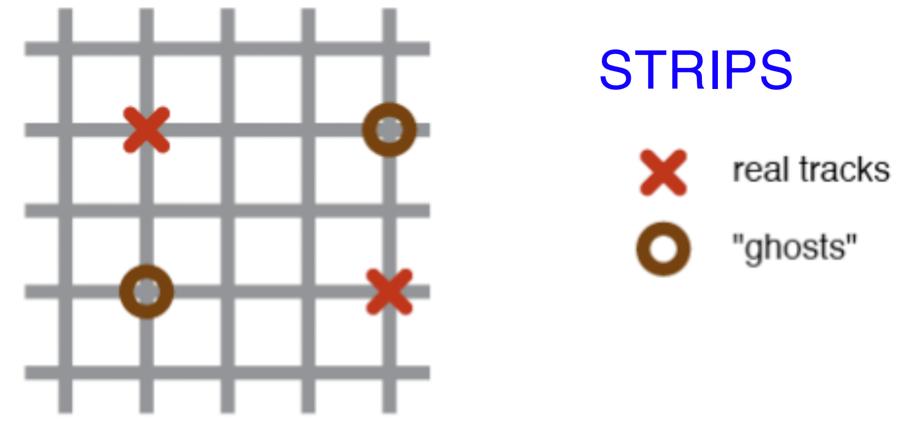


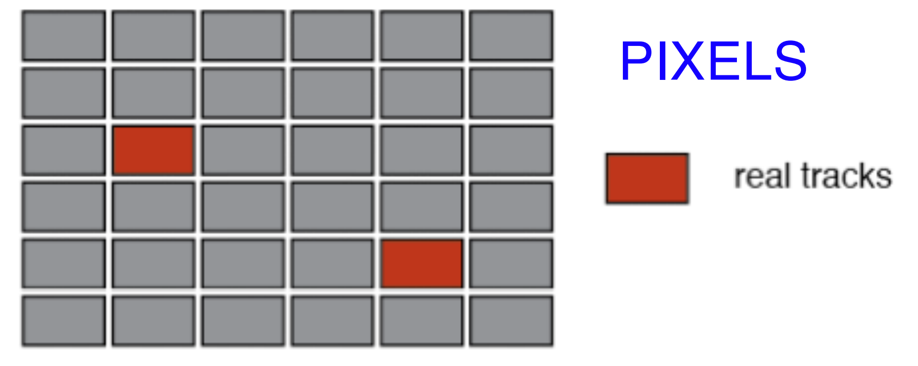
Strips versus Pixels

- A strip detector measures 1 coordinate only. Two orthogonal/angled arranged strip detectors could give a 2-dimensional position of a particle track.



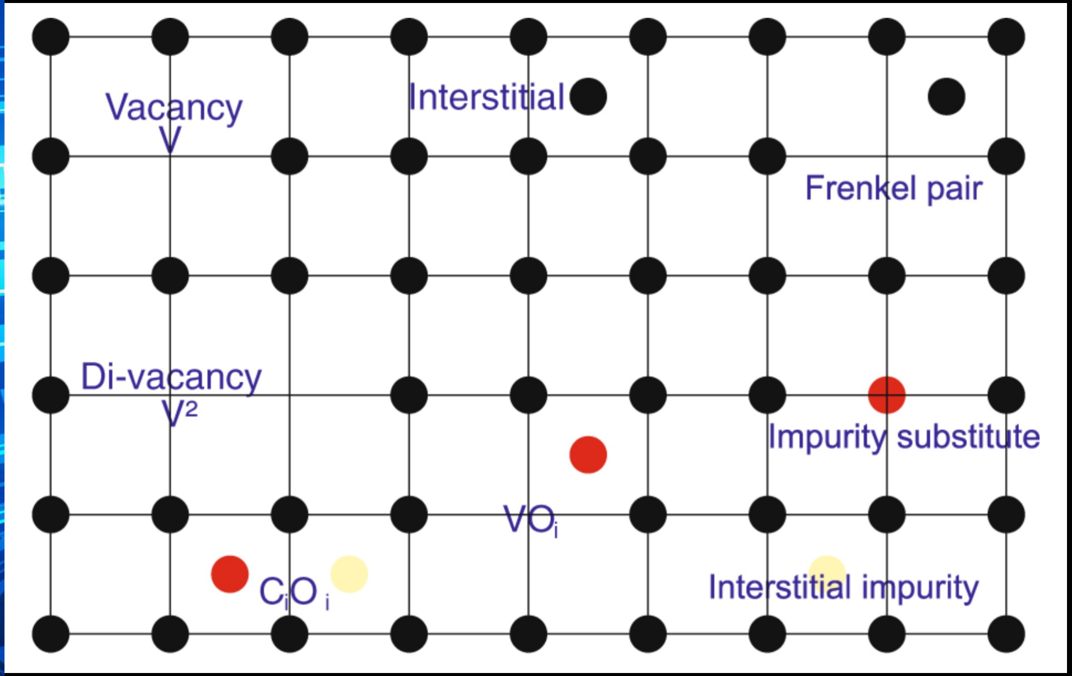
- Pixel detectors produce unambiguous hits!
  - Large number of electrical connections and large power consumption.





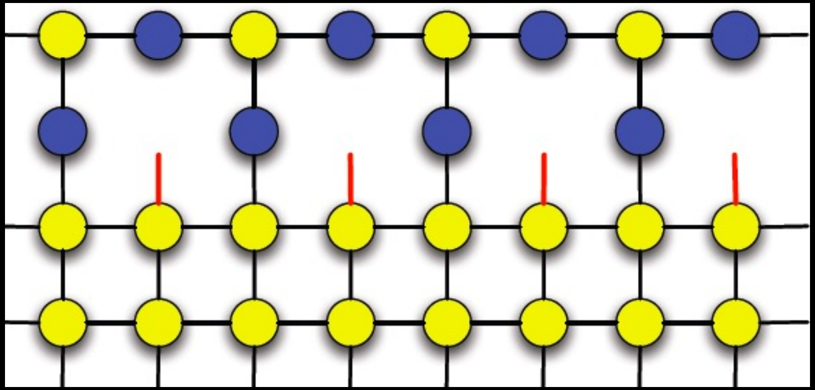
Radiation damage

- Non ionizing energy loss (NIEL)
  - Atomic displacement caused by p,n,π
  - Frenkel pair E~25eV, Defect cluster E~5keV



- Affects mainly the sensors and measured in 1 MeV n_{eq}

- Ionizing energy loss
  - Proportional to absorbed radiation dose
- Measured in 1 Gy = 100 rad
- Ionizing radiation generates bound charge in the SiO_2 layer at the surface of the detectors and at the interface between the Si and the SiO_2.

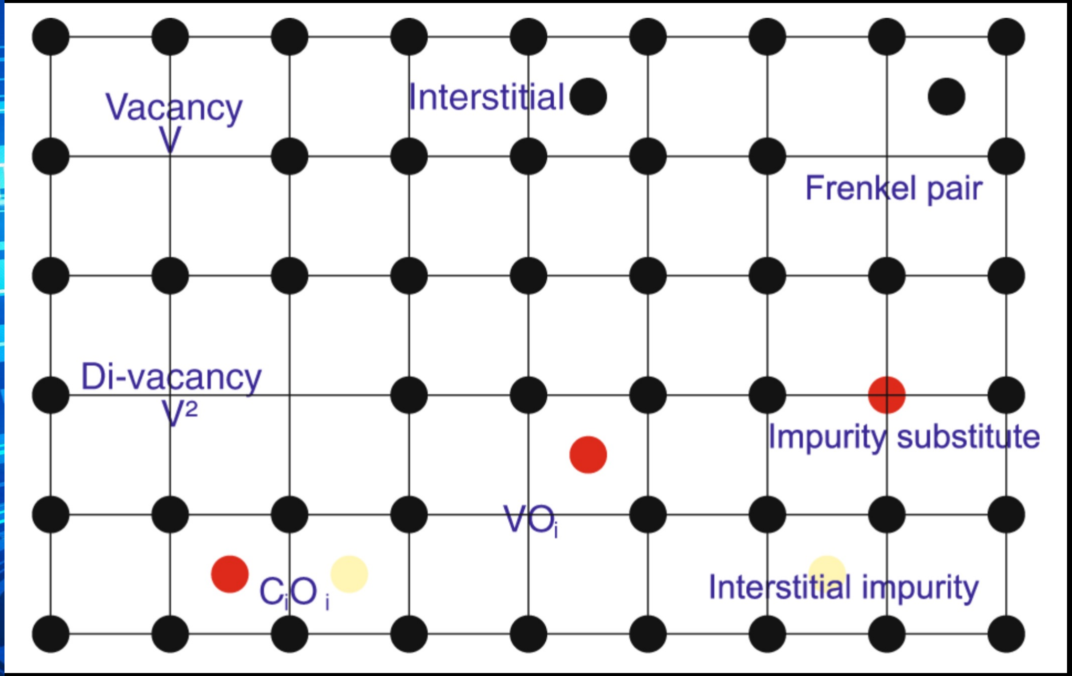


- More problematic for electronics

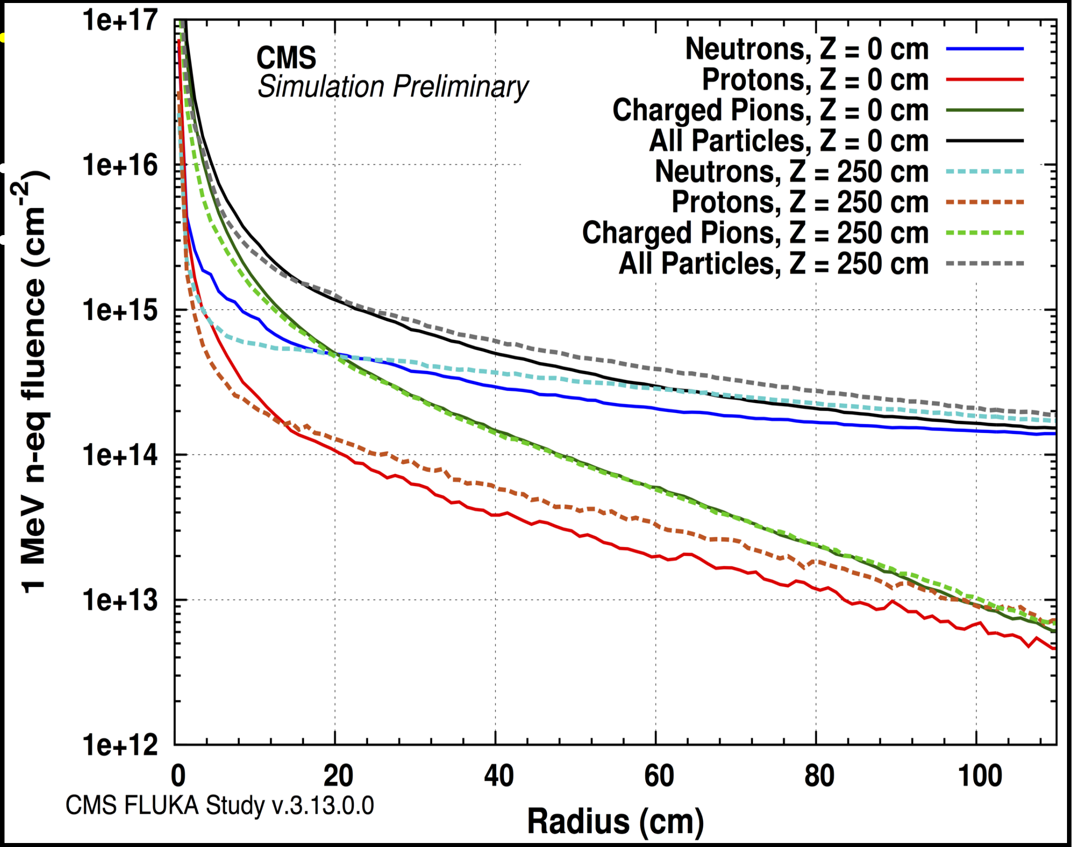
- Charged particles flux is due to the collisions at the interaction point and decreases as ~$1/r^2$.
- Neutrons flux is mainly due backsplash from the calorimeter and it depends on shielding and design

Radiation damage

- Non ionizing energy loss (NIEL)
  - – Atomic displacement caused by p,n,π
  - – Frenkel pair E~25eV, Defect cluster E~5keV

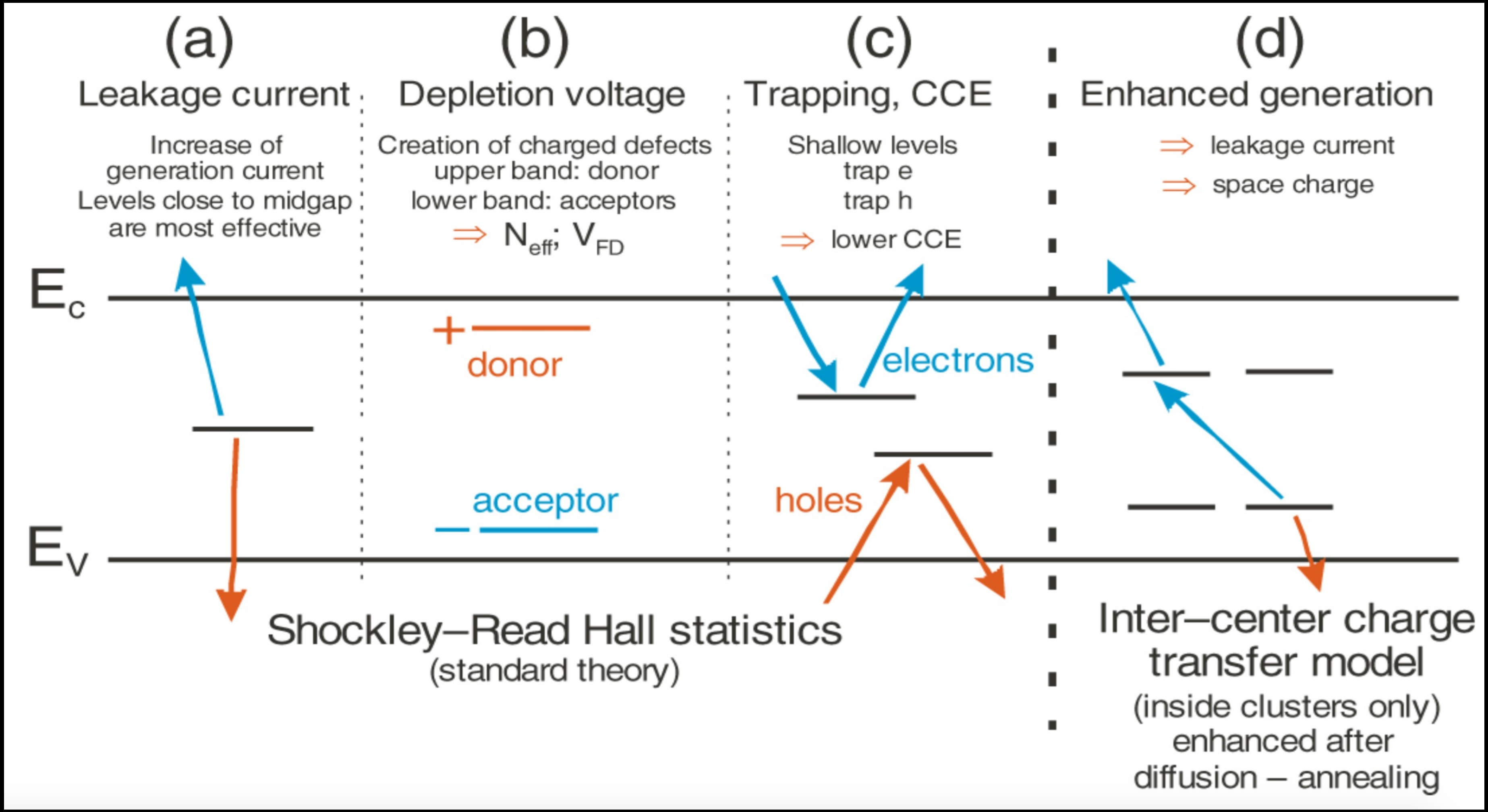


- Affects mainly the sensors and measured in 1 MeV n_{eq}



- Charged particles flux is due to the collisions at the interaction point and decreases as ~1/r^2.
- Neutrons flux is mainly due backsplash from the calorimeter and it depends on shielding and design

Radiation effects (RD50)



(a) Leakage current

Increase of generation current
Levels close to midgap are most effective

(b) Depletion voltage

Creation of charged defects
upper band: donor
lower band: acceptors
⇒ N_{eff}; V_{FD}

(c) Trapping, CCE

Shallow levels
trap e
trap h
⇒ lower CCE

(d) Enhanced generation

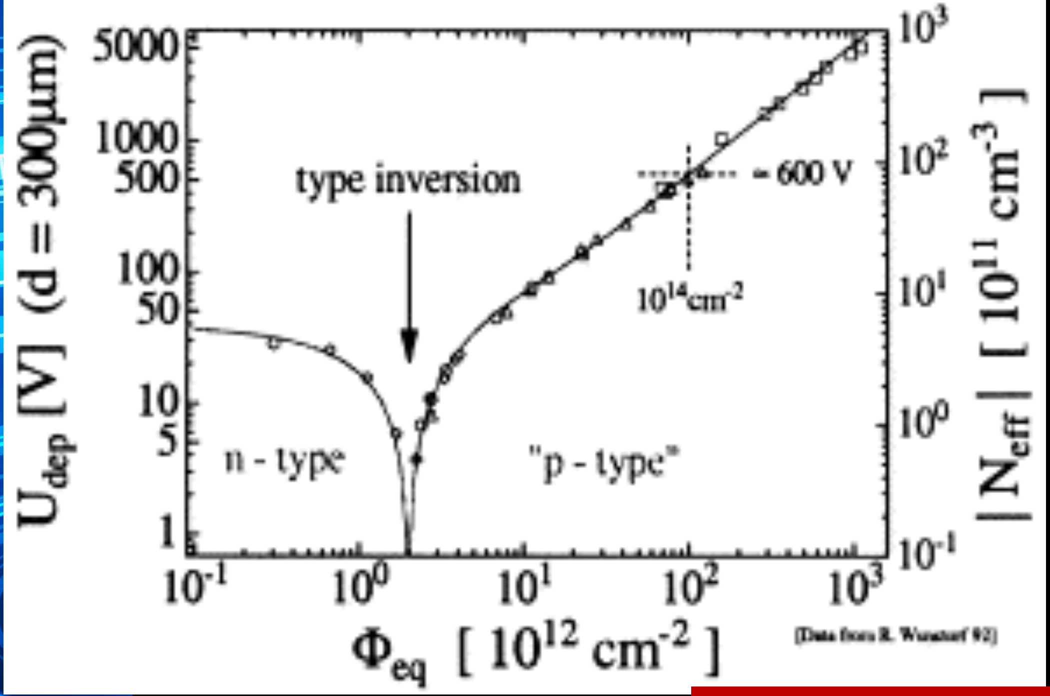
⇒ leakage current
⇒ space charge

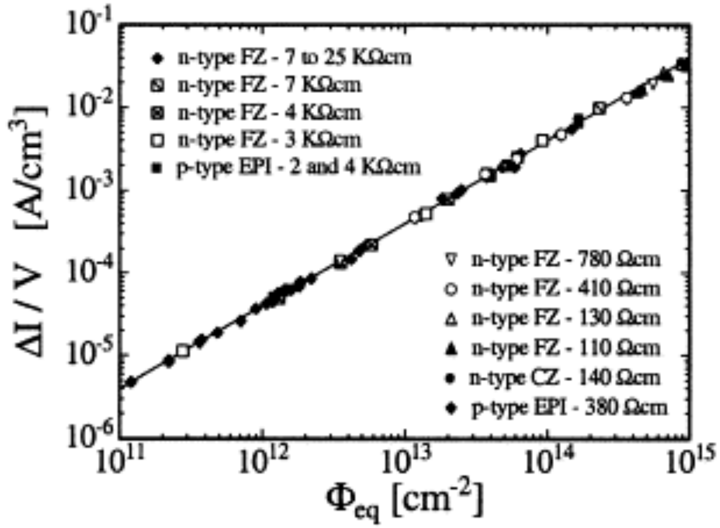
Shockley–Read Hall statistics
(standard theory)

Inter–center charge transfer model
(inside clusters only)
enhanced after diffusion – annealing

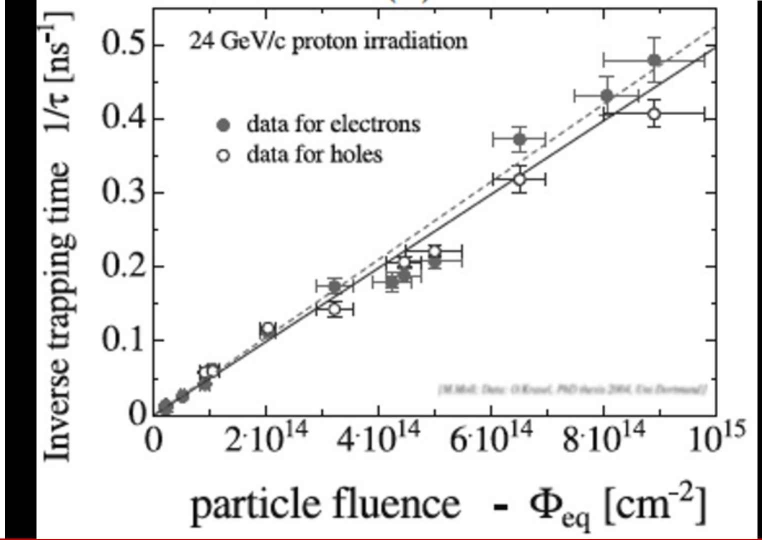
Radiation effects

Increase in V_{dep} – which becomes very large after $1x\ 10^{14}\ n_{eq}/cm^2$





Increase in I_{leak} - could lead to thermal runaway



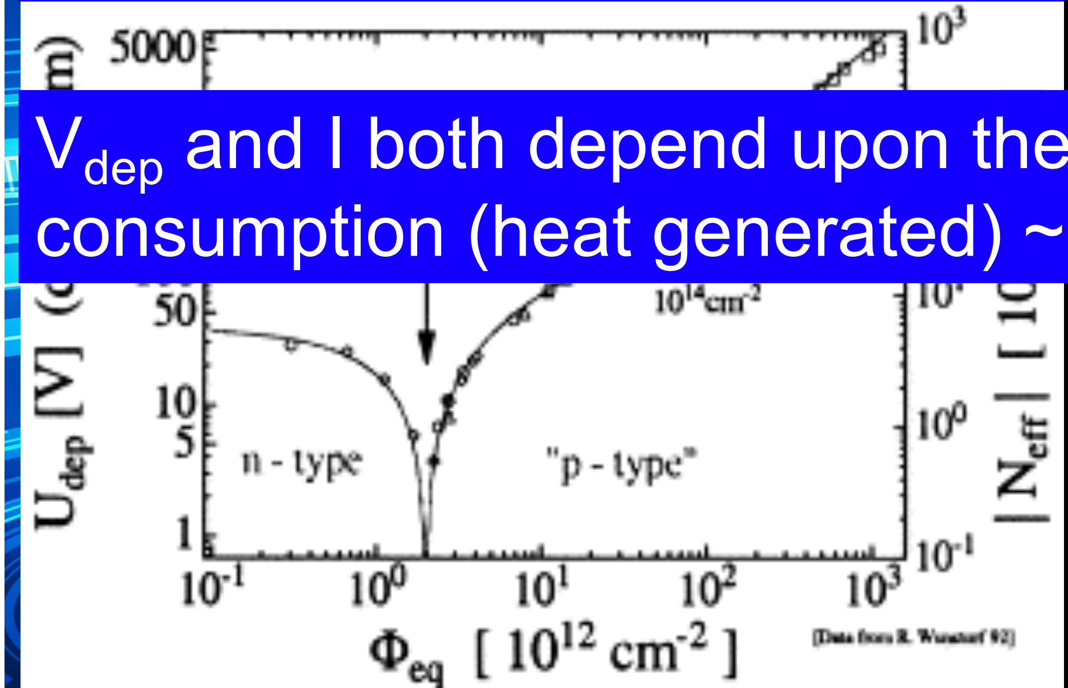
Decrease in trapping time

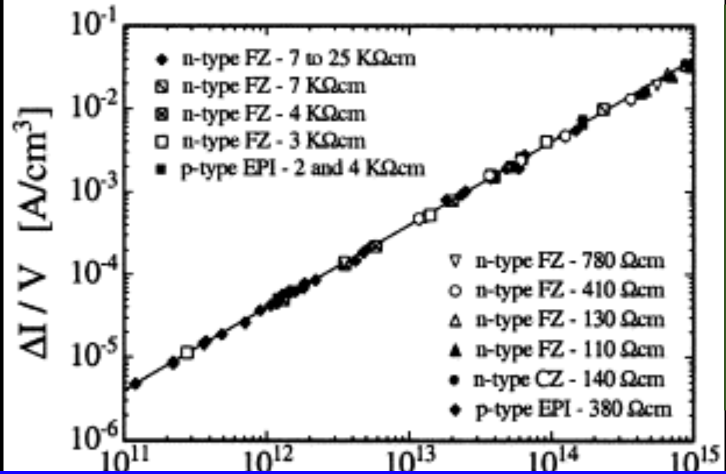
$\tau_{eff}\ (10^{15}\ n/cm^2) = 2\ ns$: $x = (10^7\ cm/s) \cdot 2\ ns = 200\mu m$

$\tau_{eff}\ (10^{16}\ n/cm^2) = 0.2\ ns$: $x = (10^7\ cm/s) \cdot 0.2\ ns = \underline{\mathbf{20\ \mu m}}$

Radiation effects

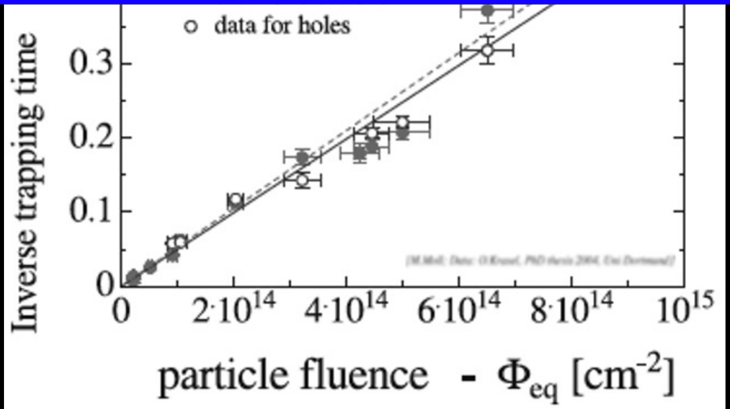
Increase in V_{dep} – which becomes very large after 1x 10^{14} n_{eq}/cm^2





Increase in I_{leak} - could lead to thermal runaway

V_{dep} and I both depend upon the fluence Φ →power consumption (heat generated) ~ fluence Φ^2 → cooling



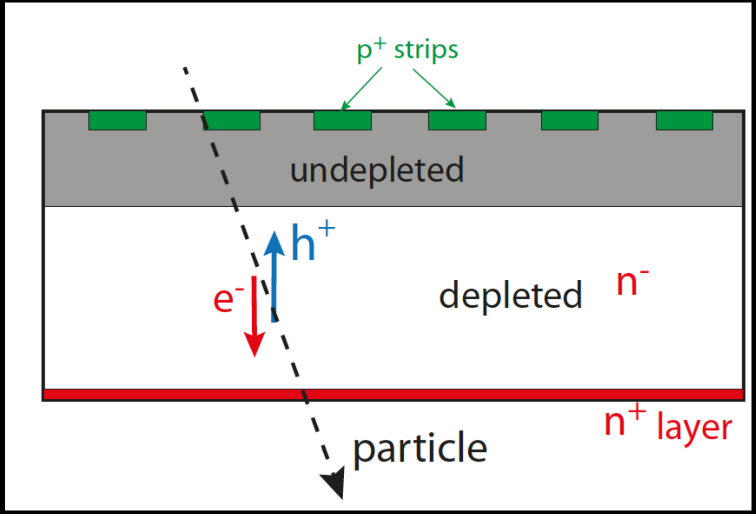
Decrease in trapping time

$$\tau_{eff}\,(10^{15}\ n/cm^2) = 2\ ns:\ x = (10^7\ cm/s)\cdot 2\ ns = 200\mu m$$

$$\tau_{eff}\,(10^{16}\ n/cm^2) = 0.2\ ns:\ x = (10^7\ cm/s)\cdot 0.2\ ns = \underline{\mathbf{20\ \mu m}}$$

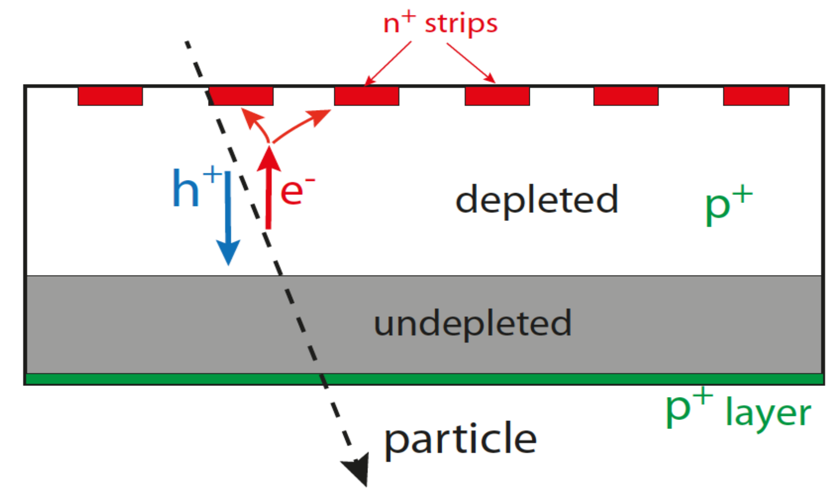
Silicon detectors for HL-LHC

- LHC and pre-LHC: p^+ in n



- Consequences:
  - signal loss
  - resolution degradation due to charge spreading

- For HL-LHC upgrade: n^+ in p

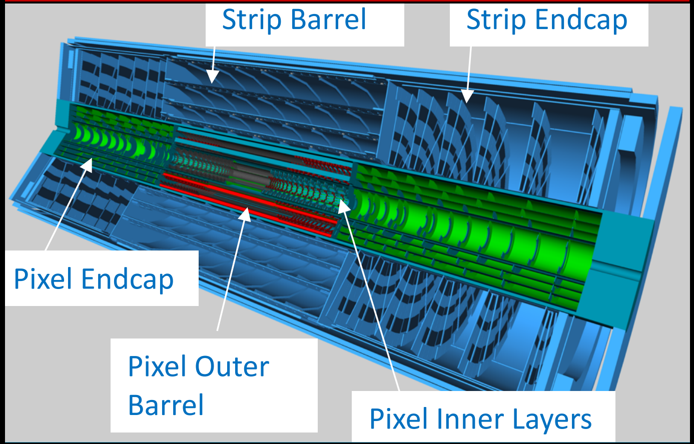


- Advantages:
  - faster charge collection (electrons have higher v_{drift})
  - Less signal and CCE degradation

p – type substrates used for both strips and pixels

ATLAS ITk

All silicon tracker: ITk



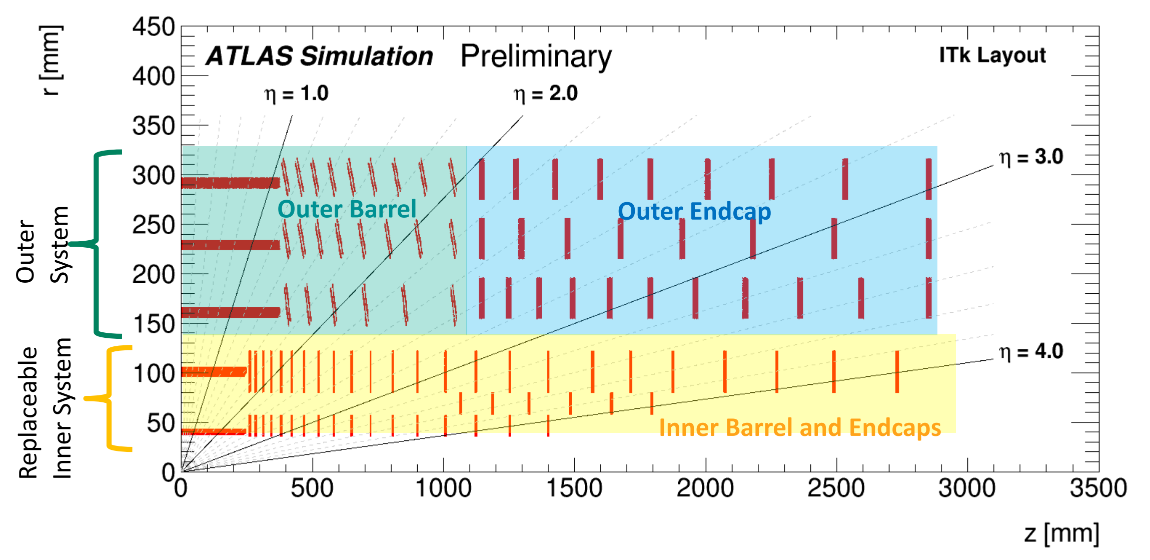
- Same or better performance than current Inner Detector
- Increased granularity to maintain occupancy <1%
- Low mass mechanics, cooling and serial power to minimize material
- Increased radiation hardness

Current pixel system
~92M pixels
~2000 modules
~1.9 m^2 active area

All sensors 50x500 μm^2
IBL 50x250 μm^2

ITk Pixel System
~1.4G pixels
~9,400 modules
~13 m^2 active area

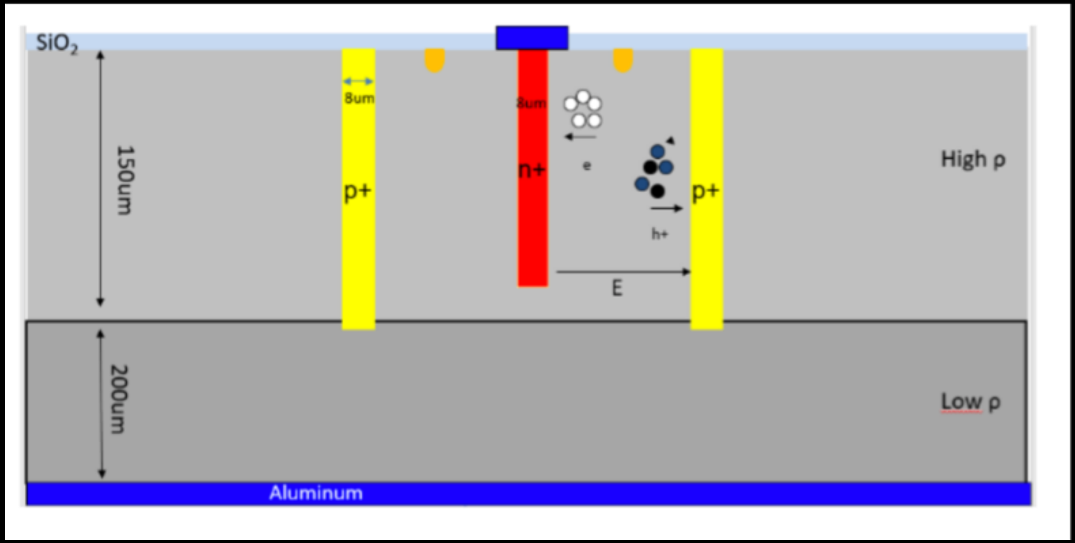
Layer 0 barrel sensors
25x100 μm^2
All other layers 50x50 μm^2

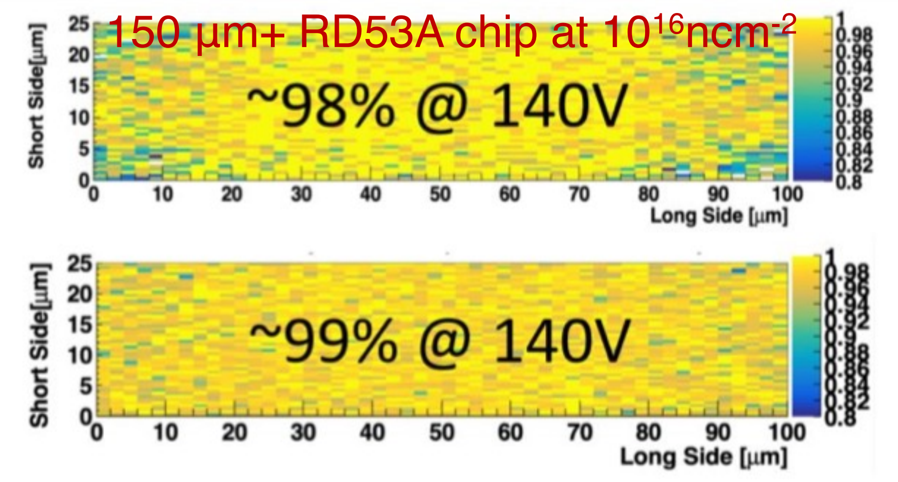


Inner System Replaceable. For (Layer-0 radius=39mm)
Fluence: 9.2x10^{15}ncm^{-2} TID: 7.3MGy @2000fb^{-1}

3D: Ultra Radiation hard sensors for L0

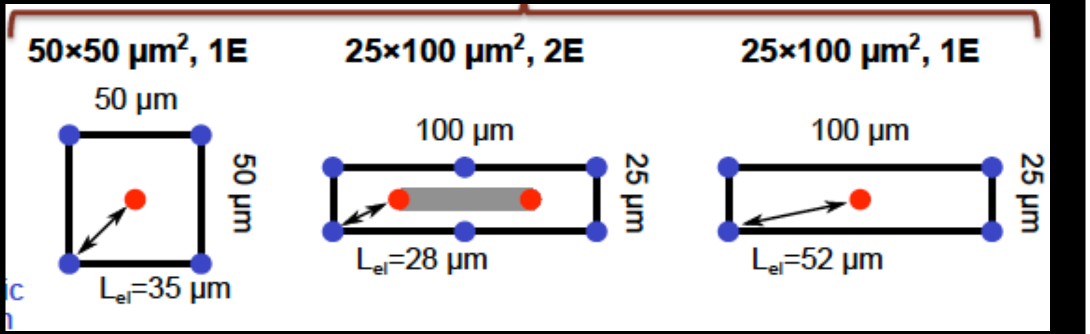
- 3D sensors are used in L0
- Requirements:
  - Radiation hard to10^{16} n_{eq} cm^{-2}
  - Operating voltage<250V
  - Power<10 $mWcm^{-2}$
  - >97% hit efficiency




150 µm+ RD53A chip at $10^{16}ncm^{-2}$

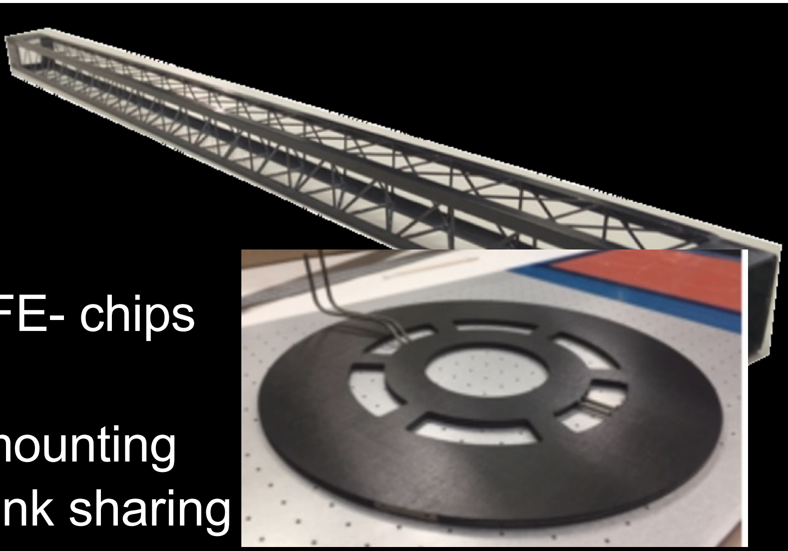
~98% @ 140V

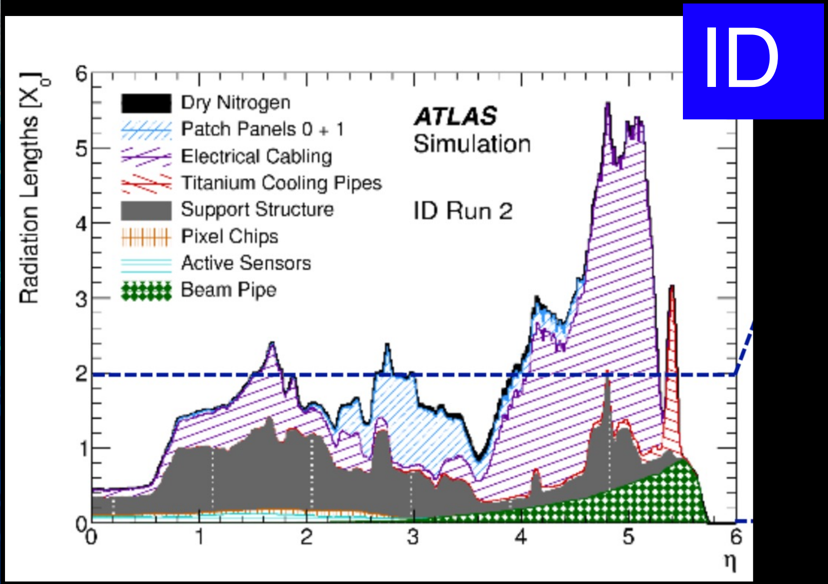
~99% @ 140V

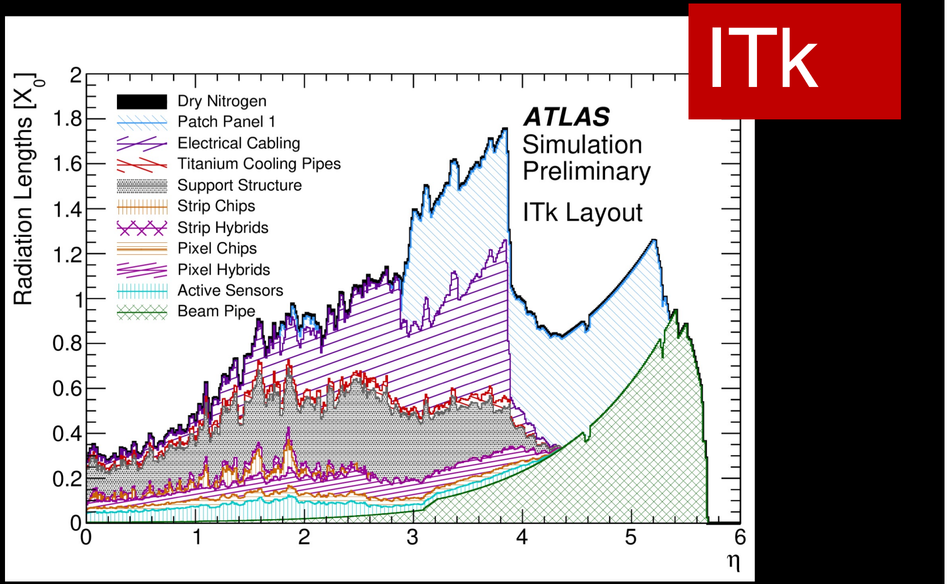


Material

- Reduce of material using
  - CO_2 cooling with thin titanium pipes
  - Minimise material in modules using thin Si and FE- chips
  - Advanced powering: serial powering for pixels
  - Carbon structures for mechanical stability and mounting
  - Optimise number of readout cables using data link sharing

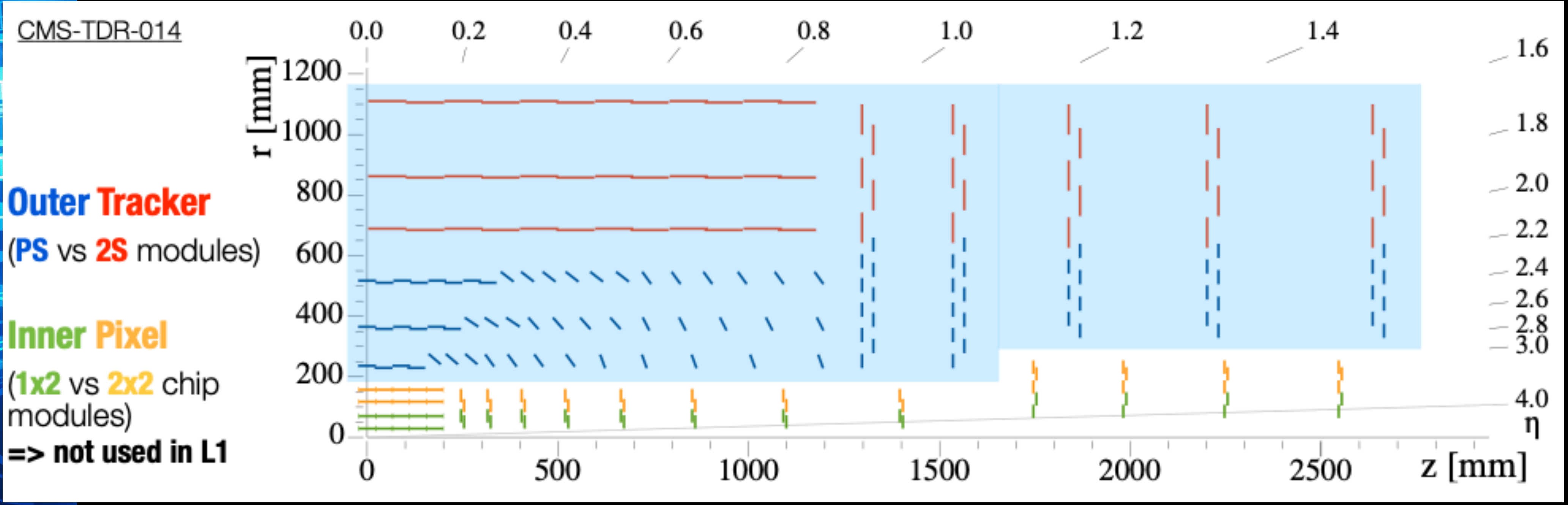






CMS HL-LHC Tracker

- New all silicon outer tracker + inner pixel detector
  - Increased granularity for HL-LHC occupancies
  - Tracking in hardware trigger



Outer Tracker

(**PS** vs **2S** modules)

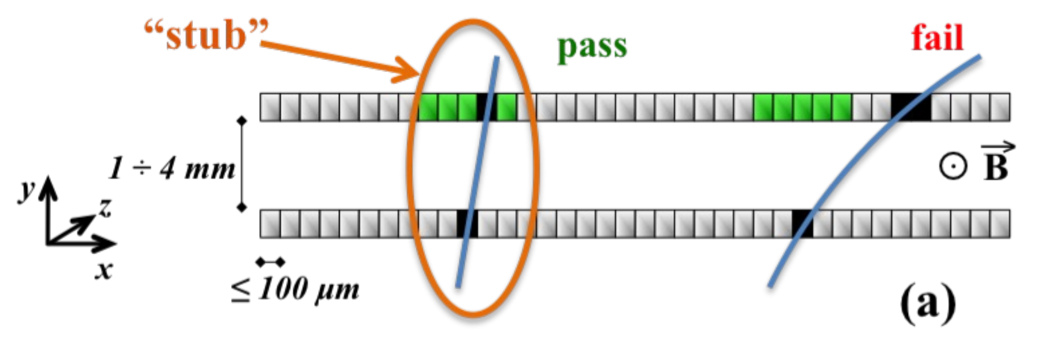
Inner Pixel

(**1x2** vs **2x2** chip modules)

=> not used in L1

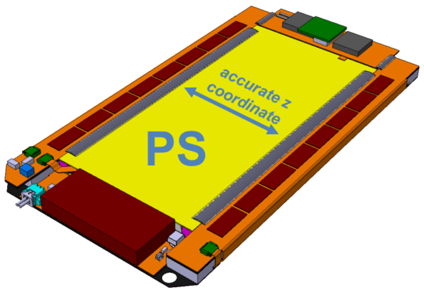
pT module concept

- Modules provide p_T discrimination in front-end electronics through hit correlations between two closely spaced sensors
- **Stubs:** Correlated pairs of clusters, consistent with ≥2 GeV track providing data reduction by factor of 20-30



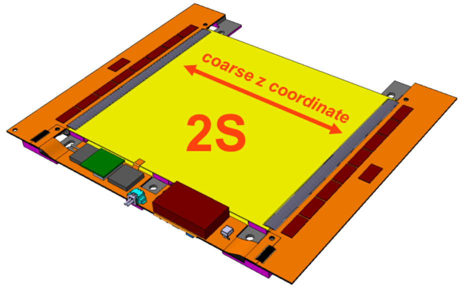
PS modules (pixel-strip)

- Top sensor: 2x2.5 cm strips, 100 µm pitch
- Bottom sensor: 1.5 mm x 100 µm pixels



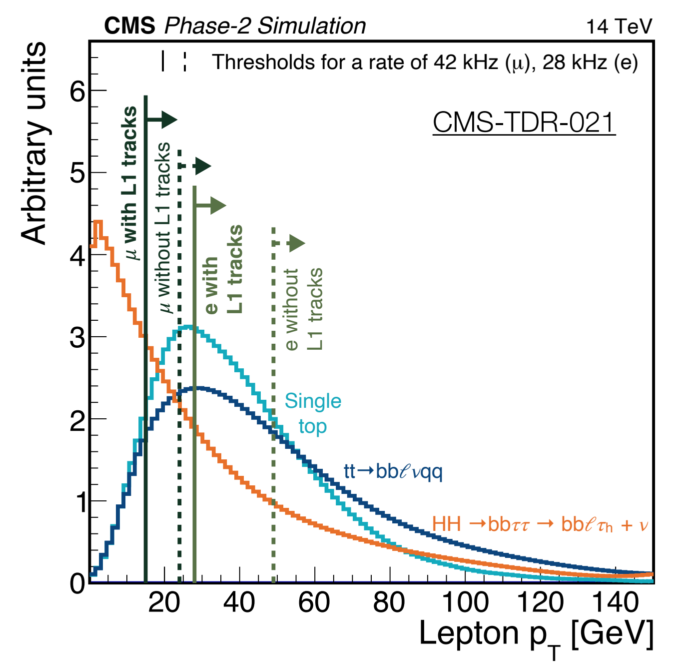
2S modules (strip-strip)

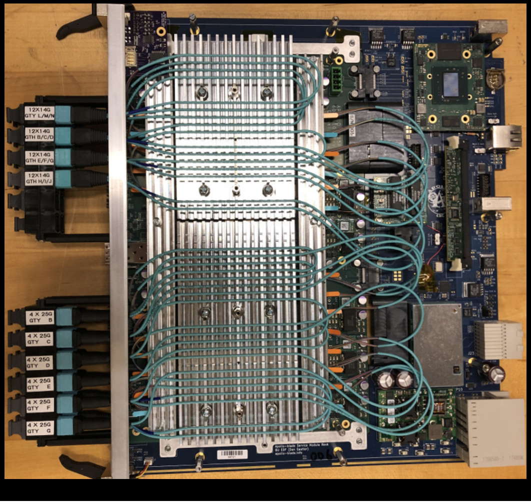
- Strip sensors 10x10 cm^2
- 2x5 cm long strips, 90 µm pitch



Track Triggering

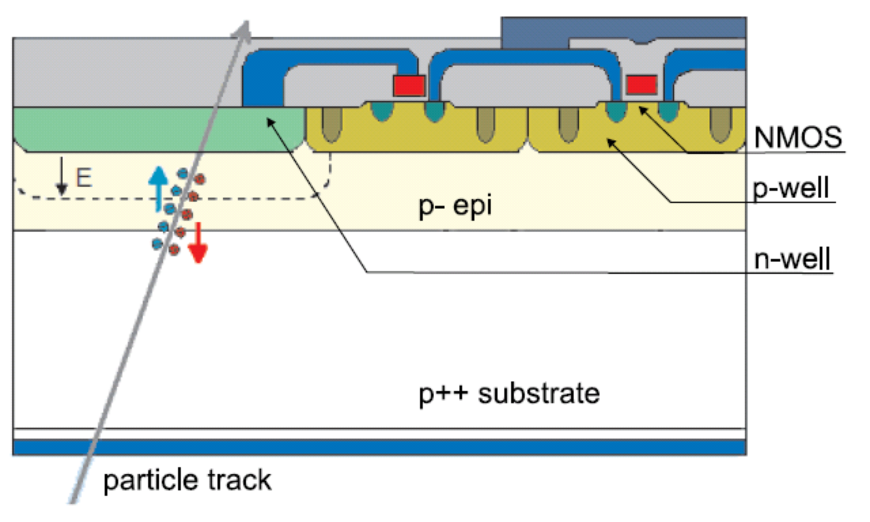
- **Track information in hardware trigger**
    - Allow lower p_T threshold
    - Improve p_T measurement & identification of charged leptons
    - Identify primary interaction vertex
    - Associate e.g. jets to common vertex when defining multi-object triggers
- Challenges
    - Combinatorics from ~15K input stubs / BX
    - Data volumes of up to ~30 Tbits/s
    - L1 trigger decision within 12.5 μs, ~4 μs available for track finding
- Utilize extensive parallel processing to tackle above challenges
- Track finding implemented as a fully FPGA-based system





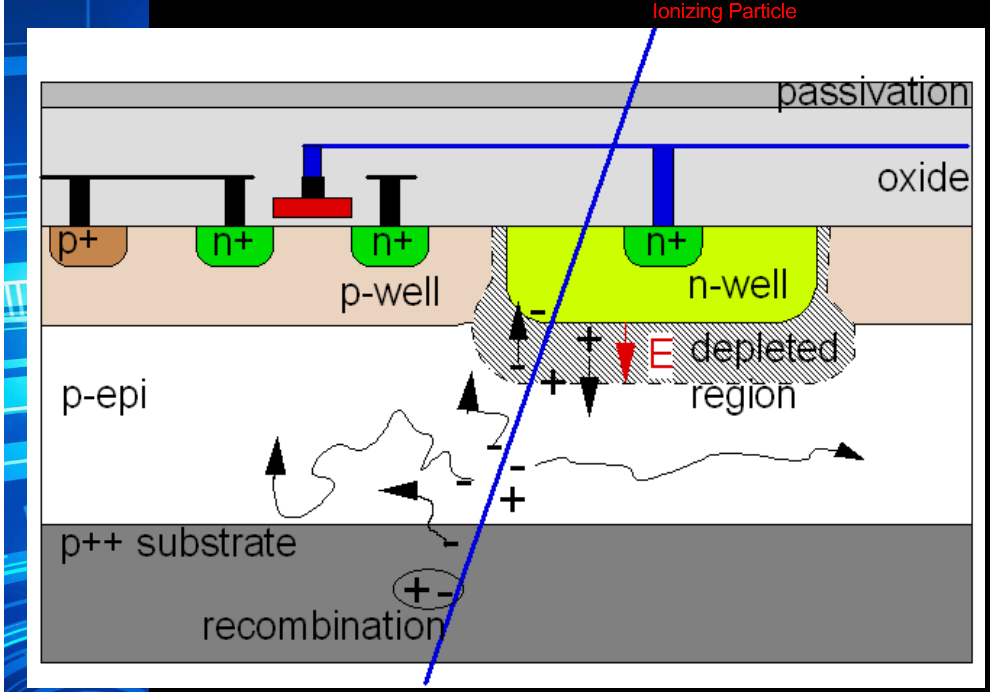
Apollo: track finding processing boards

Monolithic Silicon Pixel Detectors



- FE electronics is integrated in sensor and produced in commercial CMOS processes (many different variants).
- Allows very thin sensors to achieve ultimate low mass trackers (0.3% X_0 in Heavy-Ion experiments or <1% for pp).
- High volume and large wafers (200 mm) reduces detector cost opens possibility for large area pixel detectors.
- Saves cost and complexity of bump bonding(one of the cost drivers in hybrid silicon detector systems).

Monolithic Active Pixels



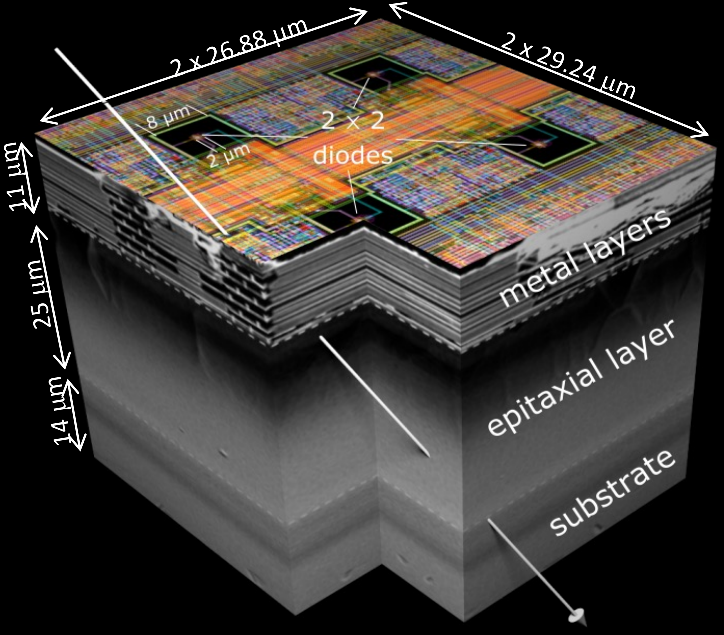
- Commercial CMOS technologies (e.g. AMS 0.35 µm)
- Lightly doped p-type epitaxial layer (~14-20 µm)
  - MIPs produce ~80 e-/h+ pairs per µm (~1000 e-)
- No reverse substrate bias:
  - Signal charge collection mainly by diffusion (~100 ns)
  - Sensitive to displacement damage
- N-well implantation used for collecting electrode
- Only n-MOS transistor in pixel (in p-well)
  - Very simple in-pixel circuit (few transistors)
  - Complex electronics at the periphery of the matrix
- Pixel size: 20 x 20 µm^2 or lower ➟ few µm resolution

Applications:, STAR-detector (RHIC Brookhaven), Eudet beam-telescope

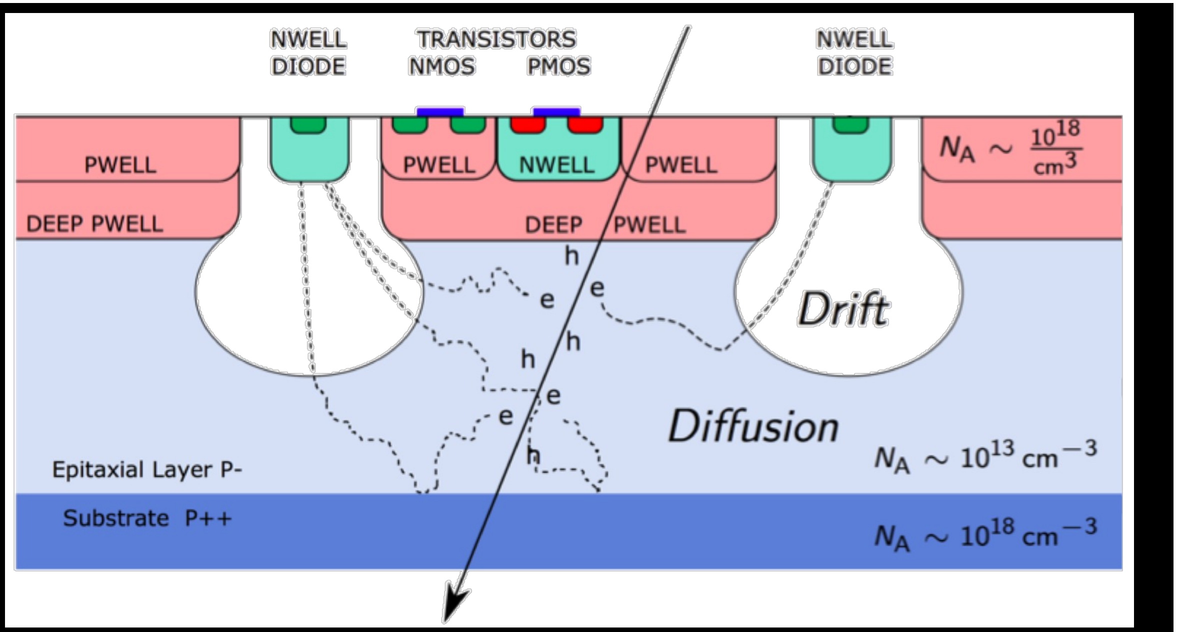
IPHC Strasbourg (PICSEL group))

ALICE ITS

- Based on the Alpide chip in TJ 180 nm



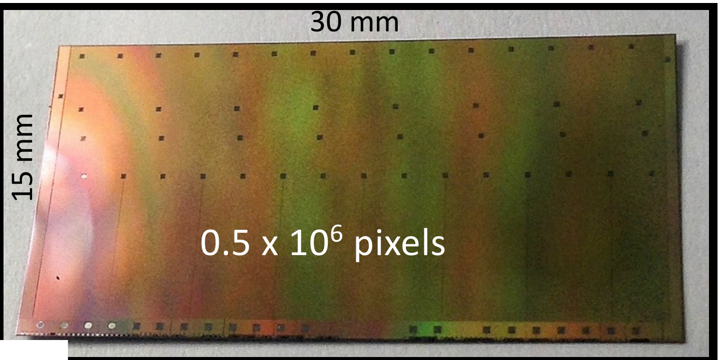
ALPIDE (ALICE)

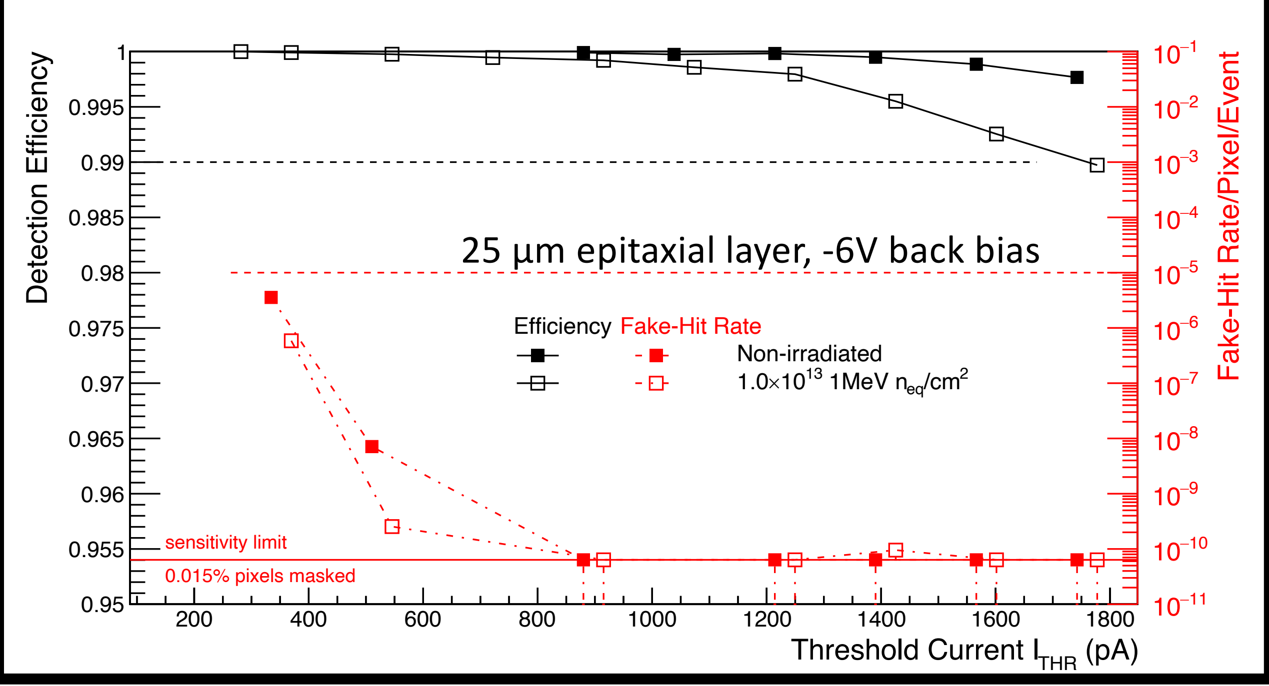


- Tremendous progress in CMOS pixel designs
  - Pixel pitch: 29 μm x 27 μm
  - Power < 40 mW/cm^2
  - Integration time <10 μs

ALPIDE

- Pixel size: 29 x 27 μm^2 with low power front-end **~40 nW/pixel**
- Extensive tests before and after irradiation

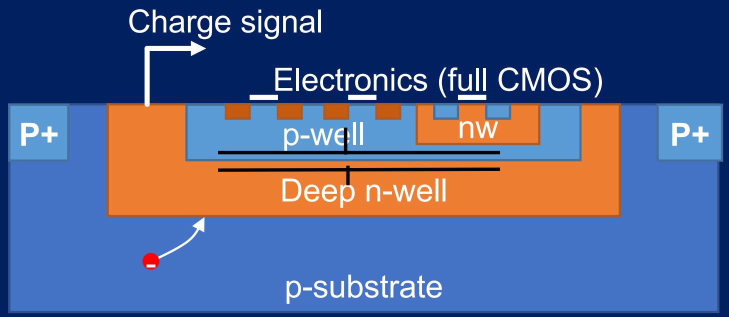




- **Efficiency > 99.5% and fake hit rate << 10^5 over wide threshold range**
- **Excellent performance also after irradiation to 10^{13} (1MeV n_{eq})/cm^2**

Design choices toward DMAPS

Electronics inside charge collection well

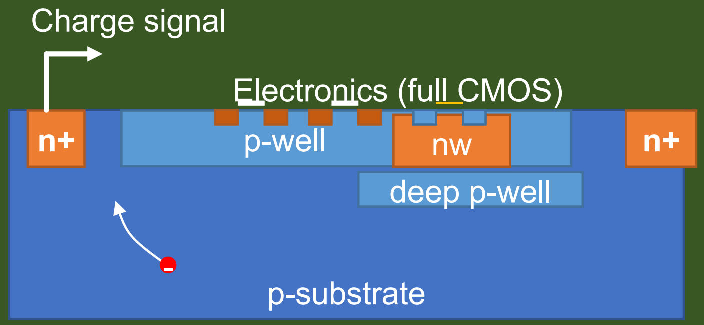


- Deep n and p wells
- Large collection node
- Shorter drift path
- Larger capacitance (DNW/PW junction!) ➠ X-talk, noise & speed (power) penalties

$$ENC^2_{thermal} \propto \frac{4}{3}\frac{kT}{g_m}\frac{\mathbf{C_d^2}}{\tau}$$

$$\tau_{CSA} \propto \frac{1}{g_m}\frac{\mathbf{C_d}}{C_f}$$

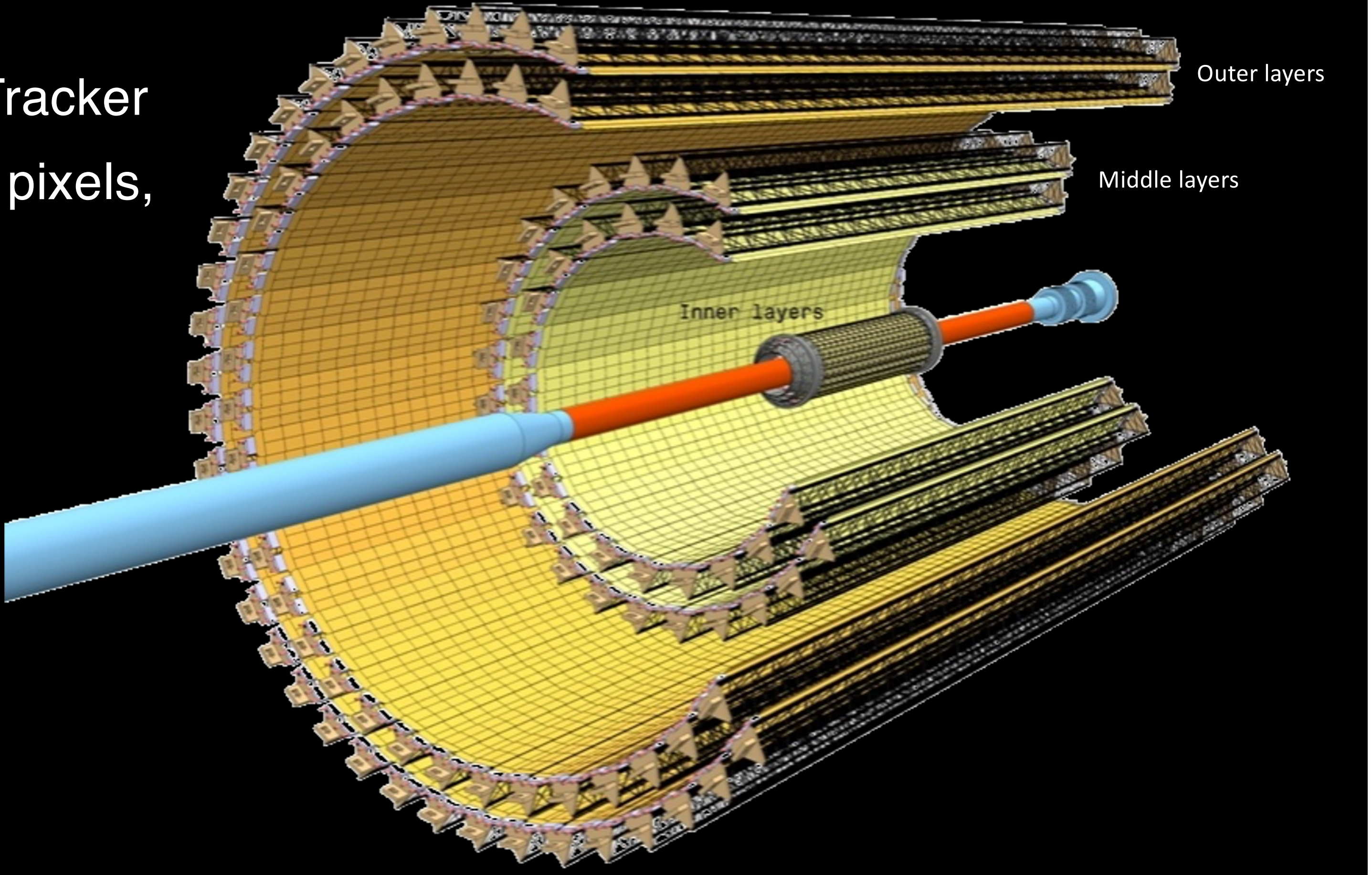
Electronics outside collection well



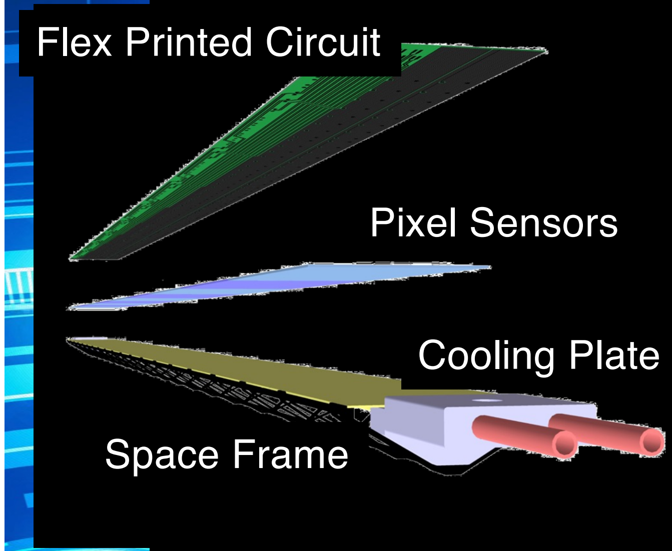
- Full CMOS with additional deep-p implant
- Small collection node
- Smaller capacitance ➠ less power
- Long drift path

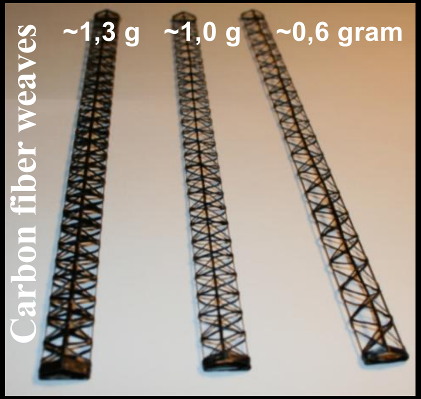
Material reduction

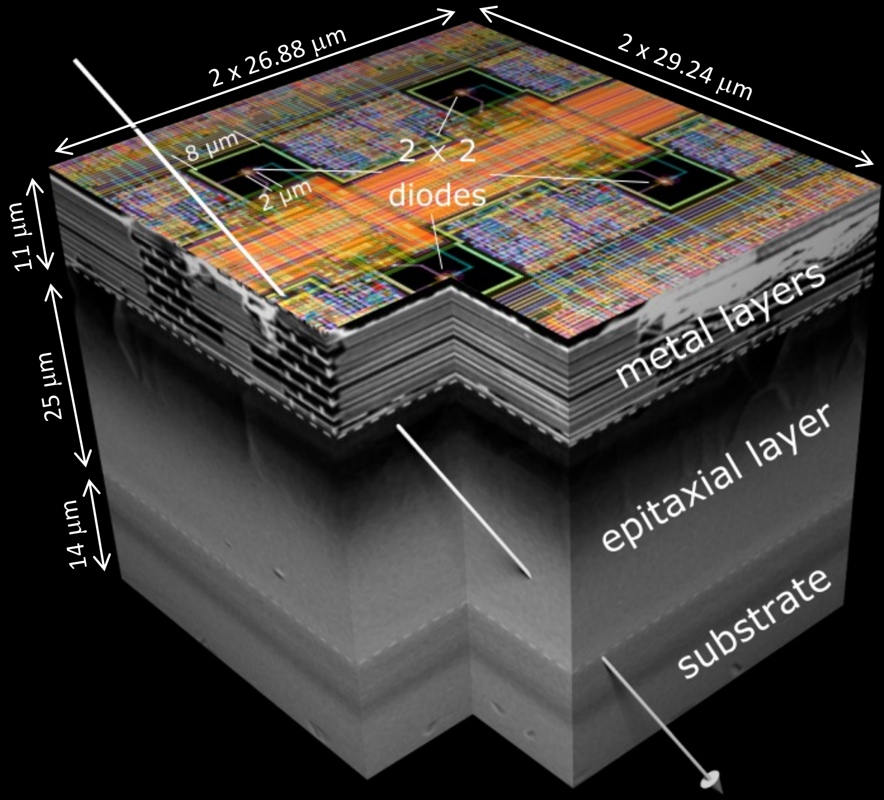
- ALICE MAPS-CMOS Tracker
  - –7-layers, 12.5 Giga pixels, 10m^2
  - –R coverage: 23 – 400 mm
- Material/layer:
  - –0.3% X_0 (IB)
  - –1.0% X_0 (OB)



CMOS Pixel Chips & Material



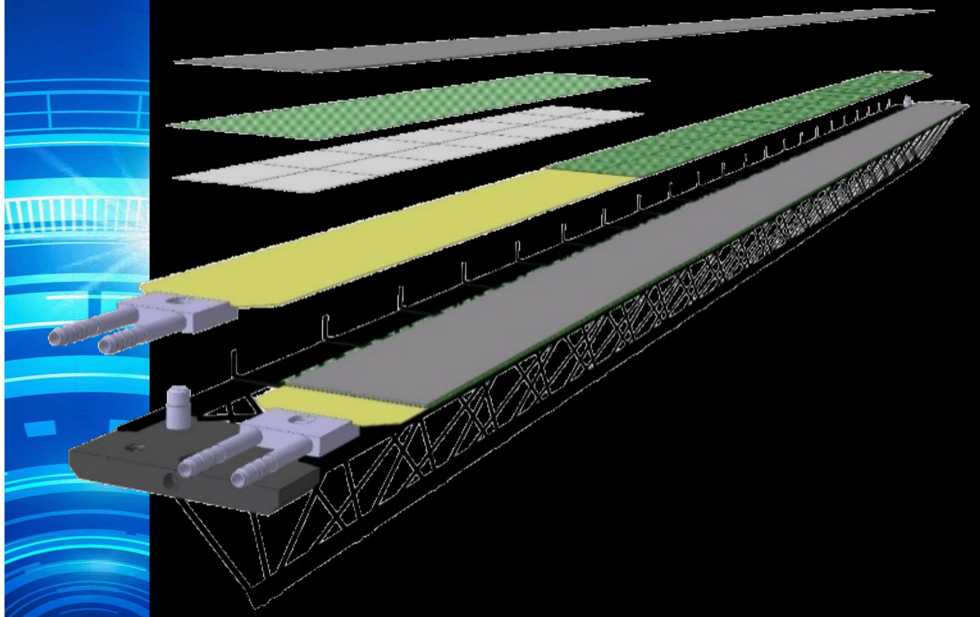




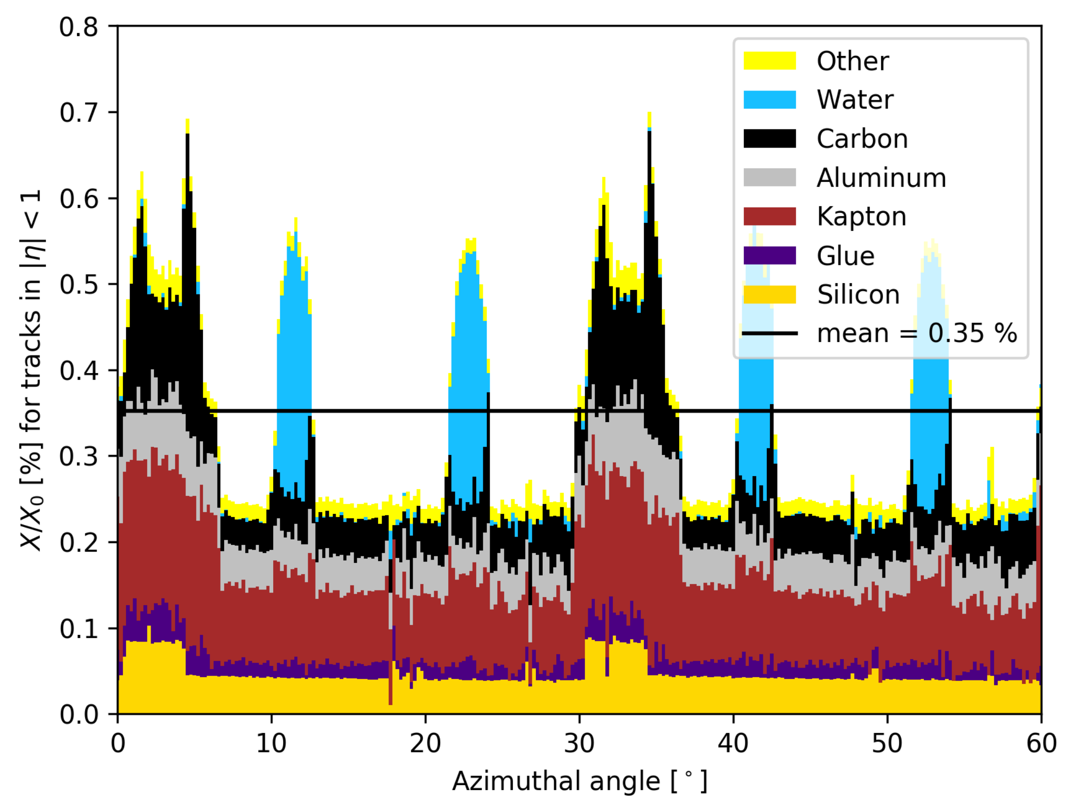
ALPIDE (ALICE)

Depleted CMOS Sensors

Minimize the material budget



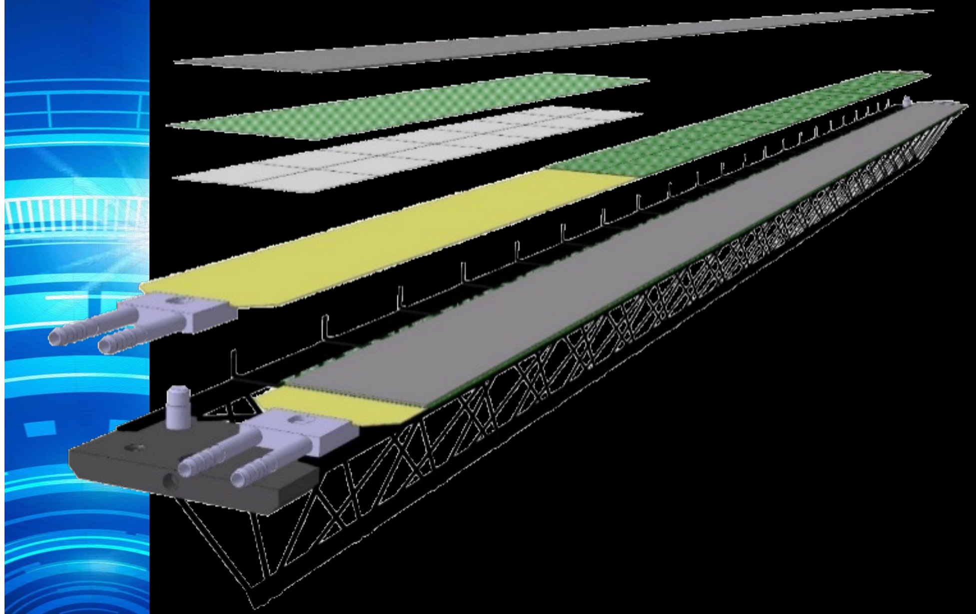
Overall Material Budget



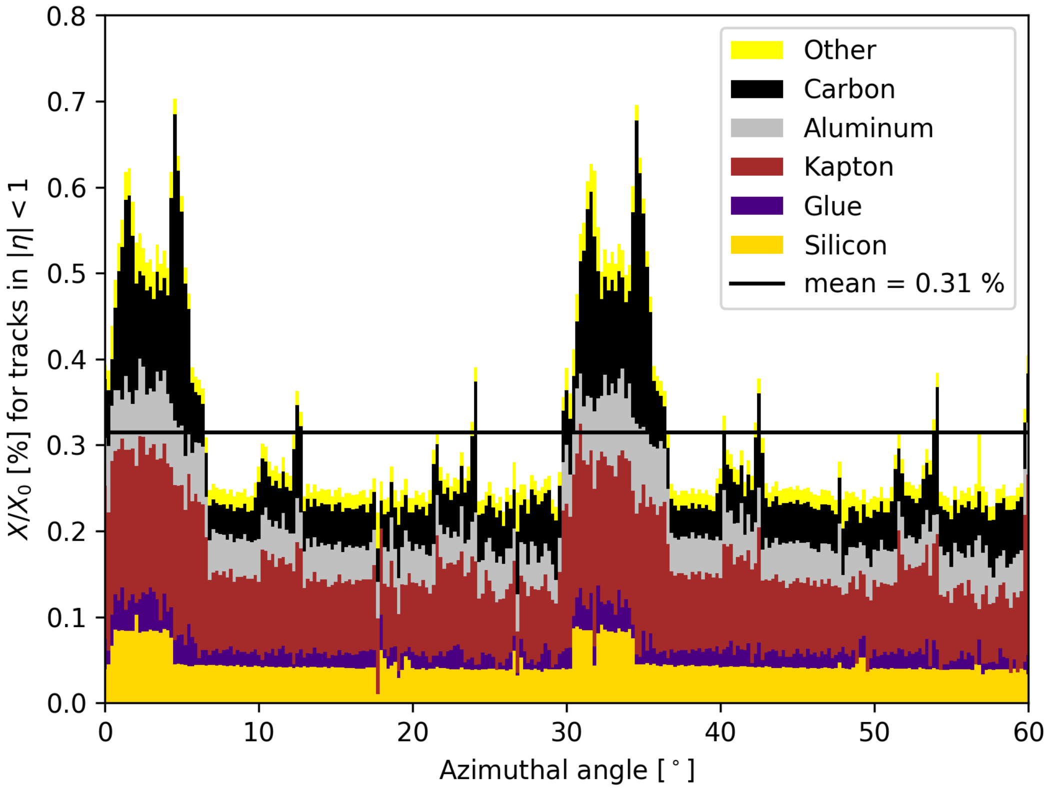
Luciano Musa, Bergen, August 2019: https://indico.cern.ch/event/836343/

Depleted CMOS Sensors

Minimize the material budget

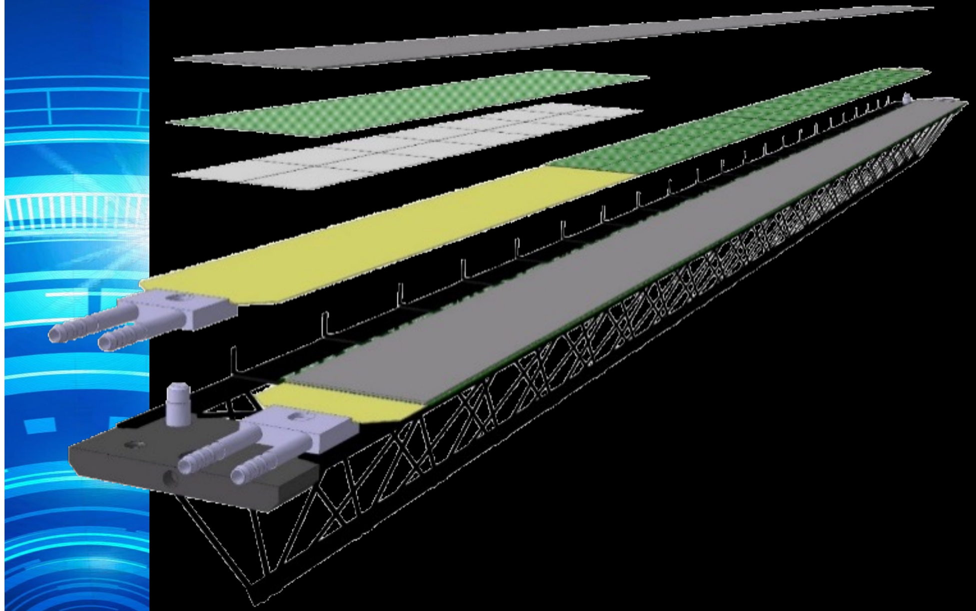


Reduce Power (< 20 mW/cm^2) and Remove Cooling

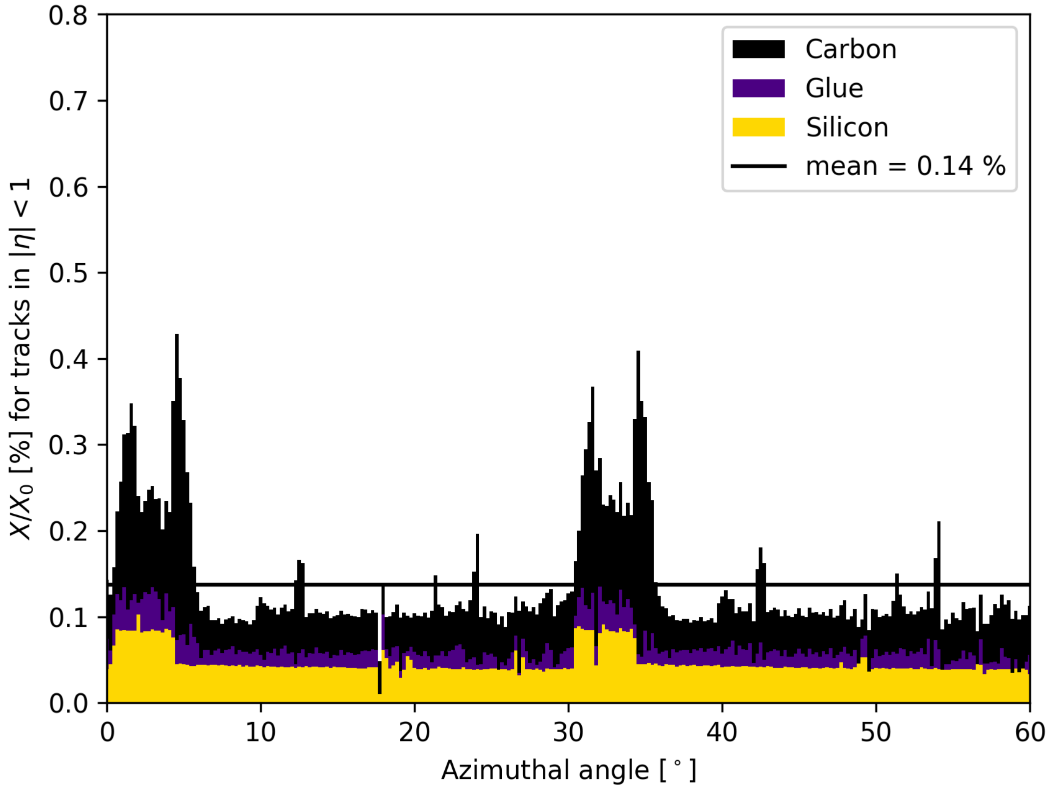


Depleted CMOS Sensors

Minimize the material budget

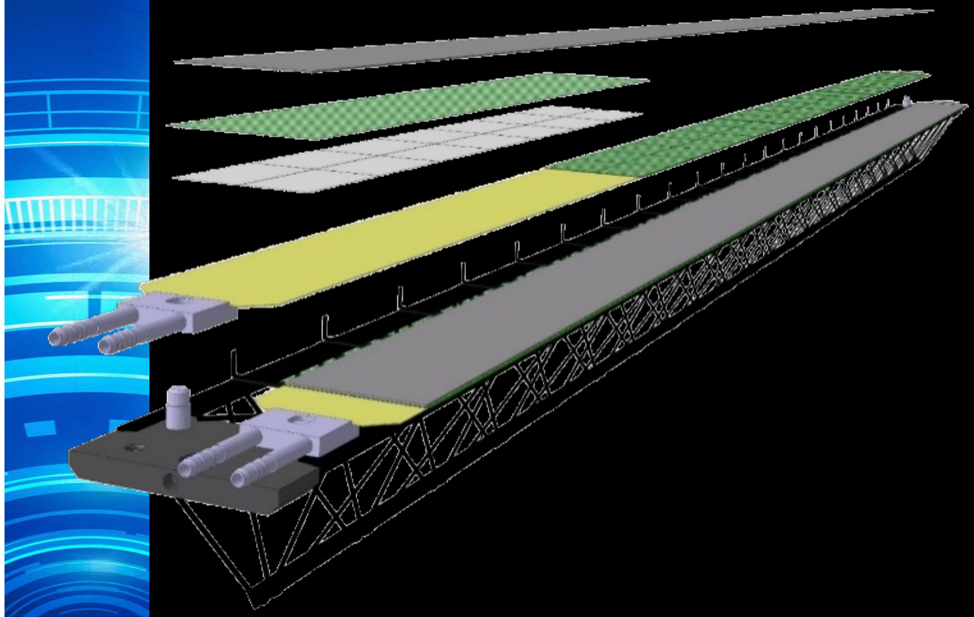


Remove PCB and integrate components on chip

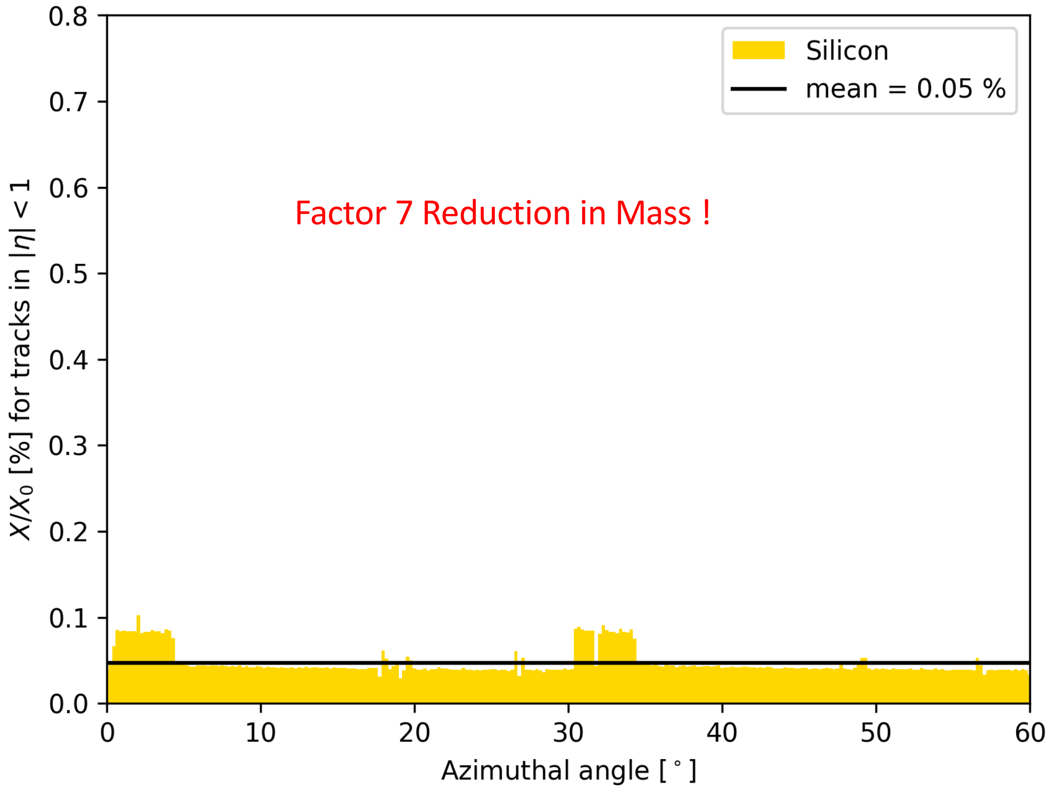


Depleted CMOS Sensors

Minimize the material budget

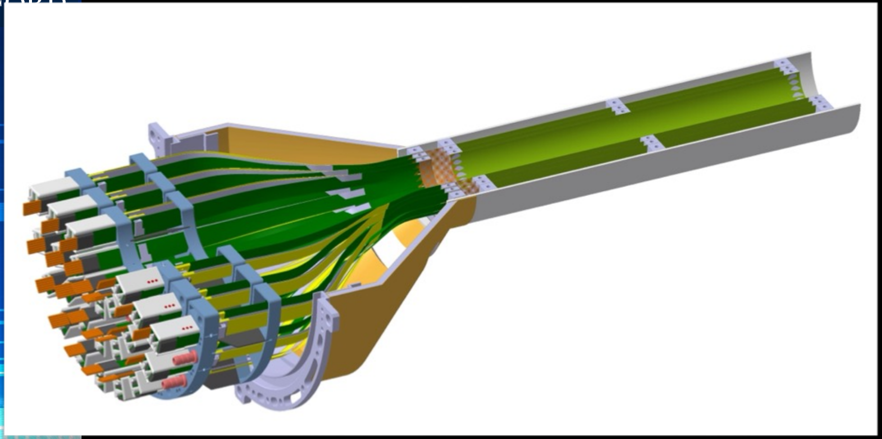


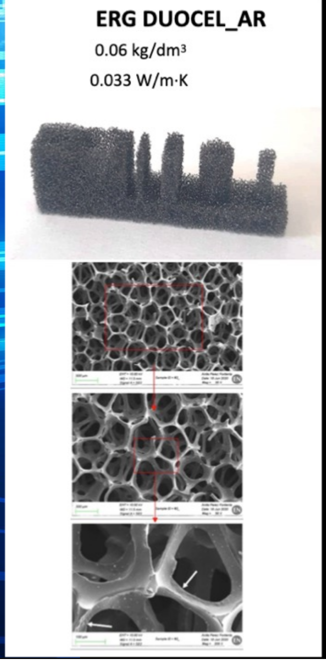
Remove mechanical support and use stiffness provided by rolling Si wafers

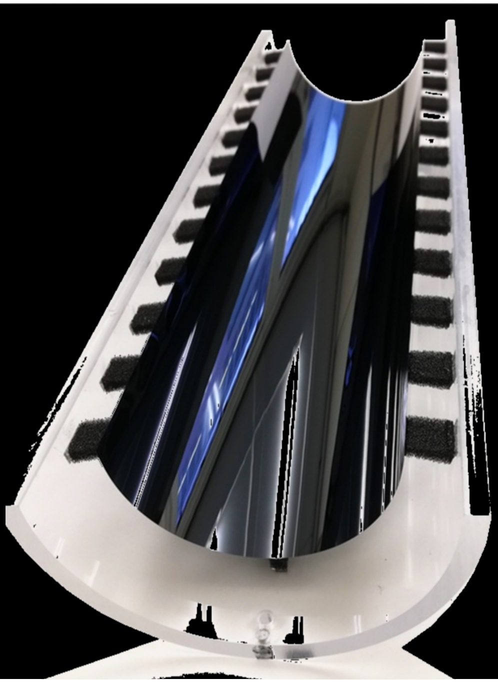


Factor 7 Reduction in Mass !

IT3 Concept





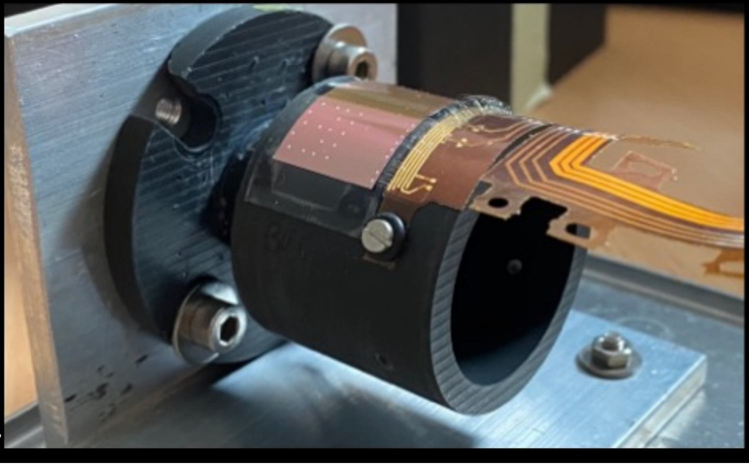


Technology advances:

- 300 mm wafer-scale chips fabricated with stitching
- thinned down to 20-40 μm bent to the target radii
- held in place by carbon foam ribs

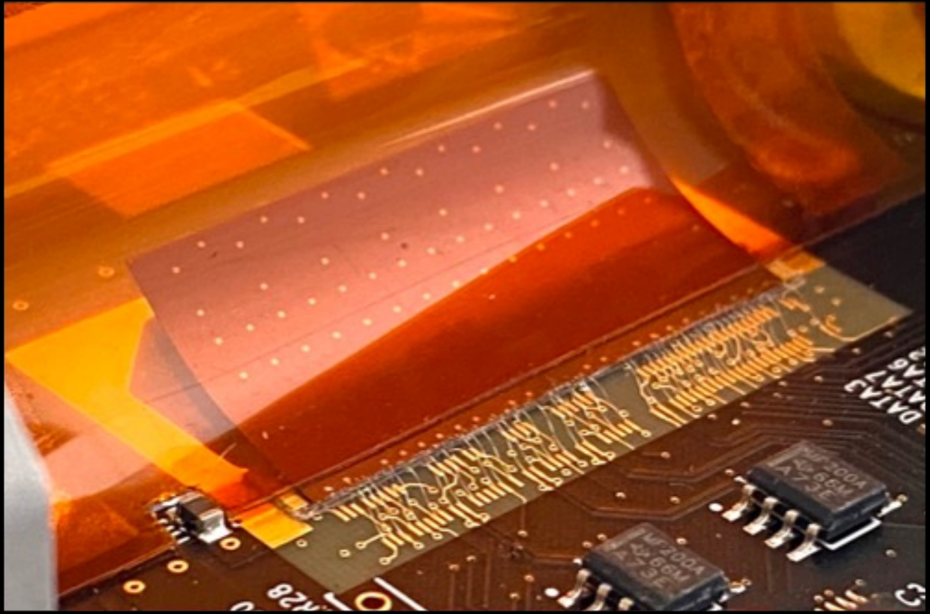
Key benefits:

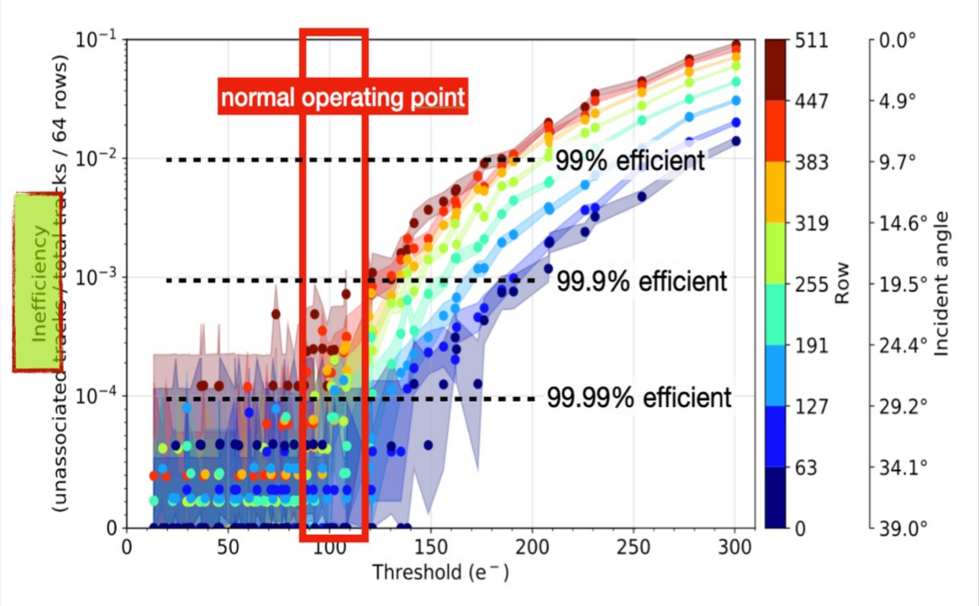
- extremely low material budget: 0.02-0.04% X_0 (beampipe: 500 μm Be: 0.14% X_0)
- homogeneous material distribution leading to smaller systematic error



Test beams

June 2020 test beam data shows that bent MAPS work perfectly



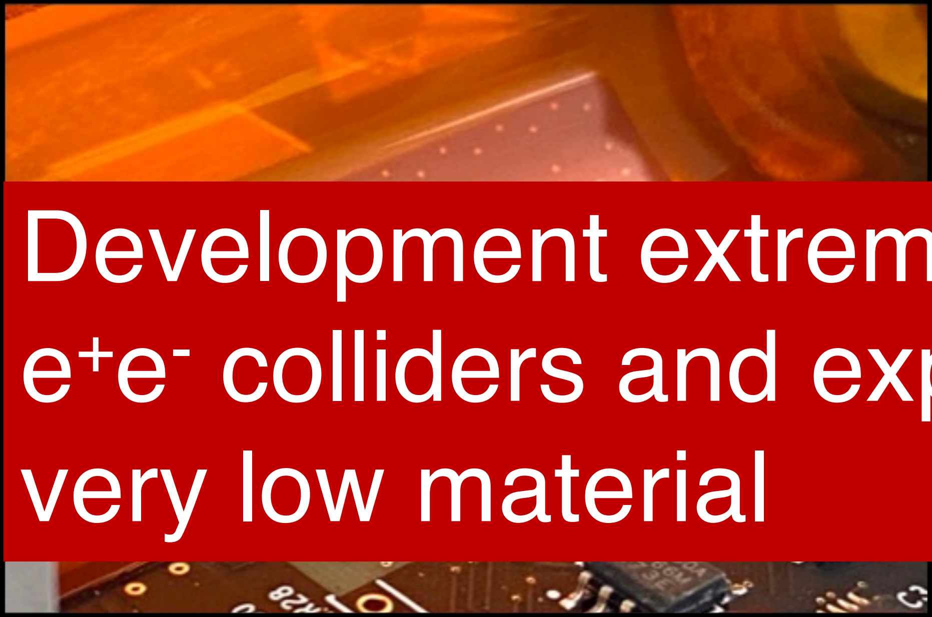


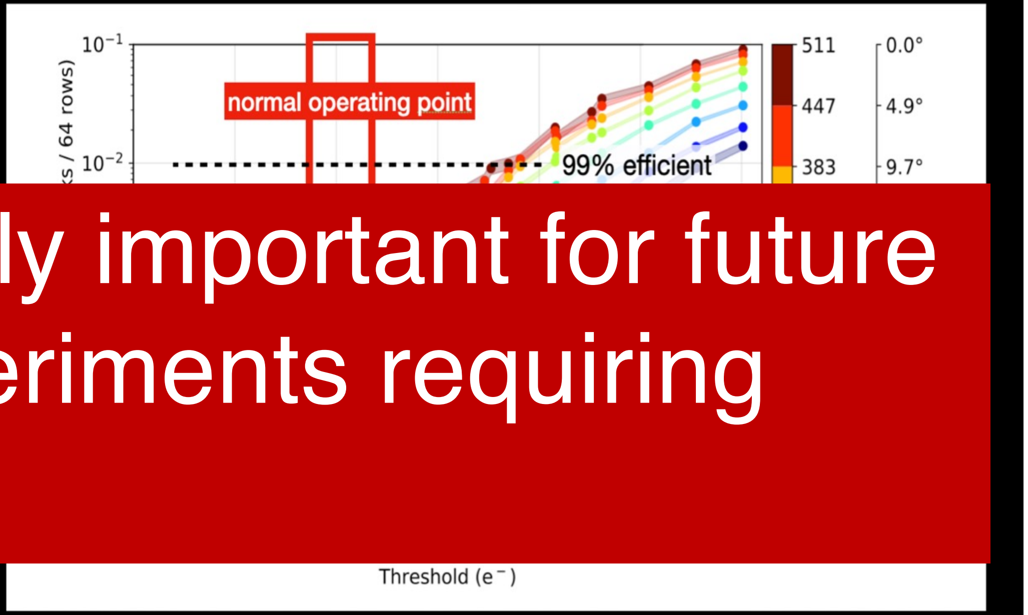
Collaboration investigating TowerJazz 65 nm

Magnus Mager (CERN) | ALICE ITS3 | TIPP 2021 | 26.05.2021 |

Test beams

June 2020 test beam data shows that bent MAPS work perfectly



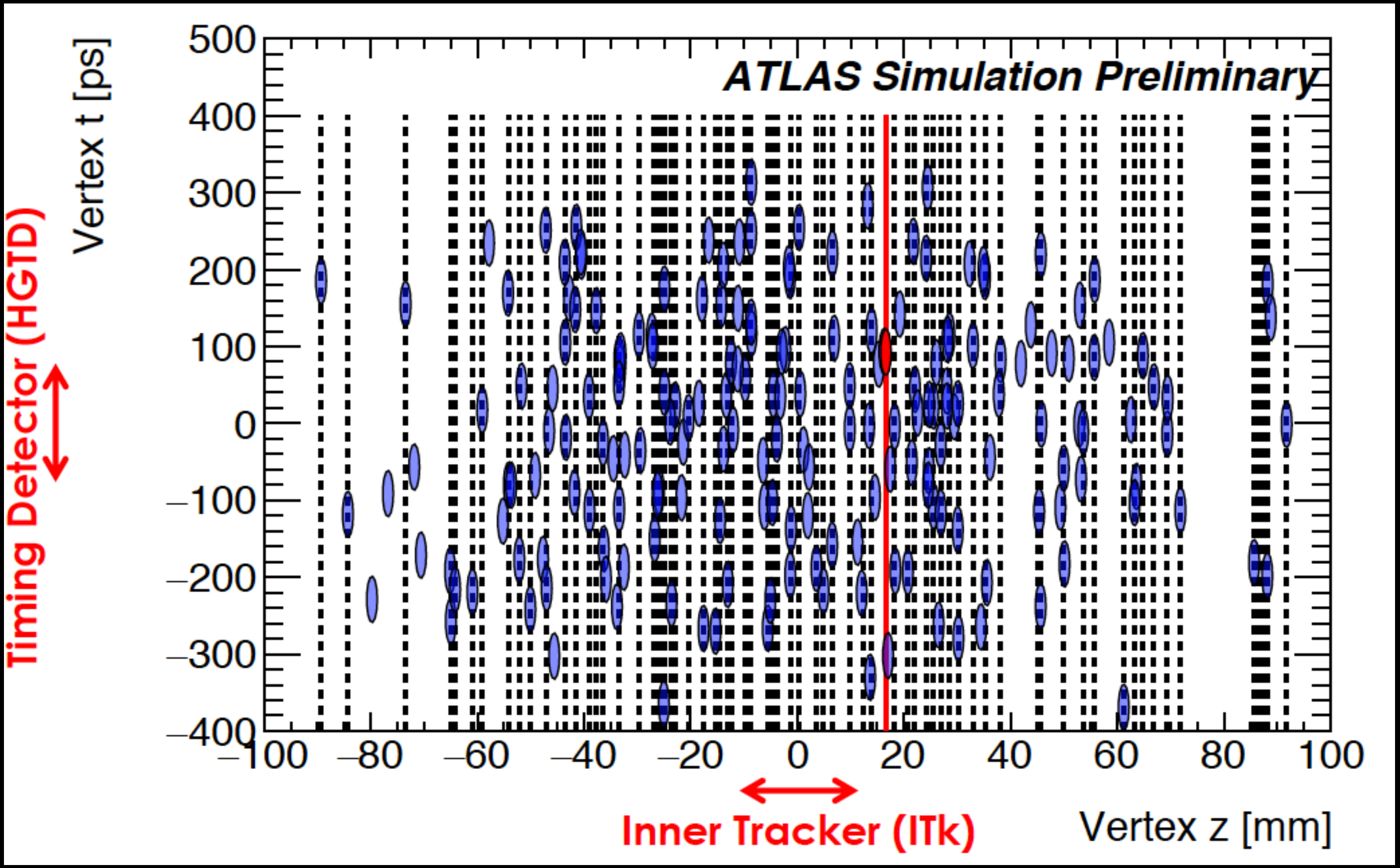


Development extremely important for future e^+e^- colliders and experiments requiring very low material

Collaboration investigating TowerJazz 65 nm

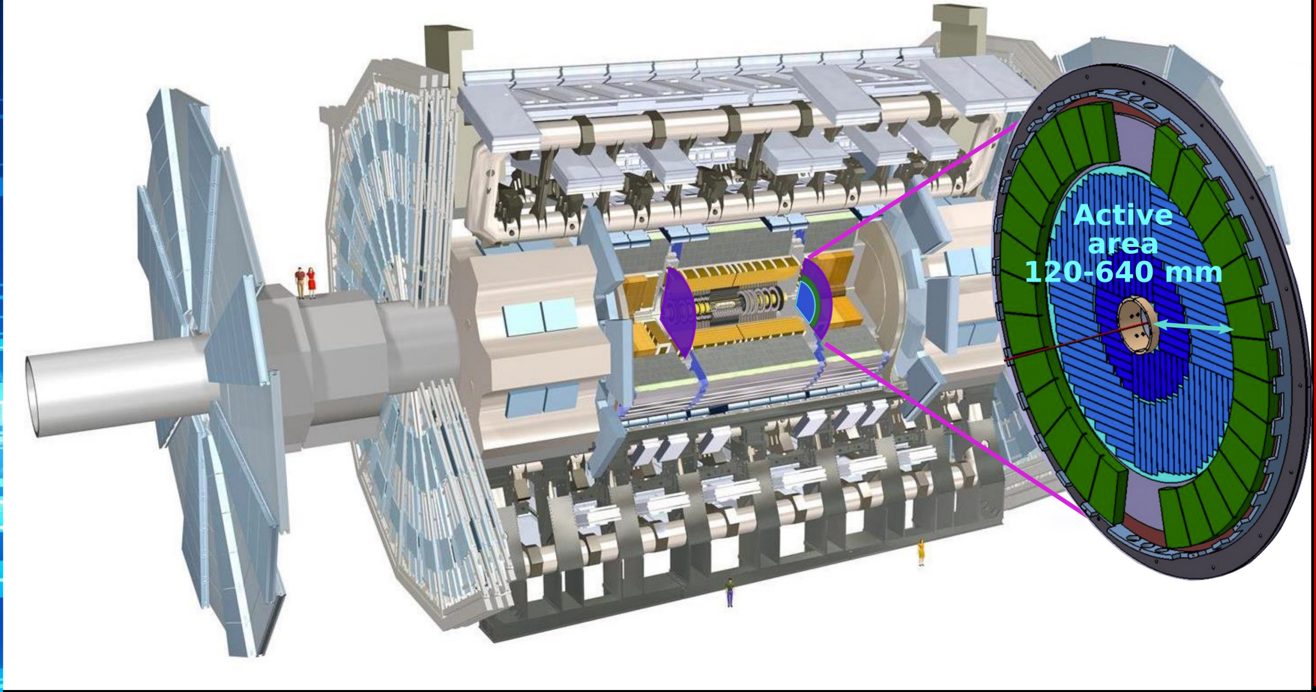
Magnus Mager (CERN) | ALICE ITS3 | TIPP 2021 | 26.05.2021 |

Timing



Exploit the time spread of collisions to reduce pileup contamination

ATLAS High Granularity Timing Detector

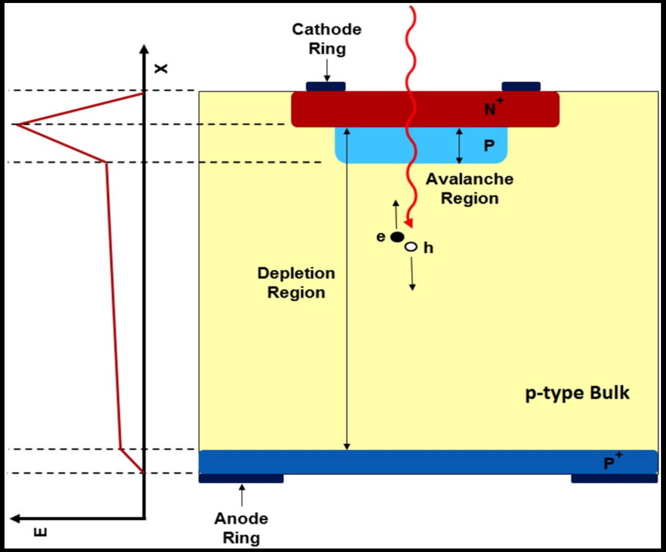


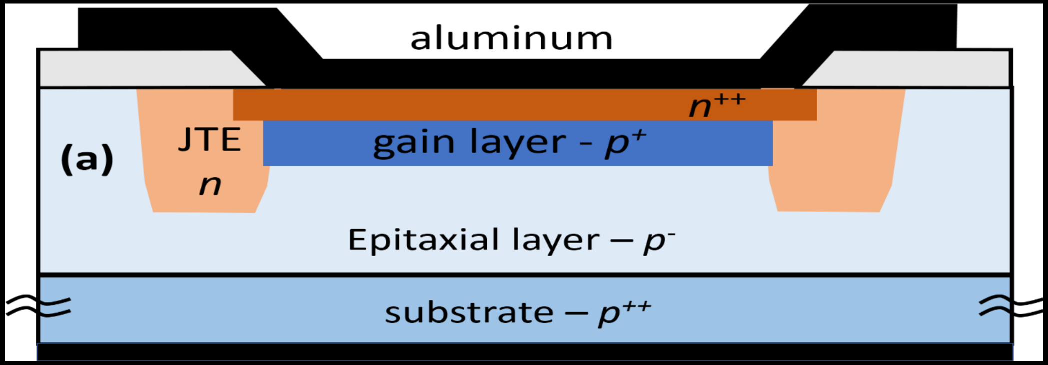
- Low Gain Avalanche Detectors (LGADs) pixel size: 1.3x1.3 mm^2
- Excellent time resolution (30-50 ps/track)
- Radiation-hard (up to $2.5\text{x}10^{15}$ n_{eq}/cm^2 and 1.5 MGy)
- Occupancy< 10%

- 2 double planar layers per endcap providing an average number of hits per track of 2-3
- Pseudorapidity coverage: $2.4<|\eta|<4.0$
- Radial extension: 12 cm < R < 64 cm
- z position: 3.5 m; Thickness in z: 7.5 cm
- Operated at -30 ^{0}C

Timing detectors will also be implemented in CMS

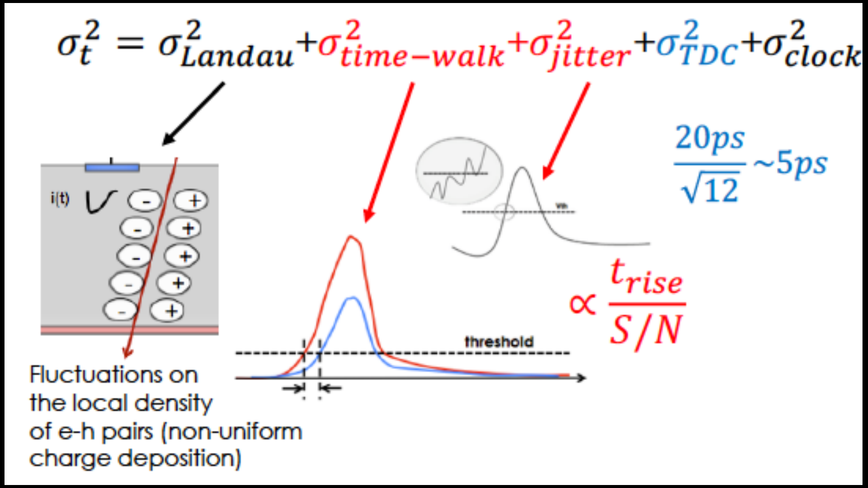
Low Gain Avalanche Diodes





- The Junction Terminating Extension (**JTE**) allows high depletion but limits position resulution

- Timing resolution: 35 - 70 ps/hit
- Gain> 20 decreases to > 8 at the end of lifetime (V_{bias}<800 V)
- Collected charge >4 fC /MIP/hit after 2.5×10^{15} n_{eq}/ cm^2
- Prototypes from CNM (Spain), HPK (Japan), BNL (USA), FBK (Italy), IME & NDL (China), T-e2v & Micron (UK)



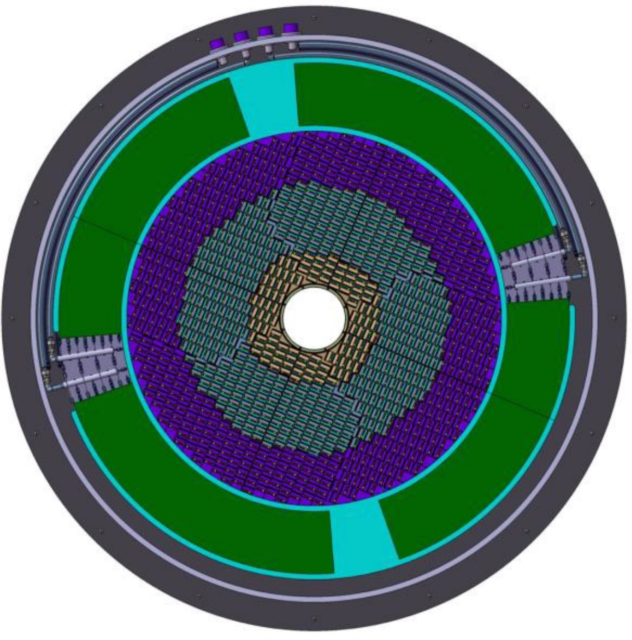
$$\sigma_t^2 = \sigma_{Landau}^2 + \sigma_{time-walk}^2 + \sigma_{jitter}^2 + \sigma_{TDC}^2 + \sigma_{clock}^2$$

$$\frac{20ps}{\sqrt{12}} \sim 5ps$$

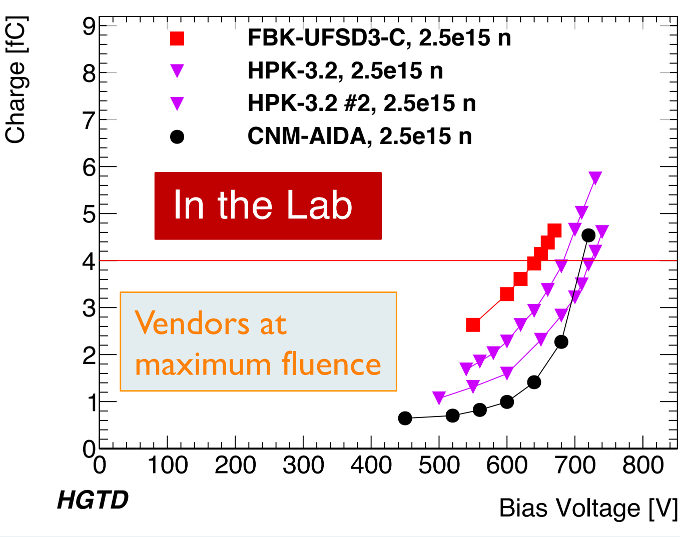
$$\propto \frac{t_{rise}}{S/N}$$

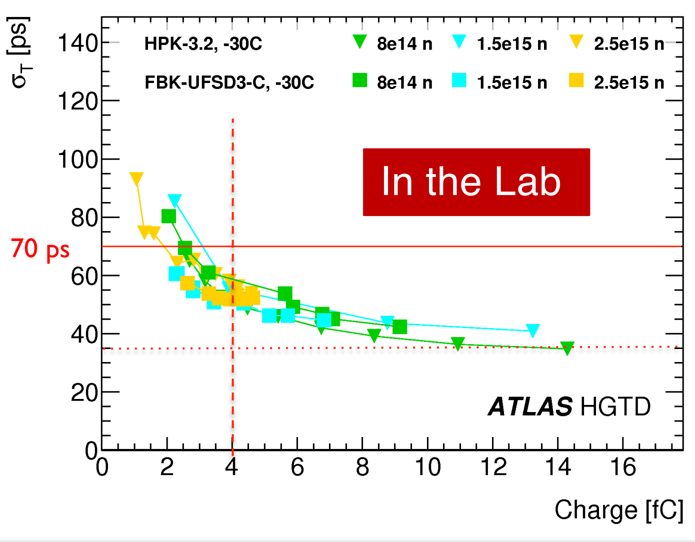
Fluctuations on the local density of e-h pairs (non-uniform charge deposition)

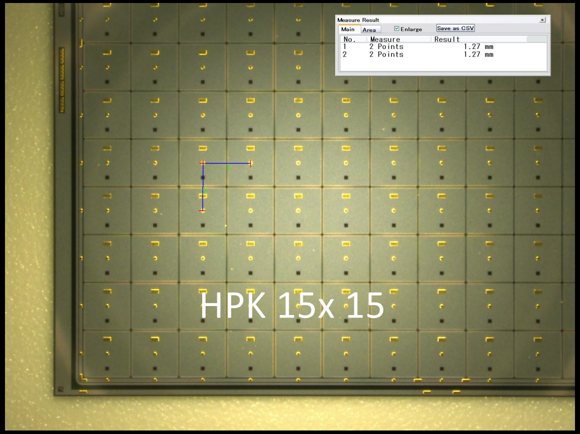
Ultra Fast Silicon Detectors

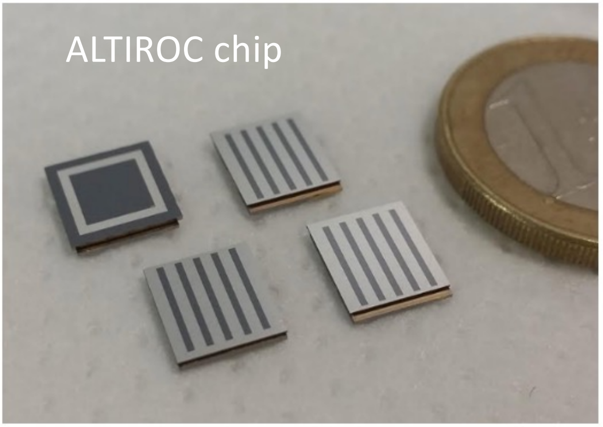


- Inner (12-23 cm) every 1000 fb^{-1}
- Middle (23-47 cm) every 2000 fb^{-1}
- Outer (47-64 cm) never replaced



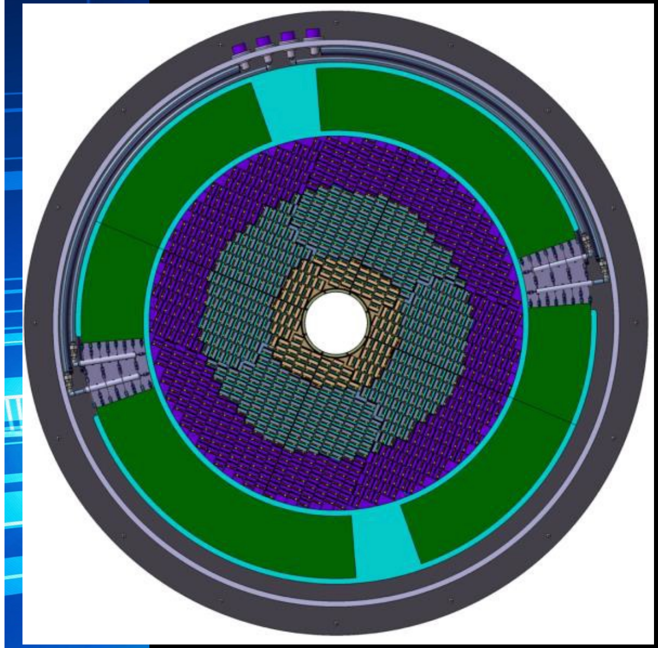


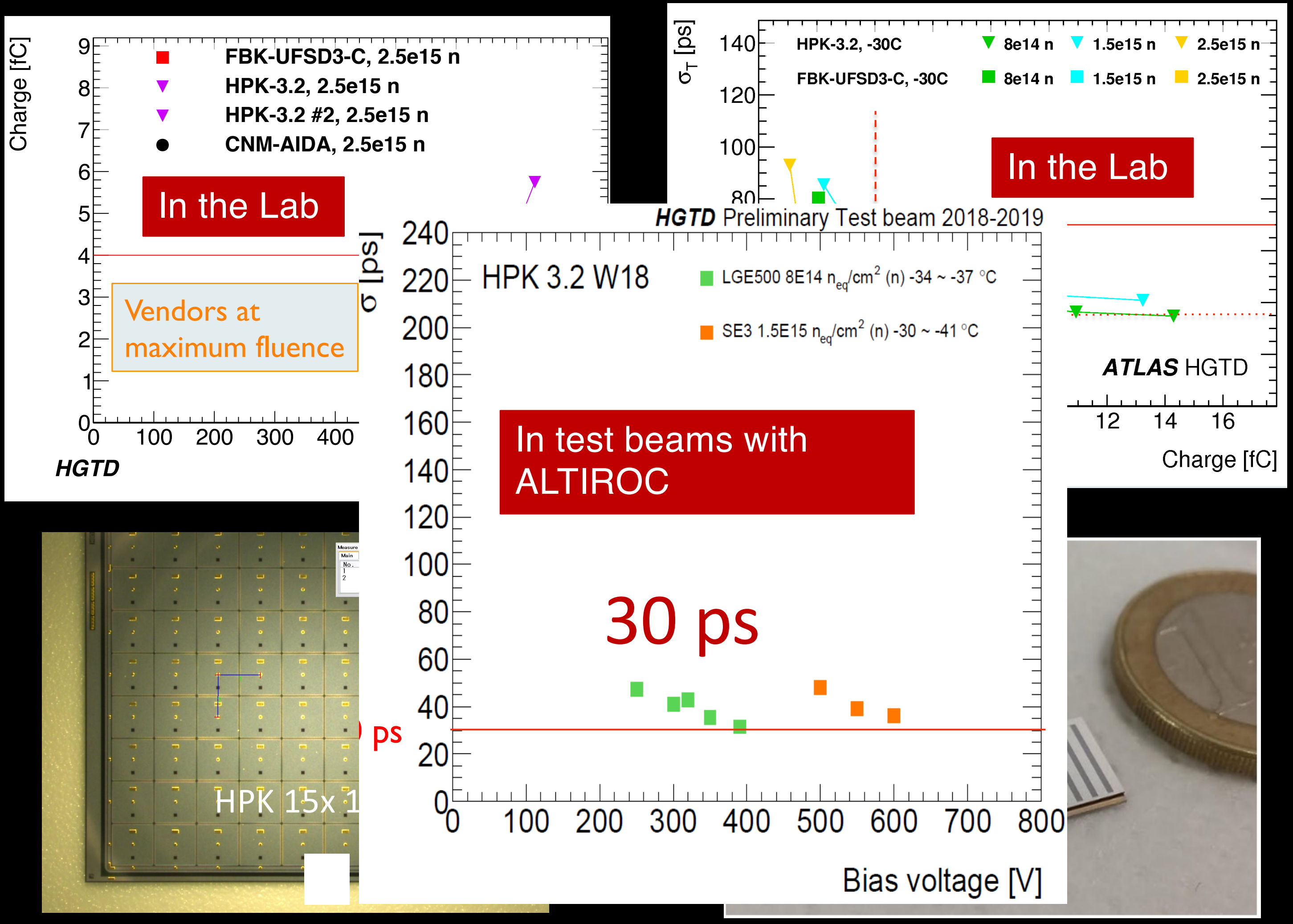




Irena Nikoloc – TIPP 2021

Ultra Fast Silicon Detectors




In the Lab

Vendors at maximum fluence

In the Lab

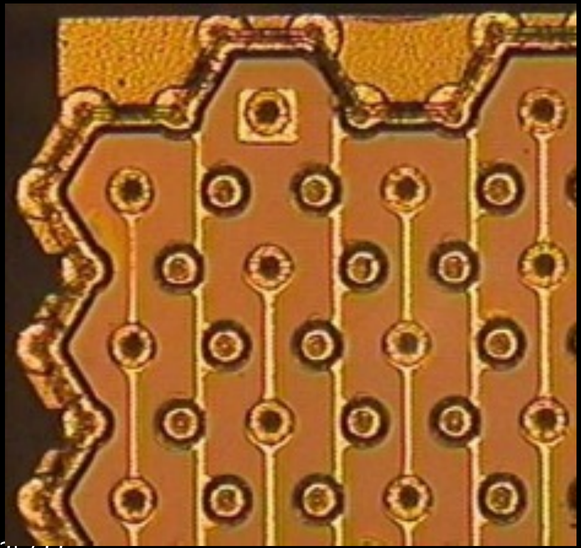
In test beams with ALTIROC

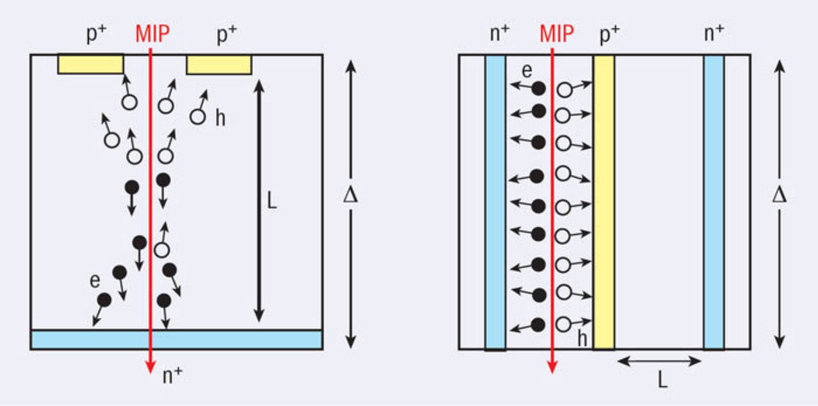
30 ps

- Inner (12-23 cm) every 1000 fb^{-1}
- Middle (23-47 cm) every 2000 fb^{-1}
- Outer (47-64 cm) never replaced

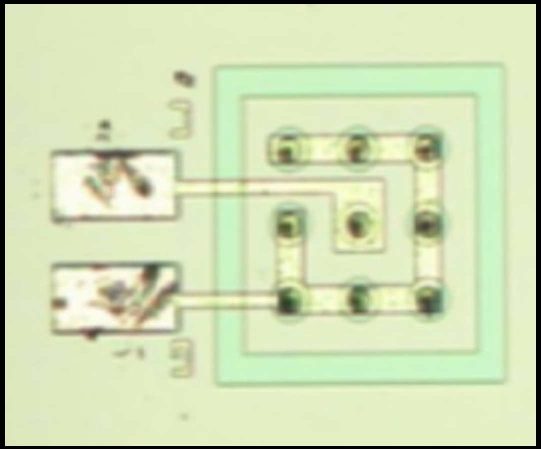
Timing with 3D sensors

- Parker et al. IEEE TNS 58(2) (2011) 404
- Hexagonal geometry L=50 μm, 20 V bias
- Tested under 90Sr β source at RT
- σ_t = 31- 177 ps (according to signal amplitude)
- Limited by RO electronics noise

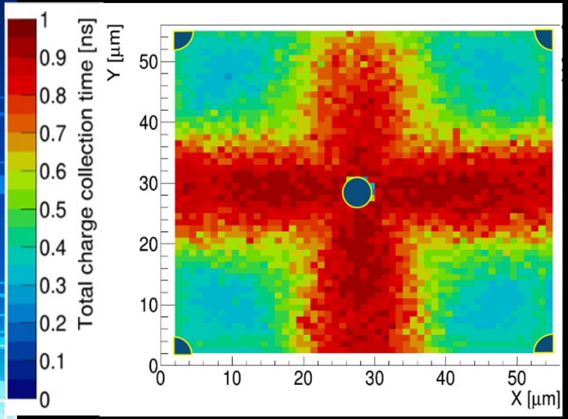




- G. Kramberger et al., NIMA 934 (2019) 26-32
- Squared geometry L=50 μm. Depth = 300 μm. 50 V bias
- Tested under 90Sr β source. Room temperature.
- σ_t = 75 ps



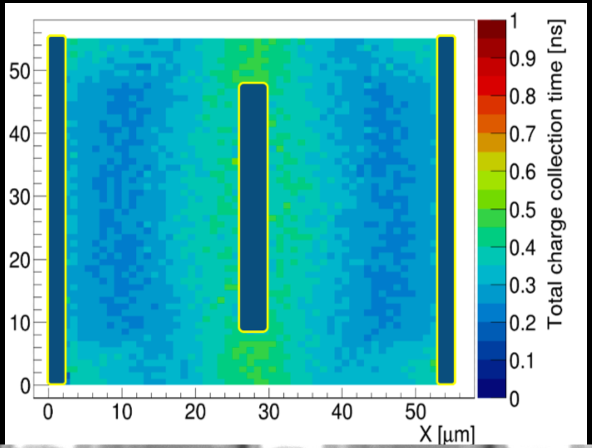
Timing with 3D sensors

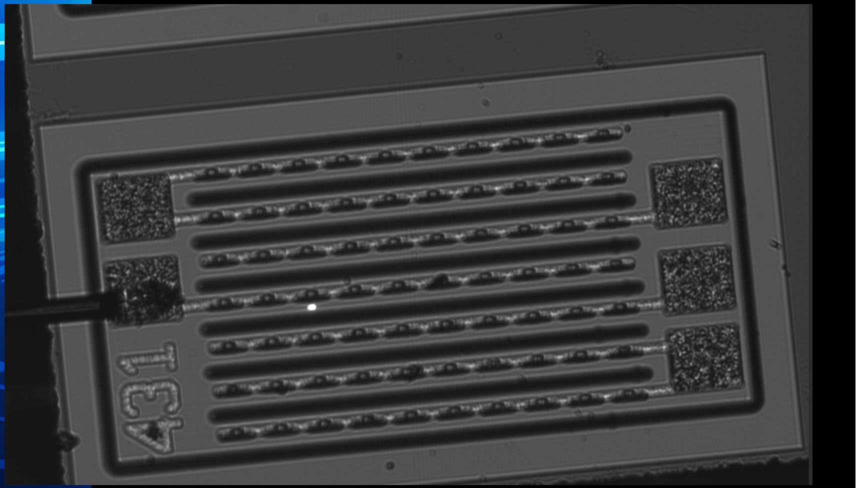


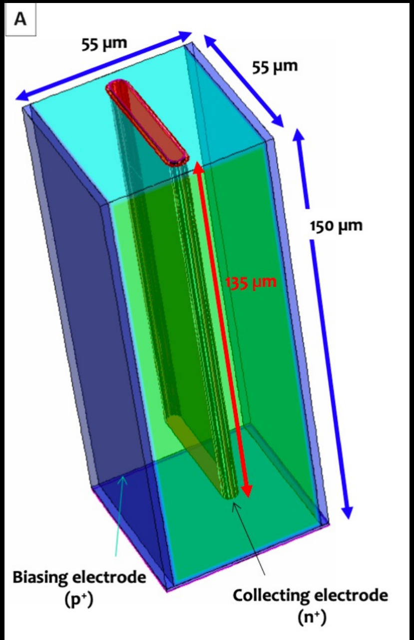
Column geometry (e.g. ATLAS IBL)

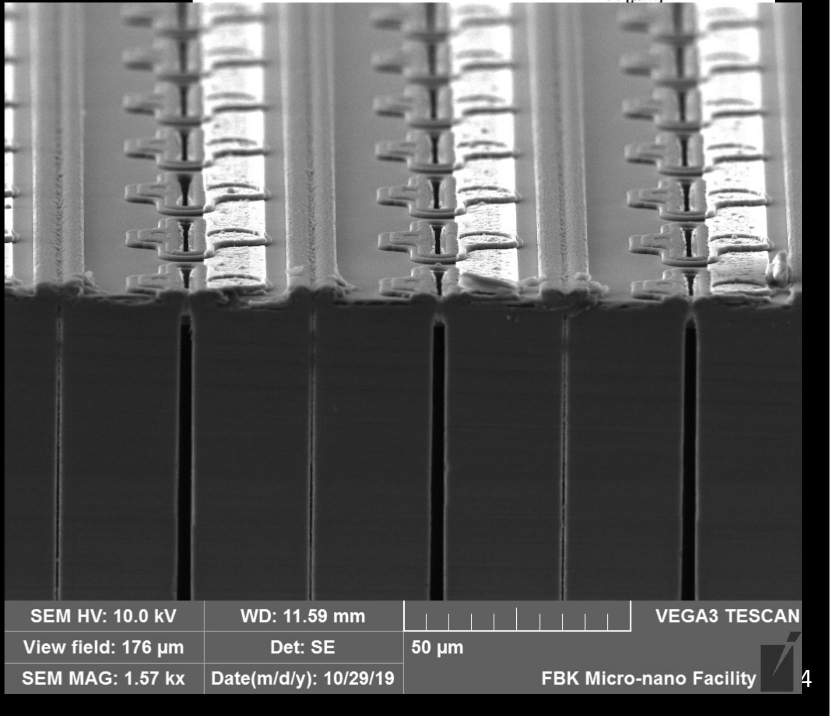
TimeSPOT

TIME and SPace real-time Operating Tracker



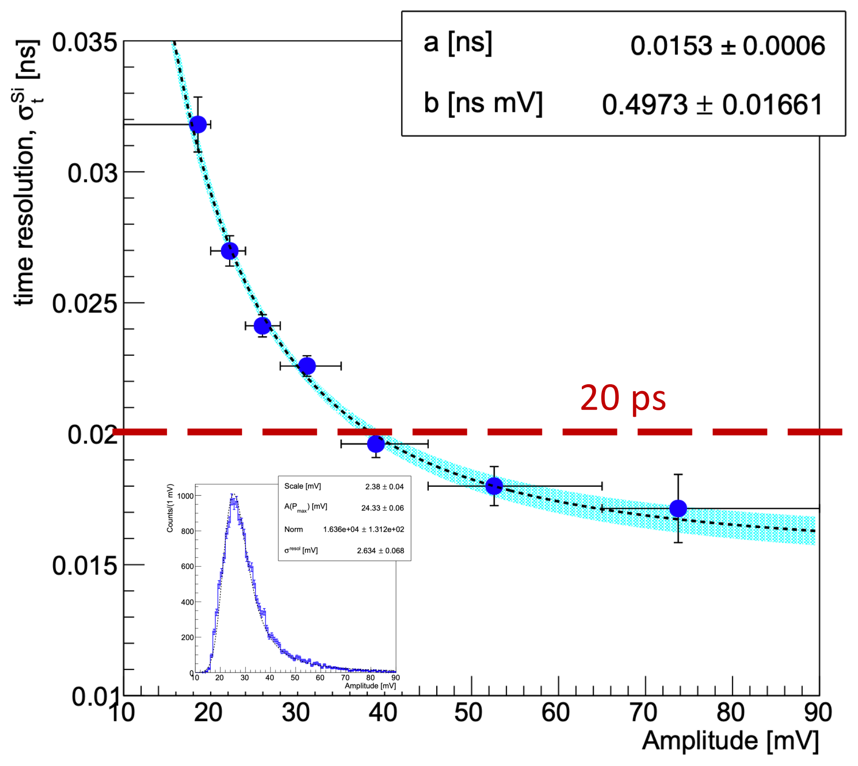




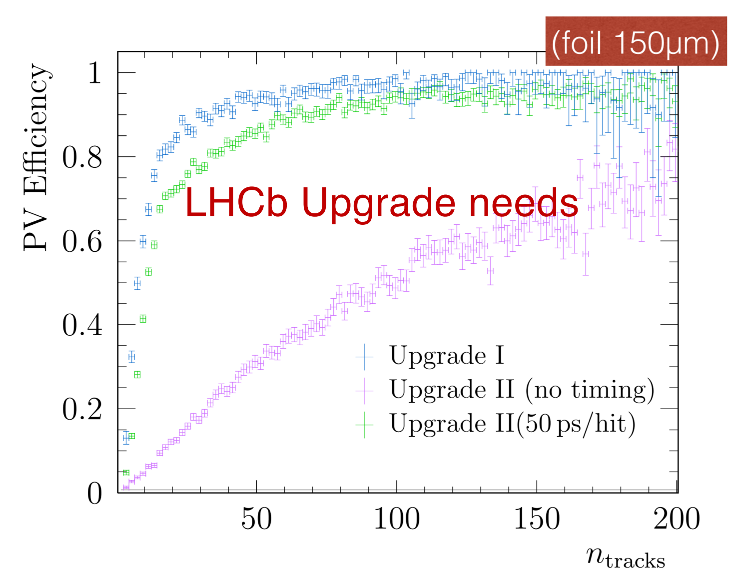


TimeSpot

- Beam test results (270 MeV/c π+ at PSI)
- Fast Front End Electronics (SiGe BJT)



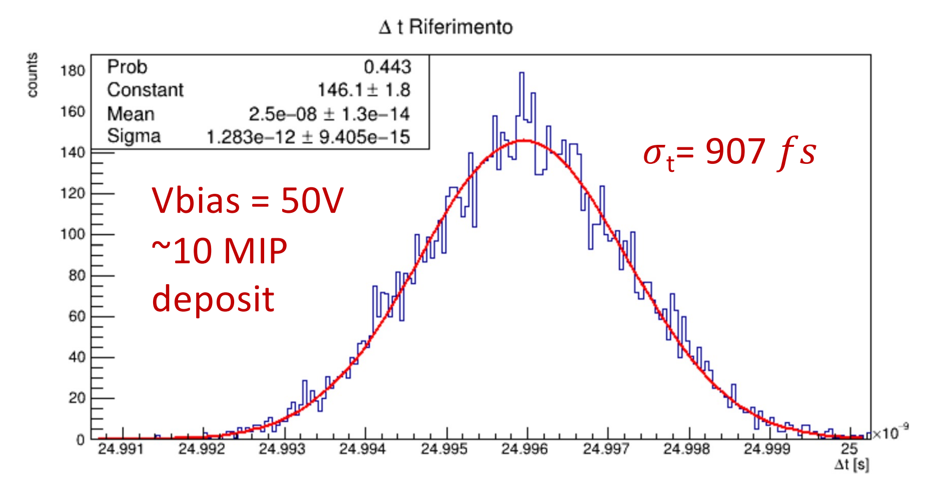
20 ps



(foil 150μm)

LHCb Upgrade needs

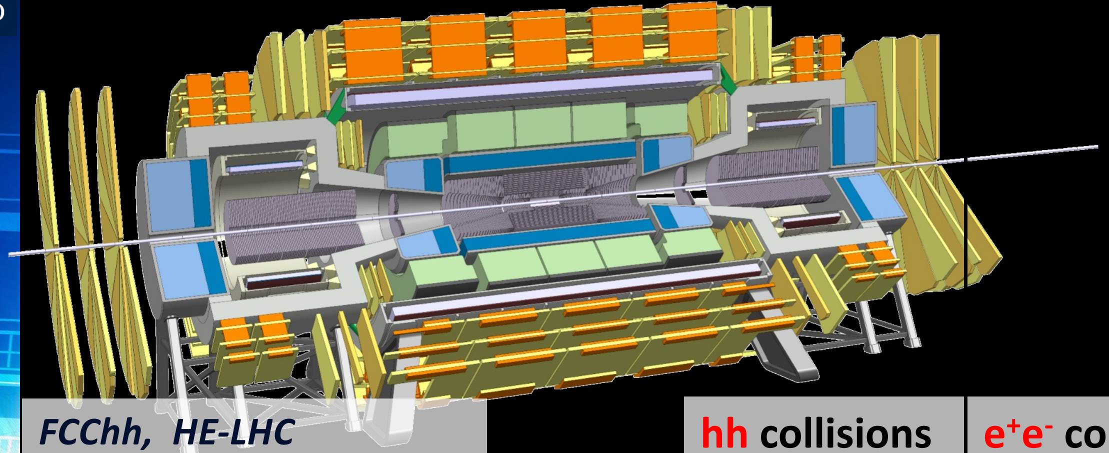
In the lab with infrared laser



Vbias = 50V
~10 MIP
deposit

σ_t= 907 fs

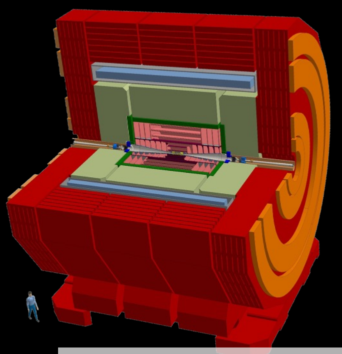
FUTURE COLLIDER DETECTORS



FCChh, HE-LHC

hh collisions

e^+e^- collisions



CLIC, FCCee, ILC, CEPC,…

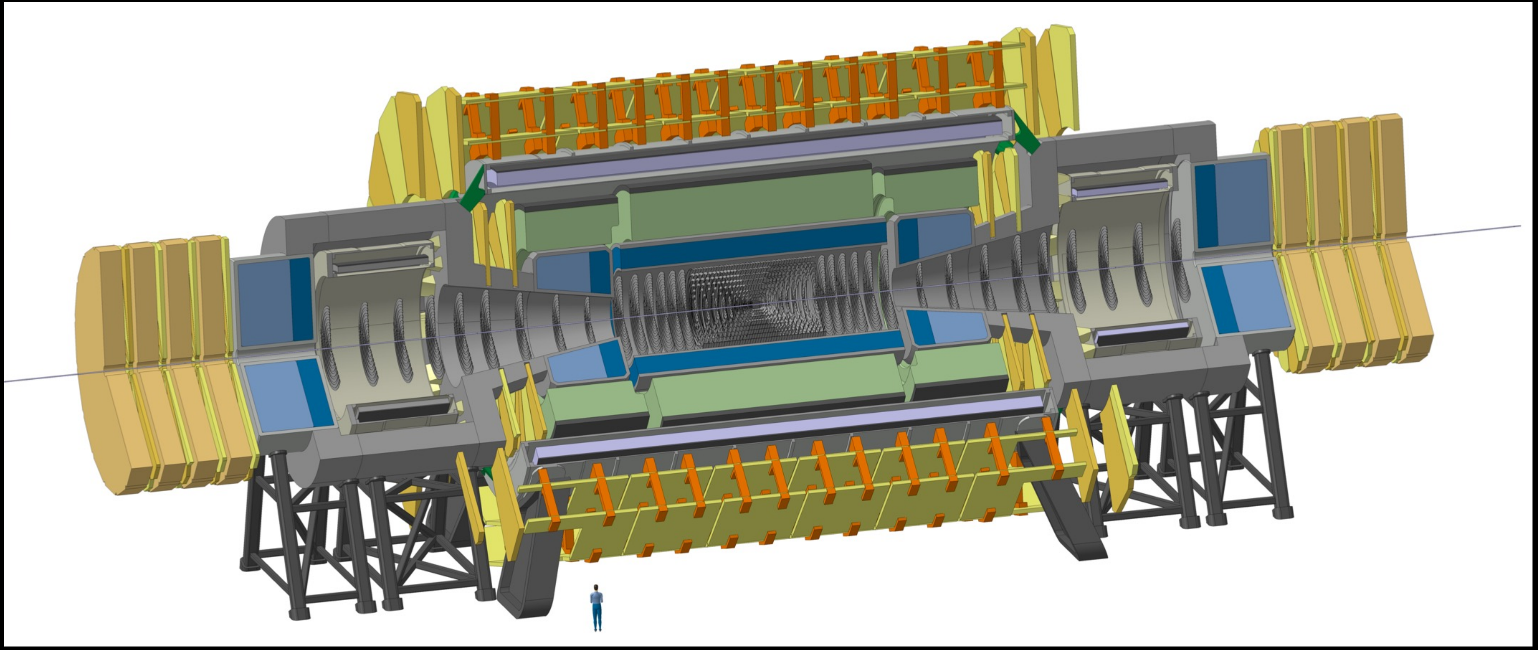
- Large dimensions (50m)
- High radiation Level (up to 90MGy, $\approx 10^{18}$ /cm^2)
- 4T 10m solenoid
- Forward solenoids 4T
- Silicon tracker Radius 1.6m, Length 32m radiation damage is a concern
- Barrel ECAL LAr/ Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forward HCAL/ECAL LAr 2-4x better granularity than e.g. ATLAS Silicon ECAL and ideas for digital ECAL with MAPS
- Muon system

- Standard dimensions
- Low radiation Level
- 4T, 2T
- Silicon tracker unprecedented spatial resolution (1-5 μm point resolution)
- very low material budget (0.1X%)
- Dissipated power (vertex) (<50mW/cm^2)
- Radiation level NIEL ($<4\times10^{10}$ neq cm^{-2}/yr)
- Radiation level TID (<200 Gy/yr)
- Barrel fine grained calorimeter
- Compact Forward calorimeter

R&D

FCC-hh Reference Detector

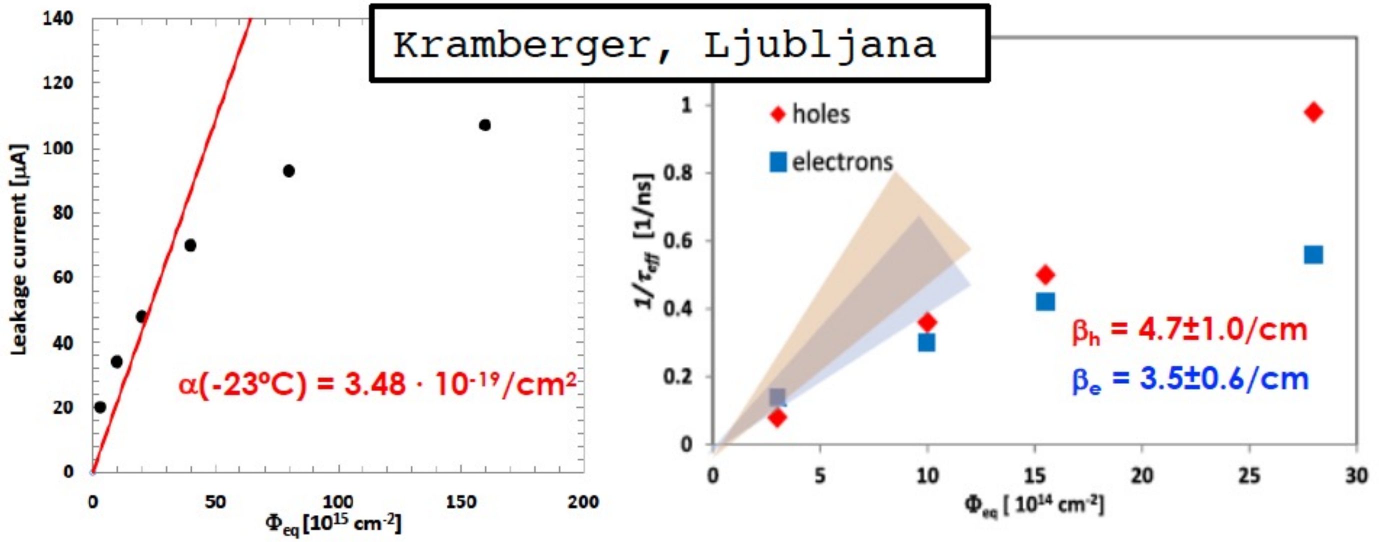
- 4T, 10m solenoid
- Forward solenoids
- Silicon tracker
- Barrel ECAL LAr
- Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forward HCAL/ECAL LAr

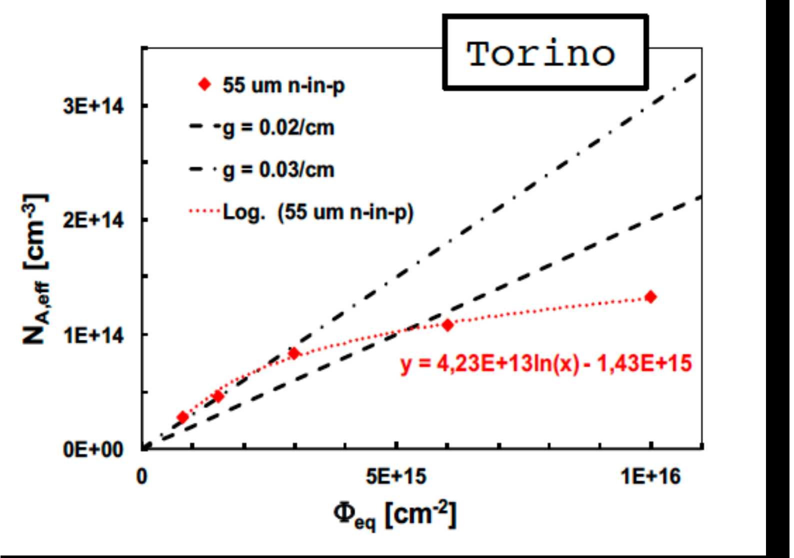


50m length, 20m diameter
similar to size of ATLAS

Silicon for the FCC-hh

about 400m^2 of silicon.





Dark current saturation

$I = aV\phi$

a from linear to logarithmic

Trapping probability saturation

$1/\tau_{eff} = b\ \phi$

b from linear to logarithmic

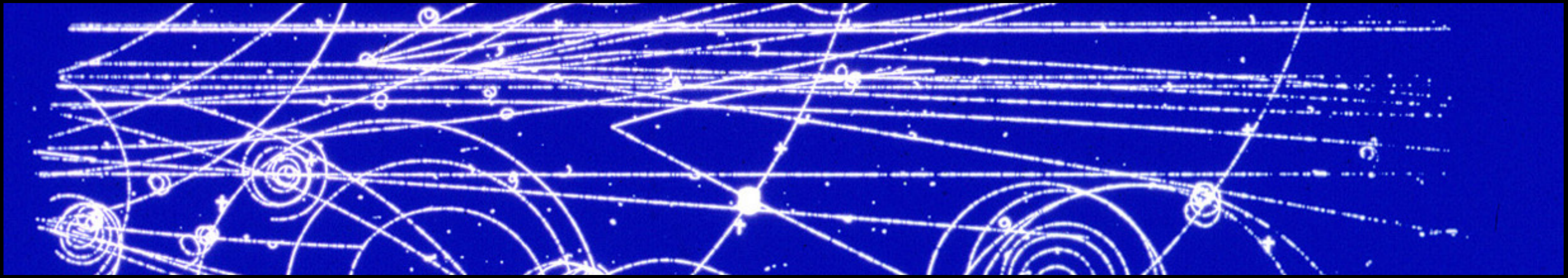
Acceptor creation saturation

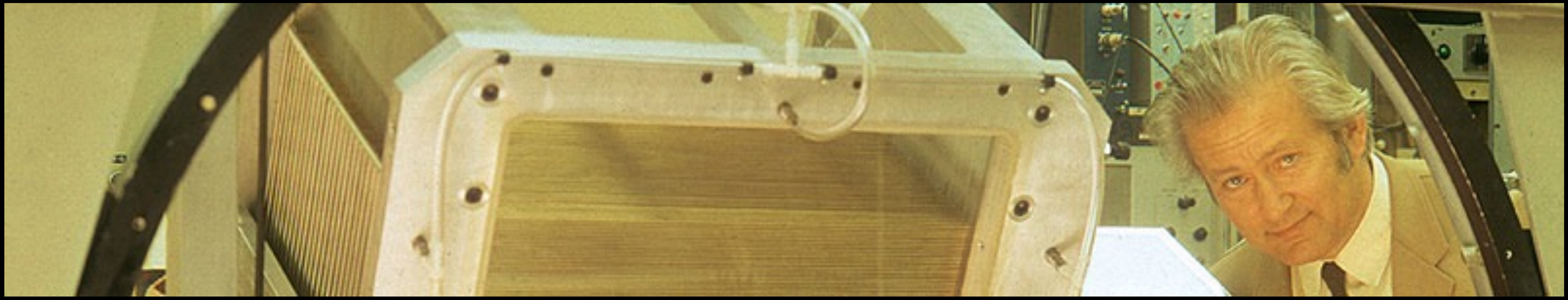
$N_{A,eff} = g\ c\ \phi$

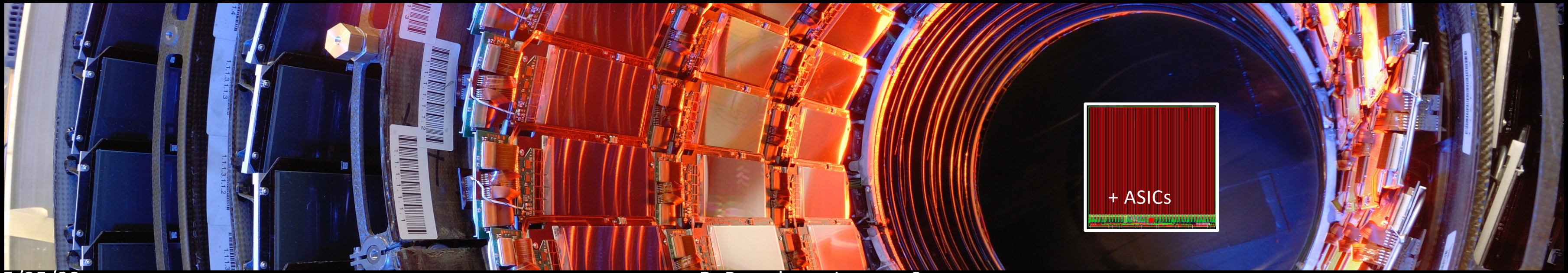
gc from linear to logarithmic

Good news! Silicon behaves better than expected at 1E16 – 1E17 n/cm^2

Perspective





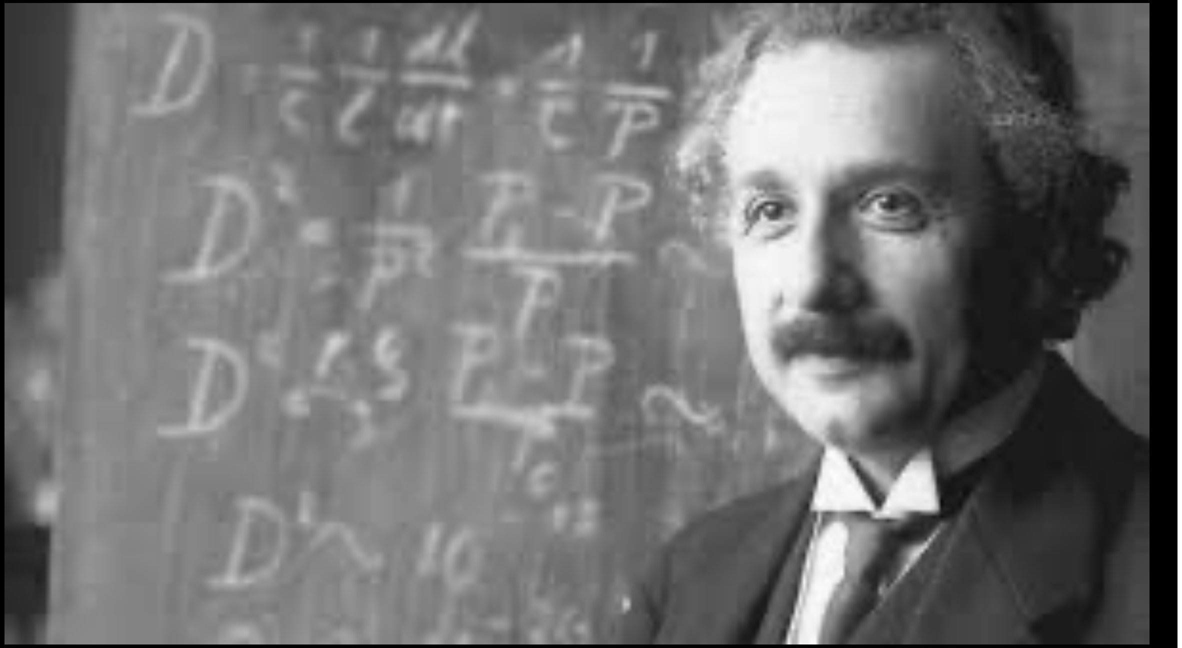


Conclusions

Imagination is more important than knowledge.

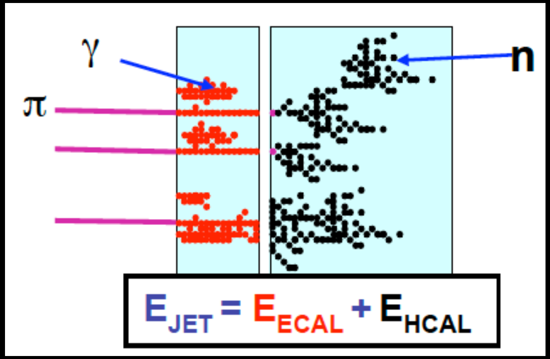
For knowledge is limited, whereas imagination embraces the entire world, stimulating progress, giving birth to evolution.

Albert Einstein, What Life Means to Einstein (1924)



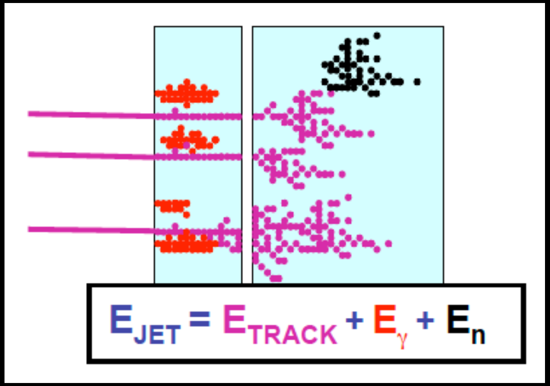
Imaging 5-D Calorimetry

- Standard calorimetry

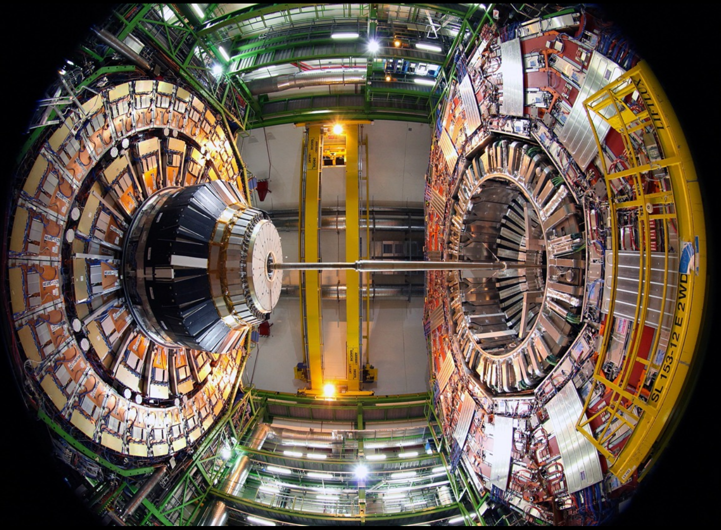


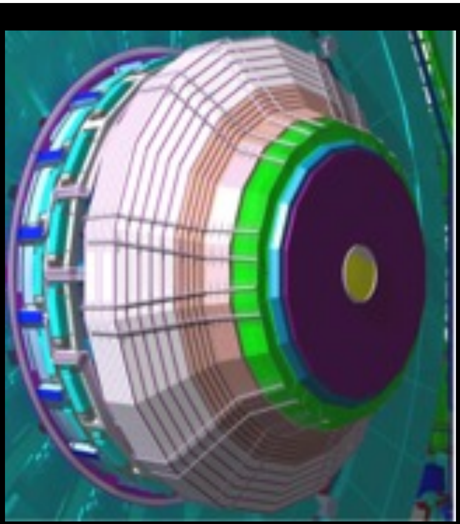
$E_{JET} = E_{ECAL} + E_{HCAL}$

- Particle Flow calorimetry



$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$



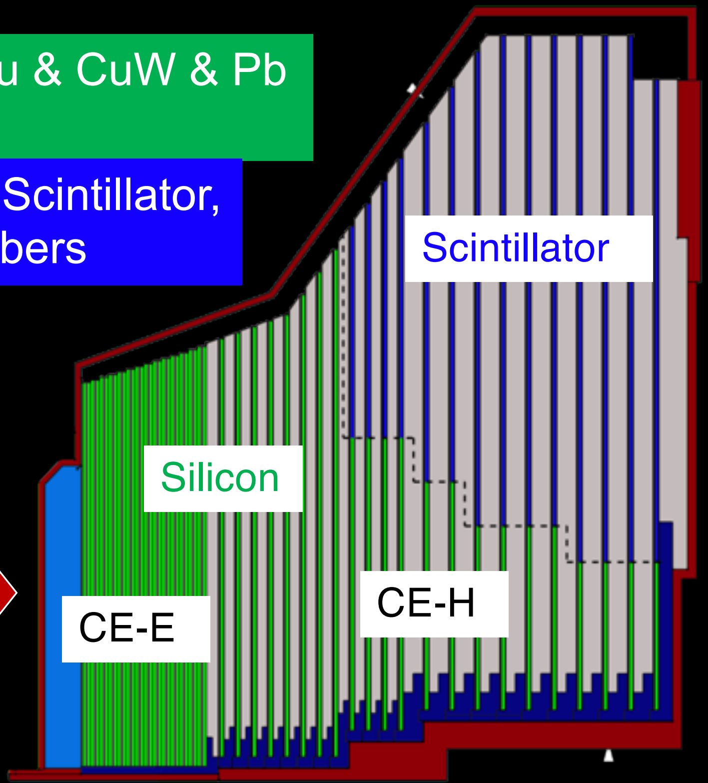


- High Granularity Calorimeter Replacing existing CMS endcap pre-shower, electromagnetic and hadronic calorimeter at HL-LHC
- Extremely challenging:
  - Fluence up to 10^{16} n/cm^2 Dose up to 200 Mrad
  - -30°C

CMS High Granularity CALorimeter

CE-E: Si, Cu & CuW & Pb absorbers

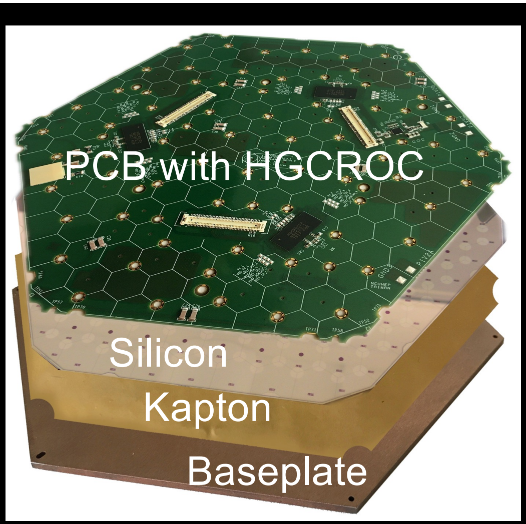
CE-H: Si & Scintillator, Steel absorbers



R&D
ILC

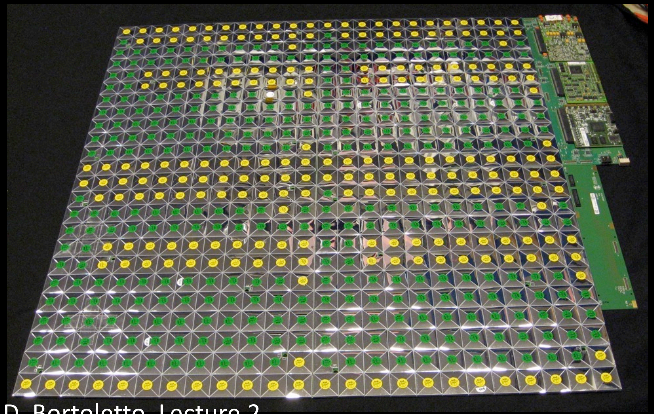
- Silicon: 620 m^2, 30K modules, 6M channels, 0.5/1 cm^2 cell size
- Scintillator: 400 m^2 , 4K boards, 240k channels, 4-30 cm^2 size

Silicon sampling calorimeter



- HGCROC electronics both for SiPM and silicon (OMEGA)
  - Measures charge and and time (TOA)
- Trigger data from ASICs fed through concentrators to the back-end system

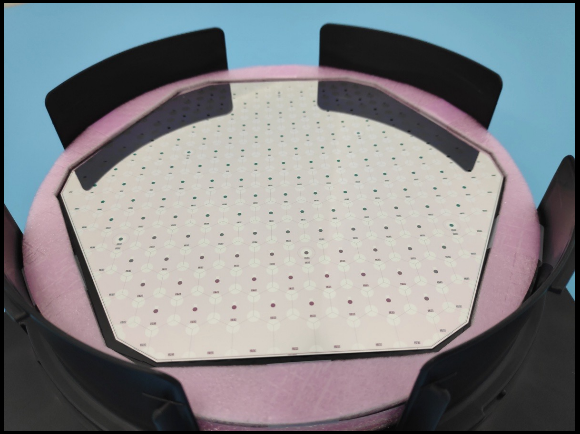
ILC
CLIC, CepC
FCC

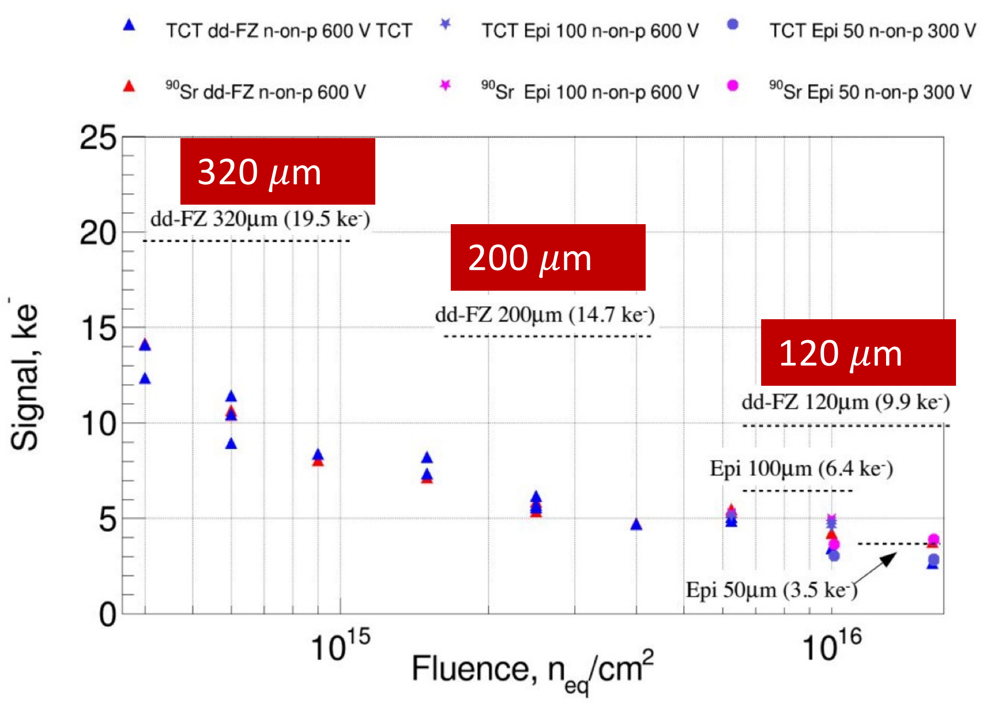


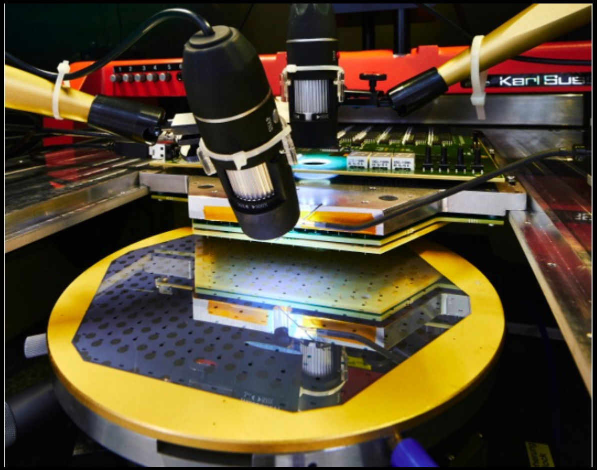
Scintillator tiles with on-tile SiPM readout

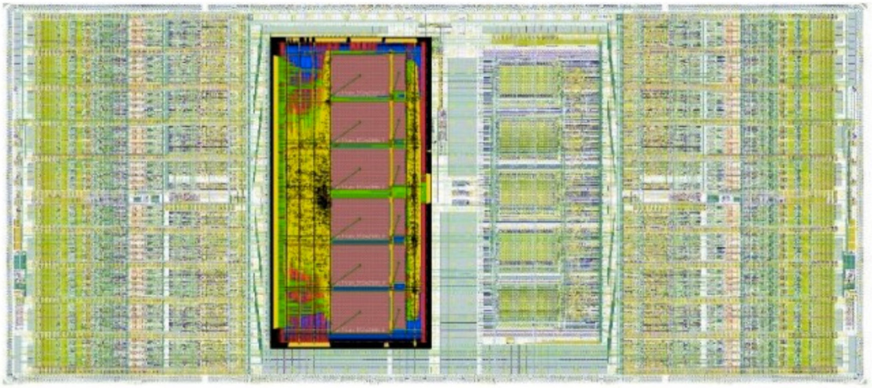
CMS HGCAL

- 8’’ prototype sensor (HPK) p-type silicon





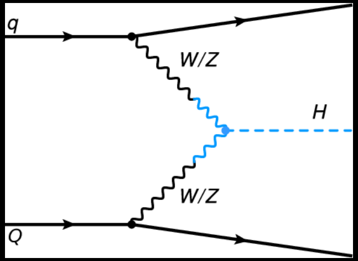




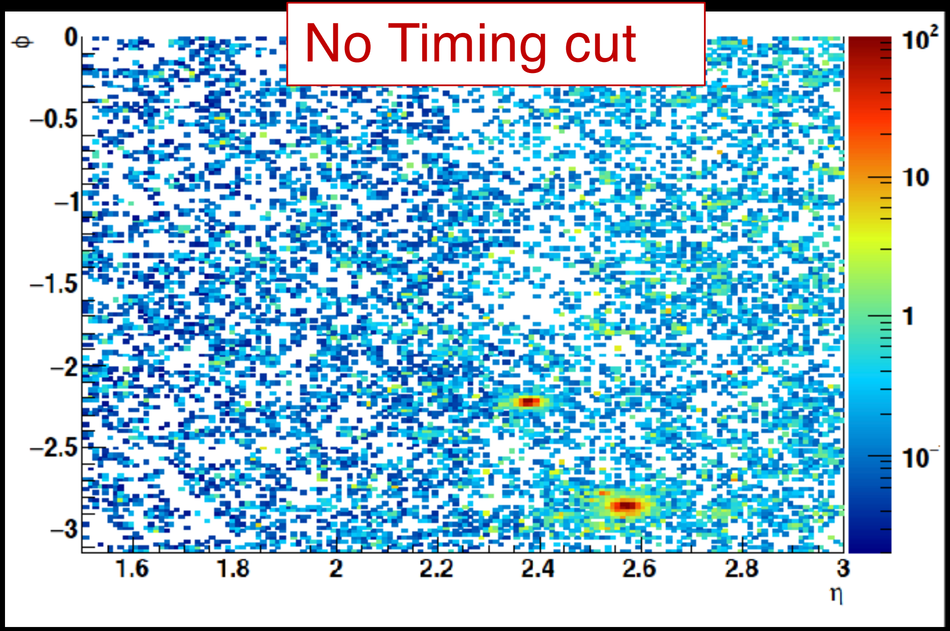
HGCAL FE electronics requirements:

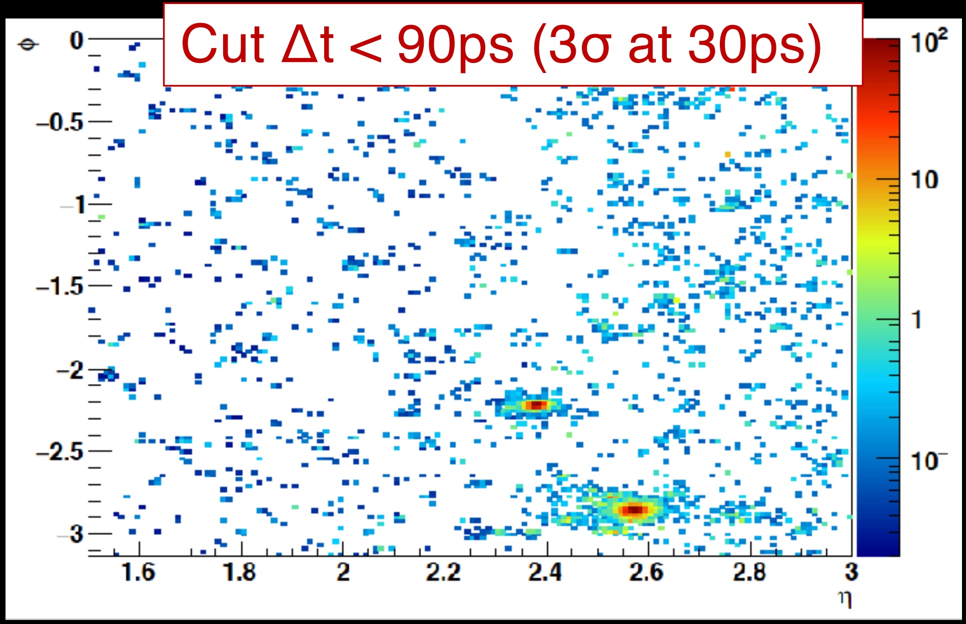
- ***Low noise*** (<2500e)
- ***high dynamic range*** (0.2fC -10pC)
- ***Timing to tens of picoseconds***.
- ***Radiation tolerant***
- ***<20mW*** per channel

HGCAL 5D Power



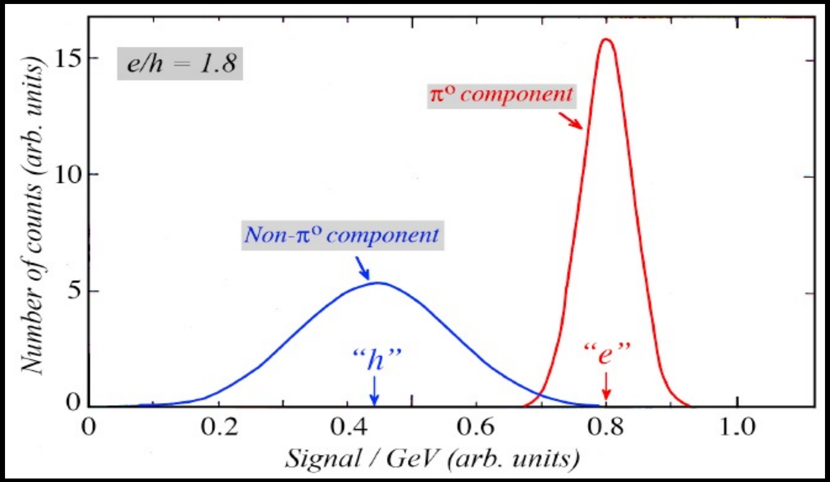
Vector Boson Fusion (H→γγ) event with one photon and one VBF jet in the same quadrant


No Timing cut


Cut Δt < 90ps (3σ at 30ps)

- Cells with Q > 12 fC projected to the front face of the endcap calorimeter.
- Identify high-energy clusters, then make timing cut to retain hits of interest

DUAL readout calorimetry



- The response to the "hadronic" portion of a hadronic shower gives a lower response limiting hadronic calorimeter performance
- Many calorimeters tried to boost the non π^0 component – Compensating calorimeters:
  - uranium (D0 and ZEUS)

- What if we could measure the two components separately and apply a separate scale factors to achieve compensation ?

Is this just a DREAM?

http://www.phys.ttu.edu/~dream/links/links.html

RD52

Dual Readout

- Hadronic component: slowly moving protons and ions
- EM component: relativistic electrons.
- Relativistic particles can emit Cherenkov radiation.

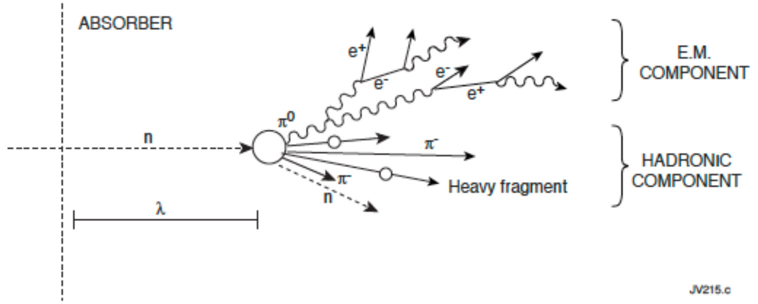
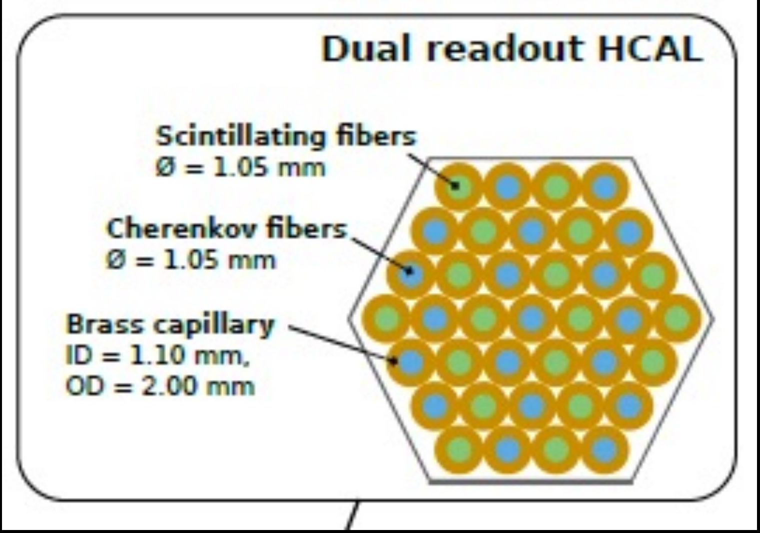


Fig. 9: Schematic of development of hadronic showers.

$$\frac{d^2N}{dx\,d\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1-\frac{1}{\beta^2 n^2(\lambda)}\right).$$

- Measure EM component with Transparent material (high n)
  - Quartz
  - Clear plastic fibers
  - Crystals like BGO, PbWO4

C



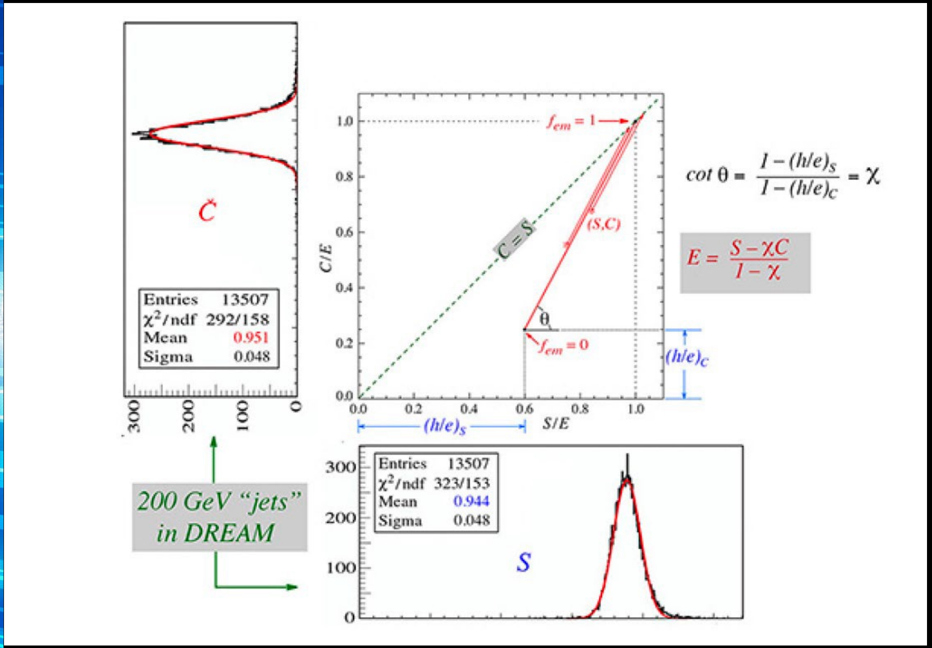
- Measure entire energy deposit with:
  - Plastic scintillator (sensitivity to neutrons)
  - Crystals like BGO, PbWO4

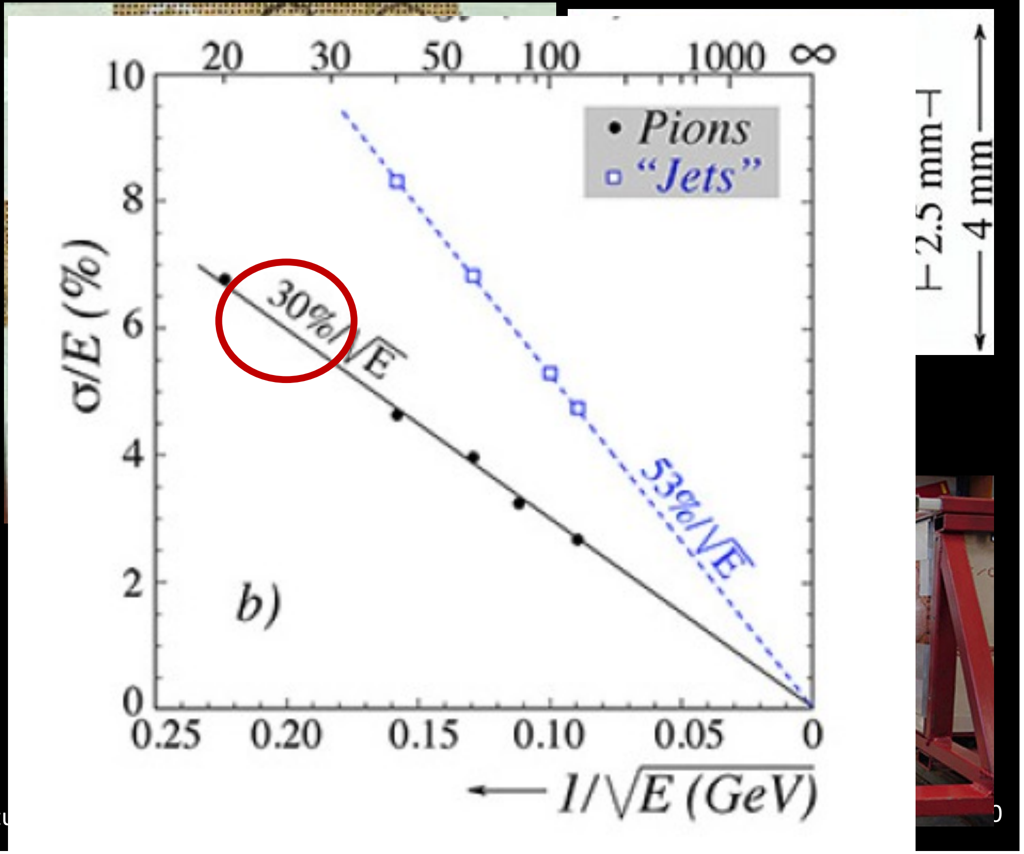
S

DREAM/RD52

$$S = E\left[f_{\mathrm{em}} + \frac{1}{(e/h)_S}(1 - f_{\mathrm{em}})\right]$$

$$C = E\left[f_{\mathrm{em}} + \frac{1}{(e/h)_C}(1 - f_{\mathrm{em}})\right]$$





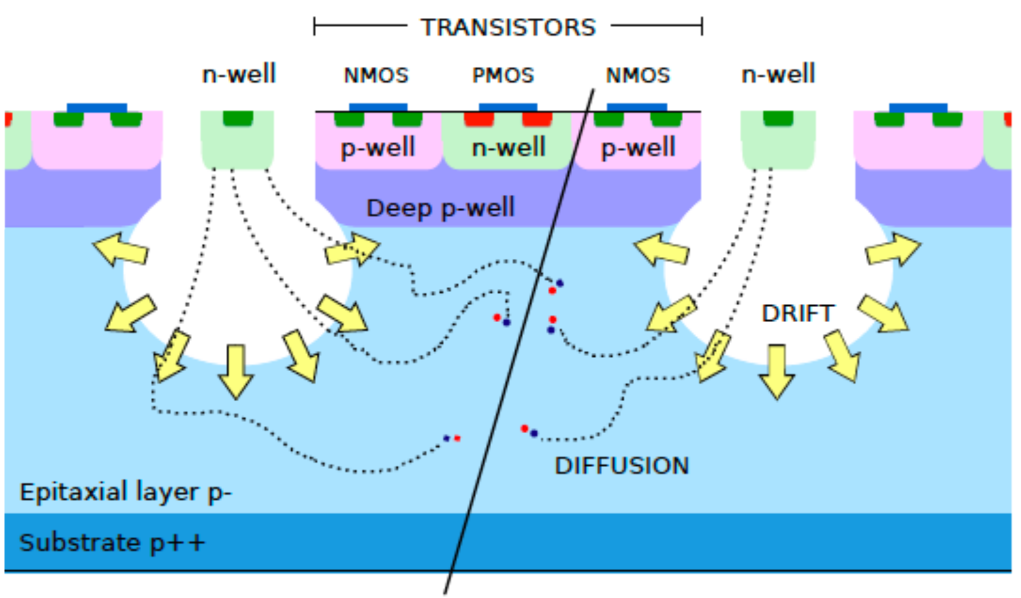
Separate readouts for scintillating and clear fibers

Useful References

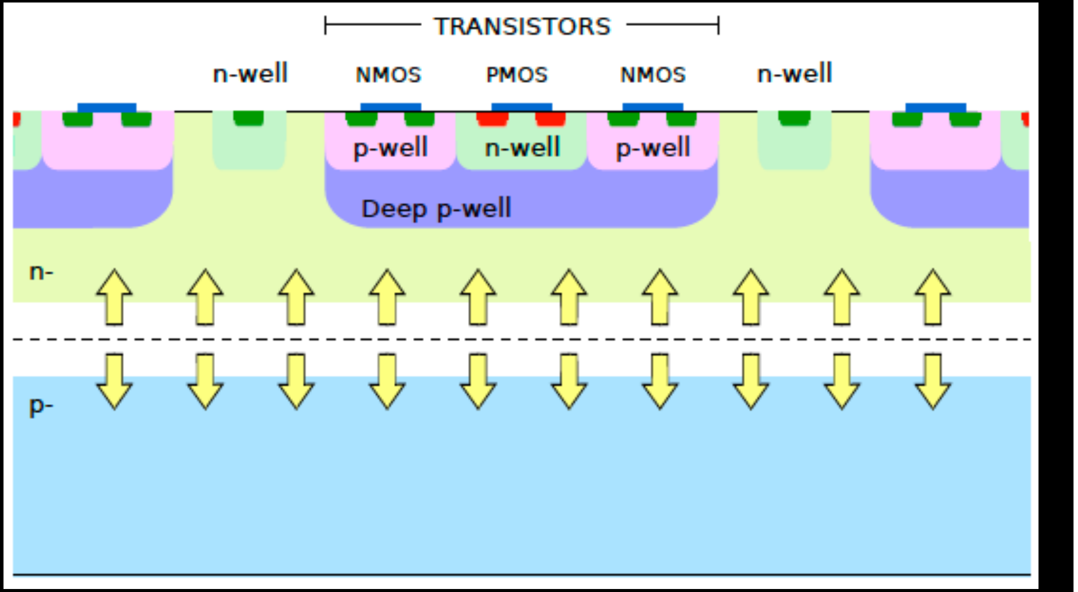
- Passage of Particles through Matter; (http://pdg.lbl.gov/2019/reviews/rpp2018-rev-passage-particles-matter.pdf

TowerJazz 180nm MALTA sensor

- Small collection electrode (few μm.)
- Small input capacitance (<3fF) allows for fast & low-power FE
- High S/N for a depletion depth of ~20 μm
- To ensure full lateral depletion, uniform n-implant in the epi layer (modified process)



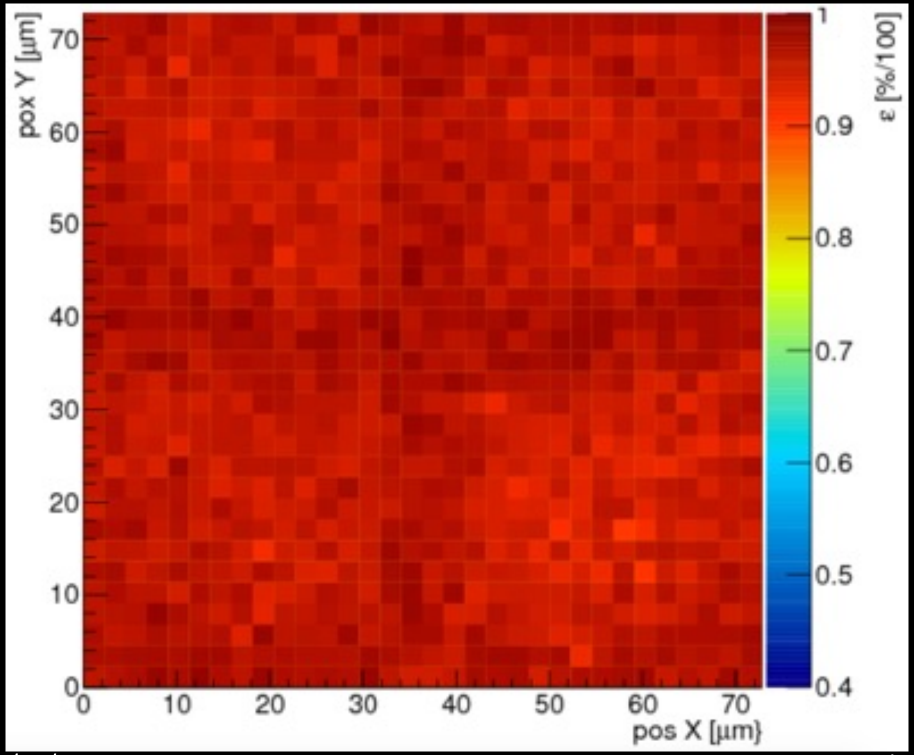
Standard Process

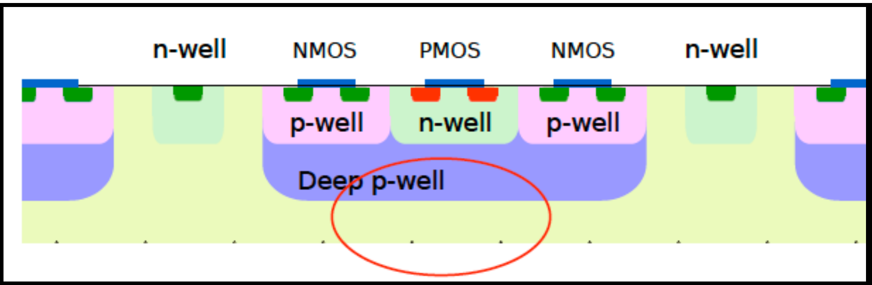


Modified Process: TowerJazz 180nm MALTA sensor
W. Snoeys et al. DOI 10.1016/j.nima.2017.07.046

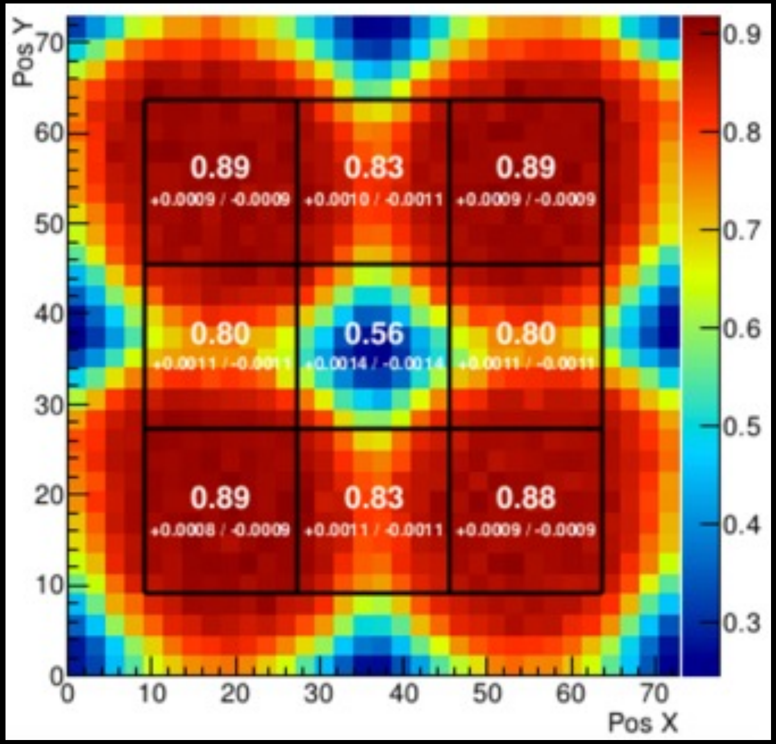
Radiation Hardness

- Unirradiated @ 250e$^-$ threshold 2x2 pixel at 36 µm pitch



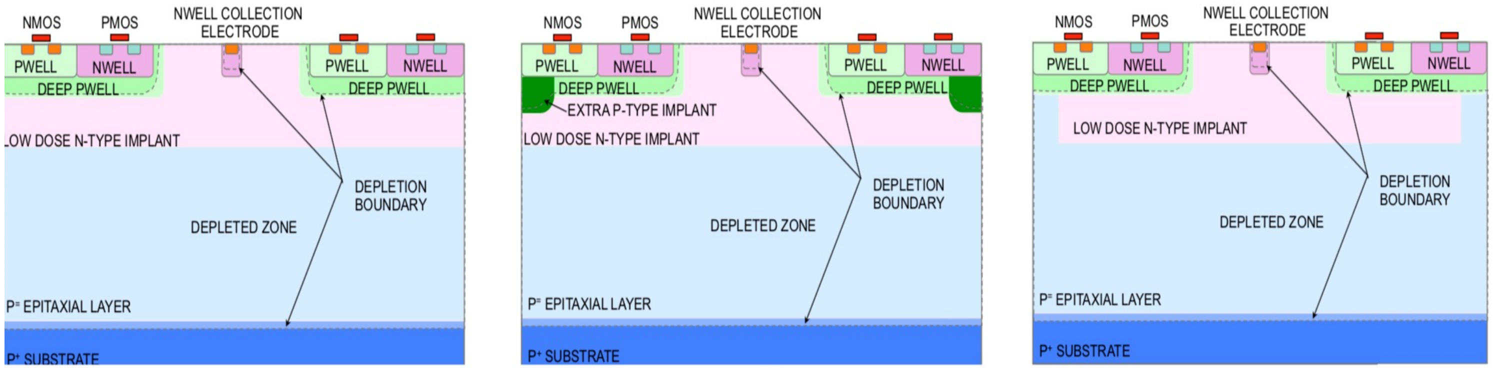


Irradiated 10^{15}n/cm^2 @ 350e$^-$ threshold 2x2 pixel at 36 µm pitch



MINIMALTA

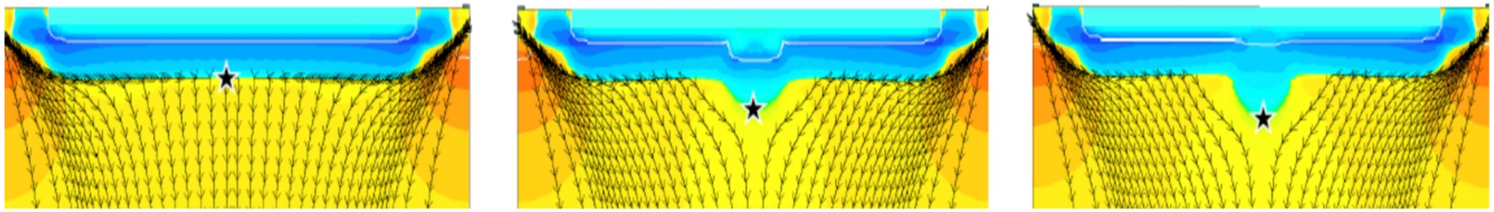
- Special layouts for deep p and n wells to optimize field configuration and charge collection
- Increase lateral field near pixel edge to “focus” charge to collection electrode



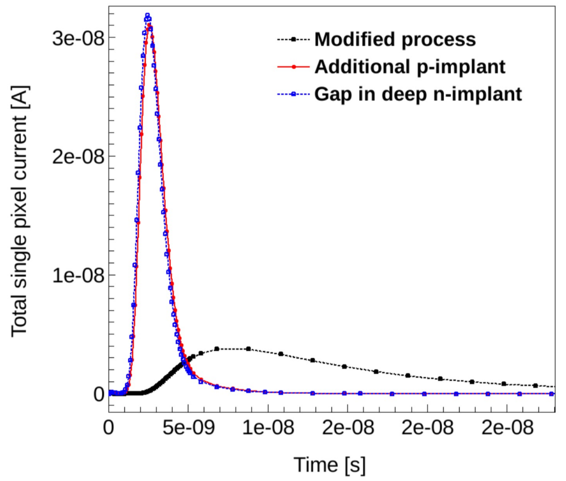
Modified process:

Modified process with additional p-implant:

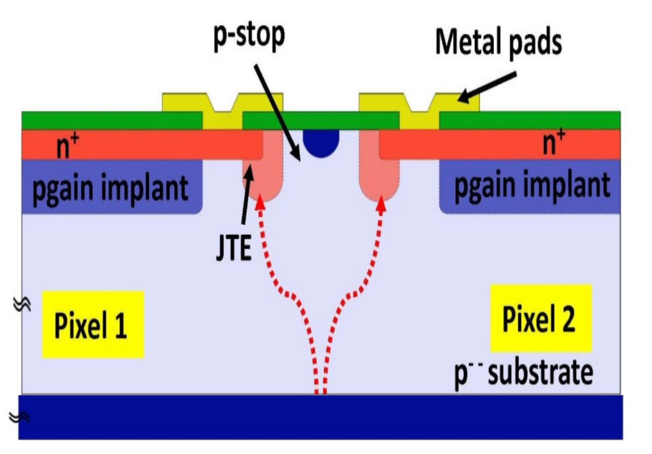
Modified process with gap in n-layer:

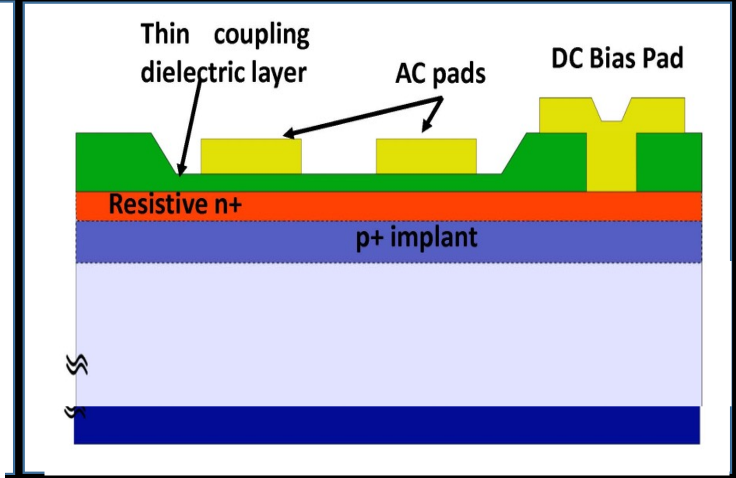


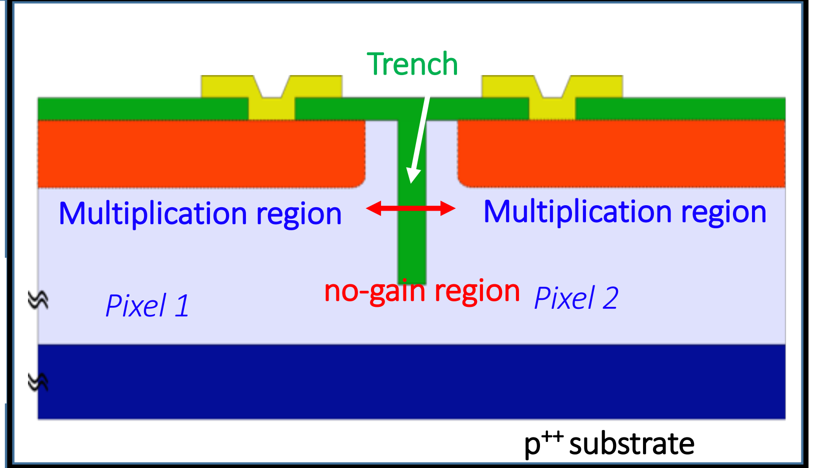
Electrostatic potential, streamlines and electric field minimum (*):



4 D tracking







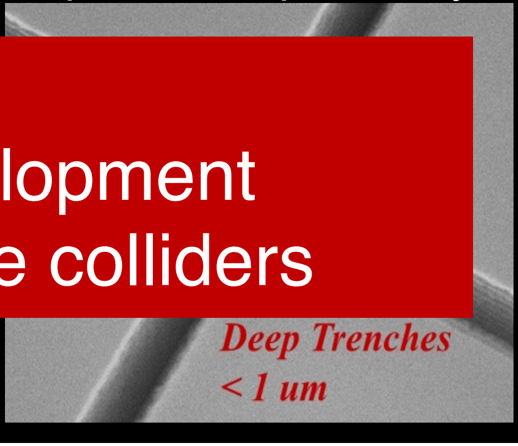
LGADS

AC LGADS

- n++-implant more resistive

Trench Isolated

- p-stop & JTE replaced by a trench



- These are just examples
- Many other ideas under development
- Timing info essential for future colliders