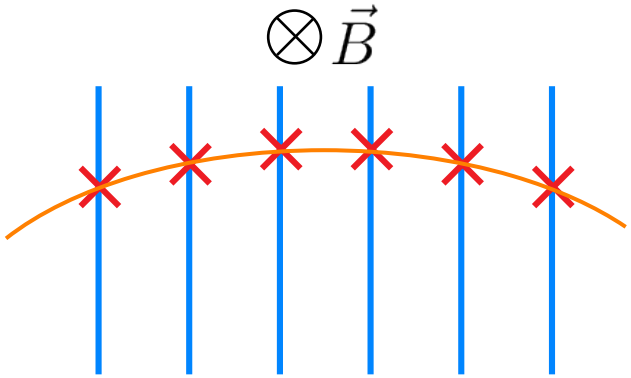
Vertex & Tracking Detectors

for… vertexing & tracking?

Momentum Reconstruction

- Relativistic particles in magnetic field:
  - $\vec{p} \perp \vec{B}$ circular track
  - $\vec{p} \parallel \vec{B}$ straight track
  - Else helical track



- Lorentz force and centripetal force in equilibrium:

$$\begin{aligned} |\vec{F}_L| &= |\vec{F}_Z| \\ |q\vec{v} \times \vec{B}| &= \frac{m\vec{v}^2}{R} \\ p_T &= qBR \end{aligned}$$

- Measurement of the radius of curved tracks yields *transverse momentum* $\mathrm{p_T}$

Simple approximation

$$p_T = 0.3|z|BR$$

$$[p_T] = \mathrm{GeV/c}$$

with $[R] = \mathrm{m}$

$$[B] = \mathrm{T}$$

$$z = q/e$$

Momentum Measurement

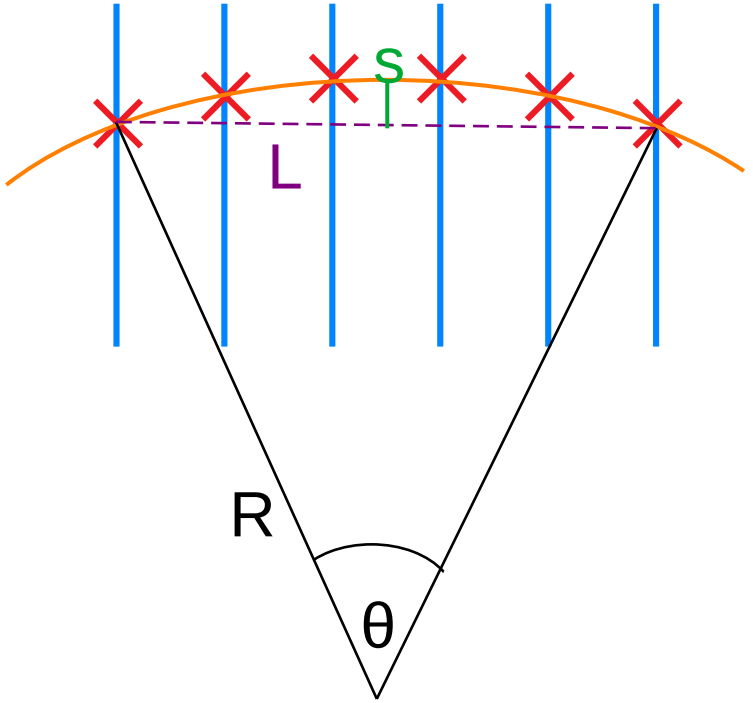
- Radius can be determined by measurement of *sagitta* length s at track length L

$$s \approx \frac{L^2}{8R}$$

- Uncertainty of momentum proportional to uncertainty of sagitta measurement:

$$p = qBR = \frac{8qB}{L^2}s \quad \Rightarrow \quad \sigma_p \propto \sigma_s$$

- Uncertainties of sagitta measurement:
  - Spatial detector resolution
  - **Multiple Coulomb scattering**

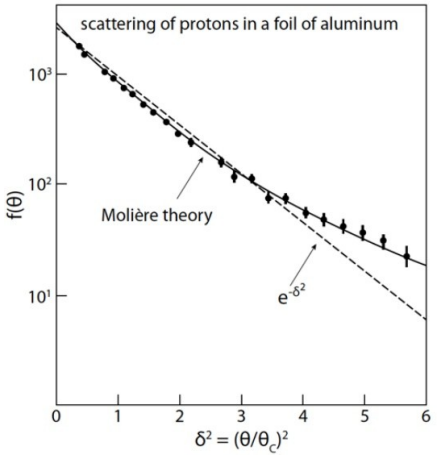


Multiple Coulomb Scattering

Charged particles traversing medium are **deflected by many small-angle scatterers**

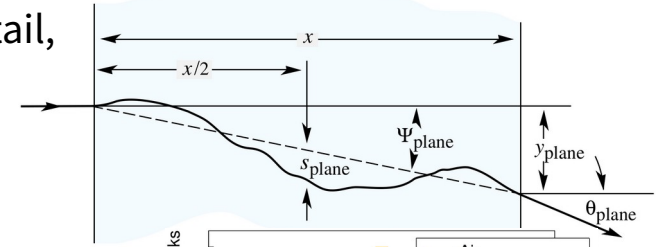
- Deflection off Coulomb potential of nuclei, Rutherford cross section:

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right|_{\mathrm{Rutherford}} = z^2 Z^2 \alpha^2 \hbar^2 \frac{1}{\beta^2 p^2} \frac{1}{4\sin^4\frac{\theta}{2}}$$



H. Bichsel, Phys. Rev. 112, 182

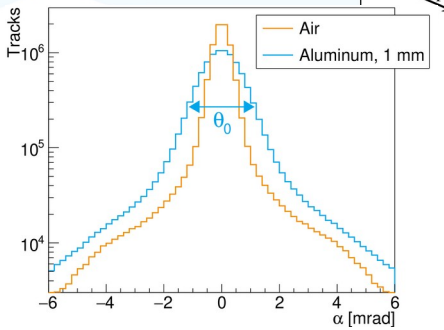
- Many small-angle scatterings → Gaussian distribution of scattering angle (**central limit theorem**)
- Sometimes “hard” scattering with large angle, produce non-Gaussian tail, described by Molière theory



PDG 2022

Often a Gaussian approximation is enough,
Standard deviation of distribution can be approximated via **Highland Formula**:

$$\theta_0 = \frac{13.6\,\mathrm{MeV}}{\beta c p} z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln\left(\frac{x}{X_0}\right)\right]$$

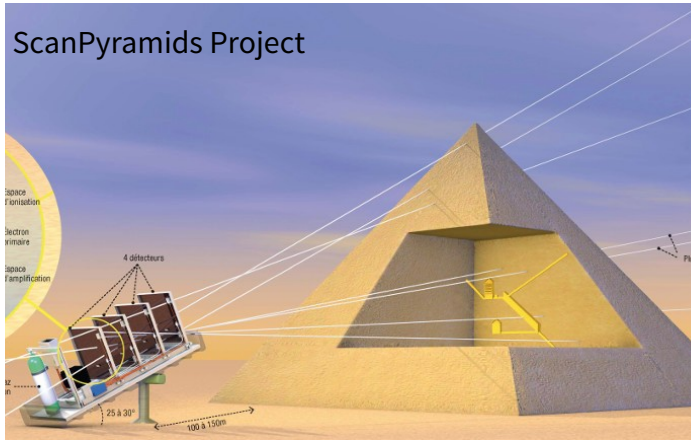


Implications of Multiple Scattering

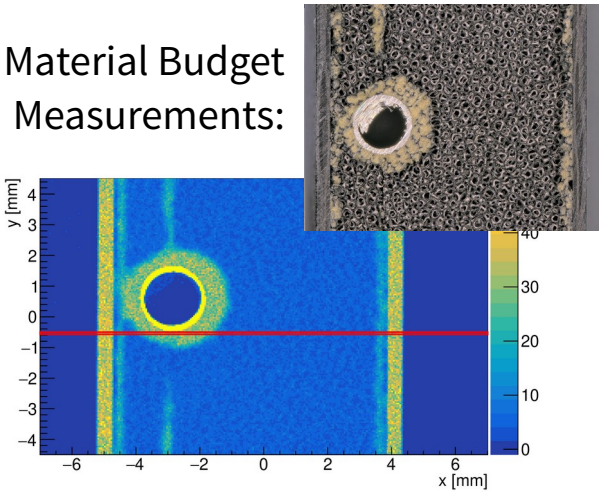
- Stochastic deflection leads to deterioration of the position resolution for tracking detectors
  - Consequently tracking precision (e.g. momentum resolution is affected)
  - Remedy by using light & thin materials

- Can be used to gain information on traversed objects:

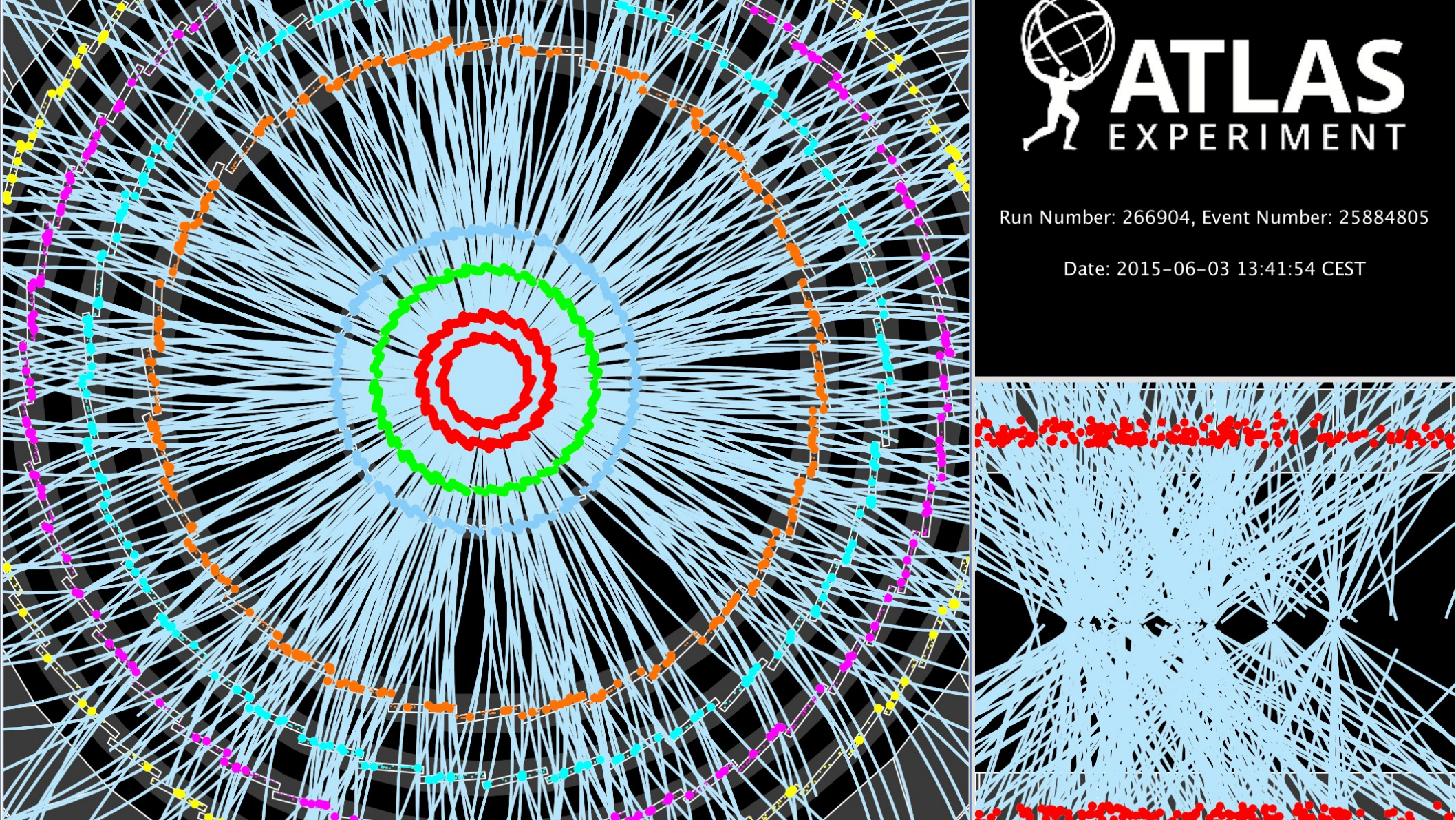
Cosmic Muon Tomography:



Material Budget Measurements:

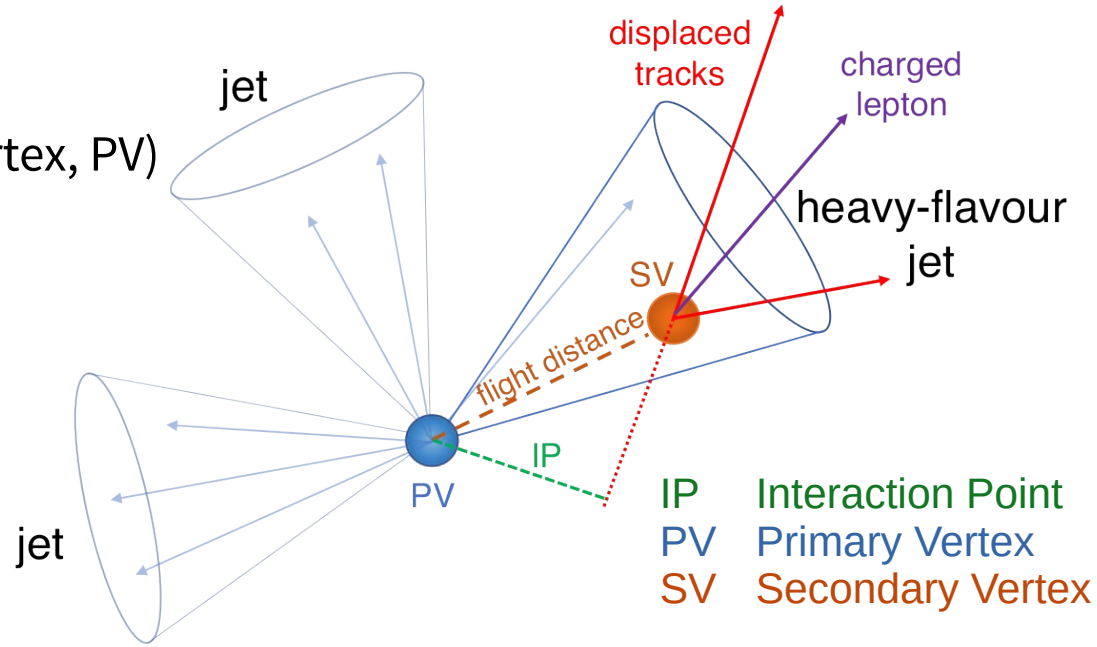


Medical Imaging electron CT:


ATLAS
EXPERIMENT
Run Number: 266904, Event Number: 25884805
Date: 2015-06-03 13:41:54 CEST

Secondary Vertex Reconstruction

- Not all particles decay immediately
  - Produced at collision (primary vertex, PV)
  - Propagation during finite lifetime
  - Decay → secondary vertex (SV)
- Lifetime of b-quarks: $\mathcal{O}(10^{-12}\ \mathrm{s})$
  - Flight distance: $\mathcal{O}(100\ \mu\mathrm{m})$
  - Can be resolved with modern tracking detectors



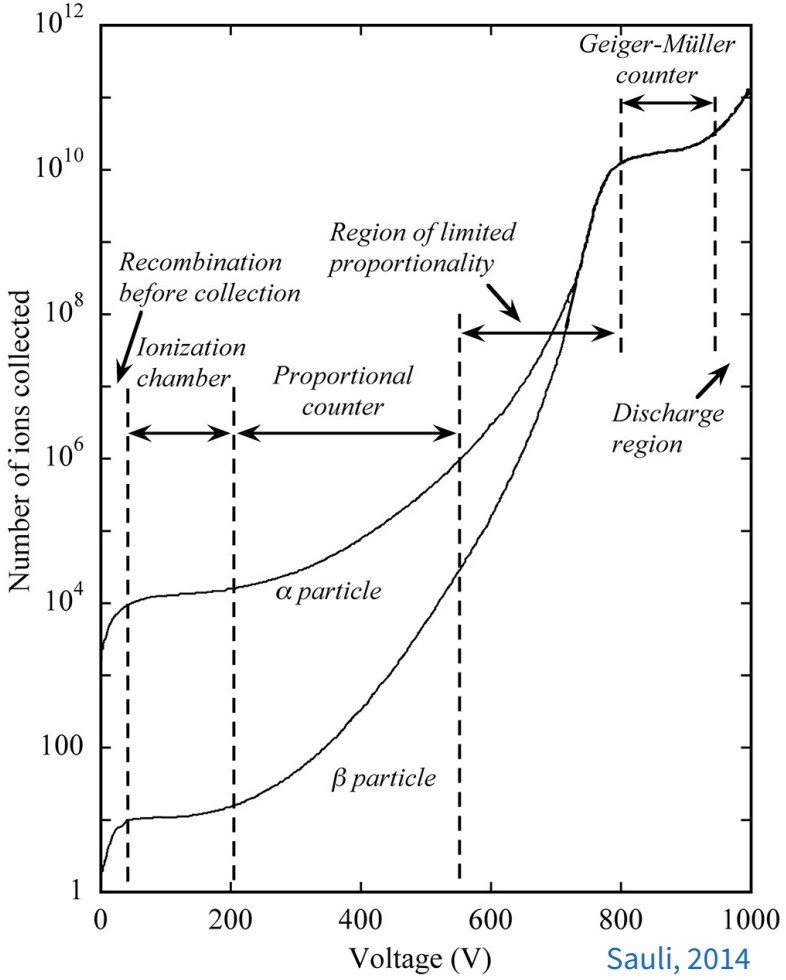
- Indication of SV hints at b-quarks, used for e.g. b-Tagging
  - Important top quarks decays
  - Lifetime of b-mesons $\tau \approx 10^{-12}$ s → $d/\gamma \approx 0.1$ mm

Gaseous Detectors

Primary & secondary ionization of gas atoms

Gaseous Detectors: Operating Principle

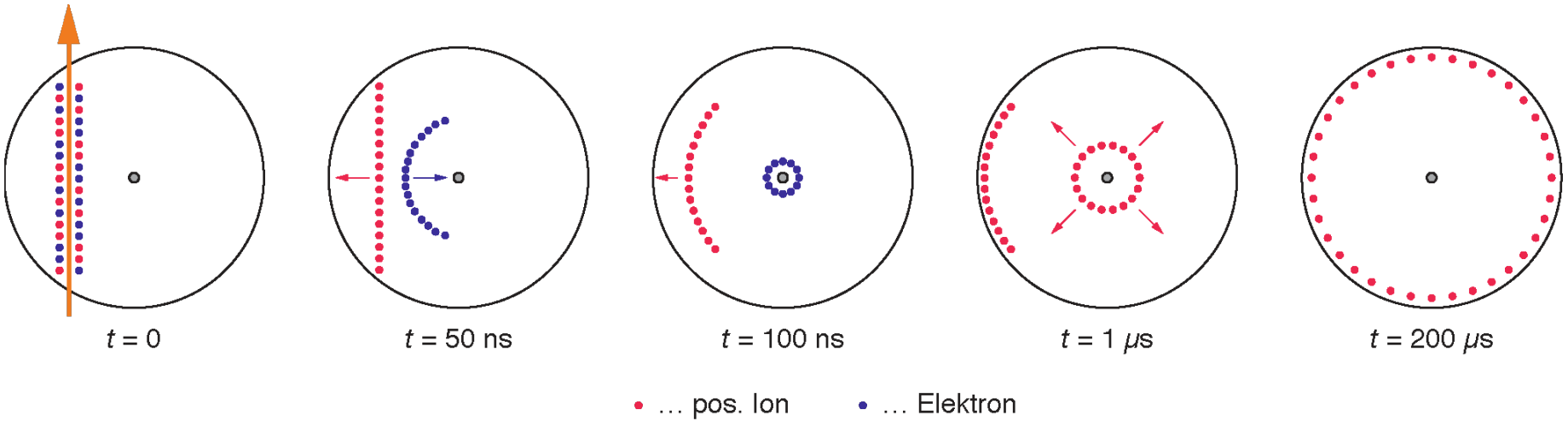
- **Primary signal:** charged particle generates electron-ion pairs by ionization
  - Noble gases: relatively low ionization energy
  - Average energy to generate a pair ~30 eV
  - Number proportional to deposited energy
- **Amplification:** different working ranges depending on applied voltage
  - Medium voltages: proportional amplification
  - High voltages: Avalanche formation due to secondary ionizations



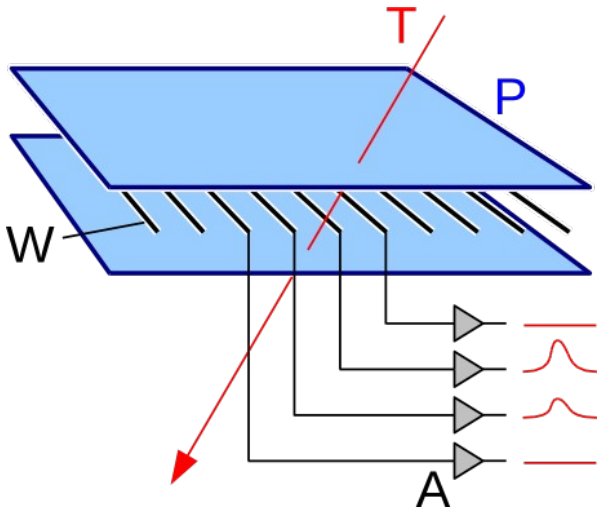
Sauli, 2014

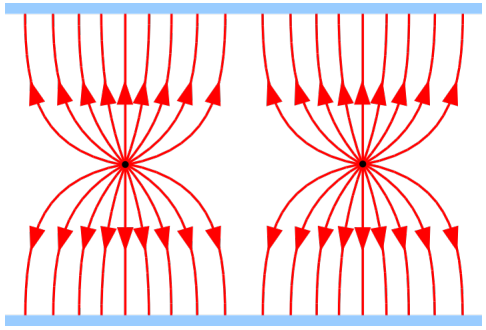
Proportional Counter

- Very similar to the Geiger counter: anode in the form of thin wire
- High field near wire leads to electron multiplication / signal amplification
- Choice of voltage: proportional range
  - Output signal proportional to original number of ionizations



Multi Wire Proportional Chamber (MWPC)

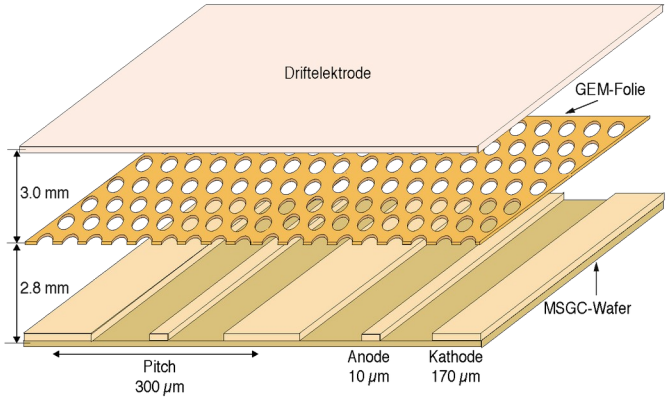




- Essentially many proportional counters next to each other, without separating walls
- Wires spaced a few millimeters apart
  - Good spatial resolution of a traversing particle
  - Large areas possible
  - Electronic selection
- High rates possible: 1000 particles/s
  for comparison, bubble chamber: 1-2 particles/s
- Nobel Prize 1992 for Georges Charpak

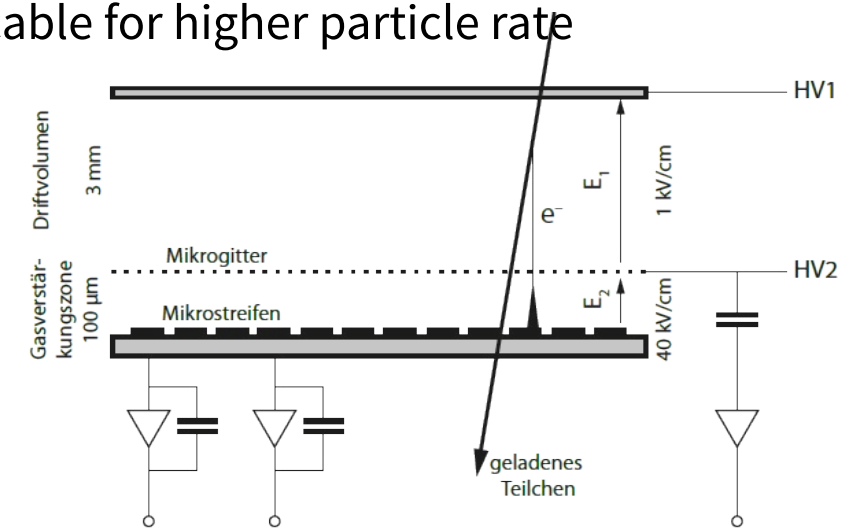
Micropattern Gas Detectors

- Replacement of fragile wires by micro structures
- Potentially better spatial resolution and applicable for higher particle rate



Gas Electron Multiplier (GEM)

- Perforated, metallized Kapton foil, High voltage between electrodes
- Strong dipole field in perforation holes: Gas amplification

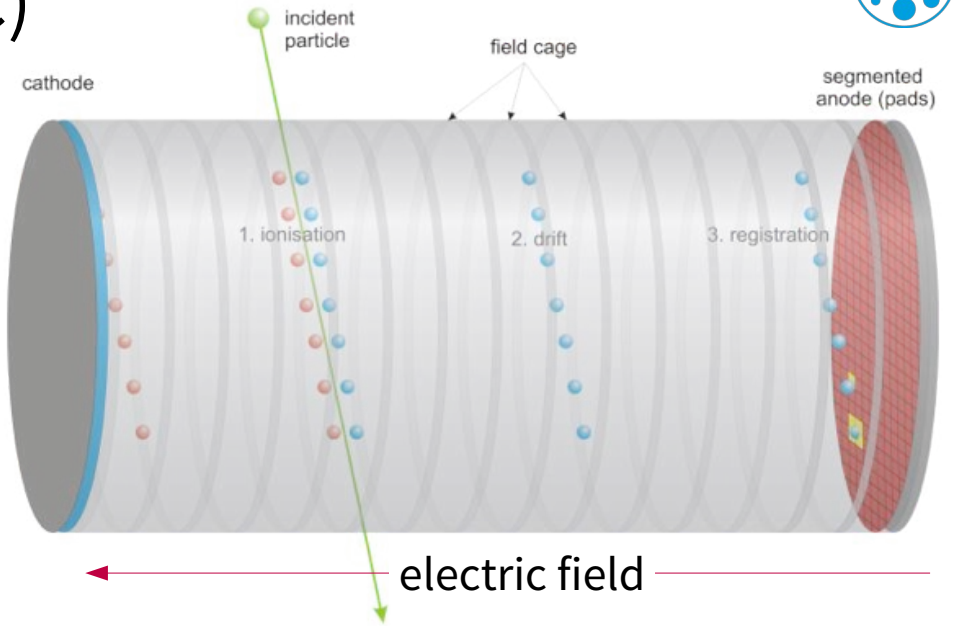


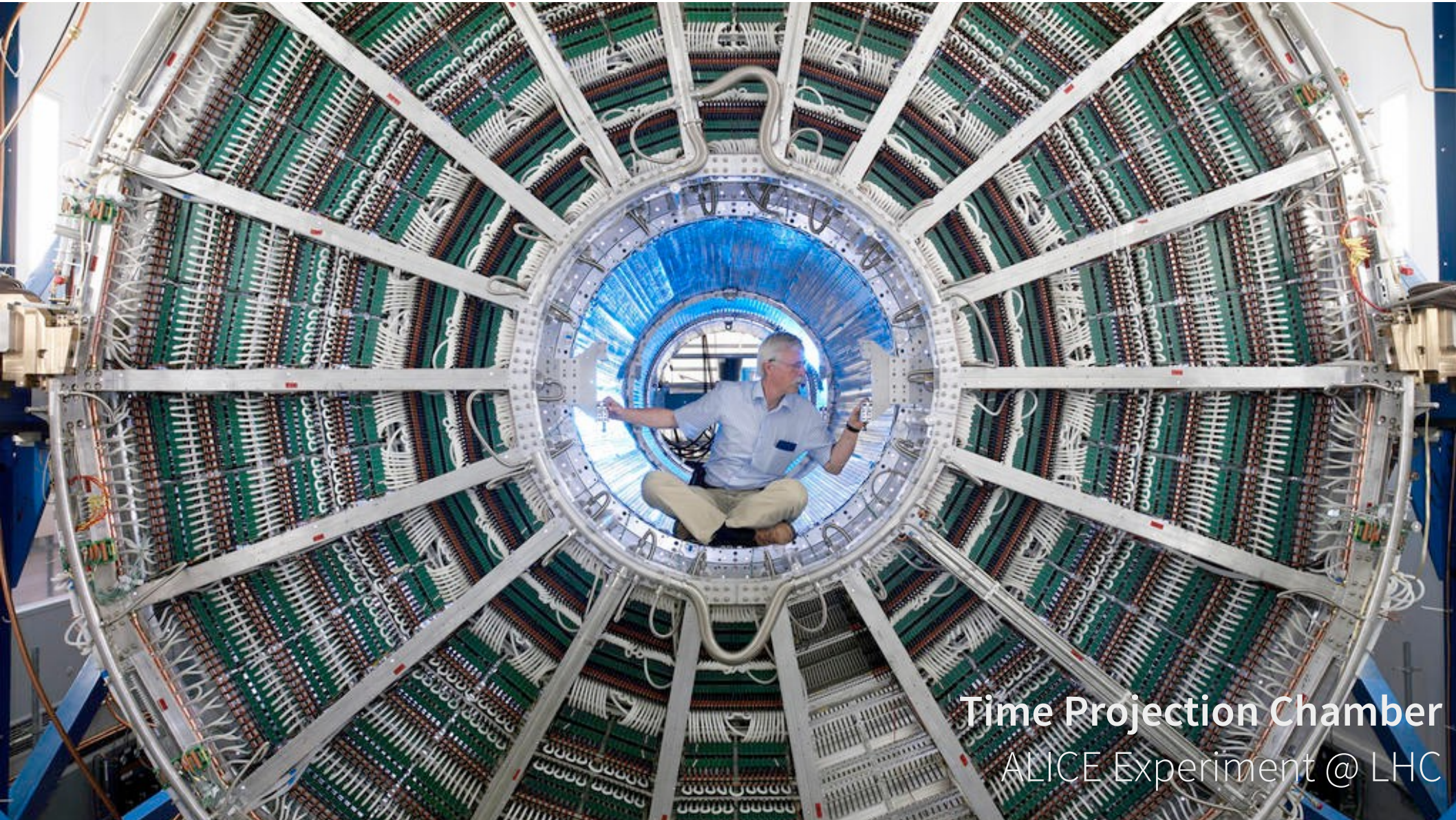
Micro-Mesh Gas Detectors (Micromegas)

- Metallic micro-grid
- Electron avalanche evolution near the lattice: Gas amplification

Time Projection Chambers (TPC)

- Large gas detector system
- Ionization along the particle track
  - Electrons and ions drifting in the E-field
  - Segmented anode: 2D information
  - Measurement of drift time:
    3D information
- Readout at anode side e.g. via
  multi-wire proportional chamber, GEMs, …

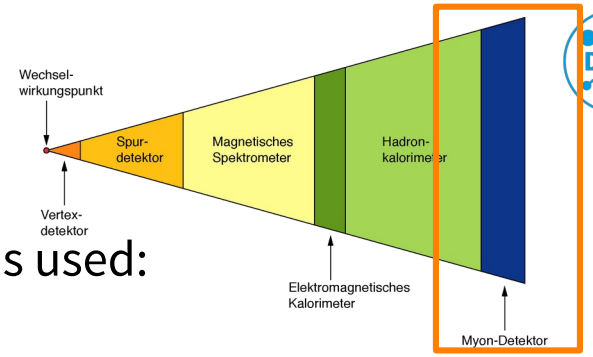




Time Projection Chamber

ALICE Experiment @ LHC

Muon Spectrometers



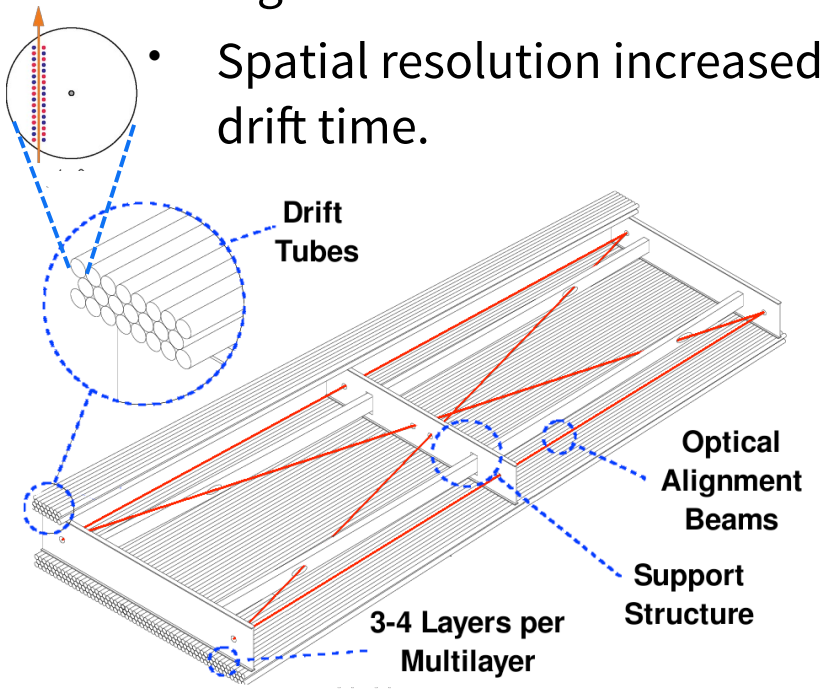
- Identification and precise momentum measurement of muons outside of the magnet – often gas detector systems used:
  - Requires huge areas to be instrumented
  - Position resolution is not extremely demanding
- Typical track in Muon System: ~ 20 hits
- Very often two possibilities for muon tracking:
  - *Standalone* – purely based on muon system
  - *Combined* – use info from inner detectors & muon system

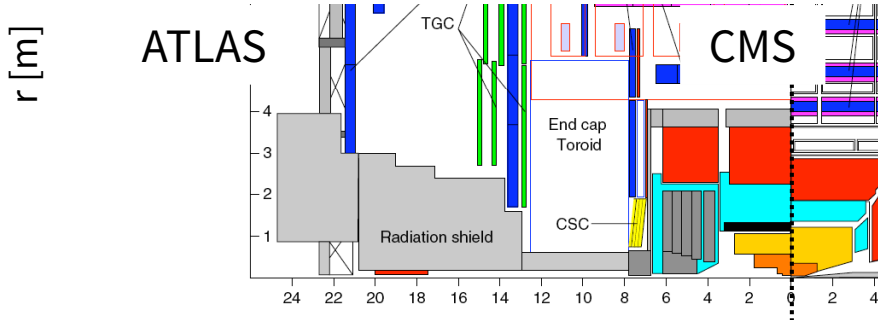
- Standalone capabilities can be crucial at high luminosities
- The momentum measurement is dominated by
  - Inner detectors @ low p_T
  - Muon system @ high p_T

ATLAS

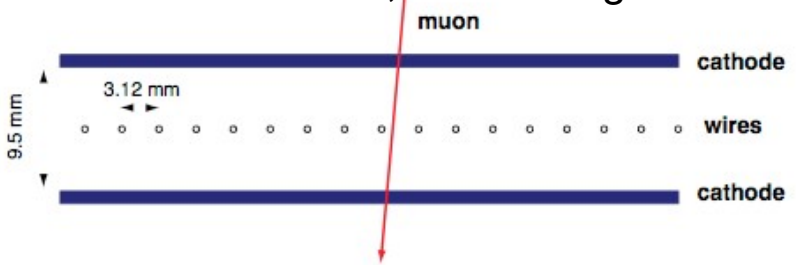
Muon Systems @ LHC

- Monitored Drift Tubes (MDT)
  - Gas-filled drift tubes with central wire
  - Signal read out on both ends
  - Spatial resolution increased by recording drift time.



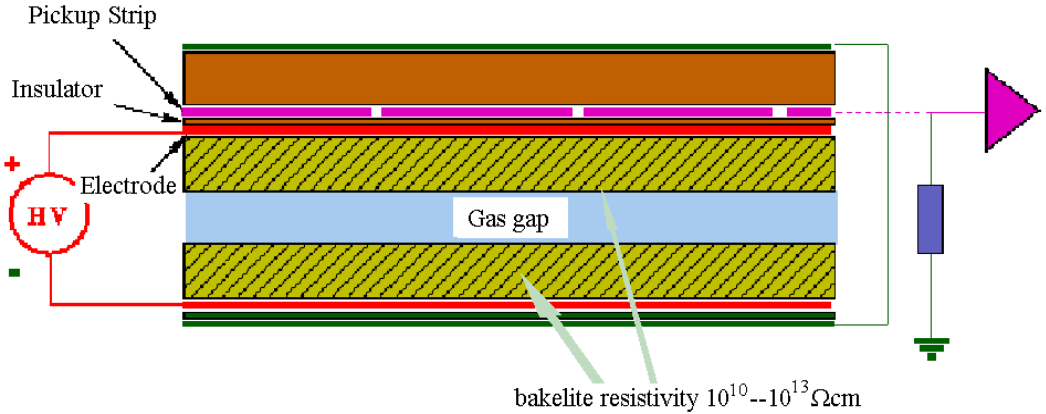


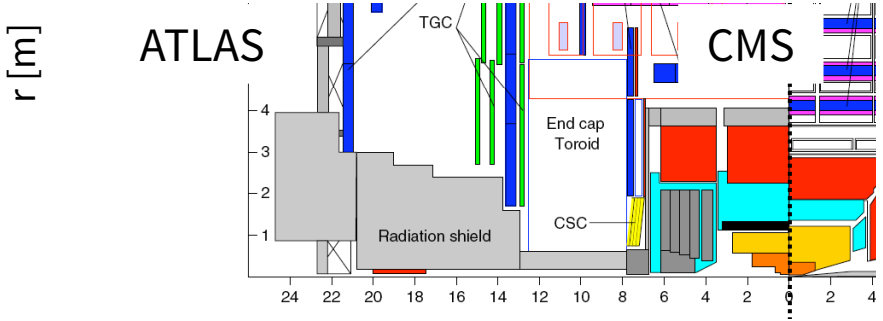
- Cathode Strip Chambers (CSC)
  - Array of anode wires crossed with copper cathode strips
  - Short drift distances, used at high-eta



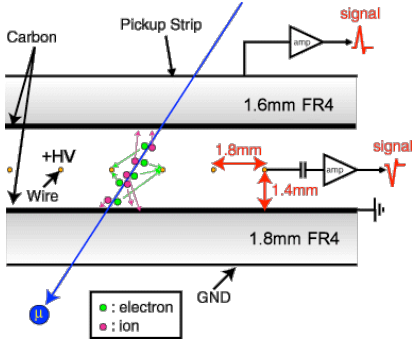
Muon Systems @ LHC (II)

- Resistive Plate Chambers (RPCs)
  - Parallel plate electrodes with HV leads to uniform electric field in the gas gap
  - Charge carriers drift towards anode, generate avalanche in high electric field
  - Large number of charge carriers induces a signal on a read out electrodes





- Thin Gap Chambers (TGCs)
  - Derivative of MWPCs



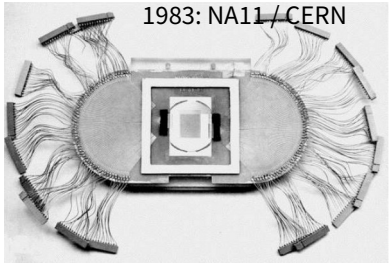
Semiconductor Detectors

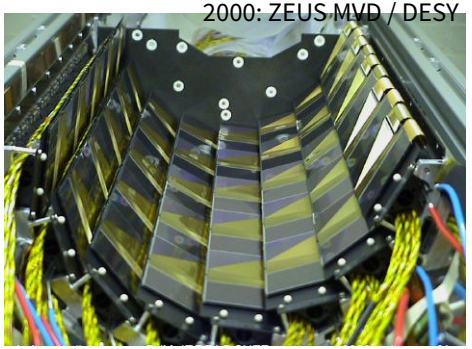
Across the band gap into the conduction band

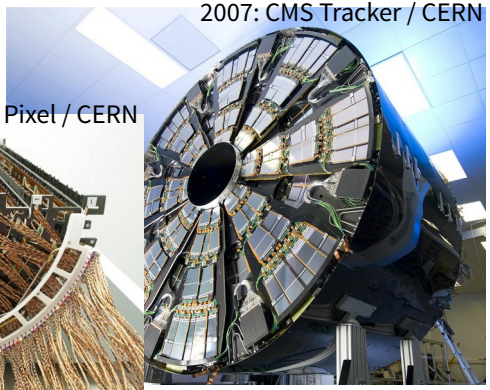
Silicon Tracking Detectors in Particle Physics

- Silicon tracking detectors have long history in particle physics
- Instrumental in discovery of Higgs boson at LHC
- Larges detectors installed in ATLAS & CMS
  - Tracking detectors: strips, 200 m^2 silicon, 70M channels
  - Vertex detectors: pixels, 1 m^2 silicon, 140M channels

- Detector upgrades for HL-LHC in preparation
  - More resilient against radiation-induced damage
  - Additional capabilities (e.g. triggering)


1983: NA11 / CERN

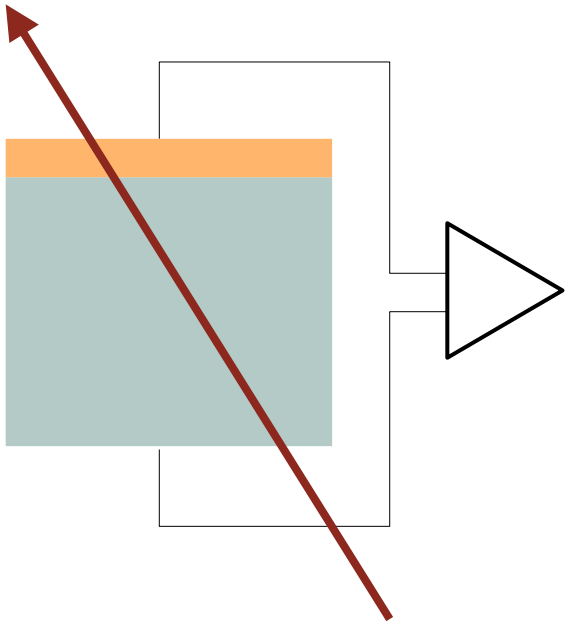

2000: ZEUS MVD / DESY


2007: CMS Tracker / CERN


2017: CMS Phase 1 Pixel / CERN

Detection Principle

- Solid state detector
  - Many higher density than gas detectors
  - High energy loss over relatively short distance
- Operating principle analogous to gas detectors
  - "Ionization" to generate free charge carriers
  - Drift due to electric field
  - Detection as electrical signal at electrodes
- Semiconductors:
  Silicon, Diamond, Germanium, GaAs, CdTe, …

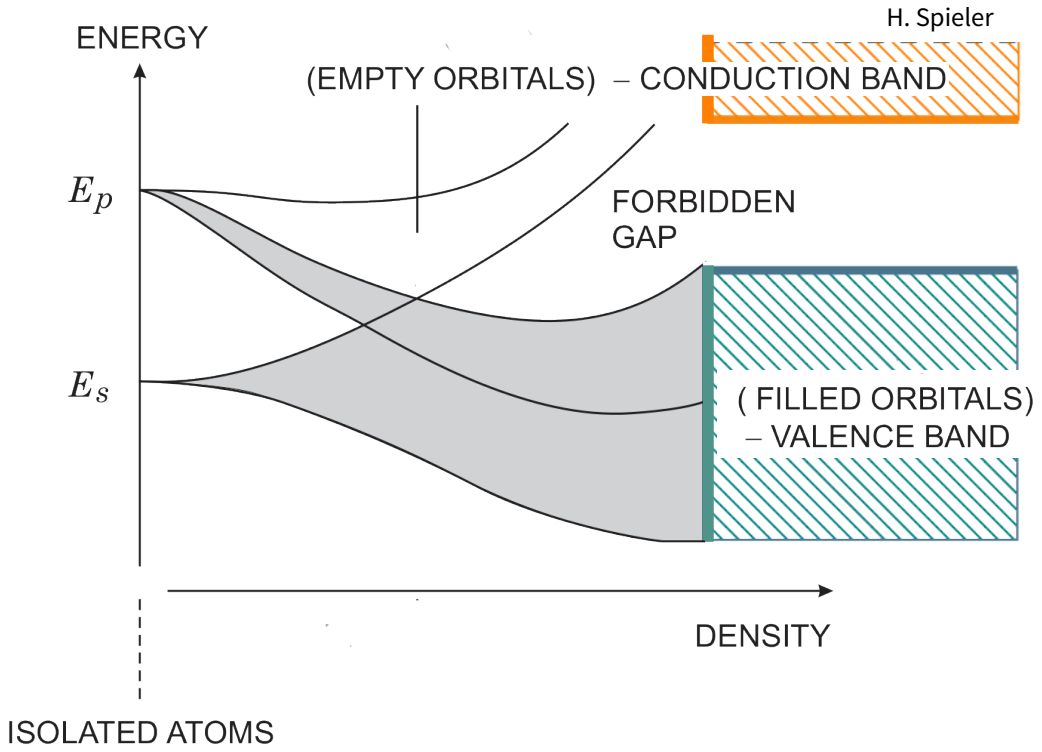


We will use many analogies to gas detectors...

Band Model

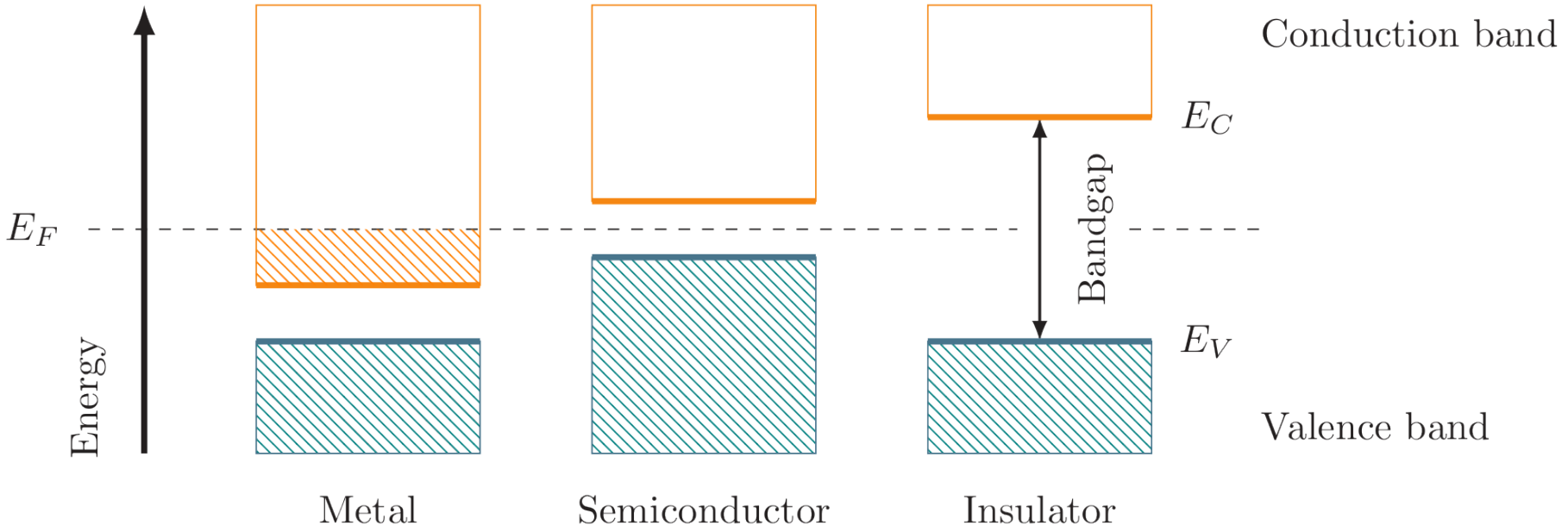
- Atom: discreet energy levels, orbitals
- Crystal lattice: energy levels blur into energy bands

- Formation of energy bands
  - Valence band – (last) fully filled
  - Band gap
  - Conduction band



Band Model: Insulator - Semiconductor - Conductor

- Position of valence and conduction band determines conduction property:



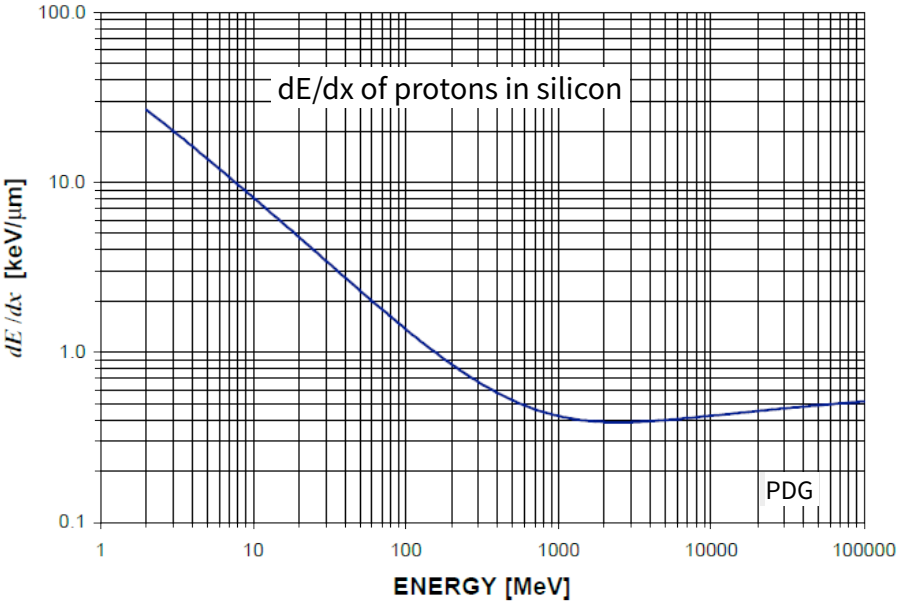
Choice of the Semiconductor

- Semiconductor detectors in high-energy physics: almost exclusively **silicon**
  - Industrially available via industry (availability, further development)
  - Band gap large enough E_G = 1.12 eV for operation at room temperature
  - Average energy for electron-hole generation: **E = 3.64 eV** (gas detector: x 10)
- Germanium: E_G = 0.74 eV
  - Too many free charge carriers at room temperature, needs cooling
  - Better energy resolution, often used in spectrometers
- Diamond: E_G = 5.4 eV, sometimes used for special radiation hardness requirements
- GaAs, CdTe, CYT... : mainly used in X-ray spectroscopy

Detecting a Particle with Intrinsic Silicon

- Silicon sensor: $A = 1\ cm^2$ and $d = 300\ \mu m$
- Signal of MIP:
  - Mean ionization: $E_0 = 3.6$ eV (silicon)
  - Mean energy loss: dE/dx = 3.9 MeV/cm

$$\frac{dE}{dx}\cdot\frac{d}{E_0} = 3.9\cdot10^6\,eV/cm\cdot0.03\,cm/3.6\,eV$$
$$\approx 3\cdot10^4\,e/h\ pairs$$



- Thermally excited charge carriers in silicon: $n_i = 1.45 \times 10^{10}\ cm^{-3}$ (at 300K)

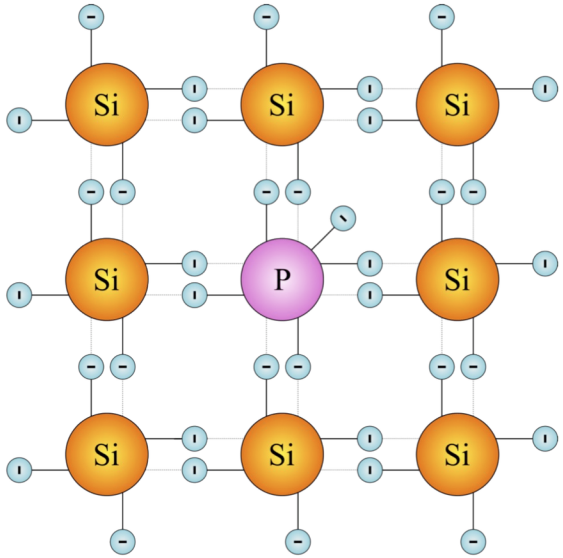
$$n_i\cdot d\cdot A = 1.45\cdot10^{10}\,cm^{-3}\cdot0.03\,cm\cdot1\,cm^2$$
$$\approx 4\cdot10^8\,e/h\ pairs$$

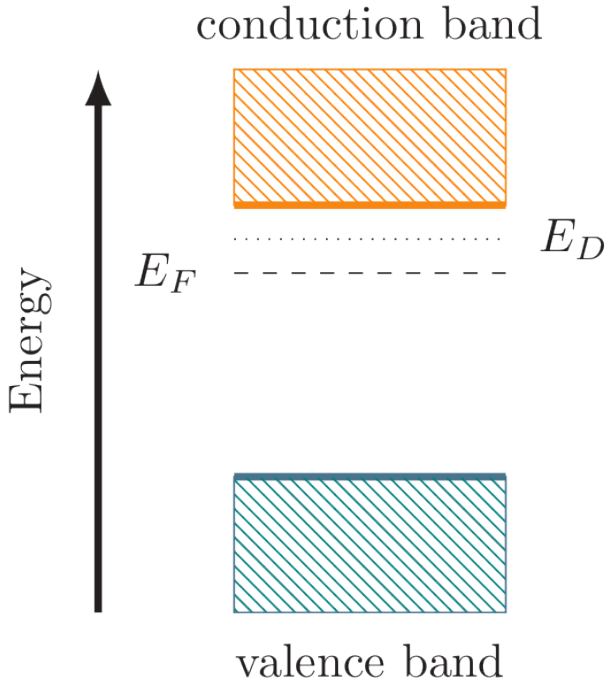
density silicon:
$N \approx 10^{22}$ atoms/cm^3

Doping Silicon – *n*-type

typical doping (p-in-n sensor):
$N_D \approx 10^{12}\ cm^{-3}$

- Adding group-V element (phosphorus, arsenic)
- Four covalent bonds, one “dangling” e
- Introduces “donor” state
- Negative majority charge carrier: *“n”*

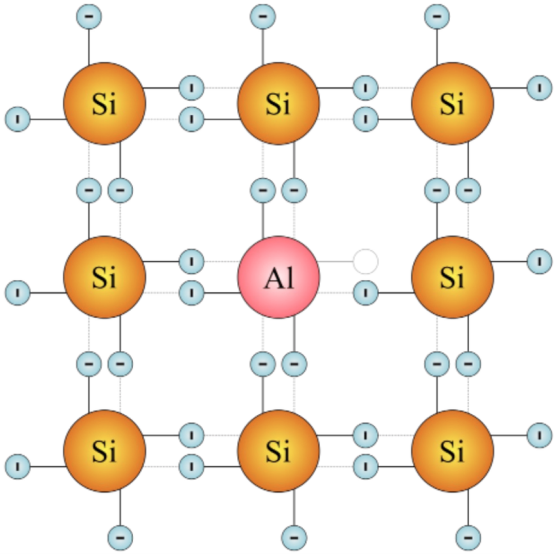


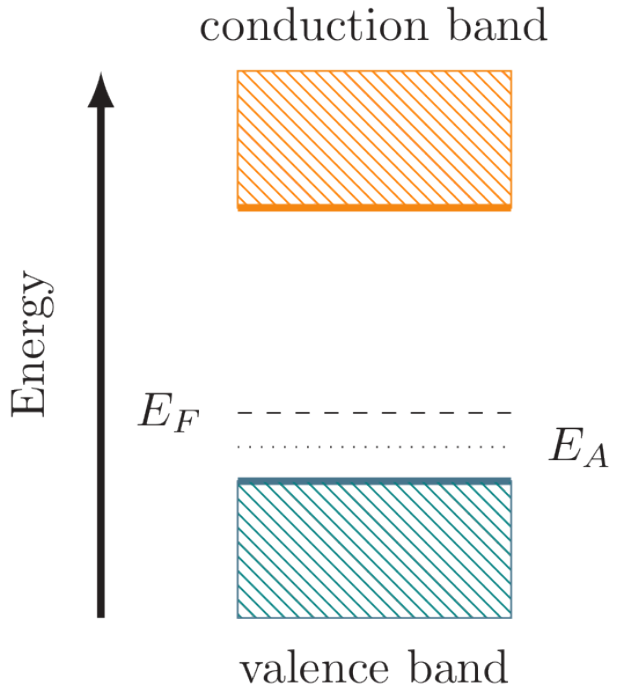


Doping Silicon – *p*-type

typical doping (p-in-n sensor):
$N_A \approx 10^{15}\ cm^{-3}$

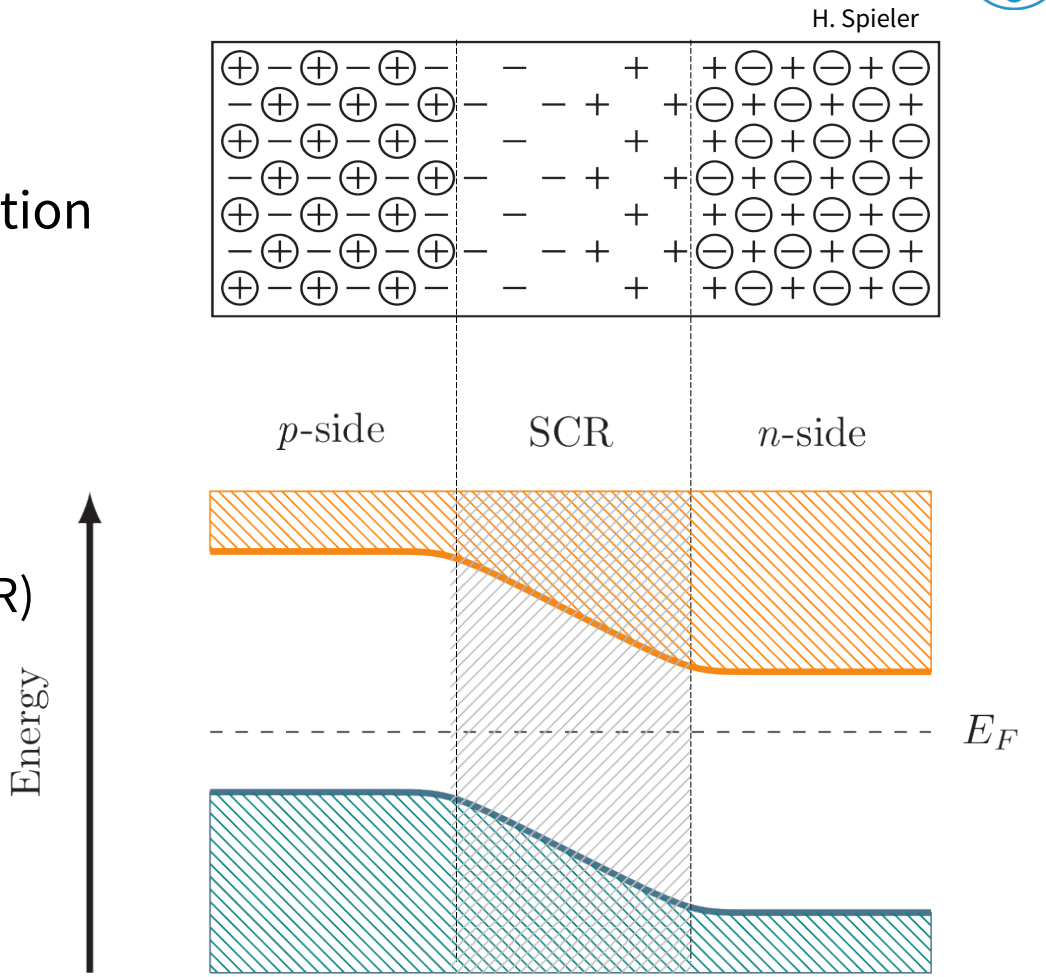
- Adding group-III element (boron, aluminum)
- Vacancy in covalent bonds – “hole”
- Introduces “acceptor” state
- Positive majority charge carrier: “*p*”





Forming a *pn*-Junction

- Electrons and holes diffuse over junction
- Constant Fermi level:
  Deformation of energy bands
- Donor/acceptor atoms remain
  - Depleted / space charge region (SCR)
  - Potential U_{bi} builds up
- Thermal equilibrium:
  Built-in potential balances diffusion



Built-in Voltage U_{bi}

silicon p-in-n sensor:

$N_A \approx 10^{15}\ cm^{-3}$

$N_D \approx 10^{12}\ cm^{-3}$

$k_B T \approx 0.026\ V$

$n_i = 1.45 \times 10^{10}\ cm^{-3}$

- Potential across the junction: difference of Fermi energies

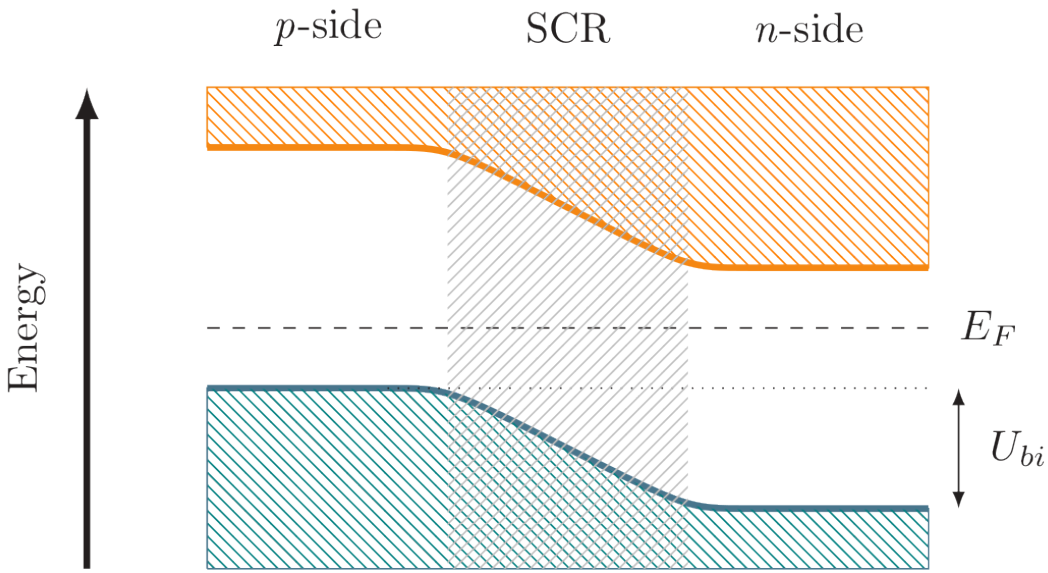
$$U_{bi} = E_{Fn} - E_{Fp} = k_B T \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

p-in-n sensor: $U_{bi} \approx 0.4\ V$

- Thickness of built-in SCR:

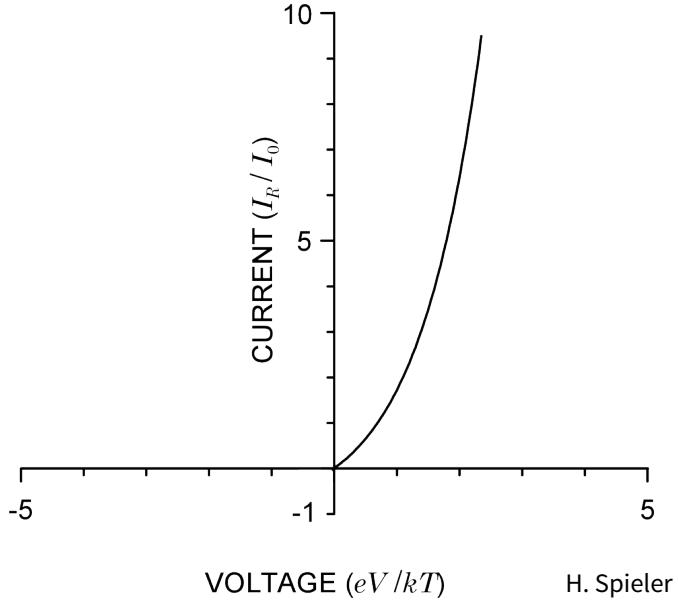
$$d(U_{bi}) = \sqrt{\frac{2\,\epsilon_r\,\epsilon_0}{|N_D - N_A|} \cdot U_{bi}}$$

p-in-n sensor: $d \approx 20\ \mu m$



pn-Junction in Forward Bias

- Lowering potential difference
- Increases flow of electrons & holes
- Shockley eq. $I = I_0\left(e^{eU/k_BT} - 1\right)$



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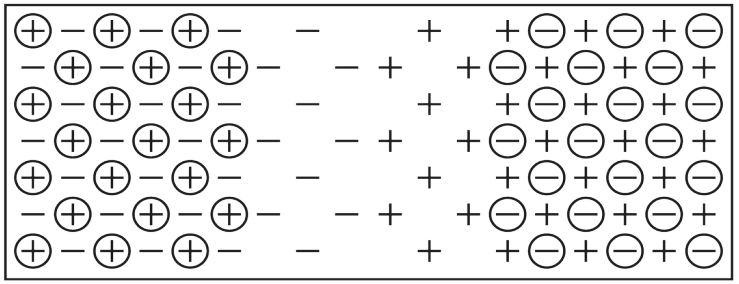
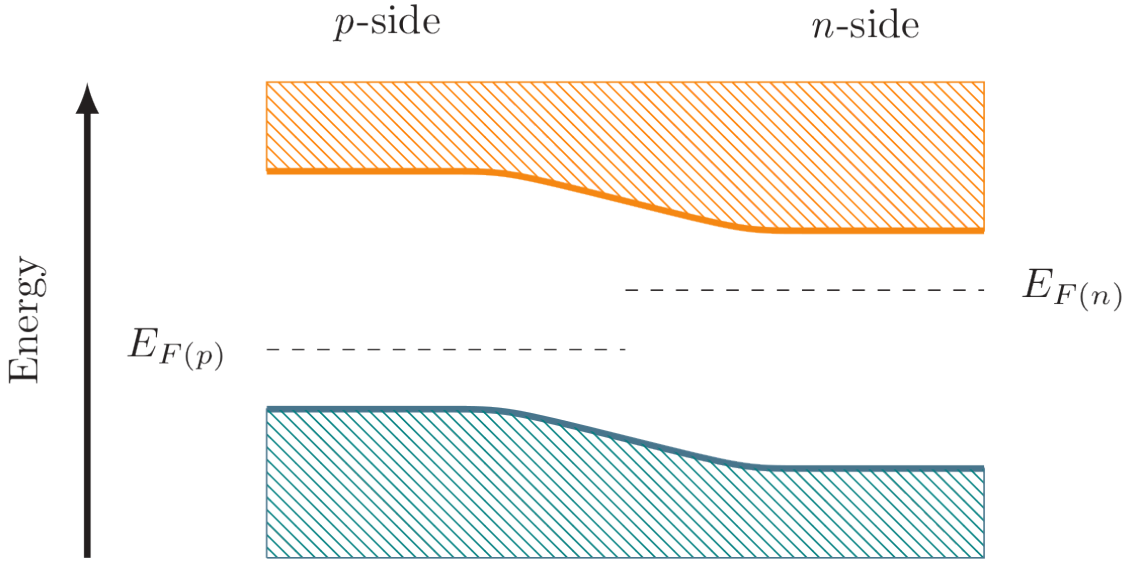
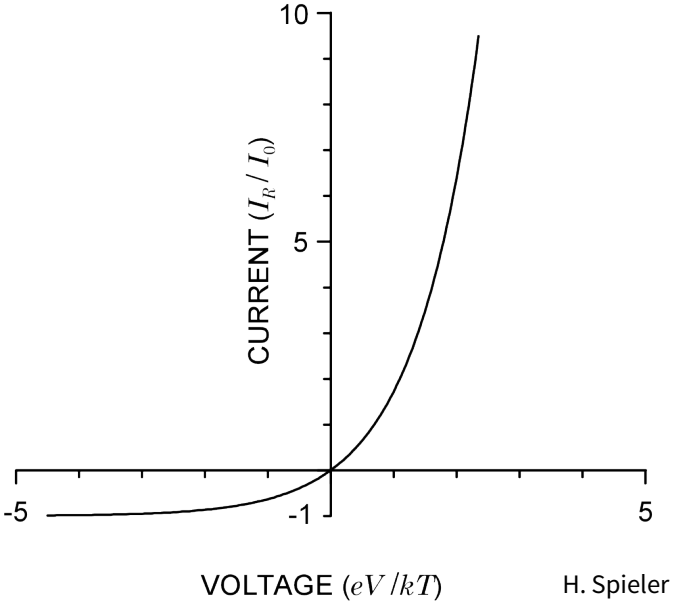




pn-Junction in Reverse Bias

- Raising potential difference
- Widens depletion region
- Shockley eq. $I = I_0\left(e^{eU/k_BT} - 1\right)$



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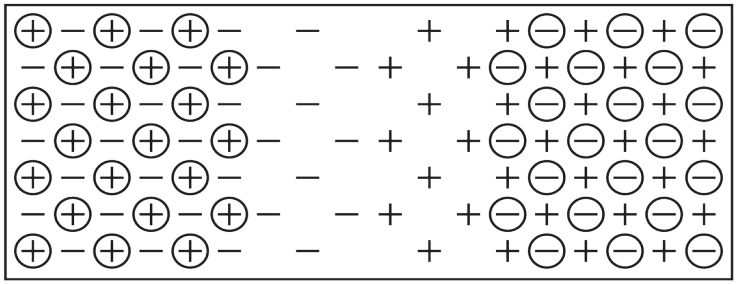
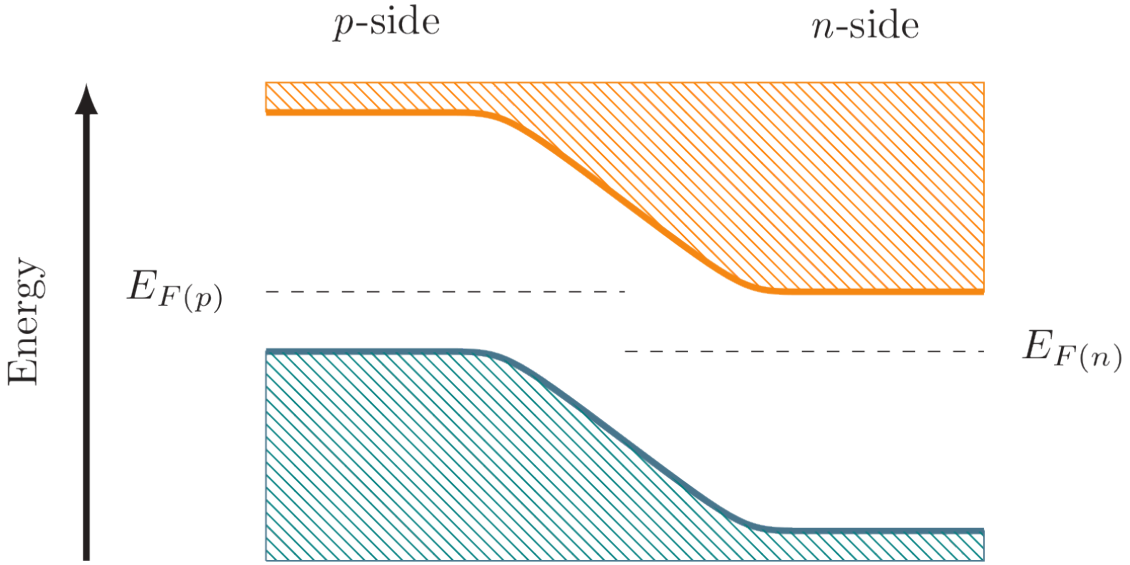
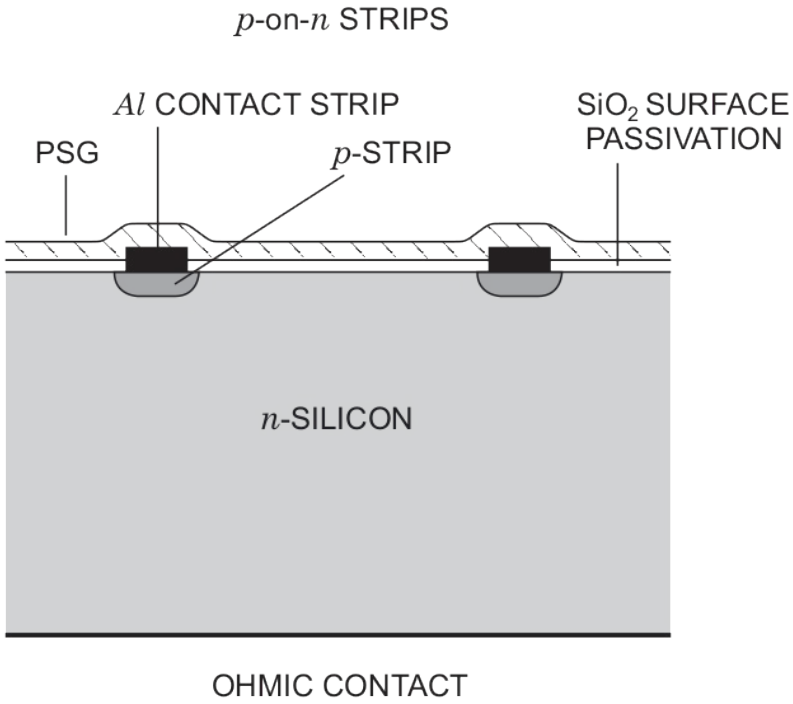




pn-Junction in a Sensor

typical doping (p-in-n):
$N_A \approx 10^{15}\ cm^{-3}$
$N_D \approx 10^{12}\ cm^{-3}$

- Asymmetric pn-junctions, here: *p*-in-*n*
- Lightly doped *n* bulk sensor material
- Thin, highly-doped *p* implant
- Segmentation of implant:
  separate channels
- Backside: layer of highly doped n^+
  as ohmic contact



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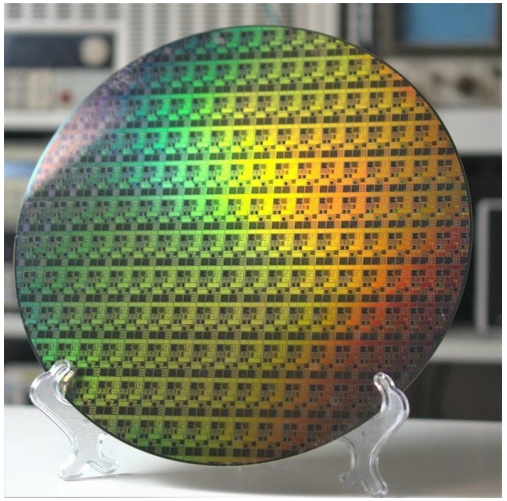
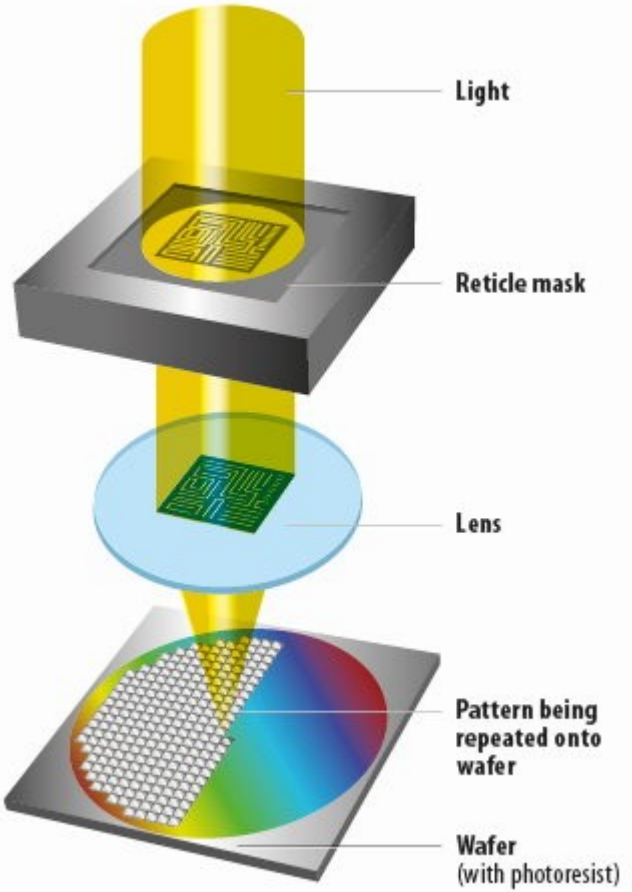
Silicon Wafer Processing

- Patterning by selectively introducing impurities (dopants)

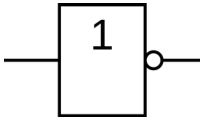
- Using photo lithography processes:
  - Photoresist, etching, implantation
  - Stepping due to limited reticle size



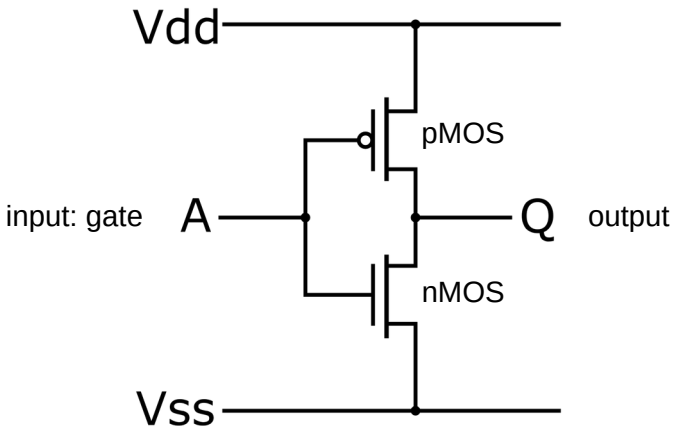


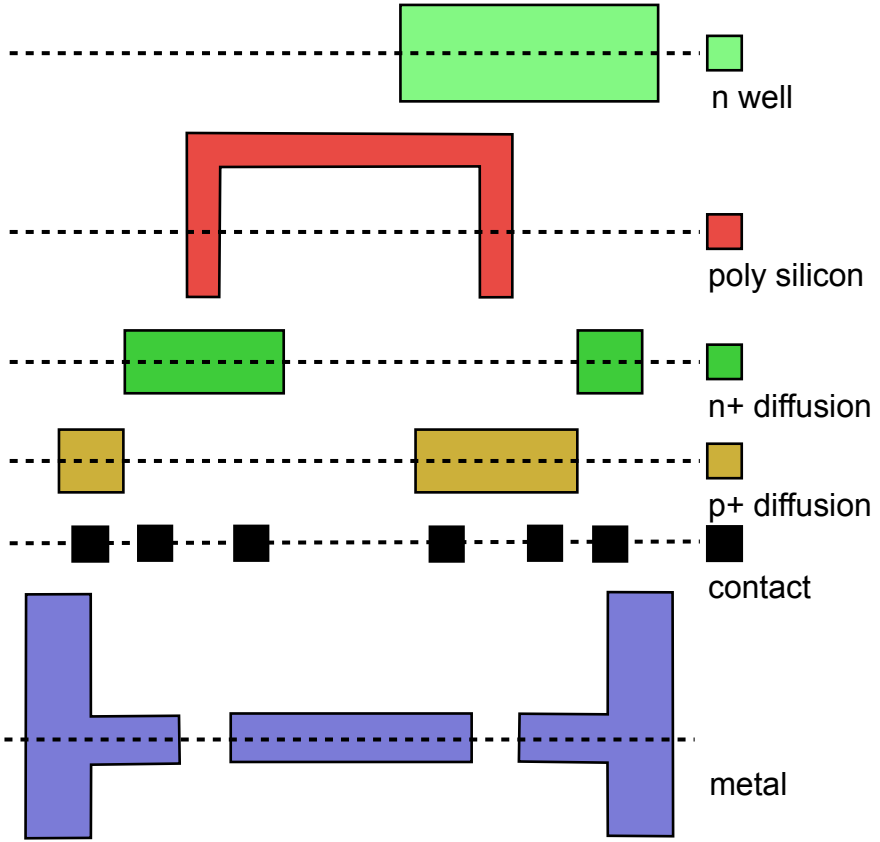
- Many steps involved in processing wafer,
  sensors: fewer, coarse structures;
  CMOS electronics: many more steps, fine structures

Example: Building a CMOS Inverter



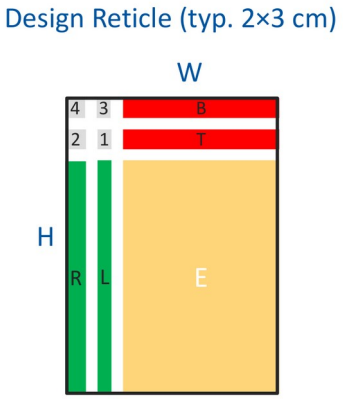
- Sensor electrodes, implants, transistors, traces are all defined via **masks**
  - Patterning of wafer surface for each type
- Example here: Inverter - requires 6 masks (and quite a few process steps…)
- Simplified representation of the process!

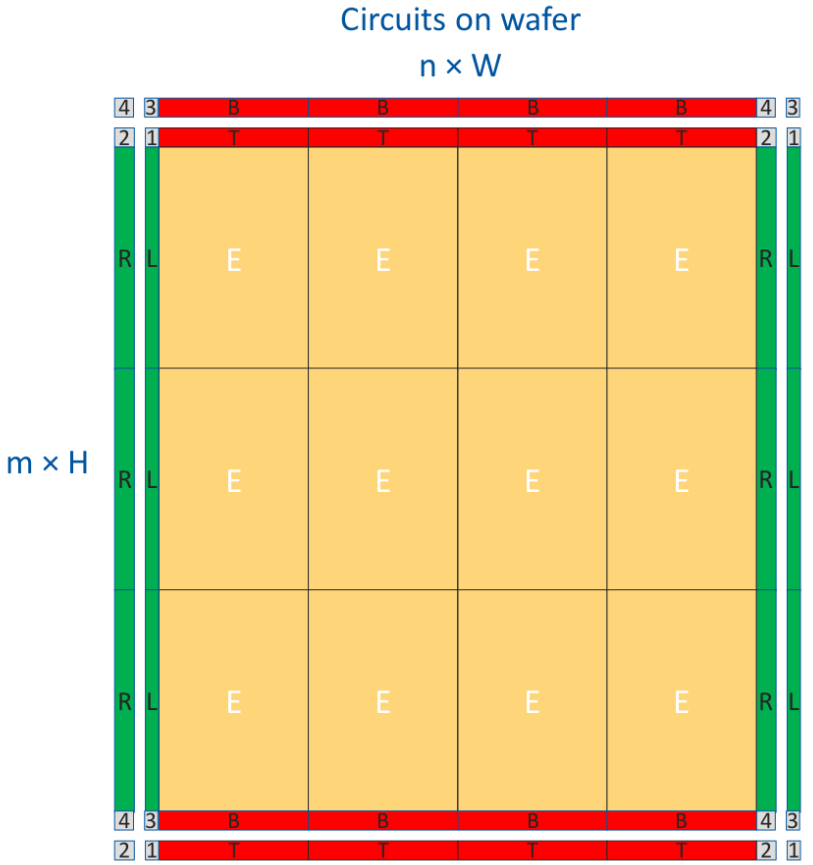




Reticles & Stitching

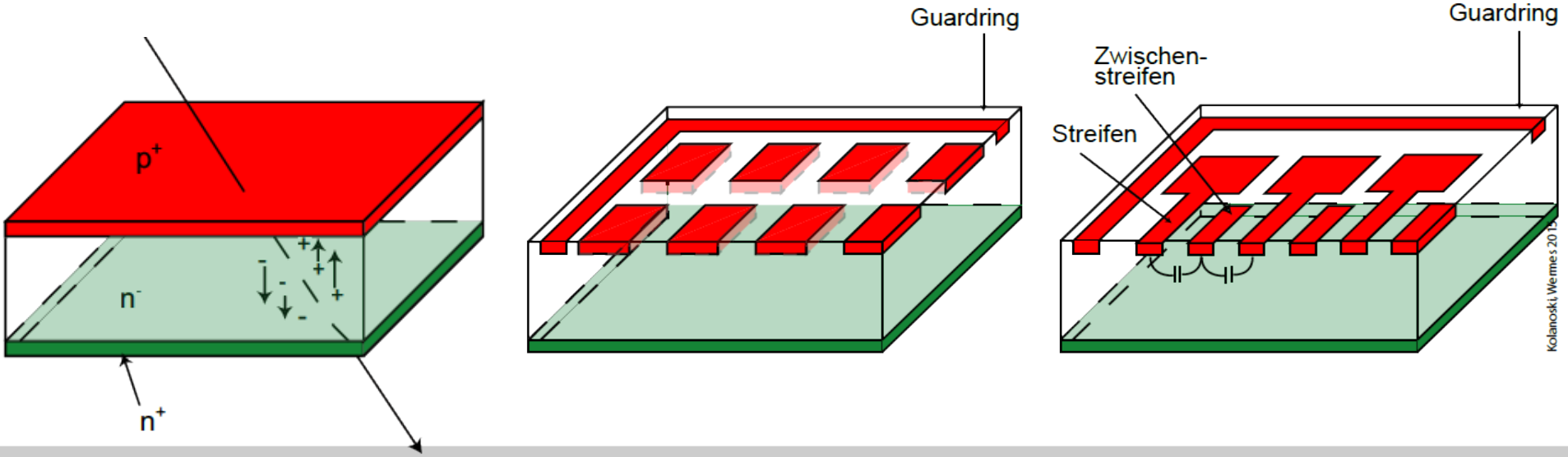
- Deep submicron processes:
  Illumination area limited by photolithography
- Reticle
  - typically 2 cm x 3 cm
  - limits maximum size of chips
- Limitation can be
  overcome with stitching:





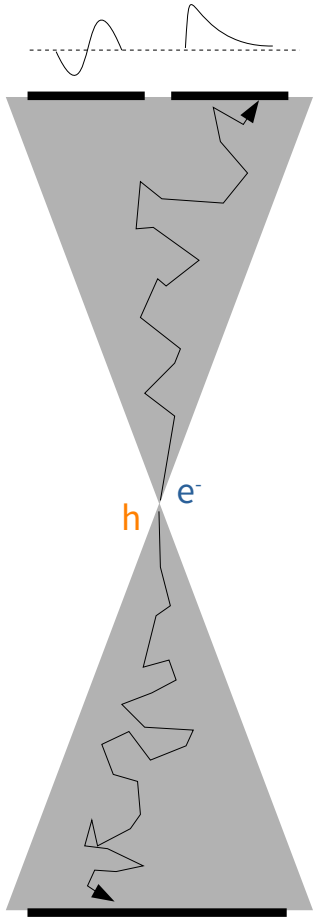
Segmentation of the Electrodes

- Ionizing particle excites e- from valence band to conduction band during passage: Generation of e/h pairs
- e/h pairs drift in electric field to electrodes, induce signal
- Segmentation of the electrode: very high spatial resolutions.
  Small structures of a few 10 µm possible; experience from electronics industry



Signal Formation in Silicon Detectors

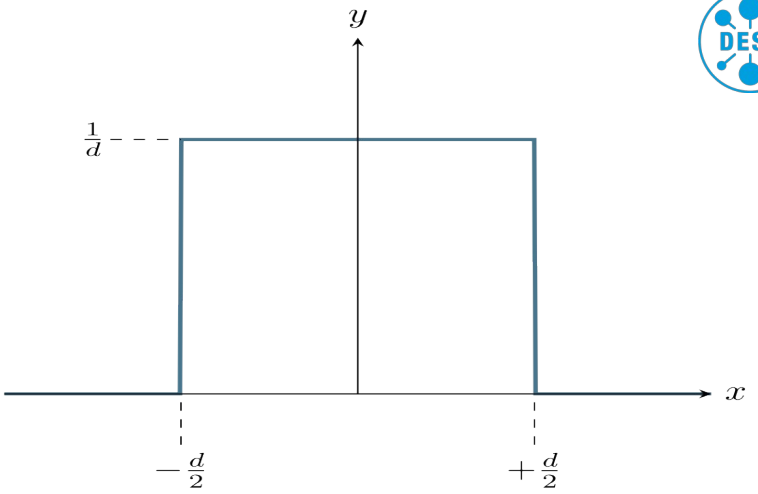
- Induced current by movement of charge carriers
- Diffusion
  - temperature-induced random motion, non-directional
  - Slow motion
- Drift
  - Directional motion due to electric field
  - Only in depleting areas
  - Fast motion
- Total motion: Superposition
- Best spatial resolution:
  Interpolation of the signal between two electrodes: $x = \frac{\sum_i Q_i x_i}{\sum_i Q_i}$



Spatial Resolution

- The probability of particle crossing particular detector channel is uniformly distributed
- Normalized probability density function:

$$\int_{-\frac{d}{2}}^{\frac{d}{2}} f(x)\,\mathrm{d}x = 1 \quad \rightarrow \quad f(x) = \frac{1}{d}$$



- Variance of position measurement:

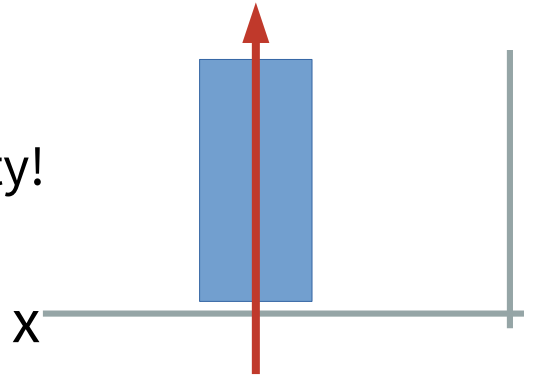
$$\sigma_x^2 = E[x^2] - \langle x \rangle^2 = \int_{-\frac{d}{2}}^{\frac{d}{2}} x^2 f(x)\,\mathrm{d}x - \left(\int_{-\frac{d}{2}}^{\frac{d}{2}} x f(x)\,\mathrm{d}x \right)^2 = \frac{1}{d} \int_{-\frac{d}{2}}^{\frac{d}{2}} x^2\,\mathrm{d}x - \left(\frac{1}{d} \int_{-\frac{d}{2}}^{\frac{d}{2}} x\,\mathrm{d}x \right)^2$$

$$= \frac{1}{d} \frac{x^3}{3} \Bigg|_{-\frac{d}{2}}^{\frac{d}{2}} - \frac{1}{d^2} \frac{x^4}{2} \Bigg|_{-\frac{d}{2}}^{\frac{d}{4}} = \frac{d^2}{12}$$

- **Uncertainty:** $\sigma_x = d/\sqrt{12}$

Spatial Resolution – Multiple Channels

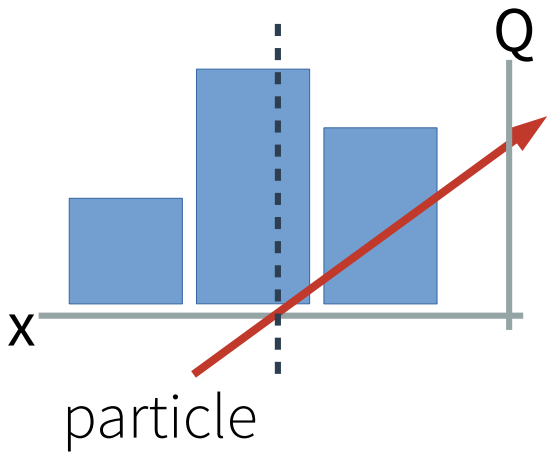
- Only approximation!
  Many detectors provide better resolution than granularity!
- Just a single channel struck:
  precision limited to variance of uniform distribution



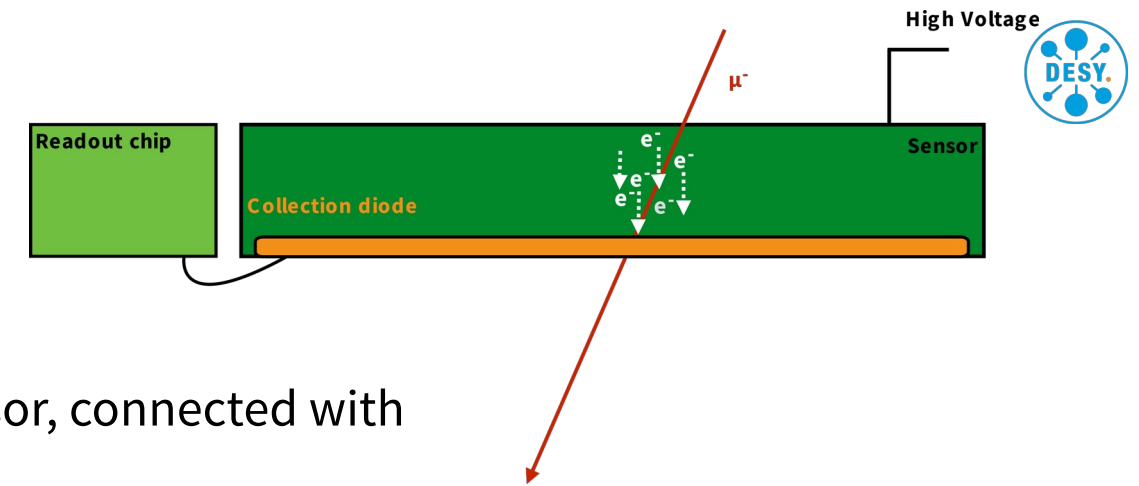
$$x = x_i \qquad \rightarrow \qquad \sigma_x = d/\sqrt{12}$$

- Multiple channels struck (charge sharing):
  interpolation using relative energy / charge distribution

$$x = \frac{\sum_{i=1}^{N} q_i x_i}{\sum_{i=1}^{N} q_i}$$

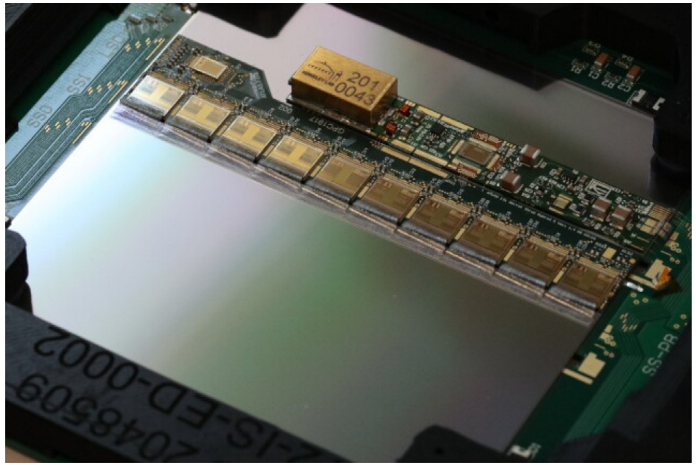


Strip Detectors



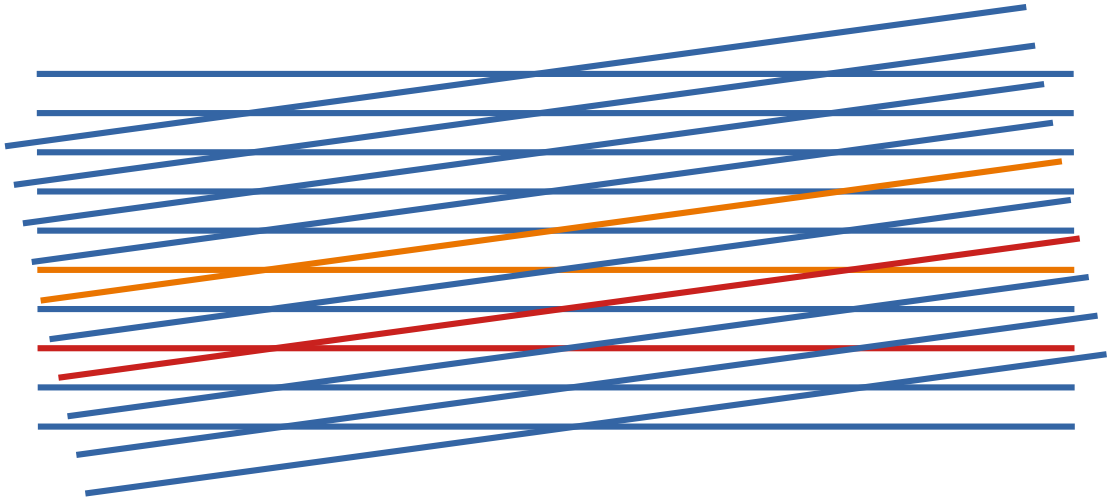
- Strips as readout electrodes
- Advantage:
  - Readout electronics next to sensor, connected with wirebonds,
  - Relatively easy to build, inexpensive, good for large areas
- Disadvantage:
  - Location measurement only along one coordinate
- Used for large areas:
  Large radii from interaction point,
  large lever arm for impulse measurement

ATLAS ITk barrel long strip module prototype

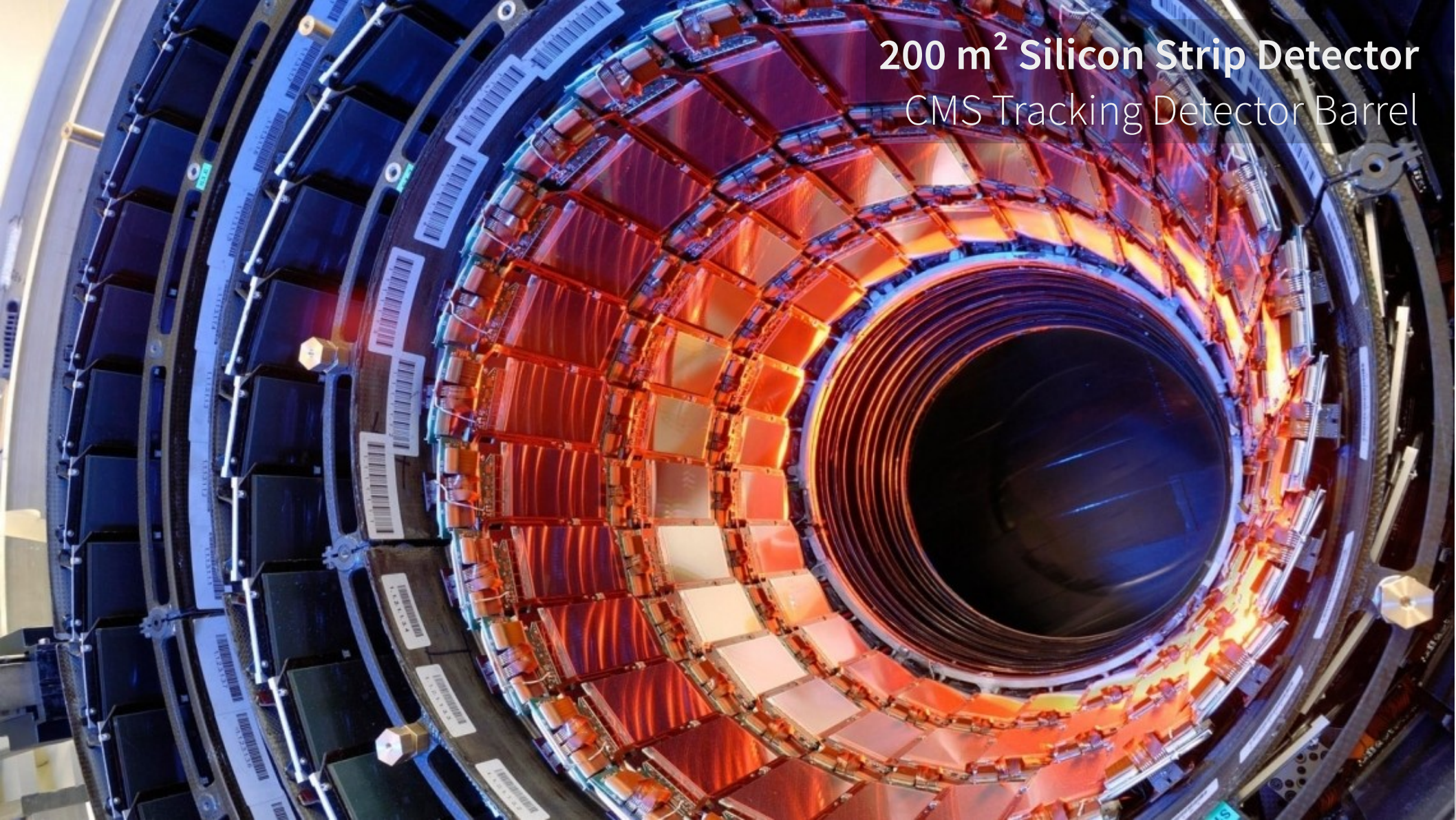


Strip Detector – Adding a 2nd Layer

- 2D measurement using stereo angle
  - Two detector modules on top of each other with a **small relative rotation angle**
  - Limit on total particle rate due to ambiguities:
- “Ghost Hits”
  - Appear with > 2 particles crossing the sensor
  - Impossible to distinguish particle crossing point from other strip coincidences



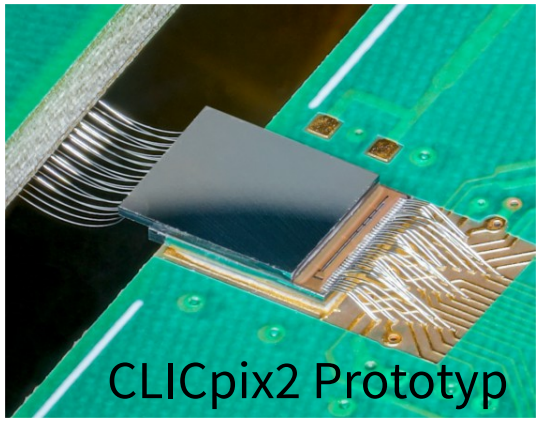
→ Reason for **small stereo angle!** Reduce number of other strips crossed



200 m² Silicon Strip Detector

CMS Tracking Detector Barrel

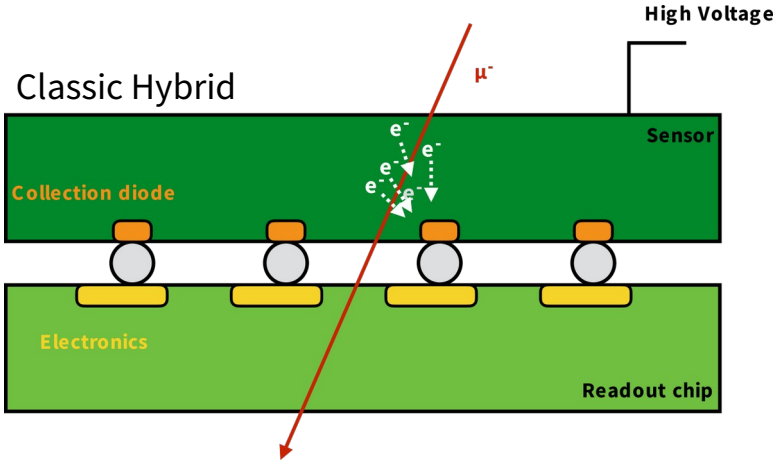
Silicon Pixel Detectors

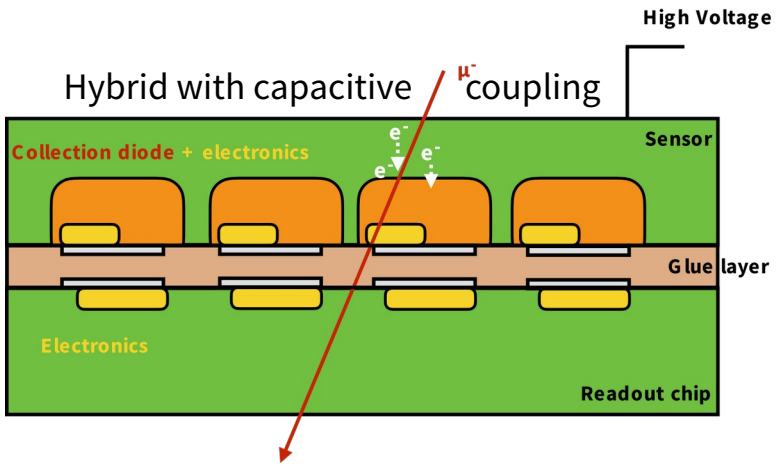

CLICpix2 Prototyp

- Segmentation in two dimensions
  - Advantage: Direct 2D spatial measurement, no stereo angles required
  - Disadvantages: Connection to readout electronics, many more channels
- Different technologies, readout concepts, sensor structures
  - Exact design of a sensor very complex (metallization, passivation...)
  - Detectors designed and optimized for specific application (experiment)
- Pixel sizes of a few 10 µm → good spatial resolution
- Sensor thicknesses of a few 100 µm → Little multiple scattering

Pixel Detector Technology: Hybrids

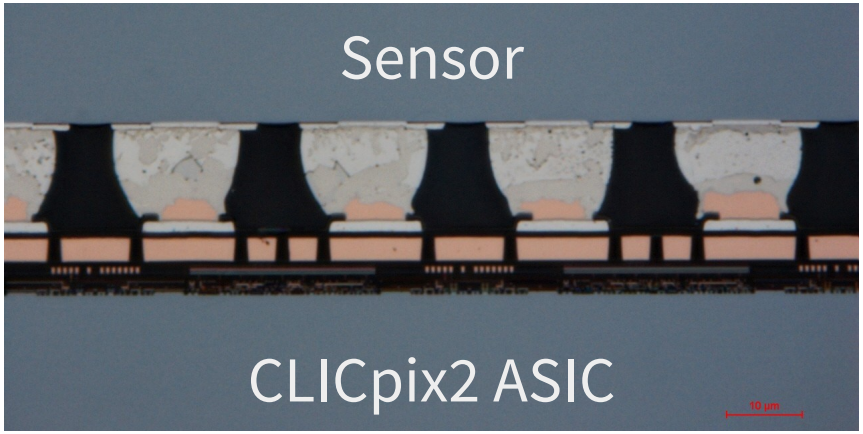
- Separation of readout electronics and sensor in two silicon chips
  - Connection via small metal balls (bump bonds) or adhesive layer
  - Sensor doping as desired, high voltage for depletion possible
  - Readout chip can exploit full potential of commercial processes
- Small pixel sizes with lots of functionality possible - but very expensive to produce



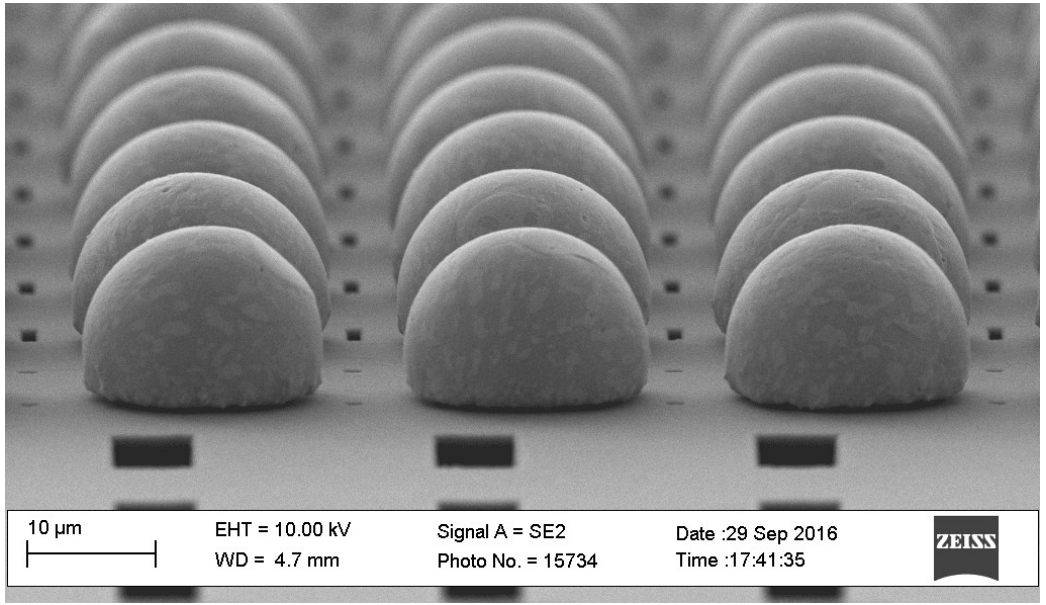


Hybridization: Bump Bond Interconnects

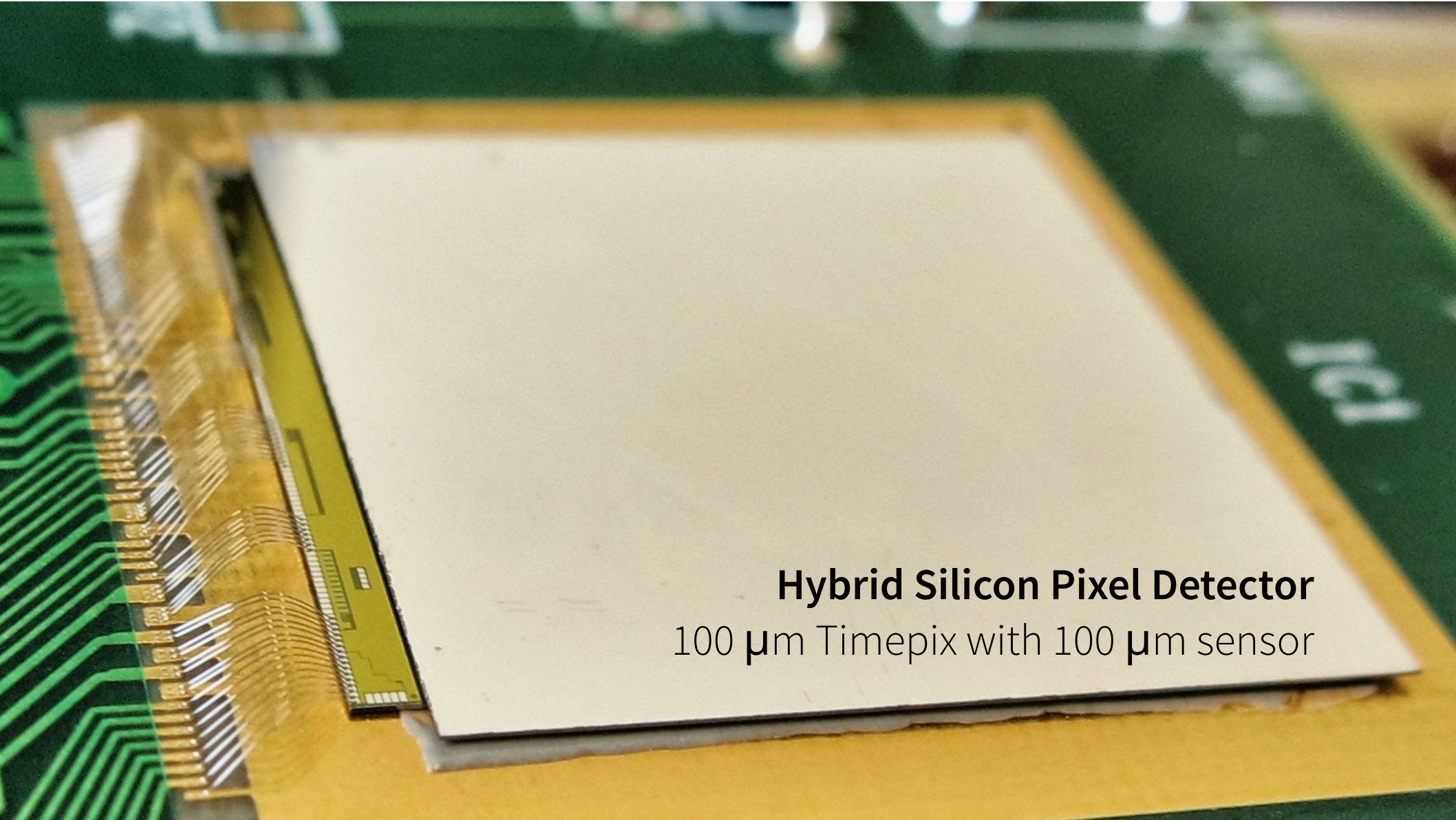
- Different technologies available
- Very common: Bump bonding
  - Size: ~ 10 – 20 µm
  - Material: Lead-Tin, Indium, …



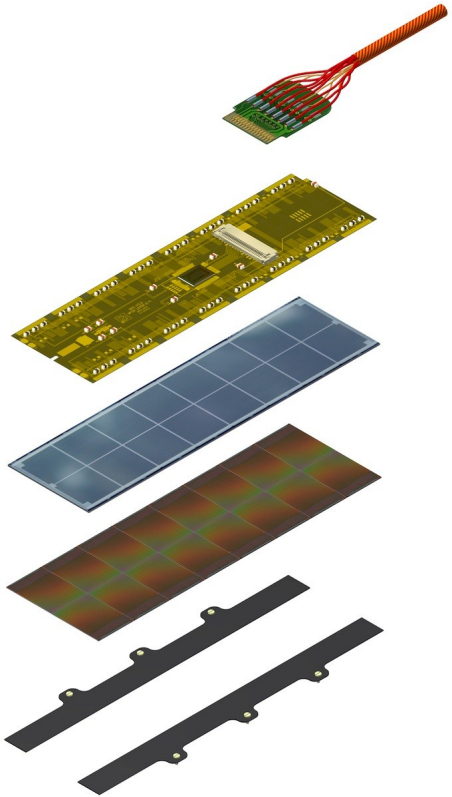
https://doi.org/10.1088/1748-0221/14/06/C06003



- Different placement techniques
  - Solder spheres → individual chips
  - Via lithography → wafer-level


Hybrid Silicon Pixel Detector
100 µm Timepix with 100 µm sensor

Example: CMS Pixel Detector



Twisted pair cable

HDI (High Density Interconnect, signal and power handling)

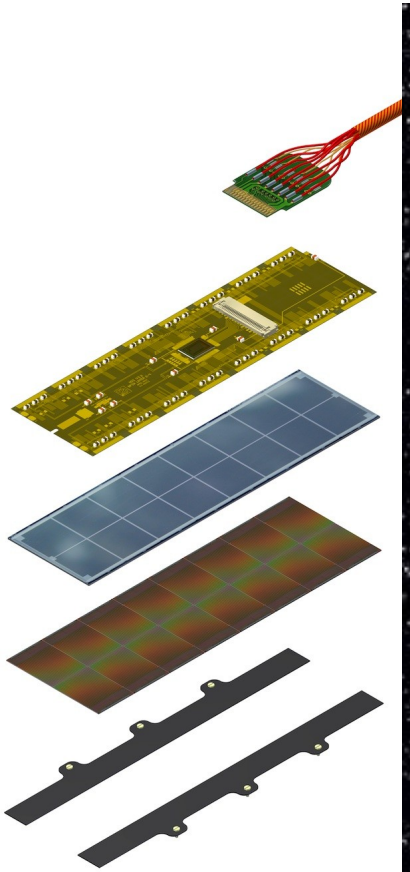
n^+-in-n silicon sensor

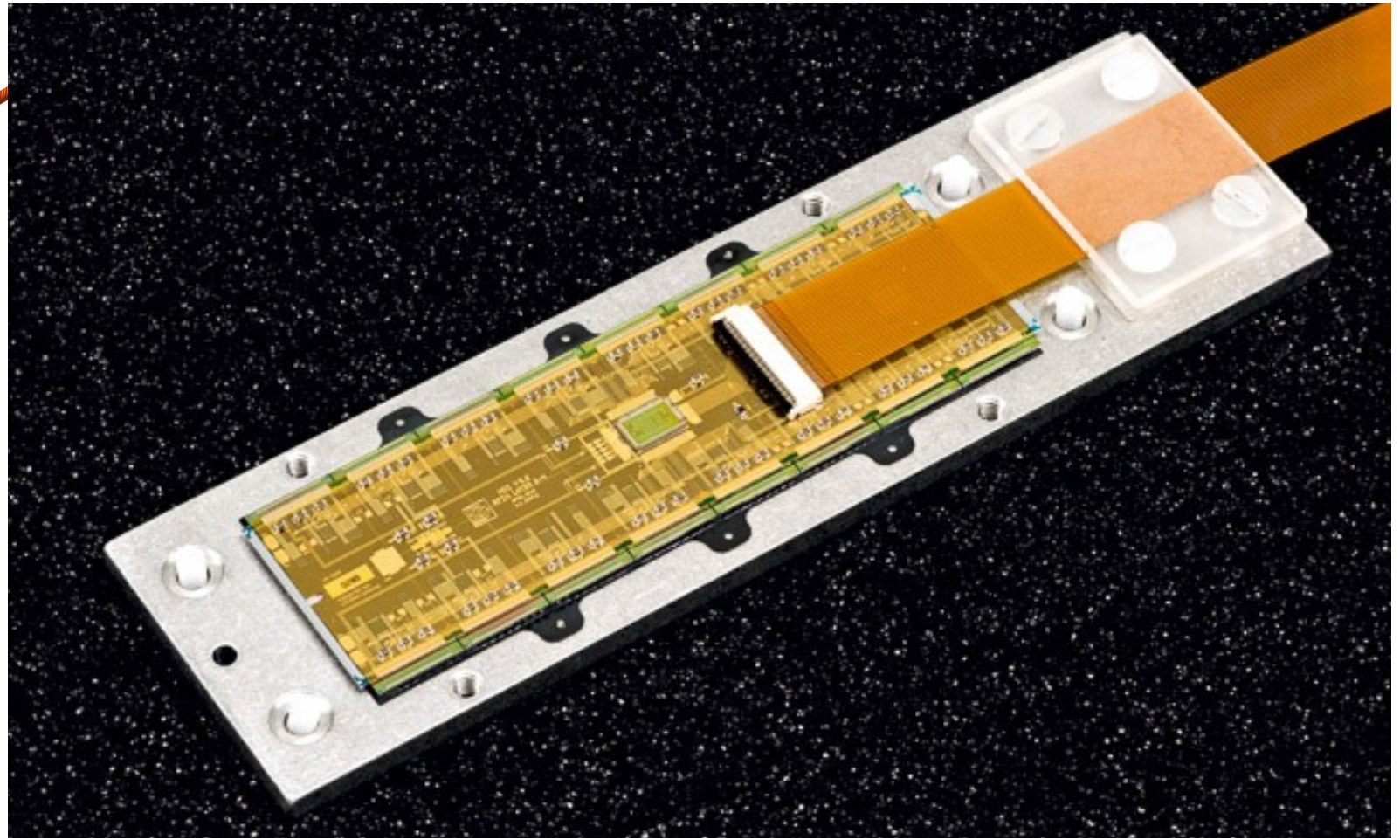
16 readout chips, bump bonded to sensor

Base strips for mounting

- Sensor:
  - n^+-in-n sensor technology
  - 285 µm thickness
  - 150 x 100 µm pitch
- Module:
  - 52 x 80 = 4160 pixels/chip
  - 16 chips → 4160 x 16 = 66560 pixels/module
  - Total size: 64.8 x 16.2 mm

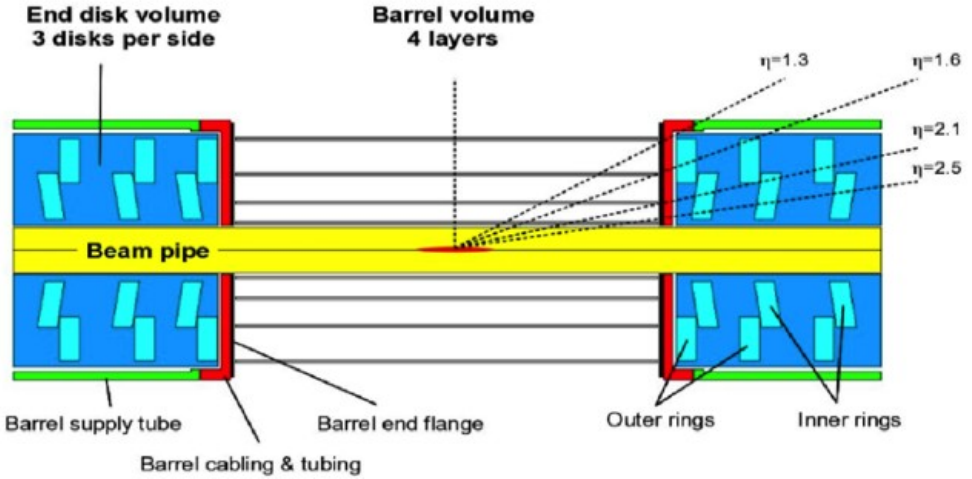
Example: CMS Pixel Detector

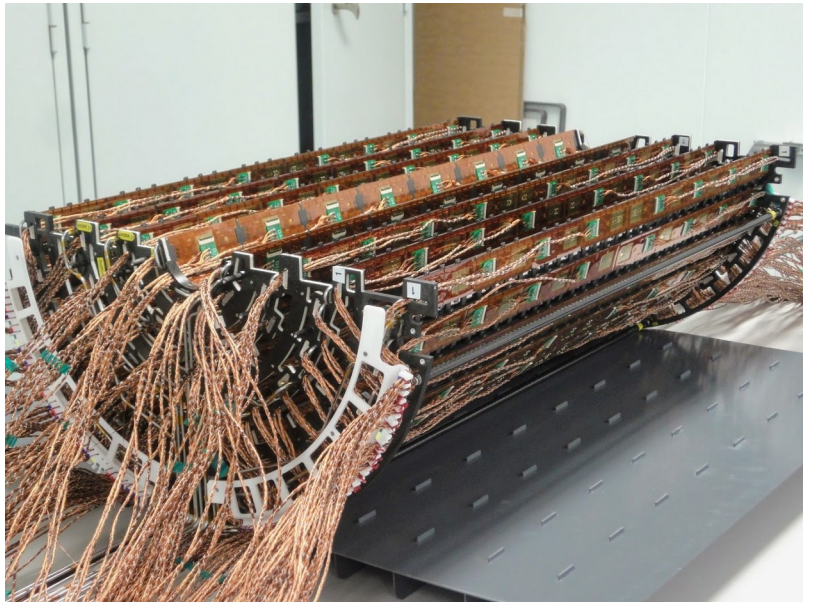


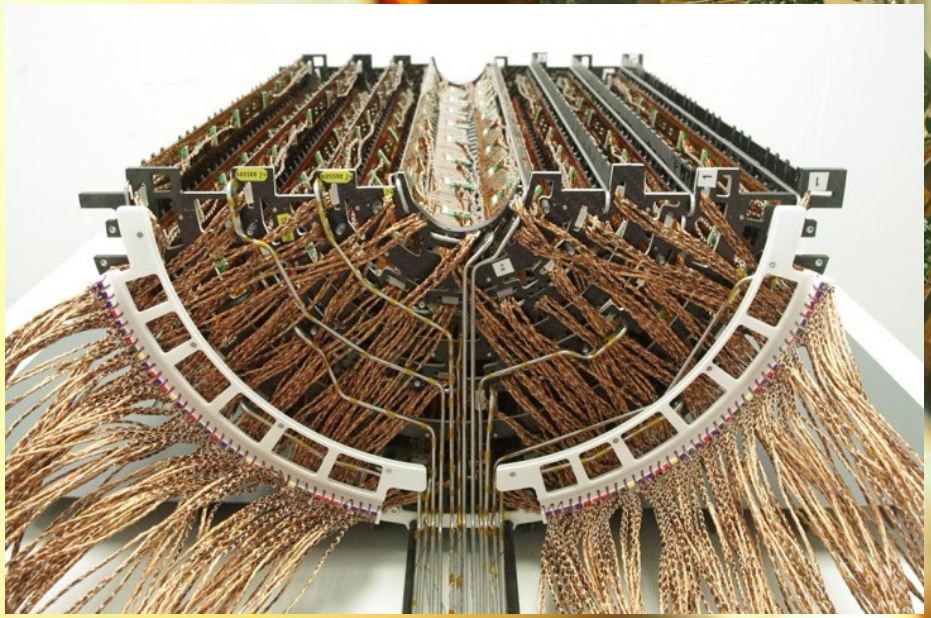


Example: CMS Pixel Detector

- Innermost part of the CMS Detector
  - Four *barrel* layers
    - Radii: 3.0, 6.8, 10.2, 16.0 cm
    - Length: 54.9 cm
  - Three *endcap* layers per side
    - Radii: 4.5 – 16.1 cm
- Total number of modules: **1856**
- *124 MPix* – with 25 ns time resolution
- Spatial resolution: > 5 µm







Endcap and Half Barrel

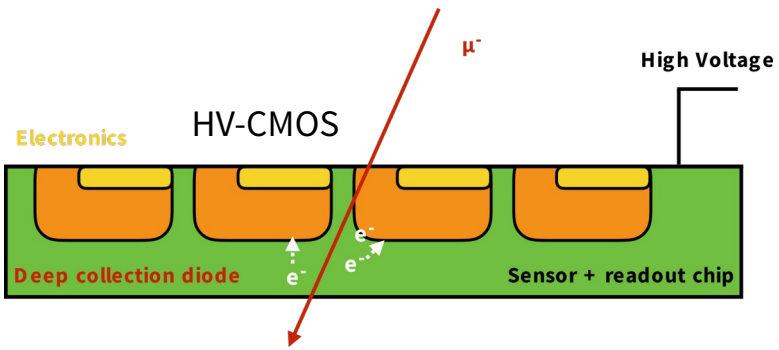
CMS Phase I Pixel Detector

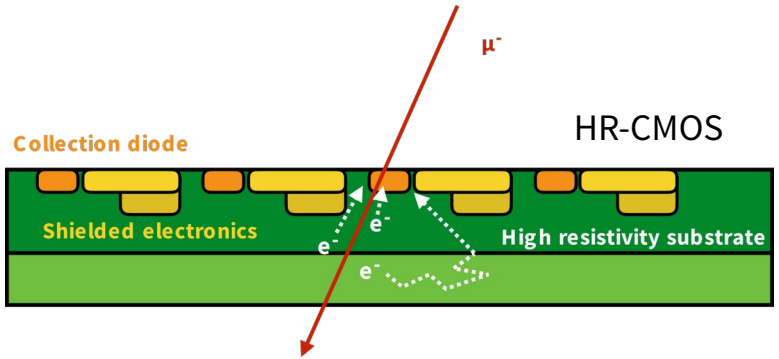
Installation of Phase I Pixel Detector

CMS-Experiment @ LHC

Pixel Detector Technology: Monolithic Sensors

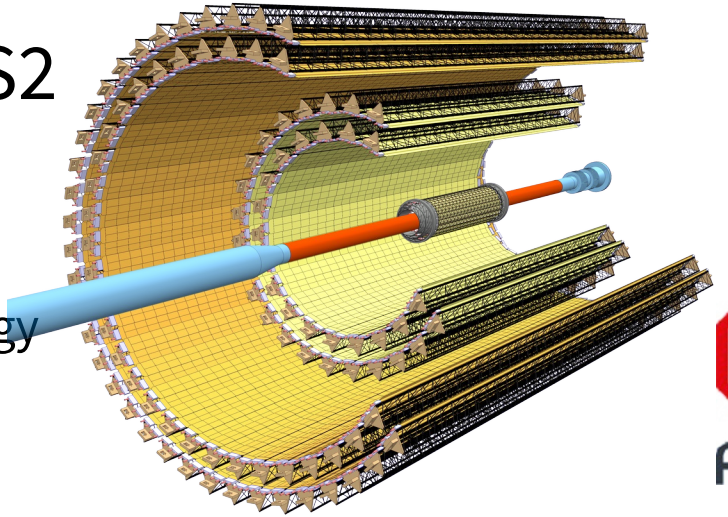
- Goal: minimal material with the greatest possible precision.
- Removal of the readout chip, implementation of the electronics in the sensor
  - Cheaper, because no bump bonding, less material
  - Problem: CMOS electronics can only tolerate low voltage, limited depletion
- Different technologies to isolate "sensor" and "electronics

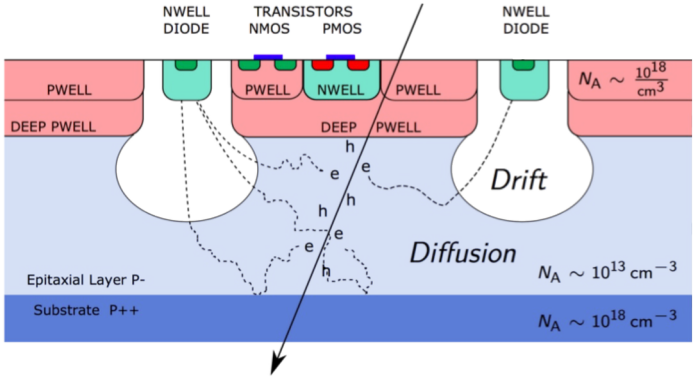


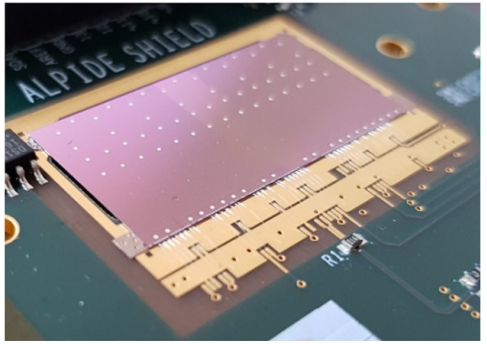


The ALPIDE Sensor of the ALICE ITS2

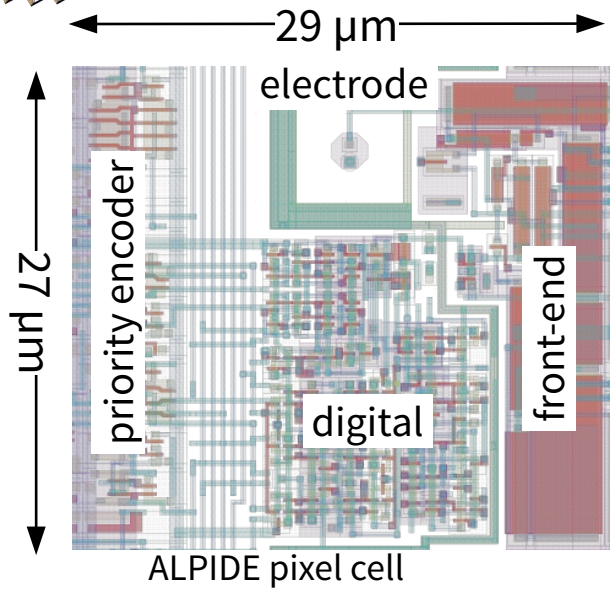
- Full Inner Tracking System: 24’000 ALPIDE chips, one of the first large-scale detectors with MAPS
- ALPIDE – MAPS in 180 nm CMOS imaging technology
  - 512 × 1024 pixels, 29 µm x 27 µm pitch
  - Binary detection & readout (hit/no hit)
  - Optimized for low power consumption
  - Produced on epitaxial layers of 18 – 30 µm



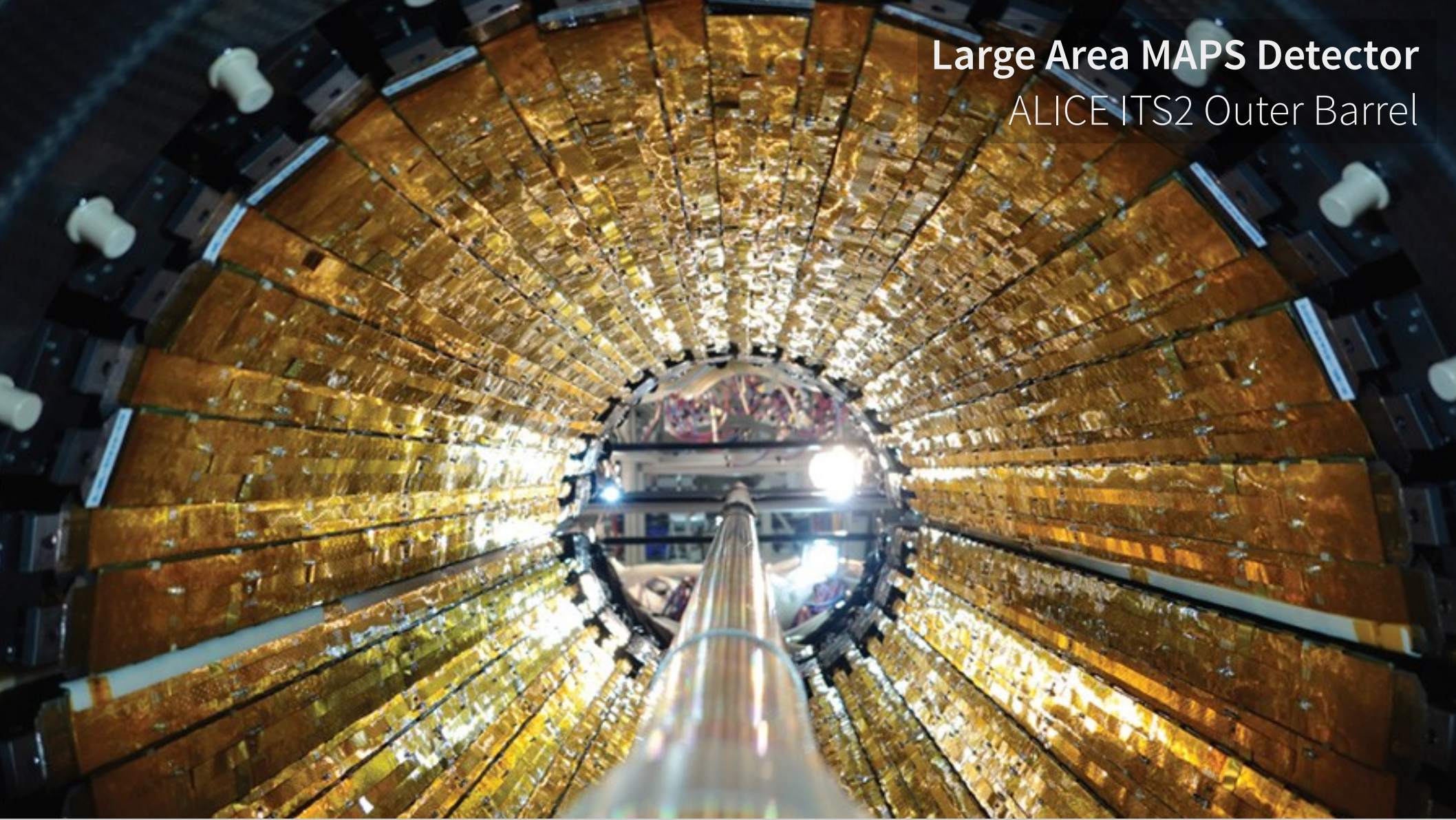




http://dx.doi.org/10.1016/j.nima.2016.05.016

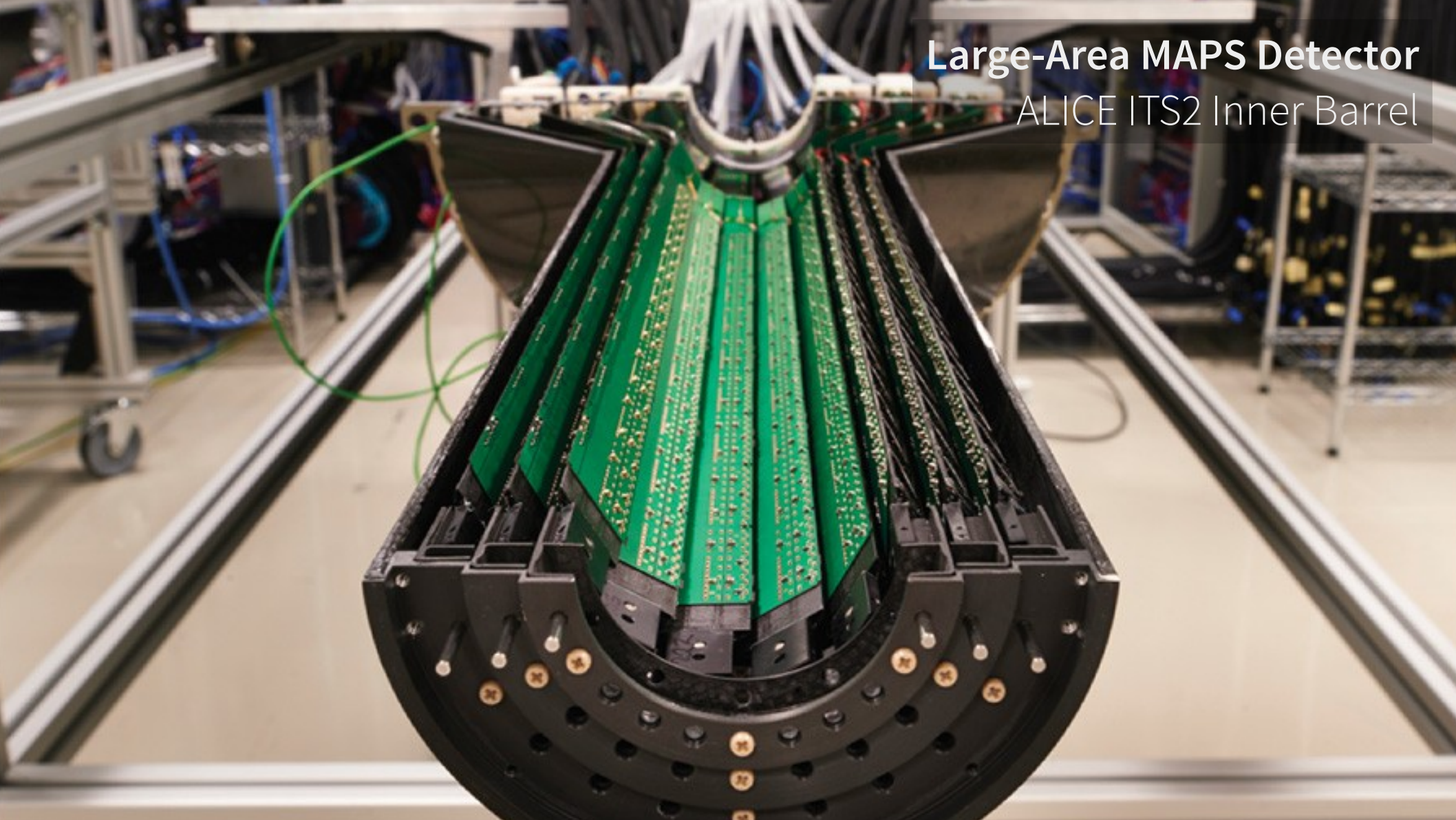


ALPIDE pixel cell



Large Area MAPS Detector

ALICE ITS2 Outer Barrel



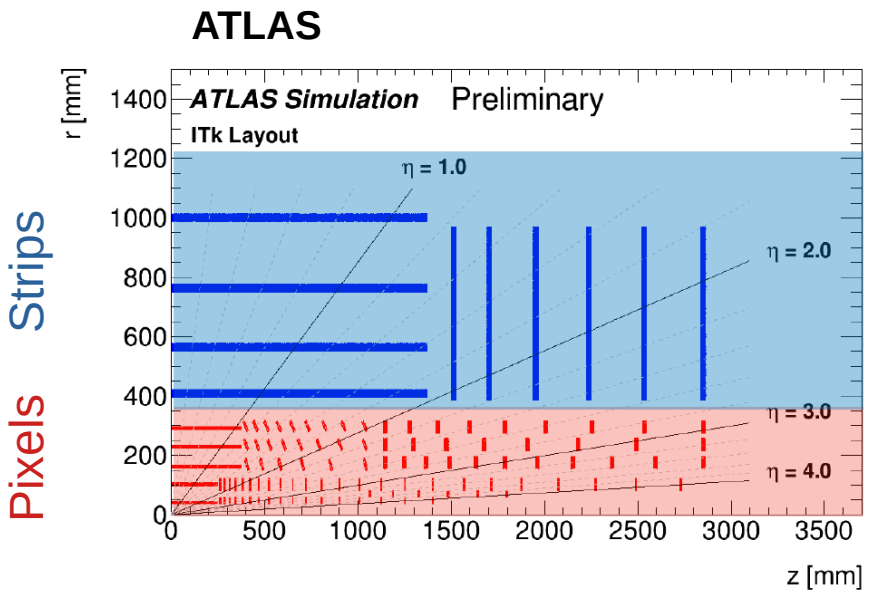
Large-Area MAPS Detector

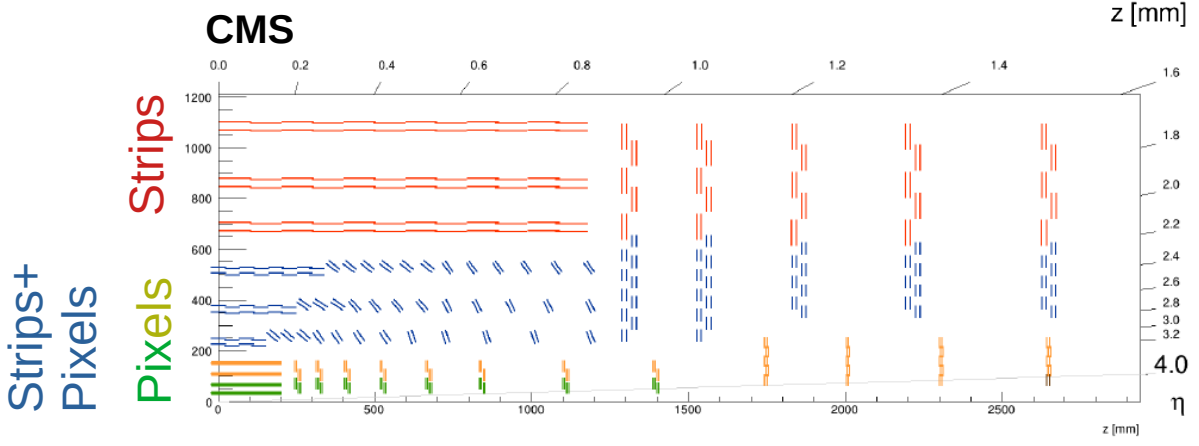
ALICE ITS2 Inner Barrel

Combining Strip & Pixel Detectors

Typical Compromise

- **Pixel detector** at center of experiment
  - Smaller size → reduces costs
  - Pixel detector can cope with high occupancy close to IP
- **Strip detector** at larger radii
  - Lower occupancy → reduced probability for ghost hits
  - Reduction in number of readout channels






DESY.