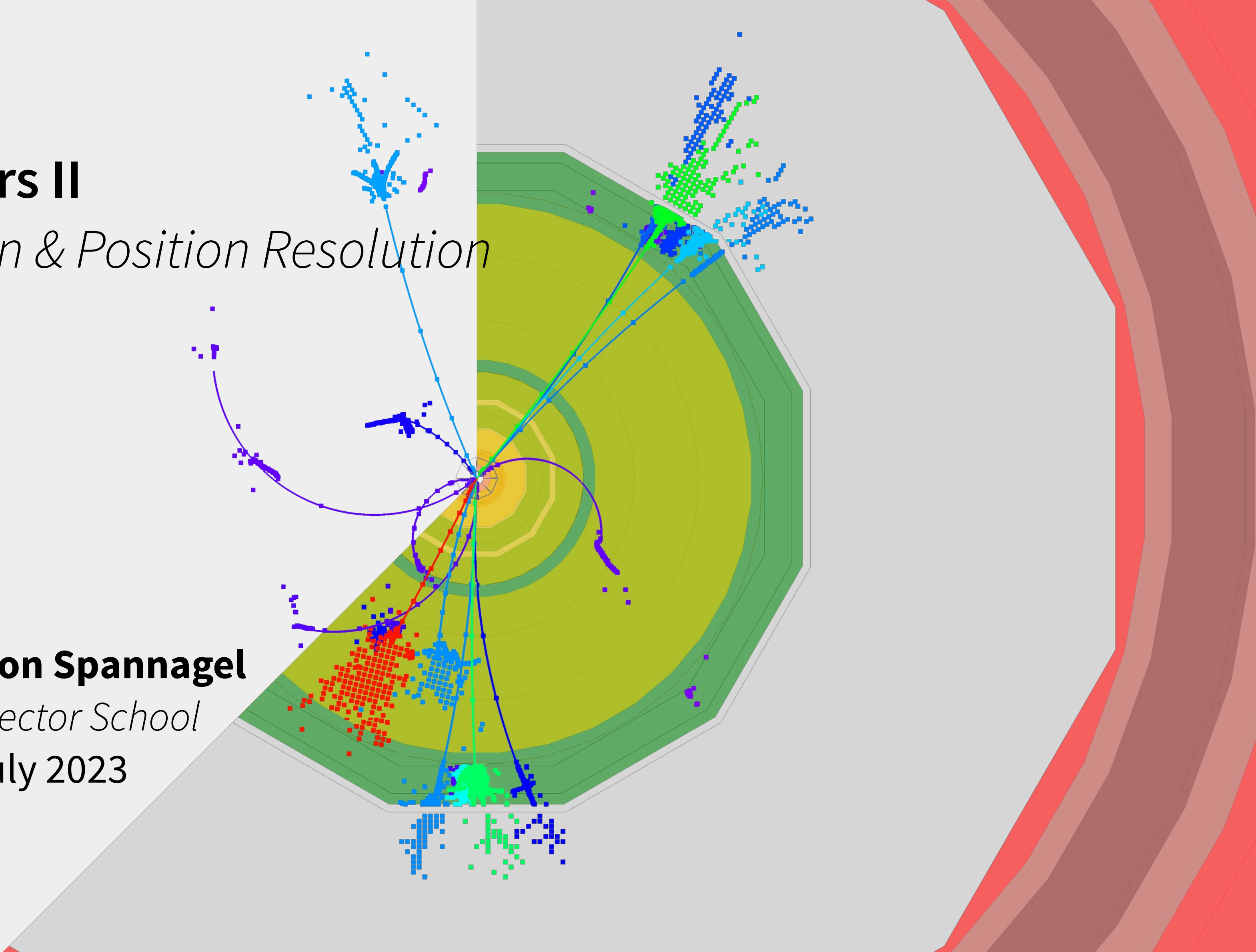
https://www.desy.de/

Silicon Detectors II

Particle Detection & Position Resolution

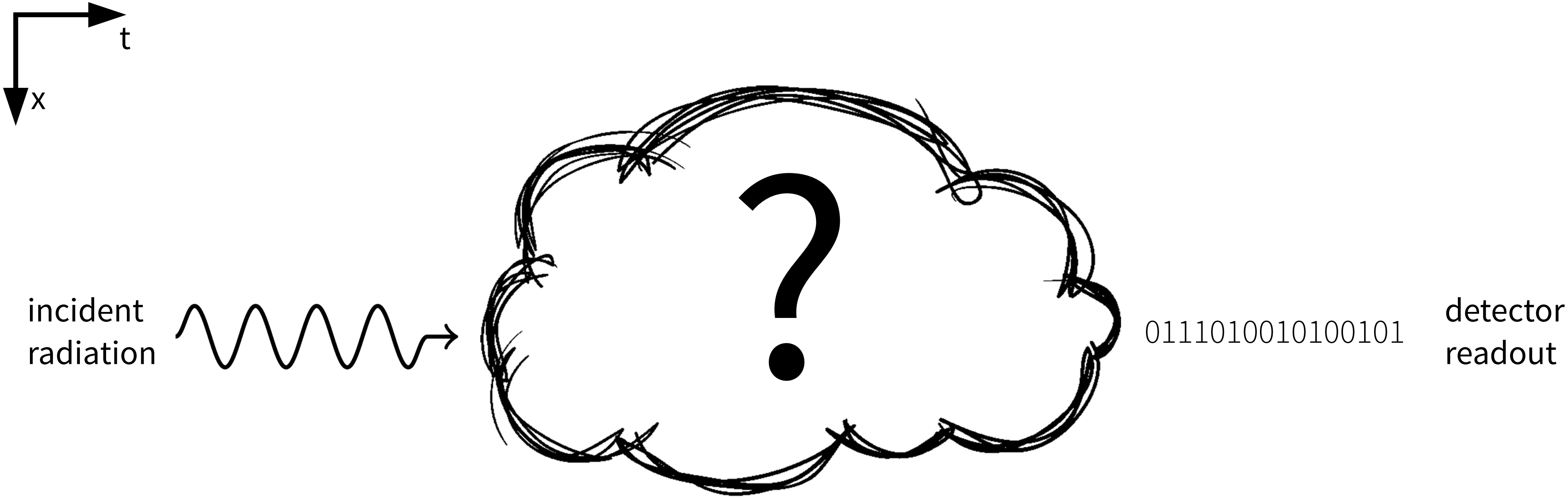


Simon Spannagel

EURIZON Detector School

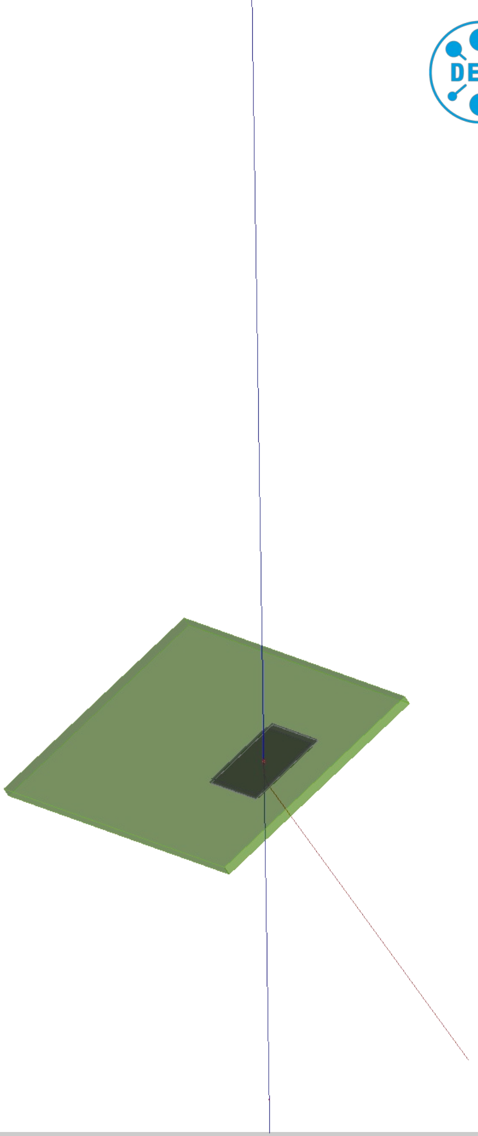
18 July 2023

Particle Detection with Semiconductor Detectors

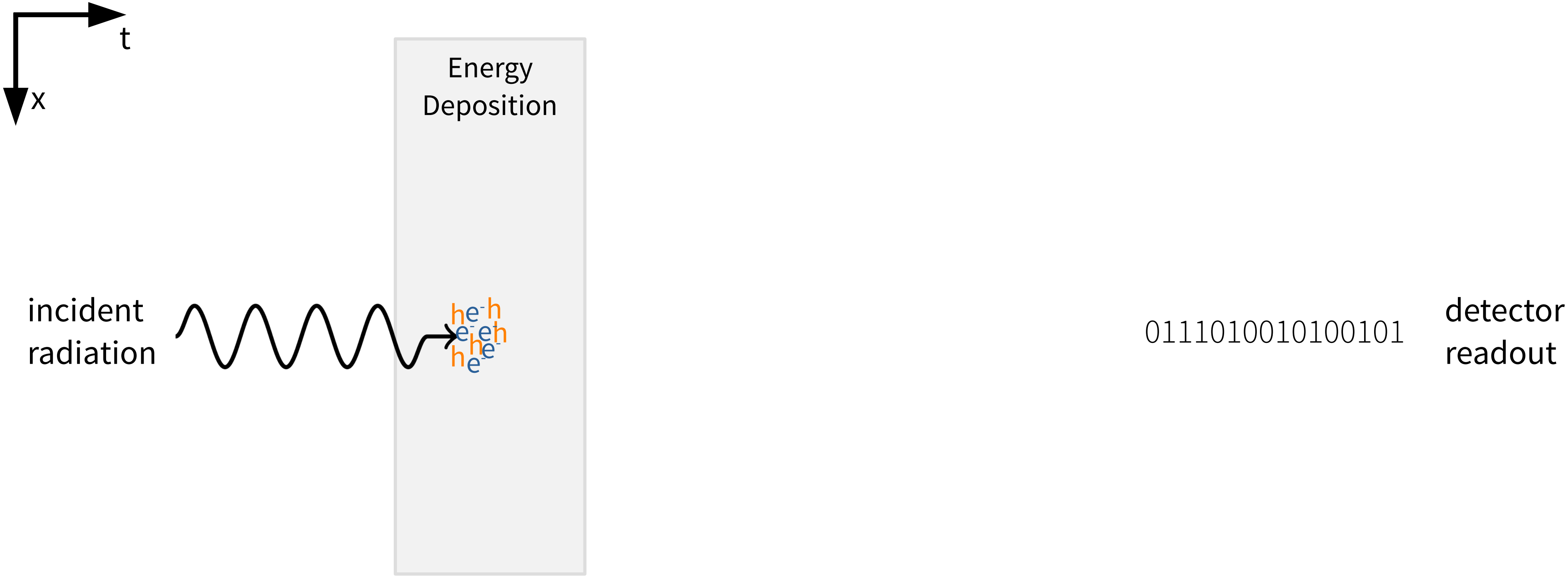


Recap:

Particle Interaction, e/h Pair Generation



Particle Detection with Silicon Detectors



incident radiation

Energy Deposition

0111010010100101

detector readout

Energy Deposition – Energy Loss

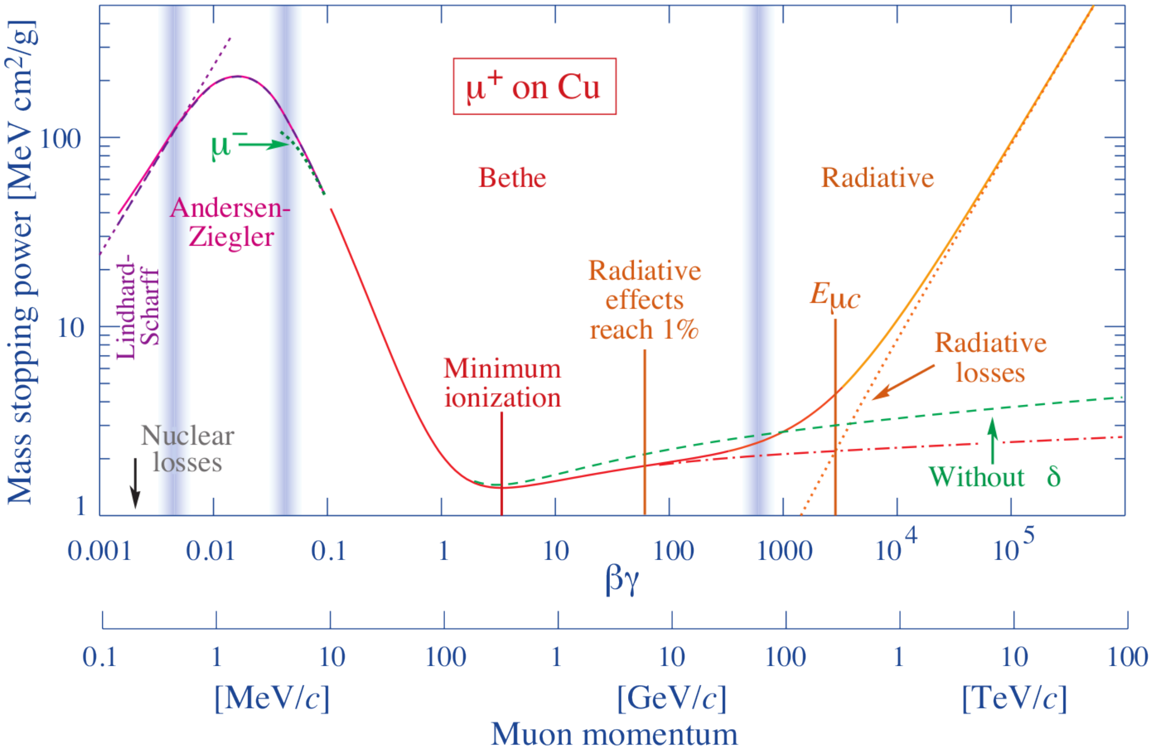
- (heavy) charged particles:
  Mean energy loss described by **Bethe** formula

  (sparing you the formula…)

- Definition of MIP:
  Minimum Ionizing Particle

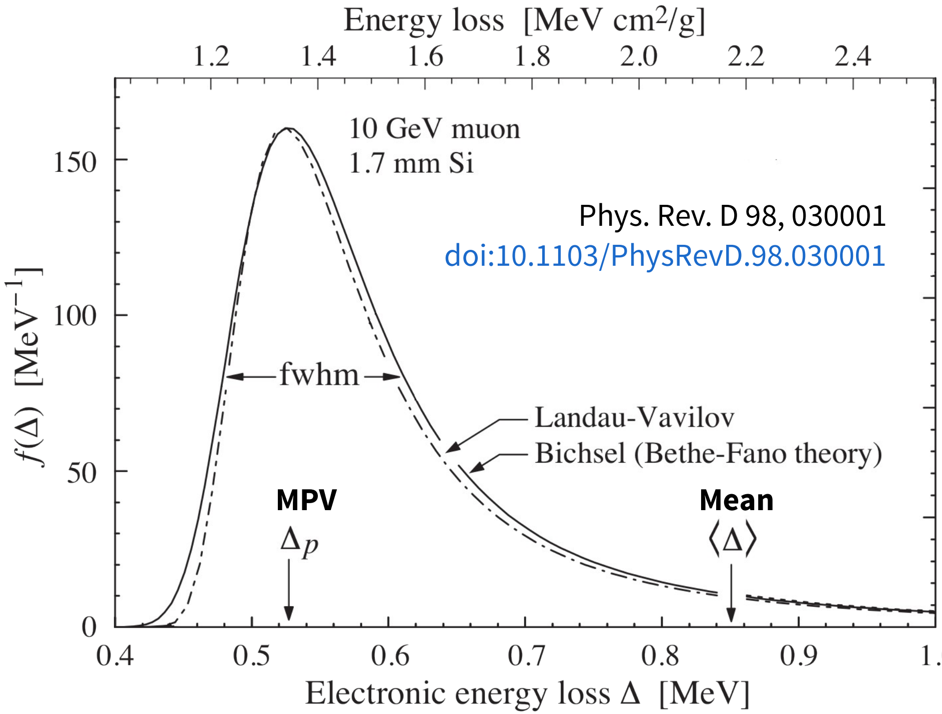
  $\beta\gamma \approx 3$

Phys. Rev. D 98, 030001
doi:10.1103/PhysRevD.98.030001



Energy Deposition – Fluctuations

- Strong fluctuations of energy loss: **Landau-Vavilov** distribution / **Bichsel** model
  - Varying number interactions, energy transfer
  - Secondary particles (e.g. delta rays)
  - Most probable value (MPV) < Mean
- Photons: Photo effect, Compton effect, pair production
- Creation of e/h pairs: 3.64 eV / pair
  Fluctuations: **Fano** Factor $\sigma_{e/h} = \sqrt{N_{e/h}}\sqrt{F}$



Phys. Rev. D 98, 030001
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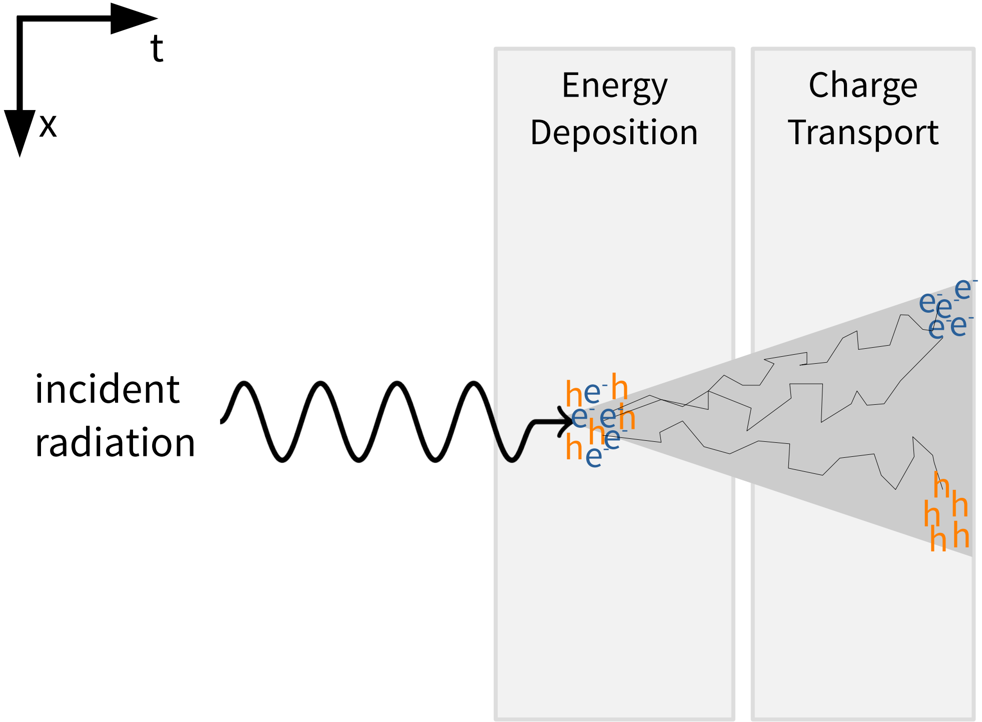
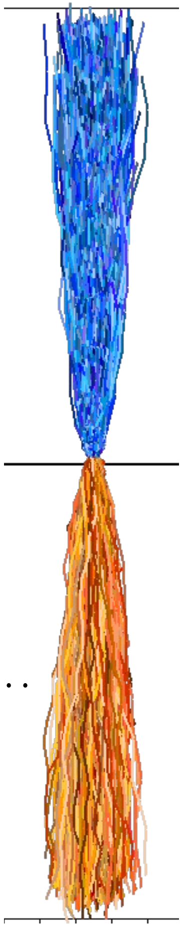
Particle Detection with Silicon Detectors



0111010010100101

detector readout

Signal Formation

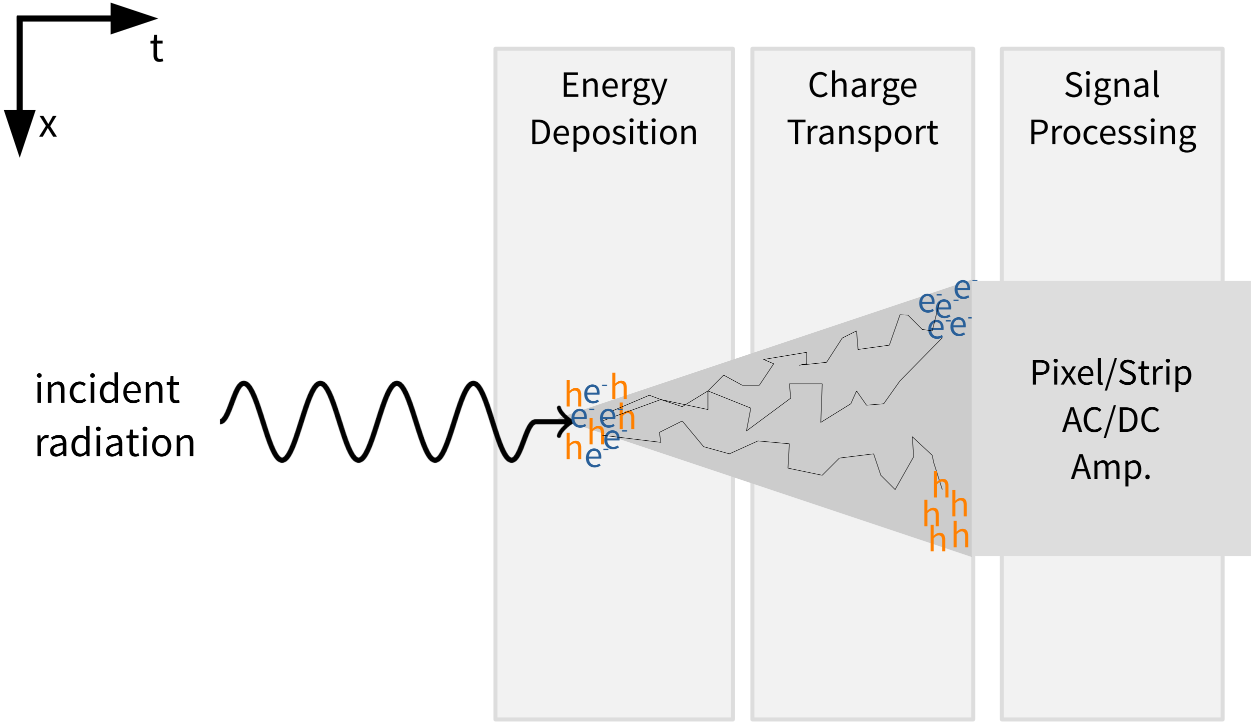


- Sensor operated as diode in reverse bias → depleted volume
- Signal formed by motion of e/h pairs in electric field

- Contribution to motion:
  - **Diffusion – Temperature-driven random motion**, mean free path ~ 0.1 µm, mean 0
  - **Drift – Directed motion**, depending on electric field and charge carrier mobility, different parametrizations for mobility available, depending on temperature, silicon, …

- Motion stops when…
  - Charge carriers reach readout electrode (conductor)
  - Charge carriers recombine/get trapped (depends on purity, doping, lattice defects, …)

Particle Detection with Silicon Detectors



incident radiation

Energy Deposition

Charge Transport

Signal Processing

Pixel/Strip
AC/DC
Amp.

0111010010100101

detector readout

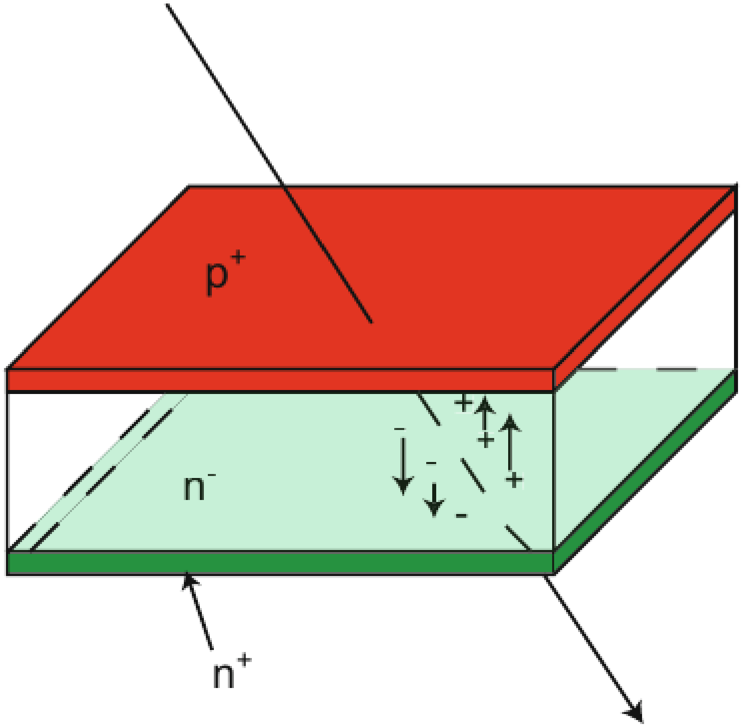
Segmented Silicon Sensors

for Position-Resolved Measurements

The Diode

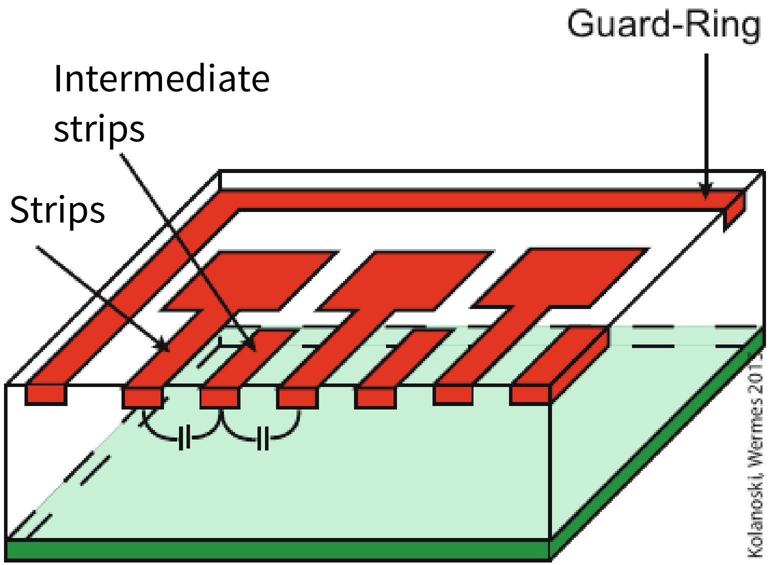
- Simplest semiconductor detector geometry
- Readout of a full area detector pad
- No spatial information
- Number of channels: 1

- Here:
  - Strong p^+ and weak n^- doping create asymmetric pn-junction at the sensor surface
  - Strong doping (n^+) at the backside for Ohmic contact to backside metallization



Strip Detector

- Segmentation of sensor surface
- Implementation of strips
- Typical pitches: 50 – 100 µm
  typical strip lengths: mm – cm



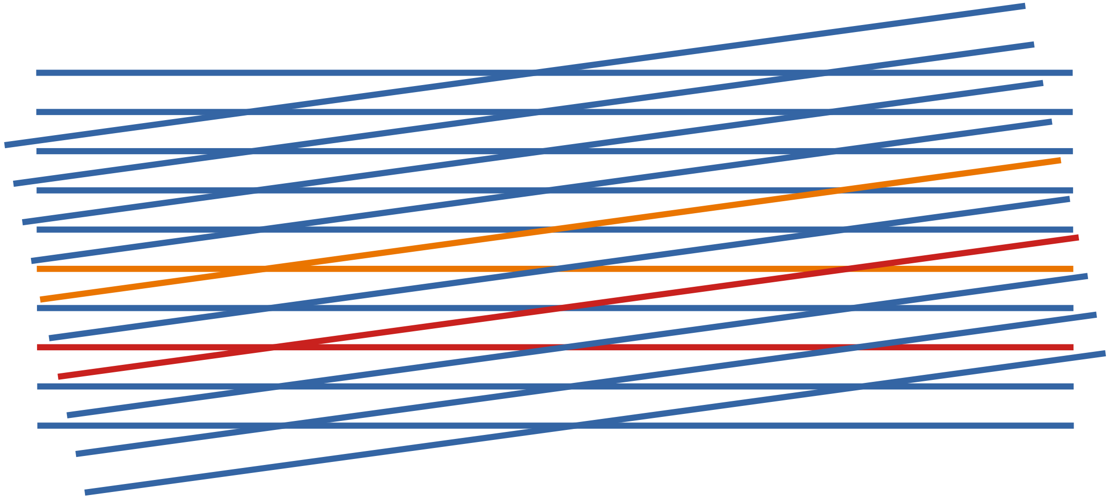
- Number of channels: N
- Charge carriers propagate towards one or few strips

  ➔ 1D spatial information on particle traversal

  ➔ Add second layer for 2D information

Strip Detector – Adding a 2^{nd} Layer

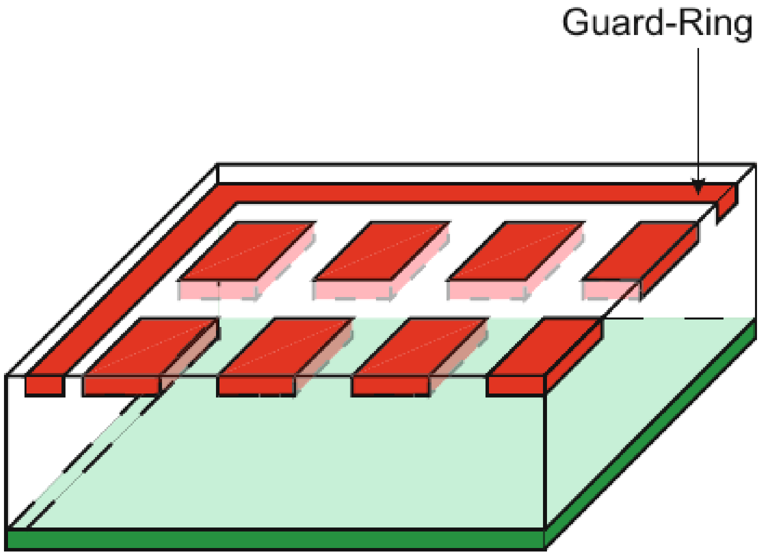
- 2D measurement using stereo angle
  - Two detector modules on top of each other with a **small relative rotation angle**
  - Limit on total particle rate due to ambiguities:
- "Ghost Hits"
  - Appear with > 2 particles crossing the sensor
  - Impossible to distinguish particle crossing point from other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



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

Pixel Detector

- Segmentation of sensor surface
- Implementation of pixels or pads
- Typical pitches: 25 – 400 µm



- Number of channels: N^2
- Charge carriers propagate towards one or few pixels

  ➔ 2D spatial information on particle traversal

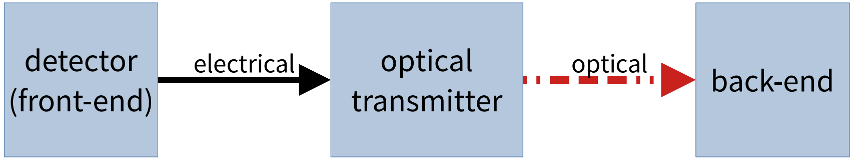
  ➔ Many channels to be read out!

Data Transmission

- Bandwidth & power consumption of data transmission **critical for future experiments**:

$$\frac{1\,cm^2\,\text{chip area}}{(15\,\mu m)^2\,\text{pixel pitch}} \geq 450\,kPix \rightarrow 450\,kPix\cdot 20\,\text{bit}\cdot 10^{-5}\,\text{occupancy} \simeq 90\,b \rightarrow \frac{90\,\text{bit}}{20\,ns} \geqslant 4.5\,Gb\,s^{-1}\,cm^{-2}$$

- **Electrical transmission** off-chip, conversion by optical transmitters
  - Limited bandwidth ~ *Gb/s*
  - Driving signals is power consuming ~ *pJ/bit*
  - Additional material, electromagnetic interference, …



- **Silicon Photonics:** external laser, modulation on ASIC
  - Increased bandwidth *>> 10 Gb/s*
  - Energy efficient, only modulation *<< pJ/bit*

Strip vs. Pixel Detectors

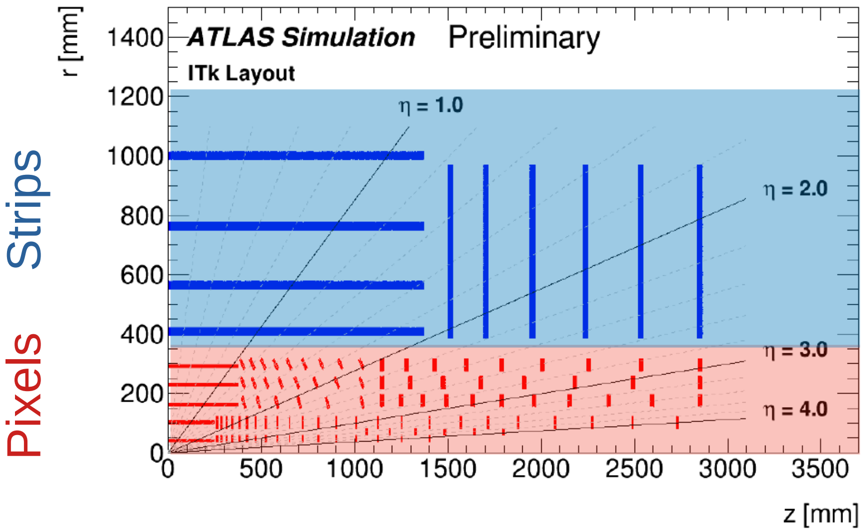
	Strip Detectors	Pixel Detector
Readout channels	N	N^2
Position information	1D Ghost hits @ high occupancy	2D –
Typical sensor size	Wafer-scale	few centimeters
Production	Lower production cost per area	Higher production cost per area
Readout	Direct interconnect at sensor edge	Complex interconnects, many channels

Combining Strip & Pixel Detectors

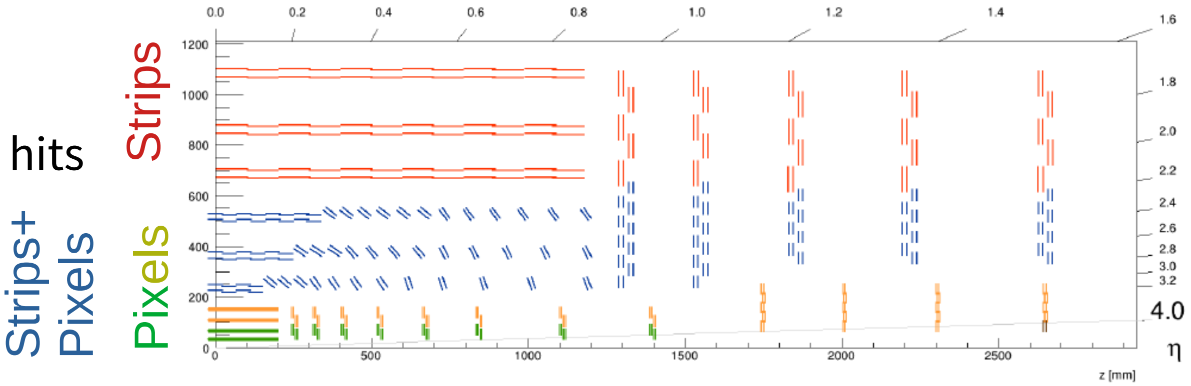
Typical Compromise

- **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

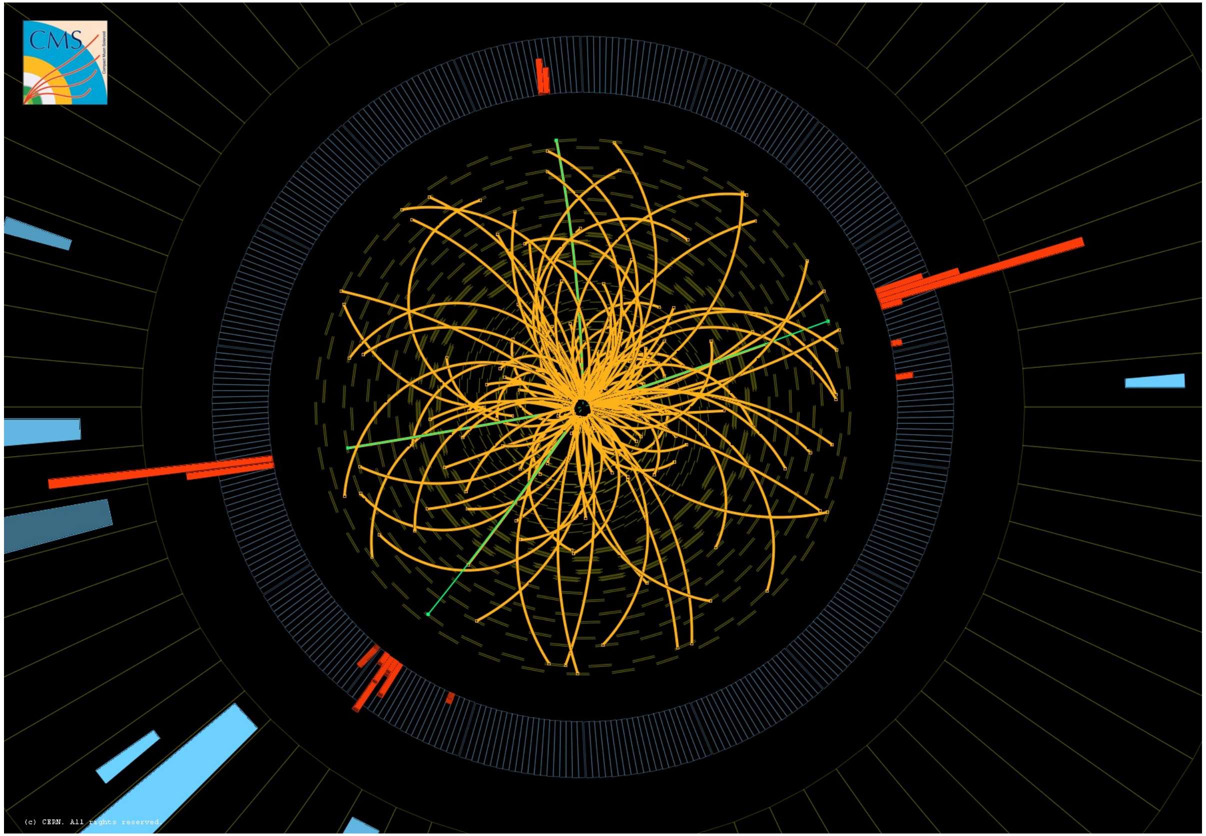
ATLAS

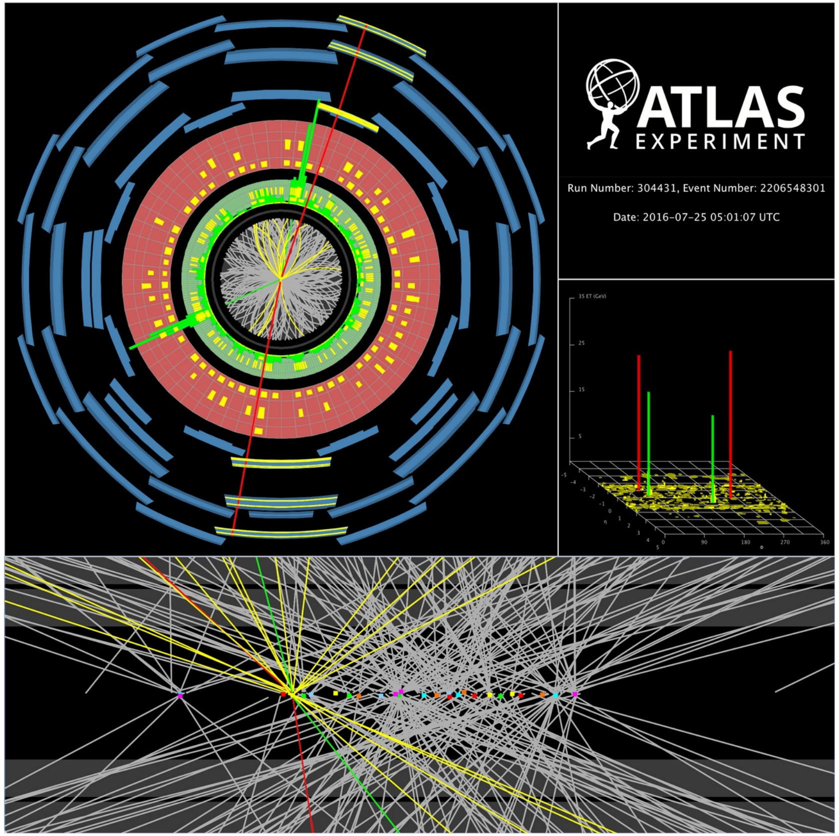


CMS



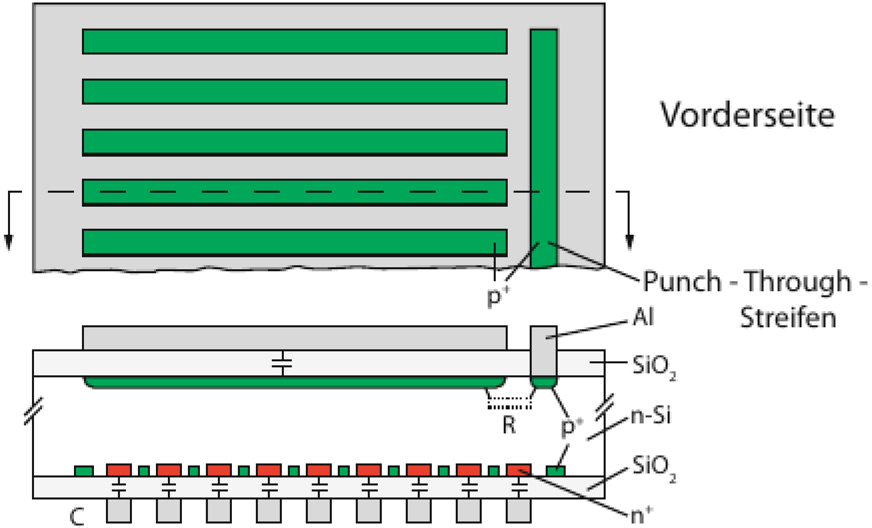
Combining Strip & Pixel Detectors





Double-Sided Strip Detectors

- Segmentation of both sensor surface and backside
- Orthogonal strips on both sides
- Electrons and holes propagate towards opposite segmented surfaces
  - ➔ 2D Spatial information on particle traversal



✔ Number of channels: 2N

✗ Disadvantage w.r.t. pixel detector:
Ghost hits possible in case of simultaneous hits

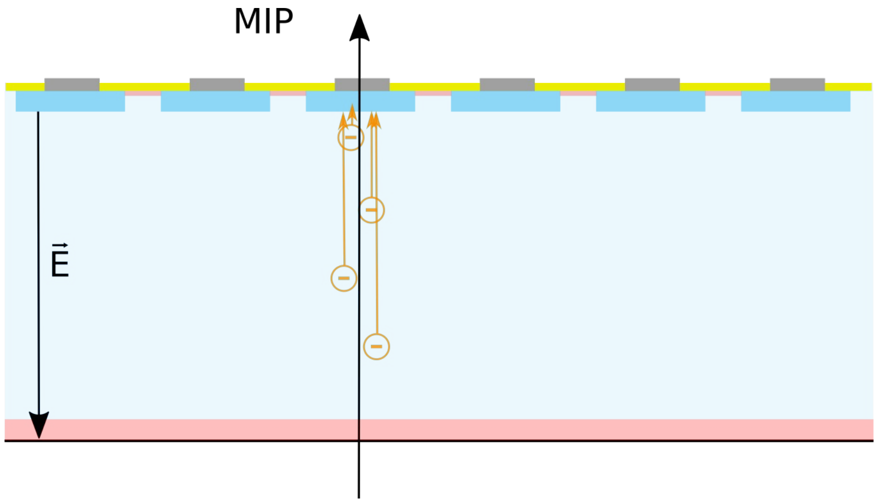
✗ Re-introduces some production/connectivity complexity w.r.t strip sensors

Resolution

Position Measurement, Charge Sharing et. al

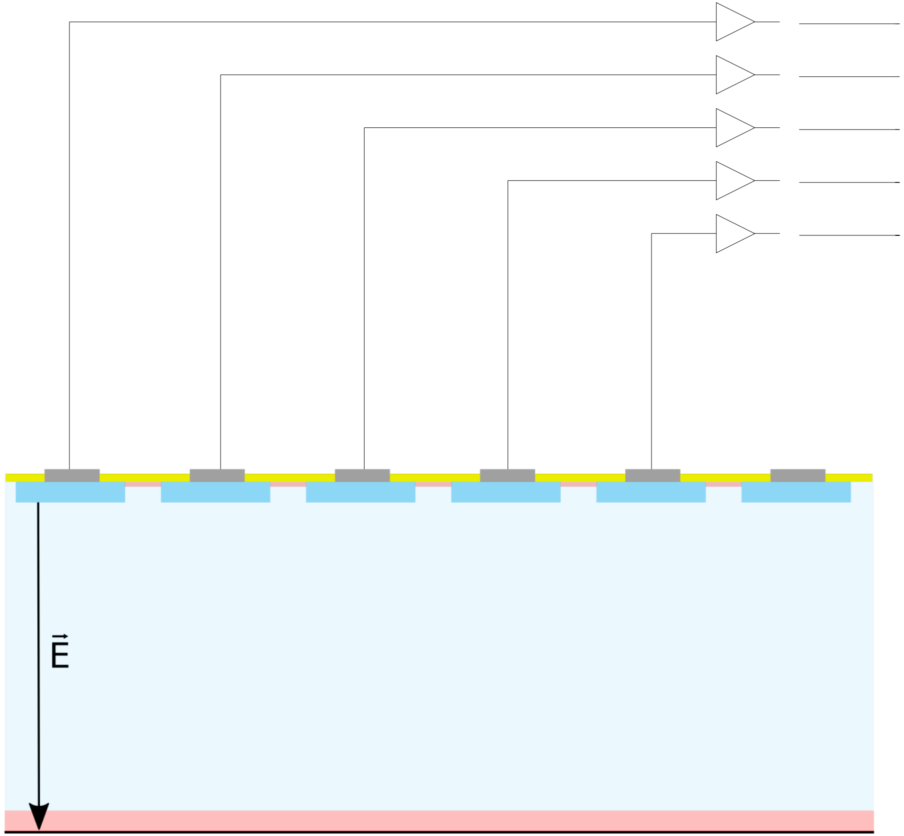
Resolution

- How well can my detector reconstruct the lateral position of a traversing particle?
- **Spatial resolution** ≡ Width of residual
- **Residual** ≡ Distance between reconstructed position and true position



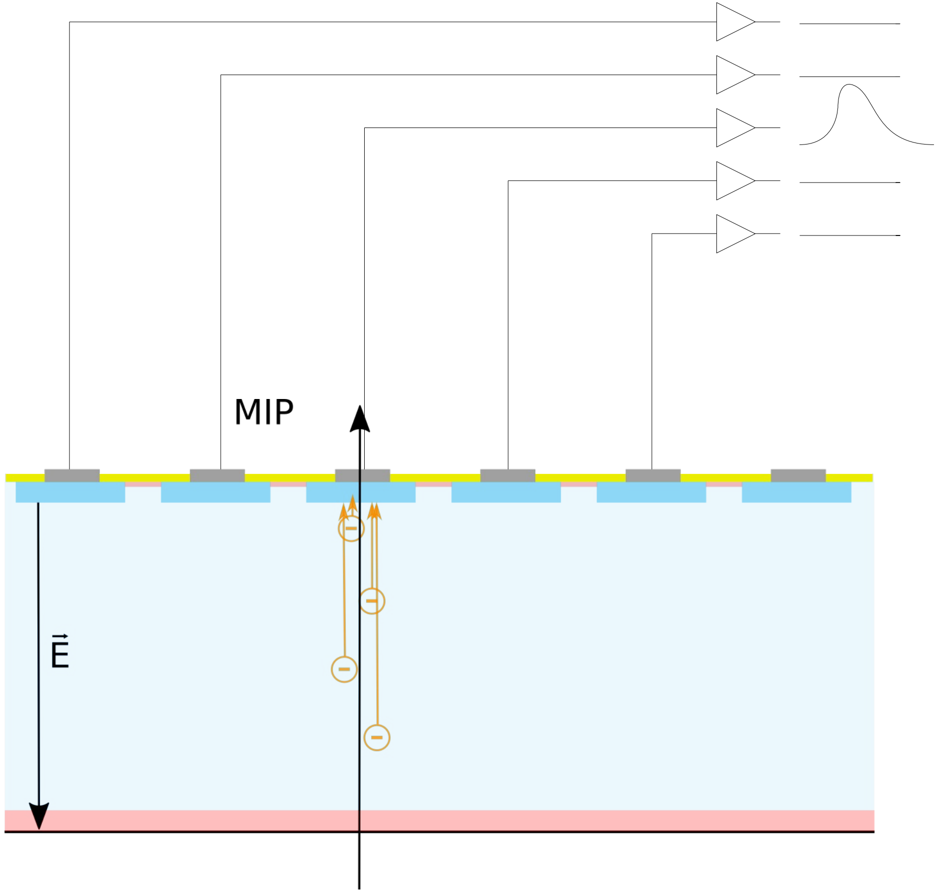
Particle Position Reconstruction

- Estimation of the lateral position of the particle traversal
- Use information of signal per strip (pixel)



Particle Position Reconstruction

- Single responding pixel:
  - “This pixel was hit”
  - No information of where inside the pixel the particle was located



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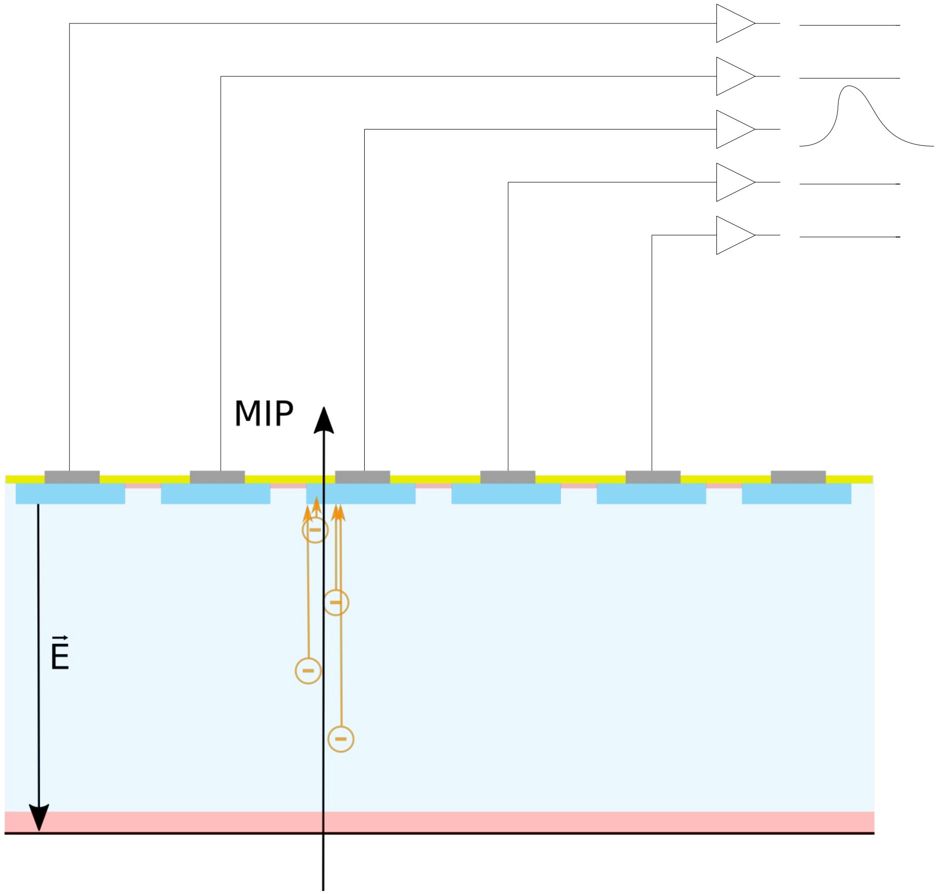

Particle Position Reconstruction

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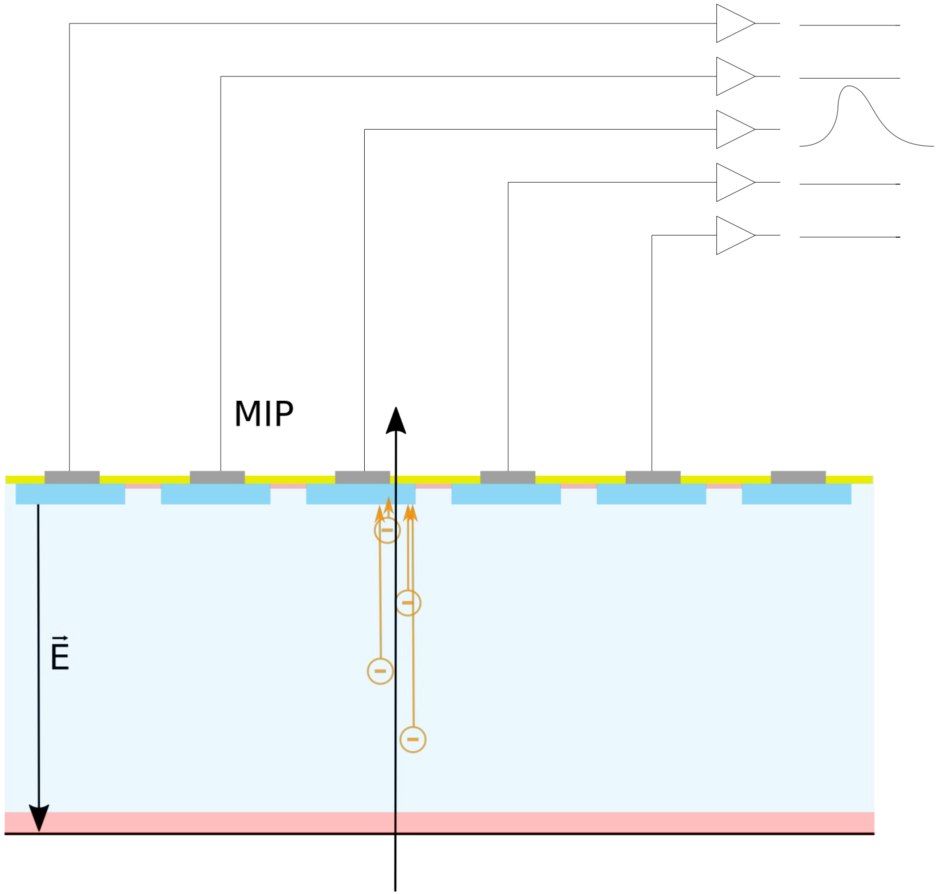
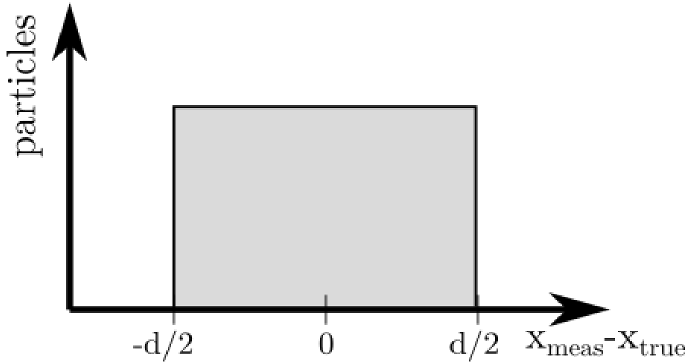
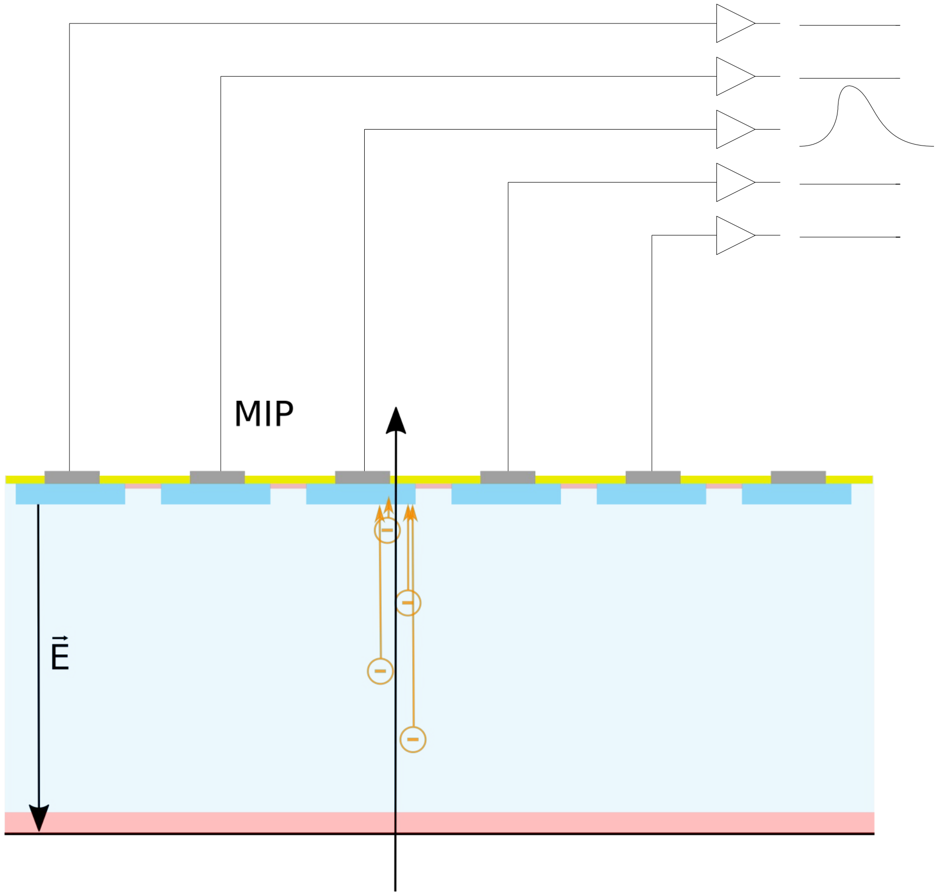


Particle Position Reconstruction

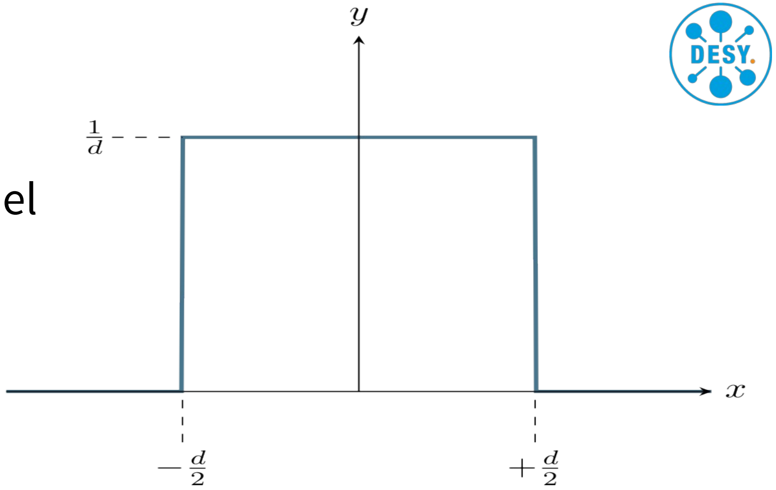
- Single responding pixel:
  - “This pixel was hit”
  - No information of where inside the pixel the particle was located

➔ Resolution: $\sigma = \frac{d}{\sqrt{12}}$





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:

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

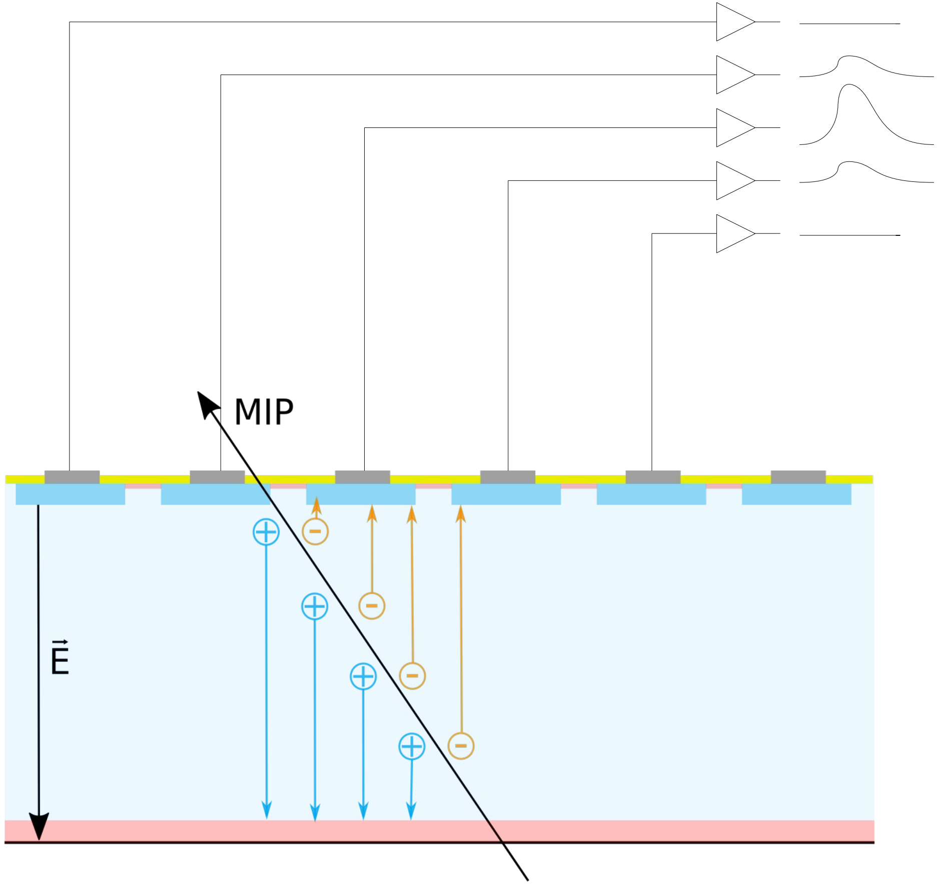
$$= \frac{1}{d}\frac{x^3}{3}\bigg|_{-\frac{d}{2}}^{\frac{d}{2}} - \frac{1}{d^2}\frac{x^4}{2}\bigg|_{-\frac{d}{2}}^{\frac{d}{4}} = \frac{d^2}{12}$$

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

Particle Position Reconstruction

- Several responding pixels:
  a) Calculate center of hit pixels
  b) Calculate **center of gravity** using signal amplitudes of individual pixels

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

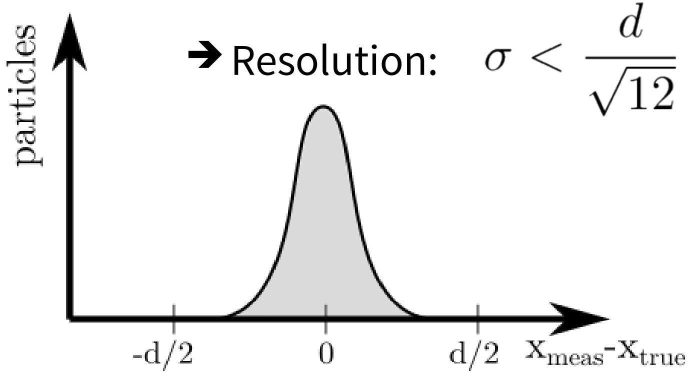


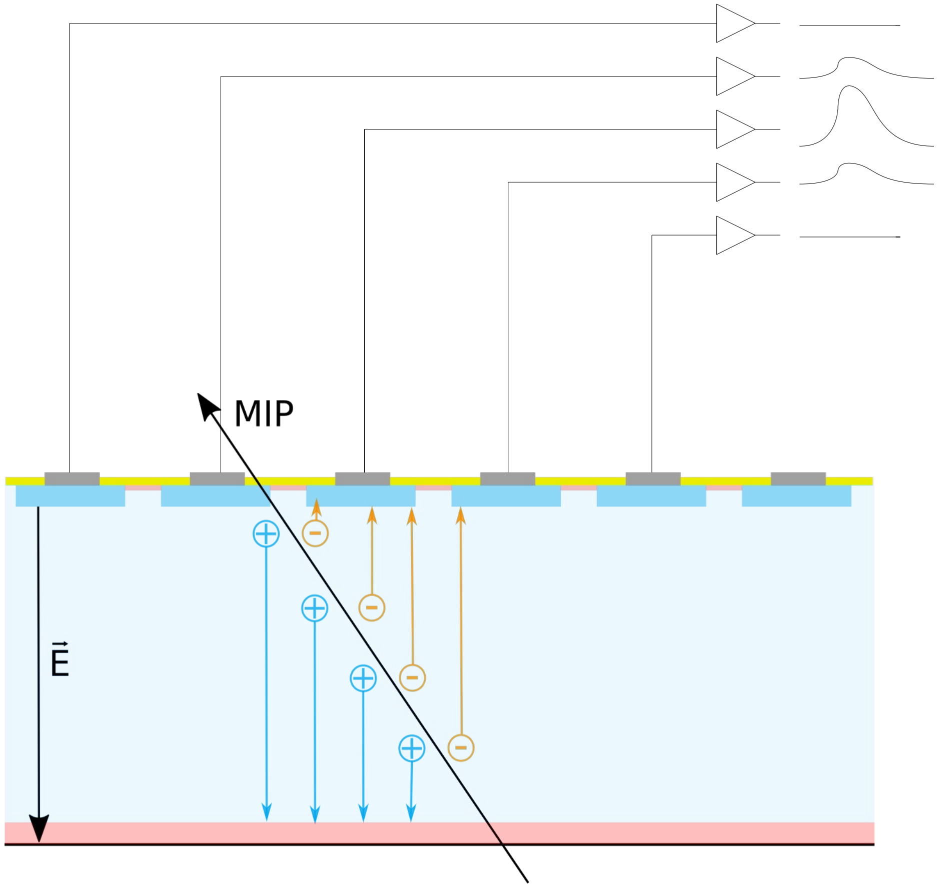
Particle Position Reconstruction

- Several responding pixels:
  a) Calculate center of hit pixels
  b) Calculate **center of gravity** using signal amplitudes of individual pixels

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

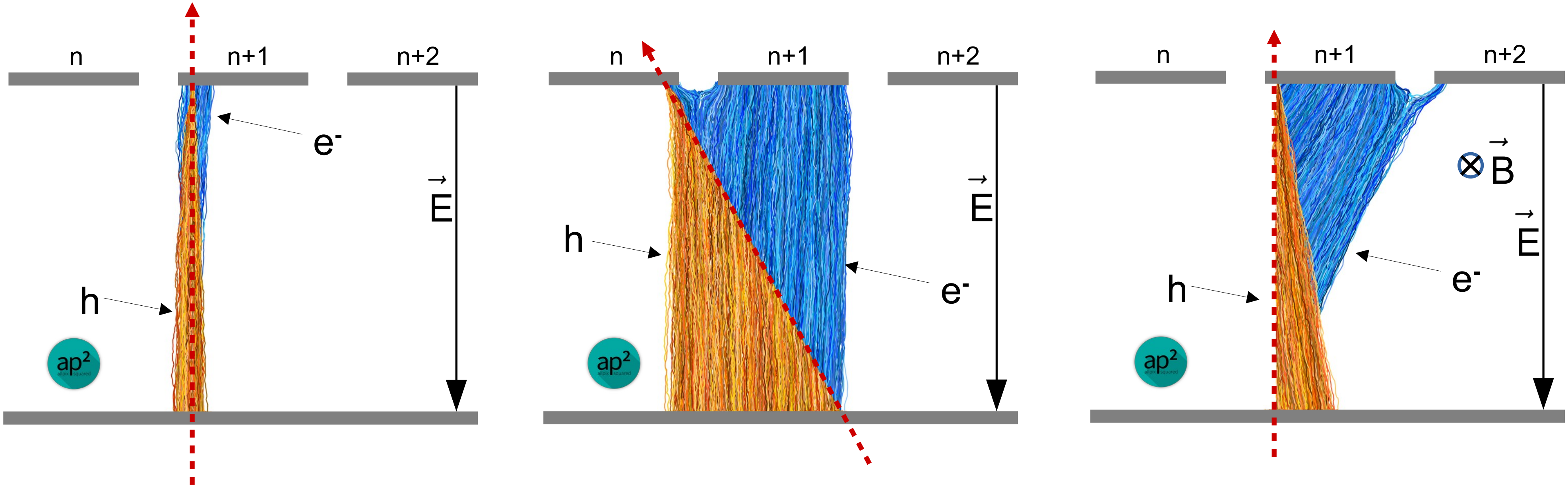
➔ Resolution: $\sigma < \frac{d}{\sqrt{12}}$





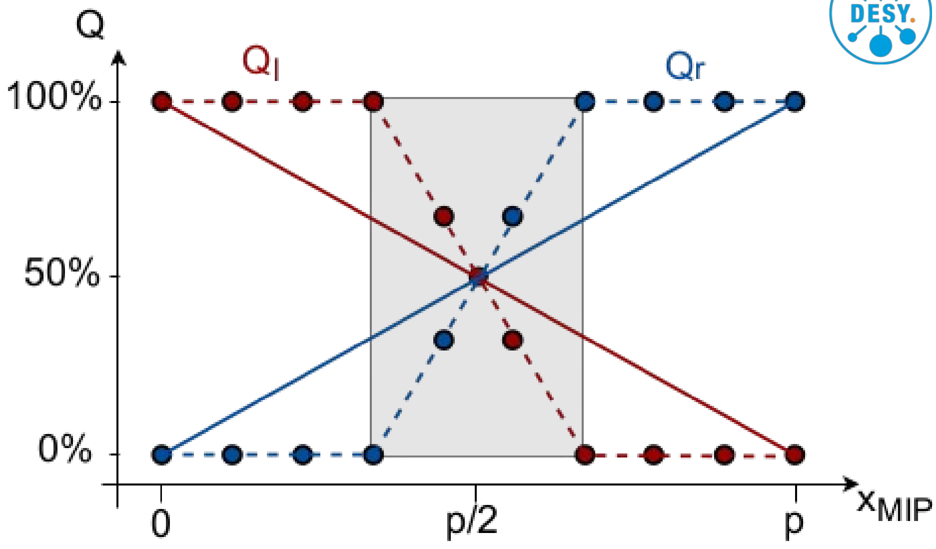
Charge Sharing – Inclined Tracks & Lorentz Drift

- Charge sharing: distribution of charge carriers / signal over several strips (pixels)
- Can significantly improve the spatial resolution
- Often used: Inclined particle incidence along *x* & Lorentz drift along *y*



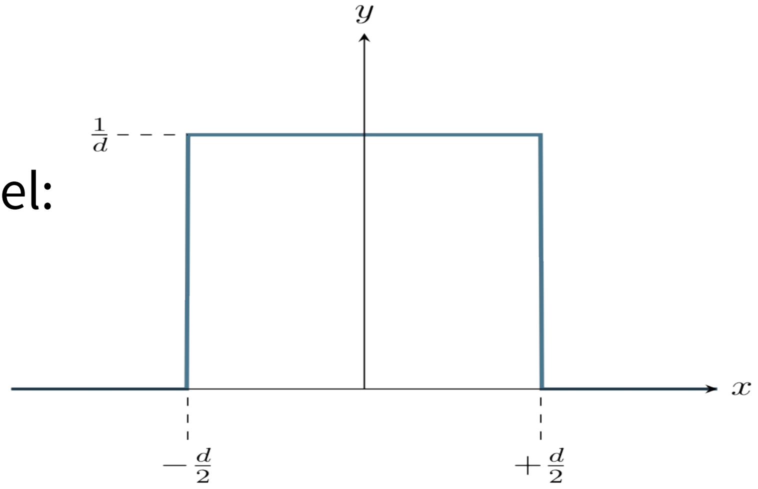
The η Correction

- COG (geometric mean)
  presumes linear charge sharing
- Mostly not the case:
  Sharing only at pixel edges
- η (“eta”) distribution encodes
  actual charge sharing & allows for correction



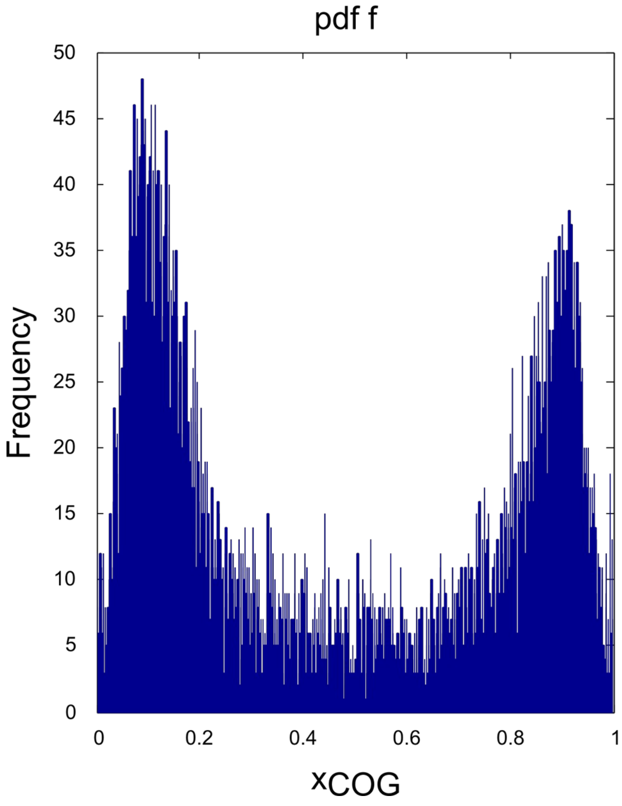
- Prerequisite: same statistics idea as for single pixel:

  The probability of particle crossing particular detector channel is uniformly distributed

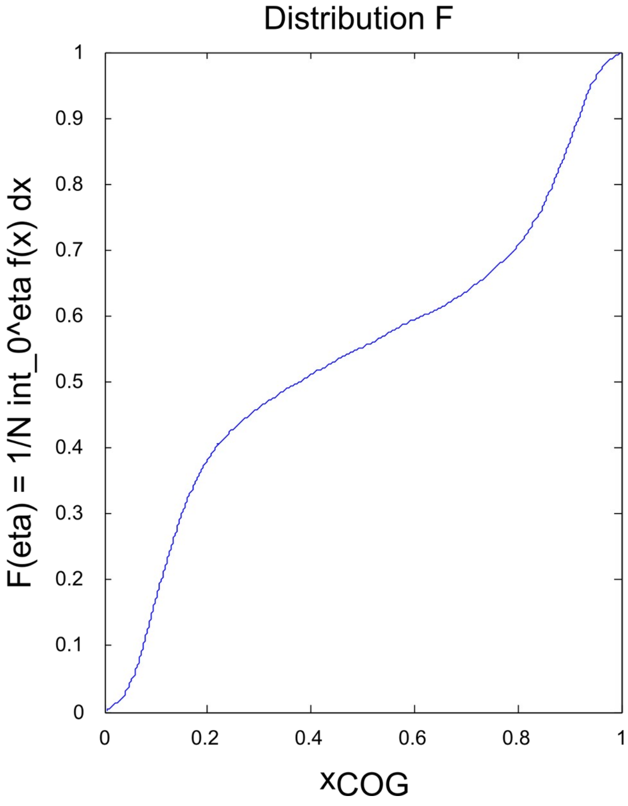


The η Correction

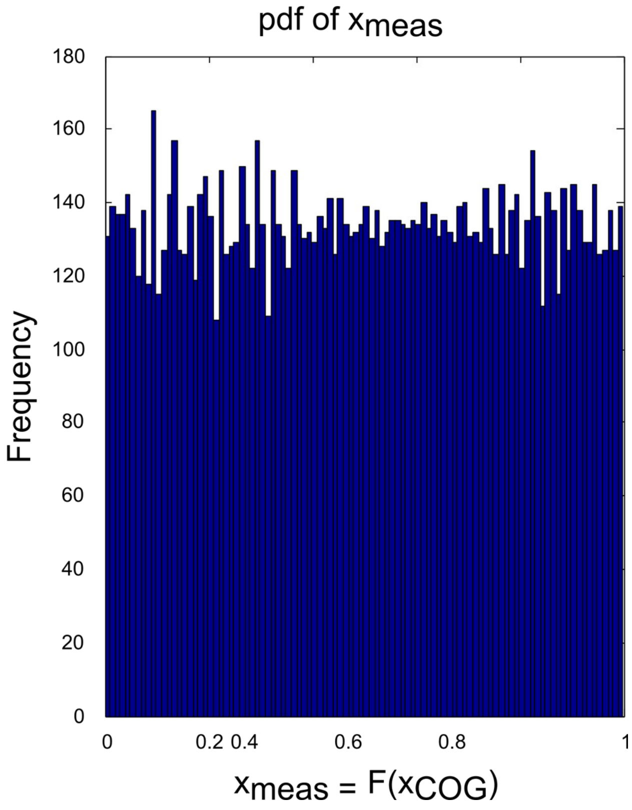
Build eta distribution



Calculate cumulative distr.



Apply as correction

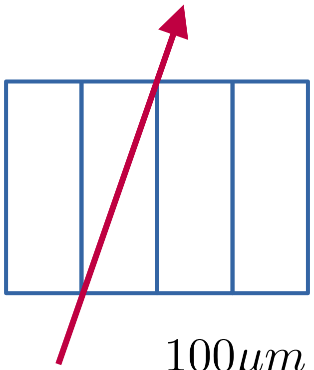


Examples – Measurements & Simulations

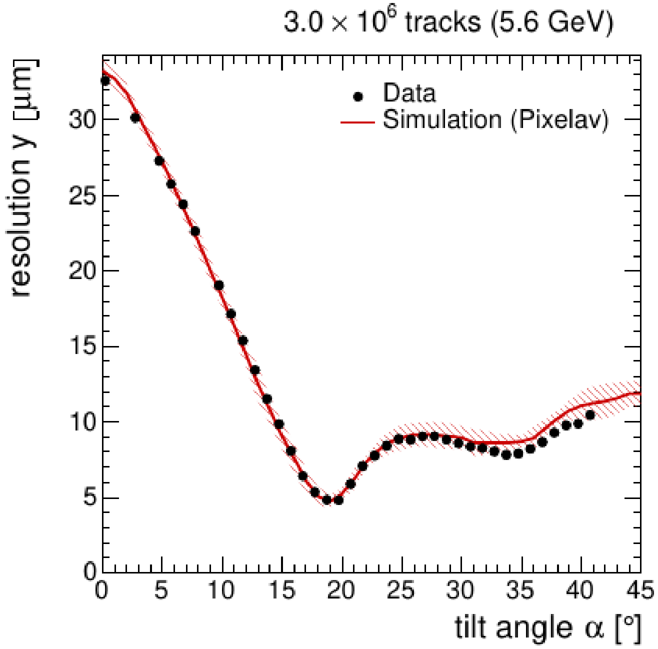
- CMS Phase I Pixel Detector, data recorded in testbeam experiments
- Detector rotated relative to beam to emulate magnetic field in CMS experiment
- Simulations with Allpix Squared with 3.8 T magnetic field

$p_y = 100\ \mu m$

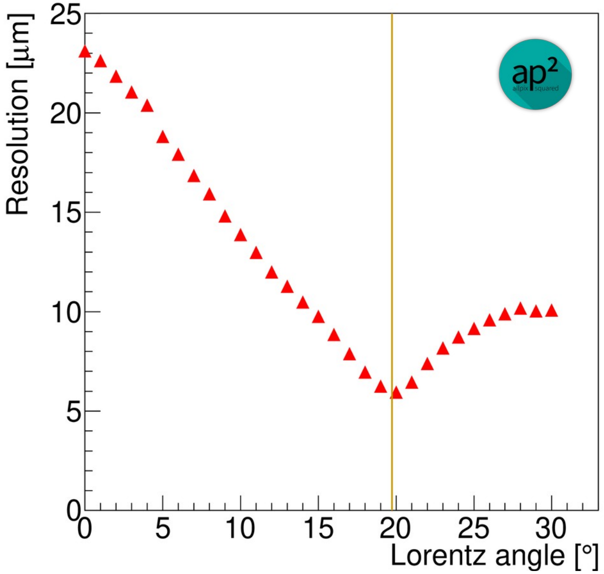
$d = 285\ \mu m$



$$\frac{100\mu m}{285\mu m} \approx 19.3°$$



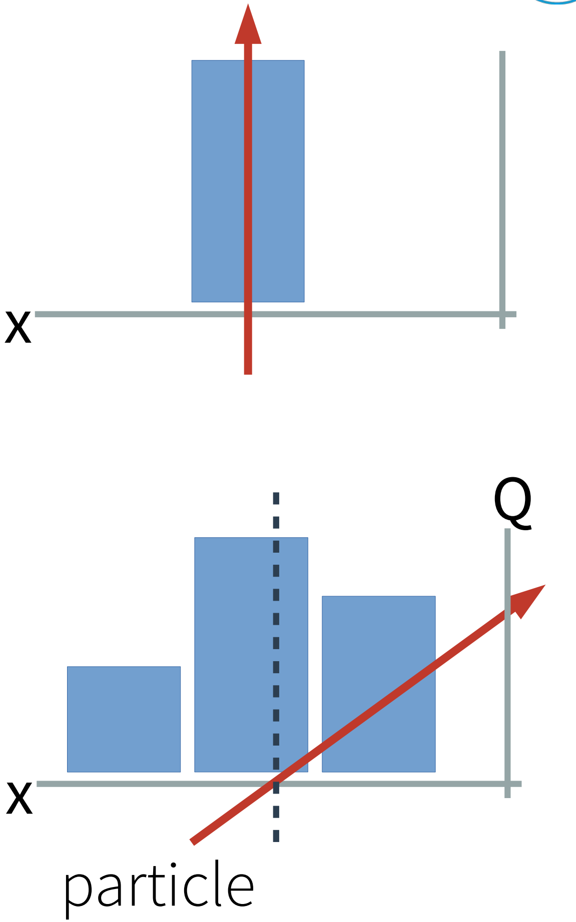
→ Lab Exercise 11



Spatial Resolution – Summary

- Just a **single channel** struck:
  precision limited to variance of uniform distribution

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

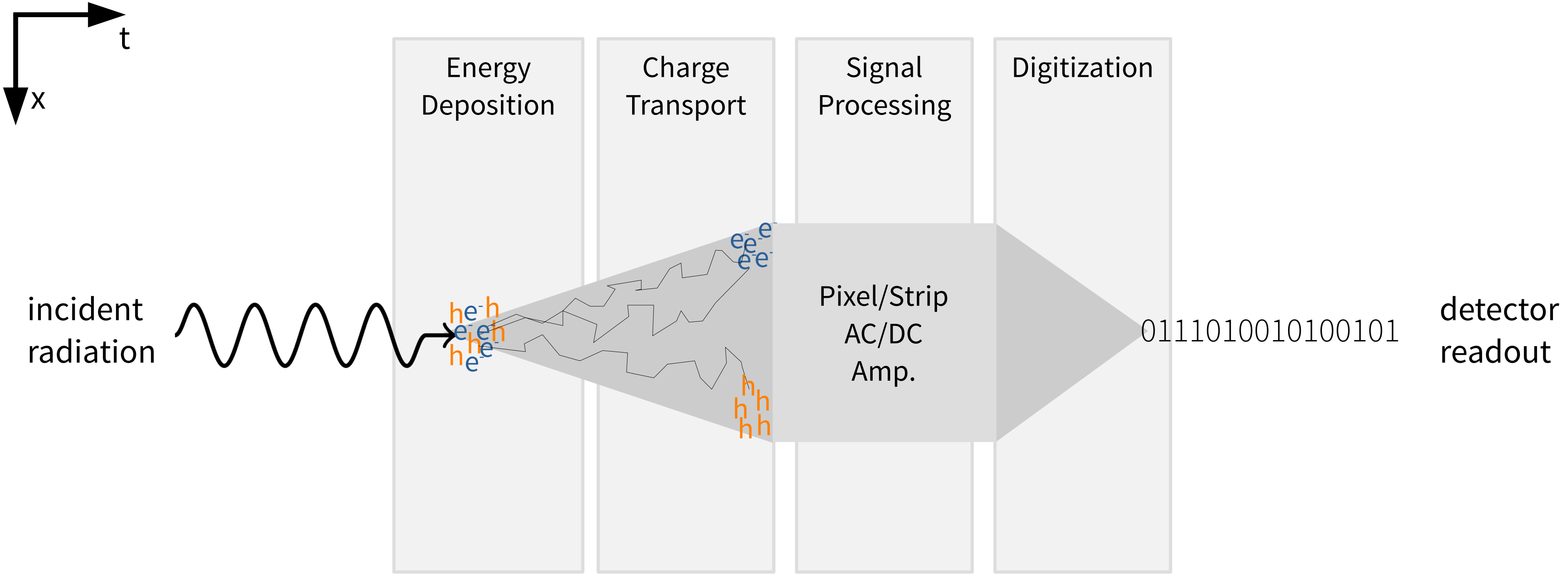


- **Multiple channels** struck (charge sharing):
  interpolation using relative energy / charge distribution

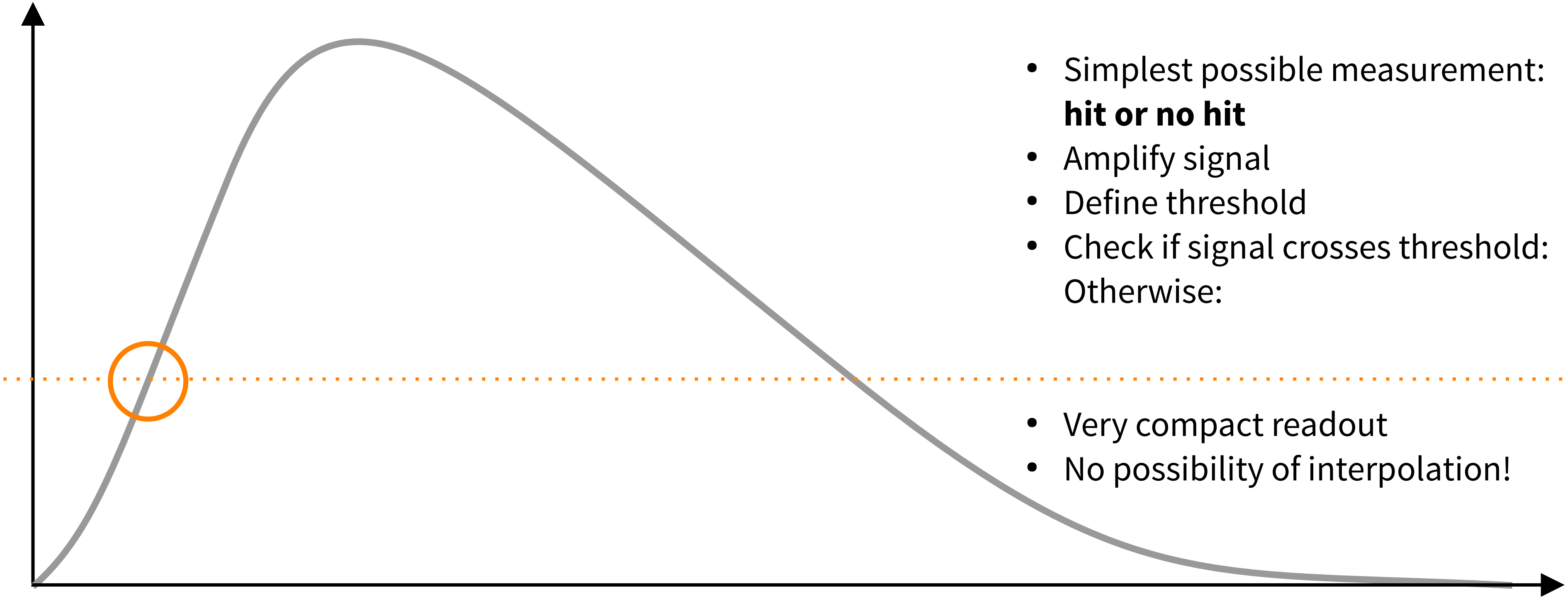
$$x = \frac{\sum_{i=1}^{N} q_i x_i}{\sum_{i=1}^{N} q_i}$$

- Thinner sensors: less charge sharing…
- η correction might be necessary…

Particle Detection with Silicon Detectors



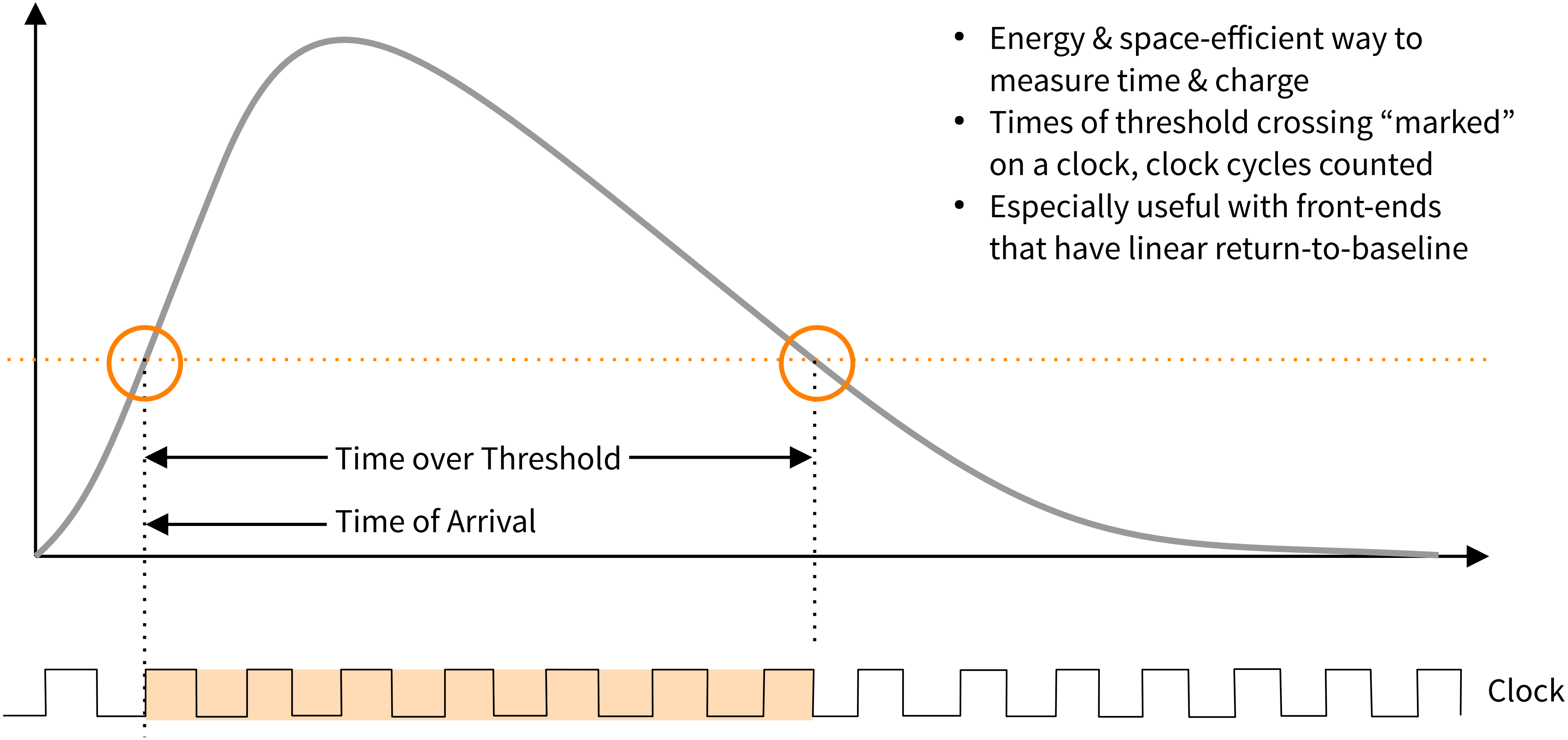
Digitization: Threshold



- Simplest possible measurement: **hit or no hit**
- Amplify signal
- Define threshold
- Check if signal crosses threshold: **1**
  Otherwise: **0**

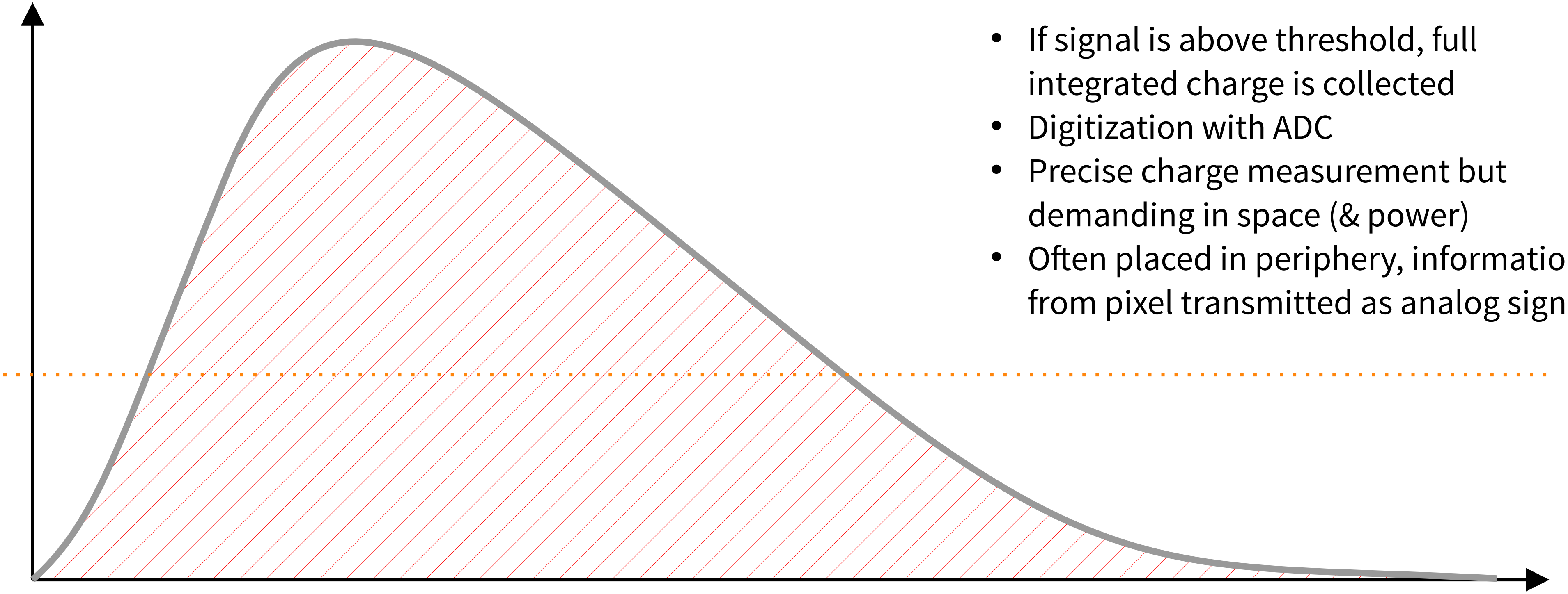
- Very compact readout
- No possibility of interpolation!

Digitization: Time of Arrival & Time over Threshold



- Energy & space-efficient way to measure time & charge
- Times of threshold crossing “marked” on a clock, clock cycles counted
- Especially useful with front-ends that have linear return-to-baseline

Digitization: Analog-to-Digital Converter

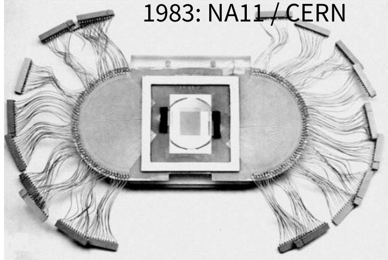


- If signal is above threshold, full integrated charge is collected
- Digitization with ADC
- Precise charge measurement but demanding in space (& power)
- Often placed in periphery, information from pixel transmitted as analog signals

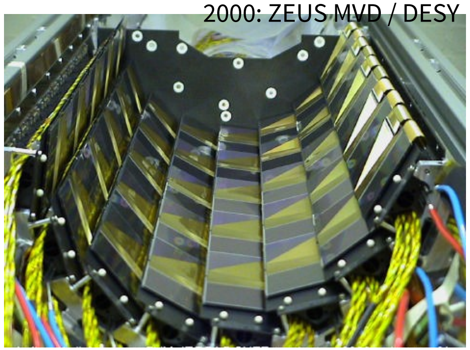
Squaring the Circle

Requirements for Current & Future Tracking Detectors

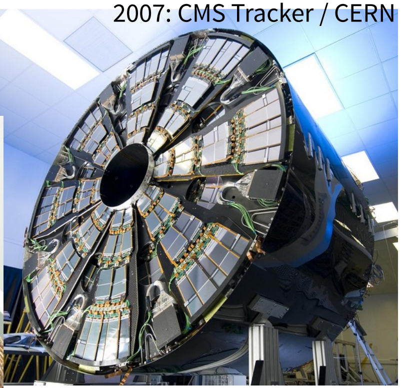
Silicon Tracking Detectors in Particle Physics

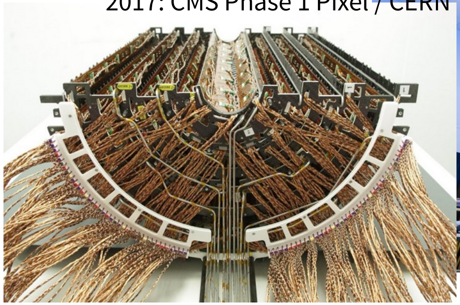

1983: NA11 / CERN

- 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

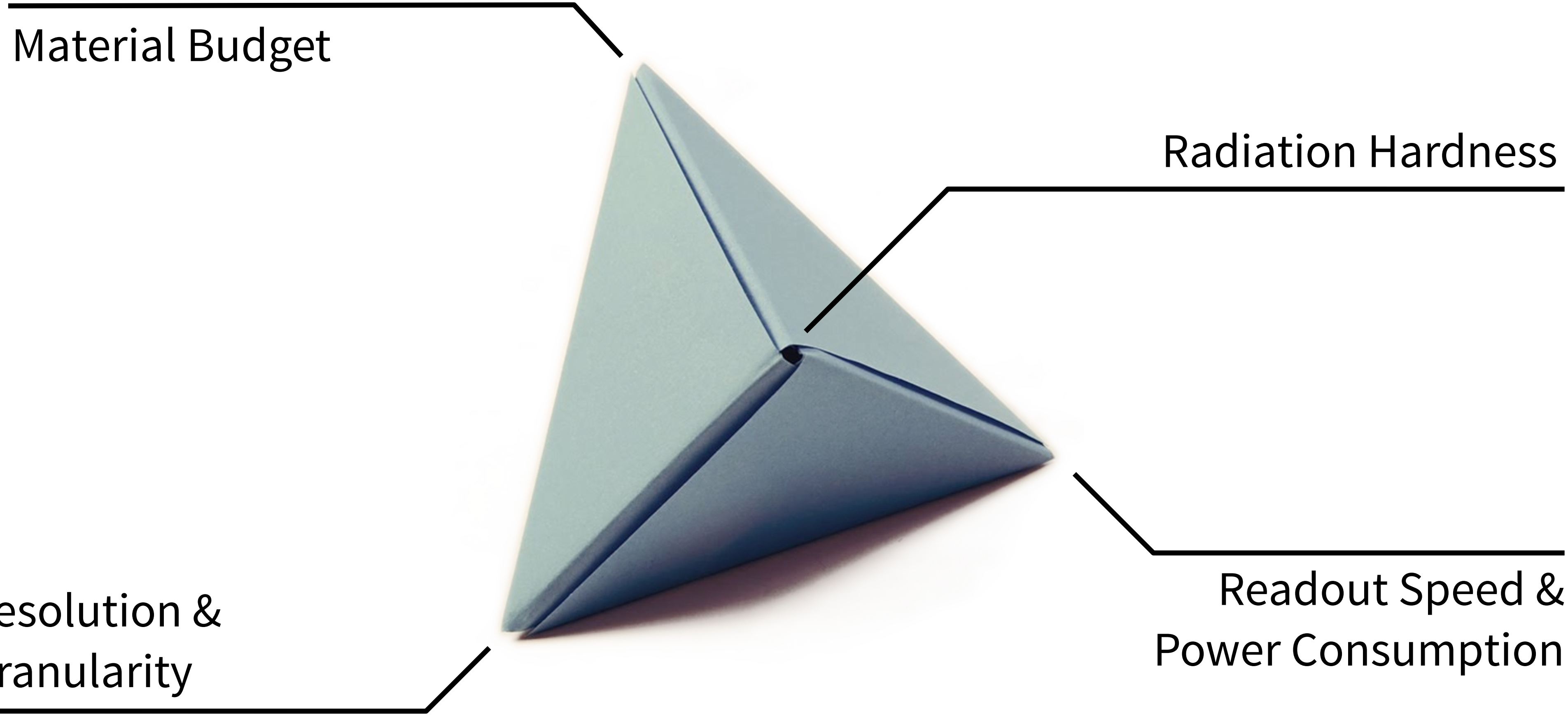

2000: ZEUS MVD / DESY

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


2007: CMS Tracker / CERN


2017: CMS Phase 1 Pixel / CERN

Challenges for Silicon Detectors

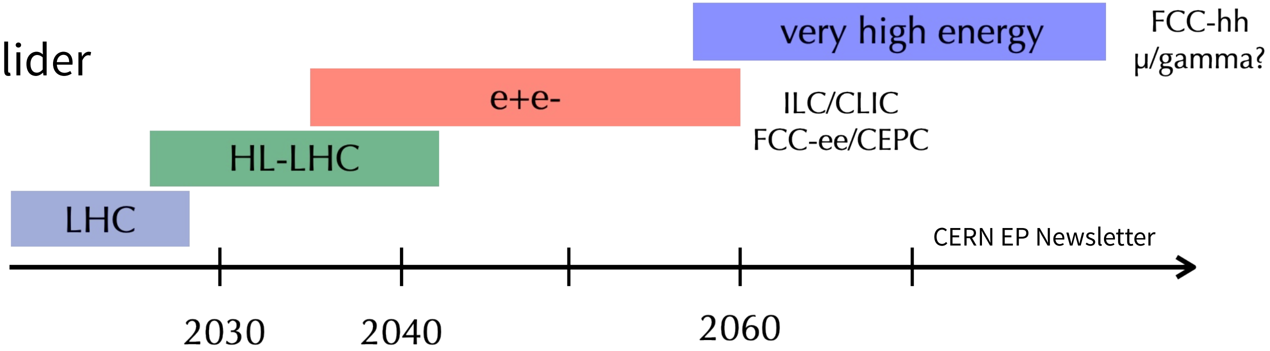


The Future of High-Energy Particle Physics

- European Strategy Update: possible directions for particle physics
  - Importance of fundamental detector R&D specifically highlighted

- Higgs boson plays unique role in extending knowledge
  - Address questions within SM, provide sensitivity to new physics
  - Yukawa couplings, self-couplings, branching ratios
  - Precision measurements required

- Highest priority: future lepton collider
  - Different initial states
  - New opportunities & challenges



CERN EP Newsletter

Silicon Detector Requirements at a Lepton Collider

- Precision measurements especially demanding on vertex & tracking detectors

Momentum resolution	–	large lever arm, minimum scattering
Impact parameter resolution	–	high resolution, minimum scattering
Time resolution	–	fast sensor response, large S/N

- Physics studies for lepton colliders provide guidelines:

	Lepton Colliders	**(HL-) LHC (ATLAS/CMS)**
Material budget	< 1% X_0	10% X_0
Single-point resolution	≤ 3 µm	~ 15µm
Time resolution	~ ps – ns	25ns
Granularity	≤ 25 µm x 25 µm	50µm x 50µm
Radiation tolerance	< 10^{11} n_{eq} / cm^2	**O(10^{16} n_{eq} / cm^2)**

Towards Next-Generation Tracking Detectors

Prospective R&D

- Define requirements from physics program, precision targets
- Explore ideas, new concepts
- Technology evaluation
- Simulations
- Proof-of-principle

Guided R&D

- Technology consolidation
- Demonstrators
- Design optimization
- Performance studies

Targeted R&D

- Full-scale prototypes, engineering
- System integration

Construction

Collisions


DESY.