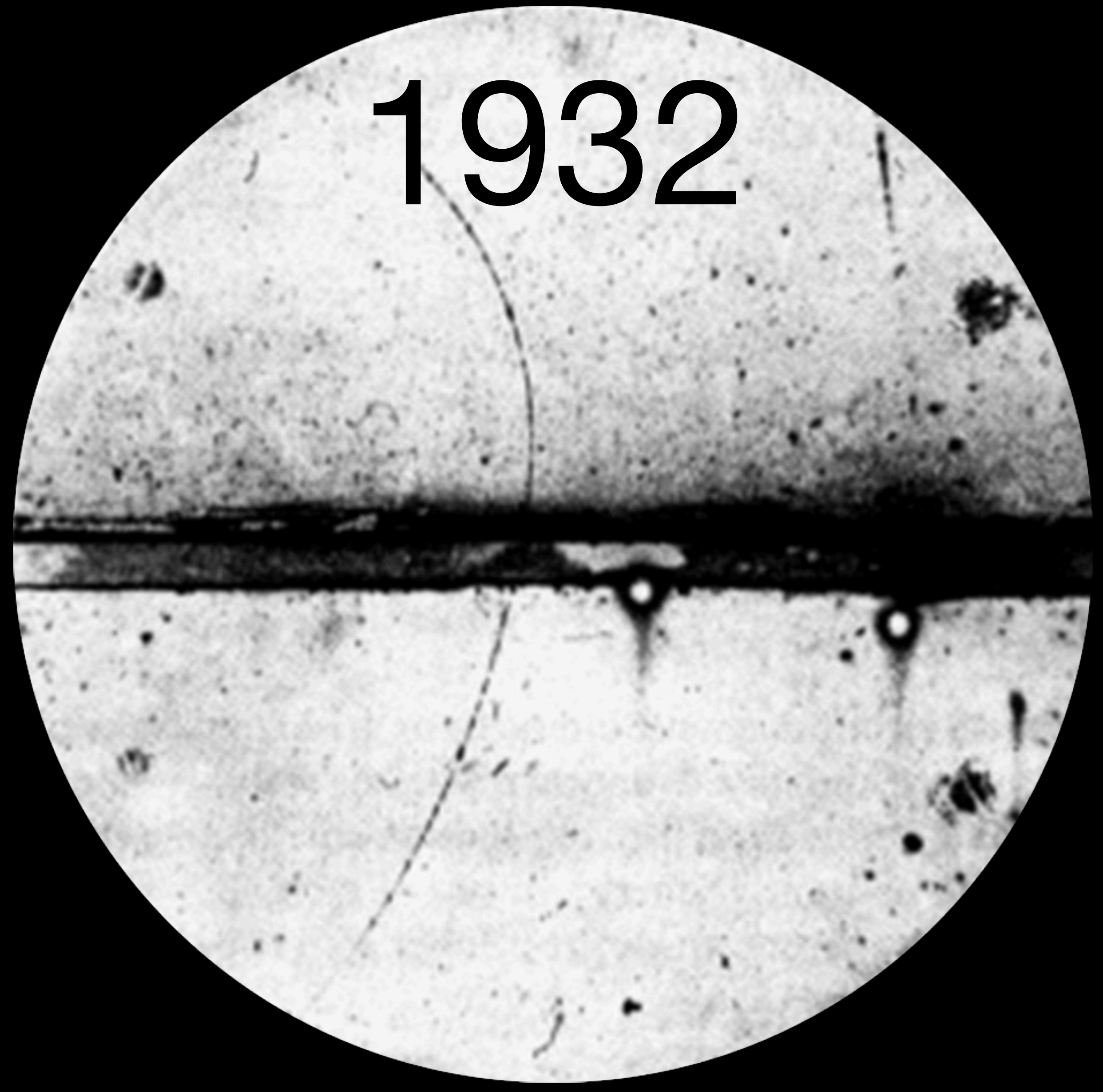
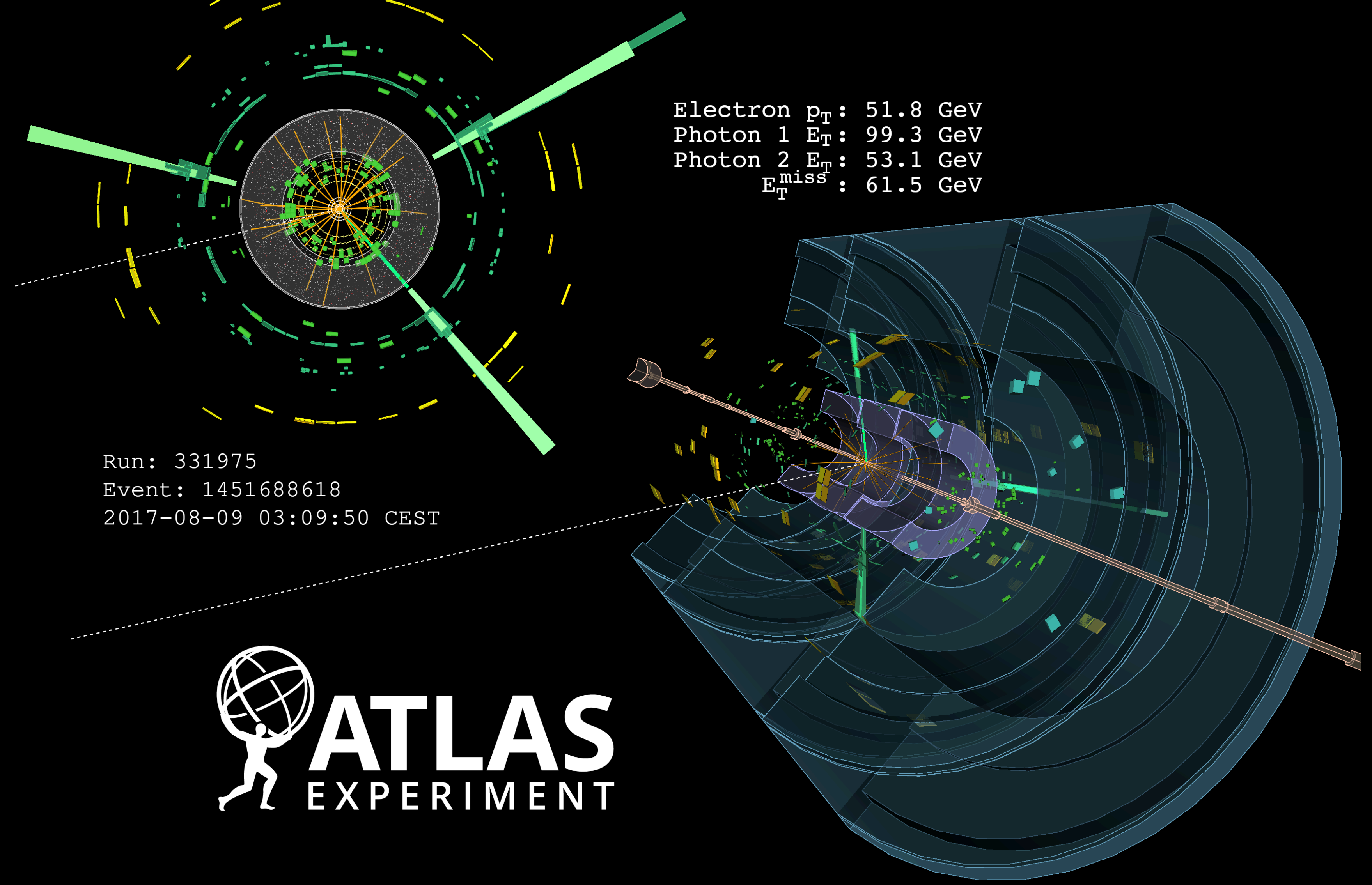
PHYS 7363 - Experimental Particle Detection and Detectors I



Particle detectors are the workhorses of experimental physics. In this course, we'll dive deep into their physics, exploring the incredible evolution of our experimental techniques over the past nine decades. You'll gain a solid understanding of *particle detection* and *identification*, examine the intricate designs of modern detectors, and learn how machine learning is being harnessed to push the boundaries of detector design. If you're intrigued by how we "see" subatomic particles, this course is for you!

2017



Detect Identify Measure

To discuss prerequisites (and any questions on the content of the course), please contact me: saptaparnab@smu.edu

Schedule

Month	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
August	18	19	20	21	22	23	24
	25 ✓	26	27	28	29 ✓	30	31
September	1	2	3 ✓	4	5 ✓	6	7
	↔ 8 ✓ 1.5 hours	9	10	11	12	13	14
	15 ✓ 1.5 hours	16	17 ✓ 1.5 hours	18	19 ✓ 1.5 hours	20	21
	22 ✓ 1.5 hours	23	24 ✓ 1.5 hours	25	26 1.5 hours	27	28
October	29 1.5 hours	30	1 1.5 hours	2	3 1.5 hours	4	5

Schedule

Month	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
October	6	7	8	9	10	11	12
	13	14	15	16	17	18	19
	20	21	22	23	24	25	26
	27	28	29	30	31	1	2
November	3	4	5	6	7	8	9
	10	11	12	13	14	15	16
	17	18	19	20	21	22	23
	24	25	26	27	28	29	30
December	1	2	3	4	5	6	7
	8	9	10	11	12	13	14

Reminders

- Remember to think about your final project
- It carries 50% of the grade
- We also need to decide on a date for the midterm (previously decided date of October 10th will not work):
  - For the midterm, we could pick the 17th
  - Questions on the midterm: Bethe-Bloch equation, Semiconductor devices, tracking, calorimetry, fitting functions and anything that we cover by the 13th

Key dates

- Weeks 1-4: Particle interaction with matter
  - Interaction of charged and neutral particles
  - Particle showers
- Weeks 5-9: Detector technologies:
  - Tracking detectors (gaseous detectors, semiconductor detectors)
  - Particle detection with photons (scintillators, Cherenkov detectors)
  - Calorimetry (electromagnetic and hadronic calorimeters)
- Weeks 10-12: Large and small scale experiments:
  - Triggering and data acquisition
  - Tracking
  - Full reconstruction (particle flow)
- Week 13-15: Preparation for final project:
  - FCC-ee: https://indico.fnal.gov/event/67484/contributions/314057/attachments/187076/257915/US%20FCC%20Tutorial_FullSim.pdf
  - Muon collider: https://mcd-wiki.web.cern.ch/software/tutorials/fermilab2024/

Semiconductor detectors

Material from the previous lectures

- While we were setting up code during the last week and visualizing showers, my lecture notes had some additional material
- We will start today’s discussion with semiconductor devices: https://www.physics.smu.edu/saptaparnab/PH7363_Fall_2025/images/Lecture7_Week4_Day7.pdf

Tracking detectors

- Semiconductor devices have become the most important type of detector for tracking detectors at the LHC
- Silicon is used as detection material
- In this class, we have also discussed another kind of Silicon detector
  - Which detector am I talking about?

Tracking detectors

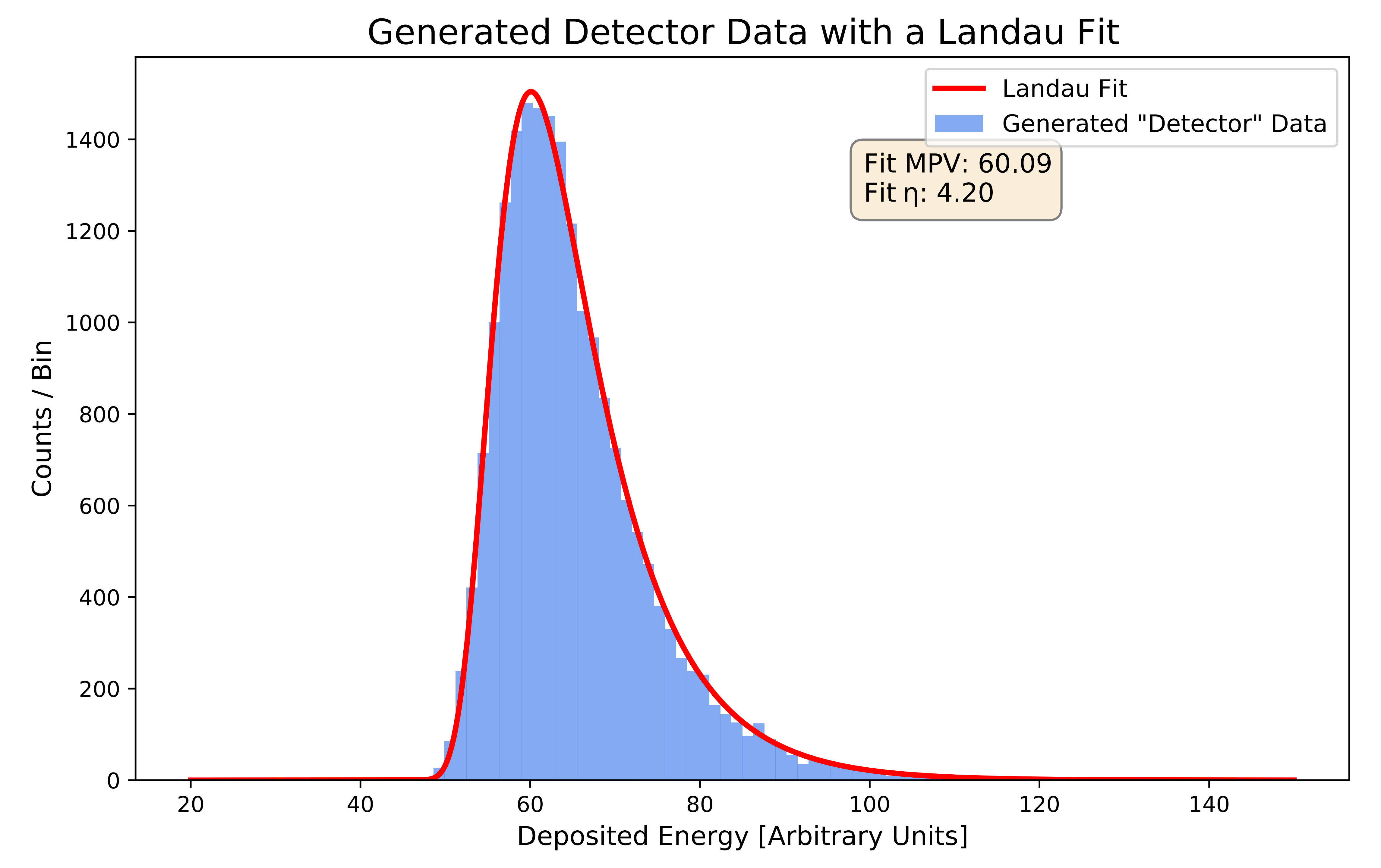
- When a charged particle loses energy by ionization or a photon is absorbed in a semiconductor detector part of the released energy is used to generate electron–hole pairs
- The charge carrier pairs are separated in the electric field applied to the semiconductor and drift inside the bulk toward the electrodes on which the movement induces an induction signal
- The bulk must be sufficiently free or depleted from other charge carriers
- The electronic signal is determined in size and shape by the generated of e/h pairs, the velocity of their drift movement, and the electrode geometry
- The drift velocity depends on the carrier mobility μ and the magnitude of the electric field in the semiconductor according to the Drude model:
    - $v_D = \mu(E)/E$, where the mobility itself is field dependent such that at high electric fields the drift velocity saturates

Tracking detectors

- In a silicon detector (*pn* diode), for full depletion, the electric field linearly drops to zero from one side to the other
- The average field is just half that of the maximum field right at the boundary
- Spatially sensitive semiconductor detectors (microstrip or pixel detectors) used in high energy physics are usually very thin (typically 200–300 μm)
- Typical velocities in such detectors are in the order of 50 μm/ns
- The maximum time that the charge carriers need to traverse the space charge region hence typically is rather short:
- $$t = \frac{d}{v_d} \approx \frac{200 - 300\ \mu m}{50\ \mu m/ns} \approx 4 - 6 ns$$

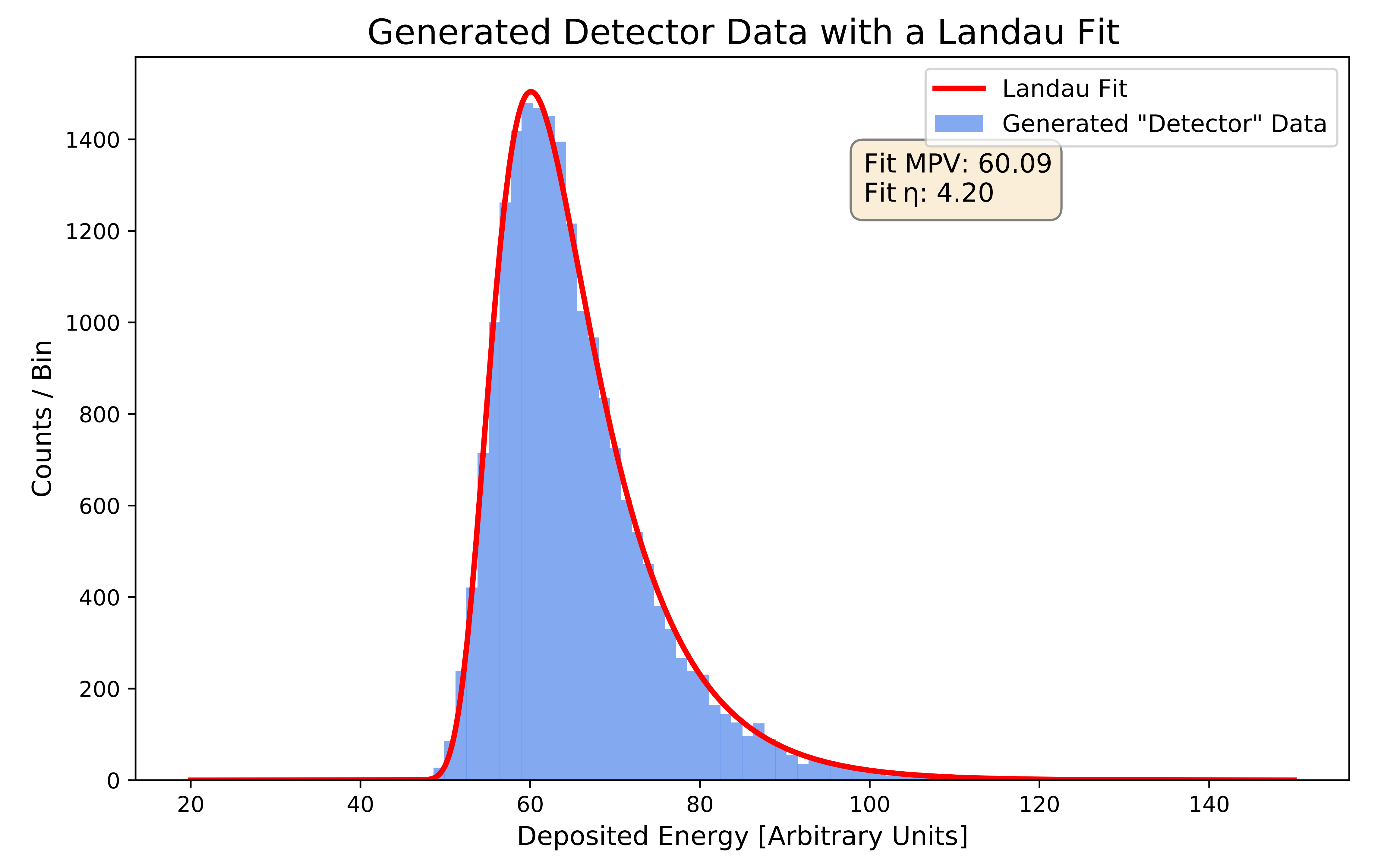
Tracking detectors

- To compute the average charge signal (total signal, integrated over time) obtained when a high energy charged particle traverses a 300 μm thick Silicon detector, we need to know the *particle's average energy loss* and the *energy w_i needed on average to generate an electron-hole pair*
- The energy loss of ionizing particles is distributed according to the Landau distribution
- It is an asymmetric distribution
- Most probable value differs from the mean energy loss: $\left\langle \frac{dE}{dx} \right\rangle$



Tracking detectors

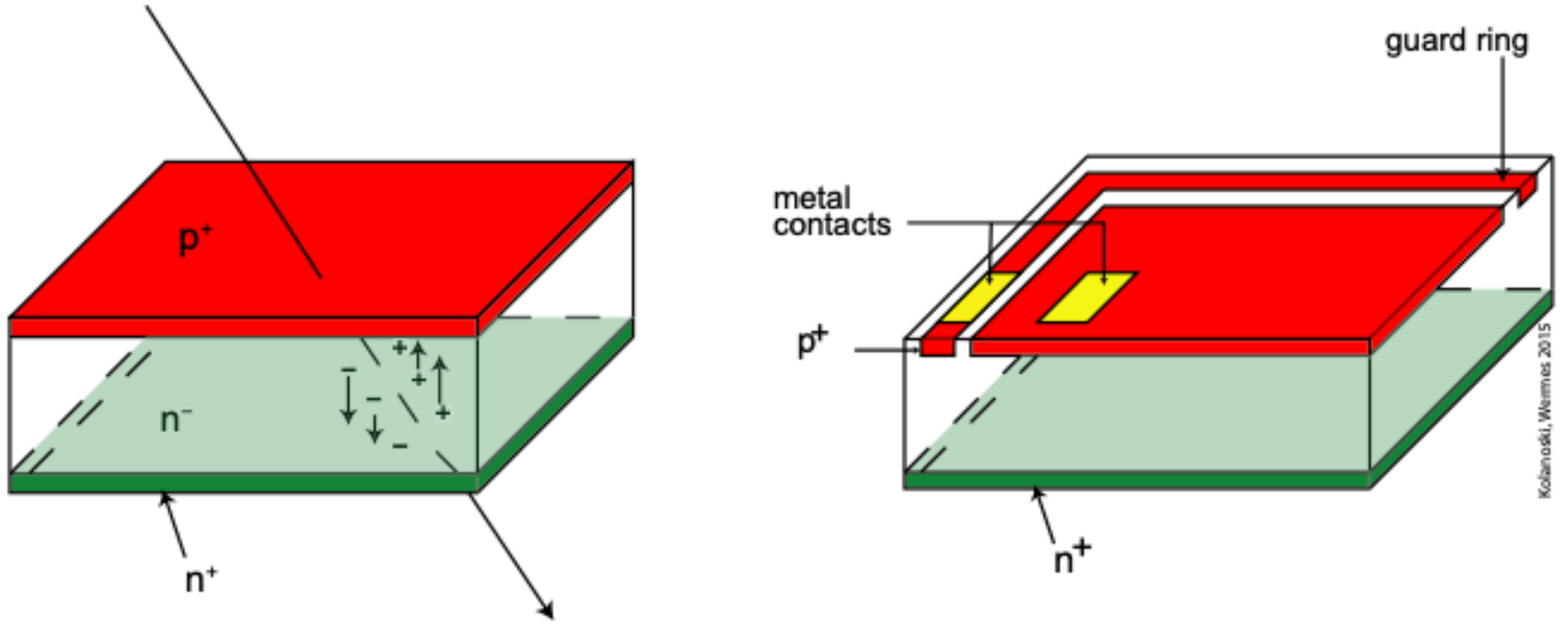
- For a minimum-ionizing particle, in a 300 μ m thick silicon detector the latter amounts to $\left\langle \frac{dE}{dx} \right\rangle \approx$ 0.39 keV/μm = 117 keV/300 μ m
- Using the most probable value, we get 84 keV/300 μm
- The average energy to create an electron-hole pair at 300 K is 3.65 eV
- Typical charge of a signal
  - $\left\langle \frac{dE}{dx} \right\rangle_{300\mu m} \times \frac{1}{w_i} = \frac{117 \times 10^3 eV}{3.65}$ = 5 fC
  - 32k electron-hole pairs are created



Position Measurement

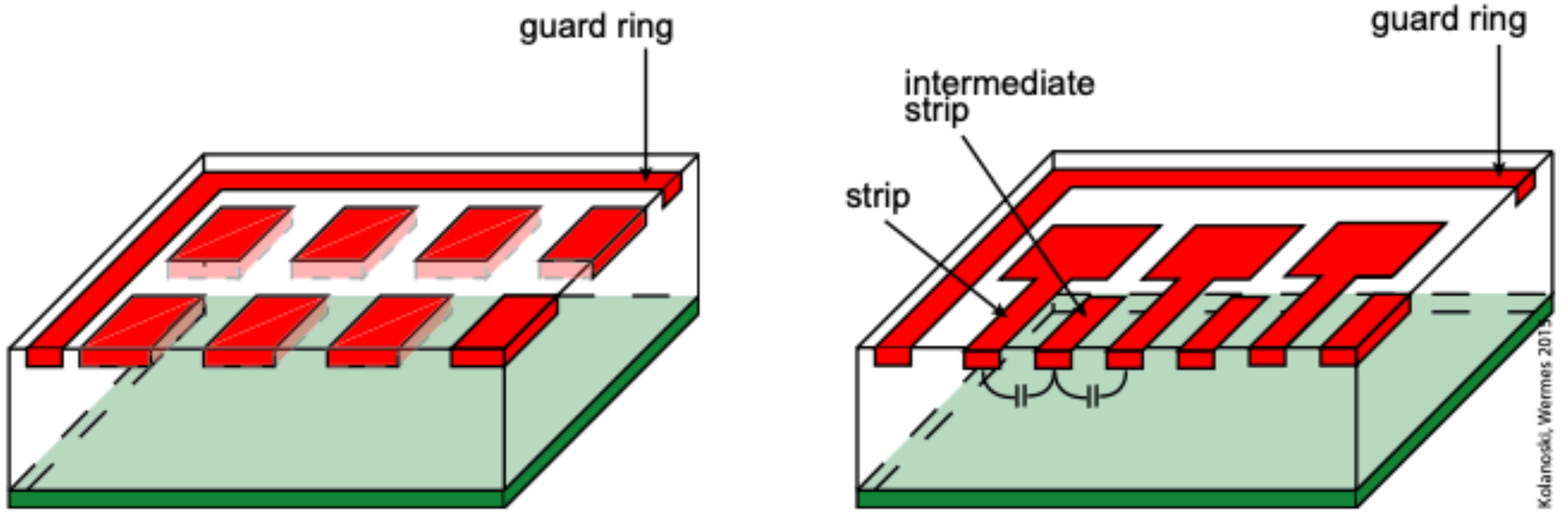
- In strip or pixel geometries, structured electrodes allow for precise space-point determination of the particle entrance. If there is only digital information available (1 = hit, 0 = no hit) the obtainable resolution is mostly given by the electrode pitch p
- The average quadratic deviation (the variance) from the true entrance point is for perpendicular particle entrance and single hit response:
  - $\sigma_x^2 = \frac{1}{p} \int_{-p/2}^{p/2} x^2 dx = \frac{p^2}{12}$ (pitch can be 20 - 100 μm)
- Averaging over 2 strips:
  - $x = \frac{S_1 x_1 + S_2 x_2}{S_1 + S_2}$
  - S_1, S_2 are the signals (charges) of two neighboring strips
- Assuming noise N,
  - $\sigma_x = \frac{N}{S} p \sqrt{\beta}$ (β depends on the distribution of the total charge on both strips)

Single sided strips



(a) pn area diode.

(b) Area diode with guard ring.



(c) Pad or pixel detector.

(d) Strip detector.

Fig. 8.35 Design concepts of single-sidedly processed pn detectors. The labels n^+ and n^-, respectively, denote strong/weak n doping, correspondingly for p doping (see also footnote on 285). Author: P. Fischer.

Double sided strips

- Double-sided microstrip detectors provide both coordinates of a particle passage from the same charge deposit in the detector layer. In addition the hits on both sides are correlated since they originate from the same charge deposition

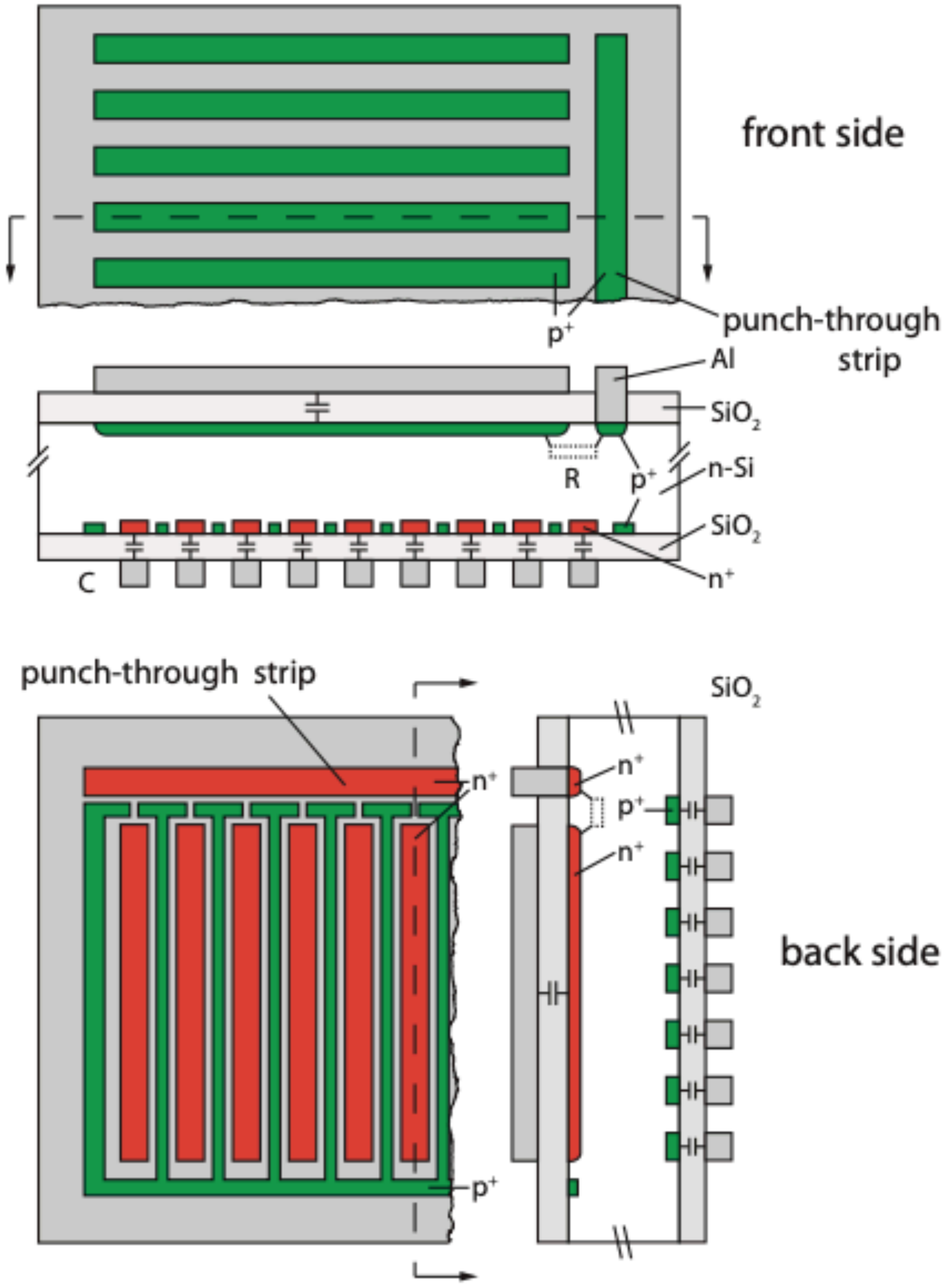


Fig. 8.46 Layout of a double-sided microstrip detector with *punch-through biasing* by means of dedicated biasing strips on both sides of the detector. The bulk is n-doped. p implants are shown in green, n implants in red. The 'front side' (diode side) is seen at the upper part of the figure in top and side view. The bottom part of the figure shows the 'back side' (non-diode side) of the detector (top and side view). The n strips are interleaved by p strips to block the electron accumulation layer (adapted from [677] with kind permission of Springer Science+Business Media).

Silicon strip detectors as vertex detectors

- Silicon microstrip detectors are used in high energy physics experiments predominantly as so-called vertex detectors which enable measurements of the decay points (vertices) of long-lived particles, which have travel distances until their decay of some hundred micrometres to some millimetres. Prominent examples are b-quarks or τ-leptons with lifetimes in the range of picoseconds.
- Large tracking detectors (trackers) based entirely or mainly on semiconductor detectors were first implemented in the LHC experiments ATLAS and CMS. Silicon-based strip and pixel detectors can tolerate higher rates and are thus used for charged particle tracking and in particular for identification of secondary decay vertices (vertexing). Especially pixel detectors fulfill the latter task.

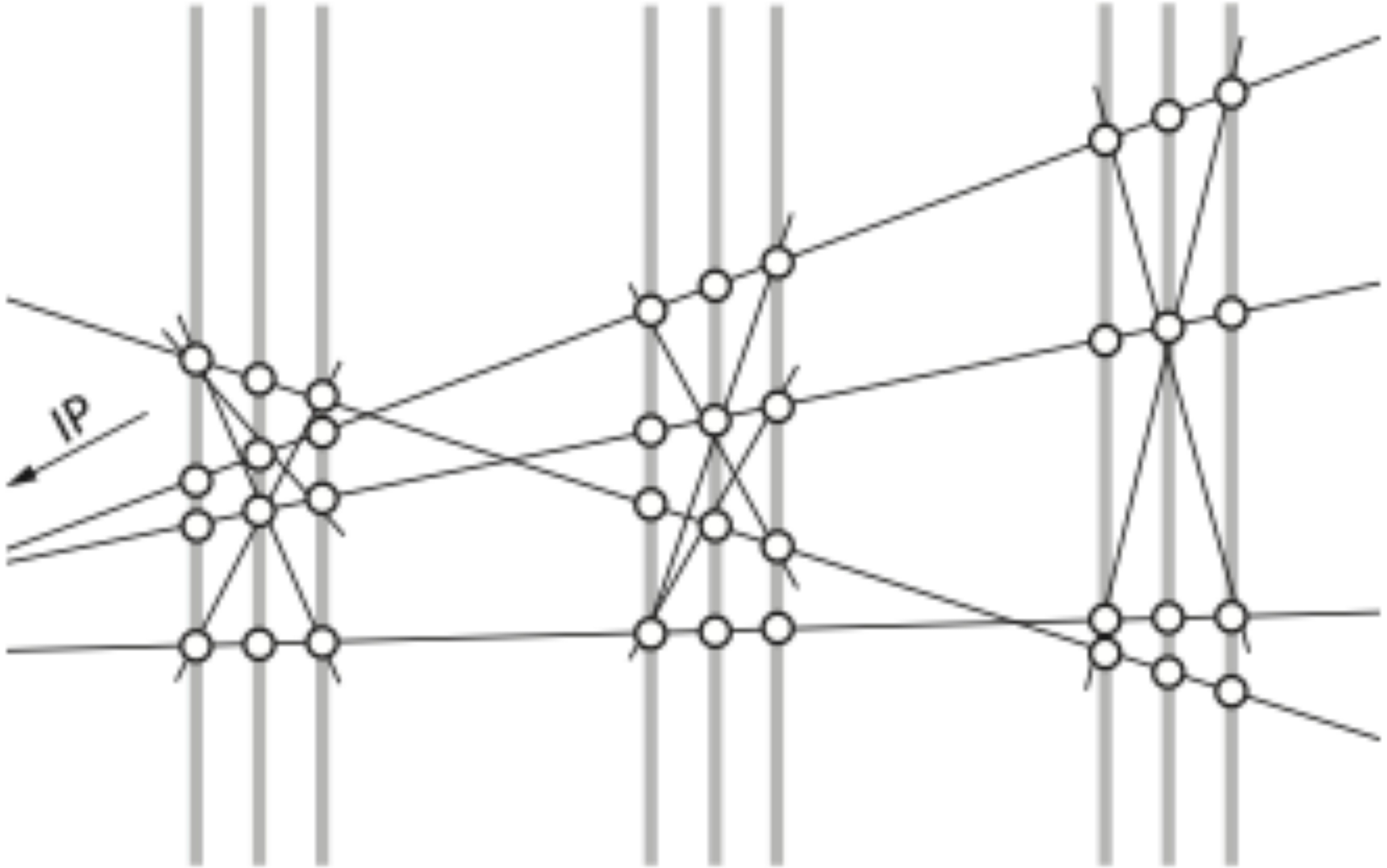
Tracking

- Charged particles in a magnetic field deflected by Lorentz force:
  - $\overrightarrow{F} = q(\overrightarrow{v} \times \overrightarrow{B})$
  - Helical trajectory with $R = \dfrac{p_T}{|q|B}$
- Parametrized description of a particle trajectory is called a 'track model'
- Often direction and momentum changes by multiple scattering and bremsstrahlung along the trajectory are also taken into account
- The track model depends on a set of m parameters which are fitted to the N measurement points by the track reconstruction program
- Usually the fitting proceeds according to the *least square method* by minimizing the expression:
  - $S = \sum_{i=1}^{N} \dfrac{\left(\xi_i^{\text{meas}} - \xi_i^{\text{fit}}(\theta)\right)^2}{\sigma_i^2}$

Key Parameters

- κ: curvature in the $r\phi$ plane
- ϕ_0: angle in the $r\phi$ plane between the x-axis and the vector from the circle centre to the position of closest approach
- d_0: closest distance of the helix to the origin in the $r\phi$ plane
- θ: slope angle of the track against the z-axis at the position of the closest distance of the origin; this angle is invariant as you follow the track around the cylinder (in a homogeneous field and without disturbance of the track) or, in other words, the track is a straight line on the unrolled cylinder surface where the helix is localised
- z_0: coordinate of the z-axis in the rz projection of the track

Tracking



Kolanoski, Wermes 2015

Fig. 9.8 Triplet combinations of hits in nine detector layers, of which three are always more closely arranged in so–called super-layers. In each super-layer hit triplets can be formed which should point into the direction of the interaction point. Obviously many possible combinations can be excluded based on this criterion.

Pattern Recognition

- The measurement points registered by a detector for a certain event have to be assigned to individual tracks which are to be reconstructed. This procedure belongs to the general subject of *pattern recognition*, which summarizes methods allowing the recognition of regularities or similarities in data which might be incomplete and noisy. Methods of pattern recognition are applied in a variety of fields, like image, voice and character recognition, radar survey and also in event recognition in particle physics

Kalman Filter

- A systematic method of pattern recognition, which provides at the same time a track fitting, is the Kalman filter algorithm

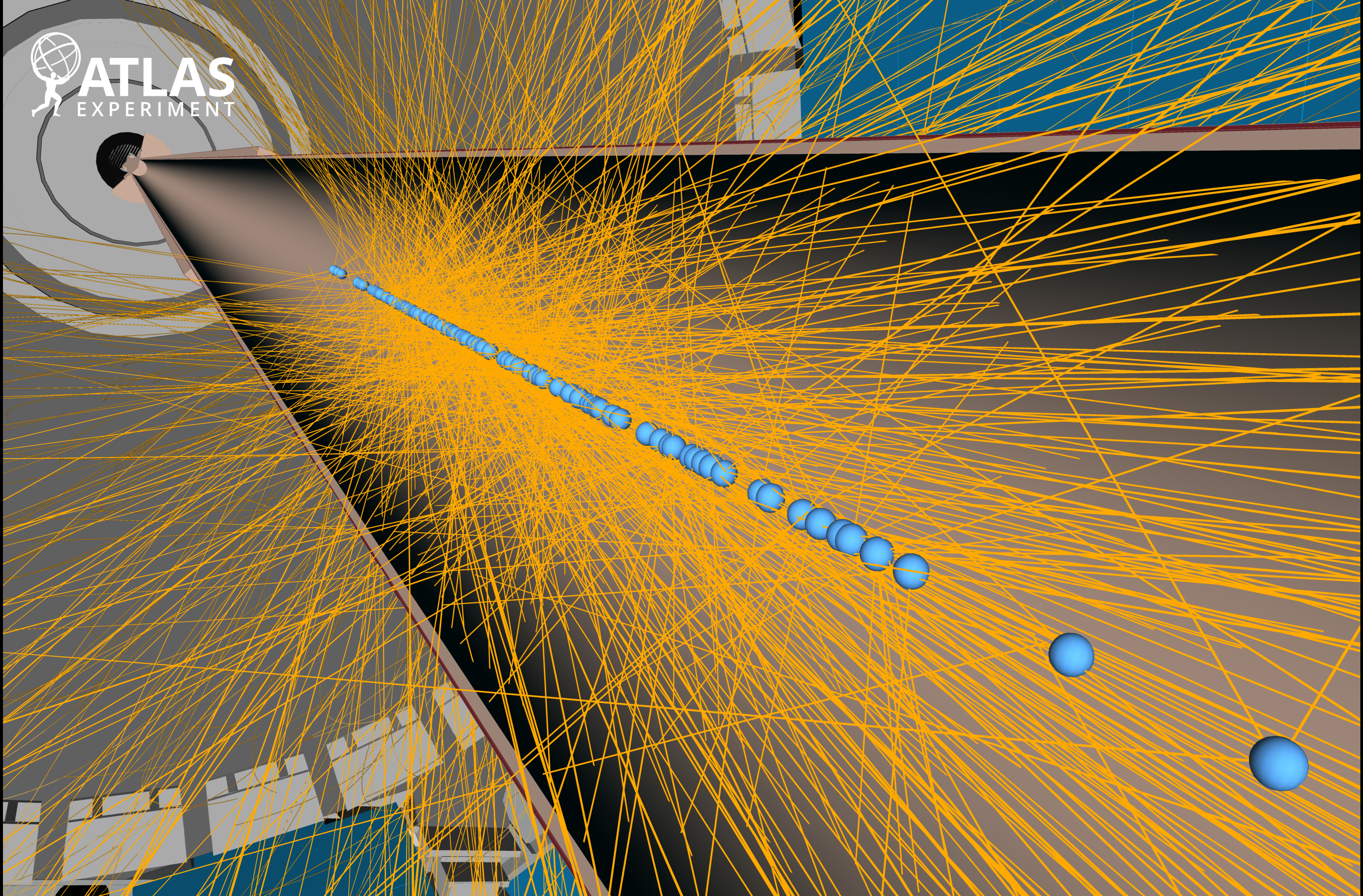
- Starting from a certain point, for example on a layer of a tracking detector, called the seed, a search region for a point in the next layer will be predicted

- The search region will be restricted by certain conditions, for example that the track should originate from the target within some allowance

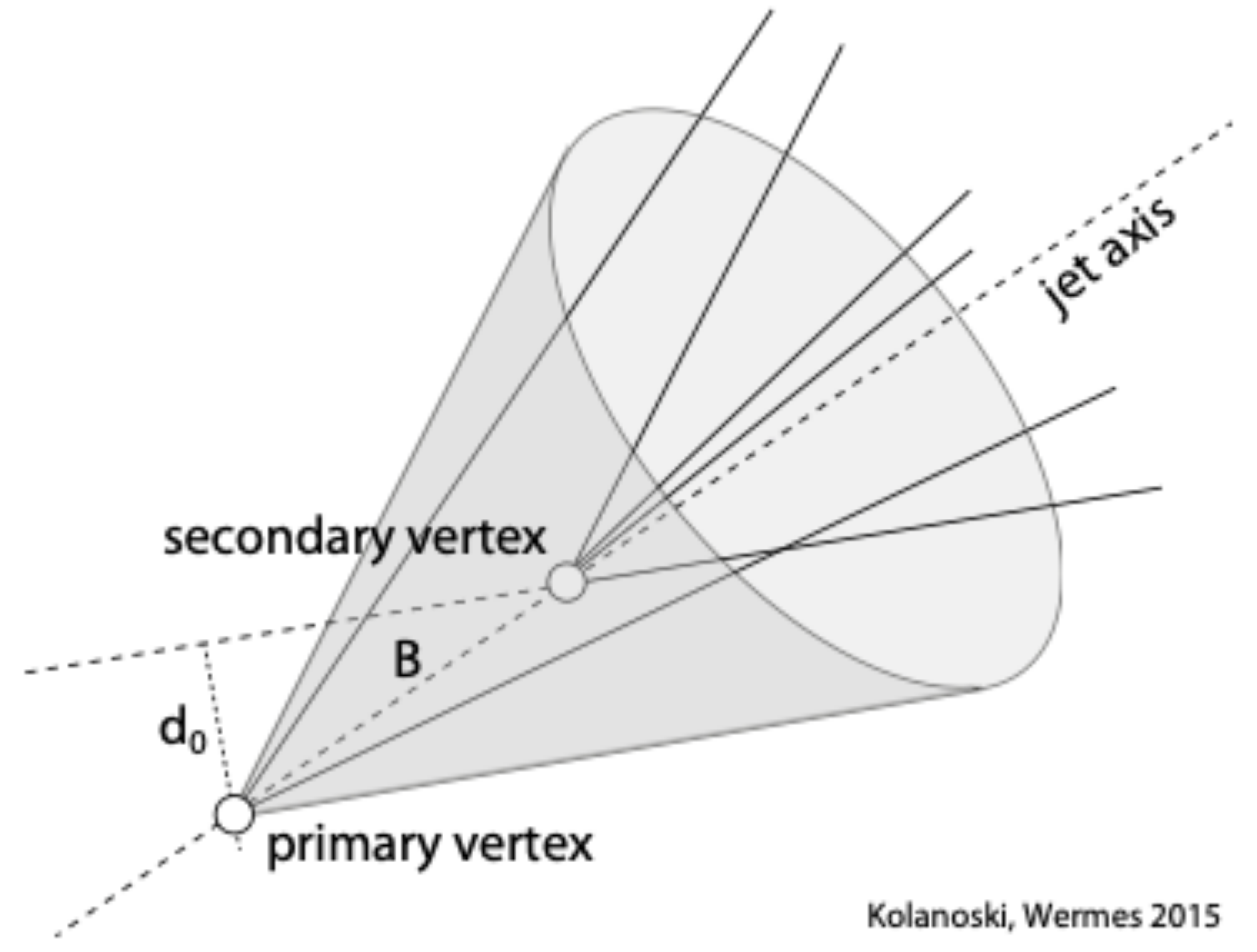
- If a point in this layer has been found, the prediction for the next layer will be refined.

- This will be repeated until the last layer before the interaction point is reached and the whole information of all points assigned to the track is available for a determination of the track parameters and their corresponding errors

Pattern Recognition in high pileup



What is going on here?



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