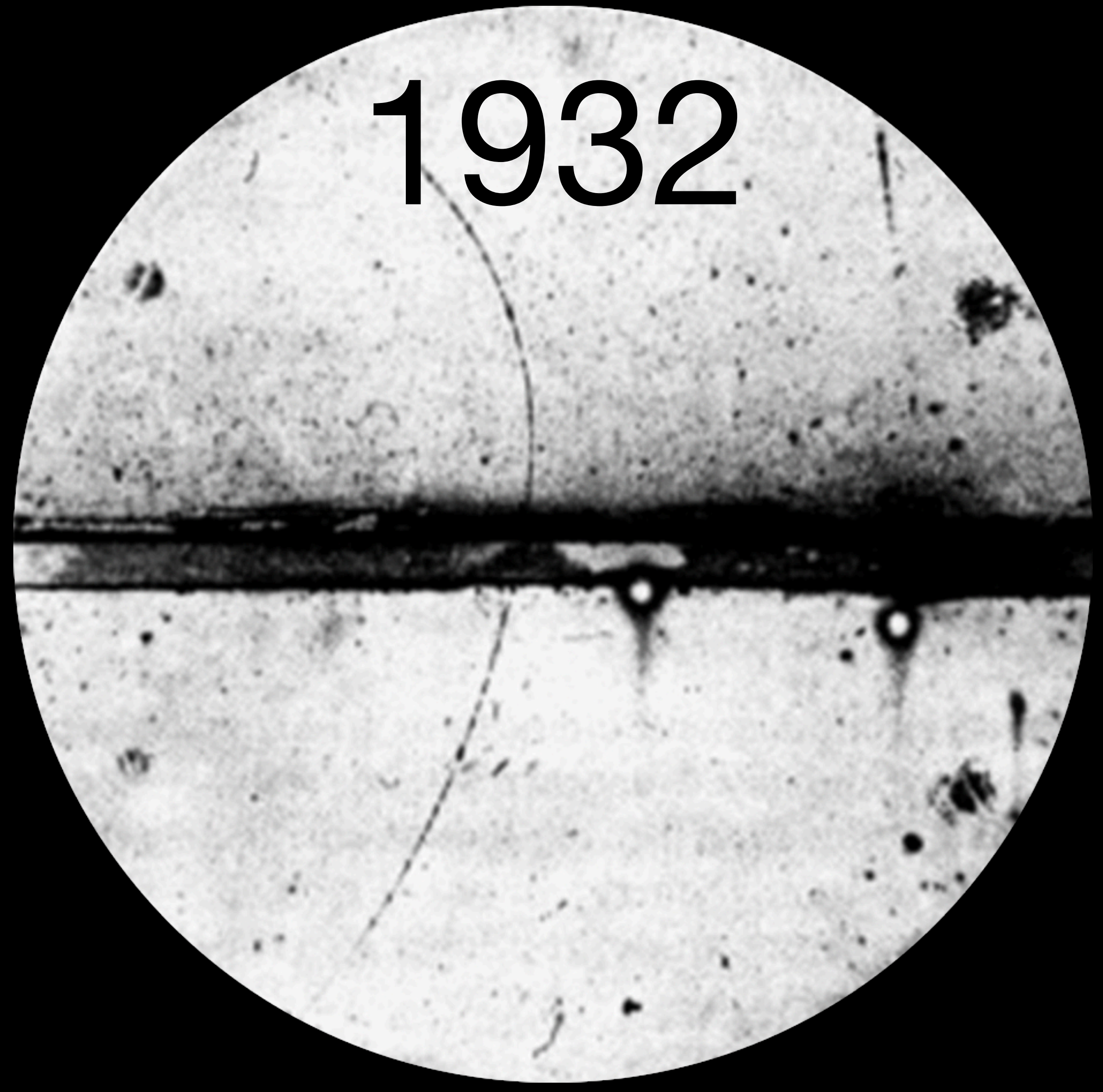
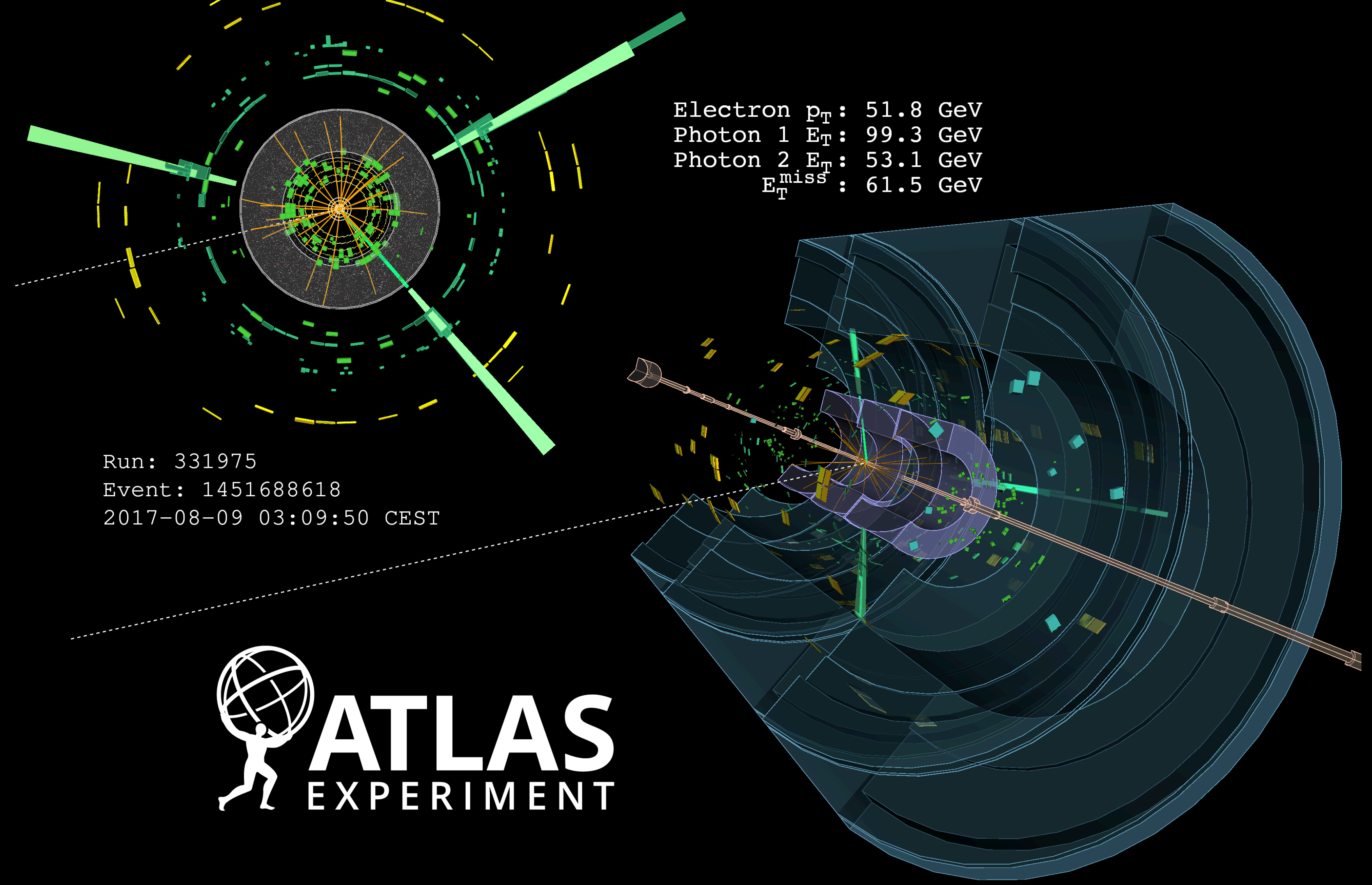
PHYS 7363 - Experimental Particle Detection and Detectors I



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

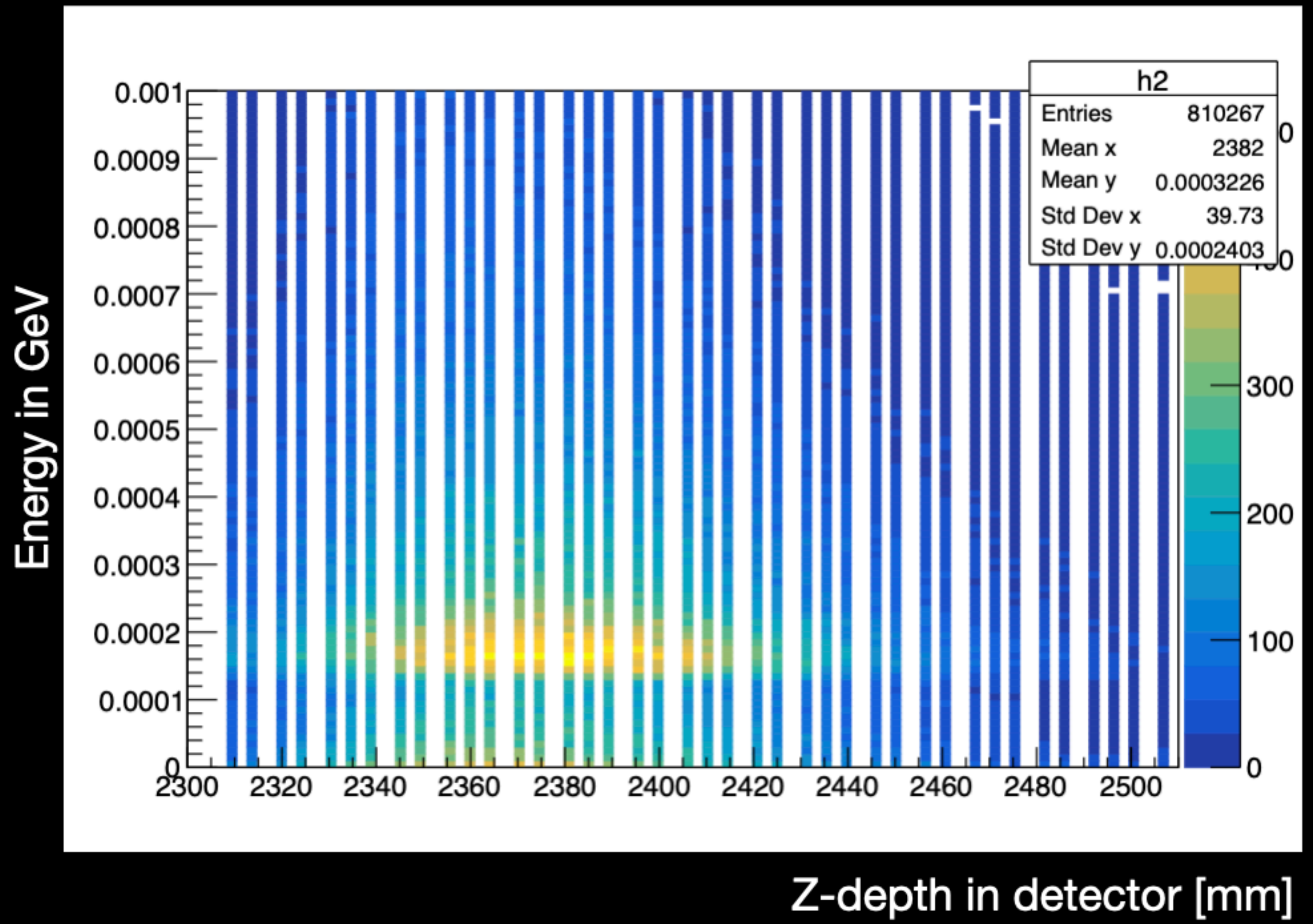
Month	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
October	6	7	8	9	10	11	12
	13	14	15	16	17	18	19
	20	21	22	23	24	25	26
	27	28	29	30	31	1	2
November	3	4	5	6	7	8	9
	10	11	12	13	14	15	16
	17	18	19	20	21	22	23
	24	25	26	27	28	29	30
December	1	2	3	4	5	6	7
	8	9	10	11	12	13	14

Reminders

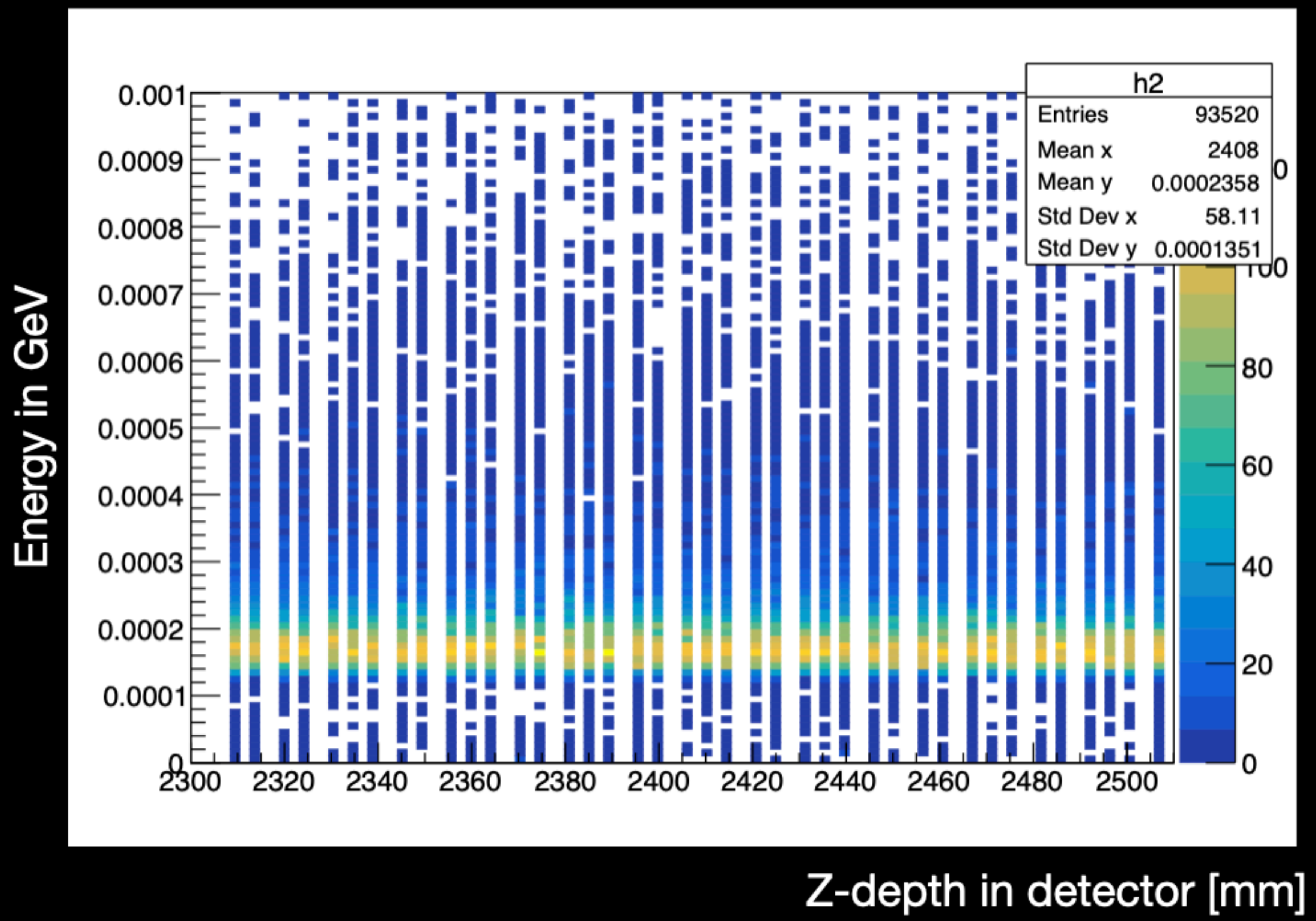
- Remember to think about your final project
- It carries 50% of the grade
  - We have decided to schedule the midterm on October 27th
- Questions on the midterm: Bethe-Bloch equation, Semiconductor devices, tracking, calorimetry, fitting functions and anything that we cover by the 22nd

Ideas for the final project

- Project can involve tracking or calorimetry or trigger systems
- Example:
  - Shoot particles in the detector, study their response and develop a way to identify different particle types
  - Two projects can have similar goals but use *very different* techniques: like convolutional neural network and graph neural network



Electrons



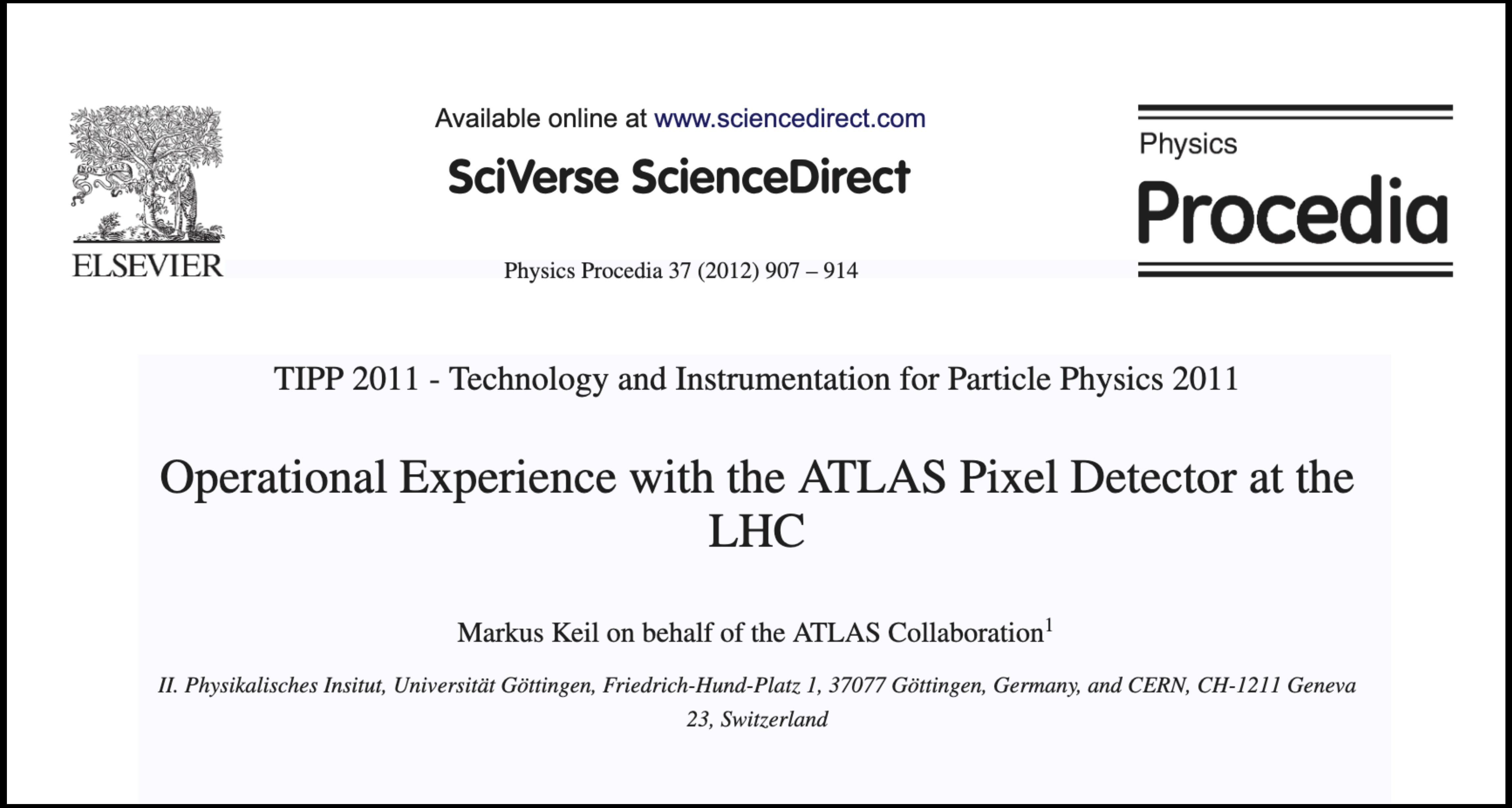
Muons

Ideas for the final project — Dipesh

- Use key4hep

Pitch and a sensor

- The pitch is the distance between the centers of sensing elements, and a smaller pitch allows for more precise measurements of particle tracks



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Physics

Procedia

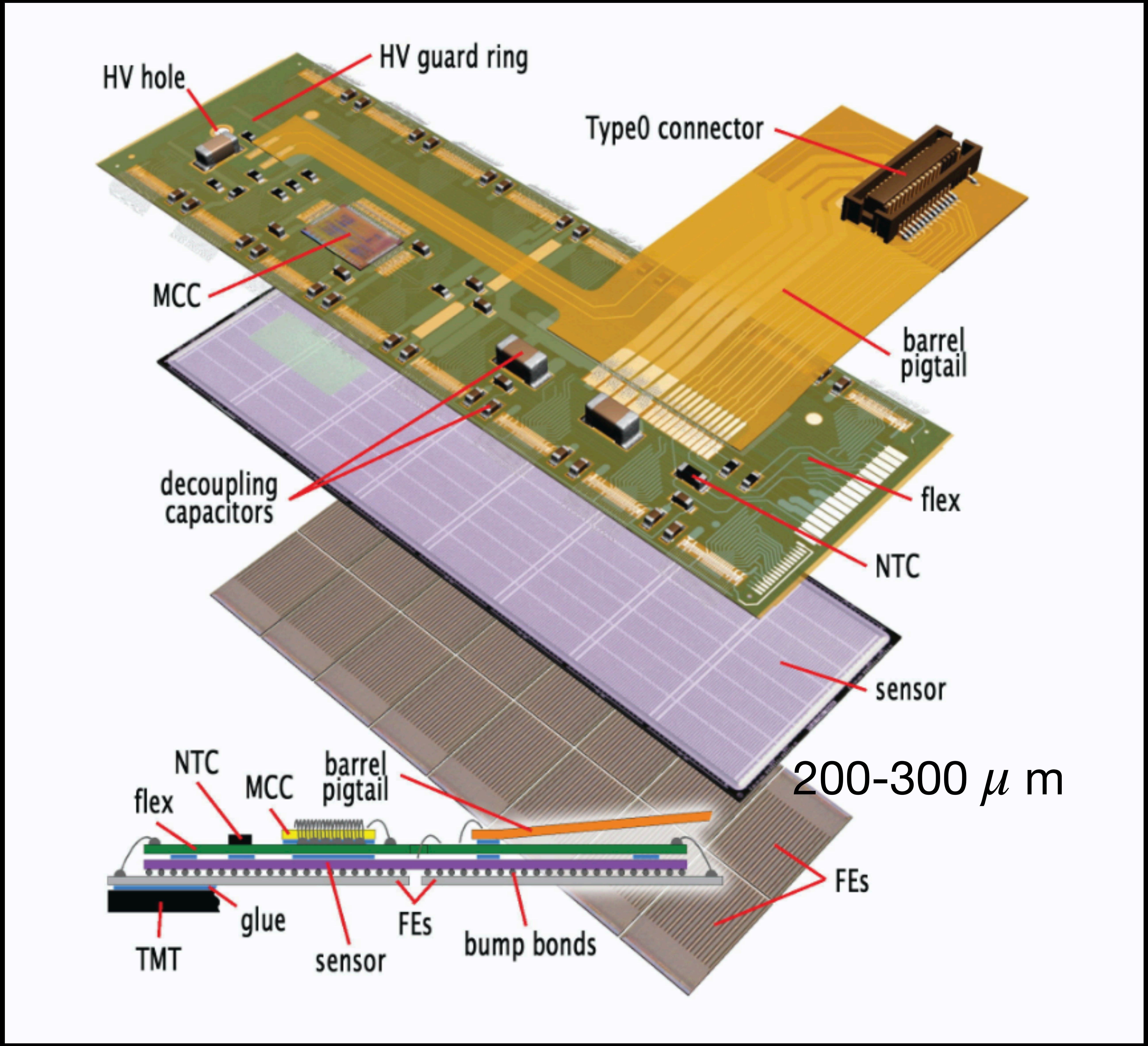
Physics Procedia 37 (2012) 907 – 914

TIPP 2011 - Technology and Instrumentation for Particle Physics 2011

Operational Experience with the ATLAS Pixel Detector at the LHC

Markus Keil on behalf of the ATLAS Collaboration[1]

II. Physikalisches Insitut, Universität Göttingen, Friedrich-Hund-Platz 1, 37077 Göttingen, Germany, and CERN, CH-1211 Geneva 23, Switzerland



200-300 μ m

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:
  - $$S = \sum_{i=1}^{N} \frac{\left(\xi_i^{\text{meas}} - \xi_i^{\text{fit}}(\theta)\right)^2}{\sigma_i^2}$$

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

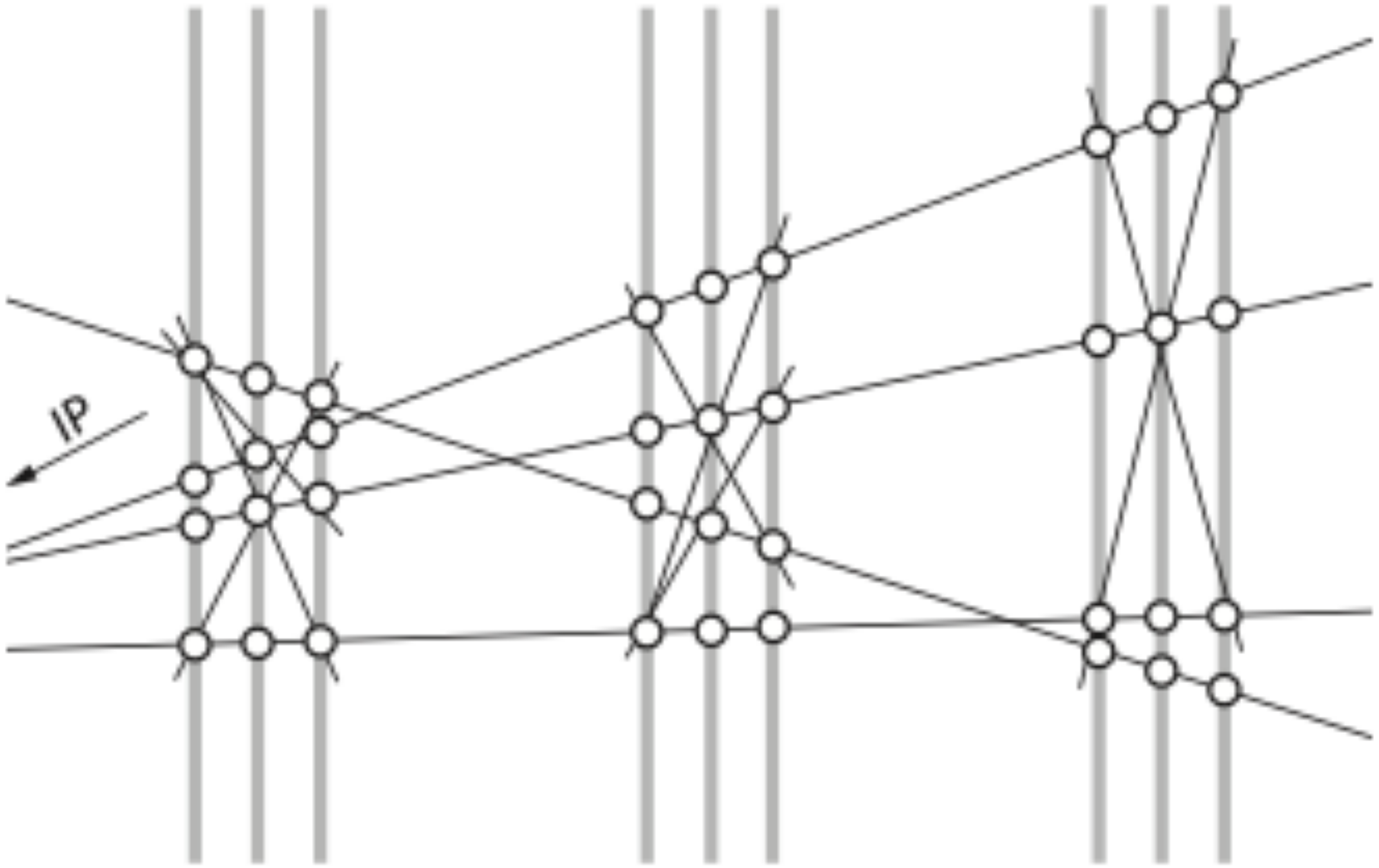


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Fig. 9.8 Triplet combinations of hits in nine detector layers, of which three are always more closely arranged in so–called super-layers. In each super-layer hit triplets can be formed which should point into the direction of the interaction point.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

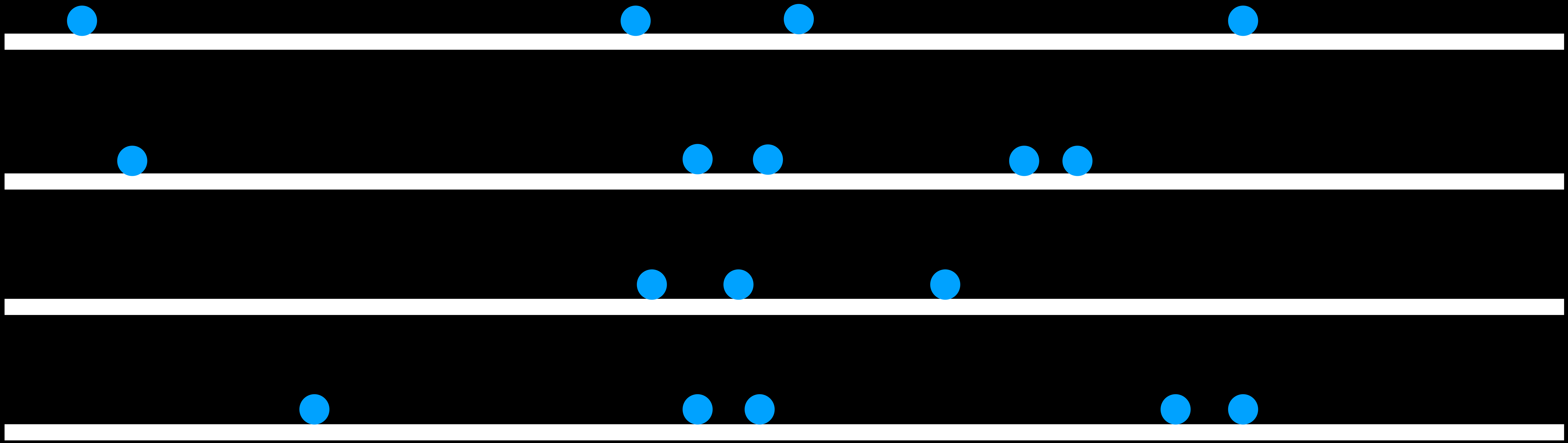
- The search region will be restricted by certain conditions, for example that the track should originate from the target within some allowance

- 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

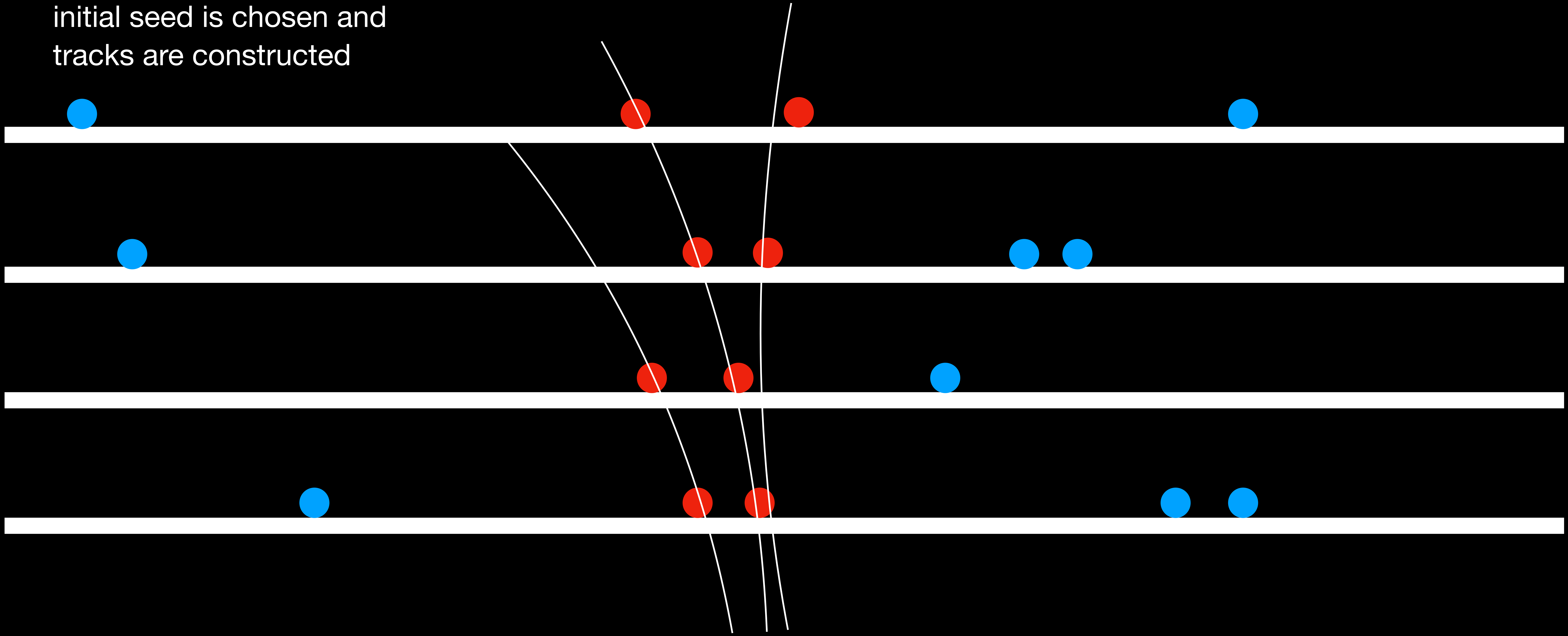
Kalman Filter

As a particle passes through the detector, it leaves hits in the detector



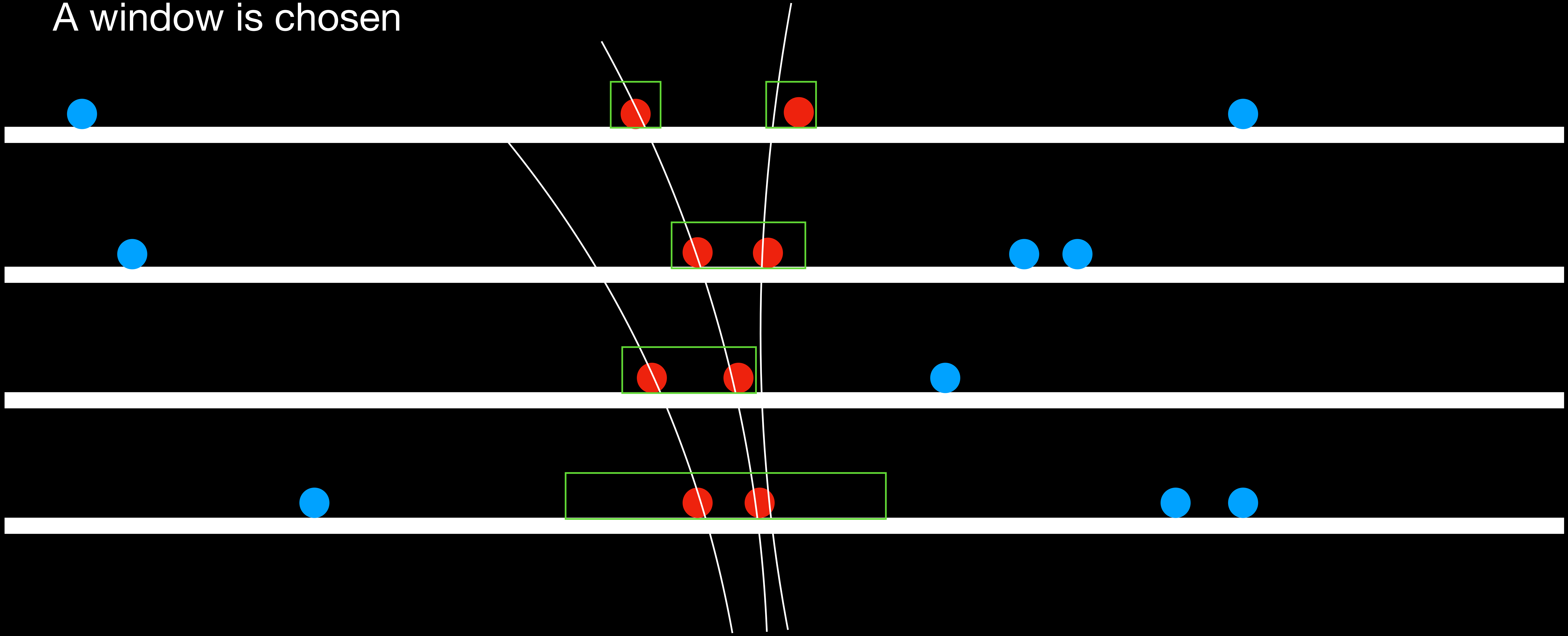
Kalman Filter

To reconstruct tracks, first an initial seed is chosen and tracks are constructed



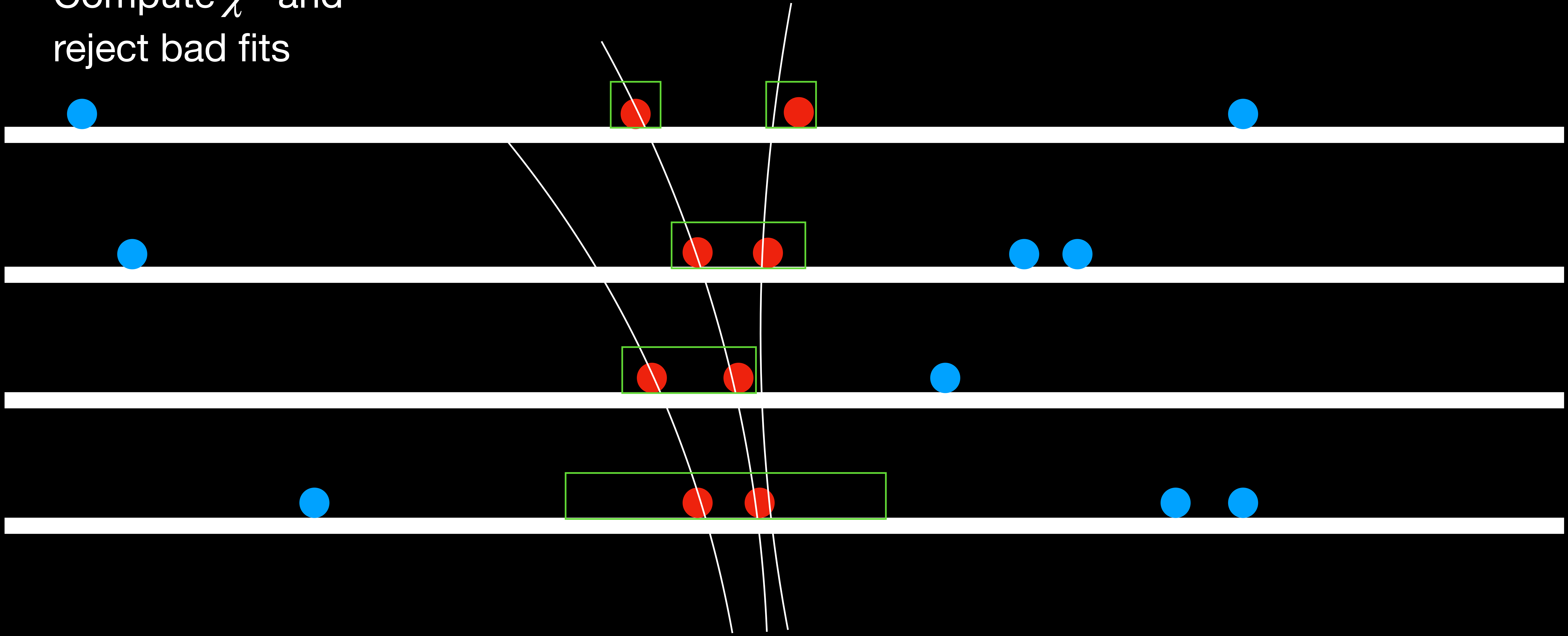
Kalman Filter

A window is chosen

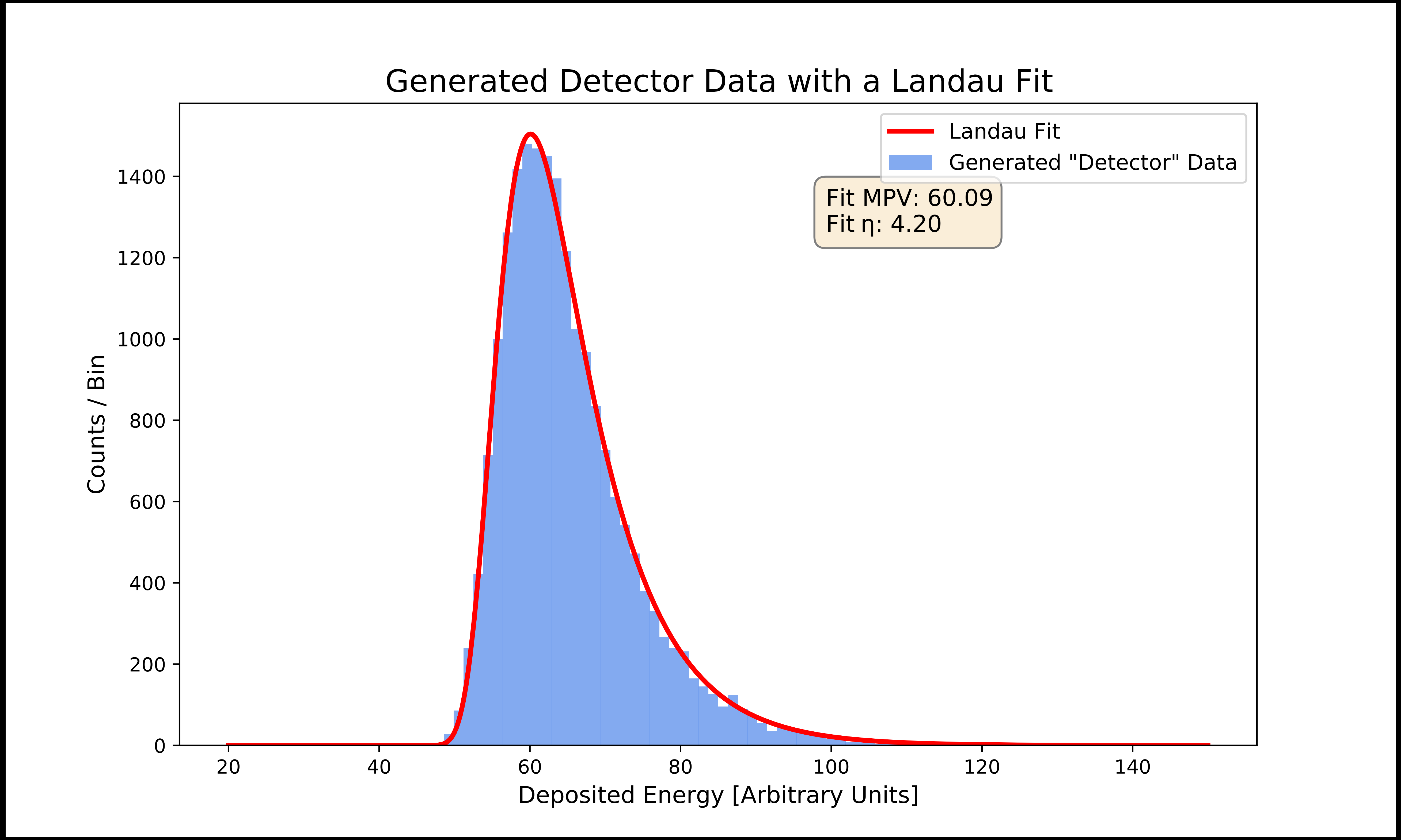


Kalman Filter

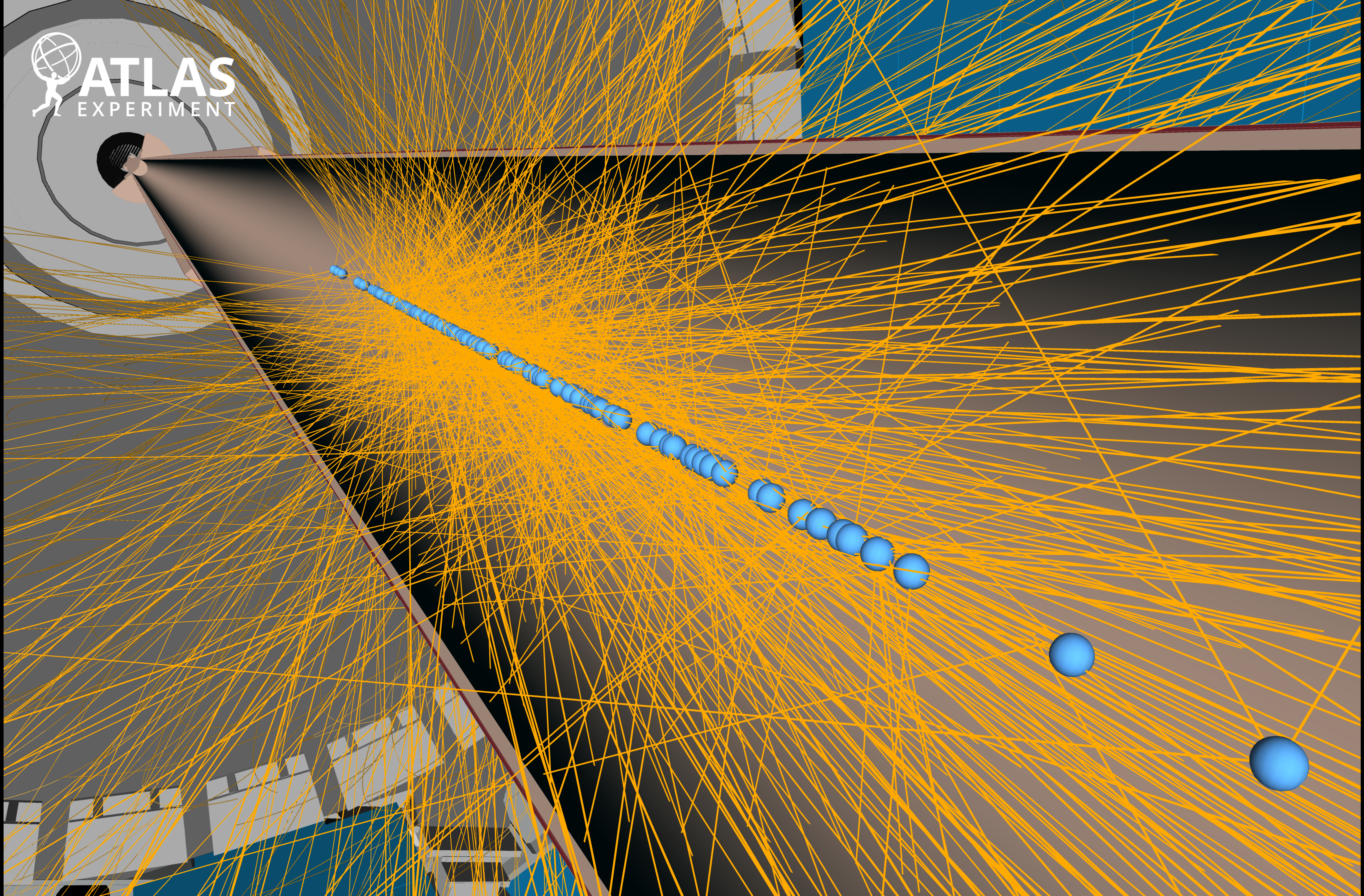
Compute χ^2 and reject bad fits



Can you calculate χ^2 for the fittings you have done



Pattern Recognition in high pileup

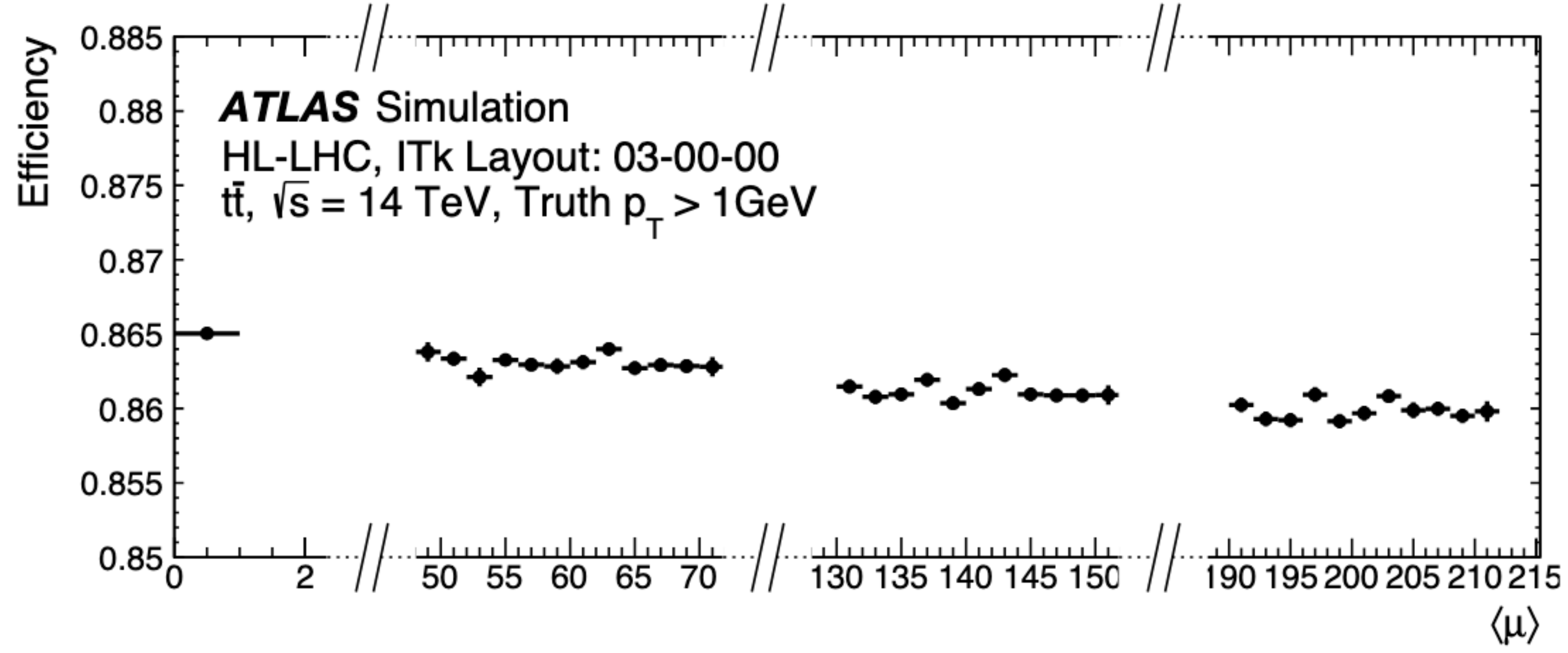


https://arxiv.org/abs/2412.15090

Tracking at the HL-LHC

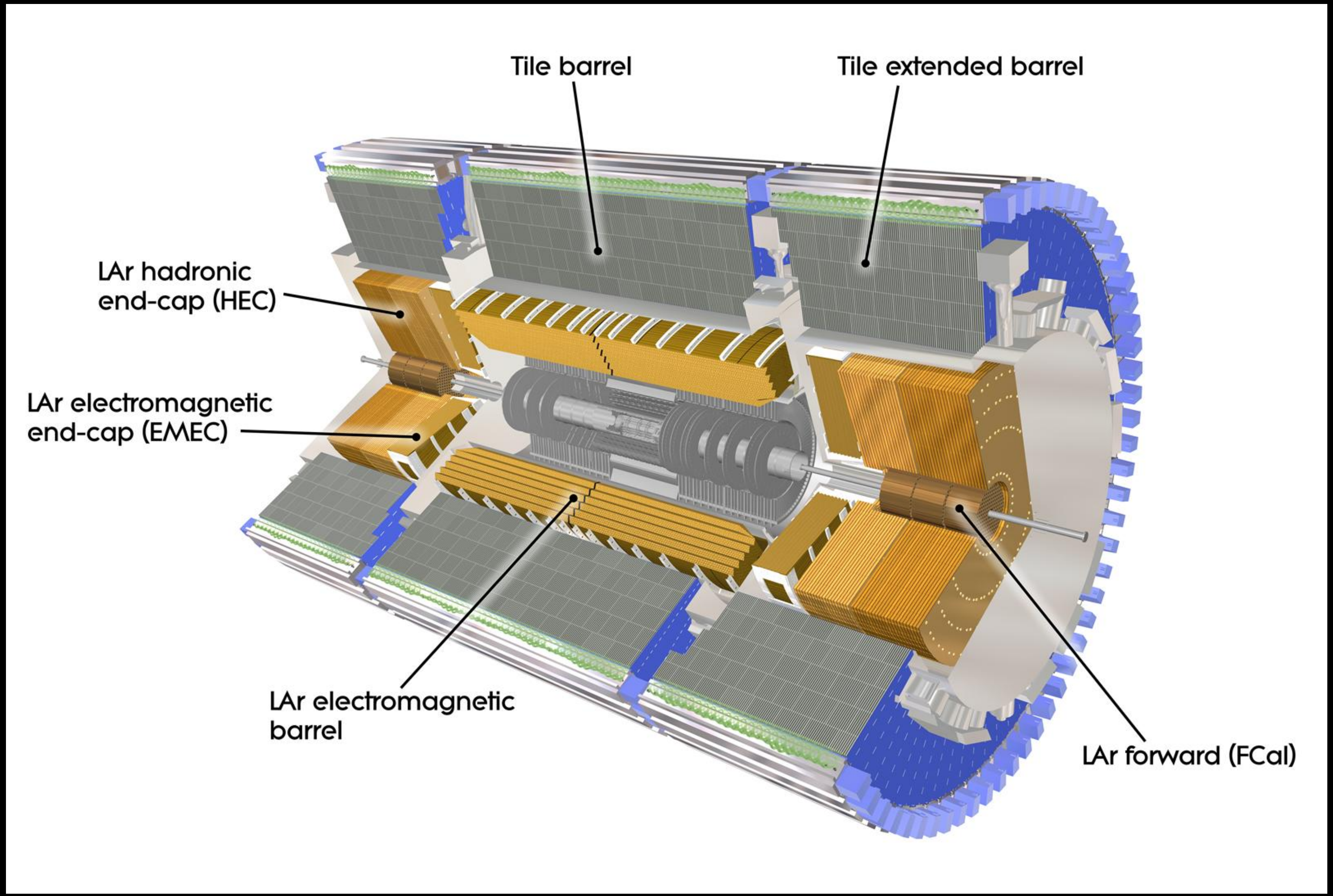
- The ATLAS Inner Tracker:
  - The ITk is designed to be a silicon-based detector that comprises a pixel and a strip subsystem. The pixel subsystem covers a pseudorapidity range of $|\eta| < 4.0$ and consists of five flat barrel layers and five layers of inclined or vertical rings for forward region coverage. The strip subsystem spans $|\eta| < 2.7$ and includes four strip layers in the barrel region and six disks in the endcaps, all using double-sided modules.
  - The ITk will operate within a solenoidal magnetic field of 2 T, which is aligned with the beam axis. This magnetic field plays a crucial role by bending the trajectories of charged particles, allowing to estimate their transverse momentum, p_T. The overall ITk configuration aims to achieve a minimum of nine measurements per track across the entire expected beam spot size, assuming a Gaussian distribution with a longitudinal width of 50 mm, and aims to reconstruct tracks left by charged particles with $p_T > 1$ GeV passing though the detector in the $|\eta| < 4.0$ range

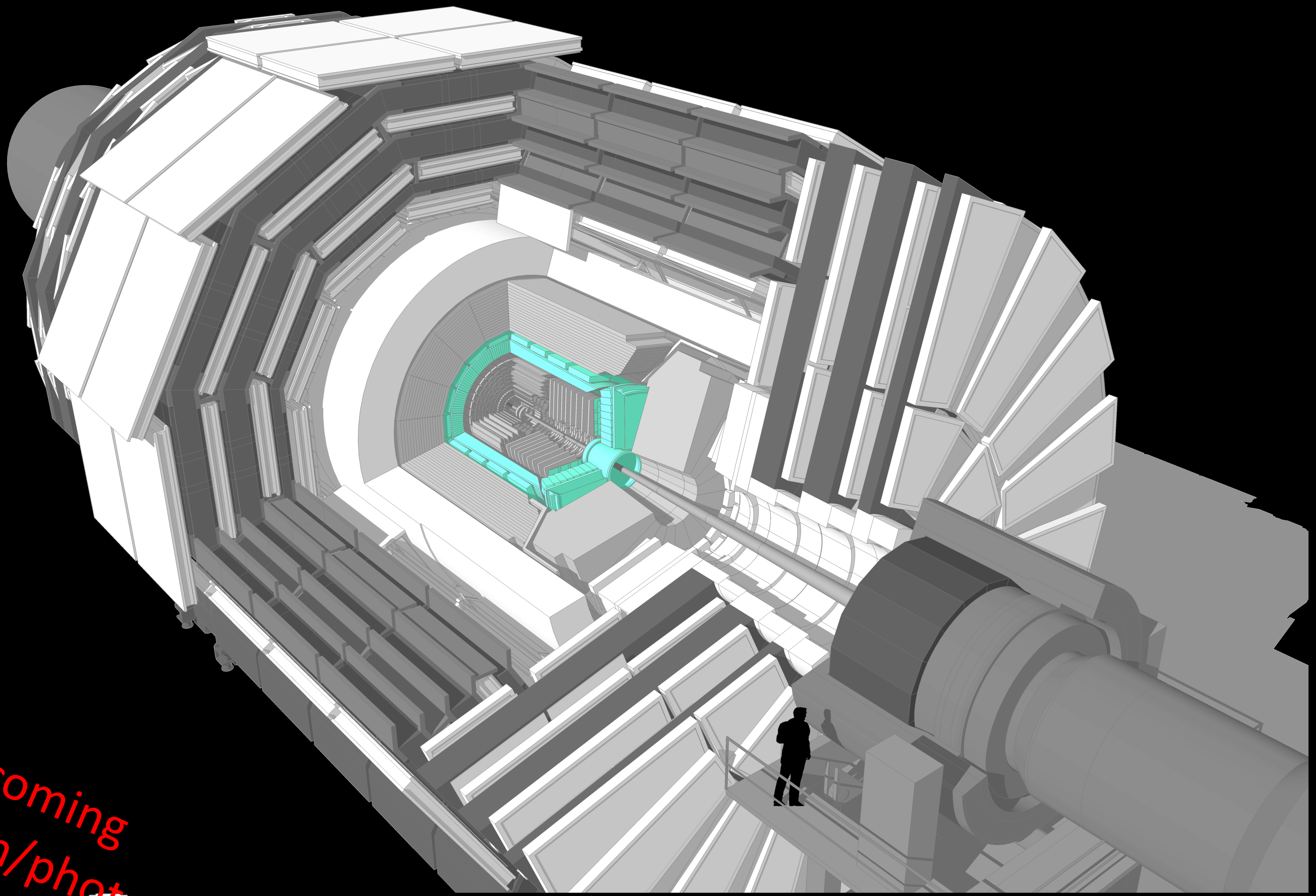
Tracking at the HL-LHC

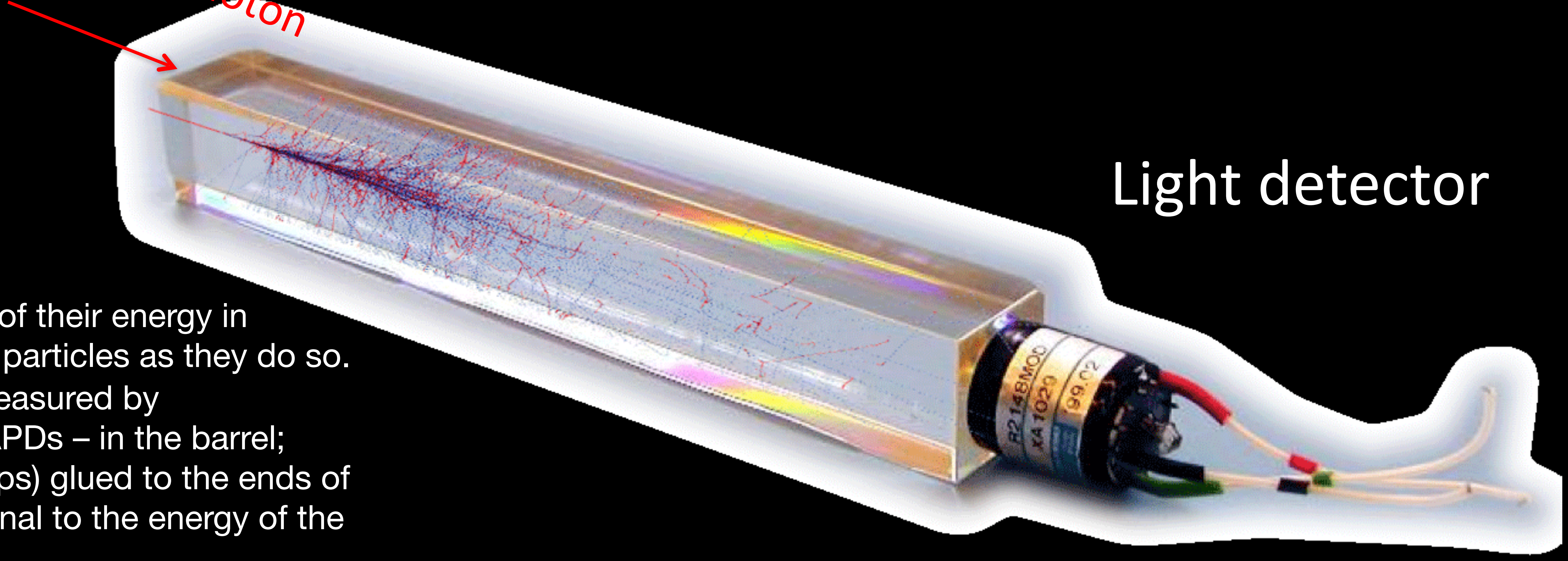


Calorimetry

ATLAS and CMS Calorimeters





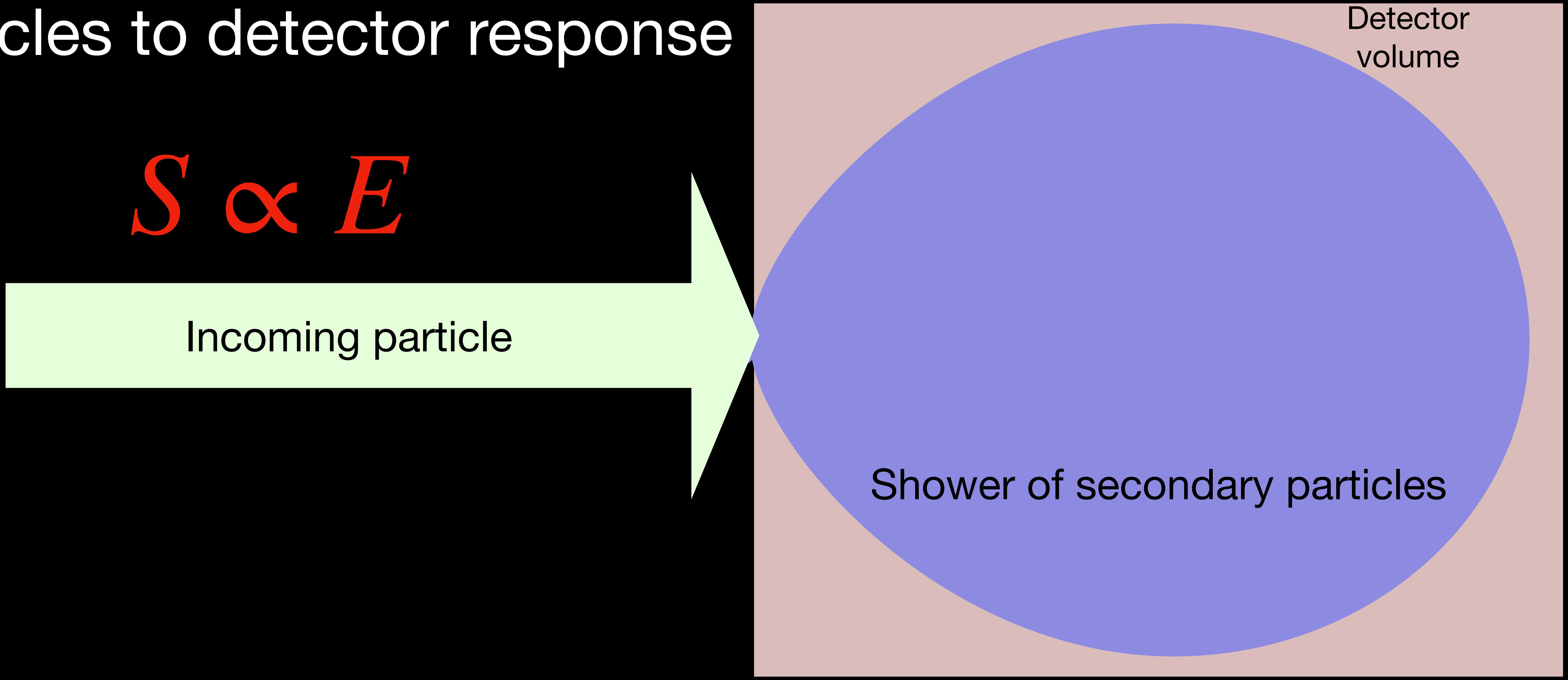


Incoming electrons and photons release all of their energy in the $PbWO_4$ crystals, producing a shower of particles as they do so. Light is also produced in the shower and measured by photodetectors (avalanche photodiodes – APDs – in the barrel; vacuum phototriodes – VPTs – in the endcaps) glued to the ends of the crystals; the amount of light is proportional to the energy of the electron/photon: more energy = more light.

Homogeneous calorimeter

Convert energy E of incident particles to detector response

$$S \propto E$$

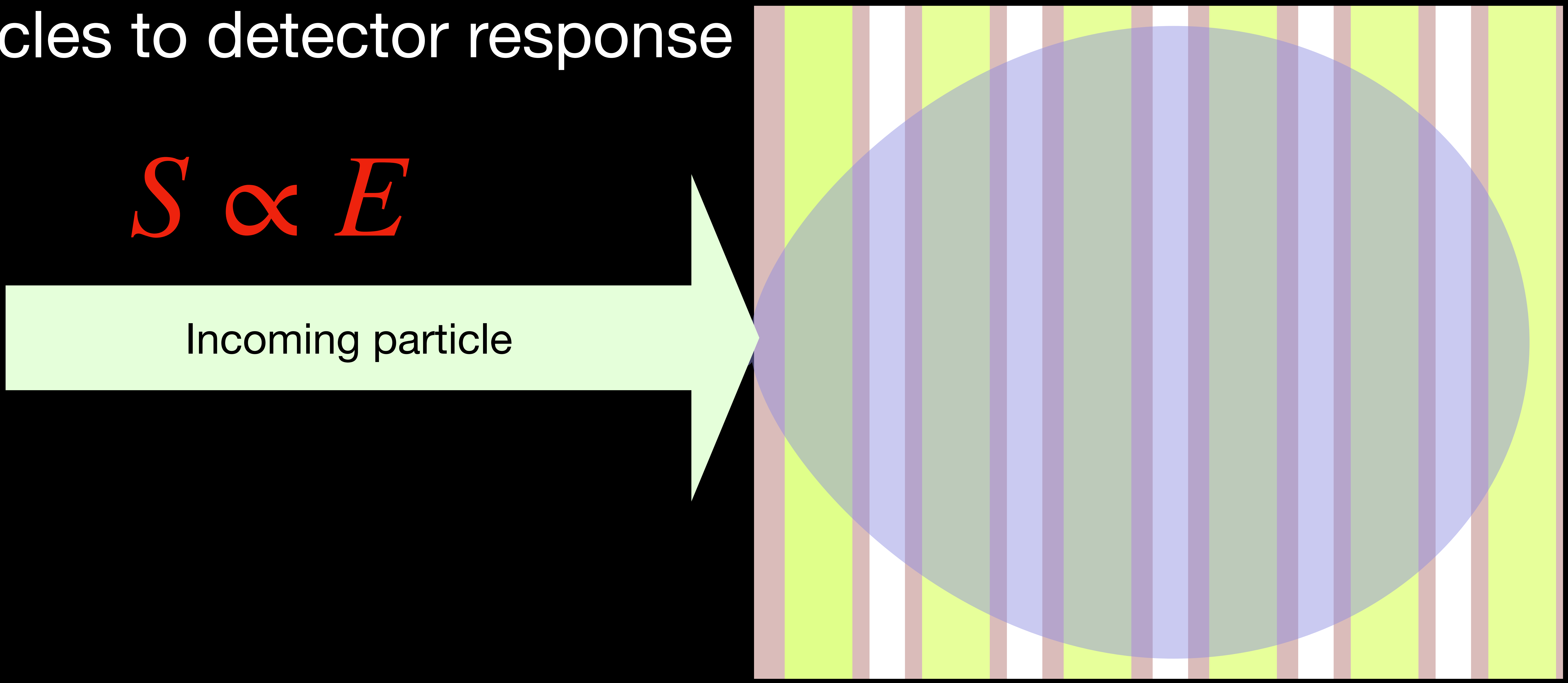


This is a homogenous calorimeter — think of lead tungstate ECAL in CMS

Sampling calorimeter

Convert energy E of incident particles to detector response

$$S \propto E$$



Detector volume

Interleaved with passive absorber material and active detectors

Shower of secondary particles

This is a sampling calorimeter — think of HighGranularity Calorimeter in CMS

Calorimeter

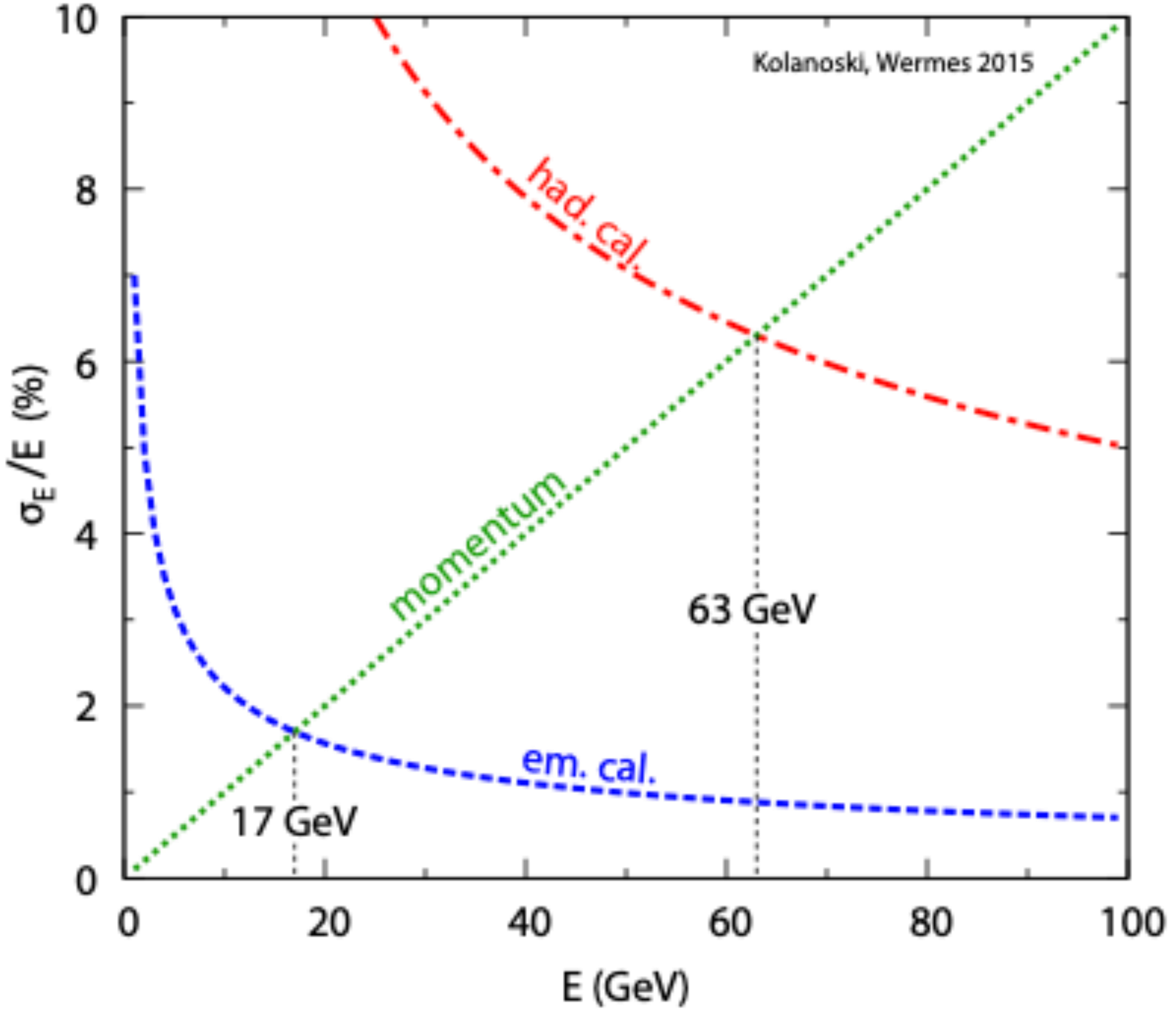
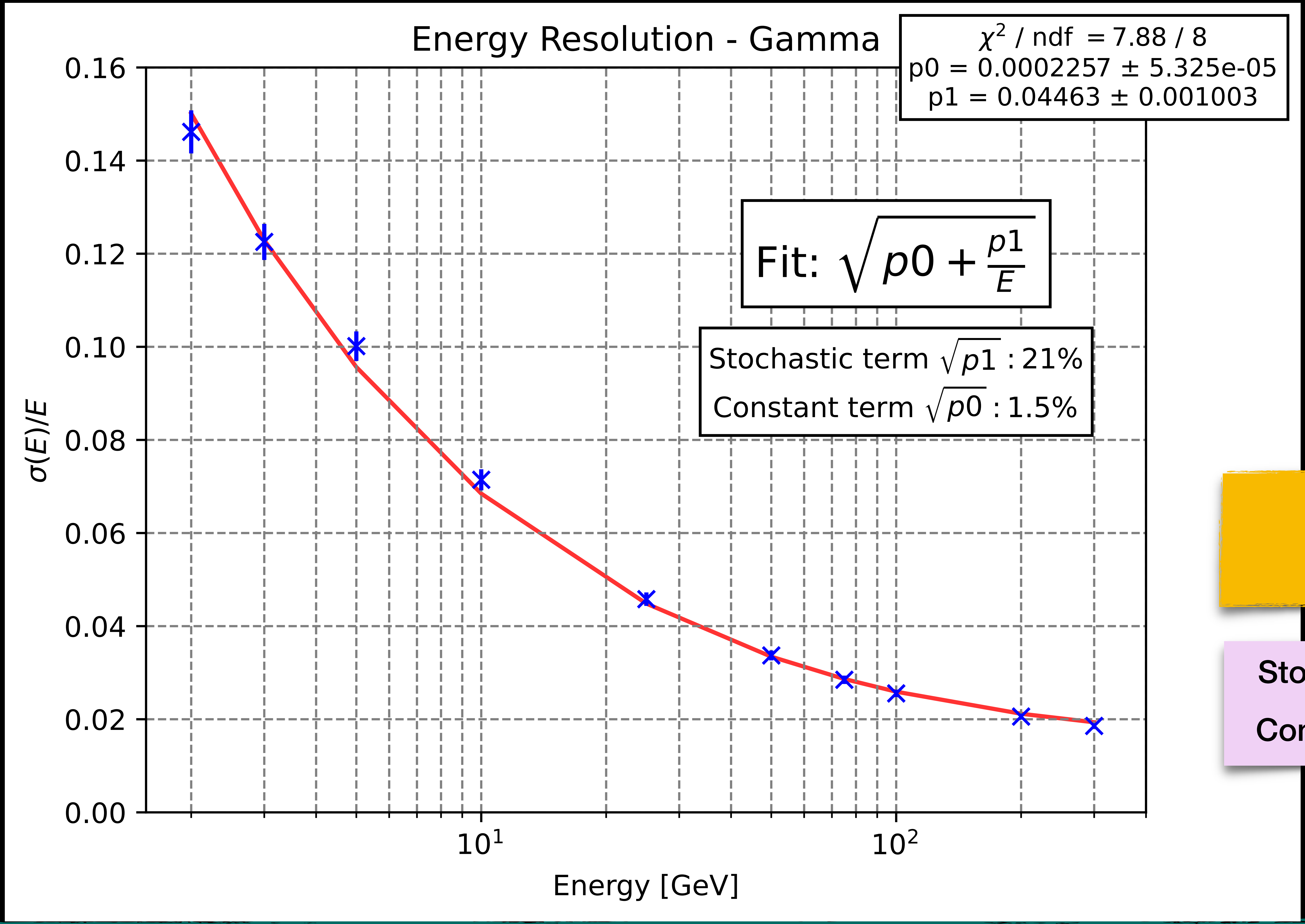


Fig. 15.1 Comparison of typical energy resolutions in a detector. In the example the energy resolutions of electromagnetic and of hadronic calorimeters are assumed to be $\sigma_E^{em}/E = 7\,\%/\sqrt{E}$ and $\sigma_E^{had}/E = 50\,\%/\sqrt{E}$, respectively. For the energy determination by momentum measurement a momentum resolution of $\sigma_p/p = 0.1\,\%\,p$ is assumed. With these values the energy determination by calorimetric measurements becomes better than by momentum measurements at 17 GeV and 63 GeV, respectively.

Energy resolution — Photons

Excellent efficiency of reconstructing low energy clusters



Fit: $\sqrt{p_0 + \frac{p_1}{E}}$

Stochastic term $\sqrt{p_1}$**: 21 %**

Constant term $\sqrt{p_0}$**: 1.5 %**

Calorimeter

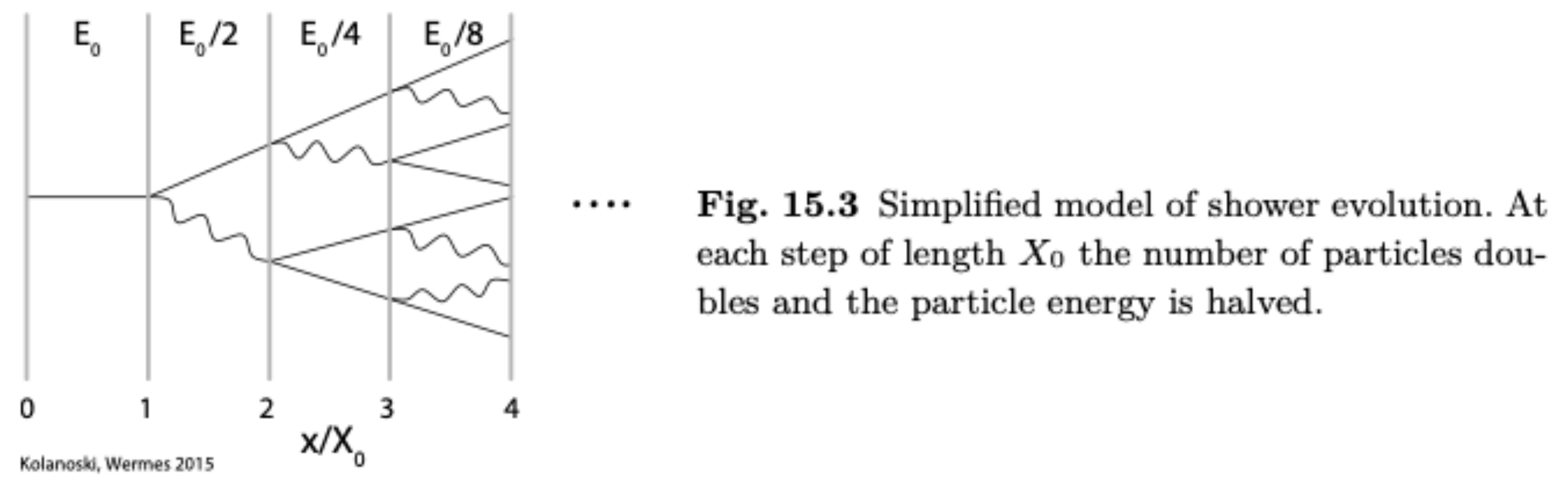


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Fig. 15.3 Simplified model of shower evolution. At each step of length X_0 the number of particles doubles and the particle energy is halved.

Calorimetry

- Distance $s = tX_0$ (t is the path length in units of radiation length)
- The maximum number and energy of particles are: $N = 2^t$, $E = \dfrac{E_0}{2^{t_{max}}}$
- $N_{max} = \dfrac{E_0}{E_c}$, $t_{max} = \dfrac{\ln E_0/E_c}{\ln 2}$

- Homogeneous Calorimeters: Lead Tungstate ($PbWO_4$) Crystals

- This technology, used by the CMS experiment, is designed for the best possible energy resolution. Principle: The entire detector volume is made of a single, dense, scintillating material. The lead tungstate crystal acts as both the material where the particle shower develops (the absorber) and the material that generates the signal (the active medium).

- **High Density & Short Radiation Length:** $PbWO_4$ is extremely dense ($8.3\ g/cm^3$) with a very short radiation length ($X_0 = 0.89$ cm). This allows for a very compact calorimeter that can contain the entire electromagnetic shower of even very high-energy particles within a relatively short depth (~25 cm).

- **Signal Generation:** The signal is scintillation light. As shower particles traverse the crystal, they excite the atoms, which then de-excite by emitting photons.

- **Low Light Yield but Fast Response:** A key feature of $PbWO_4$ is its relatively low light yield compared to other crystals like CsI(Tl). However, its scintillation light is emitted very quickly (about 80% within 25 ns). This fast response is crucial for handling the high event rates at the LHC. The low light yield means a photodetector with internal gain, like an Avalanche Photodiode (APD) or Vacuum Phototriode (VPT), is required for readout.

- **Excellent Energy Resolution:** Because the entire shower energy is converted into a detectable signal (with no sampling fluctuations), the primary limit on resolution comes from the statistics of the scintillation photons. This leads to outstanding energy resolution, especially at high energies where the constant term from calibration and non-uniformities is the limiting factor. The CMS ECAL achieves a resolution with a stochastic term of $a \approx 2.8\% \sqrt{GeV}$.

- **Radiation Hardness:** This specific crystal material was developed to be highly resistant to the extreme radiation environment at the LHC.

- Sampling Calorimeters: Lead & Liquid Argon (Pb/LAr)

- This technology, used by the ATLAS experiment, is designed for high granularity, stability, and robust operation.
  Principle: This is an inhomogeneous detector. It consists of alternating layers of a dense absorber material (lead plates) and a separate active medium (liquid argon). The shower develops primarily in the lead, and the charged particles are then "sampled" as they cross the liquid argon gaps.

- Signal Generation: The signal is ionization charge. As shower particles pass through the liquid argon, they ionize the argon atoms, creating electron-ion pairs. An applied high voltage drifts these electrons to segmented electrodes, inducing a current signal.

- Accordion Geometry: The ATLAS calorimeter uses a unique accordion-like shape for its lead plates and electrodes. This allows for a completely hermetic design (no cracks) in the azimuthal direction and enables fast signal readout since the connections are at the front and back, not on the sides.

- High Granularity: Because the signal is collected on finely segmented electrodes, it is relatively easy to achieve very high granularity both laterally and longitudinally (in depth). This is excellent for distinguishing electrons from jets, identifying photons from π^0 decays, and precisely measuring the shower position and direction.

- Intrinsic Radiation Hardness & Stability: Liquid argon is an intrinsically radiation-hard active medium. Its response does not degrade over time, and it is very stable in its properties, simplifying calibration.

- Good, but Not Superior, Energy Resolution: The energy resolution is fundamentally limited by sampling fluctuations. Since only a fraction of the total shower energy is deposited in the active medium, there are statistical fluctuations in how much energy is sampled in each event. This leads to a larger stochastic term in the resolution formula compared to a homogeneous crystal calorimeter. The ATLAS ECAL achieves a resolution with a stochastic term of a $\approx 10\% \sqrt{\text{GeV}}$.