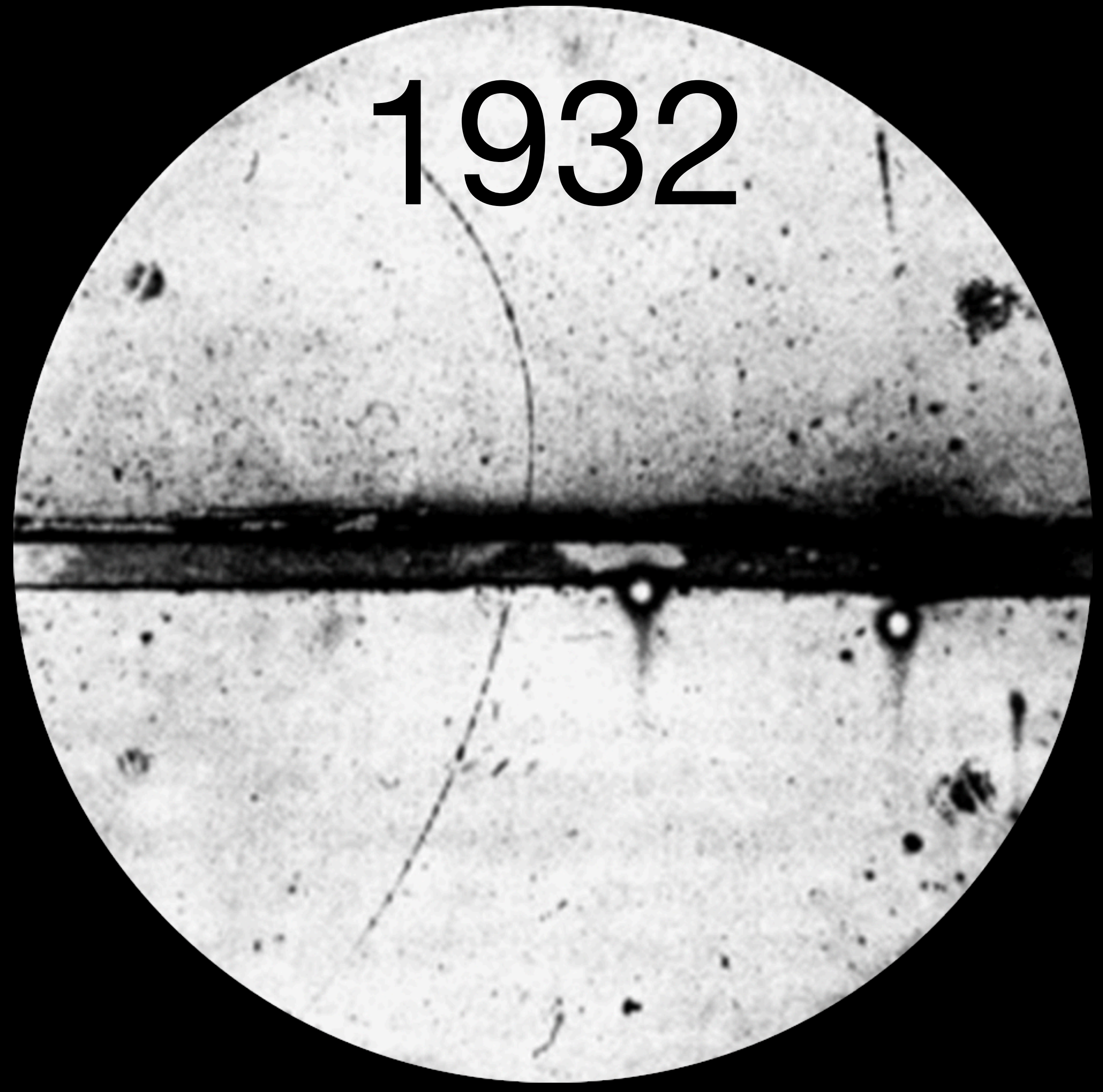
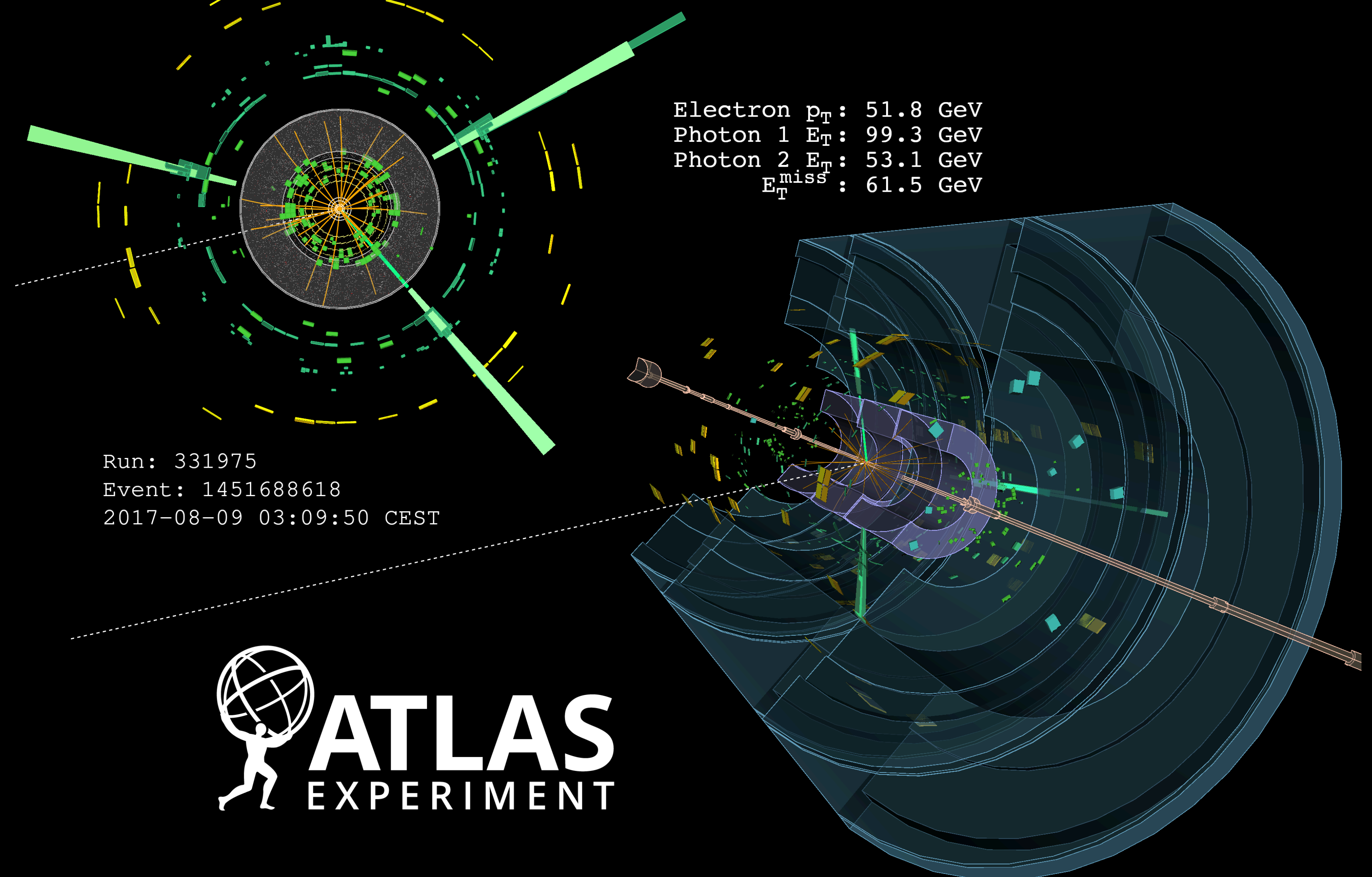
PHYS 7363 - Experimental Particle Detection and Detectors I



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

Fitting exercise 1

Fit the following data and determine what is the fitting function.

Where have you encountered this fitting function?

Fitting exercise 2

Fit the following data and determine what is the fitting function.

How is this function relevant to high energy physics?

Fitting exercise 2

Fit the following data and determine what is the fitting function.

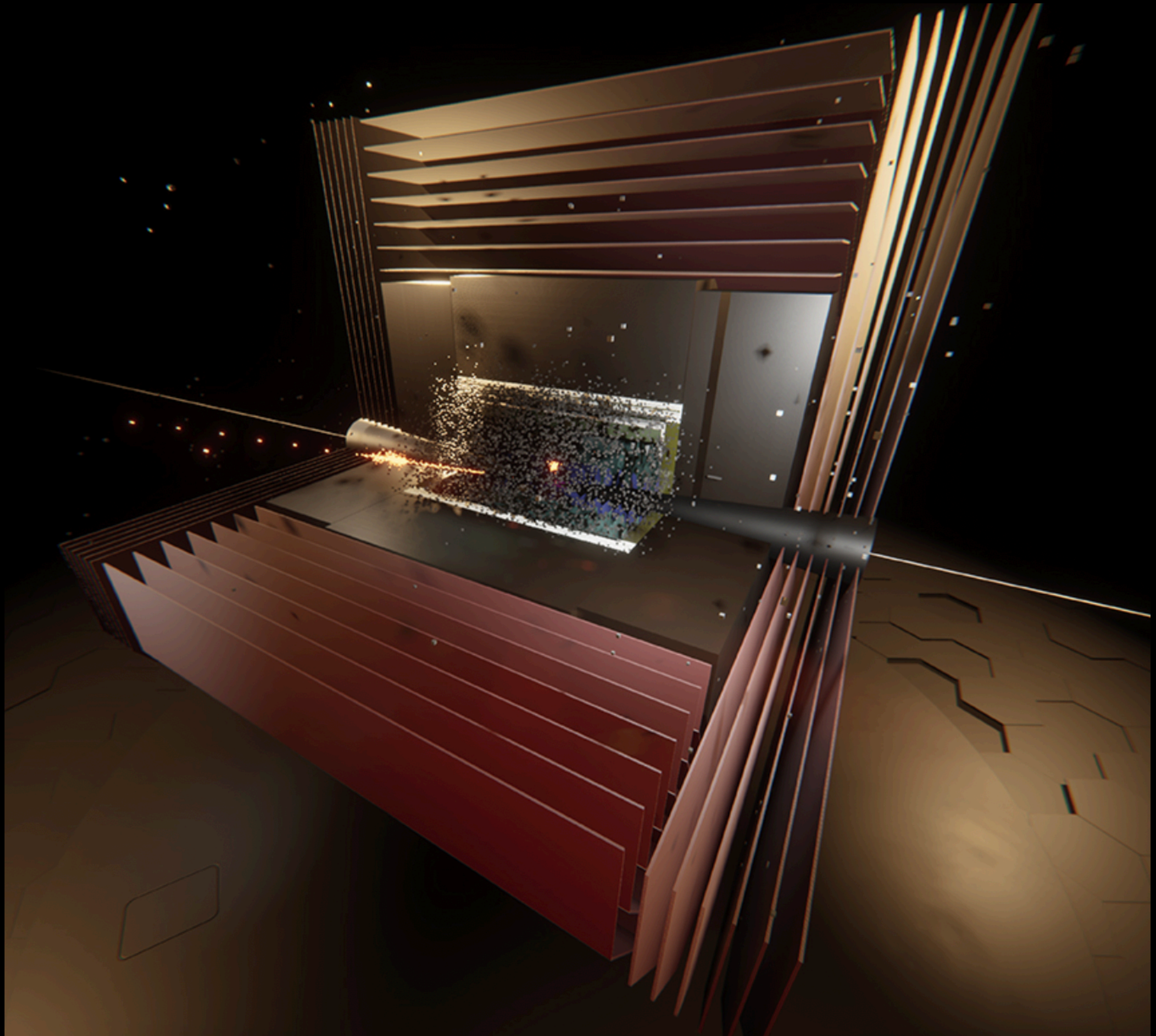
How is this function relevant to high energy physics?

The energy transfer fluctuations in individual collisions along a particle's path lead to an asymmetric distribution ($f(\Delta E; \Delta x)$) which has a Gaussian part, corresponding to the many ionization processes with small energy loss, and a tail to large energy loss value

Large energy loss corresponds to the comparatively rarely occurring hard collisions in which much energy is transferred to individual electrons

Setting up the code

- Muon collider: https://mcd-wiki.web.cern.ch/software/tutorials/fermilab2024/



Semiconductor detectors

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 $a \approx 10\% \sqrt{\text{GeV}}$.