Calorimetry

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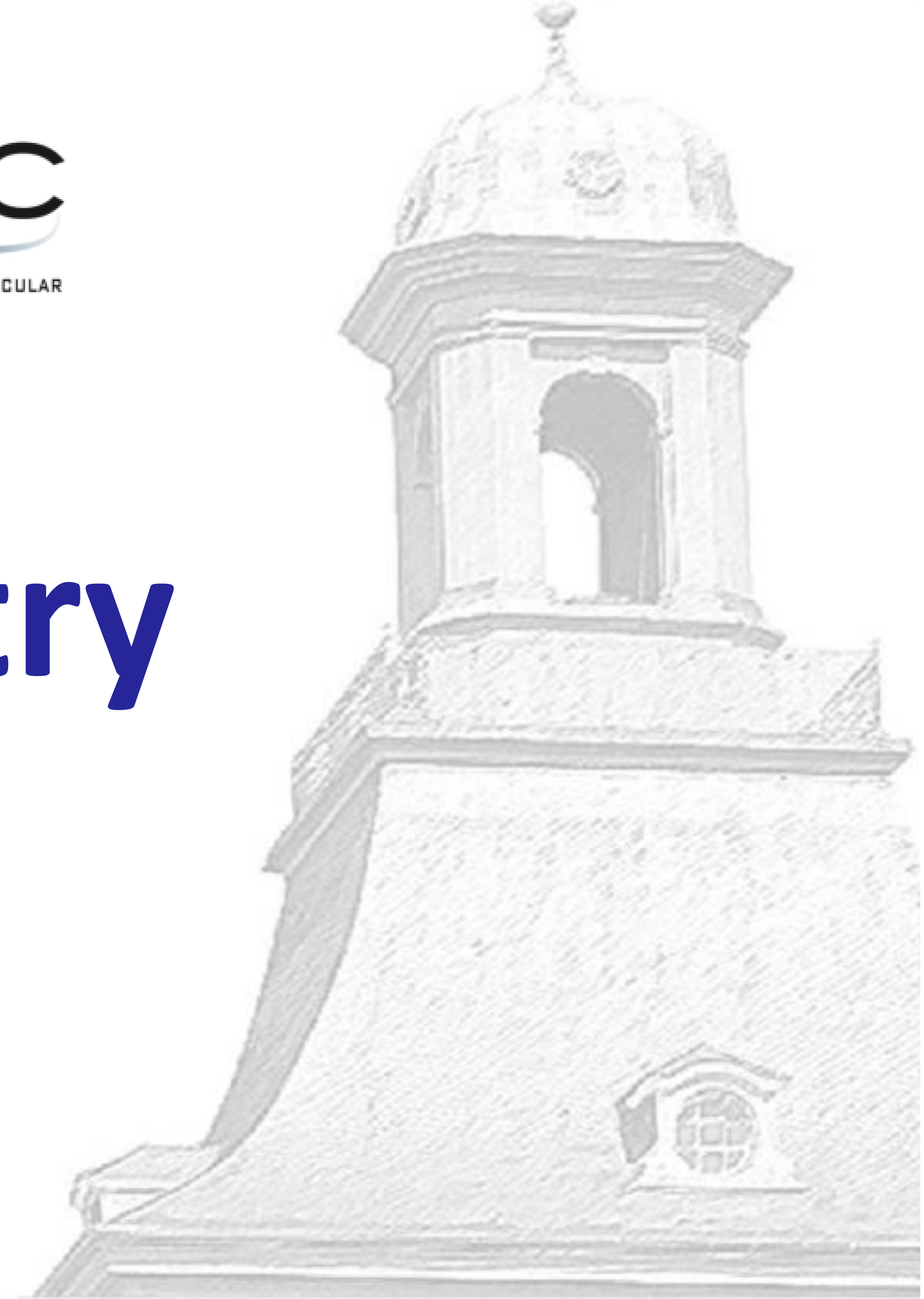

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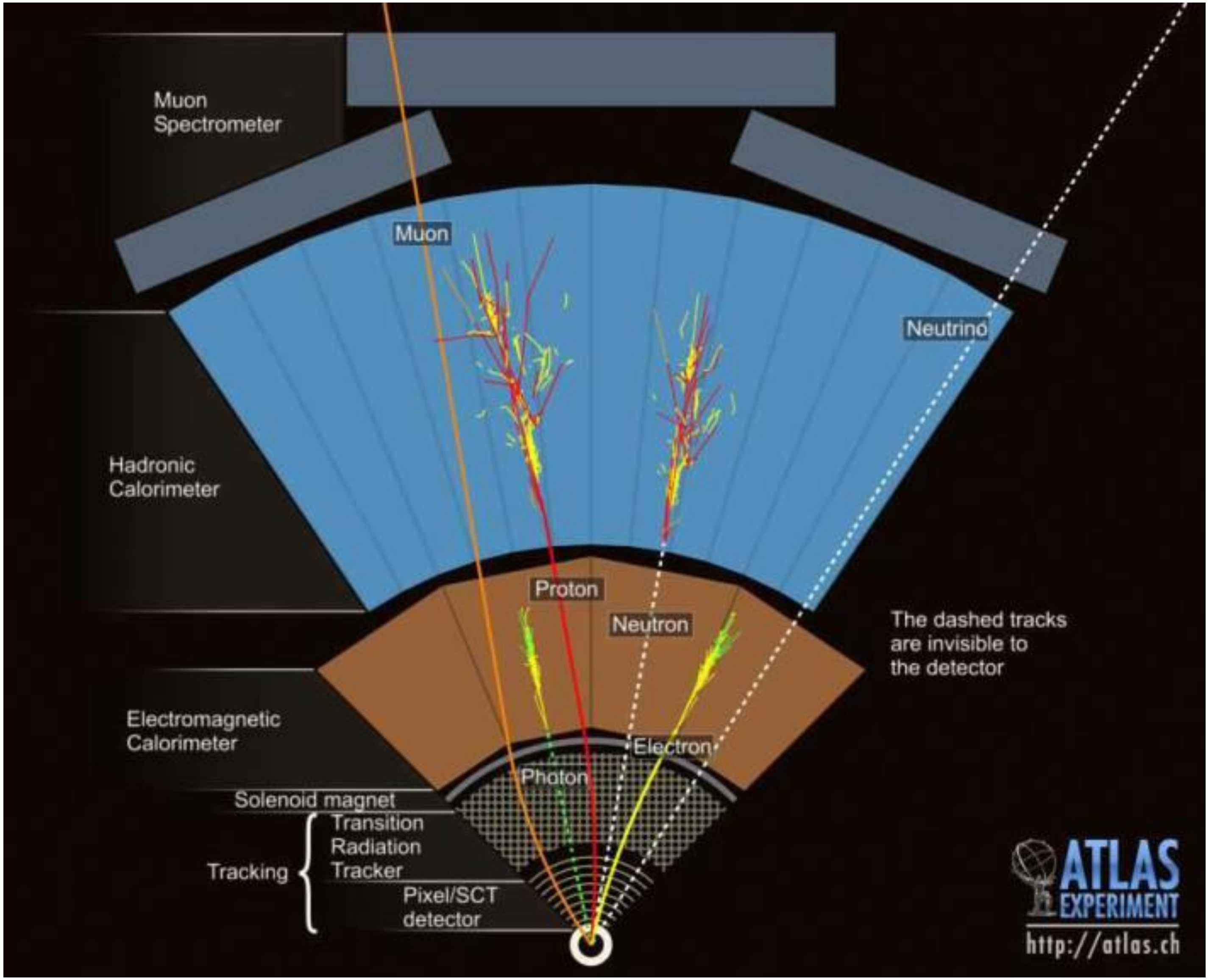
Outline

- Brief historical summary
- Electromagnetic showers
- Sampling and homogeneous calorimeters
- New calorimetric trends

Structure of one ‘generic’ detector



Calorimetry as a Particle Detection Technique

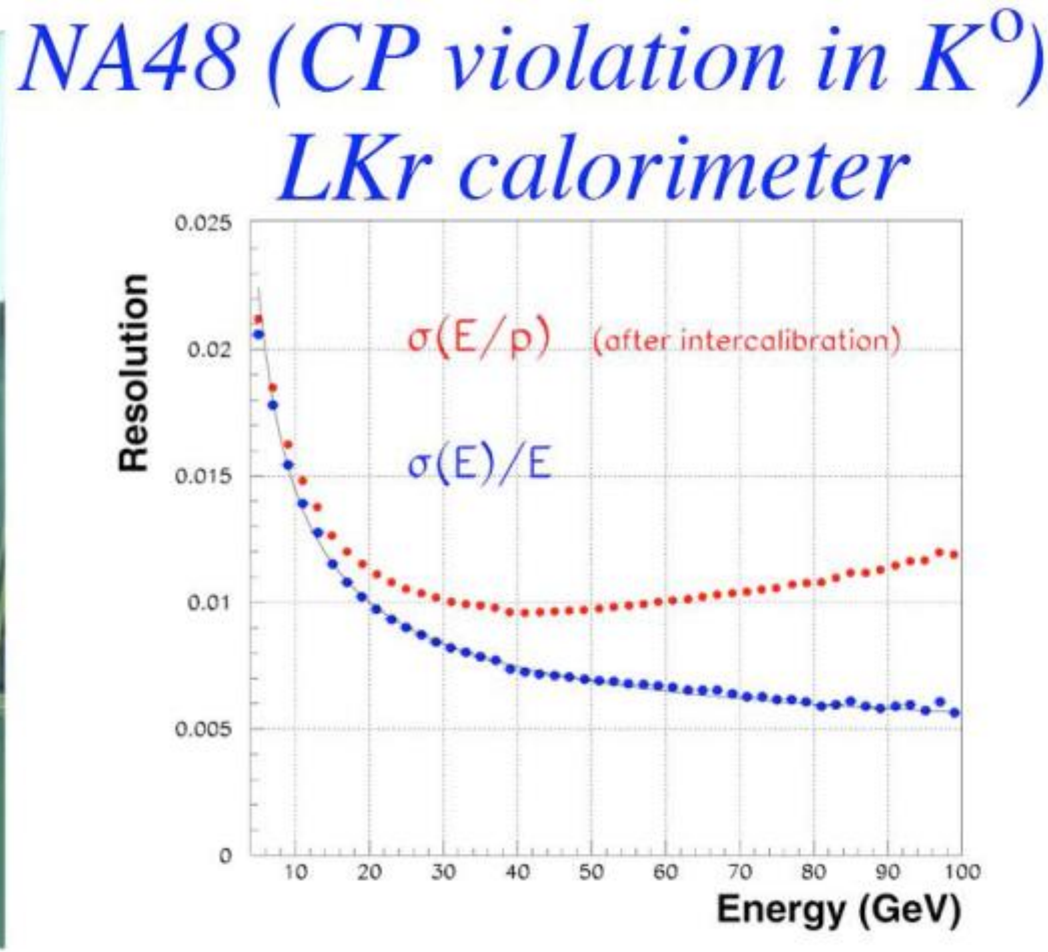
- In the 1960's, particle physics started to make the transition from the bubble chamber era to experiments based on electronic counters

- The detectors basically formed a magnetic spectrometer in which all charged particles produced in reactions on a fixed target were analyzed:
  - Momentum from effects from Lorentz force
  - Energy (mass) from time of flight or dE/dx

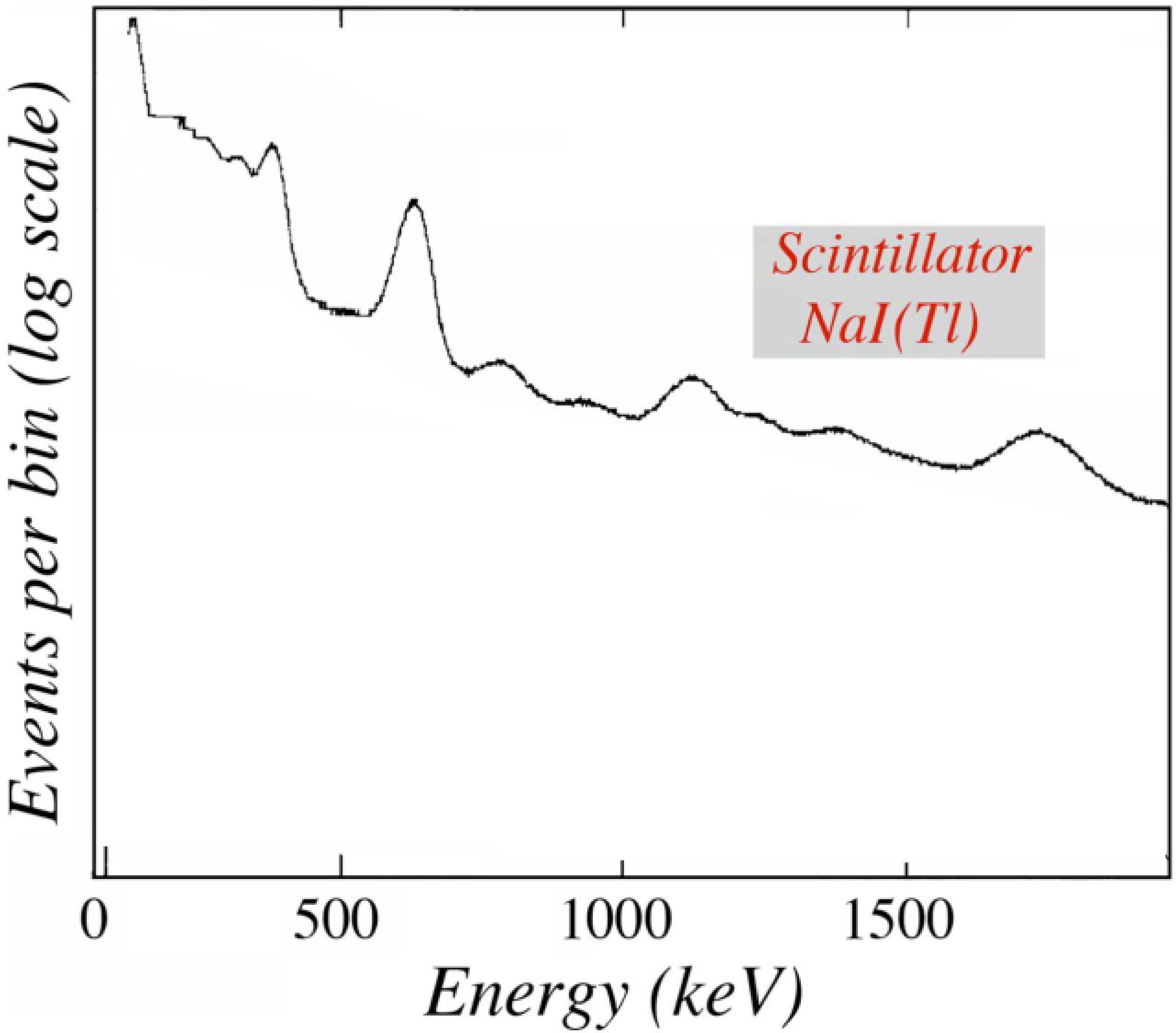
- For the detection of the neutral reaction products (gammas from π^0 decay), scintillating crystals were used, called 'shower counters'

- Using properly chosen materials (high Z), even high-energy gammas be fully absorbed in detectors of limited length (<30 cm) and be measured with spectacularly good energy resolution

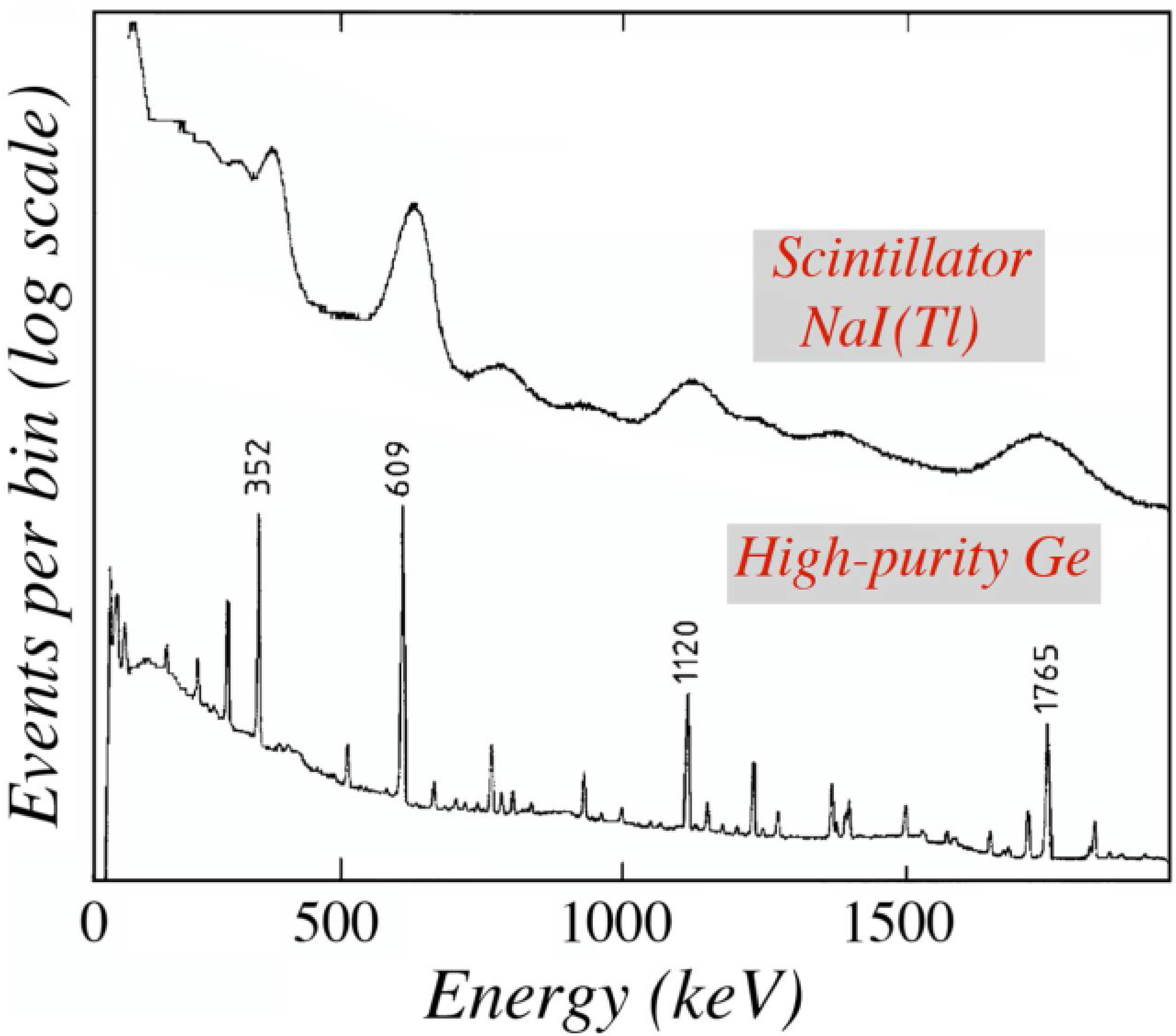
Ultra-high Energy Resolution



Importance of High Energy Resolution



Importance of High Energy Resolution



Better is always better

Brief History

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- To save money, large calorimeters were built as sampling devices: functions of absorption and signal generation carried out by different materials

- For active material, typically plastic scintillator, liquid argon, scintillating fibers and semiconductor pads.
- As for absorbers, typically lead due to the short radiation length

- But, other particles also generated in these calorimeters. The detectors were non-linear and the response depended on the type of particle (pions and protons, for example)

Additional Facts

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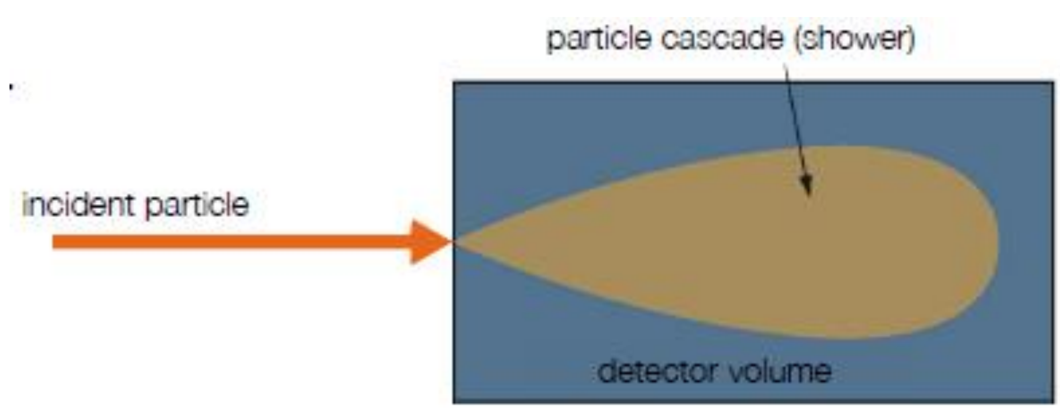
- In the 70s, the calorimetric systems took on new tasks:
  - High energy neutrino experiments as target and trigger
  - Collider experiments: Energy flow (missing E_T, jets)
  - Particle identification
- They turned out to be very suitable for such tasks and this is the reason why they have become one of the central components of any detector system at accelerator-based HEP experiments

Calorimeters

... where most of the particles end their journey...

Calorimetric methods imply total absorption of the particle energy in a bulk of material followed by the measurement of the deposited energy.

Photons, electrons and hadrons interact with media producing secondary particles which leads to a shower development. Thus calorimeters are most widely used in high energy physics to detect the electromagnetic (electromagnetic calorimeters) and hadronic (hadron calorimeters) showers.



Electromagnetic calorimeter

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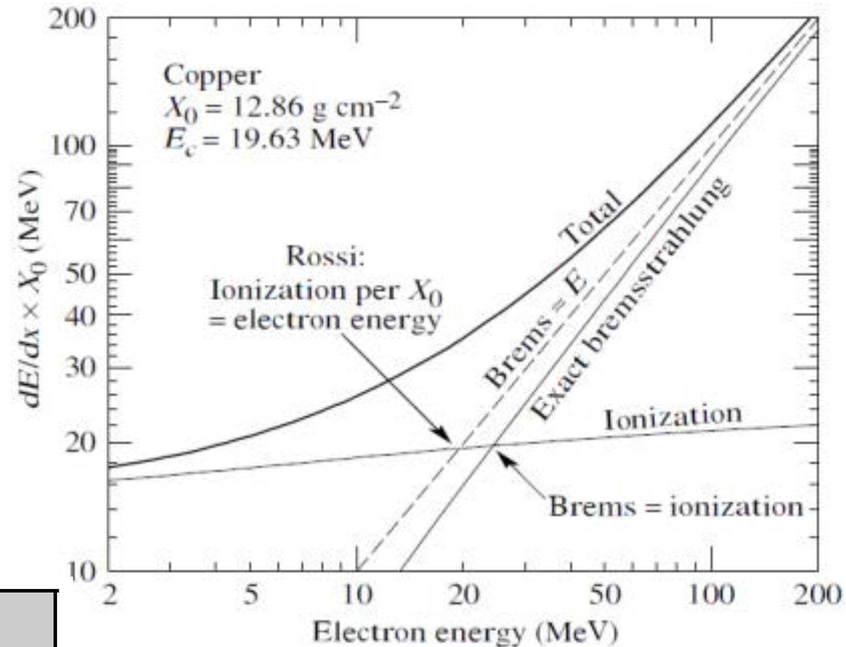
- **Radiation length** (X_0): Mean distance over which the electron energy is reduced by a factor 1/e due to bremsstrahlung, and 7/9 of the mean free path for pair production by a high energy photon.

- The **Molière radius** (R_M) is the radius of a cylinder containing on average 90% of the shower's energy deposition. It is related to X_0 by: $\boldsymbol{R_M = 21\ \mathrm{MeV} \cdot X_0/E_c}$.
A smaller Molière radius means better shower position resolution, and better shower separation due to a smaller degree shower overlaps.
The Molière radius is a good scaling variable in describing the transverse dimension of the fully contained e.m. showers initiated by an incident high energy electron, positron or photon.

- **Critical Energy** (E_c): At high energy, the energy loss of an electron from bremsstrahlung dominates over ionization loss.
At a low enough energy, the ionization loss becomes important.
The energy at which the ionization loss equals bremsstrahlung loss, is the critical energy (Ec). At this point, the cascade will stop abruptly. $\boldsymbol{E_c^{Gas} = 710\ \mathrm{MeV}/(Z_{material} + 0.92)}$

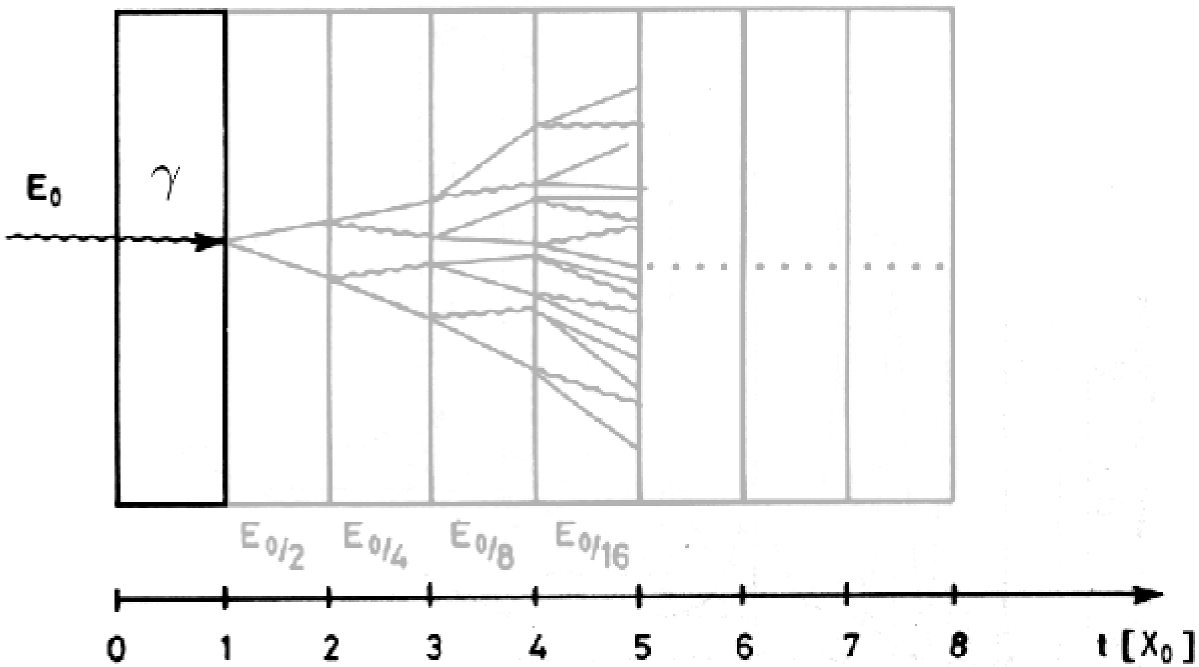
Shower depth: $L \approx \mathrm{Ln}\,(E/E_c)$

$$\left.\frac{dE}{dx}(E_c)\right|_{\text{Brems}} = \left.\frac{dE}{dx}(E_c)\right|_{\text{Ion}}$$



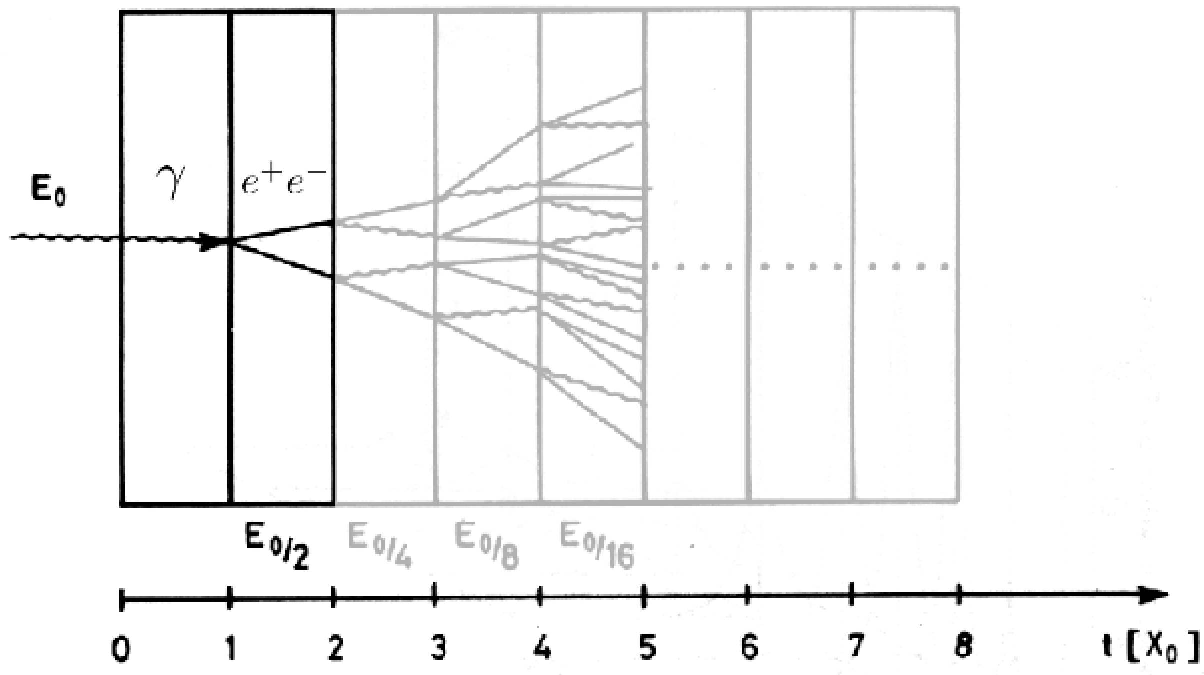
	X_0 [cm]	E_c [MeV]	R_M [cm]
Pb	0.56	7.2	1.6
Scintillator (Sz)	34.7	80	9.1
Fe	1.76	21	1.8
Ar (liquid)	14	31	9.5
BGO	1.12	10.1	2.3
Sz/Pb	3.1	12.6	5.2
PB glass (SF5)	2.4	11.8	4.3

E.m. Shower evolution



Depth of the shower

E.m. Shower evolution



Depth of the shower

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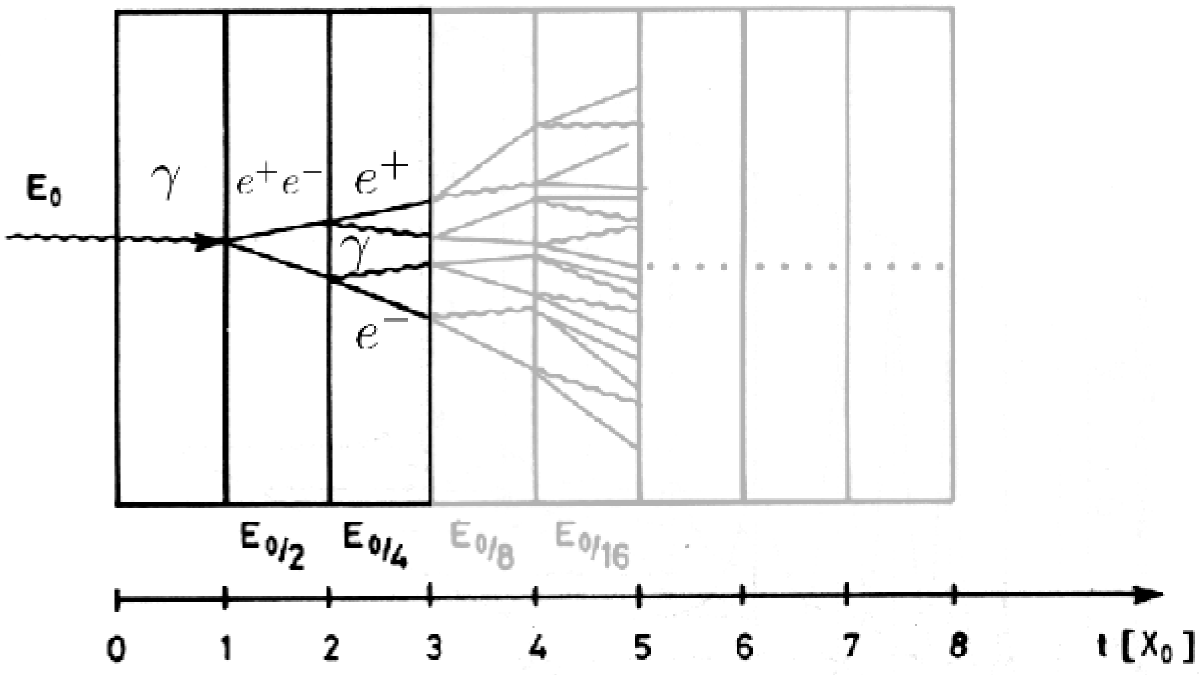
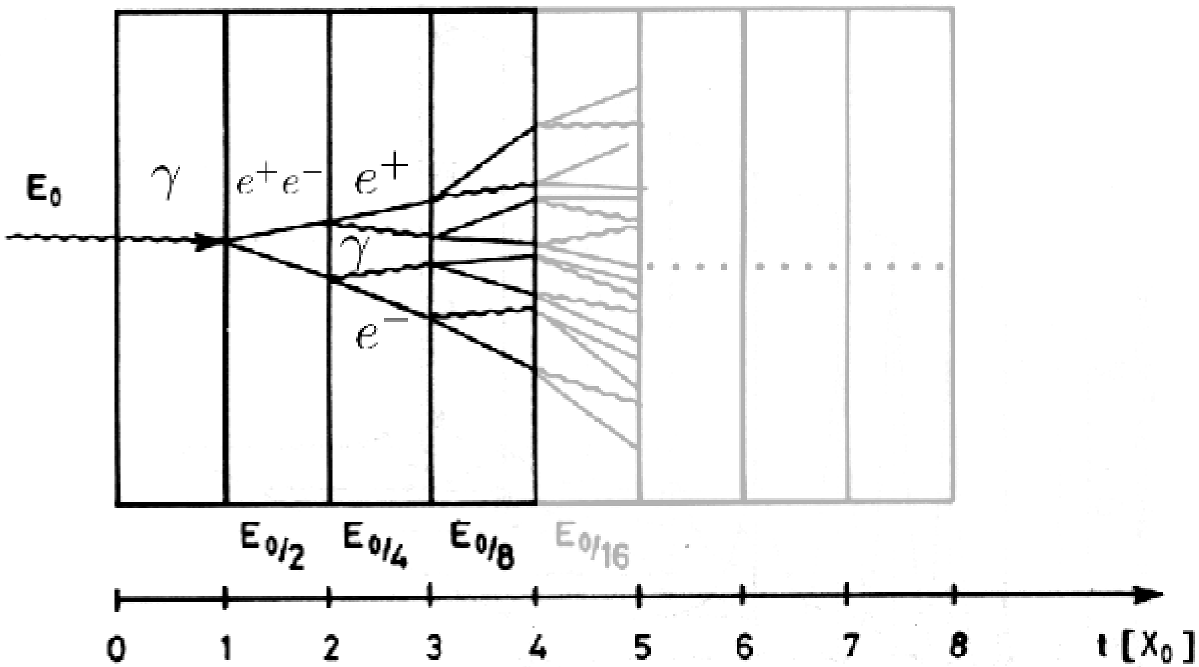


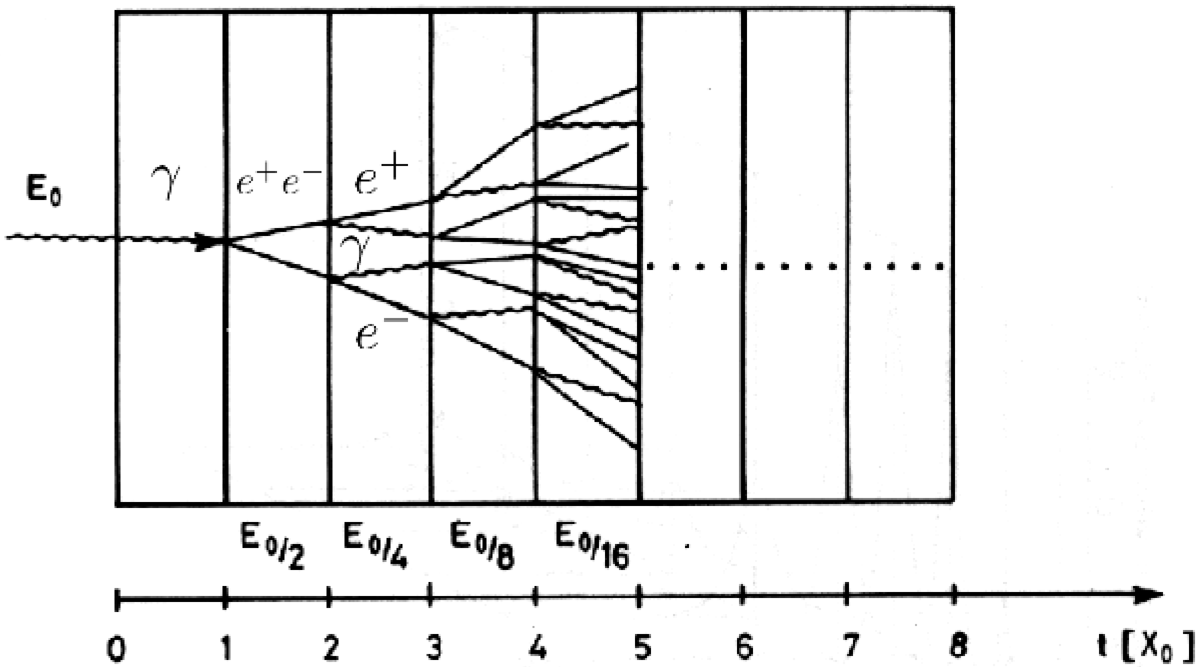
Depth of the shower

E.m. Shower evolution



Depth of the shower

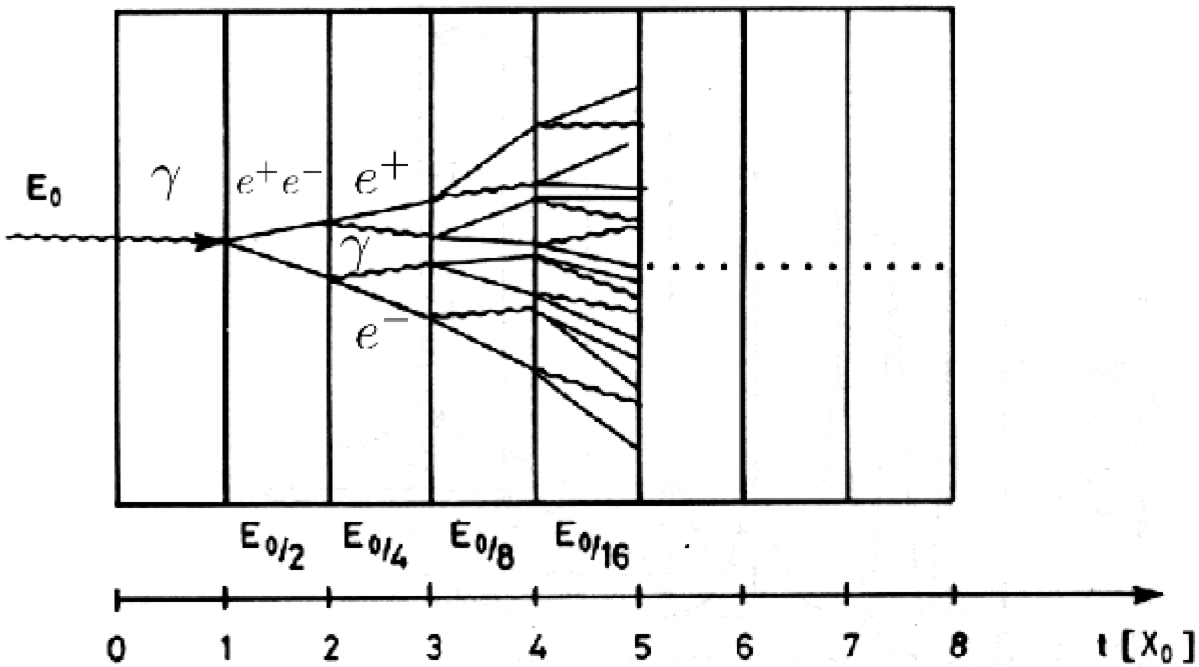
E.m. Shower evolution



The cascade is stopped if the energy of the e+e- pair produced drops below the critical energy

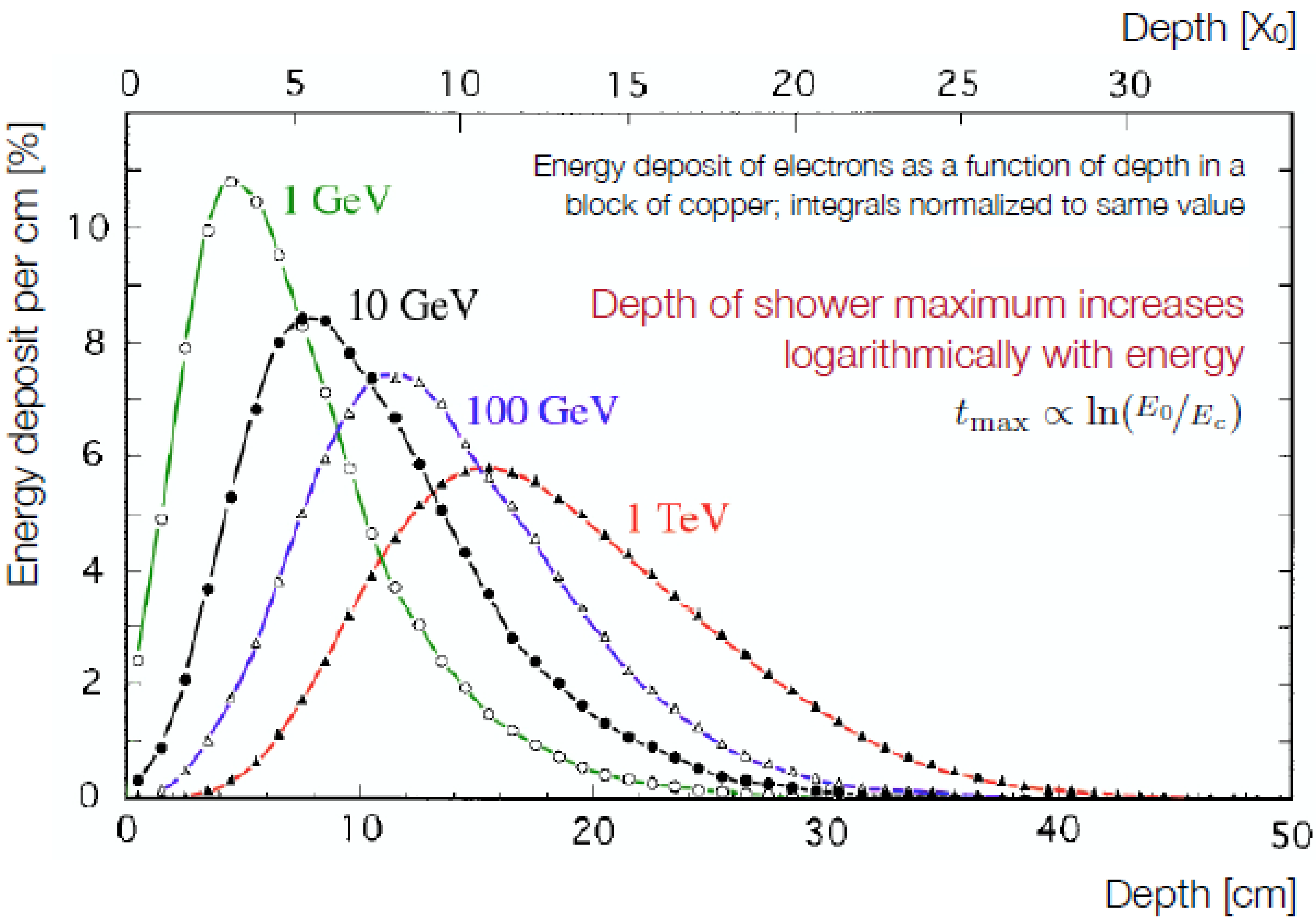
E.m. Shower evolution: simple model

ε(t) Fracc. Incident E	1	1/2	1/4	1/8	...
N(t) Number of cascades	1	2	4	8	...



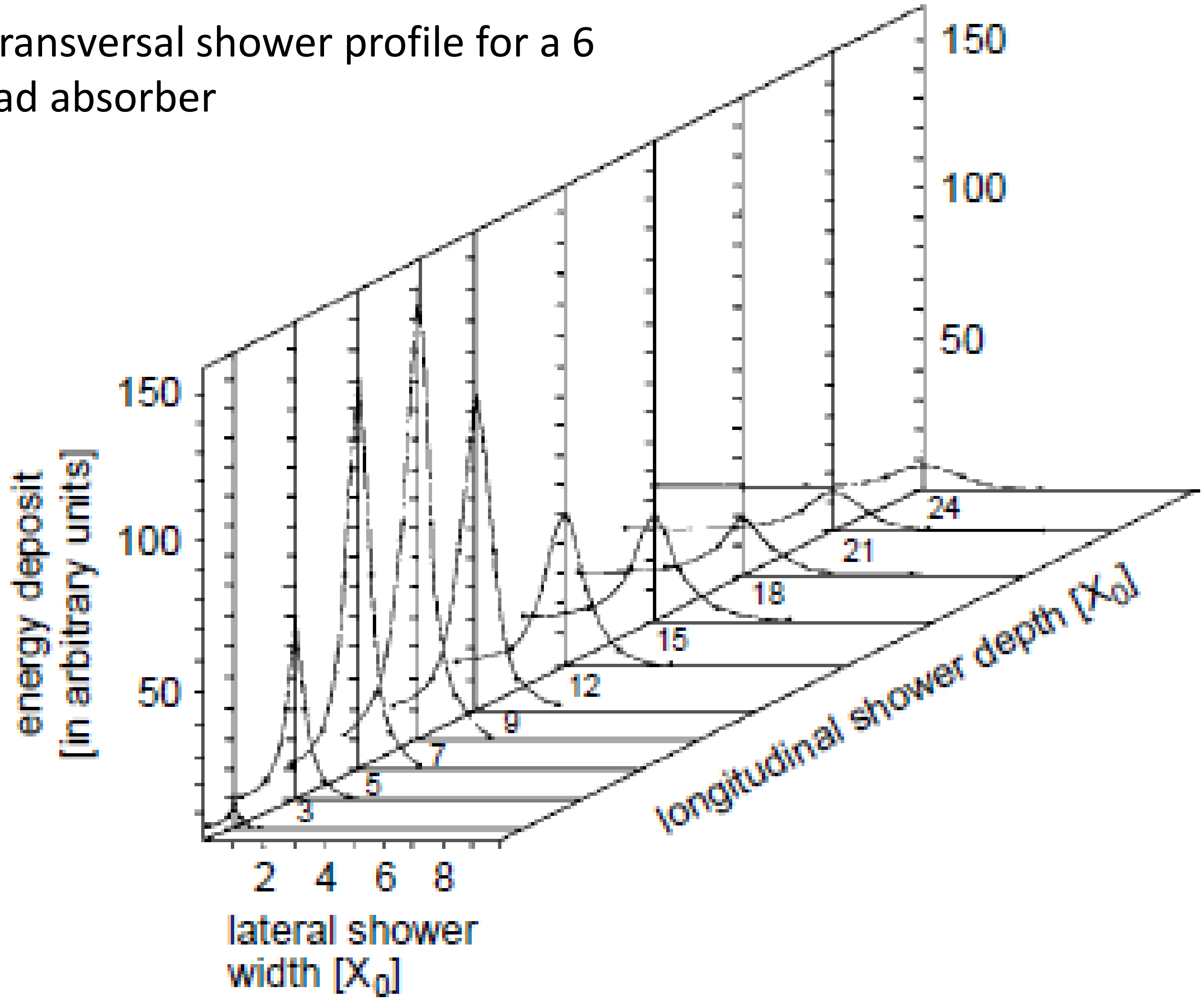
Depth of the shower

Longitudinal Shower Shape

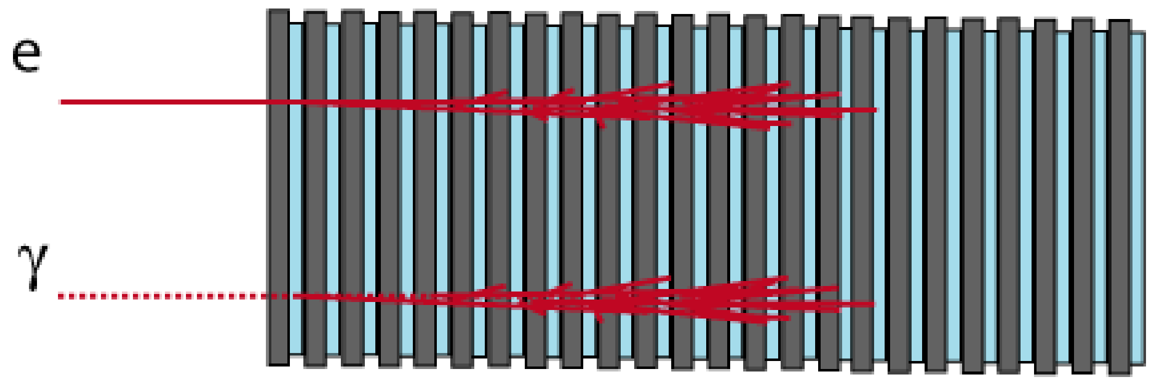


Electromagnetic Shower Profile

Longitudinal and transversal shower profile for a 6 GeV electron in lead absorber



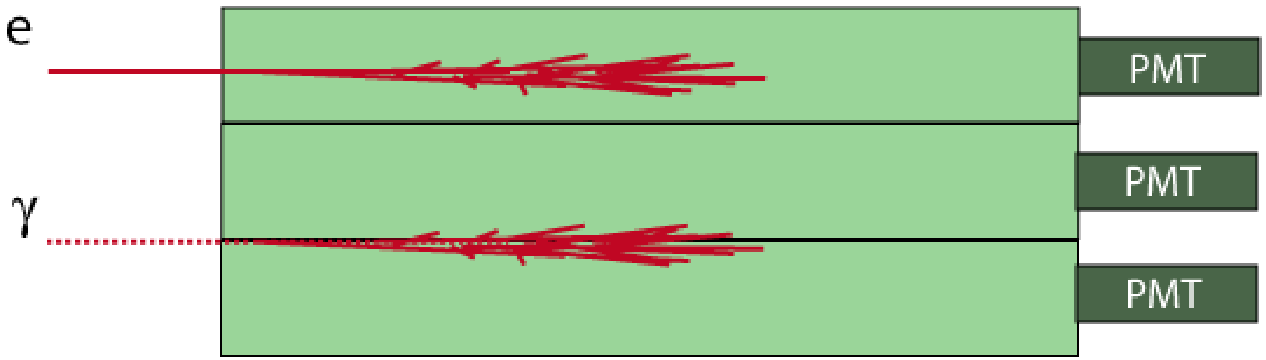
Sampling and Homogeneous Calorimeters



Sampling calorimeter
Alternating layers of absorber and active material

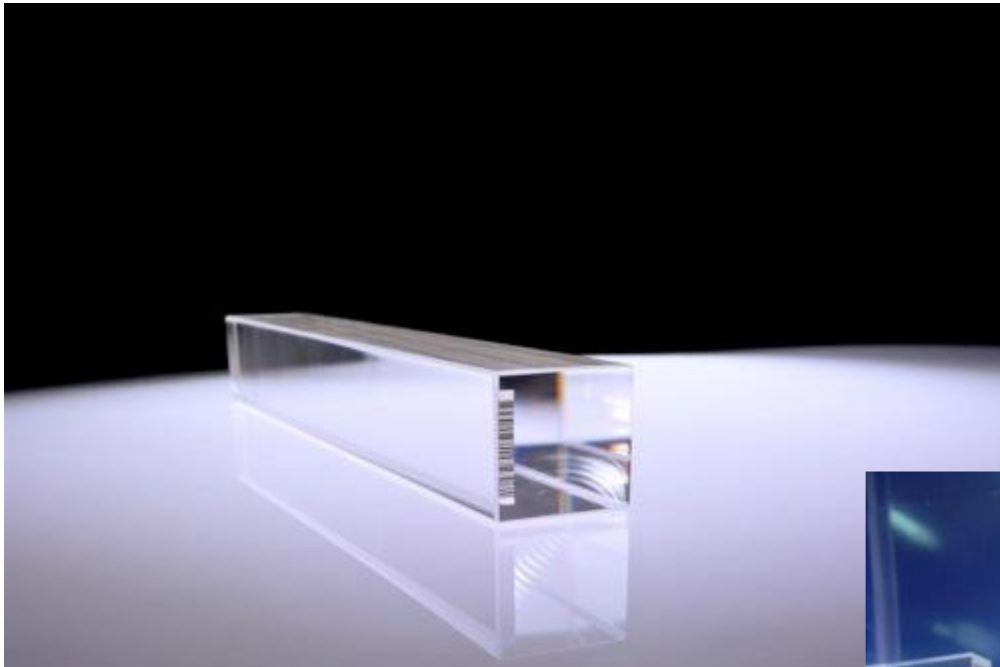
Homogeneous calorimeter
The active material y the absorber itself

Homogeneous calorimeter

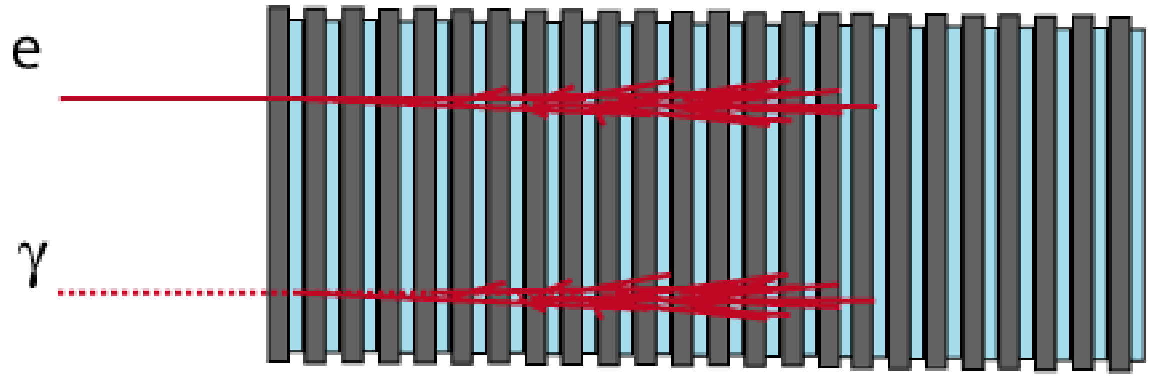


Homogeneous calorimeter
The active material y the absorber itself

- ★ Advantage: homogenous calorimeters provide optimal energy resolution
- ★ Disadvantage: very expensive
- ★ Homogenous calorimeters are exclusively used for electromagnetic calorimeter, i.e. energy measurement of electrons and photons



Sampling calorimeter



Sampling calorimeter
Alternating layers of absorber and active material

★ Advantages:

By separating passive and active layers the different layer materials can be optimally adapted to the corresponding requirements ...

By freely choosing high-density material for the absorbers one can built very compact calorimeters ...

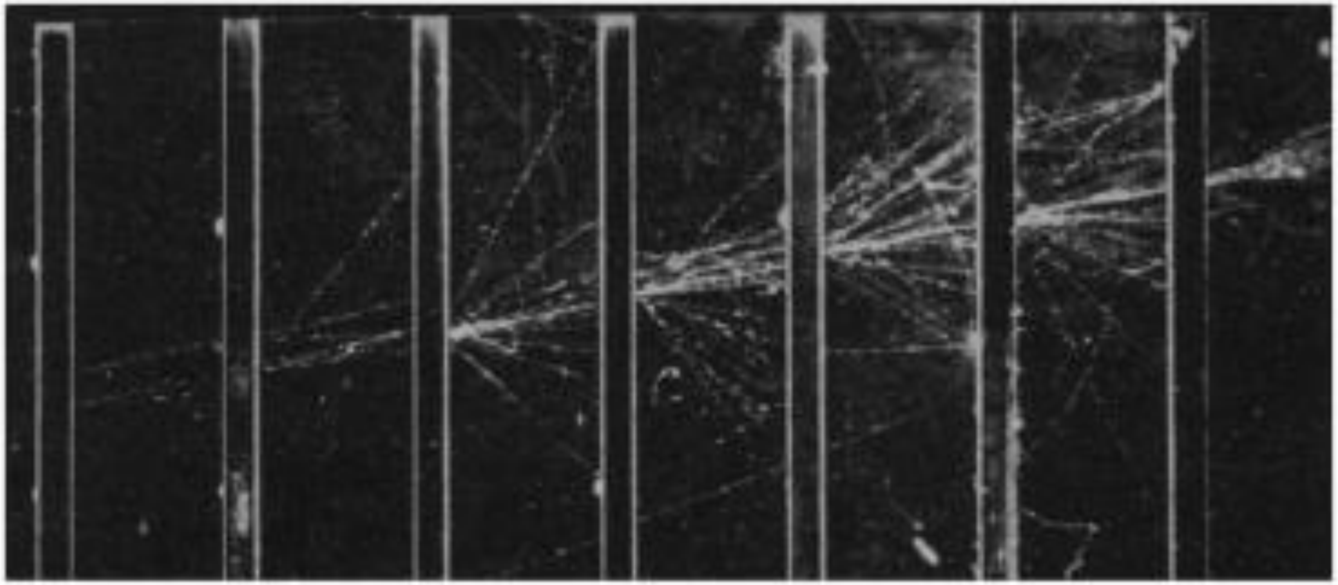
Sampling calorimeters are simpler with more passive material and thus cheaper than homogeneous calorimeters ...

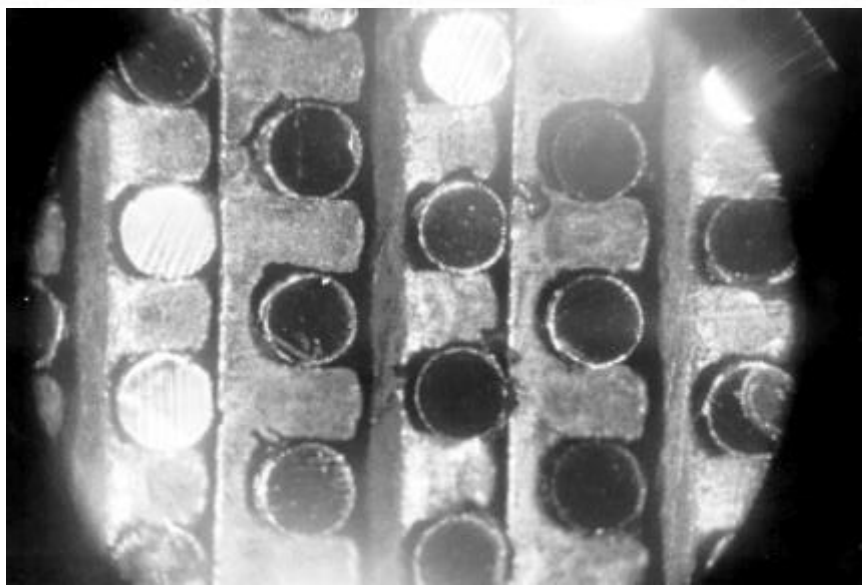
★ Disadvantages:

Only part of the deposited particle energy is actually detected in the active layers; typically a few percent [for gas detectors even only $\sim 10^{-5}$] ...

Due to this sampling-fluctuations typically result in a reduced energy resolution for sampling calorimeters ...

Examples

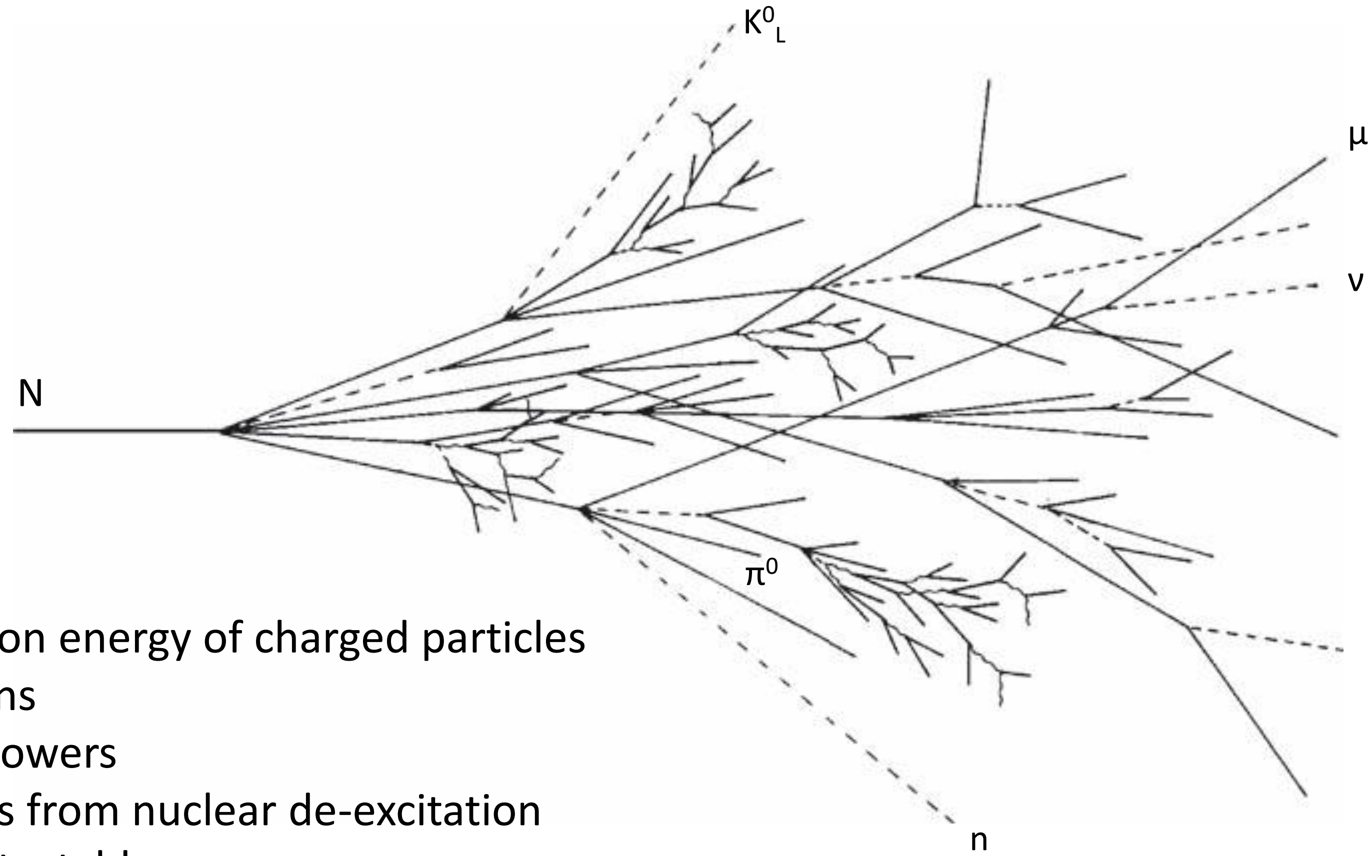




H1 Spaghetti calo

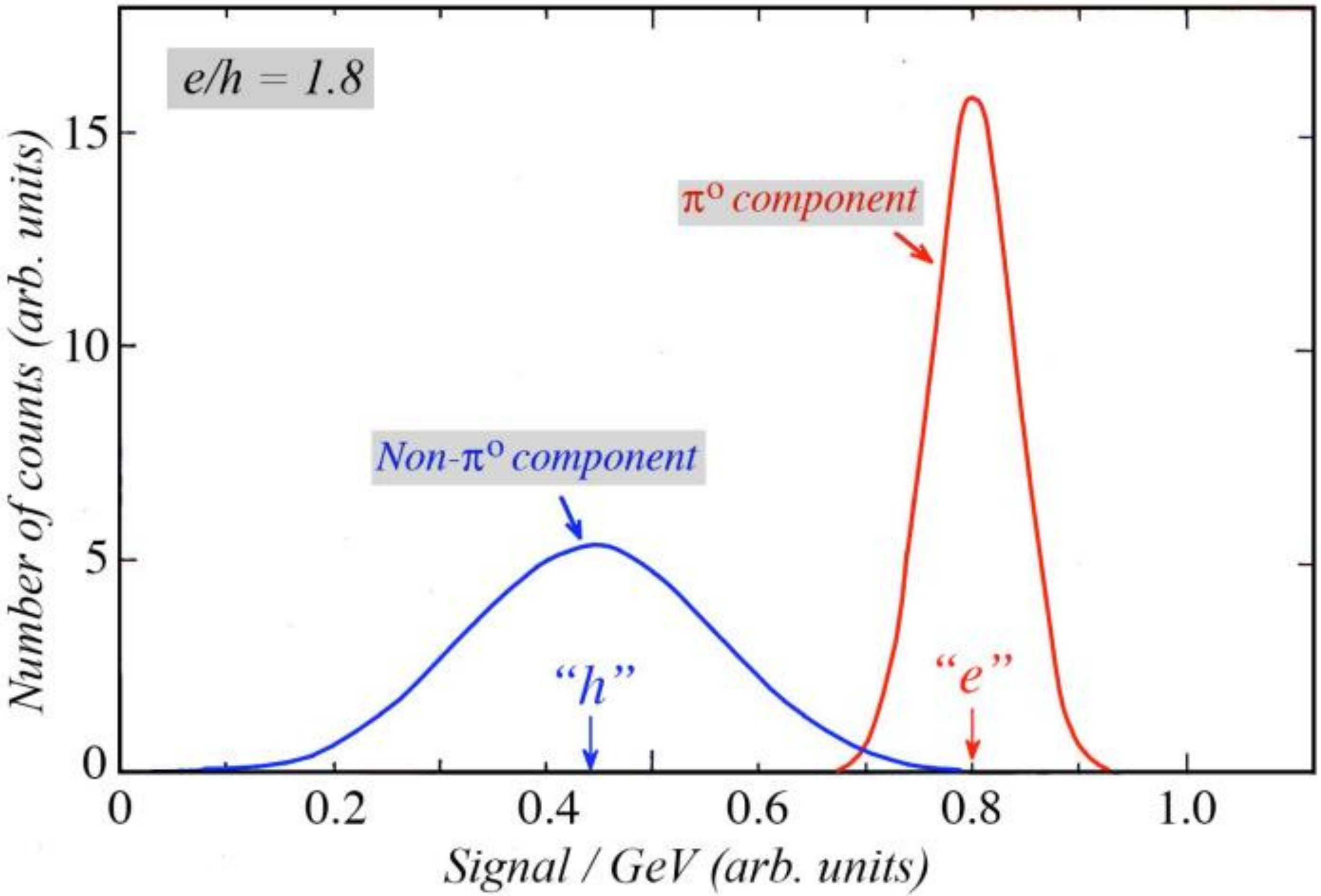
Hadronic Shower

Situation much more complex !!!



- Ionization energy of charged particles
- Neutrons
- e.m. Showers
- Photons from nuclear de-excitation
- Non detectable energy

Hadron Calorimeter Response

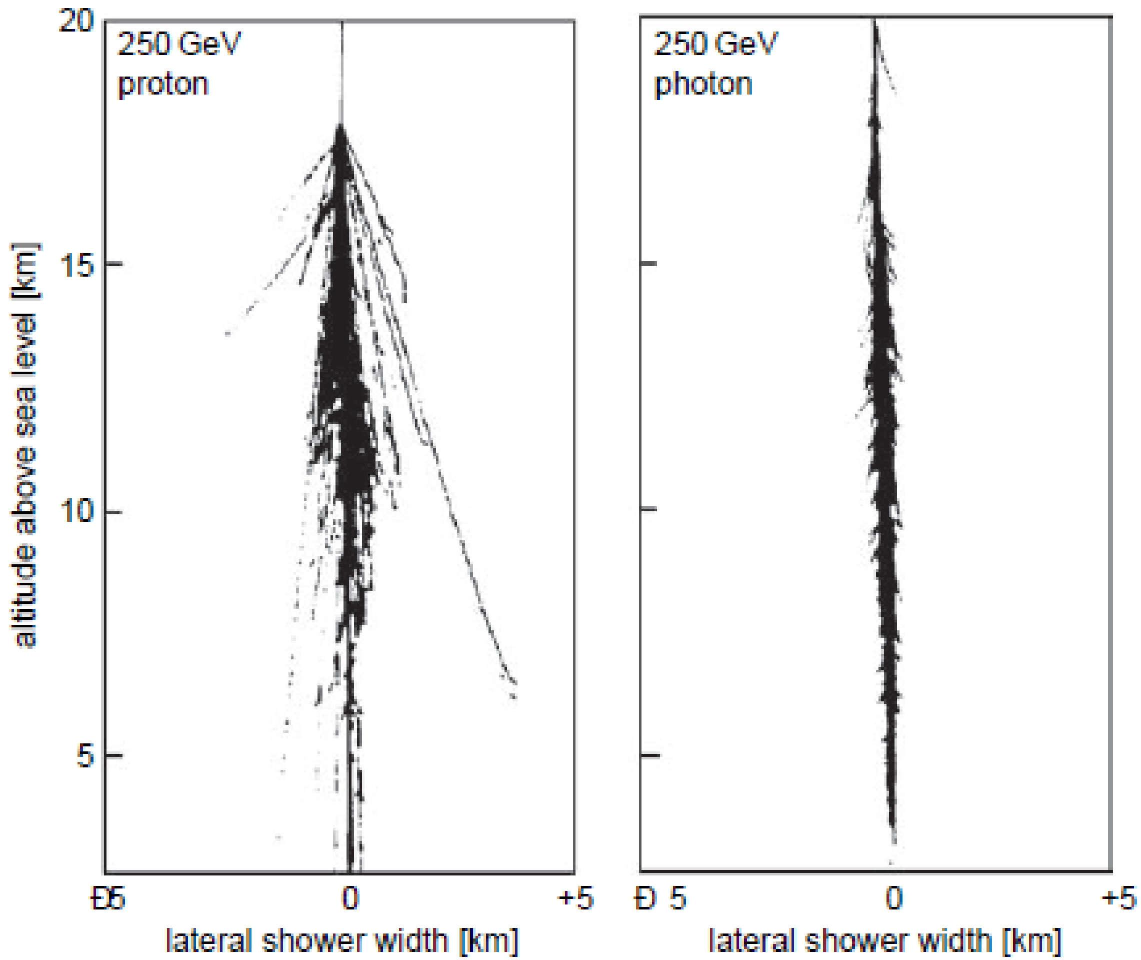


The calorimeter response to the two shower components is not the same

Large, non-Gaussian fluctuations in energy sharing em/non-em

Large, non-Gaussian fluctuations in invisible energy losses

MC Hadronic and E.M. Cascades



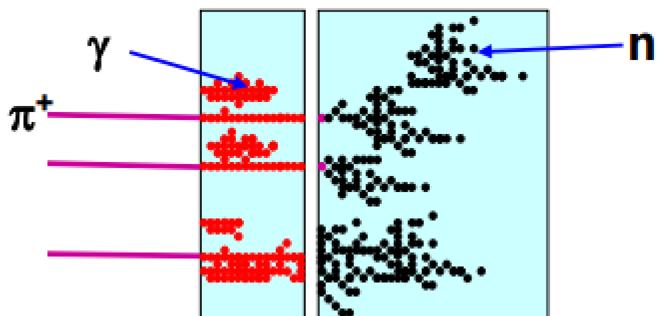
The Particle Flow Paradigm

In a typical jet:

- 60% of jet energy comes from charged hadrons
- 30% from photons
- 10% neutral hadrons

In the traditional calorimetric approach, we would use the ECAL+HCAL:

↘ Energy determination mainly limited by the HCAL resolution



$$E_{JET} = E_{ECAL} + E_{HCAL}$$

The Particle Flow Paradigm

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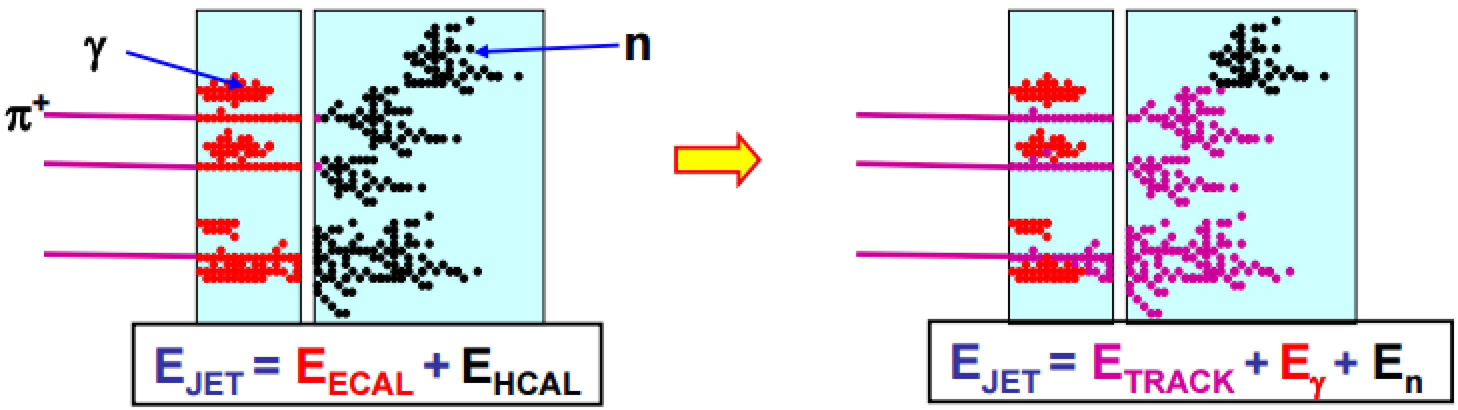
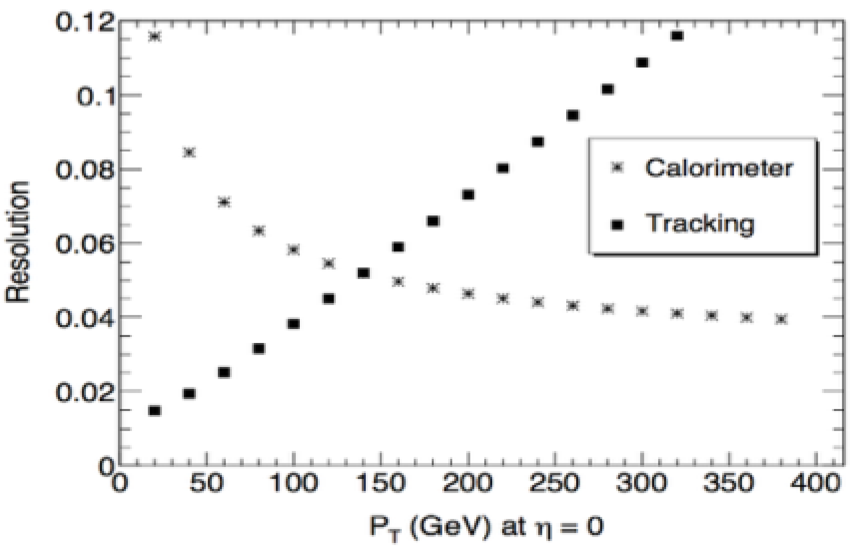
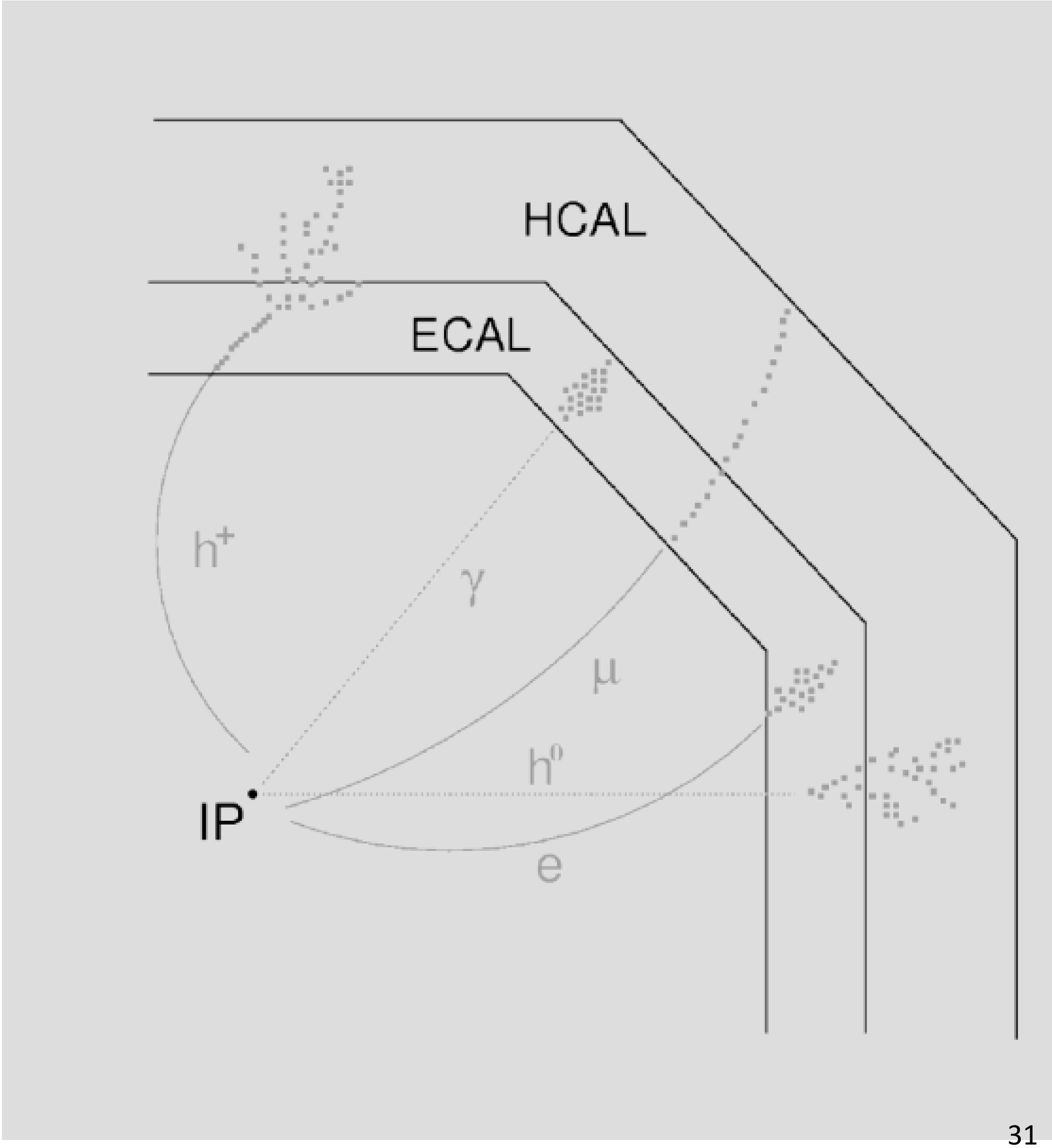


- Charged particles with **tracker**
- Photons with ECAL
- Neutral hadrons with HCAL

Particle Flow: How does it work?

PFA tries to follow the path of the particles through the detector, emphasizing the role of the trackers in jet physics





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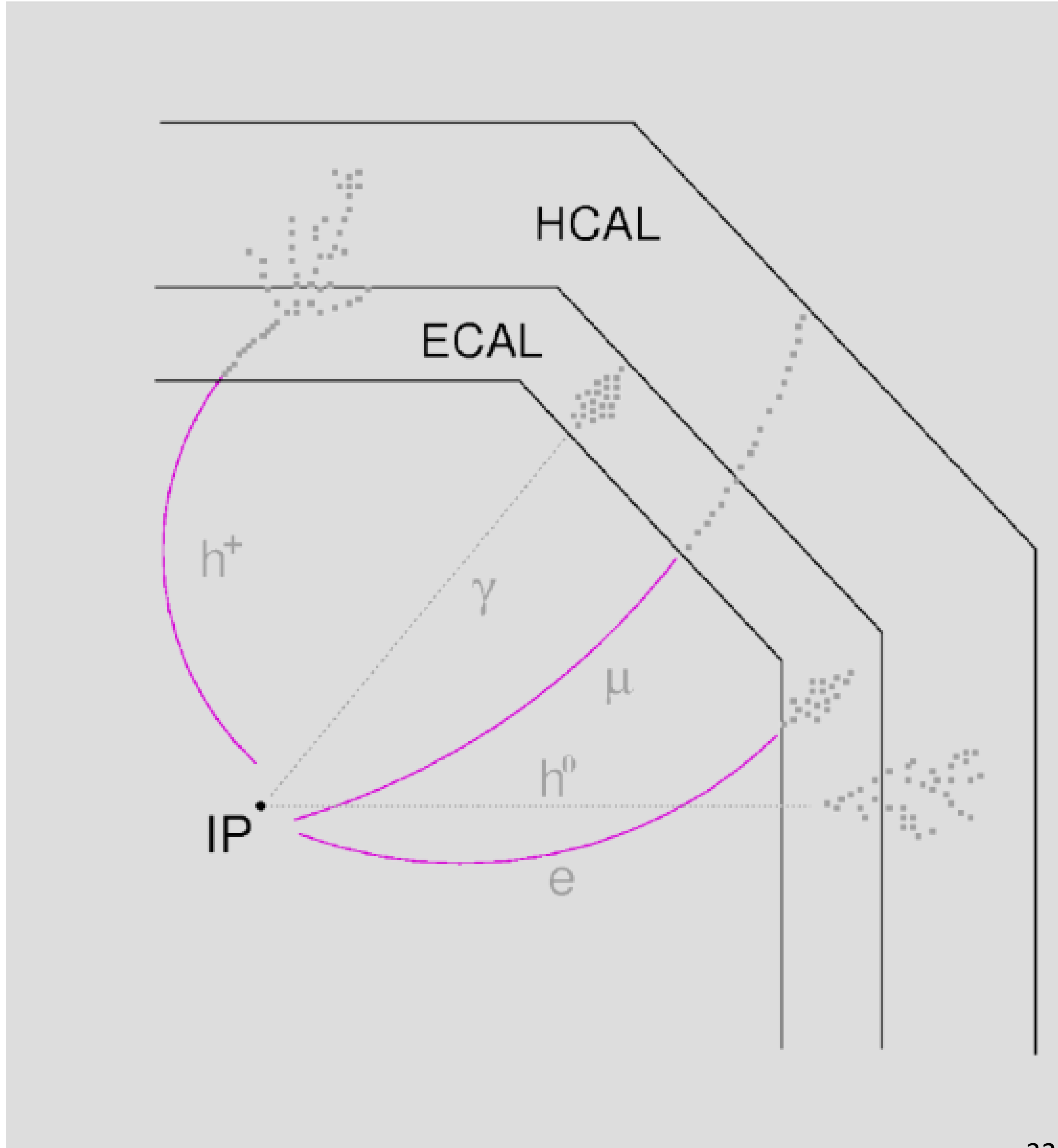
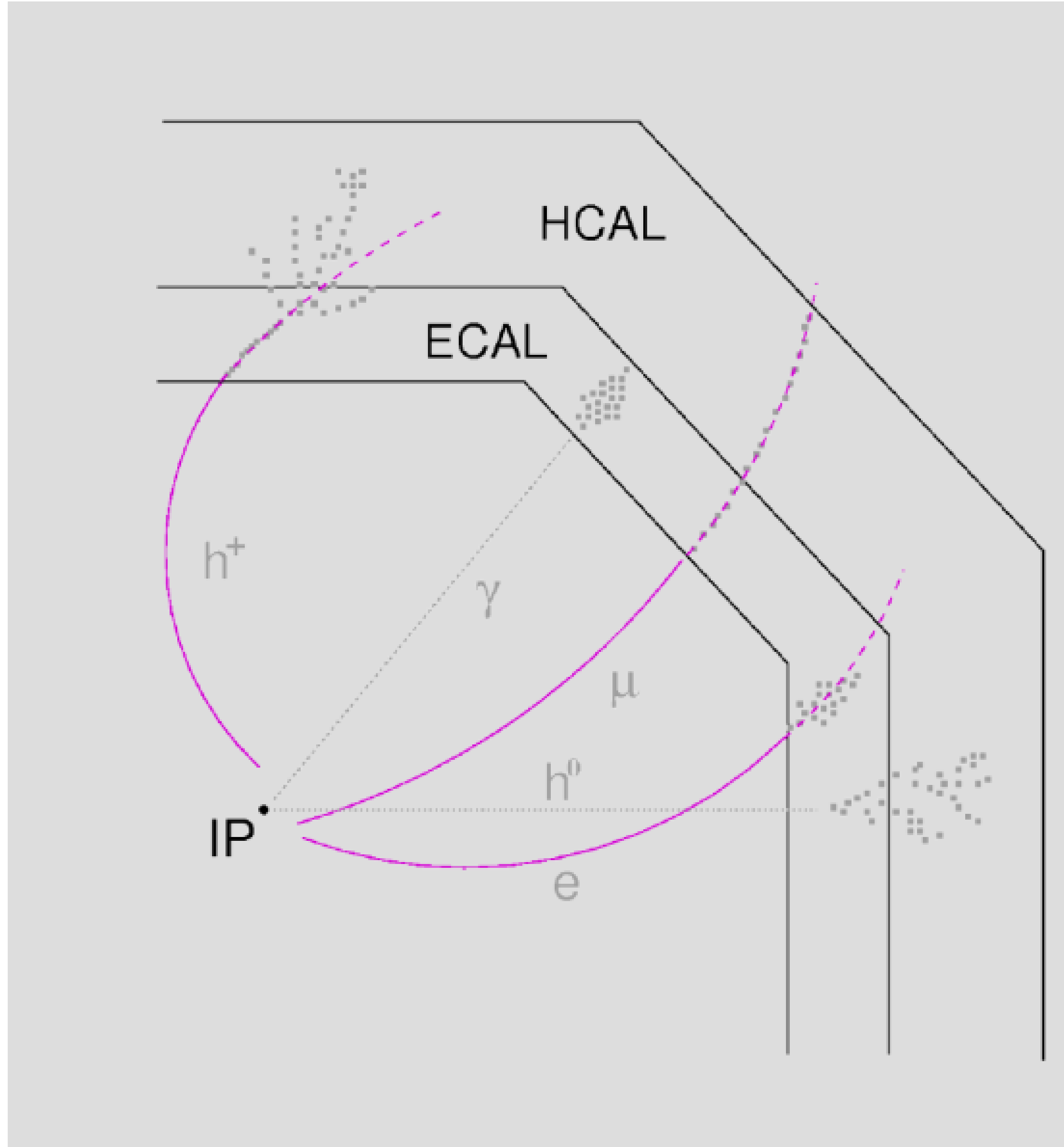
Particle Flow: How does it work?

1. Track reconstruction



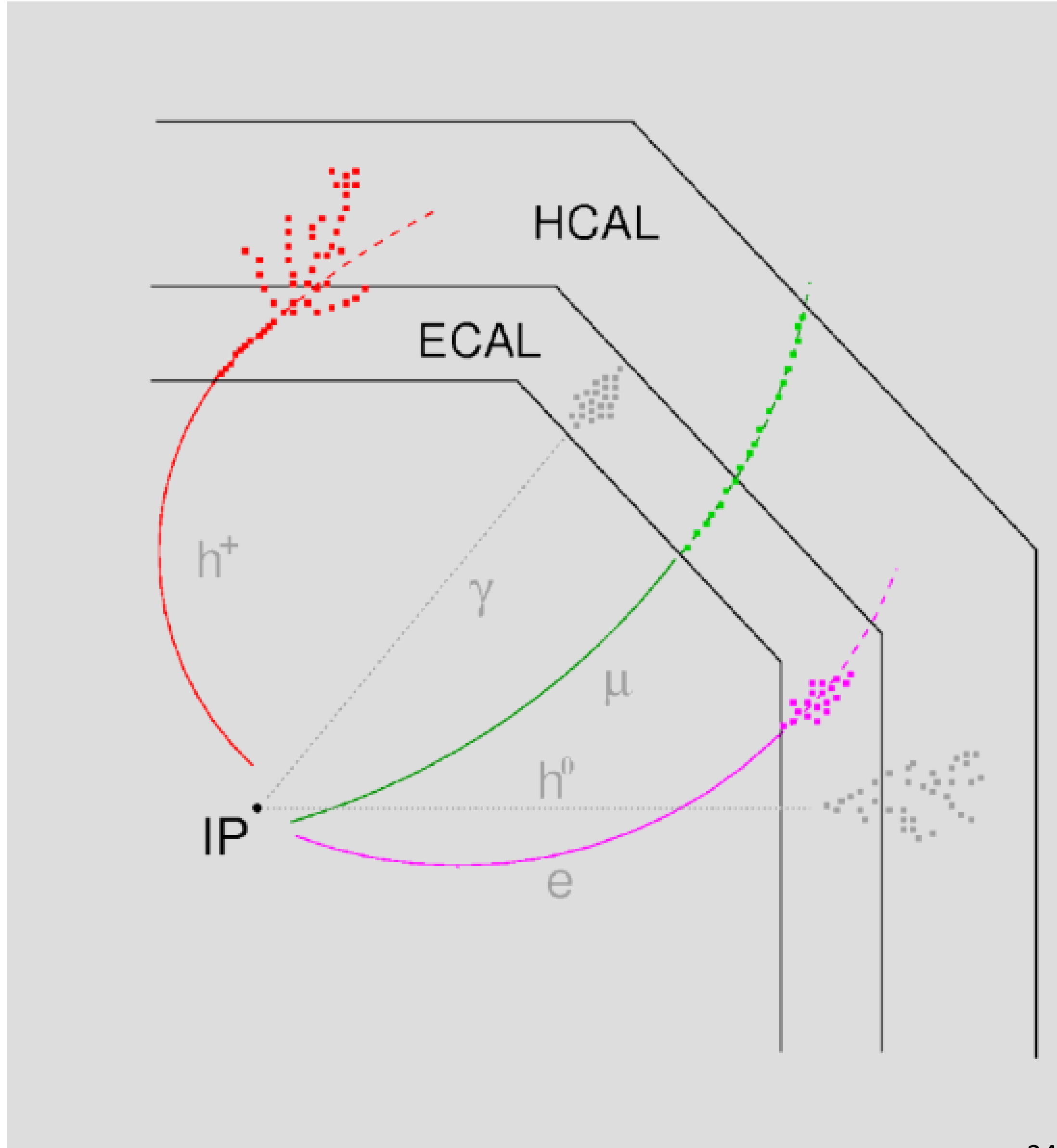
Particle Flow: How does it work?

1. Track reconstruction
2. Track extrapolation to the calos



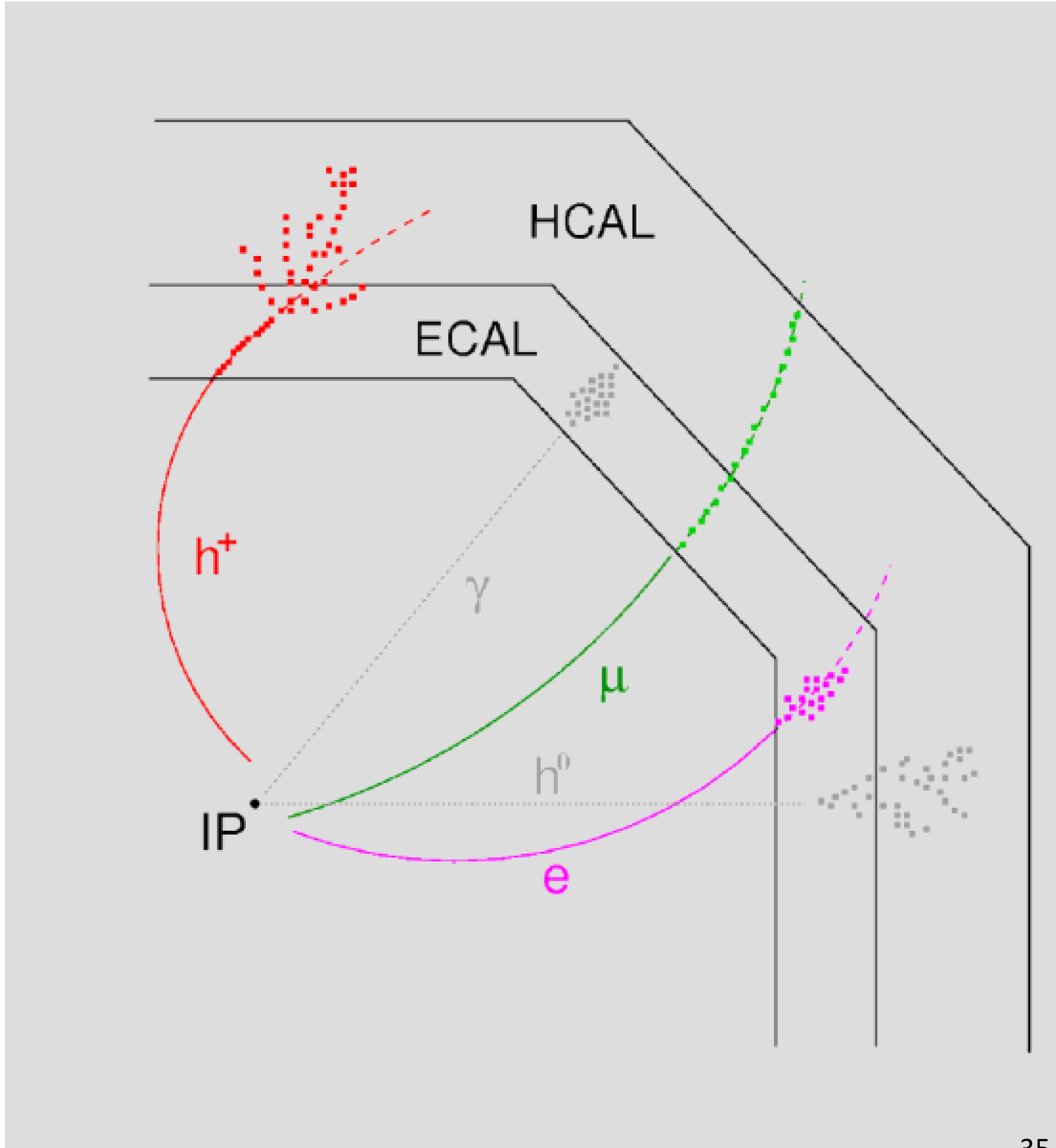
Particle Flow: How does it work?

1. Track reconstruction
2. Track extrapolation to the calos
3. Track matching to calo clusters



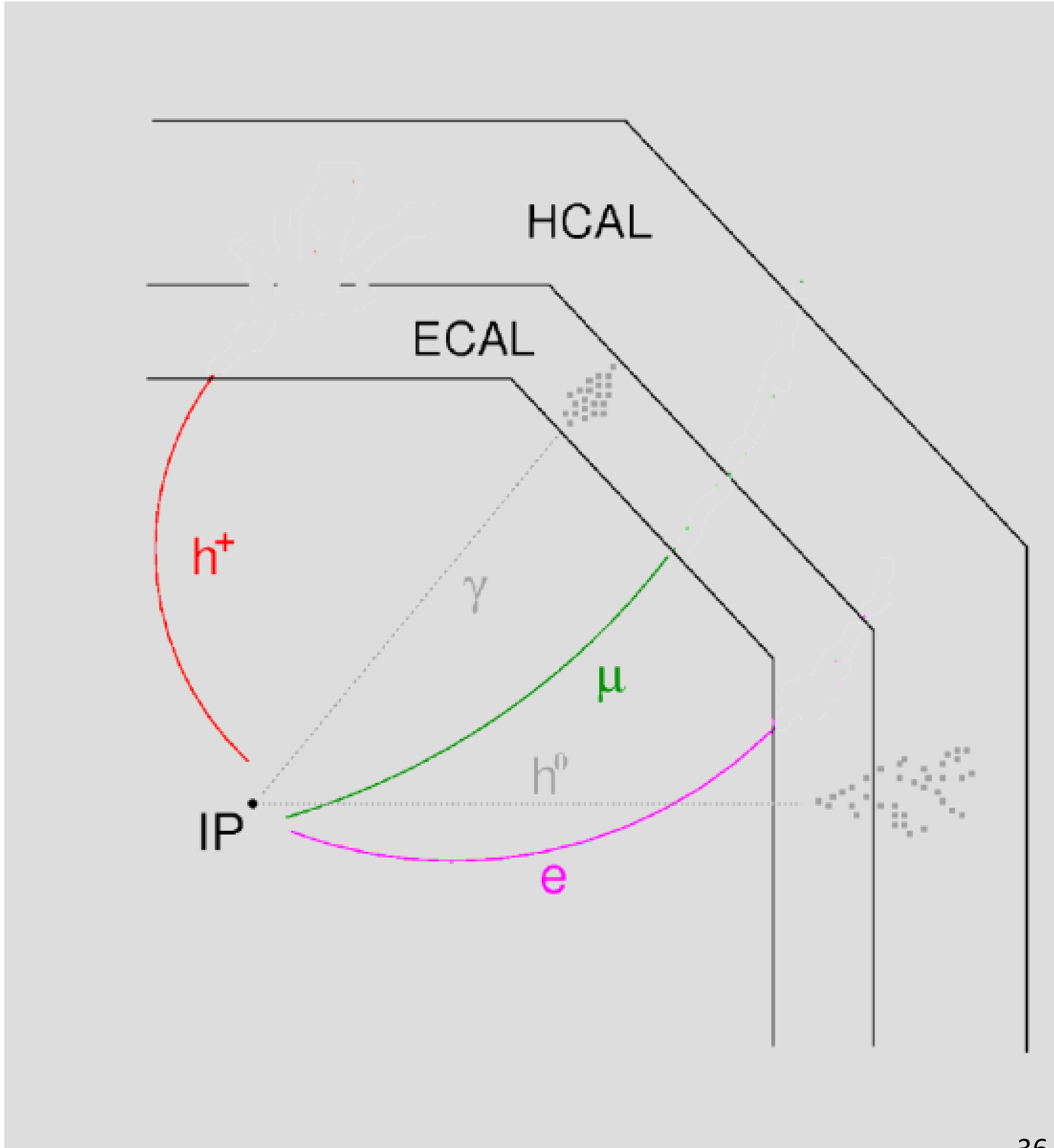
Particle Flow: How does it work?

1. Track reconstruction
2. Track extrapolation to the calos
3. Track matching to calo clusters
4. PID for charged particles



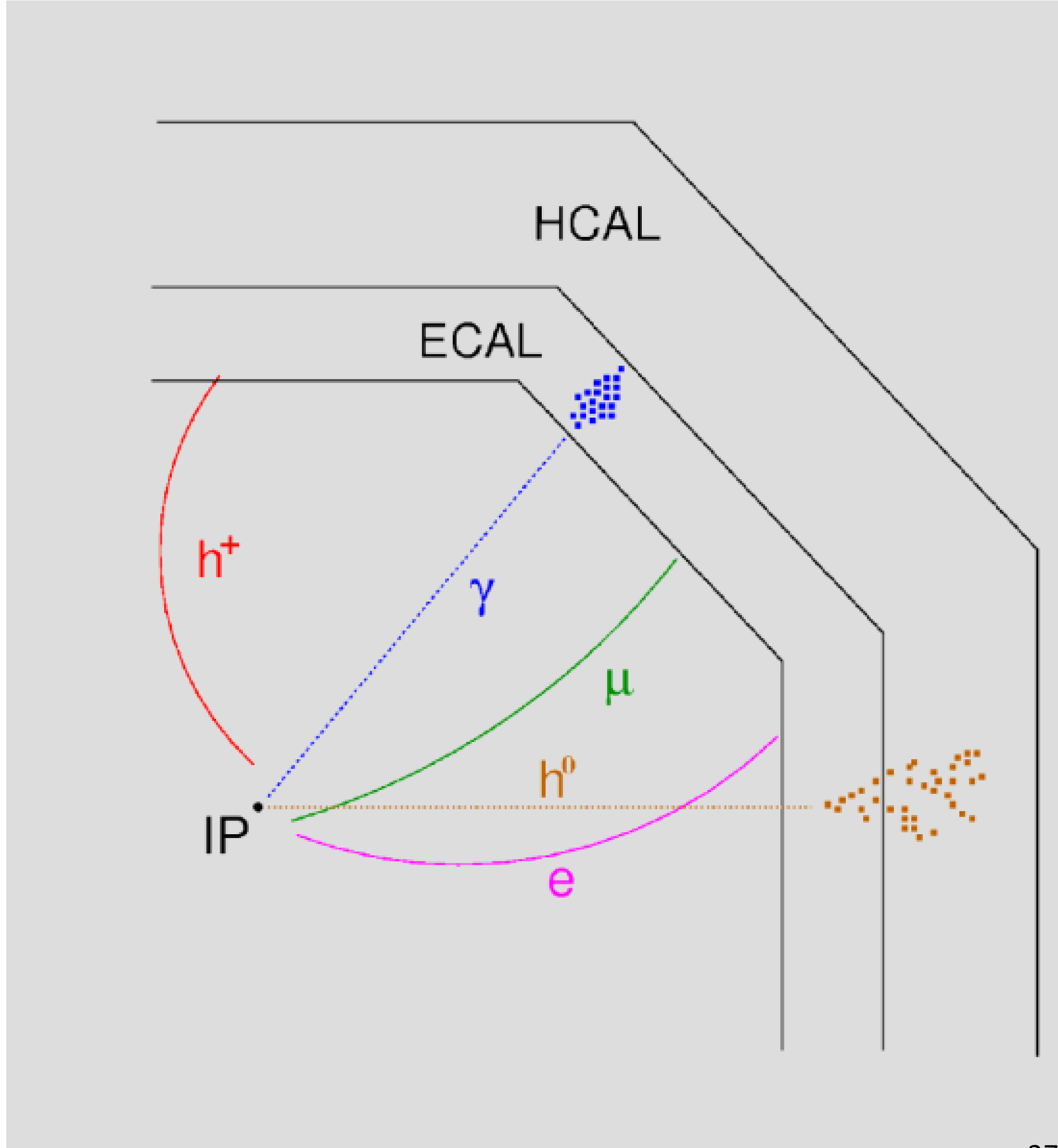
Particle Flow: How does it work?

1. Track reconstruction
2. Track extrapolation to the calos
3. Track matching to calo clusters
4. PID for charged particles
5. Remove energy associated to charged particles



Particle Flow: How does it work?

1. Track reconstruction
2. Track extrapolation to the calos
3. Track matching to calo clusters
4. PID for charged particles
5. Remove energy associated to charged particles
6. Clustering and PID of neutrals



Not that easy…

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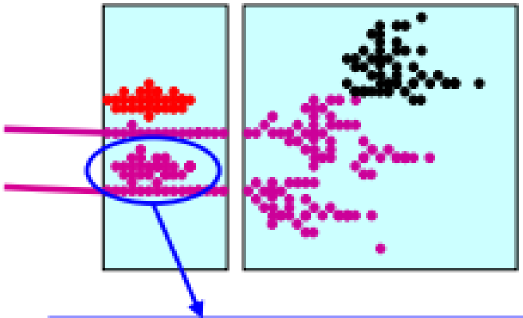
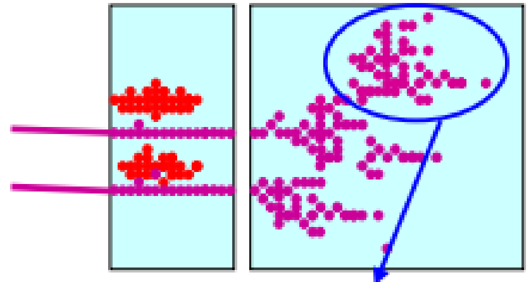
i) Photons

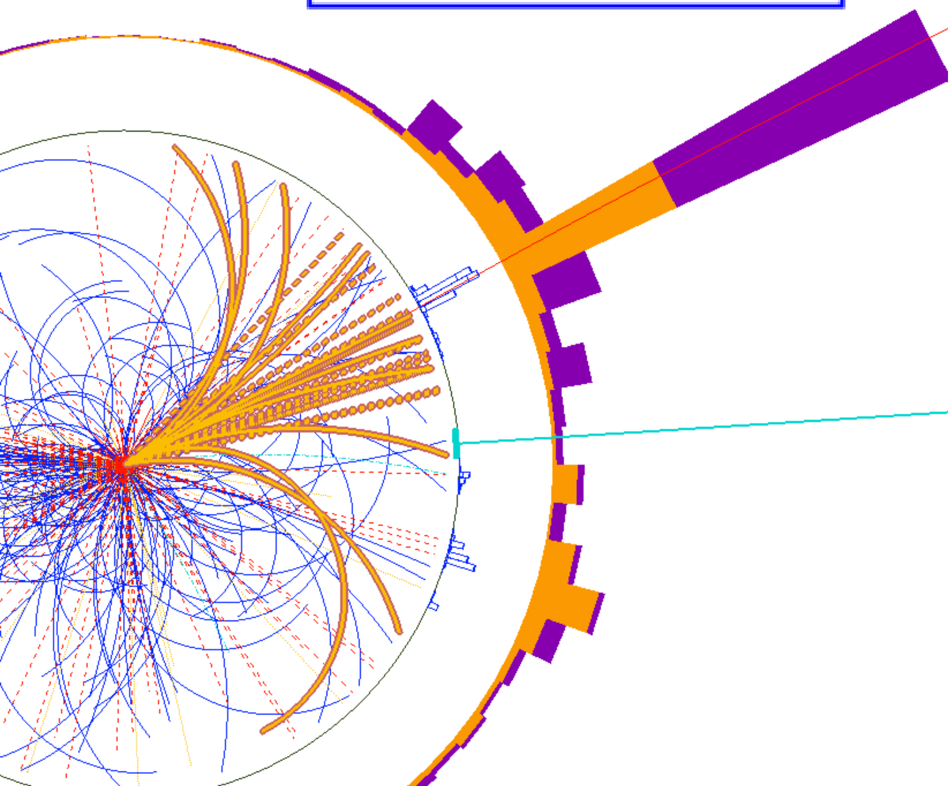


Failure to resolve photon

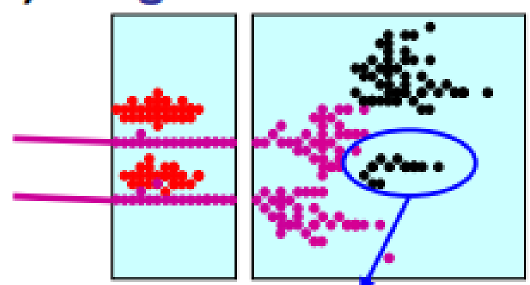
ii) Neutral Hadrons



Failure to resolve neutral hadron



iii) Fragments



Reconstruct fragment as separate neutral hadron

Which can benefit the most from PFA?

	ATLAS	CMS
Large tracking volume		
Strong magnetic field		
Excellent tracker		
Poor hadronic calorimeter		

Which can benefit more from applying particle flow techniques?

Which can benefit the most from PFA?

	ATLAS	CMS
Large tracking volume	✓	✓
Strong magnetic field		
Excellent tracker		
Poor hadronic calorimeter		

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Which can benefit the most from PFA?

	ATLAS	CMS
Large tracking volume	✅	✅
Strong magnetic field	❌	✅
Excellent tracker		
Poor hadronic calorimeter		

Which can benefit the most from PFA?

	ATLAS	CMS
Large tracking volume	✔	✔
Strong magnetic field	✘	✔
Excellent tracker	✘	✔
Poor hadronic calorimeter		

Which can benefit the most from PFA?

	ATLAS	CMS
Large tracking volume	✔	✔
Strong magnetic field	✘	✔
Excellent tracker	✘	✔
Poor hadronic calorimeter	✘	✔

ILC Detectors Design Philosophy

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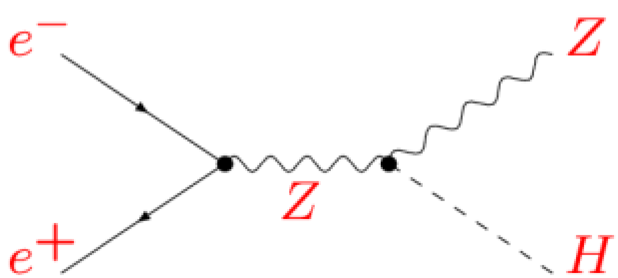
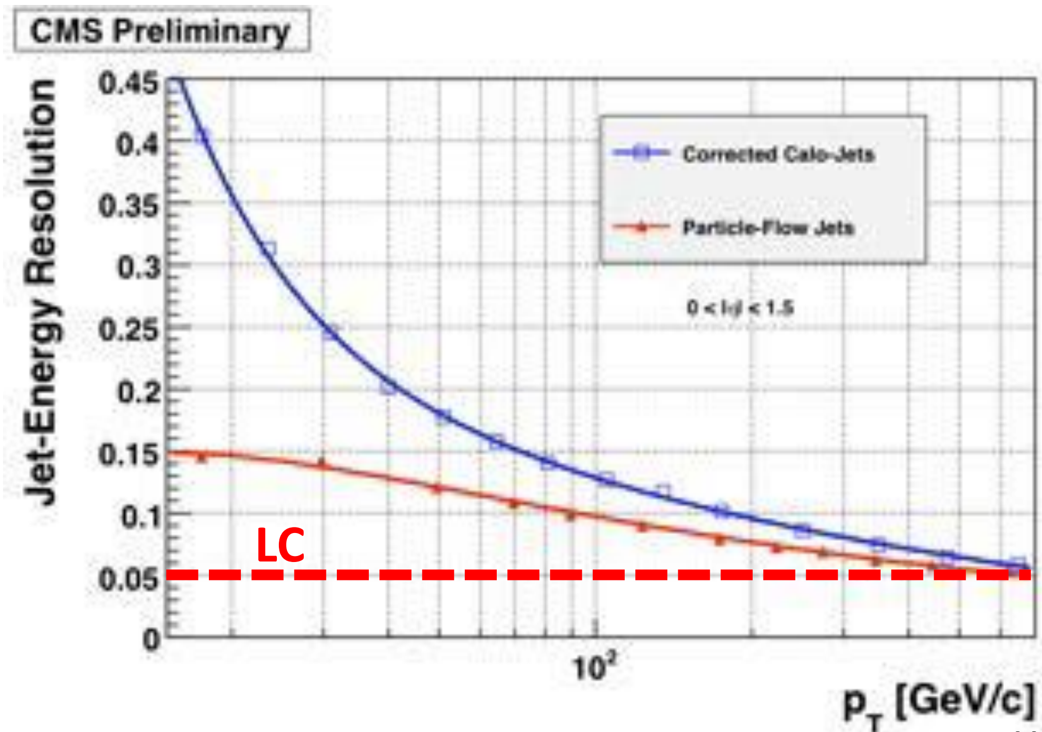
- Multipurpose detector
- Particle Flow as main reconstruction technique
  Extremely granular calorimetric system
- High power tracking
  High efficiency, robust tracking in dense environments
  High precision vertexing for heavy flavour physics

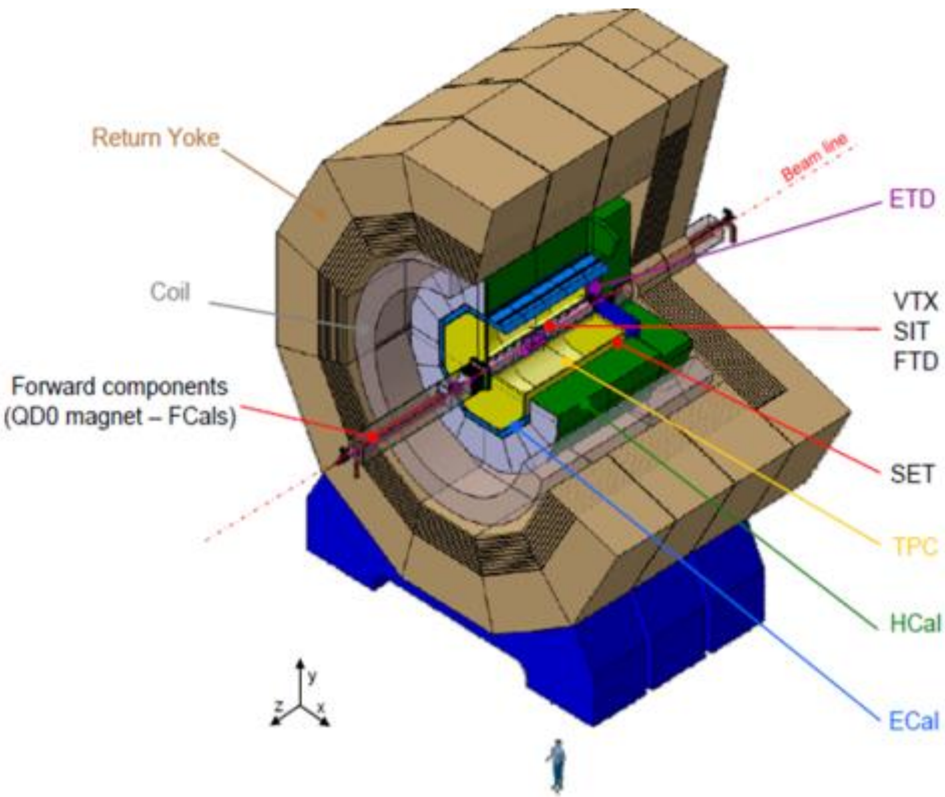
High precision physics on an e^+e^- environment

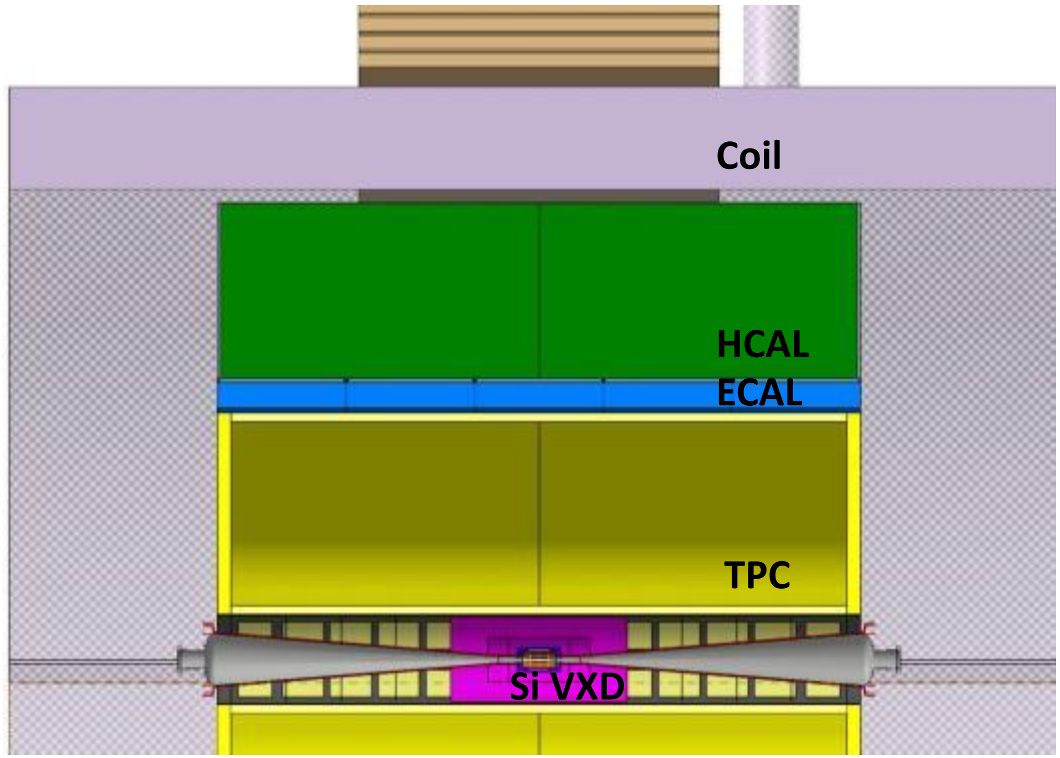




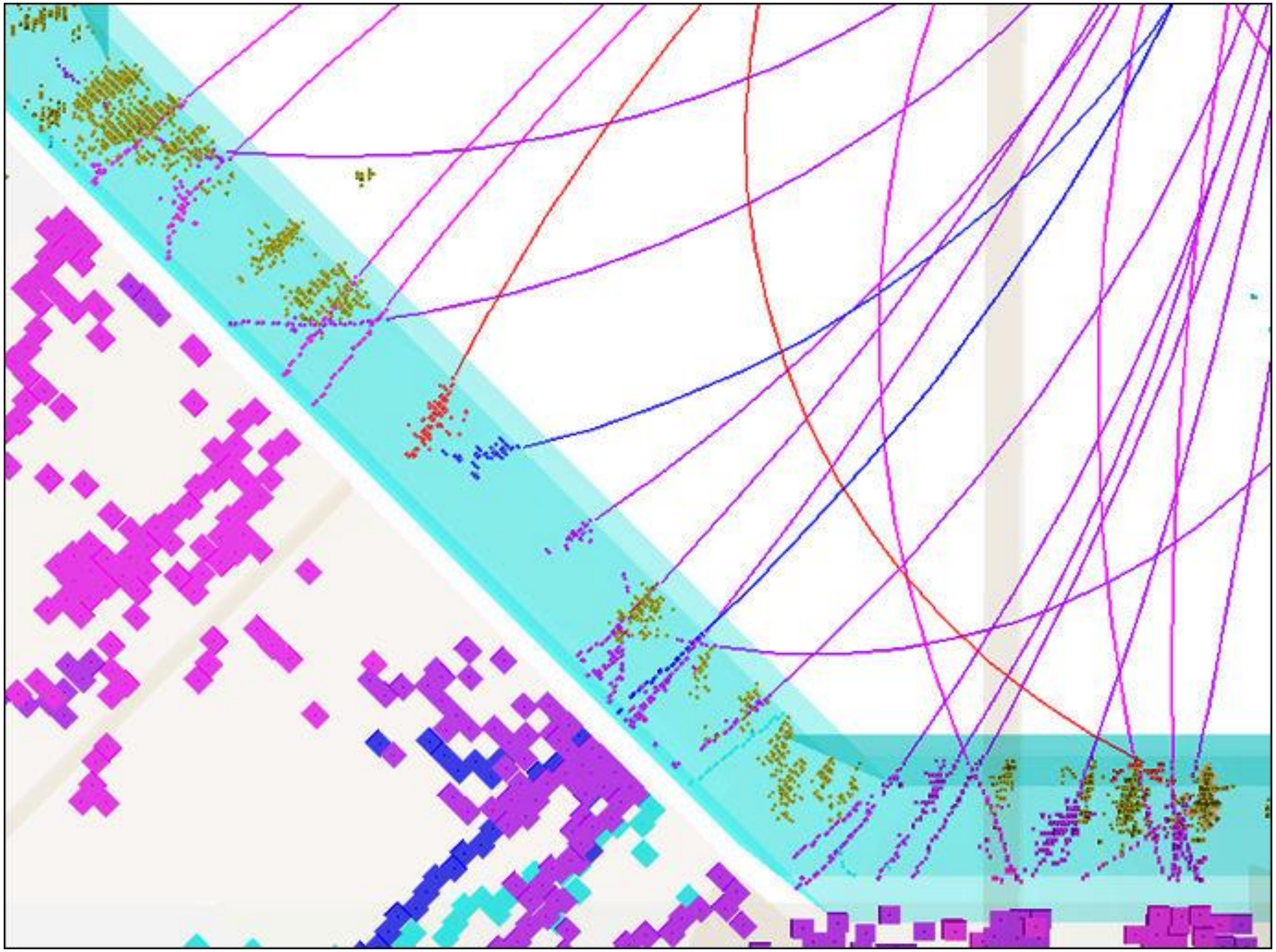
ILD Detector

- Large magnetic volume (3.5 T)
- High precision vertex detector: Highly granular ultra-transparent silicon pixels
- Low material, large redundant gaseous tracking: TPC
- Highly segmented imaging calorimetry → **Drives the detector design**





Typical 250 GeV jet in ILD



Thank you

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