Calorimetry for High-Energy Physics

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Content

- Basics on Calorimetry
- Calorimeters @Work: LHC example
- Trends in calorimetry
- Calorimeter R&D today

Calorimetry in Particle Physics

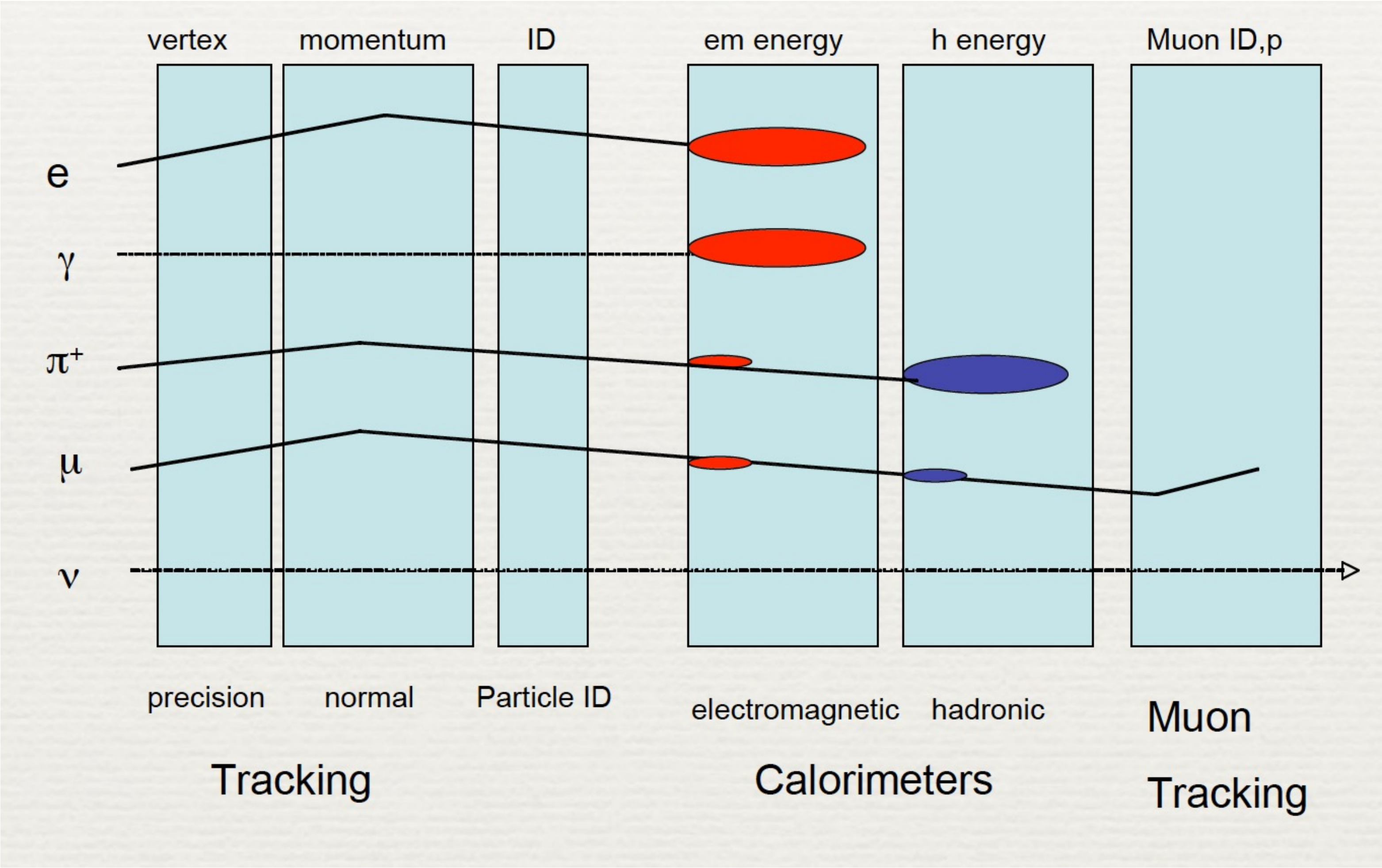
- Calorimetry is a widespread technique in Particle Physics:
  - Shower counters
  - Instrumented targets
    - Neutrino experiments
    - Proton decay/Cosmic Ray detectors
  - 4π detectors (our main topic)
- Calorimetry makes use of various detection mechanisms:
  - Scintillation
  - Ionization (Gaseous and Silicon detectors)
  - Čerenkov radiation

Why Calorimeters ?

- Sensitive to both charged and neutral particles

- Differences in the shower patterns

    - some particle identification is possible: h/e/μ/ν(missing E_T) separation



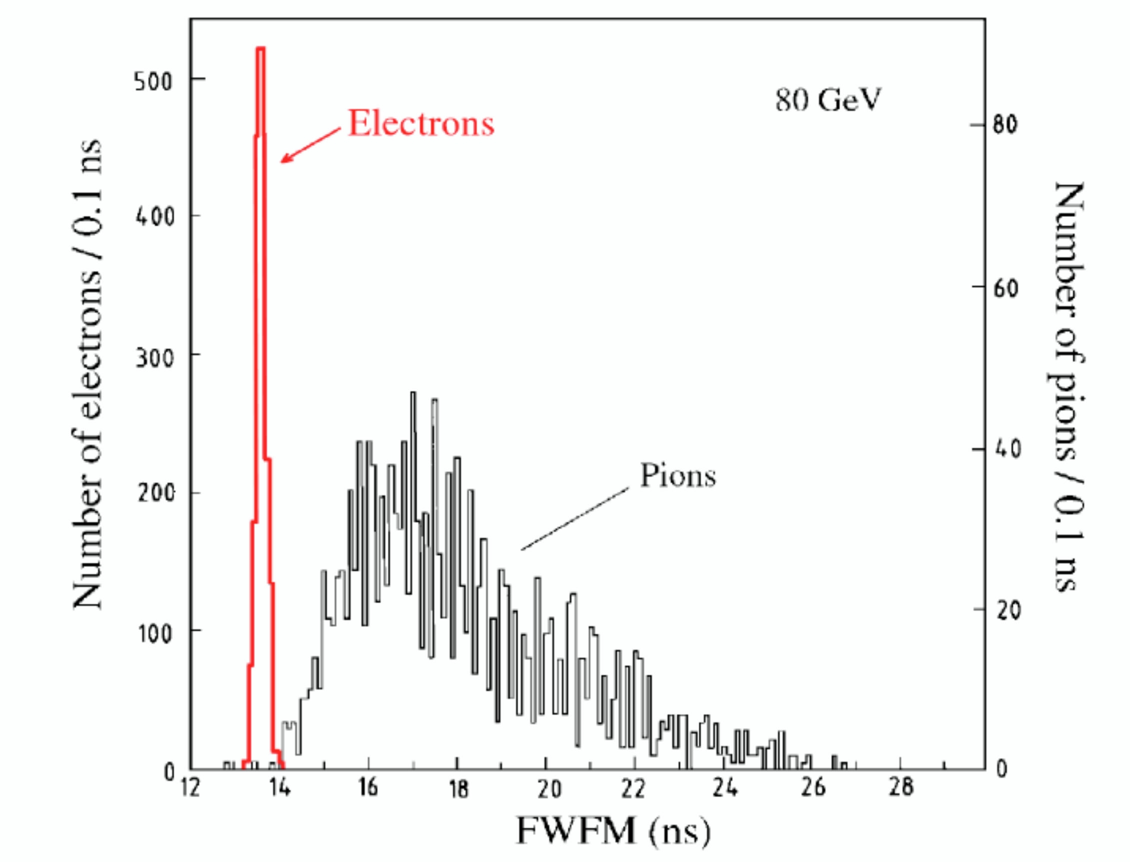


FIG. 7.33. The distribution of the full width at one-fifth maximum (FWFM) for 80 GeV electron and pion signals in SPACAL [Aco 91a]. The left-hand scale applies to the electron signals, the right-hand scale to the pion signals.

Why Calorimeters ?

- Sensitive to both charged and neutral particles
- Differences in the shower patterns
  - some particle identification is possible: h/e/μ/ν(missing E_T) separation
- Calorimetry based on statistical processes
    - $\Rightarrow \sigma(E)/E \propto 1/\sqrt{E}$
    - Magnetic spectrometers $\Rightarrow \Delta p/p \propto p$
- Increasing energy ⇒ calorimeter dimensions $\propto \log E$ to contain showers
- Fast: response times < 100 ns feasible
- No magnetic field needed to measure E
- High segmentation possible ⇒ precise measurement of the direction of incoming particles

Type of calorimeters

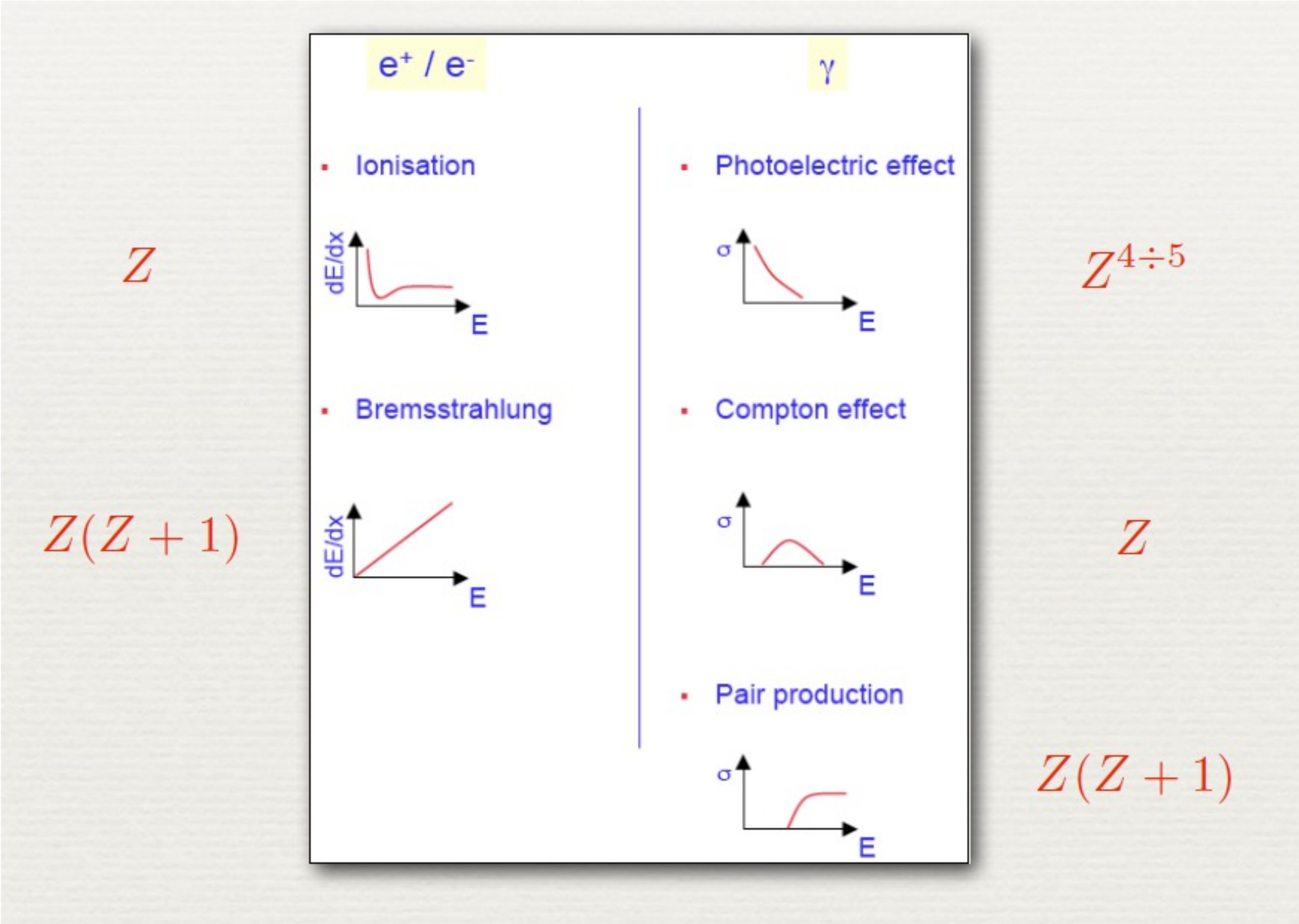
- **Homogeneous calorimeter:** absorber and active media are the same
- **Sampling calorimeter:** only part of shower energy deposited in active medium
  - Sampling fraction f_{samp} is usually determined with a MIP (dE/dx at minimum)

$$f_{samp} = \frac{energy\ deposited\ in\ active\ medium}{total\ energy\ deposited\ in\ calorimeter}$$

Which calorimeter you need?

  - Physics, radiation levels, environmental conditions, budget
  - Choices: active, passive materials, longitudinal and lateral segmentation etc.

Basic Electromagnetic Interactions



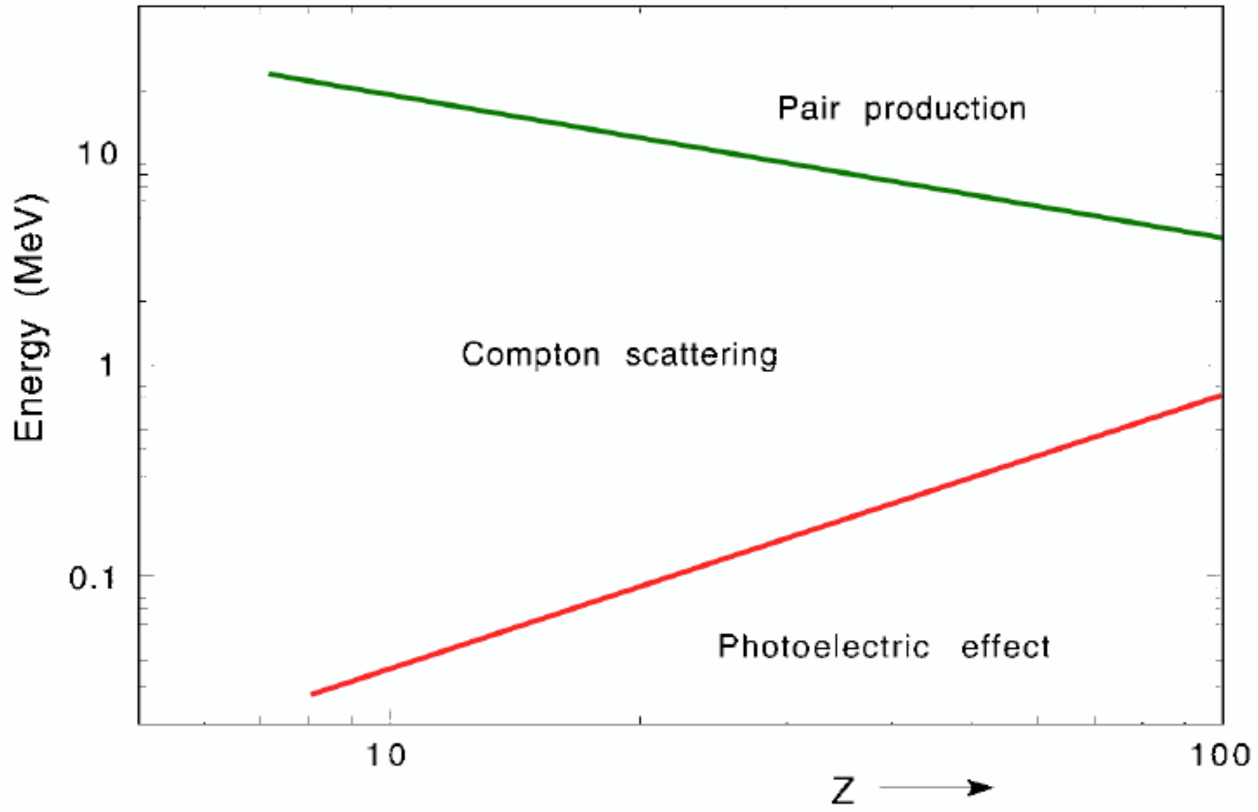
e^+ / e^-

- Ionisation Z
- Bremsstrahlung $Z(Z+1)$

γ

- Photoelectric effect $Z^{4\div5}$
- Compton effect Z
- Pair production $Z(Z+1)$

In order to be detected a photon must create charged particles and/or transfer energy to charged particles



Electromagnetic Showers: longitudinal development

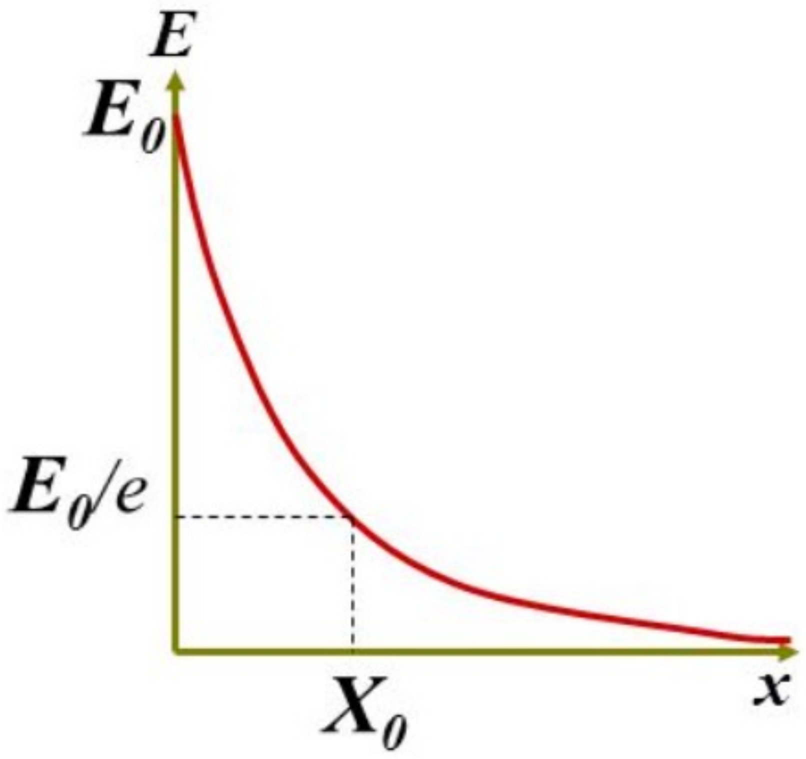
Longitudinal development governed by radiation length (X_0)

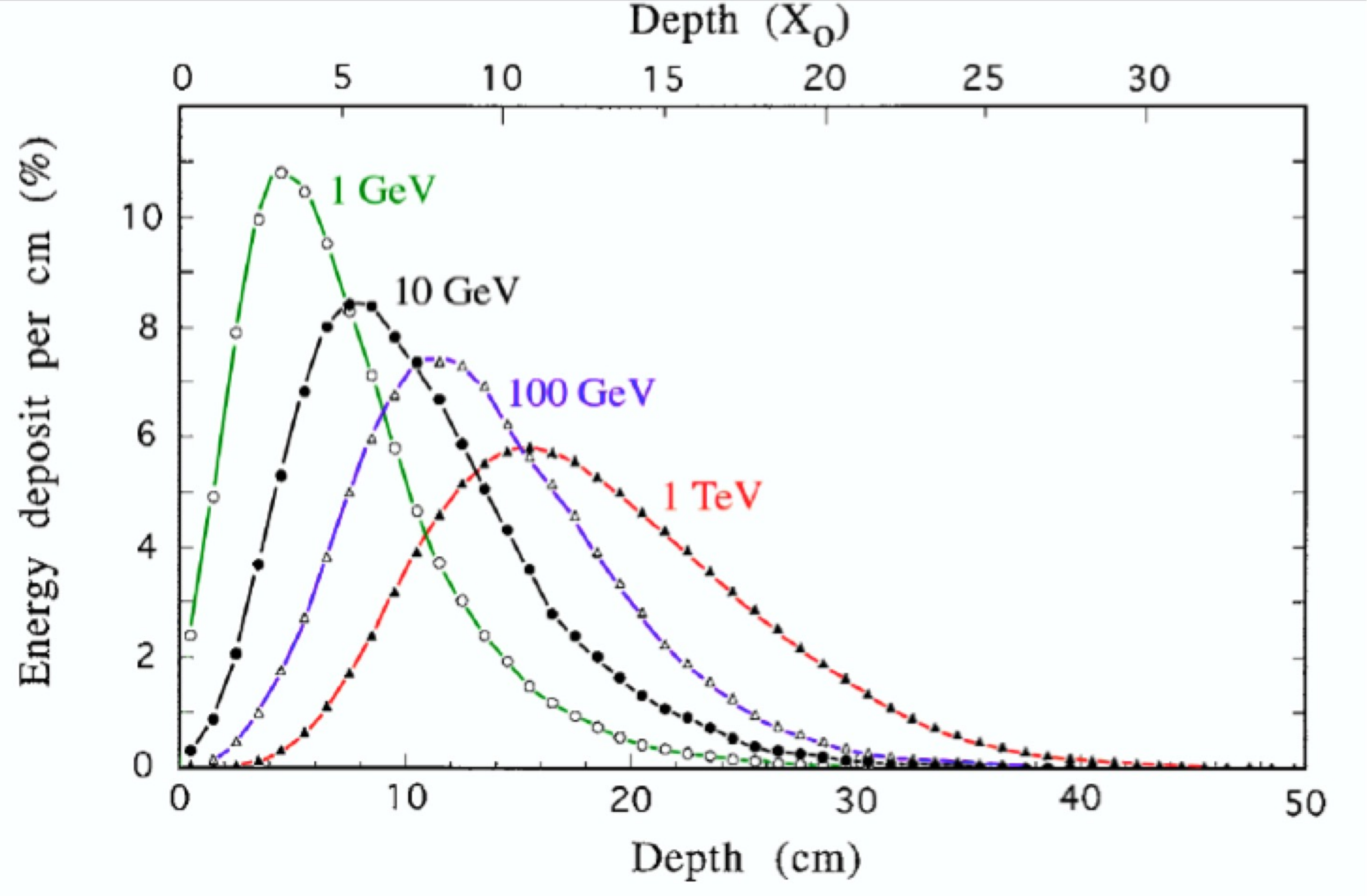
material	X0 (cm)
Cu	1.4
Pb	0.5
W	0.35
PbW04	0.89
BGO	1.12

$$X_0 = \frac{A}{4\alpha N_A \frac{Z^2}{A} z^2 r_e^2 E \ln \frac{183}{\overset{1}{Z}}}$$

$$-\frac{dE}{dx} = \frac{E}{X_0}$$

$$E = E_0 e^{-\frac{x}{X_0}}$$





Mean free path of γs = 9/7 X_0

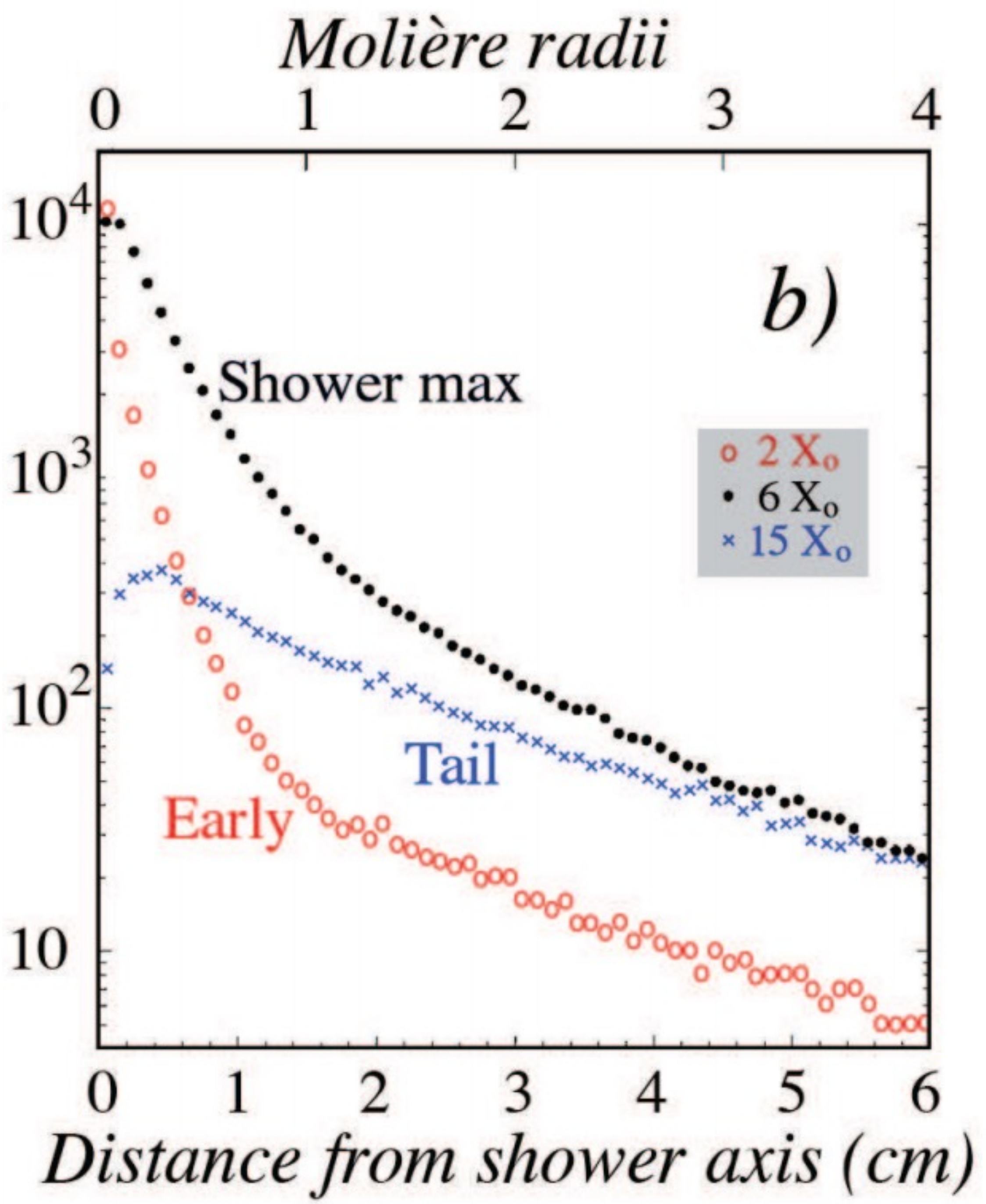
Electromagnetic Showers: lateral development

- Lateral shower width scales with Molière radius ρ_M
  - ρ_M much less material dependent than X_0

$$\rho_M = E_s \frac{X_0}{E_c} \qquad E_s = m_e c^2 \sqrt{4\pi/\alpha}$$

$$X_0 \propto A/Z^2, \quad E_c \propto 1/Z \quad \Rightarrow \quad \rho_M \propto A/Z$$

- Lateral shower width determined by:
  - Multiple scattering of e± (early, 0.2 ρ_M)
  - Compton γs travelling away from axis (1 - 1.5 ρ_M)
- Lateral containment do not show dependence on energy



Hadron showers

- Extra complication: the strong interaction
- Much larger variety may occur both at the particle level and at the level of the stuck nucleus
  - Production of other particles, mainly pions
  - Some of these particles (π^0, η) develop electromagnetic showers
  - Nuclear reactions: protons, neutrons released from nuclei
  - Invisible energy (nuclear binding energy, target recoil)
    - em showers: all energy carried by incoming e or γ goes to ionization/excitation
    - had showers: certain fraction of energy is fundamentally undetectable

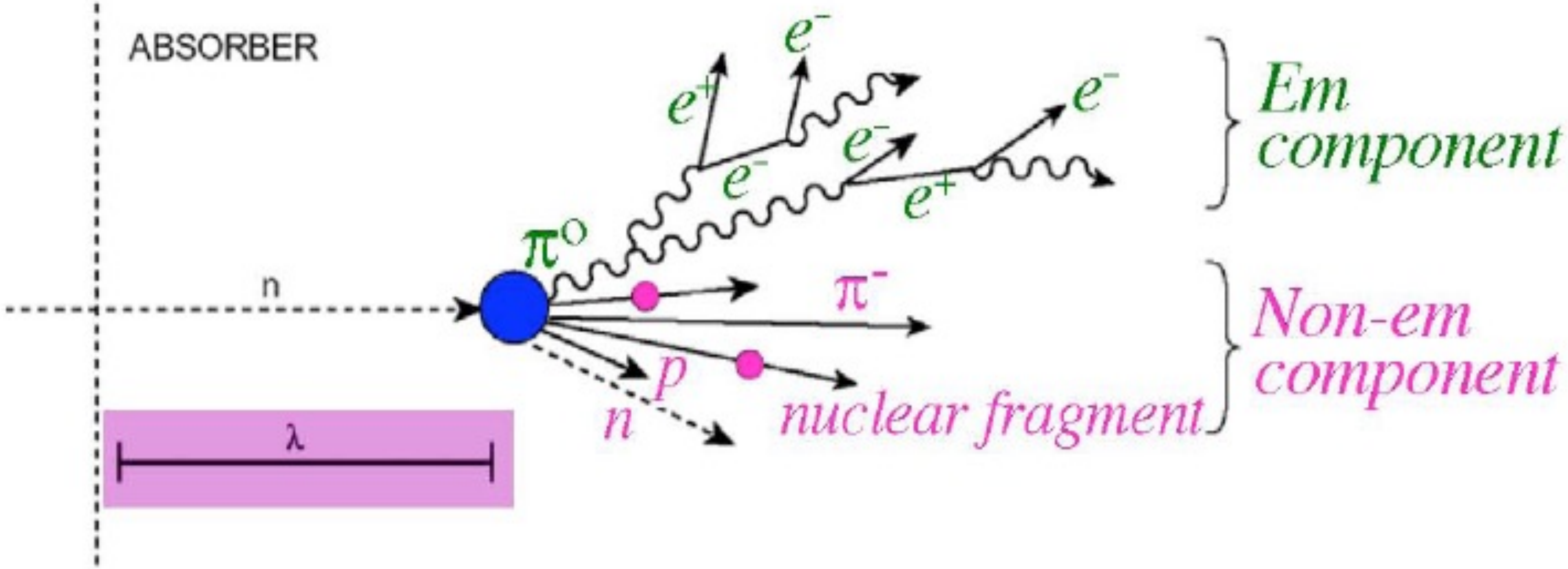
Hadronic showers

Much more complex than em showers

Made of different components

- ionization and interaction with nuclei
- development similar to em shower but different scale (λ vs. X_0)
- Particle sector
- Nuclear sector

electrons positrons, photons, π^0



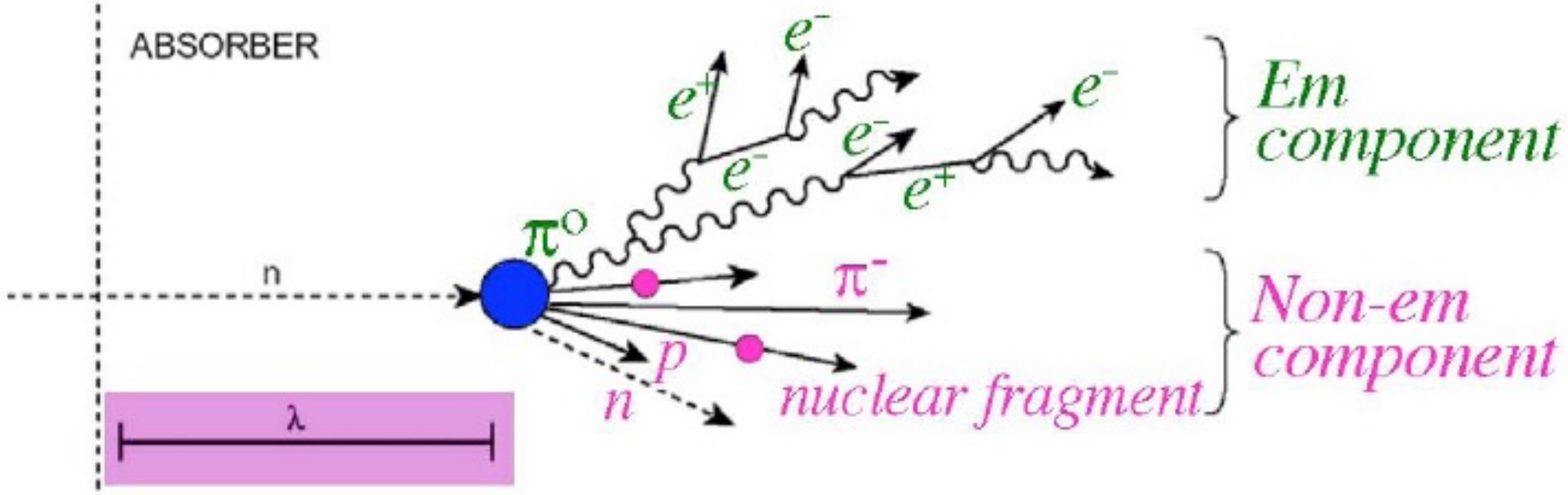
Charged hadrons (**π,k…)**, nuclear fragments, neutrons, neutrinos, breakup of nuclei (invisible energy)

The electromagnetic fraction, fem

em decaying particles : π^0, $\eta^0 \Rightarrow \gamma\ \gamma$

- % of hadronic energy going to em fluctuates heavily
- On average 1/3 of particles in first generation are π^0s
- π^0s production by strongly interacting particles is an irreversible process (a ”one-way street”)

electrons positrons, photons, π^0



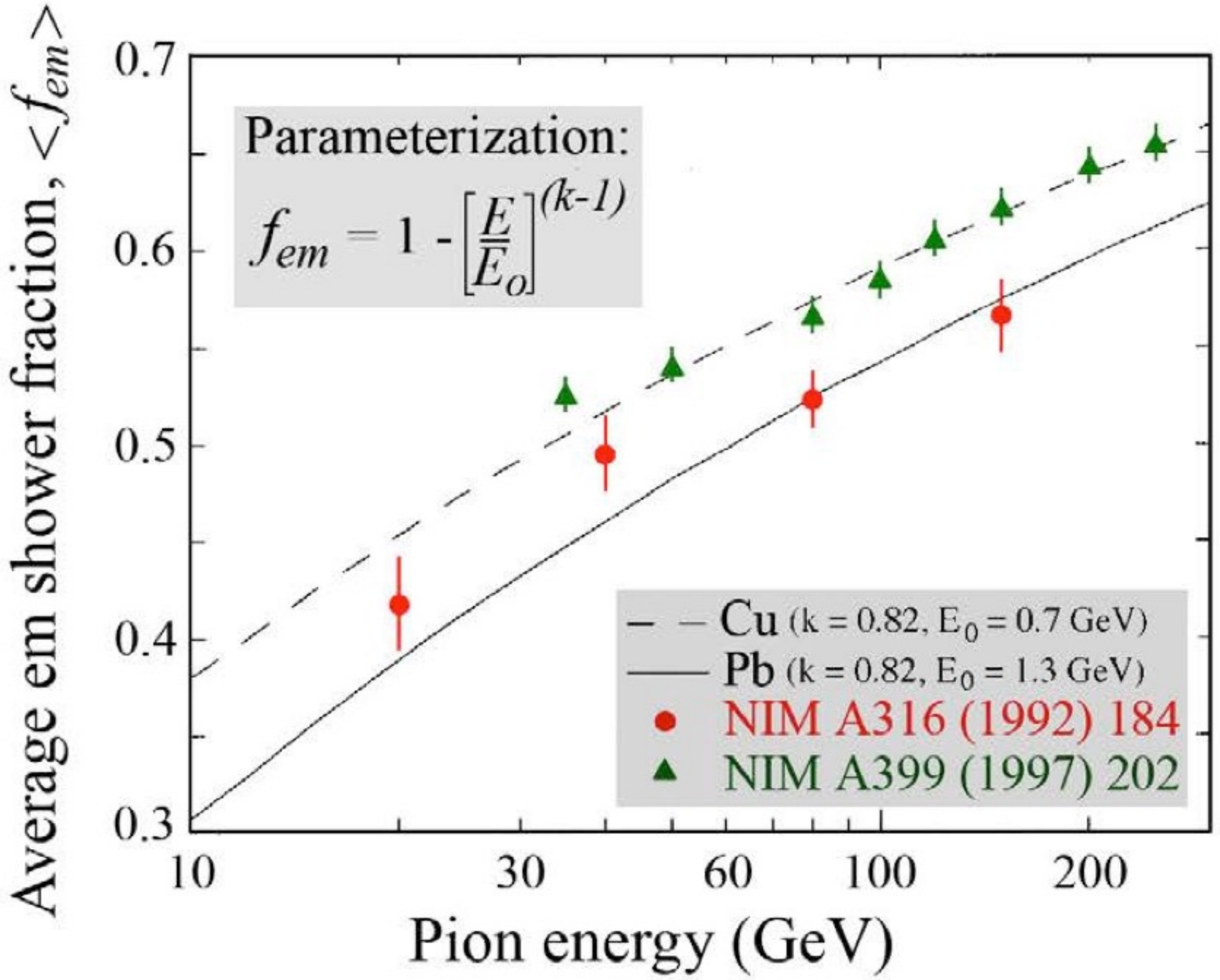
Charged hadrons (**π,k…),** nuclear fragments, neutrons, neutrinos, breakup of nuclei (invisible energy)

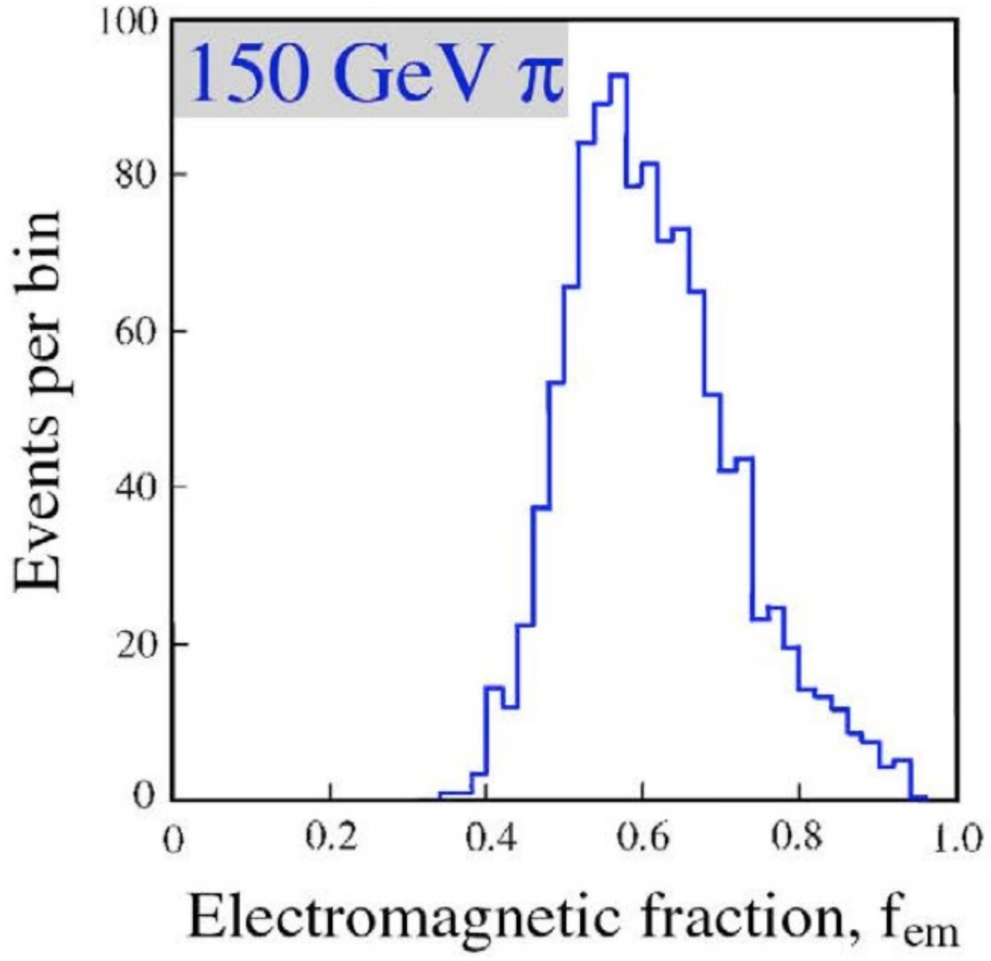
The electromagnetic fraction in hadronic showers

- π_0 decays into 2 photons start an electromagnetic shower (f_{em})
  - f_{em} grows with energy → *non-linearity*
  - f_{em} varies event-by-event → *fluctuation in calorimetry response*

$$\langle f_{em} \rangle = 1 - \left(E / E_0 \right)^{(k-1)}$$

E_0 = average energy to produce a π^0
(k-1) related to average multiplicity





Fluctuations in the em shower component (fem)

- Why are these important ?
  - calorimeter response to em-component ≠ non-em response (e/h ≠ 1)
  - Event-to-event fluctuations are large and non-Gaussian
  - $<f_{em}>$ depends on shower energy and age
- Cause of all common problems in hadron calorimeters
  - Energy scale different from electrons, in energy-dependent way
  - Hadronic non-linearity
  - Non-Gaussian response function
  - Poor energy resolution
  - Calibration of the sections of a longitudinally segmented detector
- Solutions
  - Compensating calorimeters (e/h = 1), e.g. Pb/plastic scintillator
  - Measure f_{em} event-by-event

Hadronic shower profiles

Shower profiles are governed by the nuclear interaction lenght, λ_{int}

- average distance a high-energy hadron has to travel inside a medium before a nuclear interaction occurs
  - λ_{int} (g cm^{-2}) $\propto A^{1/3}$
  - Fe 16.8 cm, Cu 15.1 cm, Pb 17.0 cm, U 10.0 cm

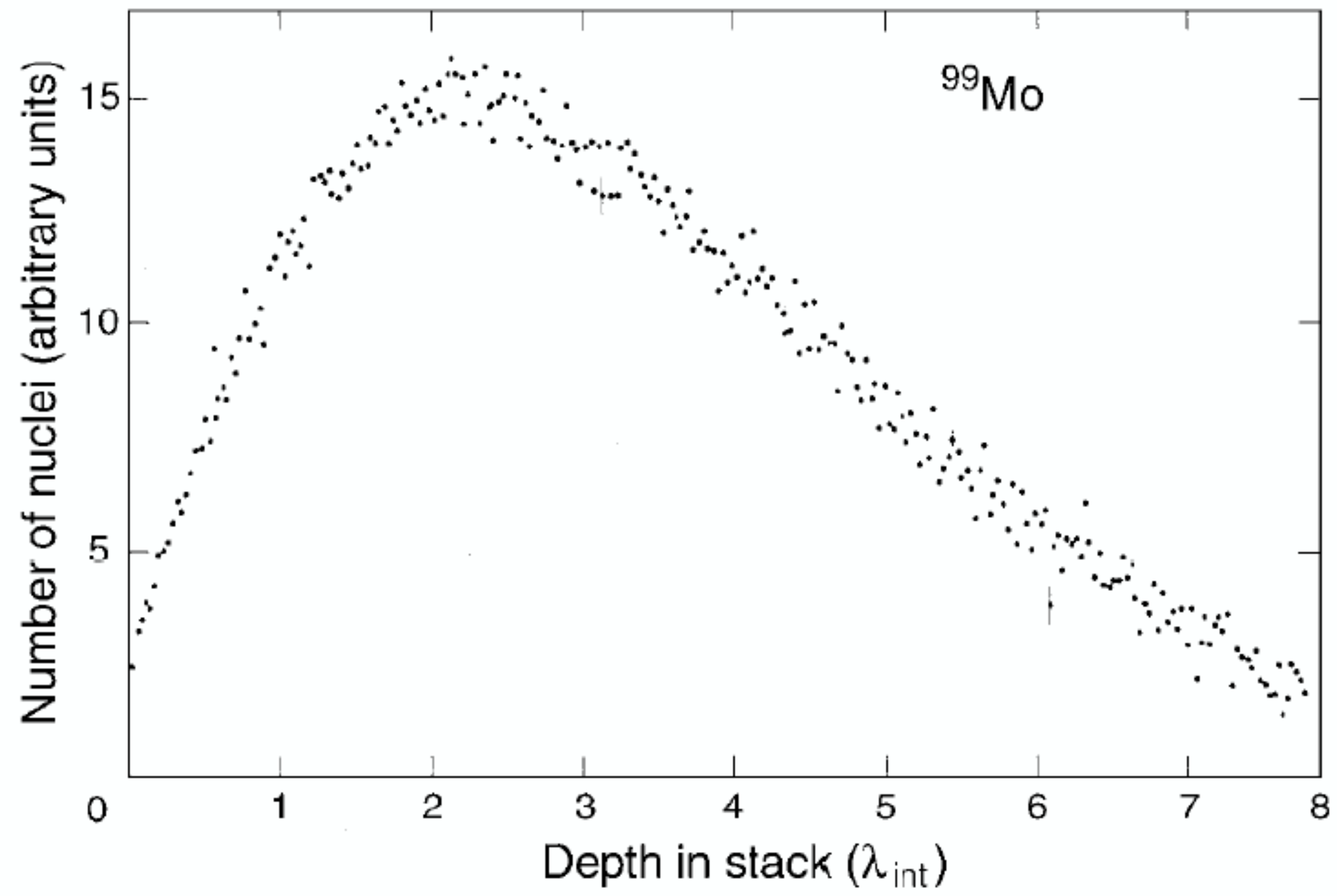


FIG. 2.31. Longitudinal shower profile for 300 GeV π^- interactions in a block of uranium, measured from the induced radioactivity. The ordinate indicates the number of radioactive decays of a particular nuclide, ^{99}Mo, produced in the absorption of the high-energy pions. Data from [Ler 86].

For comparison X_0 :
Fe 1.76 cm, Cu 1.43 cm,
Pb 0.56 cm, U 0.32 cm

Hadronic showers fluctuations

Very interesting measurements of the longitudinal energy deposition in em and hadronic showers were made with the "Hanging file calorimeter"

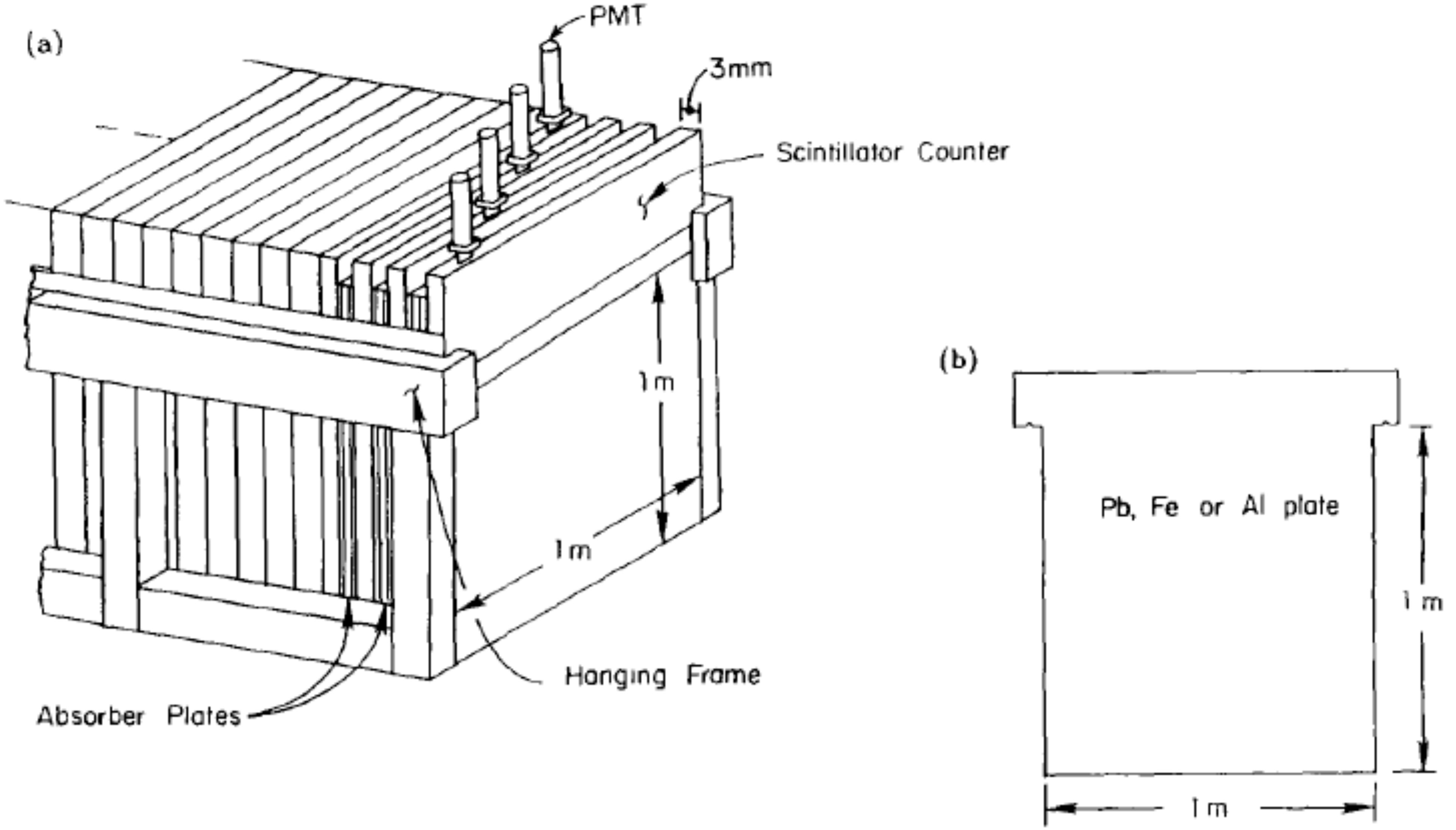
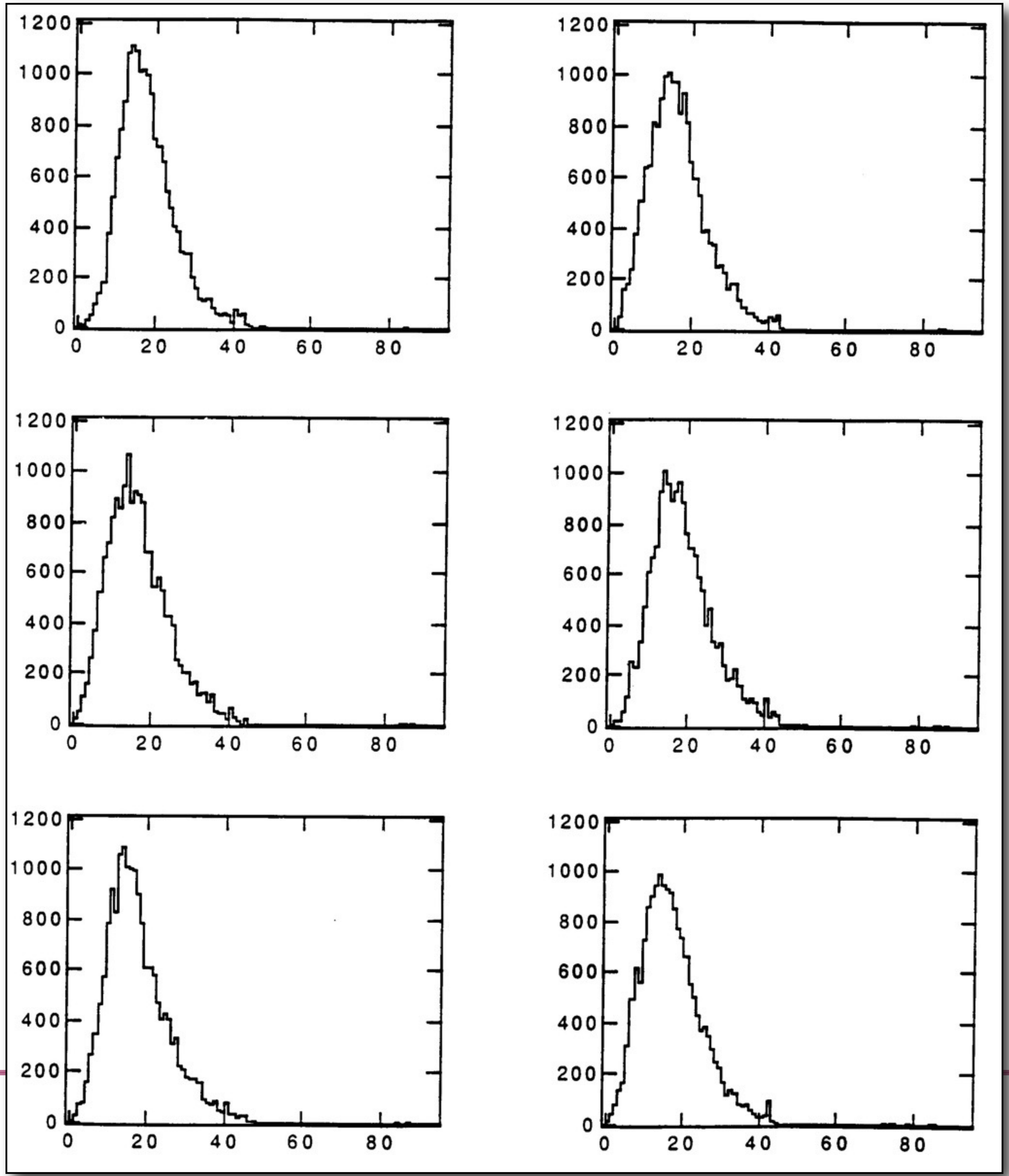


Fig. 1. (a) Schematic overview of the hanging file calorimeter (HFC). There was no transverse segmentation. The maximum depth of the calorimeter can be configured up to 2.2 m with a maximum number of 105 read-out planes. Each scintillator counter was read out separately. (b) Schematic drawing of the absorber plate.

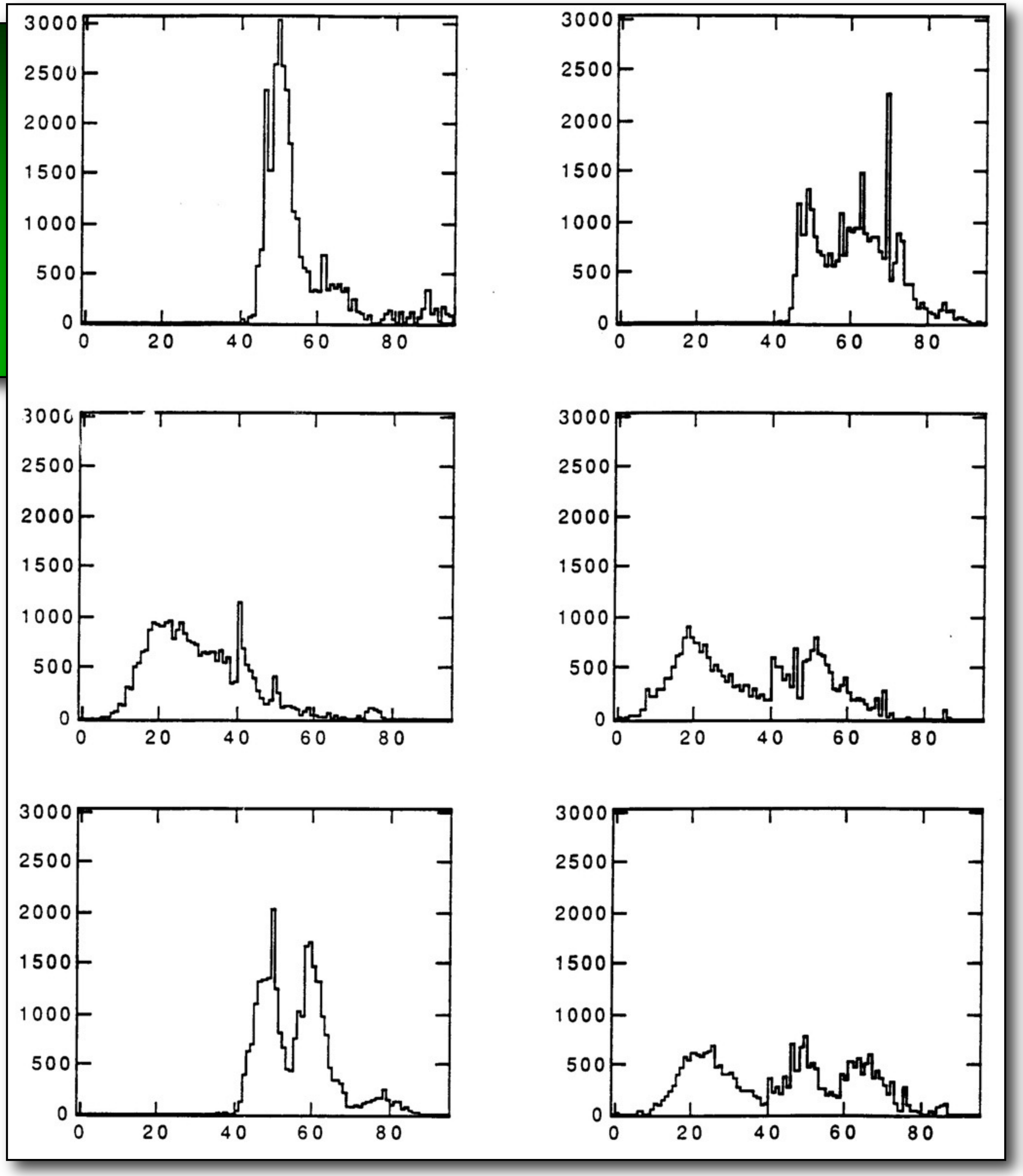
Fluctuations (em showers)

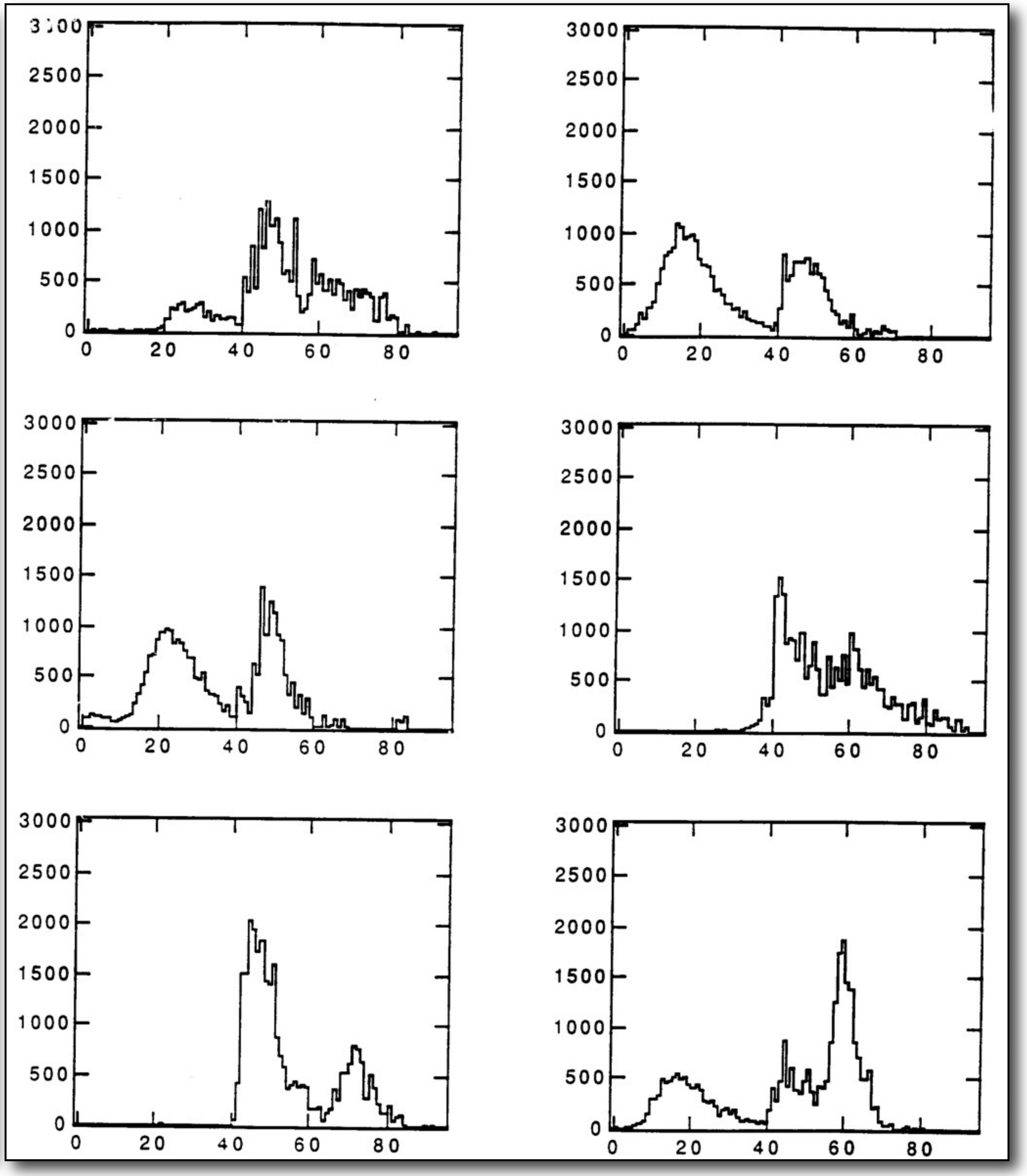
- Hanging file calorimeter
- 170 GeV electrons



Fluctuations (hadronic showers)

- Hanging file calorimeter
- 270 GeV pions





Hadronic lateral shower profiles

- Lateral shower profile has two components:
  - Electromagnetic core (π^0)
  - Non-em halo (mainly non-relativistic shower particles)
- Spectacular consequences for Čerenkov calorimetry
- Čerenkov light is emitted by particles with $\beta > 1/n$
  - e.g. quartz (n= 1.45) : Threshold 0.2 MeV for e, 400 MeV for p

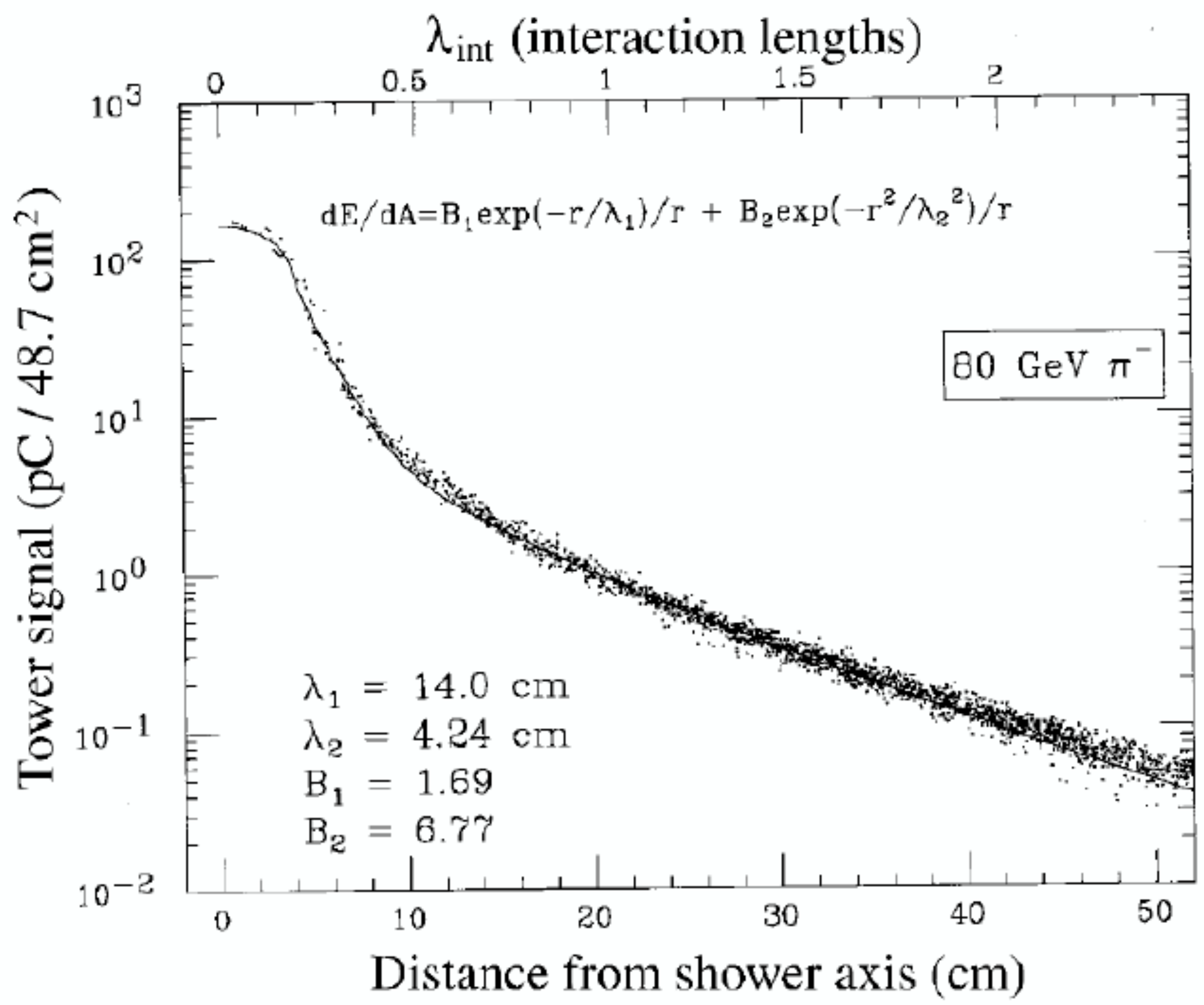


FIG. 2.32. Average lateral profile of the energy deposited by 80 GeV π^- showering in the SPACAL detector. The collected light per unit volume is plotted as a function of the radial distance to the impact point. Data from [Aco 92b].

Shower containment

- Depth to contain showers increases with log E
- Lateral leakage decreases as the energy goes up !
  - $<f_{em}>$ increases with energy
  - Electromagnetic component concentrated in a narrow cone around shower axis
  - ⇒ Energy fraction contained in a cylinder with a given radius increases with energy

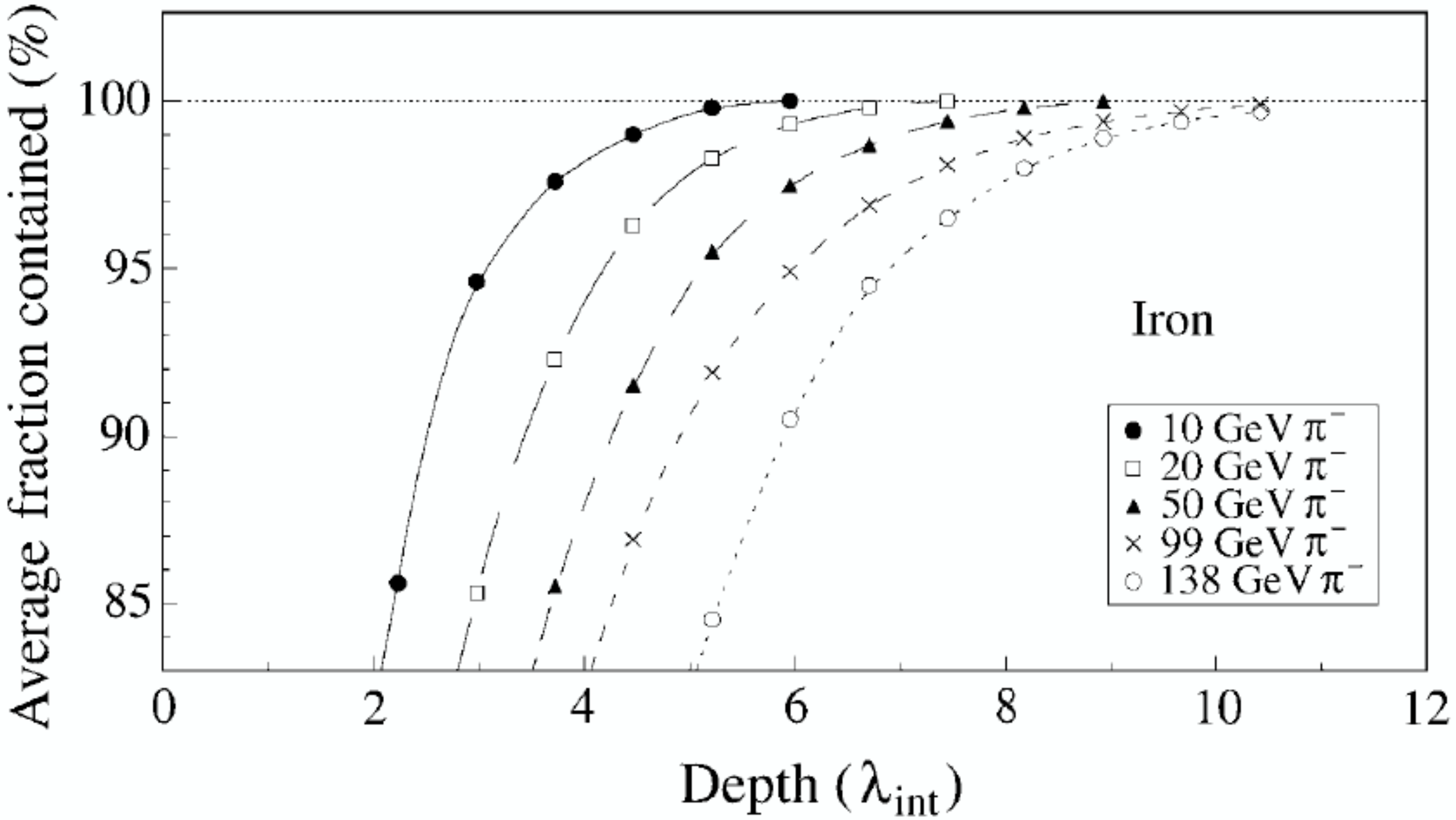


FIG. 2.37. Average energy fraction contained in a block of matter with infinite transverse dimensions, as a function of the thickness of this absorber, expressed in nuclear interaction lengths. Shown are results for showers induced by pions of various energies in iron absorber [Abr 81].

Invisible Energy

- In nuclear reactions some energy must be provided (binding energy) to free protons and neutrons.
- This energy doesn’t result in a measurable signal (*invisible energy*)
- Invisible energy accounts on average for about 30-40% of non-em shower energy

Large event-by-event fluctuations limit resolution

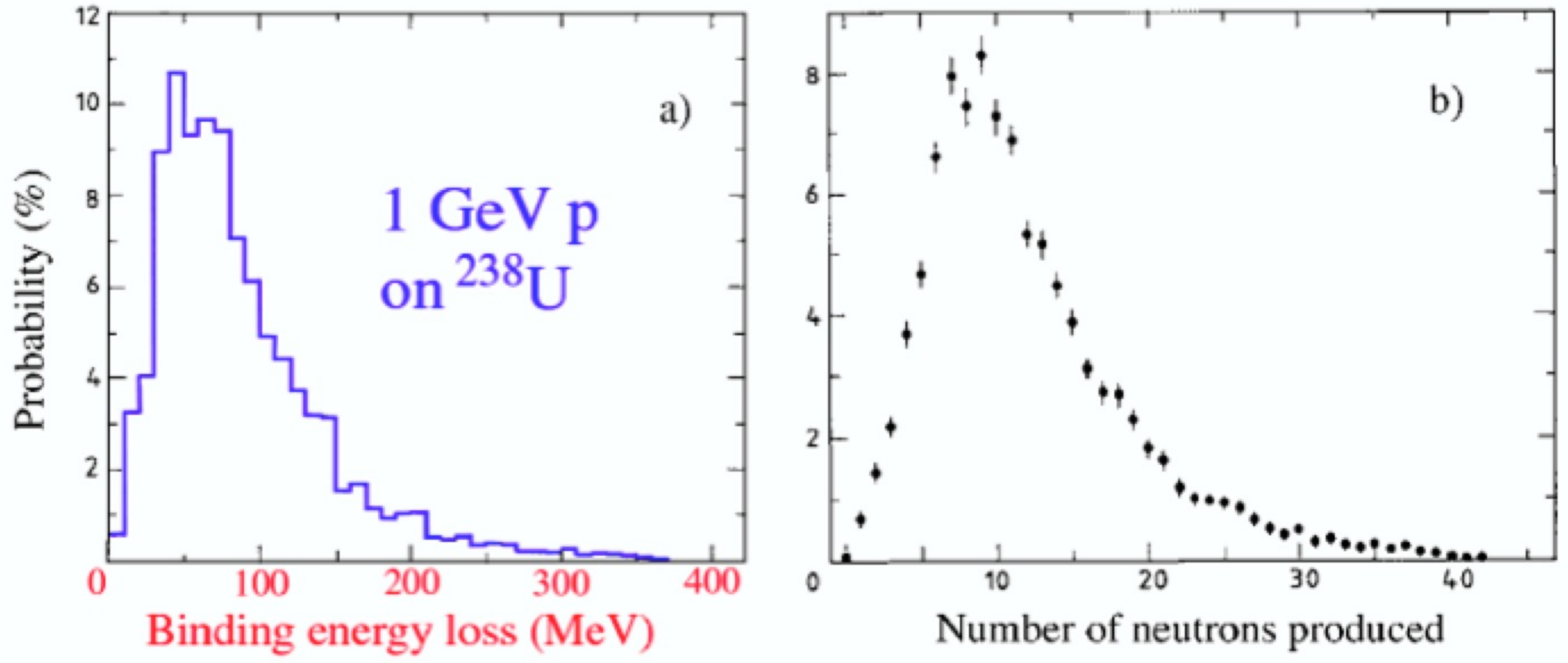


FIG. 4.43. The nuclear binding energy lost in spallation reactions induced by 1 GeV protons on ^{238}U nuclei (*a*), and the number of neutrons produced in such reactions (*b*). From [Wig 87].

Correlation between invisible energy and kinetic energy carried by released nucleons

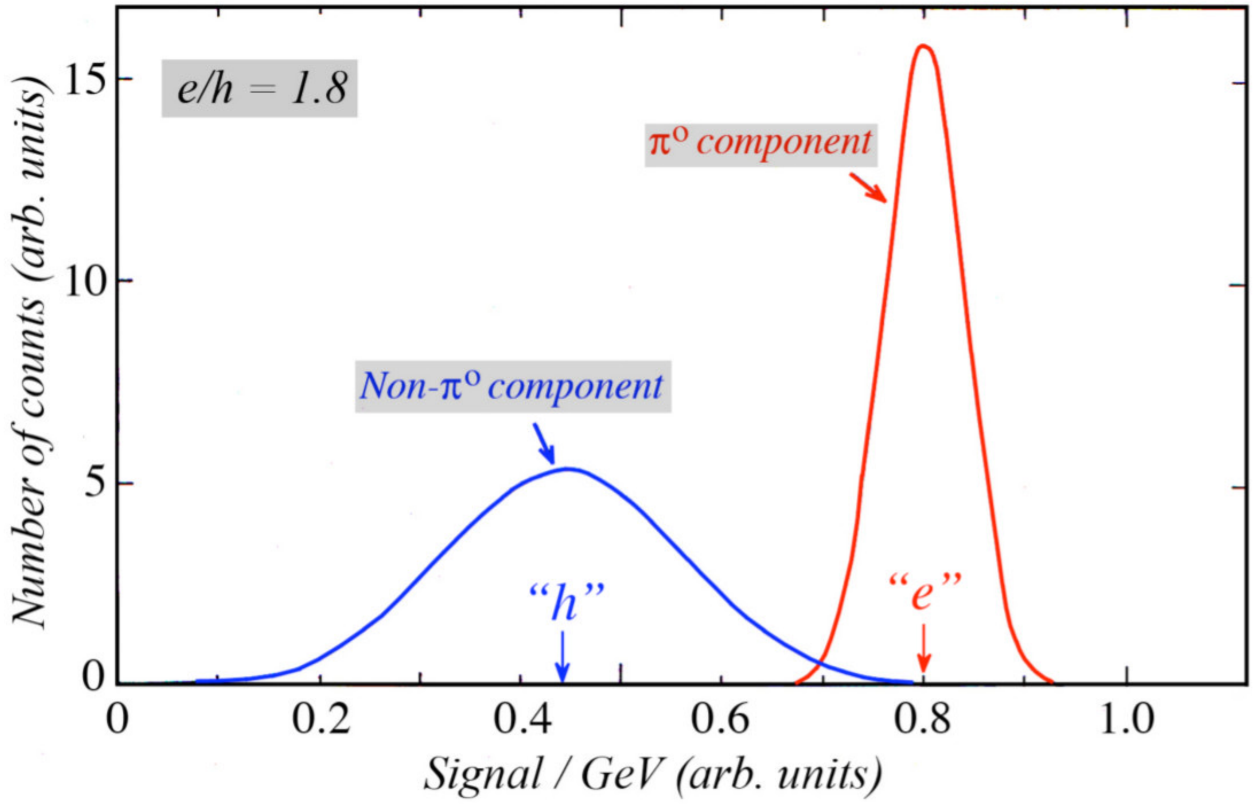
⇒ Can be used for compensation (see later)

Compensation

Energy-independent way to characterize hadron calorimeters: e/h

- e = response to the em shower component
- h = response to the non-em shower component

$$\frac{e}{h} = \frac{e/mip}{f_{rel} \cdot rel/mip + f_p \cdot p/mip + f_n \cdot n/mip}$$

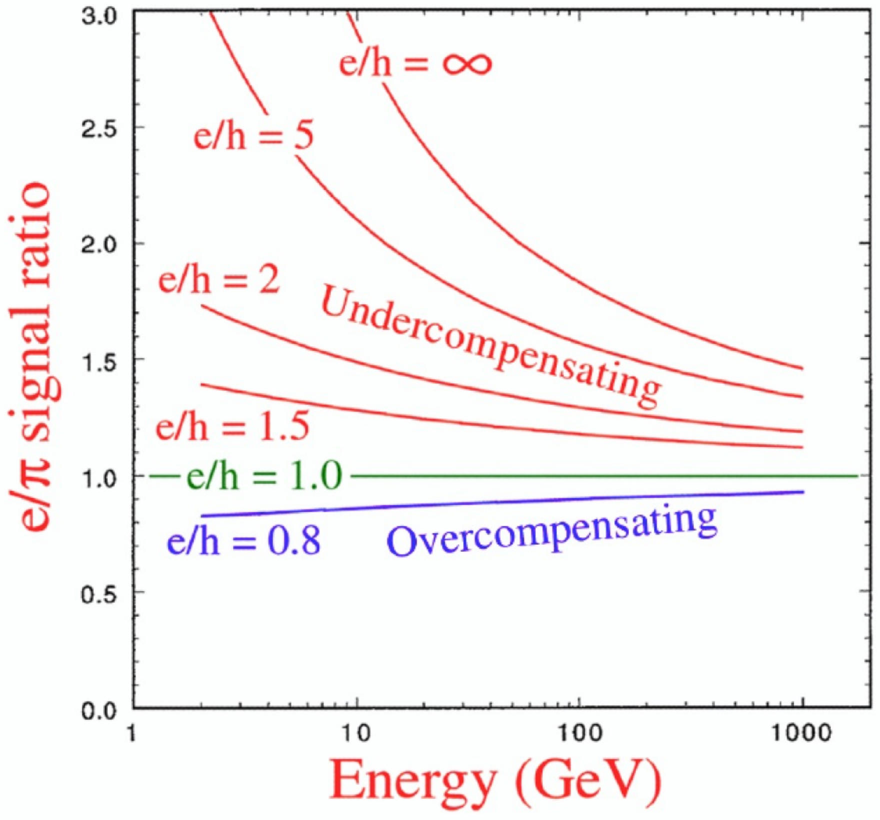


Neutrons have an enormous potential to amplify hadronic shower signals, and thus compensate for losses in invisible energy

Compensating calorimeters rely on neutron contribution to the signals

Ingredients for compensating calorimeters

- Sampling calorimeter
- Hydrogenous active medium (recoil p!)
- Precisely tuned sampling fraction



What compensation does and does not for you

- Compensation does not guarantee high resolution
  - Fluctuations in f_{em} are eliminated, but others may be very large
- Compensation has some drawbacks
  - Small sampling fraction required → em resolution limited
  - Relies on neutrons → calorimeter signals have to be integrated over large volume and time. Not always possible in practice

Fluctuations (em and hadronic showers)

Calorimeter's energy resolution is determined by fluctuations

- Many sources of fluctuations may play a role, for example:
  - Signal quantum fluctuations (e.g. photoelectron statistics)
  - Sampling fluctuations
  - Shower leakage
  - Instrumental effects (e.g. electronic noise, light attenuation, structural non-uniformity)
- but usually one source dominates
  - Improve performance ⇒ work on that source

Energy E gives N signal quanta

Poissonian fluctuations with $\sigma = \sqrt{N}$

⇒ relative width $\sigma/E \propto \sqrt{N}/N$

⇒ $\sigma/E \propto 1/\sqrt{N} \propto a/\sqrt{E}$

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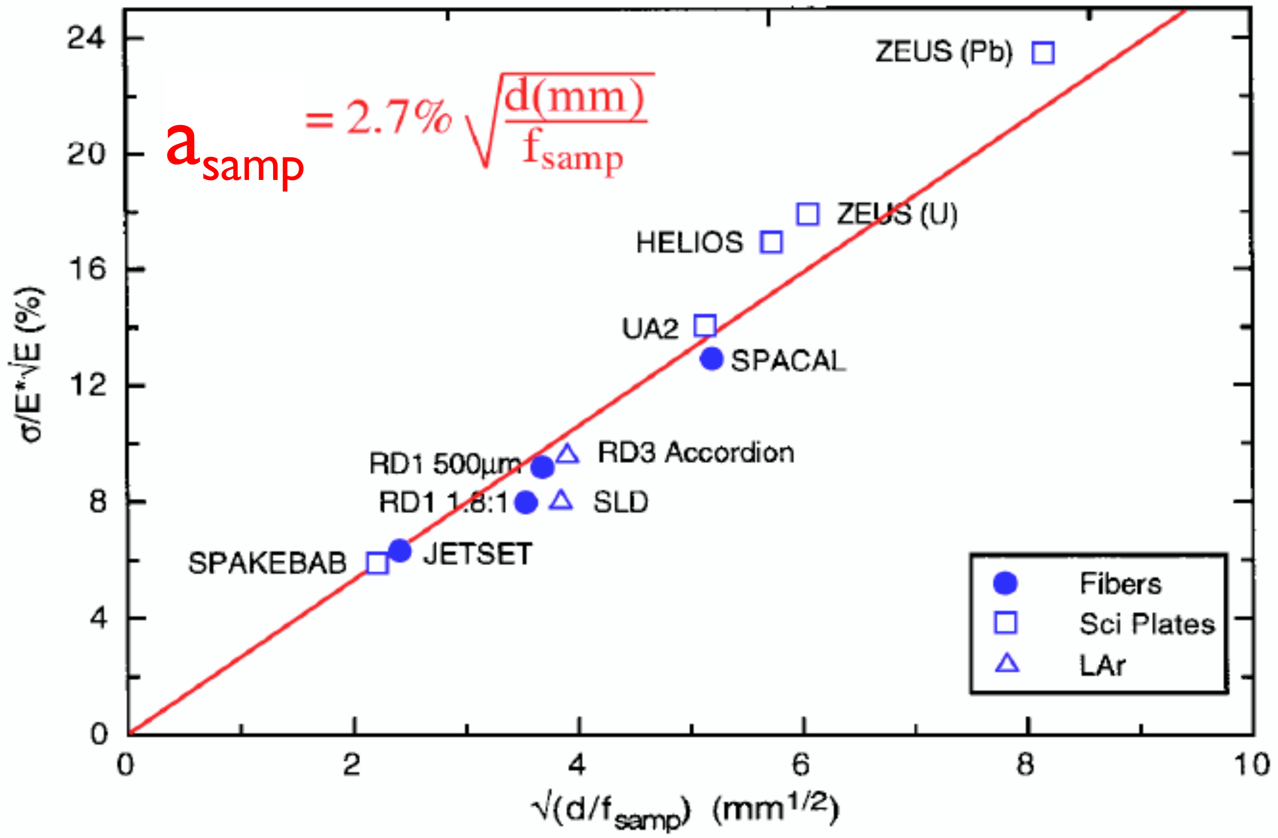
Determined by fluctuations in the number of shower particles contributing to signals

Both sampling fraction and the sampling frequency are important

Poissonian contribution : $\sigma_{samp}/E = a_{samp}/\sqrt{E}$



Fluctuations (em and hadronic showers)

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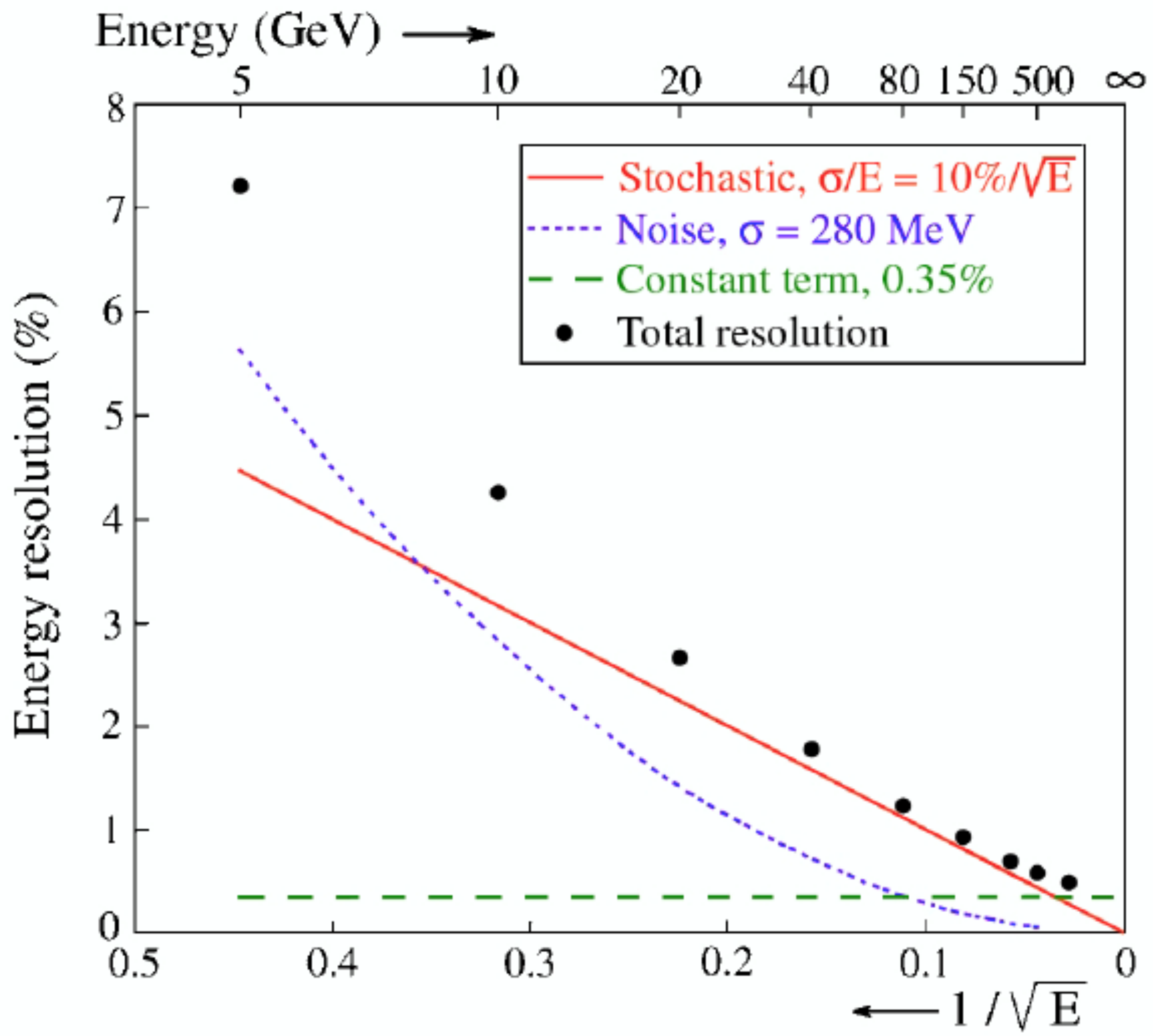
  - Sampling fluctuations
  - Shower leakage
  - Instrumental effects (e.g. electronic noise, light attenuation, structural non-uniformity)
- but usually one source dominates
  - Improve performance ⇒ work on that source

These fluctuations are non-Poissonian
For a given average containment, longitudinal fluctuations are larger that lateral ones

Structural differences in sampling fraction
"Channelling" effects
Electronic noise, light attenuation,.....

Fluctuations - summary

- Different effects have different energy dependence
  - quantum, sampling fluctuations $\sigma/E \sim E^{-1/2}$
  - shower leakage $\sigma/E \sim E^{-1/4}$
  - electronic noise $\sigma/E \sim E^{-1}$
  - structural non-uniformities $\sigma/E = \text{constant}$
- Add in quadrature $\sigma^2_{tot} = \sigma^2_1 + \sigma^2_2 + \sigma^2_3 + \sigma^2_4 + \ldots\ldots$
  - mutually uncorrelated (in general)



Fluctuations in hadron showers

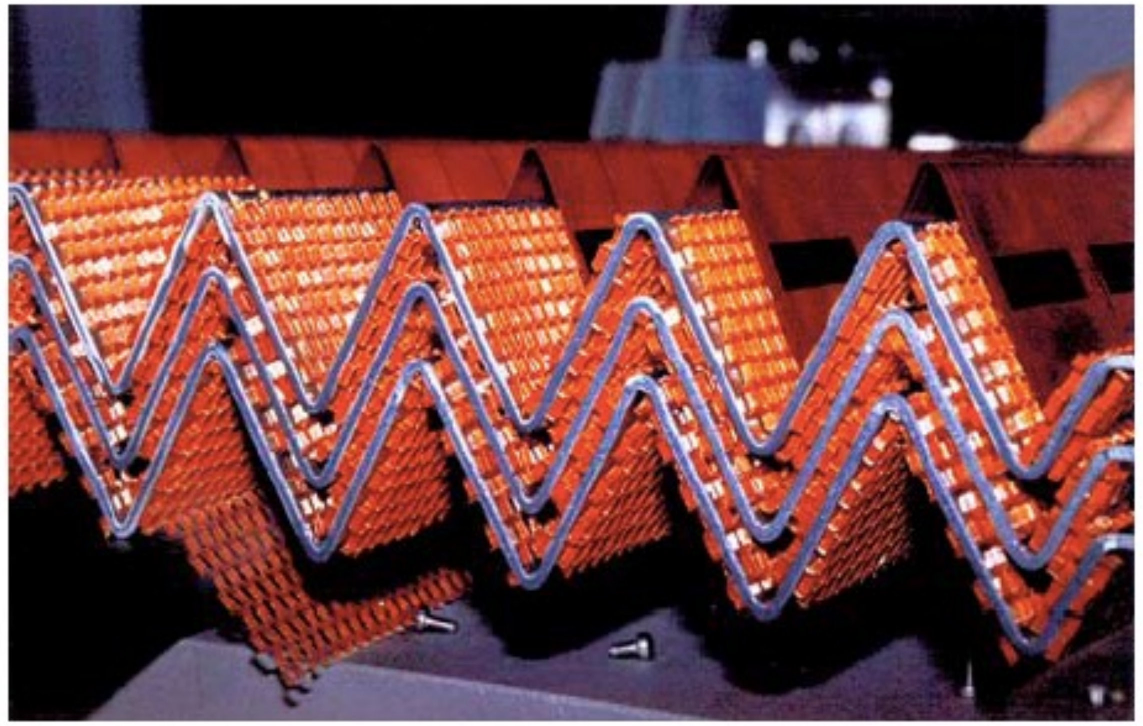
- Some types of fluctuations as in em showers, plus
- Fluctuations in visible energy
  - (ultimate limit of hadronic energy resolution)
- Fluctuations in the em shower fraction, f_{em}
  - Dominating effect in most hadron calorimeters ($e/h \neq 1$)
  - Fluctuations are asymmetric in pion showers (one-way street)
  - Differences between p, π induced showers
    - No leading π^0 in proton showers (barion number conservation)

Calorimeters @ work

Calorimeters @ LHC (examples)

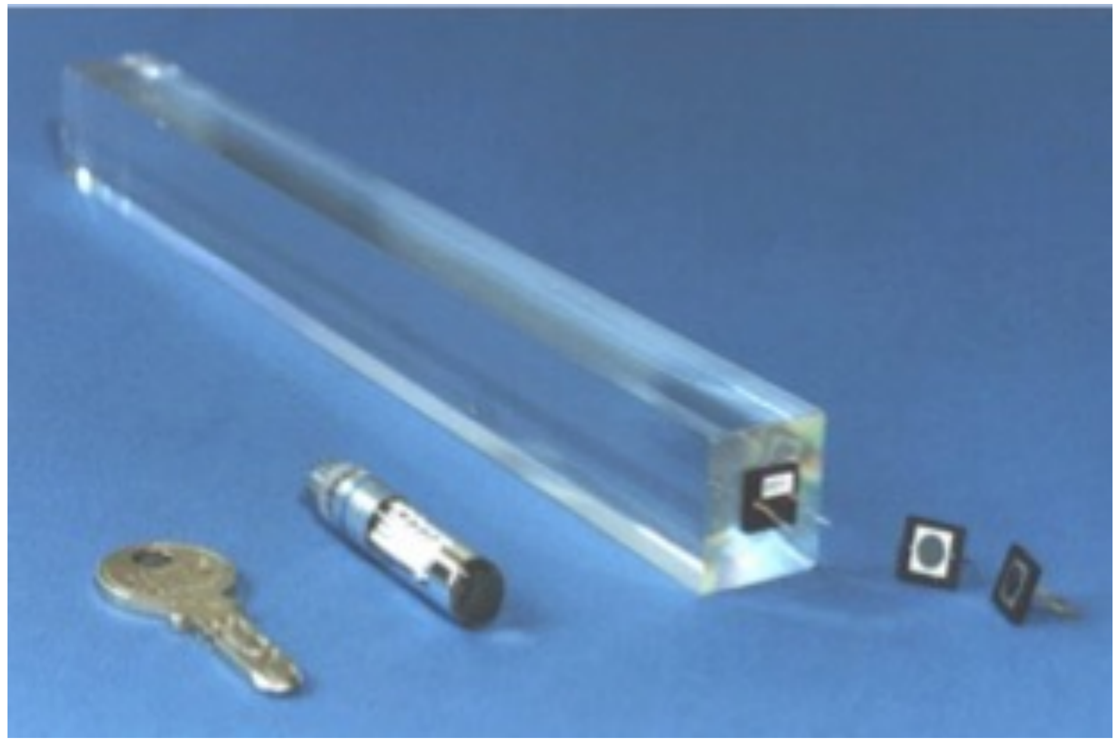
ATLAS Calorimeters:

- EM: Lead-Liquid Argon
  - $\sigma/E \sim 10\%/\sqrt{E(GeV)} \oplus 0.7\%$



CMS Calorimeters:

- EM: Lead-Tungstate (PbWO4) crystal
  - $\sigma/E \sim 3\%/\sqrt{E(GeV)} \oplus 0.5\%$



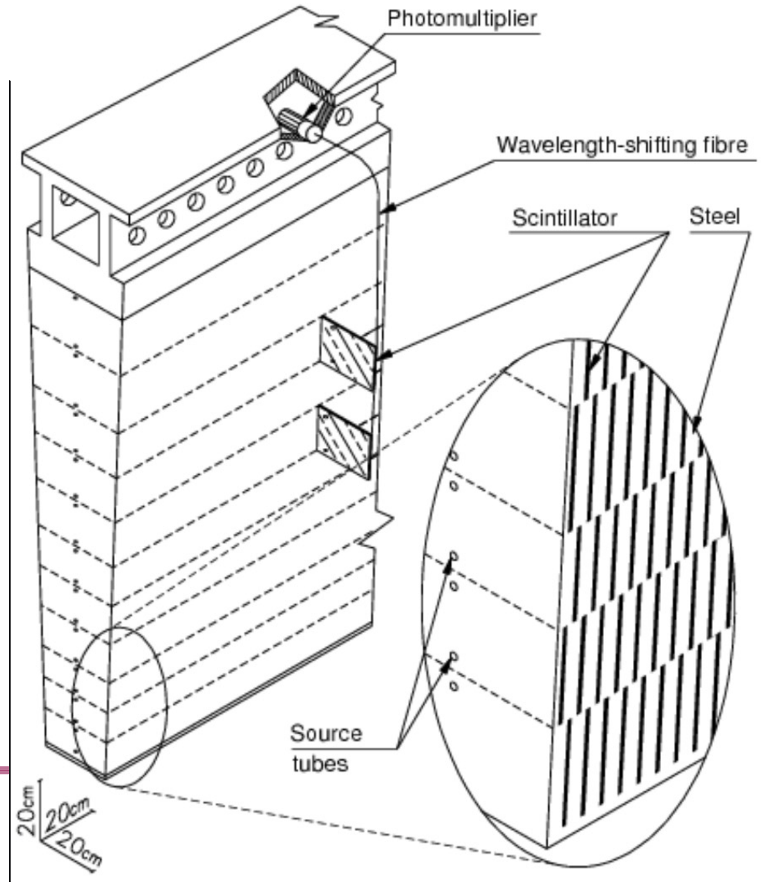
Calorimeters @ LHC (examples)

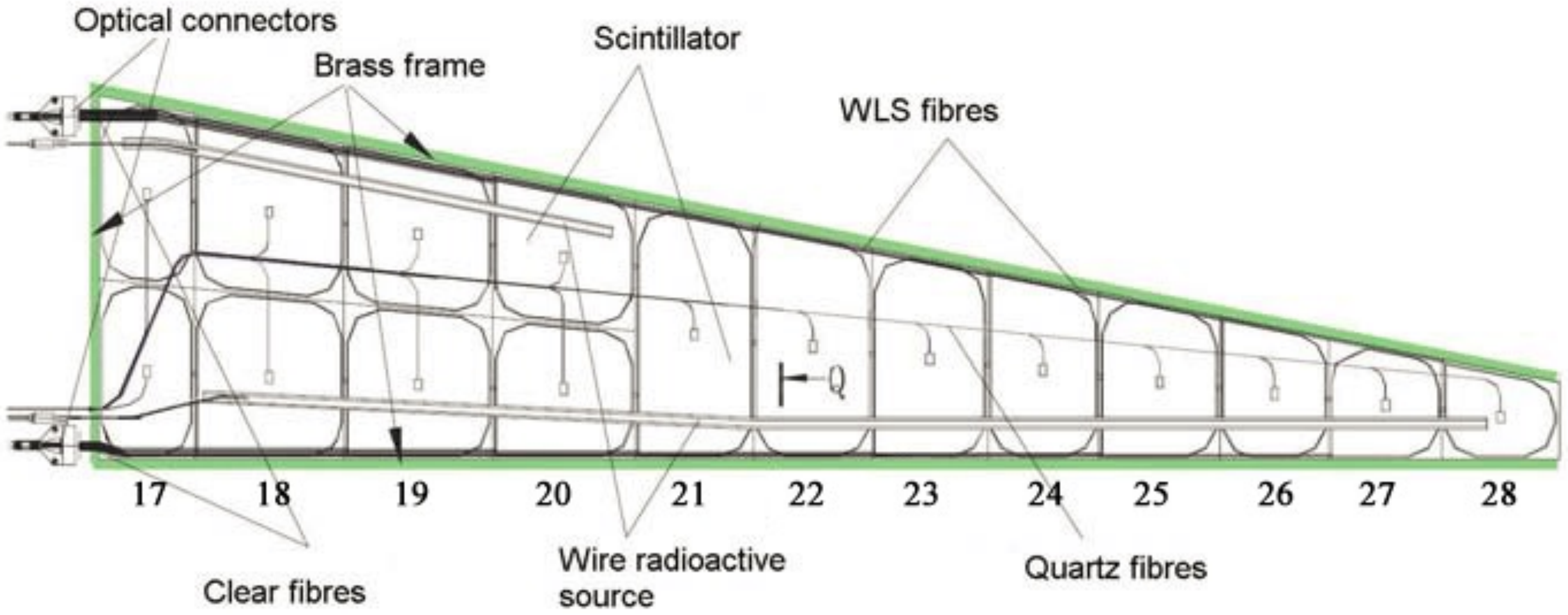
ATLAS Calorimeters:

- EM: Lead-Liquid Argon
  - $\sigma/E \sim 10\%/\sqrt{E(GeV)} \oplus 0.7\%$
- HAD: Stainless steel /Scintillator Tile
  - $\sigma/E \sim 50\%/\sqrt{E(GeV)} \oplus 3\%$

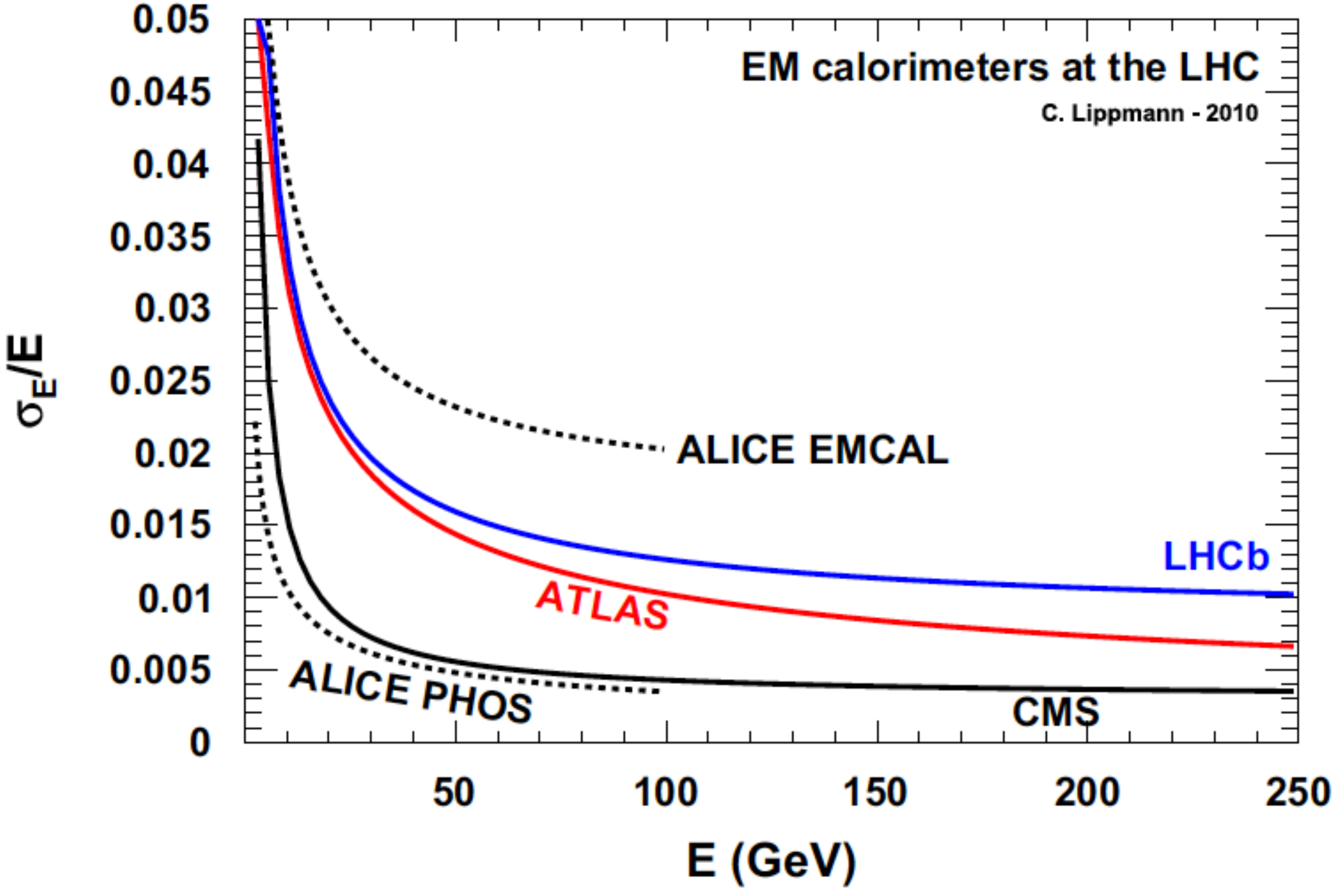
CMS Calorimeters:

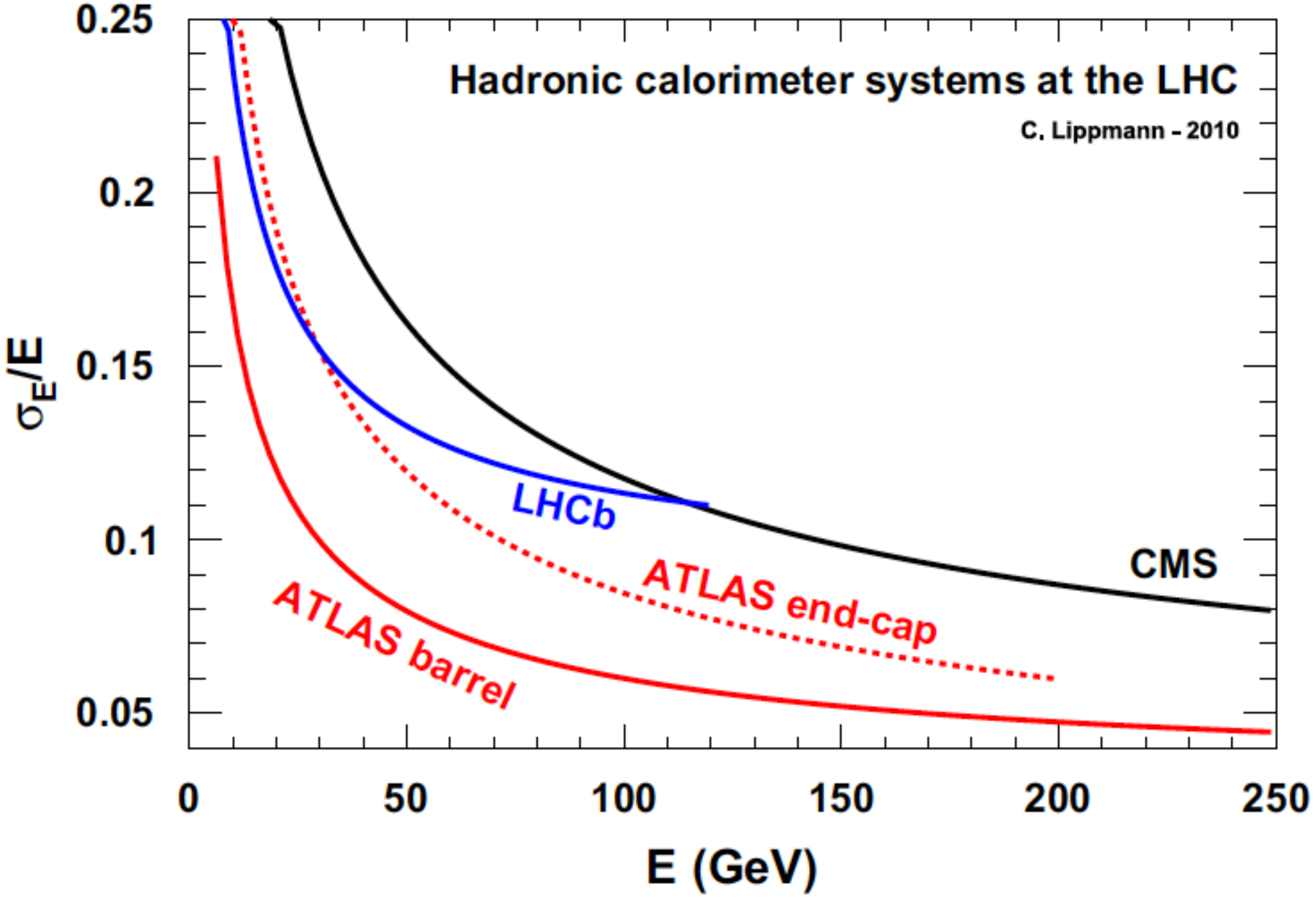
- EM: Lead-Tungstate (PbWO4) crystal
  - $\sigma/E \sim 3\%/\sqrt{E(GeV)} \oplus 0.5\%$
- HAD: Brass/Scintillator Tile
  - $\sigma/E \sim 100\%/\sqrt{E(GeV)} \oplus 5\%$





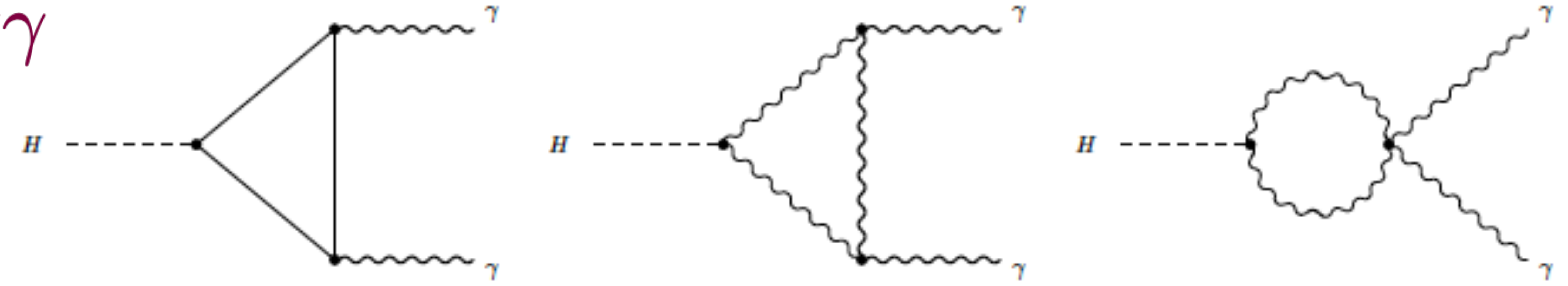
LHC calorimeters performances





A walkthrough from physics to the detector

$H \to \gamma\gamma$



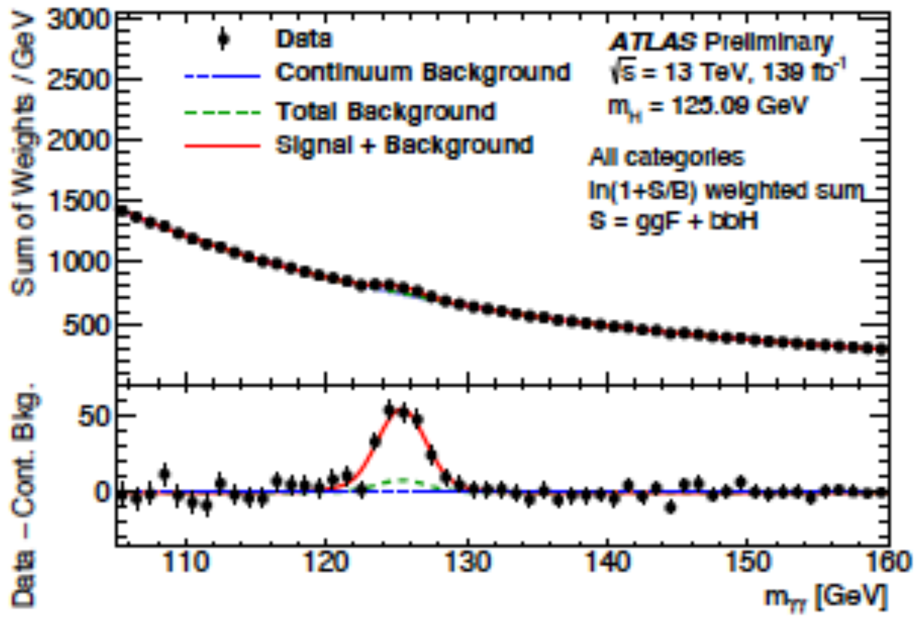
- Small Branching Ratio (2.27 ± 0.07) x 10^{-3}
- Large signal yield
  - high photon reconstruction and identification efficiency
  - high photon energy resolution → narrow pick above in the diphoton invariant mass spectrum

What to measure?

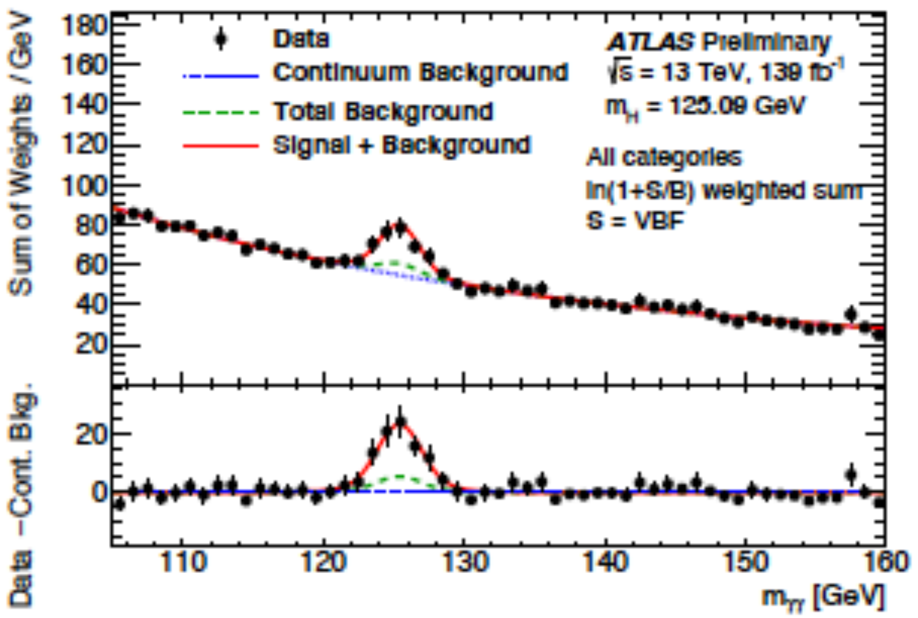
Higgs mass

$$M = E_{cm} = \sqrt{(E_1 + E_2)^2 - (\mathbf{p_1} + \mathbf{p_2})^2}$$

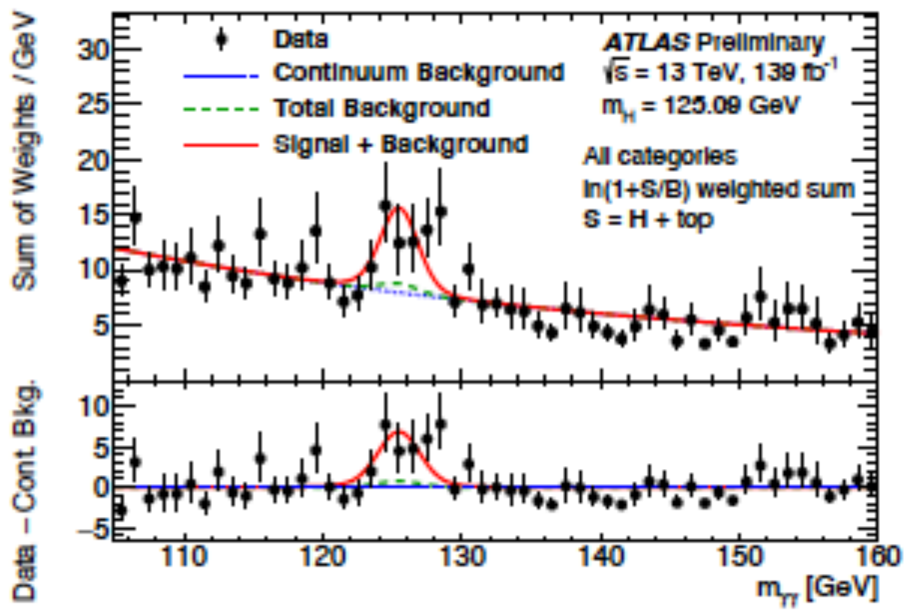
$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1 - \cos\alpha)}$$



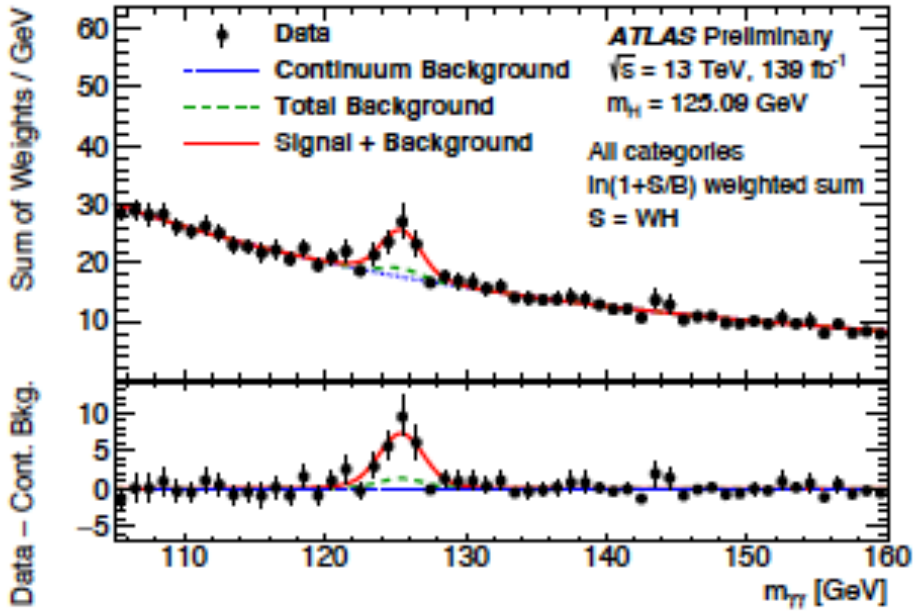
(a) ggF+ $b\bar{b}H$



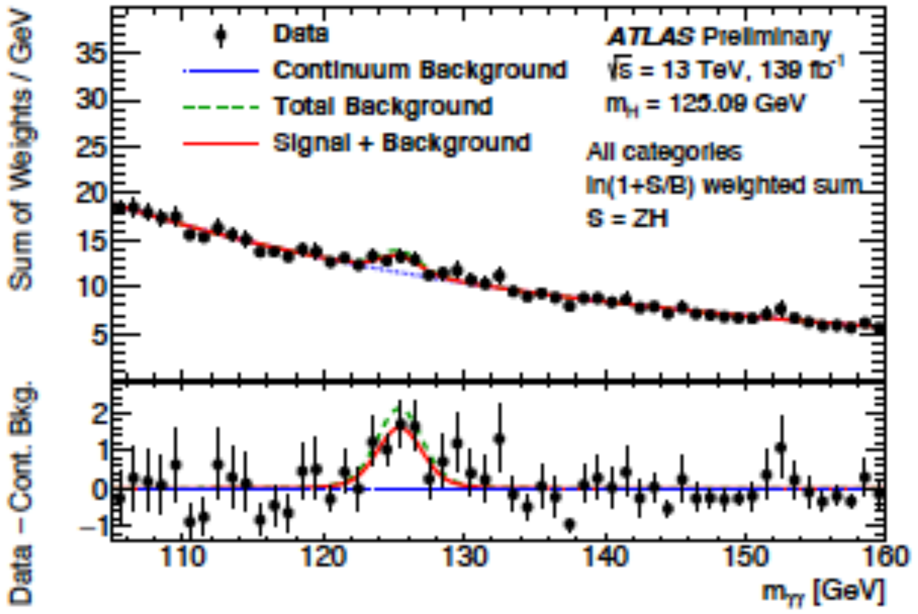
(b) VBF



(e) $t\bar{t}H + tH$



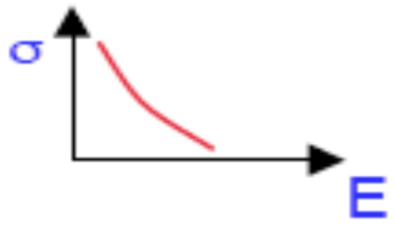
(c) WH



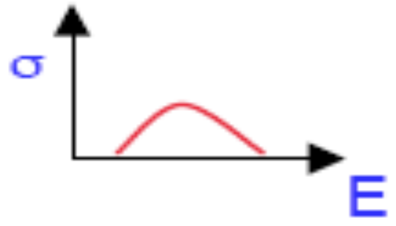
(d) ZH

Starting point: catch the photons

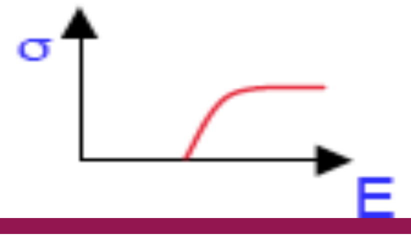
- Photoelectric effect

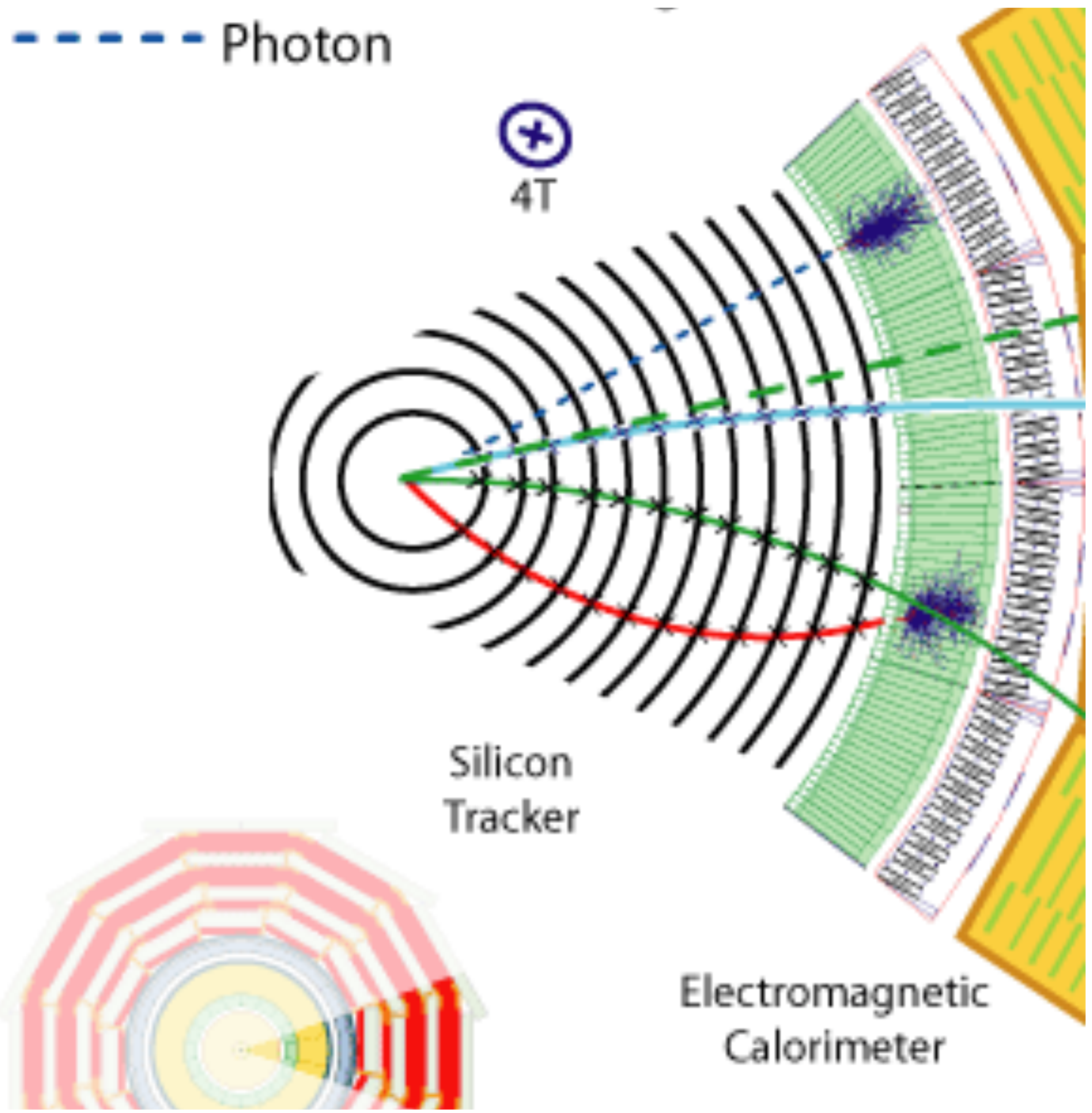


- Compton effect



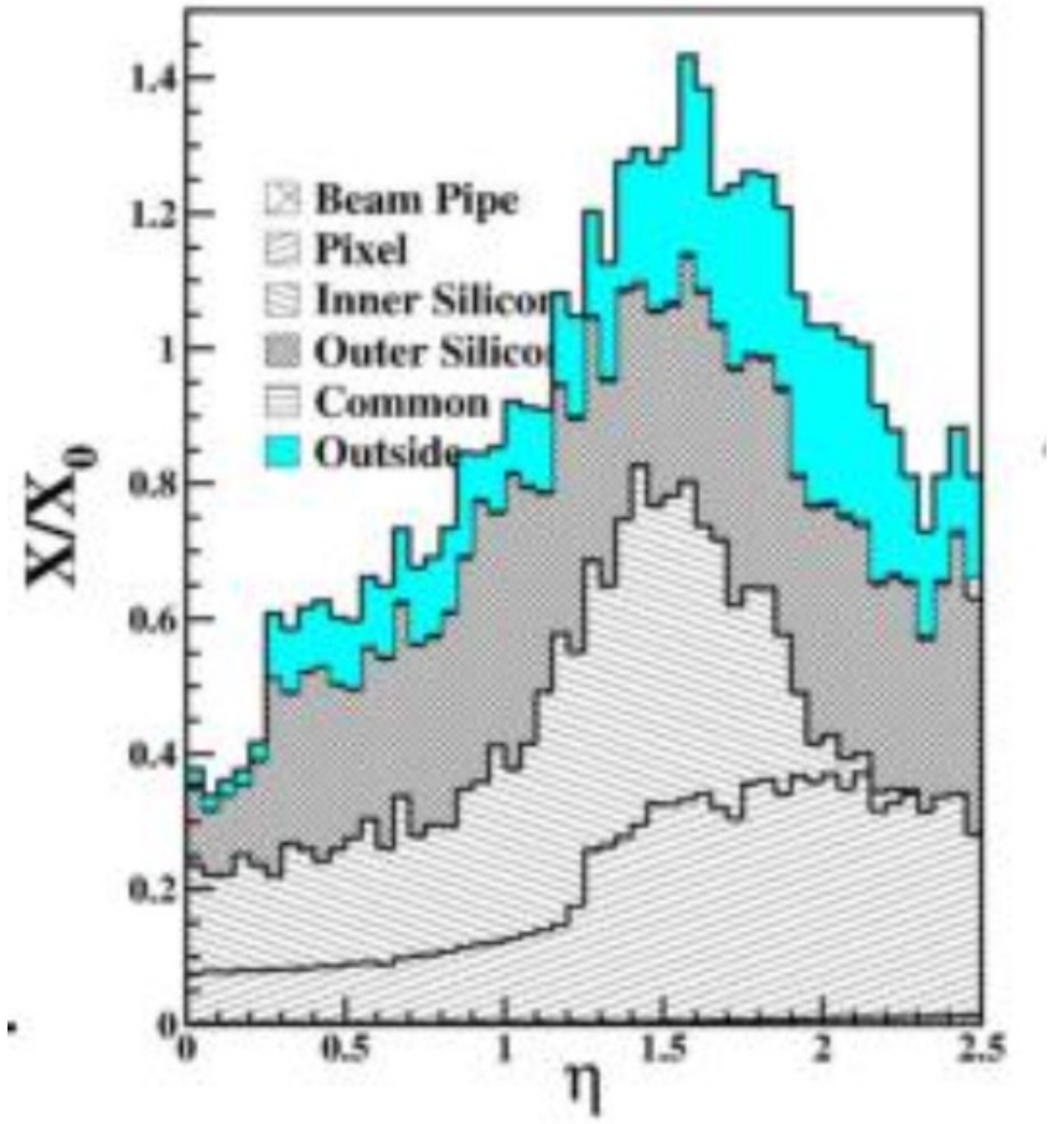
- Pair production





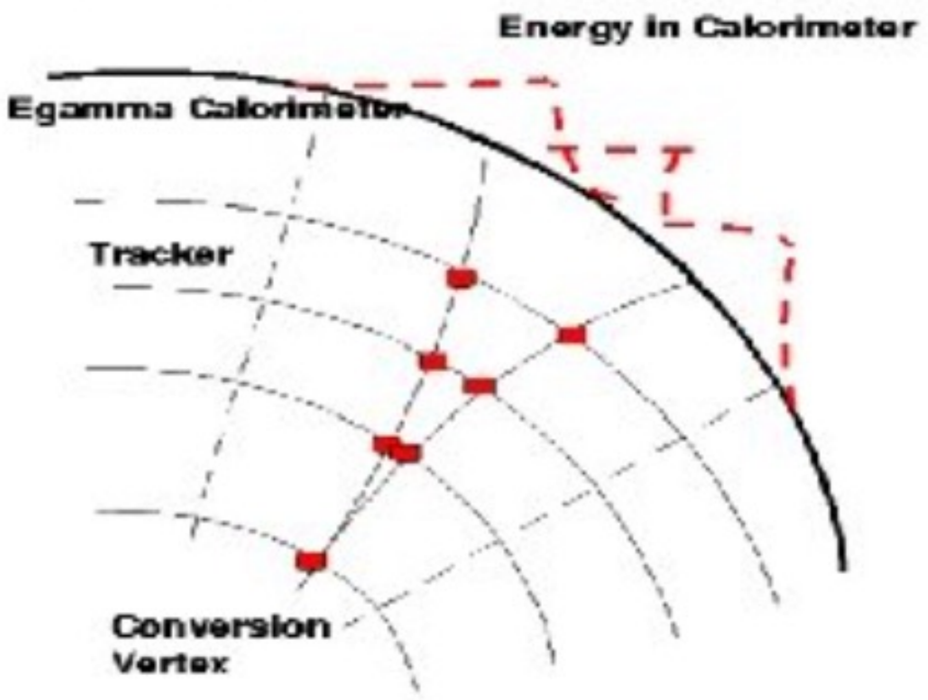
- ✦ Detected in the Electromagnetic calorimeter
- ✦ No track in the inner detector unconverted photons
- ✦ May anyway convert (= pair production) in the material upstream

Converted photons

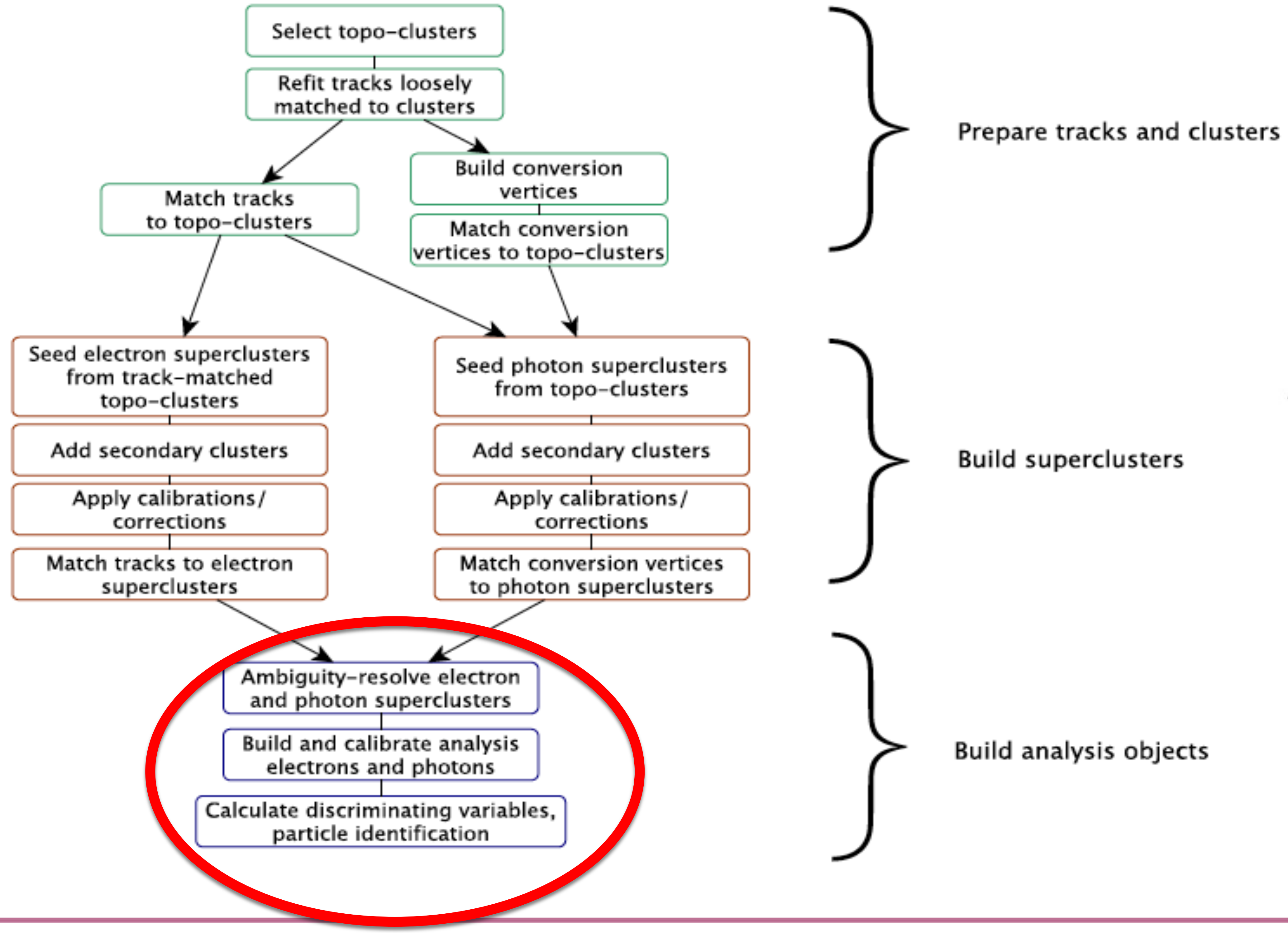


material budget in front of the calorimeter (CMS)

- A converted photon is a cluster matched to a conversion vertex
- An unconverted photon is a cluster matched to neither an electron track nor a conversion vertex.
- About 20% of photons at low |η| convert in the ID, and up to about 65% convert at |η |~ 2.3

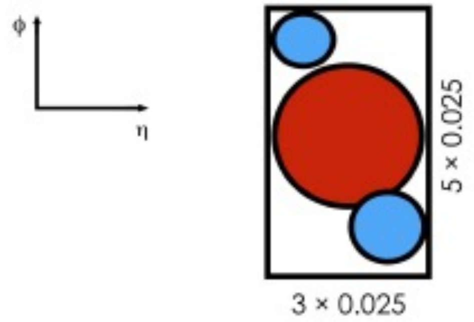


From energy deposit to clusters



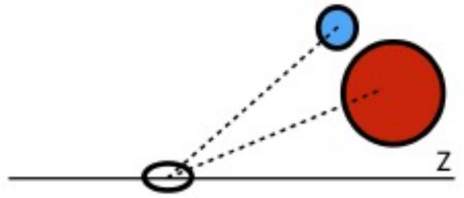
All $e^{\pm}$, γ:

Add all clusters within 3 × 5 window around seed cluster.

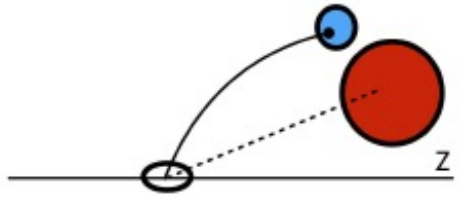


Converted photons only:

Add topo-clusters that have the **same conversion vertex** matched as the seed cluster.



Add topo-clusters with **a track match** that is **part of the conversion vertex** matched to the seed cluster.



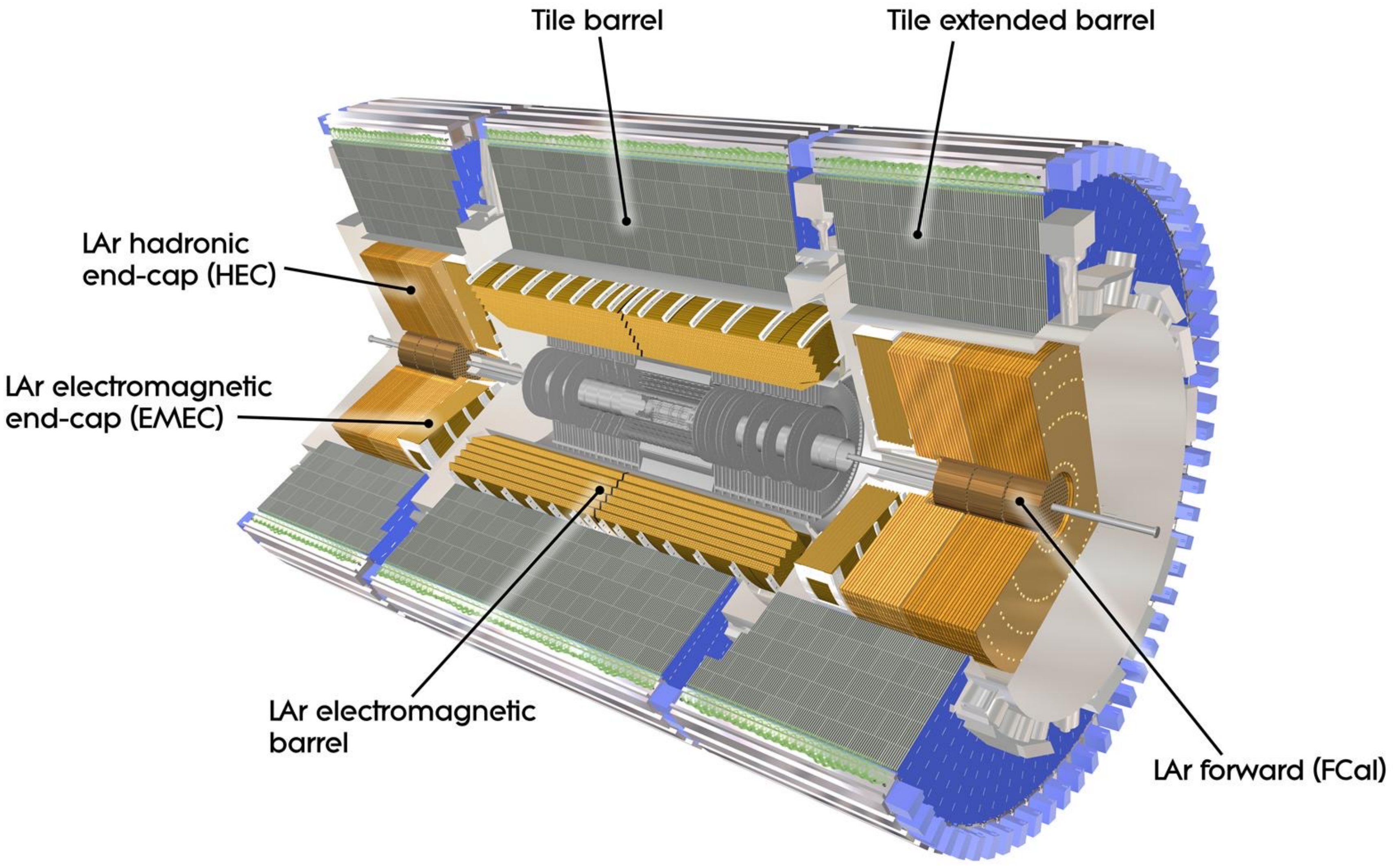
seed for topo-cluster

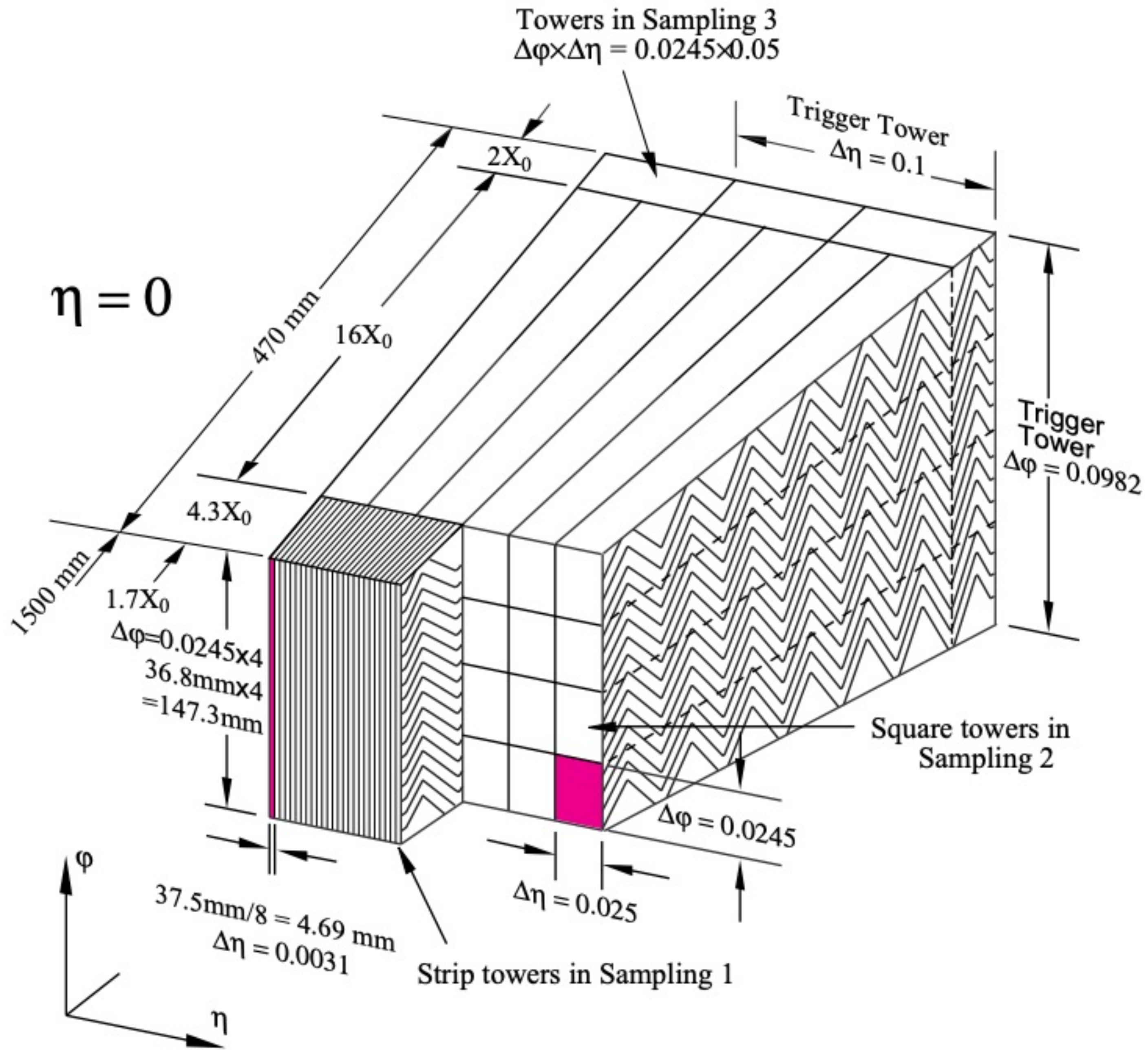
$$\varsigma^{\mathrm{EM}}_{\mathrm{cell}} = \frac{E^{\mathrm{EM}}_{\mathrm{cell}}}{\sigma^{\mathrm{EM}}_{\mathrm{noise,cell}}}, \qquad \left|\varsigma^{\mathrm{EM}}_{\mathrm{cell}}\right| \geq 4$$

From cluster to identified photons

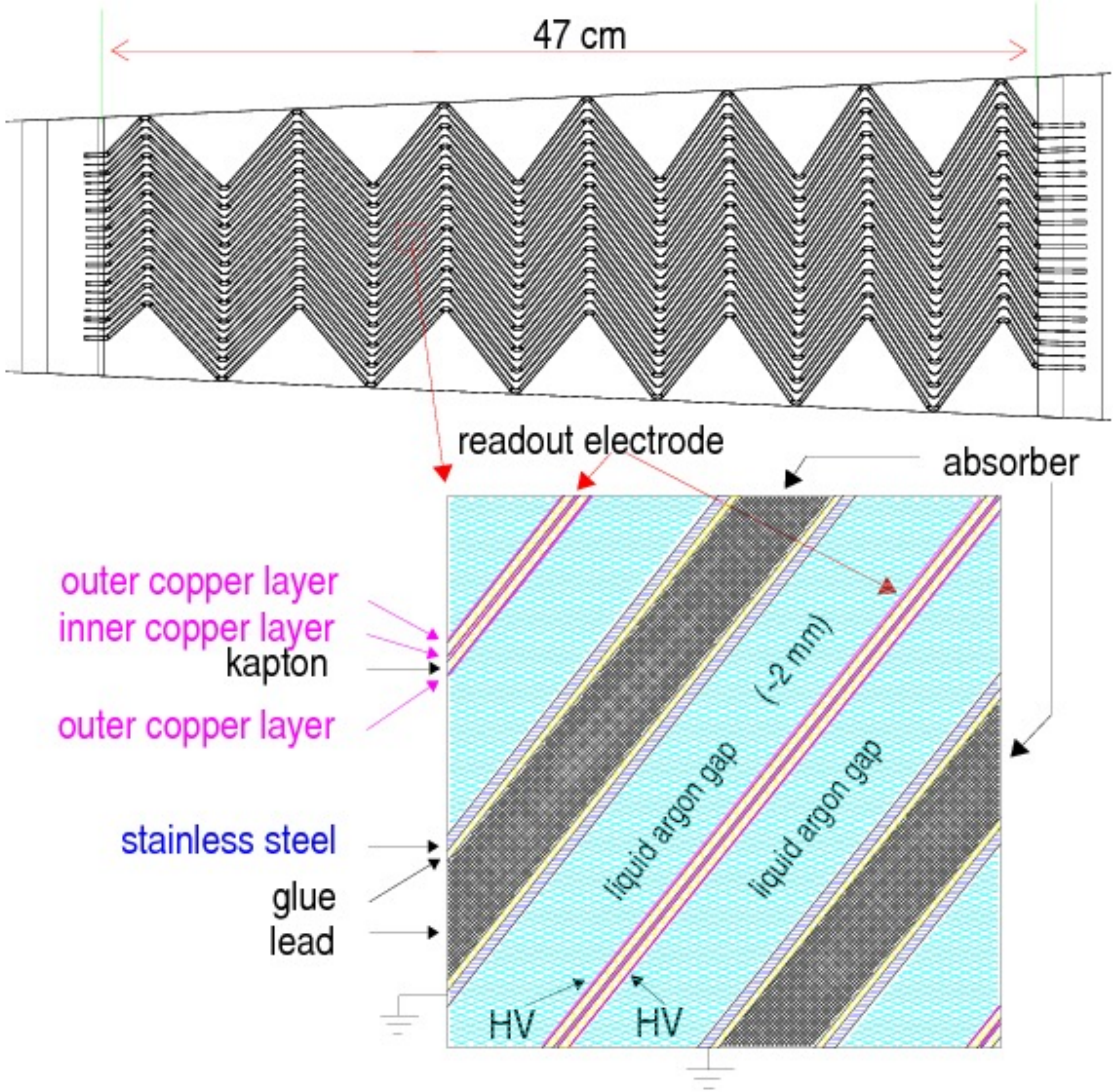
- Apply cluster calibration
- Measure direction
  - Use ϕ, η from measurement
  - Converted γ: take photon direction from conversion and pointing
- Identification parameters
  - Calorimeter shapes
    - Shower shapes
    - Leakage into the hadronic calorimeter
  - Cuts different for converted and unconverted γ's
  - They are optimised in various |η| bins (but p_T independent)
- Final energy calibration (Z→ee, Z→eeγ, J/ψ)

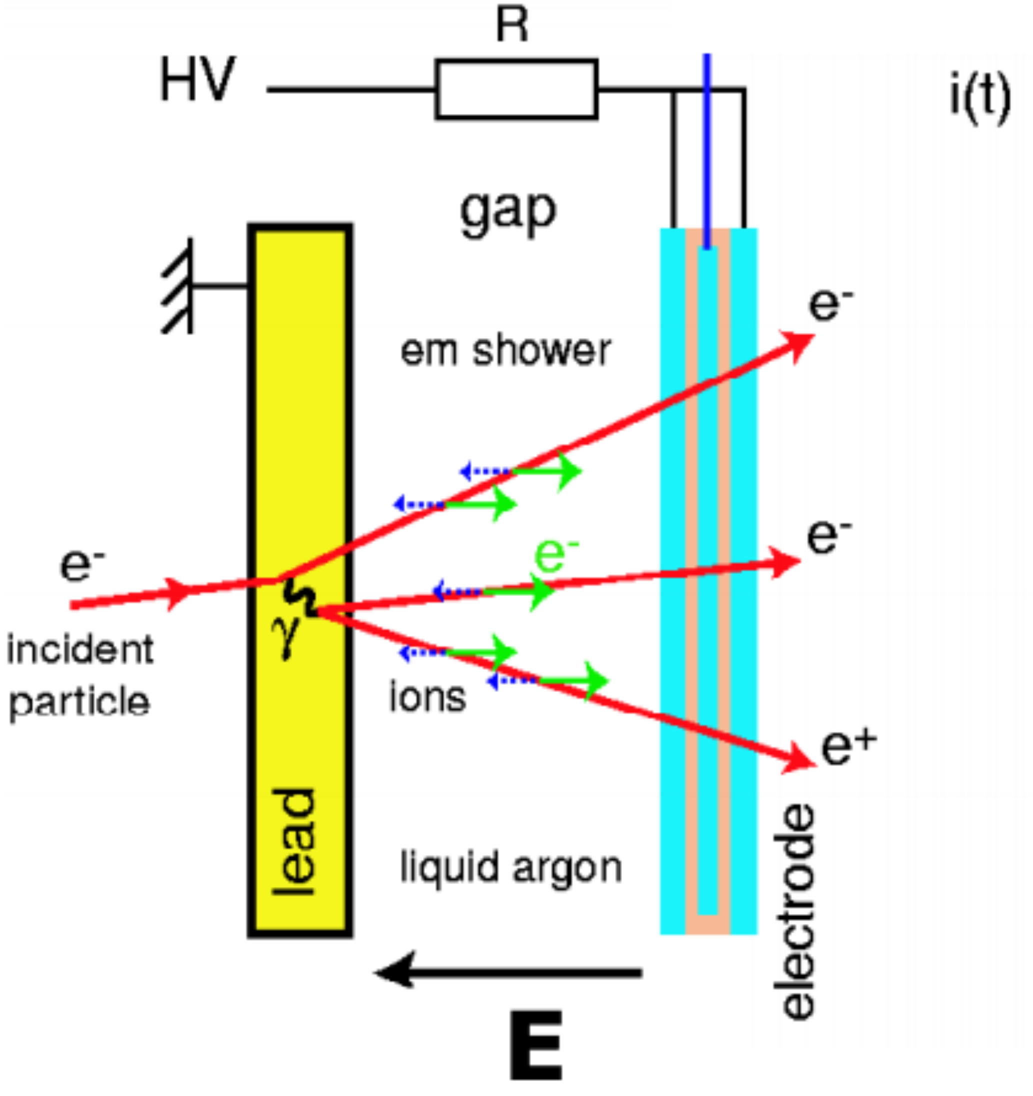
ATLAS: Lar Calorimeter





ATLAS: Lar Calorimeter

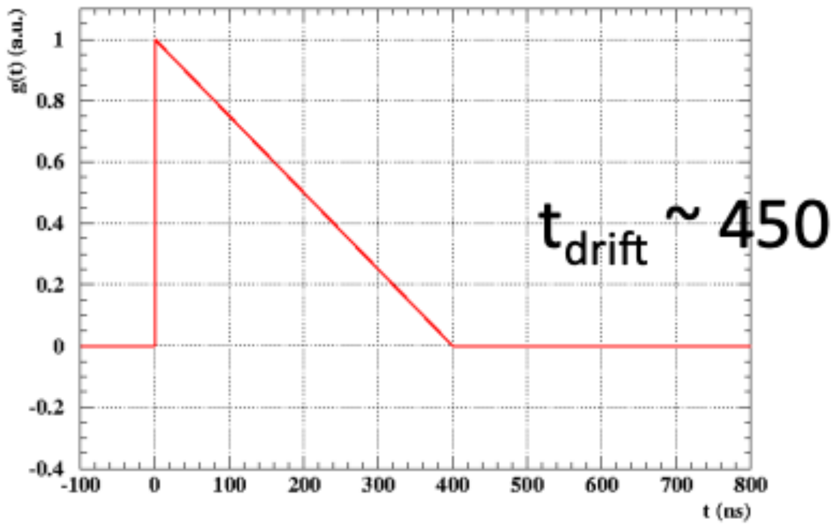




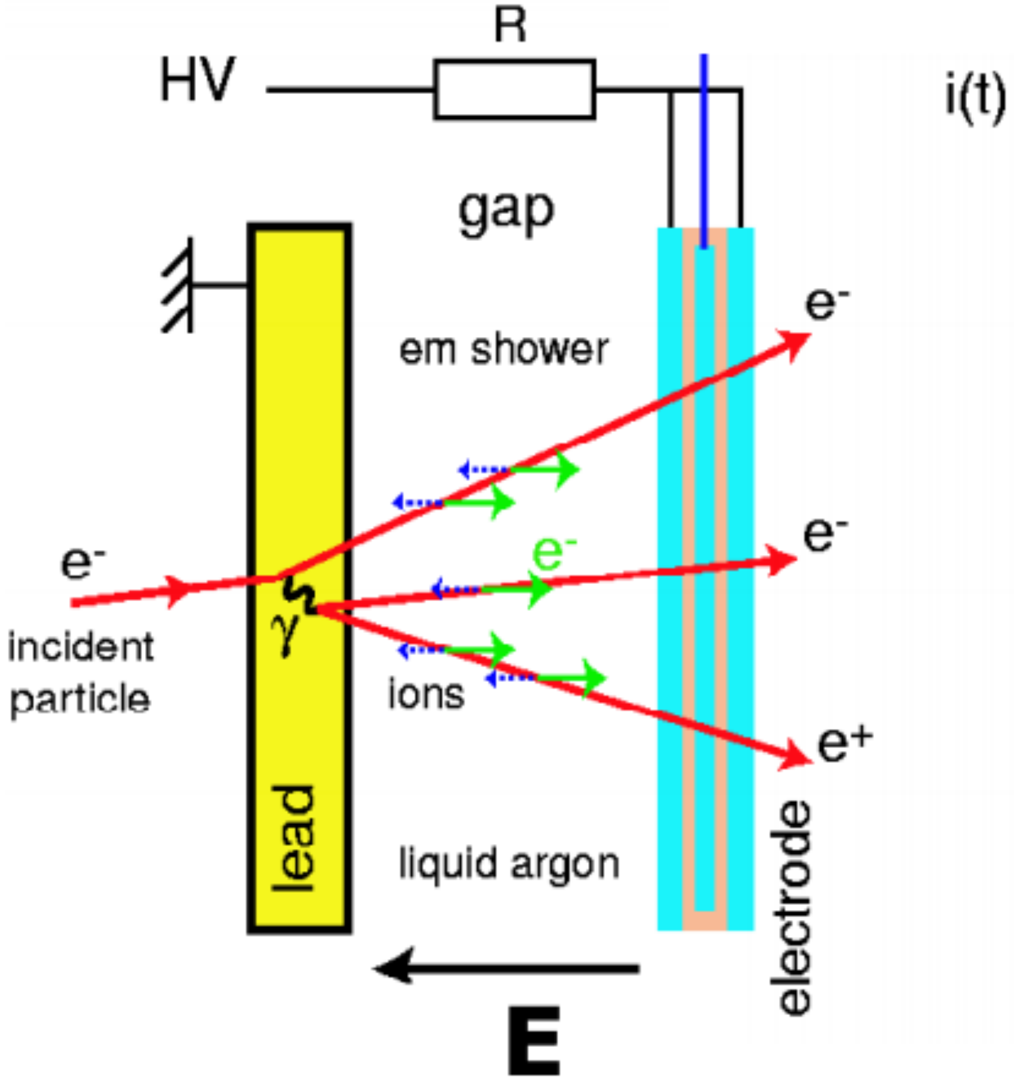
operated at a temperature of 87 K
signal dependence on the temperature of -2 %/K

ATLAS LAr readout

- Interactions mainly in lead absorber
- Charged particles ionize Ar atoms
- Elecrons drift in the LAr gap where an electric field is applied
- Signal is induced on the read-out electrodes by the moving electrons
- Induced signals have a caracteristic triangular shape current peak ~ energy lost by particles



t_{drift} ~ 450

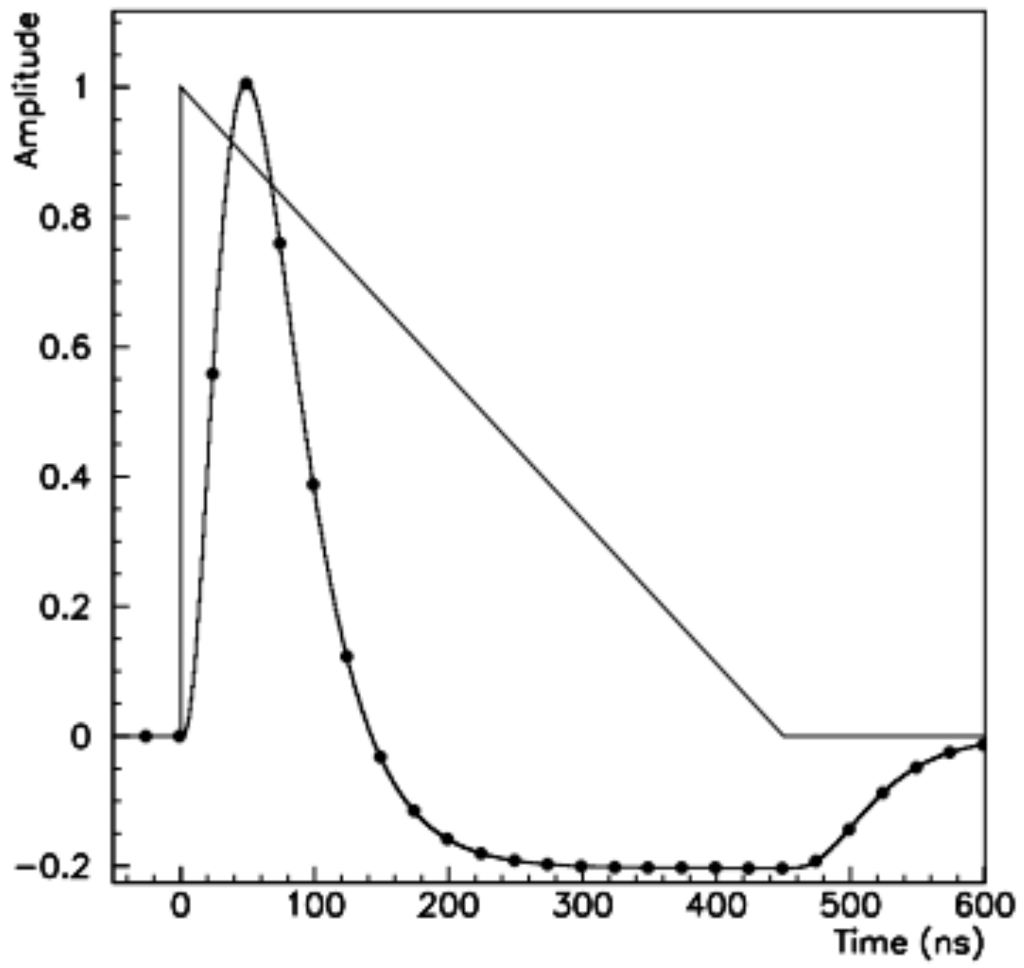


$$I(t) = \frac{dQ(t)}{dt} \propto Q_0(1 - \frac{v_d}{d}t)$$

Lar ATLAS Calorimeter

- Advantages of LAr as active material
  - Detector uniformity (easier calibration)
  - Linearity of the response (LAr high density → no electron amplification needed)
  - Stability with time
  - Radiation hard
  - High granularity possible (shaping)

- Drawbacks
  - Sampling (but longitudinal segmentation possible)
  - Criogenics → difficult operation, additional dead material
  - 'Slow' charge collection: 450ns >> 25ns = LHC BC frequency

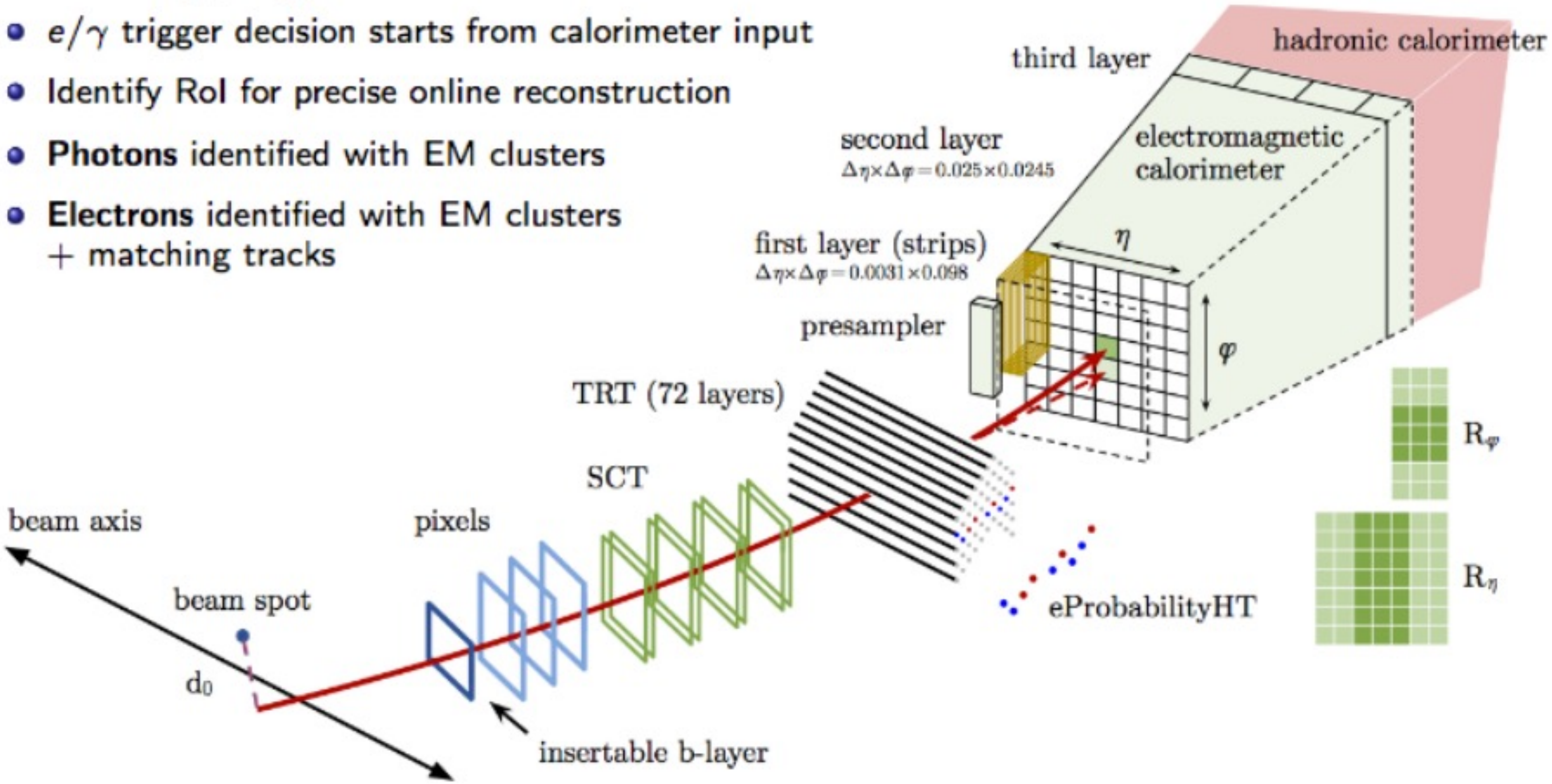


$t_d >> \tau_{BC}$ but the energy information is given by the current peak →integration of the signal over ~ 50ns

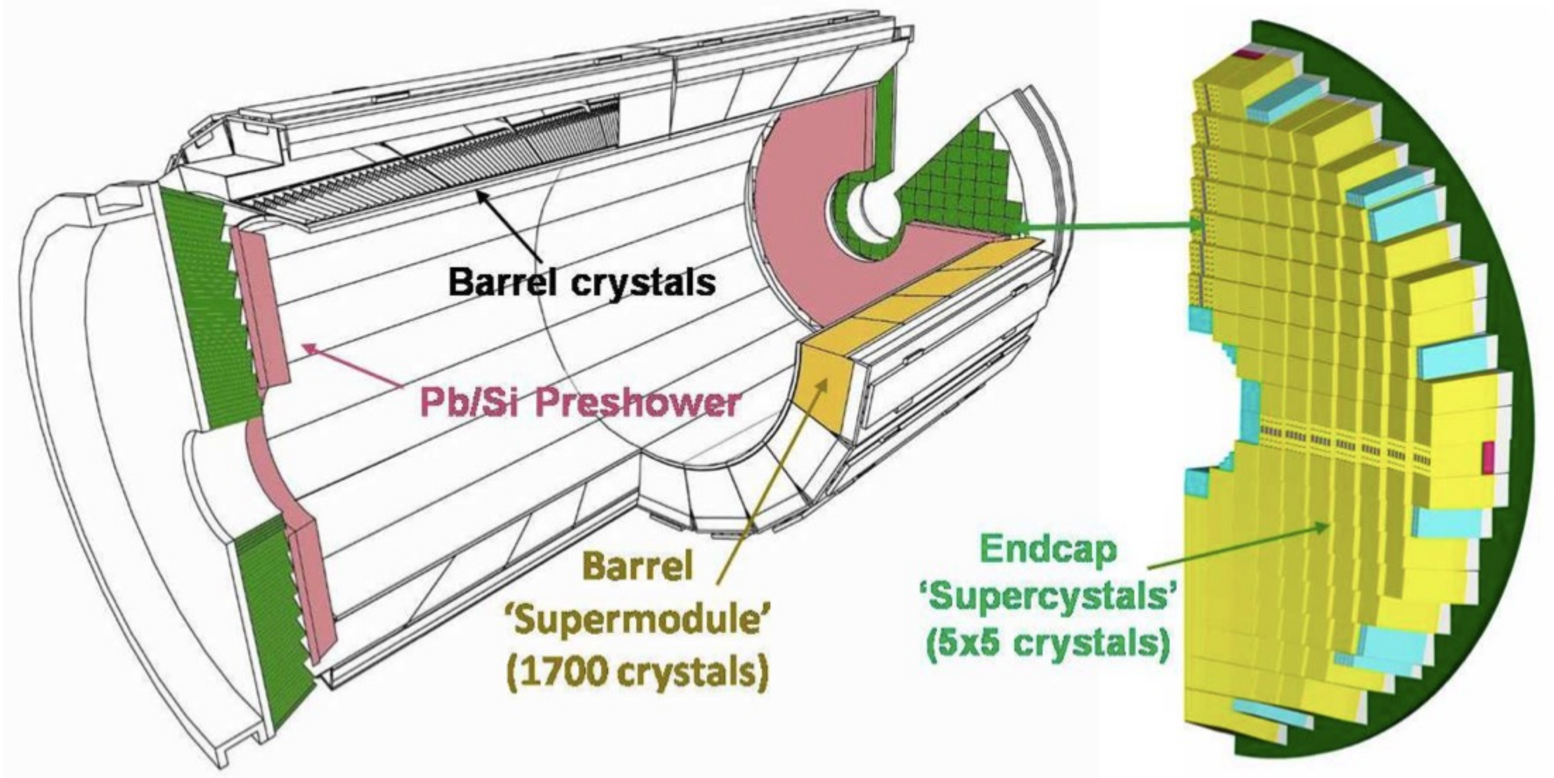
Triggering e/γ

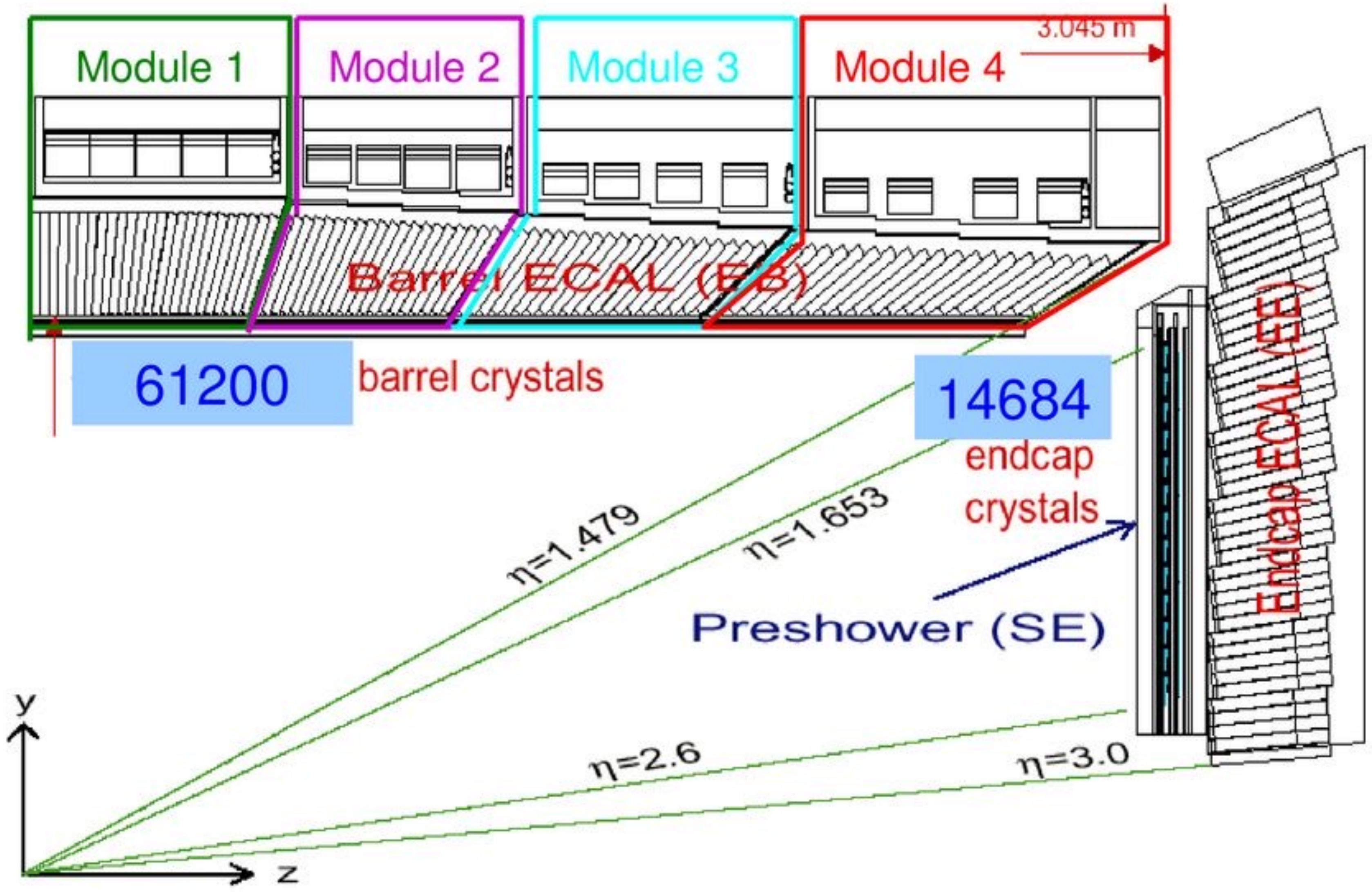
The ATLAS e/γ triggers

- e/γ trigger decision starts from calorimeter input
- Identify RoI for precise online reconstruction
- **Photons** identified with EM clusters
- **Electrons** identified with EM clusters + matching tracks



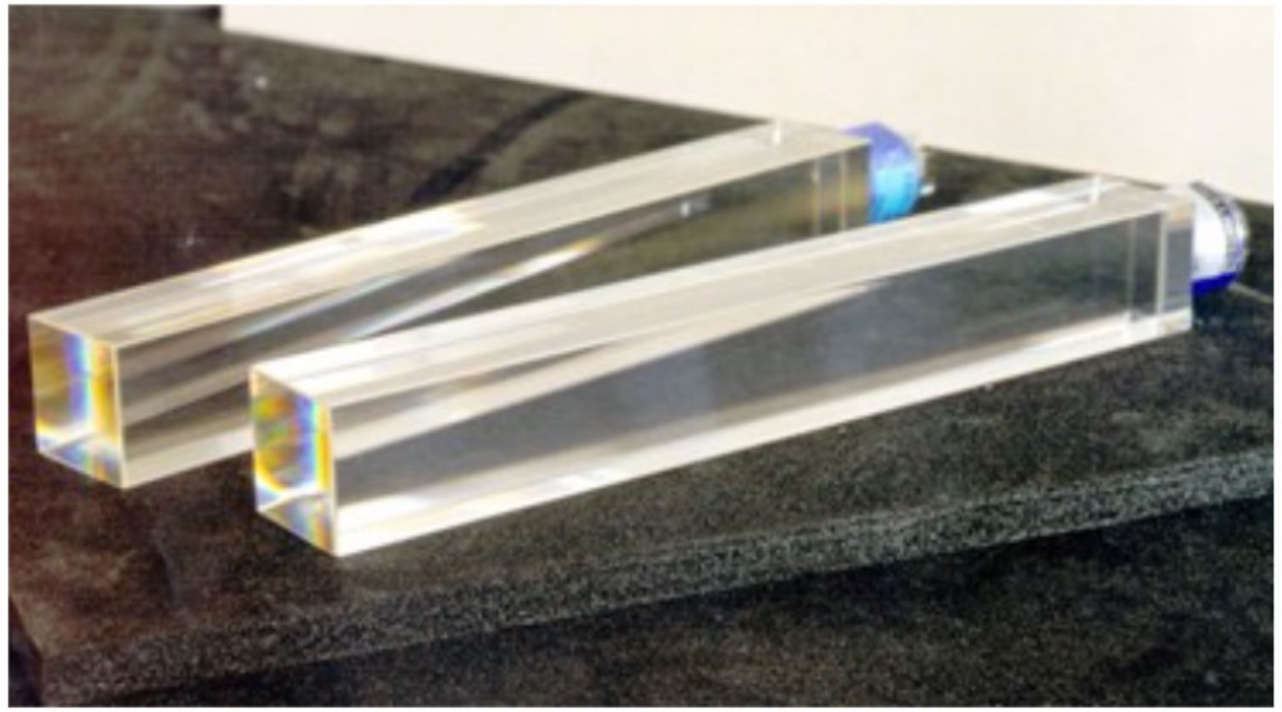
CMS ECAL


Barrel crystals
Pb/Si Preshower
Barrel
'Supermodule'
(1700 crystals)
Endcap
'Supercrystals'
(5x5 crystals)

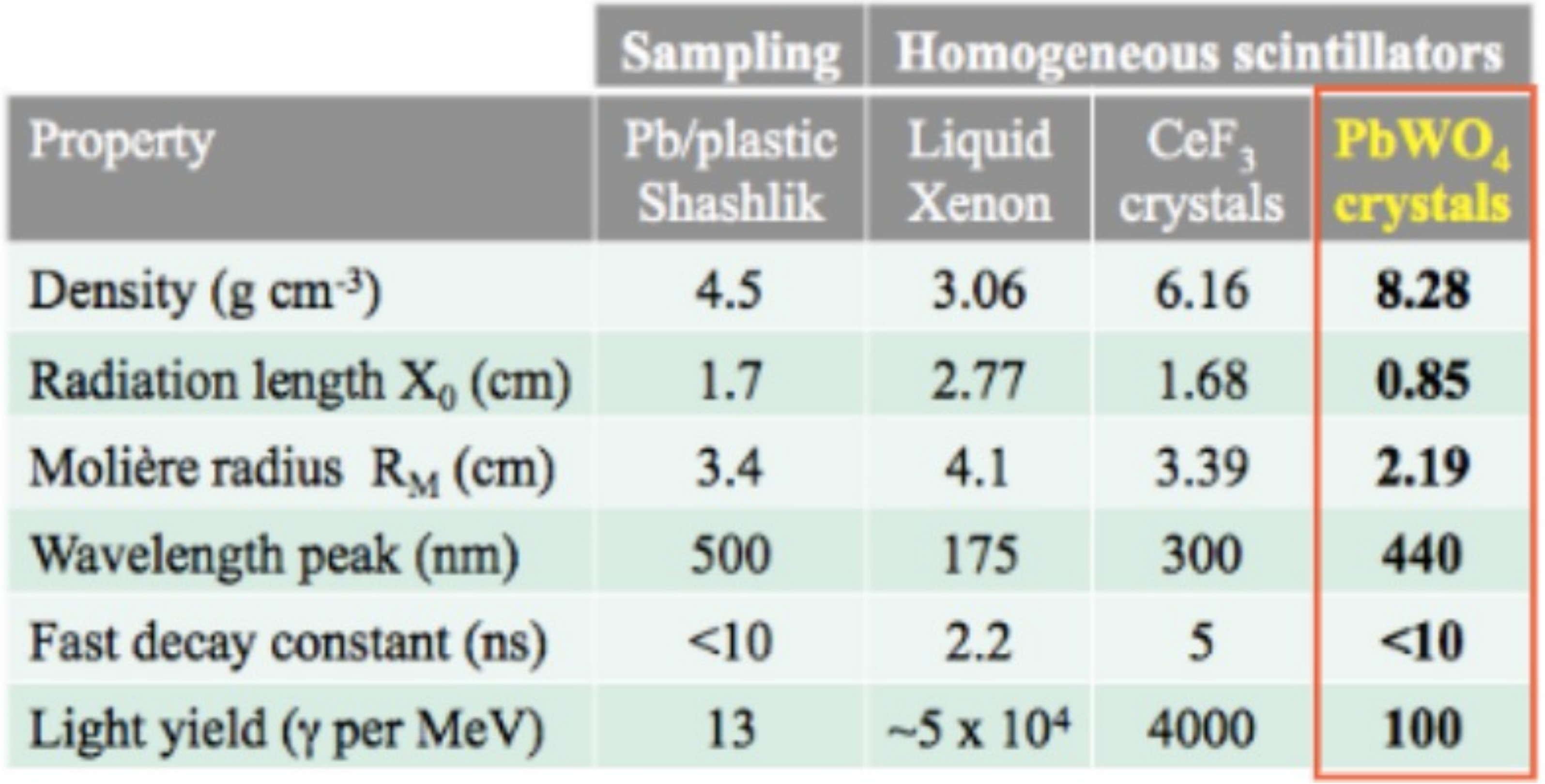

Module 1
Module 2
Module 3
Module 4
3.045 m
Barrel ECAL (EB)
61200
barrel crystals
14684
endcap
crystals
η=1.479
η=1.653
η=2.6
η=3.0
Preshower (SE)
Endcap ECAL (EE)
y
z

CMS ECAL: $PbWO_4$

- ECAL (and HCAL) within magnetic vol
- Homogenous active medium ($PbWO_4$)
- Magnetic field-tolerant photodetectors with gain:
  - Avalanche photodiode (APD) for barrel
  - Vacuum phototriode (VPT) for end caps
- Pb/Si Preshower detector in end caps



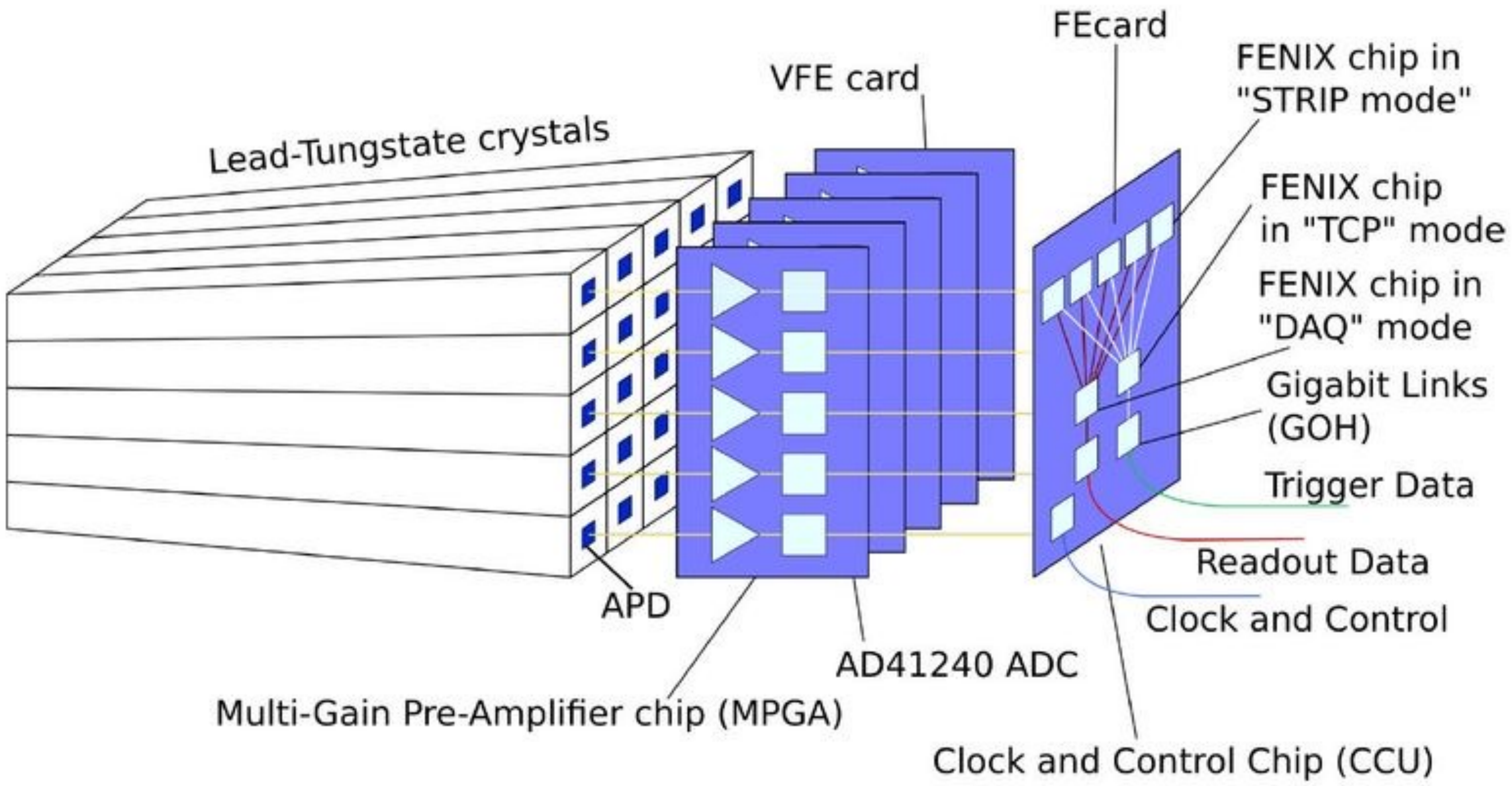
Barrel crystals: 2.2 x 2.2 x 23 cm^3



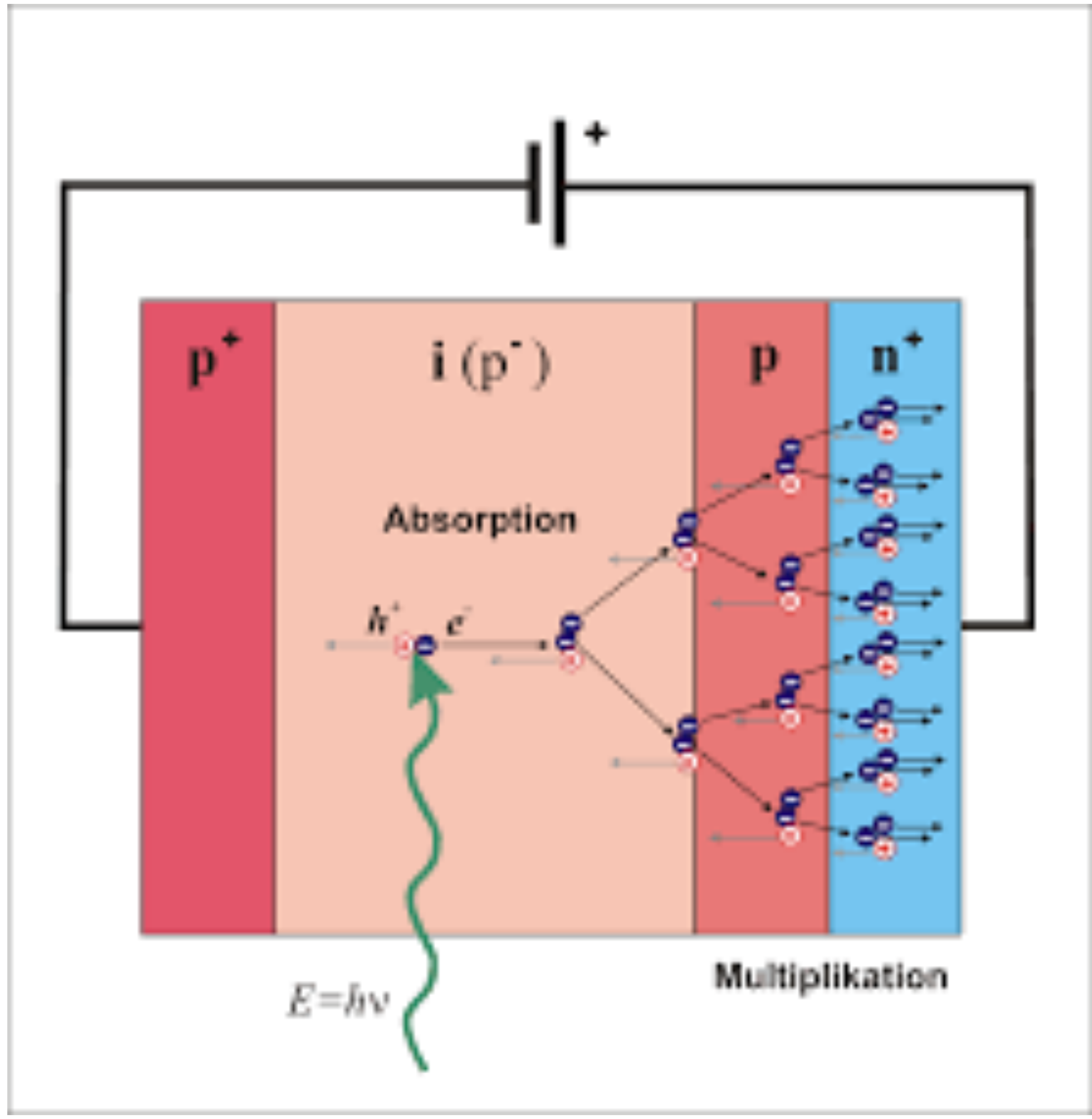
	Sampling	Homogeneous scintillators		
Property	Pb/plastic Shashlik	Liquid Xenon	CeF_3 crystals	**$PbWO_4$ crystals**
Density (g cm^{-3})	4.5	3.06	6.16	**8.28**
Radiation length X_0 (cm)	1.7	2.77	1.68	**0.85**
Molière radius R_M (cm)	3.4	4.1	3.39	**2.19**
Wavelength peak (nm)	500	175	300	**440**
Fast decay constant (ns)	<10	2.2	5	**<10**
Light yield (γ per MeV)	13	~5 x 10^4	4000	**100**

light yield: -2%/deg C
requires stable temperature operation,
within 0.05 deg C, to maintain
resolution target

CMS ECAL: Readout

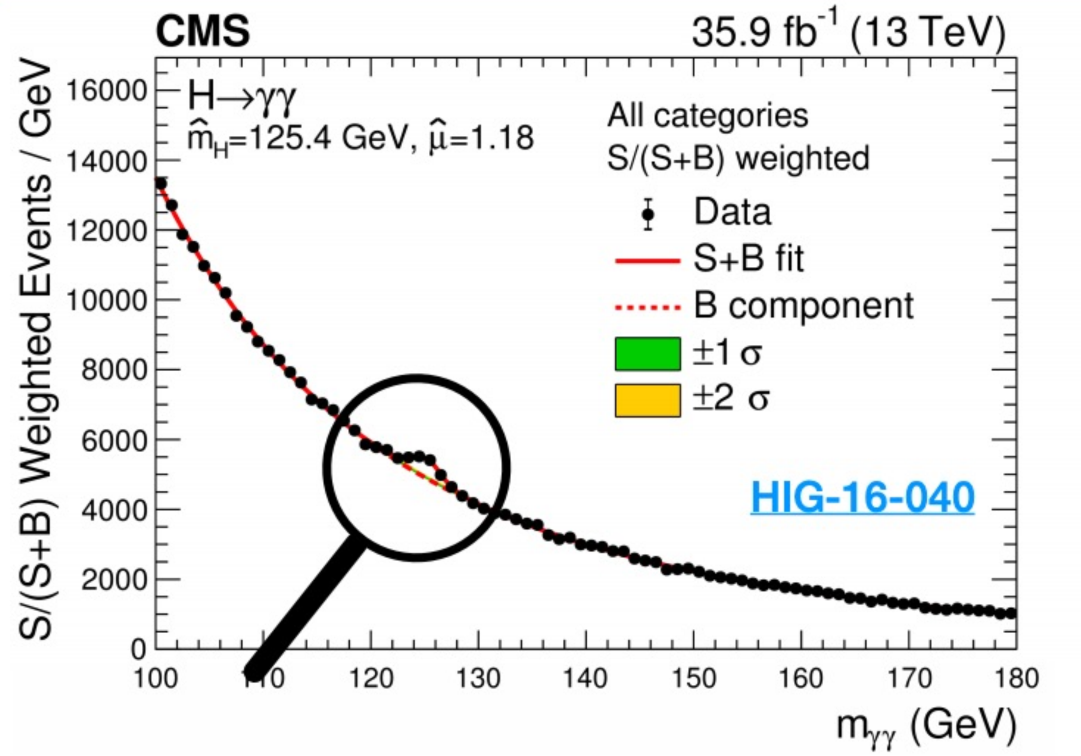


APD

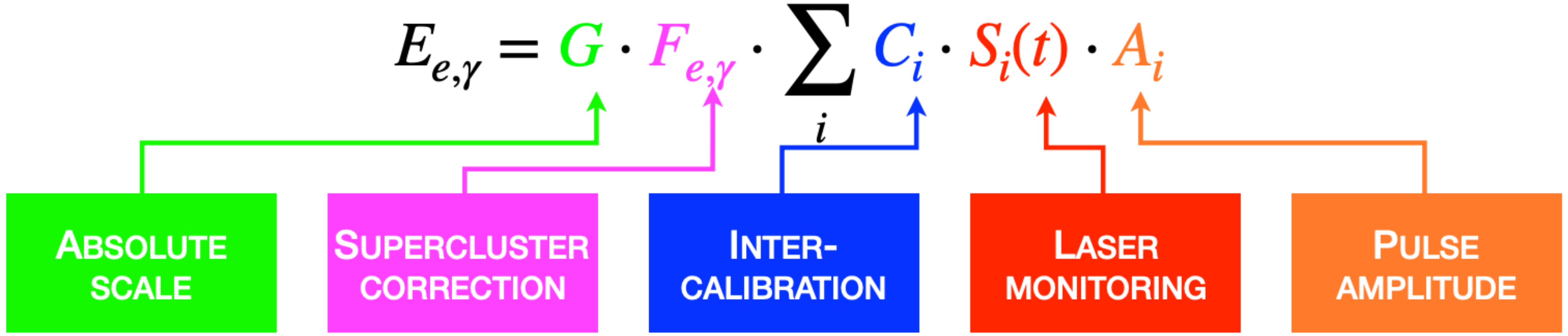


CMS crystal calorimeters

H → γγ



- **Narrow γγ resonance** on top of a **smoothly** falling background
- High **energy resolution**
- Accurate **position** measurement



$$E_{e,\gamma} = G \cdot F_{e,\gamma} \cdot \sum_i C_i \cdot S_i(t) \cdot A_i$$

ABSOLUTE SCALE

SUPERCLUSTER CORRECTION

INTER-CALIBRATION

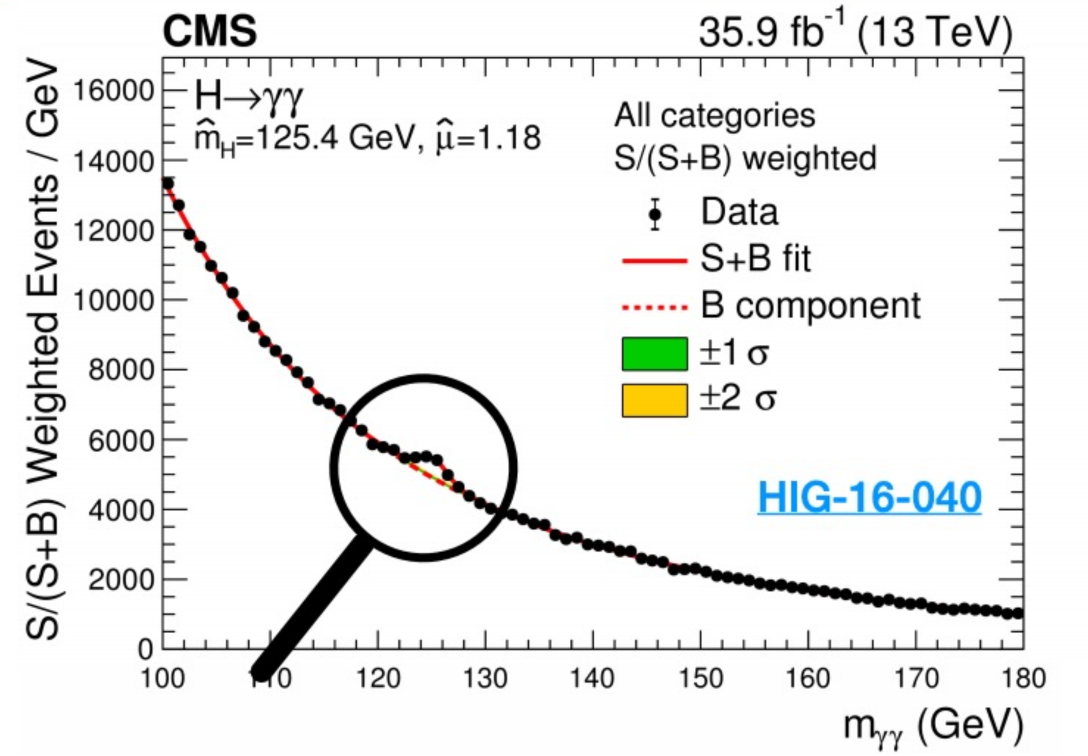
LASER MONITORING

PULSE AMPLITUDE

- ✦ monitor crystal transparency with laser: measurements and correction
- ✦ Residual mis-calibration monitored and corrected using physics channels:
  - ✦ 1. E/p ratio: electrons from W/Z decays
  - ✦ 2. Invariant mass peak in $\pi^0 \rightarrow \gamma\gamma$ decays
  - ✦ 3. Invariant mass peak in $Z^0 \rightarrow ee$ decays

CMS crystal calorimeters

$H \to \gamma\gamma$



- **Narrow γγ resonance** on top of a **smoothly** falling background
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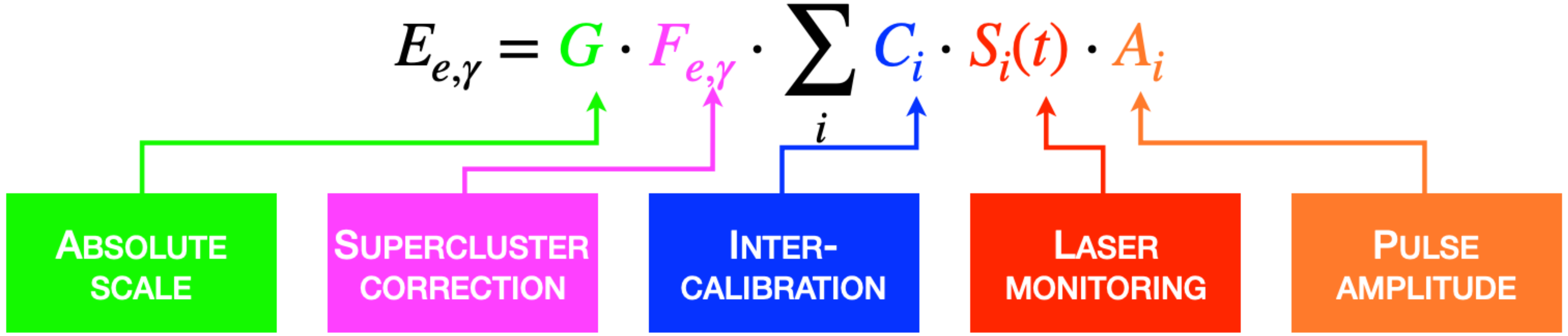


$$E_{e,\gamma} = G \cdot F_{e,\gamma} \cdot \sum_i C_i \cdot S_i(t) \cdot A_i$$

ABSOLUTE SCALE

SUPERCLUSTER CORRECTION

INTER-CALIBRATION

LASER MONITORING

PULSE AMPLITUDE

- ✦ Supercluster energy containment account for:
  - ✦ Material budget before ECAL
  - ✦ Shower containment: gaps, cracks between crystals
  - ✦ Electrons and photons different behaviours in matter
- ✦ Absolute energy scale and its η dependence calibrated with electrons from Z decays

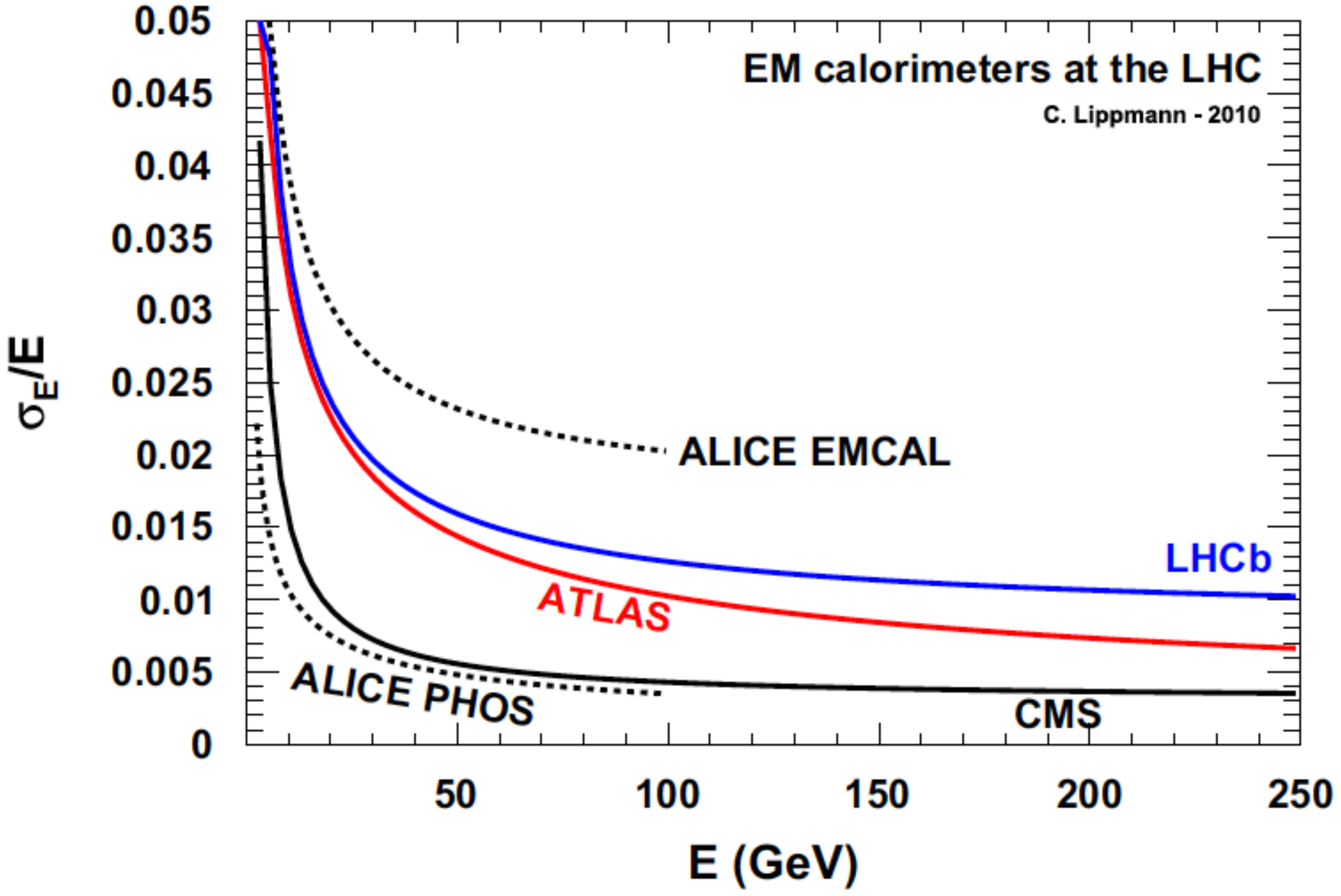
Energy Resolution

CMS

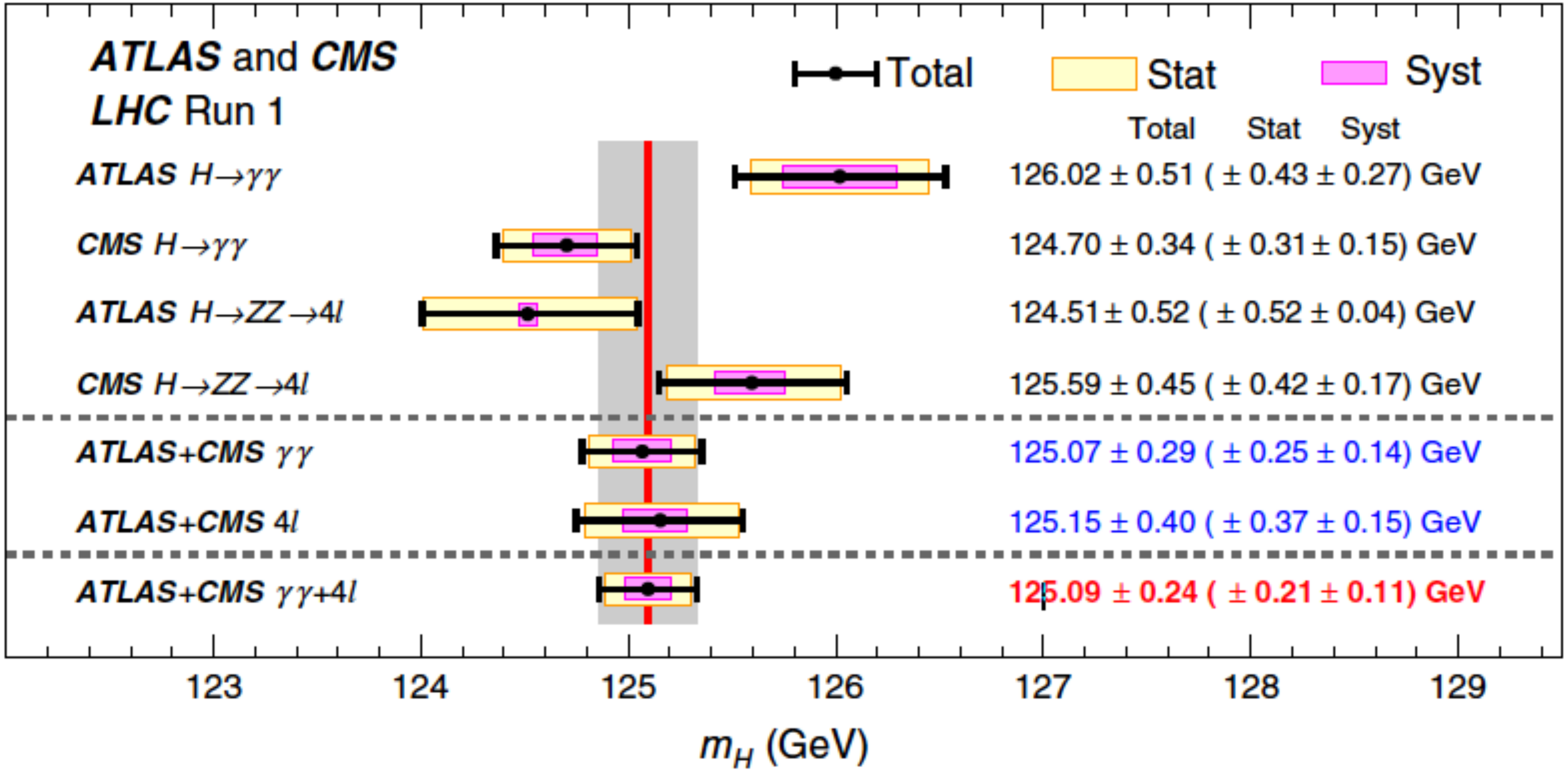
$$\frac{\sigma(E)}{E} = \frac{2.8\%}{\sqrt{E}} \oplus \frac{120MeV}{E} \oplus 0.3\%.$$

ATLAS

$$\frac{\sigma(E)}{E} = \frac{10\%}{\sqrt{E}} \oplus \frac{170MeV}{E} \oplus 0.7\%.$$

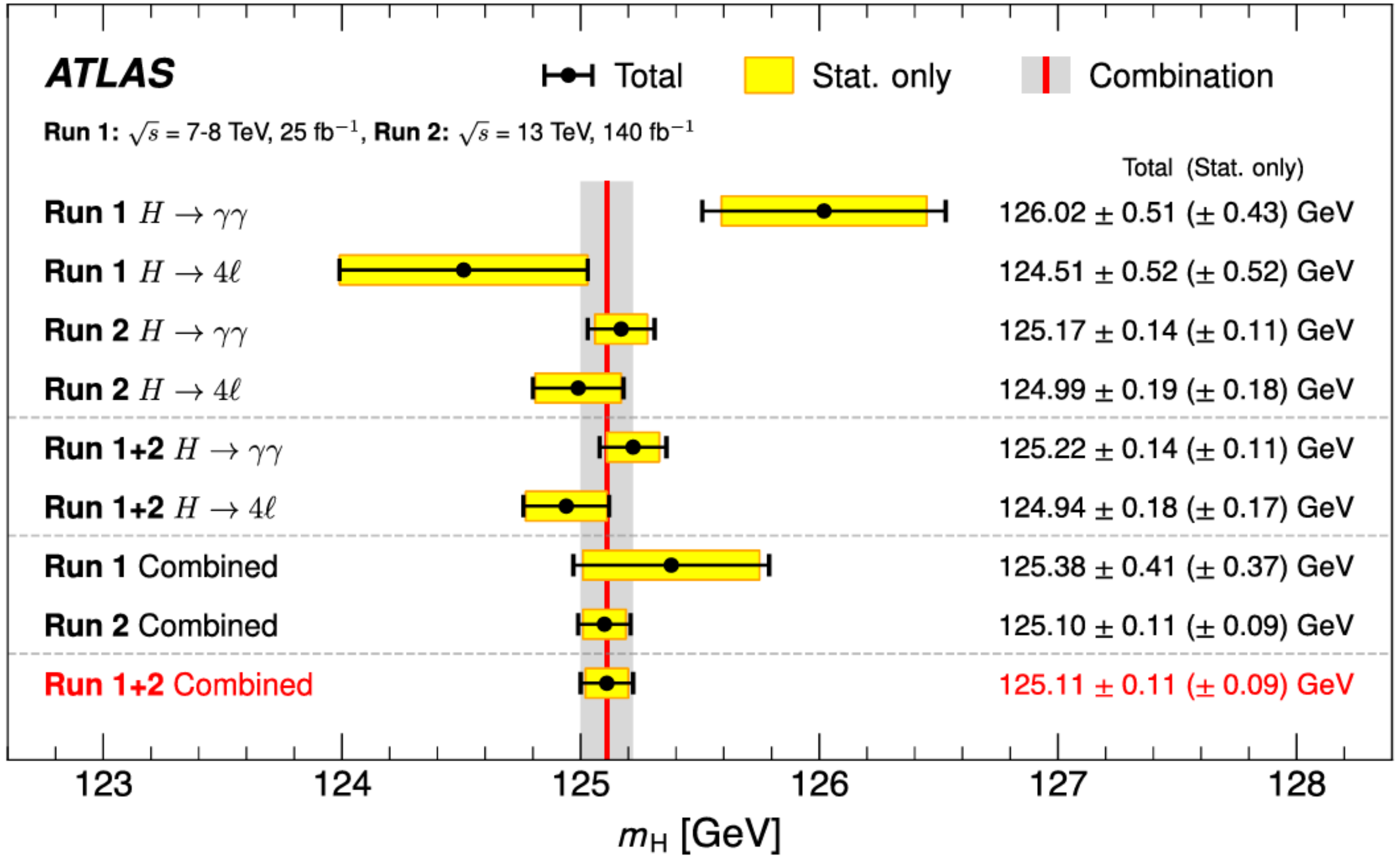


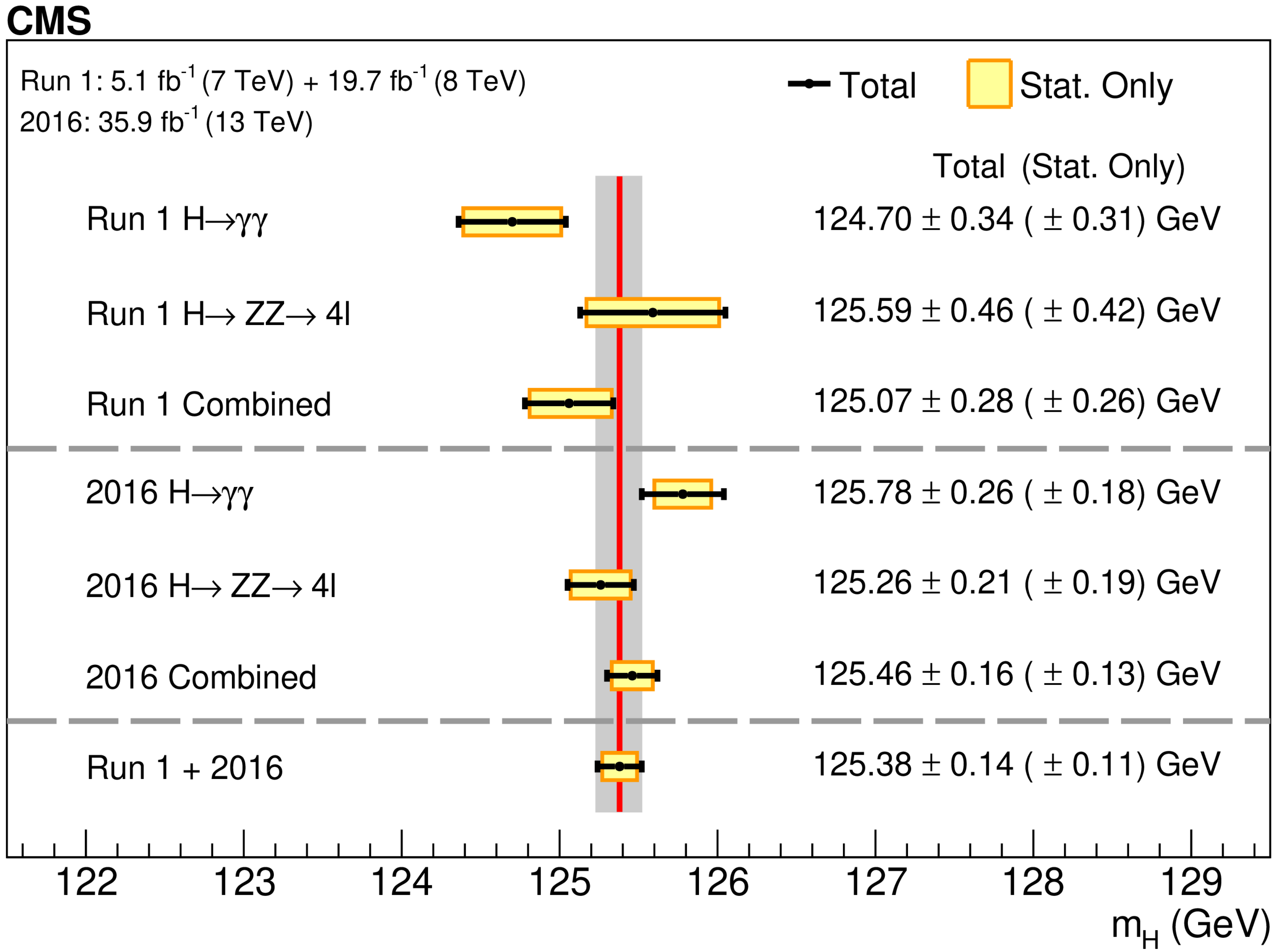
Combined (Run I) Higgs boson mass



$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos\alpha)}$$

(Run 2) Higgs boson mass

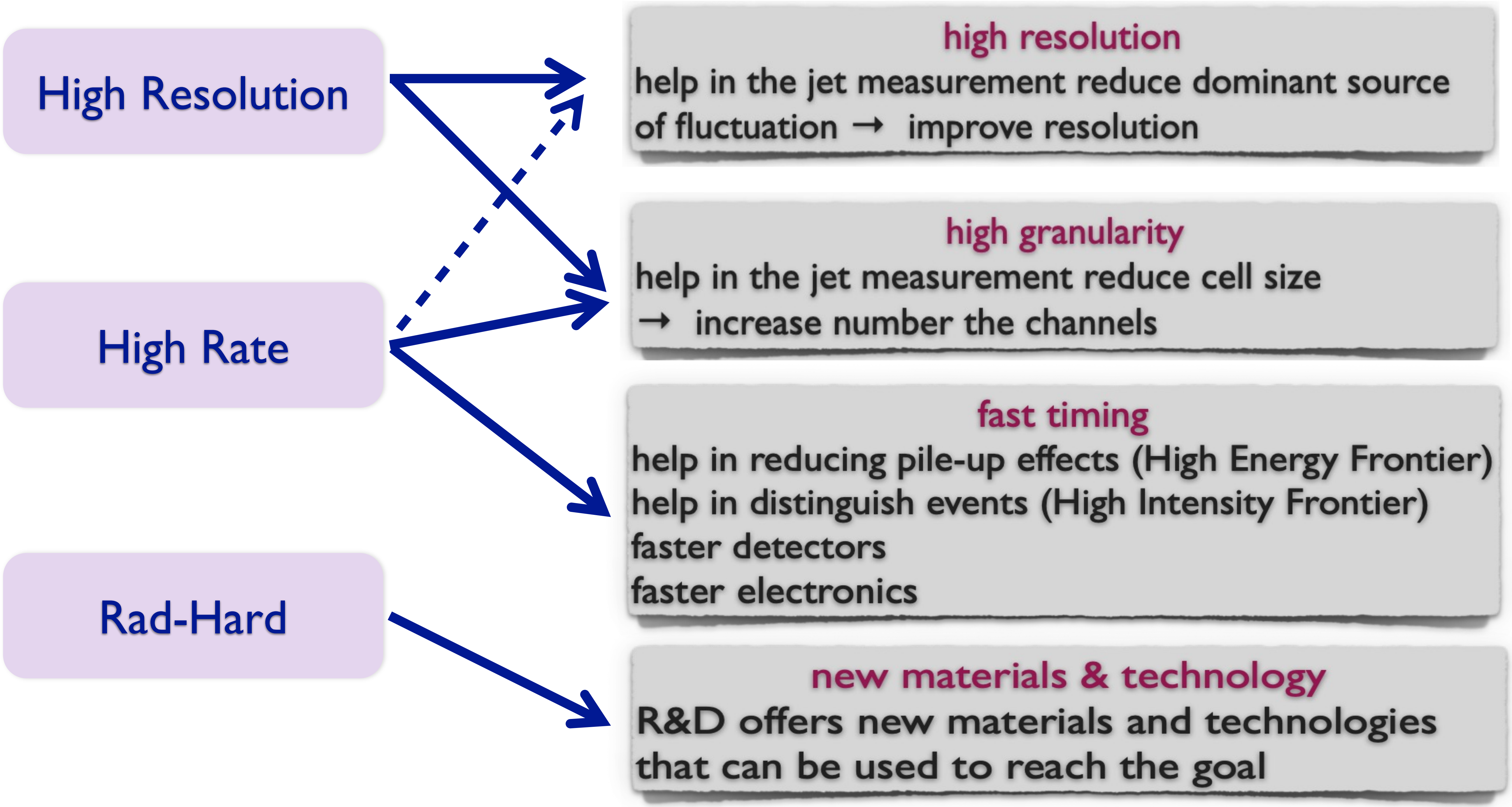




Calorimeters R&D trends

New Trends in Calorimetry

How to cope with physics and performance requirements?



High Resolution

High Rate

Rad-Hard

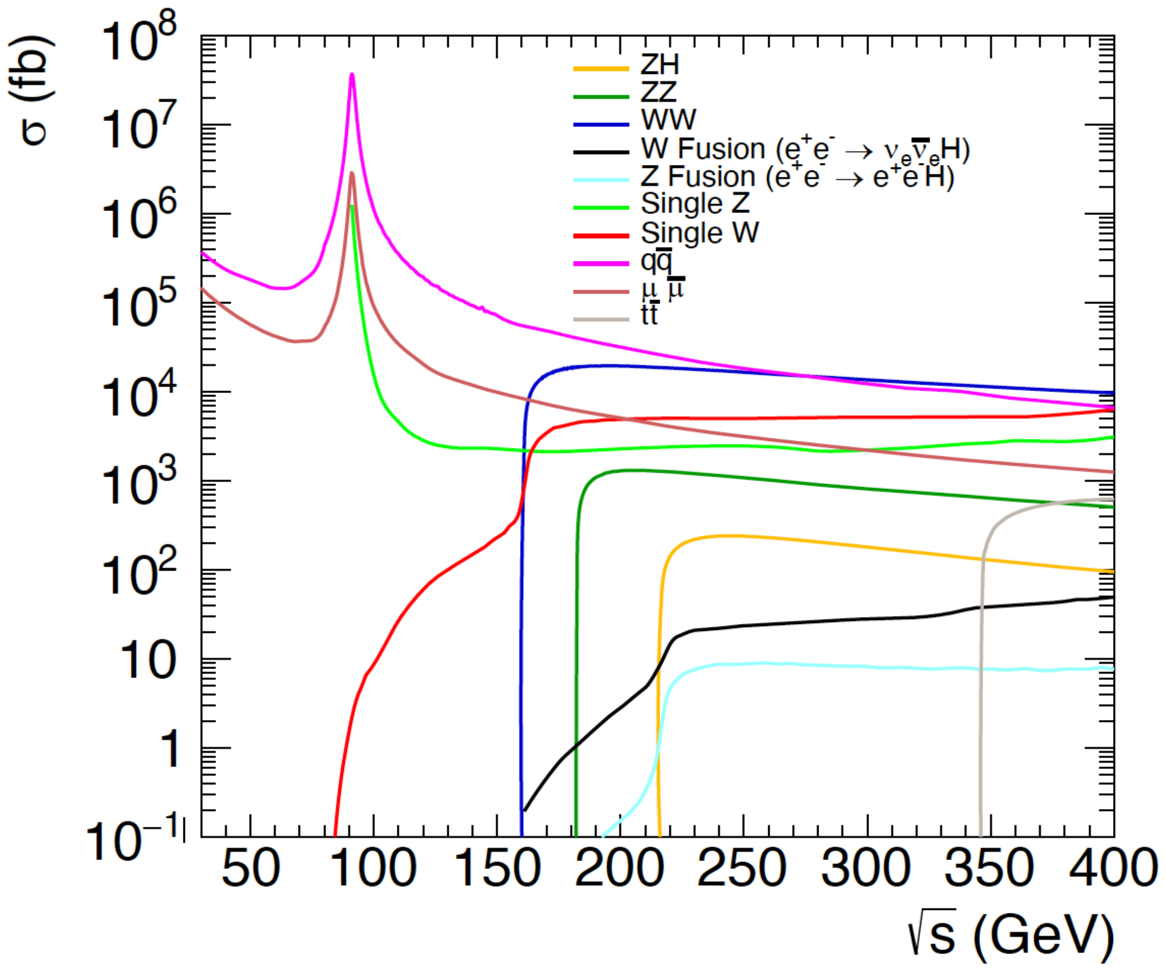
high resolution
help in the jet measurement reduce dominant source of fluctuation → improve resolution

high granularity
help in the jet measurement reduce cell size
→ increase number the channels

fast timing
help in reducing pile-up effects (High Energy Frontier)
help in distinguish events (High Intensity Frontier)
faster detectors
faster electronics

new materials & technology
R&D offers new materials and technologies that can be used to reach the goal

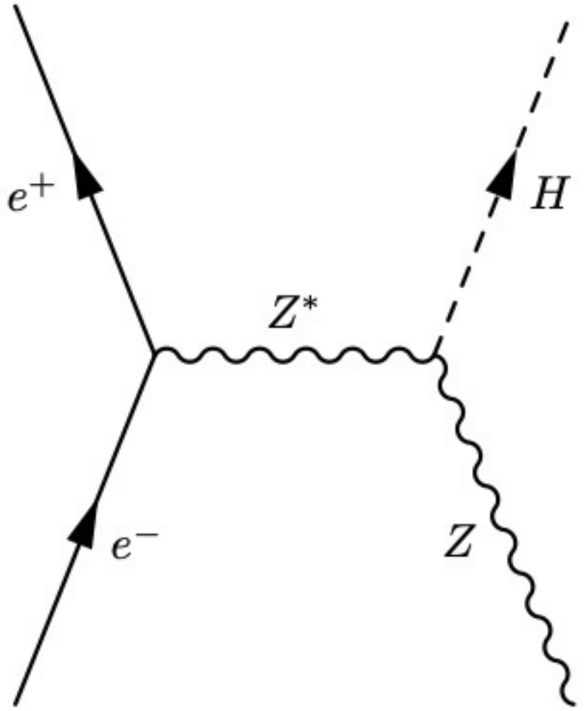
High Resolution Calorimetry



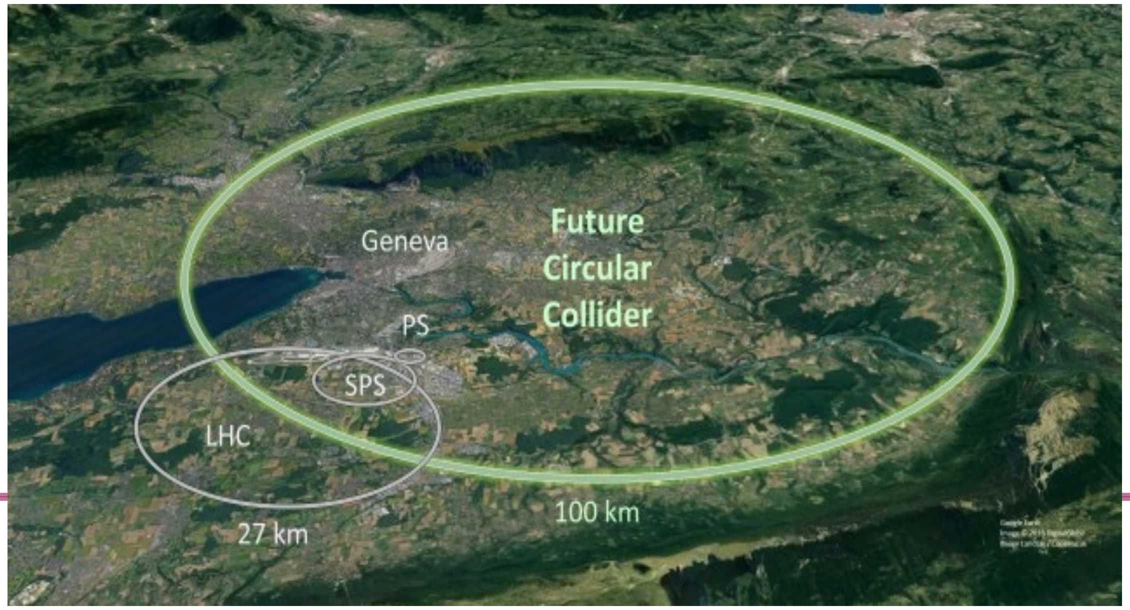
e^+e^-

91.2 GeV Z-pole
161 GeV WW
240 GeV ZH
365 GeV tt

pp 100 TeV



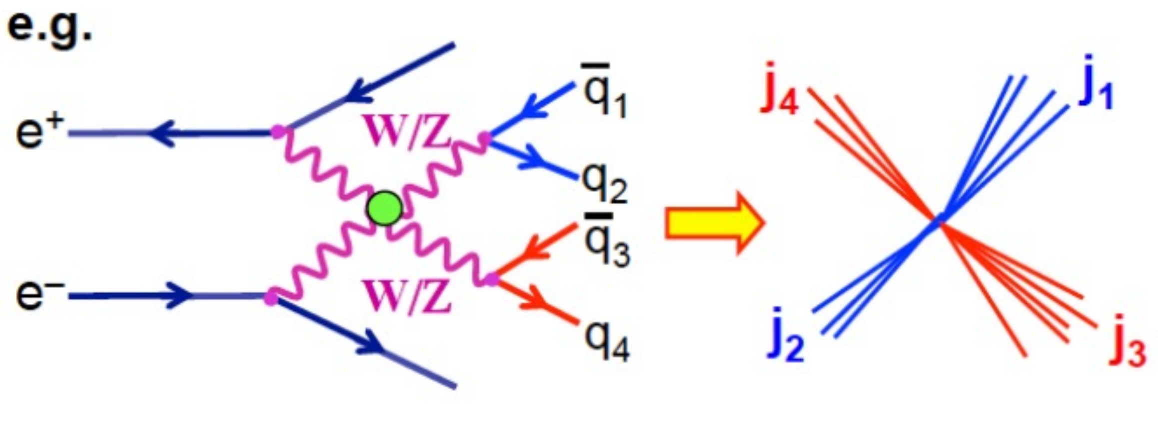
97% of the SM Higgsstrahlung signal has jets in the final states

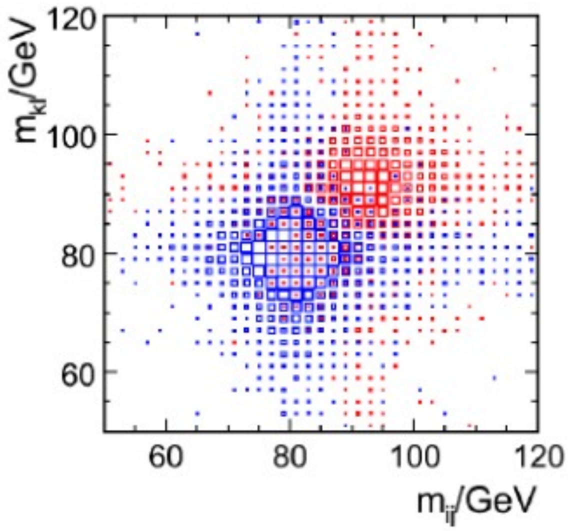


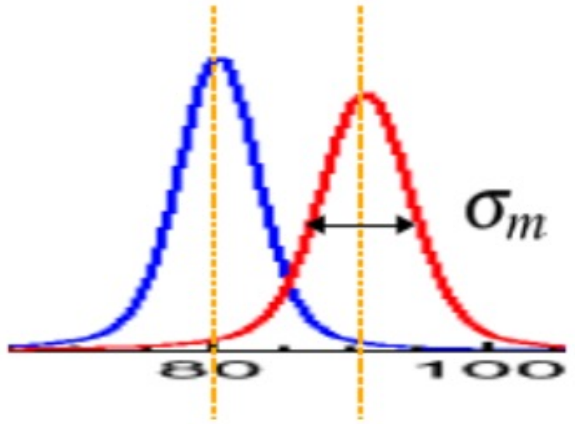
High resolution Calorimetry

For future colliders, jet energy resolution will be a determinant factor of understanding high energy physics.

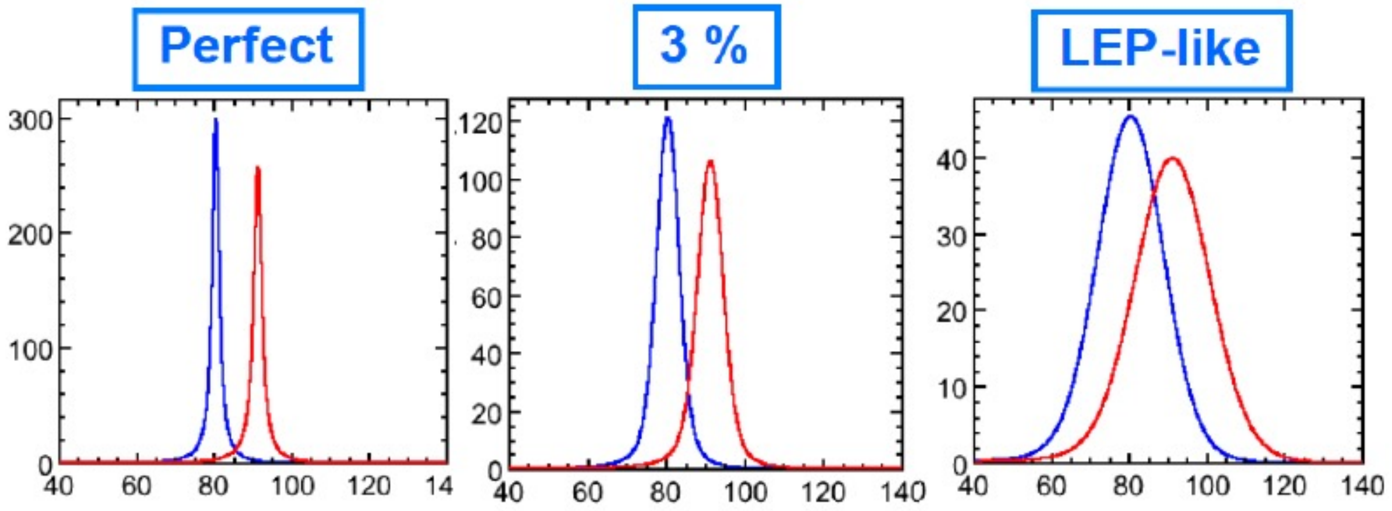
Required to have best possible di-jet mass resolution for narrow resonance observation
At very least one need to distinguish W/Z hadronic decays







$$\mathrm{W/Z\ sep} = (m_Z - m_W)/\sigma_m$$



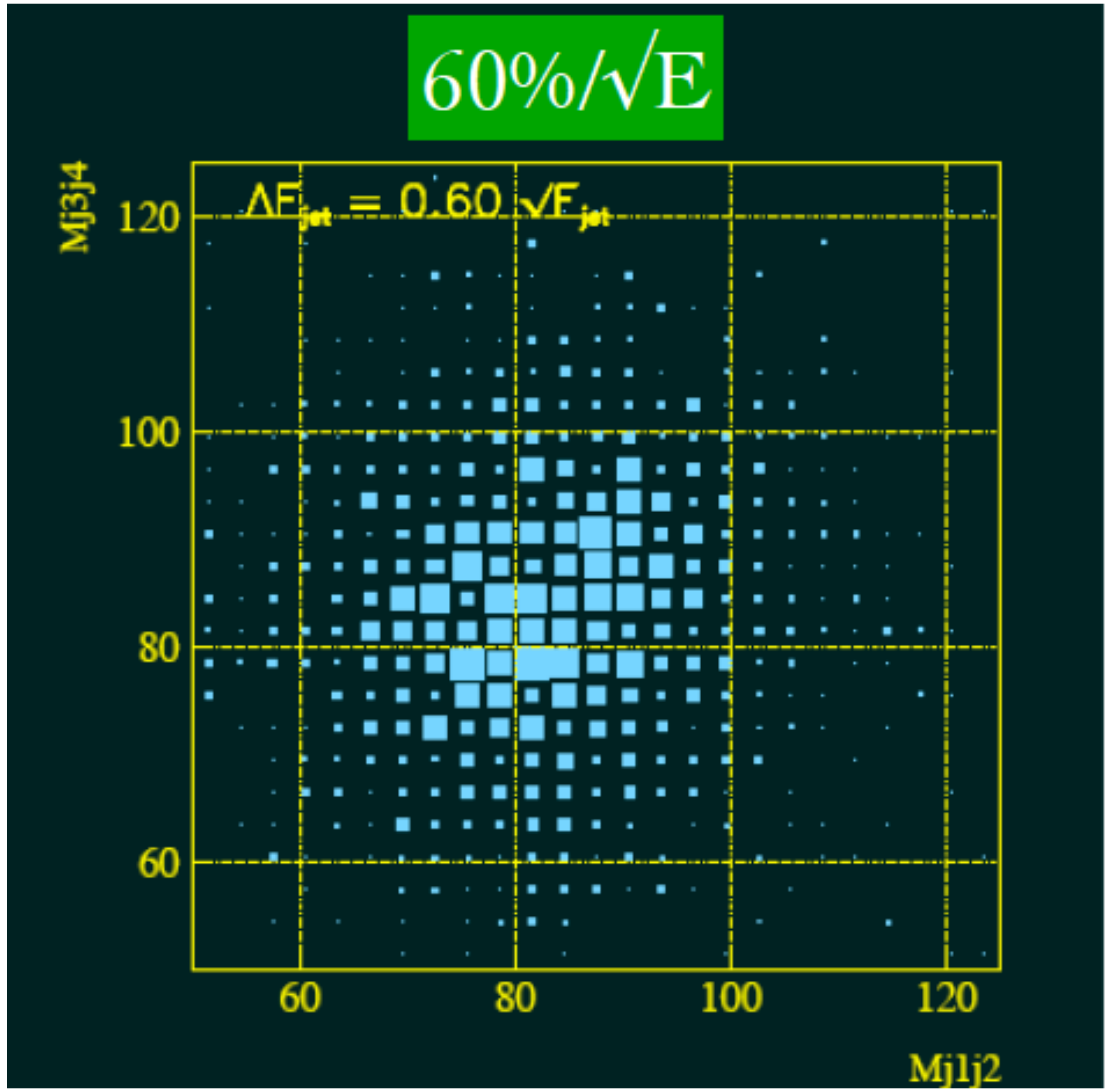
Jet E res.	W/Z sep
perfect	3.1 σ
2%	2.9 σ
3%	2.6 σ
4%	2.3 σ
5%	2.0 σ
10%	1.1 σ

W/Z sep: 3σ

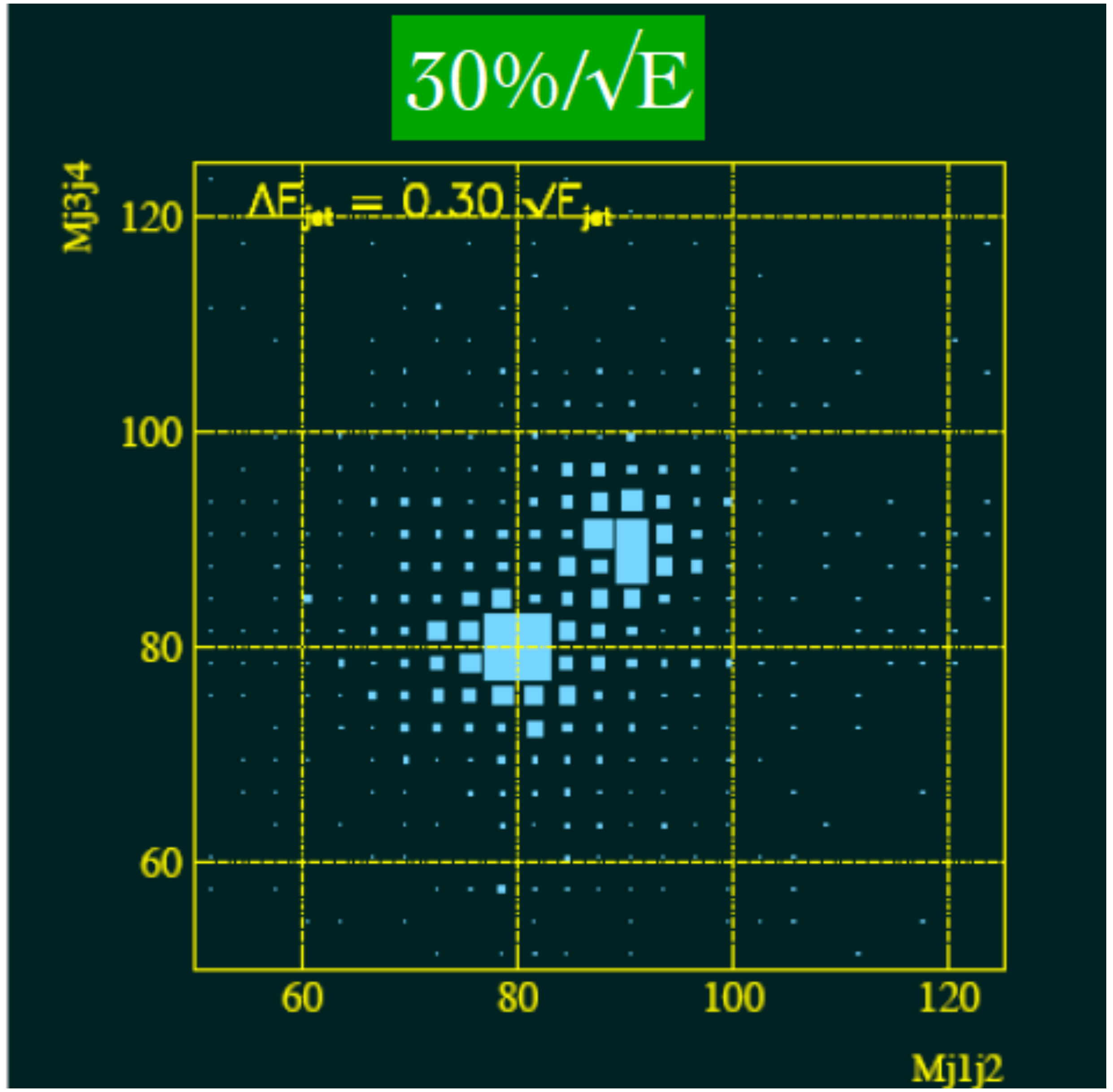
$$\frac{\sigma}{E} \sim \frac{30\%}{\sqrt(E)}$$

Design goal future accelerators: separate W, Z → qq

LEP-like detector



Future accelerators design goal



M_{jj}

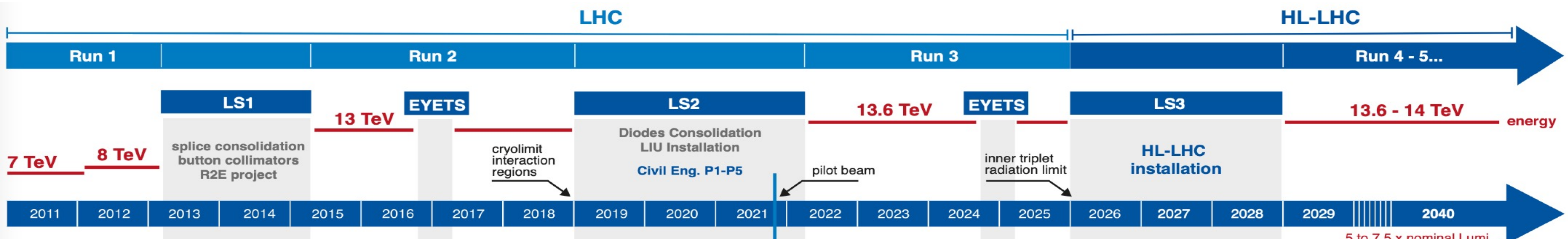
M_{jj}

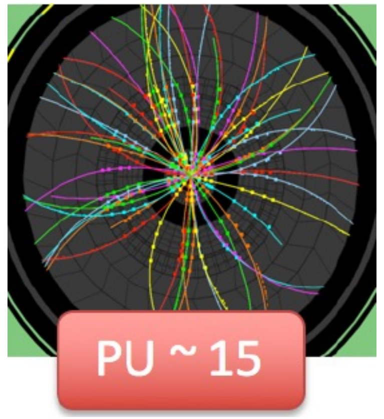
High Rate Calorimetry

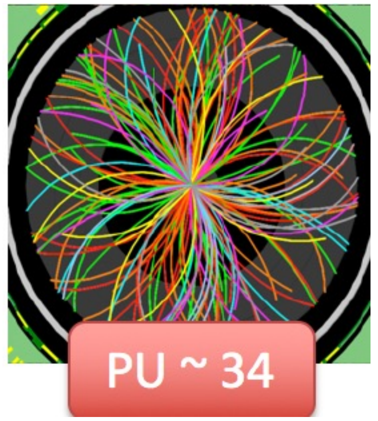
<μ> ≈ 20-40 evts/crossing RunI
<μ> ≈ 50 evts/crossing RunII
<μ> ≈ 60 evts/crossing RunIII
<μ> ≈ 140 evts/crossing HL-LHC

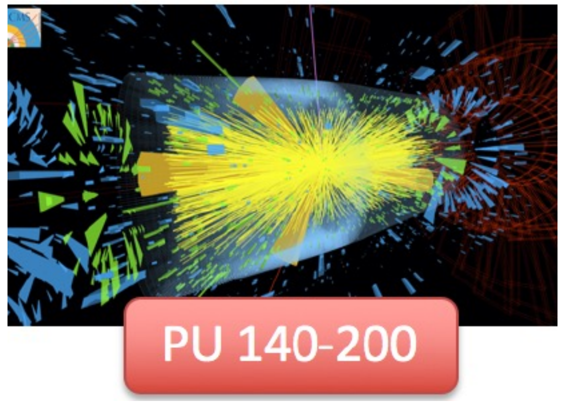
$40\text{x}10^6$ bunch crossing/s
20 collisions/bunch crossing
140 PU evt/bunch crossing

} ~ 10^{10} evt/s
⬇
time scale ~ 100 ps

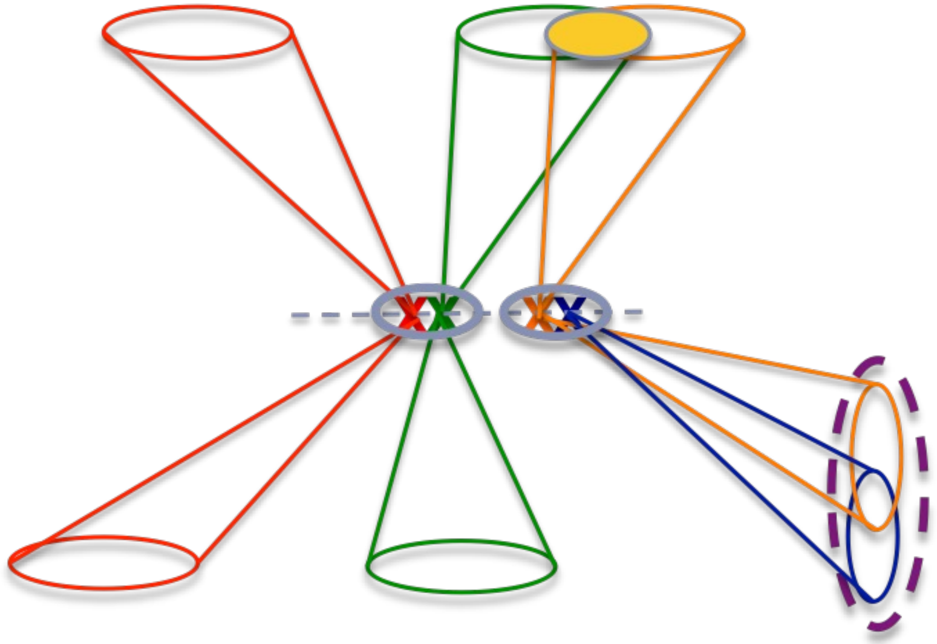




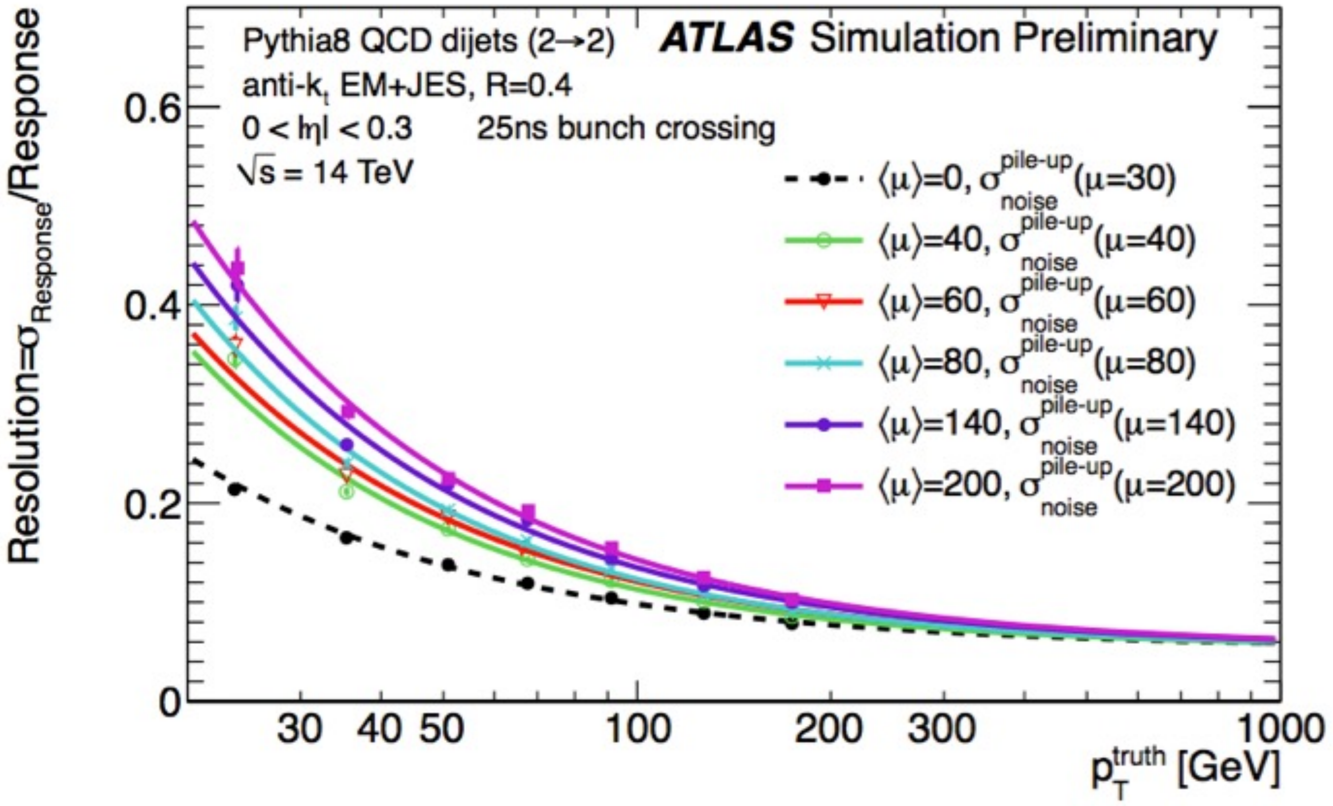


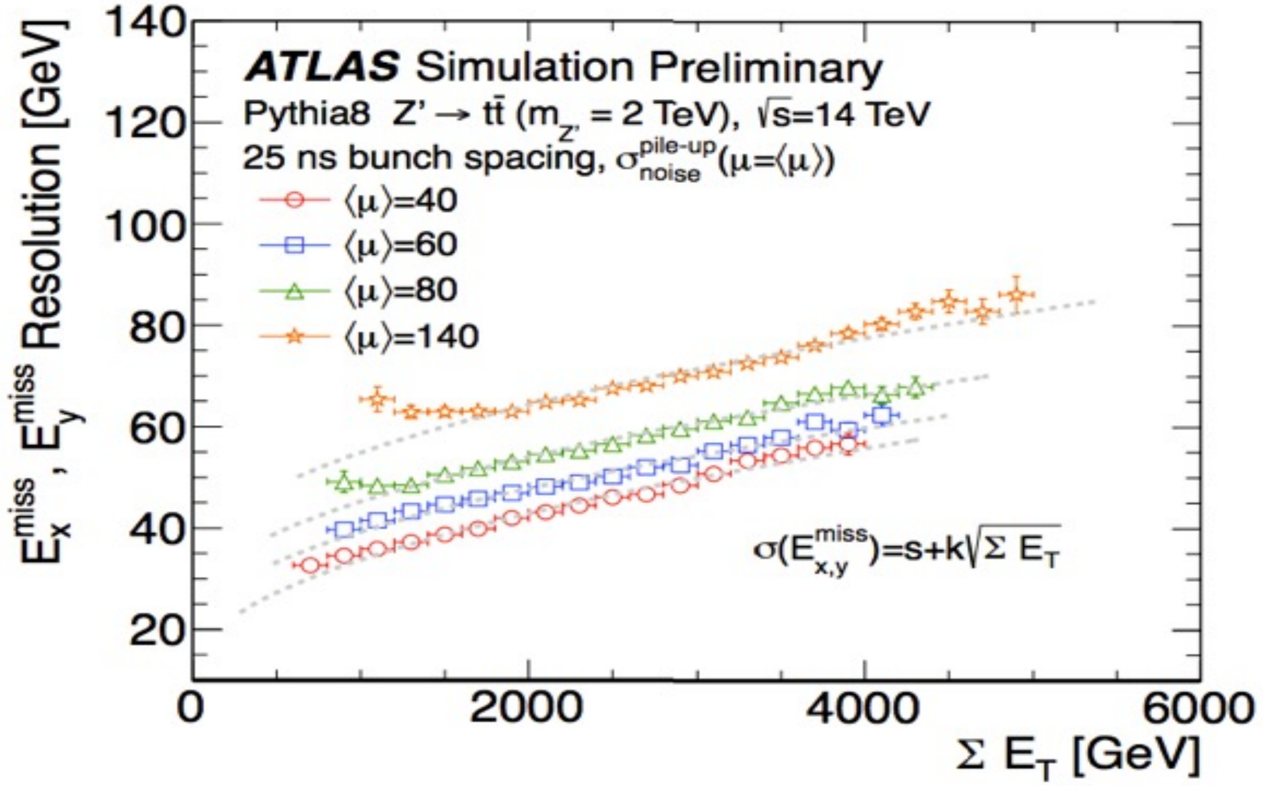


High Rate Calorimetry



Effect on Jet and E_T^{miss} resolution @high pileup



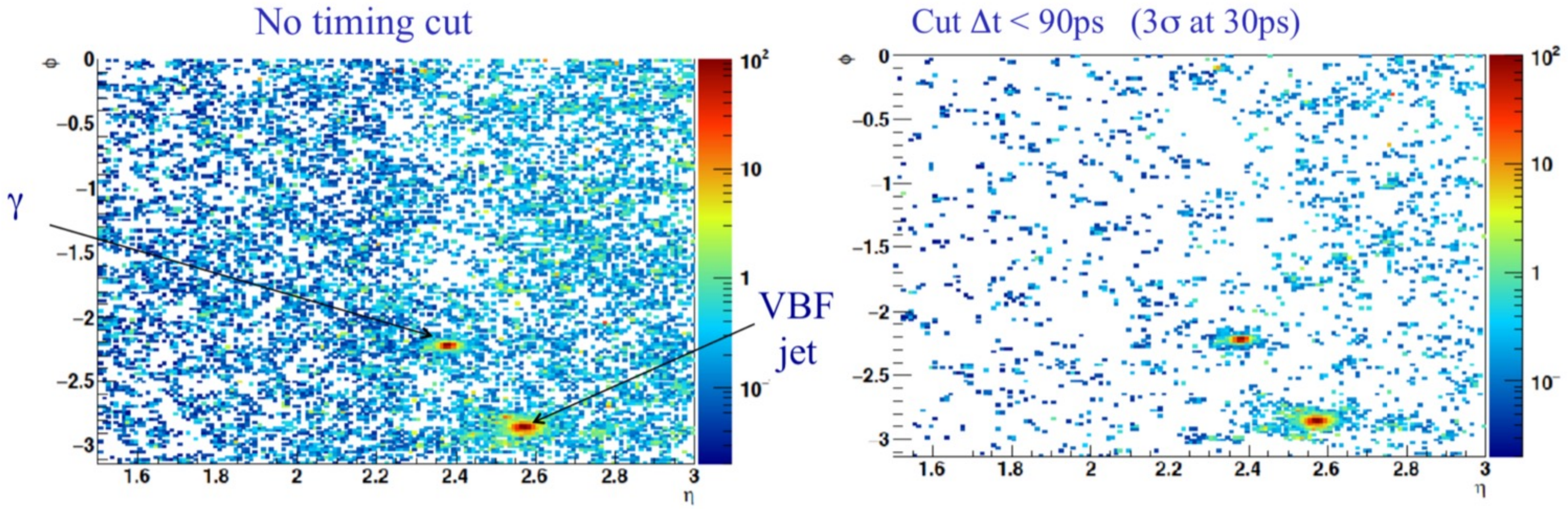


High-Rate Calorimetry

Pile up suppression:

identify high-energy clusters, then make timing cut to retain hits of interest

VBF (H→γγ) event with one photon and one VBF jet in the same quadrant,



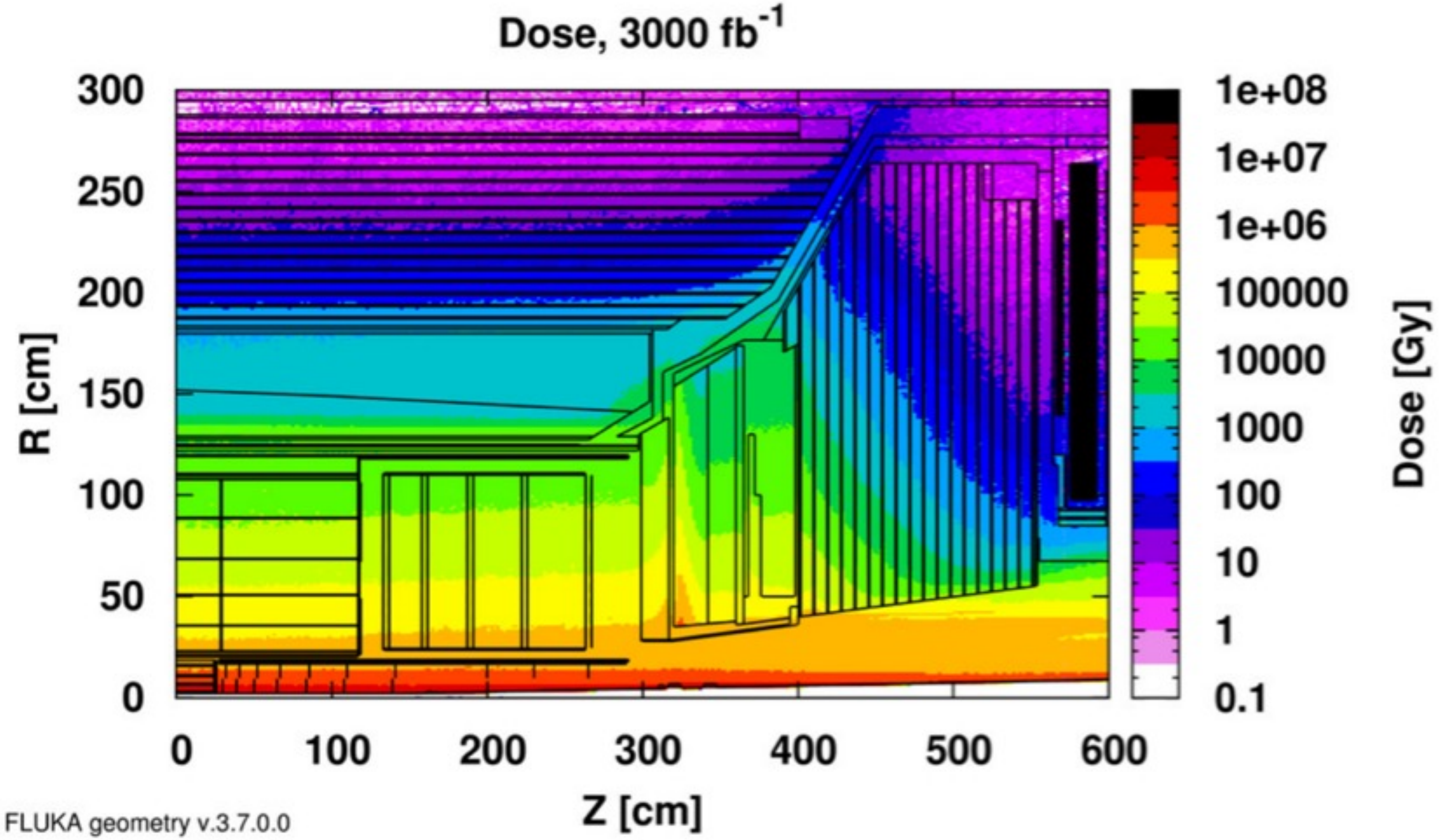
No timing cut

Cut Δt < 90ps (3σ at 30ps)

Rad-Hard Calorimetry

Irradiation changes the performance of detectors and electronics

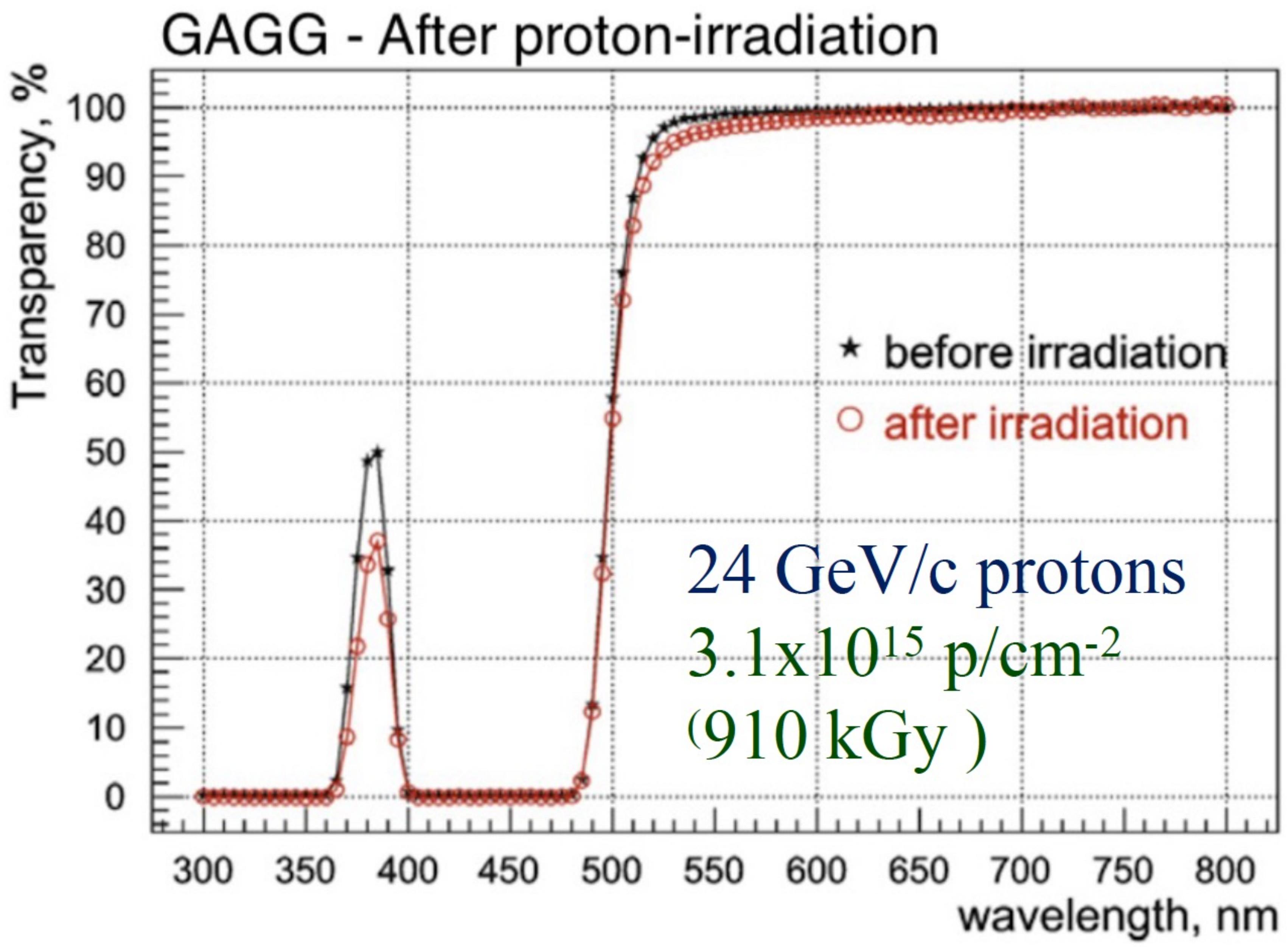
- Total Ionizing Dose (TID)
  - Mainly due to photons, electrons and positrons
  - Measured in Gray (Gy), 1 Gy = 1 J/kg = 100 rad
- Non Ionizing Energy Loss (NIEL) / equivalent fluence (Φeq)
  - Expressed in 1 MeV neutron equivalent fluence (n/cm^2)
- Thermal neutron fluence



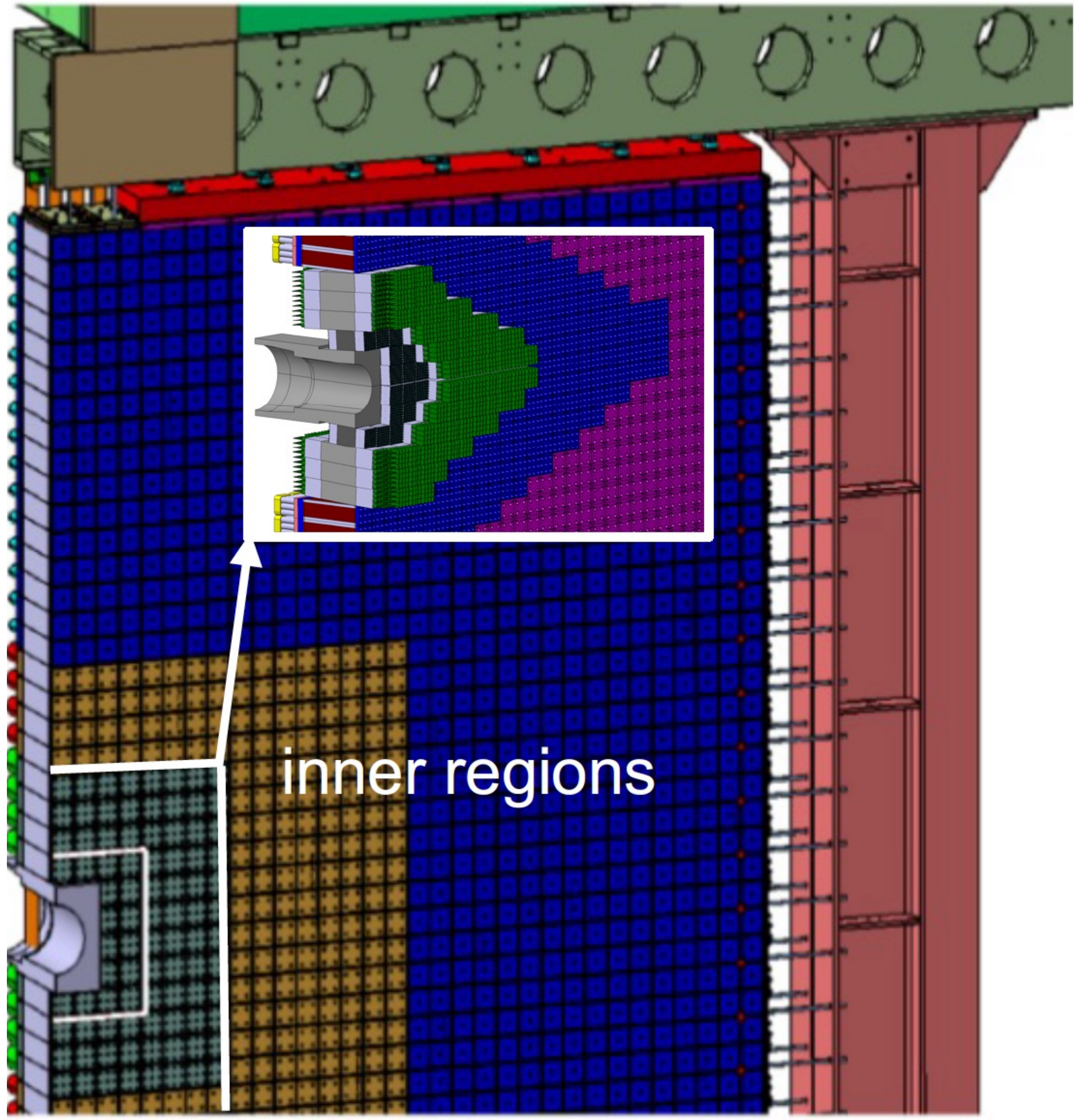
CMS FLUKA geometry v.3.7.0.0

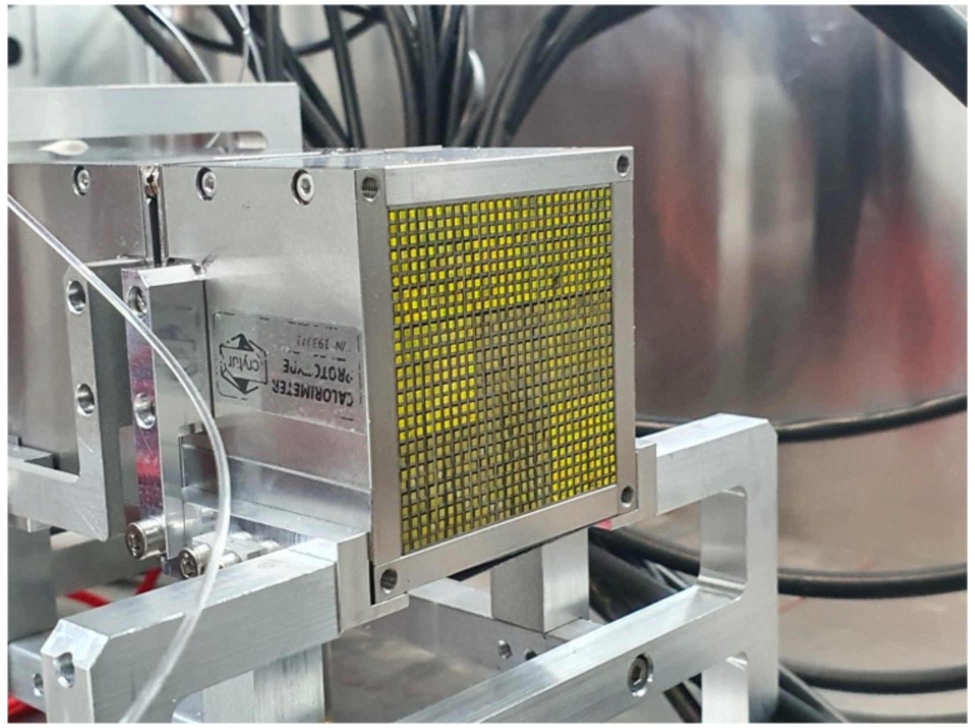
Garnet Fiber Crystals readout

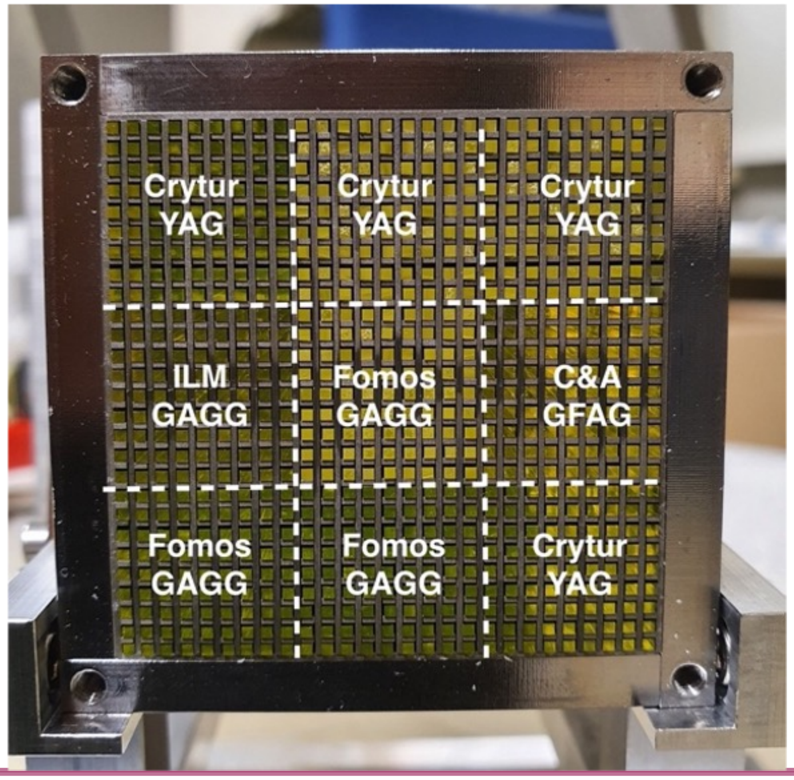
- Garnet Fiber Crystals
  - YAG: Yttrium Aluminum Garnet
  - GAGG: Gadolinium Aluminum Gallium Garnet
  - GFAG: Gadolinium Fine Aluminum Gallate
- Garnet crystals are radiation hard
- Scintillation properties can be tuned with different levels of dopants (Ce,Mg) and growth conditions



SPACAL prototype with garnet crystal fibres







LHCb ECAL upgrade

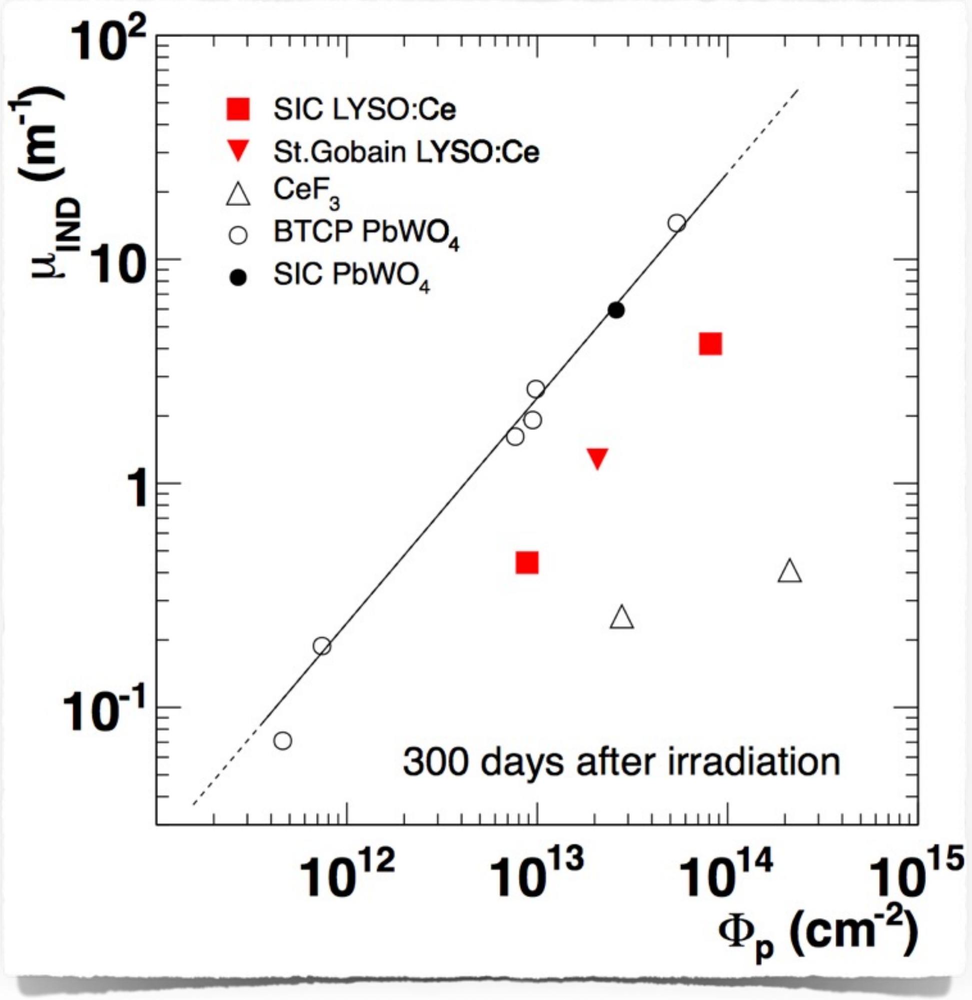
		Measurements on TB modules [%]
SPACAL-W	*Sampling term*	10.6 ± 0.1
	Constant term	1.9 ± 0.5
SPACAL-Pb	*Sampling term*	10.0 ± 0.6
	Constant term	1.16 ± 0.06

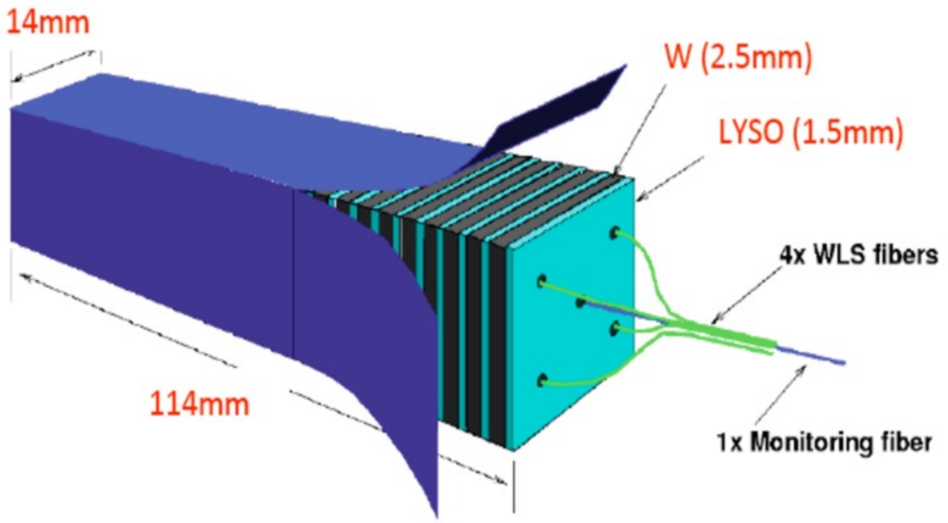
R&D: Rad-hard optical calorimeters

R&D for optical calorimeters who can cope with O(300 kGy) & O($10^{14\text{-}15}$) hadrons cm^{-2}

Shashlik design to minimise the optical path in the scintillator.
Also rad-hard WLS fibres & photodetectors

hadron damage for PbWO$_4$, LYSO, CeF$_3$

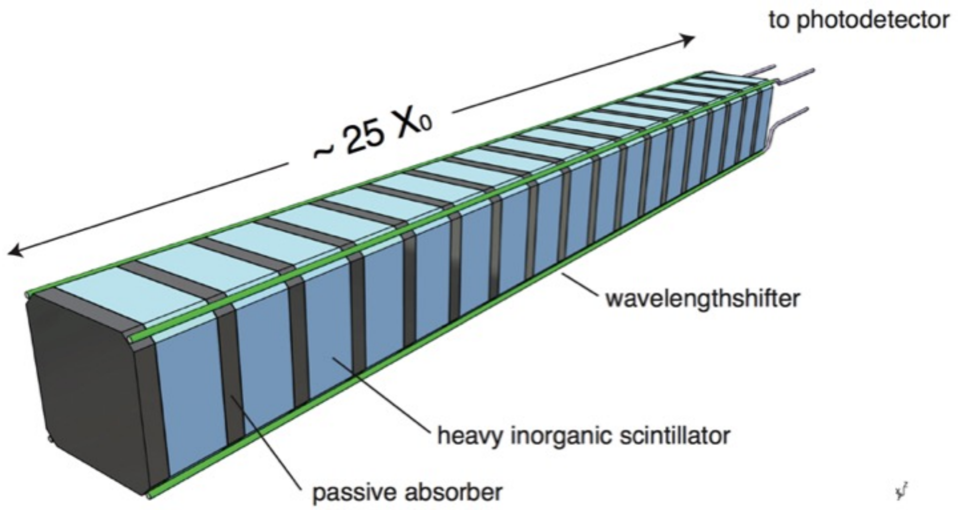




W/LYSO shashlik cell designed 14x14x114 mm^3

Quartz capillaries with WLS liquid
R&D for InGaAs SiPM

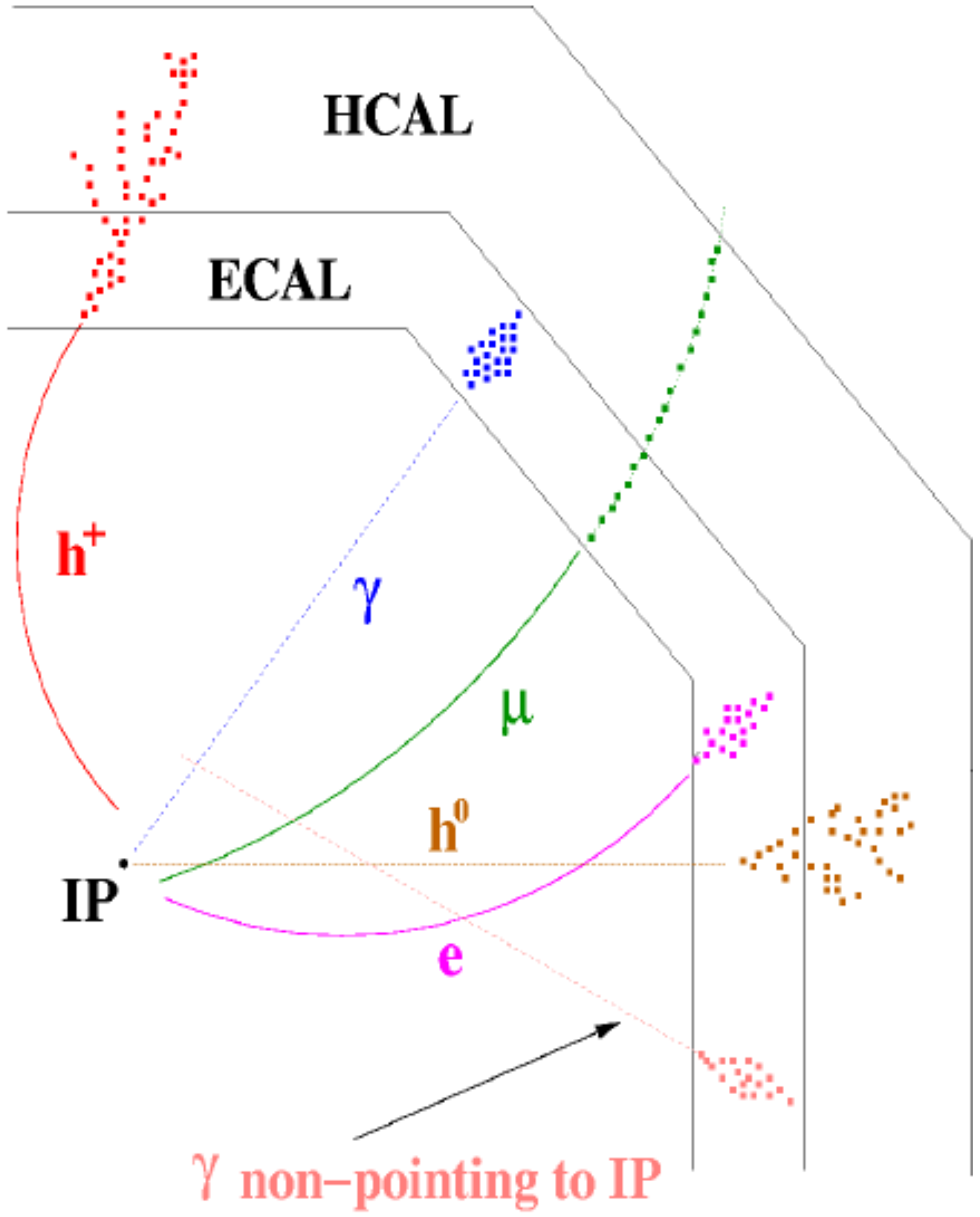
σ(E)/E ~ 10%/√E/GeV



W/CeF$_3$ as an alternative:

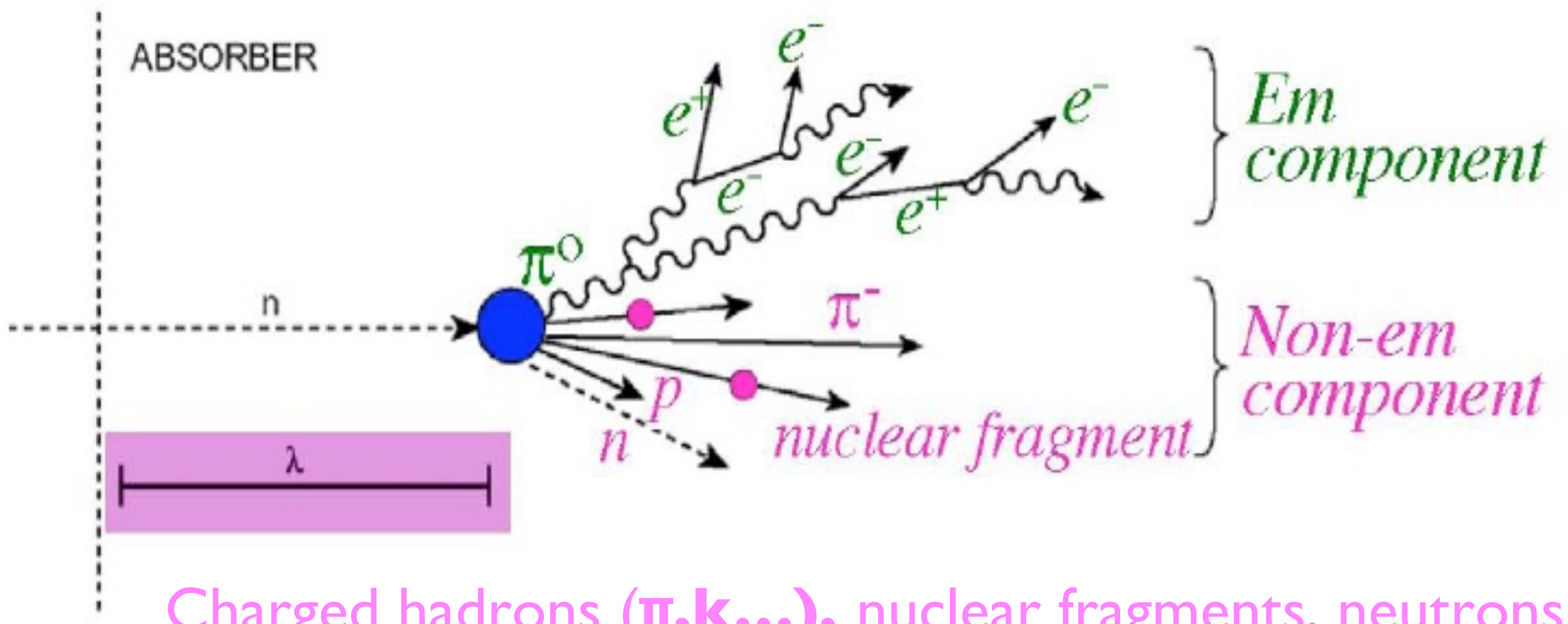
CeF$_3$ excellent hadron damage radiation hardness
Can use SiO$_2$:Ce as radiation hard WLS

Two Calorimetry Approaches



Particle Flow

electrons positrons, photons, π^0

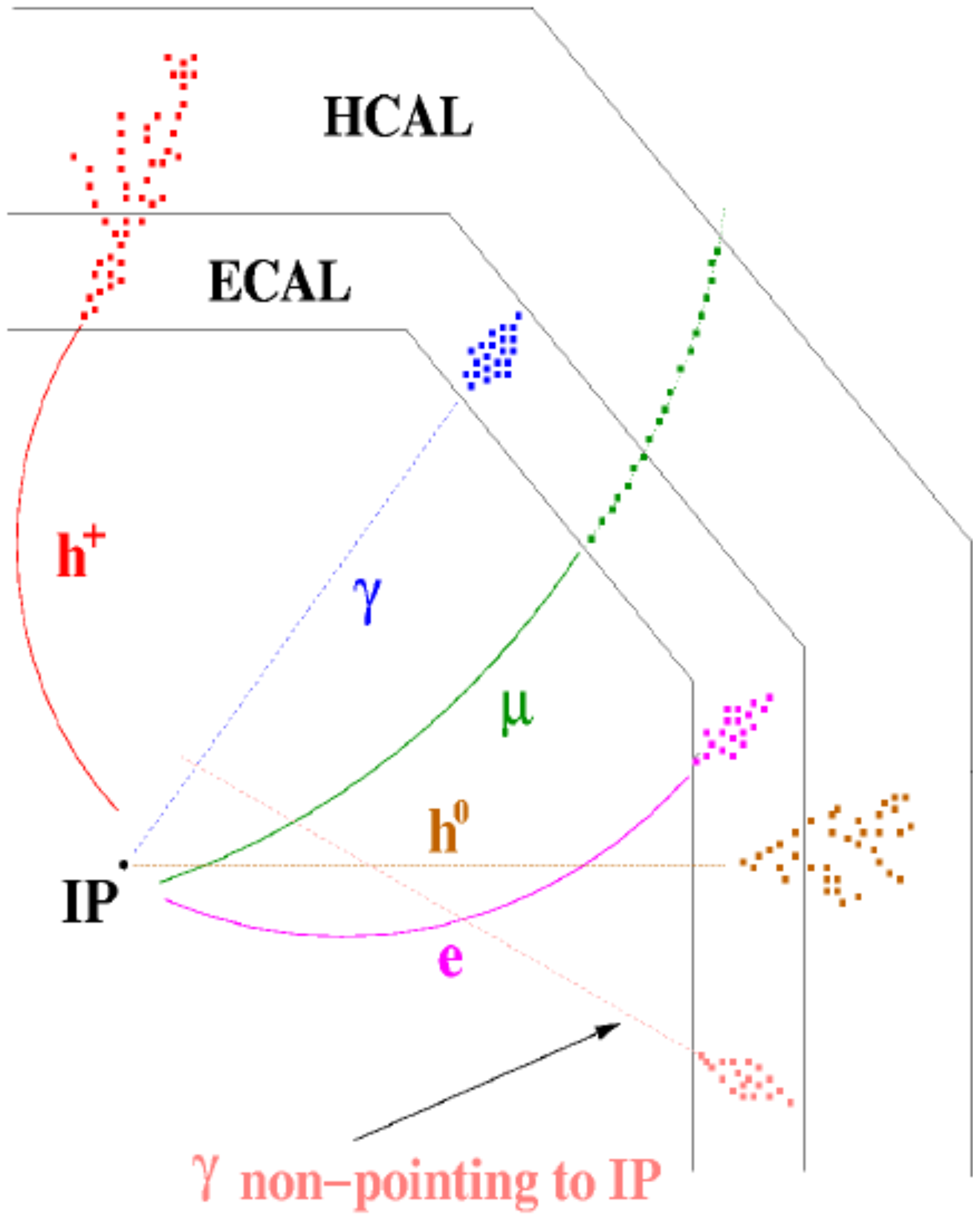


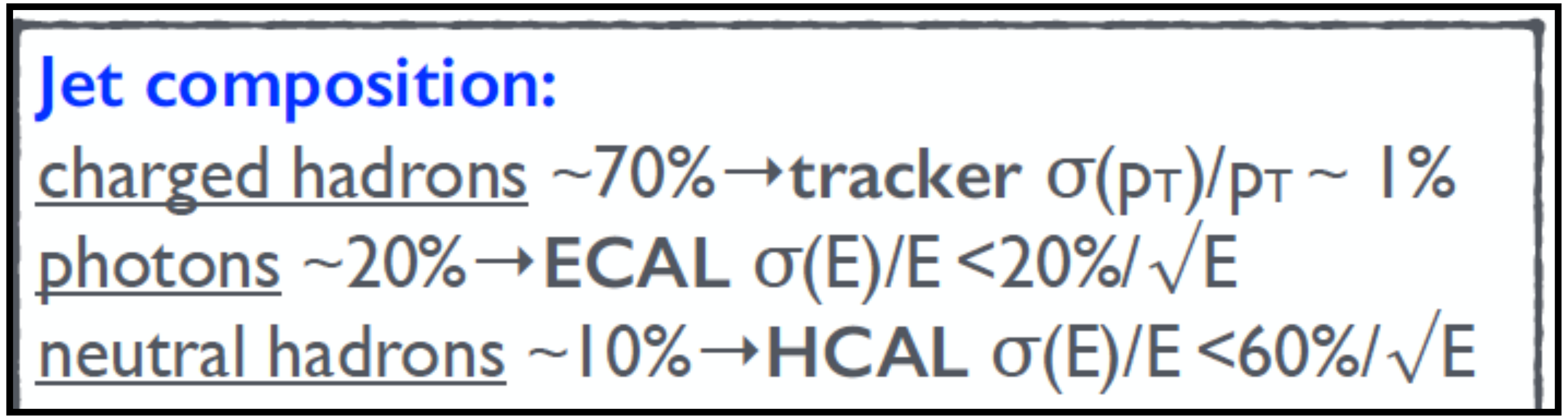
Charged hadrons (**π,k…),** nuclear fragments, neutrons, neutrinos, breakup of nuclei (invisible energy)

Dual Readout

Particle Flow & “High granularity paradigm”

Particle Flow combines tracking and calorimeter for optimal jet reconstruction





Jet composition:

charged hadrons ~70%→**tracker** $\sigma(p_T)/p_T \sim 1\%$

photons ~20%→**ECAL** $\sigma(E)/E < 20\%/\sqrt{E}$

neutral hadrons ~10%→**HCAL** $\sigma(E)/E < 60\%/\sqrt{E}$

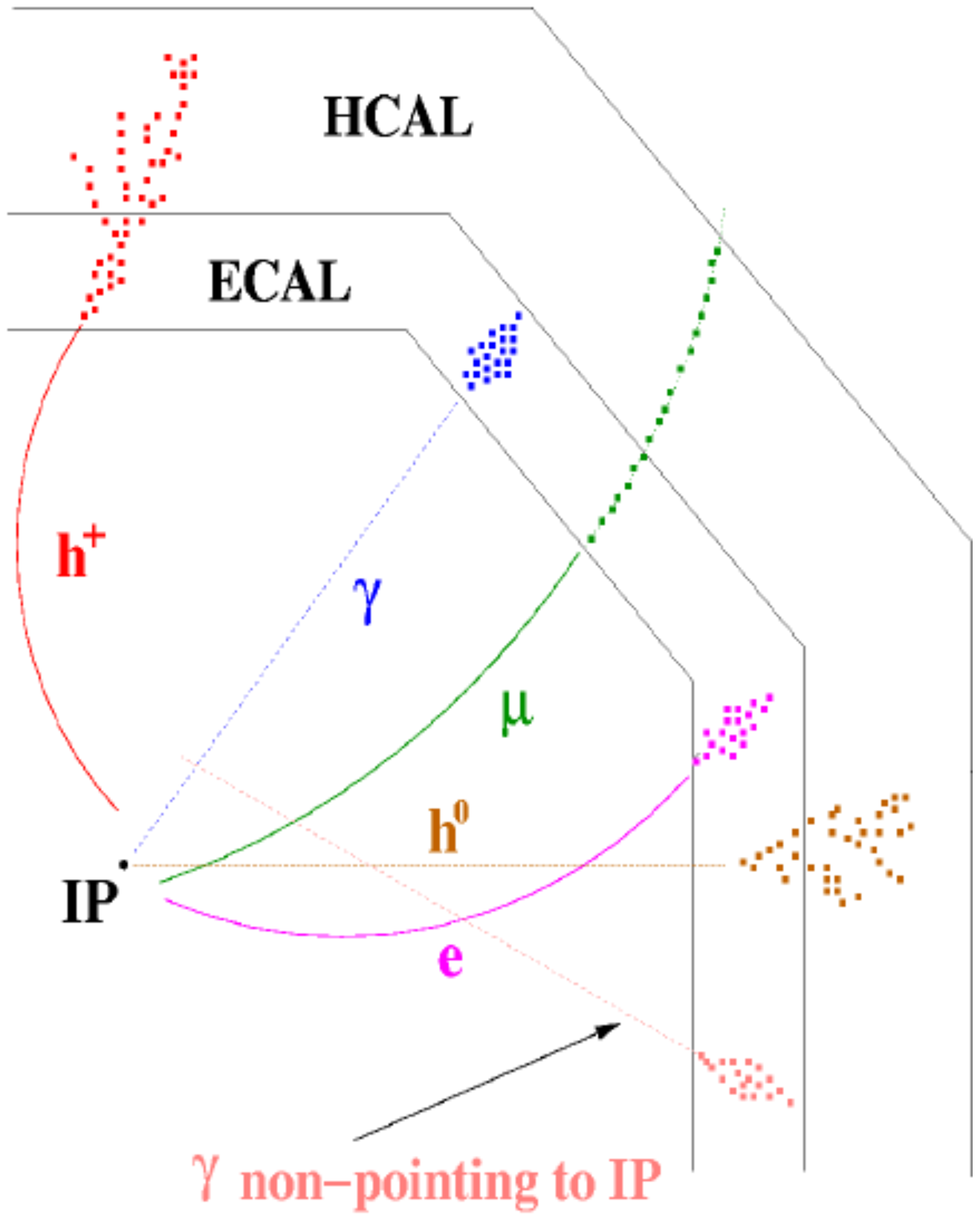
Jet energy measurement by measurement of individual particles

Maximal exploitation of precise tracking measurement

Need to minimize the confusion term as much as possible !!!

Particle Flow & "High granularity paradigm"

Particle Flow combines tracking and calorimeter for optimal jet reconstruction

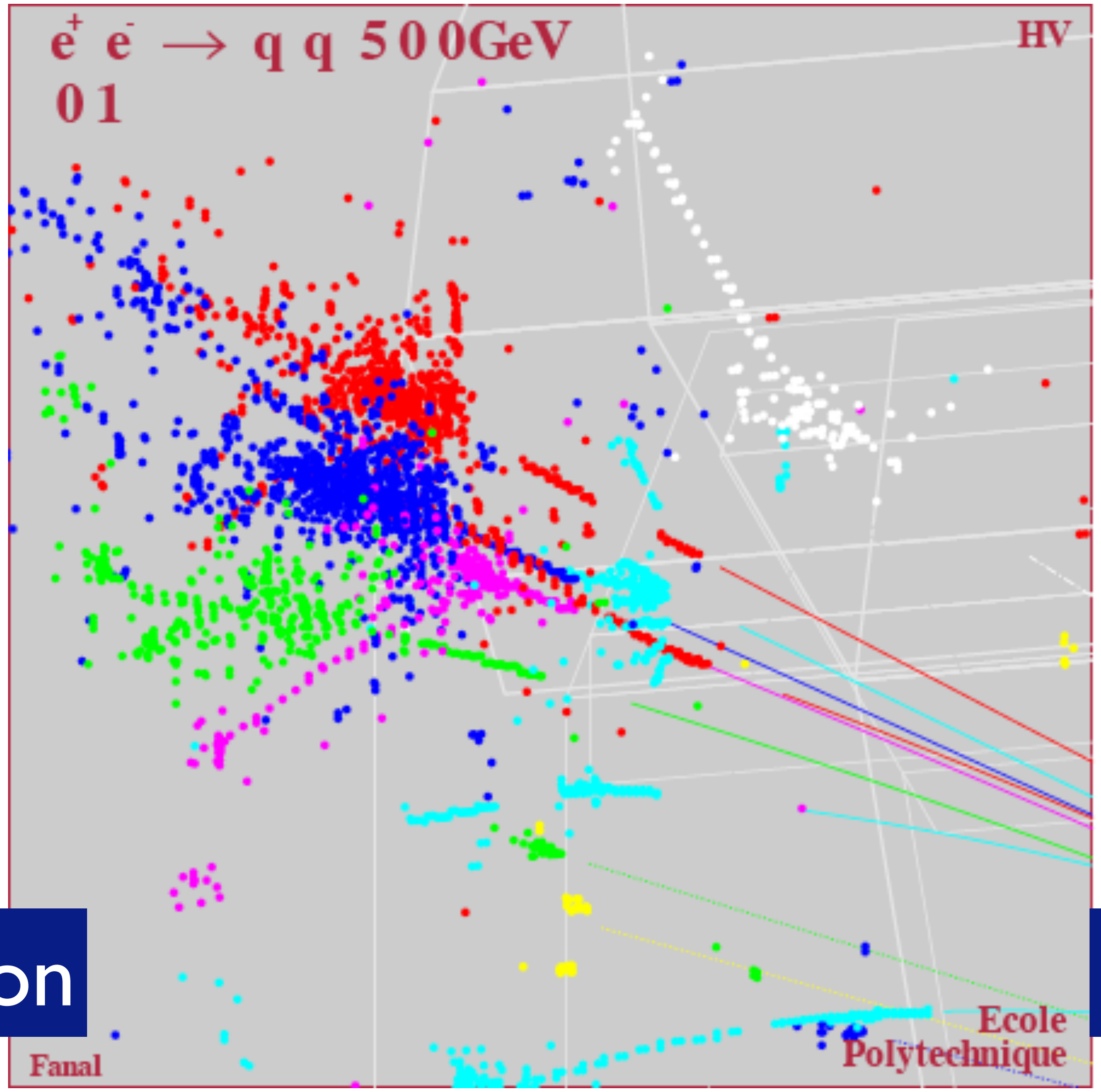


- large radius and length
  ➔ to separate the particles
- large magnetic field
  ➔ to sweep out charged tracks
- "no" material in front of calorimeters
  ➔ stay inside coil
- small Moliere radius of calorimeters
  ➔ to minimize shower overlap
- high granularity of calorimeters
  ➔ to separate overlapping showers
- High λ/X_0 ratio
  ➔ to distinguish Hadronic/EM showers

PFA: High Density + Fine Granularity

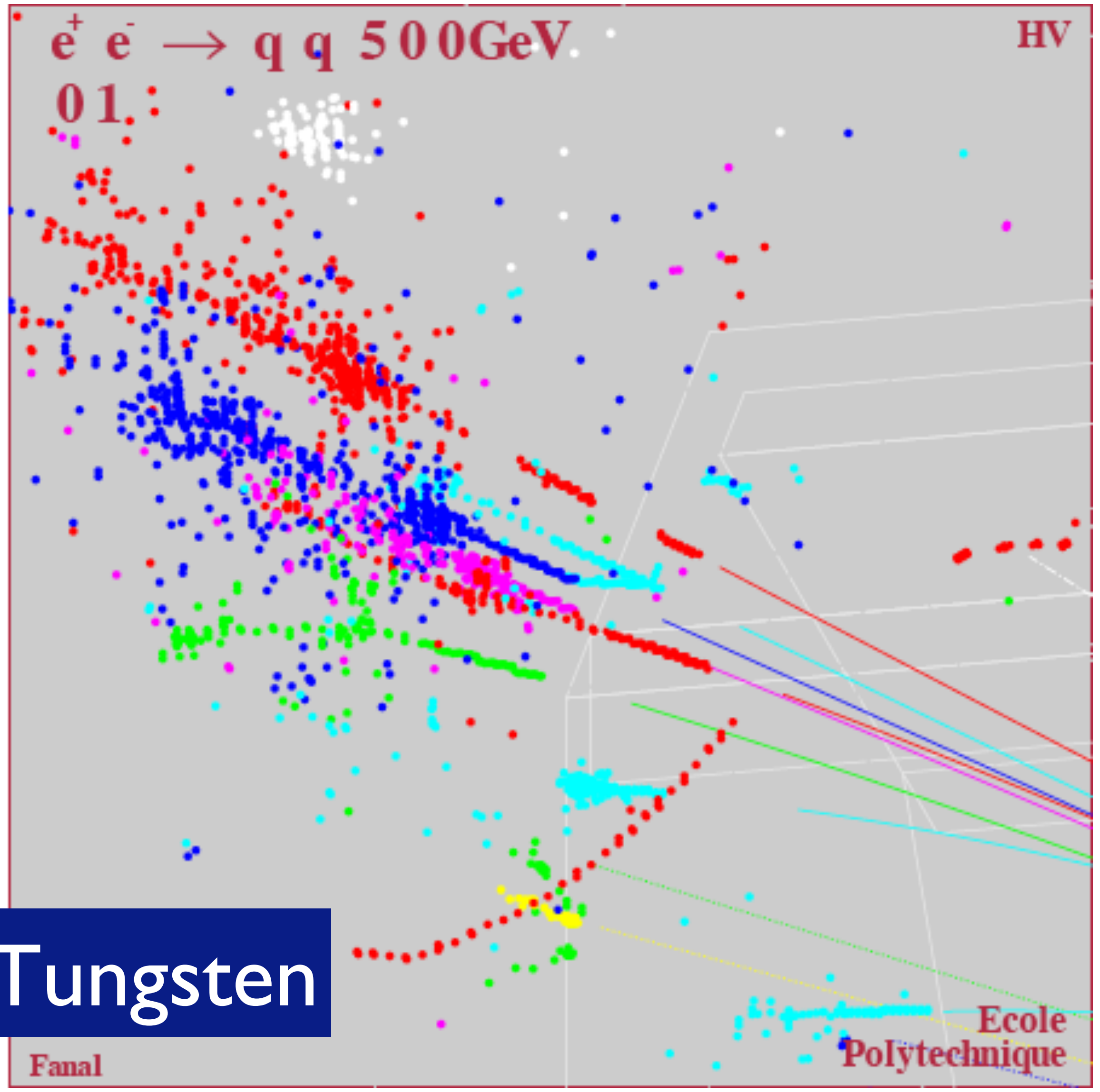
In order to reduce problems of shower overlap, R&D focuses on reducing the shower dimensions and decreasing the calorimeter cell size

$X_0 = 1.8$ cm, $\lambda_I=17$ cm



Iron

$X_0 = 0.35$ cm, $\lambda_I=9.6$ cm

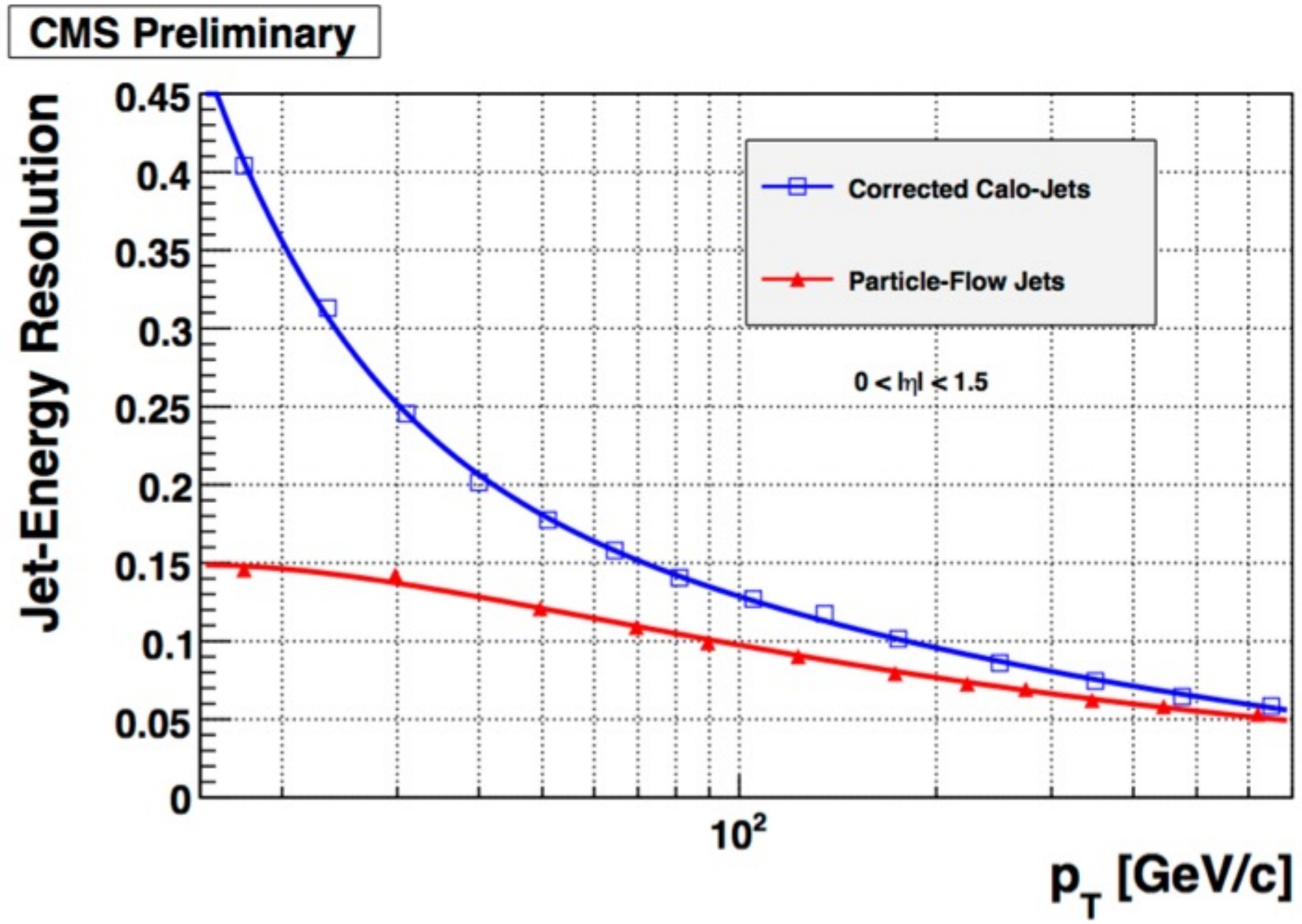


Tungsten

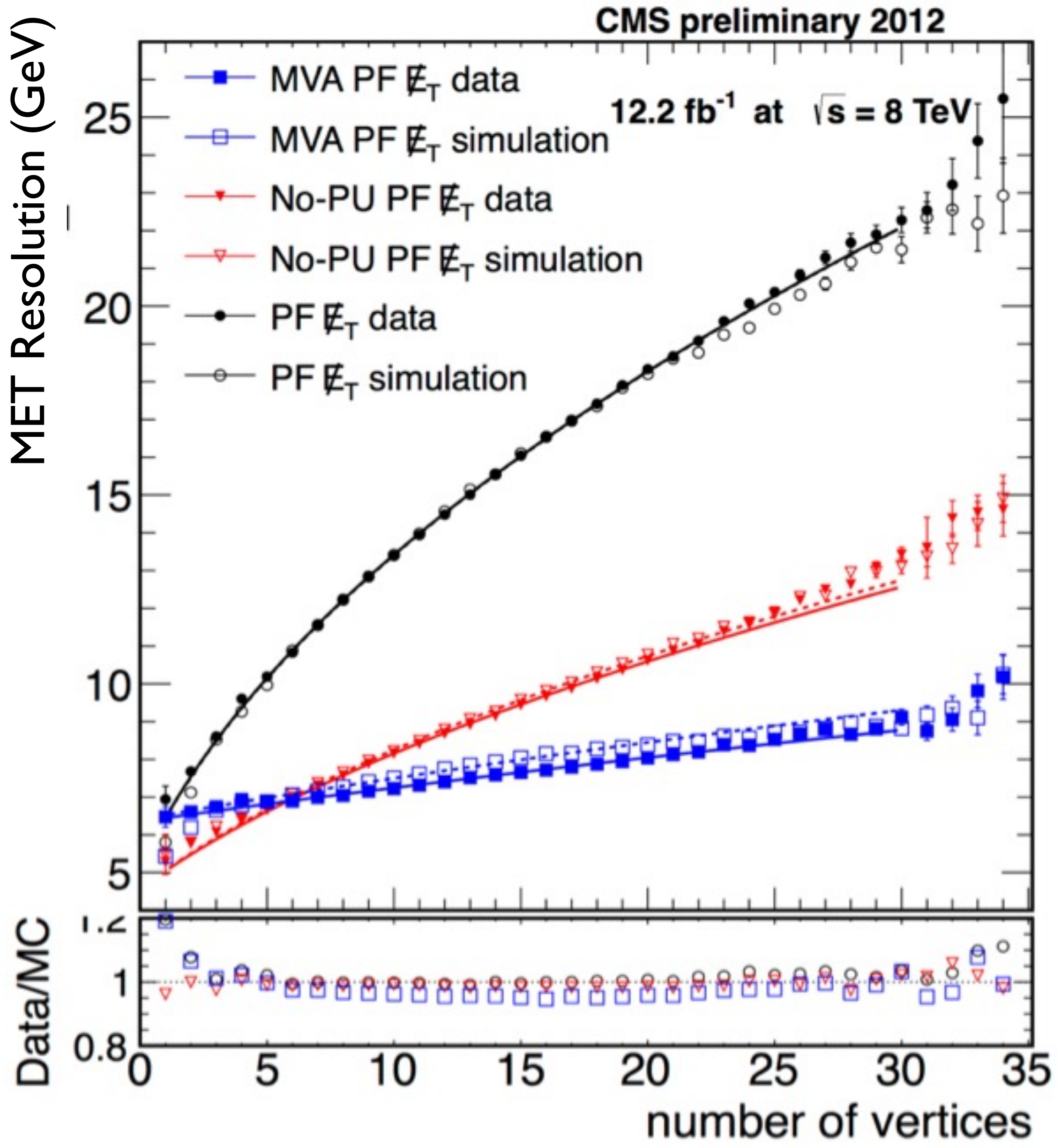
Particle Flow & "High granularity paradigm"

PF in action already at LHC, CMS (non optimised for PF)

- B=3.8 T
- track $\sigma(p_T)/p_T \sim 1\%$
- photons $\sigma(E)/E \sim 3\%/\mathrm{sqrt}(E)$
- neutral hadrons $\sigma(E)/E \sim 120\%/\mathrm{sqrt}(E)$



PF approach also beneficial for PU mitigation (tracks can be easily associated with production vertices)



Particle Flow and the CALICE collaboration

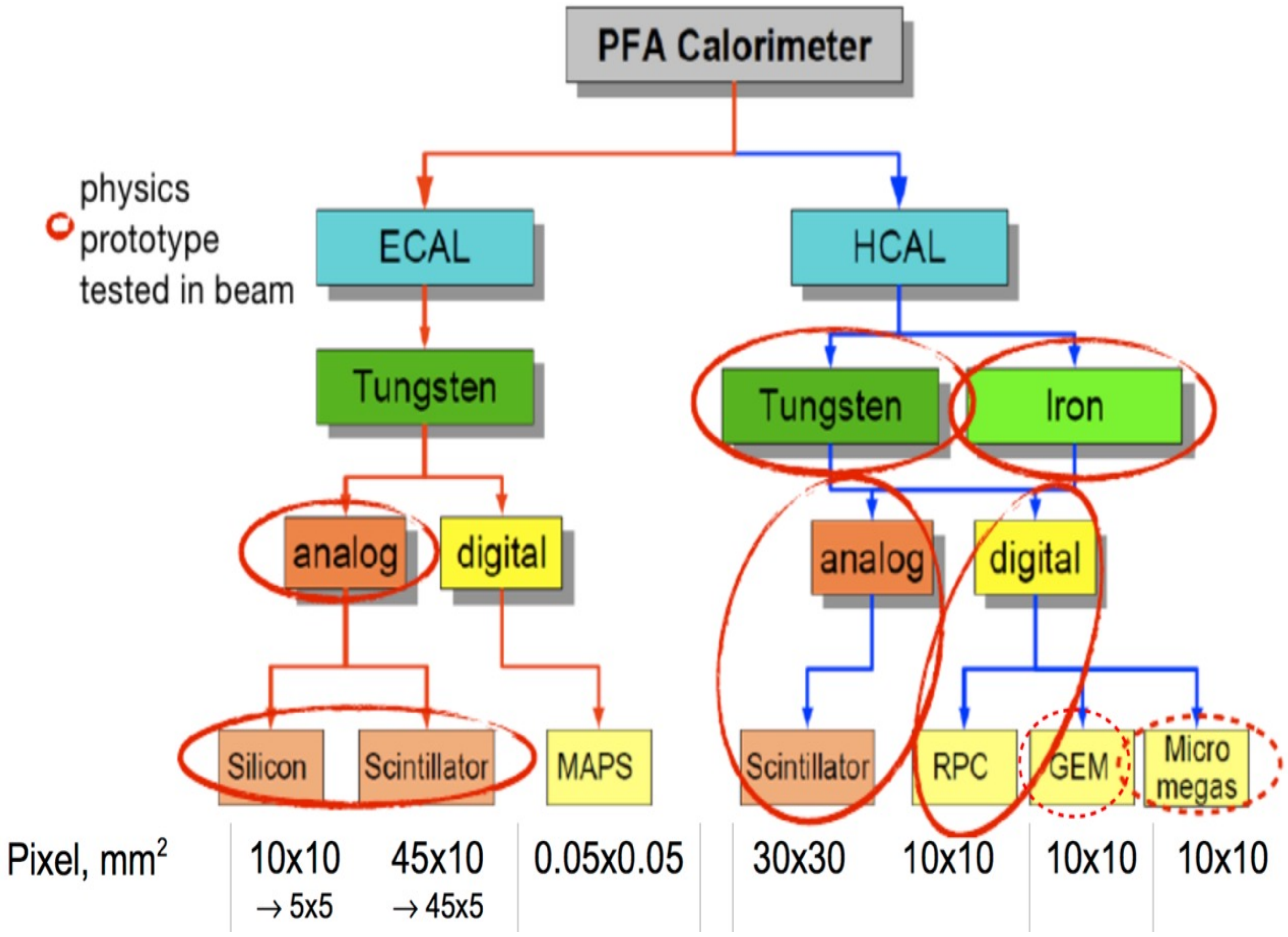
The CALICE Collaboration

336 physicists/engineers from around 60 institutes and 18 countries coming from the 4 regions (Africa, America, Asia and Europe)

R&D pursued within CALICE collaboration, a 15 year long R&D

R&D moving from 1st generation prototypes demonstrating the PF concept, to 2nd generation prototypes addressing technical issues to demonstrate experimental application (mechanics, power, integration…)

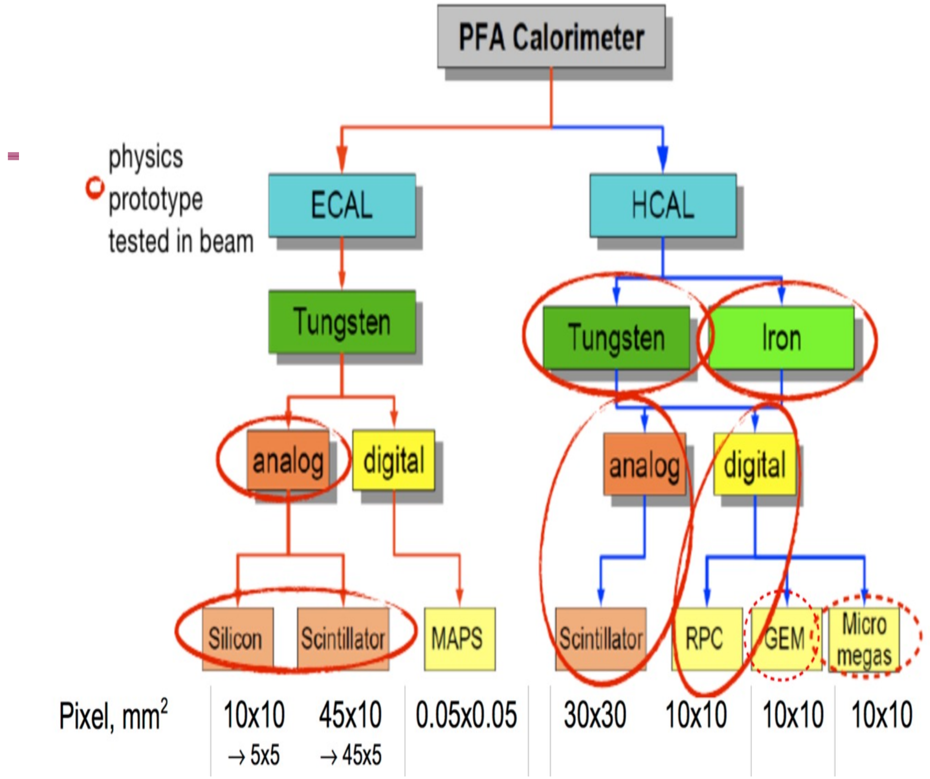
High granularity calorimeter design

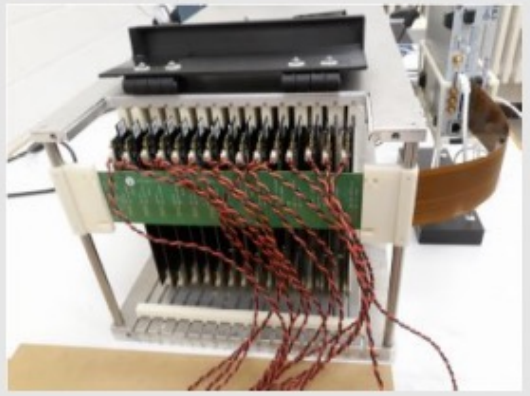
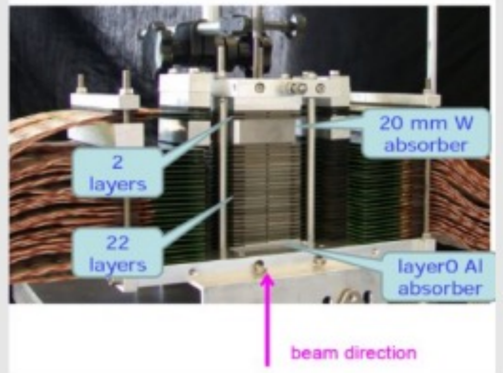


A "Calice" calorimeter is:

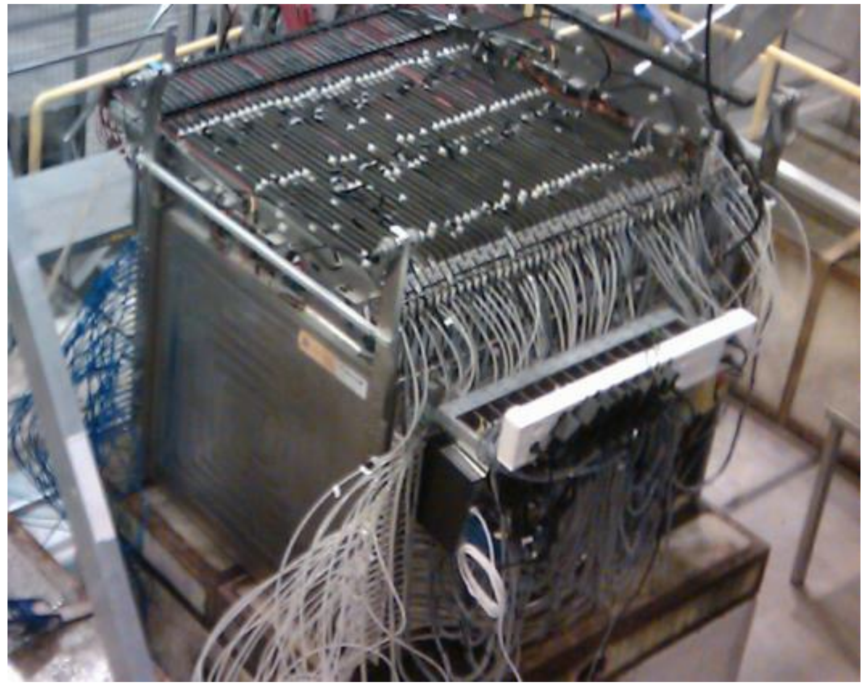
- a calorimetric system including ECAL+HCAL+X_0-thin High-Performance Tracker
- It's optimised for Particle Flow

High granularity calorimeter design



Si-W ECAL	(ALICE FoCAL)	[Scint-W ECAL]	AHCAL	SDHCAL
				
0,5×0,5 cm² ×15 (→30) Si layers + W	0,003×0,003 cm² × 24 MIMOSA layers + W	0,5×4,5 cm² ×30 Scint+SiPM lay. + SS	3×3 cm² × 38 Scint+SiPM lay. + SS	1×1 cm² × 48 layers GRPC + SS

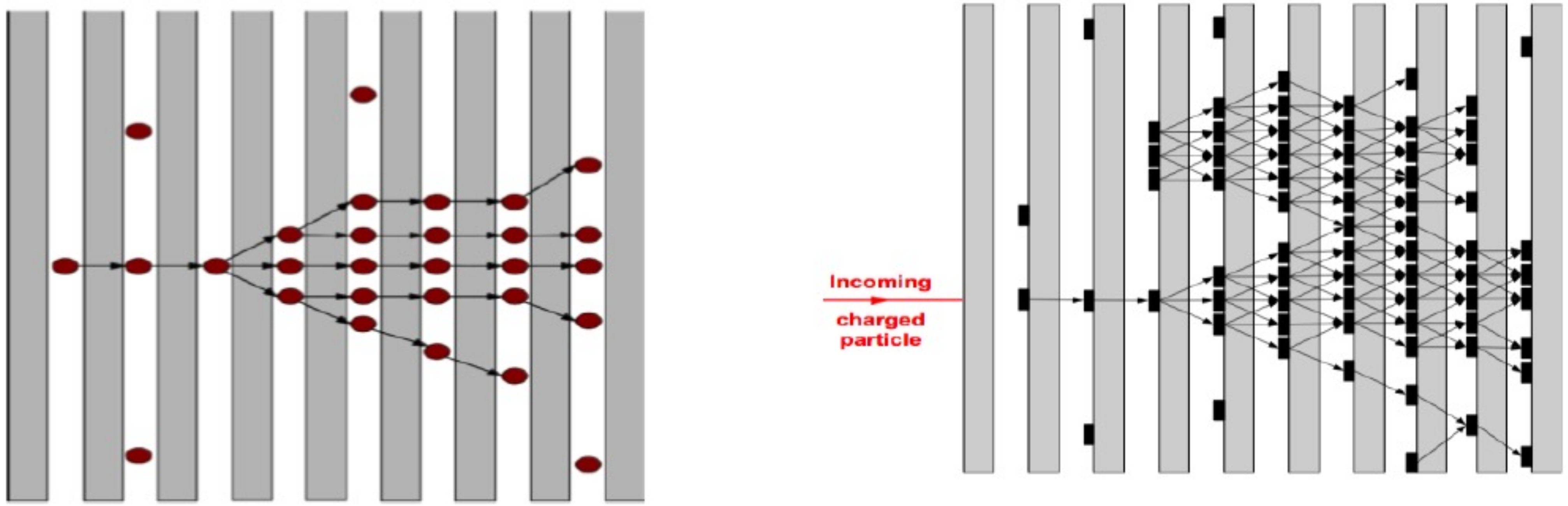
Example: Semi-Digital HCAL



SDHCAL with gas: RPC, Micromegas or GEM

cheaper alternative to scintillator
advantages for 2 bits readout (1, several, many MIPS) over 1 bit
Micromegas and GEM have potential to improve RPC dynamic range & proportionality

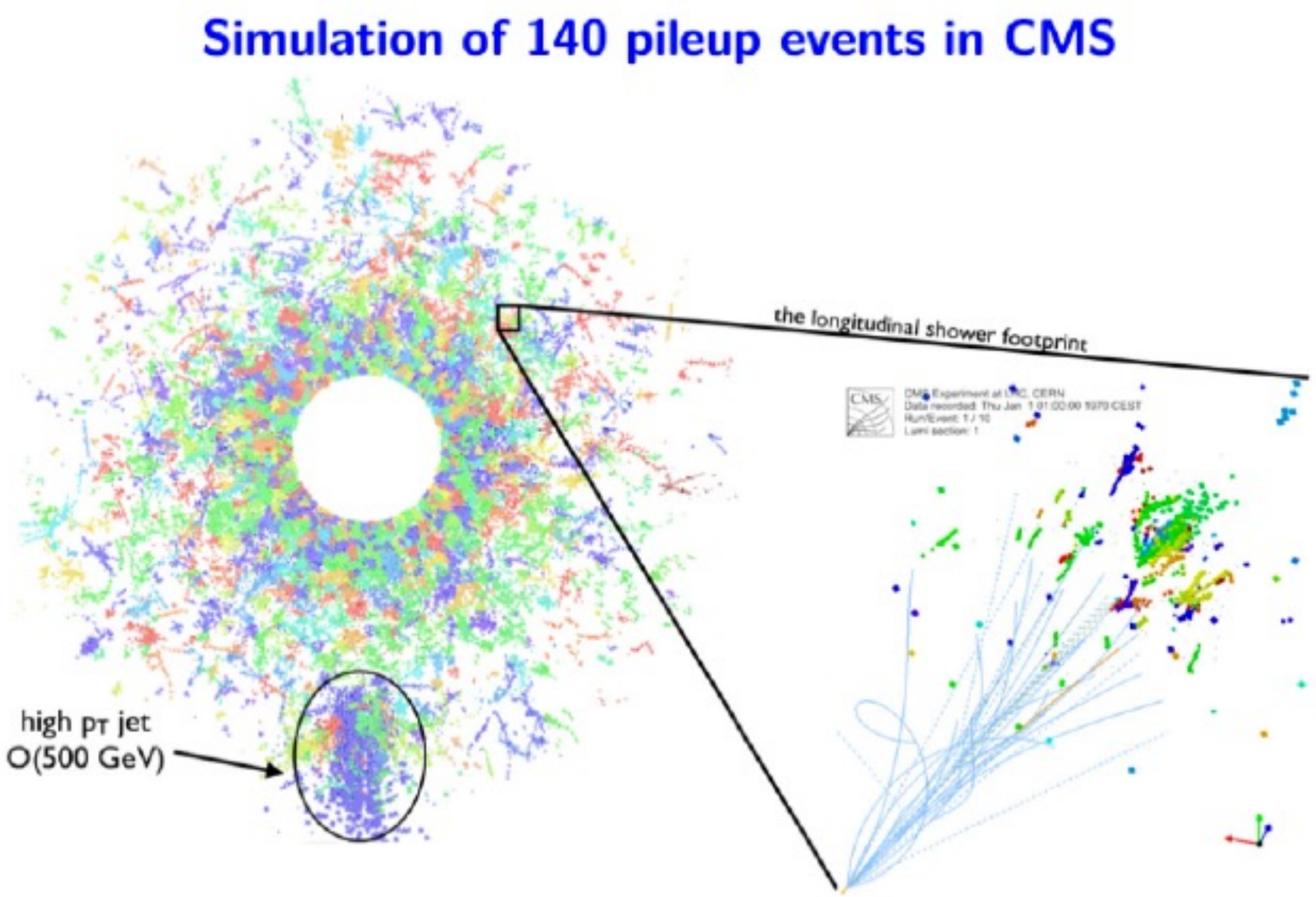
ArborPFA algorithm*:
It connect hits and then their clusters using distance and orientation information then correct using tracker information (momentum)

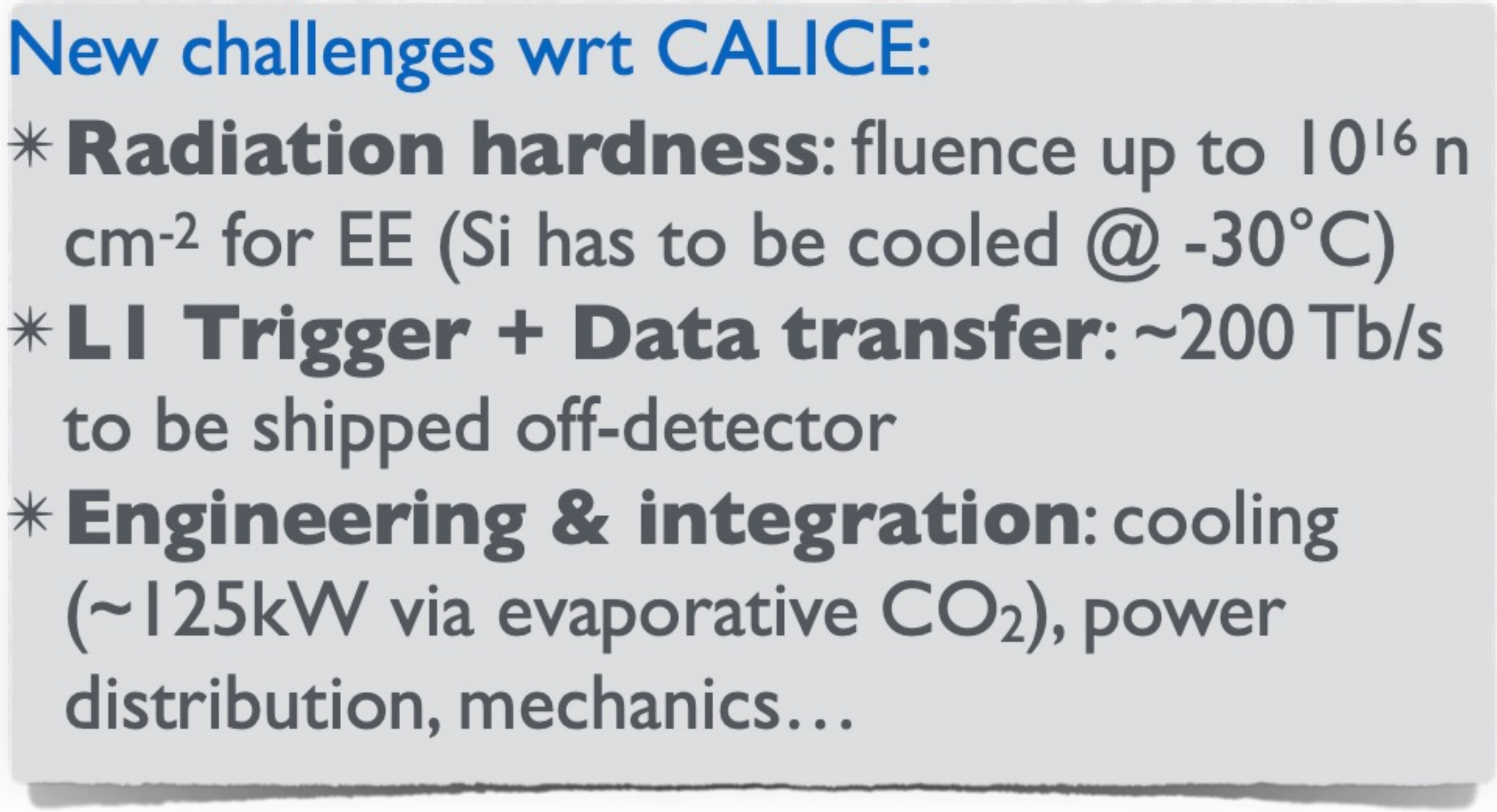


CMS: HGCAL for HL-LHC

CMS Phase II upgrade: High Granular CALorimeter for the forward region ($1.5 < |\eta| < 3$)

High granularity (transverse & longitudinal) for PF in very dense environment: <PU> at HL-LHC 140-200





New challenges wrt CALICE:

- **Radiation hardness**: fluence up to 10^{16} n cm^{-2} for EE (Si has to be cooled @ -30°C)
- **L1 Trigger + Data transfer**: ~200 Tb/s to be shipped off-detector
- **Engineering & integration**: cooling (~125kW via evaporative CO_2), power distribution, mechanics…

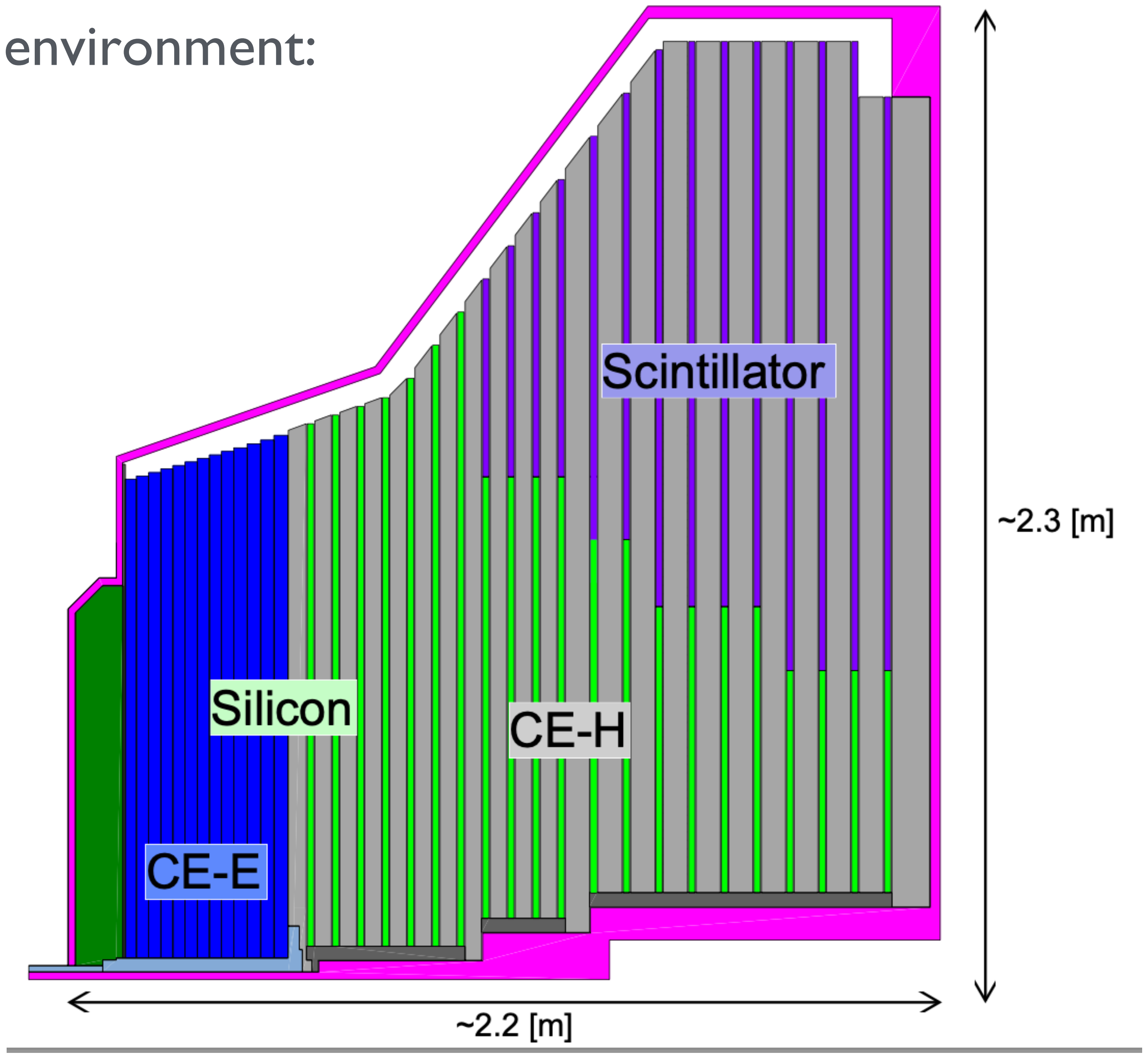
CMS: HGCAL for HL-LHC

CMS Phase II upgrade: High Granular CALorimeter for the forward region (1.5 < |η| < 3)

High granularity (transverse & longitudinal) for PF in very dense environment:
<PU> at HL-LHC 140-200

Per Endcap	**CE-E**	**CE-H**	
		Si	**Si+Scint**
Absorber	**Pb, CuW, Cu**	**Stainless steel, Cu**	
Depth	**27.7 X_0**	**10 λ**	
Layers	**26**	**7**	**14**

Both Endcaps	**Silicon**	**Scintillator**
Area	**~620 m²**	**~370 m²**
Channel Size	**0.5 - 1.2 cm²**	**4 - 30 cm²**
# Channels	**~6 M**	**~240 k**



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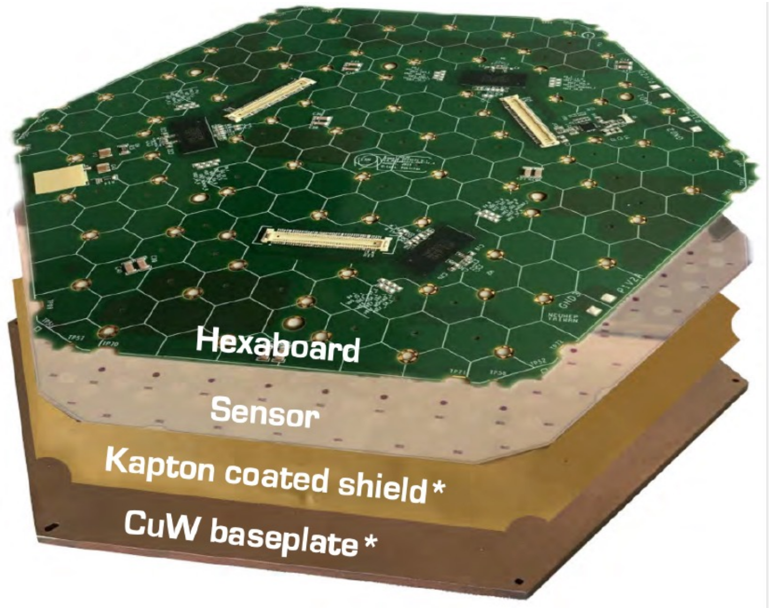

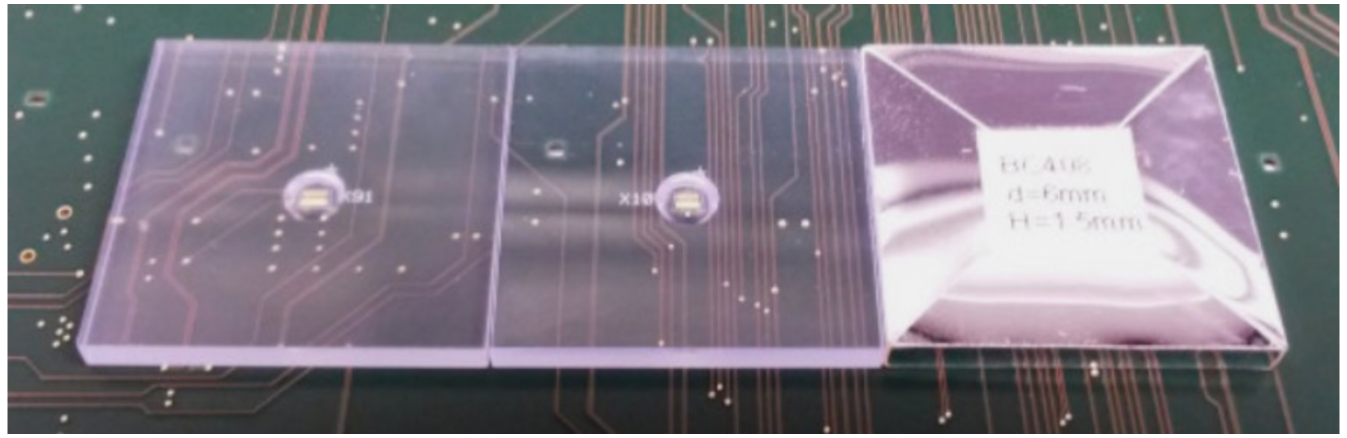

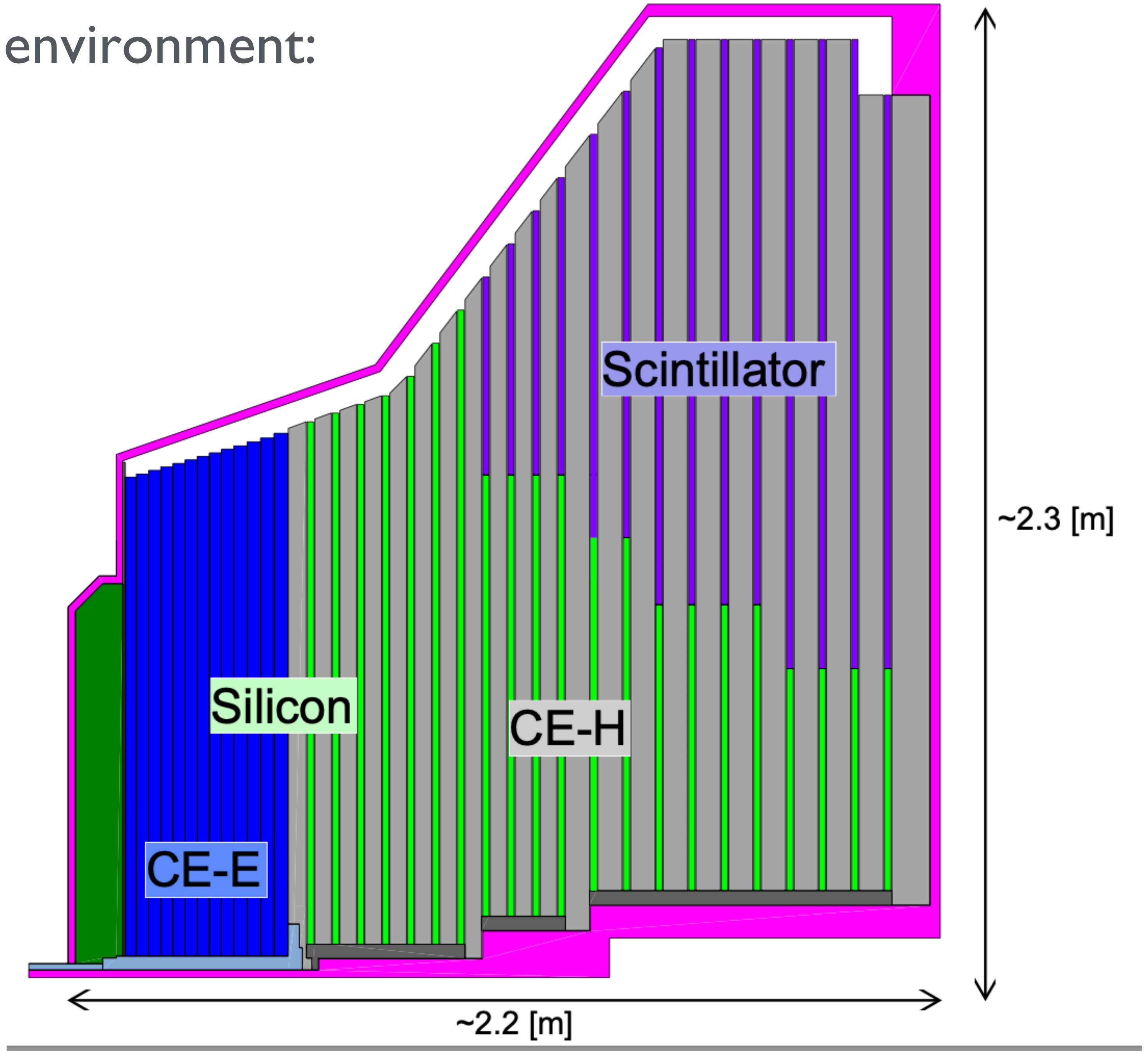

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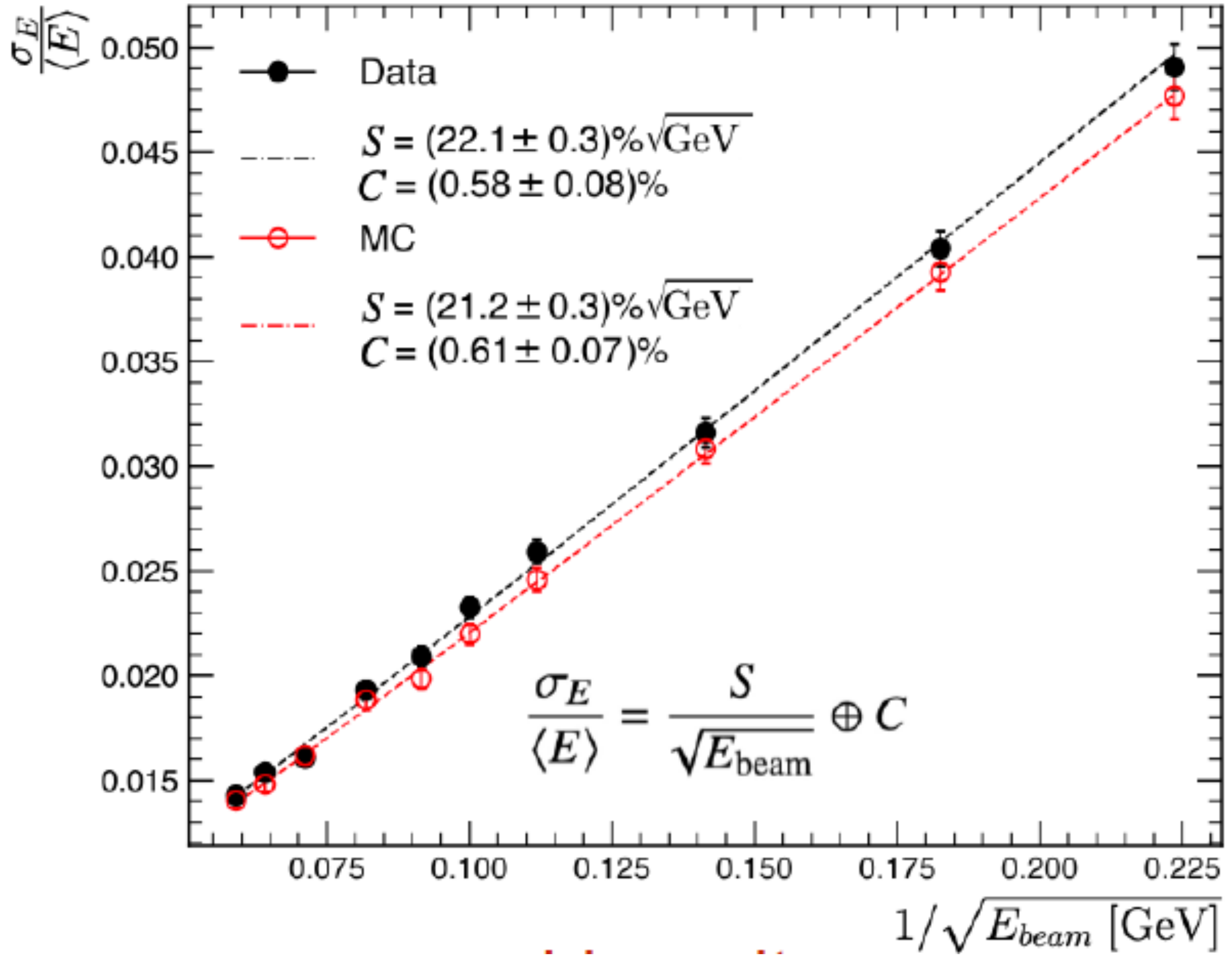
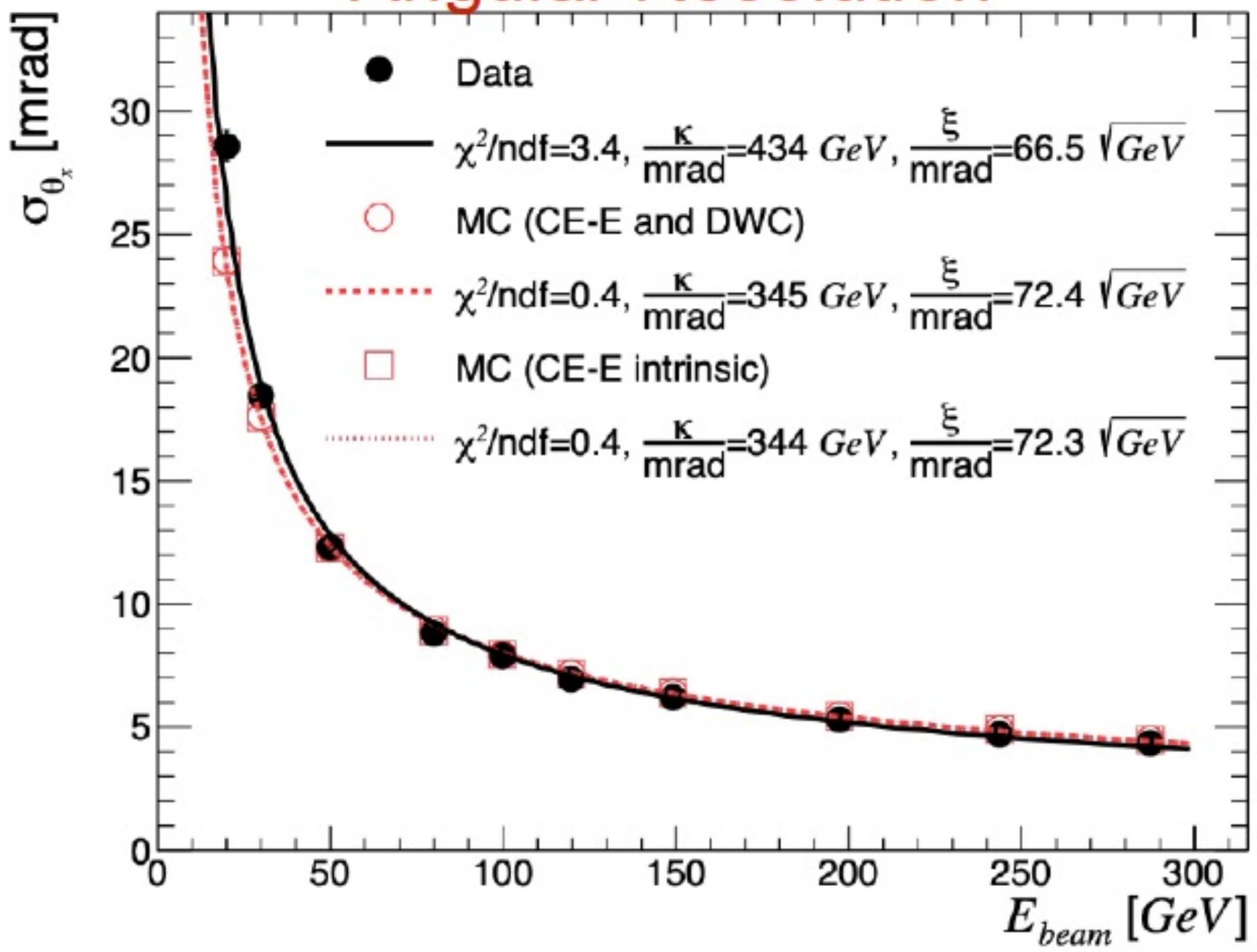
High granularity (transverse & longitudinal) for PF in very dense environment: <PU> at HL-LHC 140-200

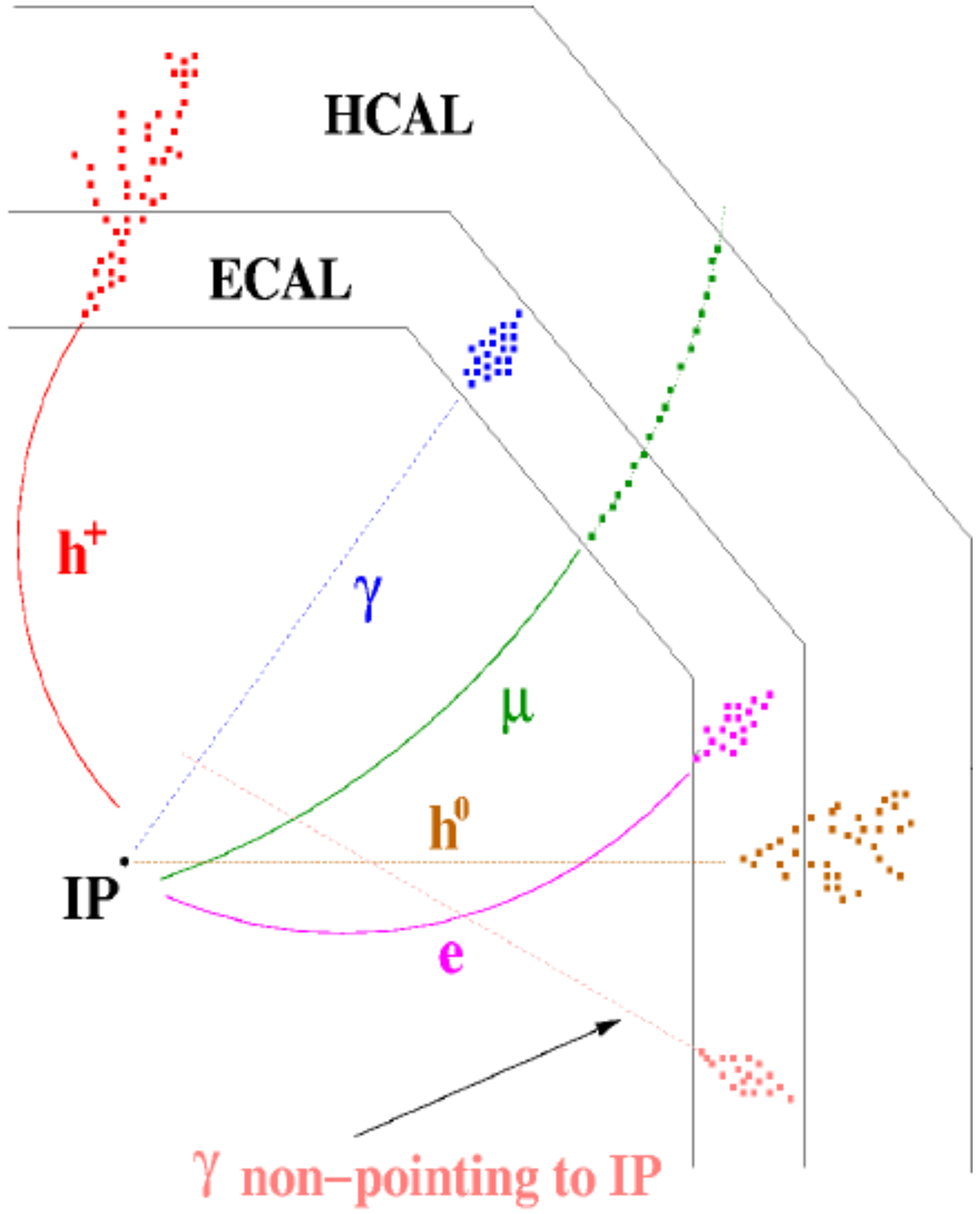
Energy Resolution

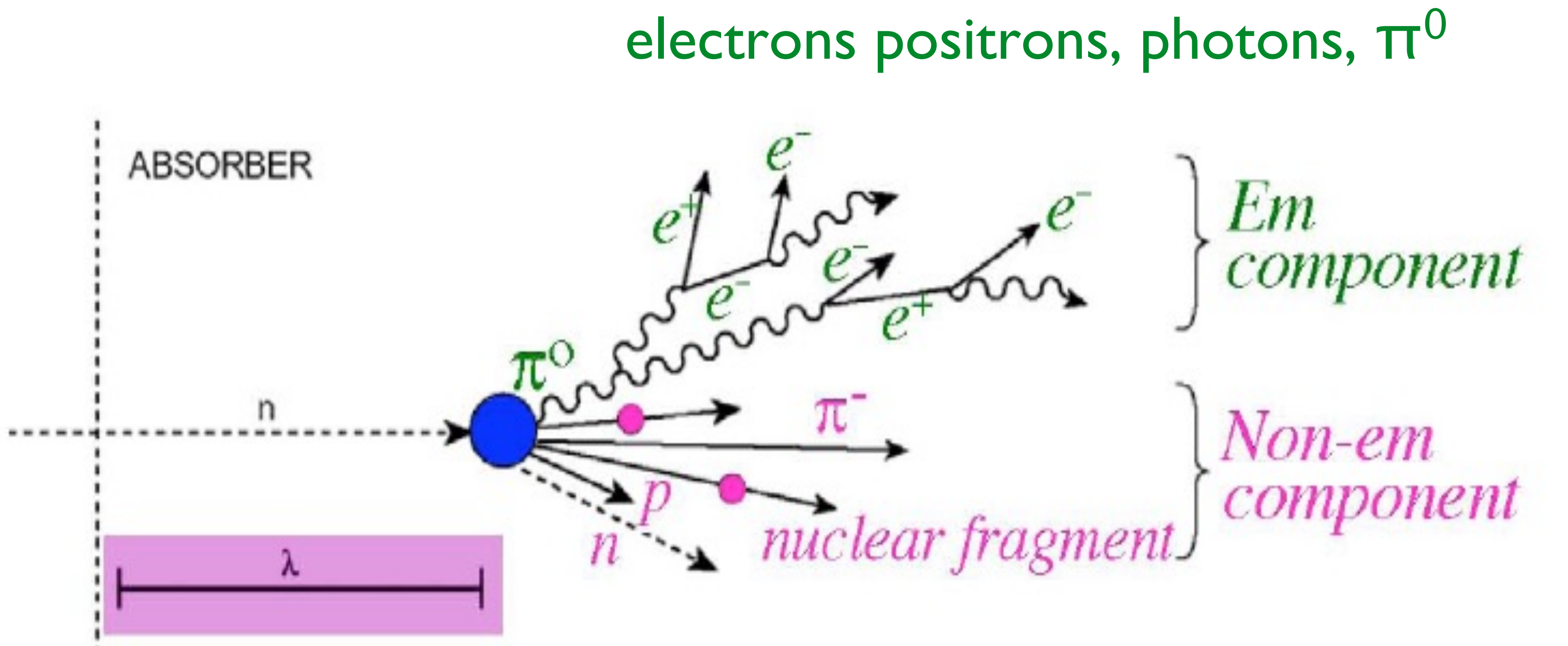


Angular Resolution



Two Calorimetry Approaches





Charged hadrons (**π,k…),** nuclear fragments, neutrons, neutrinos, breakup of nuclei (invisible energy)

Particle Flow

Dual Readout

Aims of Dual Readout Project

- Address the factors which limit the resolution of hadron calorimeter to reach the theoretical resolution limit
  - Calibration of the calorimeter can be done with electrons
  - High resolution EM and HAD calorimetry
  - Can comply with the requirements for Future collider physics
- Study and eliminate/reduce dominant source of fluctuation

Principles of Dual Readout Calorimetry

Simultaneous measurement on event-by-event basis of elm fraction of hadron showers

Cherenkov light C	only produced by relativistic particles, dominated by electromagnetic shower component
Scintillation light S	measure dE/dx

$$S = [\ f_{em} + (h/e)_s \times (1 - f_{em})\ ] \times E$$
$$C = [\ f_{em} + (h/e)_c \times (1 - f_{em})\ ] \times E$$

e/h ratio of the C (S) calorimeter structure (measured)

$$c = (h/e)_C$$
$$s = (h/e)_S$$

It is possible to evaluate

$$f = \frac{c - s(C/S)}{(C/S)(1-s) - (1-c)}$$

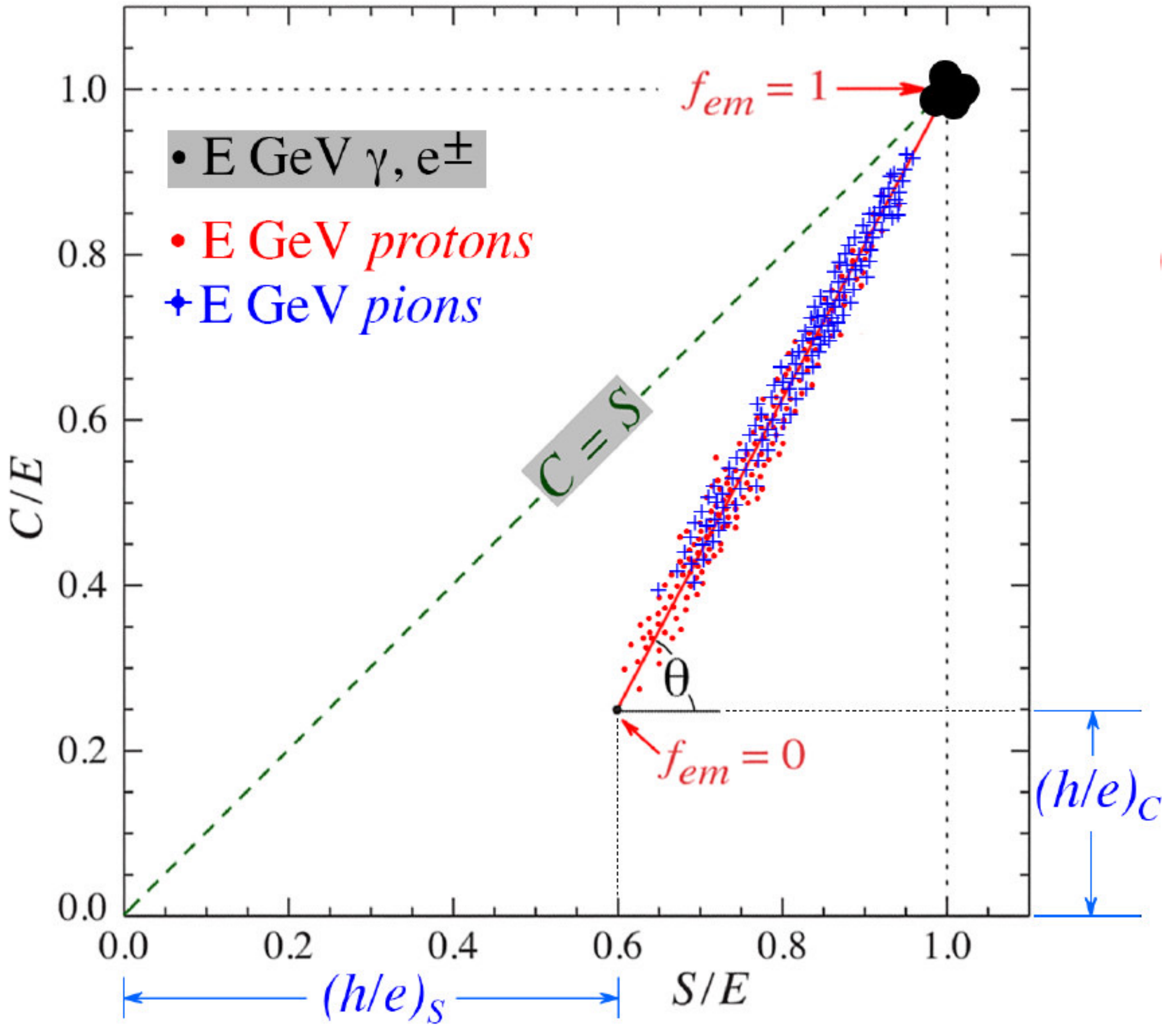
and

$$E = \frac{S - \lambda C}{1 - \lambda}$$

Principles of Dual Readout Calorimetry

$$S/E = f_{em} + (h/e)_s \times (1 - f_{em})$$

$$C/E = f_{em} + (h/e)_c \times (1 - f_{em})$$



$$cotg\,\theta = \frac{1-(h/e)_S}{1-(h/e)_C} = \chi$$

Θ, χ independent of both

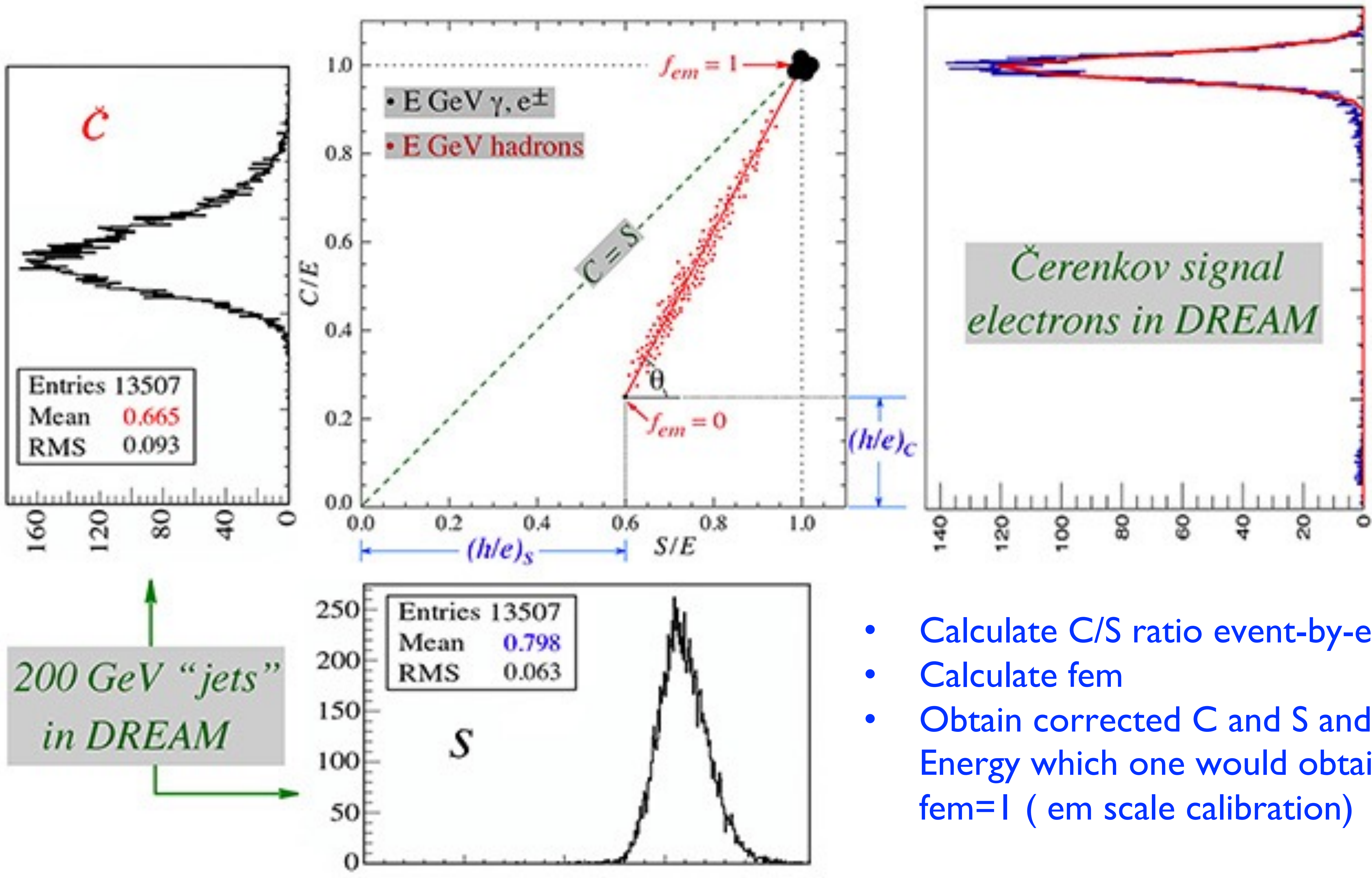
- energy
- type of hadron

$$E = \frac{S - \chi C}{1 - \chi}$$

is universally valid

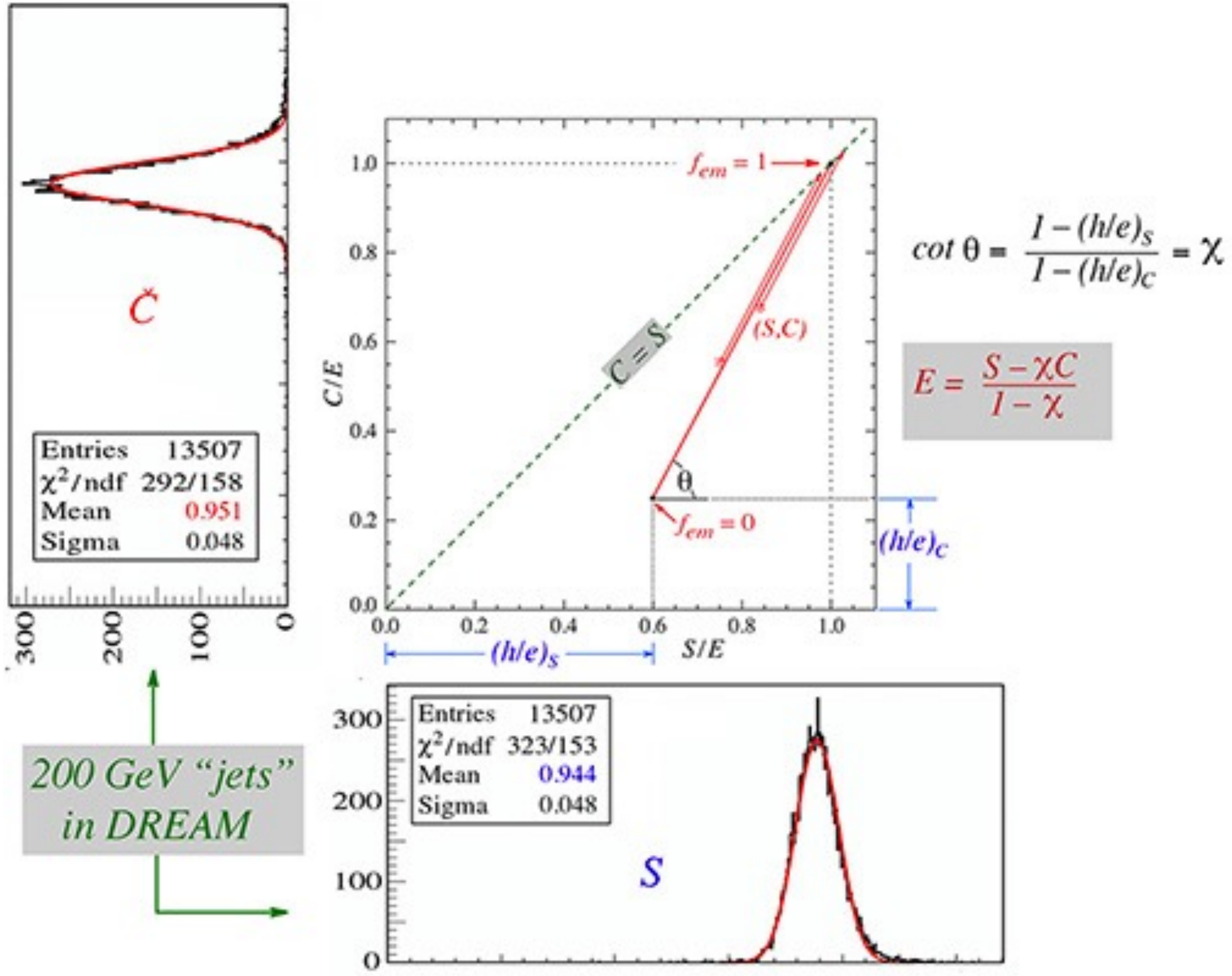
Calorimeter calibration done with electrons

Before Correction



- Calculate C/S ratio event-by-event
- Calculate fem
- Obtain corrected C and S and Energy which one would obtain if fem=1 (em scale calibration)

After Dual Readout approach



$$\cot\theta = \frac{1-(h/e)_S}{1-(h/e)_C} = \chi$$

$$E = \frac{S-\chi C}{1-\chi}$$

Dual-readout R&D

Homogeneous Calorimeter	Sampling Calorimeter
Possibility to solve light yield and sampling fluctuation problem. Need to separate C and S light.	Two types of fibers, either sensitive to Cherenkov and Scintillation Separated by construction

Proof of concept phase

RD52 coll

2007-11 **Crystals DRC**

Single Xtals, prove of principles

- PbWO$_4$ + Pr, Mo doped PbWO$_4$
- BGO
- BSO

NIM A 638 (2011) 47
NIM A 640 (2011) 91
NIM A 621 (2010) 212
NIM A 604 (2009) 512
NIM A 593 (2008) 530
NIM A 595 (2008) 359

Matrixes + DREAM, em section

- PbWO$_4$
- Doped PbWO$_4$
- BGO

NIM A 598 (2009) 710
NIM A 686 (2012) 125
NIM A 610 (2009) 488
NIM A 584 (2008) 273

DREAM coll

2003 - 11 **DREAM Cu-fiber**

NIM A 533 (2005) 305
NIM A 536 (2005) 29
NIM A 537 (2005) 537
NIM A 548 (2005) 336
NIM A 550 (2005) 185
NIM A 581 (2007) 643
NIM A 598 (2009) 422

RD52 coll

2010 **Pb - Tile DRC**

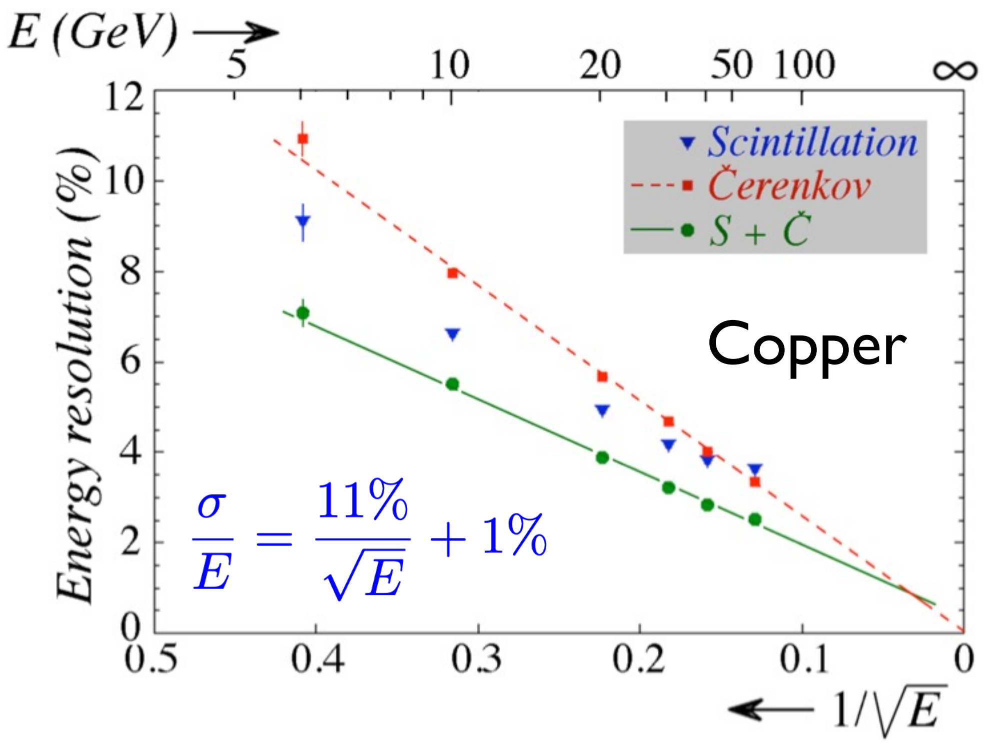
INST 9, (2014) C05009

2012- 16 **Cu, Pb Fiber DRC**

NIM A 762 (2014) 110
NIM A 735 (2014) 120
NIM A 735 (2014) 130
NIM A 808 (2016) 41

Dual Readout method in sampling calorimeter

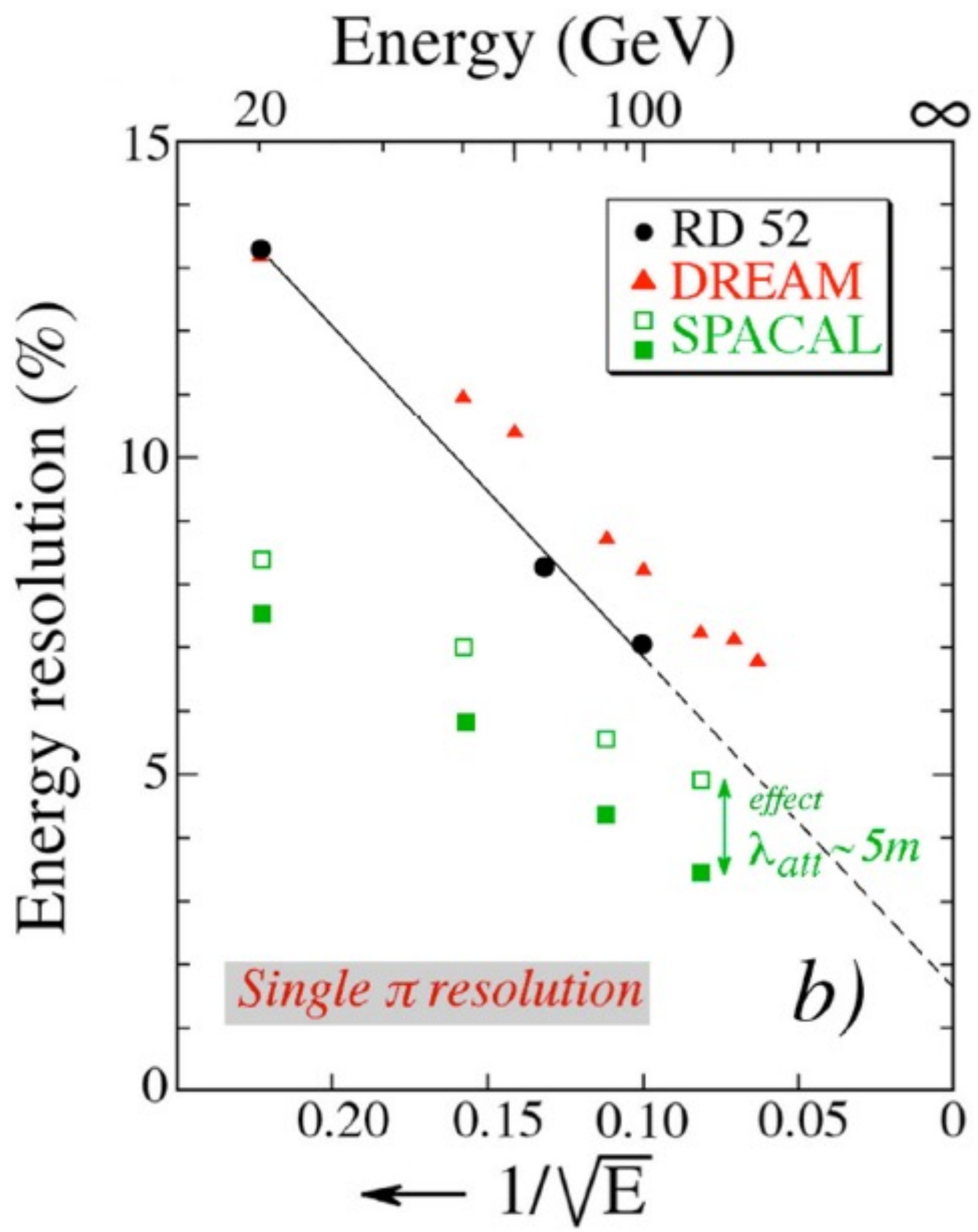
Electromagnetic Resolution



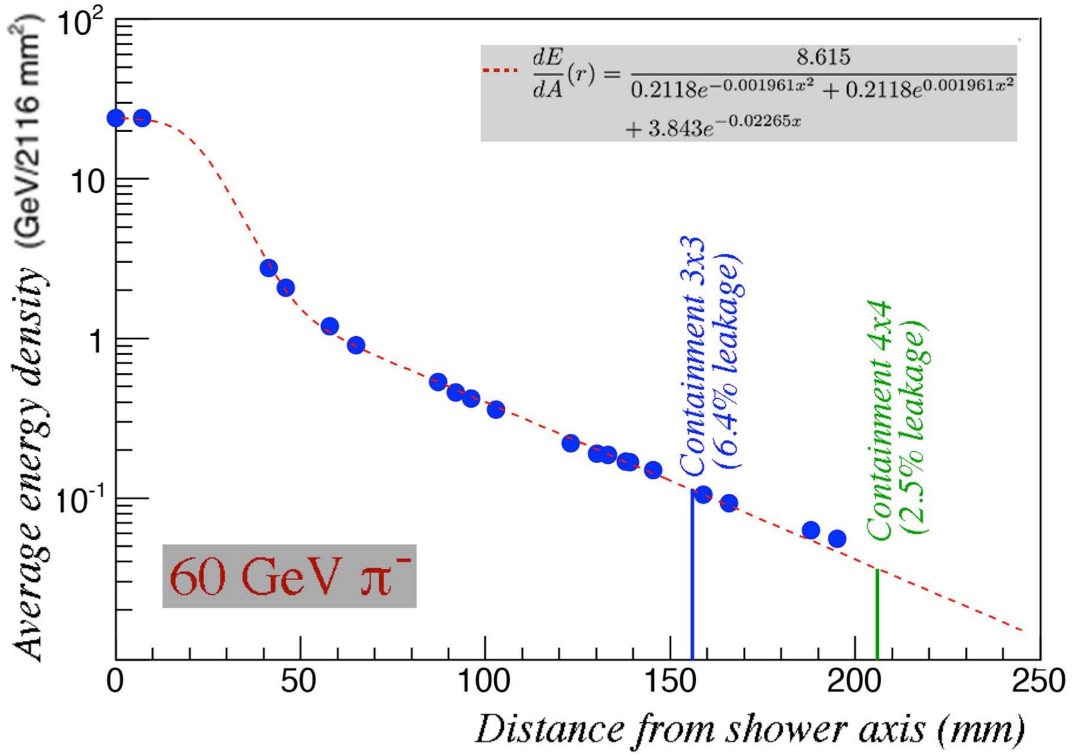
$$\frac{\sigma}{E} = \frac{11\%}{\sqrt{E}} + 1\%$$

Hadronic Resolution (Pb Module)

$$\frac{\sigma}{E} = \frac{53\%}{\sqrt{E}} + 1.7\%$$



Expected to improve (based on MC simulation) by including corrections on:
- light attenuation
- lateral leakage



DR recent development: PMT vs SiPM readout

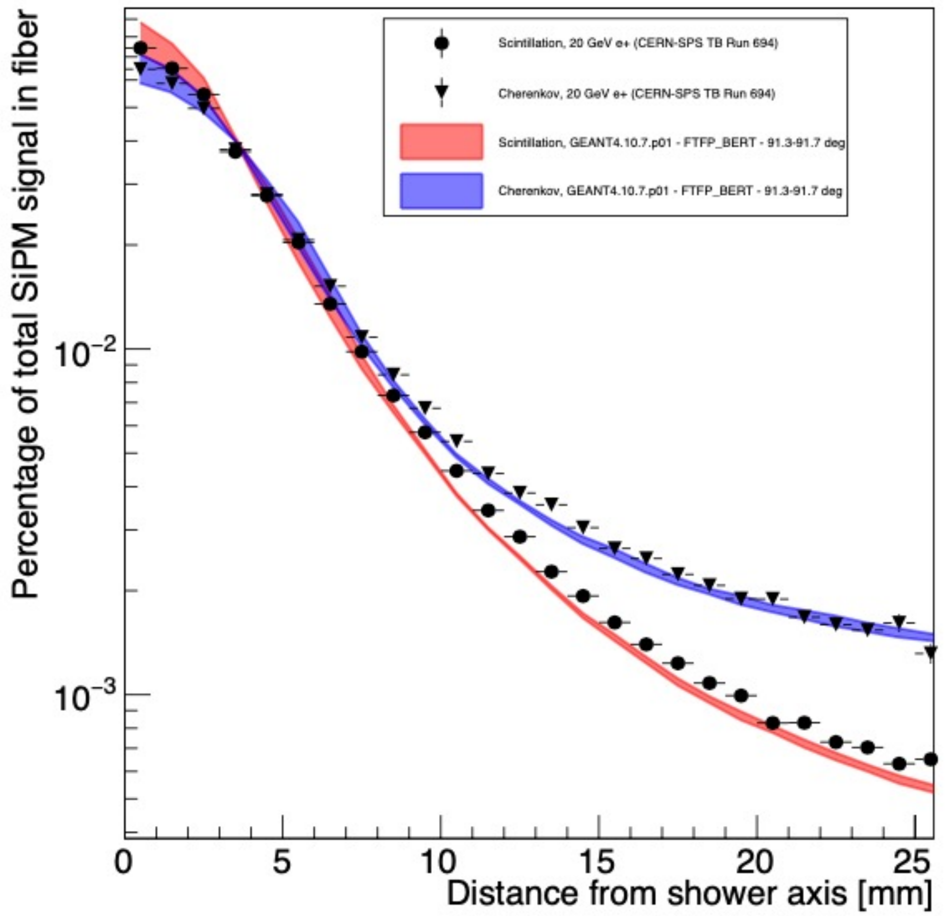
SiPM advantages:

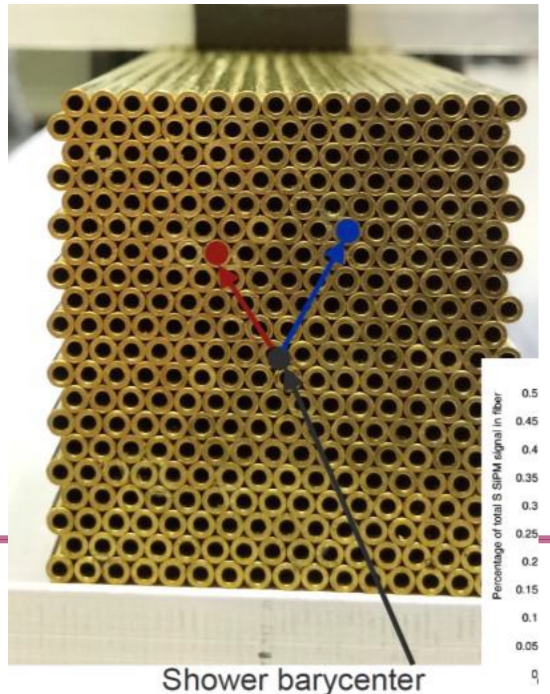
- compact readout (no fibres sticking out)
- operation in magnetic field
- larger light yield (# of Čerenkov p.e. limits resolution)
- very high readout granularity → particle flow “friendly”

SiPM (potential) disadvantages:

- signal saturation (digital light detector)
- cross talk between Čerenkov and scintillation signals
- dynamic range
- instrumental effects (stability, afterpulsing, ...)

CERN SPS 20 GeV e^+ - GEANT4 (log scale)





PMT vs SiPM readout

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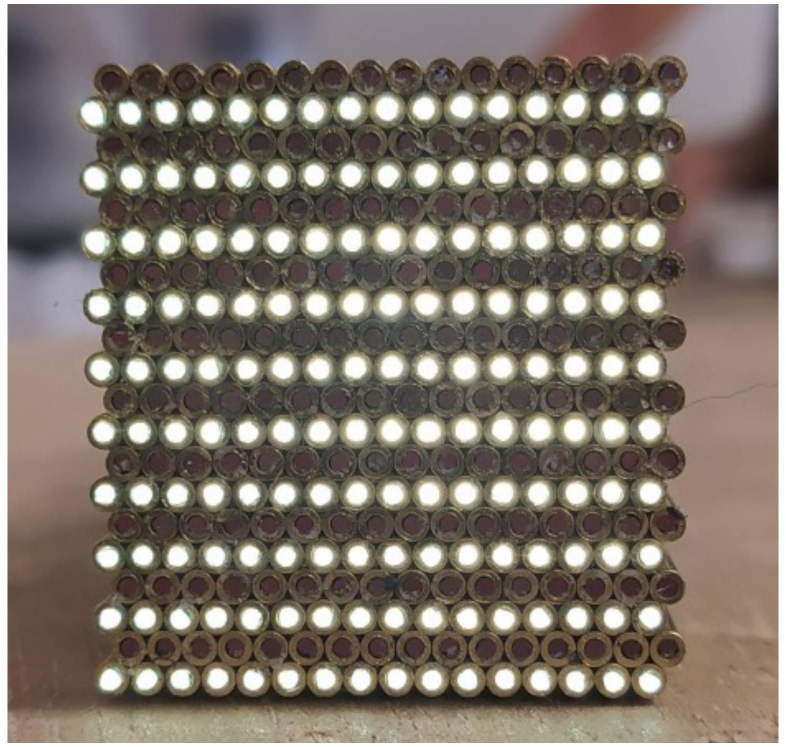
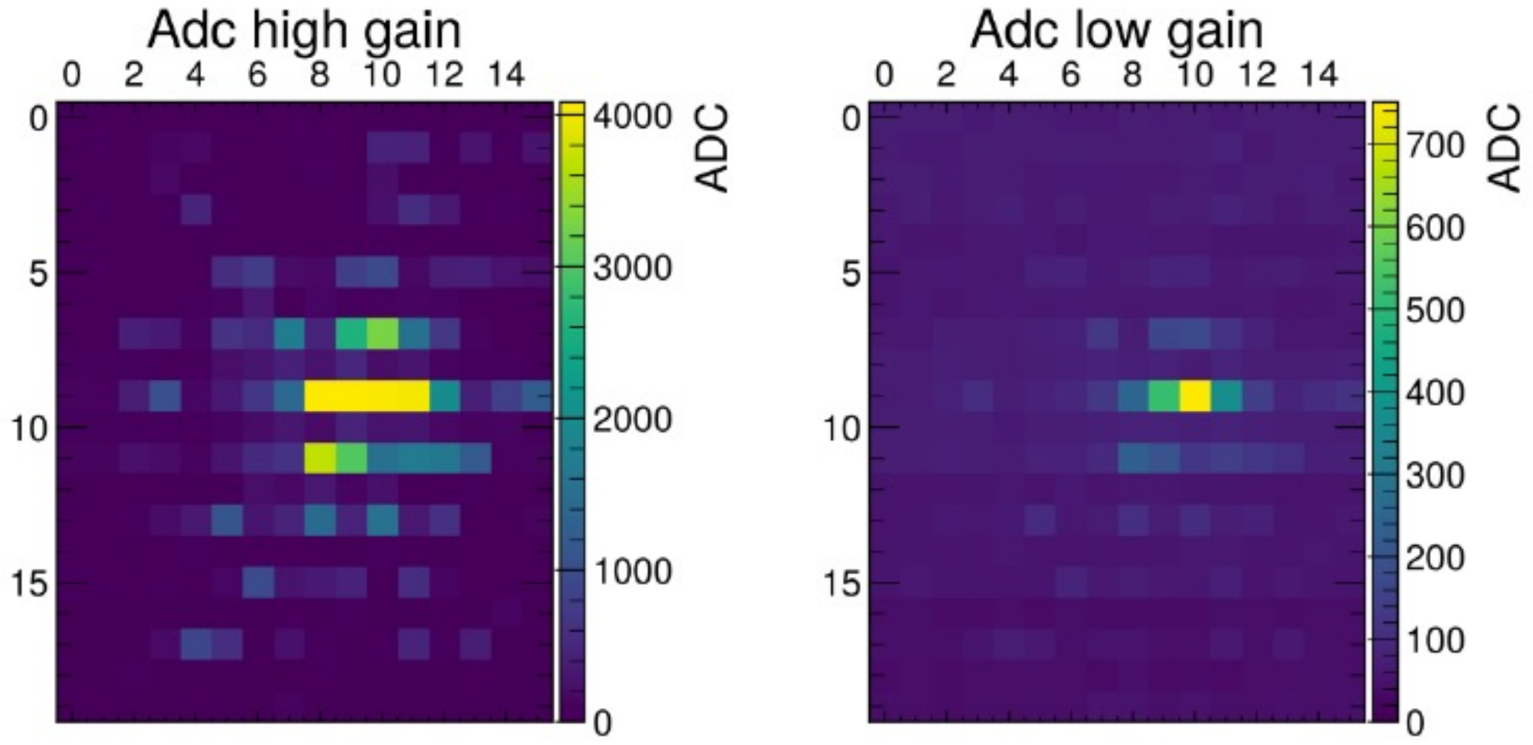
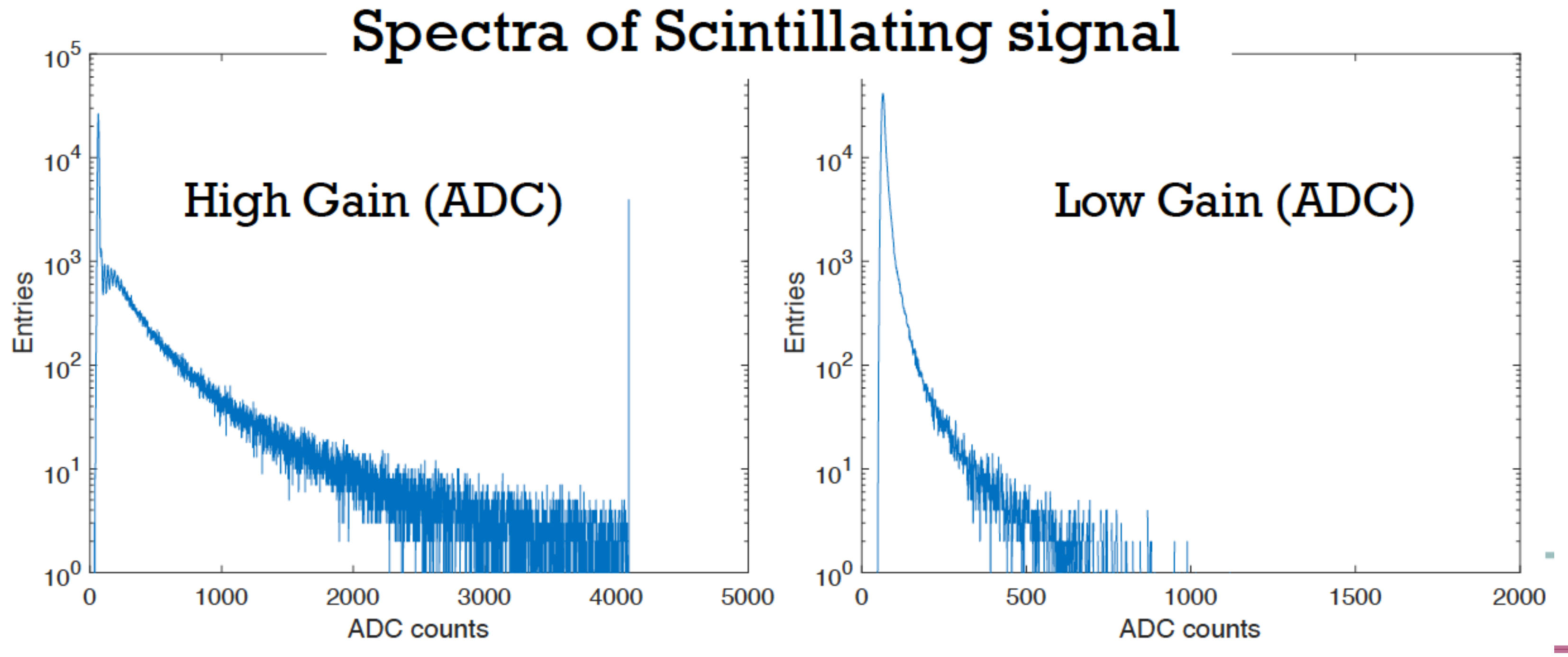
SiPM linearity

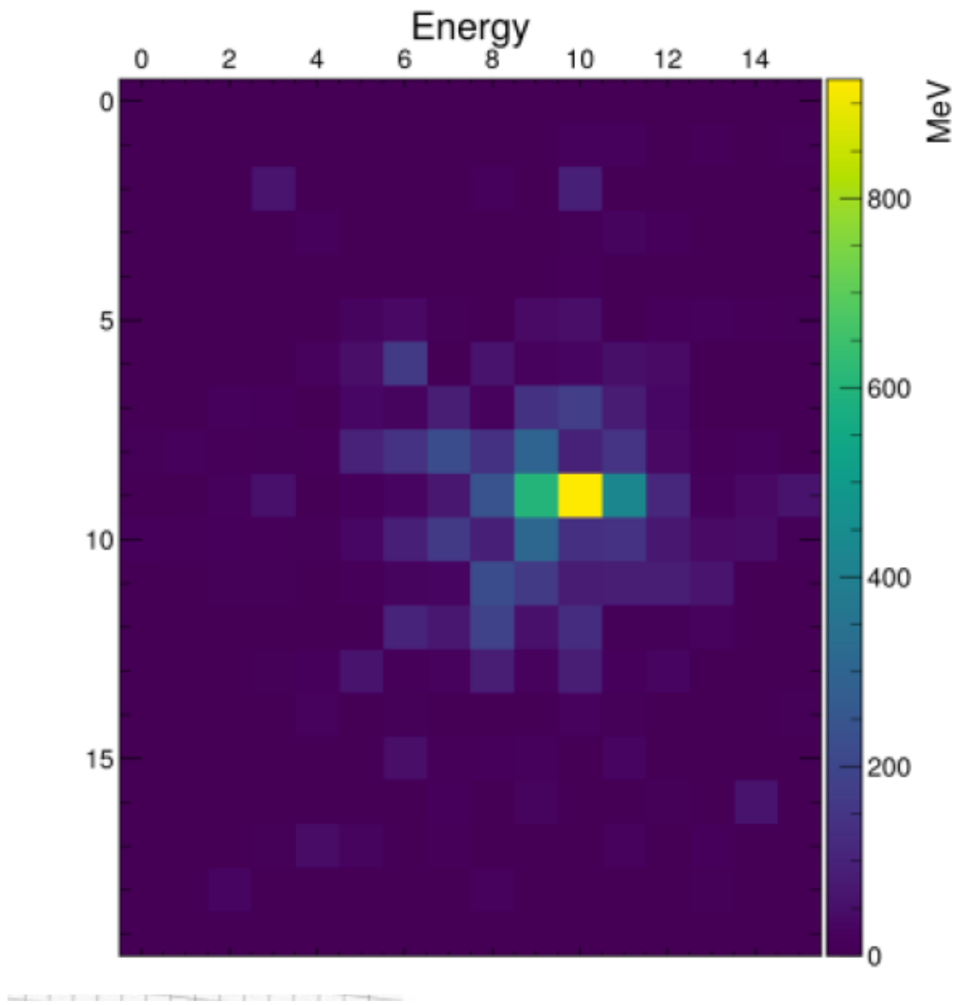


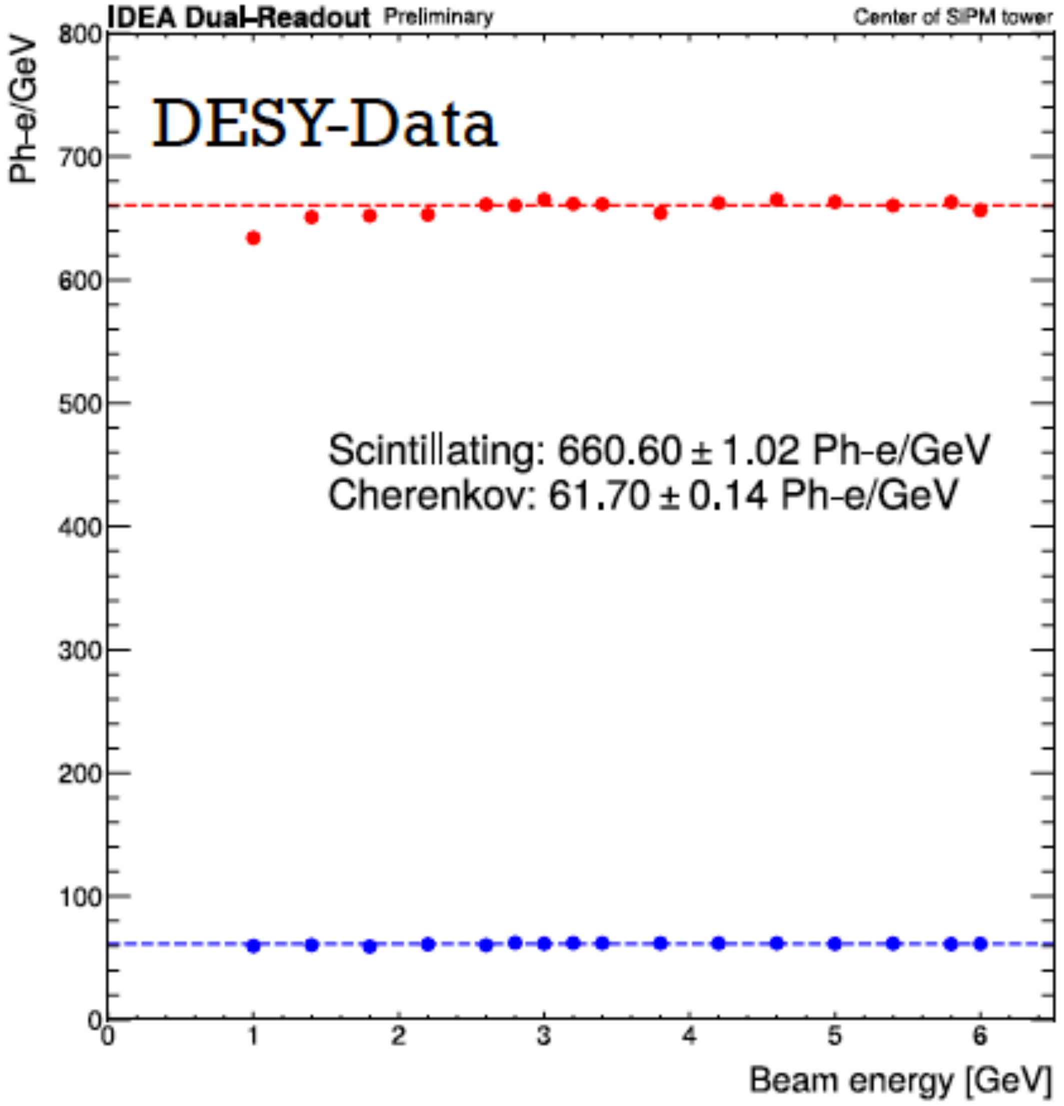


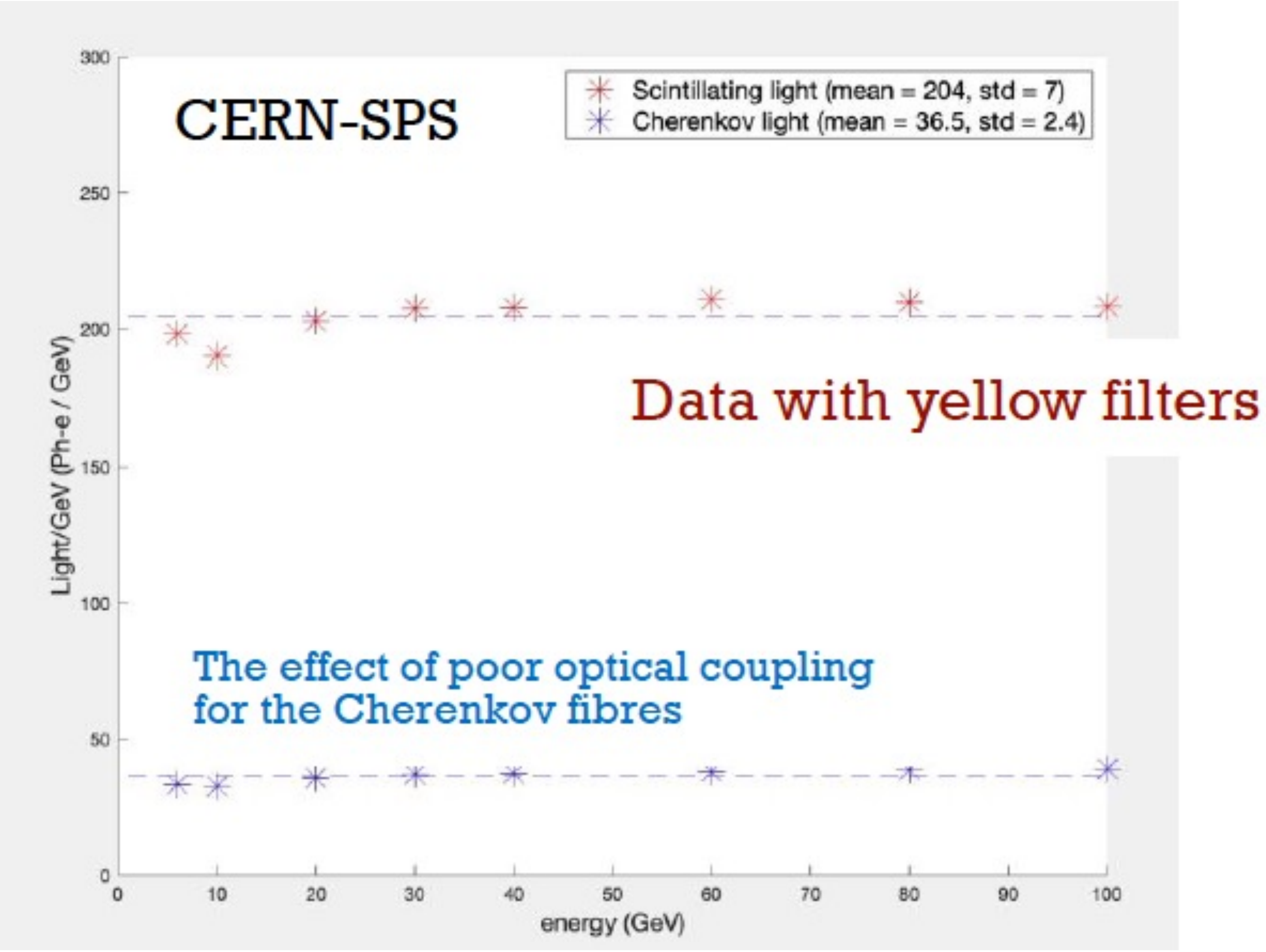
- One SiPM per fiber
- Using multiphoton spectrum for the calibration
- Cross-calibrate high and low gain



SiPM linearity



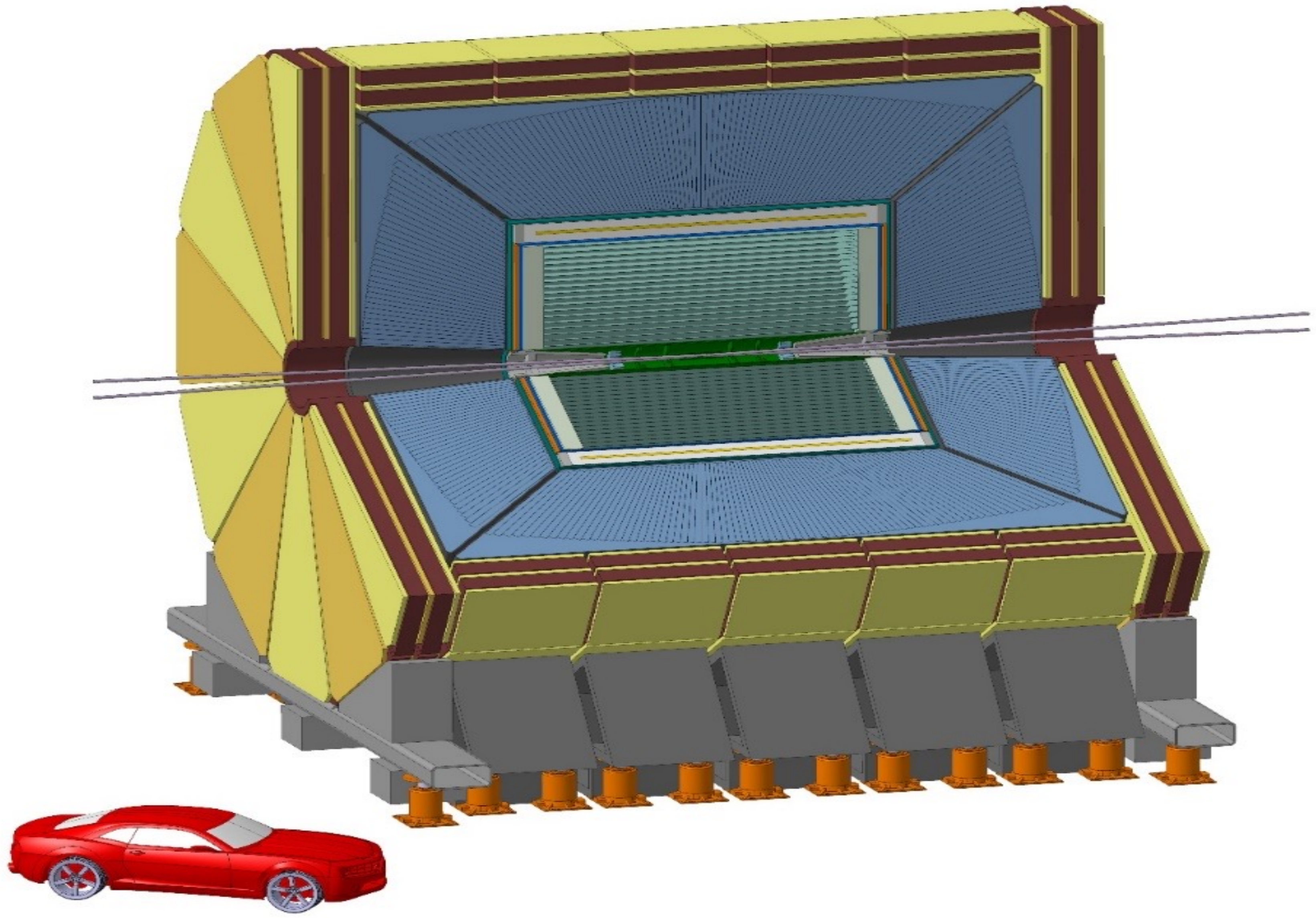




Data with yellow filters

The effect of poor optical coupling for the Cherenkov fibres

Moving towards experiments



IDEA
Innovative Detector for E+e- Accelerator

Successfully pioneered SiPM readout to replace PMT
→ High granularity

- Studying scalable solution for
  - Mechanical construction
  - Sensors and RO system
- Full scale prototypes
  → Assess performance

Dual Readout method in homogeneous calorimeter

Motivations:

- High density scintillating crystal widely used in particle physics experiment: ensure excellent energy resolution for electromagnetic showers

- Calorimeters with a crystal EM compartment usually have a poor had. resolution due to
  - fluctuation of the starting point of the hadronic shower in the EM section
  - different response to the em and non-em component of the shower in the two calorimeters

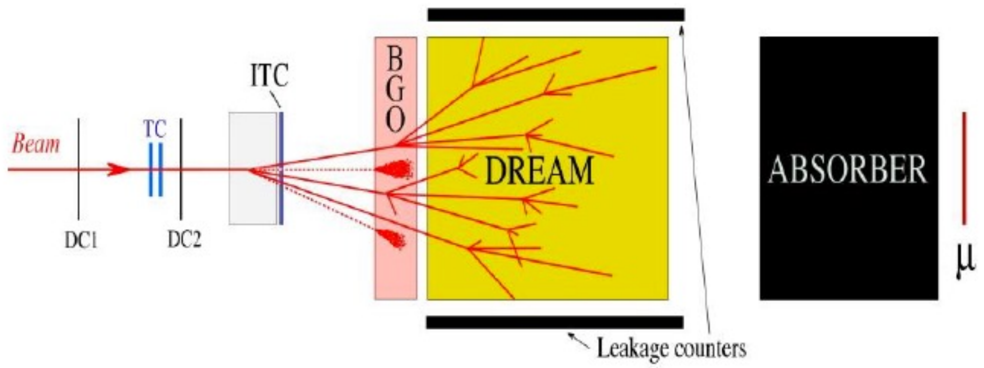
Dual readout applied to an hybrid system:

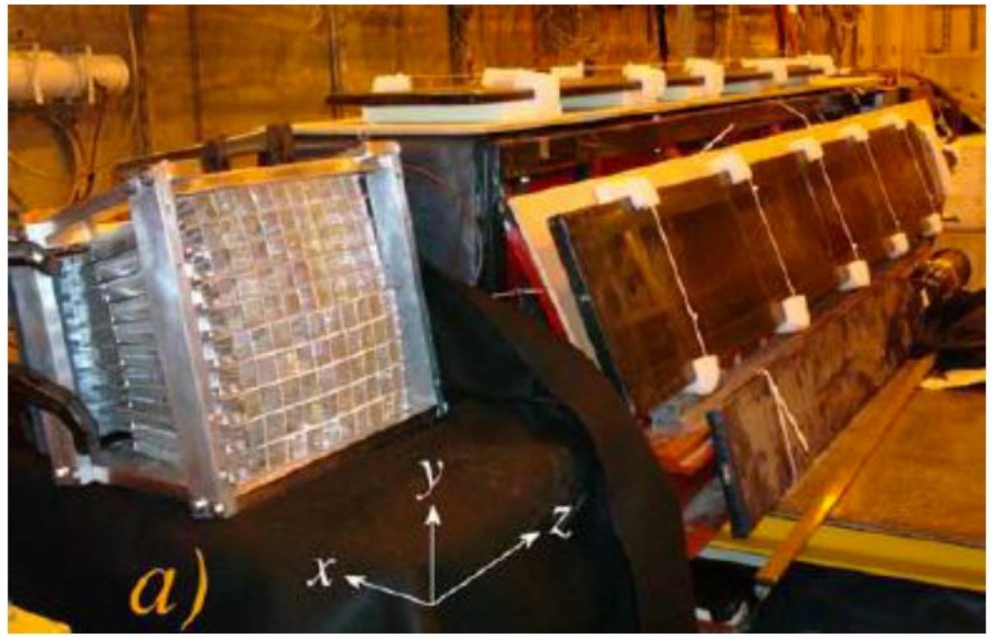
Measuring fem on an event-by-event basis allows to correct for such fluctuations and allows to eliminate the main reasons for poor hadronic resolution

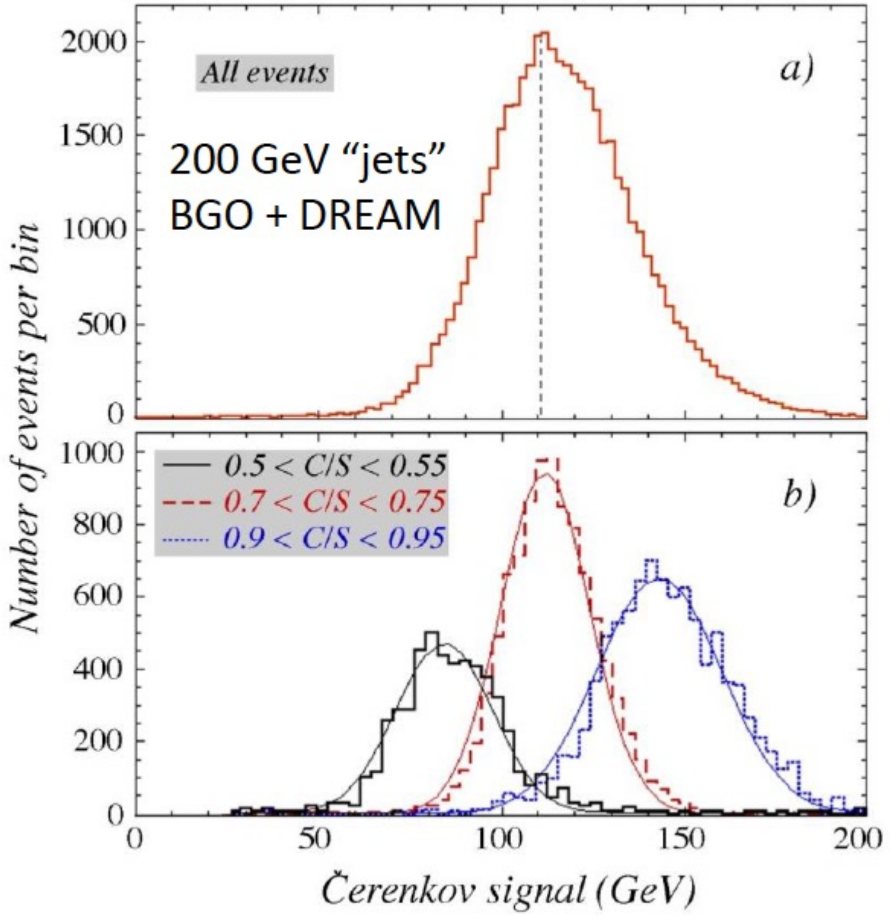
Crystal matrix + fiber sampling calo

Purpose of these tests: to see to what extent the dual readout principle (that worked so well to improve the hadronic performance of the DREAM in stand alone) are applicable when most of the shower is deposited in a crystal calorimeter section

Performed tests: PbWO4 matrix, BGO single Xtal, BGO matrix from L3 experiment (100 crystals) read first with 4 and then with 16 PMT







The dual-readout principle also worked well for this hybrid calorimeter system.

$$E_{HCAL} = \frac{S_{HCAL} - \chi_{HCAL} C_{HCAL}}{1 - \chi_{HCAL}}$$

$$E_{ECAL} = \frac{S_{ECAL} - \chi_{ECAL} C_{ECAL}}{1 - \chi_{ECAL}}$$

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

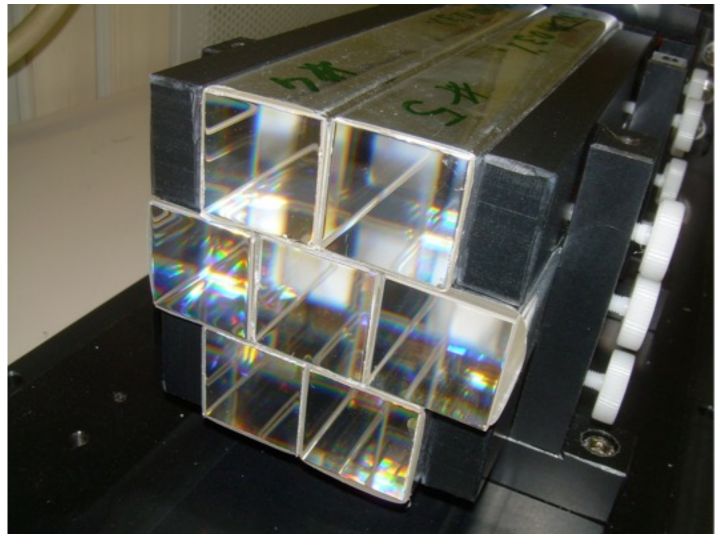
$$\chi_{HCAL} = \frac{1 - (h/e)_s^{HCAL}}{1 - (h/e)_c^{HCAL}}$$

$$\chi_{ECAL} = \frac{1 - (h/e)_s^{ECAL}}{1 - (h/e)_c^{ECAL}}$$

Dual Readout method in homogeneous calorimeter

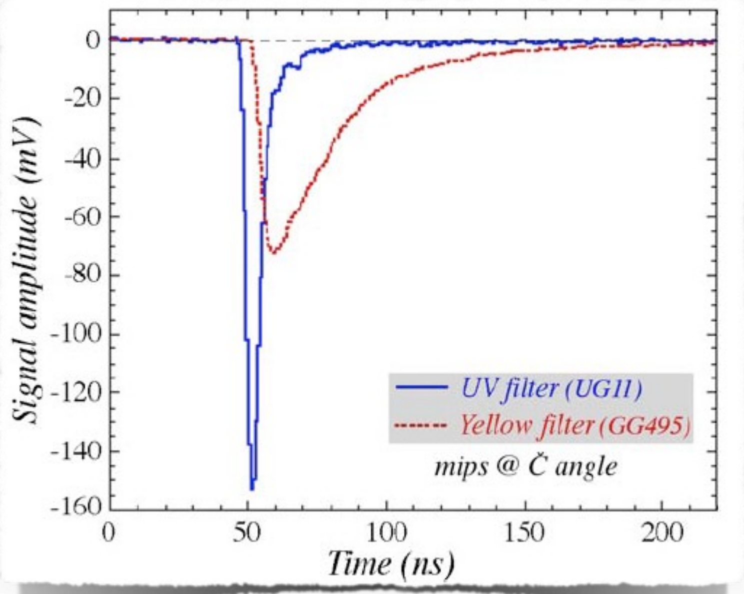
Requirements for using crystals in dual readout based calorimeter:

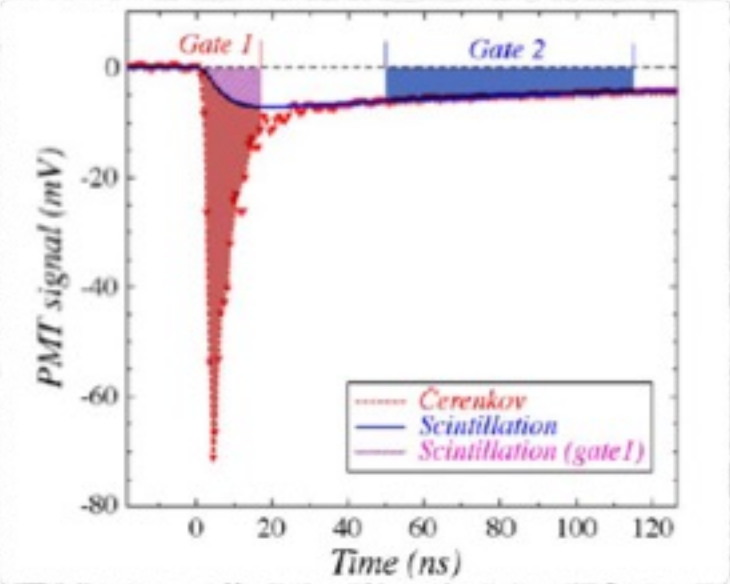
- Good Čerenkov vs Scintillation separation
- Response uniformity
- High light yield (to reduce contribution of p.e. fluctuation to the resolution)



Separation can be achieved by:

- optical filters: exploit different spectral region of Č and S
- time integration: exploit different time structure of Č and S





In order to have the best possible separation a crystal must have a scintillation emission:

- ✳ in a wavelength region far from the Cherenkov one
- ✳ with a decay time of order of hundreds of nanoseconds
- ✳ not too bright to get a good C/S ratio (<50% BGO emission)

2011 Conclusion from testing homogeneous DRC

2011: Outcomes from performed tests :

To separate the C and S component, crystals have to be *readout in non conventional way*
→ results not good as the ones obtained by standard EM calorimetry

Extraction of pure C and S signals implies
- *To sacrifice a large fraction of available C photons* (optical filters)
- *C photons are attenuated by crystal UV self absorption*

Crystal + optical filters don't offer a benefit in term of C light yield in dual readout calorimetry
(comparable with the one measured with the RD52 fiber calorimeter)

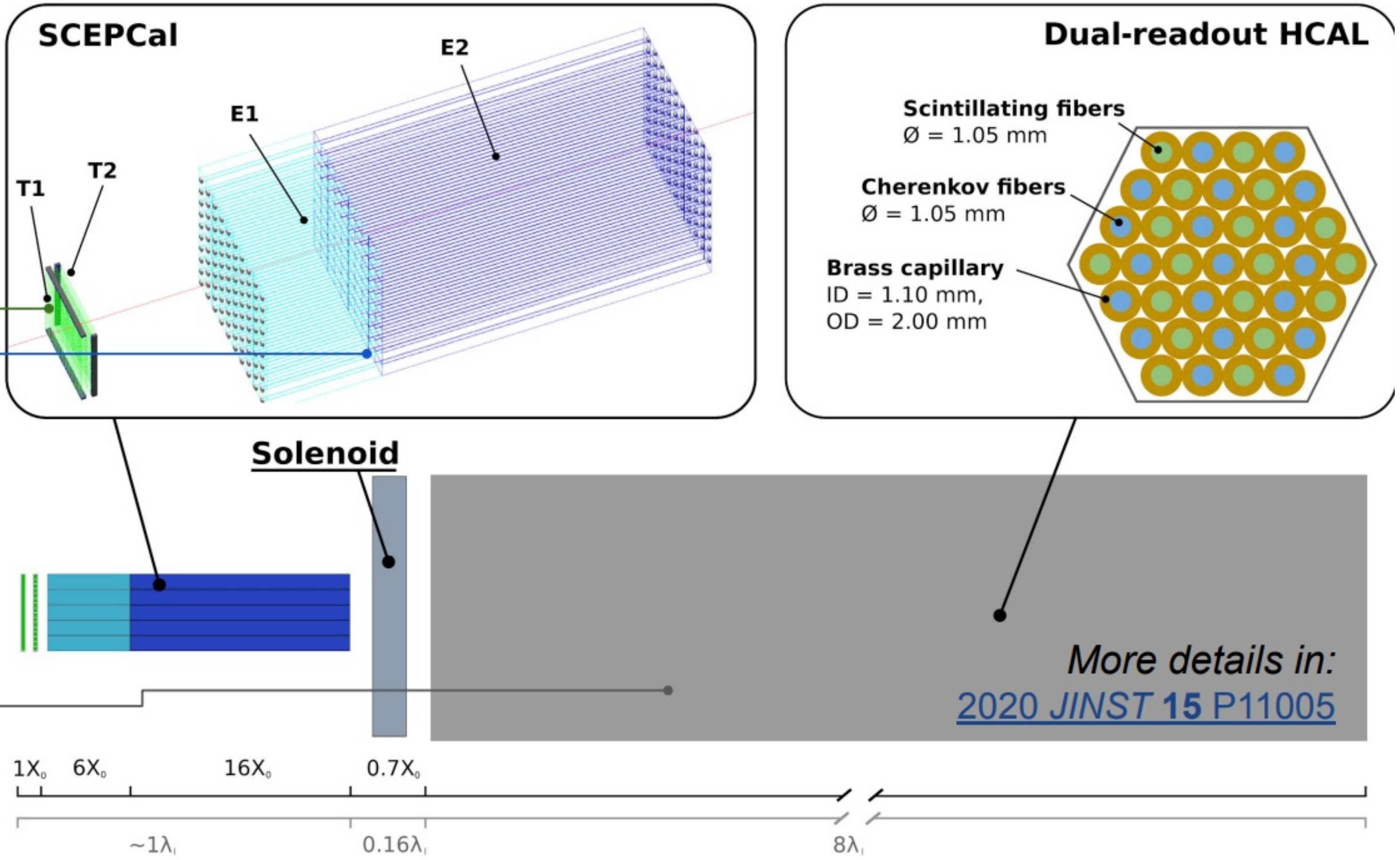
but this is not the end of the story …

DR crystals: “A new hope”

Conceptual layout

- **Transverse and longitudinal segmentations** optimized for particle identification and particle flow algorithms
- Exploiting **SiPM readout** for contained cost and power budget

- **Timing layers** — $\sigma_t \sim 20$ ps
    - LYSO:Ce crystals (~1X_0)
    - 3x3x60 mm³ active cell
    - 3x3 mm² SiPMs (15-20 um)
- **ECAL layers** — $\sigma^{EM}_E/E \sim 3\%/\sqrt{E}$
    - PWO crystals
    - Front segment (~6X_0)
    - Rear segment (~16X_0)
    - 10x10x200 mm³ crystal
    - 5x5 mm² SiPMs (10-15 um)
- **Ultra-thin IDEA solenoid**
    - ~0.7X_0
- **HCAL layer** — $\sigma^{HAD}_E/E \sim 26\%/\sqrt{E}$
    - Scintillating and “clear” PMMA fibers (for Cherenkov signal) inserted inside brass capillaries



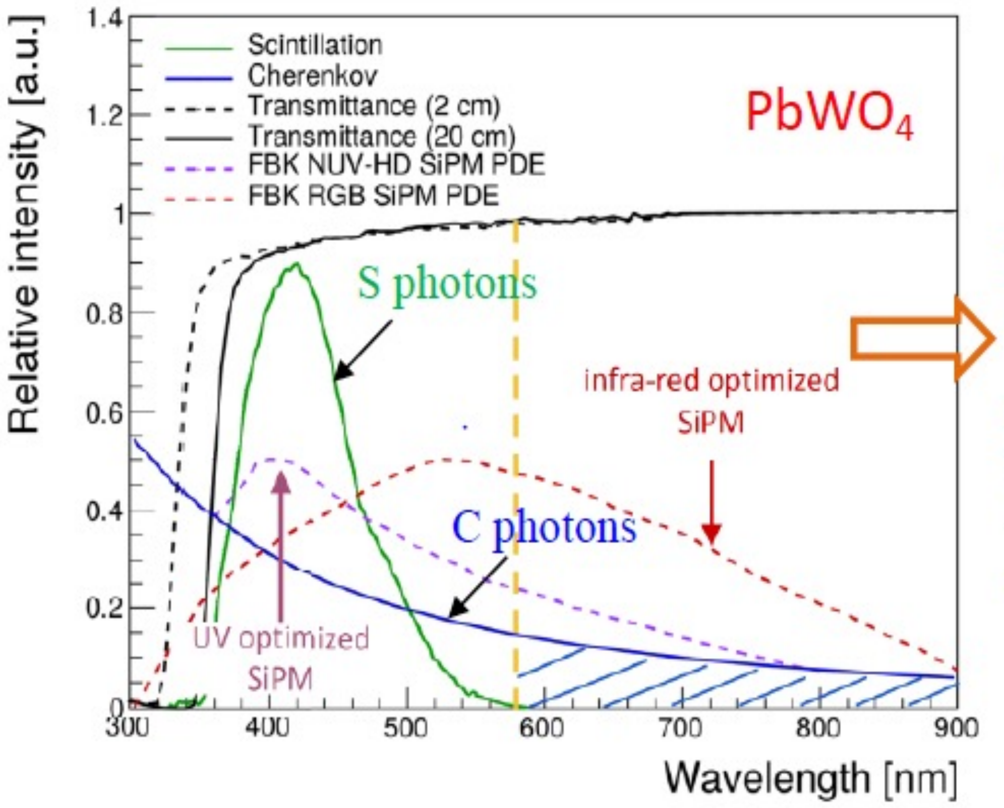
More details in:
2020 *JINST* **15** P11005

DR crystals: "A new hope"

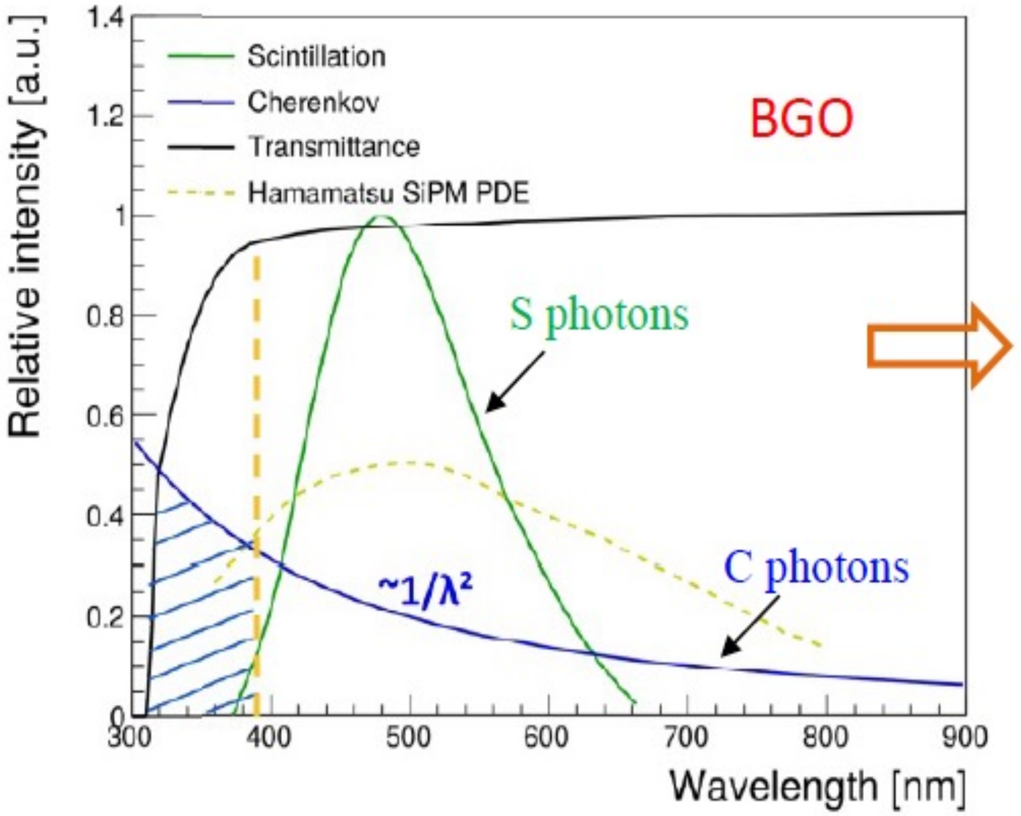
- 5×5 mm^2 SiPM (10-15 μm cell size)
  - ○ Rely on optical filters to separate S and C
- 3 SiPMs (one on entrance, two on exit)
  - ○ Front: optimized for scintillation light
  - ○ Rear: two SiPMs optimized for scintillation and Cherenkov light
- Different crystals require different optimization strategy for S and C detection

$PbWO_4$	Scintillation [photons/GeV]	f_S [%]	Cherenkov [photons/GeV]	f_C [%]
Generated	200000	100	56000	100
Collected	10000	5.0	2130	3.8
Detected by NUV SiPM #1 ($\lambda < 550$ nm)	2000	1.0	140	0.25
Detected by RGB SiPM #2 ($\lambda > 550$ nm)	< 20	< 0.01	160	0.3

~50 C photons/GeV is enough to achieve 3% energy resolution

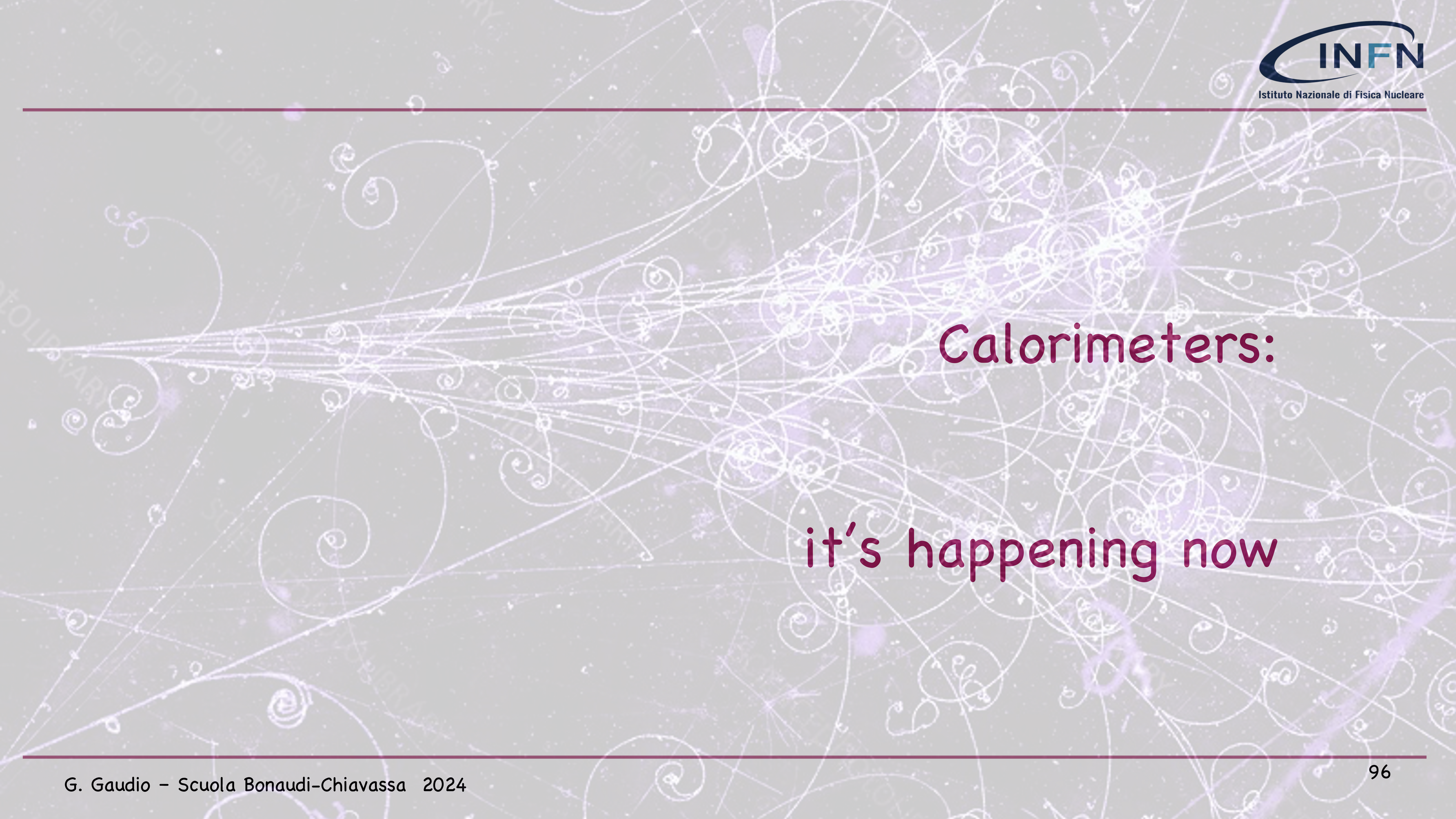


Cherenkov photons above the scintillation peak are much less affected by self-absorption



Larger detection window for Cherenkov photons below the scintillation peak

11



Calorimeters:

it's happening now

The Roadmap document and process

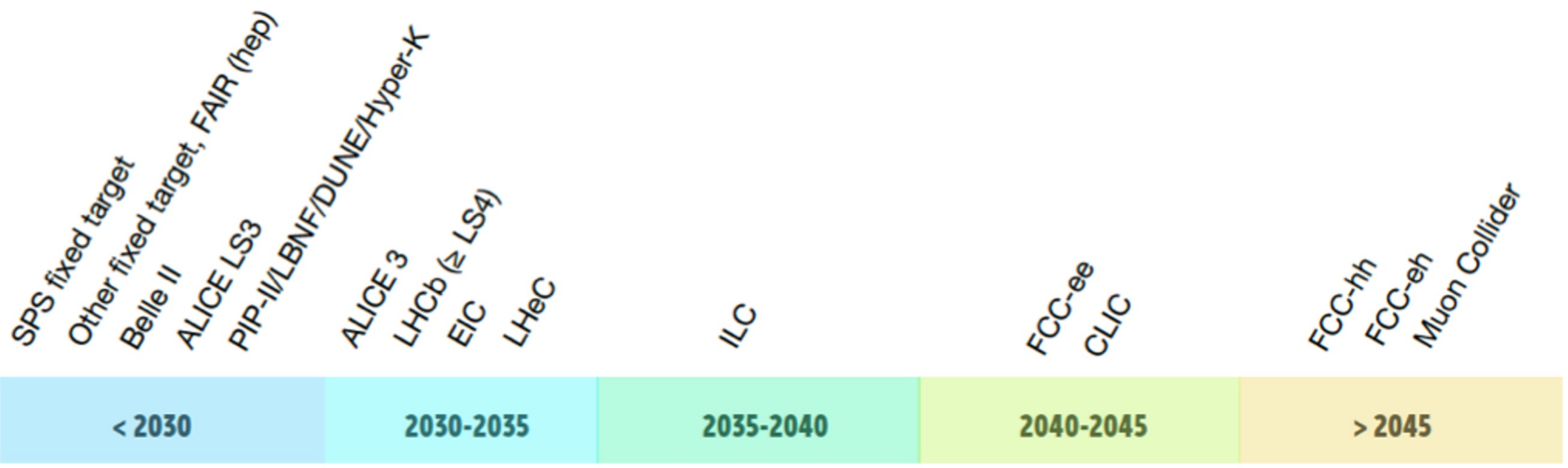
ECFA R&D Roadmap

- CERN-ESU-017 https://cds.cern.ch/record/2784893
- 248 pages full text and 8 page synopsis

Endorsed by ECFA and presented to CERN Council in December 2021

- The Roadmap has identified
- General Strategic Recommendations (GSR)
- Detector R&D Themes (DRDT) for each of the taskforce topics
- Concrete R&D Tasks

Timescale of projects as approved by European Lab Director Group (LDG)

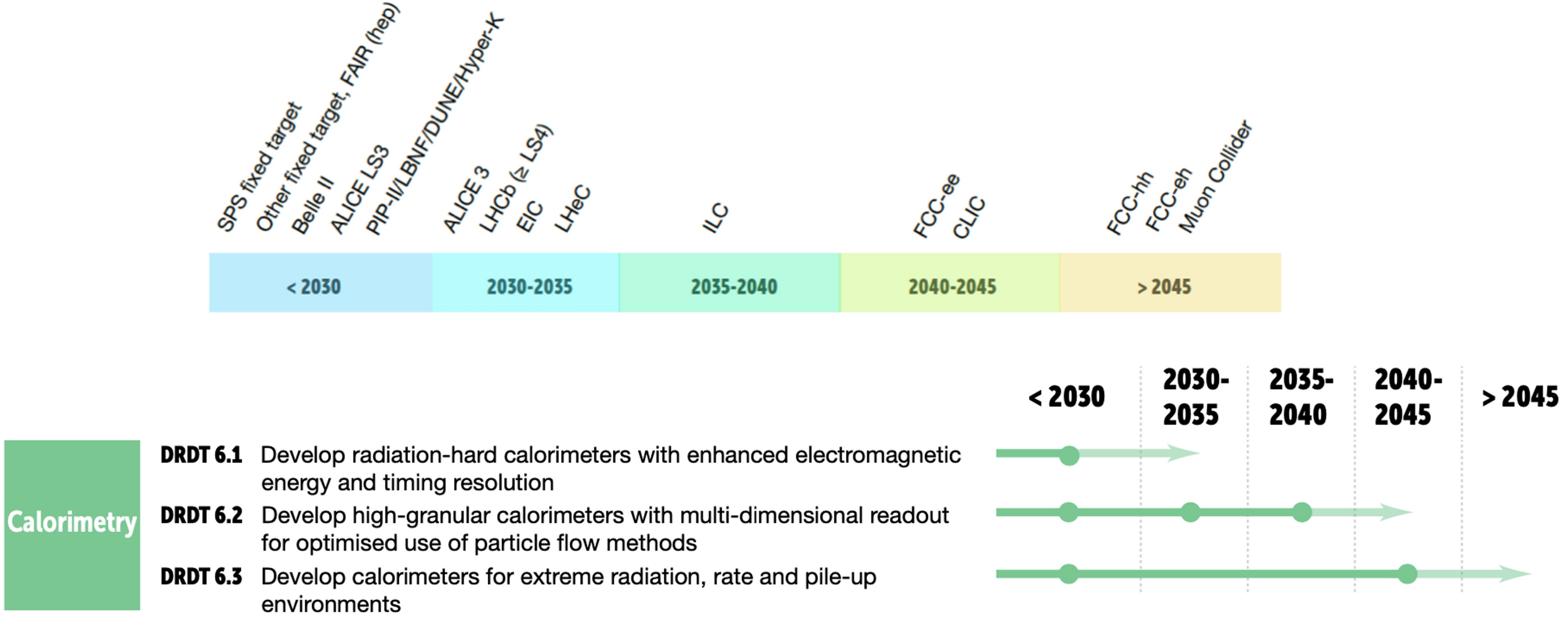


Guiding principle: Project realisation must not be delayed by detectors


THE 2021 ECFA DETECTOR
RESEARCH AND DEVELOPMENT ROADMAP

The European Committee for Future Accelerators
Detector R&D Roadmap Process Group

Future Facilities and DRDT for Calorimetry



< 2030	2030-2035	2035-2040	2040-2045	> 2045
SPS fixed target Other fixed target, FAIR (hep) Belle II ALICE LS3 PIP-II/LBNF/DUNE/Hyper-K	ALICE 3 LHCb (≥ LS4) EIC LHeC	ILC	FCC-ee CLIC	FCC-hh FCC-eh Muon Collider

Calorimetry

DRDT 6.1 Develop radiation-hard calorimeters with enhanced electromagnetic energy and timing resolution

DRDT 6.2 Develop high-granular calorimeters with multi-dimensional readout for optimised use of particle flow methods

DRDT 6.3 Develop calorimeters for extreme radiation, rate and pile-up environments

- The DRDT and the provisional time scale of facilities set high-level boundary conditions
- Both as well as the GSR should be taken into account when formulating the R&D proposal(s)

Calorimetry Identified Key Technologies and R&D Tasks

Key technologies and requirements are identified in Roadmap

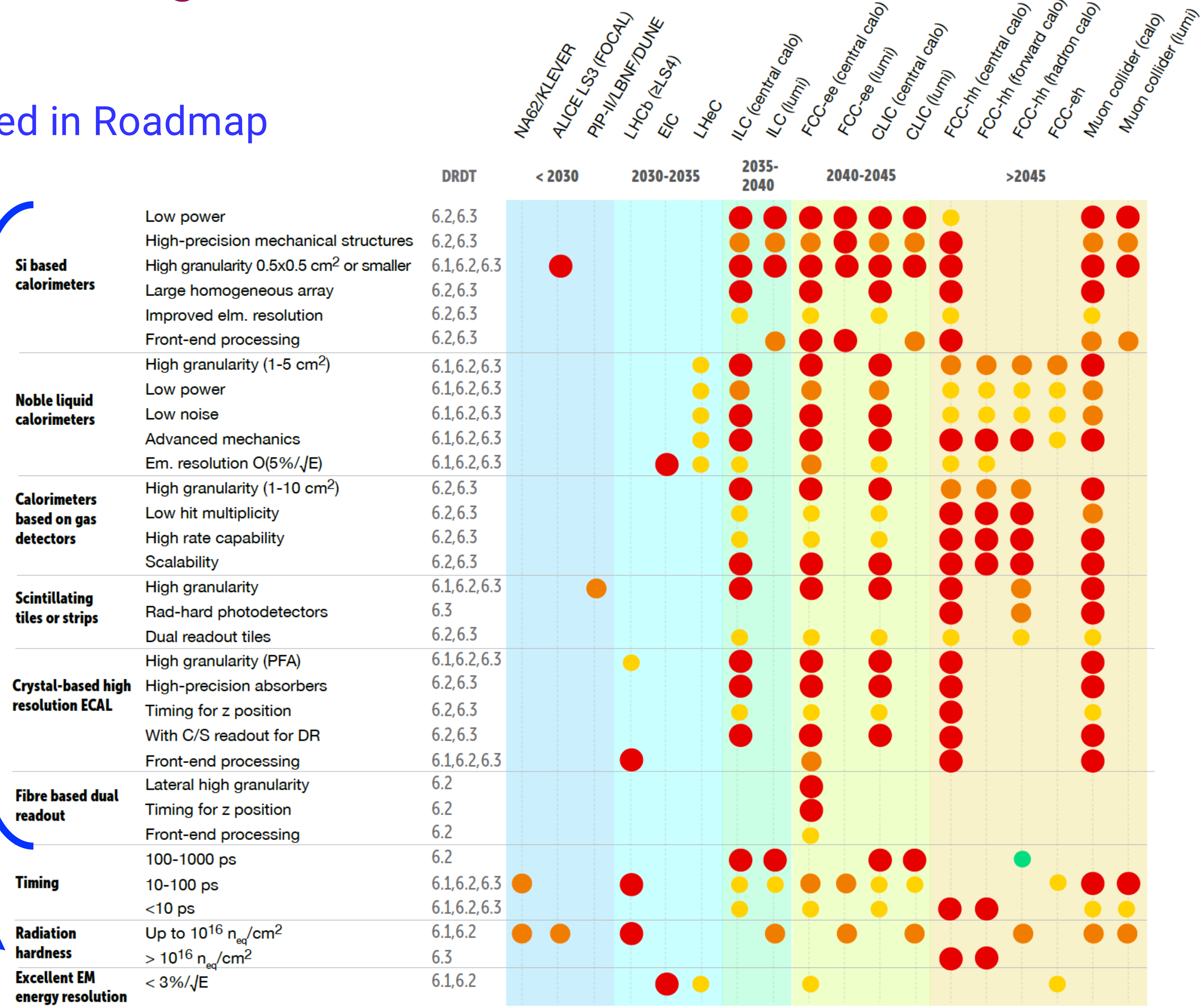
- Si based Calorimeters
- Noble Liquid Calorimeters
- Calorimeters based on gas detectors
- Scintillating tiles and strips
- Crystal based high-resolution ECALs
- Fibre based dual readout

R&D should in particular enable

- Precision timing
- Radiation hardness

R&D Tasks are grouped into

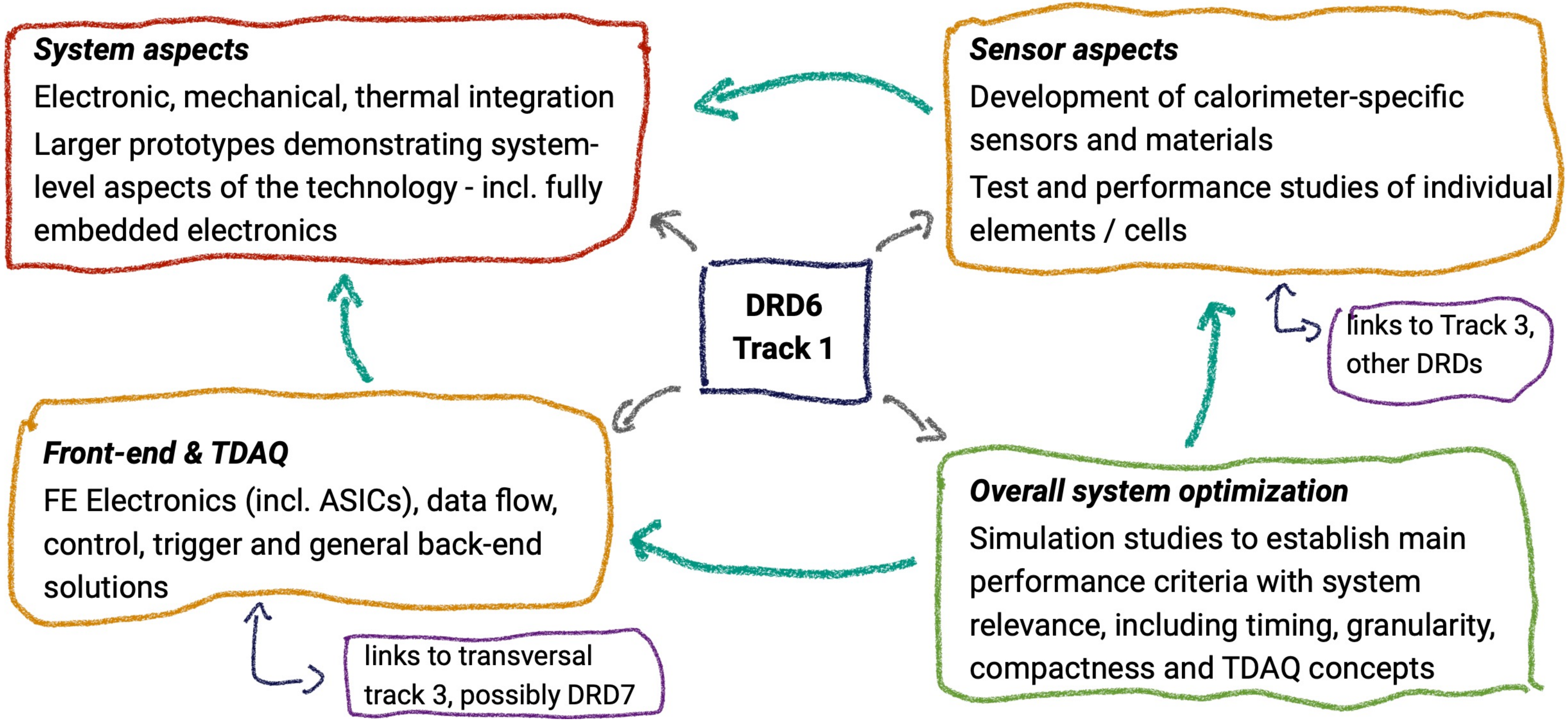
- Must happen
- Important
- Desirable
- Already met



		DRDT	NA62/KLEVER	ALICE LS3 (FOCAL)	PIP-II/LBNF/DUNE	LHCb (≥LS4)	EIC	LHeC	ILC (central calo)	ILC (lumi)	FCC-ee (central calo)	FCC-ee (lumi)	CLIC (central calo)	CLIC (lumi)	FCC-hh (central calo)	FCC-hh (forward calo)	FCC-hh (hadron calo)	FCC-eh	Muon collider (calo)	Muon collider (lumi)
			< 2030			2030-2035			2035-2040		2040-2045				>2045					
Si based calorimeters	Low power	6.2,6.3							🔴	🔴	🔴	🔴	🔴	🔴	🟡				🔴	🔴
	High-precision mechanical structures	6.2,6.3							🟠	🟠	🟠	🔴	🟠	🟠	🔴				🟠	🟠
	High granularity 0.5x0.5 cm^2 or smaller	6.1,6.2,6.3		🔴					🔴	🔴	🔴	🔴	🔴	🔴	🔴				🔴	🔴
	Large homogeneous array	6.2,6.3							🔴		🔴		🔴		🔴				🔴	
	Improved elm. resolution	6.2,6.3							🟡		🟡		🟡		🟡				🟡	
	Front-end processing	6.2,6.3								🟠	🔴	🔴		🟠	🔴				🟠	🟠
Noble liquid calorimeters	High granularity (1-5 cm^2)	6.1,6.2,6.3						🟡	🔴		🔴		🔴		🟠	🟠	🟠	🟠	🔴	
	Low power	6.1,6.2,6.3						🟡	🟠		🟠		🟠		🟡	🟡	🟡	🟡	🟠	
	Low noise	6.1,6.2,6.3						🟡	🔴		🔴		🔴		🟡	🟡	🟡	🟡	🟠	
	Advanced mechanics	6.1,6.2,6.3						🟡	🔴		🔴		🔴		🔴	🔴	🔴	🟡	🔴	
	Em. resolution O(5%/√E)	6.1,6.2,6.3					🔴	🟡	🟡		🟠		🟡		🟡	🟡				
Calorimeters based on gas detectors	High granularity (1-10 cm^2)	6.2,6.3							🔴		🔴		🔴		🟠	🟠	🟠		🔴	
	Low hit multiplicity	6.2,6.3							🟡		🟡		🟡		🔴	🔴	🔴		🟠	
	High rate capability	6.2,6.3							🟡		🟡		🟡		🔴	🔴	🔴		🔴	
	Scalability	6.2,6.3							🔴		🔴		🔴		🔴	🔴	🔴		🔴	
Scintillating tiles or strips	High granularity	6.1,6.2,6.3			🟠				🔴		🔴		🔴		🔴		🟠		🔴	
	Rad-hard photodetectors	6.3													🔴		🟠		🔴	
	Dual readout tiles	6.2,6.3							🟡		🟡		🟡		🟡		🟡		🟡	
Crystal-based high resolution ECAL	High granularity (PFA)	6.1,6.2,6.3				🟡			🔴		🔴		🔴		🔴				🔴	
	High-precision absorbers	6.2,6.3							🔴		🔴		🔴		🔴				🔴	
	Timing for z position	6.2,6.3							🟡		🟡		🟡		🔴				🟡	
	With C/S readout for DR	6.2,6.3							🔴		🔴		🔴		🔴				🔴	
	Front-end processing	6.1,6.2,6.3				🔴					🟠				🔴				🔴	
Fibre based dual readout	Lateral high granularity	6.2									🔴									
	Timing for z position	6.2									🔴									
	Front-end processing	6.2									🟡									
Timing	100-1000 ps	6.2							🔴	🔴			🔴	🔴			🟢			
	10-100 ps	6.1,6.2,6.3	🟠			🔴			🟡	🟡	🟠	🟠	🟡	🟡				🟡	🔴	🔴
	<10 ps	6.1,6.2,6.3							🟡		🟡		🟡		🔴	🔴			🟡	🟡
Radiation hardness	Up to 10^{16} n_{eq}/cm^2	6.1,6.2	🟠	🟠		🔴				🟠		🟠		🟠			🟠		🟠	🟠
	> 10^{16} n_{eq}/cm^2	6.3													🔴	🔴				
Excellent EM energy resolution	< 3%/√E	6.1,6.2					🔴	🟡			🟡							🟡		

🔴 Must happen or main physics goals cannot be met 🟠 Important to meet several physics goals 🟡 Desirable to enhance physics reach 🟢 R&D needs being met

Sandwich calorimeters with fully embedded elx



DRD6 Track 1

System aspects

Electronic, mechanical, thermal integration

Larger prototypes demonstrating system-level aspects of the technology - incl. fully embedded electronics

Sensor aspects

Development of calorimeter-specific sensors and materials

Test and performance studies of individual elements / cells

links to Track 3, other DRDs

Front-end & TDAQ

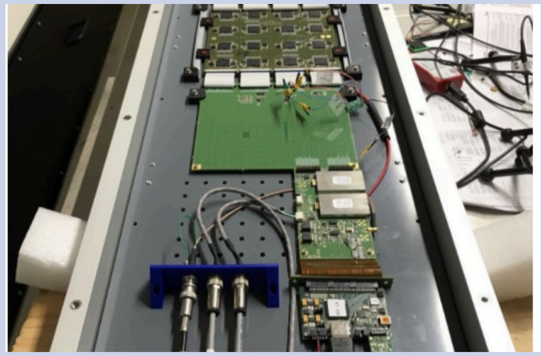
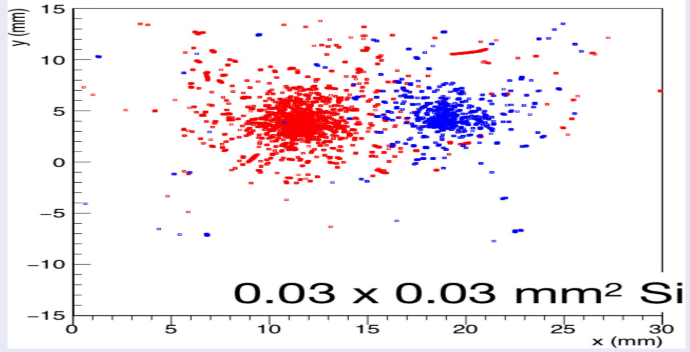
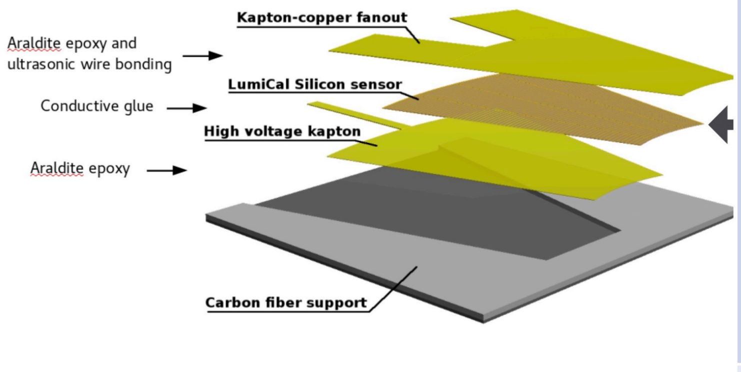
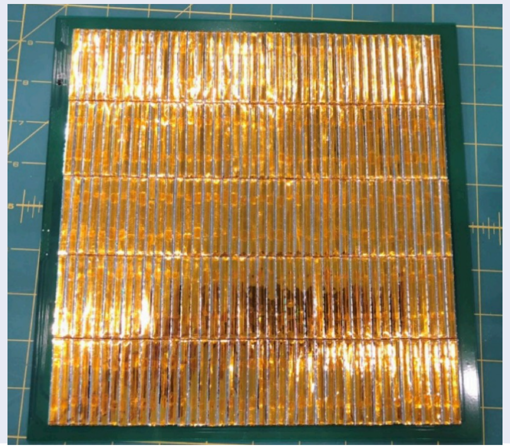
FE Electronics (incl. ASICs), data flow, control, trigger and general back-end solutions

links to transversal track 3, possibly DRD7

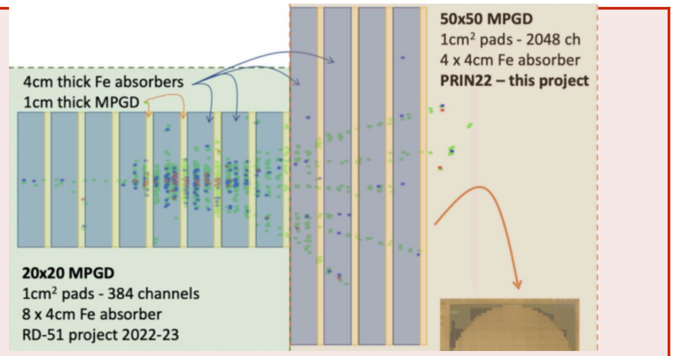
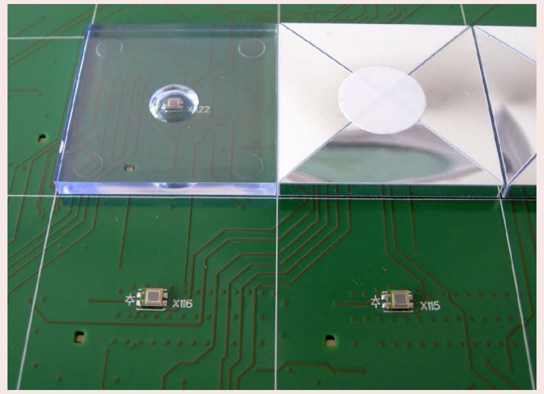
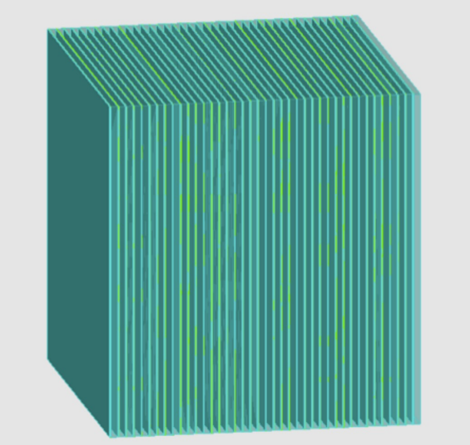
Overall system optimization

Simulation studies to establish main performance criteria with system relevance, including timing, granularity, compactness and TDAQ concepts

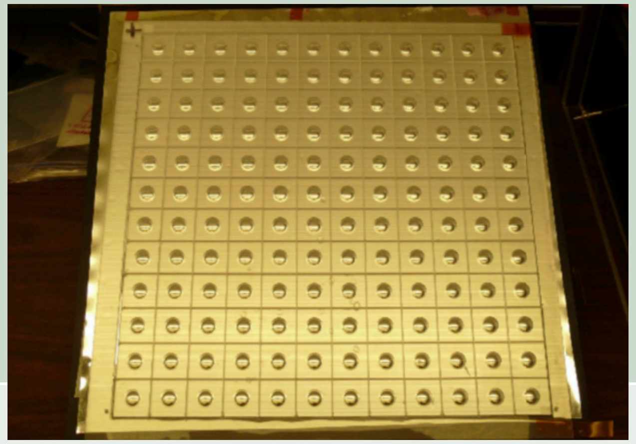
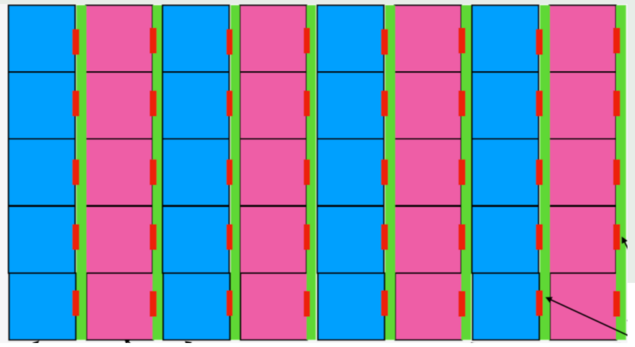
Sandwich calo with fully embedded elx – ECAL

SiW ECAL	A SiW-ECAL using silicon pad sensors with analog readout Builds on CALICE SiW ECAL technological prototype Extension of current prototype for continuous readout, reduction of power consumption and cooling, • Study of the addition of timing,	
DECAL Digital ECAL based on MAPS	A MAPS-based digital Silicon-Tungsten ECAL, Building on current DECAL and EPICAL projects. Establish requirements of a sensor dedicated for digital calorimetry and design of next-generation sensor with calorimeter-specific optimisation	
Highly Compact ECAL	Highly compact electromagnetic calorimeter with semiconductor sensors, R&D on Si and GaAs sensors, including optimisation of readout integration • Development of thin conductive gluing. Development of readout electronics. Mechanics with minimal tolerances	
Highly Granular Scintillator-strip Calorimeter	A tungsten-scintillator-strip (with SiPM readout) calorimeter . Engineering study for large-scale production • Timing performance Scintillator material • Scintillator strip design • Active cooling system • Mechanical structure and services	

Sandwich calo with fully embedded elx – HCAL

MPGD-based Hadronic Calorimeter	Inspired by CALICE DHCAL & SDHCAL • Using MPGDs (examples uRWELL, resistive Micromegas) for higher-rate environments	
T-SDHCAL	A RPC-based semi-digital HCAL with timing capability Builds on CALICE SDHCAL technological prototype. Simulation studies extending to time information • Study and development of cooling and cassette concepts • Fast timing electronics	
SiPM-on-Tile AHCAL	SiPM-on-tile / steel HCAL Builds on CALICE AHCAL Technological Prototype. Extension of current detector concept to circular colliders with continuous readout snd higher data rate • re-evaluate need for cooling • re-optimisation of detector to ensure optimal performance while respecting new constraints	
Highly Granular HCAL with Glass Scintillator Tiles	A variation of the CALICE AHCAL concept: Using glass scintillator tiles instead of plastic • Increased sampling fraction - with the potential for improved energy resolution. R&D of scintillator material: high density, high light yield, low cost	

Sandwich calo with fully embedded elx - HCAL

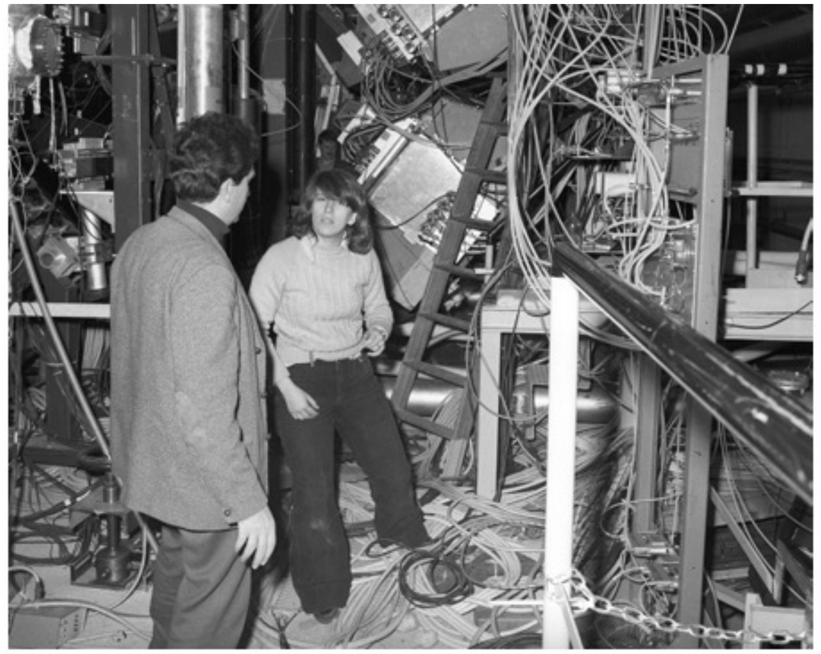
ADRIANO3 Triple Readout Calorimeter	Extension of ADRIANO2 (fully active granular dual readout calorimeter) to three readout modes. High-density glass as Cherenkov Medium (and absorber) • Plastic scintillator tiles • RPCs. optimization of the construction technique in terms of: • light yield, RPC efficiency, timing resolution, and cost	
Double Readout Sandwich Calorimeter	Concept for an (almost) fully active hadron calorimeter • Alternating layers of heavy scintillator (PWO) and Cherenkov medium (lead glass) Each read out by embedded SiPMs	

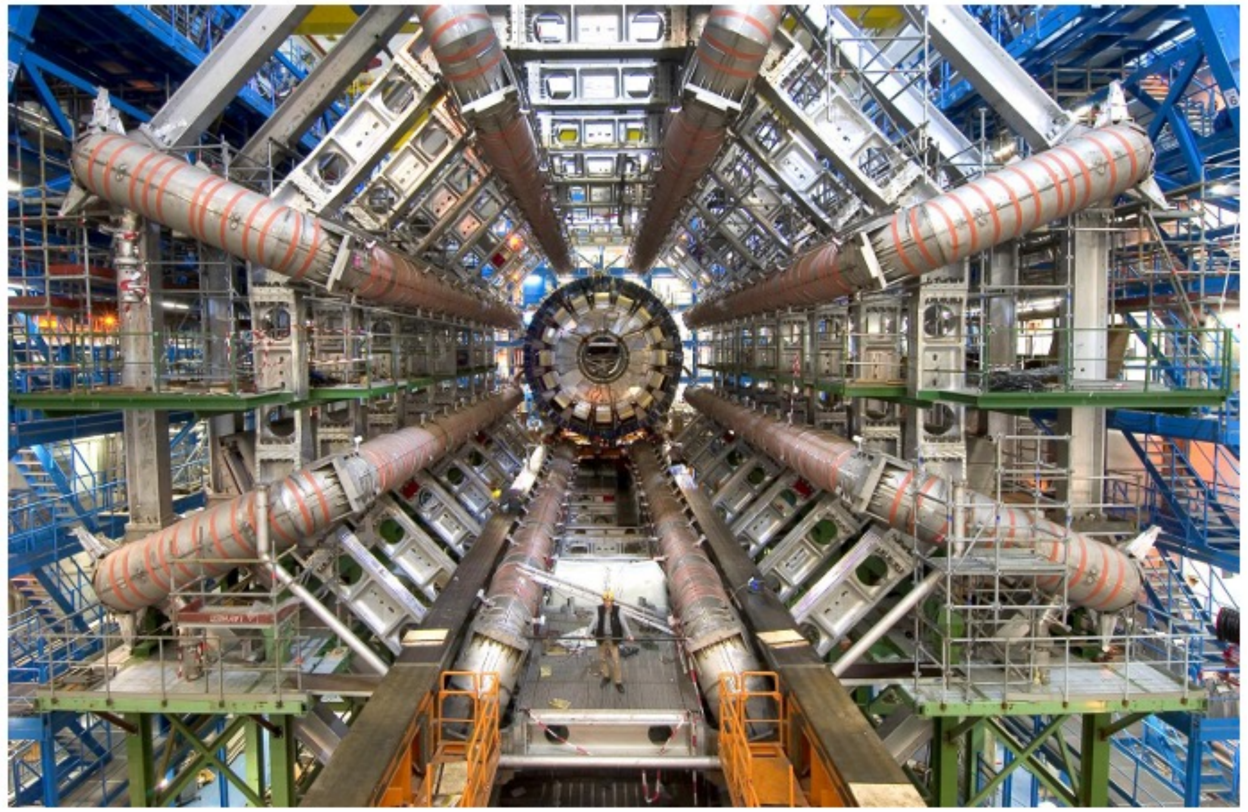
Liquified Noble Gas calorimeters

- Decades of success at particle physics experiments: from R806 to ATLAS
  - Mostly LAr, a bit of LKr
- An appealing option for FCC-ee
  - Good energy resolution
  - High(-ish) granularity achievable
  - Linearity, uniformity, long-term stability
  - Easy to calibrate

Excellent solution for small systematics

- Lots of interesting studies / R&D to do
  - Optimization for PFlow reconstruction
  - Achieving very low noise
  - Lightweight cryostats to minimize X_0
  - Designing for improved energy resolution





Optical Calorimeters

Scintillator based sampling calorimeters

Scintillating Tile HCAL
for FCC-hh, FCC-ee

Dual Readout Fiber Calorimeter
for Higgs Factories

R&D on Spaghetti (EM) Calorimeter technologies for LHCb Upgrade II, Higgs factories, FCC-hh

Fast-timing, ultracompact, radiation hard, EM calorimetry (*RADiCAL*)
for FCC-hh

High sampling fraction EM calorimeter with crystal grains (*GRAiNITA*) for FCC-ee

Homogeneous EM crystal calorimeters

Maximum Information Crystal Calorimeter for Higgs Factories

High Granularity Crystal Calorimeter for Higgs Factories

Fast, segmented Crystal calorimeter
for Muon Collider (*CRILIN*)

Large mass cryogenic calorimeters

Large mass cryogenic calorimeters
for neutrinoless double beta decay

ScintCal: **Scintillator** material for future calorimeters

Commonalities:
- Use of SiPMs
- Particle-Flow Friendly approach
- Targeting 10-100 ps timing precision

Optical Calorimeters

Scintillator based sampling calorimeters

Scintillating Tile HCAL
for FCC-hh, FCC-ee

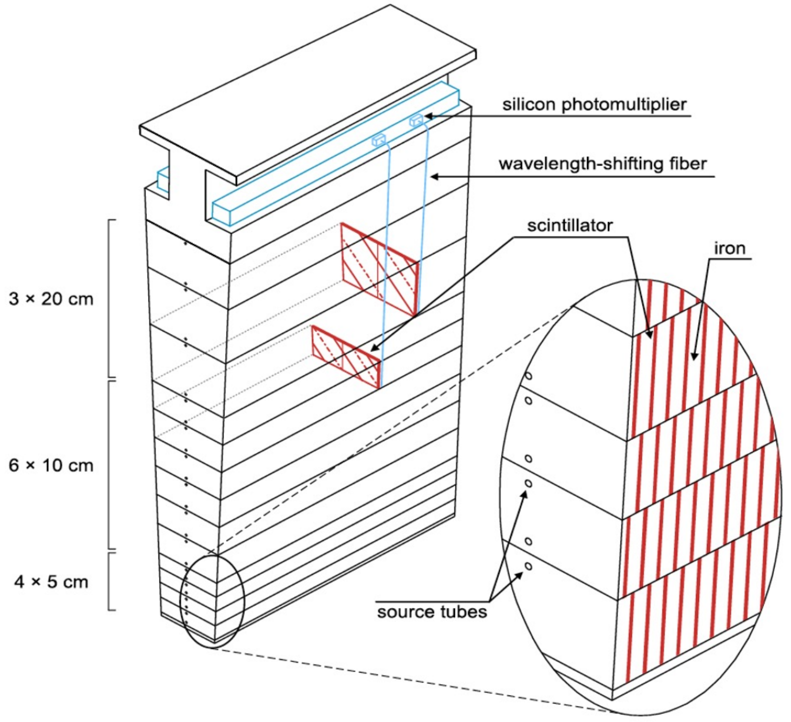
Dual Readout Fiber Calorimeter
for Higgs Factories

R&D on Spaghetti (EM) Calorimeter technologies for LHCb Upgrade II, Higgs factories, FCC-hh

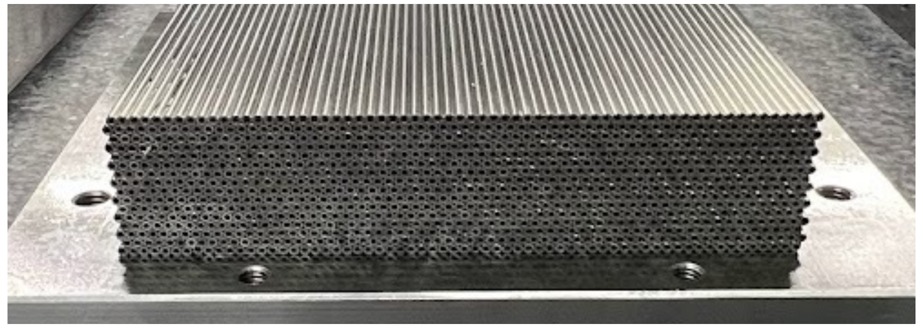
Fast-timing, ultracompact, radiation hard, EM calorimetry (*RADiCAL*)
for FCC-hh

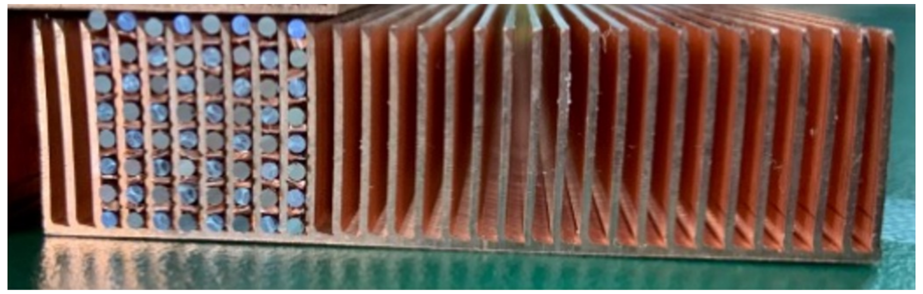
High sampling fraction EM calorimeter with crystal grains (*GRAiNITA*) for FCC-ee

Hadron calorimeter with scintillating tiles and WLS fibre readout and SiPMs
Cost-effective production of tiles, radiation hardness for FCC-hh
Organic scintillating tiles, Steel (+Pb for FCC-hh) absorber



High resolution Electromagnetic and hadronic calorimeter
Organic scintillating fibres in brass or steel absorber(different solutions under development),
SiPM or MCP-PMT photon detectors
integration of a large number of SiPMs





Optical Calorimeters

Scintillator based sampling calorimeters

Scintillating Tile HCAL
for FCC-hh, FCC-ee

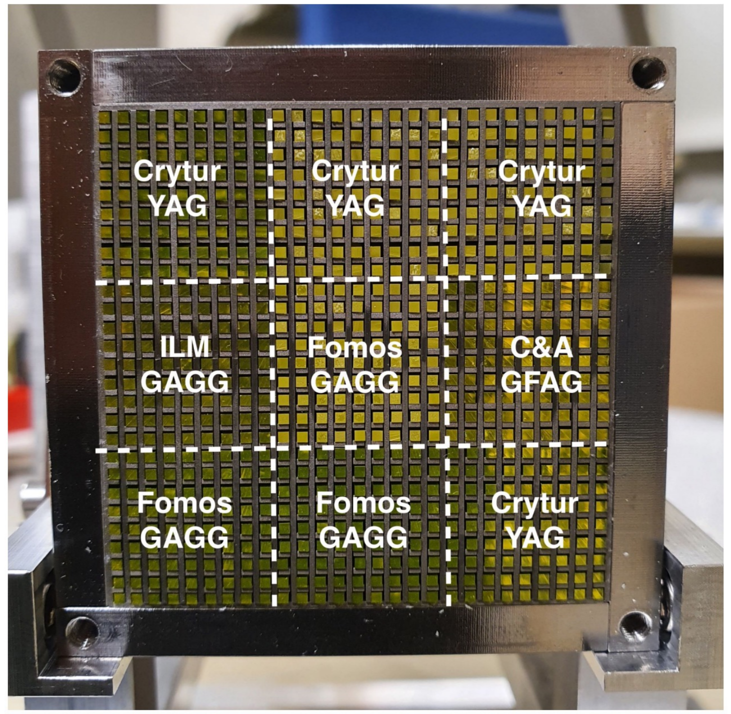
Dual Readout Fiber Calorimeter
for Higgs Factories

R&D on Spaghetti (EM) Calorimeter technologies for LHCb Upgrade II, Higgs factories, FCC-hh

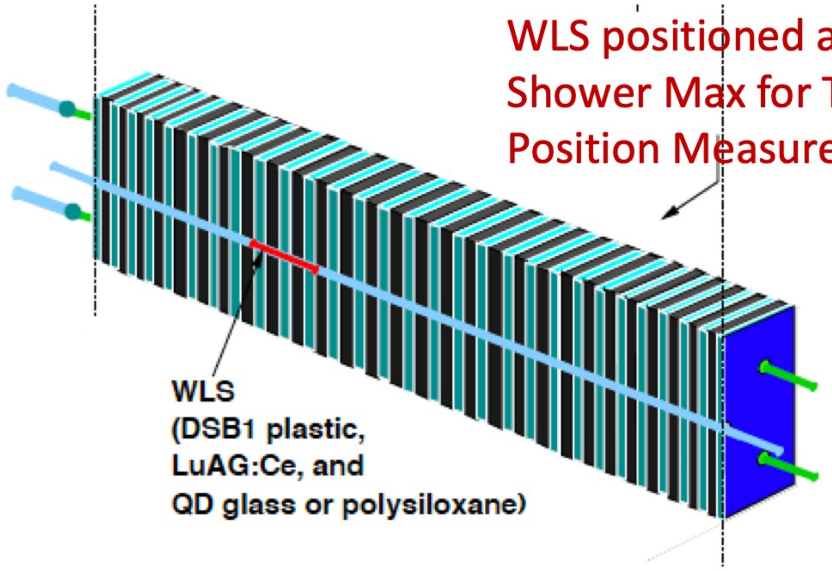
Fast-timing, ultracompact, radiation hard, EM calorimetry (*RADiCAL*)
for FCC-hh

High sampling fraction EM calorimeter with crystal grains (*GRAiNITA*) for FCC-ee

SpaCal (ECAL made of scintillating fibres in dense absorbers) with O(10-20) ps time resolution
Radiation-hard (and radiation-tolerant) scintillating fibres
Crystal or organic fibres in lead or tungsten absorber, hollow light guides, PMT/SiPM photon detectors, SPIDER ASIC for timing

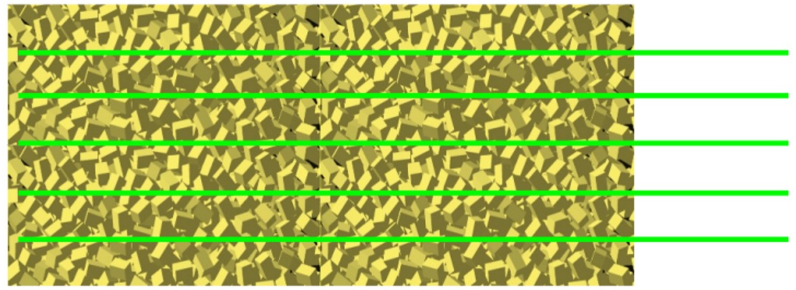


Radiation-hard EM calorimeter with 10%/√E energy resolution and 25 ps timing resolution
Radiation-hard WLS filament and SiPM
Shashlik/type ECAL modules with tungsten absorber and LYSO:Ce tiles, WLS (full-length or in shower maxi



WLS positioned at region of Shower Max for Timing and Position Measurement

Innovative technique inspired by Shashlyk-type calorimeters. Extremely fine granularity. Grain of scintillator in dense liquid



Optical Calorimeters

Homogeneous EM crystal calorimeters

Maximum Information Crystal Calorimeter for Higgs Factories

Homogeneous EM calorimeter based on segmented crystals with SIPMs readout and dual-readout capability Simultaneous readout of scintillation and cherenkov light signals from the same active element (heavy inorganic scintillator) High density scintillating crystals with good cherenkov yield instrumented with dedicated optical filters and SiPMs

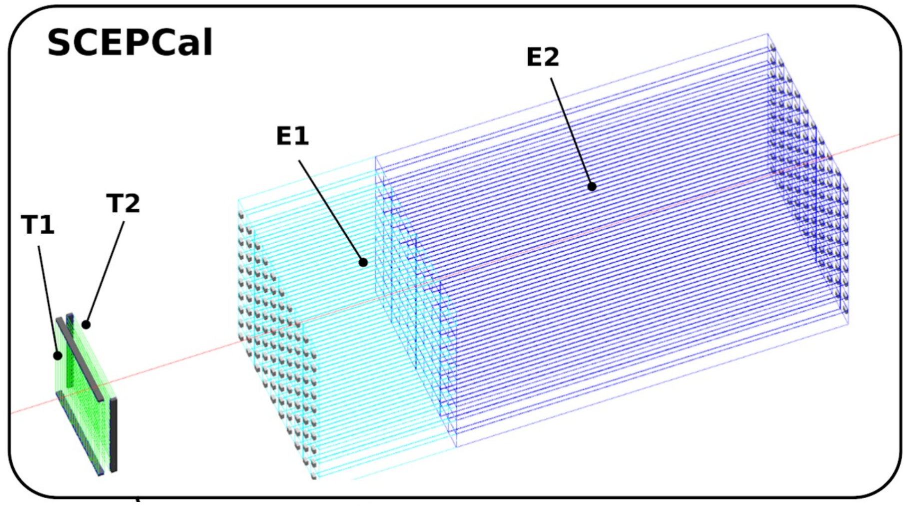
High Granularity Crystal Calorimeter for Higgs Factories

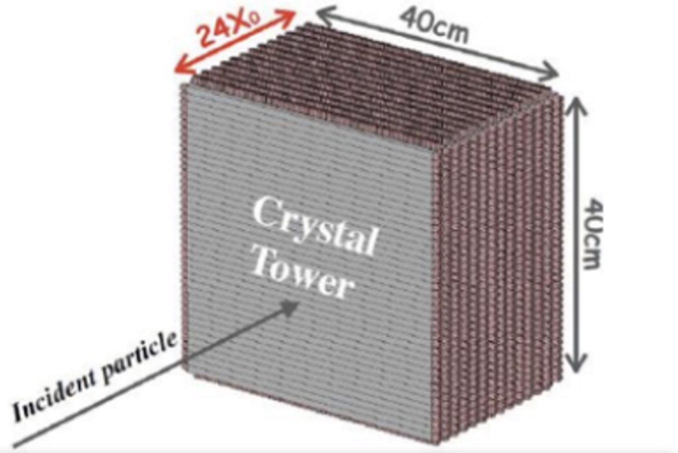
Highly granular EM crystal based calorimeter to exploit maximum potential of PFA algorithms Integration (readout, minimize gaps, material budget), reconstruction driven by grid layout High density scintillating crystals with double-ended SiPM readout

Fast, segmented Crystal calorimeter for Muon Collider (*CRILIN*)

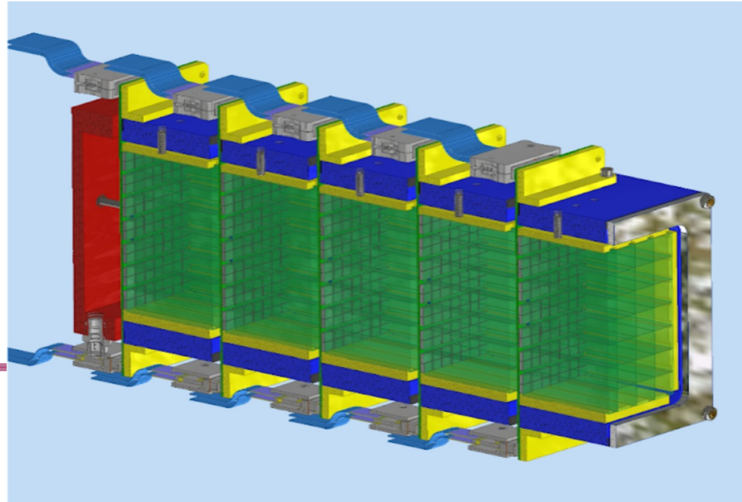
Radiation tolerant design of a longitudinally segmented crystal EM calorimeter ($10\%/\sqrt{E}$) for mitigation of beam induced background at muon colliders.

Very harsh radiation environment for SiPMs, high rate of operation, large beam induced background (BIB) Lead fluoride (PbF_2) crystals, each readout with 2 channels consisting of a pairs of SiPMs connected in series





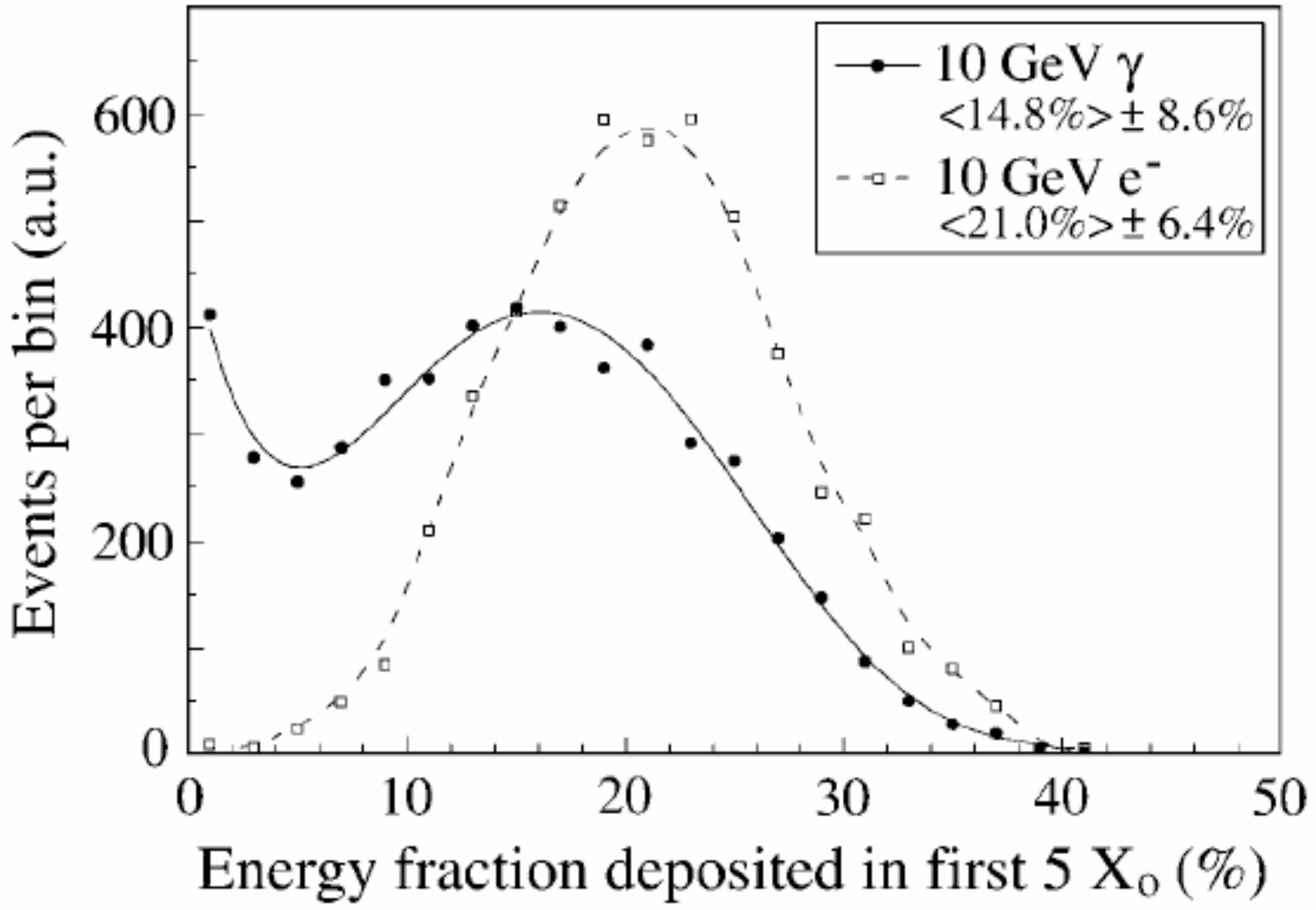
EM calorimeter module: a grid of ~1x1x40cm³ crystal bars



Backup

Electromagnetic Showers

- Longitudinal development governed by radiation length (X_0)
  - Defined only for GeV regime
- There are important differences between showers induced by e, γ:
  - e.g. Leakage fluctuations, effects of material upstream, ...
  - Mean free path of γs = 9/7 X_0



Distribution of energy fraction deposited in the first 5 X_0 by 10 GeV electrons and γs showering in Pb.Results of EGS4 simulations

Electromagnetic Showers

Pb Z = 82
Fe Z = 26
Al Z = 13

Scaling with X_0 is not perfect

- In high-Z materials, particle multiplication continues longer and decreases more slowly than in low-Z materials
  - $E_C \propto Z^{-1}$
- The number of positrons strongly increases with the Z value of the absorber material
  - Example: number of e^+/GeV in Pb is 3 times larger than in Al
  - Need more X_0 of Pb to contain shower at 90% level

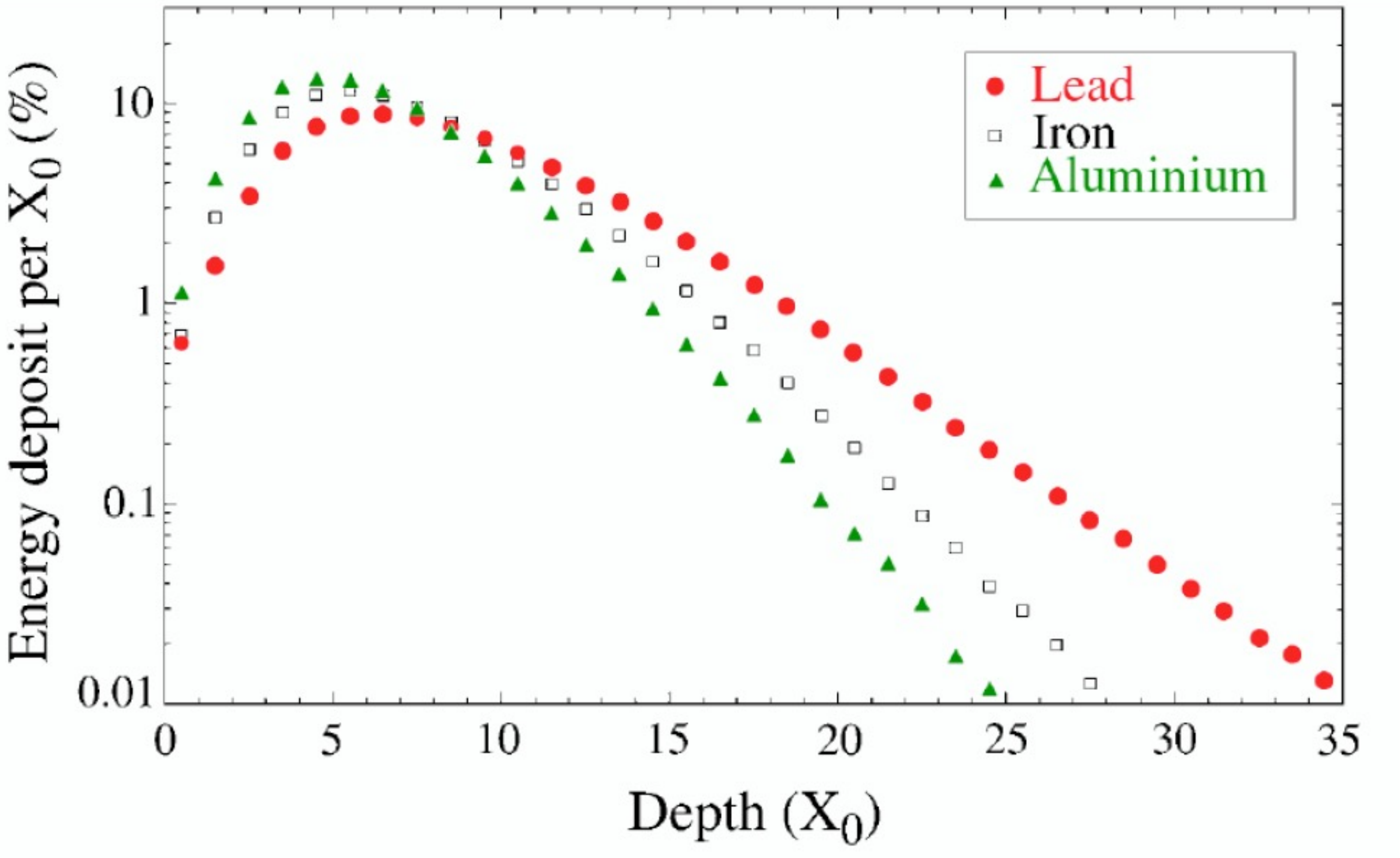


FIG. 2.12. Energy deposit as a function of depth, for 10 GeV electron showers developing in aluminium, iron and lead, showing approximate scaling of the longitudinal shower profile, when expressed in units of radiation length, X_0. Results of EGS4 calculations.

Electromagnetic shower leakage (longitudinal)

- The absorber thickness needed to contain a shower increases logarithmically with energy
- The number of X_0 needed to fully contain the shower energy can be as much as 10 X_0 going from high Z to low Z absorbers
- More X_0 needed to contain γ initiated showers

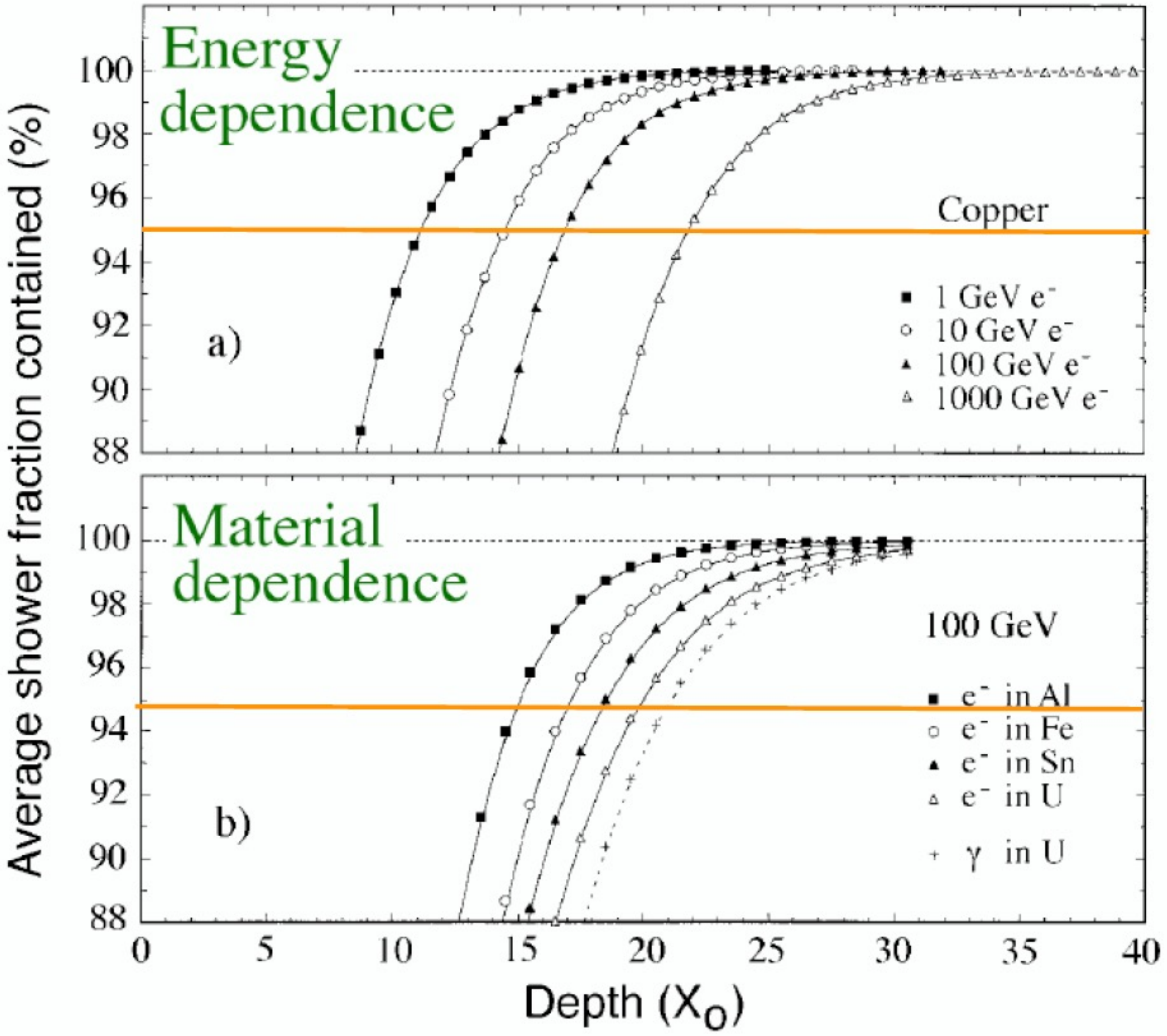


FIG. 2.17. Average energy fraction contained in a block of matter with infinite transverse dimensions, as a function of the thickness of this absorber. Shown are results for showers induced by electrons of various energies in a copper absorber (*a*) and results for 100 GeV electron showers in different absorber materials (*b*). The lower figure also shows the results for 100 GeV γ showers in ^{238}U. Results of EGS4 calculations.

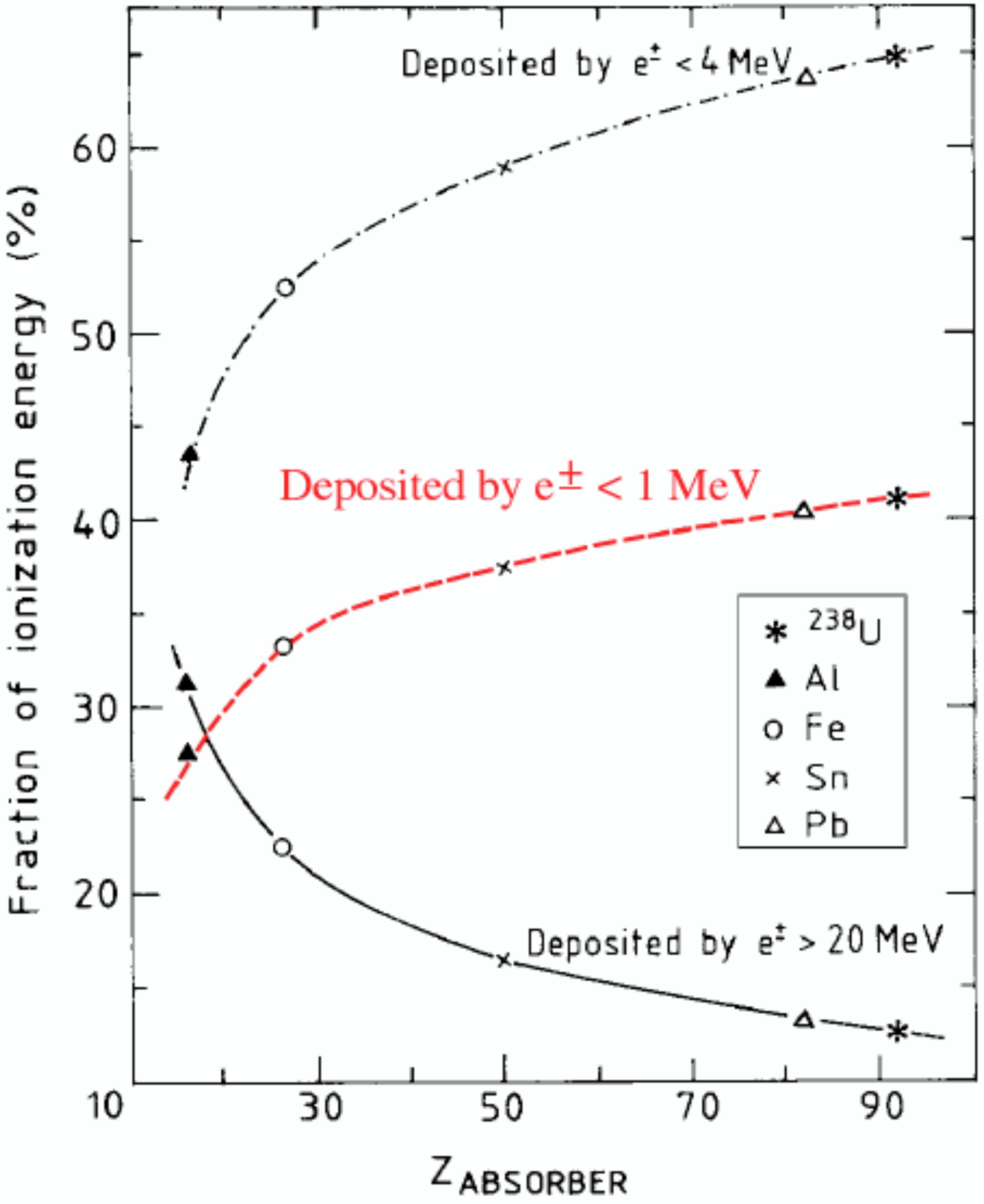
Importance of SOFT particles

Phenomena at $E < E_c$ determine important calorimeter properties

- ✦ In lead > 40% of energy deposited by $e^{\pm}$ with E < 1 MeV
- ✦ Only 1/4 deposited by e^+, 3/4 by e^- (Compton, photoelectrons!)
- ✦ The e^+ are closer to the shower axis, Compton and photoelectrons in halo

The composition of em showers:

Shown are the percentages of the energy of 10 GeV electromagnetic showers deposited through shower particles with energies below 1 MeV, below 4 MeV or above 20 MeV as function of the Z of the absorber material.



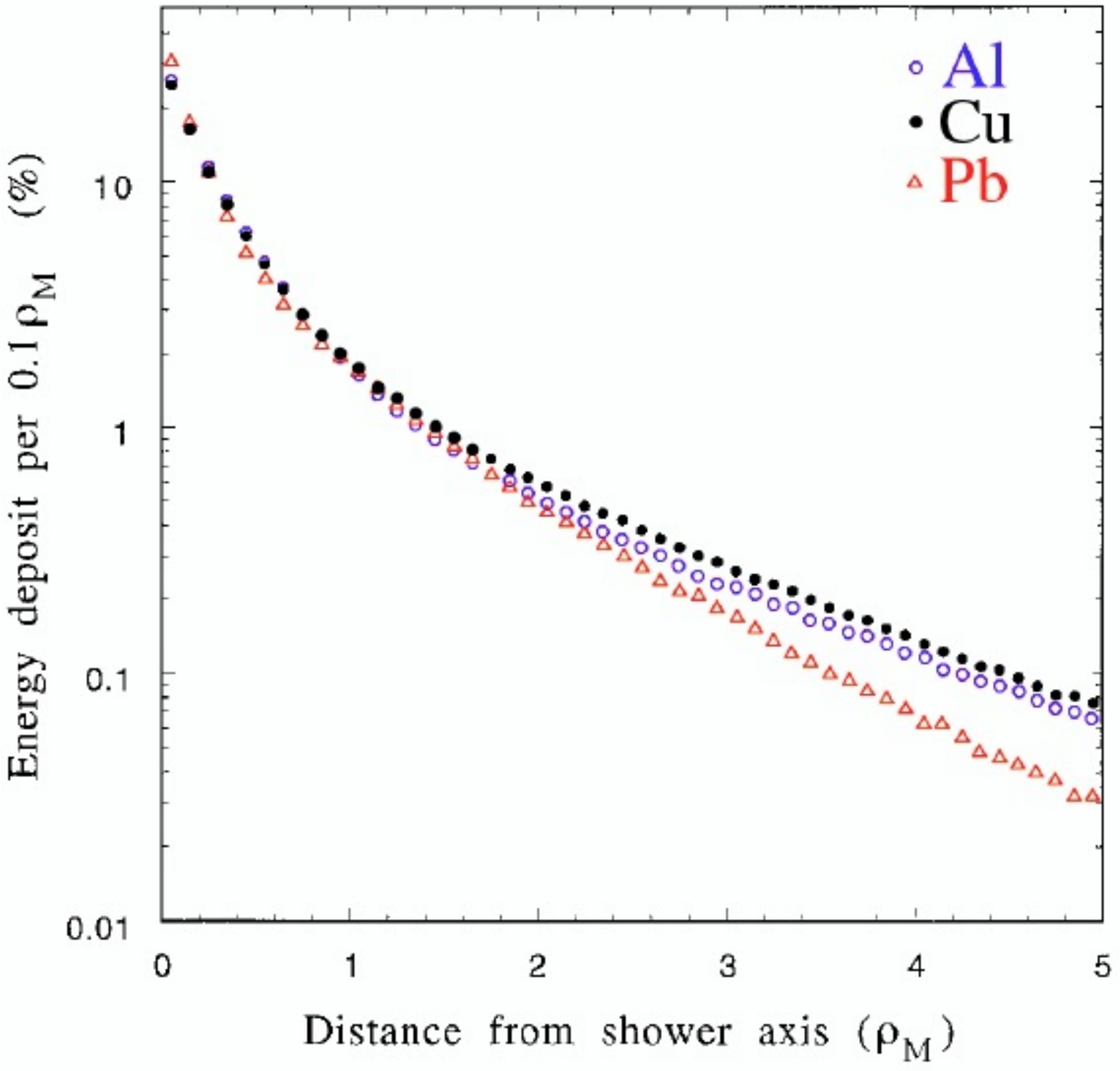
Results of EGS4 simulations

Lateral profile

Tails made out of Compton electrons.

Mean free path of MeV gammas becomes smaller as Z increases

- ✦ Material dependence
- ✦ Radial energy deposit profiles for 10 GeV electrons showering in Al, Cu and Pb
- ✦ Results of EGS4 calculations



Lateral shower leakage

No energy dependence

A (sufficiently long) cylinder will contain the same fraction of energy of a 1 GeV or 1 TeV em shower

Results of EGS4 simulations

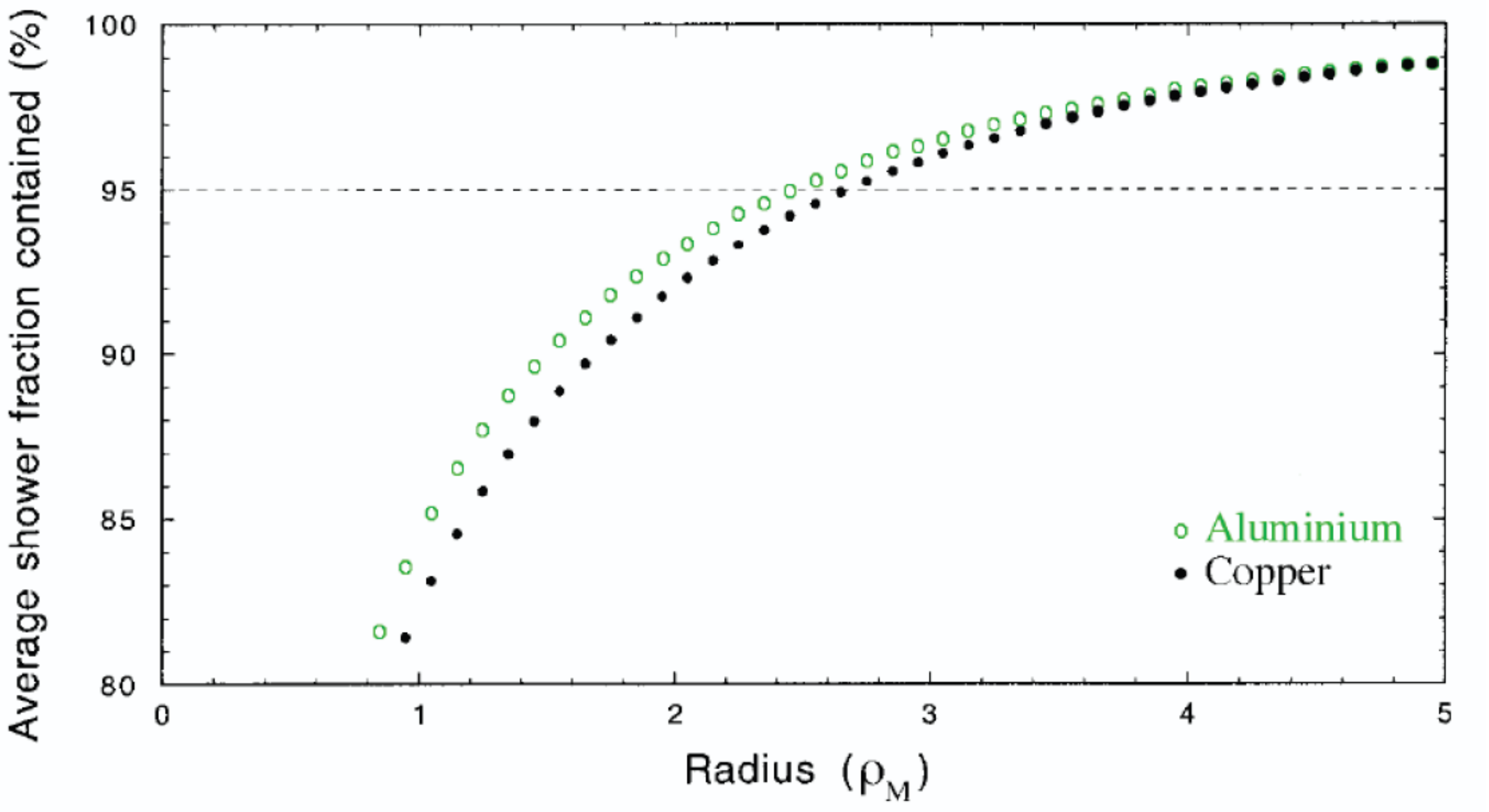
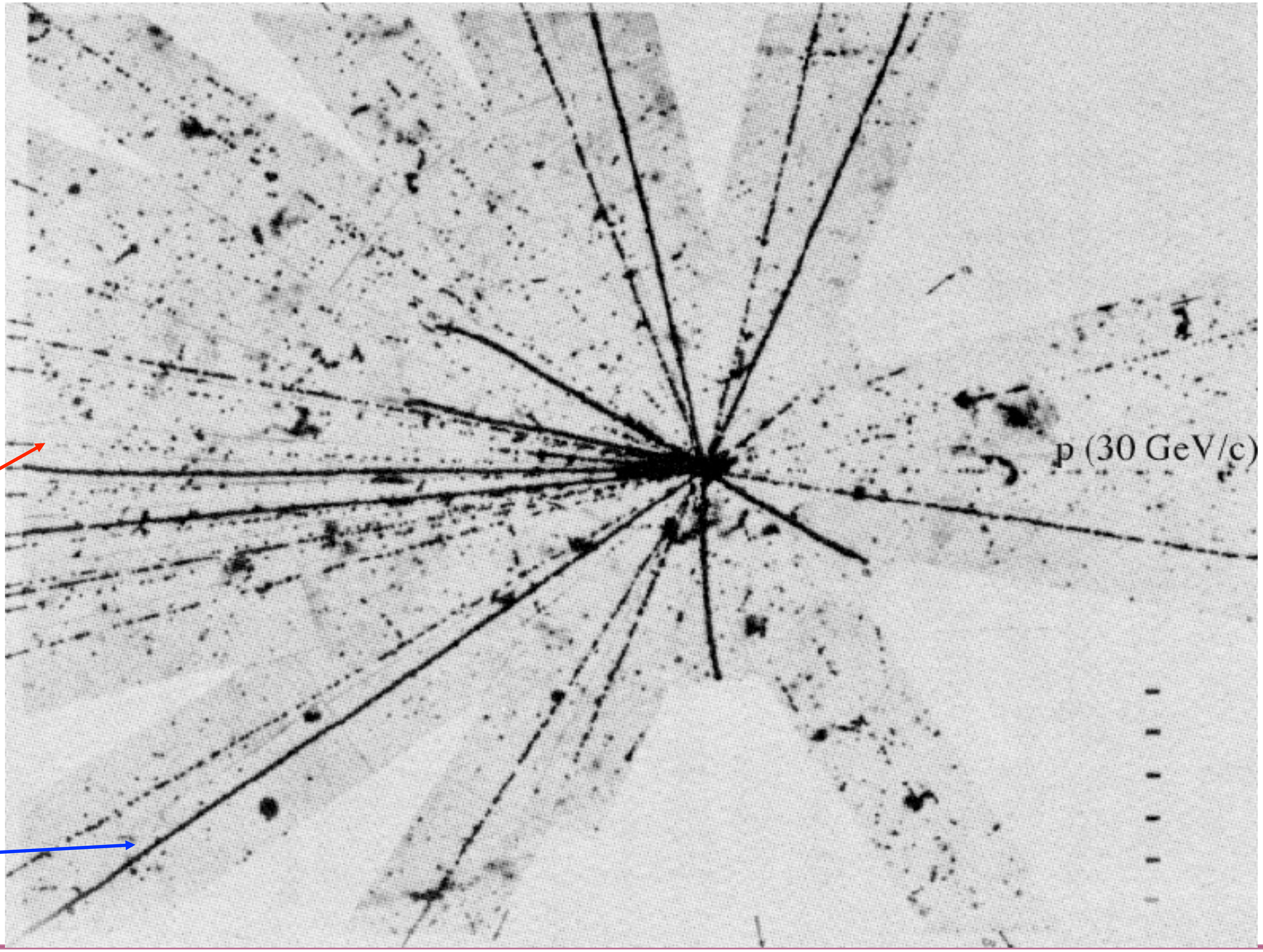


FIG. 2.18. Average energy fraction contained in an infinitely long cylinder of absorber material, as a function of the radius of this cylinder. Results of EGS4 calculations for various absorber materials and different energies.

A typical process

Nuclear interaction (nuclear star) induced by a proton of 30 GeV in a photographic emulsion



Spallation neutrons
(non-visible)

Fast pions and fast spallation protons
(non-isotropic)

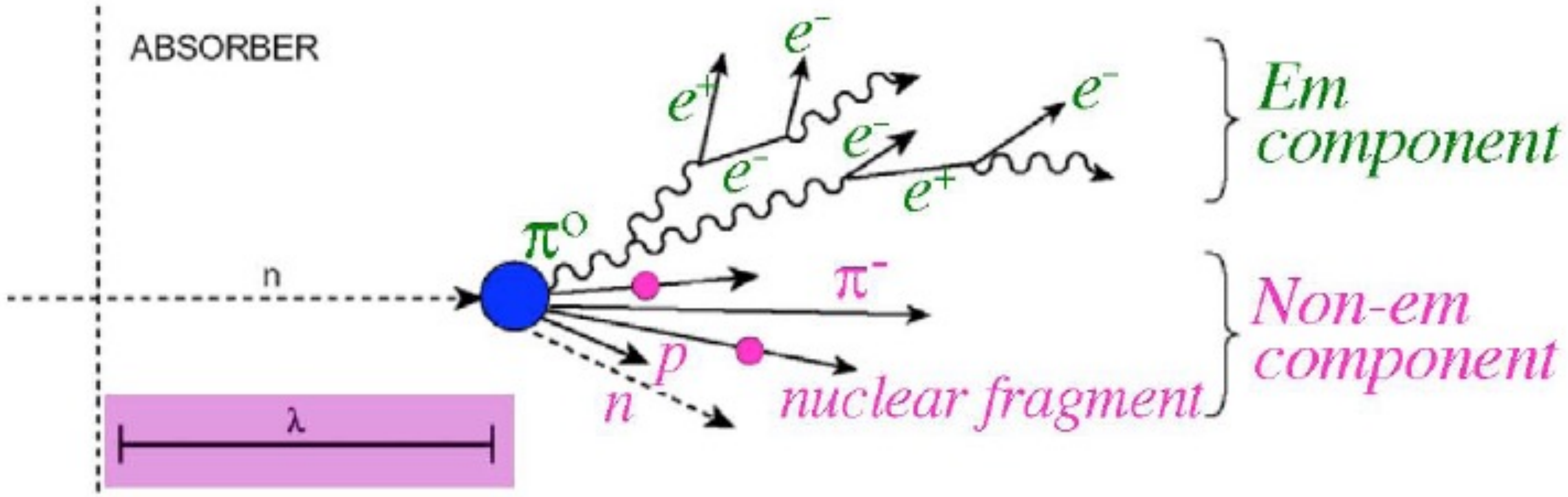
Protons
(isotropic)

Hadronic showers

Shower development in Lead

- π_0 decays into 2 photons start an electromagnetic shower (f_{em})
- the remaining energy
  - *56% ionizing particles* (2/3 spallation protons, typically 100 MeV each, range 1cm)
  - *10% neutrons* (evaporation neutrons, typically 3 MeV each)
  - *34% invisible energy*

electrons positrons, photons, π^0



Charged hadrons (**π,k…**), nuclear fragments, neutrons, neutrinos, breakup of nuclei (invisible energy)

Spallation

- Energy needed to release nucleons in nuclear reactions doesn’t result in a measurable signal (binding energy ⇒ invisible)

- Spallation is the most probable process in hadronic shower. It is a 2-stage process

Fast intranuclear cascade
  - Quasi-free collision of incoming hadron with nucleon
  - Nucleus excitation by distribution of nucleon energy
  - Cascade of fast nucleons, pions produced

Slower evaporation
  - Due to de-excitation of intermediate nucleus
  - Evaporation of nucleons
  - Remaining energy (few MeV) released through -rays

Neutron production spectra

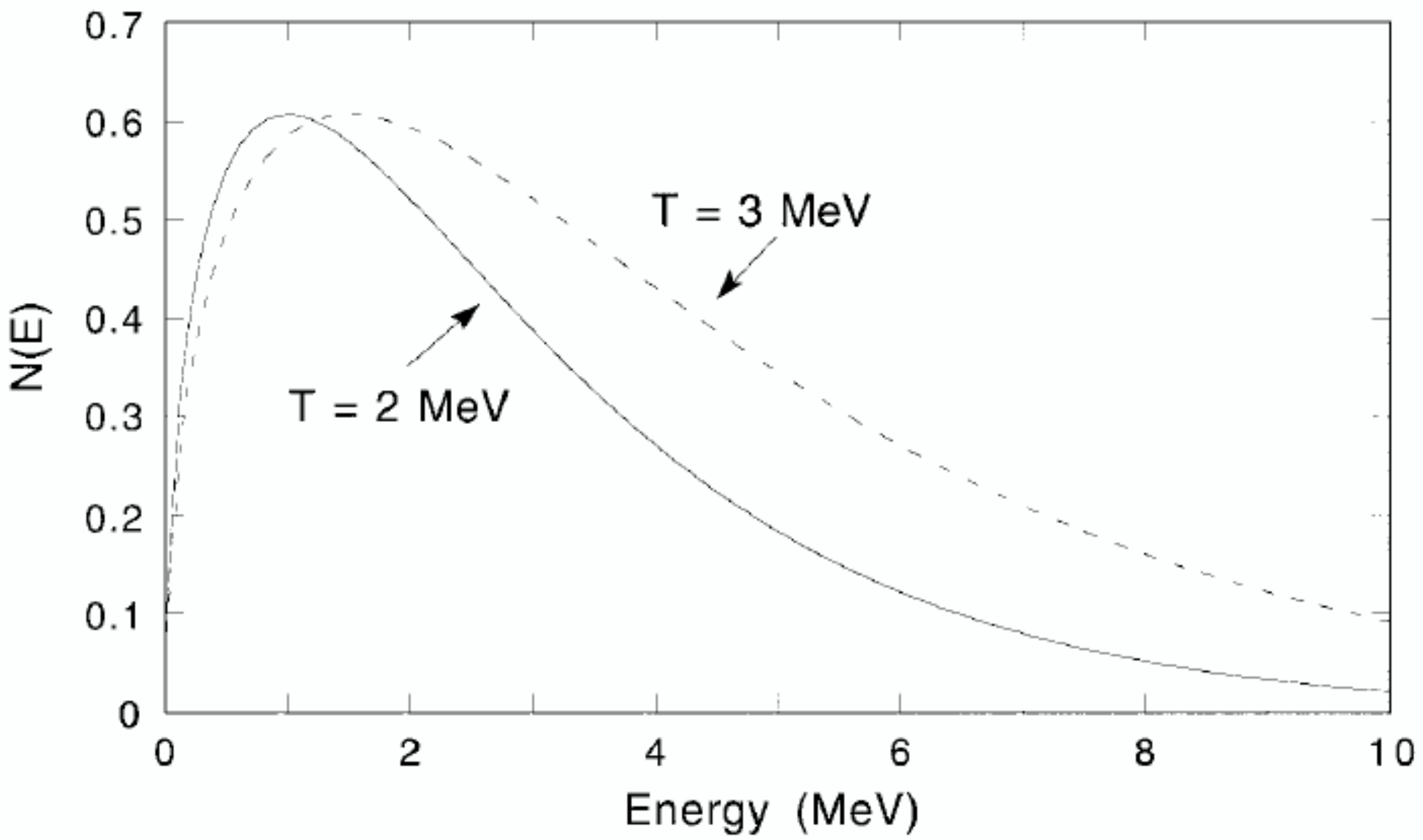


FIG. 2.29. Kinetic energy spectrum of evaporation neutrons, produced according to a Maxwell distribution with a temperature of 2 MeV. For comparison, the spectrum for a temperature of 3 MeV is given as well.

Kinetic energy spectrum of evaporation neutrons (Boltzmann-Maxwell distribution)

$$\frac{dN}{dE} = \sqrt{E}\exp(-E/T)$$

Hadronic shower profiles

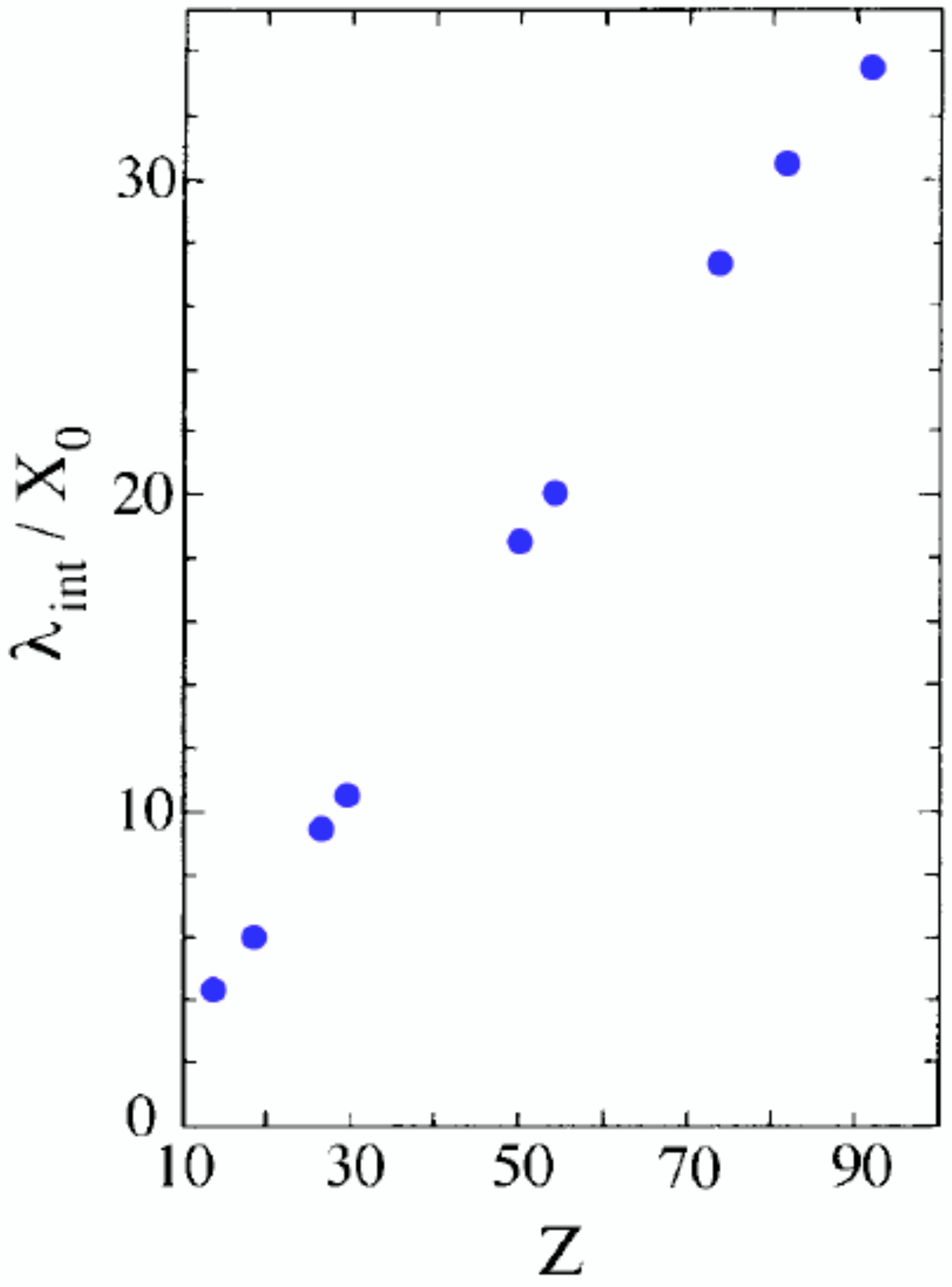
- The λ_{int}/X_0 ratio is important for particle ID

$$\lambda_{int}\ (\mathrm{g\ cm^{-2}}) \propto A^{1/3}$$

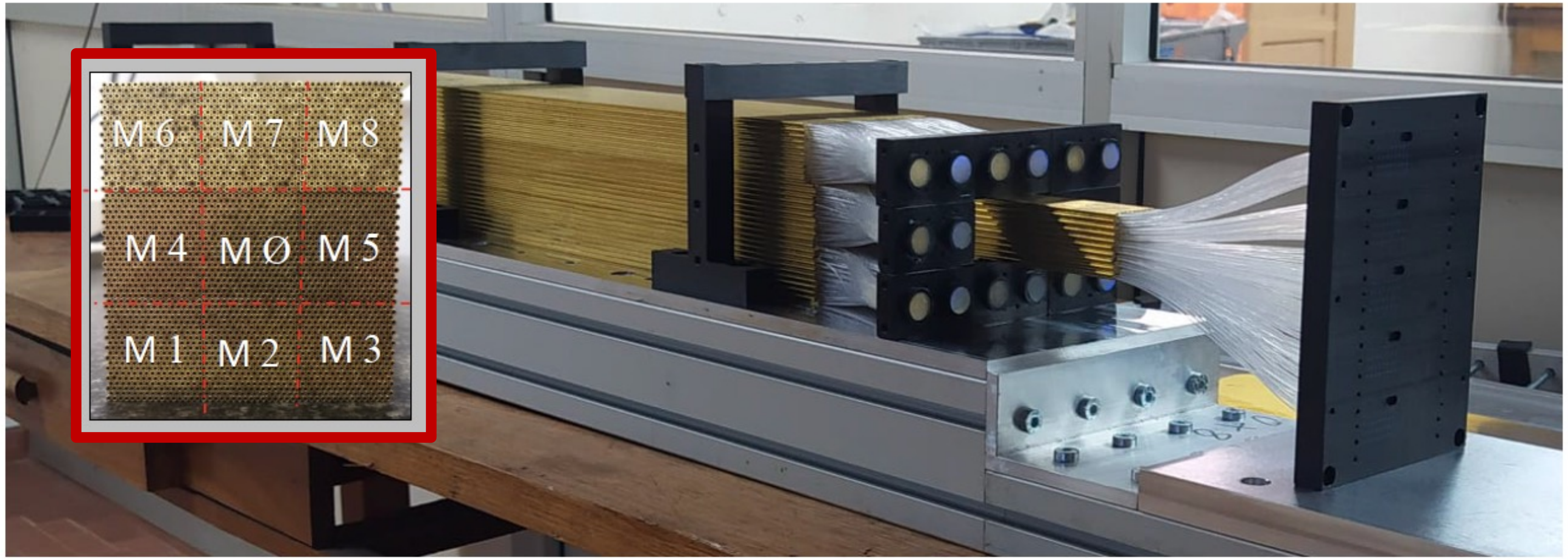
$$X_0 = \frac{A}{4\alpha N_A \frac{Z^2}{A} z^2 r_e^2 E \ln \frac{183}{Z^{\frac{1}{3}}}}$$

- In high-Z materials: $\lambda_{int}/X_0 \sim 30 \Rightarrow$ excellent e/π separator
- 1 cm PB + scintillator plate makes spectacular preshower detector

Ratio of the nuclear interaction length and the radiation length as a function of Z



The 2021 test beam prototype



10x10 cm^2 divided in 9 towers, 1m long
16x20 capillary each (160 C + 160 S fibres)

Capillary:
2mm OD, 1.1 mm ID
Material: Brass

- Hi-quality commercially available capillary tubes
- Quite easy and fast assembly system
- Test the viability of this mechanical solution