LHC detectors

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Course on Physics at the LHC

LIP, 13th-15th March 2023

Outline

- From collision remnants to physics
- Connecting the dots: tracking
- Si-based detectors
- Calorimetry for pedestrians
- Getting data on tape: trigger systems

1st part

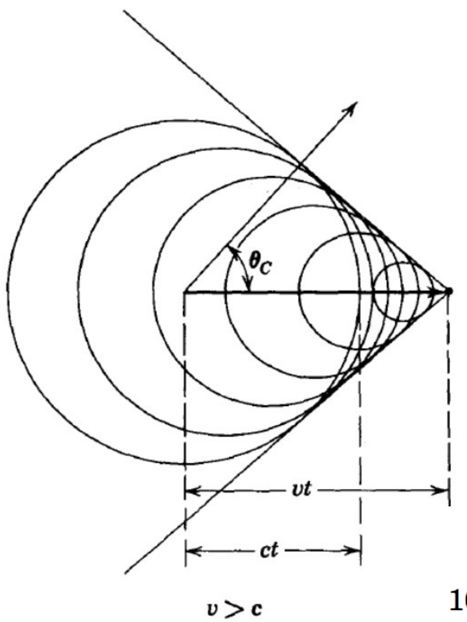
2nd part

Calorimetry for pedestrians

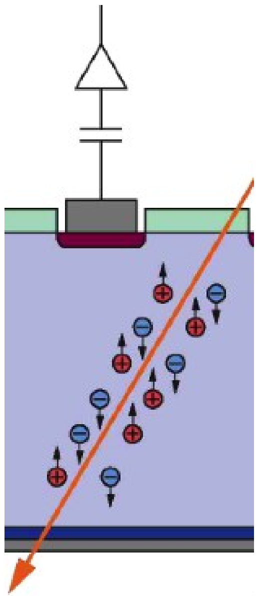
Recall: we measure what collapses in the detector

Particles need to interact in matter ⇒ destructive interaction

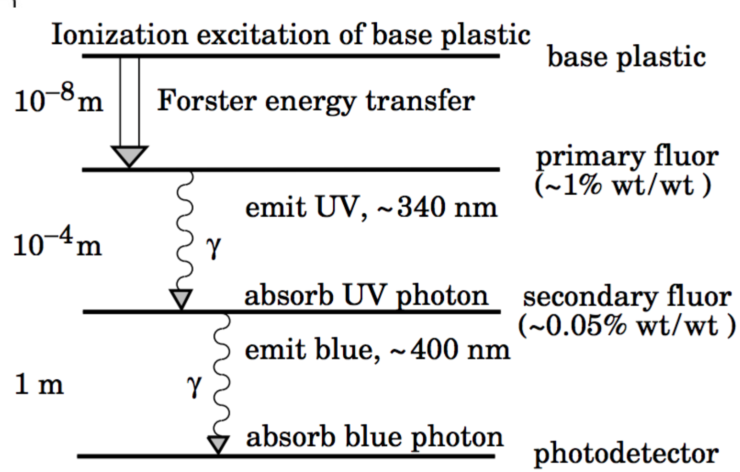
- dE/dx is converted in a signal
- collect: charge, light, heat



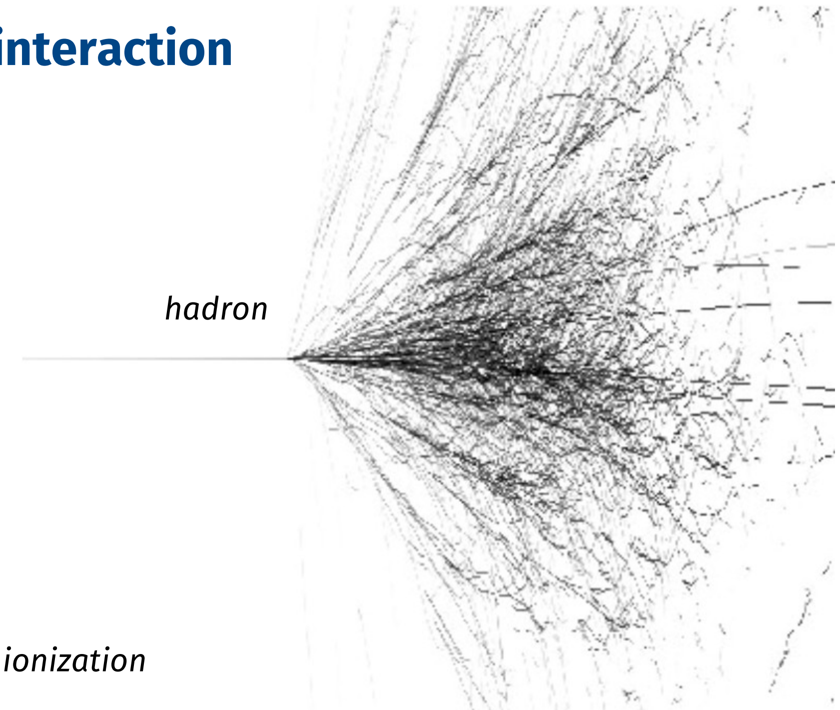
Cerenkov radiation



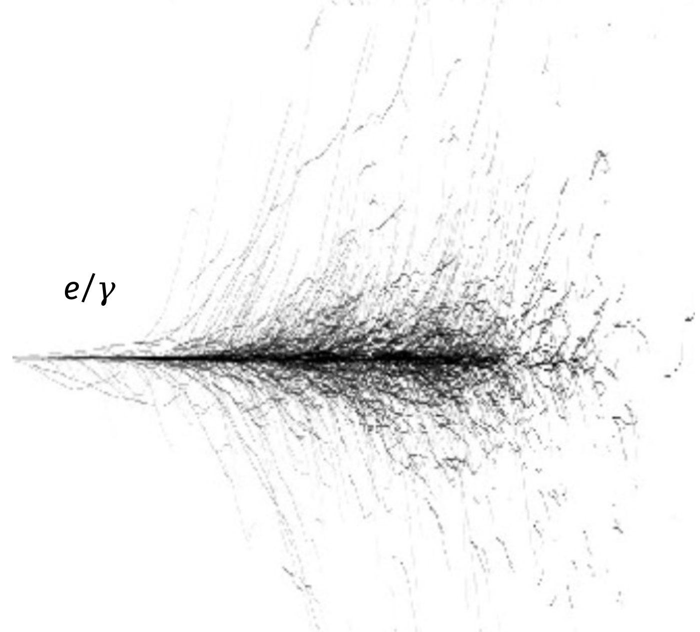
ionization



scintillation



hadron



e/γ

Purpose of a calorimeter

Calorimeters measure the total energy of a particle, but they are versatile

- can measure position, angle and timing
- particle identification from shower/cascade properties
- infer energy of neutrinos after energy balance

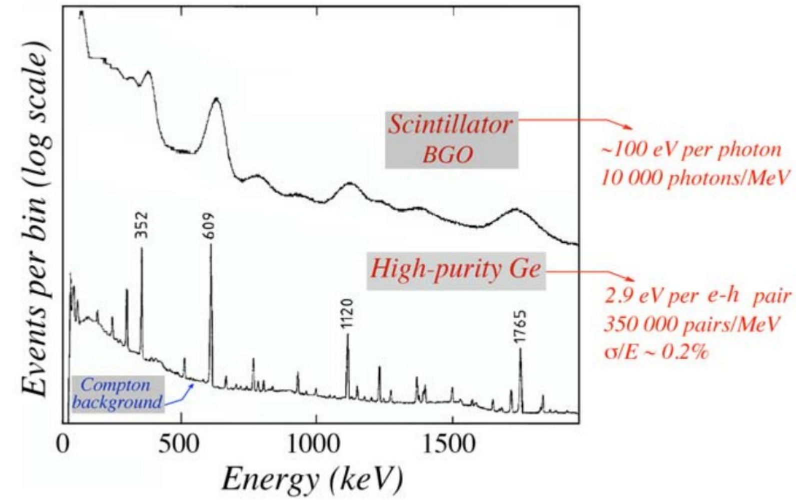
General properties

- length of showers induced in calorimeters increase logarithmically with E
- energy resolution improves with E
- fast signals, easy to reconstruct (unlike tracking) $\Rightarrow$ trigger

Almost impossible to do high energy physics without calorimeters

(a very brief) historical overview

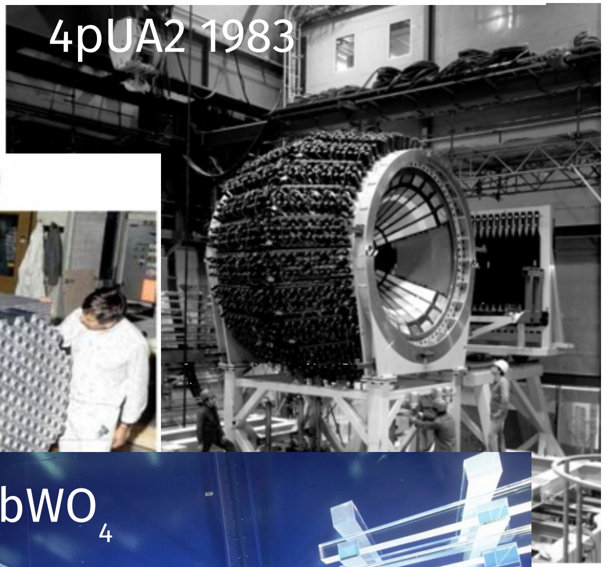
Nuclear Physics in the 50's usage of semi-conductor devices improving the energy measurement of radiation energy



Cosmic Rays (1958) - the first sampling calorimeter

Particle Physics: adoption of electromagnetic and some times hadronic calorimeters as crucial components in experiments

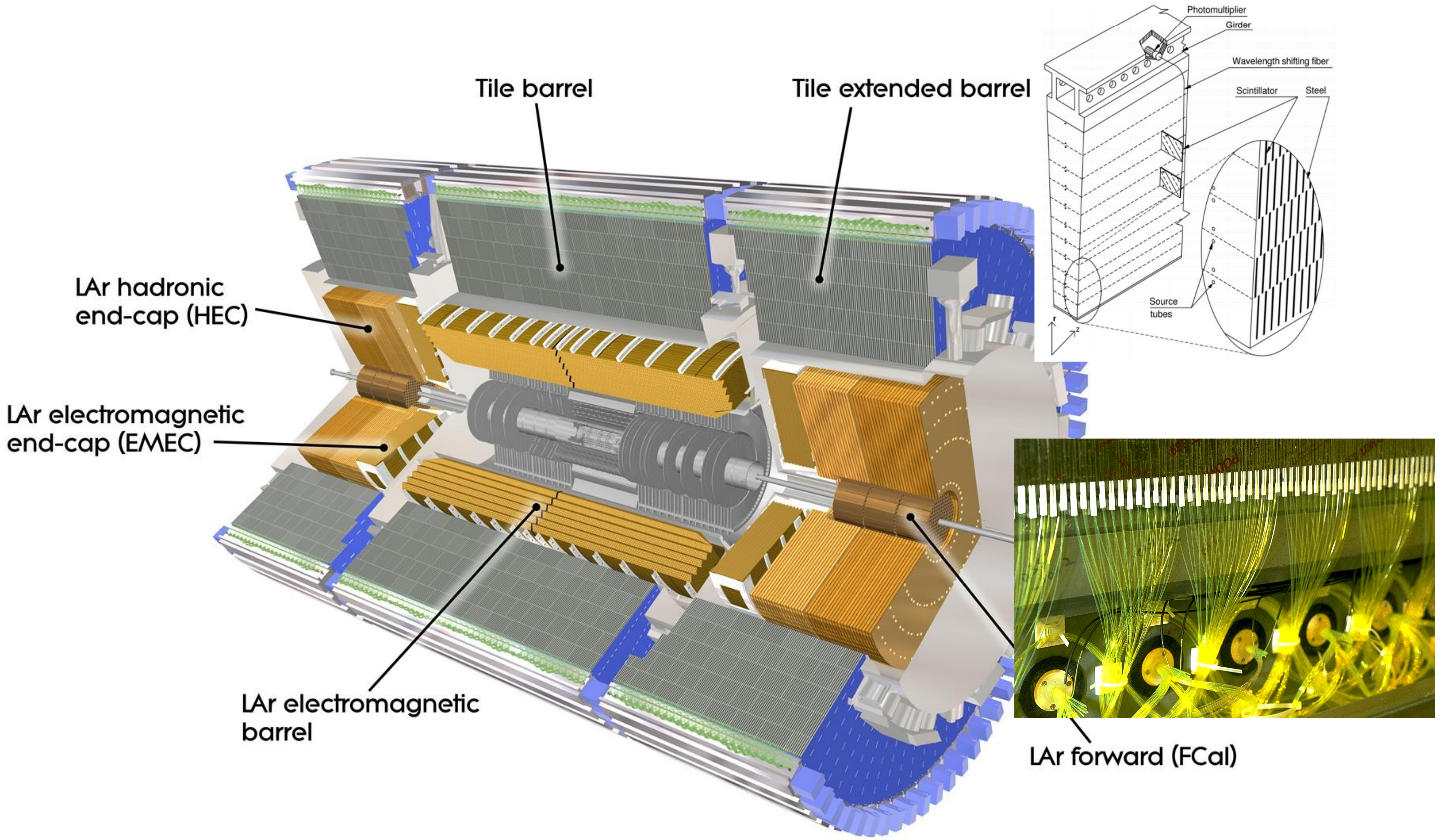
- Uranium/compensation (1975) - uniformize response to e/γ and hadrons to improve resolution
- 4π calorimeters
- High precision calorimetry with crystals, liquid Argon, scintillating fibers



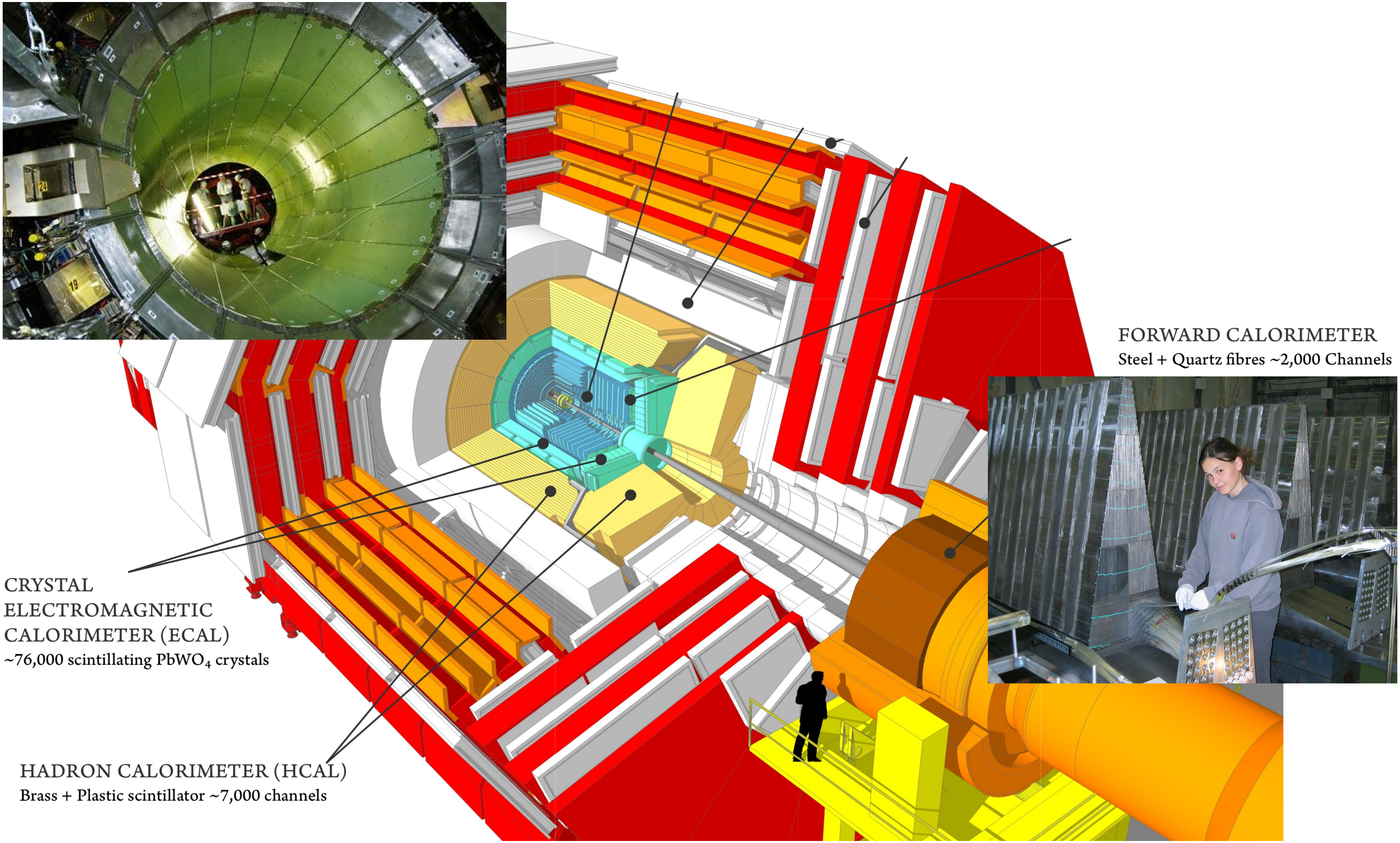
Particle flow calorimeters for HL-LHC, CLIC/ILC

(weighing more on reconstruction than hardware...)

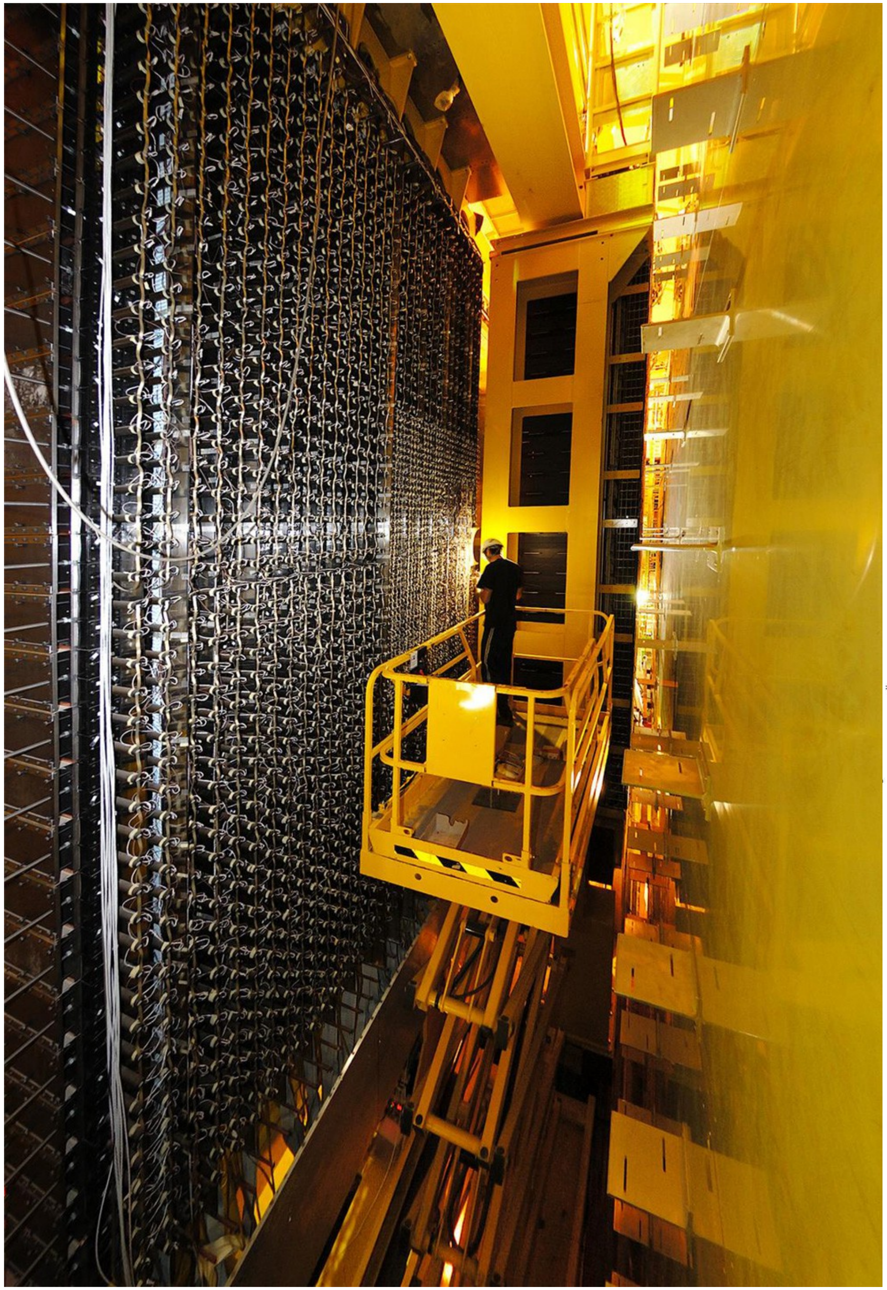
ATLAS calorimetry system



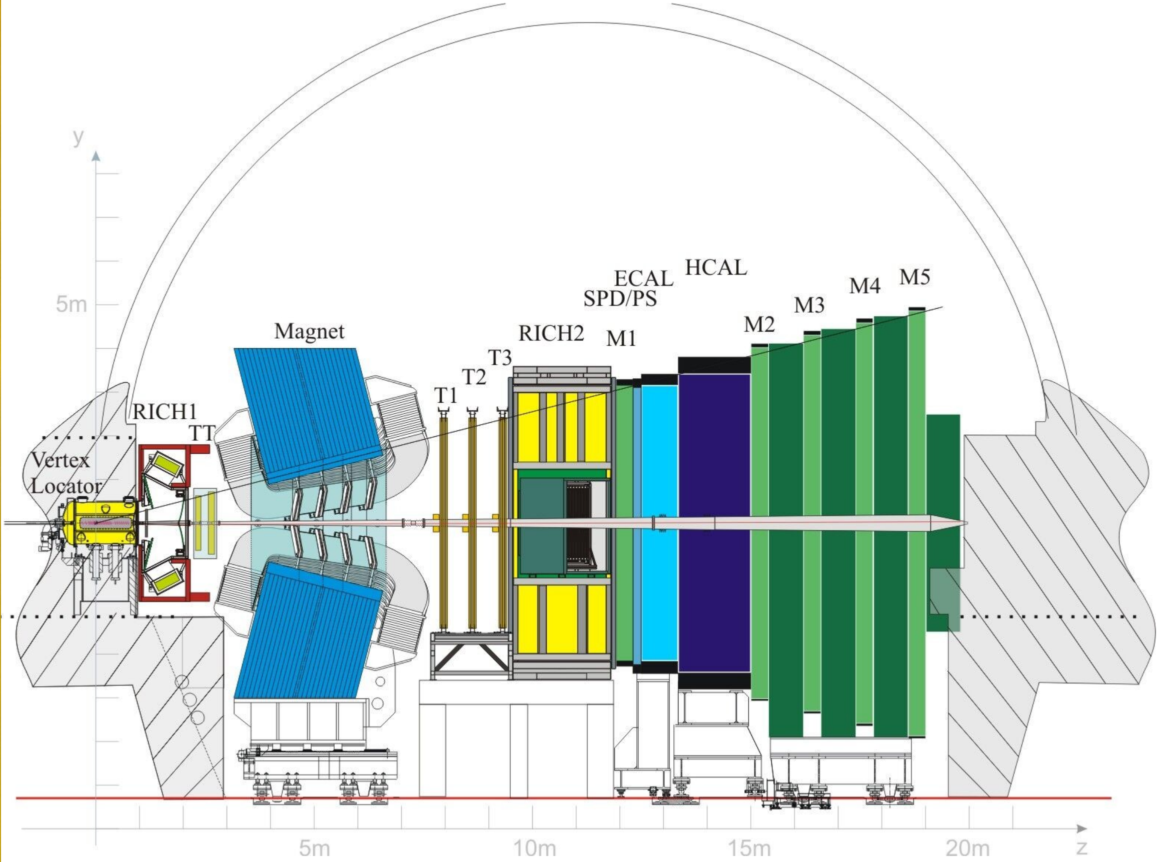
CMS calorimetry system



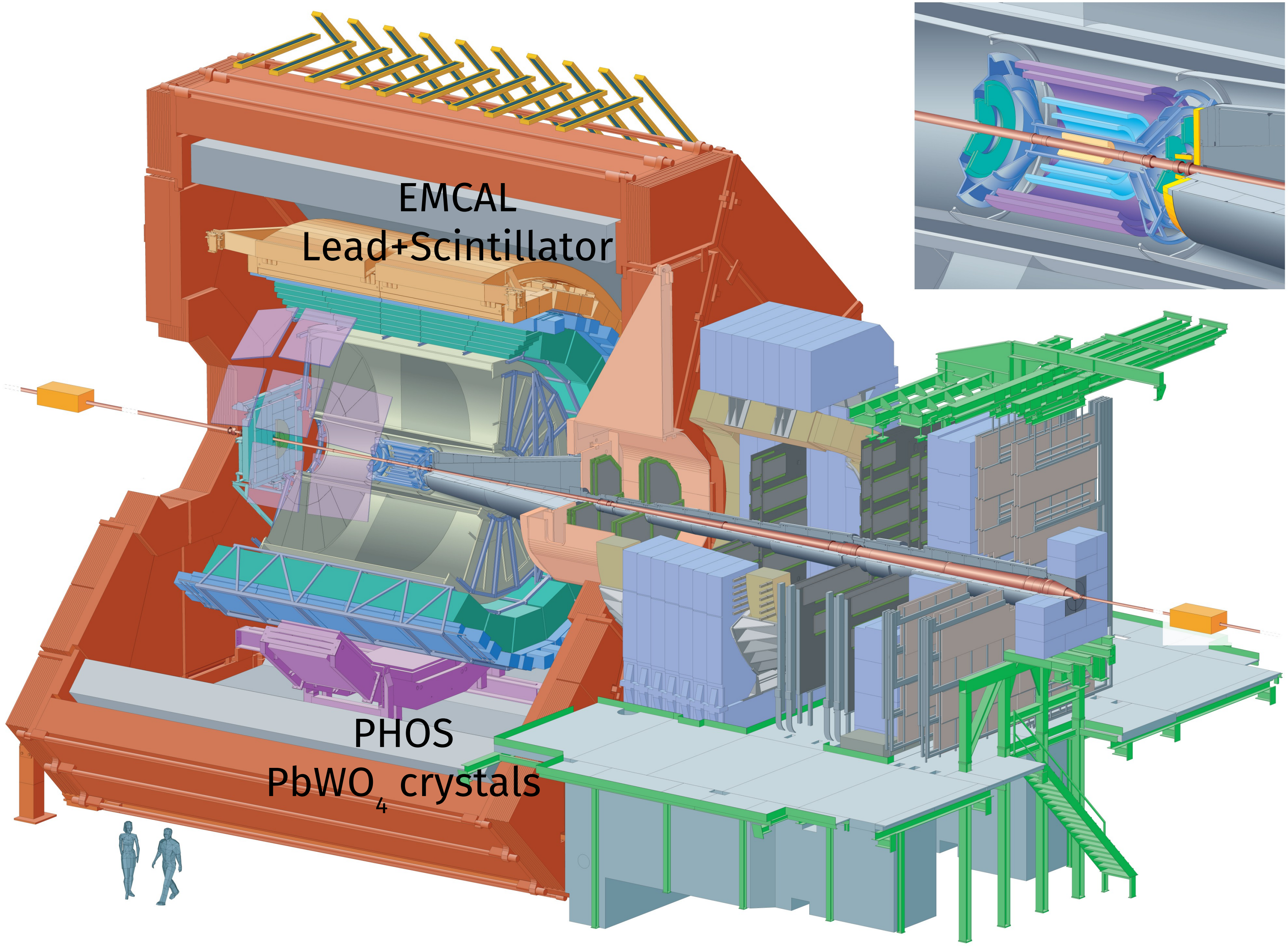
Calorimetry in LHCb



Plastic+metal sandwiches



Calorimetry in ALICE



Electromagnetic calorimeters

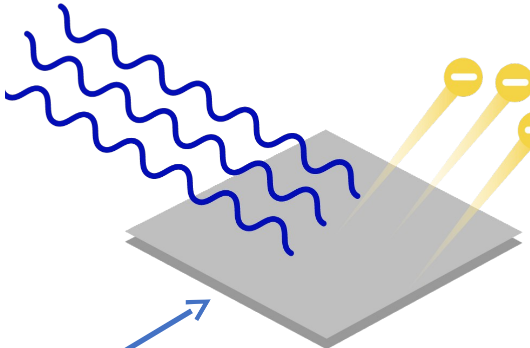
e/g loose energy interacting with nuclei and atomic electrons

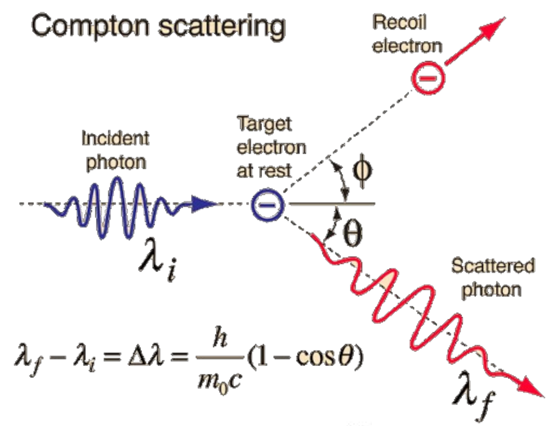
e

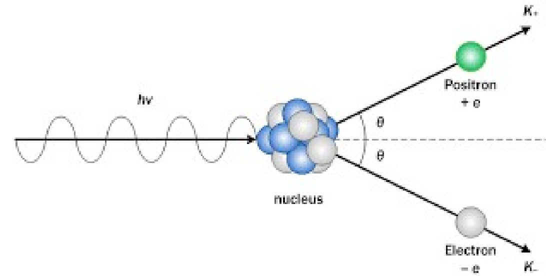
- ionization
- bremmstrahlung

g

- photoelectric effect
- Compton scattering
- pair production



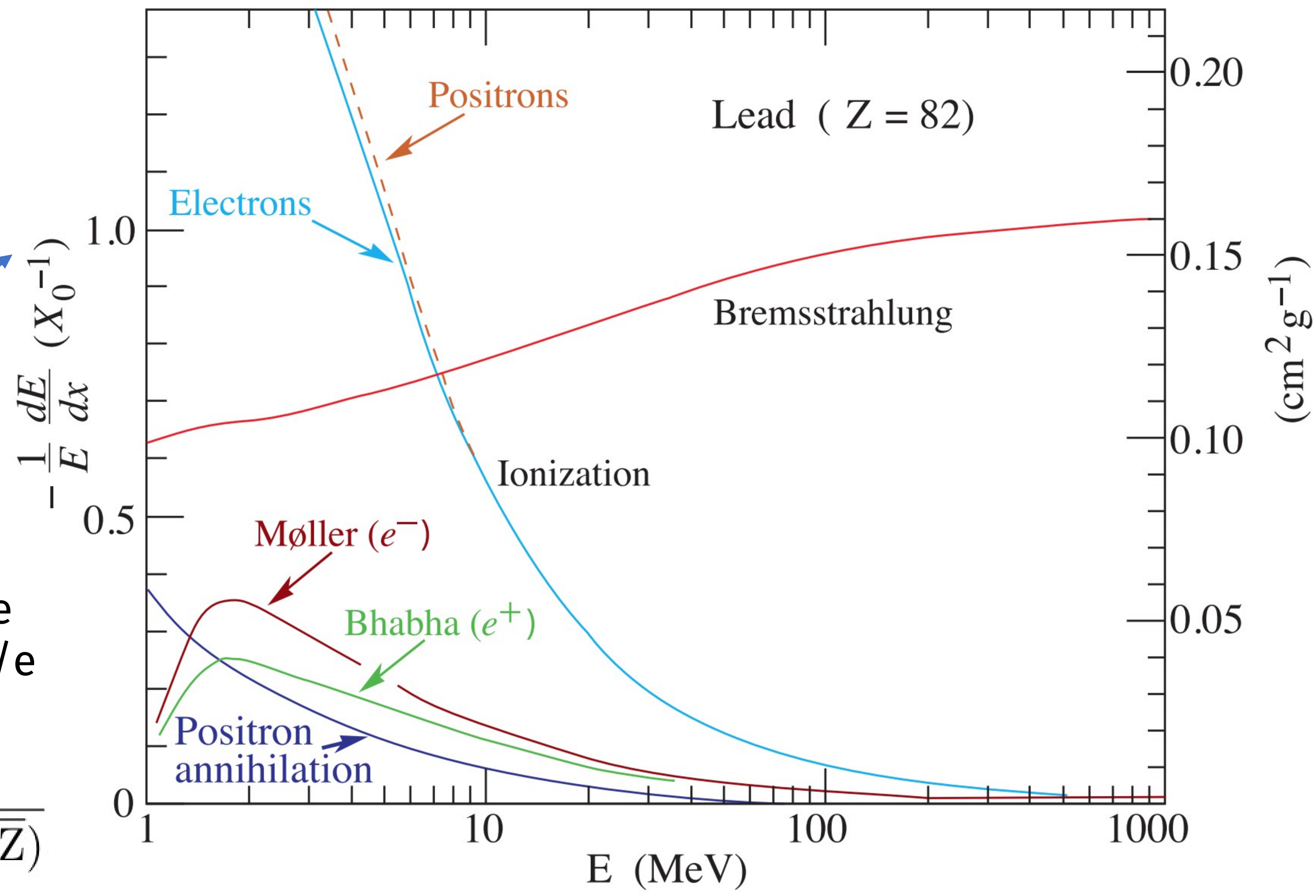




e.m. showers will evolve very similarly independently on how they start

- subsequent e or γ will branch according to these interactions

Processes initiated by electrons



Radiation length (X_0):
quantifies by how much the energy flux is reduced by 1/e

$$X_0 \propto \frac{716\ \mathrm{g/cm^2}\cdot \mathrm{A}}{\mathrm{Z(Z+1)\log(287/\sqrt{Z})}}$$

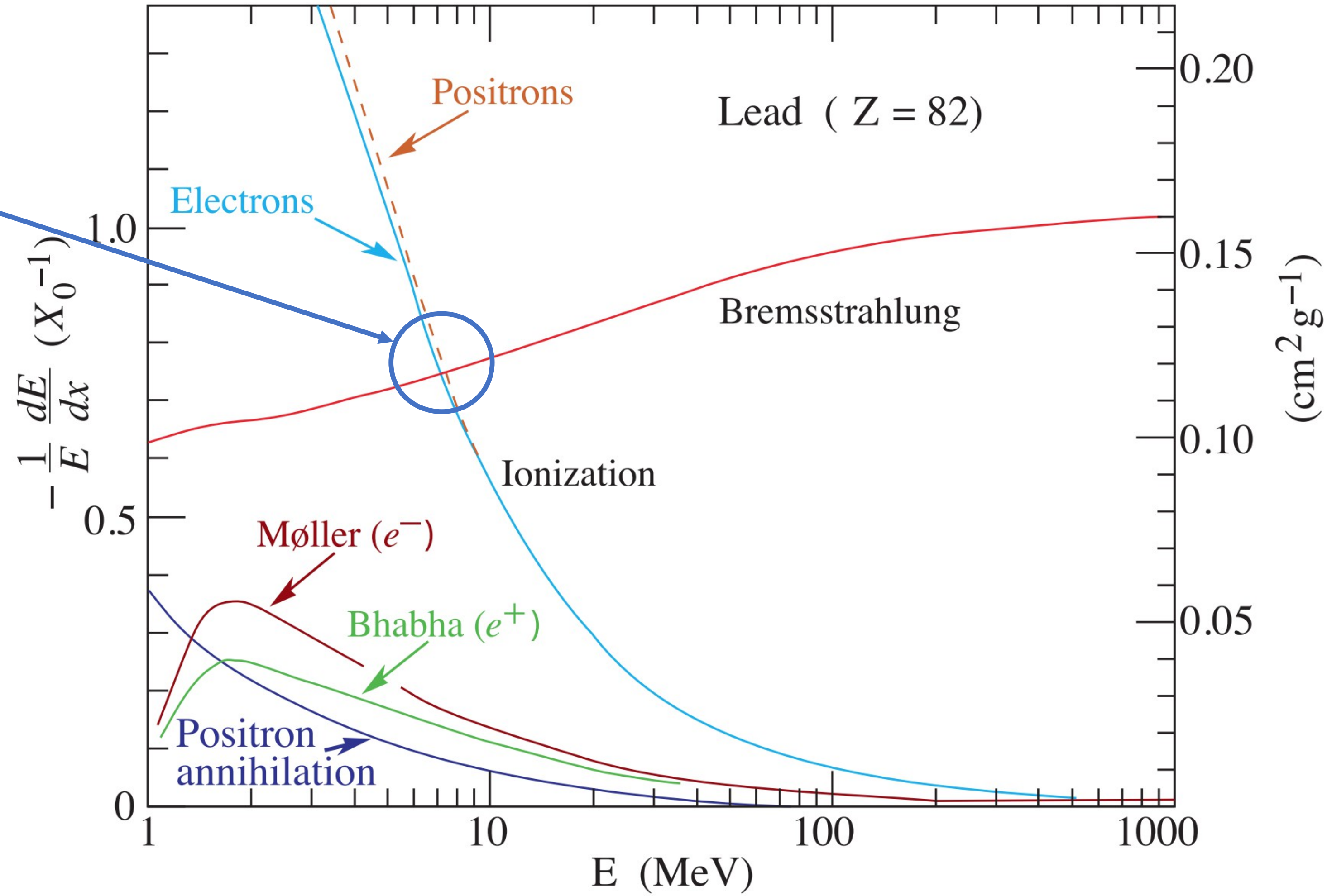
0.56cm for Lead

Processes initiated by electrons

Critical energy (E_c):
ionization and radiation are at the same level

$$E_c \propto \frac{1}{\mathrm{Z} + \mathrm{cte.}}$$

7 MeV for Lead



Processes initiated by photons

Photo-electric effect

$$\sigma \approx Z^5 \alpha^4 \left(\frac{m_e c^2}{E}\right)^{-7/2}$$

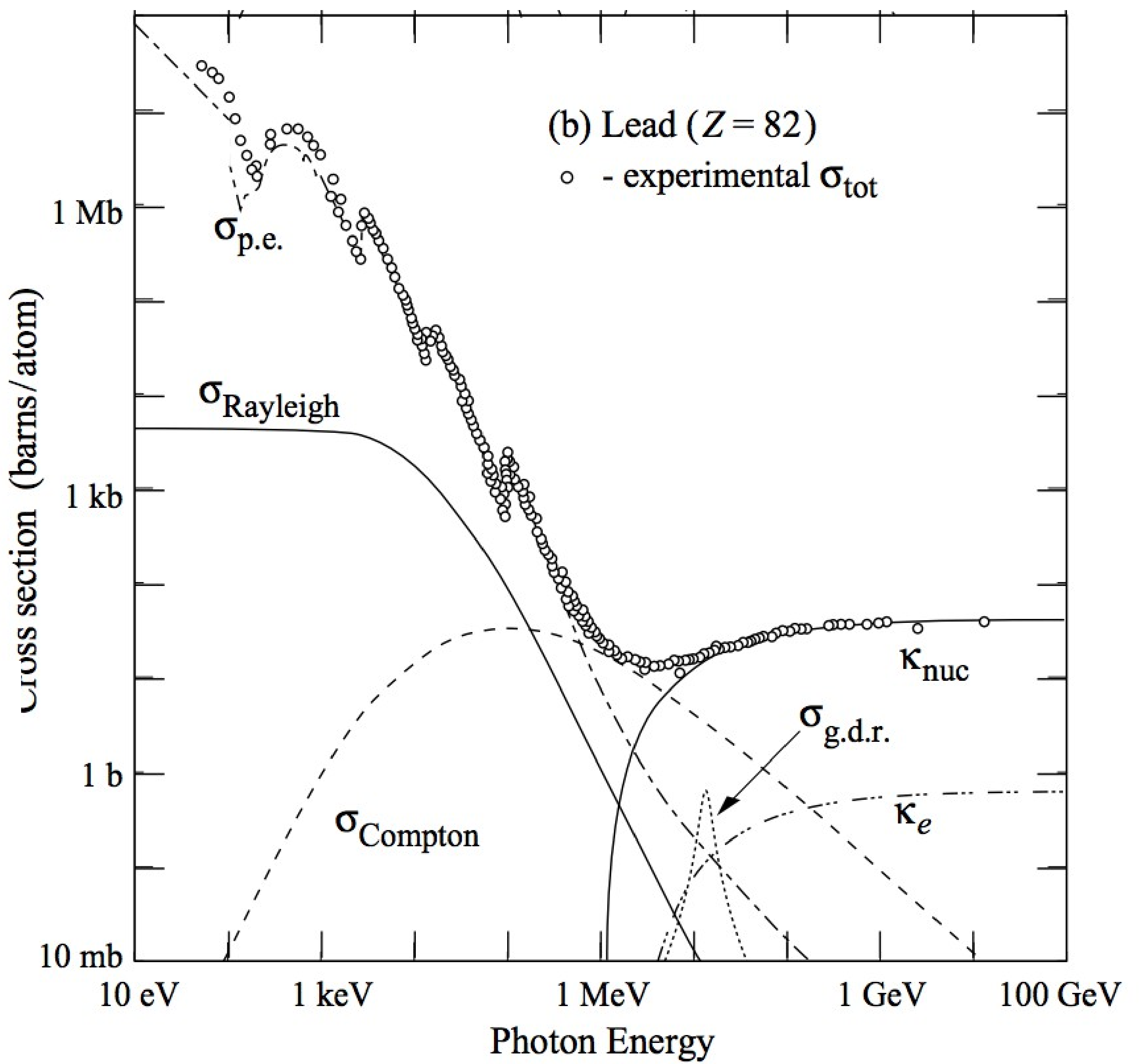
Compton scattering

$$\sigma \approx Z \frac{\log E}{E}$$

Pair production

$$\sigma \approx \frac{7}{9} \frac{A}{N_A} \frac{1}{X_0} \propto Z(Z+1)$$

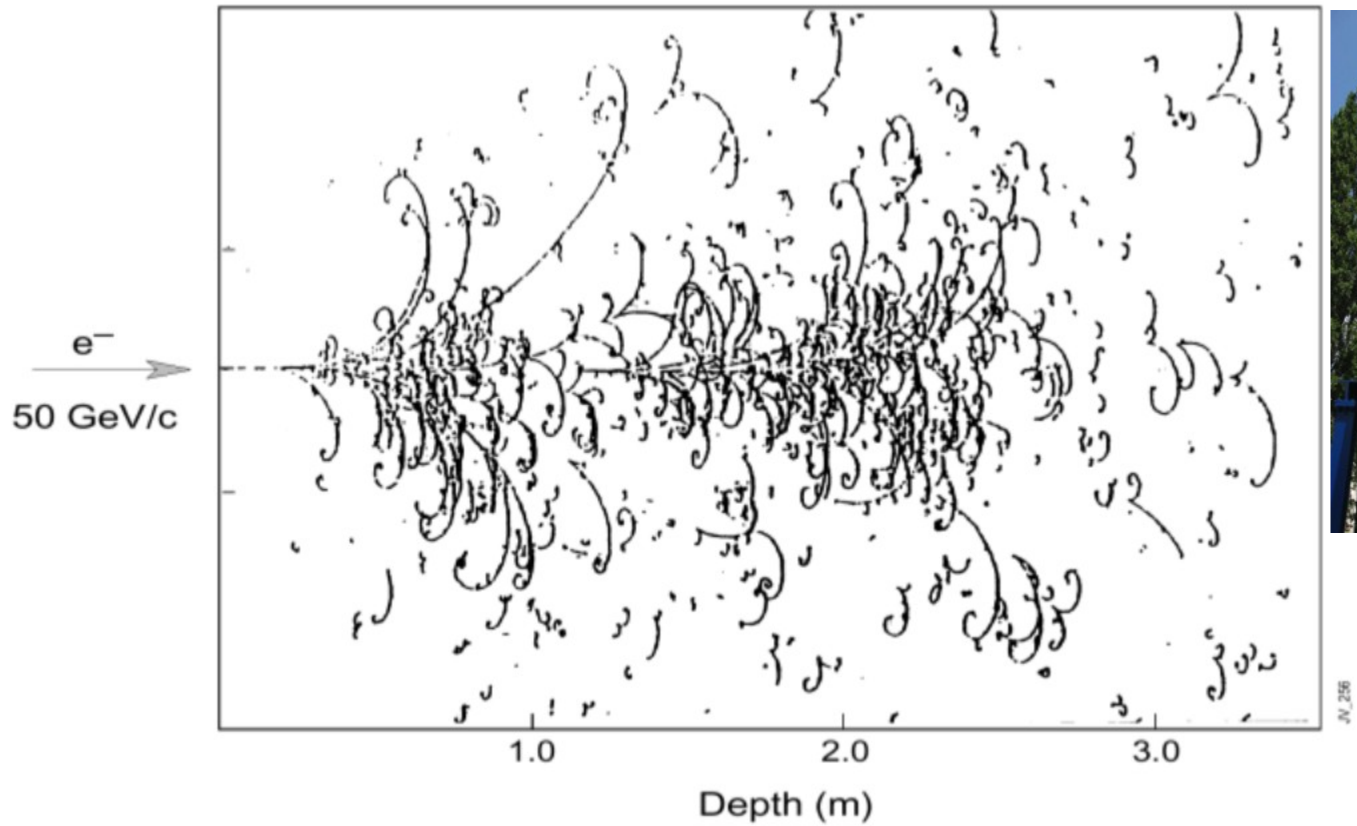
probability to convert after $1X_0$ is $e^{-7/9}$



Electromagnetic showers

High energy e/γ will start a cascade of pair production and bremmstrahlung

- multiplicative regime until secondaries start falling below E_c



e- in bubble chamber (70% Ne: 30% H2) under 3T field

Electromagnetic showers

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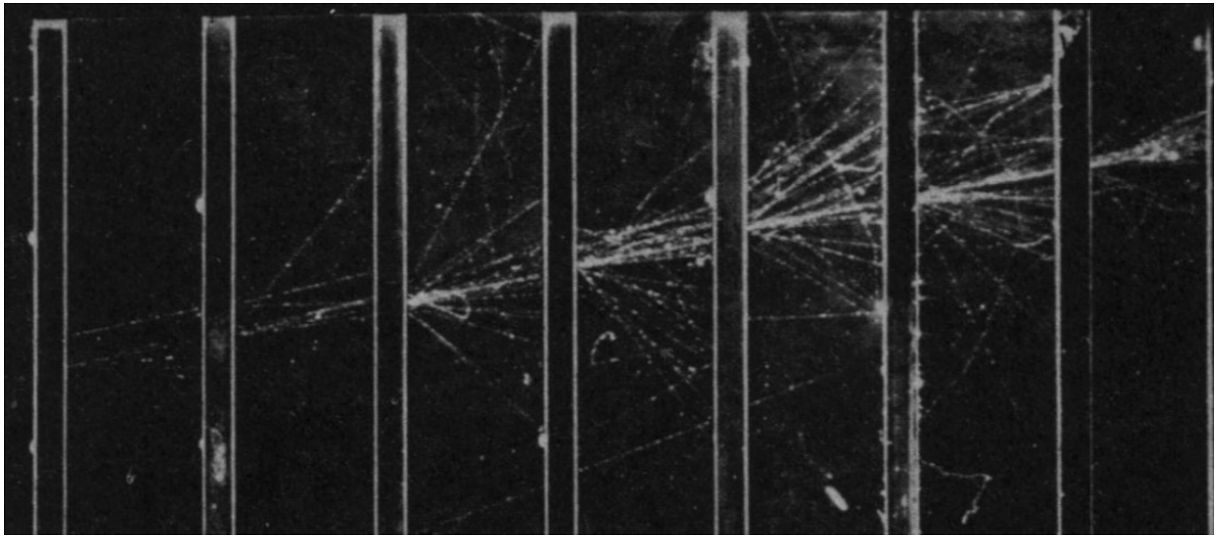
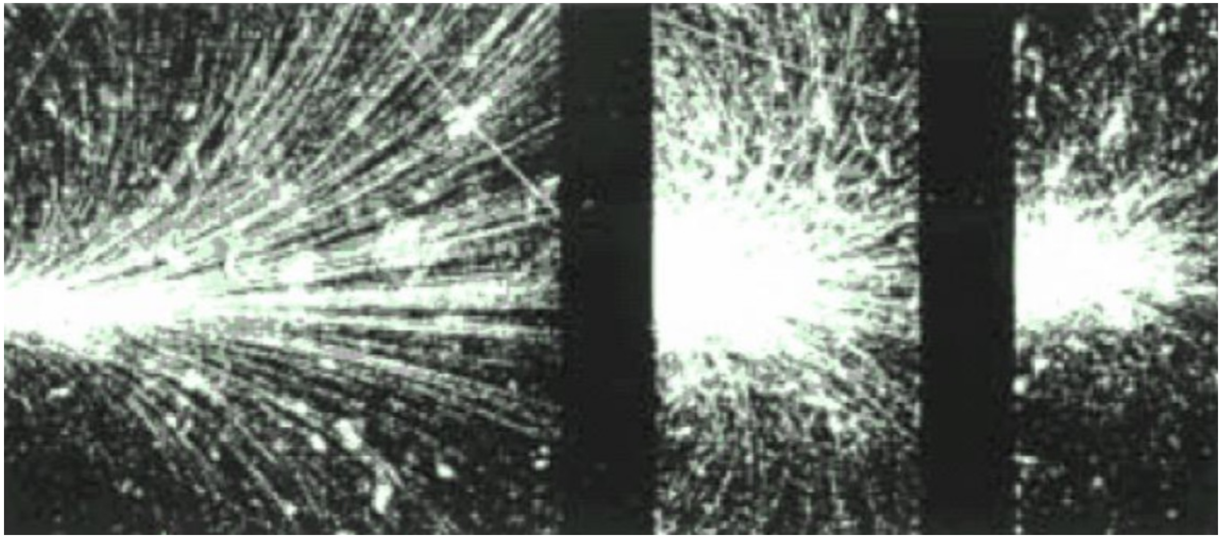
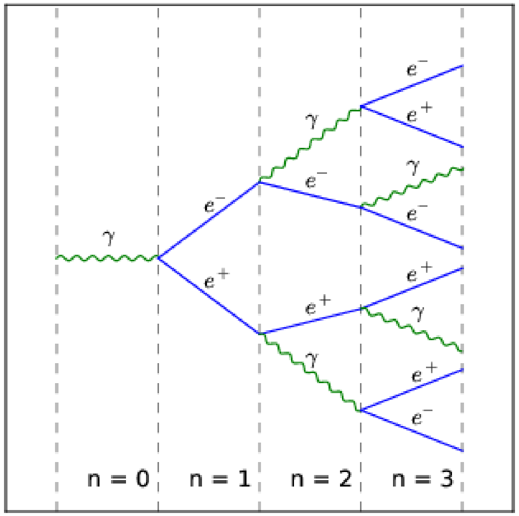




showers from two different energy photons in bubble chambers

A toy model for electromagnetic showers



Start with a pair conversion followed by radiation,… E → E/2 → E/4 → …

Scaling properties

$$\boxed{N(x) = 2^{x/X_0}}$$

$$\boxed{E(x) = E_0 \ / \ 2^{x/X_0}}$$

Splitting energy reaches EC limit, shower starts to be absorbed

$$\boxed{x_{max} = X_0 \log_2 \frac{E}{E_c}}$$

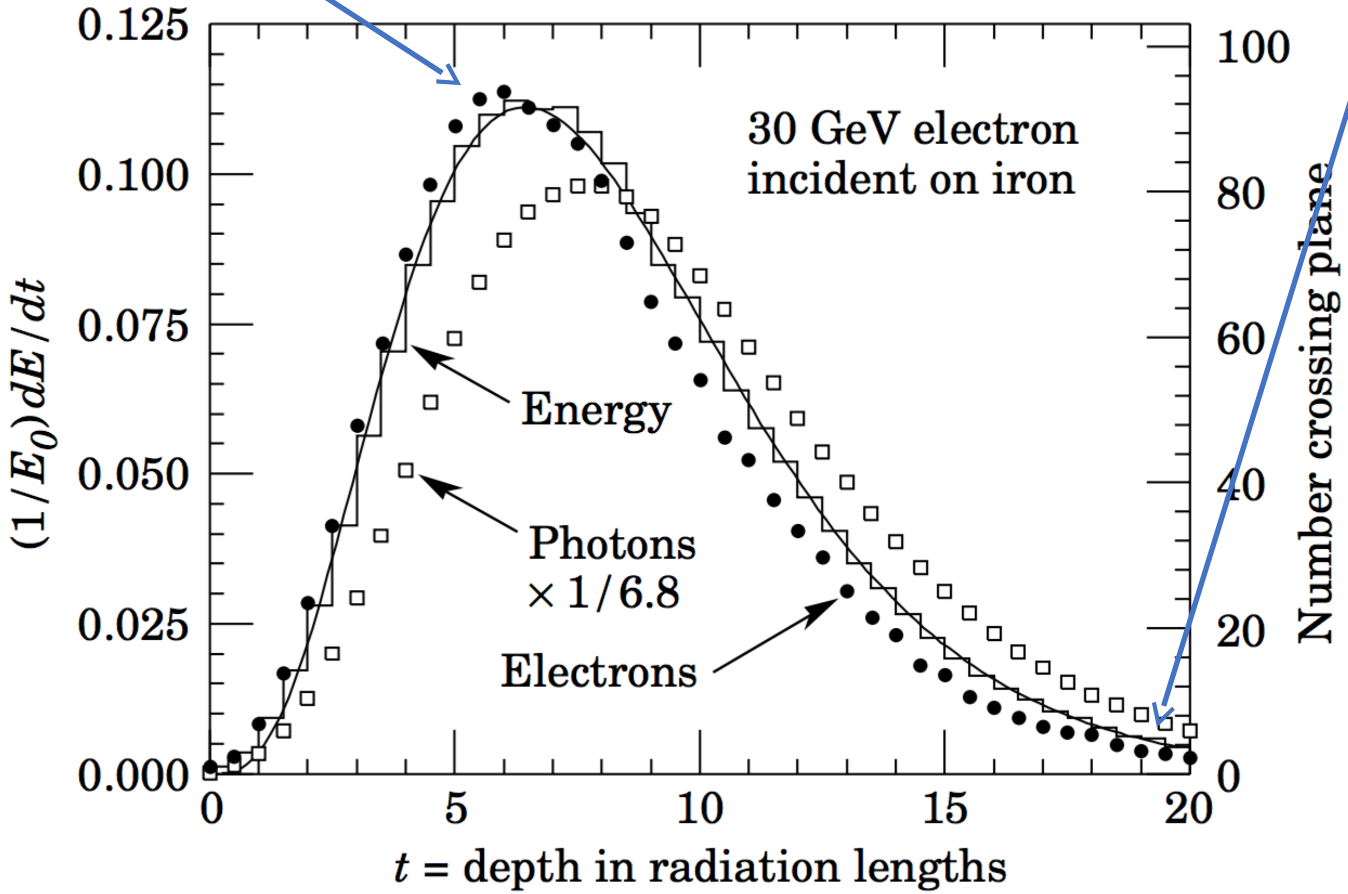
$$\boxed{E_{max} = E_0 / E_c}$$

not so far from reality

Detailed simulation of an electromagnetic shower

$$t_{max} \approx \log \frac{E}{E_c} \pm 0.5$$

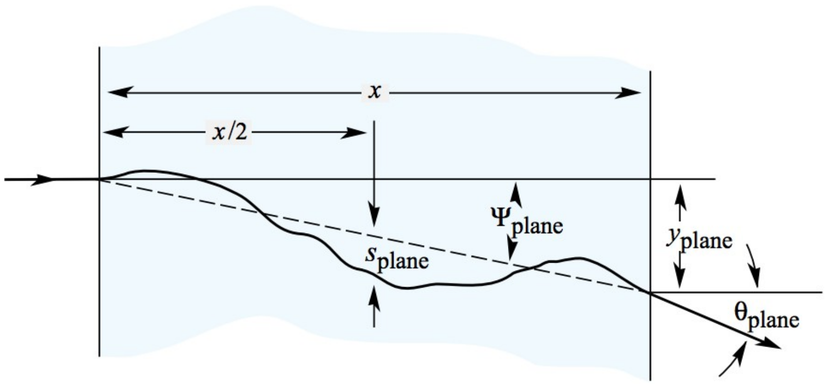
$$t_{95\%} = t_{max} + 0.08Z + 9.6$$



Spread in the transverse plane

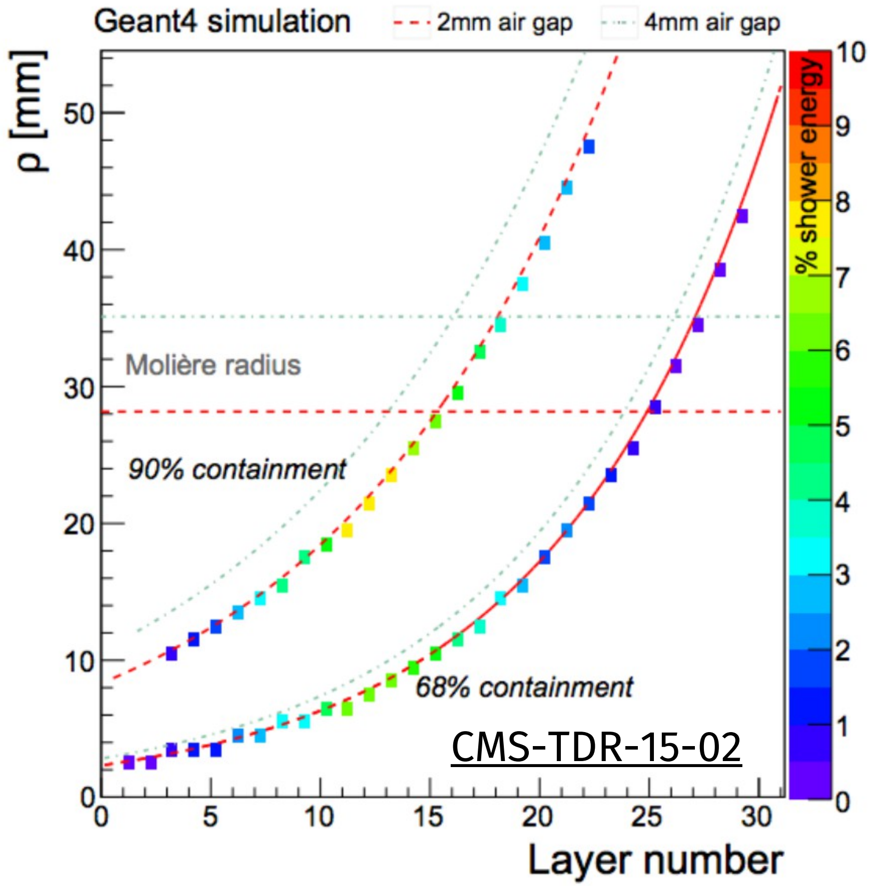
Particles disperse with respect to initial axis

- decay openings
- multiple scattering of charged particles
- γ in the region of minimal absorption traveling longer



- **Define the Moliere radius as lateral size containing 90% of the shower energy**

$$R_M = \frac{21\ MeV}{E_c} X_0 \propto \frac{A}{Z}$$



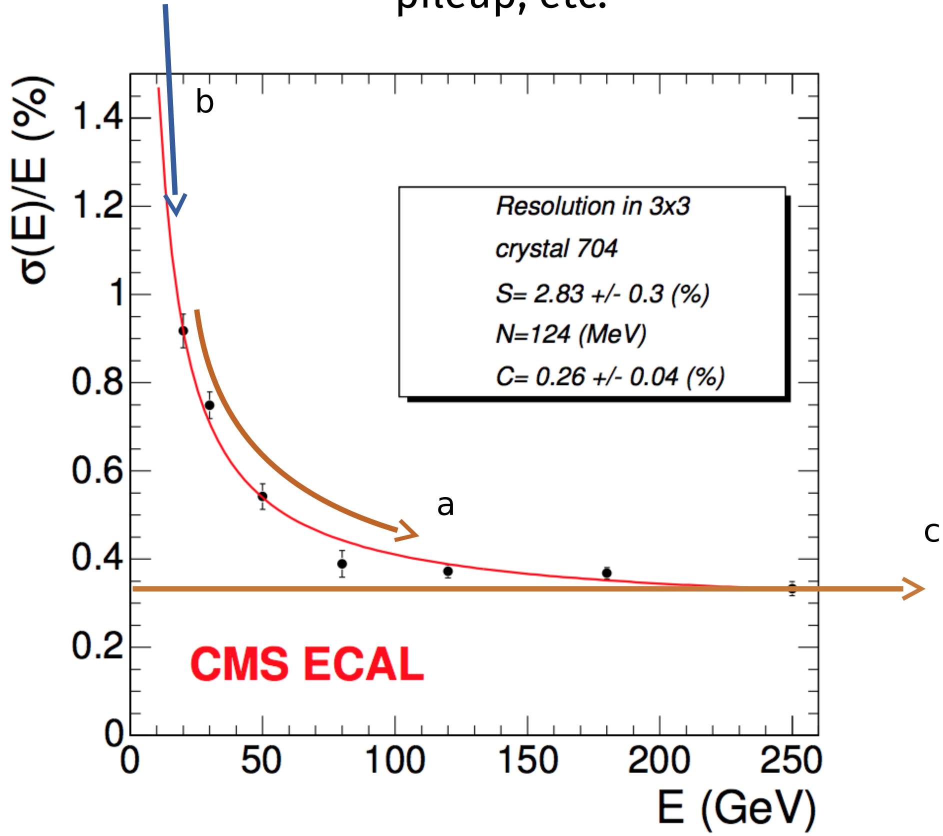
Electromagnetic energy resolutions

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Stochastic term - fluctuations in the shower development, energy deposited. Enhanced if sampling is made, if Cerenkov radiation starts later, etc.

Noise term - additional degradation at low energy due to electronics noise, pileup, etc.

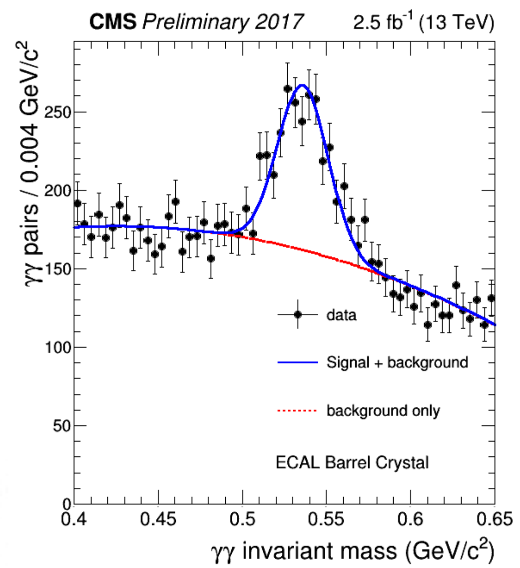
Constant term - energy leakage, calibration, non uniformity, radiation damage, ...



Some challenges in maintaining energy resolution

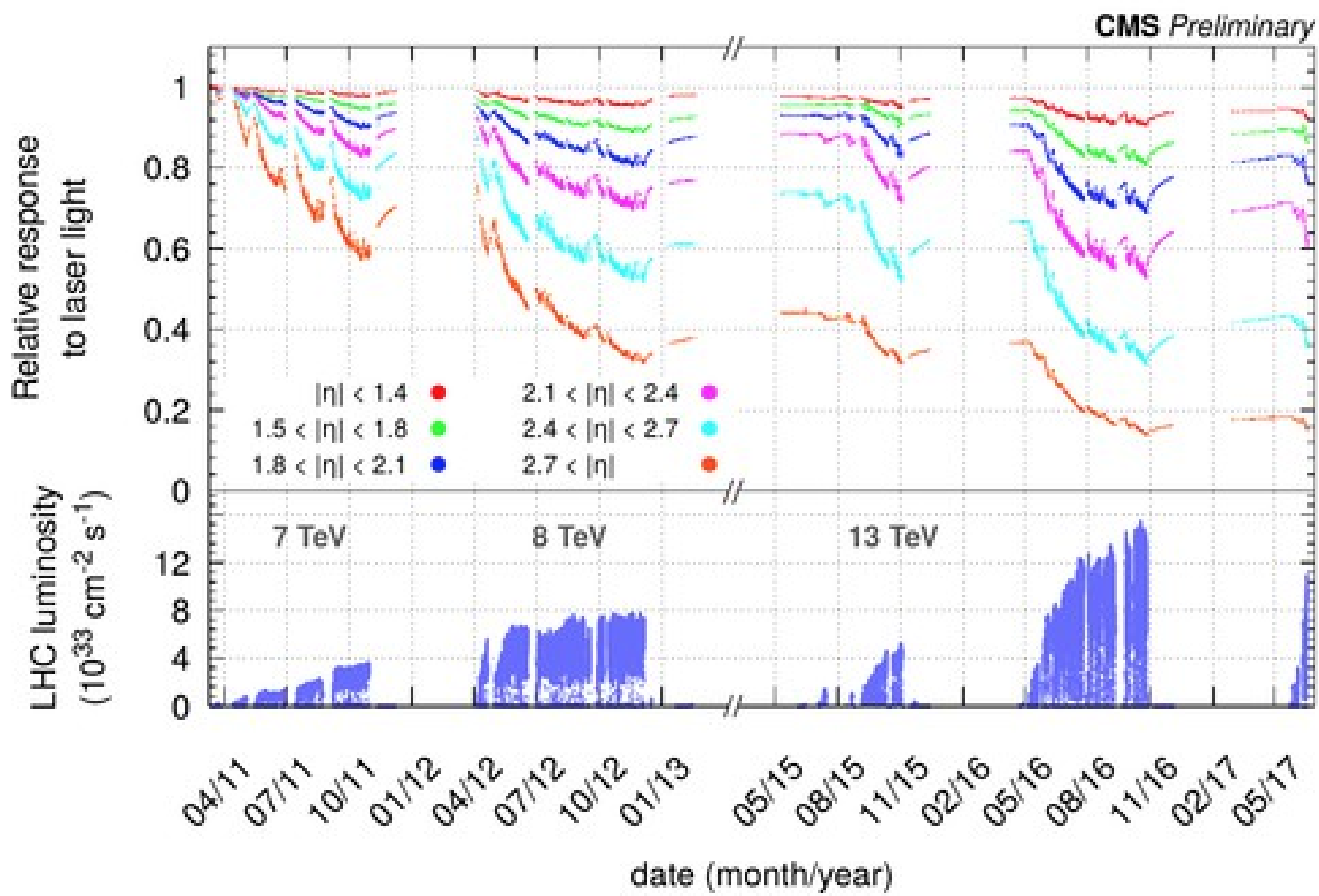
Intercalibration between cells needs to attain 1% level or better

- use $\eta/\pi^0 \to \gamma\gamma$, $Z \to ee$ and ϕ symmetry in minimum bias events



Track radiation damage / recovery of the crystals with a laser

- inject light into crystals and normalize to PN diodes

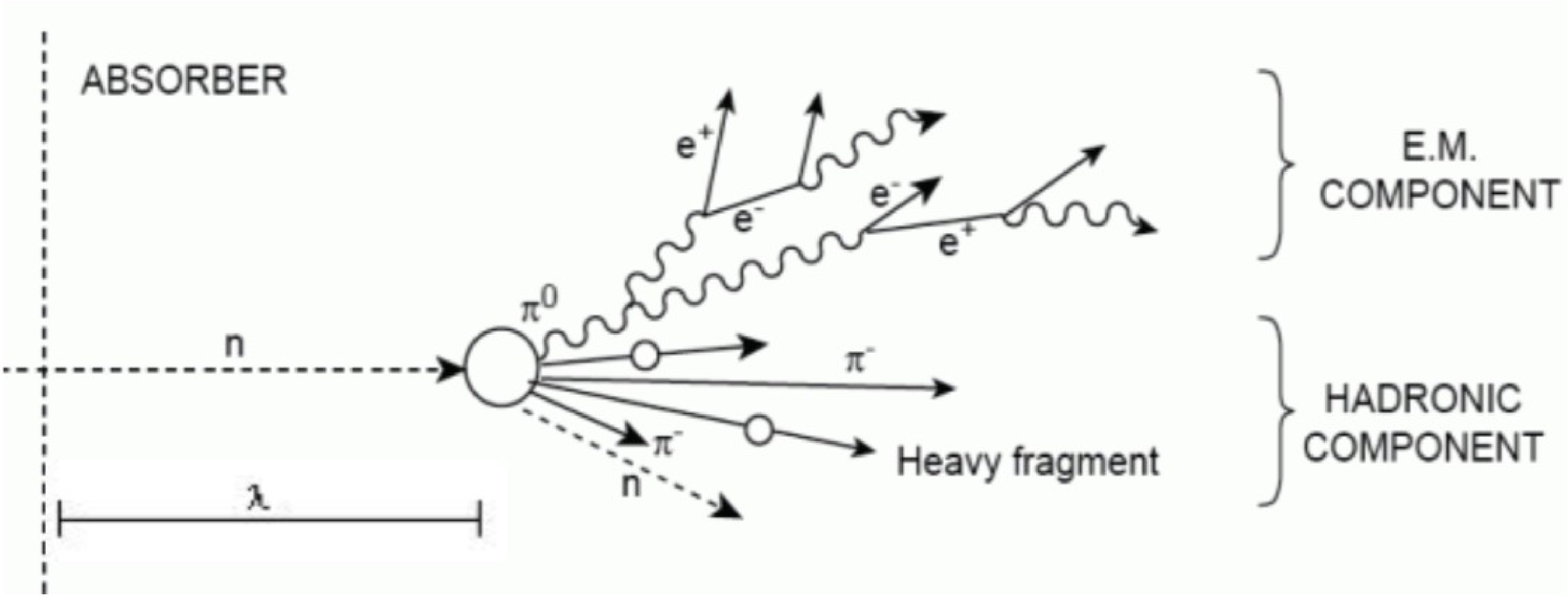


A comparison of different e.m. calorimeters

Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/\mathrm{E}^{1/4}$	1983
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	$16–18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5$ GeV	1998
$PbWO_4$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
Lead glass (OPAL)	$20.5X_0$	$5\%/\sqrt{E}$	1990
Liquid Kr (NA48)	$27X_0$	$3.2\%/\sqrt{E} \oplus 0.42\% \oplus 0.09/E$	1998
Scintillator/depleted U (ZEUS)	$20–30X_0$	$18\%/\sqrt{E}$	1988
Scintillator/Pb (CDF)	$18X_0$	$13.5\%/\sqrt{E}$	1988
Scintillator fiber/Pb spaghetti (KLOE)	$15X_0$	$5.7\%/\sqrt{E} \oplus 0.6\%$	1995
Liquid Ar/Pb (NA31)	$27X_0$	$7.5\%/\sqrt{E} \oplus 0.5\% \oplus 0.1/E$	1988
Liquid Ar/Pb (SLD)	$21X_0$	$8\%/\sqrt{E}$	1993
Liquid Ar/Pb (H1)	$20–30X_0$	$12\%/\sqrt{E} \oplus 1\%$	1998
Liquid Ar/depl. U (DØ)	$20.5X_0$	$16\%/\sqrt{E} \oplus 0.3\% \oplus 0.3/E$	1993
Liquid Ar/Pb accordion (ATLAS)	$25X_0$	$10\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996

Hadronic showers

What is an hadronic shower?



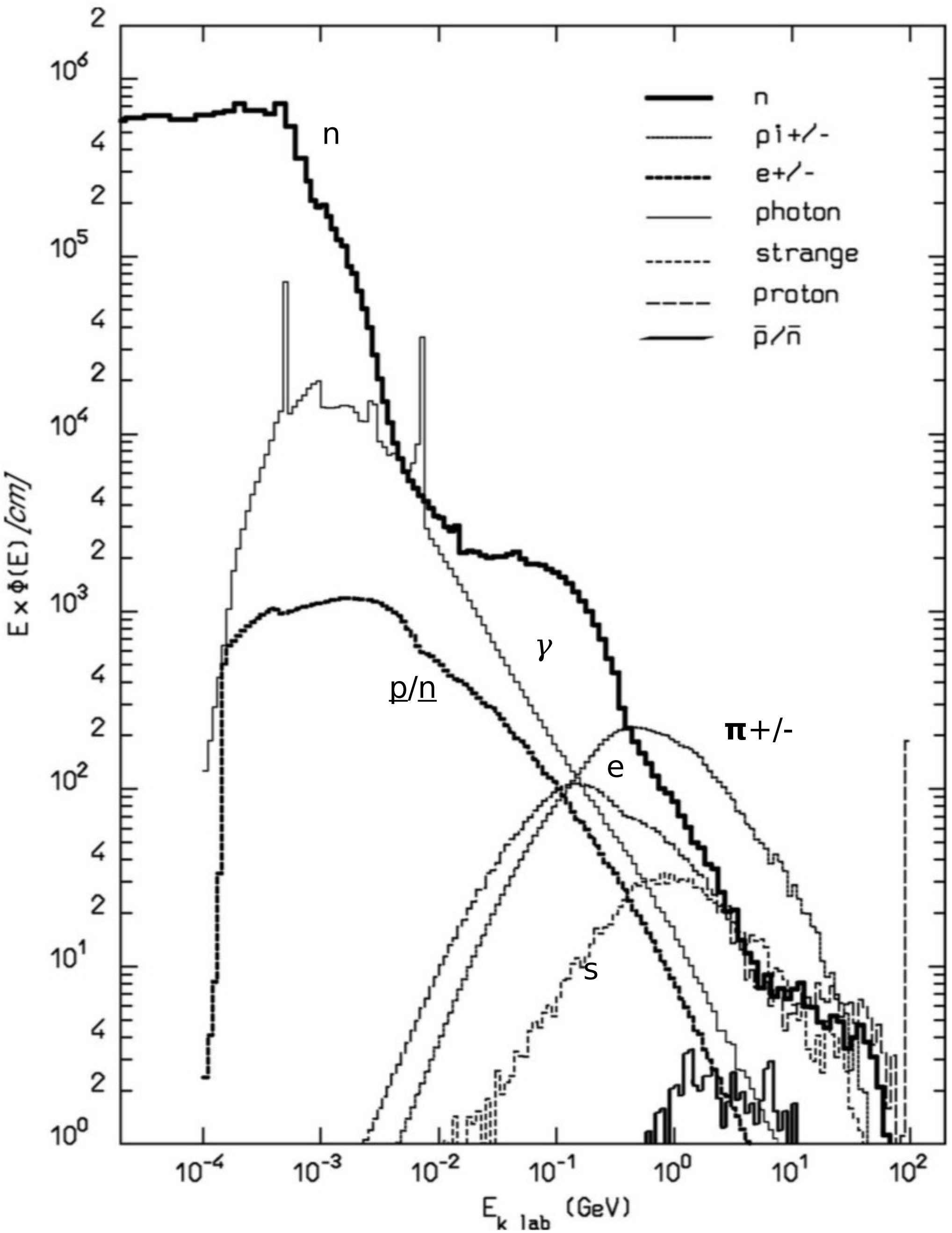
Charged pions, kaons, protons, neutrons, etc…

Products of strong interactions will start "mixed" showers

Requires longer containment than e.m showers

Particle spectra in a proton shower

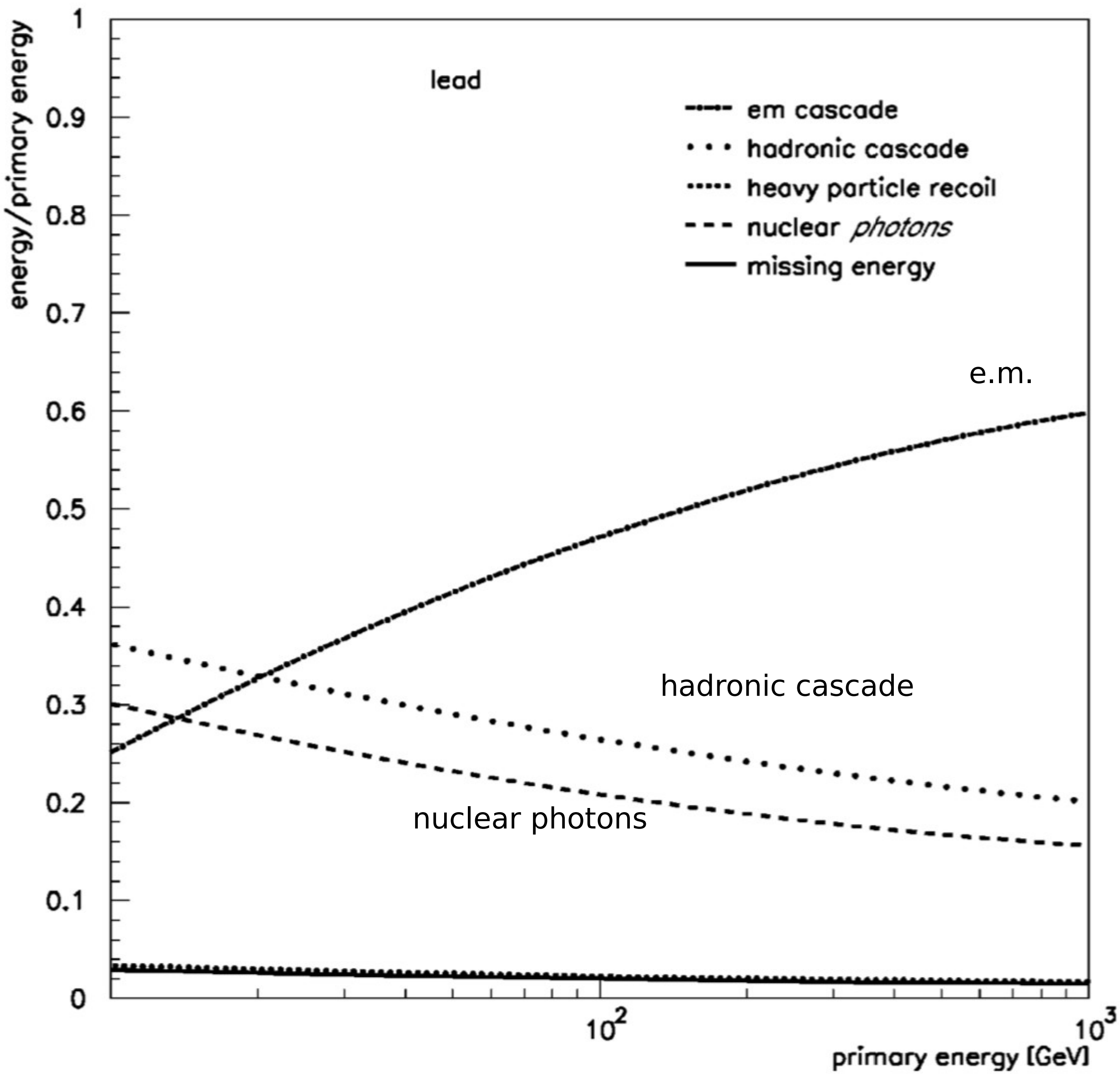
Showers depend heavily on the incident particle (type and energy) …



Based on simulation. The integral of each curve gives the relative fluence of each particle. →

Particle spectra in a proton shower

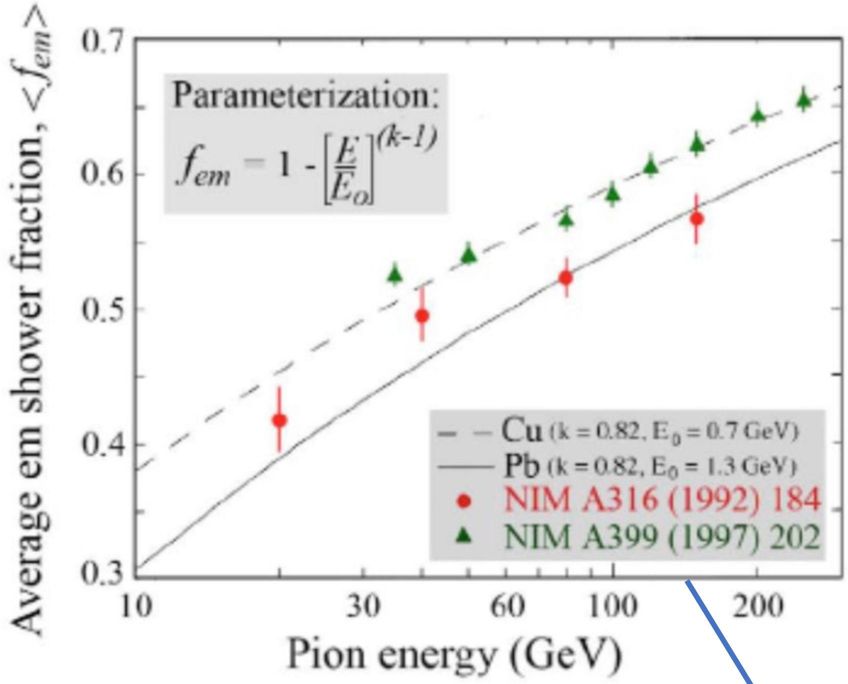
Showers depend heavily on the incident particle (type and energy) ...



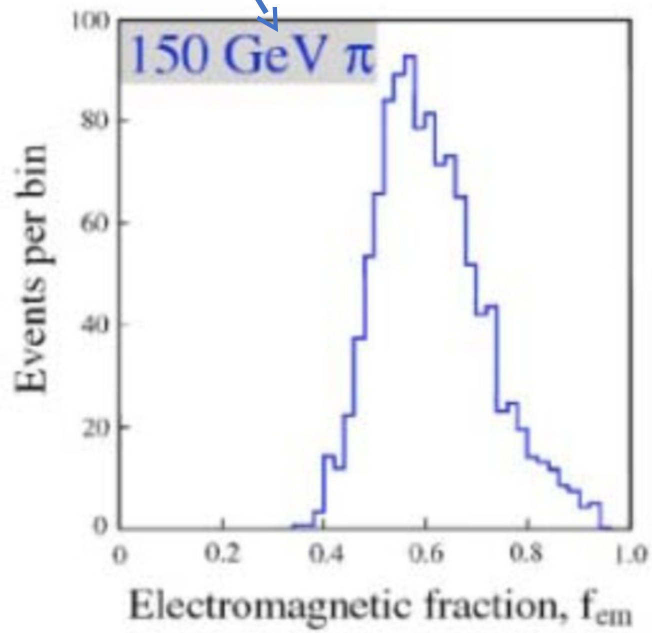
Based on simulation. →

Particle spectra in a proton shower

Showers depend heavily on the incident particle (type and energy) ...



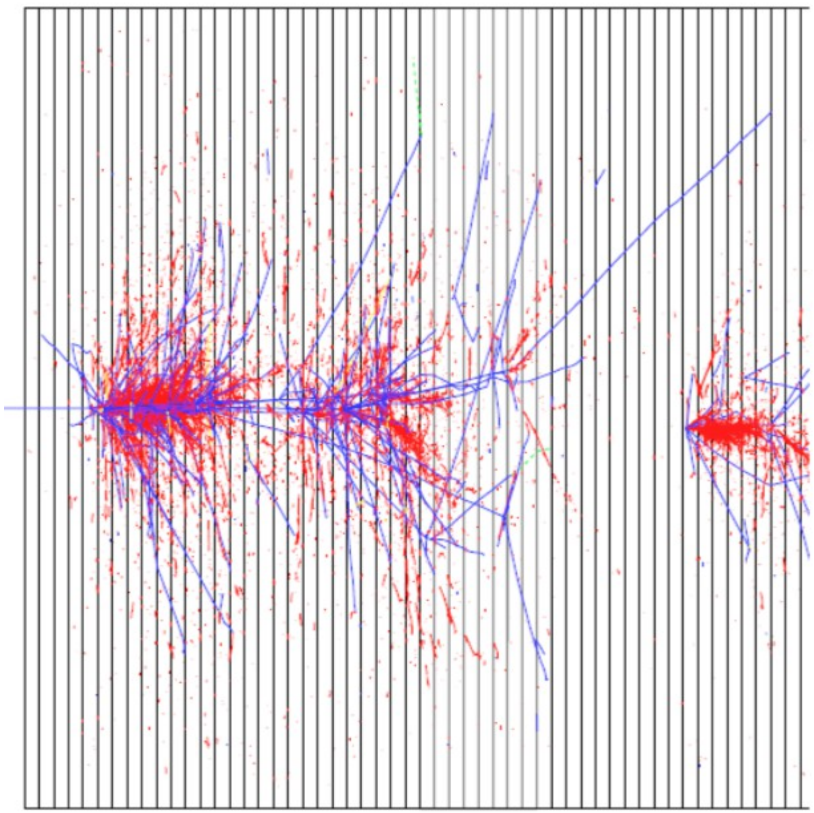
...and fluctuations are non-gaussian!

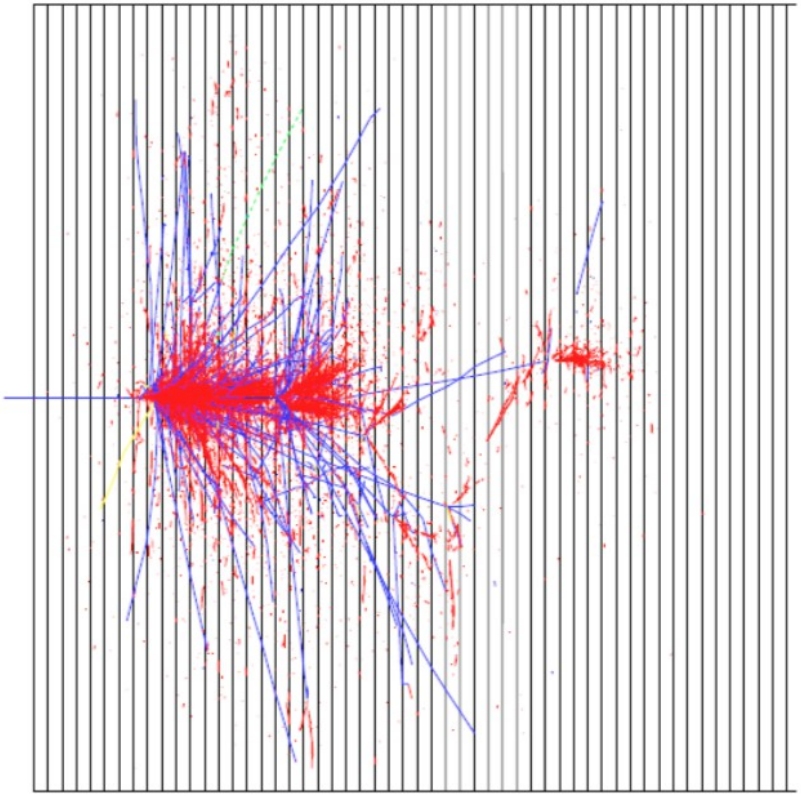


Hadronic showers are unique

There are never two alike and need to be analyzed case-by-case

- hardware compensation: enhance the nuclear energy through materials
- high granularity calorimeter: enable feature extraction and cluster-by-cluster calibration
- dual-readout: measure the e.m. energy fraction
- particle flow: calorimeter identifies particle type, energy used only if no track





e.m. (hadronic) component is shown in red (blue)

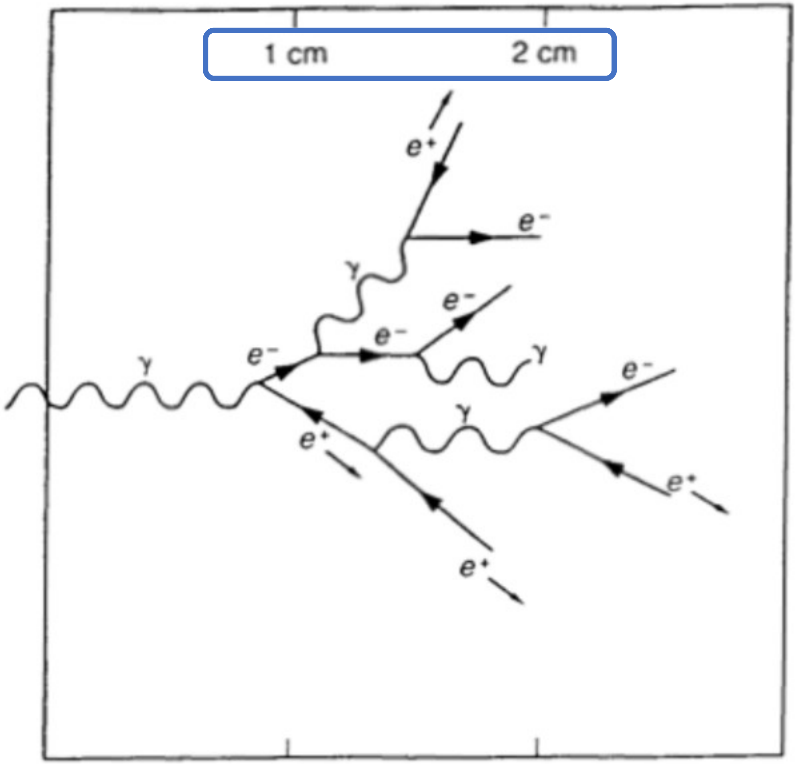
Containment of an hadronic shower

The interaction length quantifies the mean distance before undergoing a nuclear interaction

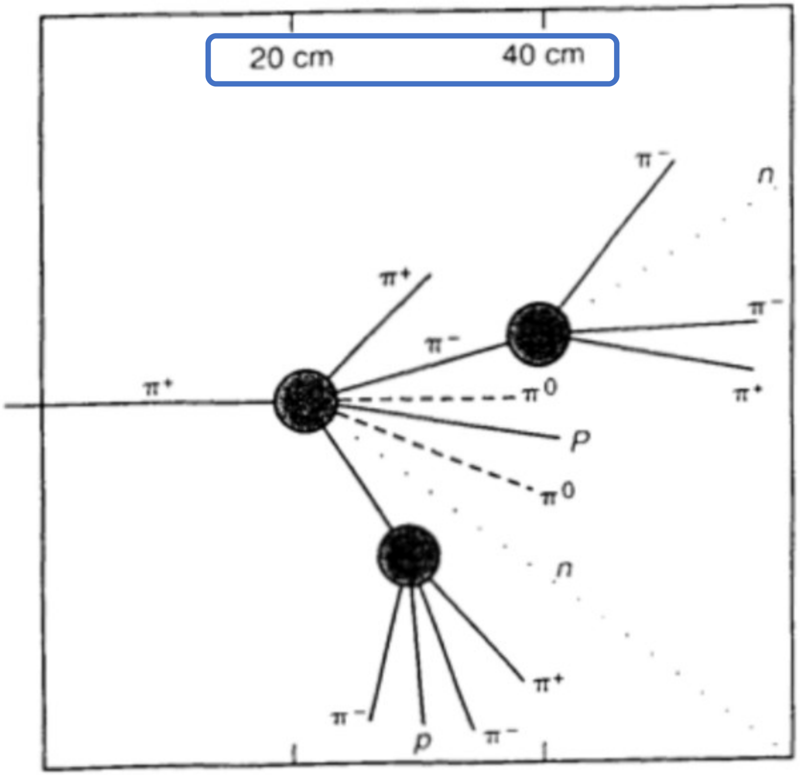
Interaction length (λ) is significantly larger than the radiation length (X_0)

$$\boxed{\lambda = 35\ A^{1/3} \mathrm{g/cm}^2}$$

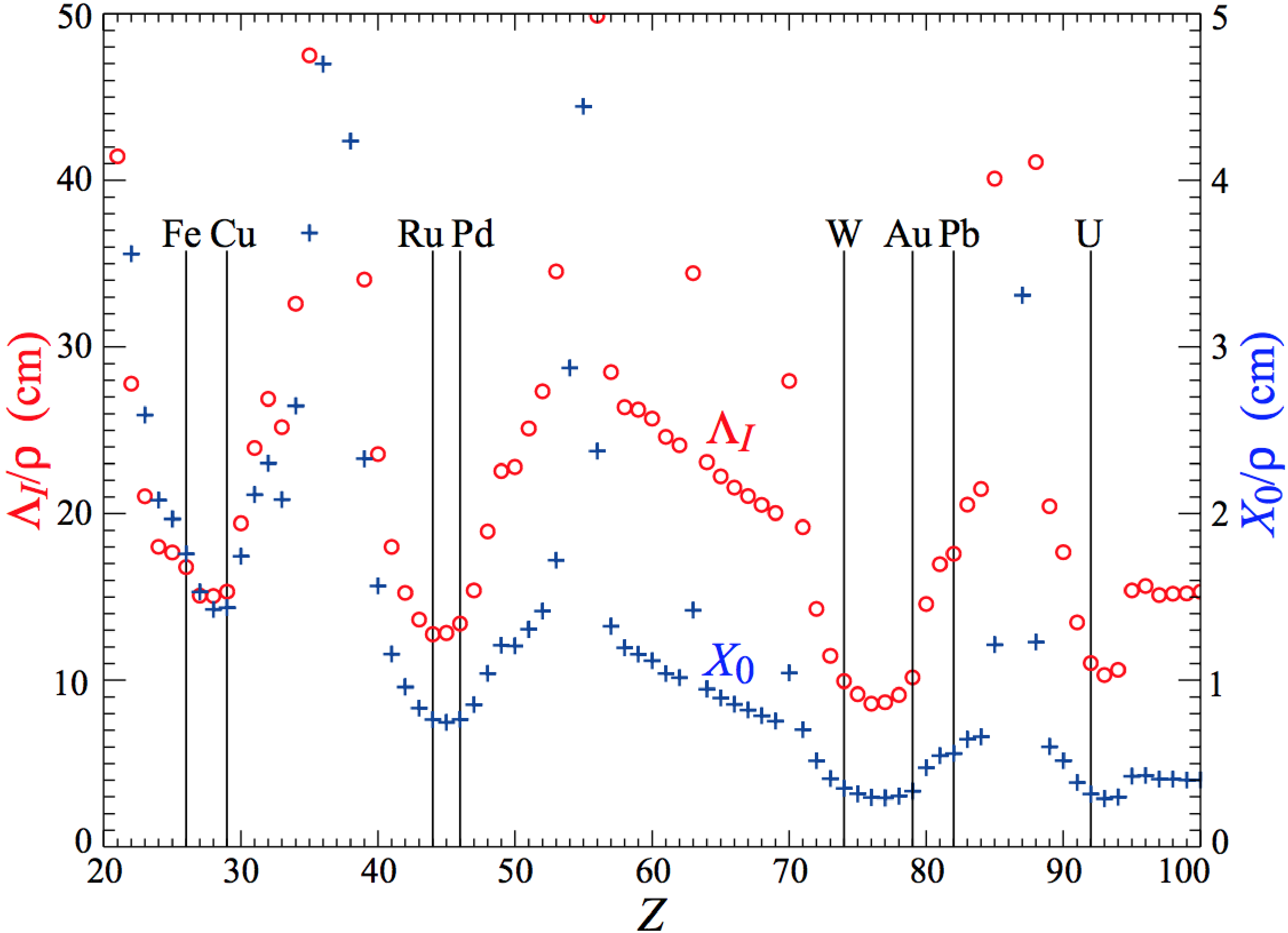
e.m. shower



hadronic shower



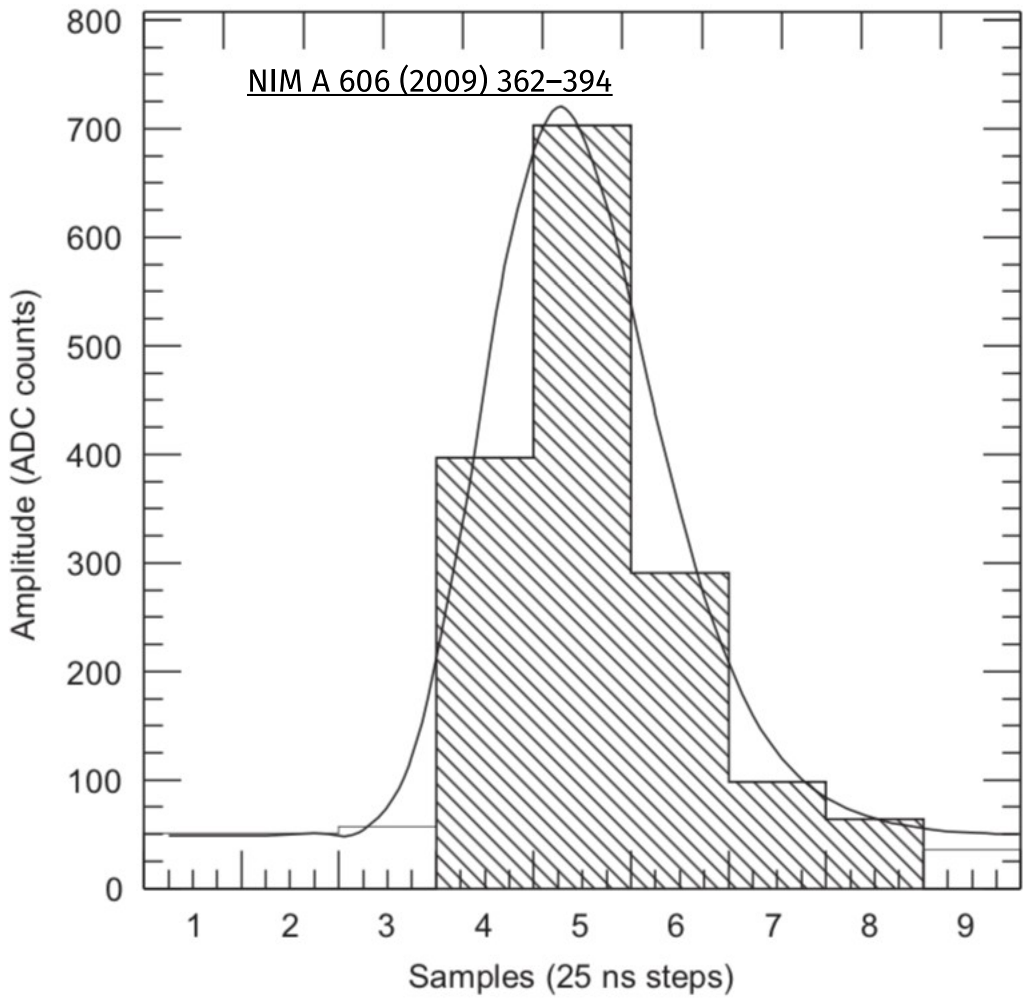
Characteristics of different materials



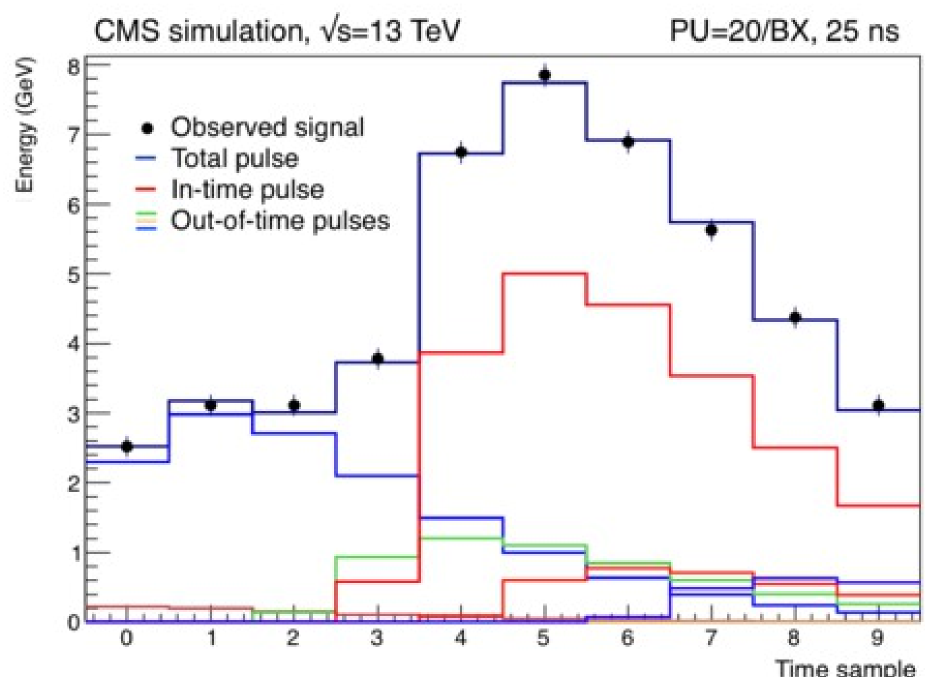
Energy reconstruction I

Need to gather energy spread in time: integrate pulse shape by weighting / fitting

- calorimeters often need more time to integrate signals with respect to tracking devices
- hadron showers: slow neutron component can appear significantly delayed in time (>100ns)



...and then there is pileup

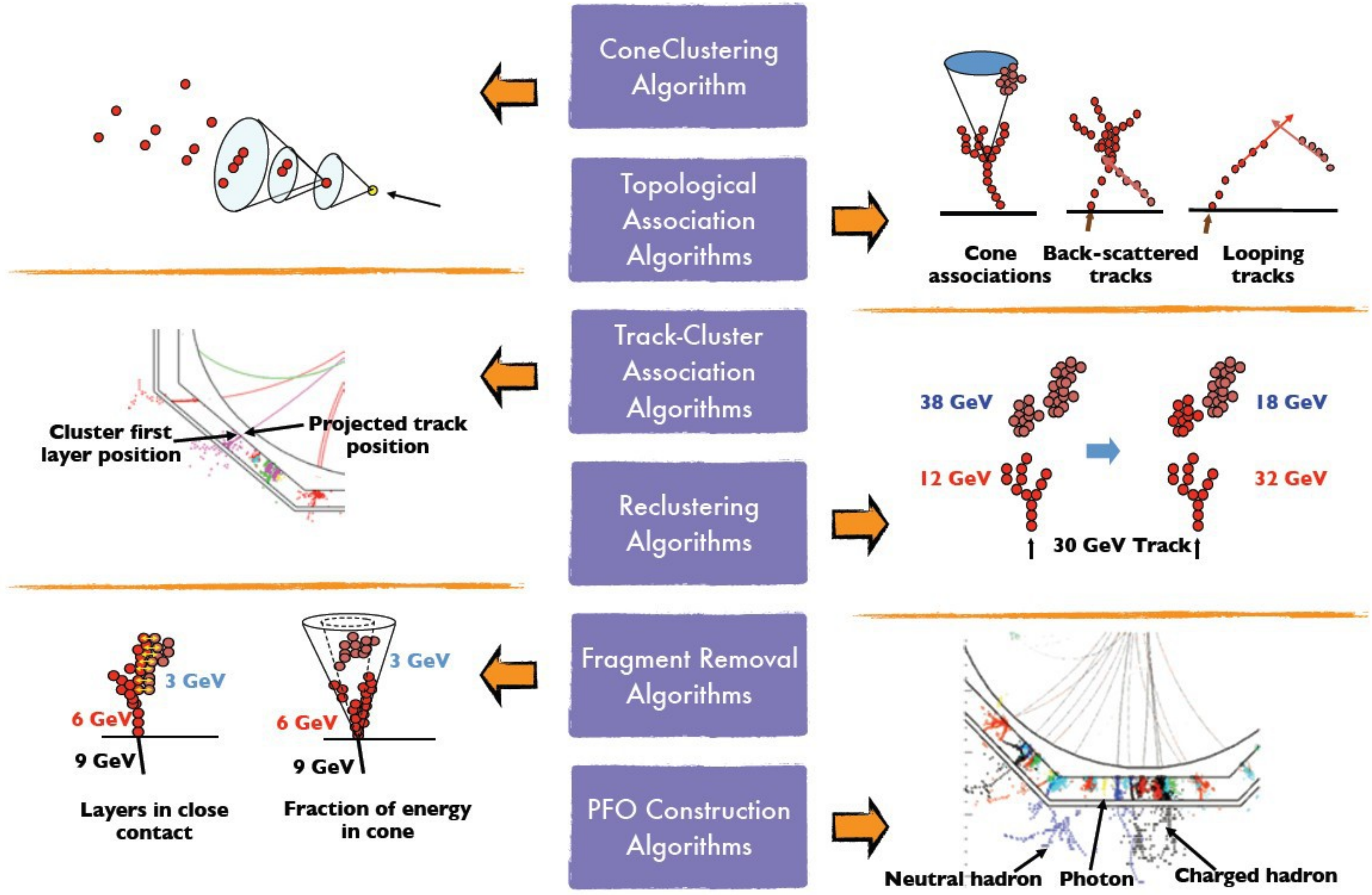


CMS DPS 2015-016

Energy reconstruction II

Need to gather energy spread in space : clustering algorithms are needed

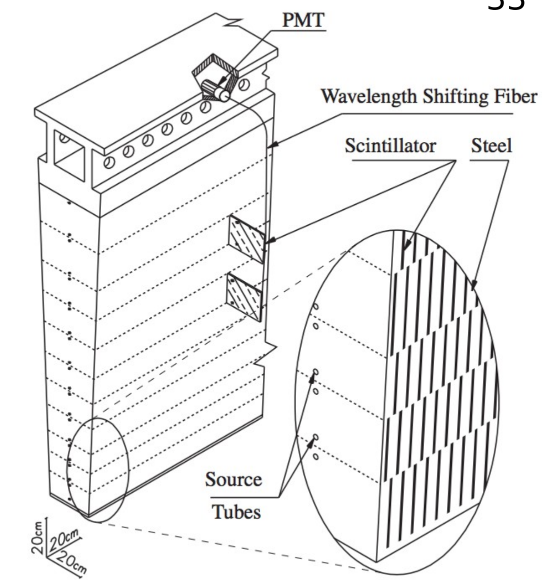
- algorithm needs to be adapted to the particle, segmentation, material upfront, shower components
- often several iterations needed, depending on how busy an event is

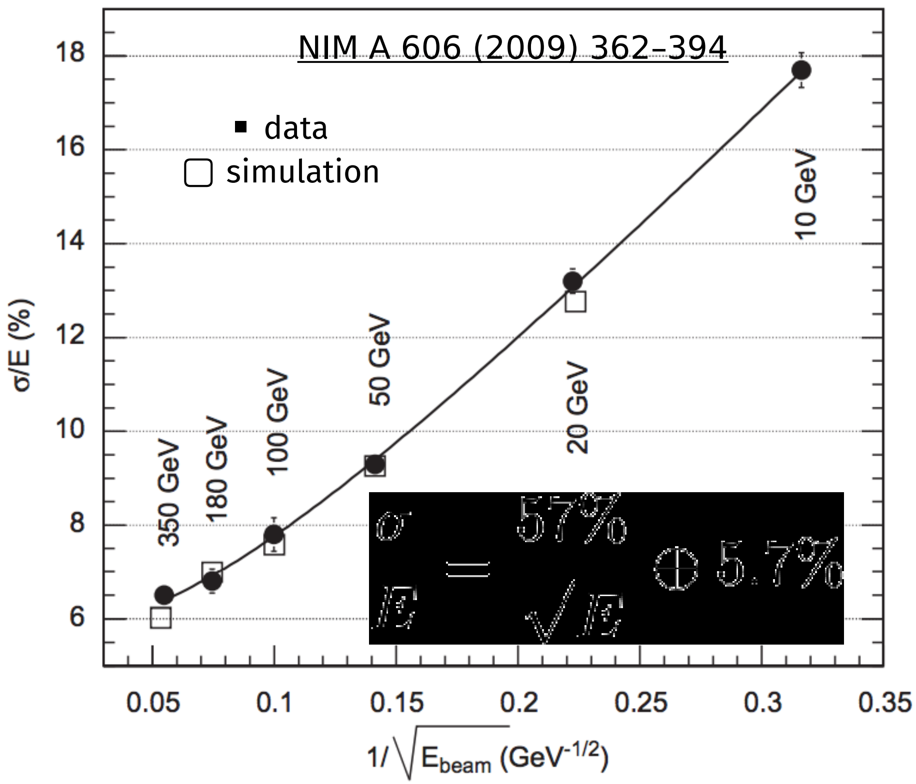


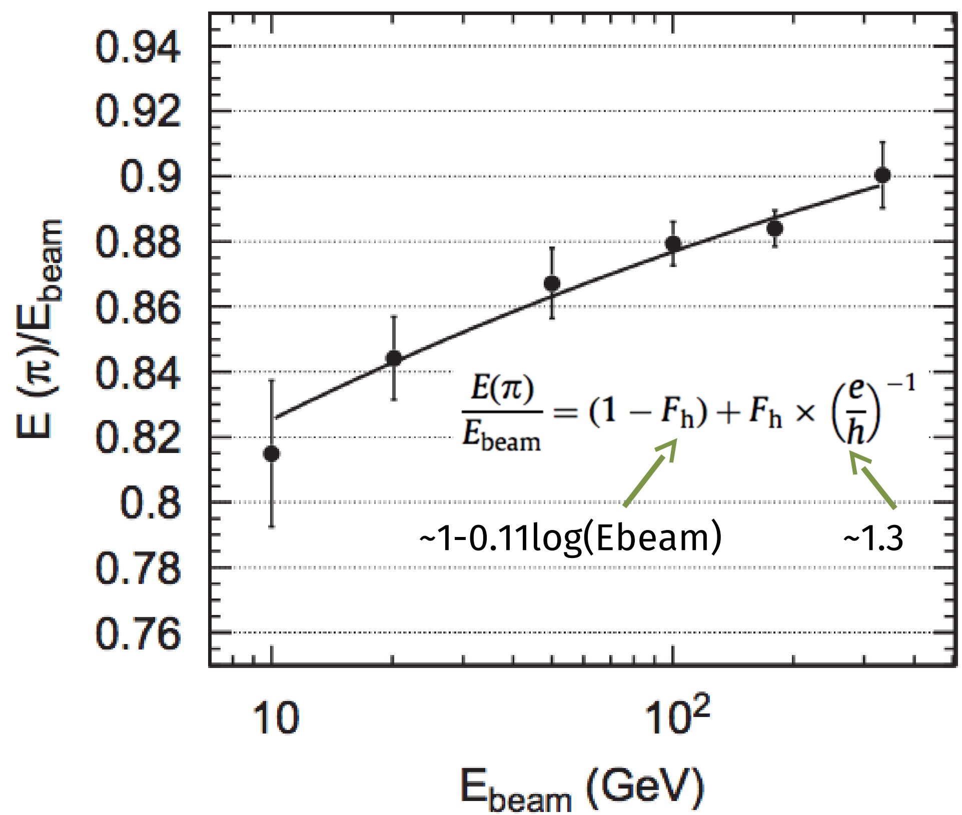
typical PF algorithms (implemented in Pandora)

Resolutions and response - ATLAS TileCal

- **Typically hadronic calorimeters exhibit**
  - non-linearity, different response to e/γ and hadrons (compensation)
  - significantly poorer resolutions compared to e.m. Calorimeters
  - Both characteristics are present in the ATLAS TileCal

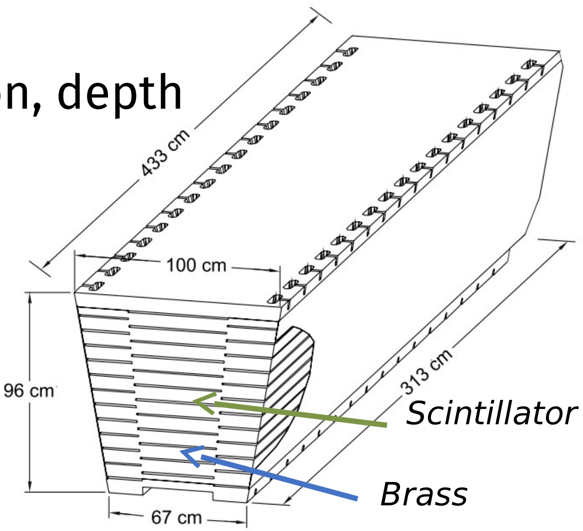




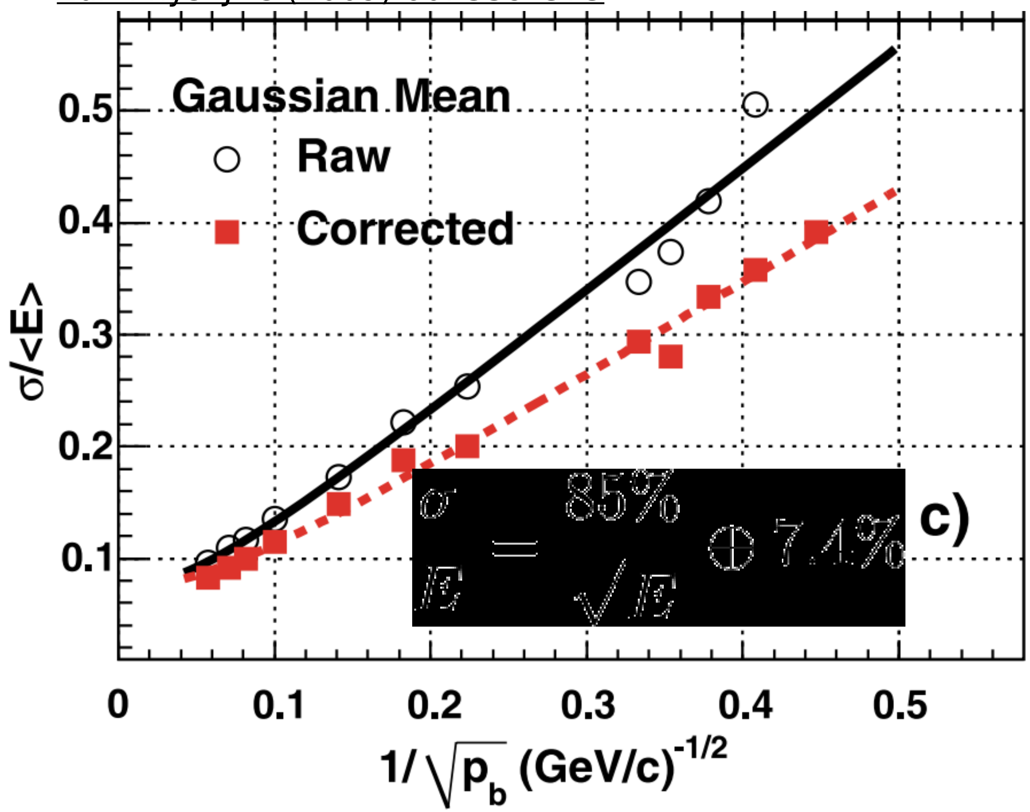


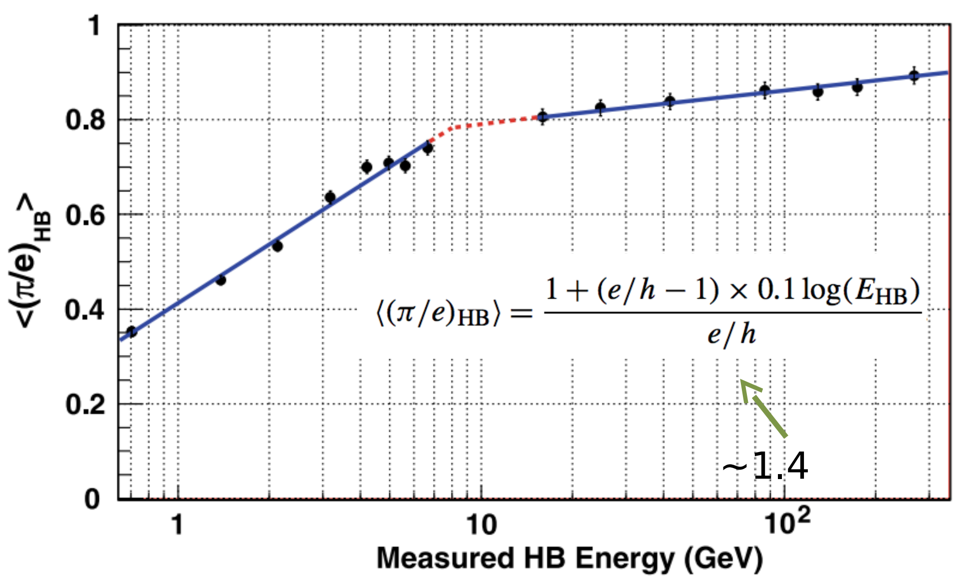
Resolutions and response - CMS HCAL

- Performance is mainly driven by materials used, segmentation, depth
  - but also material upfront and readout
  - partially compensated by reconstruction (next slide)

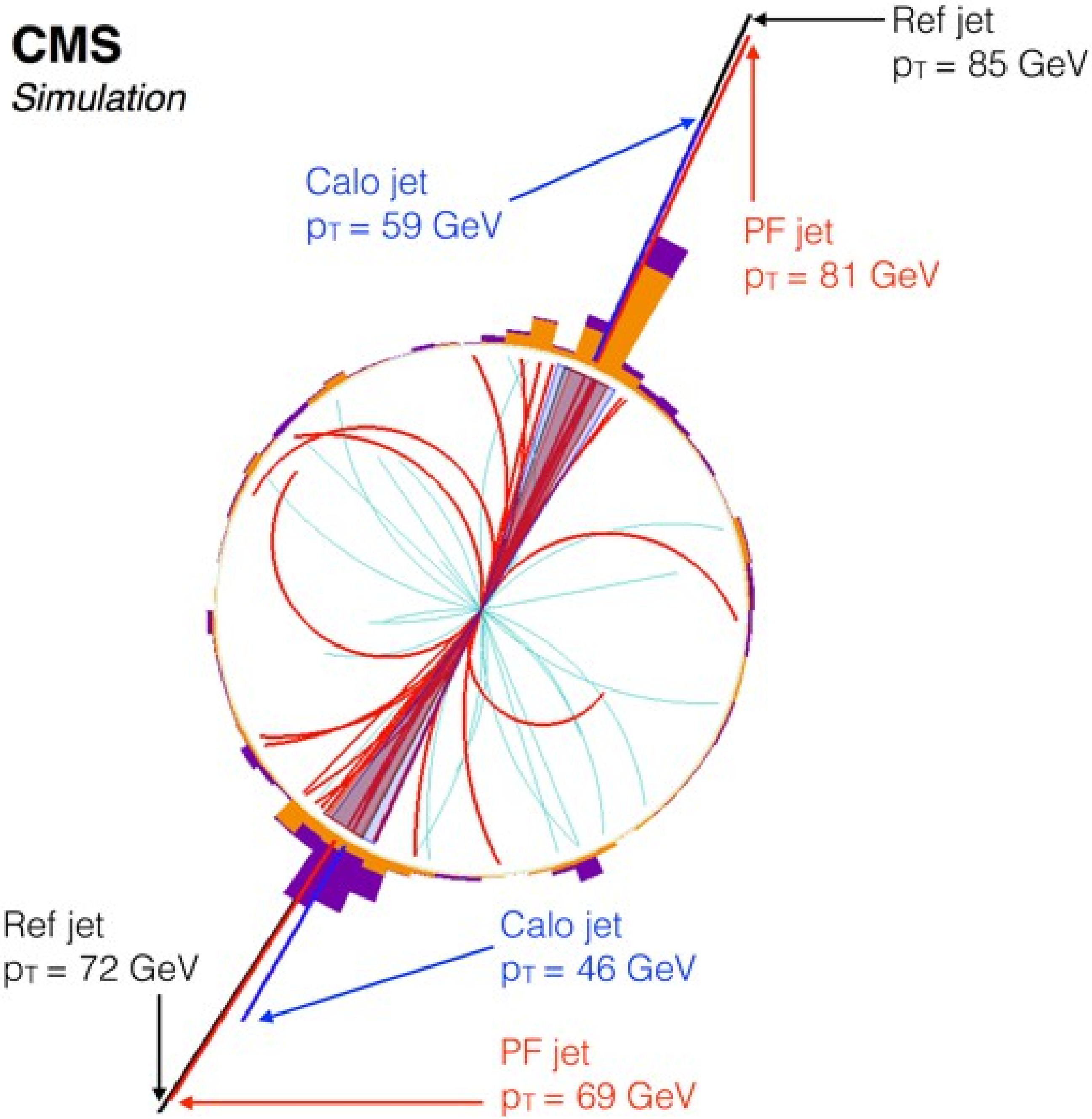


Eur. Phys. J. C (2009) 60: 359–373





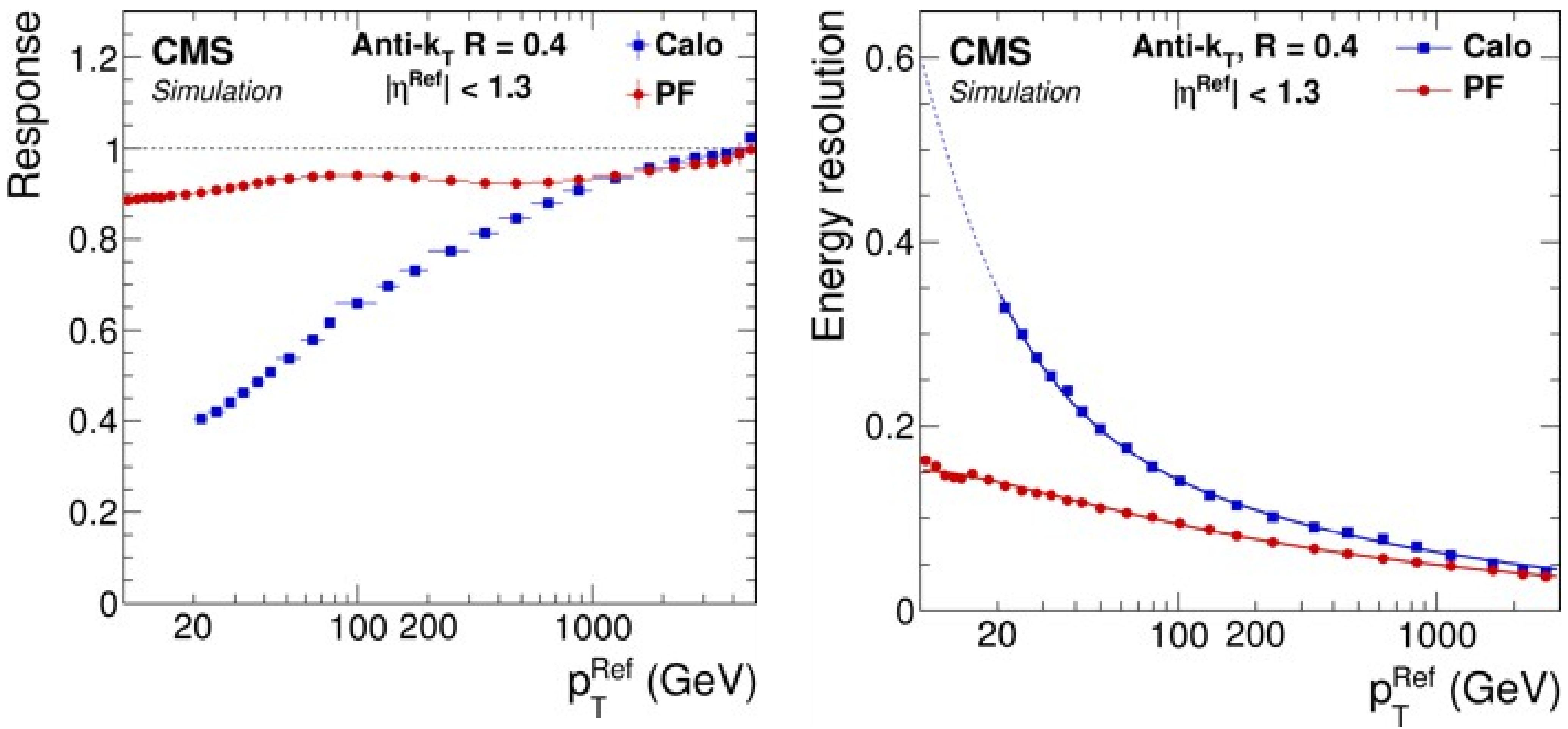
Recall: particle flow algorithm is a reconstruction paradigm



Compensating resolution performance with particle flow

Particle flow optimizes the usage of the detector

- most energy energy ends-up being estimated by tracks and the electromagnetic calorimeter
- recover linearity and significantly improve in energy resolution



CMS High Granularity Calorimeter for Phase-2 of the LHC

Based on a CERN seminar by D. Barney – April 2018

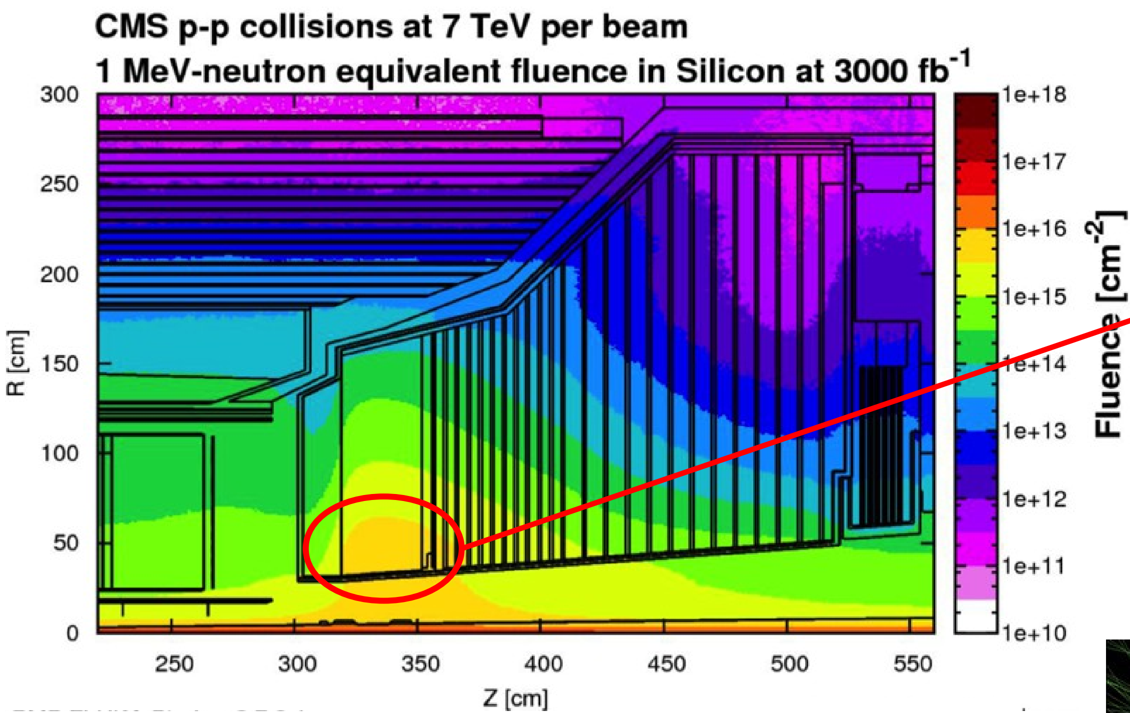
High-Luminosity LHC

The main physics goal is SM and Higgs coupling measurements at the TeV scale

- Focus on jets: boosted, heavy-flavour, vector boson fusion (forward)
- Unprecedented integrated luminosity 3-4 ab^{-1}
- instantaneous luminosity leveled throughout a fill @ 5 x 10^{34} $cm^{-2}s^{-1}$ ⇨ ≥140 pileup events

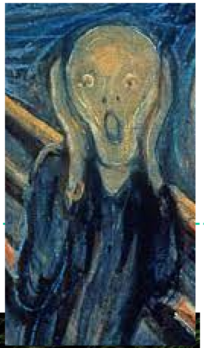
Good jet measurements are crucial at HL-LHC ⇨ focus on calorimetry

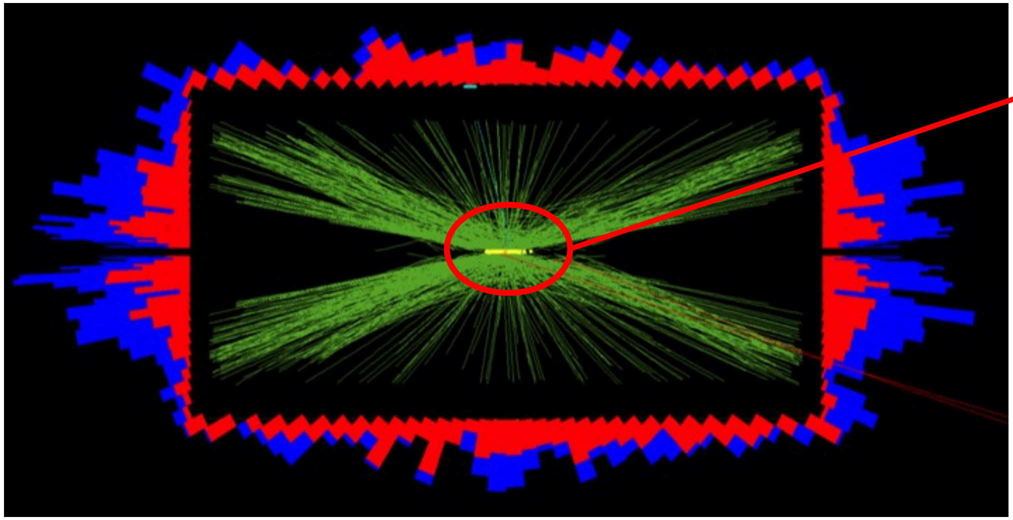
Drastic change of environment for detectors

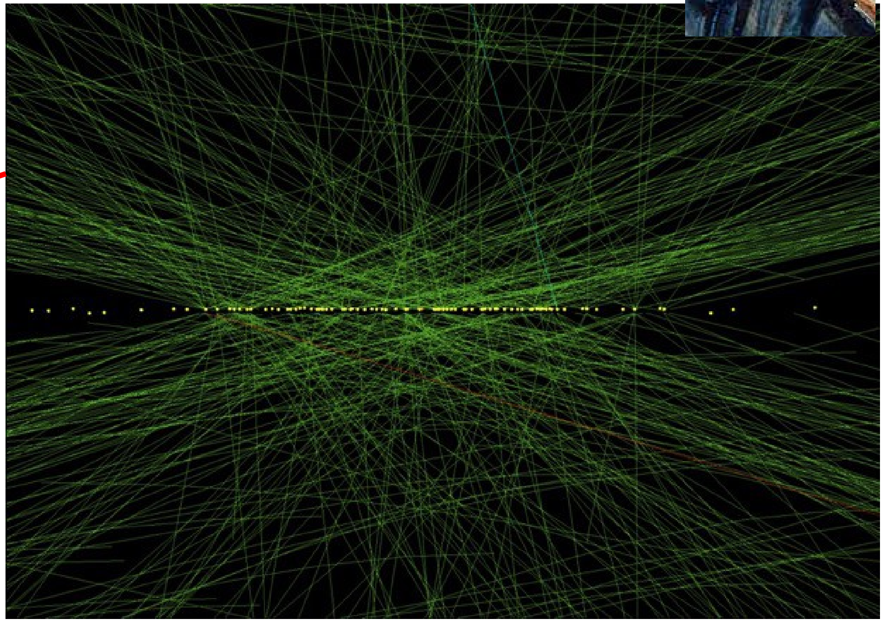


CMS endcap region @ HL-LHC:
~1x10^{16} 1 MeV neq cm^{-2} @ 3ab^{-1}
and up to **2 MGy** absorbed dose in endcap calorimeters

Current calorimeters wouldn't survive →







78 pileup events in Run 1/2. Expect **140-200 @ HL-LHC**

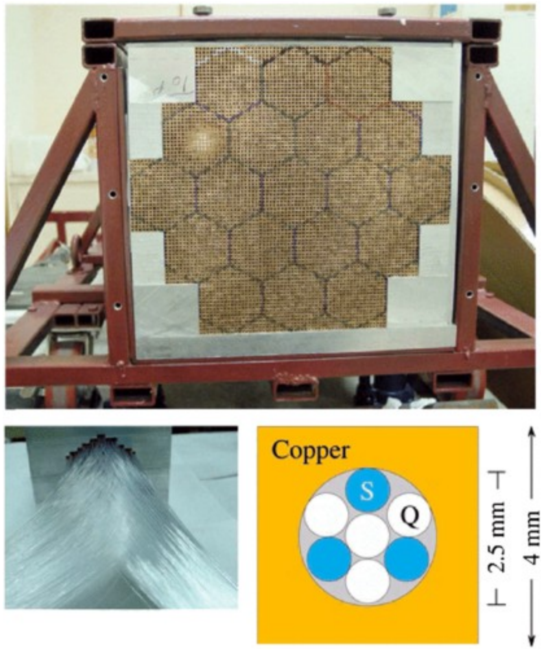
Improving jet measurements: two paths

Dual (or triple) readout calorimeters can identify:

- EM component from Cerenkov light for relativistic particls
- Hadronic component from scintillation light

⇨ optimal energy resolution, driven by hardware

e.g. **DREAM** calorimeter



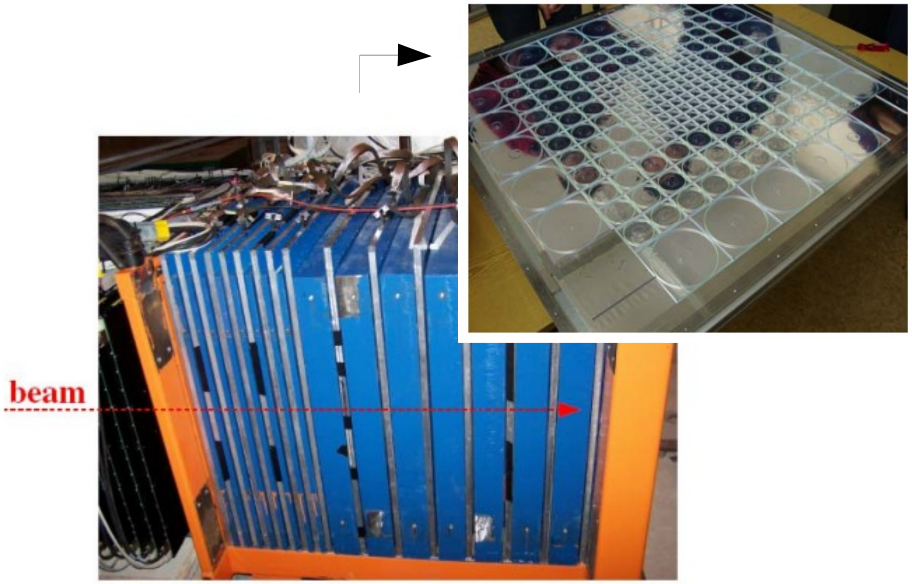
Fine sampling calorimeters loose stochastically in resolution but:

- Allow fine separation of nearby showers
- Imaging from hit spray

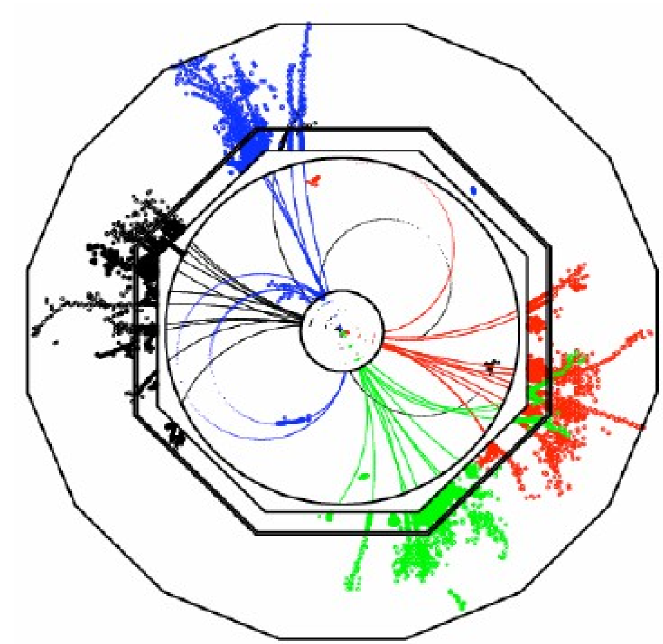
⇨ fine-grained particle ID, pileup subtraction,

driven by software

e.g. **CALICE** calorimeter



Particle flow: calorimeters are integrated in the full detector



For a Particle-Flow calorimeter

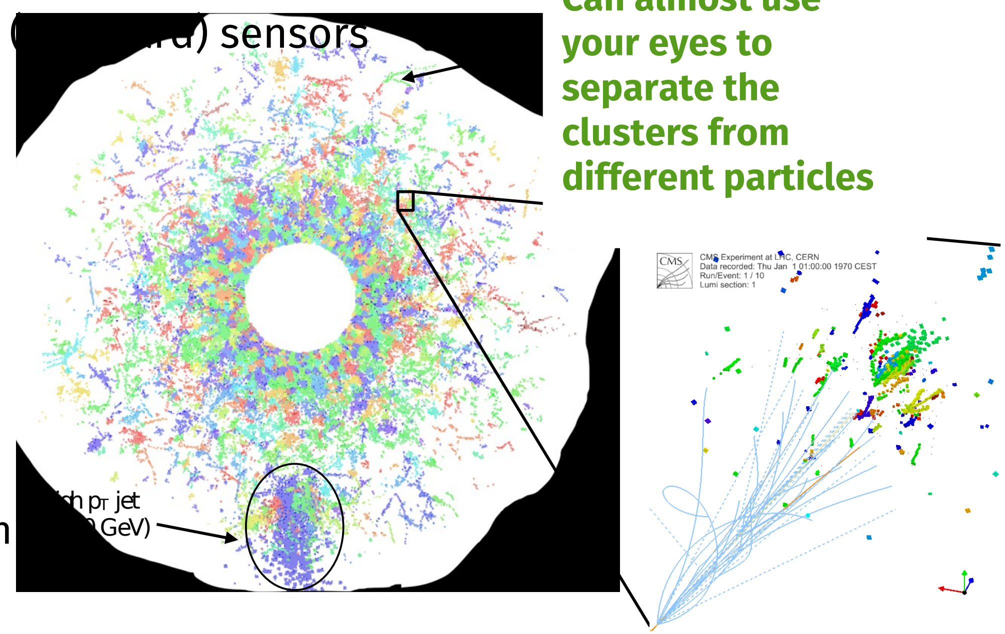
- Privilege granularity over energy resolution (recall matching of tracks to calorimetric hits)

- Lateral granularity should be below Molière radius (otherwise obtain large overlapping showers which would render discrimination of signal from pileup impossible)

- Dense absorbers (contain showers) and thin (...) sensors

Sophisticated software needed!

- but we have come a long way with
  - heterogenous computing (CPU+GPU)
  - smarter clustering algorithms
  - machine learning regression/classification



Can almost use your eyes to separate the clusters from different particles

Designing HGCAL for HL-LHC

To realise HGCAL we need:
low cost/area active material(s), radiation-tolerant on-detector electronics, high-bandwidth data transmission, powerful FPGAs for off-detector electronics

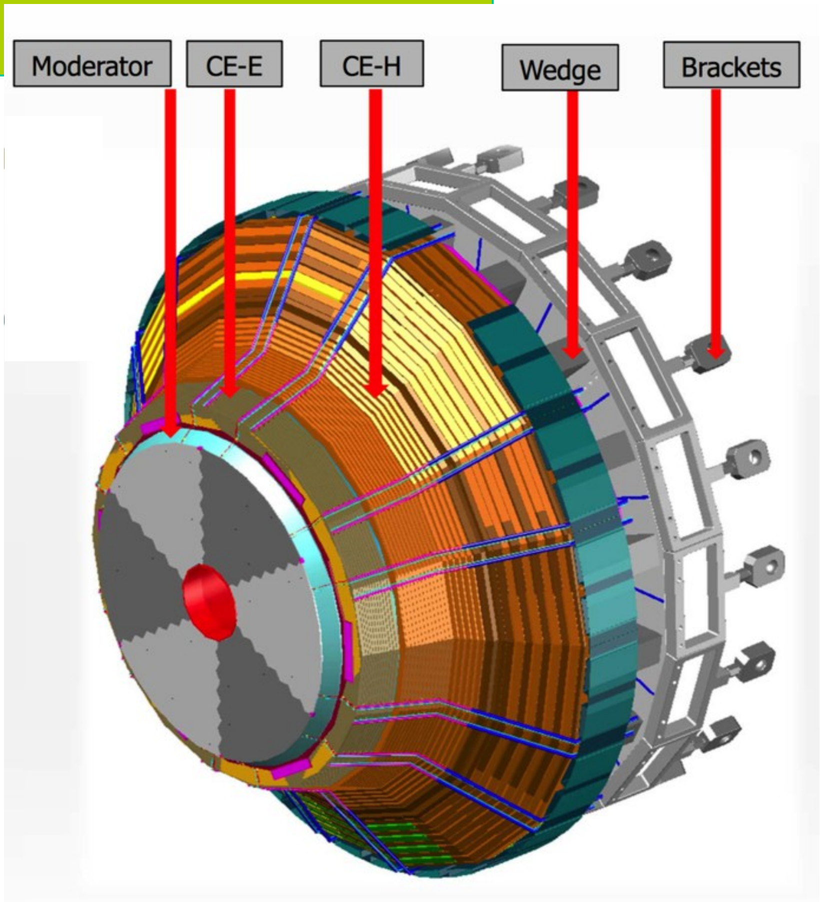
+

Look for proven and adequately radiation-hard active materials
To build a dense e.m./hadronic calorimeter with a good energy resolution, small R_M, good two-shower separation (e.m. and hadronic), with high lateral and longitudinal readout granularity

=

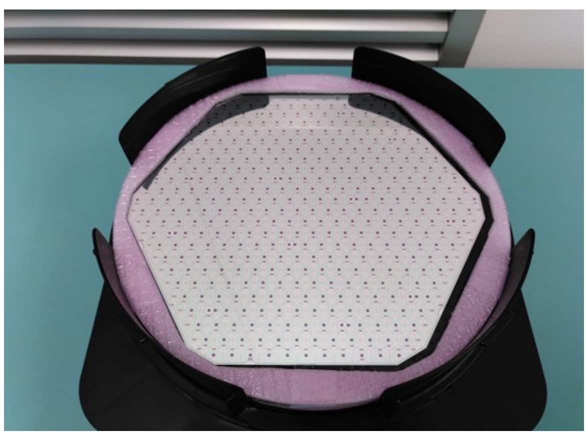
A Si-sensor-based sampling calorimeter
(absorber materials: W, Pb, Cu, Stainless Steel)

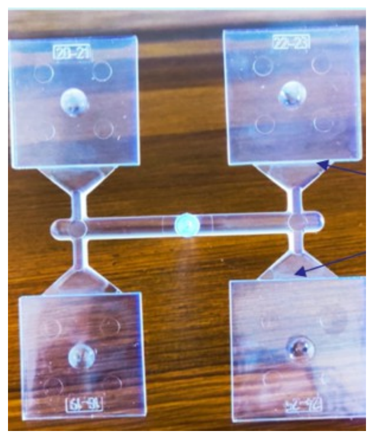
And in lower radiation regions
plastic scintillator tiles readout by SiPMs
(absorber materials: Cu & SSteel)

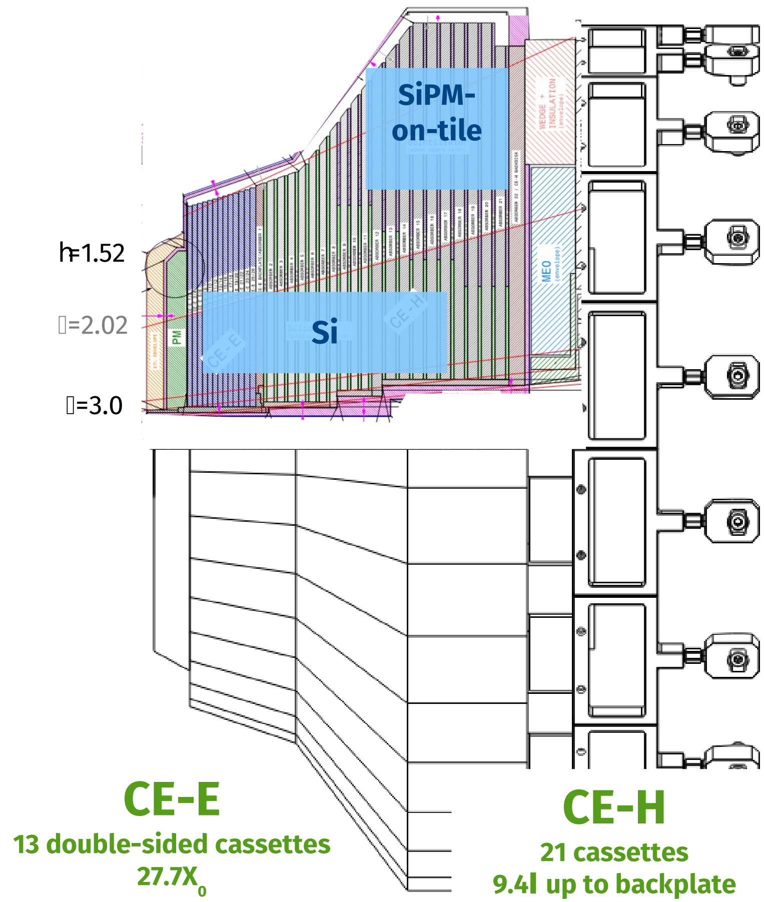


A 47-layer calorimeter with >6M channels

<u>Active Elements:</u>
- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- Scintillating tiles with SiPM readout in low-radiation regions of CE-H

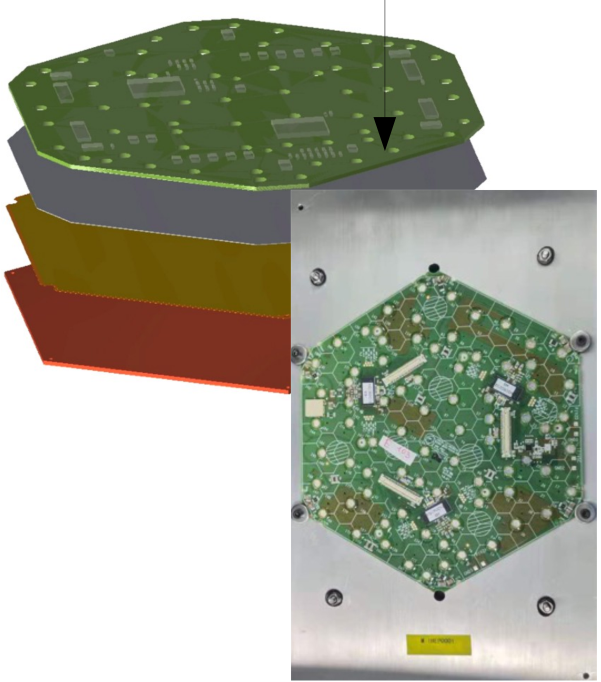


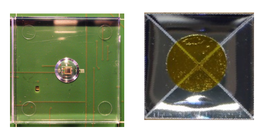


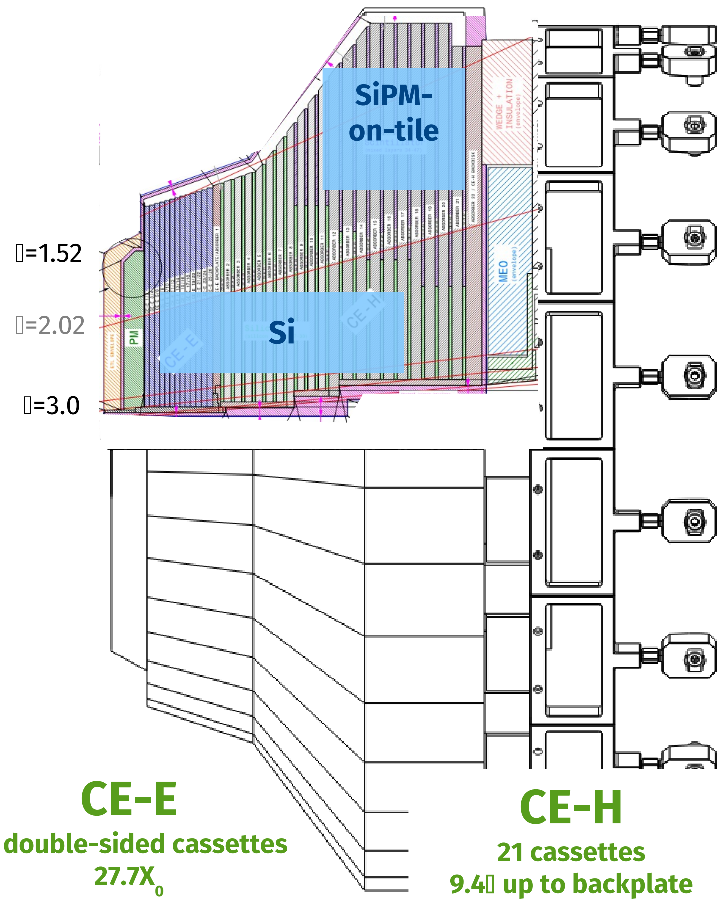


A 47-layer calorimeter with >6M channels

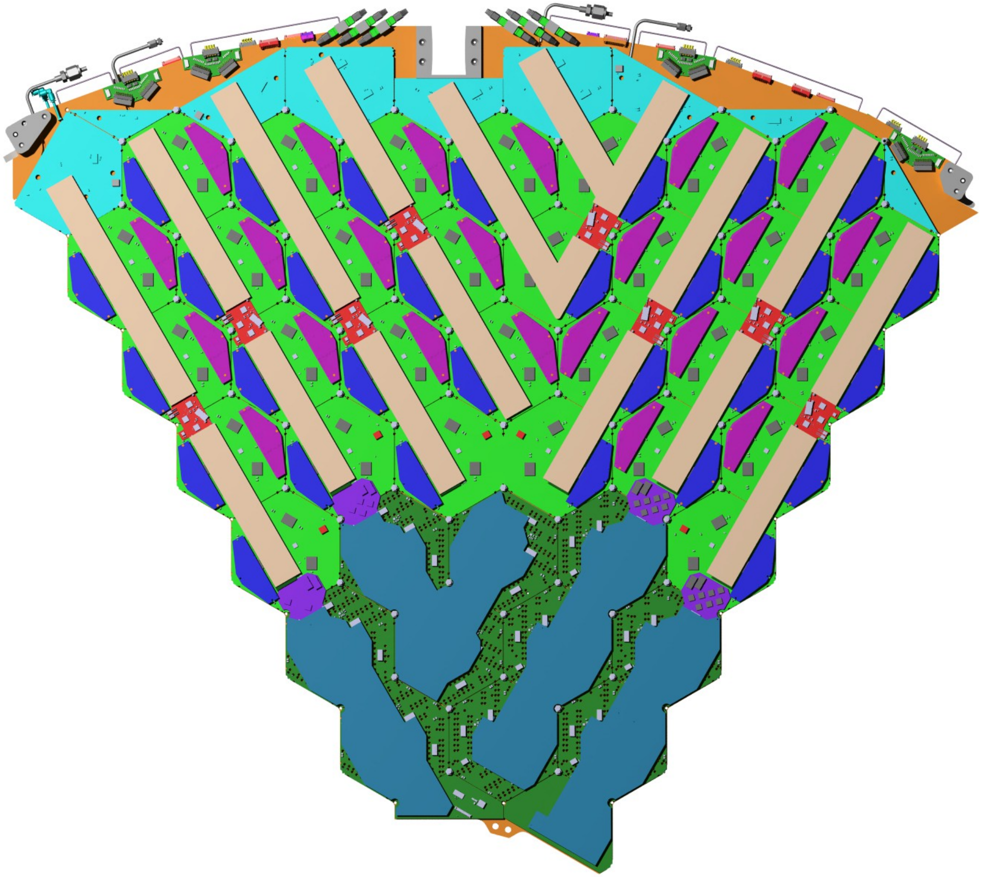
Key Parameters:
- HGCAL covers 1.5 < h< 3.0
- **Full system maintained at -30°C**
- **~600m²** of silicon sensors
- **~500m²** of scintillators
- 6M Si channels, 0.5 or 1.1 cm² cell size
  - Data readout from all layers
  - Trigger readout from alternate layers in CE-E and all layers in CE-H
- ~27000 Si modules

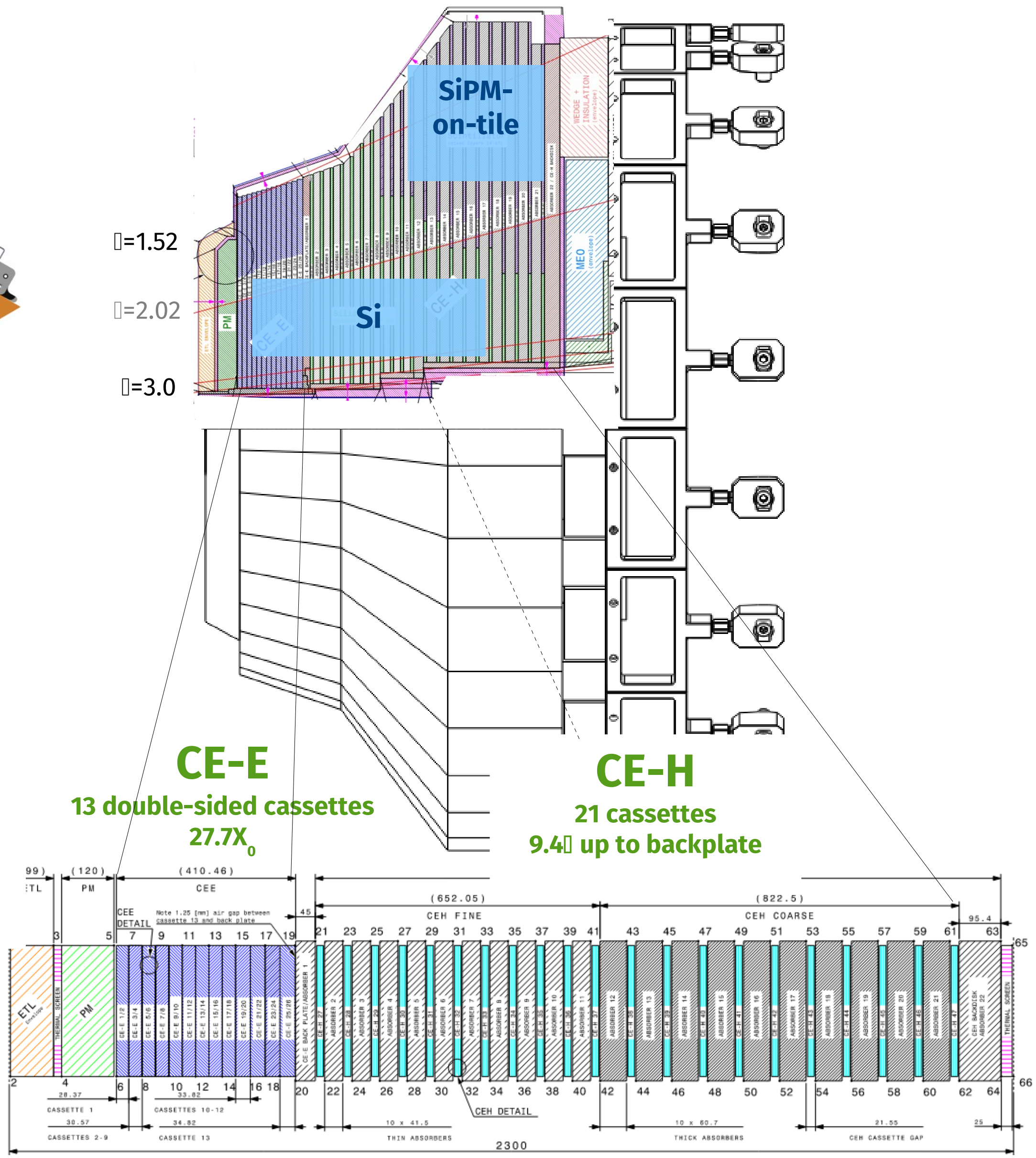






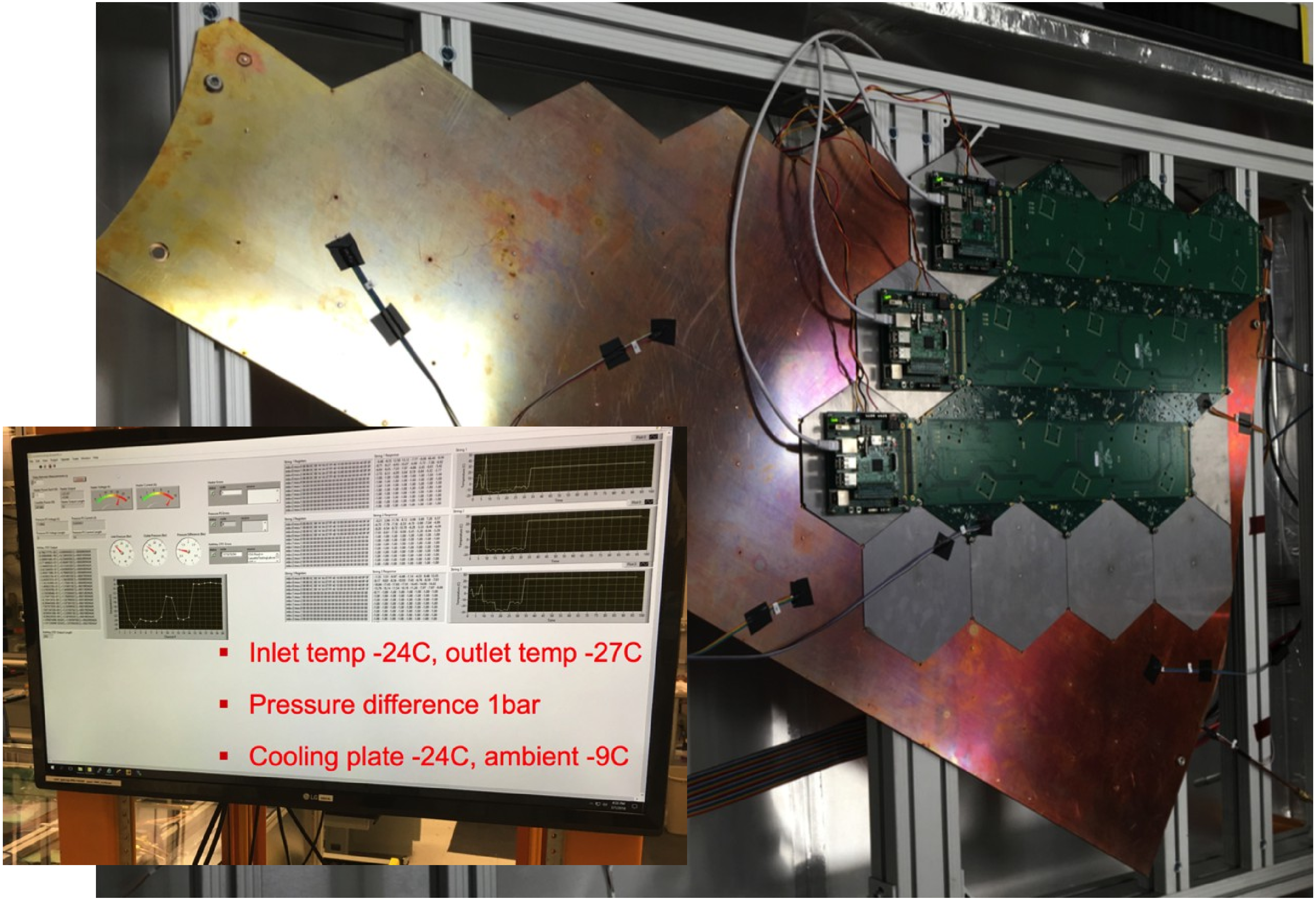
A 47-layer calorimeter with >6M channels



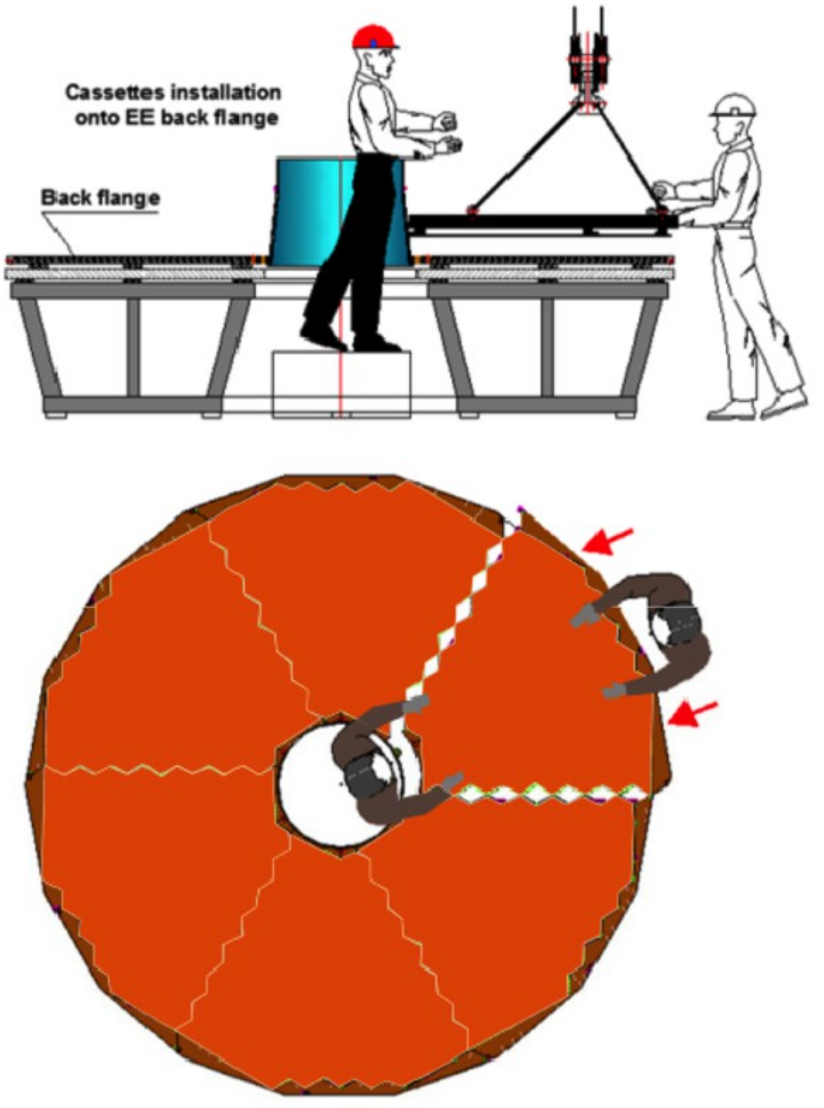


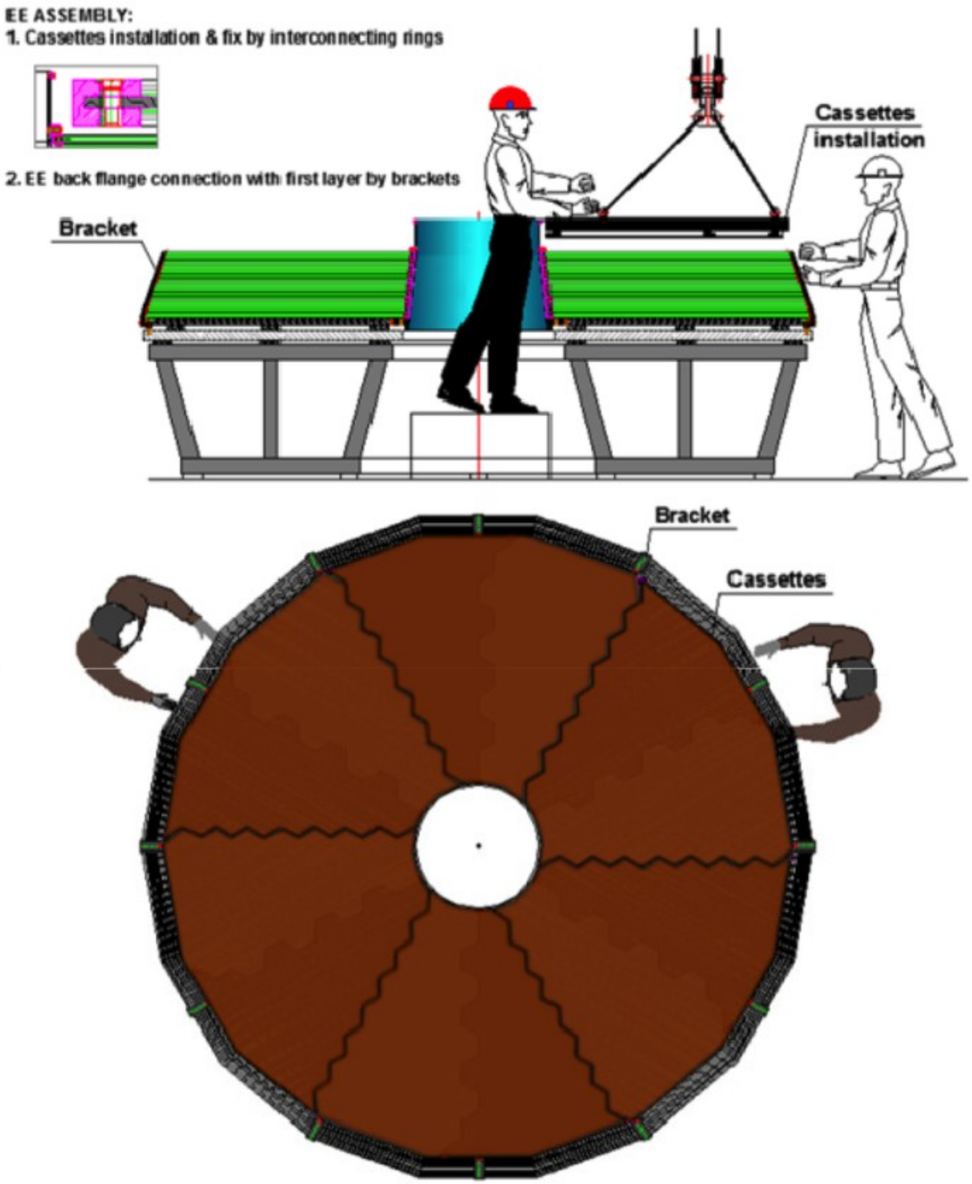
Assembly in cassette structures (60^0 or 30^0)
All electronics, services, cooling, sensors must fit in tiny space (~25mm in CE-E)

Dummy cassette is installed in a cold box to study heat-transfer characteristics – works well!

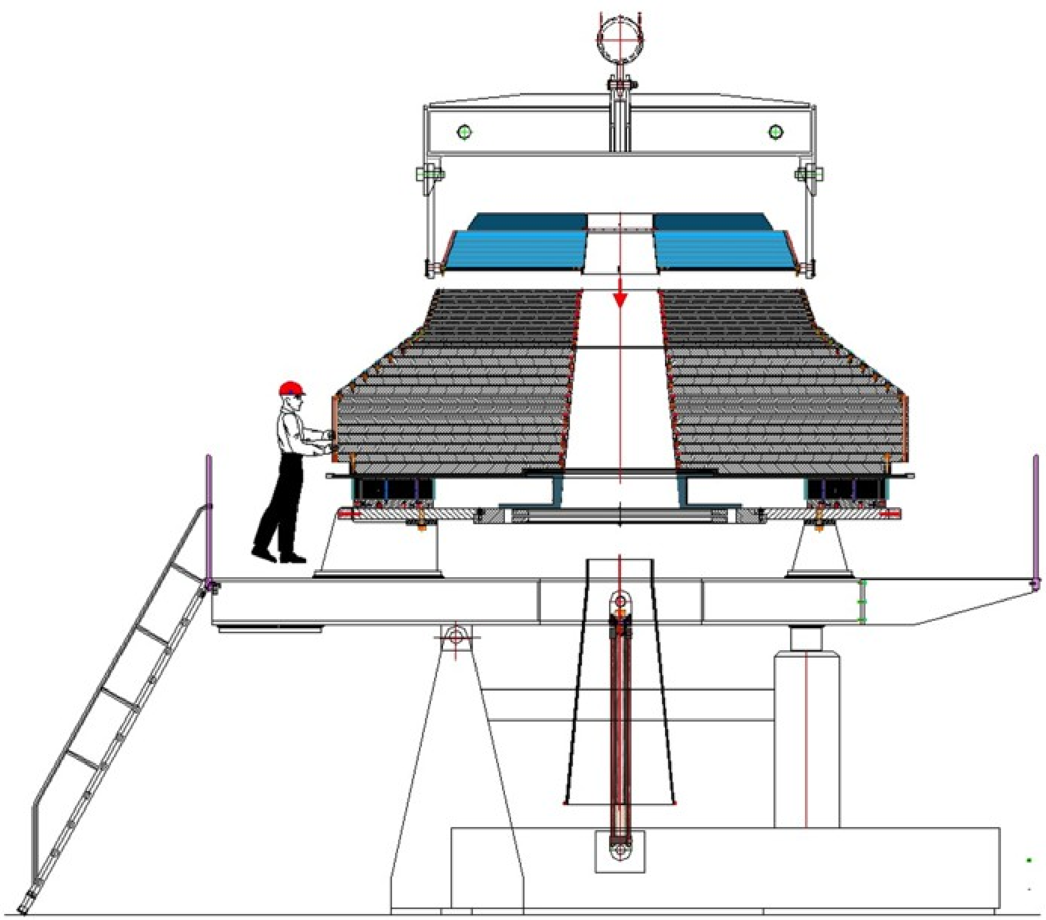


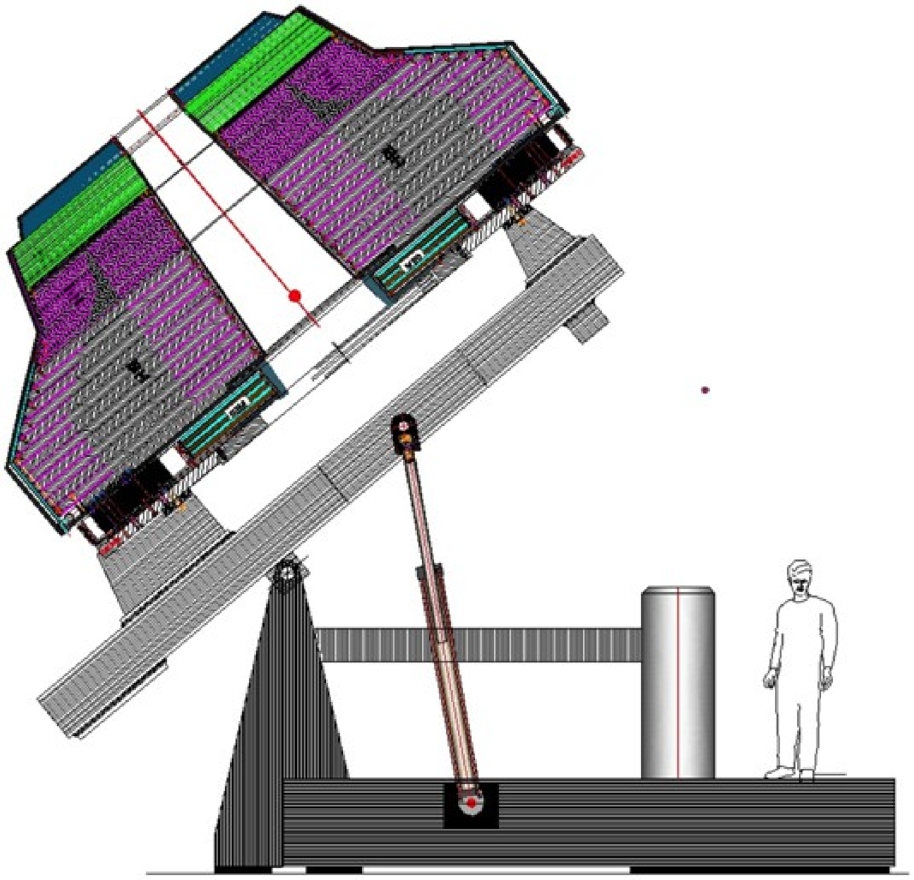
Plans for cassette installation (CE-E)





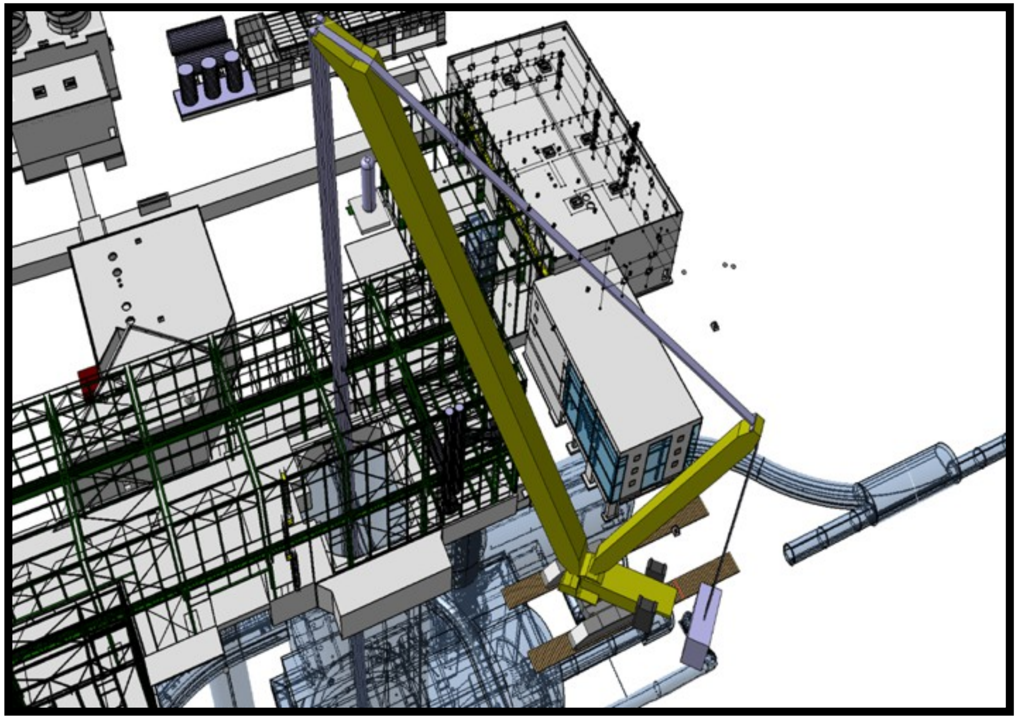
Final assembly steps





Rescue engineer in the middle!
Then attach CE-E to CE-H, then rotate whole CE to vertical for lowering
220 tonnes!

Lowering to the cavern (100m underground)

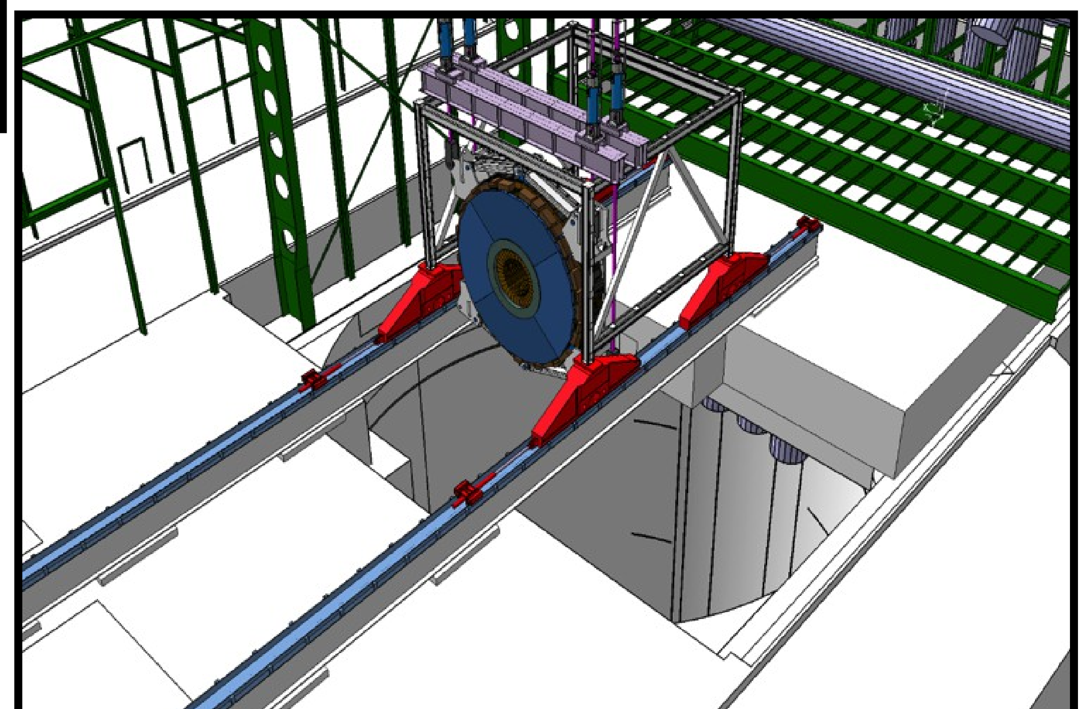


← Crawler crane (rented)

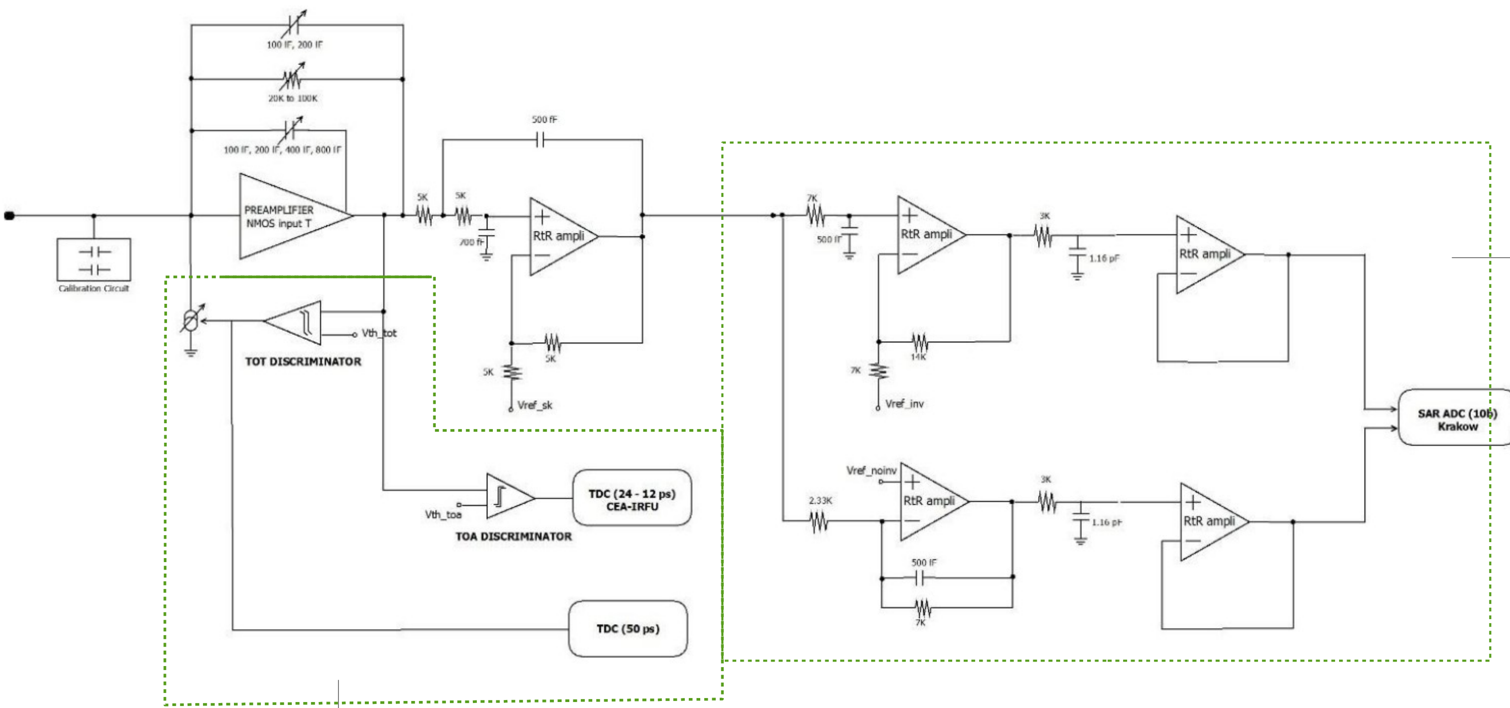
- ~1400 tonnes, transported in 75 trucks!
- Needs large roof openings
- Can move around the site

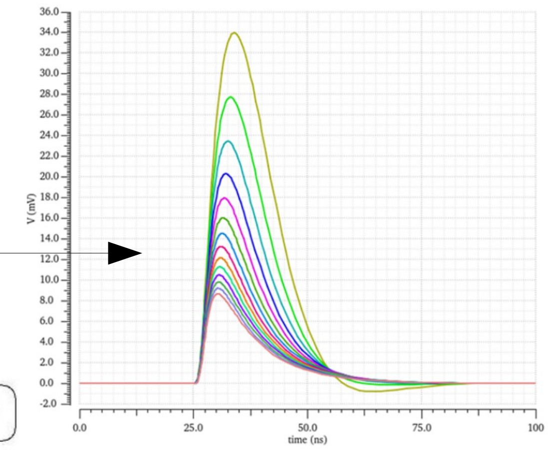
Linear winch crane (custom made) →

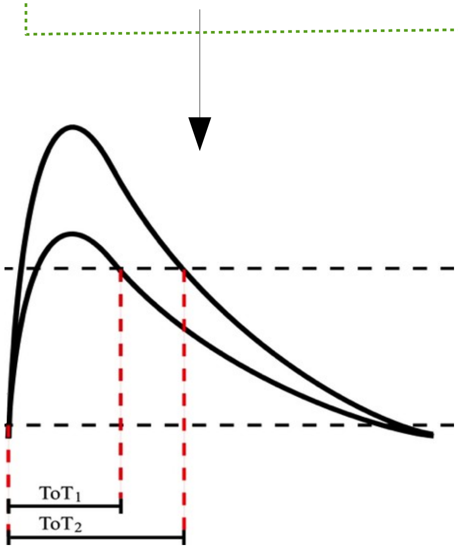
- Similar in principle to original CMS crane
- Calorimeter can be rotated in this system (no need for separate rotating table)



A glimpse of the on-detector electronics







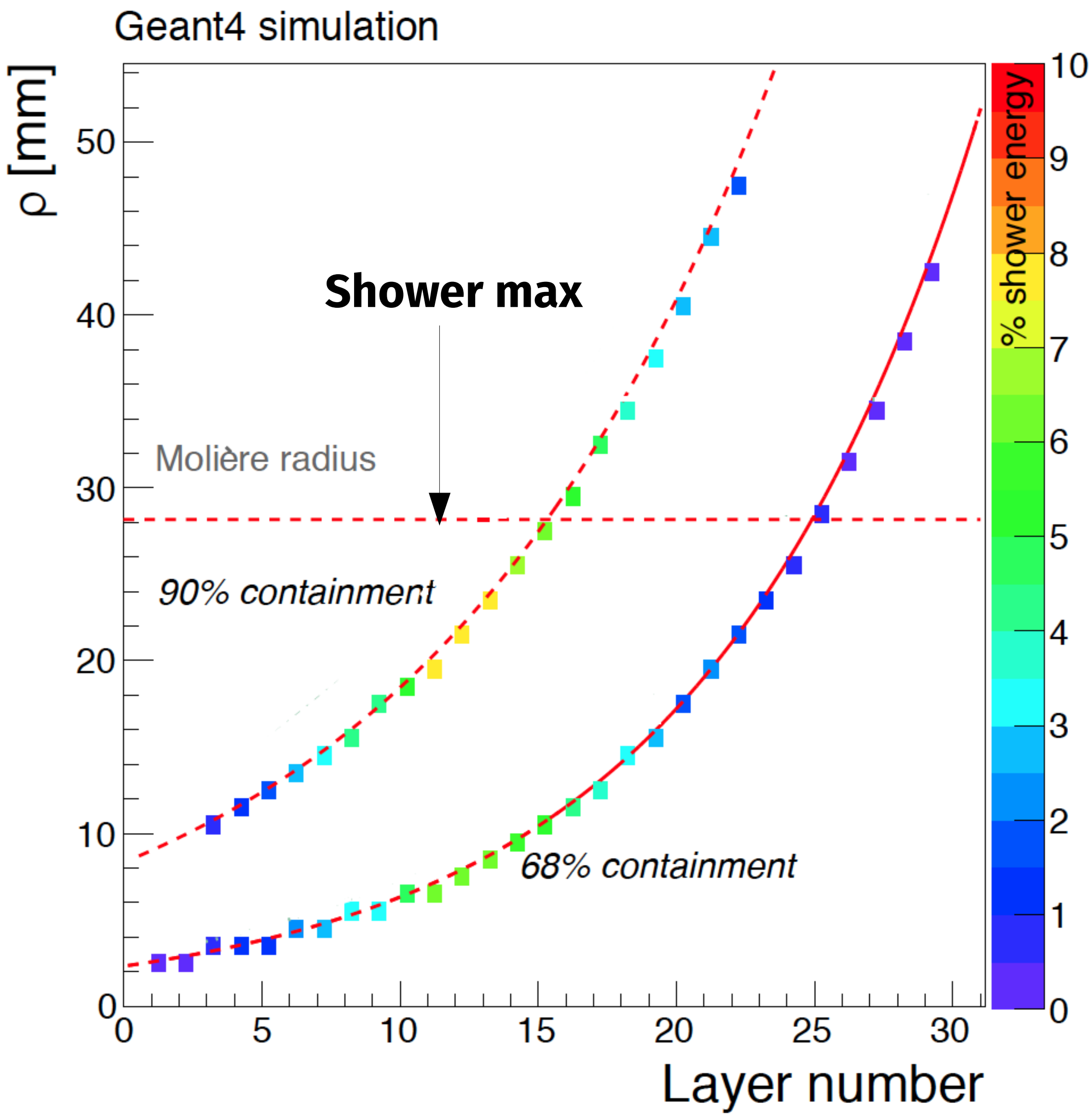
Front-end electronics are in charge of the sensor readout

- **Energy** measured using a 10b *fast-shaping ADC* (<100 fC), or using a 12b TDC for time-over-threshold (measure "discharge" time, >100 fC)
- **Time** measured from the moment charge > threshold through TDC O(30 ps)

Challenging! Low noise, fast shaping, accommodate data in 12.5ns latency, high-speed readout, low consumption (<20mW) high radiation resistence (~2MGy and 10^{16} n_{eq}/cm^2)...

Specifically designed for HGCAL with contributes from engineering and physics

Physics performance: e.m. showers will be narrow

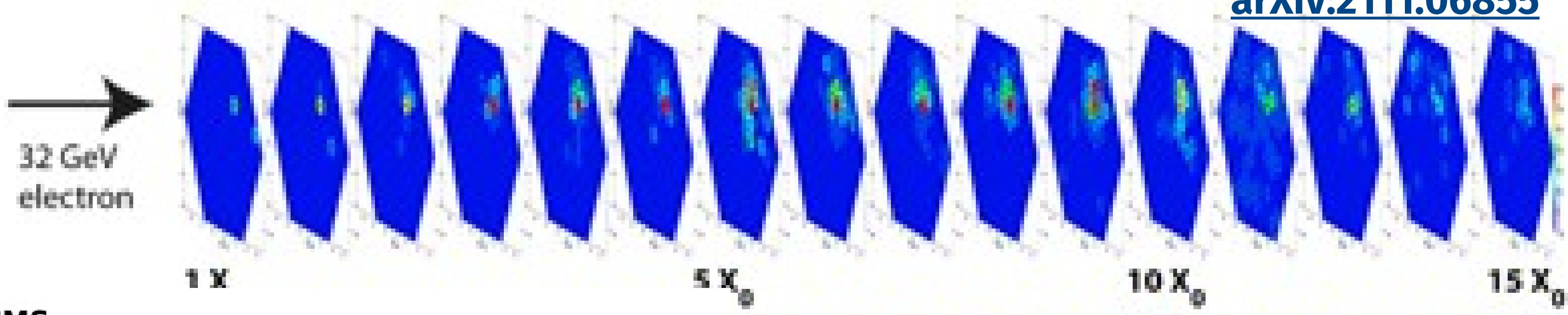


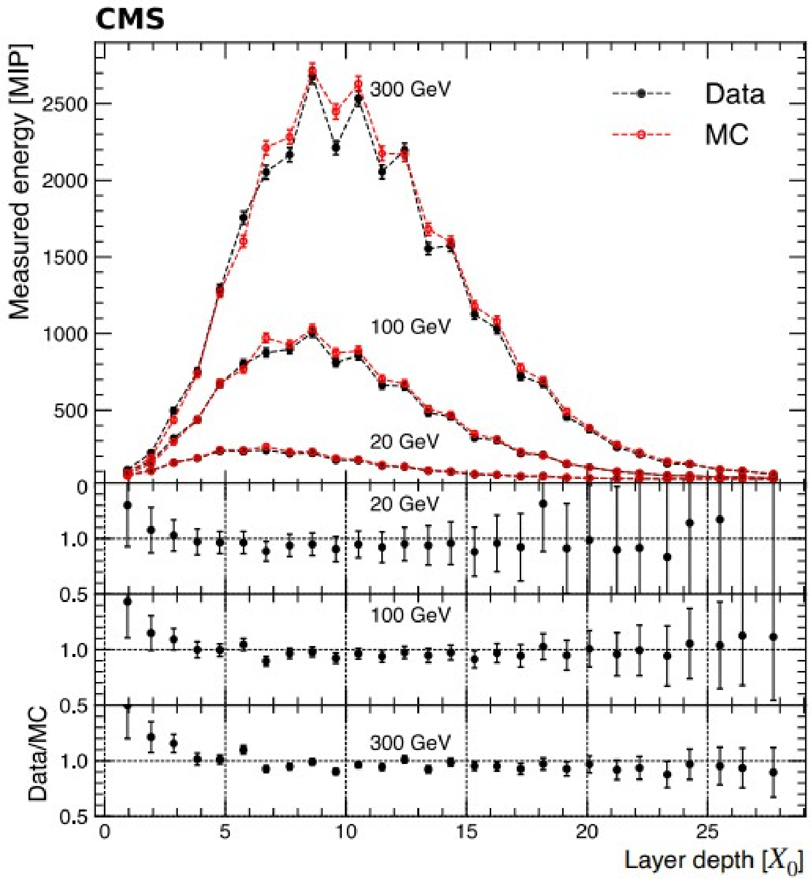
Energy containment in CE-E

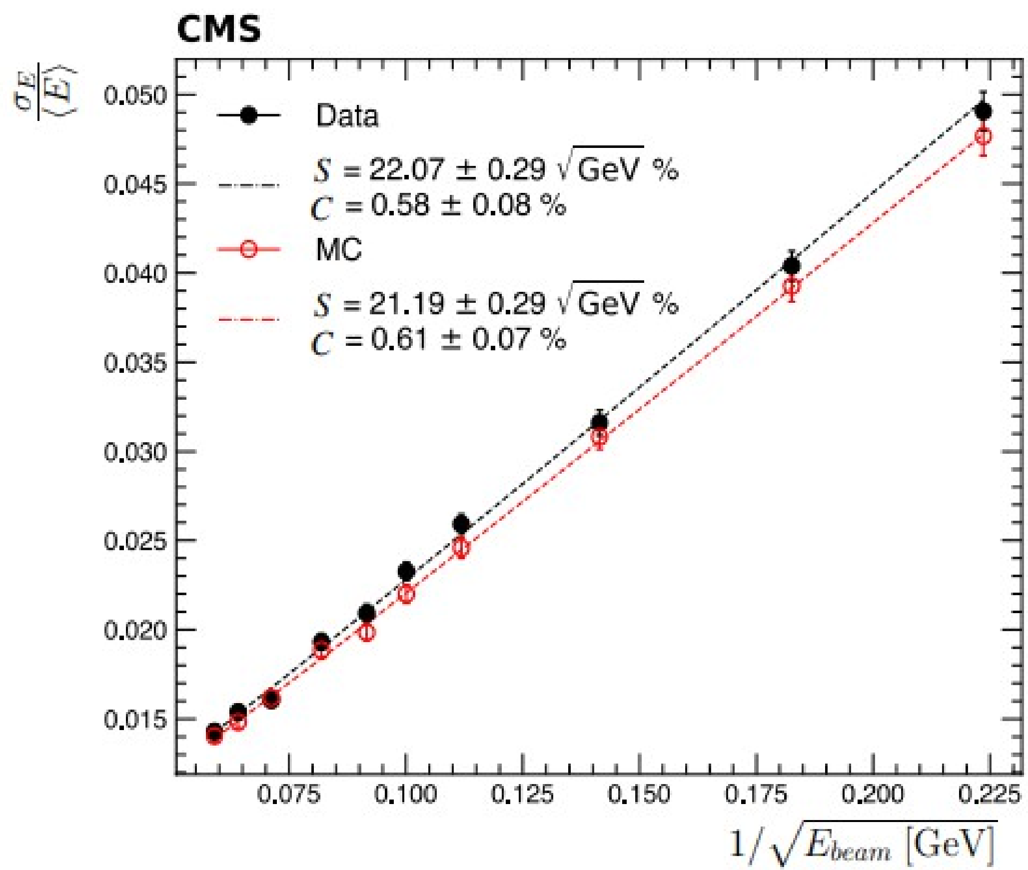
Coloured rectangles: % shower energy deposited in that layer

Physics performance: e.m. showers ~~will be~~ *are* narrow

arXiv:2111.06855





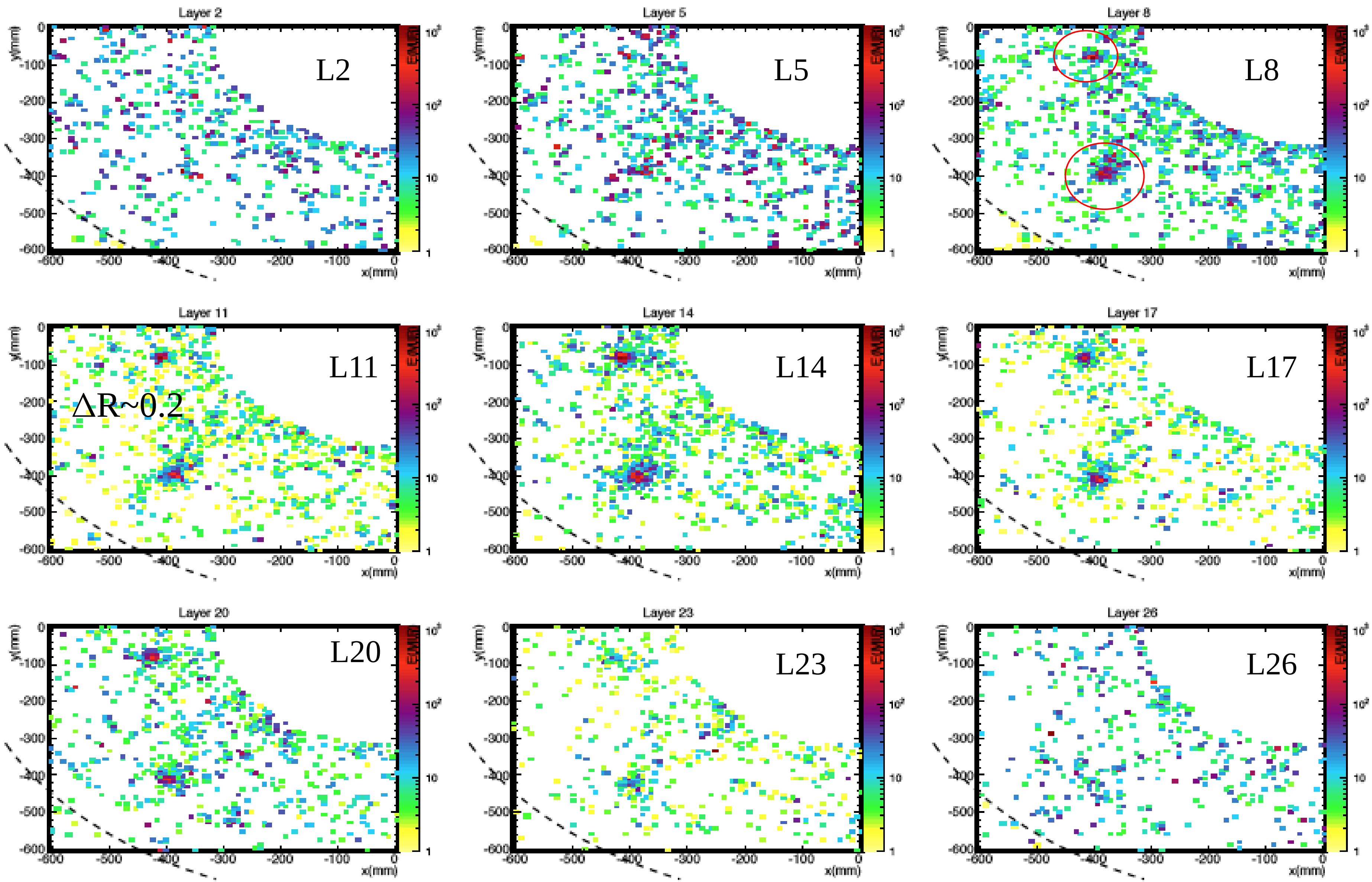


Beam-test results indicate performance within specifications and good agreement with simulation.

Physics performance: imaging VBF H → γγ

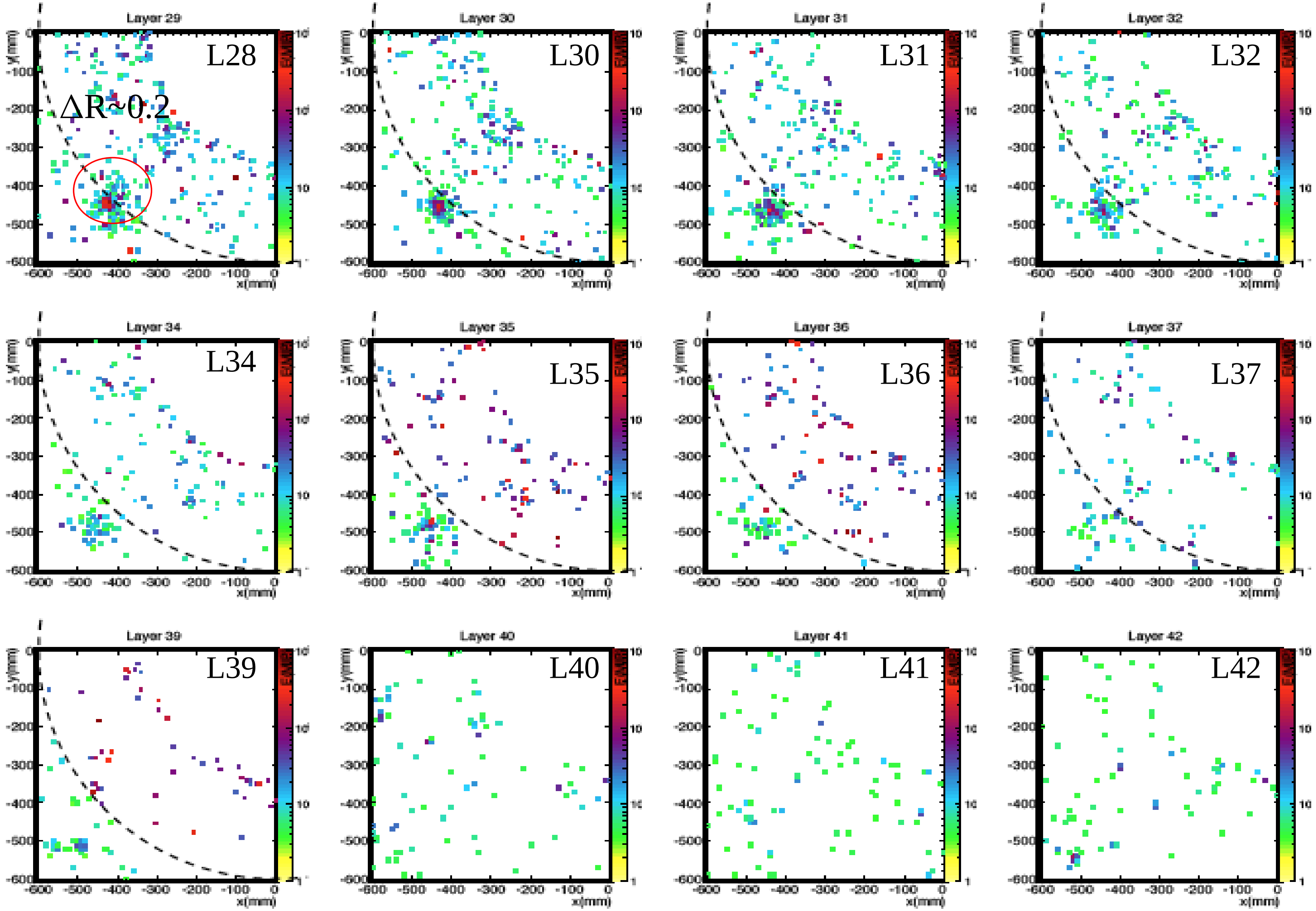
Photon from H decay (175 GeV) + jet [2π + 1γ] (720 GeV)

Showers from the **two photons** are visible in the layers of the electromagnetic part – CE-E



Physics performance: imaging VBF H → gg

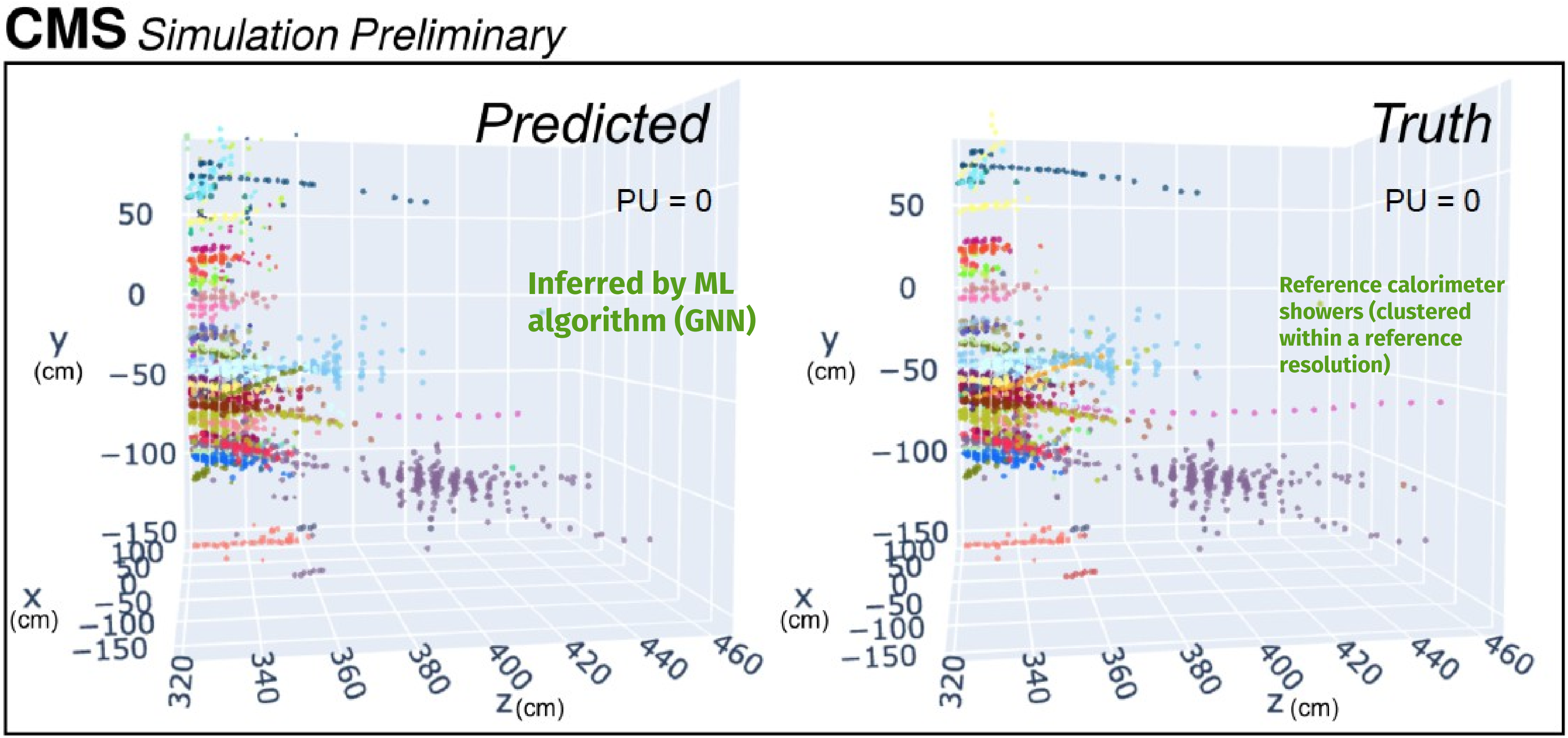
Photon from H decay (175 GeV) + jet [2π + 1γ] (720 GeV)
Pions surface the image once showers enter in hadronic section



A new level of particle flow

Open door to unleash your imagination

- develop robust (human-driven) clustering algorithms
- aim to finer reconstruction with end-to-end machine learned reconstruction↓



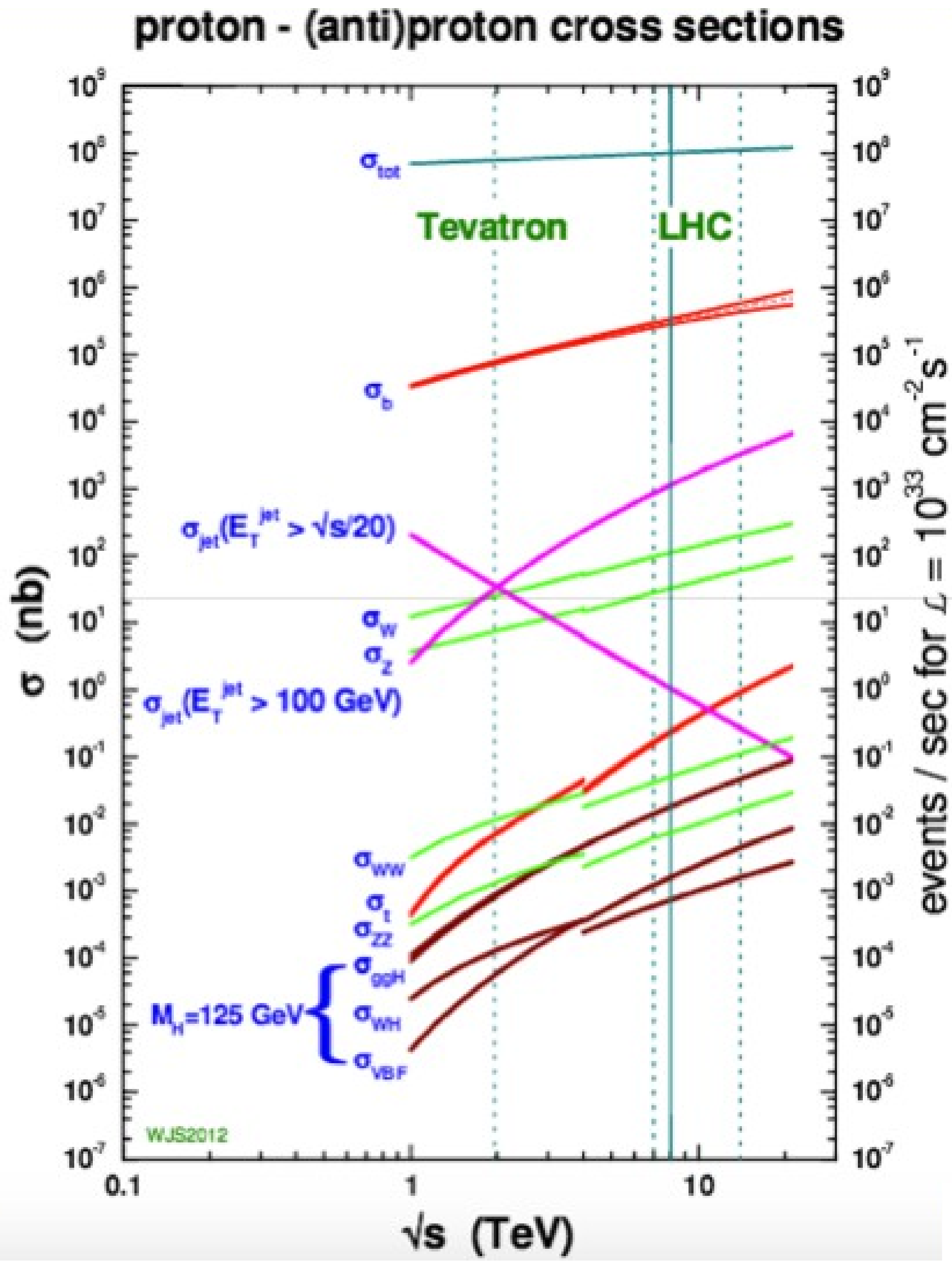
Getting data on tape: trigger systems

Recall: the proton-proton cross section

10^8 / s

10 / s

1 / day



15 nb x 10^{34} $cm^{-2}s^{-1}$

=

150 Hz

Reminder

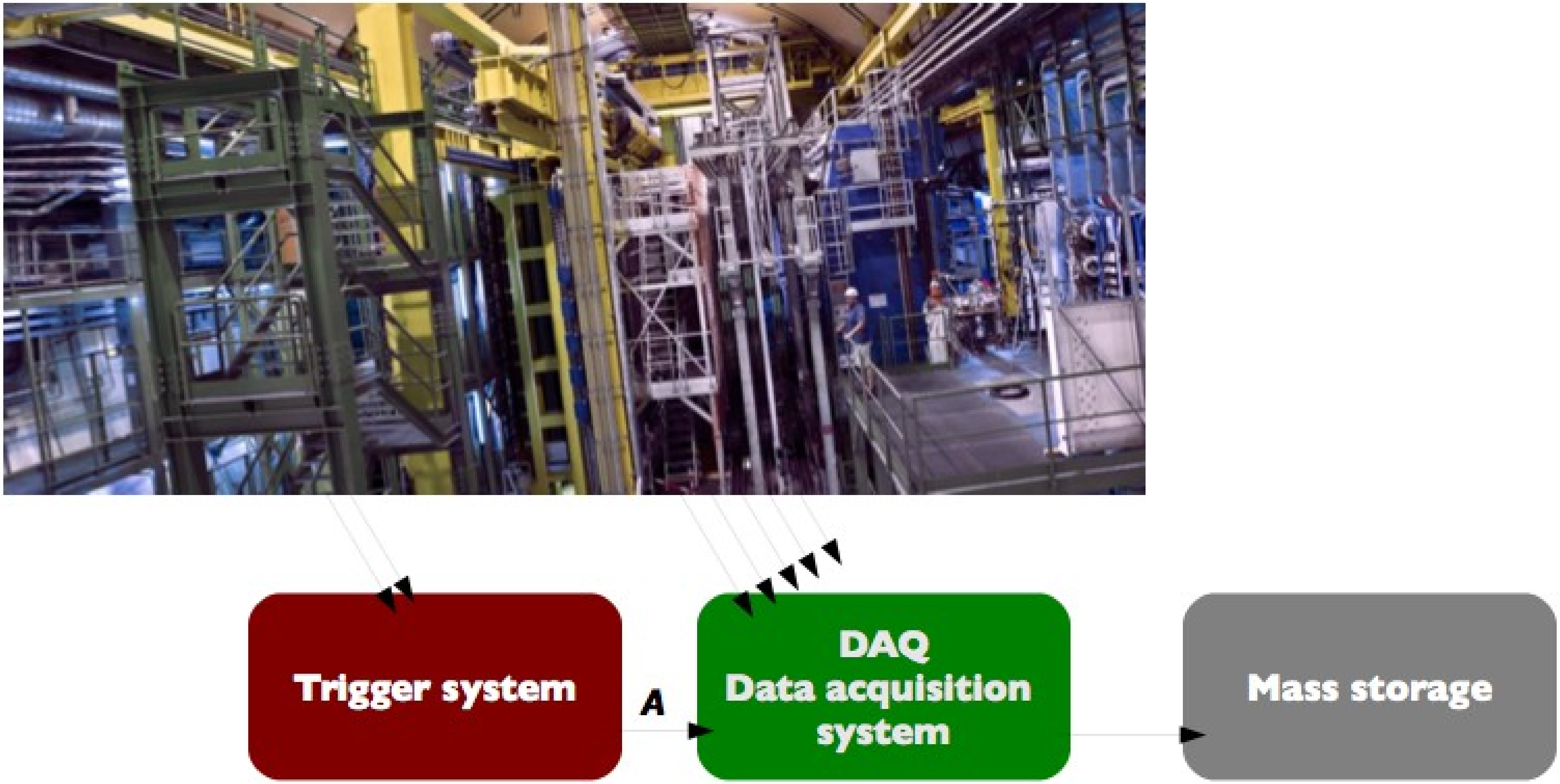
1 pb = 10^{-36} cm^2

Why do we trigger?

- **Data rates at hadron colliders are too high**
  - most events are expected not to be interesting anyway
  - save to tape only relevant physics
  - need a trigger = online selection system which reduces rates by a factor of ~10^5

Collider	Crossing rate (kHz)	Event size (MB)	Trigger rate	Raw data rate (PB/year)	Data rate after trigger (PB/year)
LEP	45	0.1	5 Hz	10^2	~0.01
Tevatron	2.5	0.25	50-100 Hz	10^4	0.1
HERA	10	0.1	5 Hz	10^4	0.01
LHC	**40**	**1**	**100-200 Hz**	**10^5**	**1**

How do we trigger?



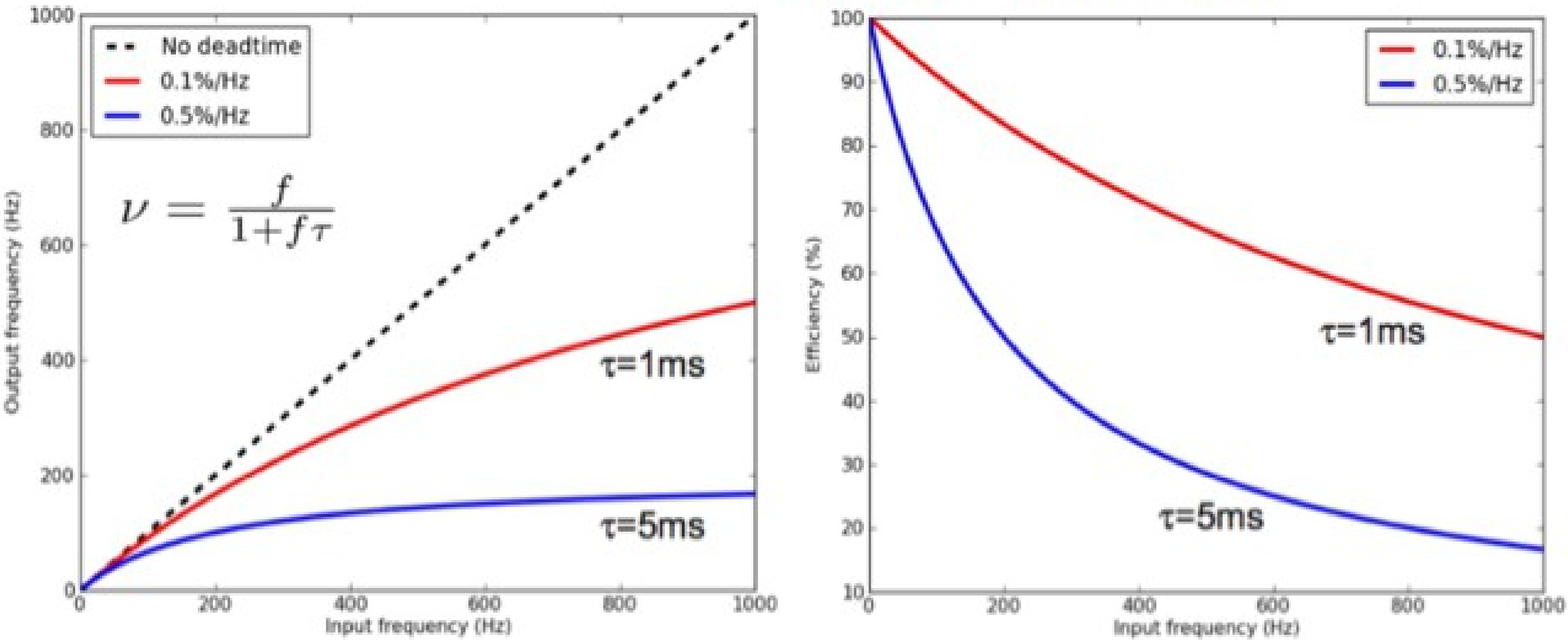
Performs real-time selection based on a subset of the data to record

Collects the data from all the sub-detectors and trigger systems and sends them to mass storage for offline analysis

Readout+decisions=dead-time

- **Signals are random but incoming at an approximate fixed rate**
- Need a busy logic
  - Active while trigger decides whether the event should be kept or not
  - Induces a deadtime in the system
  - System will only accept a fraction of the triggers $\nu = f(1-\nu\tau) \Rightarrow \nu = \dfrac{f}{1+f\tau} < f$

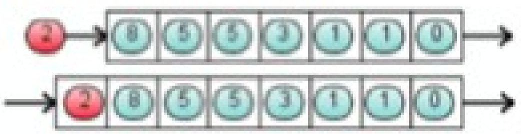
input rate readout time



- **System tends to be inefficient for long readout times**

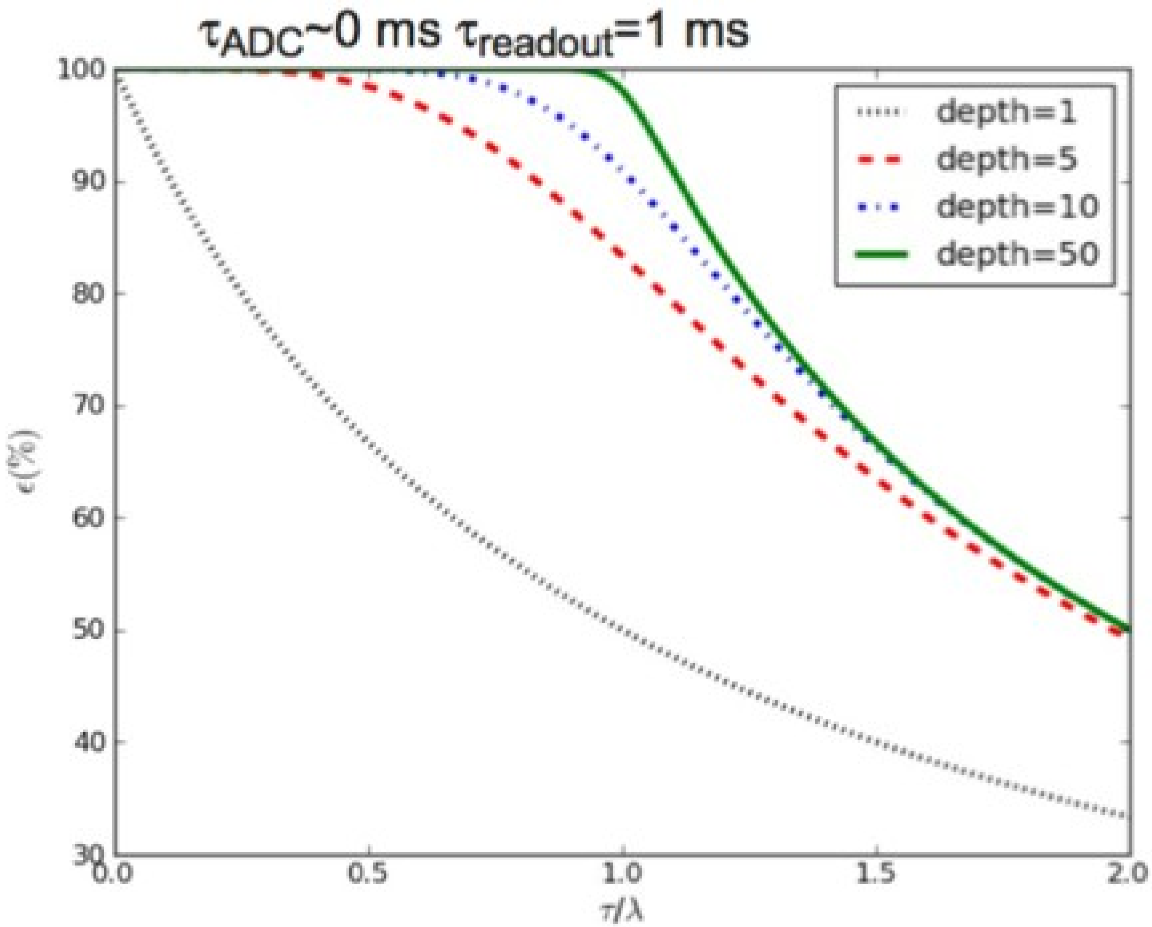
Solution: de-randomize with a buffer

- **A fast, intermediate buffer can be introduced**
    - Works as a FIFO queue
      (First In First Out)



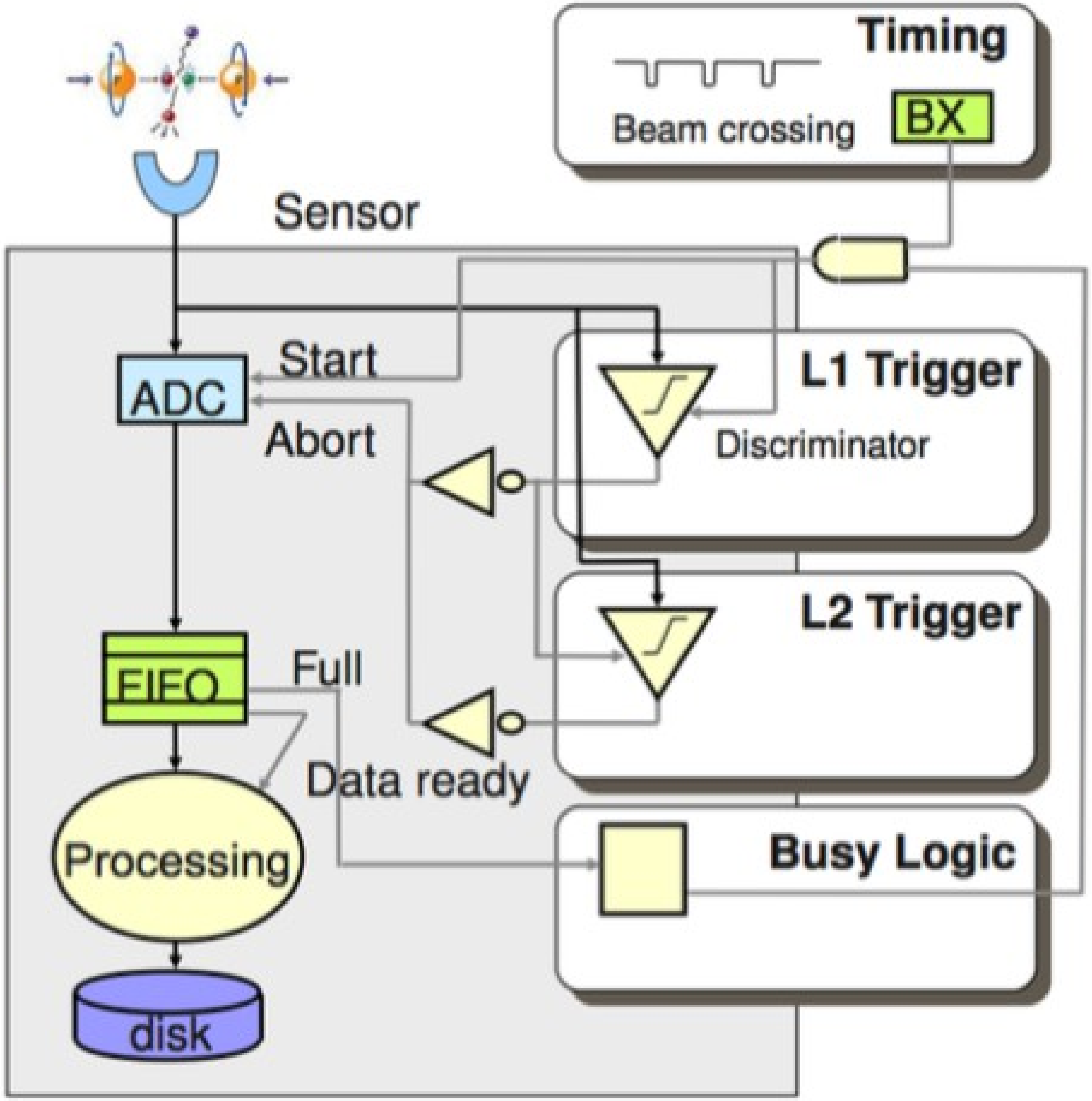
    - Smooths fluctuations = derandomizes
    - Decouples the slow readout from the fast front-end

- **A moderate size buffer is able to retain good efficiency**



Trigger system architecture for bunched collisions

- The ADC are synchronous with beam crossings
- Trigger output is stochastic
  - FIFO is needed to derandomize
- **ATLAS LHC Run I architecture**
  - May need to accommodate several levels with increased complexity
  - If first layer latency is smaller than bunch crossing than the combined latency is $v_{L1} \times t_{L2}$



Trigger system architecture for bunched collisions

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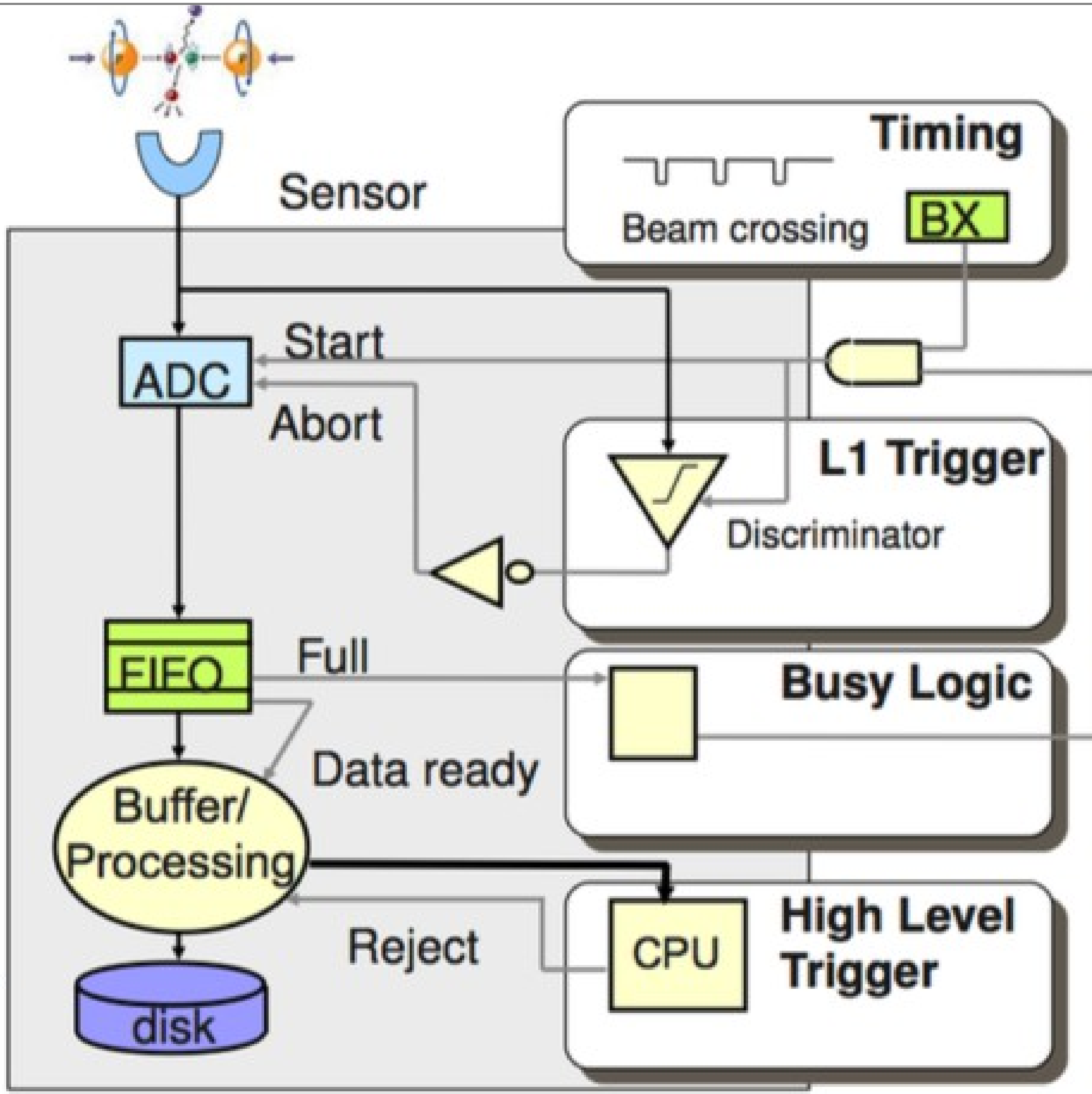
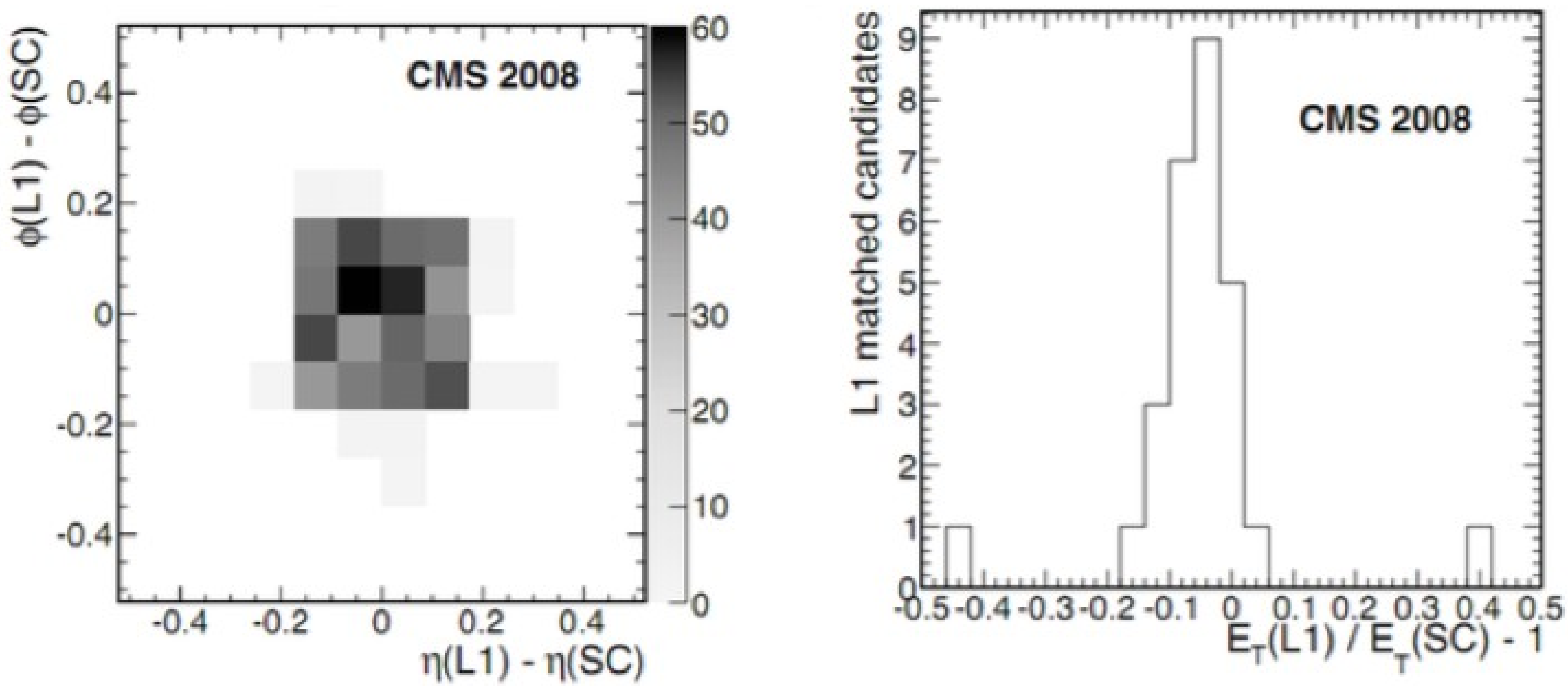
- **ATLAS LHC Run I architecture**
  - May need to accommodate several levels with increased complexity
  - If first layer latency is smaller than bunch crossing than the combined latency is $v_{L1} \times t_{L2}$
- **CMS architecture**
  - Add trigger level between readout and storage
  - CPU Farm used for high level trigger
  - Can access some/all processed data
  - Perform partial/full reconstruction



Be fast = keep it to the point, details come later

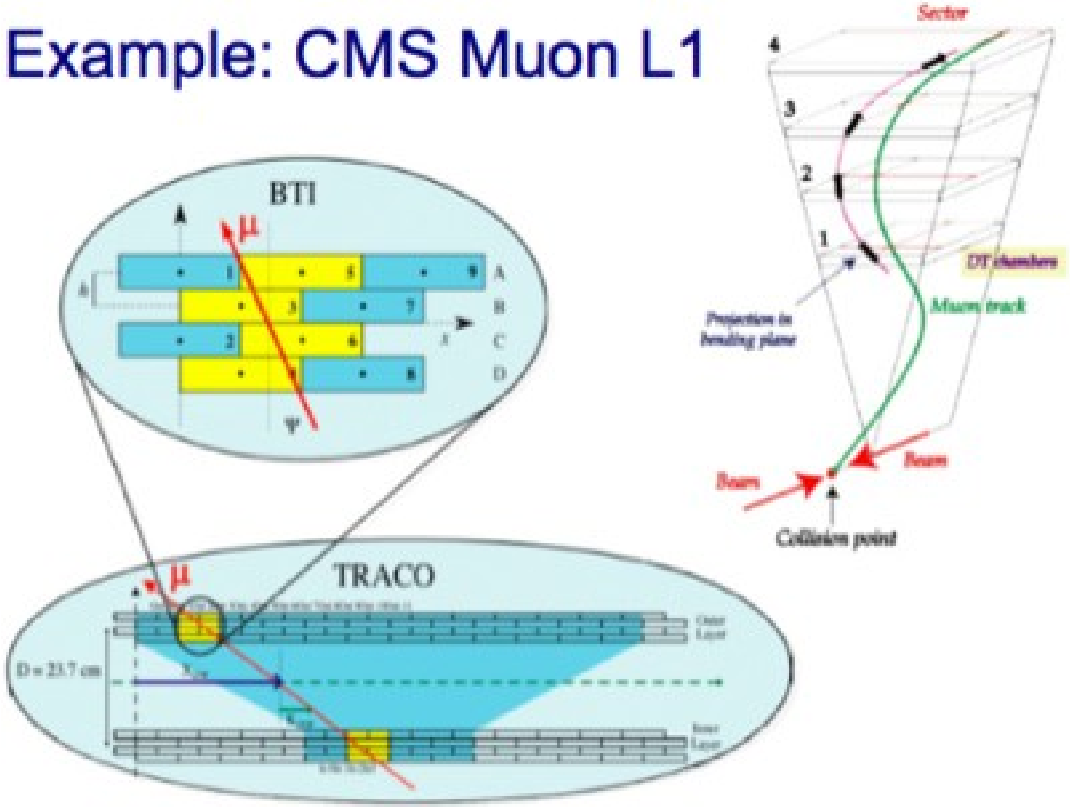
- **Can only use a sub-set of information**
  - Typically energy sums, threshold flags, coarser detector, tracklets
  - Resolutions (energy and position) are coarser by definition

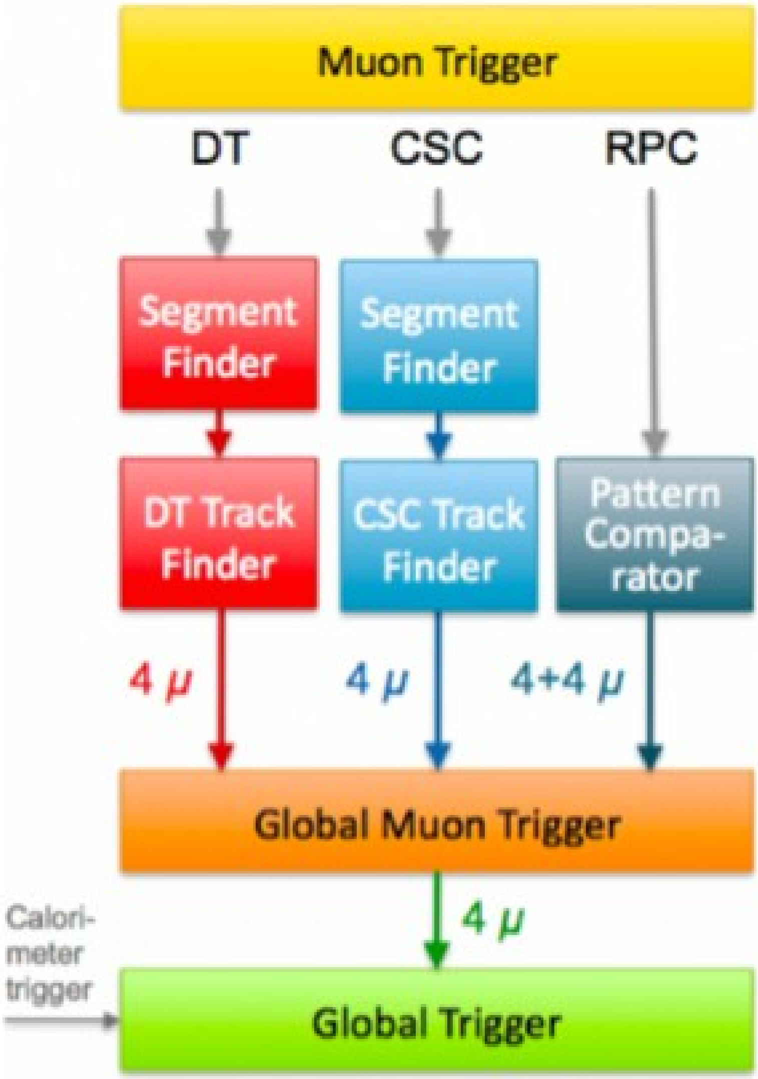


Tracking at L1 (muon case)

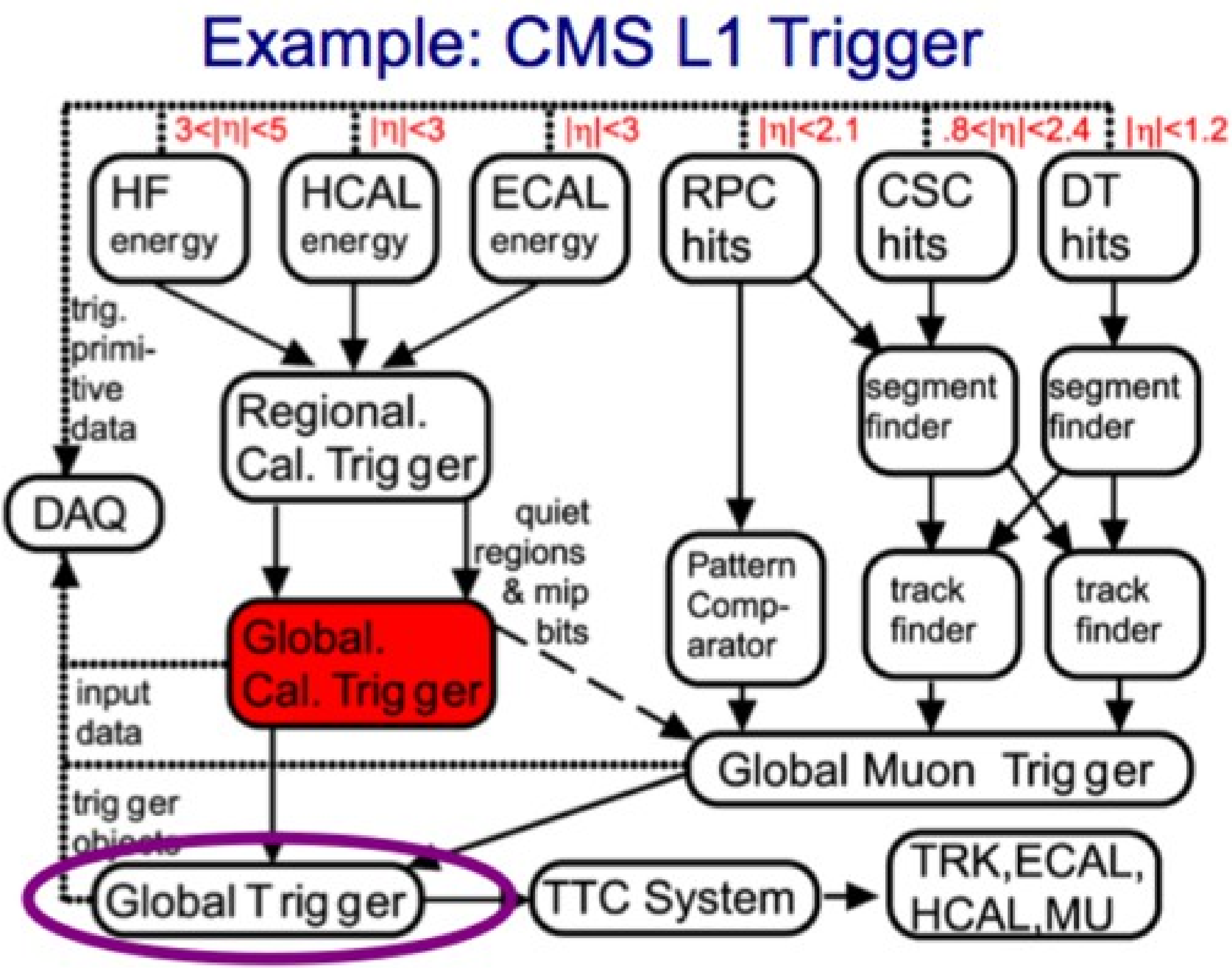
Reconstruct segments in each muon chamber
Combine segments to form track
and measure p_T (rough)

Example: CMS Muon L1



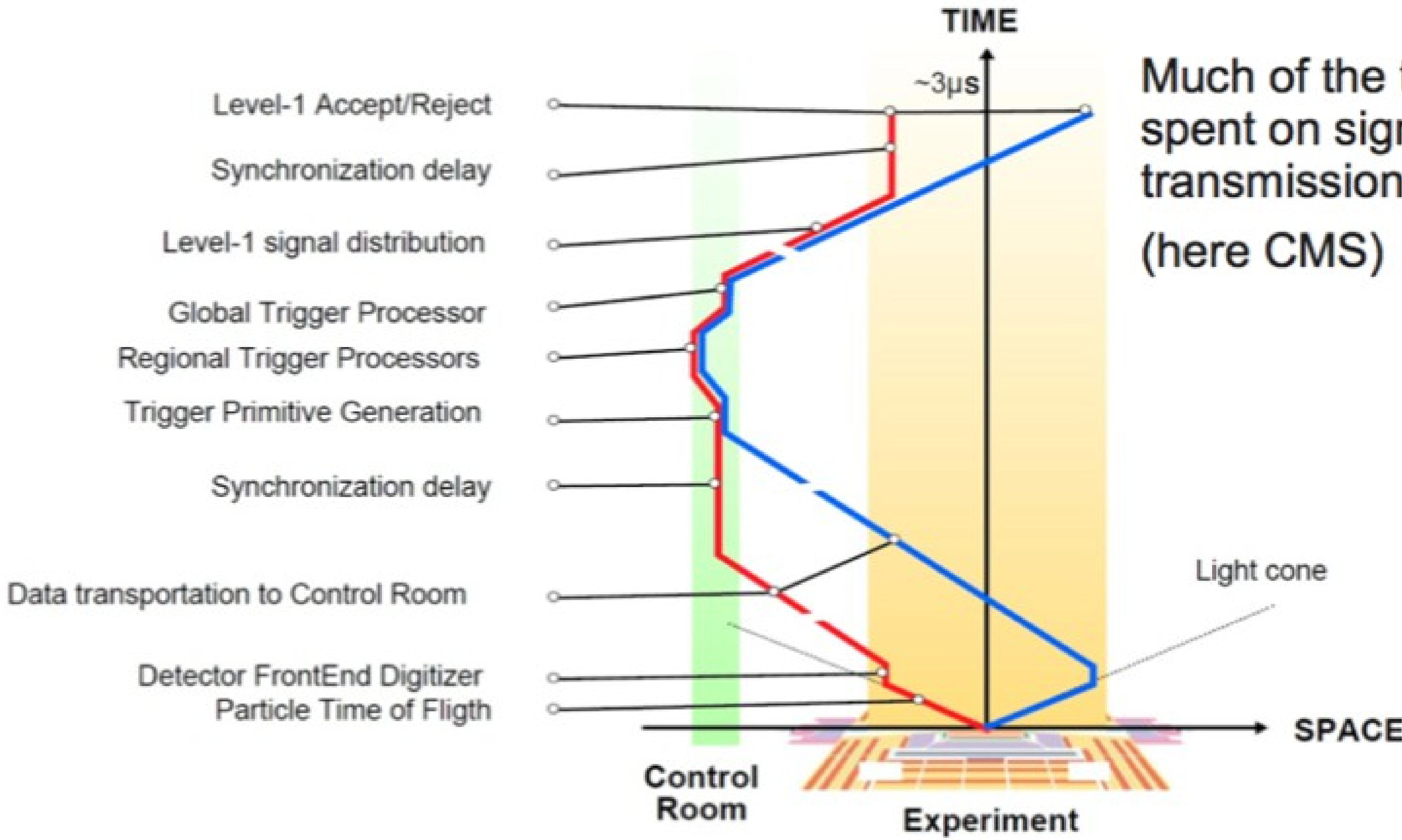


Combining information from different sub-detectors



- **Accommodate several sources**
  - Busy logic needs to be included
  - Can perform a global OR
  - Or combine certain trigger objects and apply simple topological cuts
  - High level quantities (masses, square roots are expensive! Avoid if possible

Overall L1 trigger latency

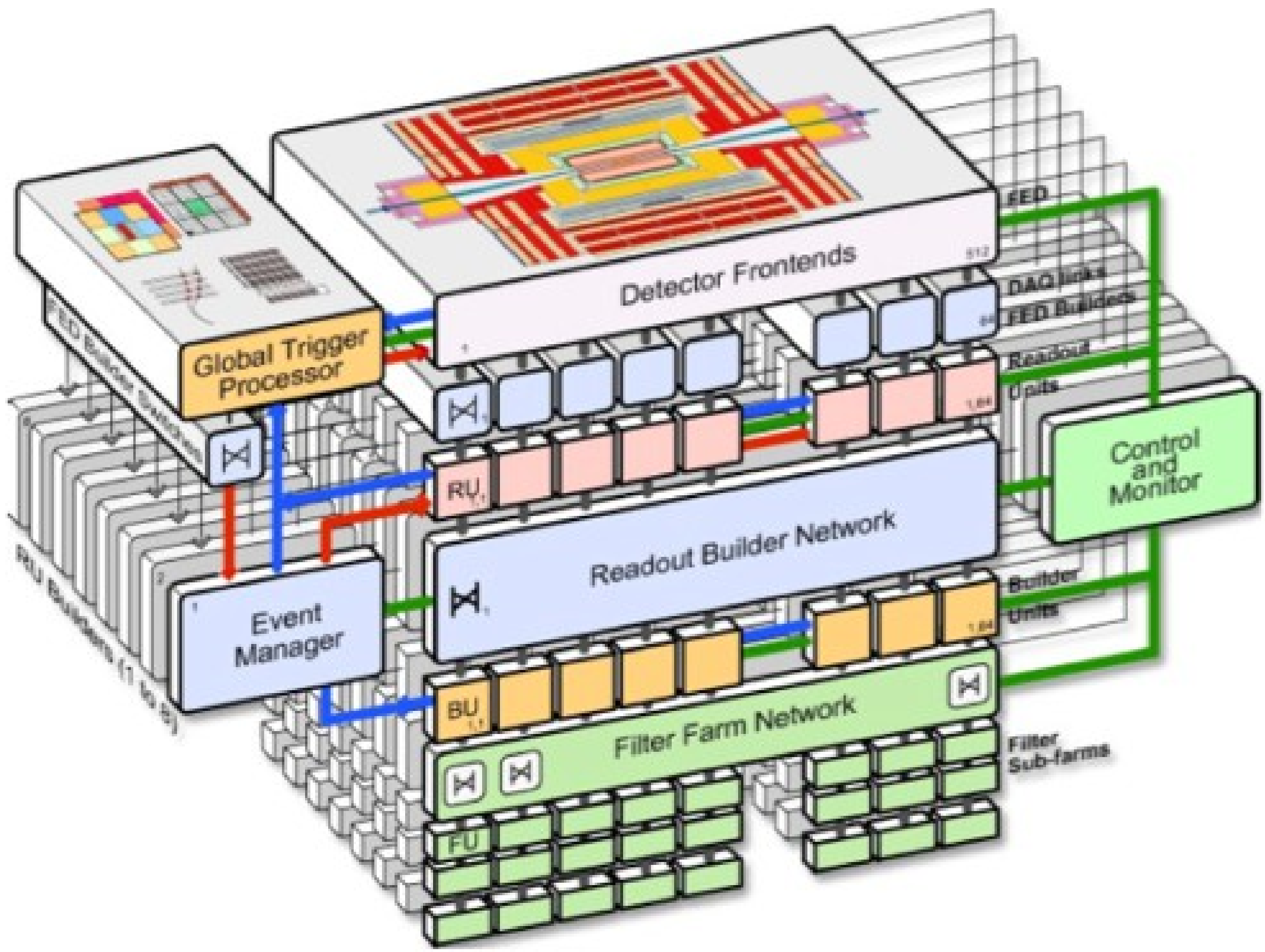


Much of the time spent on signal transmission

(here CMS)

Event building

- Parallelize the sum of the parts of the event to build = slicing
- At CMS 8 independent "slices" are used in order to achieve a 100 kHz rate

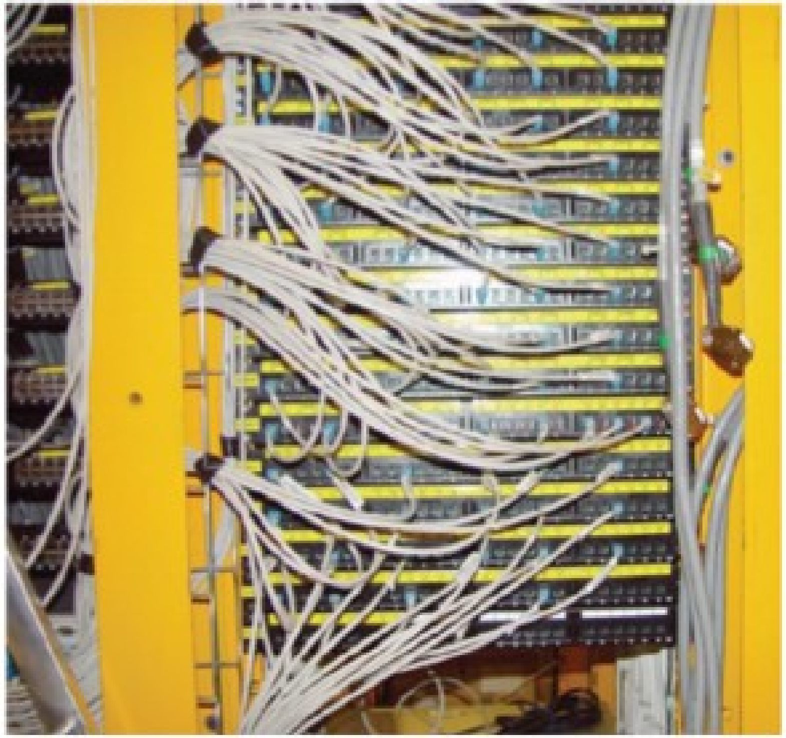


High level trigger

- After event is built can be shipped to a farm for processing before storage
- Events are independent : easy to parallelize
- Keep out rate at ~300Hz / latency at ~40-50 ms, can afford to use
    - high granularity of the detectors
    - offline reconstruction-like algorithms

ATLAS HLT farm:

LHCb readout switch:



Trigger/DAQ performance in LHC experiments

- Typical values for LHC run I
  - May depend on luminosity
- Notice that the final bandwidth has to be kept
  - total trigger rate must not exceed allocated bandwidth
  - prescale triggers if needed

Collider	**ATLAS**	**CMS**	**LHCb**	**ALICE**
L1 latency [μs]	2.5	3.2	4	1.2/6/88
L1 output rate [kHz]	75	100	1000	2
FE readout bandwidth [GB/s]	120	100	40	25
Max. average latency at HLT [ms]	40 (EF 1000)	50	20	
Event building bandwidth [ms]	4	100	40	25
Trigger output rate [Hz]	200	300	2000	50
Output bandwidth [MB/s]	300	300	100	1200
Event size [MB]	1.5	1	0.035	Up to 20

Wrap-up

Summary I

Hunting for new physics: wide variety of final states to be reconstructed

- general purpose detectors attempt to cover all signatures, rejecting background
- choice of technology: trade-off between particle identification, resolution and budget

Particle flow as a paradigm

- use the best out of the detectors for optimal performance
- yields a close 1:1 physics reconstruction of the hard process final state

Magnetic field and tracking play a crucial role and set the base

- B field is at the heart of the experiment
- tracking detectors are at the base of the reconstruction

Summary II

Calorimeters make the particles collapse to measure its energy, direction, time

- electromagnetic interactions have scaling properties, easy to reconstruct
- hadronic interactions depend on energy, particle, have distinct properties
- best performance conjugates careful detector design and reconstruction
- calorimeters provide most input to the trigger: coarse, fast information

Trigger systems take decisions based on a preview of (parts of) the event

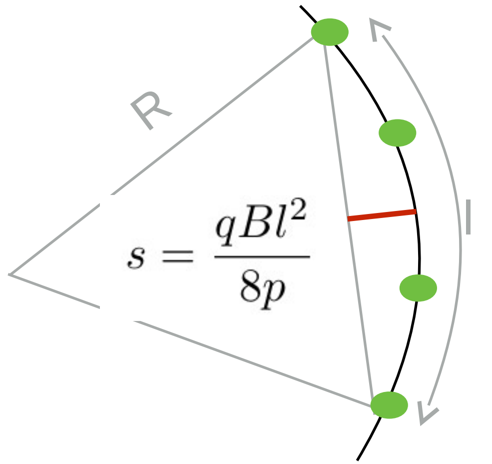
- layered structure to allow to store ~1-1.5MB events at a rate of 300-200 Hz
- first layers usually implemented in hardware, last layer in CPU farms

References

- W. R. Leo, "Techniques for Nuclear and Particle Physics Experiments", Springer
- H. Spieler, "Semiconductor Detector Systems", Oxford Science Publications
- R. Wigmans, "Calorimetry", Oxford University Press
- Fabjan and Gianotti, "Calorimetry for particle physics", Rev. Mod. Phys. 75, 1243
- Particle Data Group, "Experimental Methods and Colliders", Chin. Phys. C, 40, 100001 (2016)
- CMS Collaboration, "The Phase-2 Upgrade of the CMS Endcap Calorimeter", CMS-TDR-019

Backup

The magnet is the heart of an experiment I



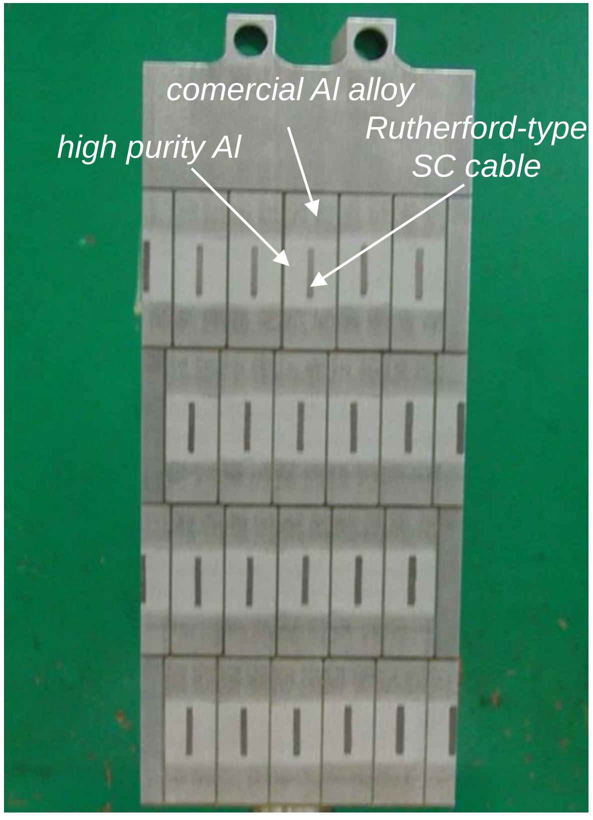
Goal: measure 1 TeV muons with δpT/pT=10% without charge error

- $\frac{\sigma_{p_T}}{p_T} = \frac{8p_T}{0.3Bl^2}\sigma_s$ this implies ~50μm uncertainty in measuring *s*
- either use "continuous tracking" or "extreme field"

From Ampere's theorem: $\oint \vec{B} \cdot d\vec{s} = \mu_0 I \rightarrow B = \mu_0 n I$

⇒ n= 2168 (120) turns per coil in CMS (ATLAS)

- special design needed for superconducting cable in CMS
- size limited by magnetic pressure (P≈6.4 MPa)



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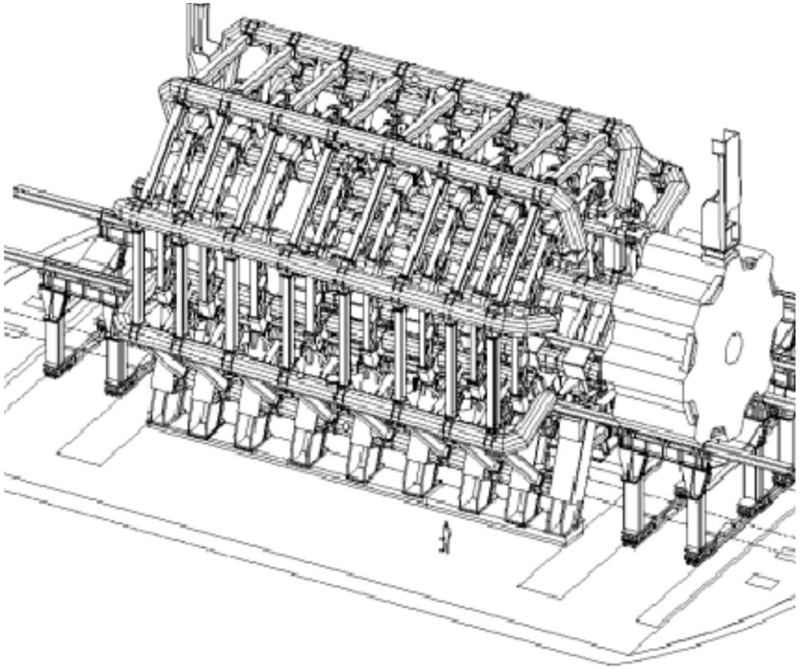
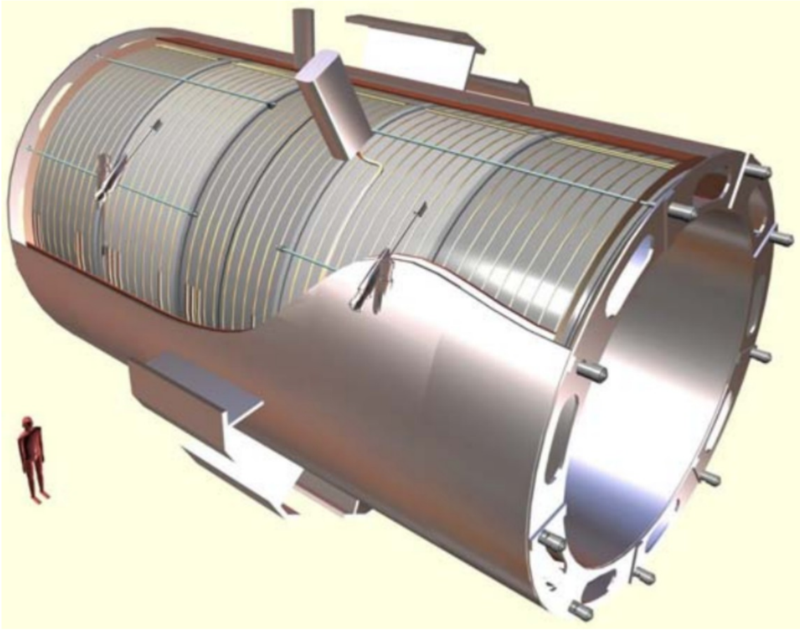
The magnet is the heart of an experiment II



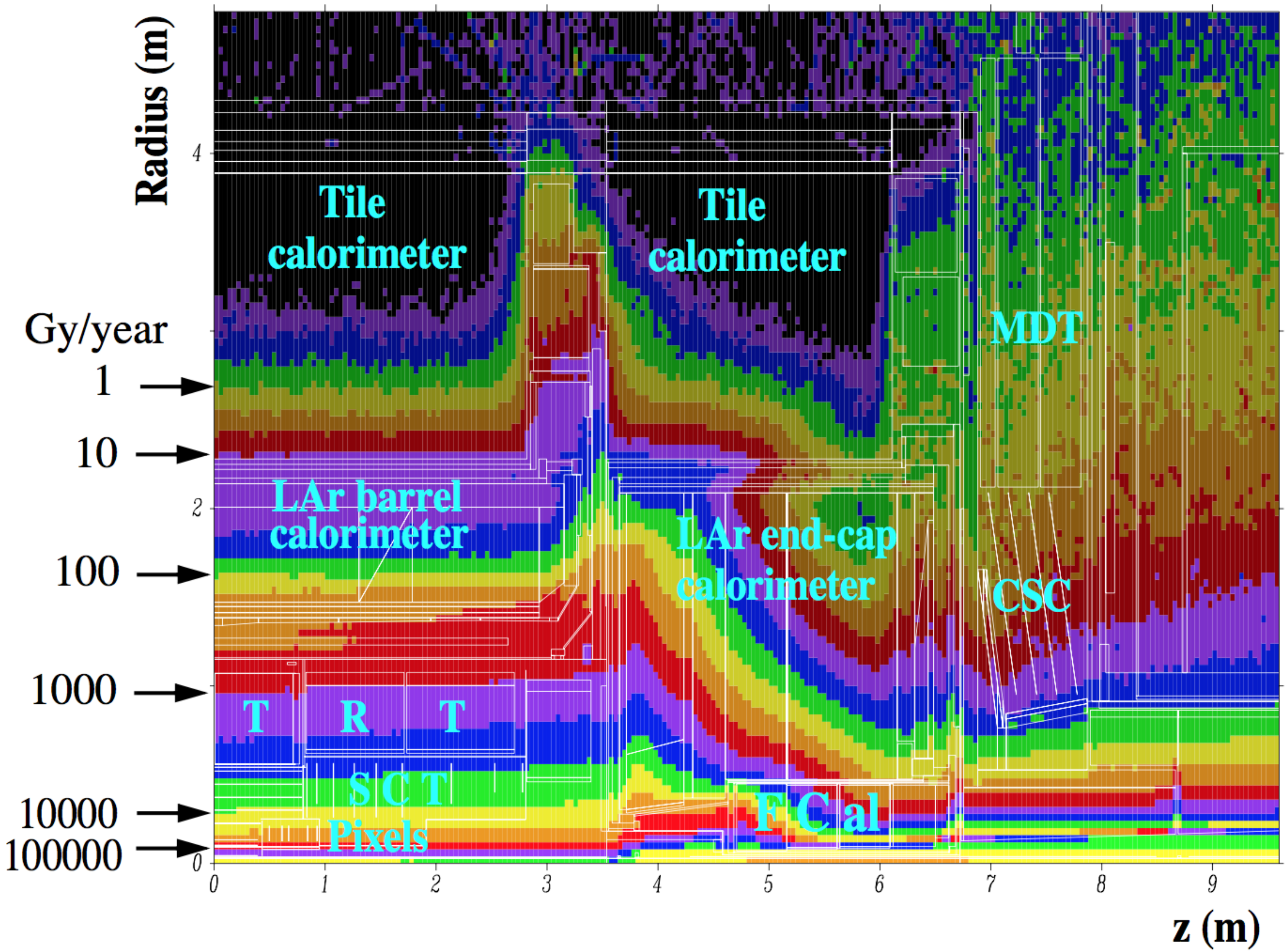


	ATLAS	CMS
B	0.6T (8 coils, 2x2x30 turns)	4T (1 coil, 2168 turns/m)
Challenges	• spatial/alignment precision over large surface • 1.5GJ energy stored	• design and winding of the cable • 2.7GJ energy stored
Drawbacks	• limited pointing capabilities • non-trivial B • additional solenoid (2T) needed for tracking • space needed	• limits space available for calorimetry • no photomultipliers for calorimeters • multiple scattering in iron core • poor bending at large angles

Radiation levels: a challenge for detectors and electronics

Activation of materials, impurities, loss of transparency/response, spurious hits …

- additional shielding/moderators needed to limit radiation impact in the detectors



Reminder: 1Gy = 1 J/kg = 100 rad

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~1 million trigger cells (TC) in HGCAL, c.f. <10000 in present CMS endcap calorimeters

Stage-1: Dynamical clustering techniques based on the Nearest Neighbour TCs to generate 2D-clusters in each HGCal trigger layer.

Stage-2: Generation of 3D-clusters relying on the longitudinal development of the shower, exploiting the projected position of each 2D-cluster to identify its direction.

The Stage-1→Stage-2 data transmission is x24 time-multiplexed to allow all data from one endcap to be processed by one FPGA