LHC detectors

P. Ferreira da Silva (CERN)

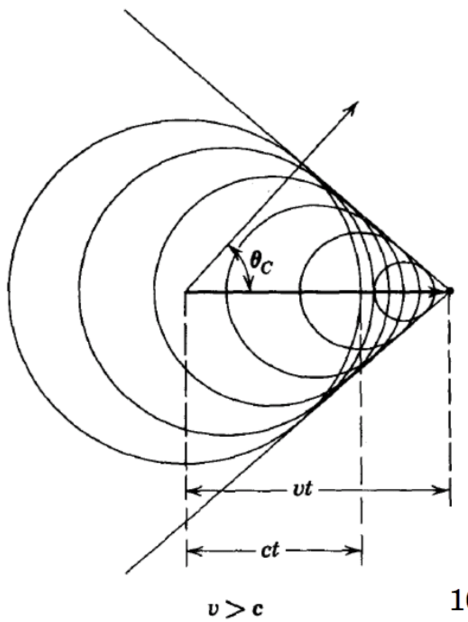
Course on Physics at the LHC

LIP, 15th March 2018

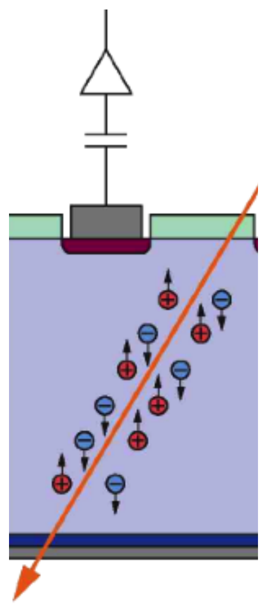
Calorimetry for pedestrians

Recall: we measure what collapses in the detector

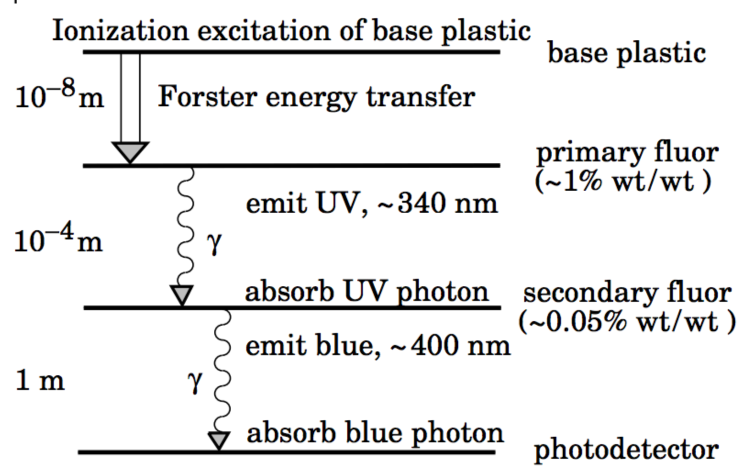
- Particles need to interact in matter ⇒ destructive interaction
  - dE/dx is converted in a signal
  - collect: charge, light, heat



Cerenkov radiation

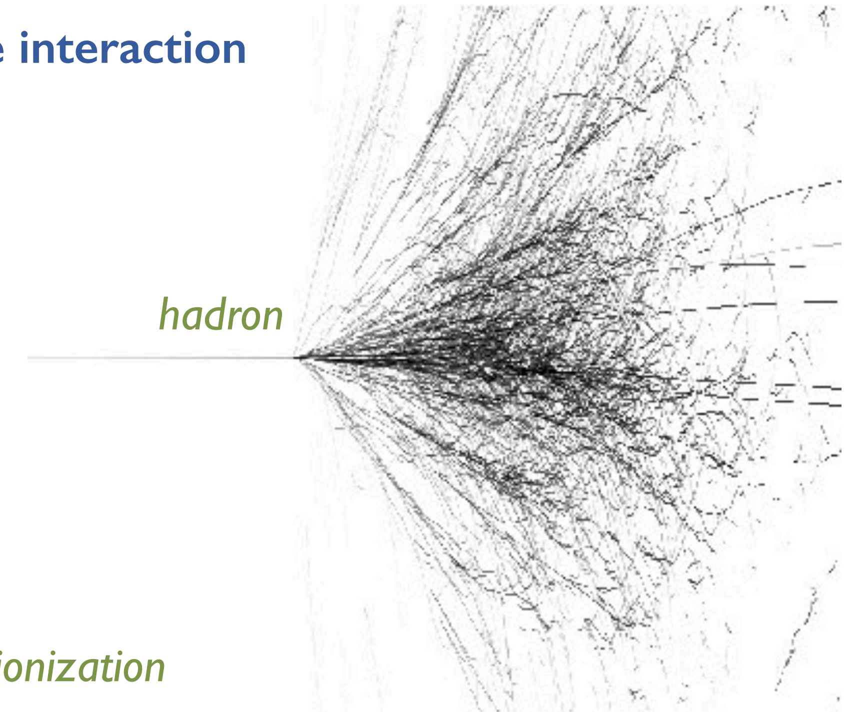


ionization

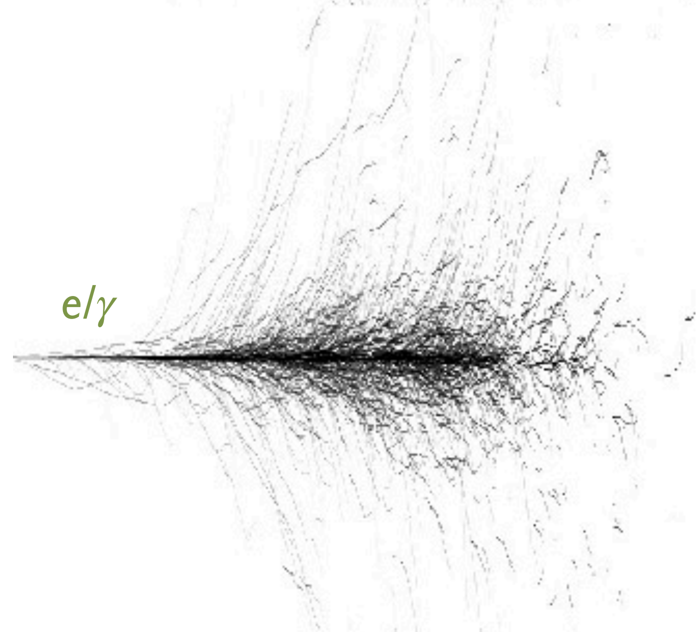


scintillation

hadron



e/γ

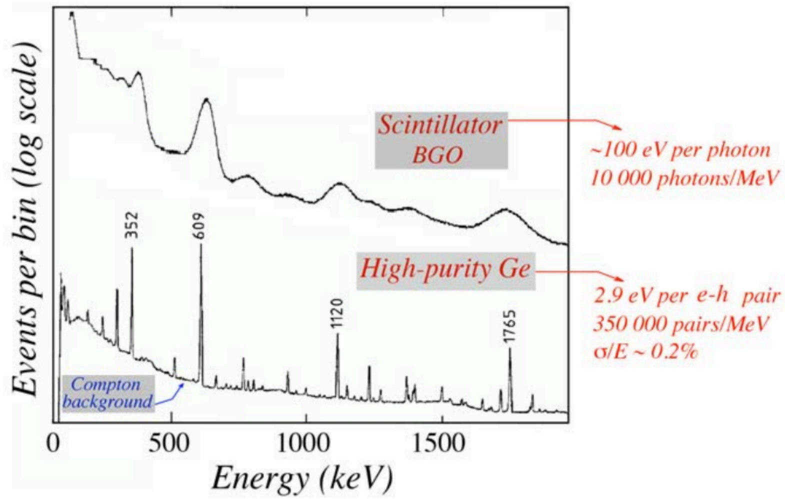


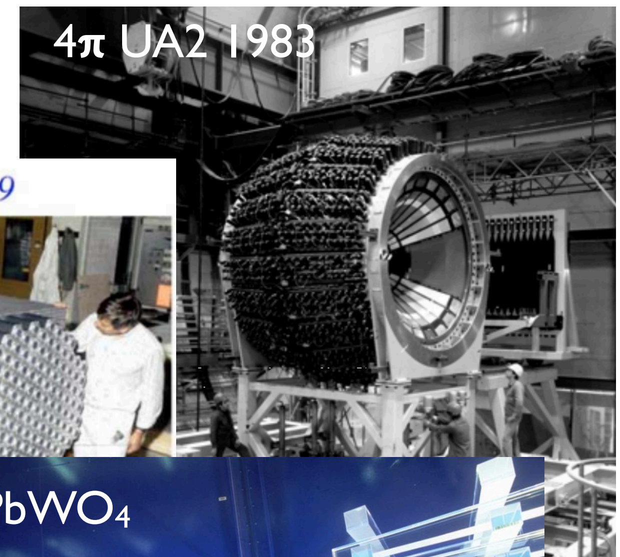
Purpose of a calorimeter

- **Primarily they measure the total energy of a particle, but they are versatile**
  - can measure position, angle and timing
  - 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) ⇒ trigger
- **Almost impossible to do high energy physics without calorimeters**

A very brief historical overview

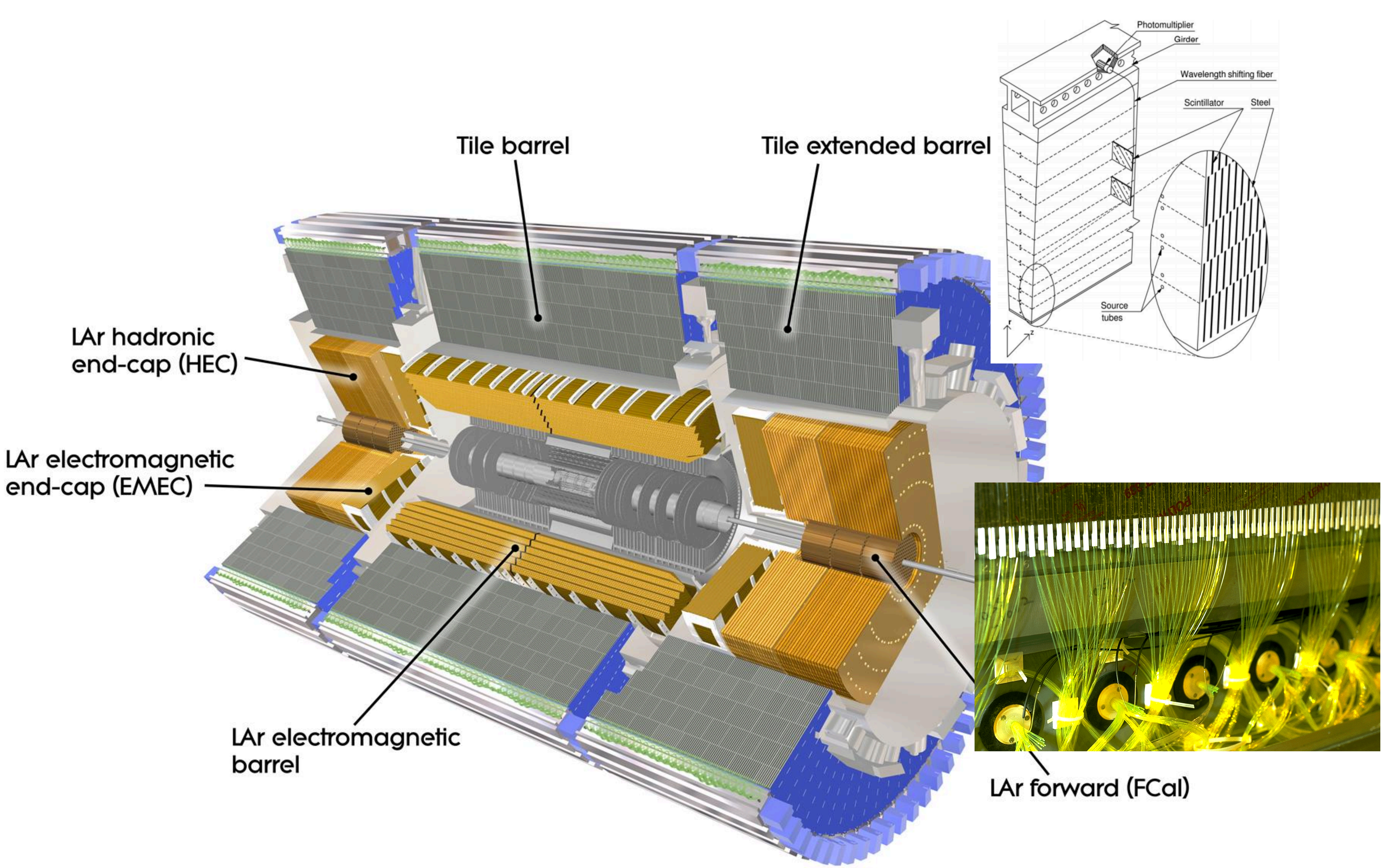
- Nuclear Physics in the 50's usage of **semi-conductor devices** improving the energy measurement of radiation energy
- Cosmic Rays (1958) - the first **sampling** calorimeter
- Particle Physics: adoption of electromagnetic and some times hadronic calorimeters as crucial components in experiments
  - 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…)



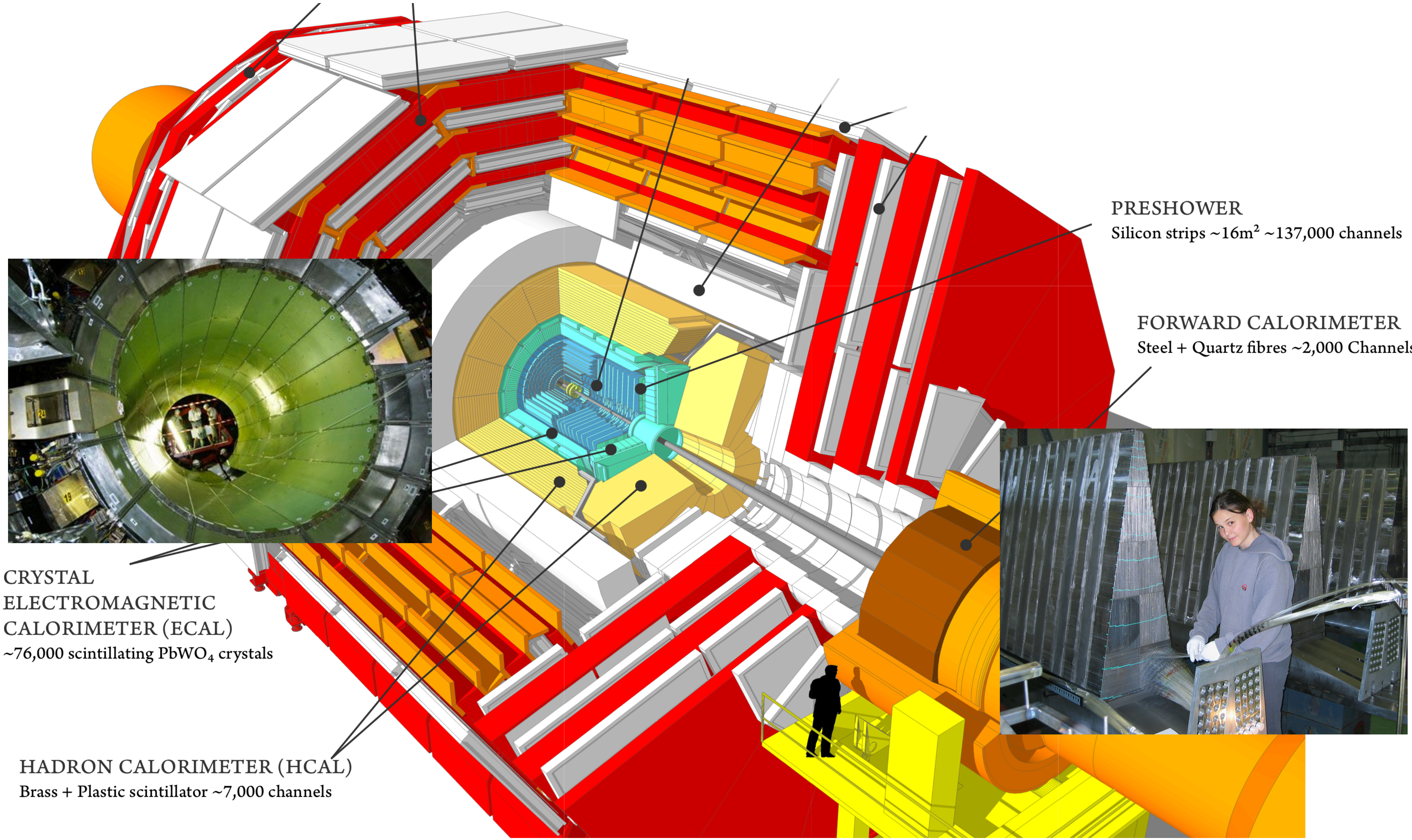


SPACAL 1989

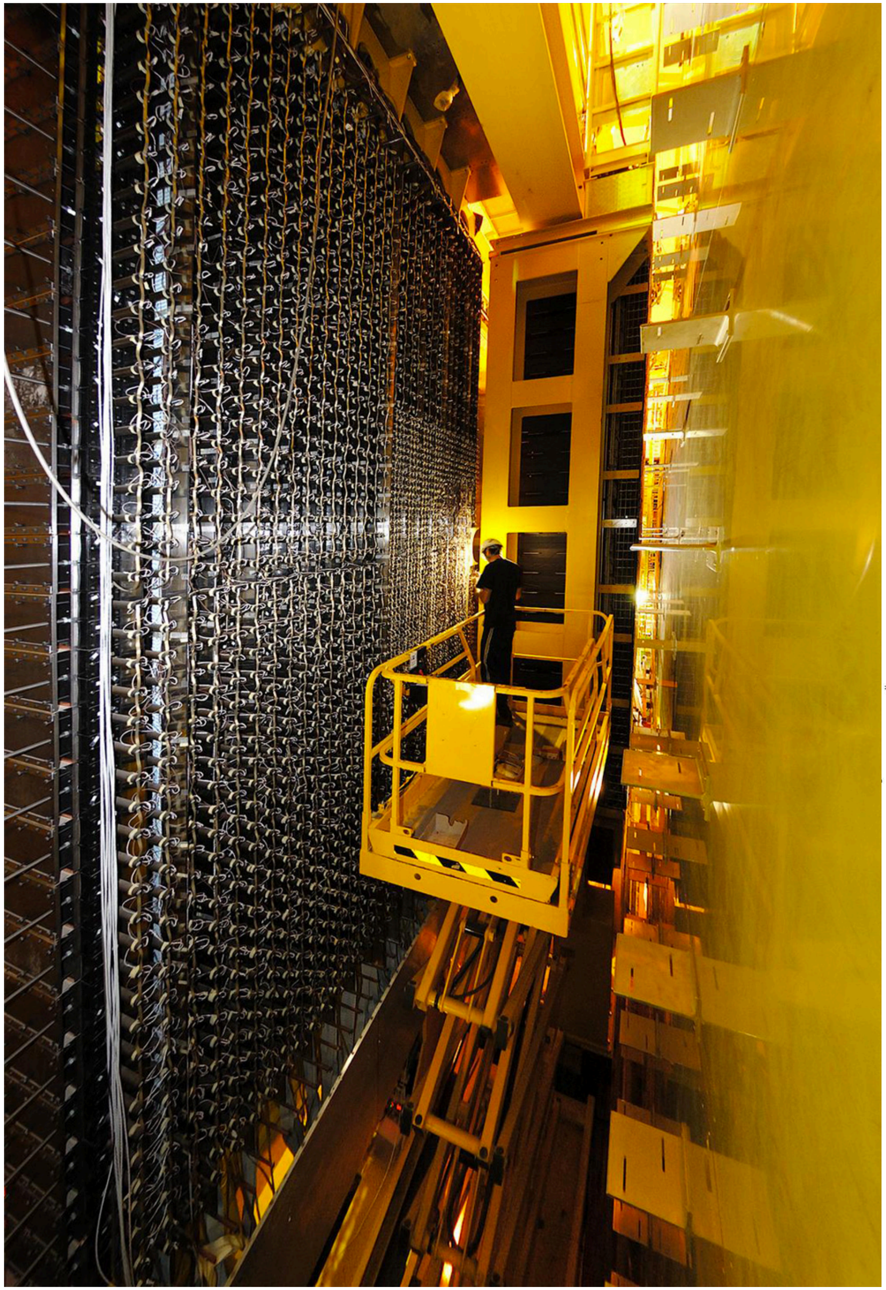
ATLAS calorimetry system



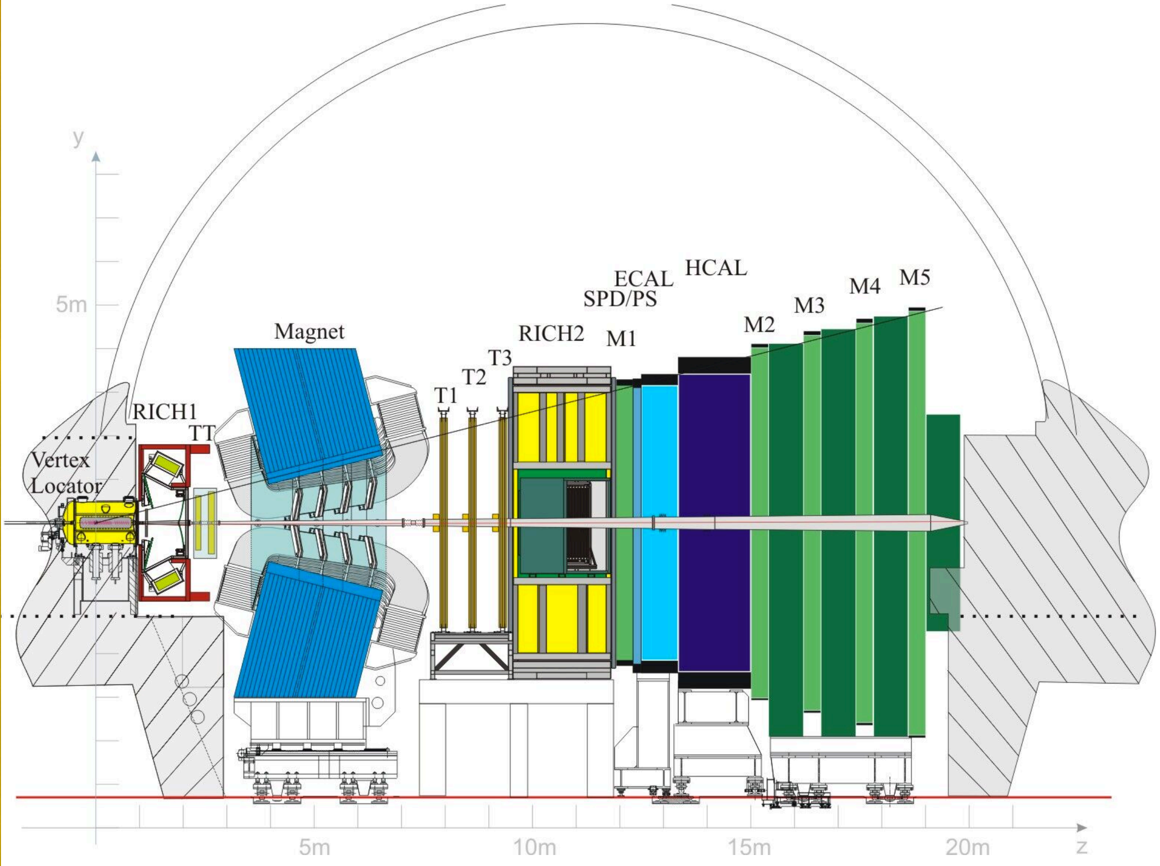
CMS calorimetry system



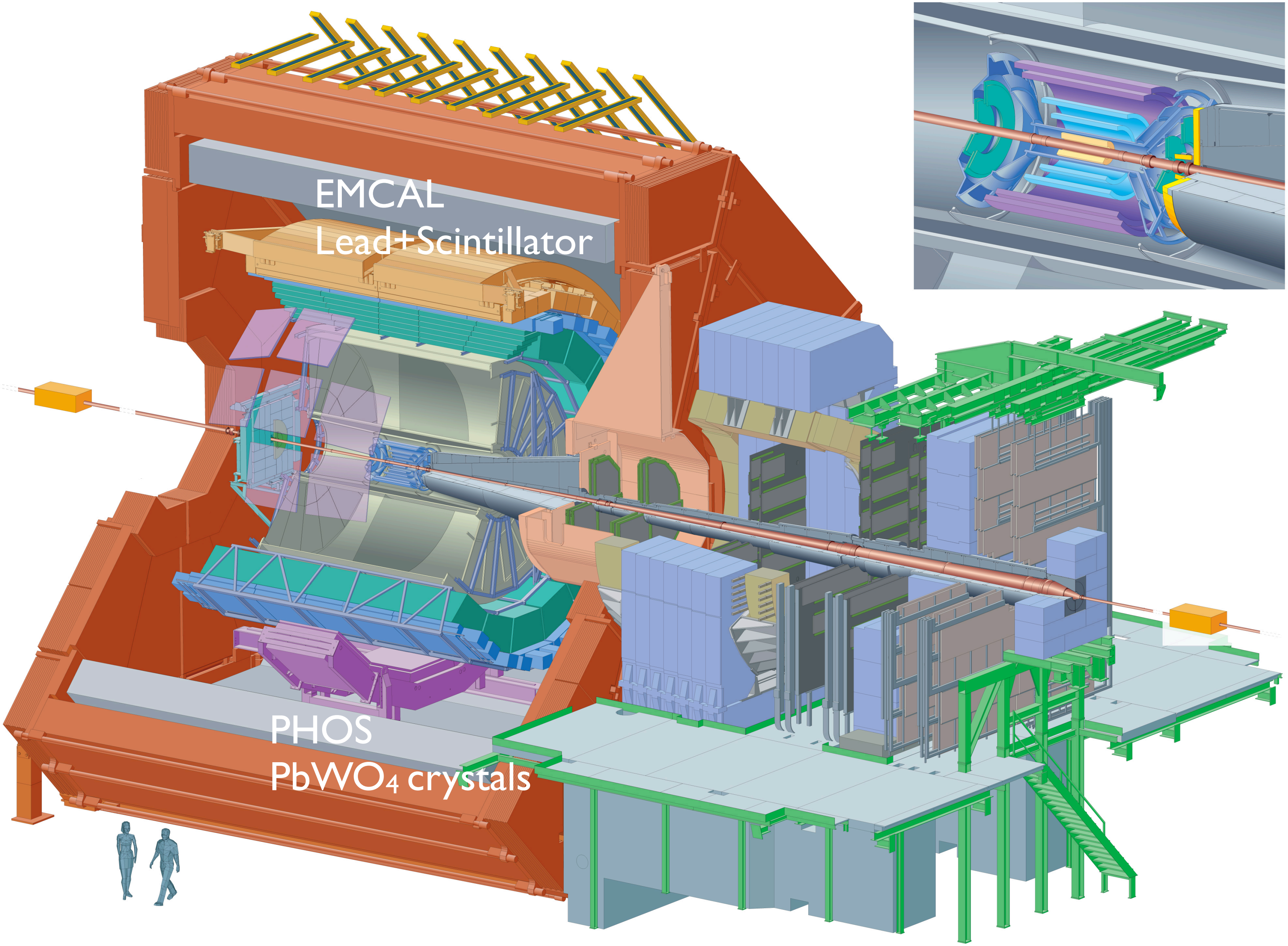
Calorimetry in LHCb



Plastic+metal sandwiches



Calorimetry in ALICE

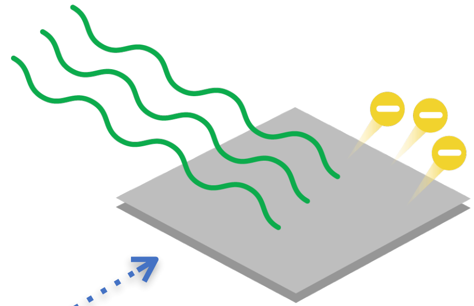


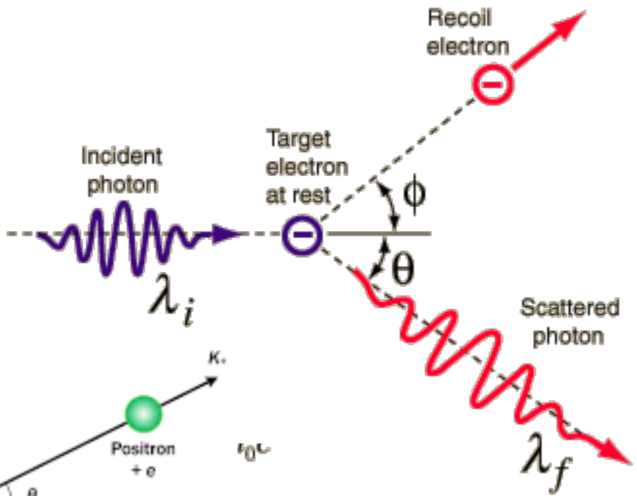
Electromagnetic calorimeters

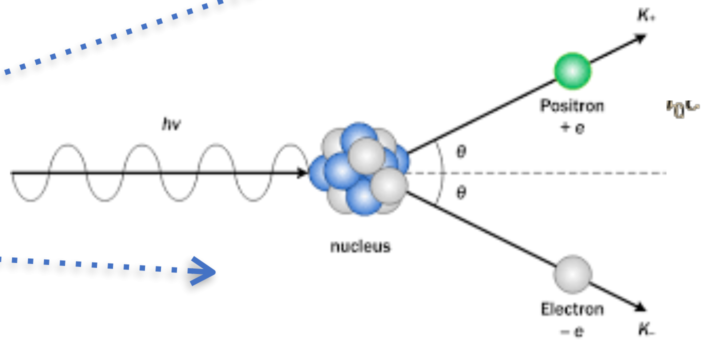
- e/γ loose energy interacting with nuclei and atomic electrons

e
- ionization
- bremmstrahlung

γ
- 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

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

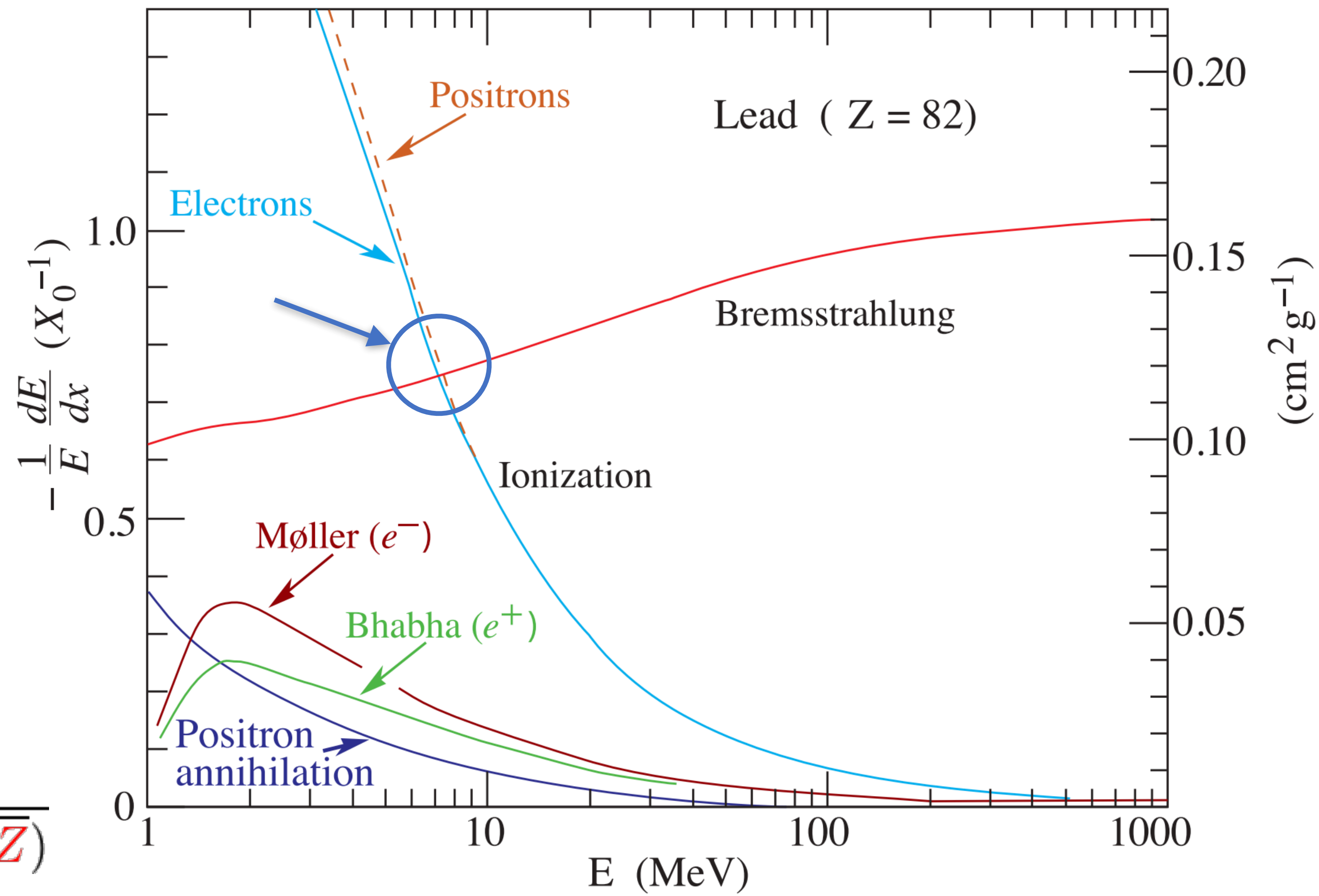
$$E_c \propto \frac{1}{Z + \mathrm{cte}}$$

7 MeV for Lead

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

$$X_0 \approx \frac{716\ [\mathrm{gcm}^{-2}]\ A}{Z(Z+1)\ln(287/\sqrt{Z})}$$

0.56cm for Lead



Processes initiated by photons

- Photo-electric effect

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

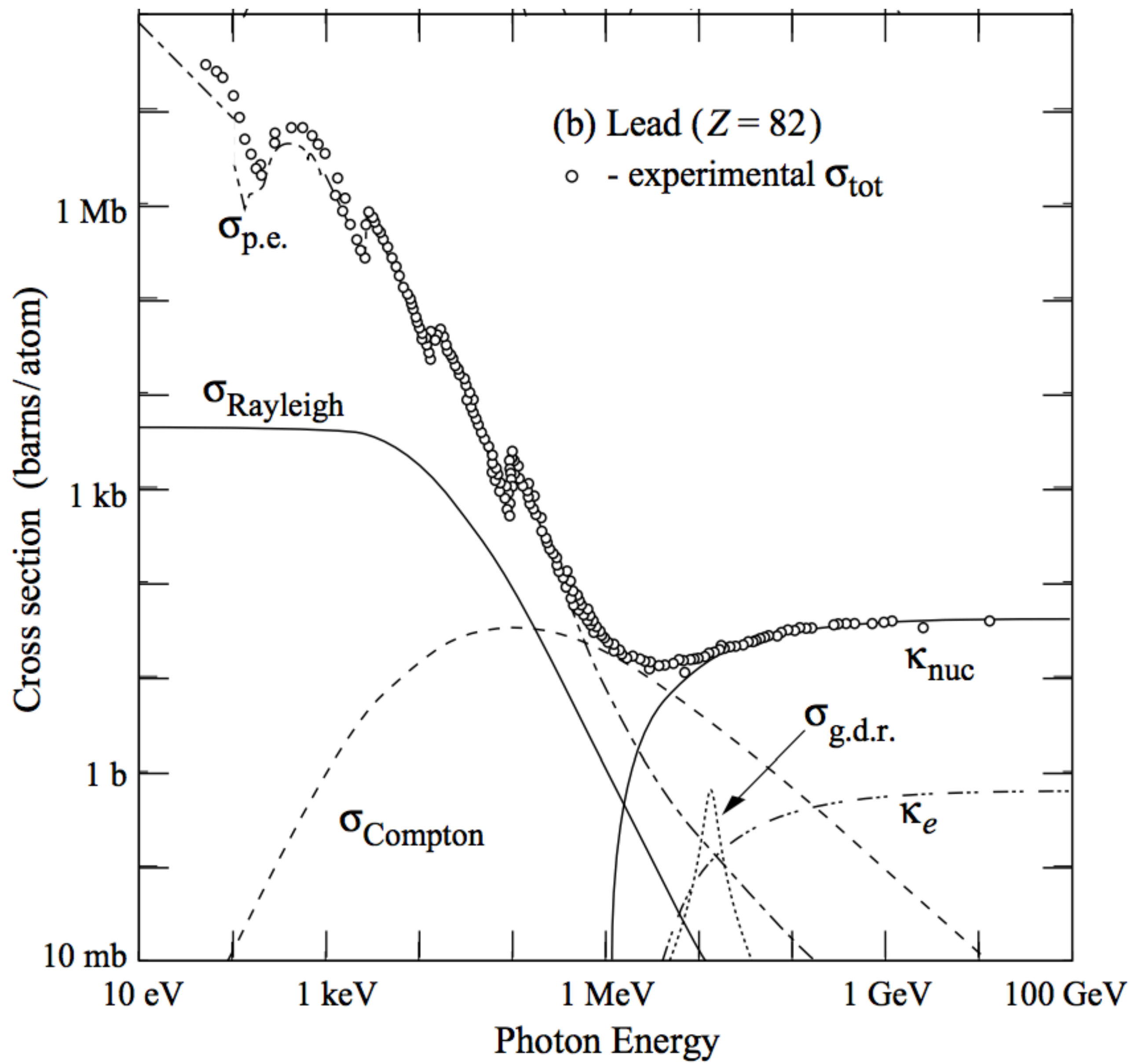
- Compton scattering

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

- Pair production

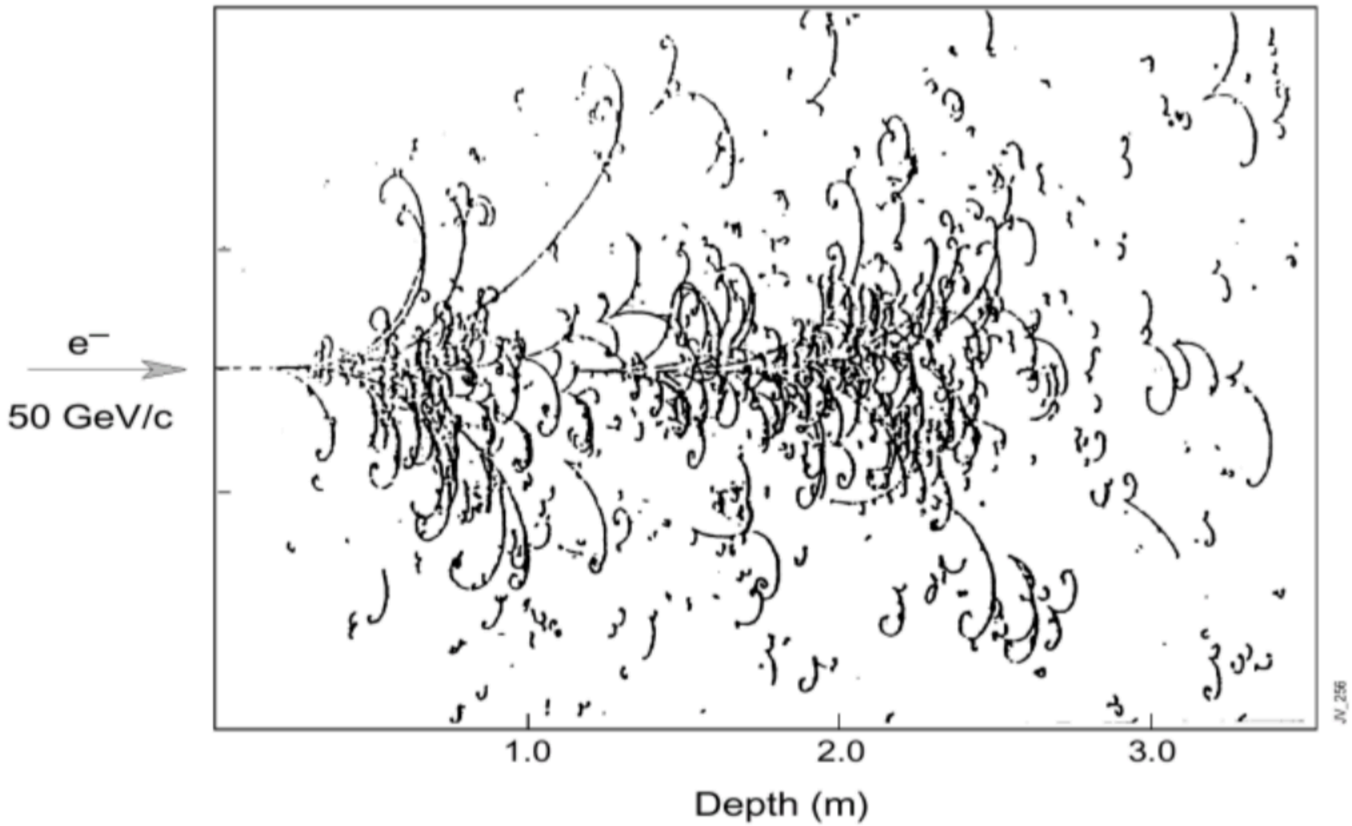
$$\sigma \approx \frac{7}{9} \frac{A}{N_A} \frac{1}{X_0} \propto Z(Z+1)$$

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



Electromagnetic showers

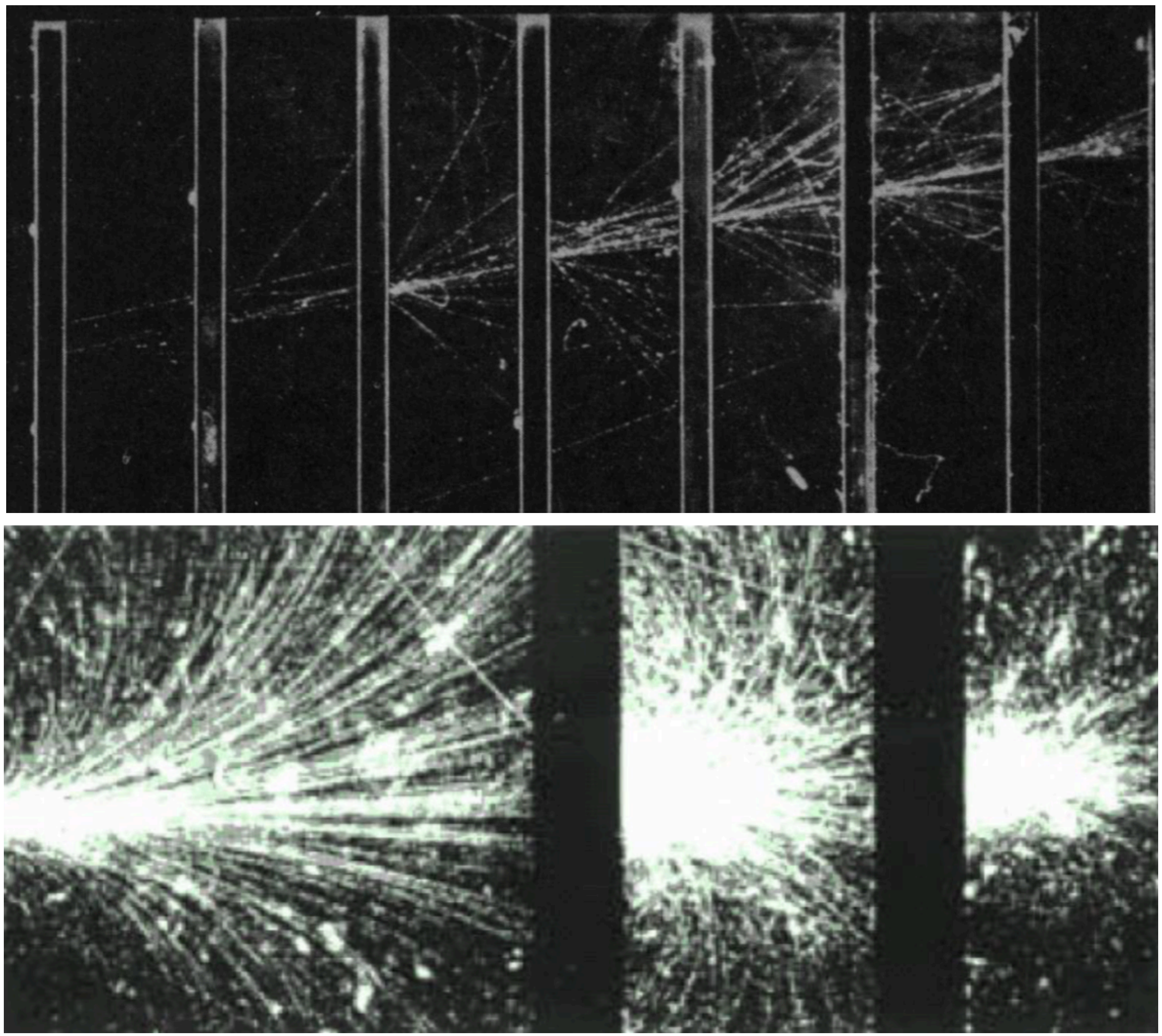
- **High energy e/γ will start a cascade of pair production and bremmstrahlung**
  - multiplicative regime until secondaries start falling below E_c



e- in bubble chamber (70% Ne: 30% H_2) under 3T field

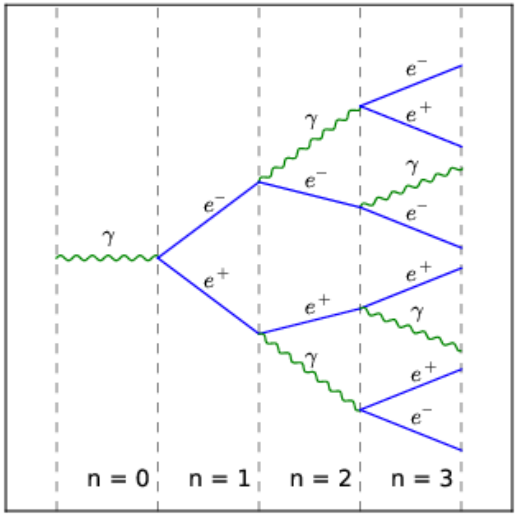
Electromagnetic showers

- **High energy e/γ will start a cascade of pair production and bremmstrahlung**
  - multiplicative regime until secondaries start falling below E_c



showers from two different energy photons in bubble chamber

A toy model for electromagnetic showers



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

- **Scaling properties** $N(x) = 2^{x/X_0}$ $E(x) = E_0/2^{x/X_0}$

- **Splitting energy reaches E_C limit, shower starts to be absorbed**

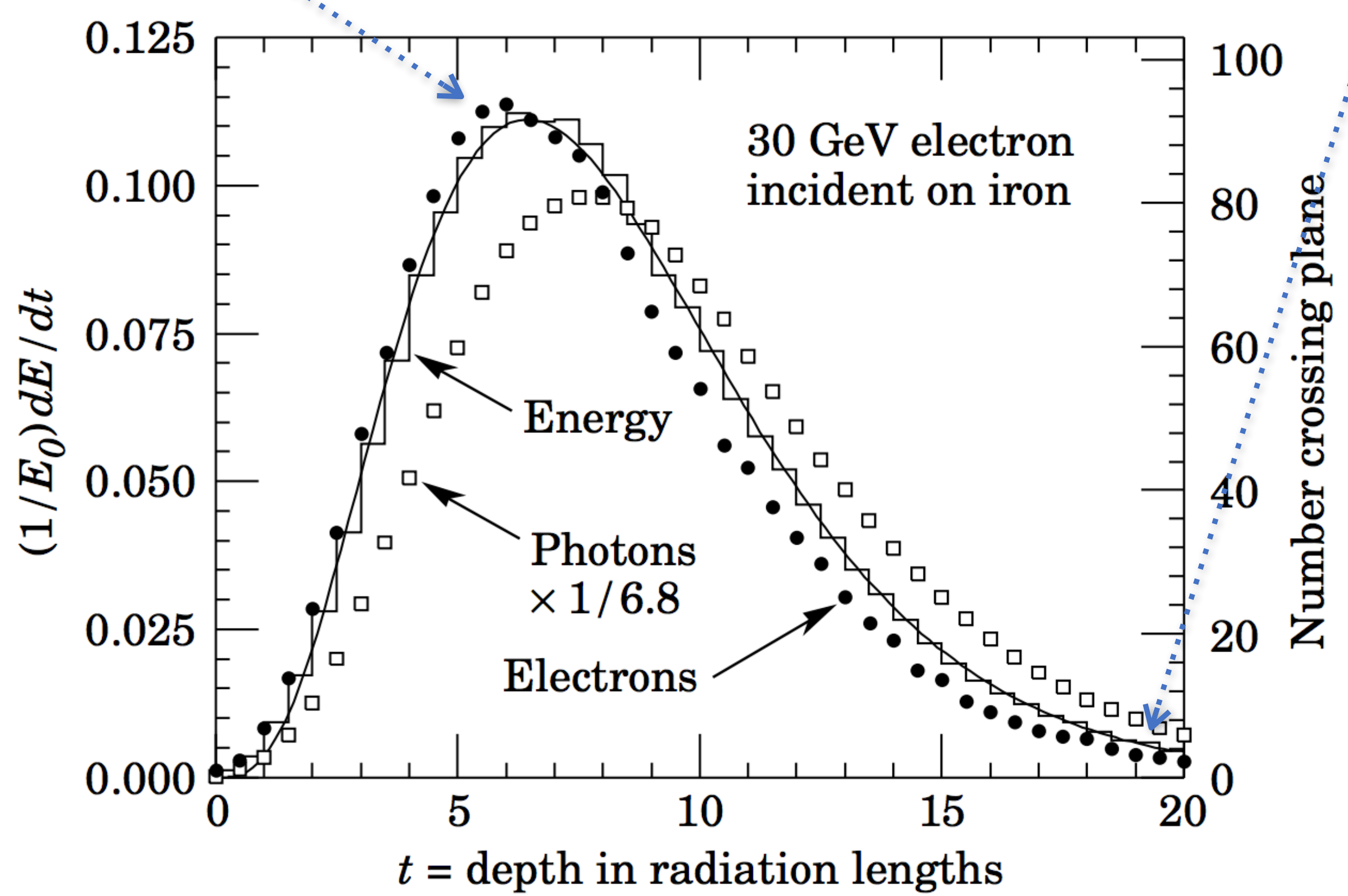
$$x_{max} = X_0 \ln_2 \frac{E}{E_c}$$ $$N_{max} = \frac{E}{E_c}$$

not so far from reality

Detailed simulation of an electromagnetic shower

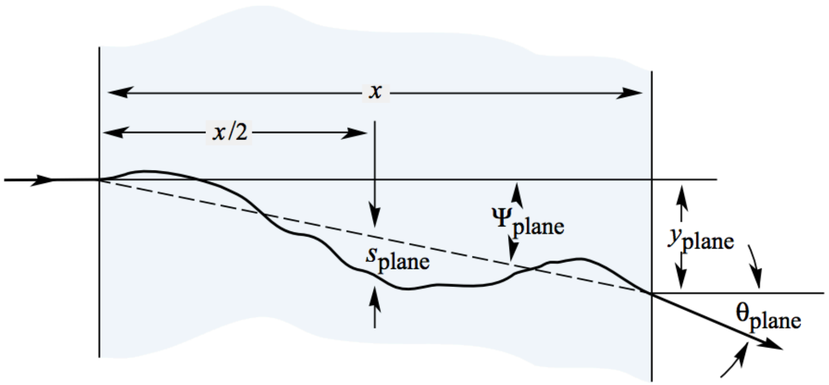
$$t_{\max} \sim \ln \frac{E}{E_c} \pm 0.5$$

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



Spread in the transverse plane

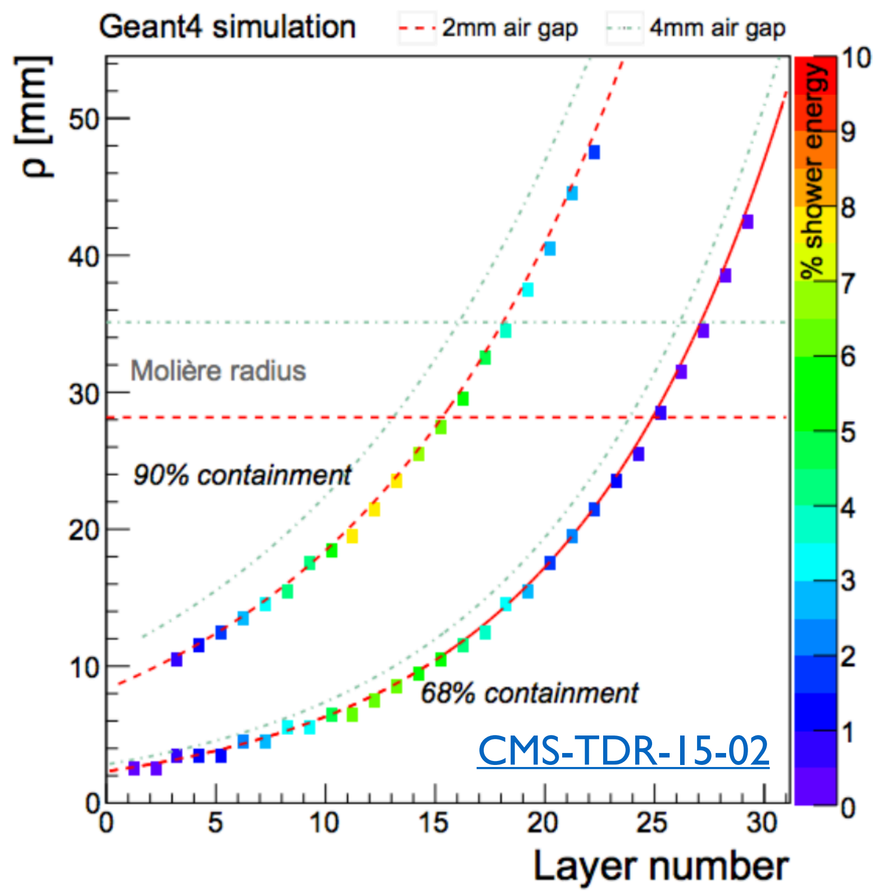
- **Particles disperse with respect to initial axis**
  - decay openings
  - multiple scattering of charged particles
  - γ in the region of minimal absorption travelling longer



- **Define the Moliere radius as**

  lateral size containing 90% of the shower energy

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



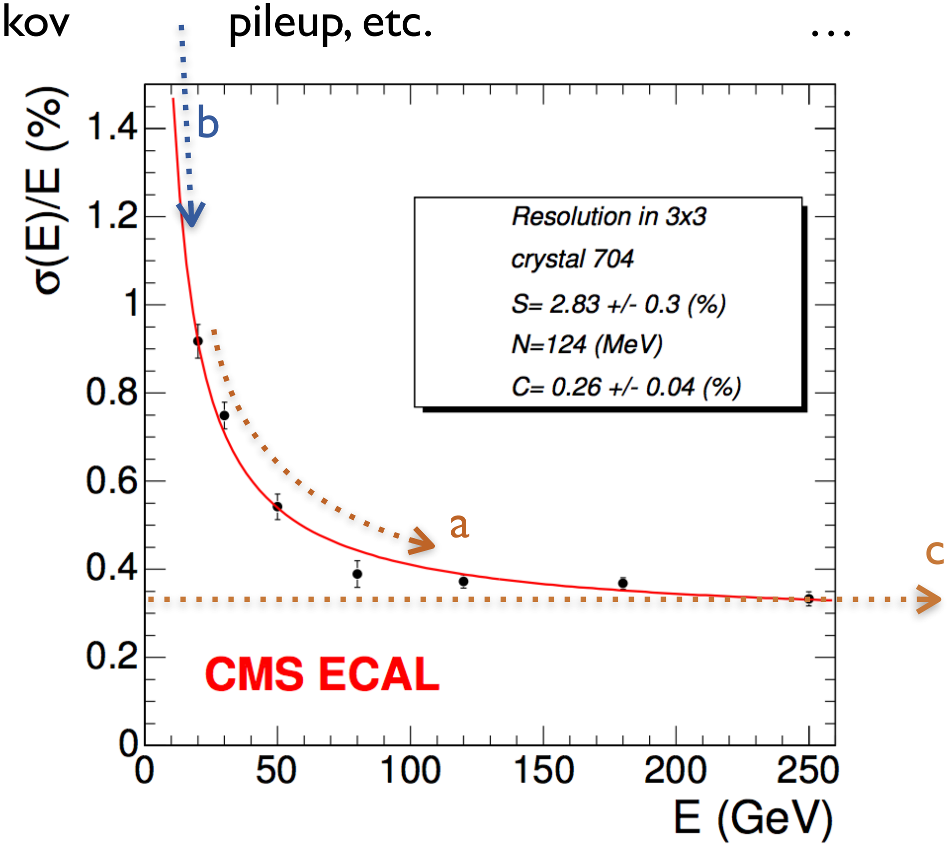
Electromagnetic energy resolutions

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

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

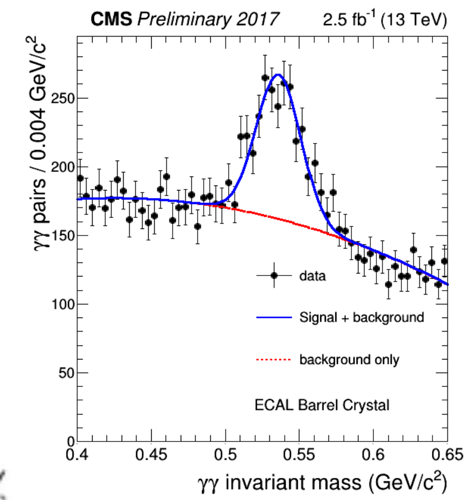
Noise term - additional degradation at low energy due to electronics noise, pileup, etc.

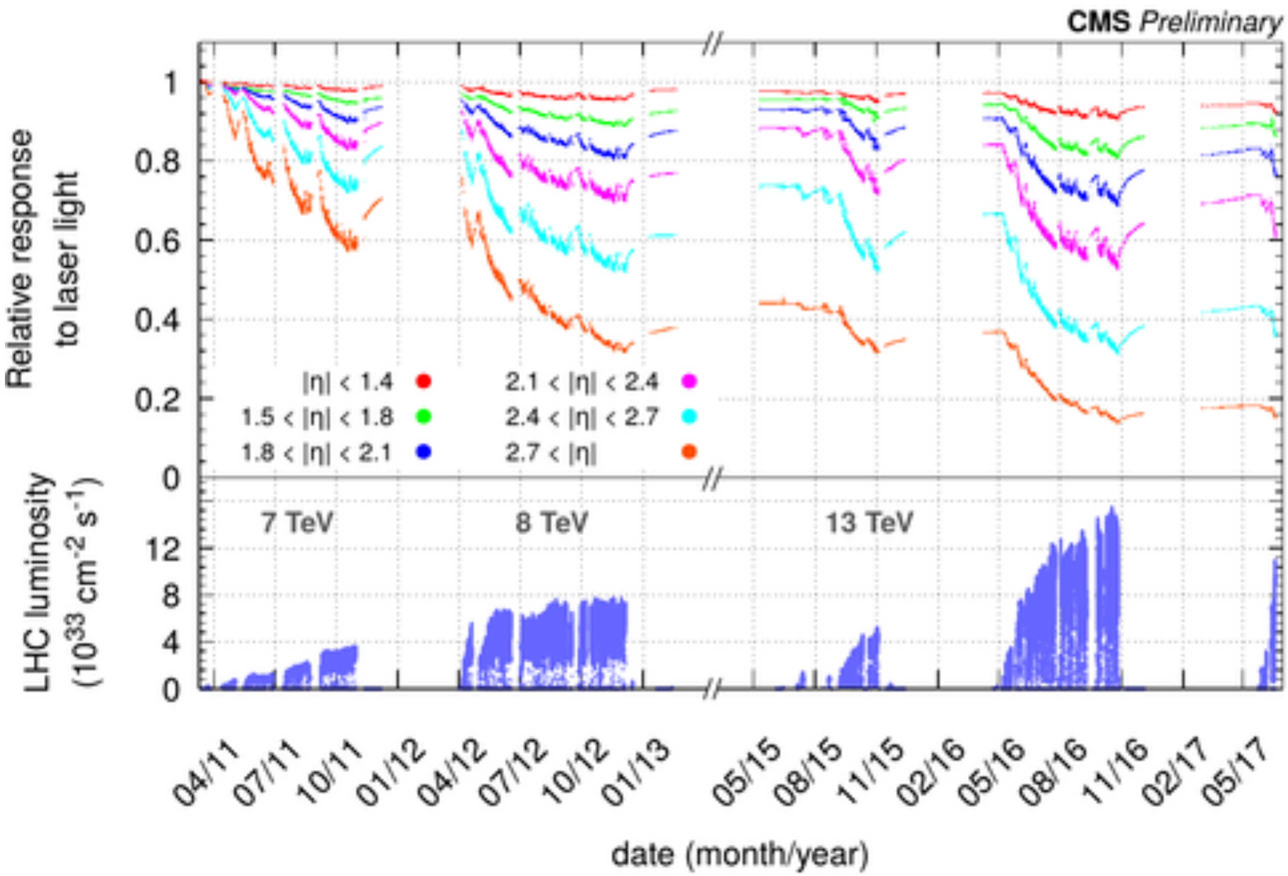
Constant term - energy leakage, calibration, non uniformity, radiation damage, …



Some challenges in maintaining energy resolution

- **Intercalibration between cells needs to attain 1% level or better**
  - use $\eta/\pi^0\rightarrow\gamma\gamma$, $Z\rightarrow ee$ and ϕ symmetry in minimum bias
- **Track radiation damage / recovery of the crystals with a laser**
  - inject light into crystals and normalize to PN diodes



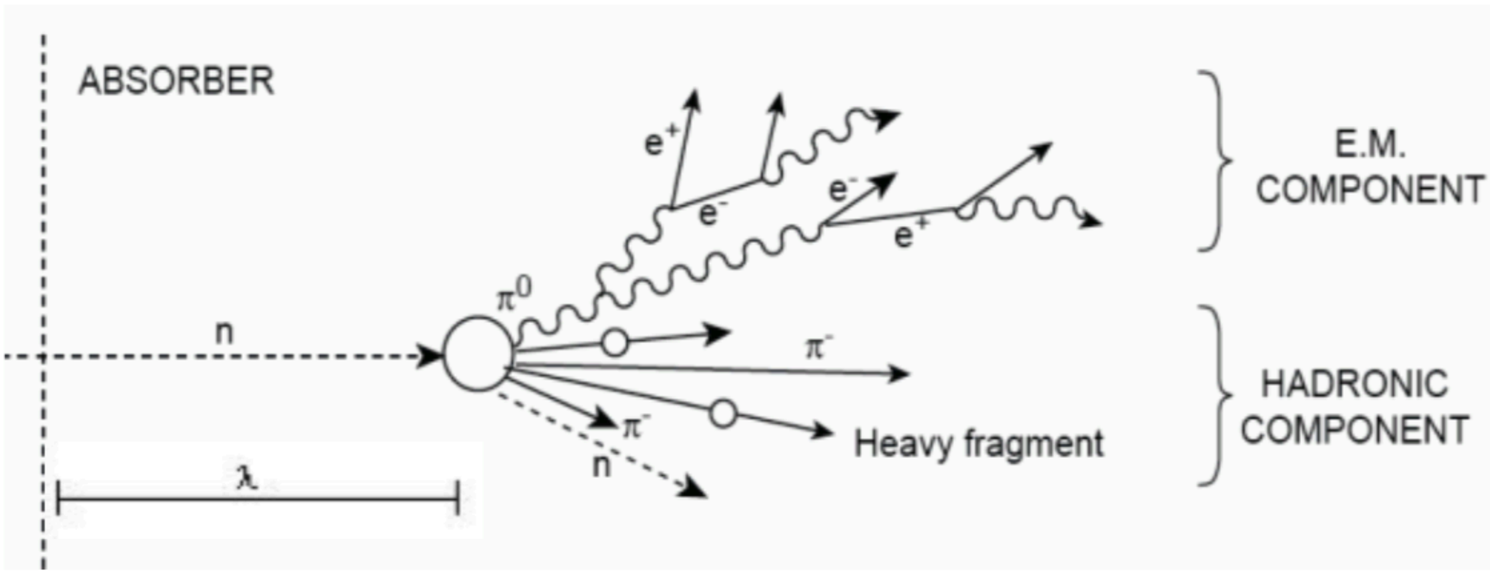


A comparison of different e.m. calorimeters

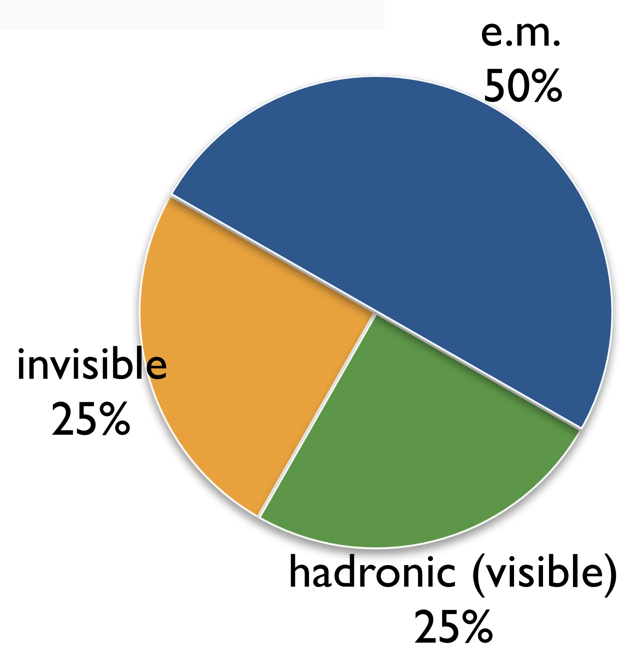
Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/E^{1/4}$	1983
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	$16–18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	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?

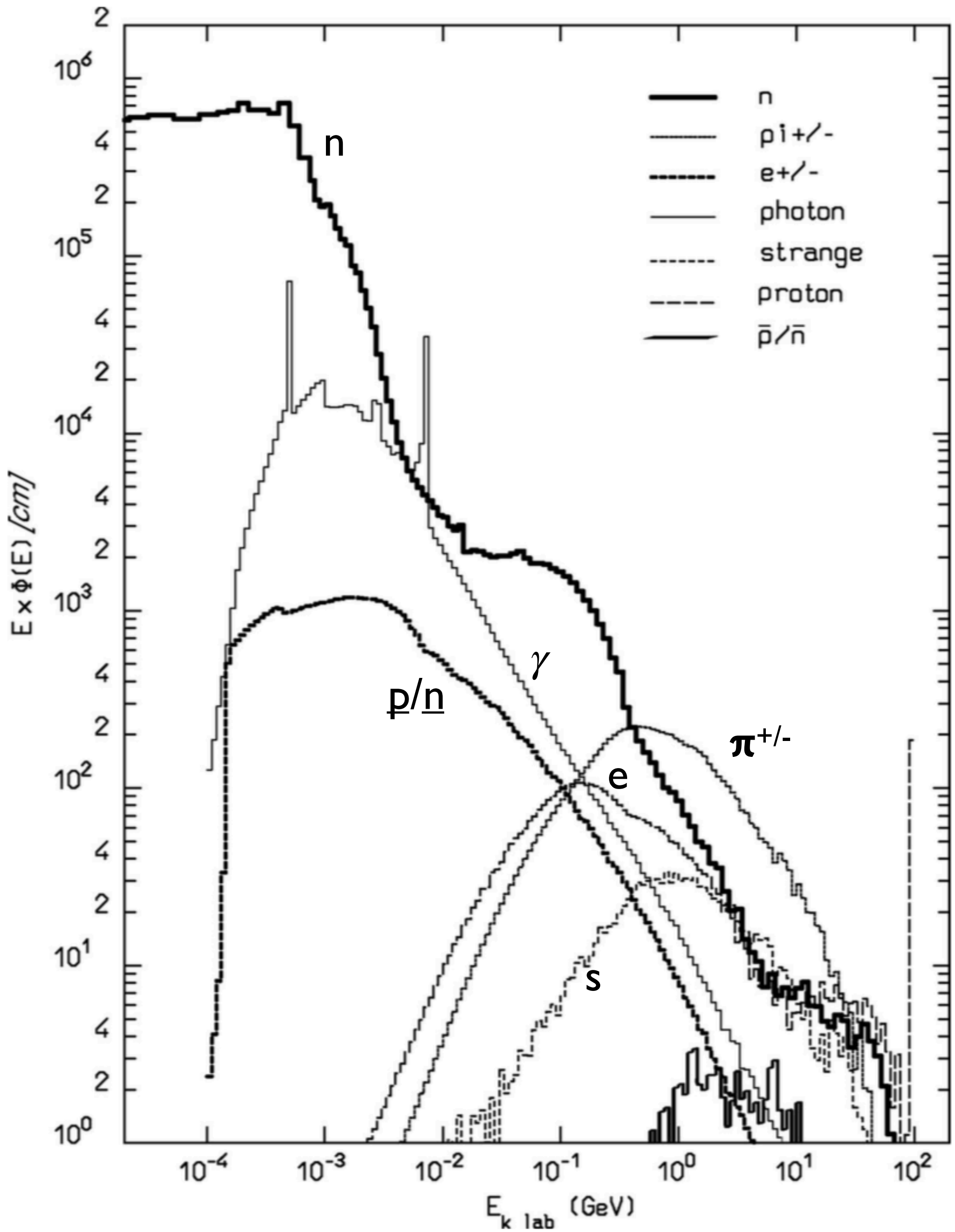


- Charged pions, kaons, protons, neutrons, etc…
- Products of **strong interactions** will start "mixed" showers
- Requires longer containment than e.m showers



Particle spectra in a proton shower

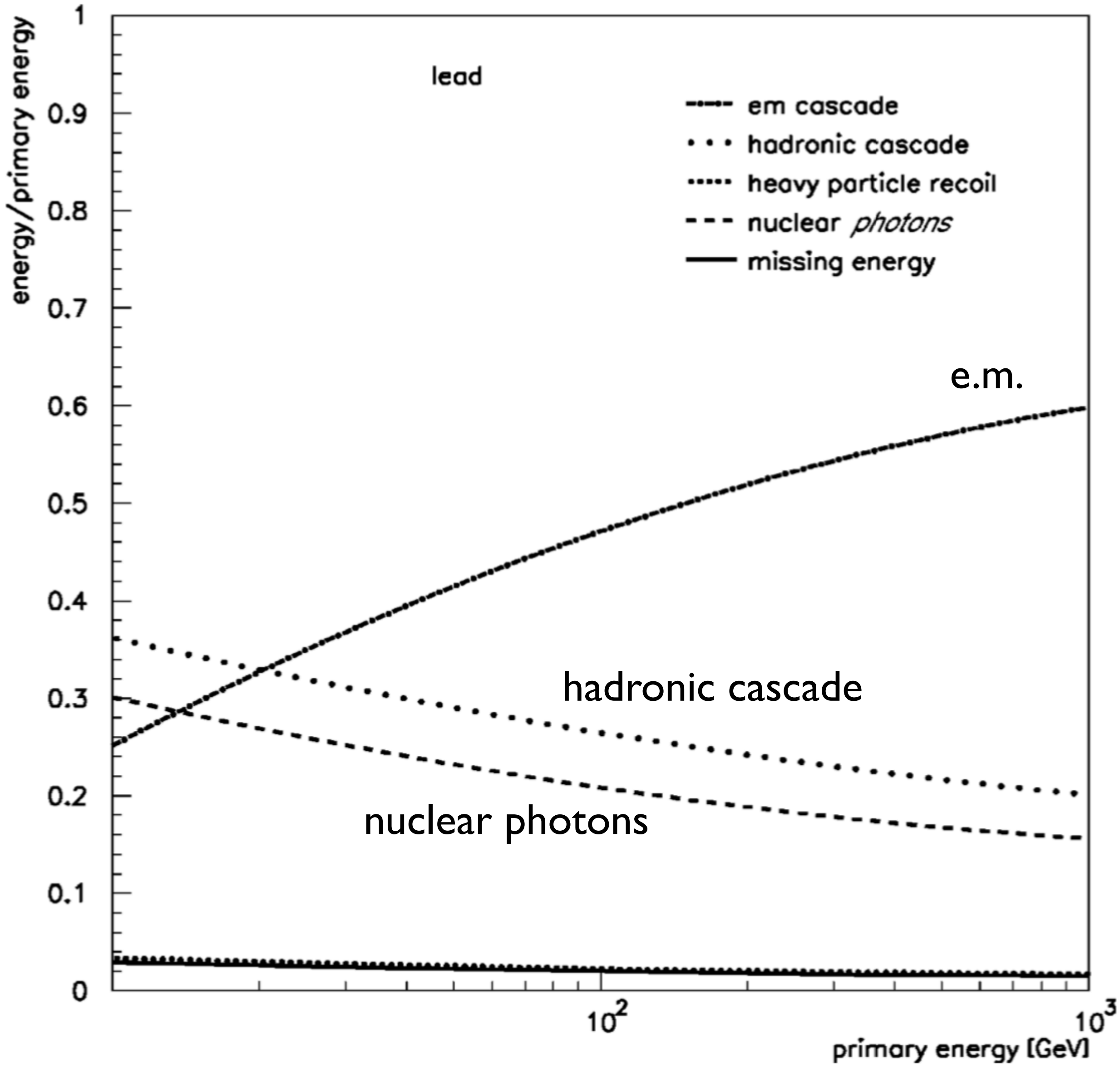
Showers depend heavily on the incident particle…



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

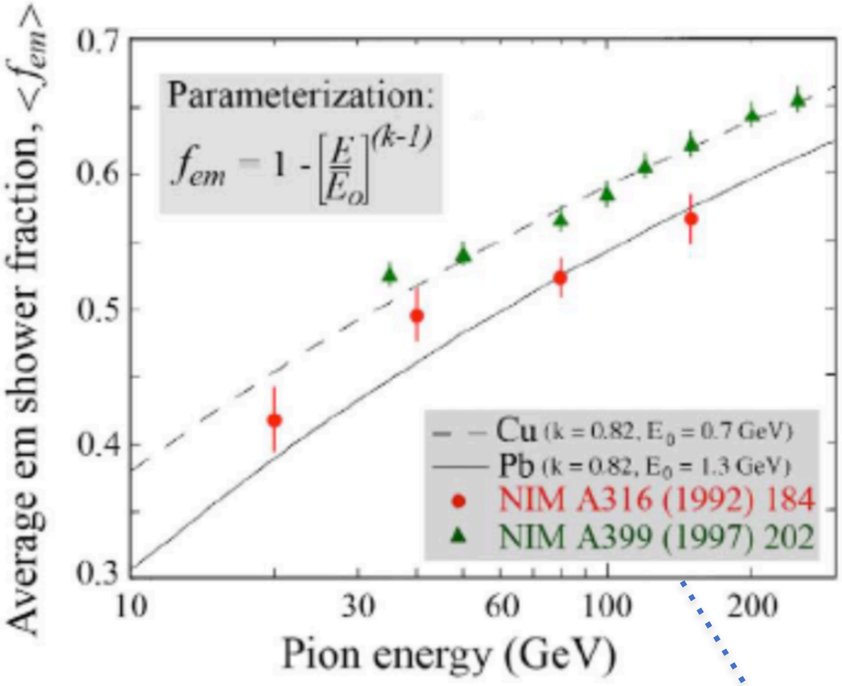
Particle spectra in a proton shower

Showers depend heavily on
the incident particle <u>and its energy</u>…

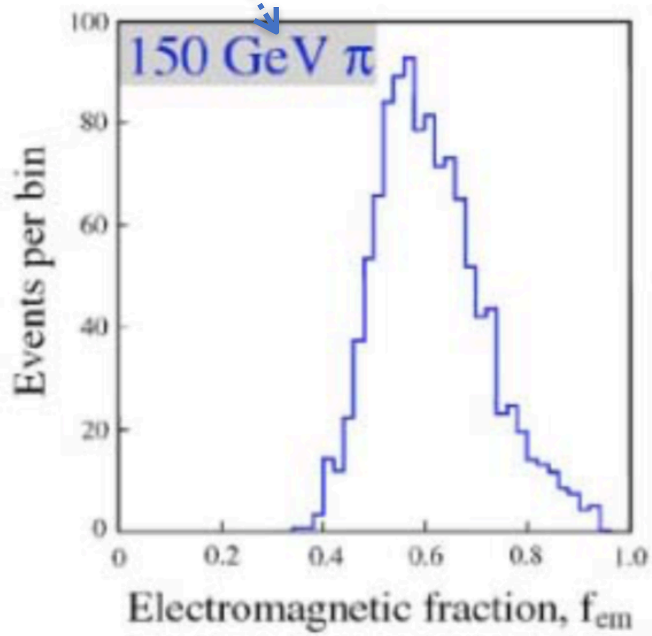


Based on simulation.

Particle spectra in a proton shower



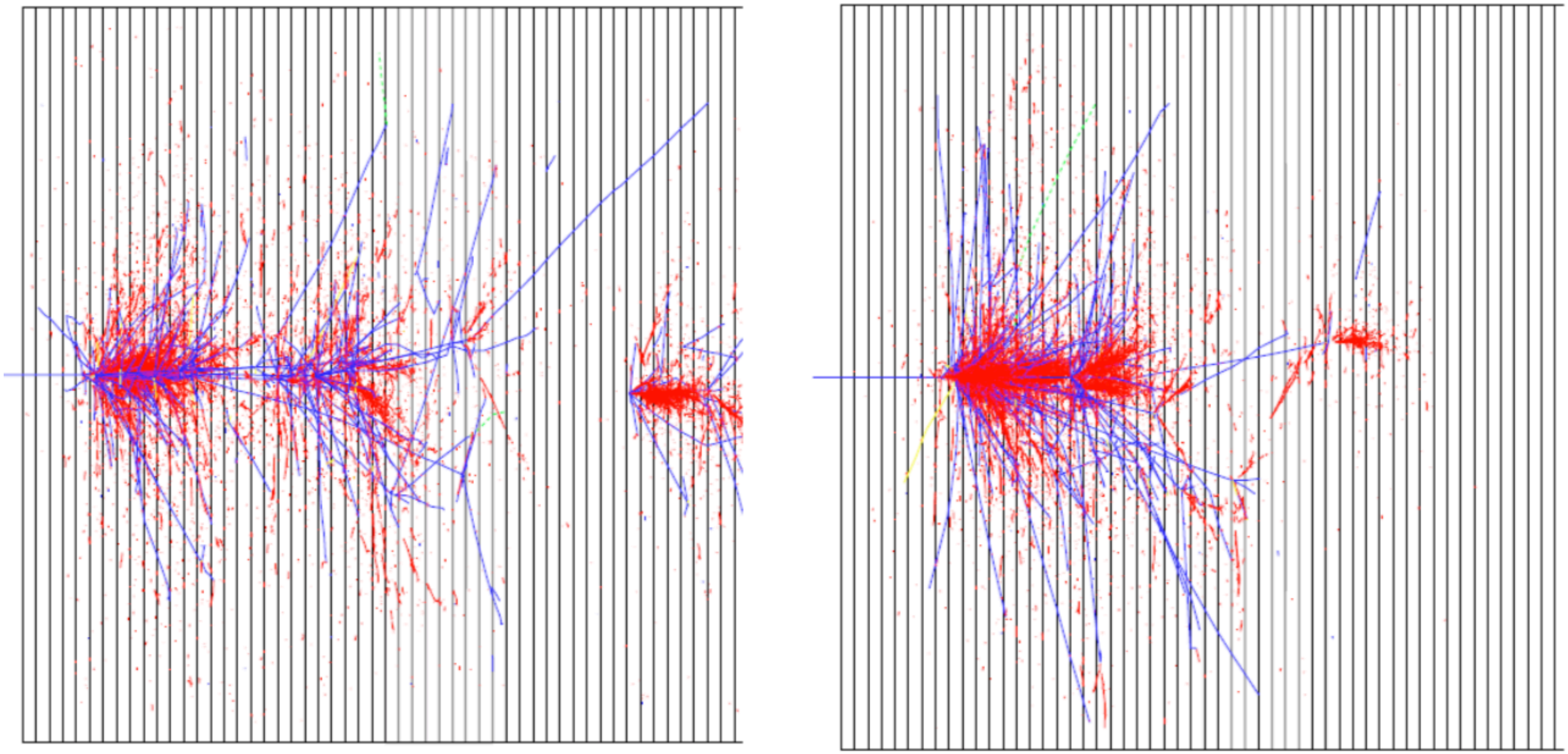
Showers depend heavily on
the incident particle and its energy…



…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



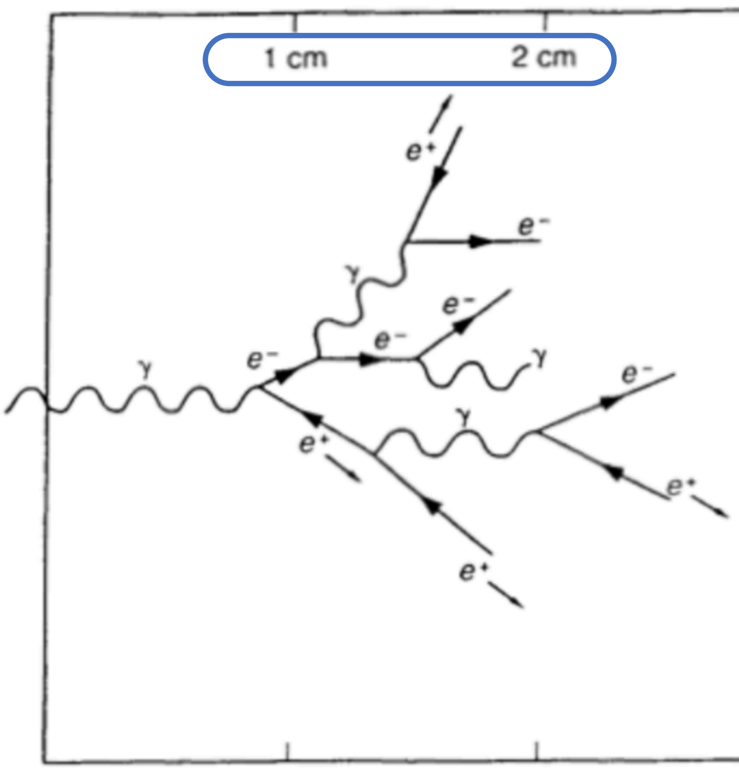
e.m. (hadronic) component is shown in red (blue)

Containment of an hadronic shower

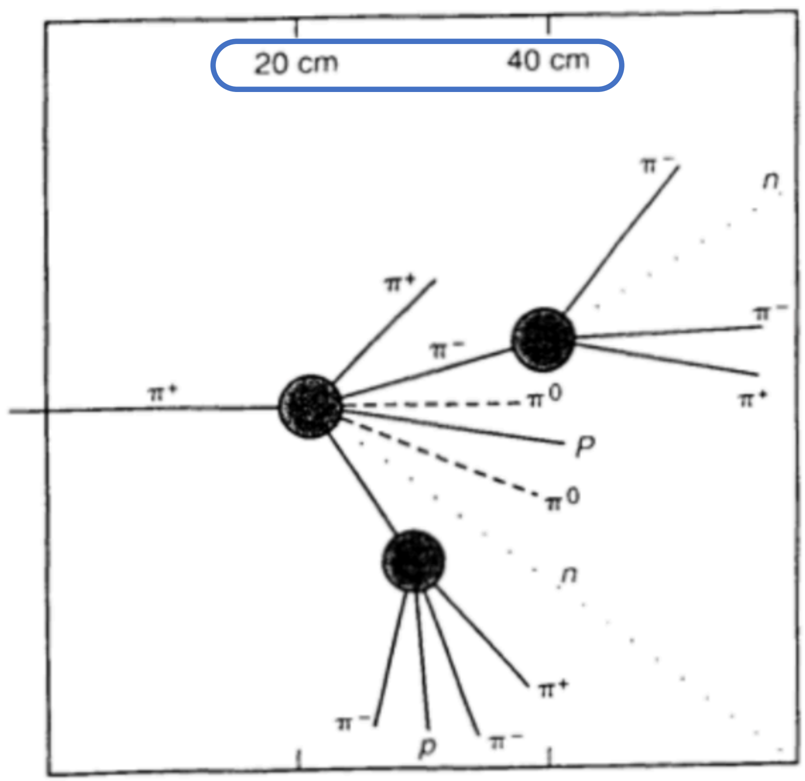
- The interaction length quantifies the mean distance before undergoing a nuclear interaction
- Interaction length (λ) is significantly larger than the radiation length (X_0)

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

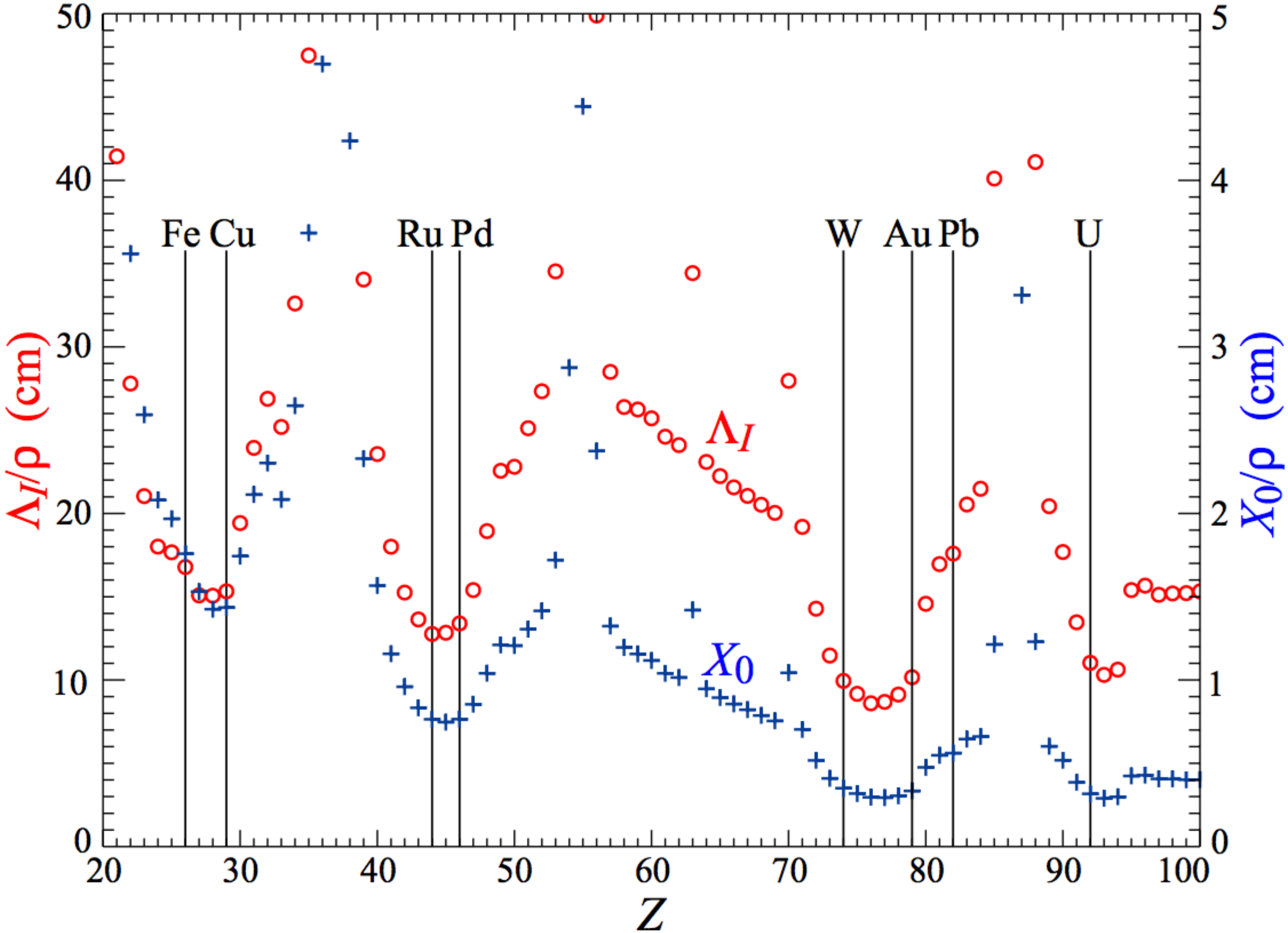
e.m. shower



hadronic shower

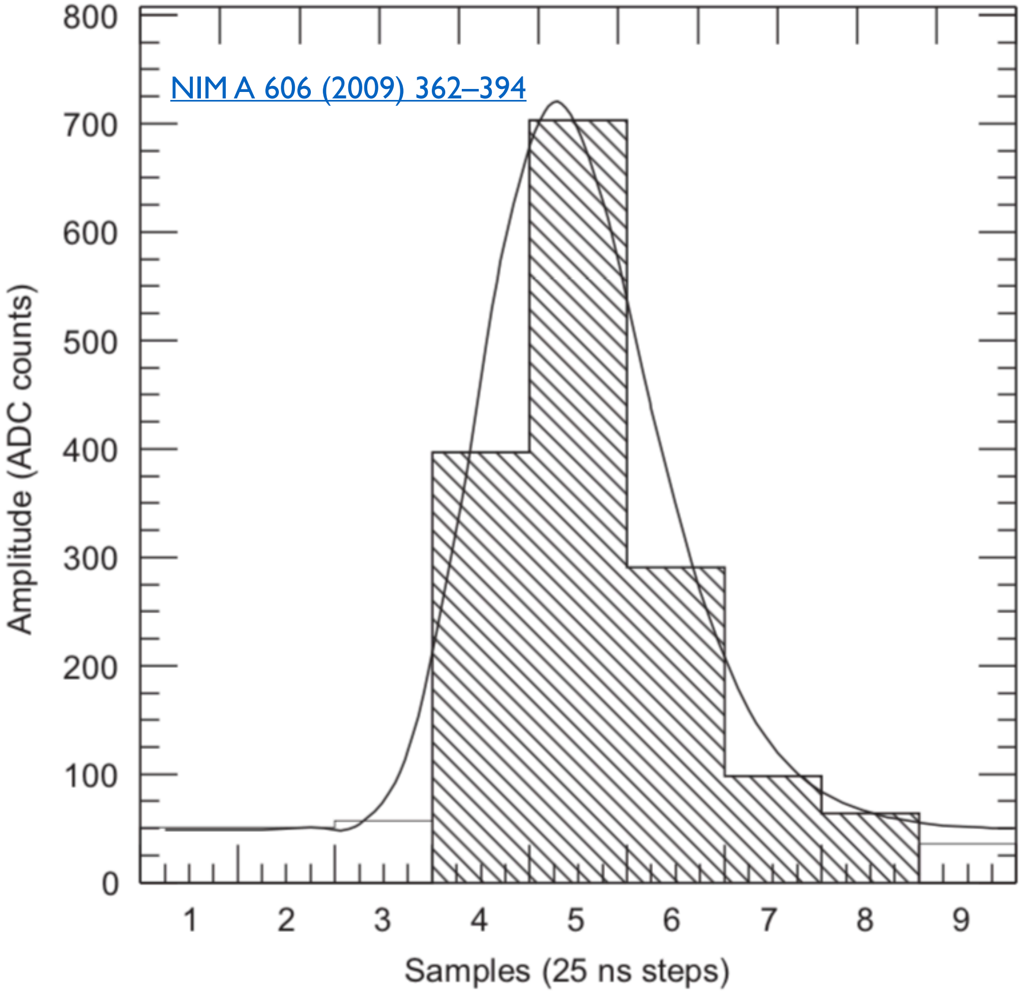


Characteristics of different materials

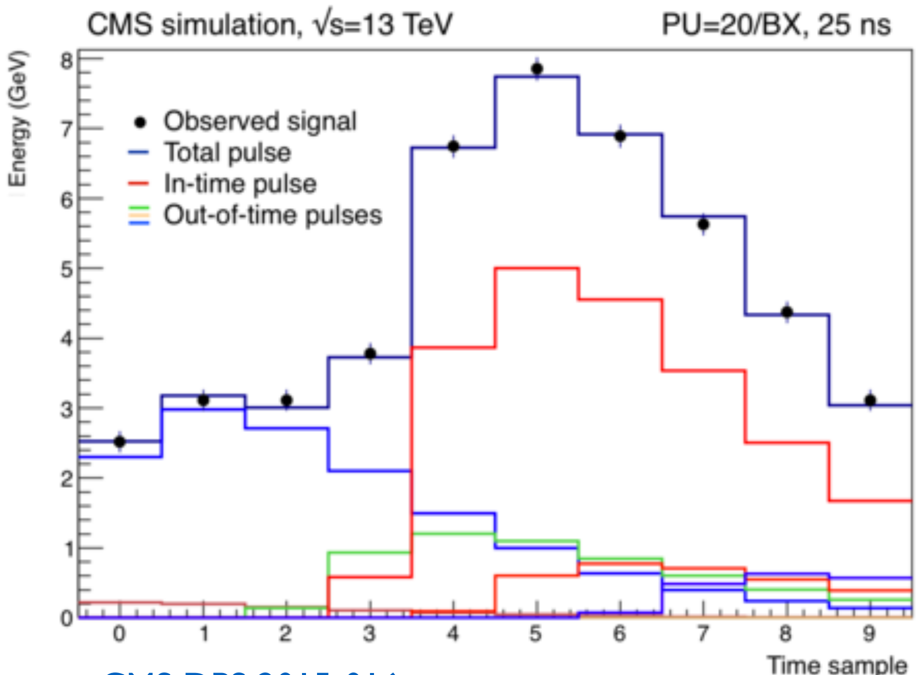


Energy reconstruction I

- 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)



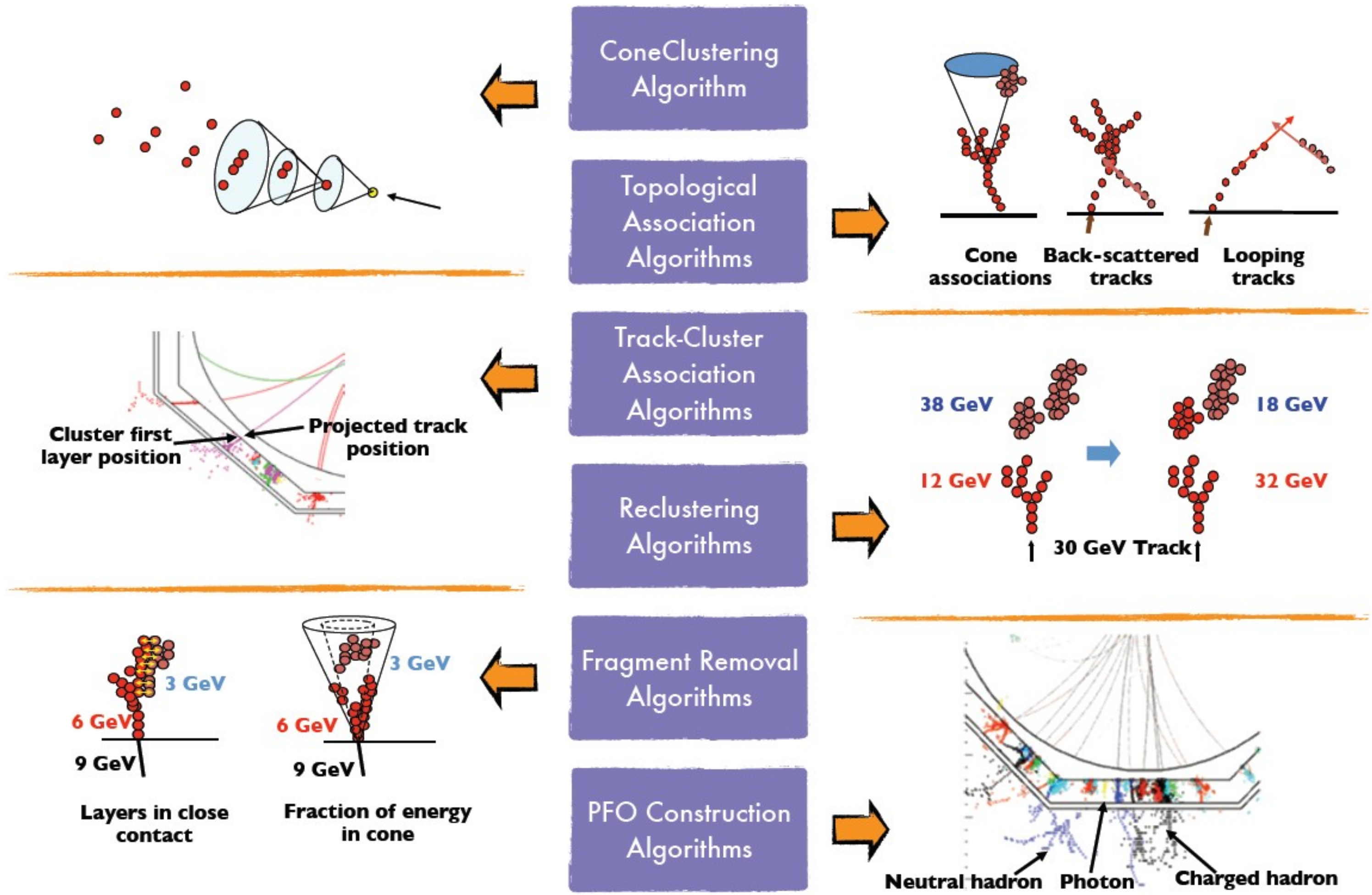
…and then there is pileup



CMS DPS 2015-016

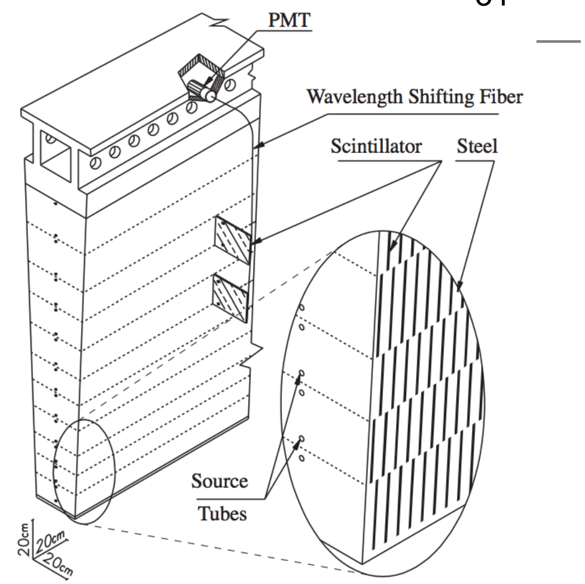
Energy reconstruction II

- Need to gather energy spread in **space** : clustering algorithms are needed
  - algorithm needs to be adapted to the particle type, segmentation, material upfront, shower components
  - often several iterations needed, depending on how busy an event is

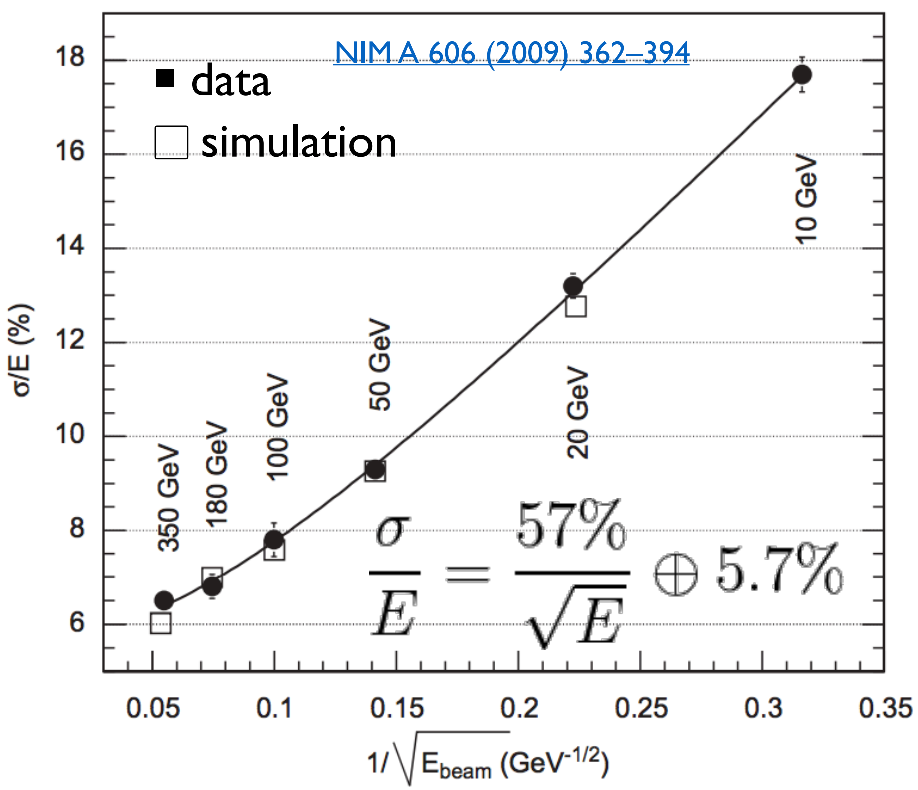


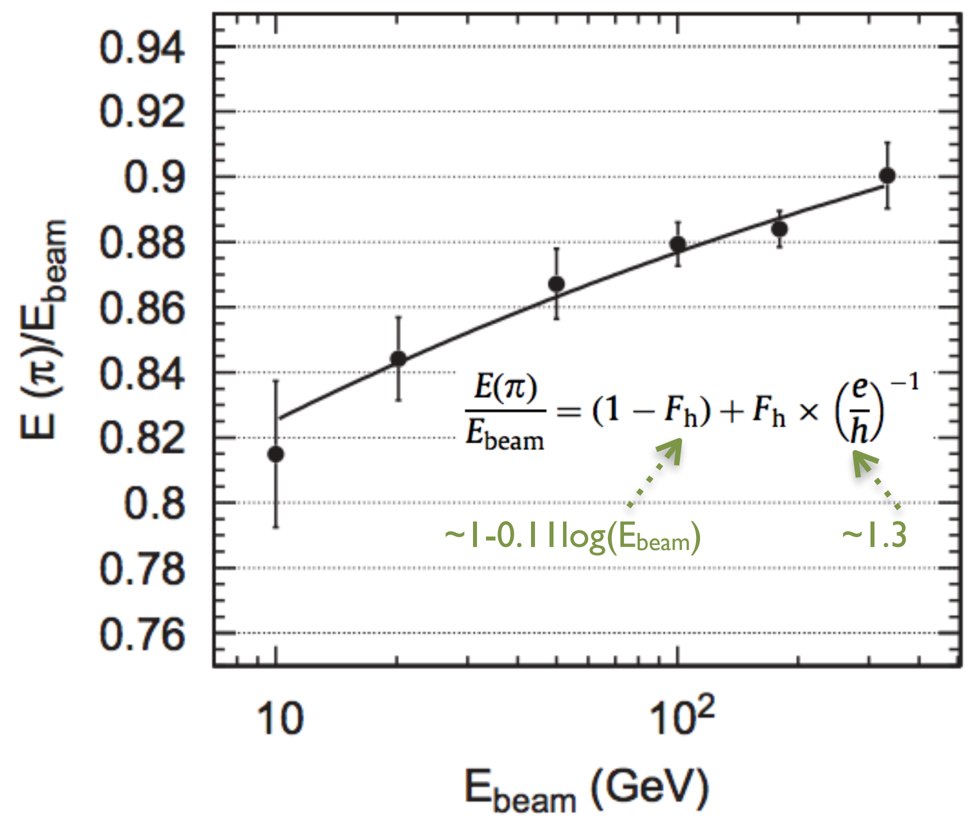
typical PF algorithms (implemented in Pandora)

Resolutions and response - ATLAS TileCal



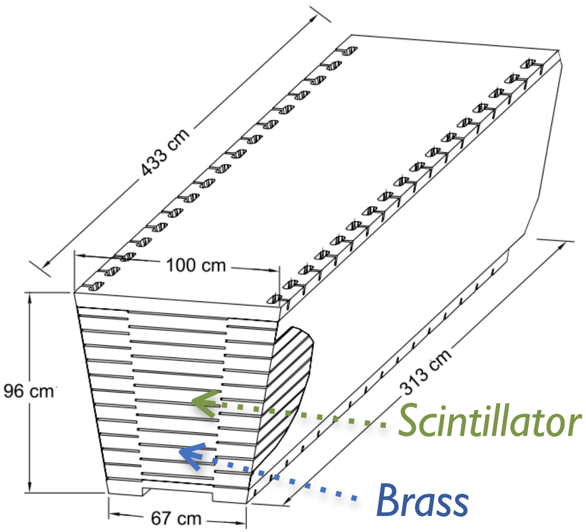
- Typically hadronic calorimeters exhibit
  - **non-linearity,** different response to e/γ and hadrons (compensation)
  - significantly **poorer resolutions** compared to e.m. calorimeters



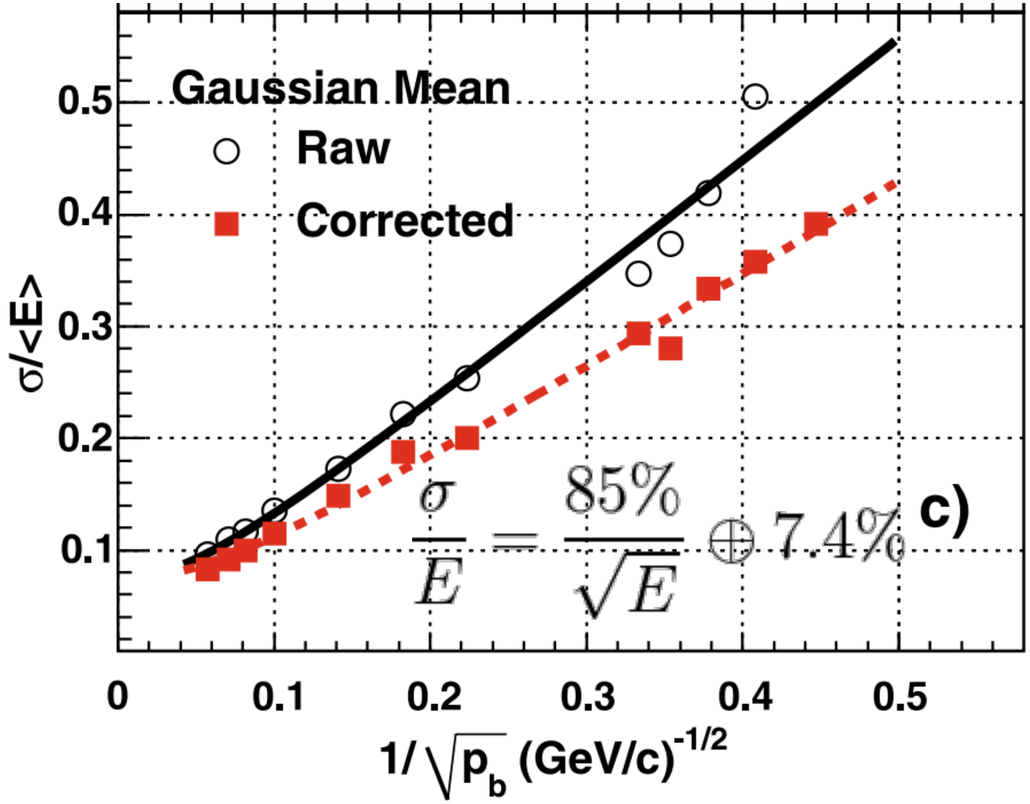


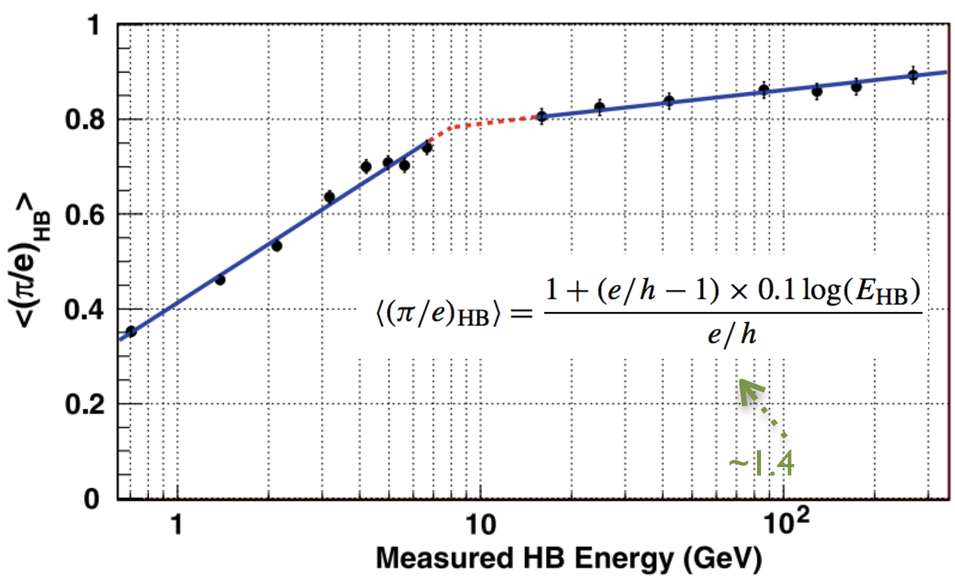
Resolutions and response - CMS HCAL

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

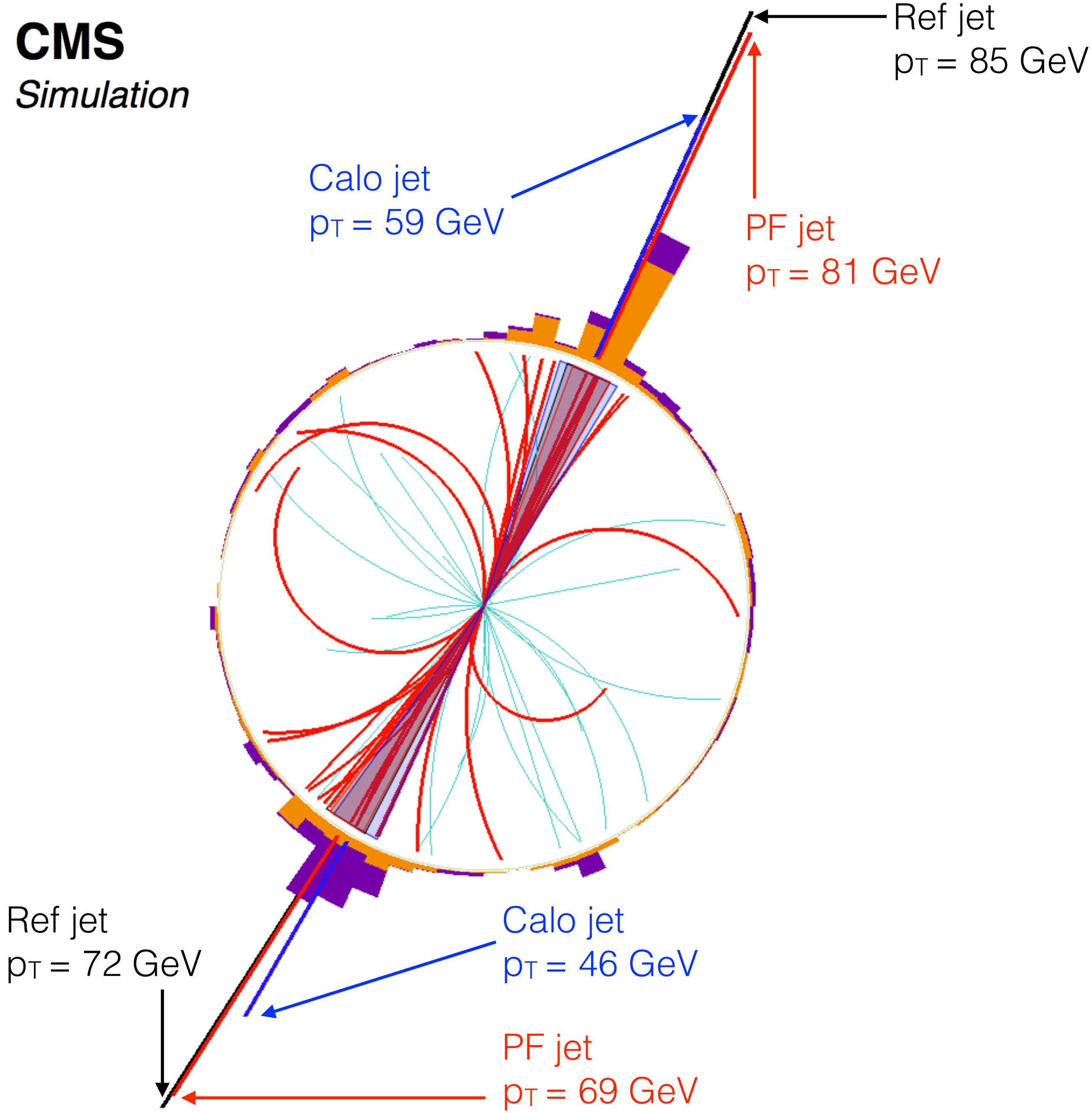


Eur. Phys. J. C (2009) 60: 359–373



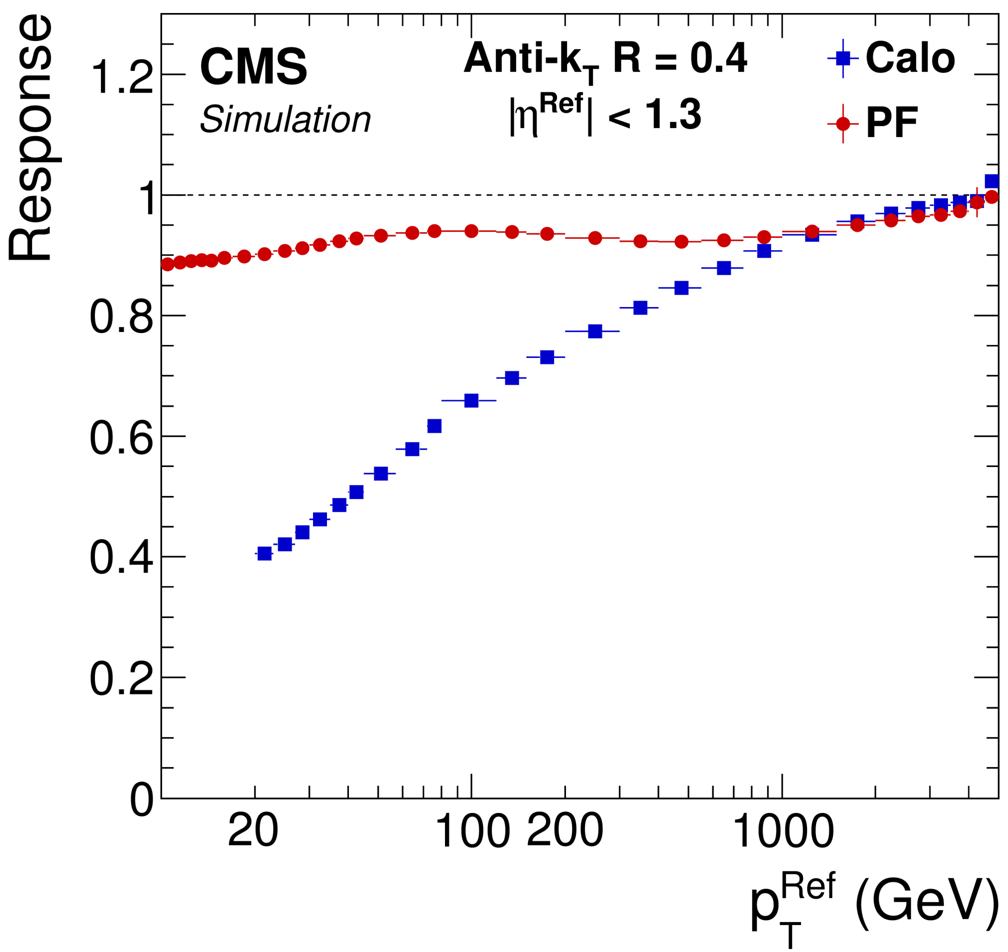


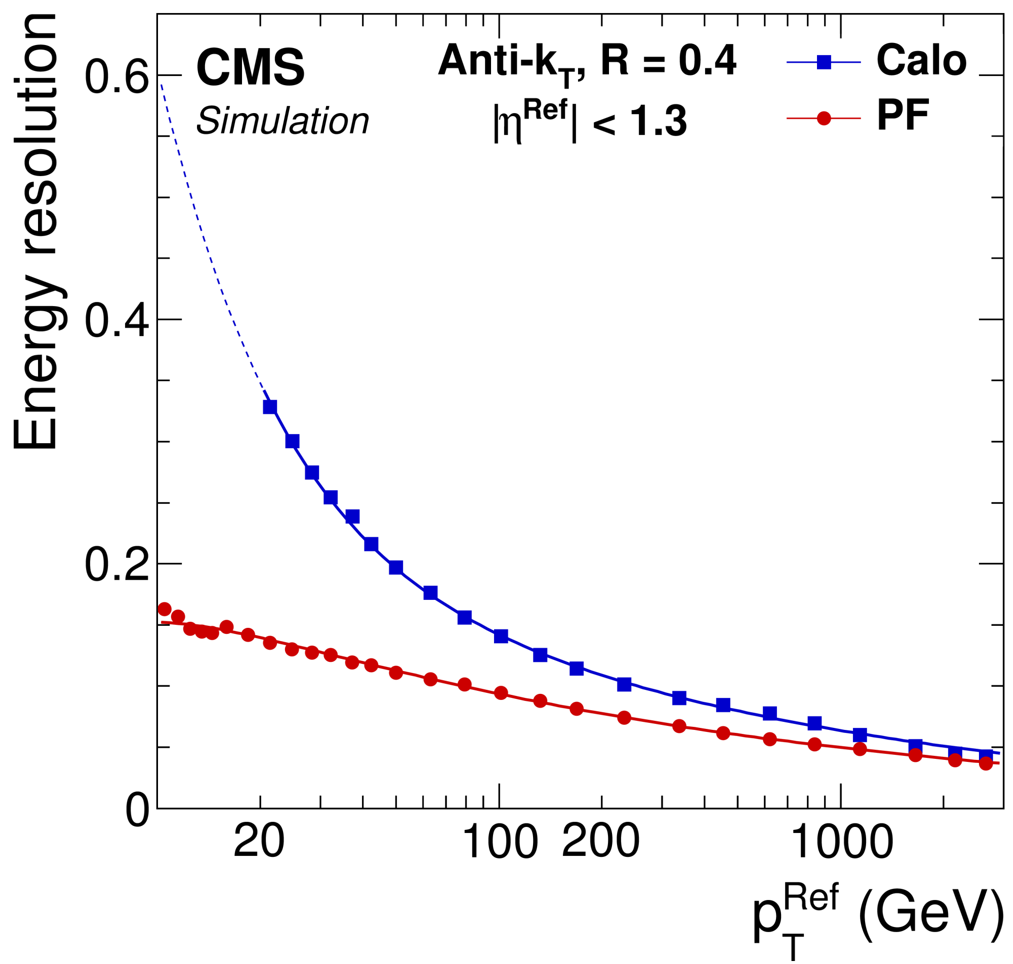
Particle flow algorithm is a reconstruction paradigm



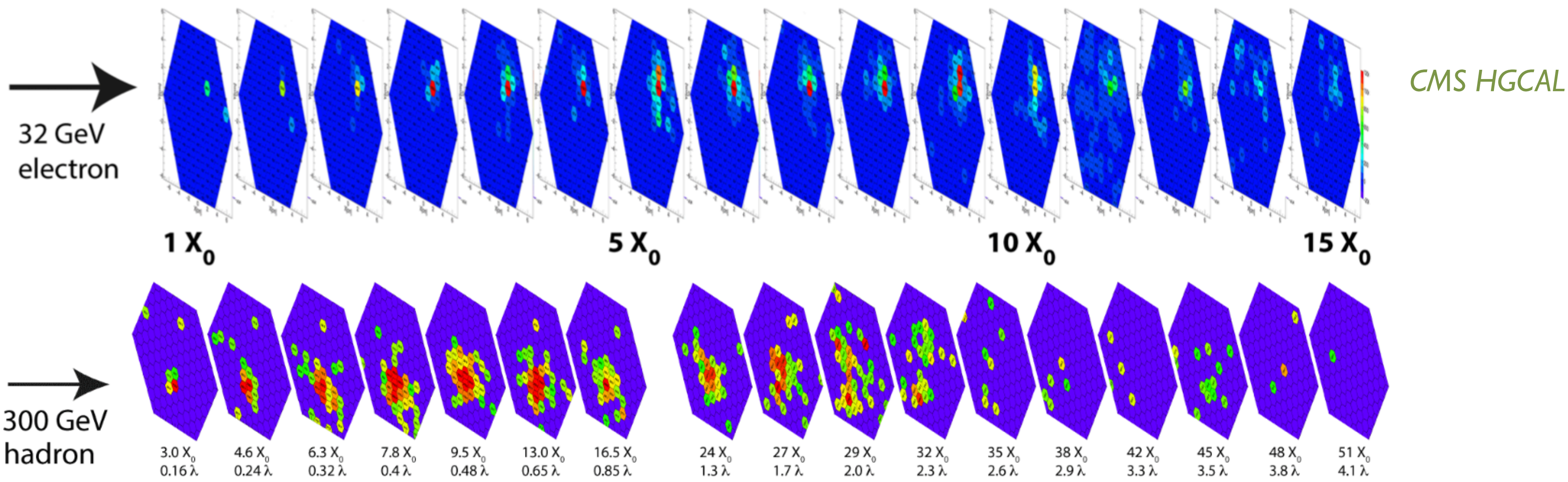
Compensating resolution performance with particle flow

- 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



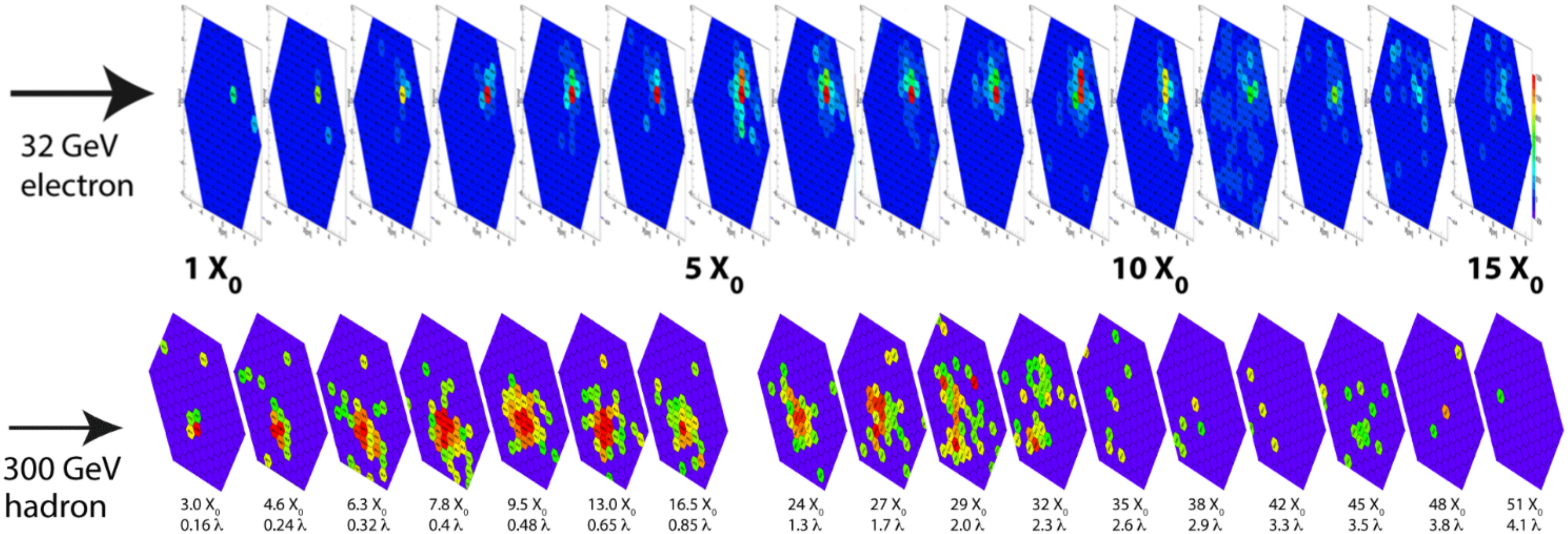


Possible directions in calorimetry: high granularity

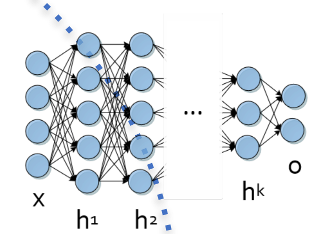


- 52 Si sensor layers interleaved with Pb, Cu, stainless steel
  - **small cell sizes** (~0.5cm^2) to cope with 200 pileup events and allow feature extraction
  - **timing capabilities** (~30-50ps) per cell to allow association to primary vertex
- **Sampling limits resolution…**

Possible directions in calorimetry: high granularity

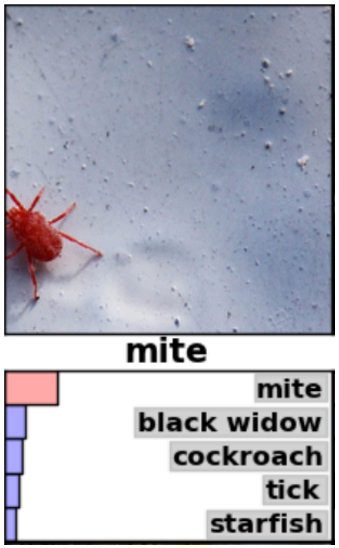


CMS HGCAL



- 52 Si sensor layers interleaved with Pb, Cu, stainless steel
  - **small cell sizes** (~0.5cm²) to cope with 200 pileup events and allow feature extraction
  - **timing capabilities** (~30-50ps) per cell to allow association to primary vertex
- **Sampling limits resolution…**

  … but can **we see deposits in layers as images ⇒ machine learned PFlow?**



from TensorFlow's image recognition API

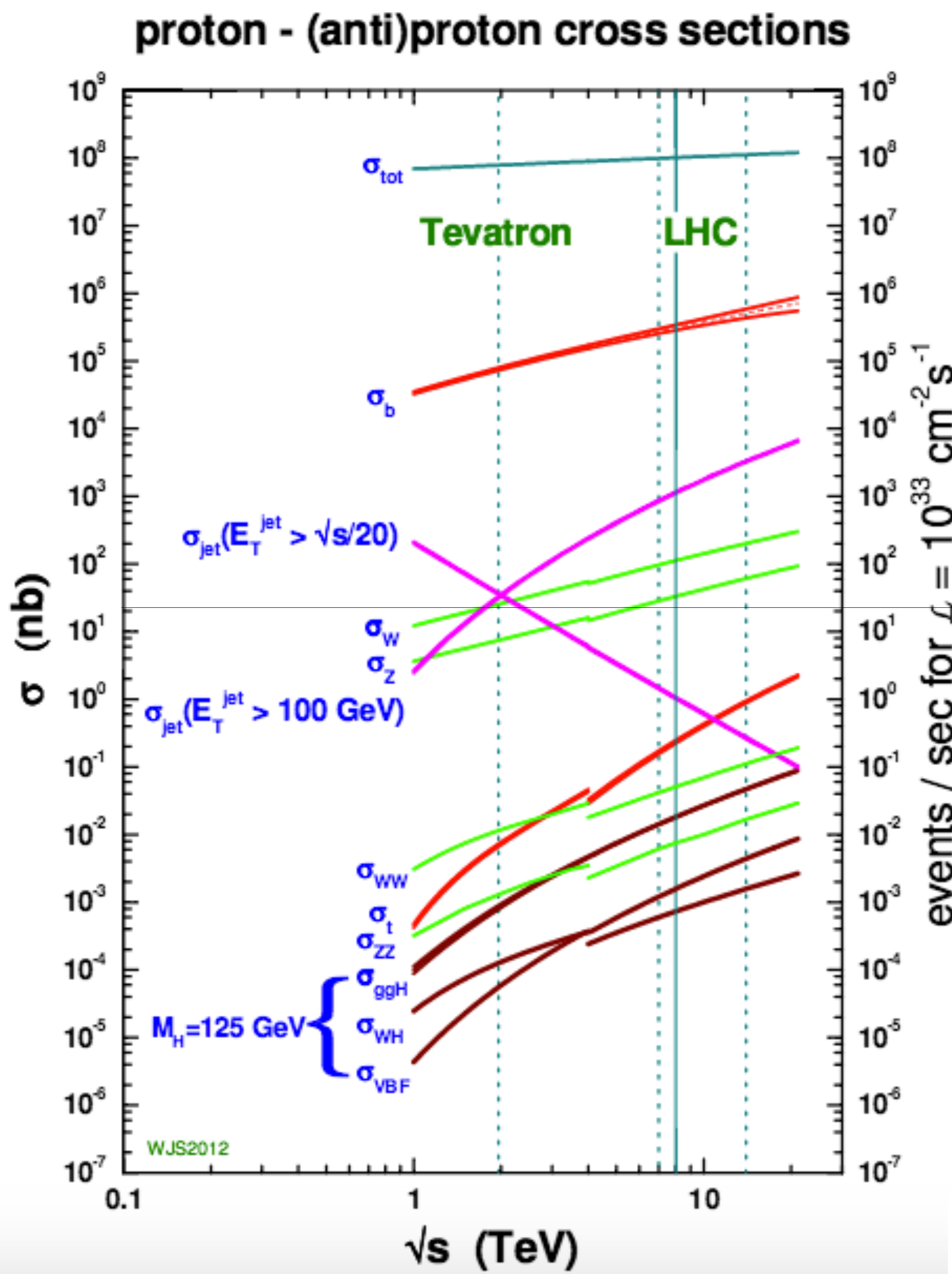
Getting data on tape: trigger systems

Recall: the proton-proton cross section

10^8 / s

10 / s

1 / day



15 nb x 10^{34} cm^{-2}s^{-1}
=
150 Hz

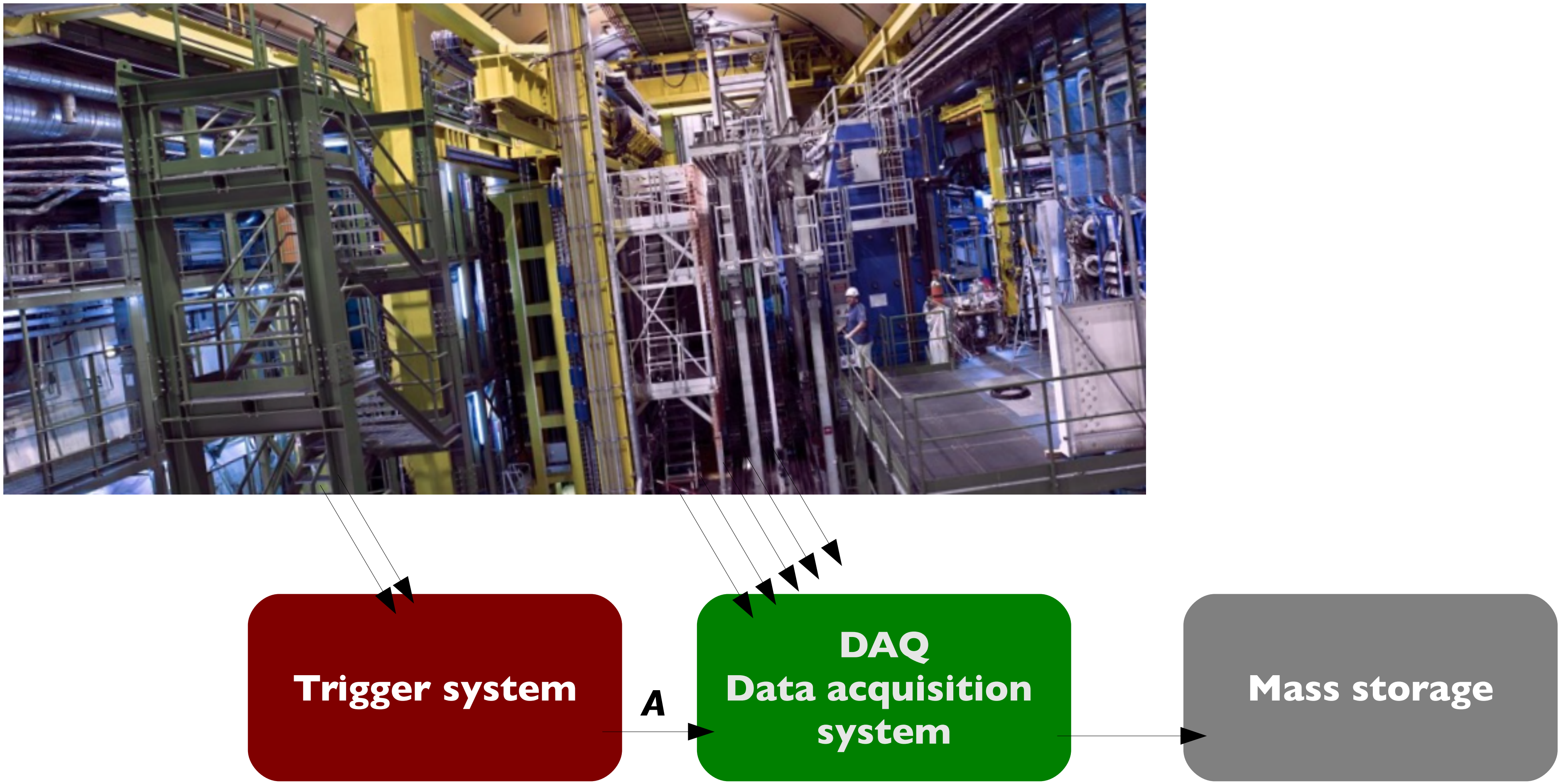
Reminder
1 pb = 10^{-36} cm^2

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?



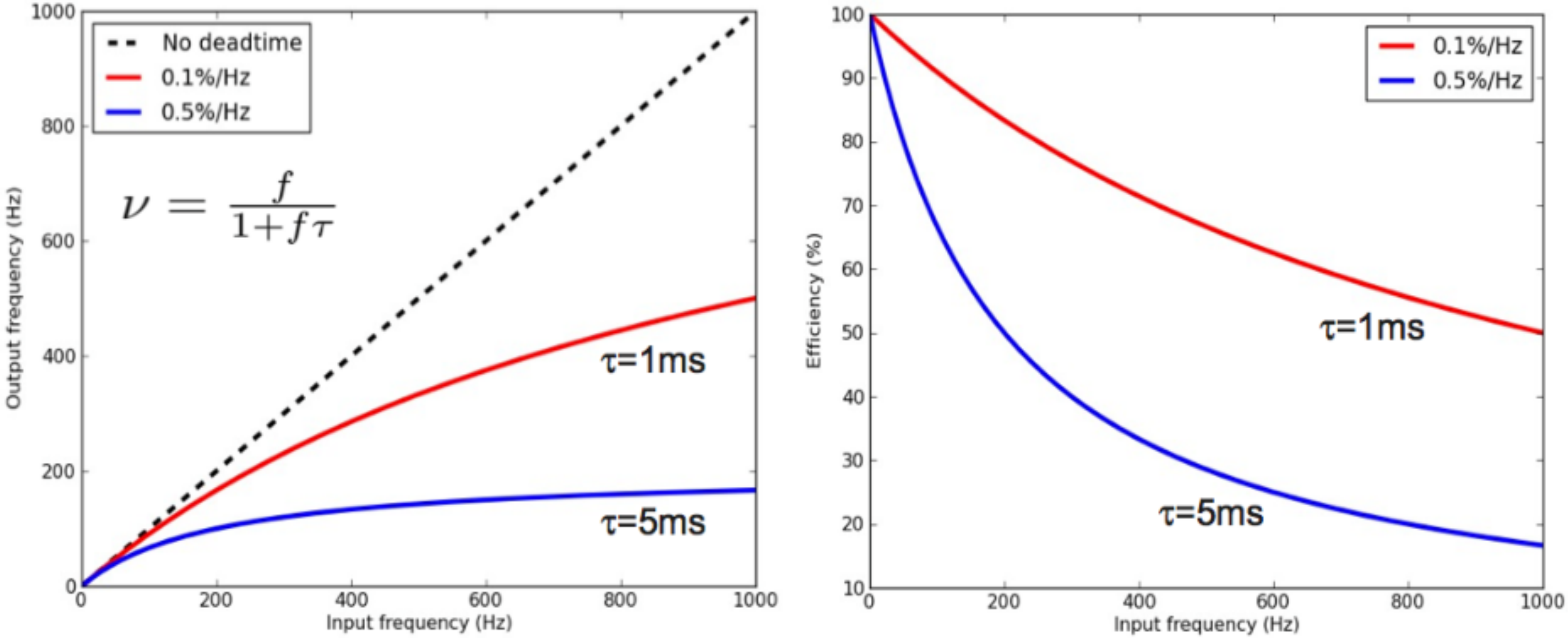
Performs real-time selection based on a subset of the data to record

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
  - <u>System will only accept a fraction of the triggers</u> $\nu = f(1 - \nu\tau) \Rightarrow \nu = \frac{f}{1 + f\tau} < f$

input rate readout time

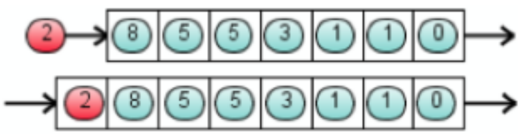


- **System tends to be inefficient for long readout times**

Solution: de-randomize with a buffer

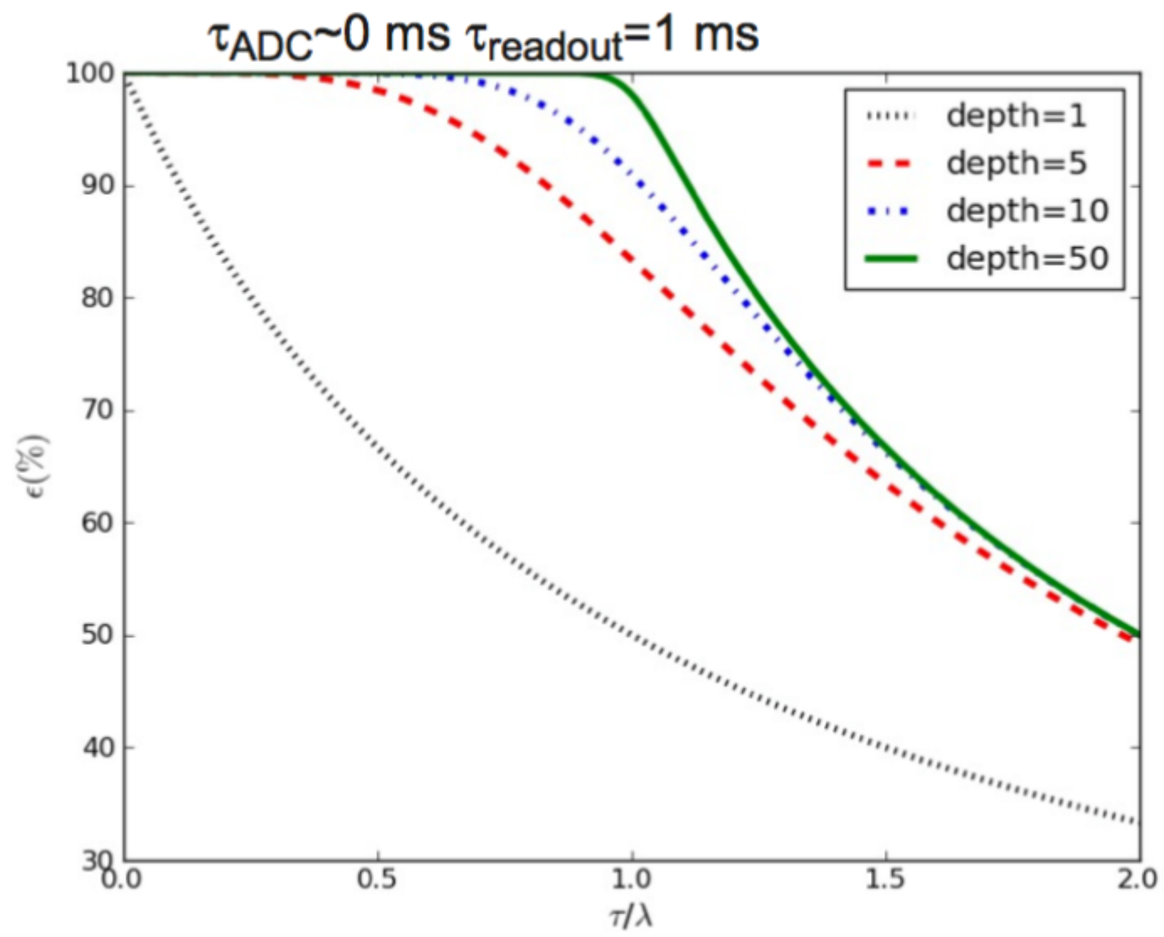
- **A fast, intermediate buffer can be introduced**
  - Works as a FIFO queue

    (First In First Out)



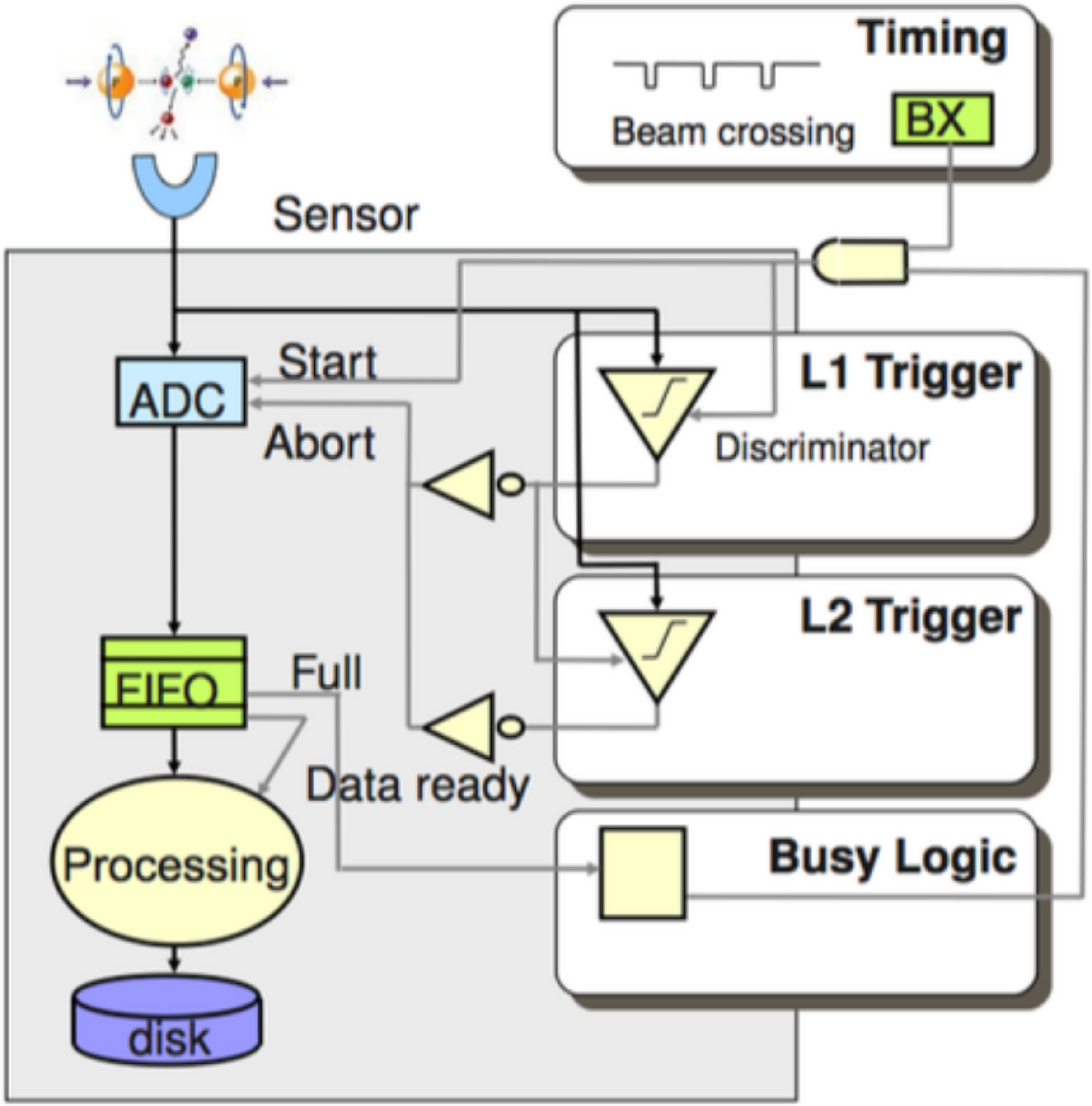
  - Smooths fluctuations = derandomizes
  - Decouples the slow readout from the fast front-end

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



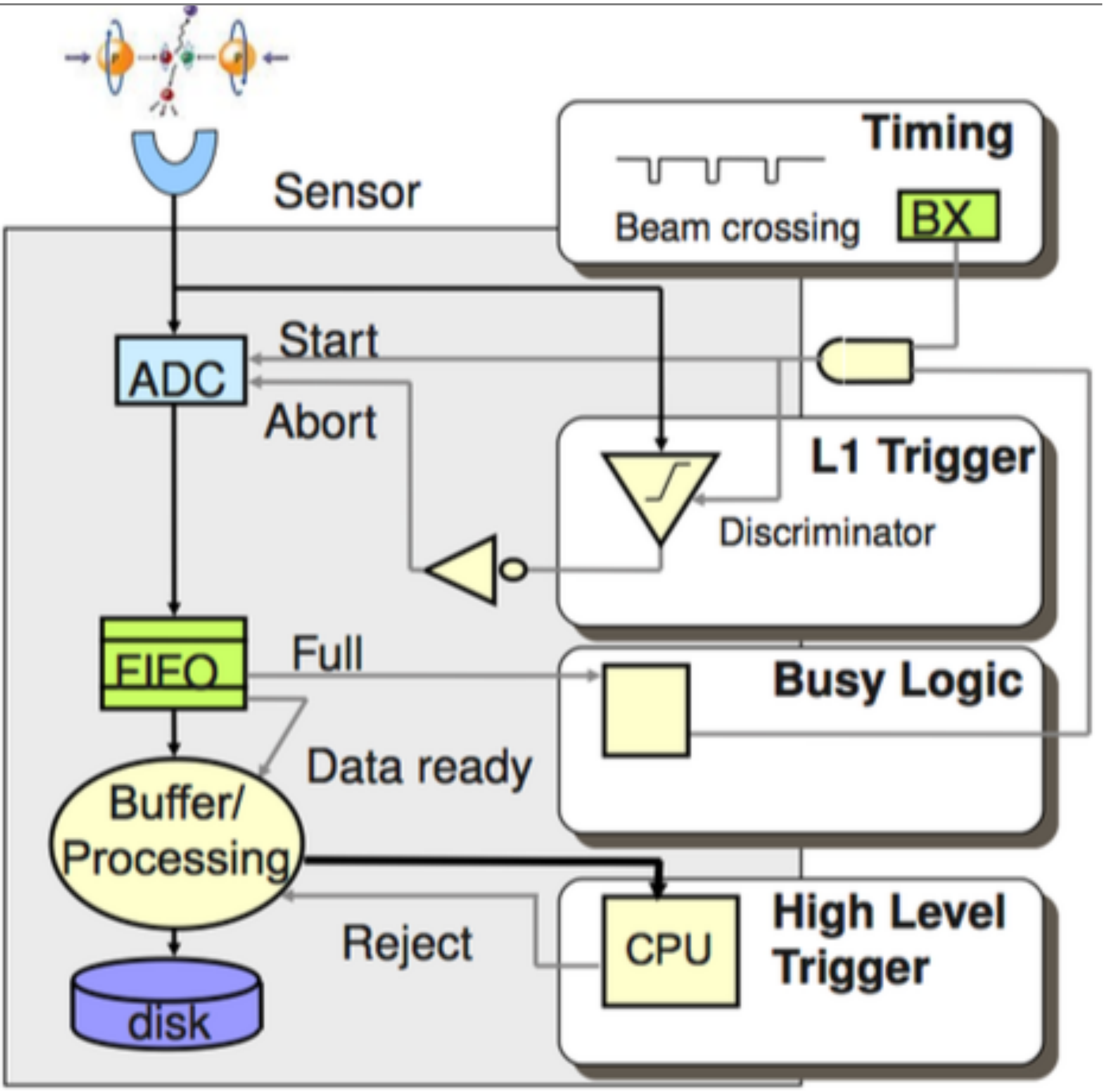
Trigger system architecture for bunched collisions

- 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 $v_{L1} \times t_{L2}$



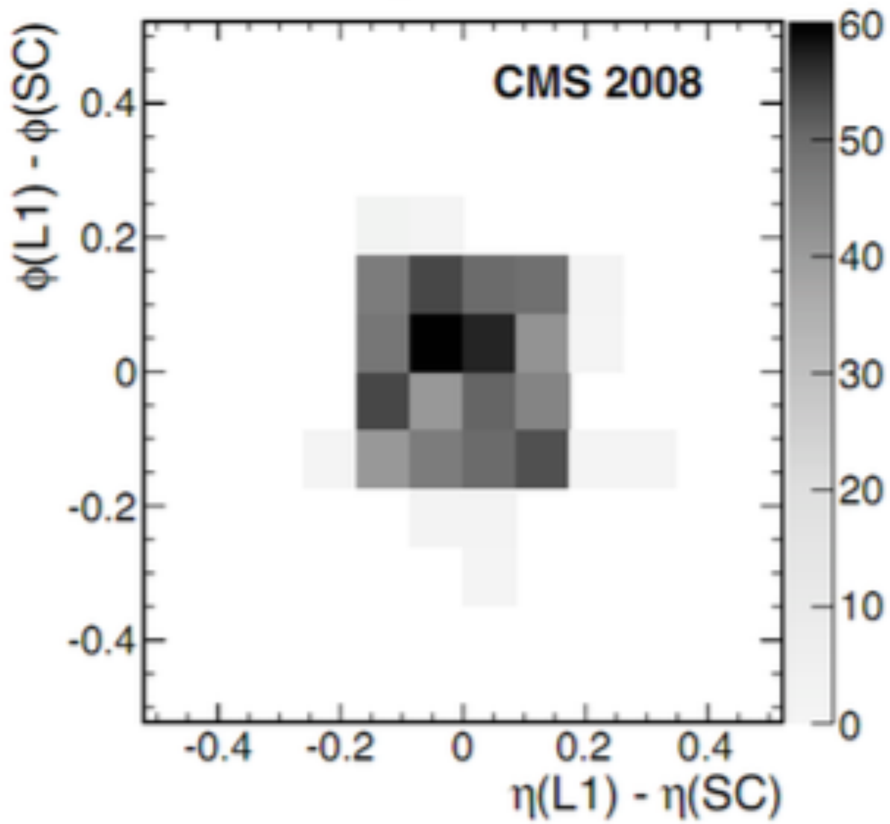
Trigger system architecture for bunched collisions

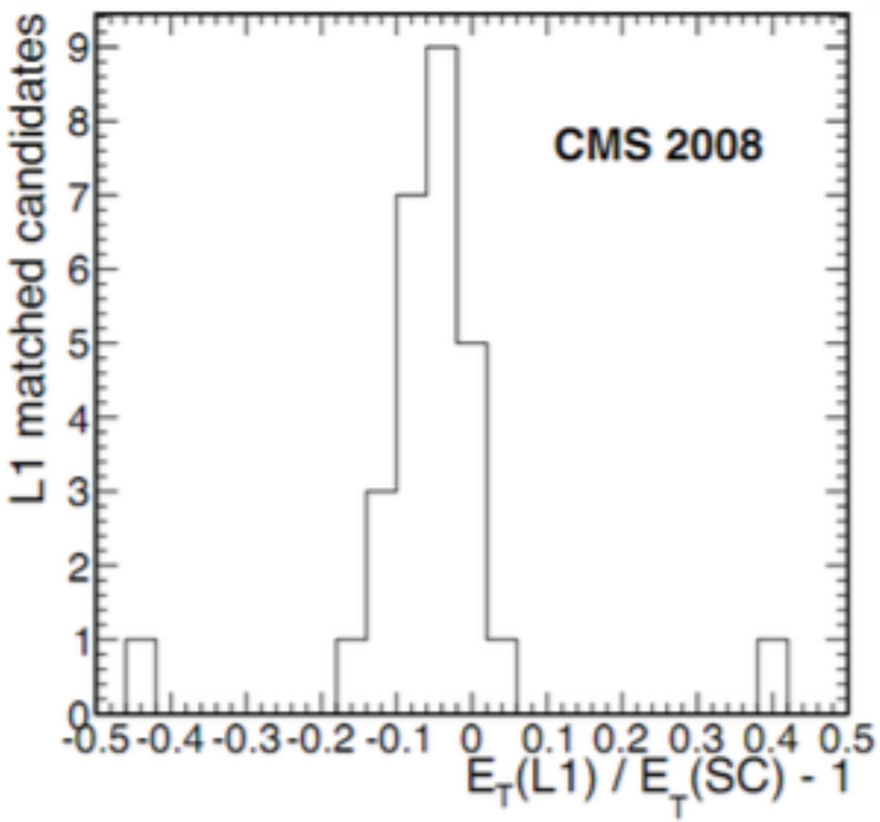
- The ADC are synchronous with beam crossings
- Trigger output is stochastic
  - FIFO is needed to derandomize
- **ATLAS LHC Run I architecture**
  - May need to accommodate several levels with increased complexity
  - If first layer latency is smaller than bunch crossing than the combined latency is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

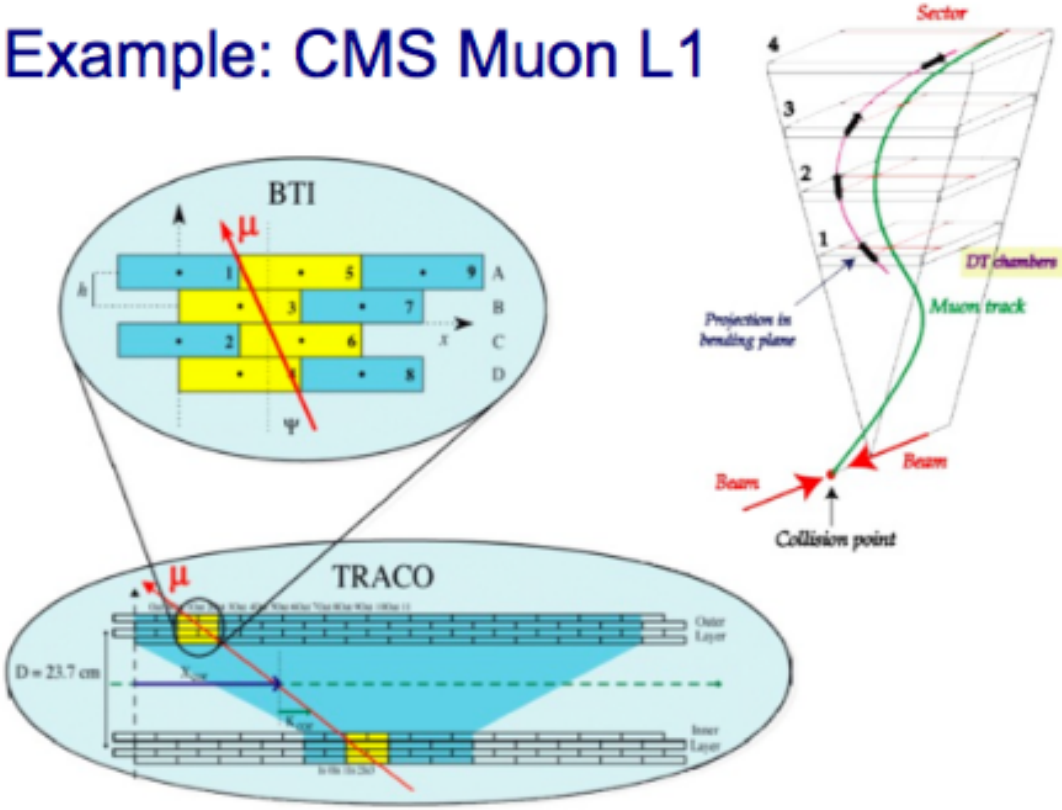


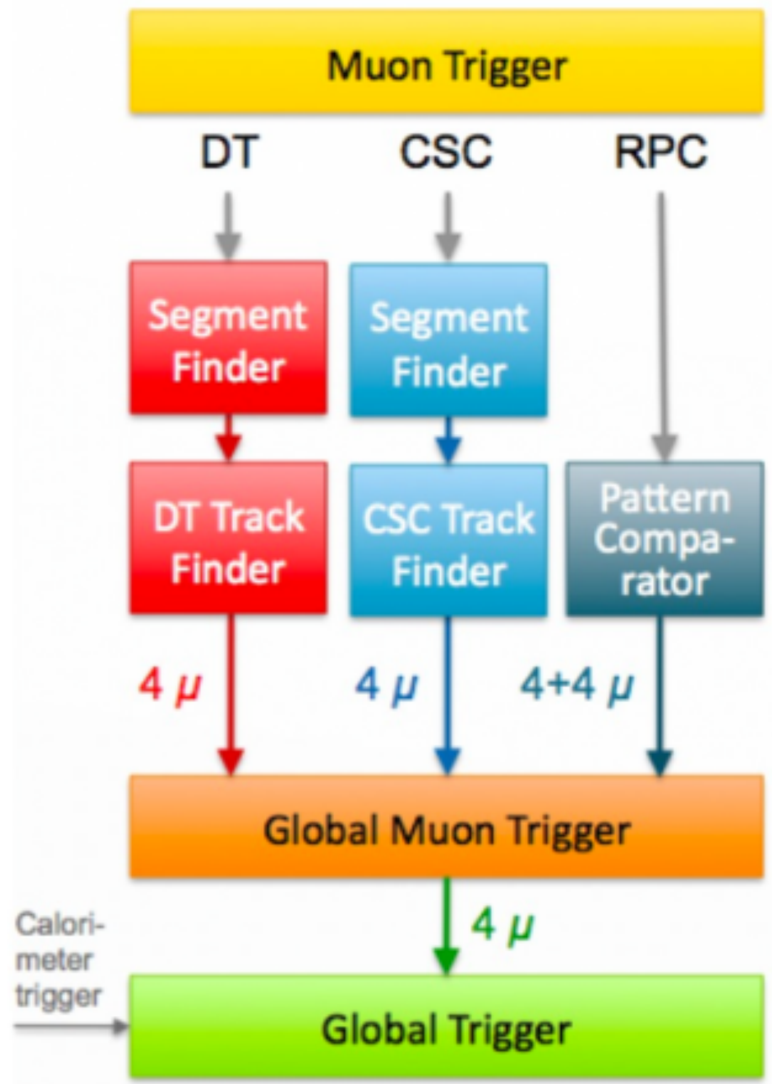


Tracking at L1 (muon case)

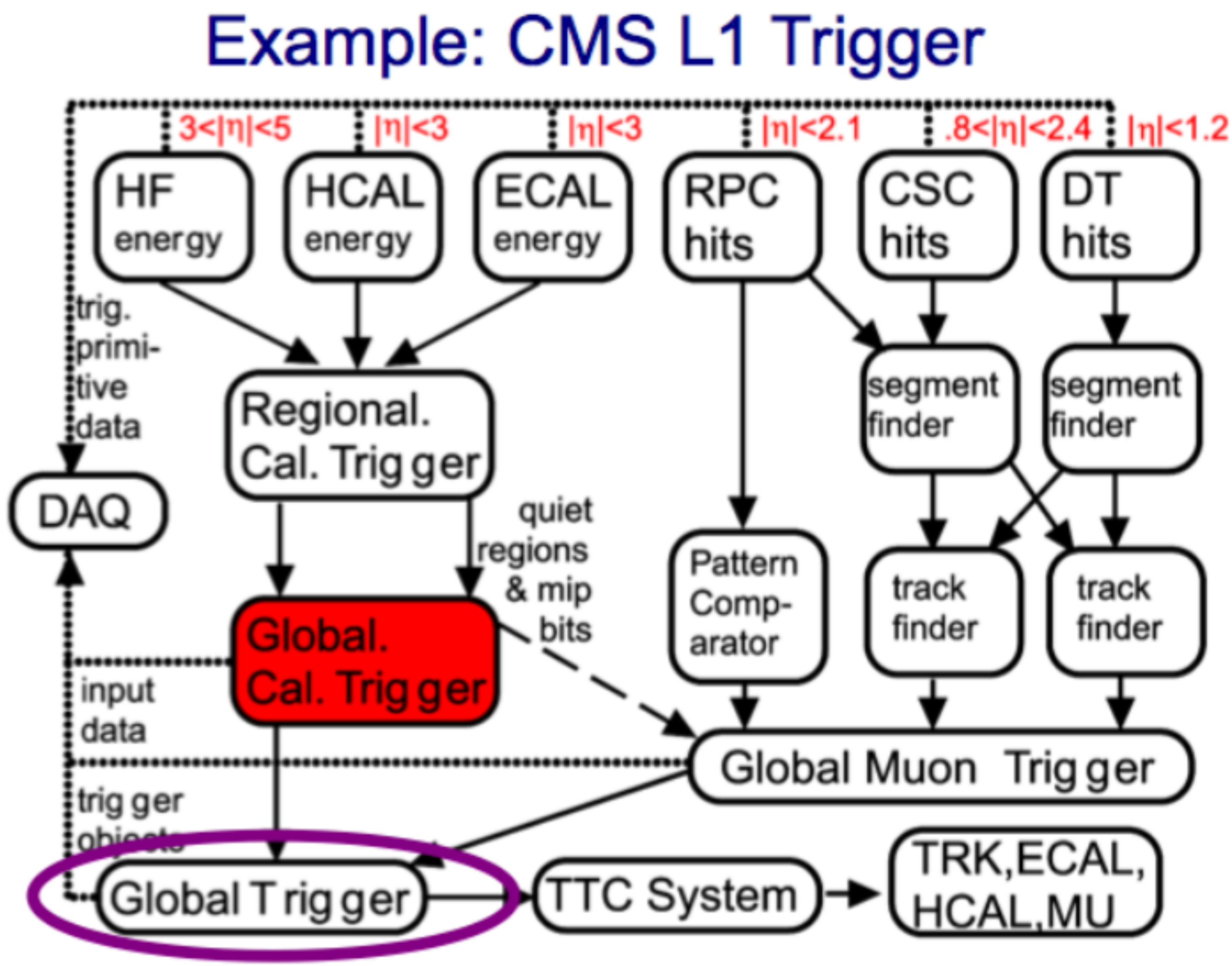
Reconstruct segments in each muon chamber
Combine segments to form track
and measure p_T (rough)

Example: CMS Muon L1



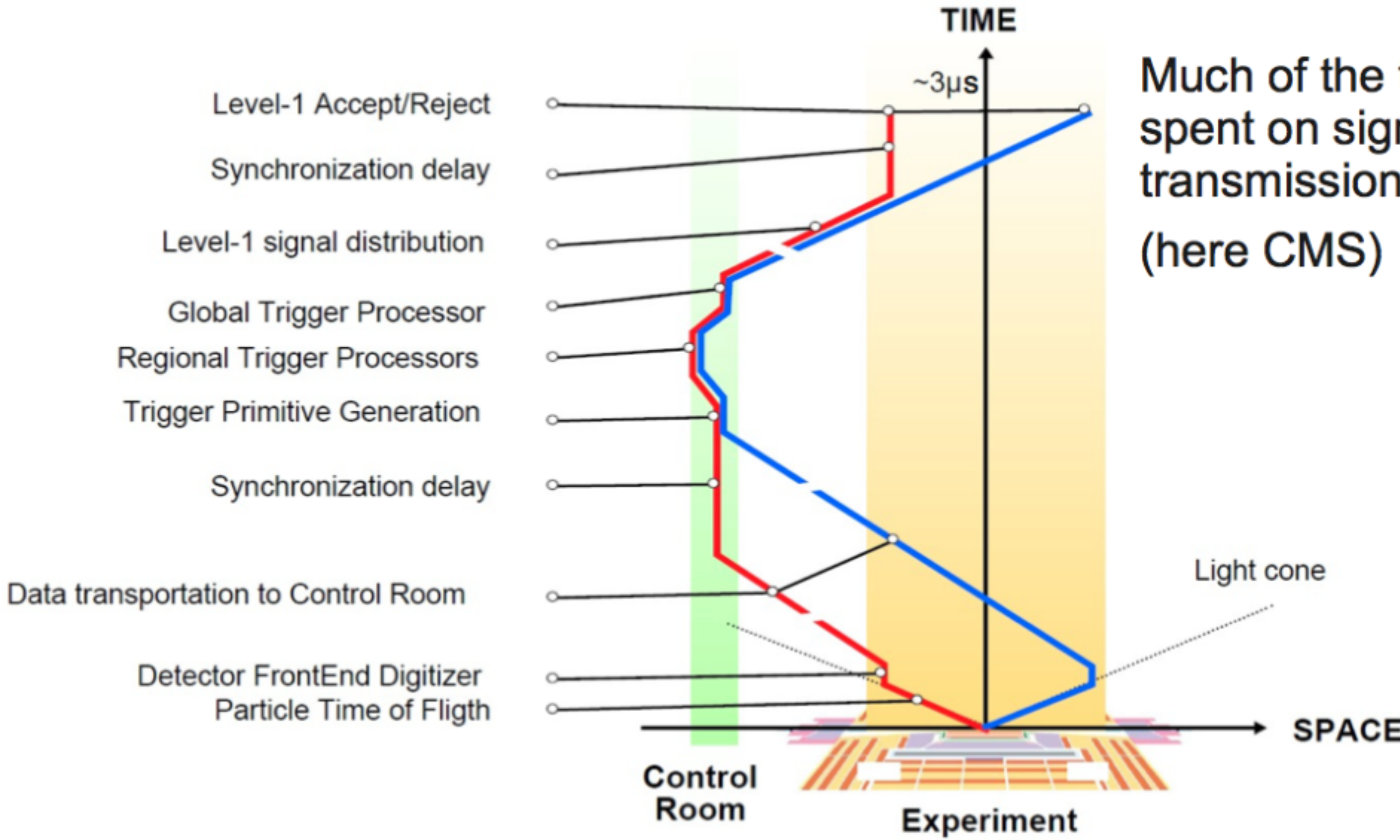


Combining information from different sub-detectors



- **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

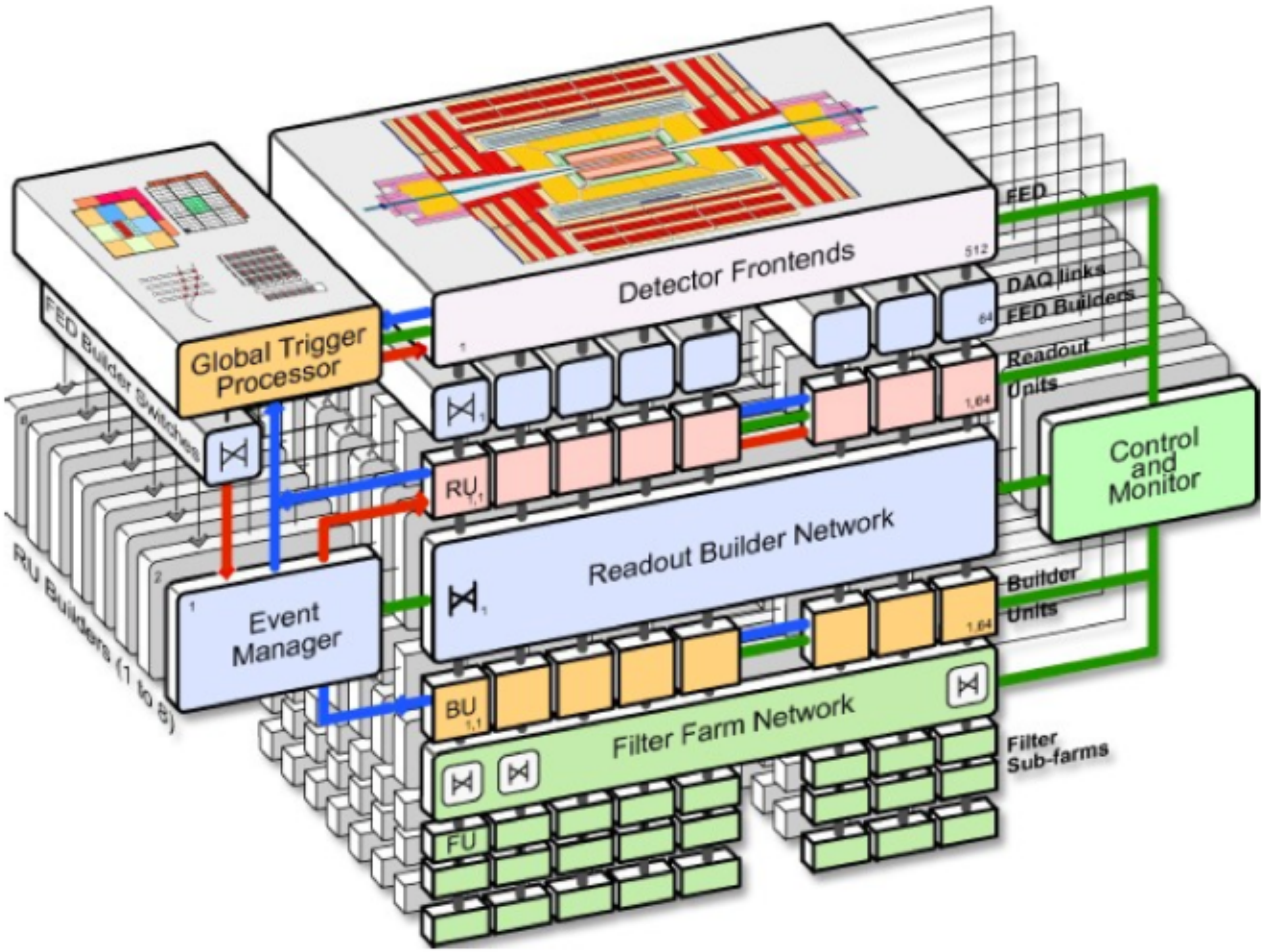


Much of the time spent on signal transmission

(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

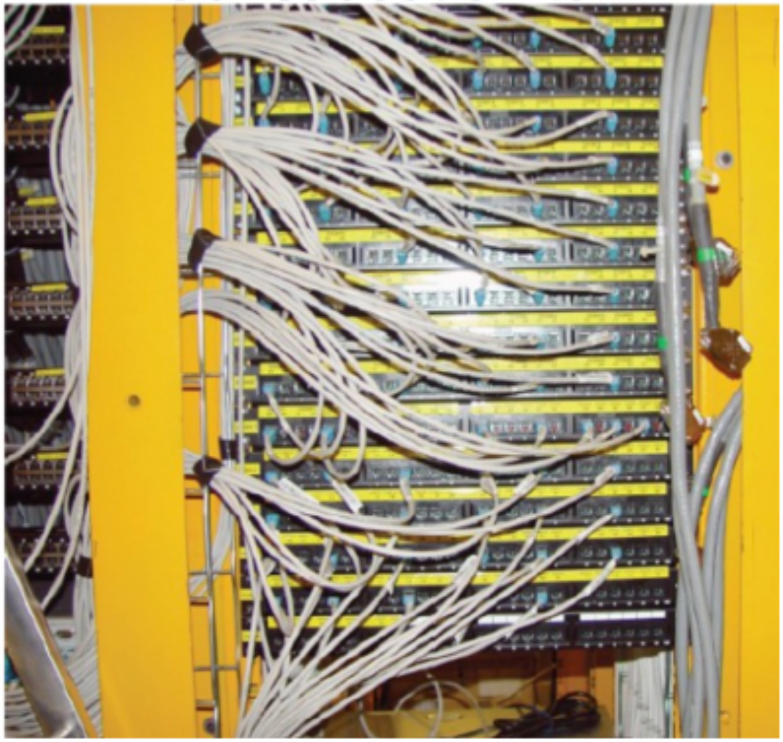


High level trigger

- 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

- **Calorimeters make the particles collapse to measure its energy, direction time**
  - electromagnetic interactions have scaling properties, easy to reconstruct
  - hadronic interactions depend on energy, incoming particle, have distinct properties
  - best performance conjugates careful/clever 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)