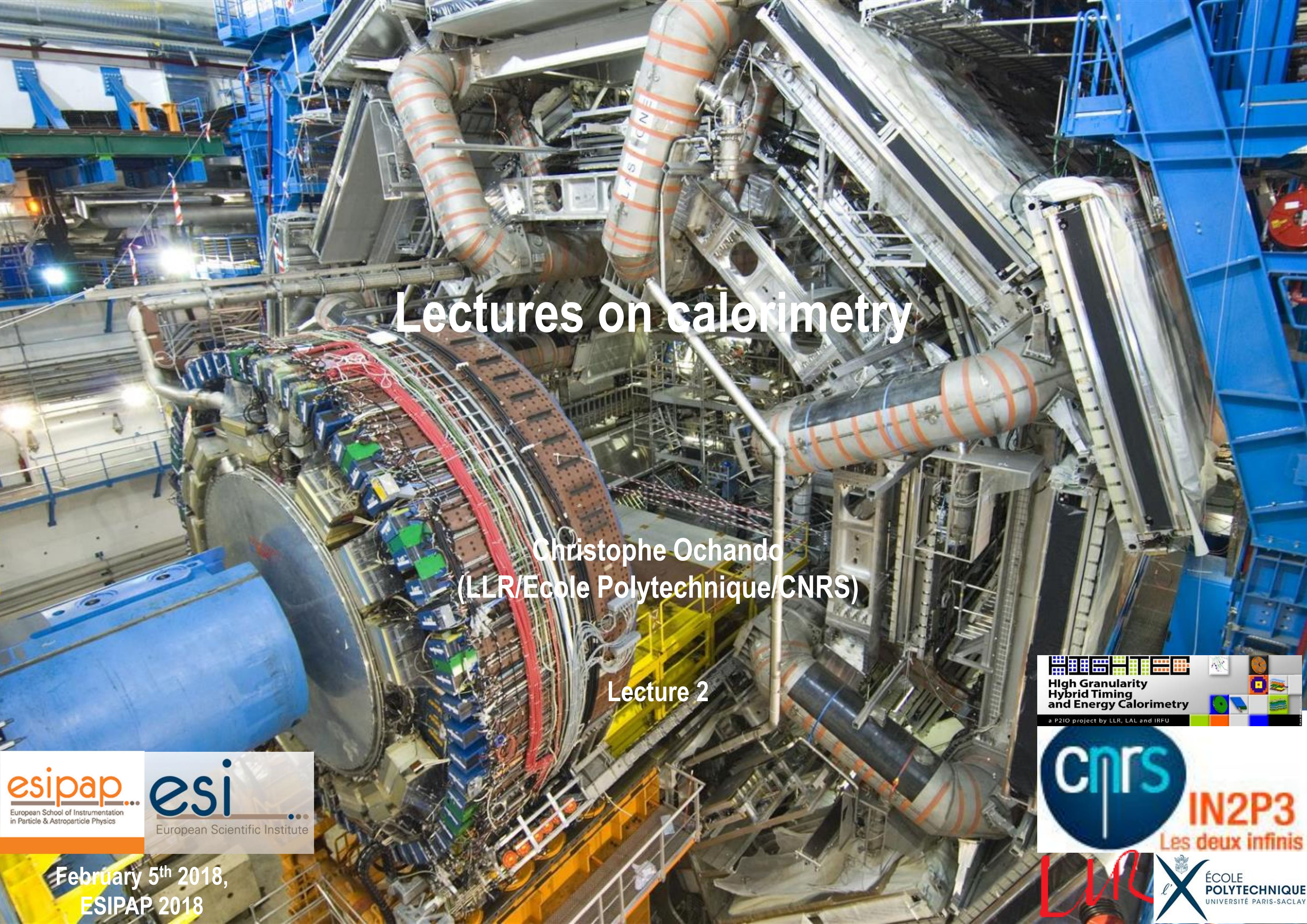


Lectures on calorimetry

Christophe Ochando
(LLR/Ecole Polytechnique/CNRS)

Lecture 2

esipap
European School of Instrumentation in Particle & Astroparticle Physics

esi
European Scientific Institute

HIGHTEC
High Granularity Hybrid Timing and Energy Calorimetry
a P2IO project by LLR, LAL and IRFU

cnrs
IN2P3
Les deux infinis

LLR

ÉCOLE POLYTECHNIQUE
UNIVERSITÉ PARIS-SACLAY

February 5th 2018,
ESIPAP 2018

Plan of lectures

Lecture 1

- Why/what calorimeters ?
- Physics of EM & HAD showers
- Calorimeter Energy Resolution

Lecture 2

- ATLAS & CMS calorimeters
- Calorimeter Objects
- Triggering

Lecture 3

- Example of calorimeters (suite)
- Future of calorimetry

Lecture 4

Tutorial
Exercises

KEEP
CALM
AND
RECAP

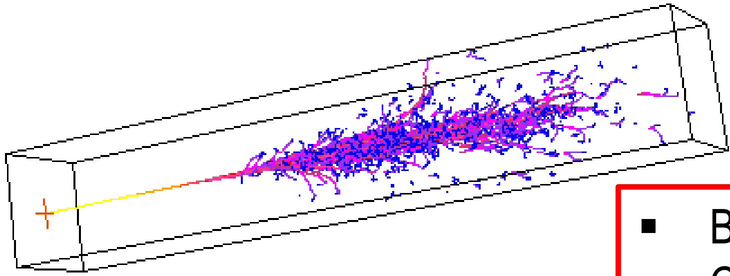
Calorimeter Features

- Measure energy of charged (p, π, K, e, …), and neutral (γ, n,…) particles
- Precision improves with energy
- Position Measurement
  - Important for neutral particles
- Particle ID
  - Longitudinal (if sampling calorimeter) and lateral profiles different for e and π.
- Timing
- Triggering
- Can be built at 4π detectors
  - Hermiticity ! Important for missing energy measurement (see later)

Two types of calorimeter

1. Particles interact with matter
depends on particle and material

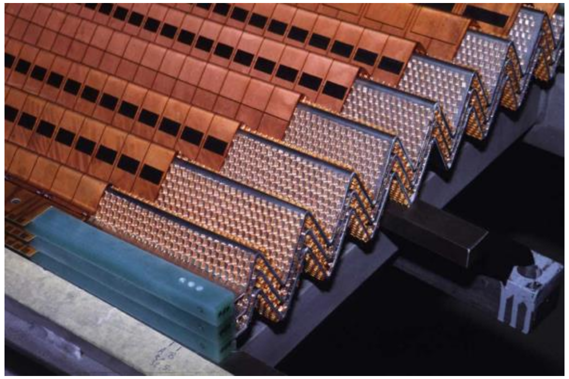
- Two types of calorimeters:
  - **Homogenous:**
    - Absorber == active medium
    - Material **dense** enough to contain shower, **scintillating** and **transparent** (for light transportation) or non-scintillating **Cerenkov**
      - Ex: CMS (PbWO4 scintillating crystals), L3 (BGO scintillating crystals), Lead Glass (Cerenkov), …

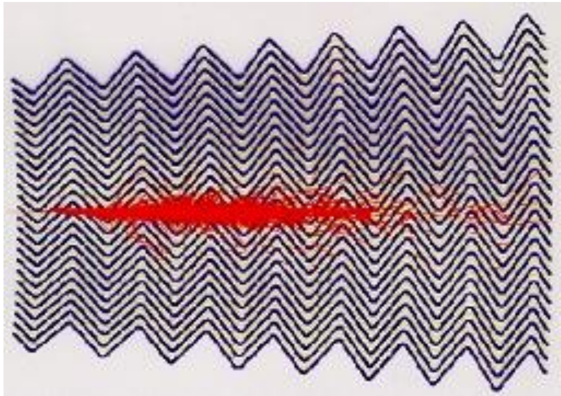


- Best resolution
- Compact
- Very expensive

  - **Sampling**
    - Sandwich of **high-Z absorber** (Pb, W, Ur,…) and **low-Z active media** (liquid, gaz, …)
      - Ex: ATLAS (Pb/LAr), DØ (Ur/LAr), …

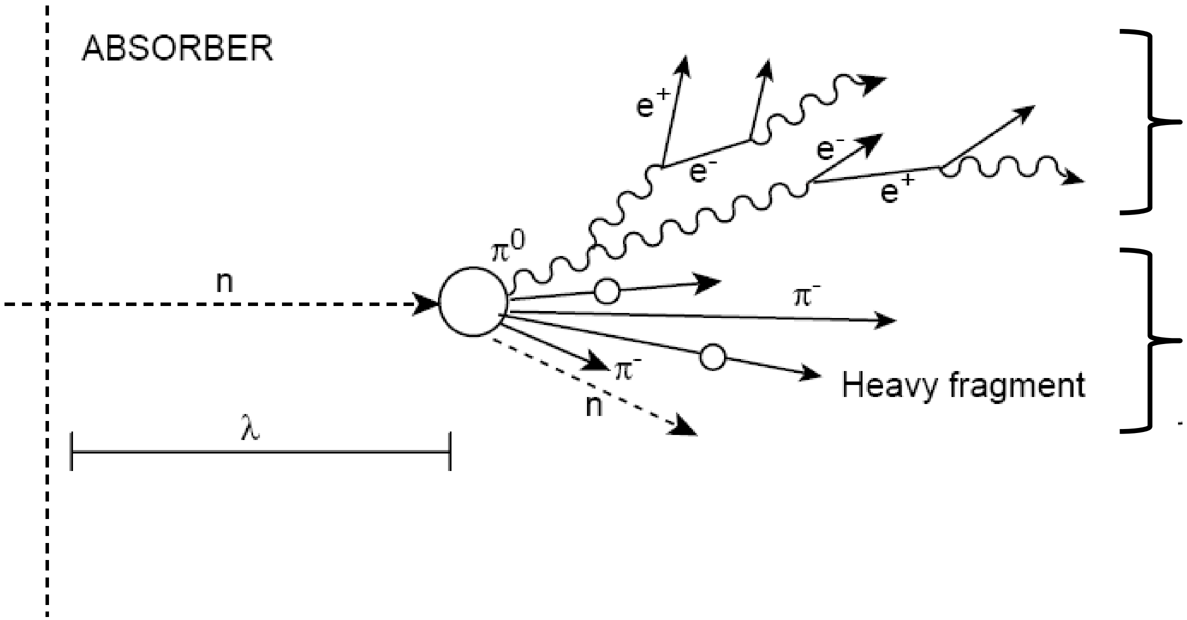
- Longitudinal segmentation
  - Good for particle ID, position measurement,…
- Cheaper than homogenous…
- … but worst resolution (only part of the shower is sampled)





Hadronic Showers

HAD showers have **two components**:



Electromagnetic component:

- Electrons, photons (from excitation, radiation, decay of hadrons, photo-effect, …)
- Neutral pions (eg, $\pi^0 \rightarrow \gamma\gamma$, $\eta \rightarrow \gamma\gamma$)

Hadronic component:

- Charged hadrons $\pi^{\pm}$, $K^{\pm}$, p, …
  - ionization, excitation, nuclei interaction (spallation p/n production, evaporation n, spallation products)
- Neutrons,
  - Elastic collisions, thermalization+capture (=>γ's)
- Break-up of nuclei

➢ Part of the energy is lost in breaking nuclei (nuclear binding energy)

⇒ **Invisible part** of the shower ! **Only part of the shower energy is sampled !**

- Large, **non-Gaussian** fluctuations of each component (EM vs non-EM)
- Large, **non-Gaussian** fluctuations in "invisible" energy losses.

Hadronic Showers properties

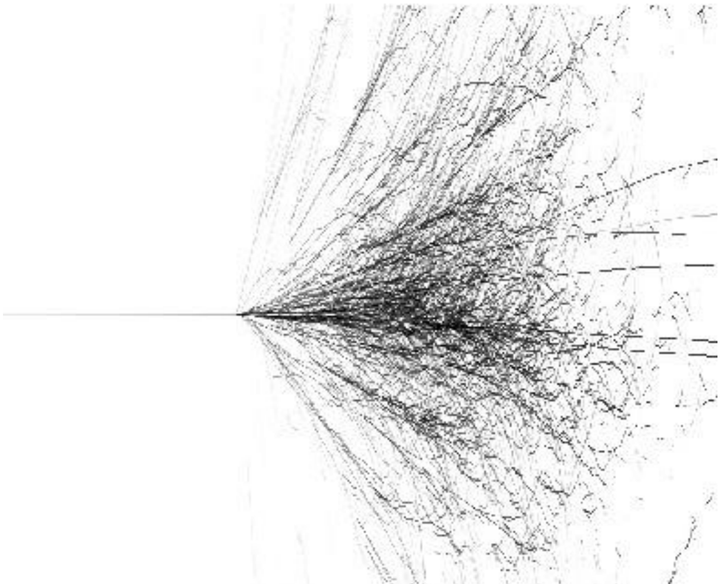
- The hadronic shower is governed by the interaction length λ_{int}
  - λ_{int}: Mean free path between inelastic interaction

$$\lambda_{\text{int}} \approx 35A^{1/3}(g.cm^{-2})$$

- Need about **~10 λ_{int}** to contain most of the hadronic showers

- Lateral containment increases with energy !
  - **Transverse radius for 95% containment ~ 1.5 λ_{int}**

<f_{EM}>=E_{EM}/E_{tot} is large, energy dependent (↑ with energy) and material dependent



Compensation

$$\frac{e}{\pi} = \frac{(e/h)}{1 - f_{EM}(1 - e/h)}$$

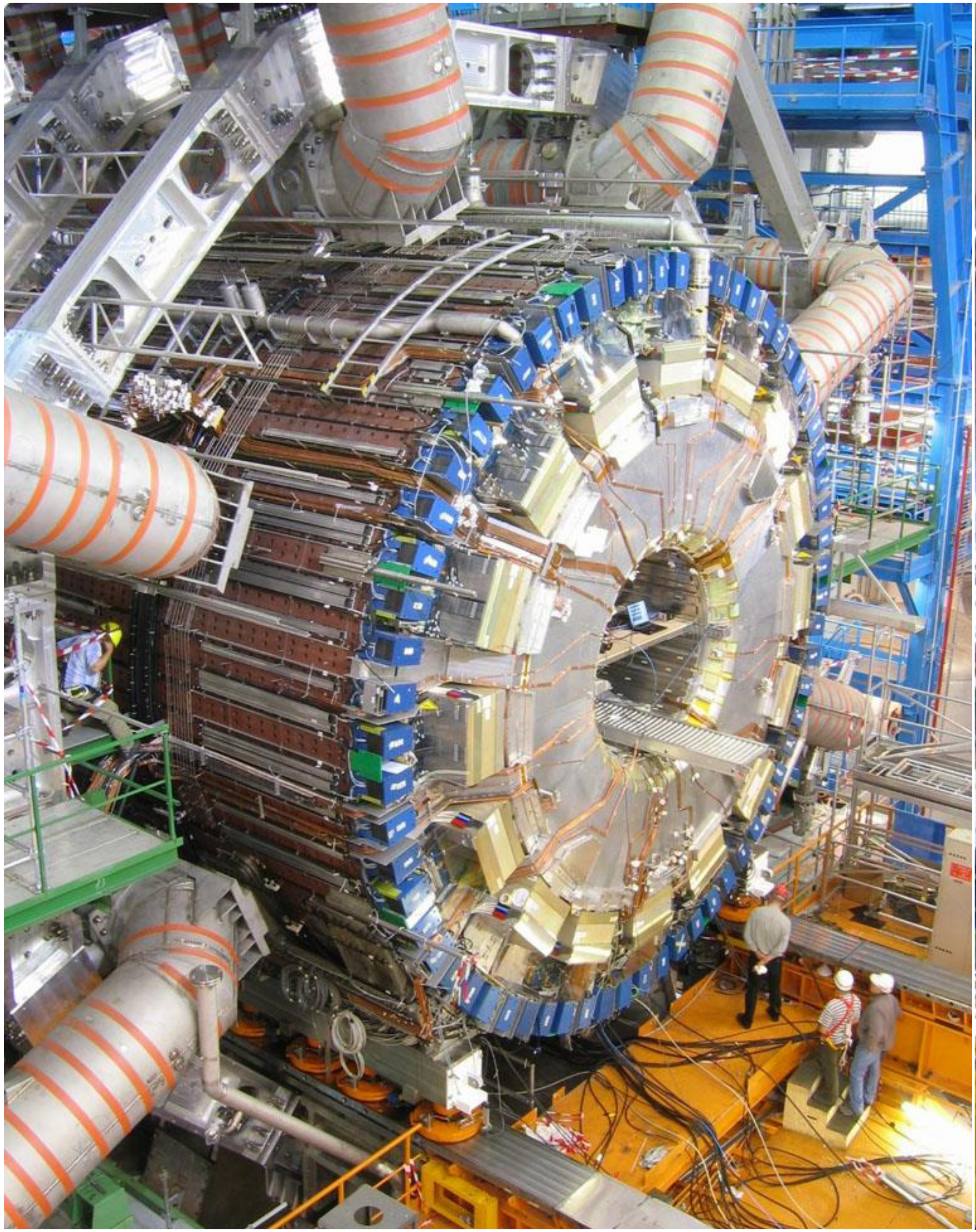
π: response to pions-induced showers
e: response to em shower component
h: response to non-em shower component

- Compensation if e/h = 1

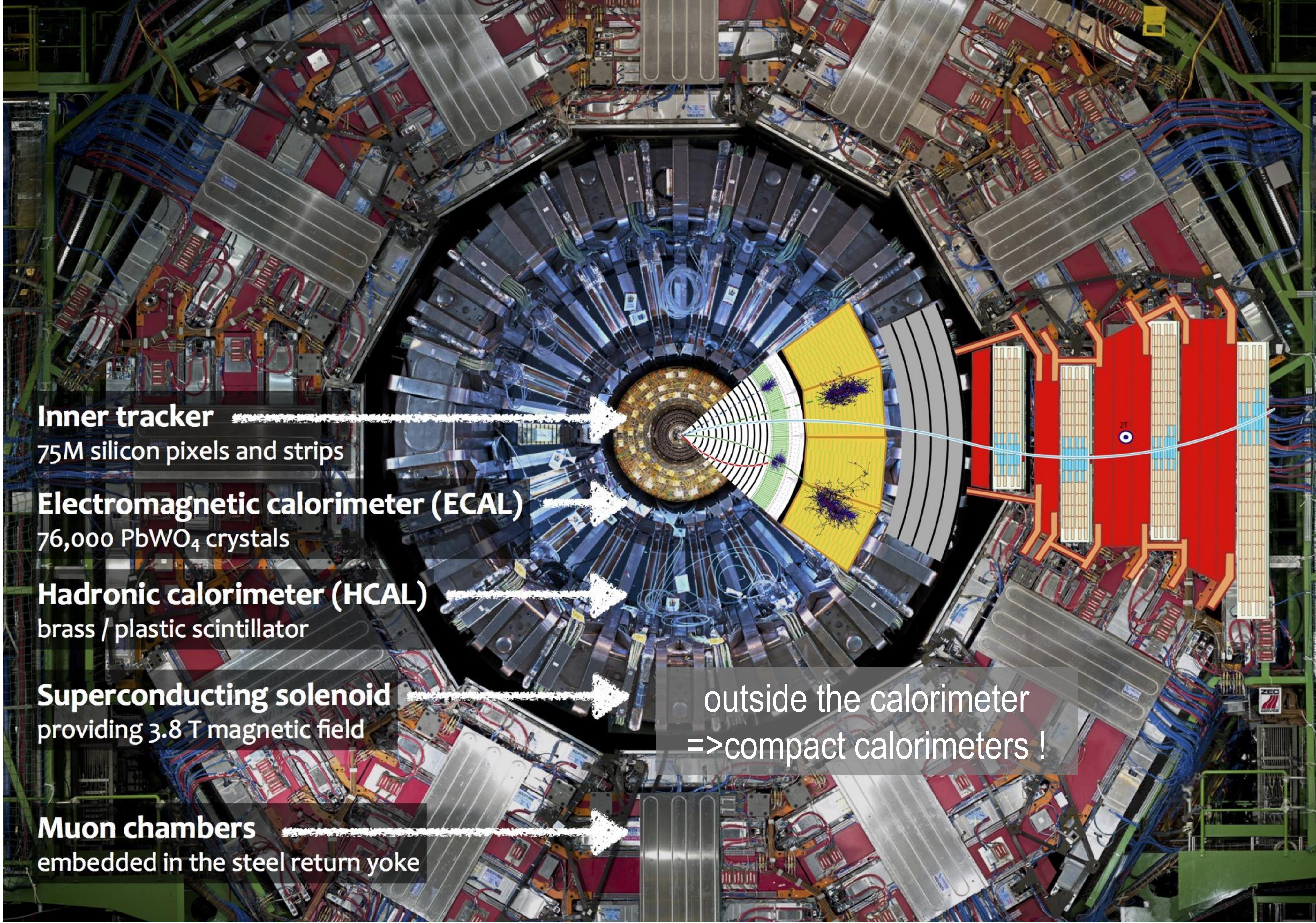
- If compensated calorimeter
  - Same energy scale for electrons/photons and hadrons
    - Calibrate with electrons and you are done !
  - Better resolution on hadrons
  - Response linearity

- How ?
  - **Build a sampling calorimeter**
  - **Boost the non-EM response**
    - Amplify neutron and soft photons component
      - fission, content of H in active material to capture neutrons,…
      - long integration time in electronics
  - **Suppress EM response**
  - **Offline compensation**

ATLAS & CMS calorimeters



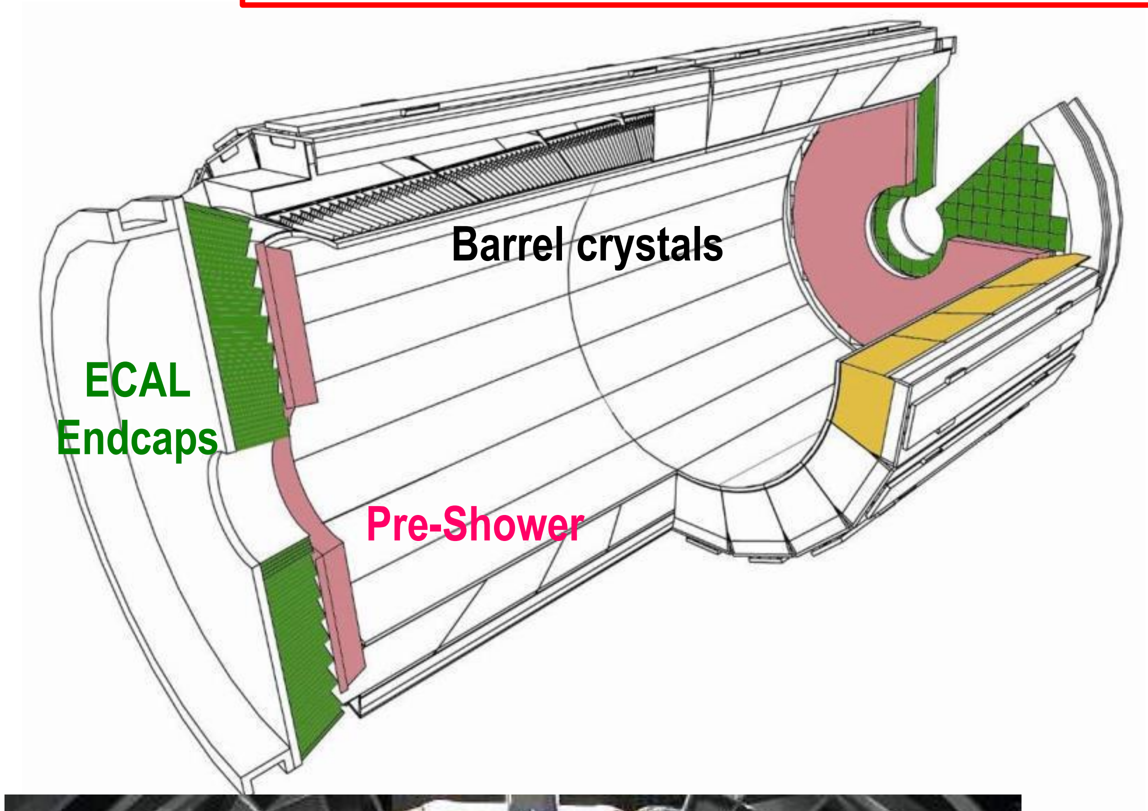
The CMS detector

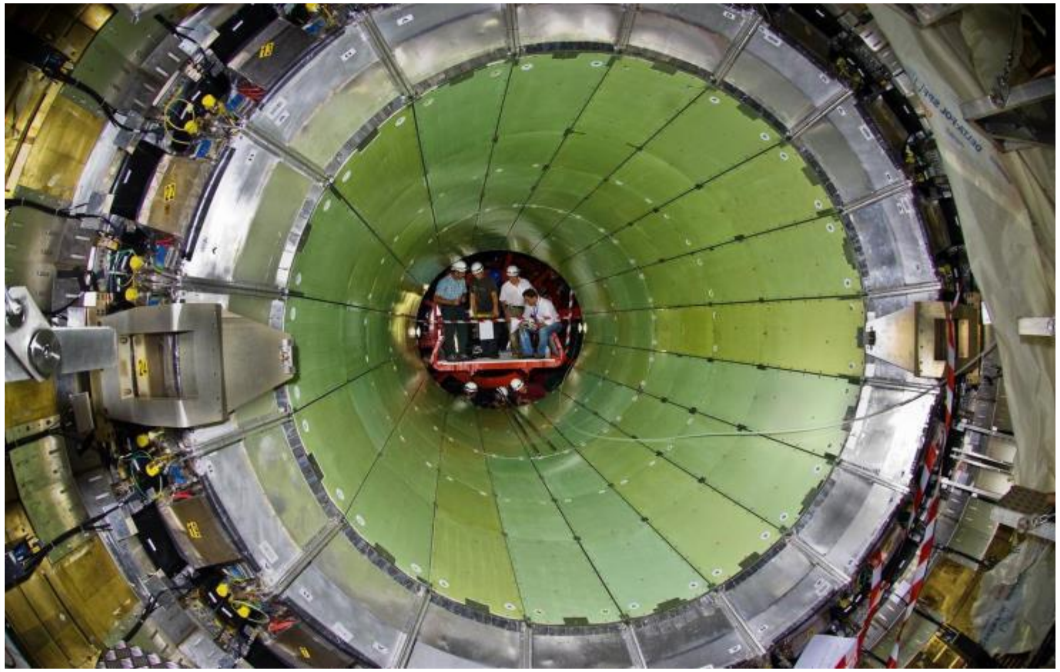


Courtesy of S. Regnard, R. Salerno

CMS ECAL

Homogenous calorimeter made from 75848 $PbWO_4$ scintillating crystals

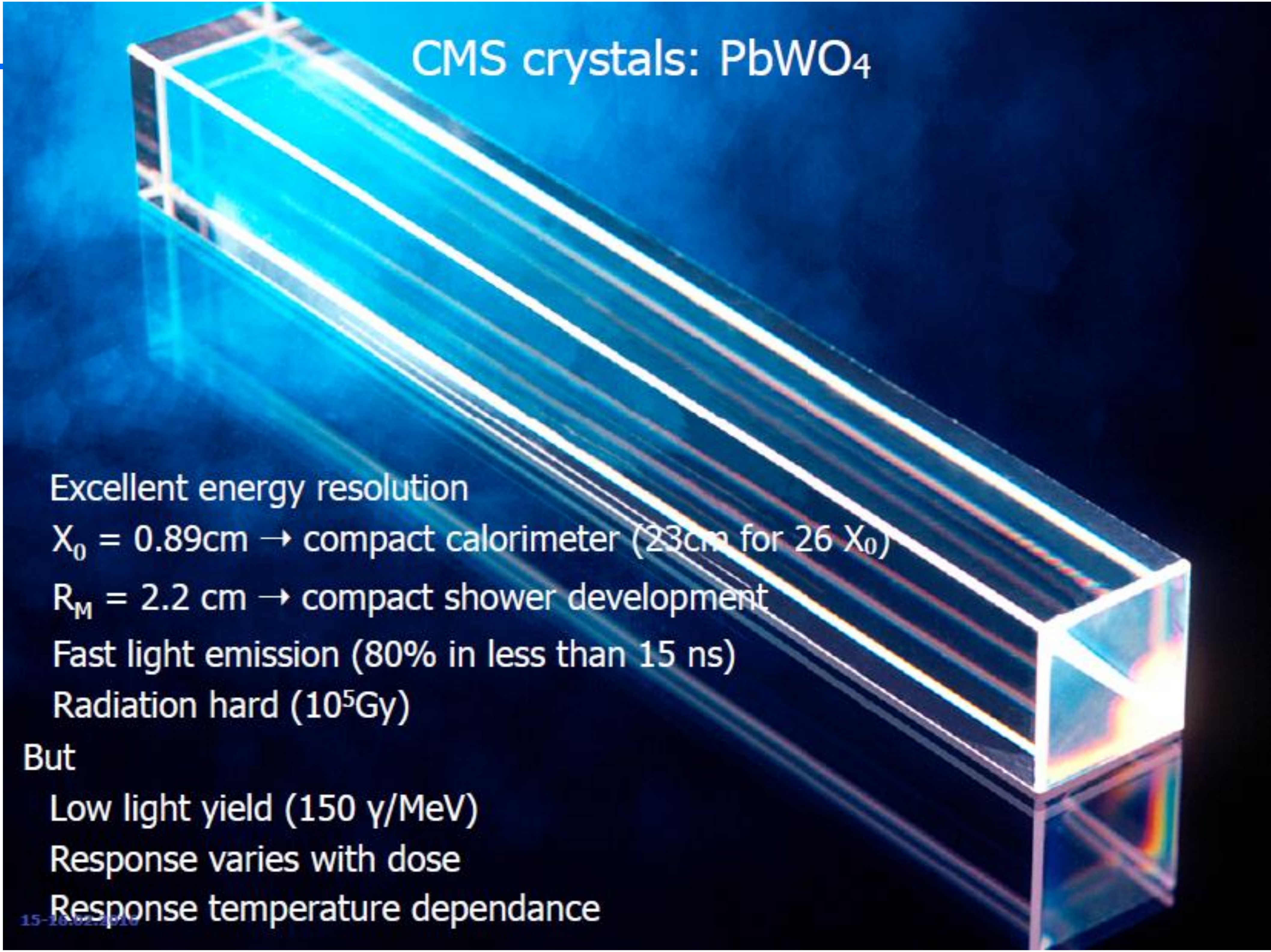




- Barrel ($|\eta|<1.48$), ~67 t
- 61200 crystals over 36 super-modules

- Endcaps ($1.48<|\eta|<3$), ~23 t
- 14648 crystals over 4 Dees (2 per endcap)
- Preceded by Pb/Si Pre-Shower

CMS crystals: $PbWO_4$

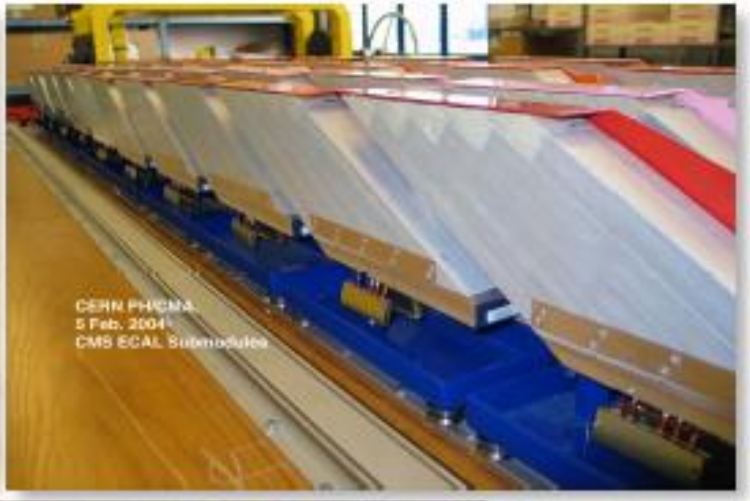


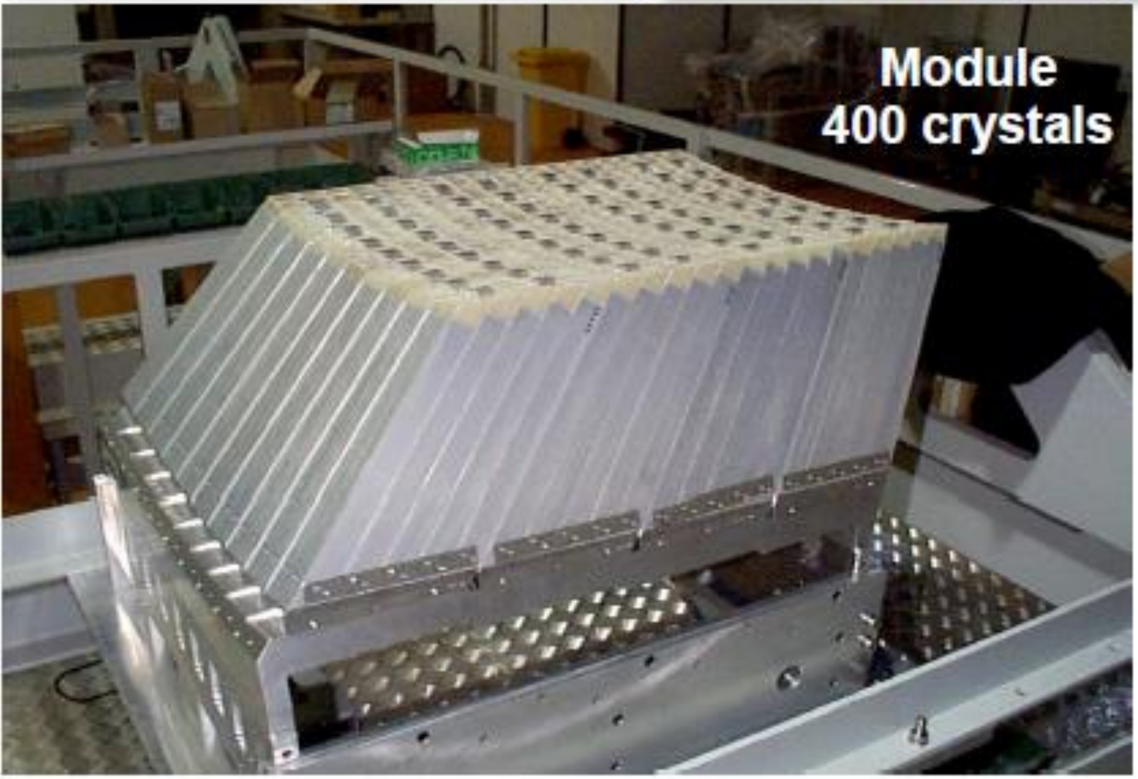
- Excellent energy resolution
- $X_0 = 0.89cm \rightarrow$ compact calorimeter (23cm for 26 X_0)
- $R_M = 2.2$ cm $\rightarrow$ compact shower development
- Fast light emission (80% in less than 15 ns)
- Radiation hard (10^5Gy)

But

- Low light yield (150 γ/MeV)
- Response varies with dose
- Response temperature dependance

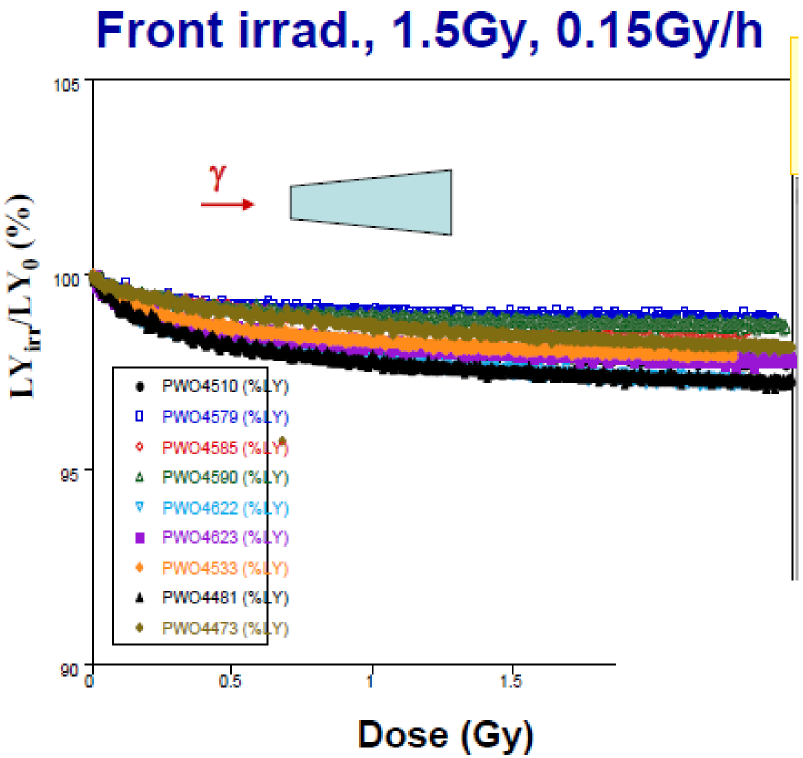
CMS ECAL Construction





Total 36 Supermodules

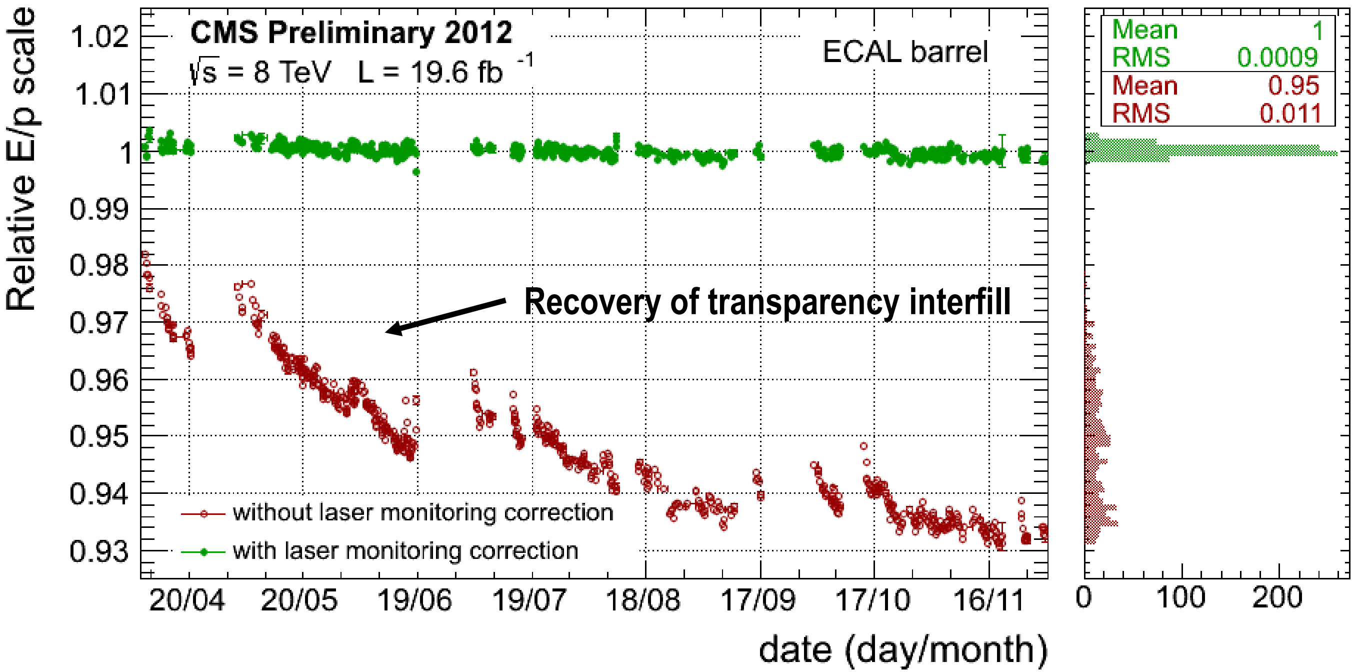
CMS ECAL: monitoring



- Response of PbWO4 crystal change with irradiation
  - Loss of transparency

- Damage and recovery during LHC cycles tracked with a laser monitoring system

E/p with W→eν events

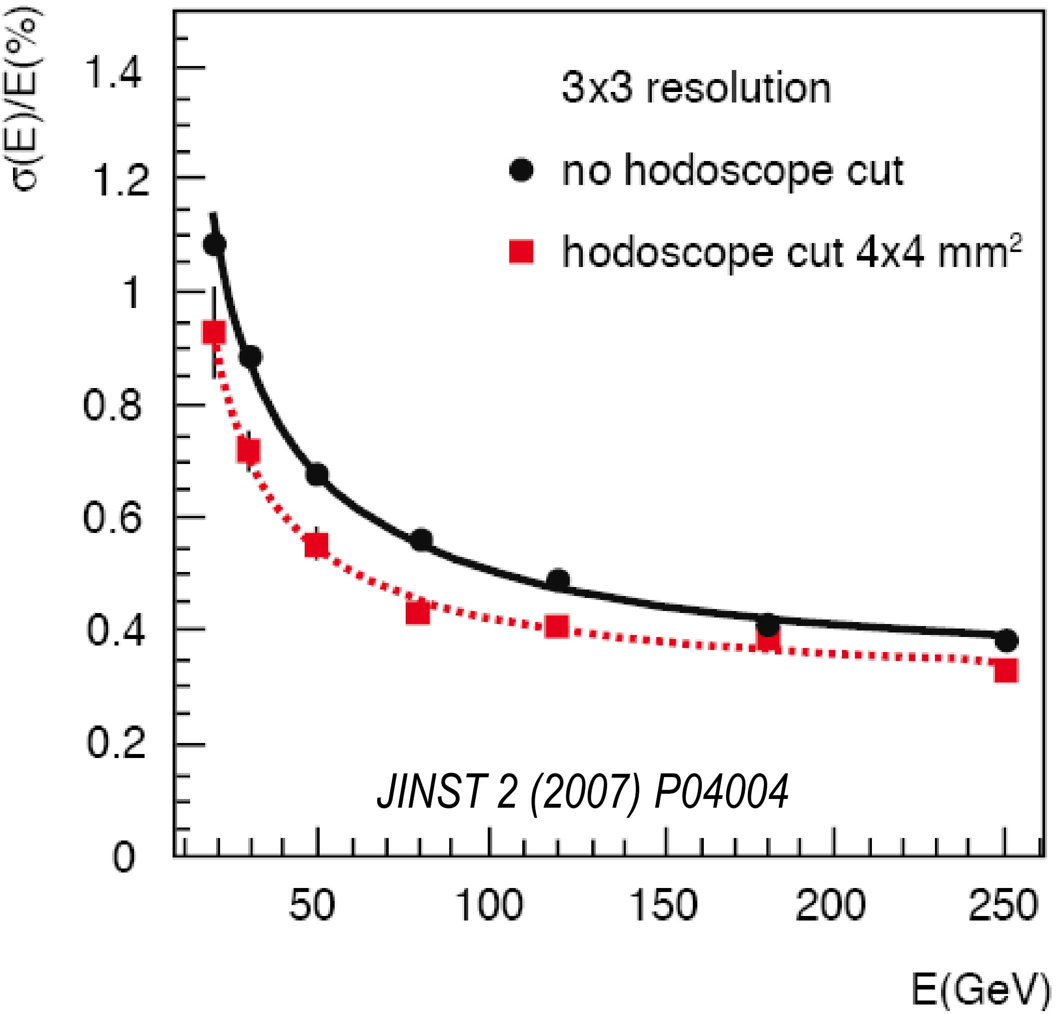


After laser correction

Before laser correction

CMS ECAL: performance

Stand-alone performance assessed during extensive test Beam campaigns at CERN...

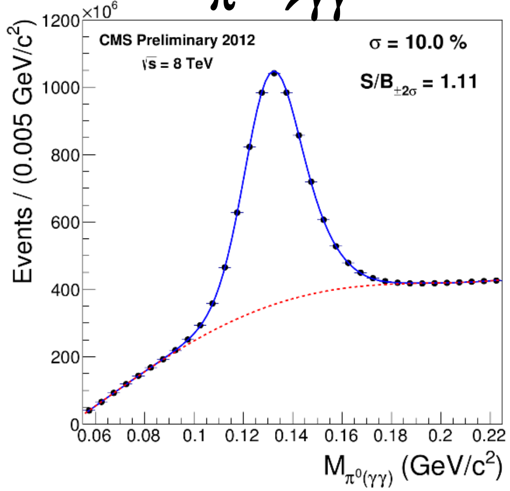


$$\frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E(\mathrm{GeV})}} \oplus \frac{125}{E(\mathrm{MeV})} \oplus 0.3\%$$

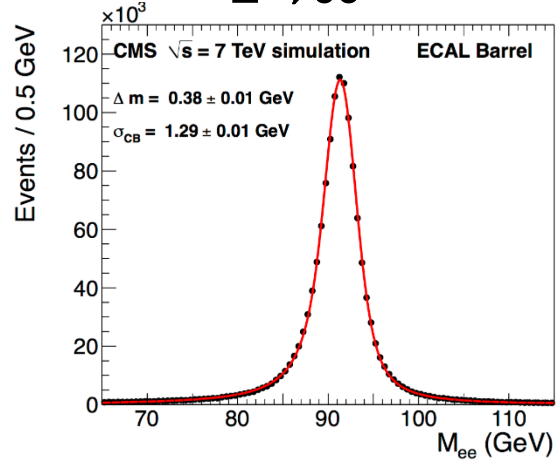
(test beam)

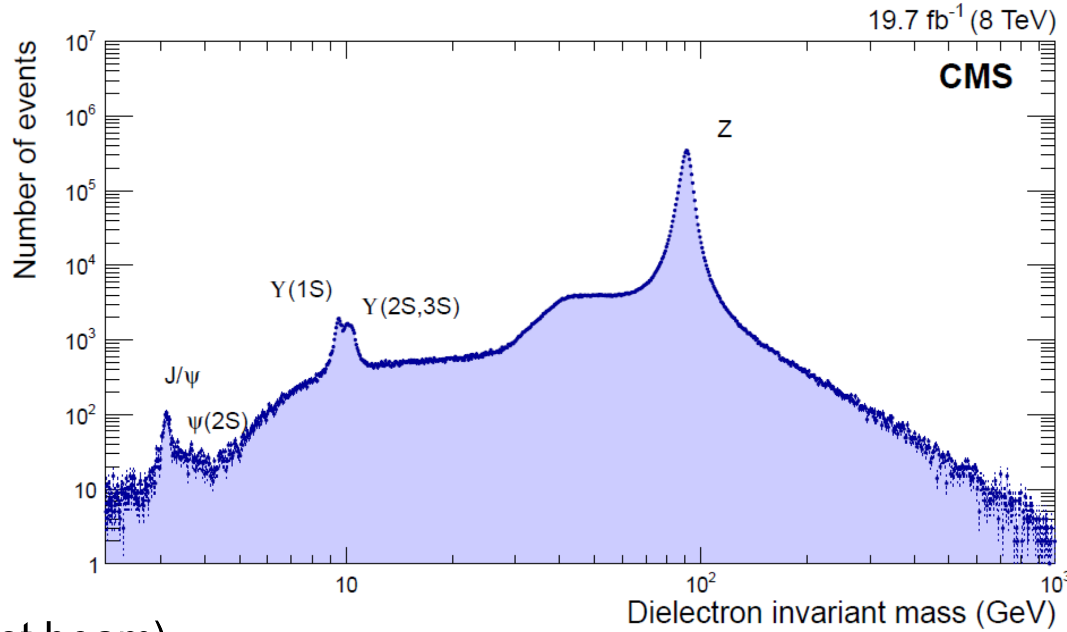
Combined performance measured in-situ

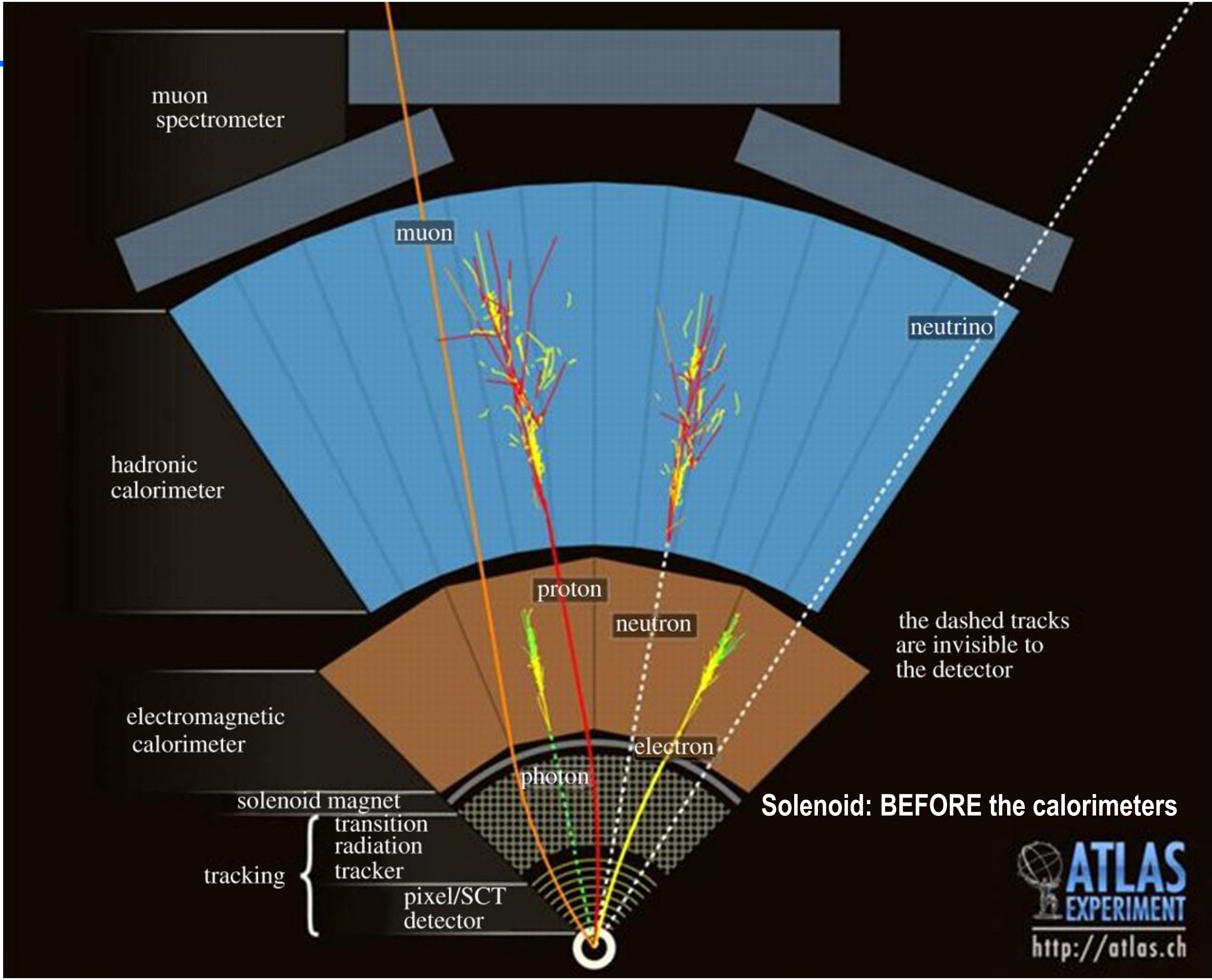
$\pi^0 \rightarrow \gamma\gamma$



$Z \rightarrow ee$



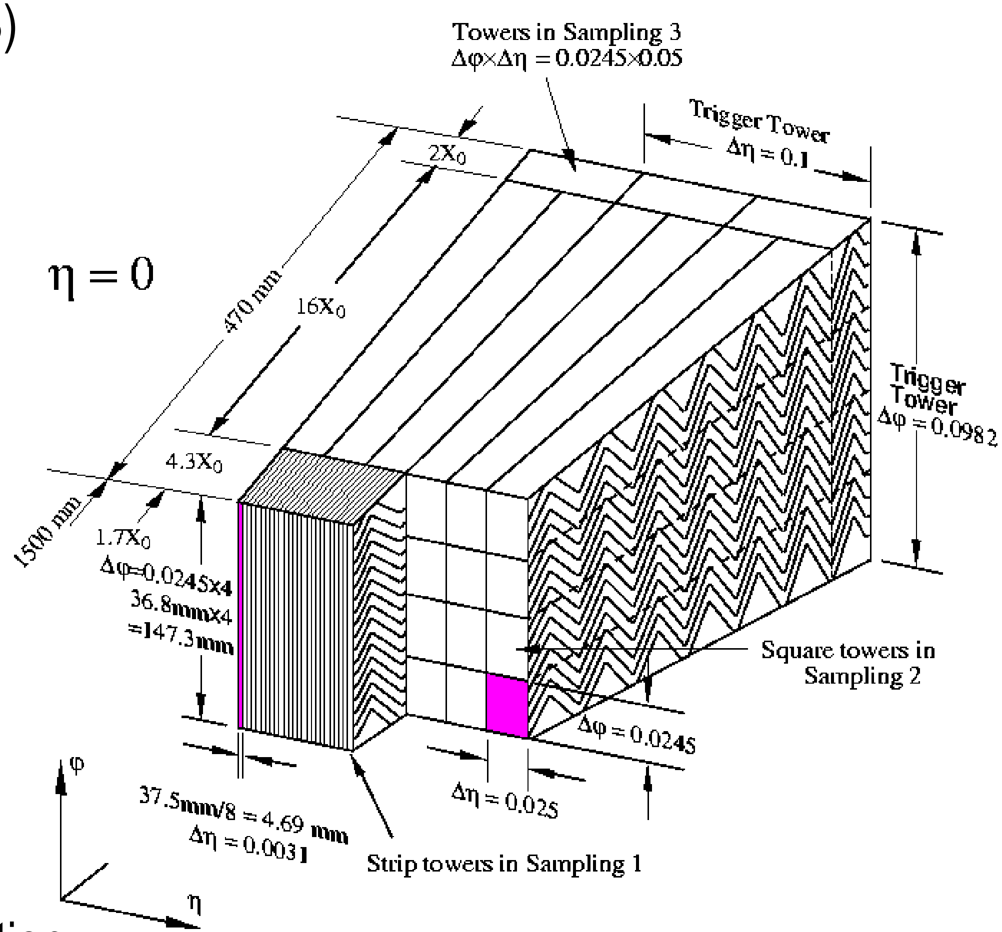



muon spectrometer
hadronic calorimeter
electromagnetic calorimeter
solenoid magnet
tracking
transition radiation tracker
pixel/SCT detector
muon
neutrino
proton
neutron
electron
photon
the dashed tracks are invisible to the detector
Solenoid: BEFORE the calorimeters
ATLAS EXPERIMENT
http://atlas.ch

The ATLAS ECAL

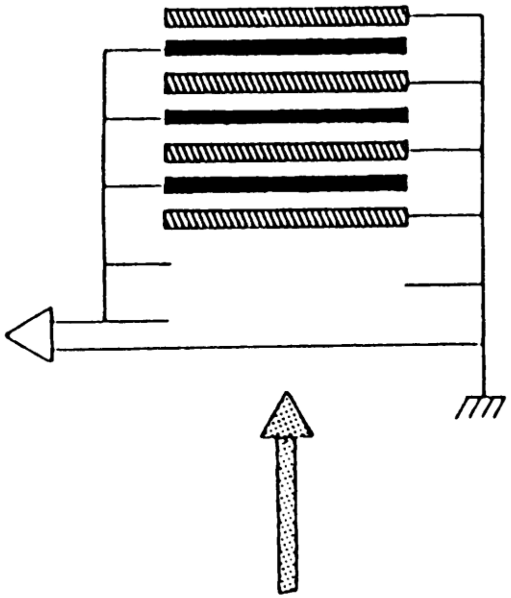
Sampling Pb/LAr calorimeter with innovative "accordion" geometry

- Longitudinal dimension ~25 X0, 47 cm (vs 22 cm for CMS)
  - 3 layers up to |η|=2.5 + presampler |η|<1.8
  - 2 layers 2.5<|η|<3.2
    - Layer 1 (γ/π⁰ rej. + angular meas.)
    - Δη.Δφ = 0.003 x 0.1
    - Layer 2 (shower max)
    - Δη.Δφ = 0.025 x 0.0.25
    - Layer 3 (Hadronic leakage)
    - Δη.Δφ = 0.05 x 0.0.025
- ~170 000 channels
- **Usage of Liquid Argon**
  - Radiation Hard
  - High number of electron-ion pair produced by ionization (1 GeV deposit -> 5.10^6 e-)
  - Stable vs time
  - **BUT:**
    - Need a cryostat (90K)
    - Slow time response (400 ns vs 25 ns LHC bunch crossing)

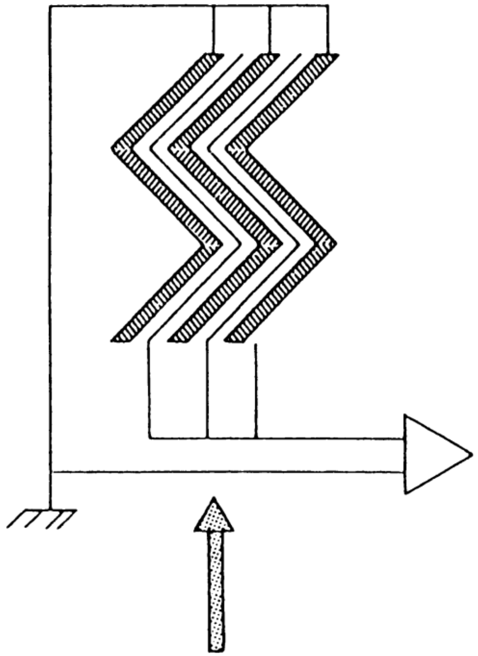


ATLAS ECAL: accordion geometry (1)

Standard Liquid Argon



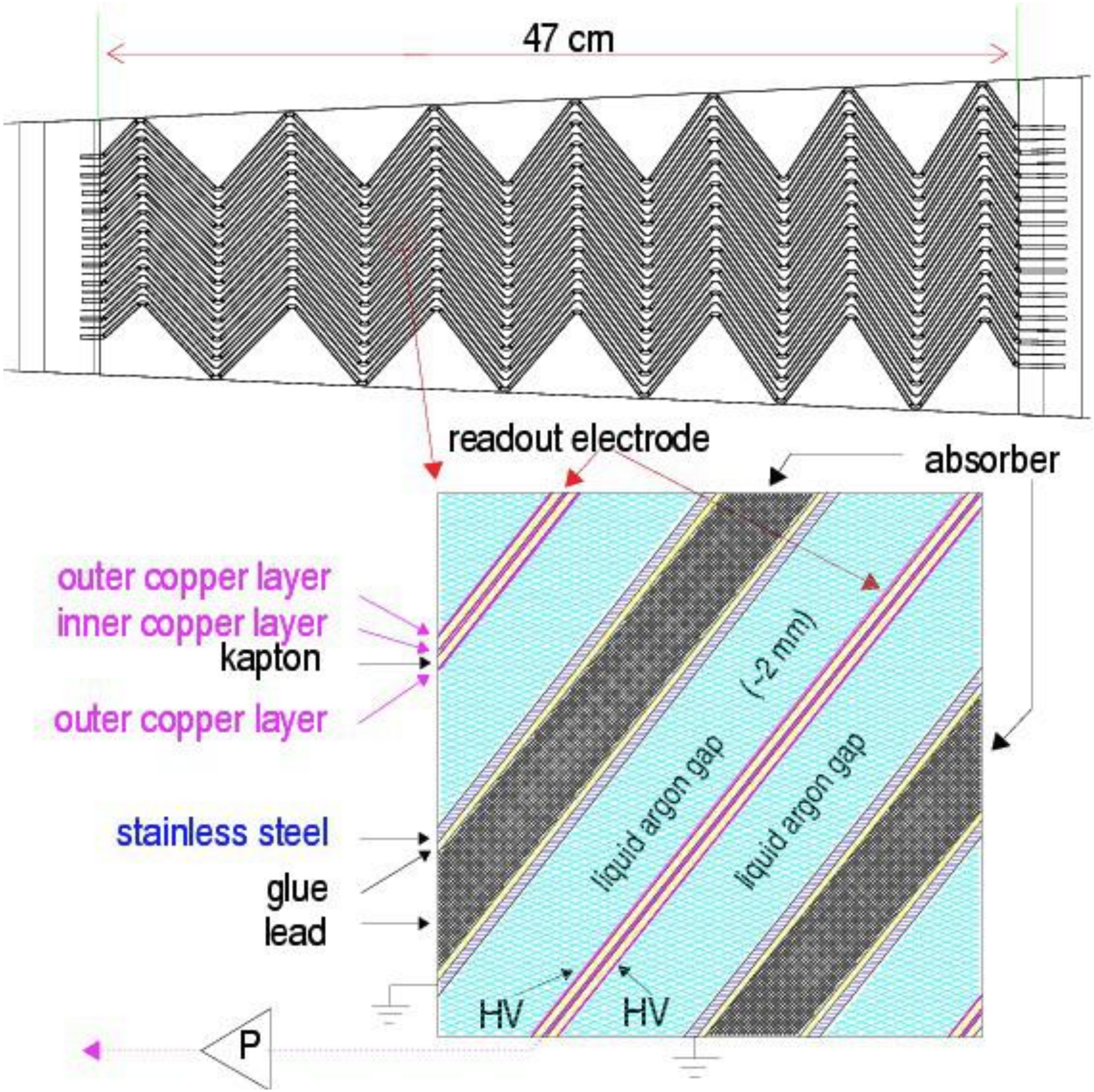
Accordion Liquid Argon

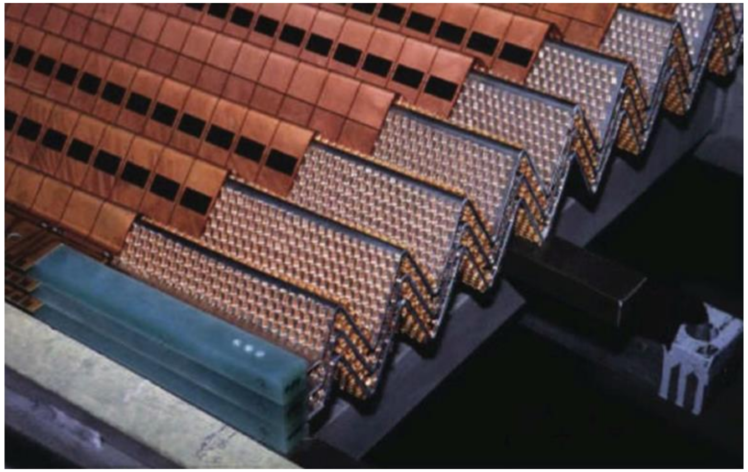


- Slow response (long integration time)
- Electrodes ⊥ particles
- Long cables
  - To bring signal to pre-amplifiers
  - Regroup gaps
- Dead zones due to cables

- Accordion geometry: **fast**
- Electrodes // to incident particles
  - Signal read out forward & backward
  - No long connection
- **No cracks (in azimuth)**

ATLAS ECAL: accordion geometry (2)

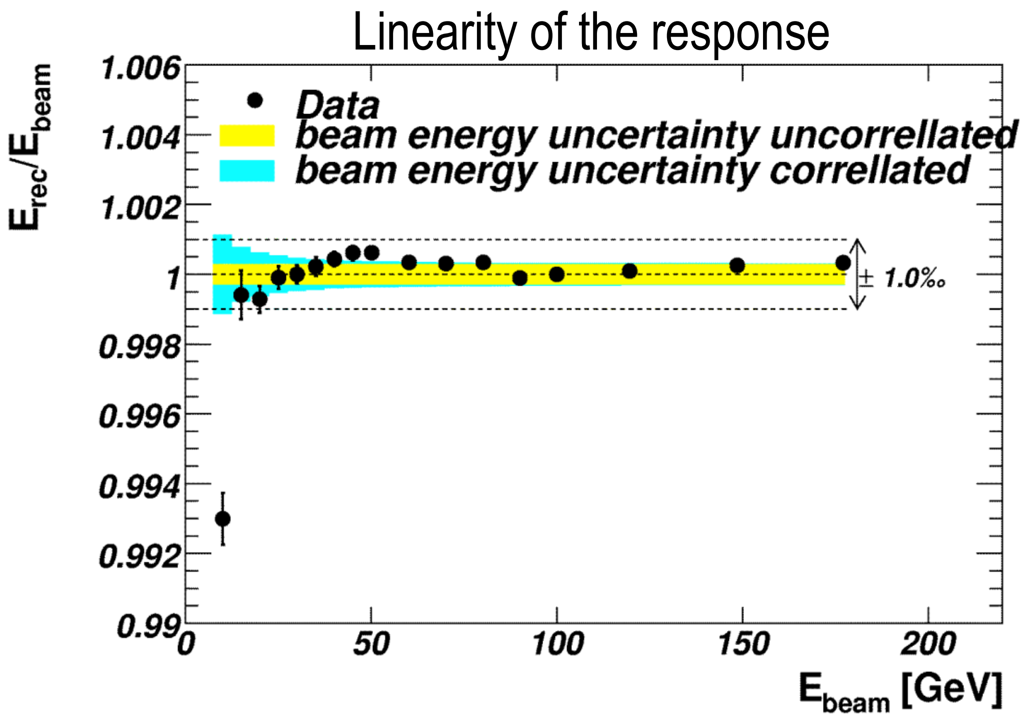


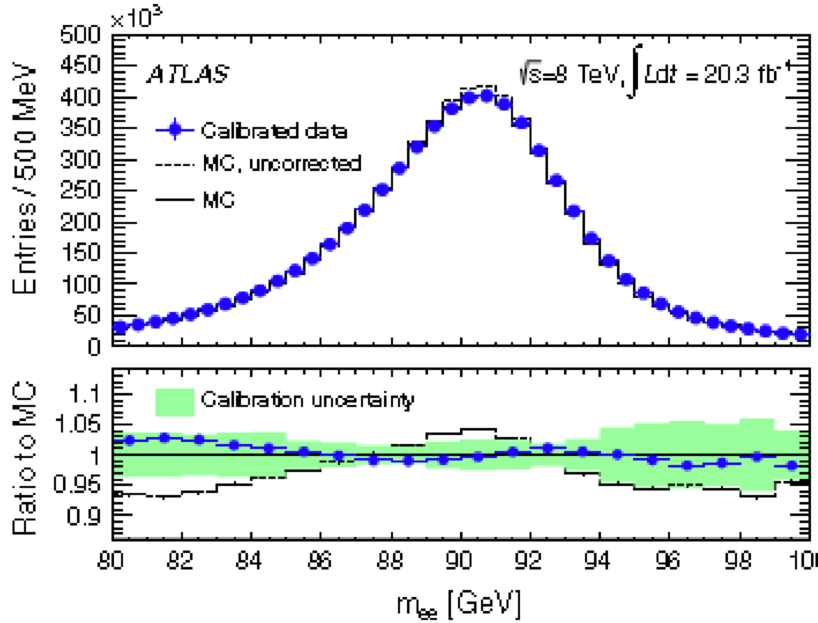


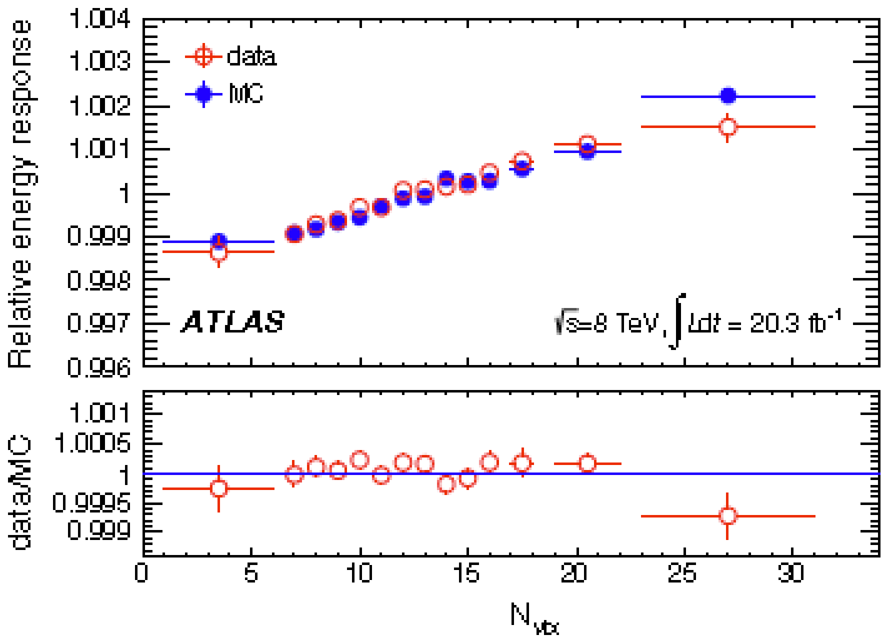
ATLAS ECAL: Performance

Stand-alone performance assessed during extensive test Beam campaigns at CERN...

Combined performance measured in-situ



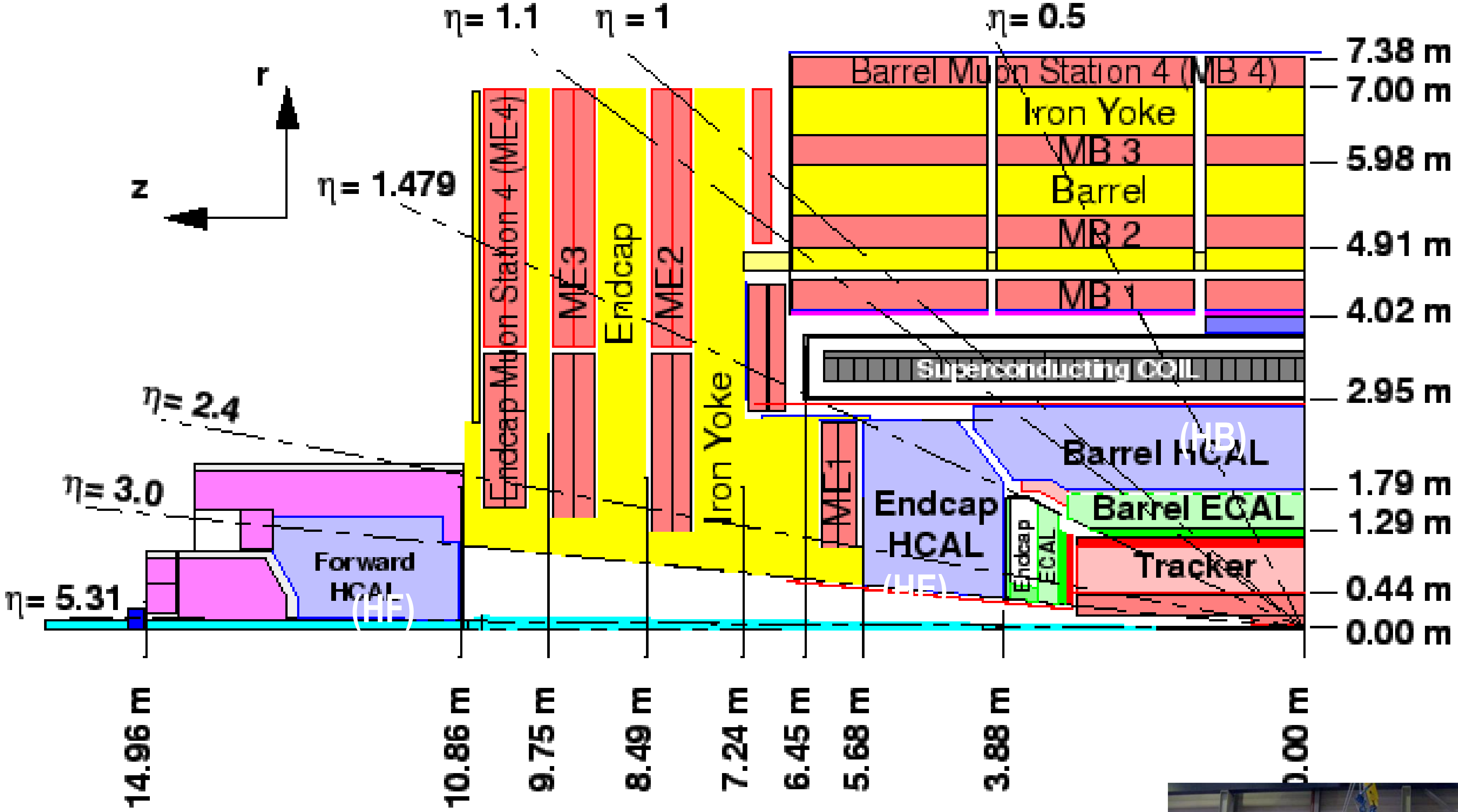




$$\frac{\sigma}{E} = \frac{10\%}{\sqrt{E}} \oplus \frac{0.3}{E} \oplus 0.7\%$$

(test beam)

CMS HCAL



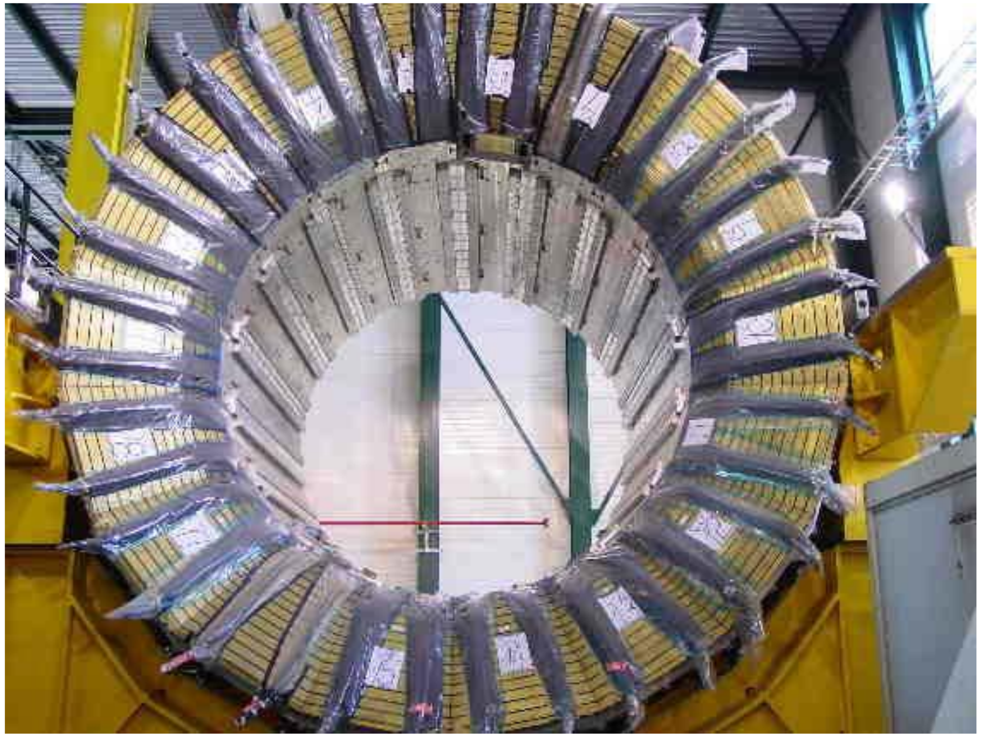
- HCAL Barrel (HB): $|\eta|<1.3$
- HCAL Endcap (HE): $1.3<|\eta|<3$
- Forward HCAL (HF): $3<|\eta|<5$, Fe+Quartz Fiber

See next

CMS HCAL

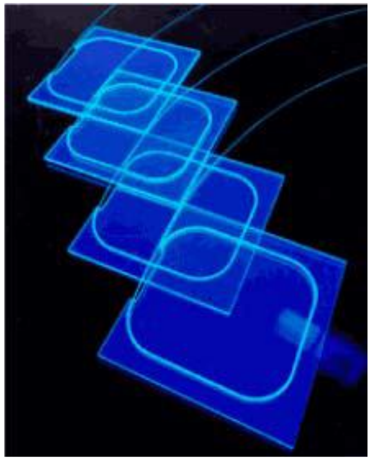
HB/HE: Sampling Brass/plastic scintillator calorimeter

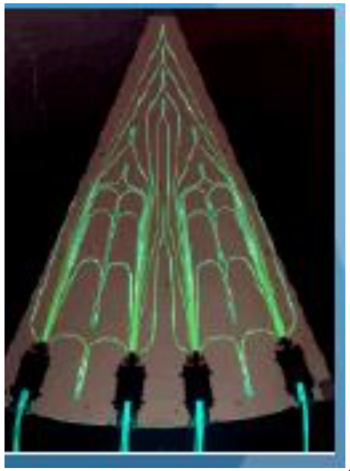
HB **(17 longitudinal layers)**



HE **(19 longitudinal layers)**

- Segmentation: $\Delta\eta x \Delta\phi$=0.087x0.087 (larger at high η)
- 18x20° "wedges" with alternate brass plates (5-8 cm) and "tiles" embedded with Wave Length Shifter (WLS).
  - Light from scintillator: blue-violet
  - WLS: absorb light then fluorescence in green
  - Green light read by Hybrid Photo Diode (HPD)





CMS HCAL: Brass absorber preparation

Workers in Murmansk sitting on brass casings of **decommissioned shells of the Russian Northern Fleet**

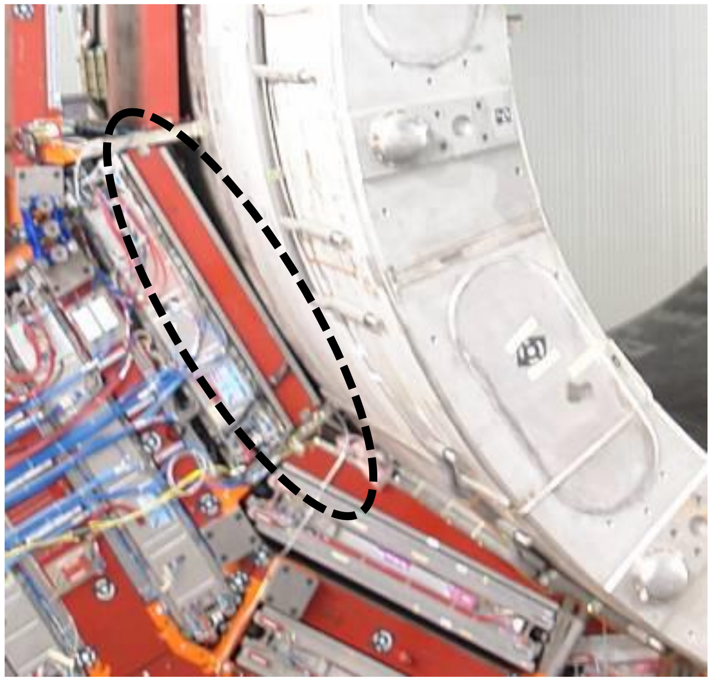
Explosives previously removed!

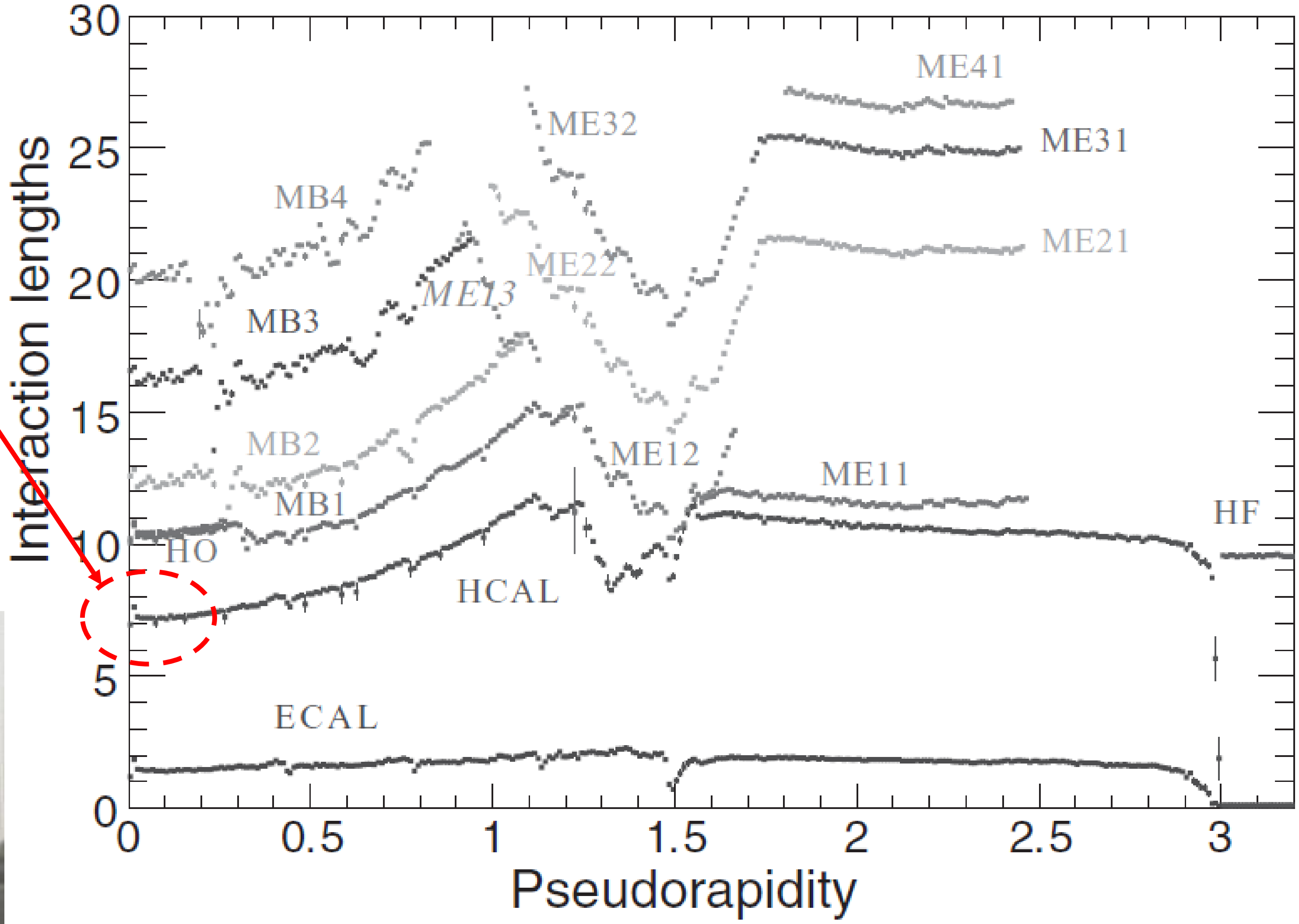
Casings melted in St Petersburg and turned into raw brass plates

Machined in Minsk and mounted to become absorber plates for the CMS Endcap Hadron Calorimeter

CMS HCAL: Containment

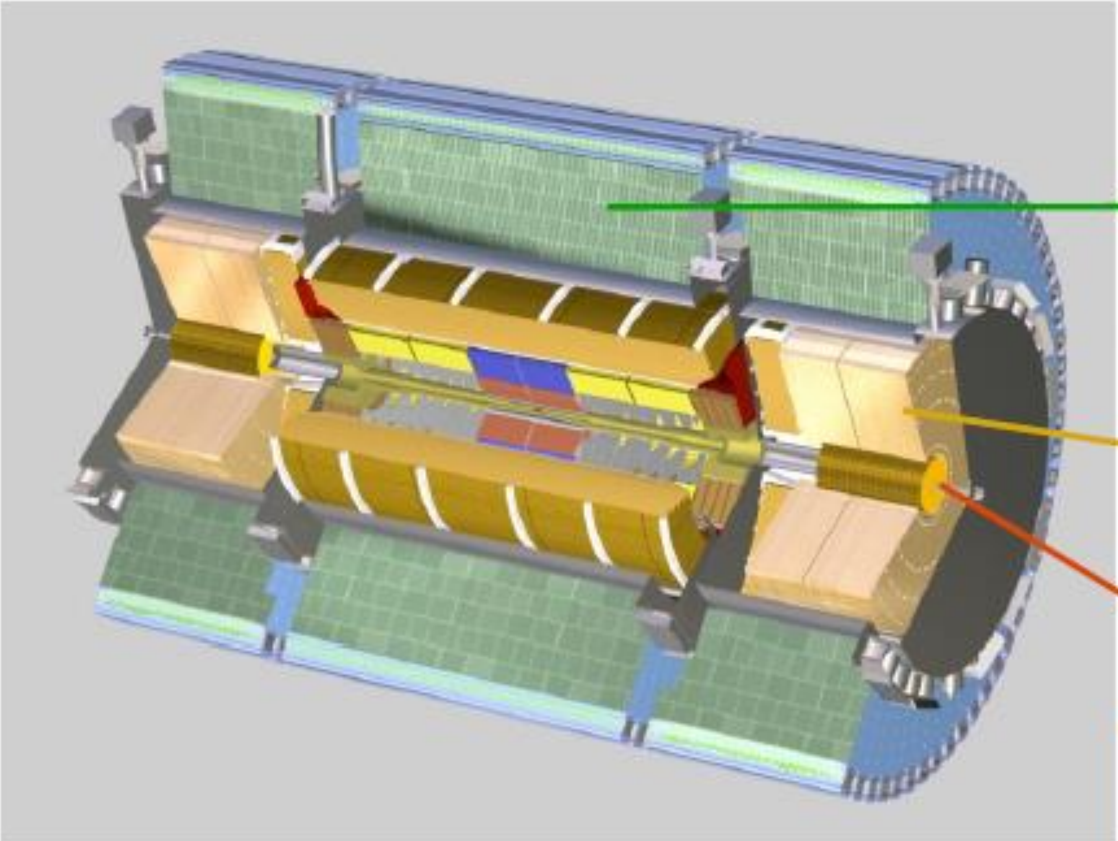
- At |η|=0, λint from HB =5.8 ! (7.2 with ECAL)
  - Large leakage…
- CMS adds HCAL Outer (HO):
  - Scintillator + WLS outside coil acting as "tail catcher".





Poor Resolution: ~100% / √E

ATLAS HCAL



Tiles Calorimeter $|\eta| < 1.7$

Fe / Scintillator

3 layers in depth

LAr/Cu $1.7 < |\eta| < 3.2$

4 layers in depth

Forward: 1 layer EM, 2 HAD

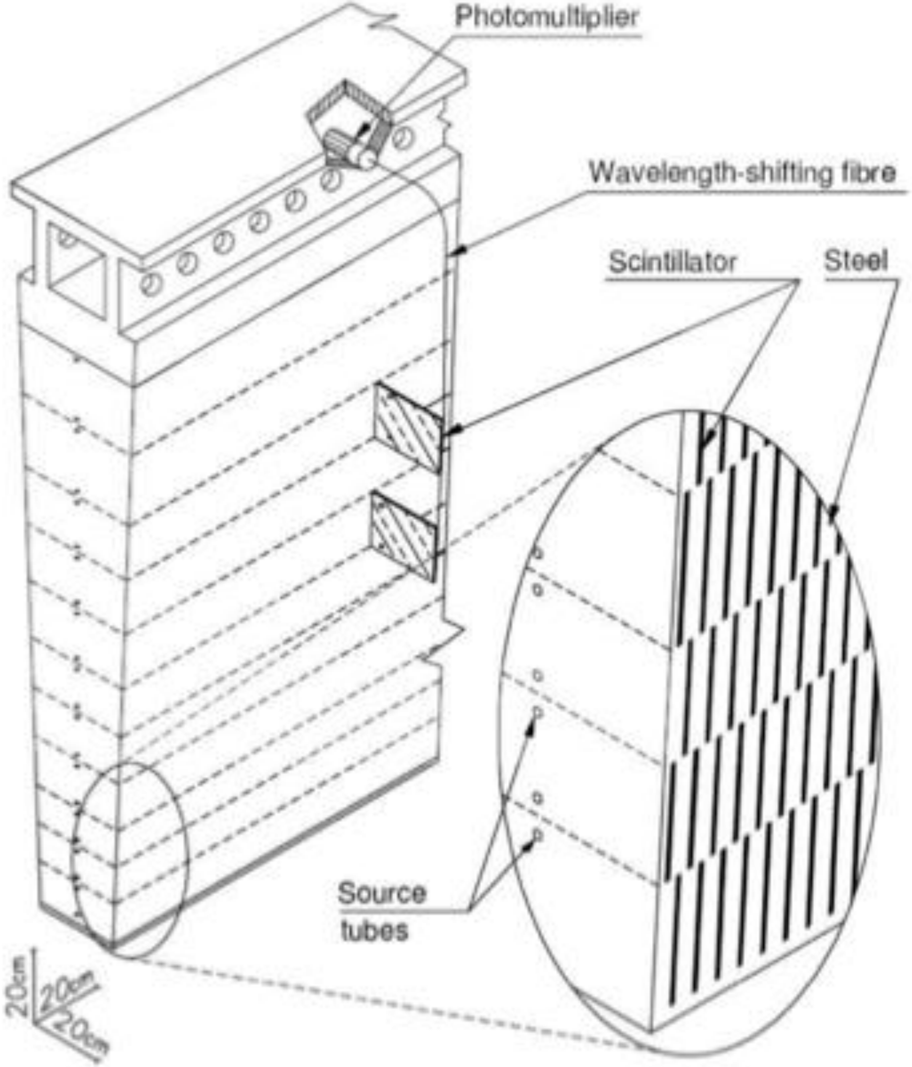
LAr/Cu or W $3.2 < |\eta| < 4.9$

Total thickness: ~ 8 -10 λ

Use of different technics: cope with radiations in forward region

ATLAS TileCal

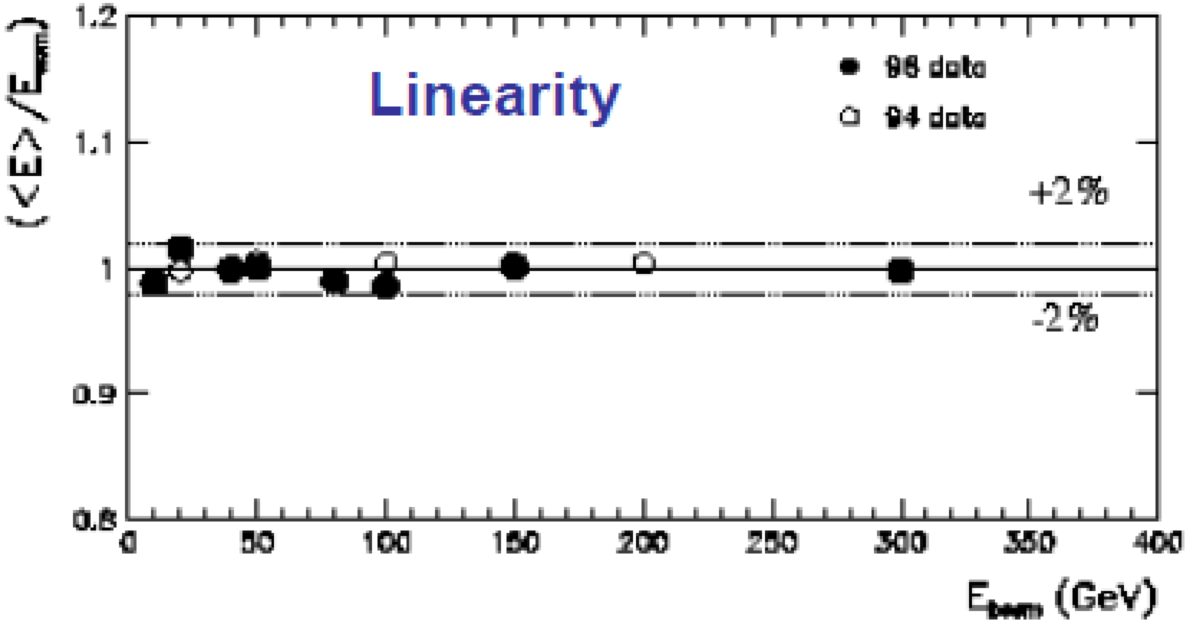
TileCal: Sampling Fe/plastic scintillator calorimeter

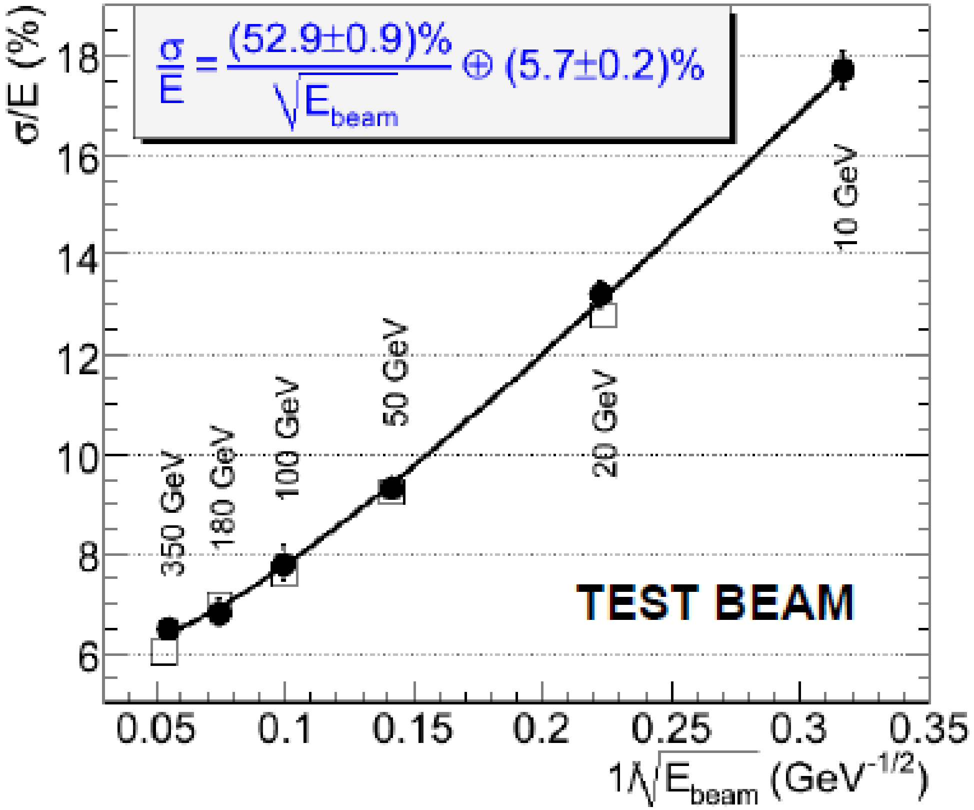


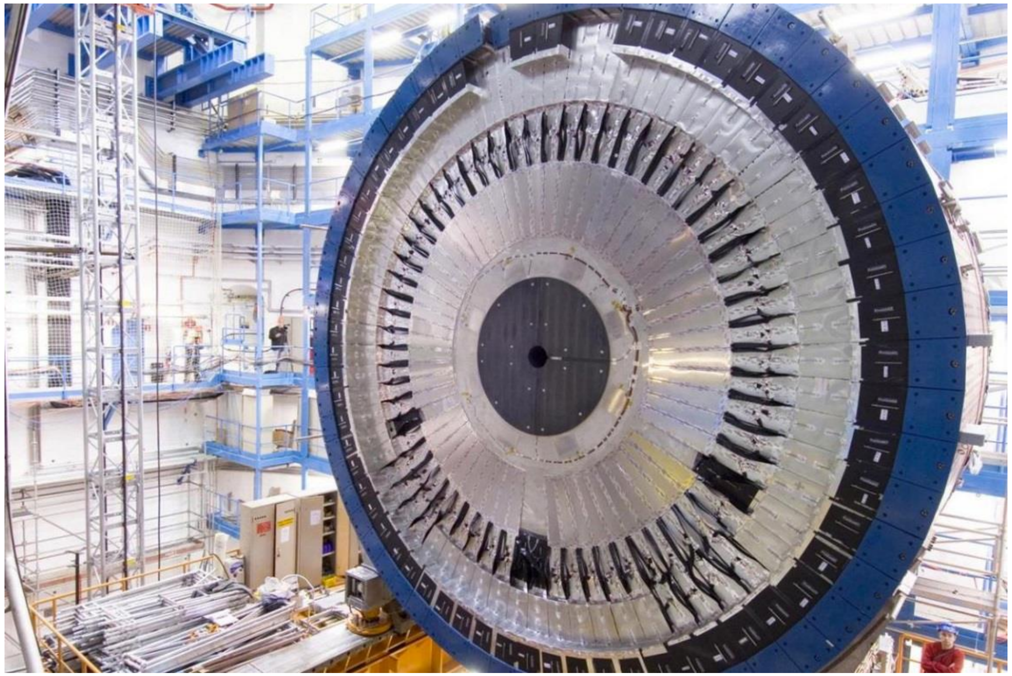
- Coverage: $|\eta|<1.7$
- 3 cylinders (1 barrel, 2 extended barrel)
- 3 longitudinal sampling
- Segmentation: $\Delta\eta x \Delta\phi$=0.1 (0.2) x0.1
- ~10 000 channels

➢ Key element: Tile
  - Perpendicular to beam axis
  - WLS carry light to PMT

ATLAS TileCal: Performance







Resolution: ~50% / √E

ATLAS/CMS ECAL Resolution

TABLE 8 Main parameters of the ATLAS and CMS electromagnetic calorimeters

	ATLAS		CMS	
Technology	Lead/LAr accordion		$PbWO_4$ scintillating crystals	
Channels	Barrel	End caps	Barrel	End caps
	110,208	63,744	61,200	14,648
Granularity	$\Delta\eta \times \Delta\phi$		$\Delta\eta \times \Delta\phi$	
Presampler	0.025×0.1	0.025×0.1		
Strips/ Si-preshower	0.003×0.1	0.003×0.1 to 0.006×0.1		32×32 Si-strips per 4 crystals
Main sampling	0.025×0.025	0.025×0.025	0.017×0.017	0.018×0.003 to 0.088×0.015
Back	0.05×0.025	0.05×0.025		
Depth	Barrel	End caps	Barrel	End caps
Presampler (LAr)	10 mm	2×2 mm		
Strips/ Si-preshower	$\approx 4.3\ X_0$	$\approx 4.0\ X_0$		$3\ X_0$
Main sampling	$\approx 16\ X_0$	$\approx 20\ X_0$	$26\ X_0$	$25\ X_0$
Back	$\approx 2\ X_0$	$\approx 2\ X_0$		
Noise per cluster	250 MeV	250 MeV	200 MeV	600 MeV
Intrinsic resolution	Barrel	End caps	Barrel	End caps
Stochastic term a	10%	10 to 12%	3%	5.5%
Local constant term b	0.2%	0.35%	0.5%	0.5%

Note the presence of the silicon preshower detector in front of the CMS end-cap crystals, which have a variable granularity because of their fixed geometrical size of $29 \times 29\ mm^2$. The intrinsic energy resolutions are quoted as parametrizations of the type $\sigma(E)/E = a/\sqrt{E} \oplus b$. For the ATLAS EM barrel and end-cap calorimeters and for the CMS barrel crystals, the numbers quoted are based on stand-alone test-beam measurements.

ATLAS/CMS HCAL Resolution

TABLE 10 Main performance parameters of the different hadronic calorimeter components of the ATLAS and CMS detectors, as measured in test beams using charged pions in both stand-alone and combined mode with the ECAL

	ATLAS				CMS	
	Barrel LAr/Tile		End-cap LAr			
	Tile	Combined	HEC	Combined	Had. barrel	Combined
Electron/hadron ratio	1.36	1.37	1.49			
Stochastic term	$45\%/\sqrt{E}$	$55\%/\sqrt{E}$	$75\%/\sqrt{E}$	$85\%/\sqrt{E}$	$100\%/\sqrt{E}$	$70\%/\sqrt{E}$
Constant term	1.3%	2.3%	5.8%	$< 1\%$		8.0%
Noise	Small	3.2 GeV		1.2 GeV	Small	1 GeV

The measured electron/hadron ratios are given separately for the hadronic stand-alone and combined calorimeters when available, and the contributions (added quadratically except for the stand-alone ATLAS tile calorimeter) to the pion energy resolution from the stochastic term, the local constant term, and the noise are also shown, when available from published data.

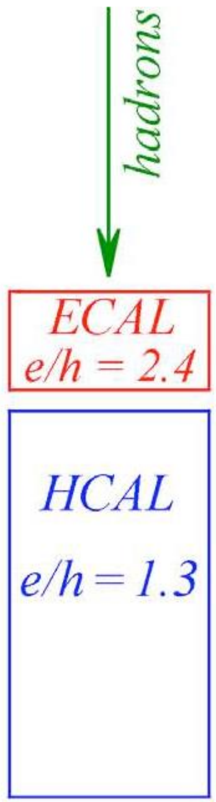
How can CMS can compete with ATLAS on the jet physics given these numbers ?
=> **Particle Flow** (**see next lecture**)

Last note on ATLAS / CMS Calorimeters

ATLAS and CMS are NON-compensating calorimeters

- **Numbers** (*):
  - ATLAS Tile Barrel e/h ~ 1.4

  - CMS ECAL: e/h ~ 2.4
  - CMS HCAL: e/h ~ 1.3
  - CMS HF: e/h ~ 4.7

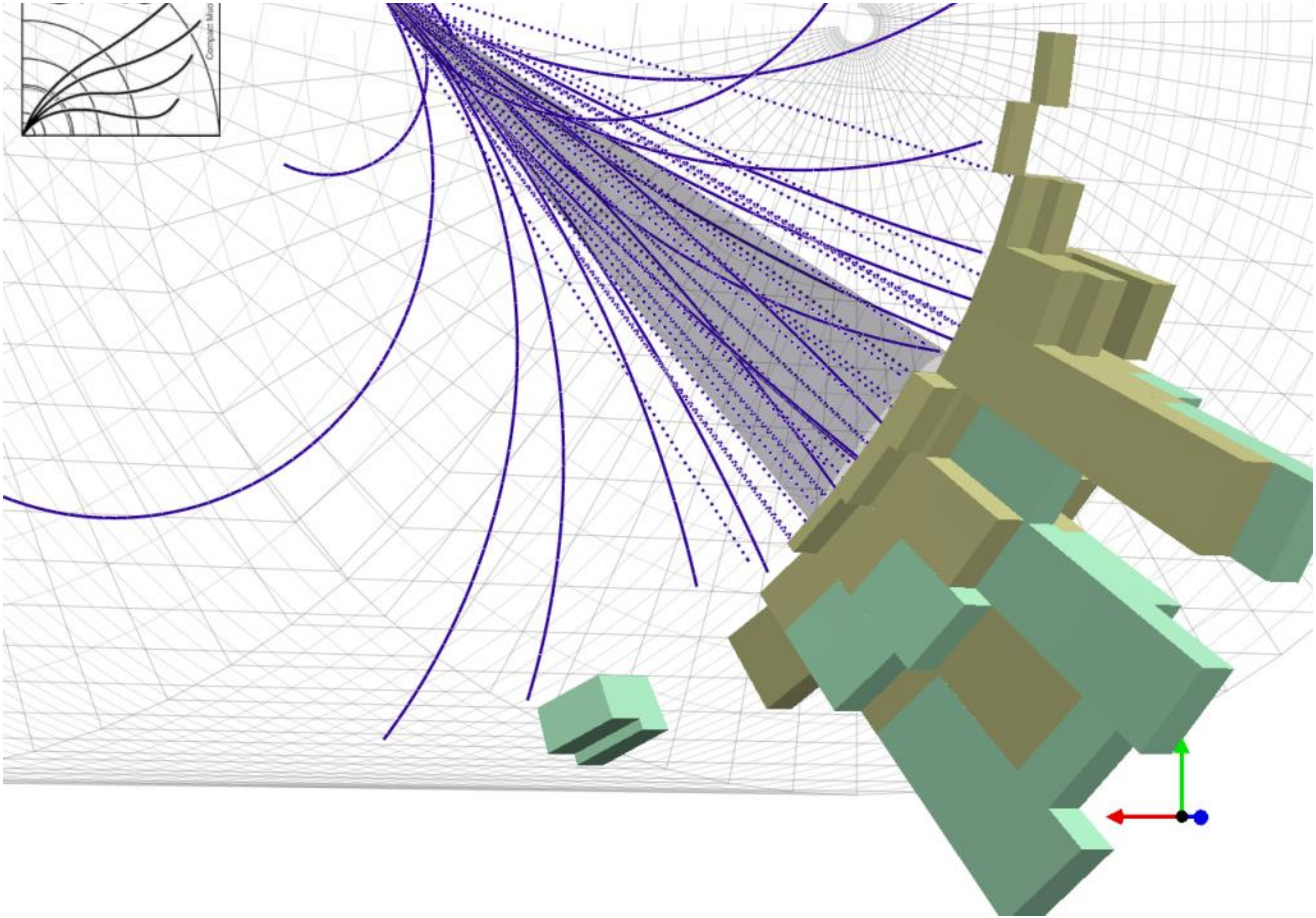


- Ex: CMS calibrates:
  - ECAL for electrons/photons
  - HCAL with pions non-interacting in ECAL
  - But pions DO interact with ECAL. And thus get wrong calibration.
  - Degrades the resolution.

Again, **Particle Flow technics will help there** (by separating charged and neutral pions). **See Lecture 3.**

(*) to be verified…

Calorimeter Objects



Calorimeter objects

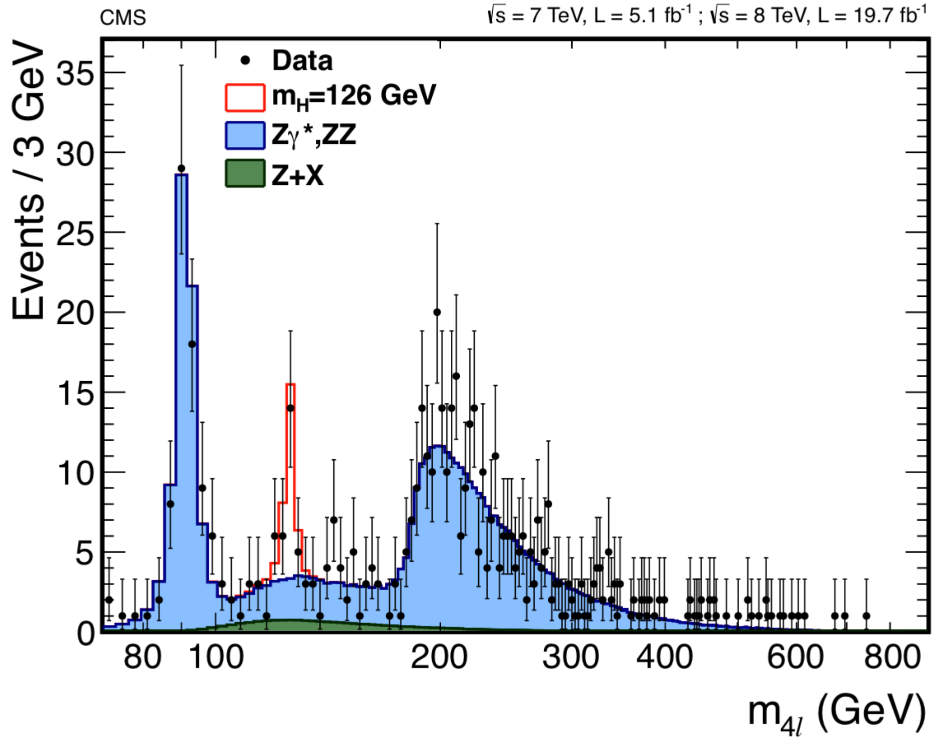
- In hadron colliders, calorimeters are meant to trigger, reconstruct, identify and measure energy of charged and neutral particles produced during the collisions:
  - Electrons & photons
  - Jets
  - Neutrinos (and other invisible particles)

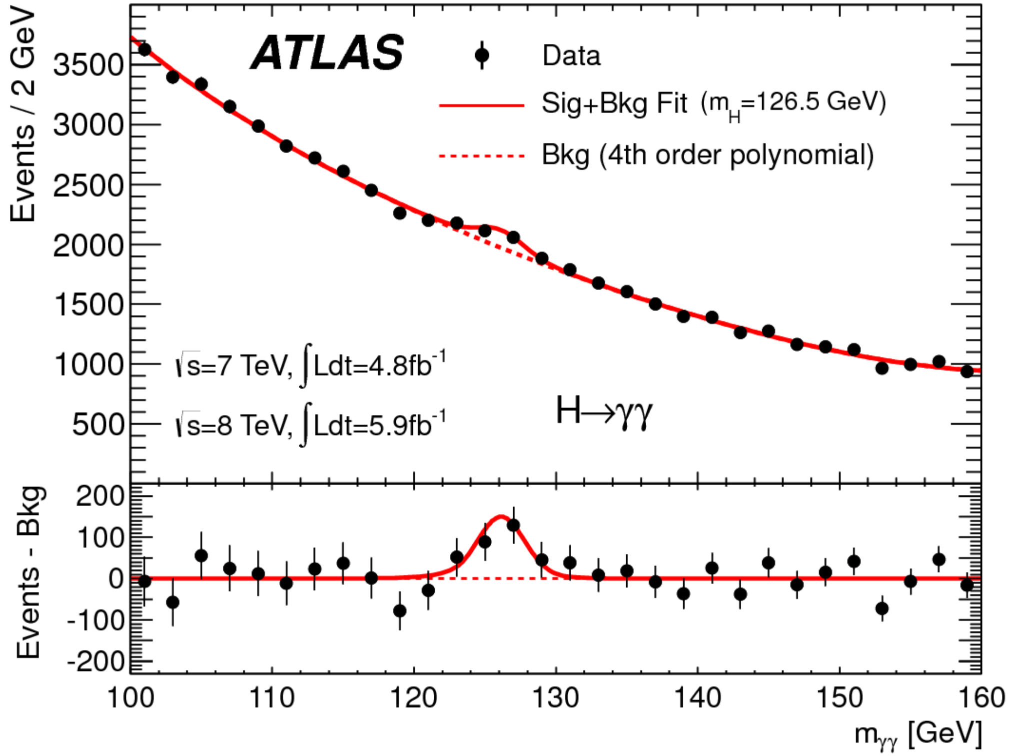
- Real conditions are different from standalone device or test beams:
  - Magnetic field (constraint for the readout electronics, photodetectors, …)
  - Material in front of the calorimeter
  - Radiations,
  - (inter-)calibrations,
  - Pile-up,
  - …

=> Degrade ultimate performance.

Electrons/Photons at LHC (1)

- Final states with electrons and photons are **major experimental signatures at LHC:**
  - $H \rightarrow \gamma\gamma$
  - $H \rightarrow ZZ^* \rightarrow$ 4 leptons (e, μ)
  - SUSY $\rightarrow$ multileptons cascade
  - …





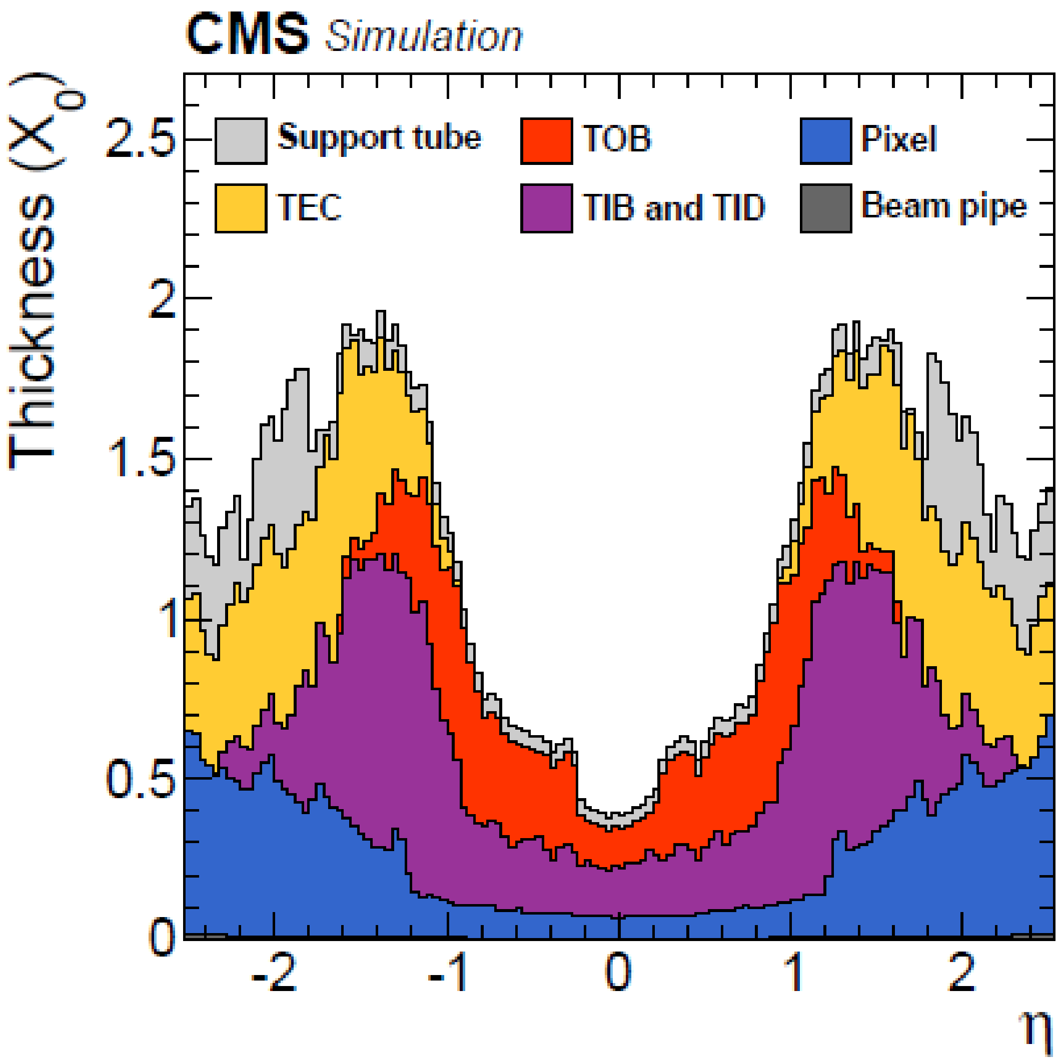
- **Naively:**

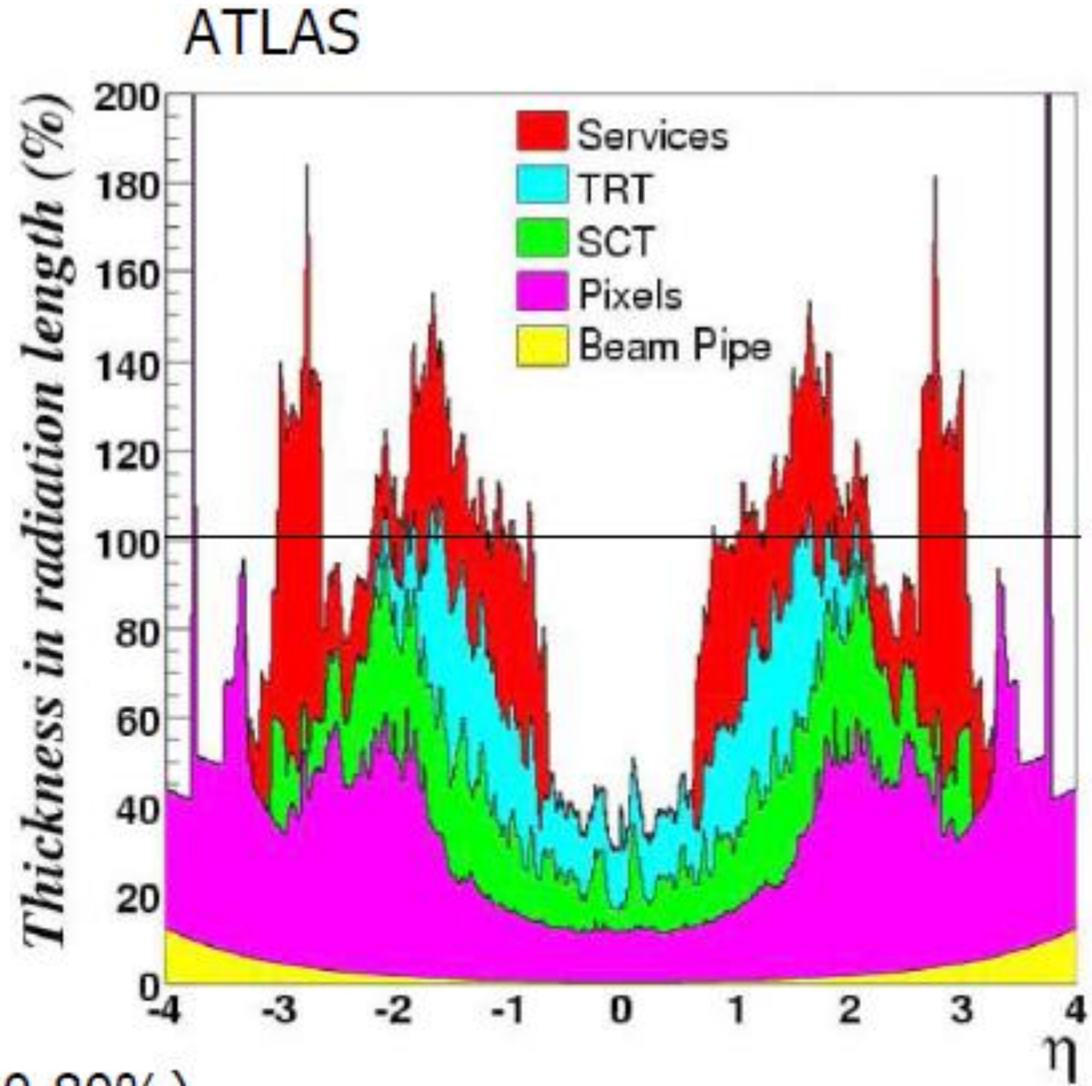
Photon = (isolated) energy deposited in ECAL only (not leakage in HCAL), no track

Electrons = (isolated) energy deposited in ECAL only + associated track (from Tracking detector)

Electrons/Photons at LHC (2)

➢ **Material in front of calorimeter:** cables, cooling, mechanical support, …
+ B-field (radiated energy spread in φ)





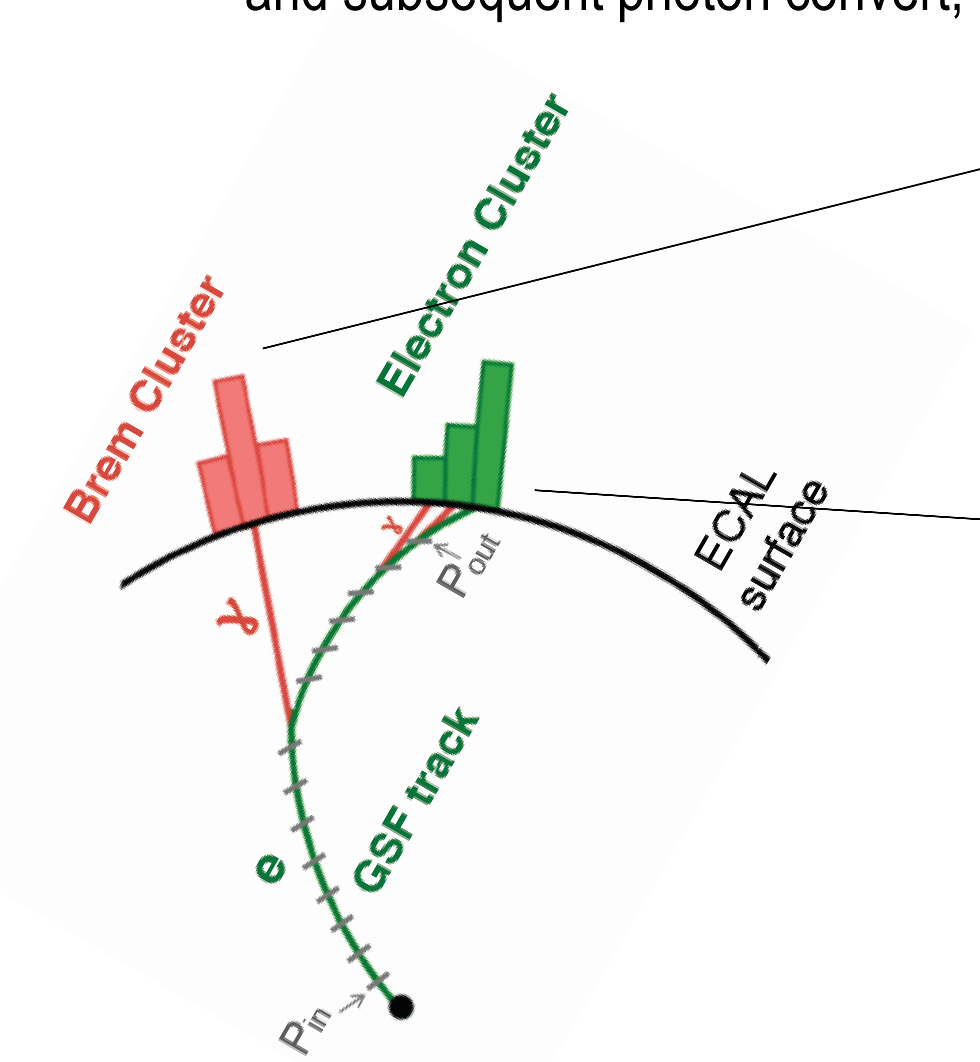
The electrons initiate showers (e.g. 40-80%)

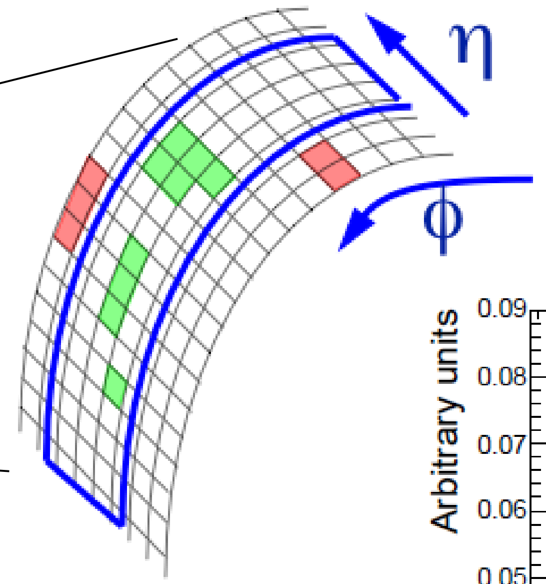
⇒ Identification and efficiency problems, charge mis-identification

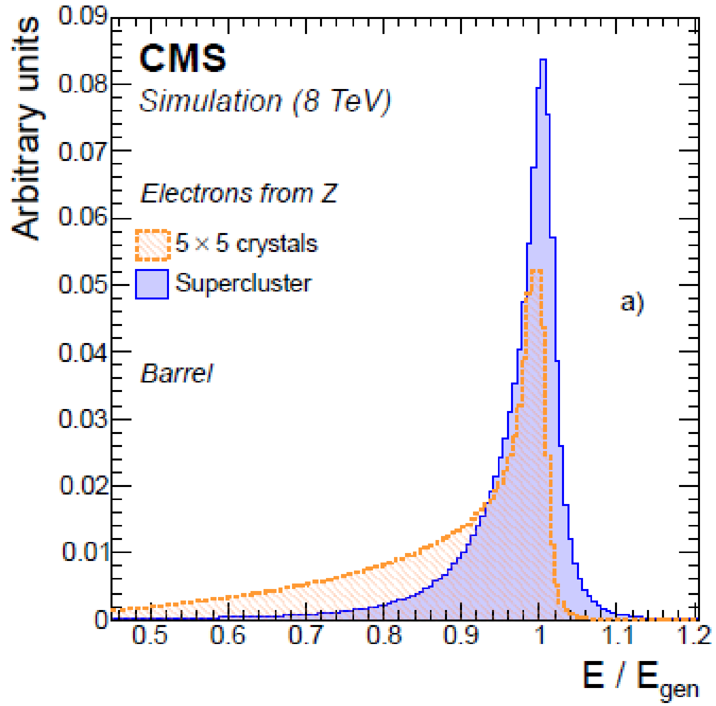
The photons convert (e.g. 20-40%) in e+e– pairs before reaching the ECAL

Electrons/Photons at LHC (3)

- Electrons (and photons) undergo **complicated pattern**:
  - electrons radiates brem photons, which may convert in e+e-, possibly also “breming”, and subsequent photon convert, … **BEFORE reaching the ECAL surface**

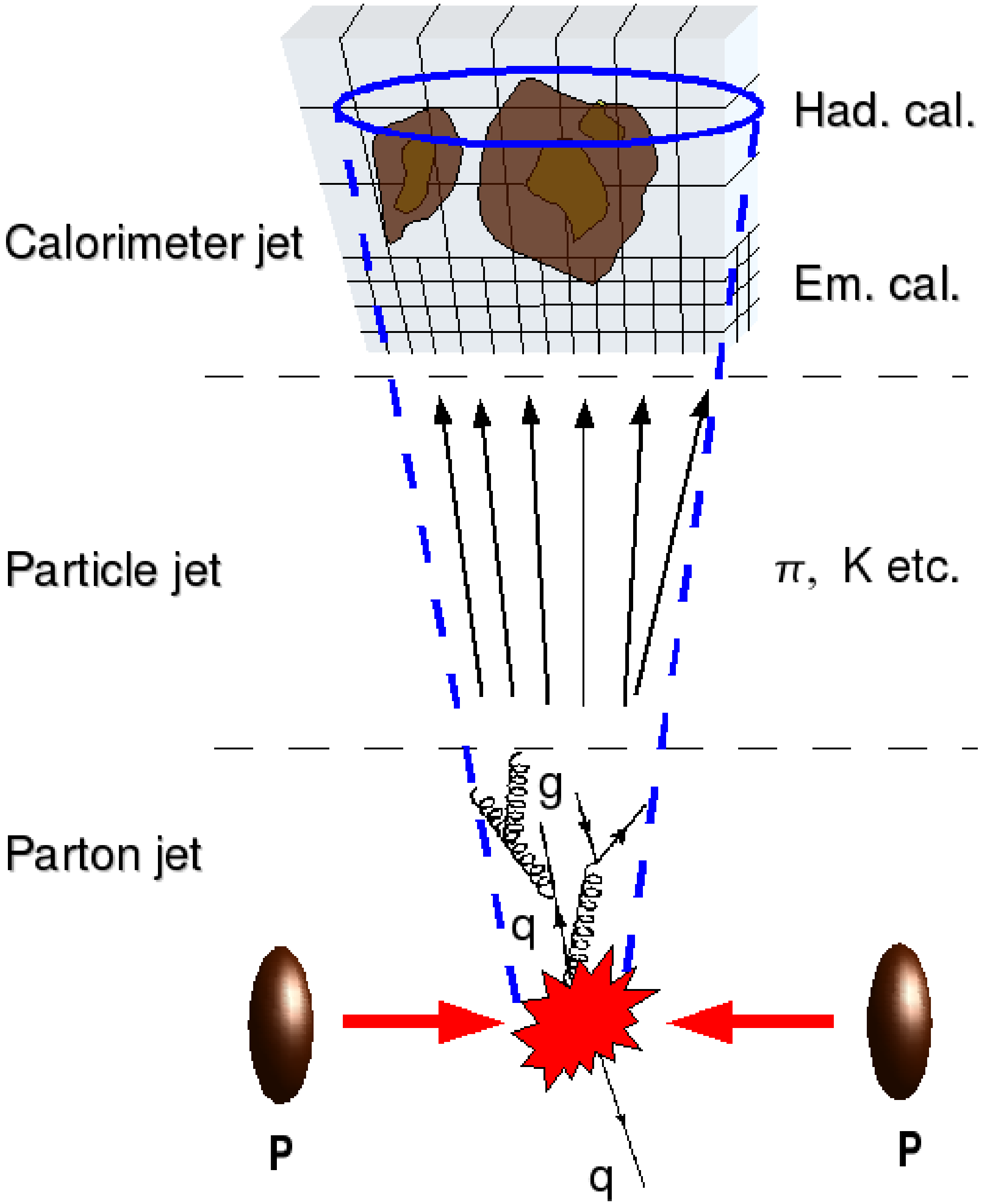






- Need to develop **complex reconstruction algorithm** to collect brem/conversion: super-clustering, extension of Kalman filter, …

From single hadrons to Jets

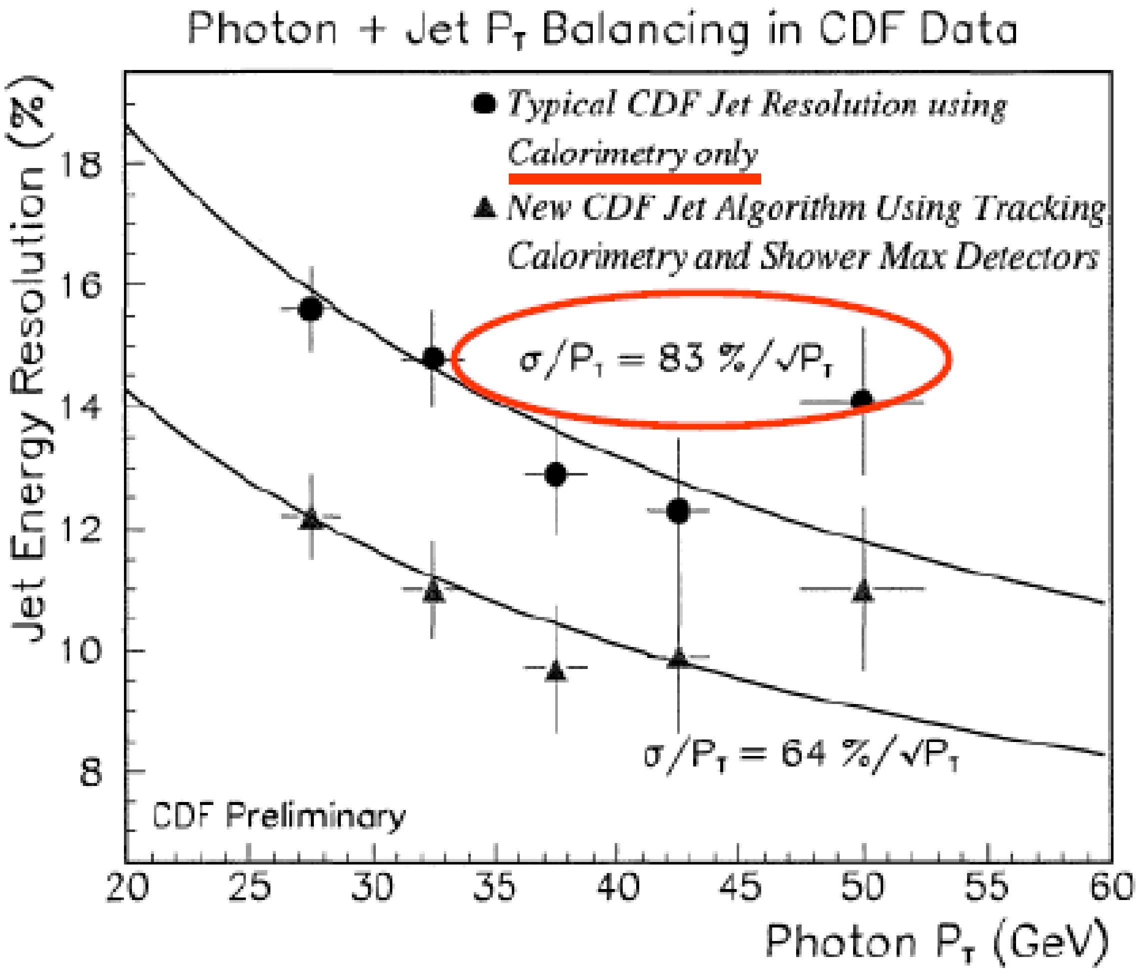


- At (hadrons) colliders, quarks & gluons produced a collection of particles via fragmentation.
- This **(collimated) sum of particles** (pions, kaons, p, n, electron/γ, ..) is **called a jet**.
- Reconstructed with "cone" algorithms
  - Various flavors…
- Jets are important signatures at LHC too (dijet resonance, VBF, …)

Jets vs single particle resolution

Jets at CDF @ TeVatron

	Central	Plug
EM thickness	$19\,X_0,\ 1\lambda$	$21\,X_0,\ 1\lambda$
sample(Pb)	$0.6\,X_0$	$0.8\,X_0$
sample(scint.)	5 mm	4.5 mm
wavelength sh.	sheet	fiber
resolution	$\frac{13.5\%}{\sqrt{E_T}} \oplus 2\%$	$\frac{14.5\%}{\sqrt{E}} \oplus 1\%$
HAD thickness	$4.5\,\lambda$	$7\,\lambda$
sample(Fe)	25-50 mm	50 mm
sample(scint.)	10 mm	6 mm
wavelength sh.	finger	fiber
resolution	$\frac{50\%}{\sqrt{E_T}} \oplus 3\%$	$\frac{70\%}{\sqrt{E}} \oplus 4\%$

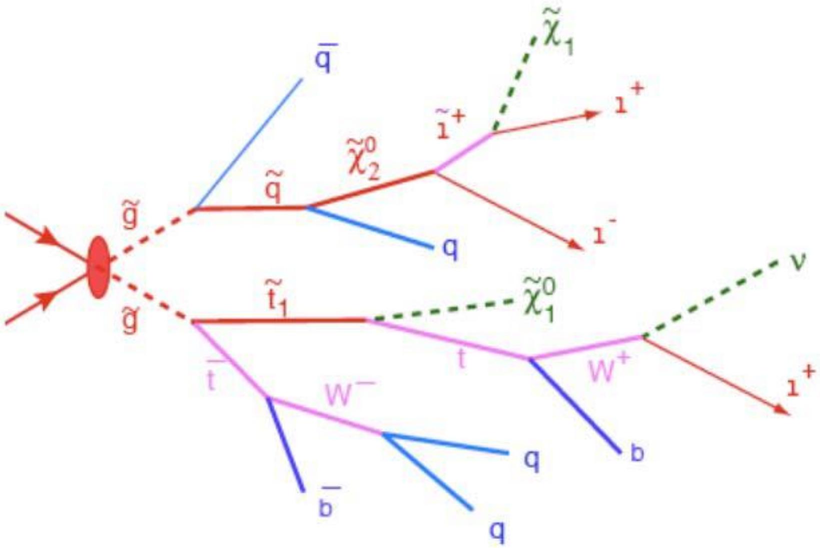


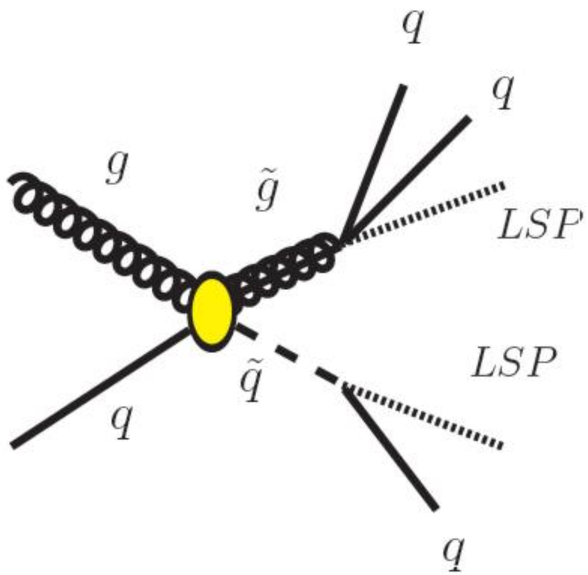
Jets performance in calorimeter worst than single hadron performance

Contribution from physics (parton shower/fragmentation, ISR/FSR, Underlying Event, …), detector (granularity, resolution, …) and clustering algorithm (out of "cone" energy losses) !

Measuring the invisible…

- Neutrinos produced in collisions escape detection: W→eν, Z→νν, …
- Many BSM processes involves “invisible” particles: Dark Matter, Neutralinos from SUSY, …





- Way to quantify these “invisible” particles, Missing Transverse Energy (MET):

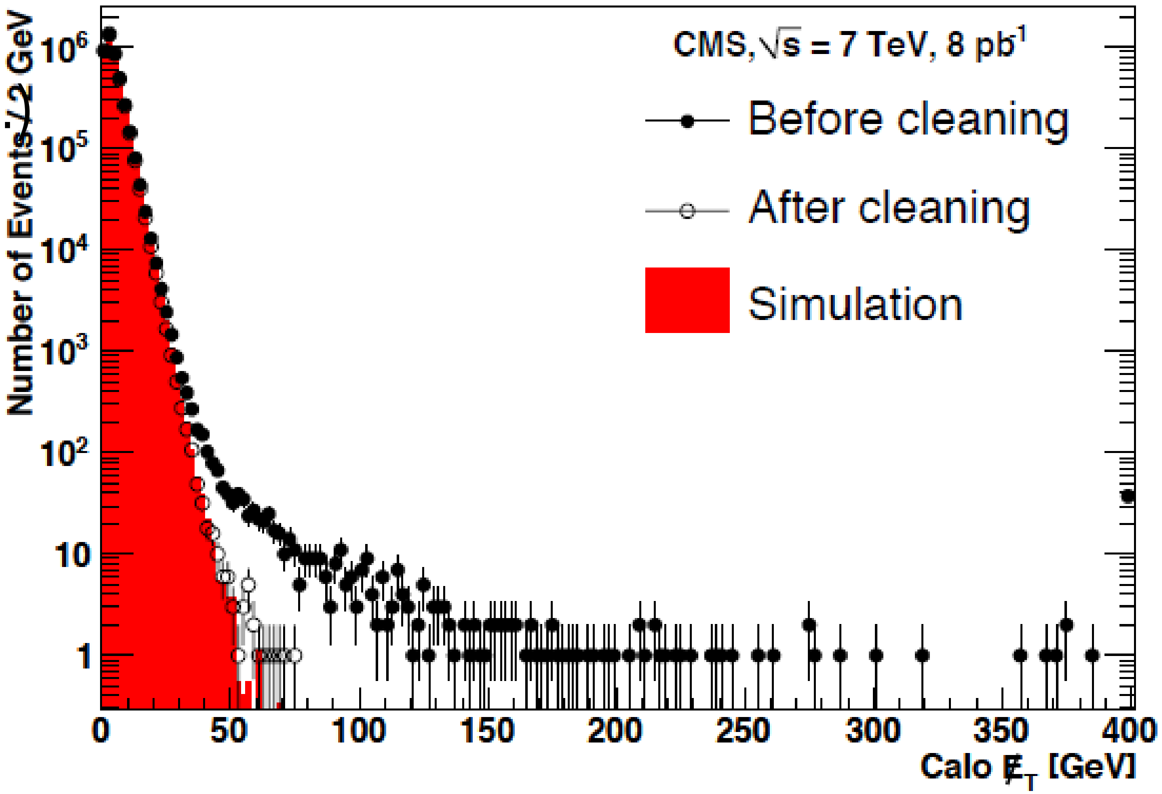
$$\vec{E}_T^{miss} = -\sum_i \vec{E}_T^{i}$$

final states particles transverse momenta
(or the way they are reconstructed in a given
device: calo cluster/tower, …)

Missing Transverse Energy (1)

- In practice, very difficult quantity to understand, calibrate, …

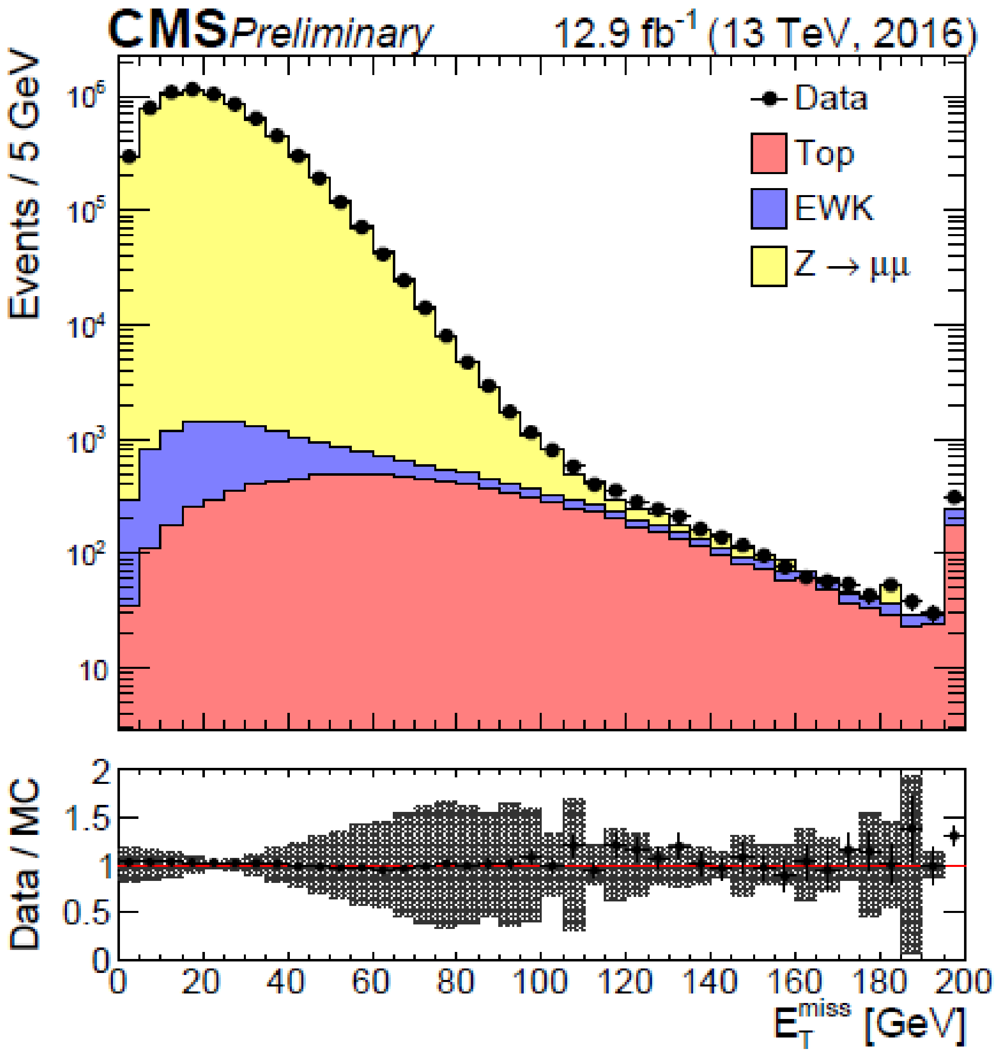
- **Affected by:**
  - Mis-reconstructed objects (e/g, jets, …)
  - Instrumental effects:
    - Noise
    - Dead of hot calorimeters cells
  - Cosmic ray brem,
  - beam halo,
  - Poorly instrumented area
  - Pile-up (PU),
  - ….



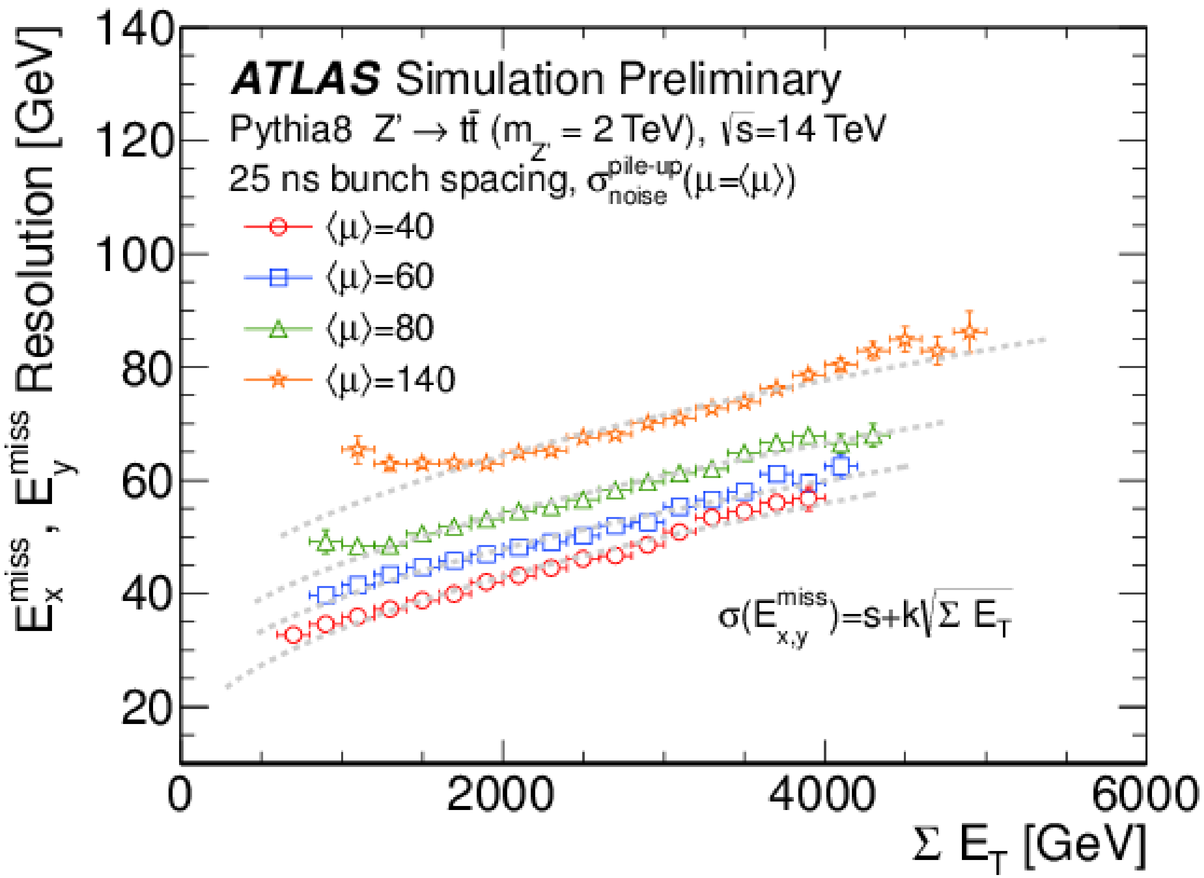
- Fake MET thus appears naturally from various sources.
  - **Need dedicated cleaning in order NOT to make fake discoveries**
    (e.g., BSM models tends to produced very high MET signals)

Missing Transverse Energy (2)

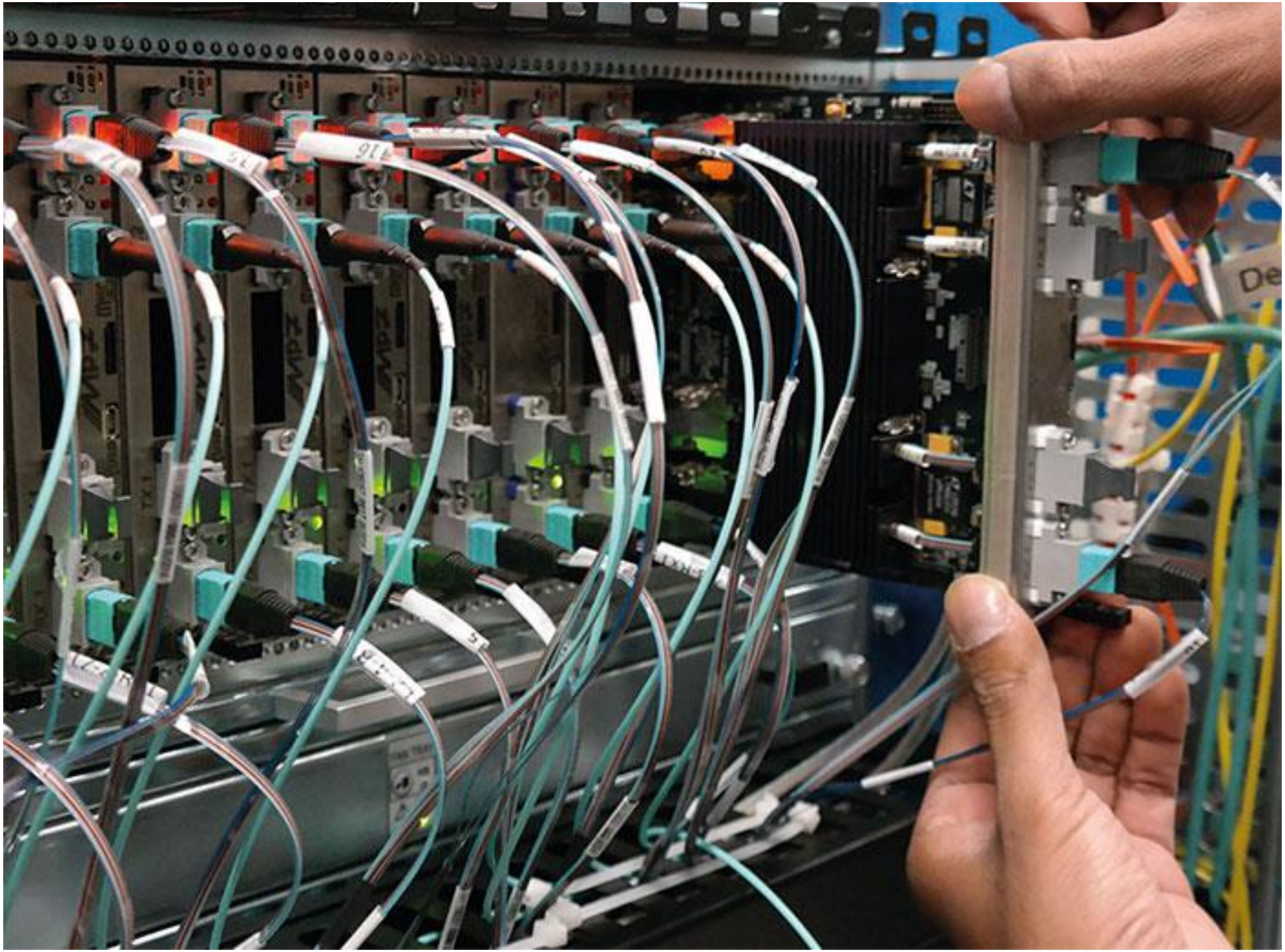
MET well understood



Effect of Pile-Up on MET resolution



Triggering



Why Trigger ?

- It's a question of:
  - rate of experiment,
  - physics processes to look at,
  - Storage & computing capacity
  - (<=> cost)

In general:

- **CANNOT** record all data
- and… **DON'T WANT** to record all data
  ("new physics" buried under tons of "old" physics)

- Need an **online** filtering.

data not recorded is lost **forever**!

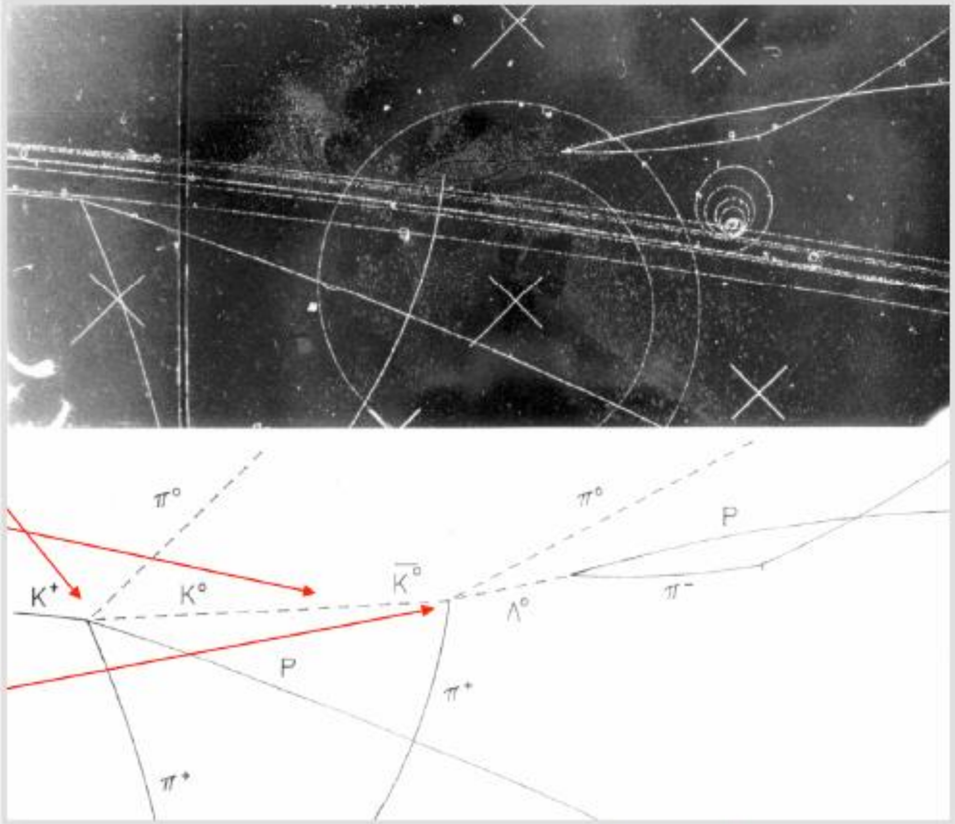
In the following, mainly focus on LHC experiments where challenges are by far the more important.

Early Accelerator Expts: Bubble Chambers

[page from: Babukhadia *et al.* "Triggering in Particle Physics Experiments", IEEE Nuclear Science Sypmosium, 10 Nov 2002]

Bubble Chambers, Cloud Chambers, etc

- DAQ was a stereo photograph
- Effectively no Trigger:
  - Each expansion was photographed (based on accelerator cycle)
  - High-level trigger was human (scanning teams)
- Slow repetition rate (observe only most common processes)
- Later some triggering attempts with higher repetition rate (> 40 Hz)



K^0 mixing event, Graham Thompson, 1971
(careful, this is fixed target – example for photograph only!)

Emulsions still used in some experiments (*e.g.* CHORUS, DONUT)

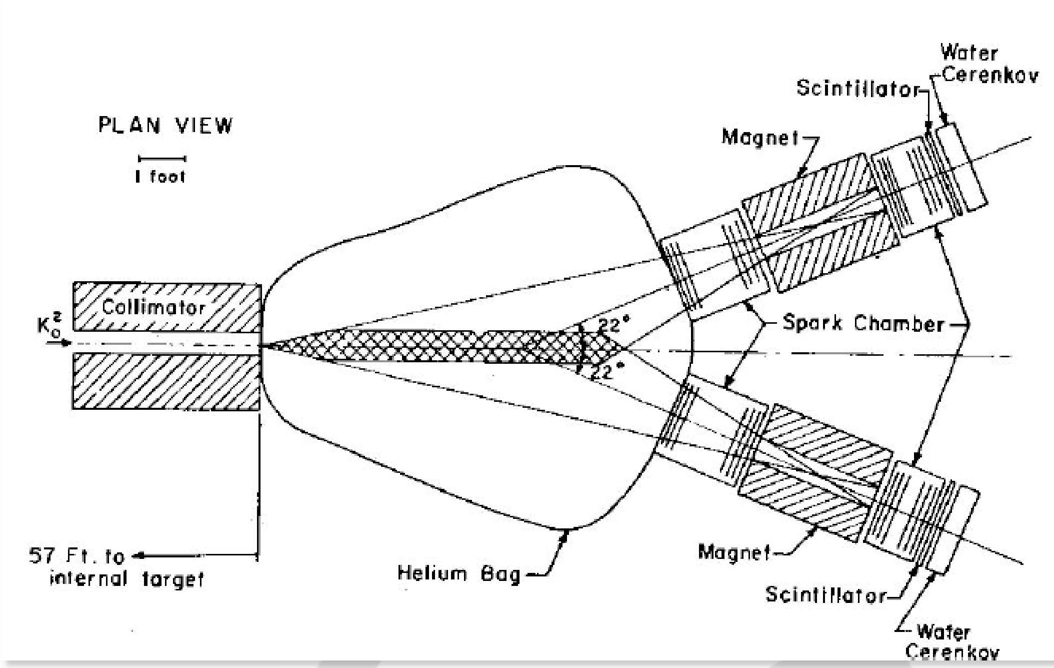
- Events selected with electronically readout detectors → scanning of emulsion seeded by external tracks

Early Fixed Target Trigger

[page from: Babukhadia *et al.* "Triggering in Particle Physics Experiments", IEEE Nuclear Science Sypmosium, 10 Nov 2002]

Cronin-Fitch *et al.* experiment 1964 – discovery of *CP* violation

- K_L mesons produced from protons bombarding Be target
- Two arm spectrometer with Spark Chambers, Chernkov counters and Trigger scintillators
- Spark chambers require fast (~20ns) HV pulse to develop spark, followed by triggering camera to photograph tracks
- Trigger on coincidence of Scintillators and Water Cherenkov counters
- Only one trigger level
- Dead-time incurred while film advances

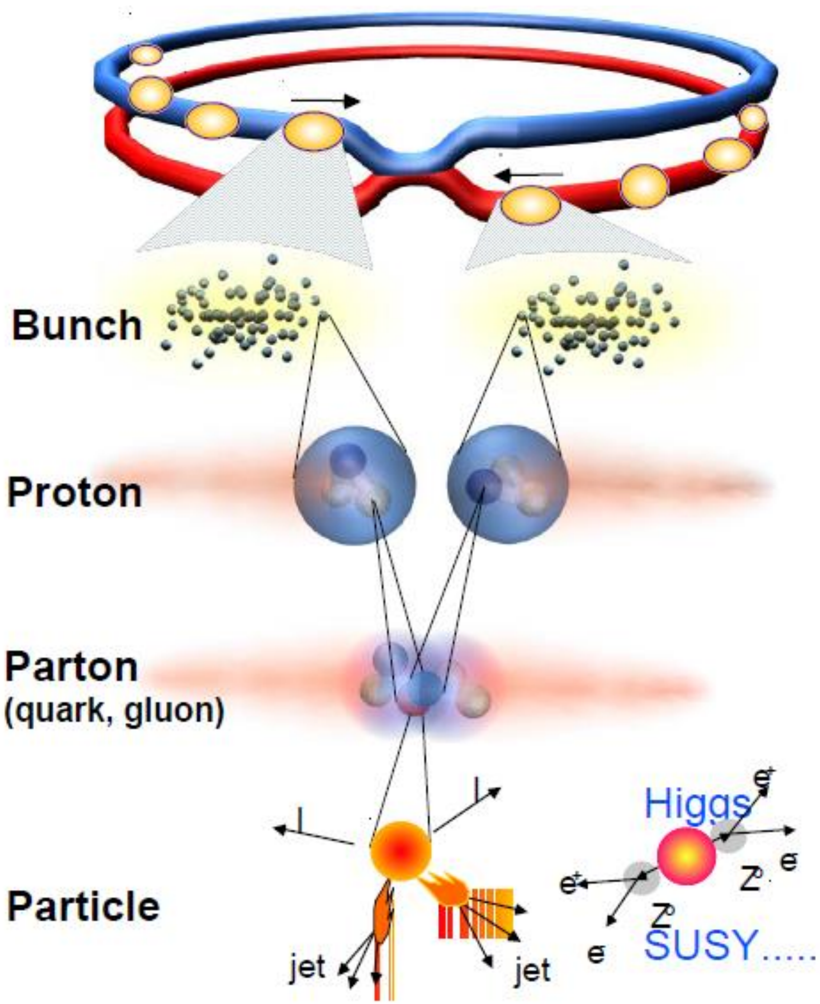


Jim Cronin

Val Fitch

Measurement of opening angle of pion tracks and their invariant mass to spot $K_L \rightarrow \pi\pi$ decay

Collisions at the LHC



Proton - Proton	2804 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	$10^{34} cm^{-2} s^{-1}$
Crossing rate	40 MHz

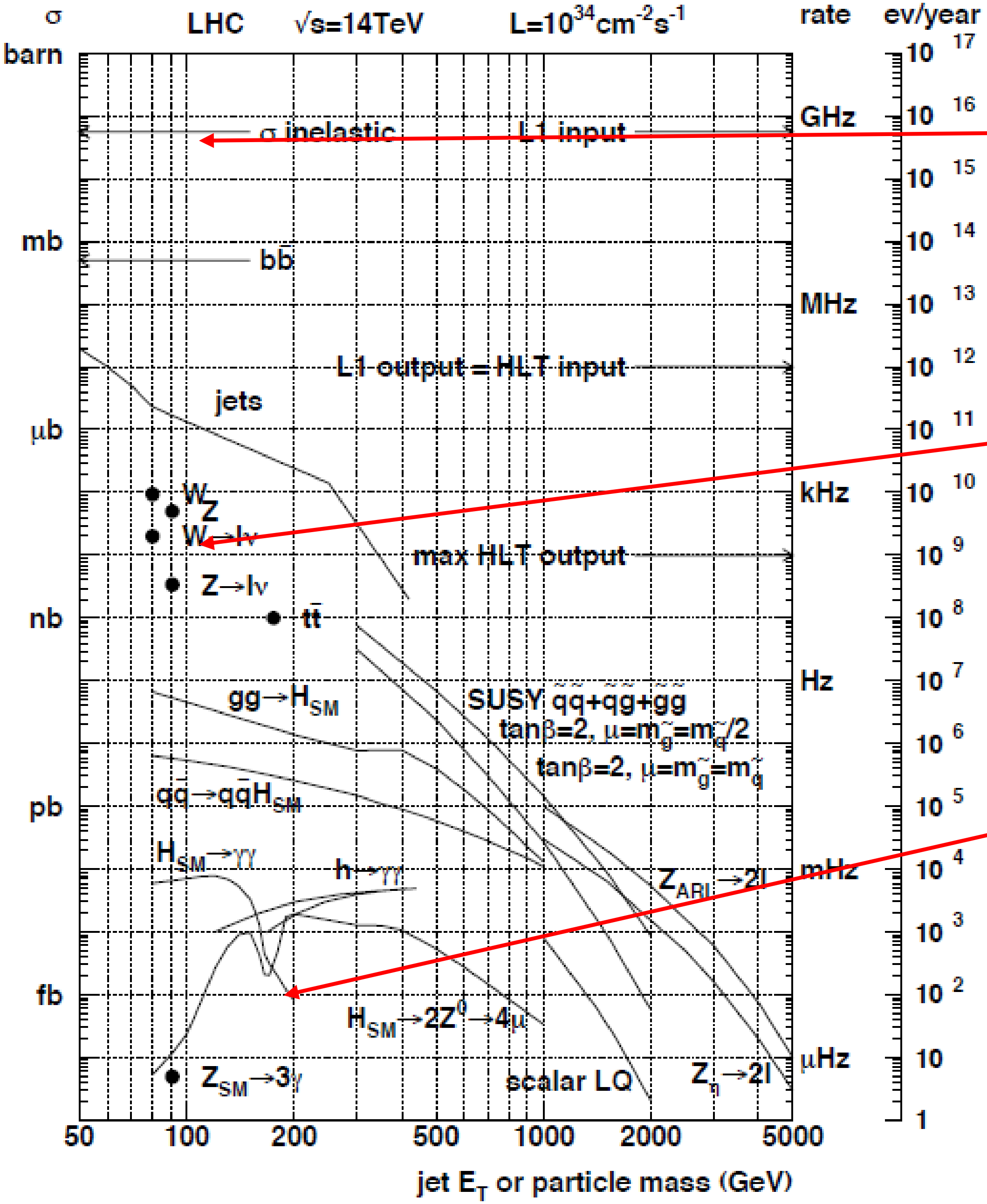
Collisions every 25ns !

Collision rate ≈ 10^7-10^9

For comparison:

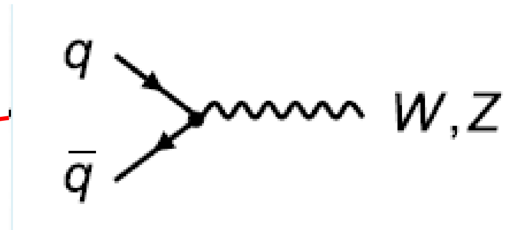
	√s	Peak L	Bunch Crossing period
LEP (e+e-)	~90-200 GeV	$10^{32} cm^{-2} s^{-1}$	22 μs
Tevatron (p-pbar)	1.96 TeV	$3.5 \times 10^{32} cm^{-2} s^{-1}$	392 ns
FC-hh (pp)	100 TeV	$5\text{-}29 \times 10^{34} cm^{-2} s^{-1}$	5-25 ns

LHC: the rate/selectivity problem

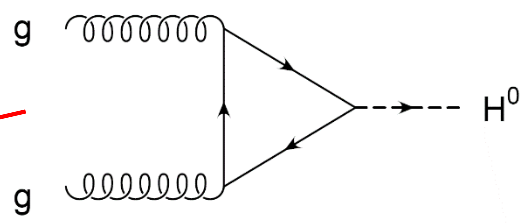


inelastic

$\sigma(\surd=14\ \text{TeV}) \sim 10^{11}$ pb



$\sigma(\surd=14\ \text{TeV}) \sim 2000\text{-}15000$ pb



$\sigma(\surd=14\ \text{TeV}) \sim 50$ pb

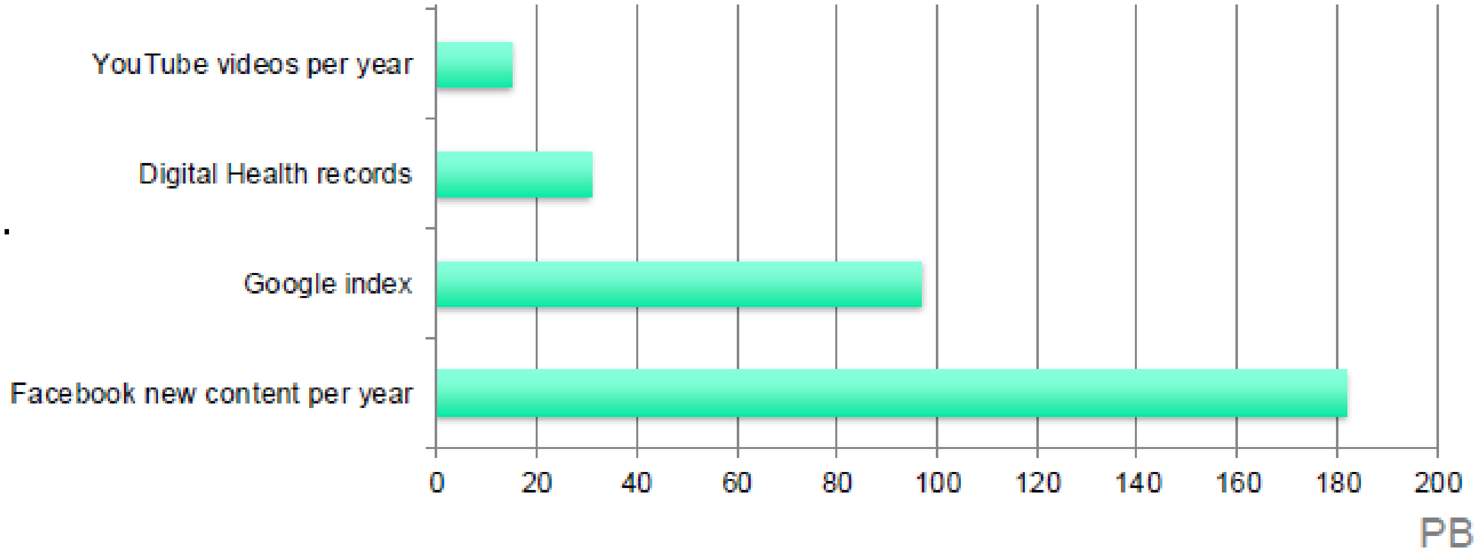
Need a **inhuman rejection factor** of more than 10 orders of magnitude !!!

LHC: the data storage problem

	Bunch Crossing Rate	Event size	Trigger Rate Output	Data rate without trigger (PB/year*)	Data rate with trigger (PB/year*)
LEP	45 kHz	~ 100 kB	~ 5 Hz	O(100)	O(0.01)
Tevatron	2.5 MHz	~ 250 kB	~ 50-100 Hz	O(10 000)	O(0.1)
HERA	10 MHz	~ 100 kB	~ 5 Hz	O(10000)	O(0.01)
LHC	40 MHz	~ 1 MB	~ 100-200 Hz	O(100 000)	O(1)

* Assume 50% accelerator duty cycle

To be compared to…



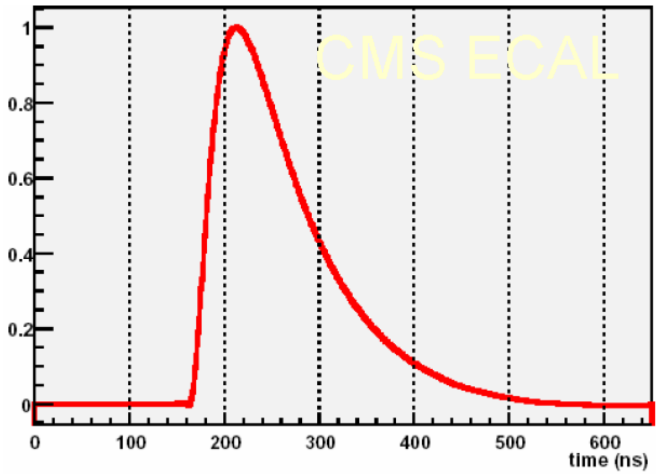
+ problem to have the CPU capacity to process them…

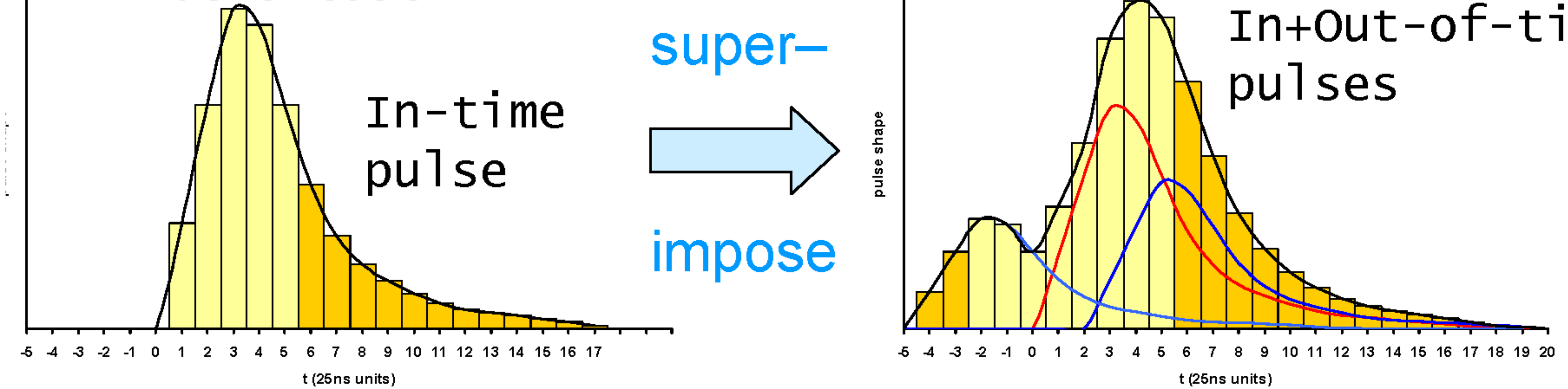
LHC: the Pile-Up problem !

- At LHC, each bunch crossing contains on average 25-50 additional interactions (“pile-up”)

- **“In-time” pile-up: particles from the same crossing but from a different pp interaction**

- **Long detector response/pulse shapes:**
  - **“Out-of-time” pile-up: left-over signals from interactions in previous crossings**
  - **Need “bunch-crossing identification”**





What is required for a good trigger system ?

- **Detectors must have fast response**
  - Take fast decision (new data every 25 ns!)
  - Minimize out-of-time PU effect
    - **Challenges for the electronics !**

- **Detectors must have high granularity**
  - To improve separation of particles
    - high number of electronic channels !

- **Architecture must be flexible**

Data taking conditions are changing often during a year…

- **Various detectors have to be synchronized !**

- In general, **only calorimeter and muon system** enters in the first steps of the trigger decision

Multi-Stage Trigger

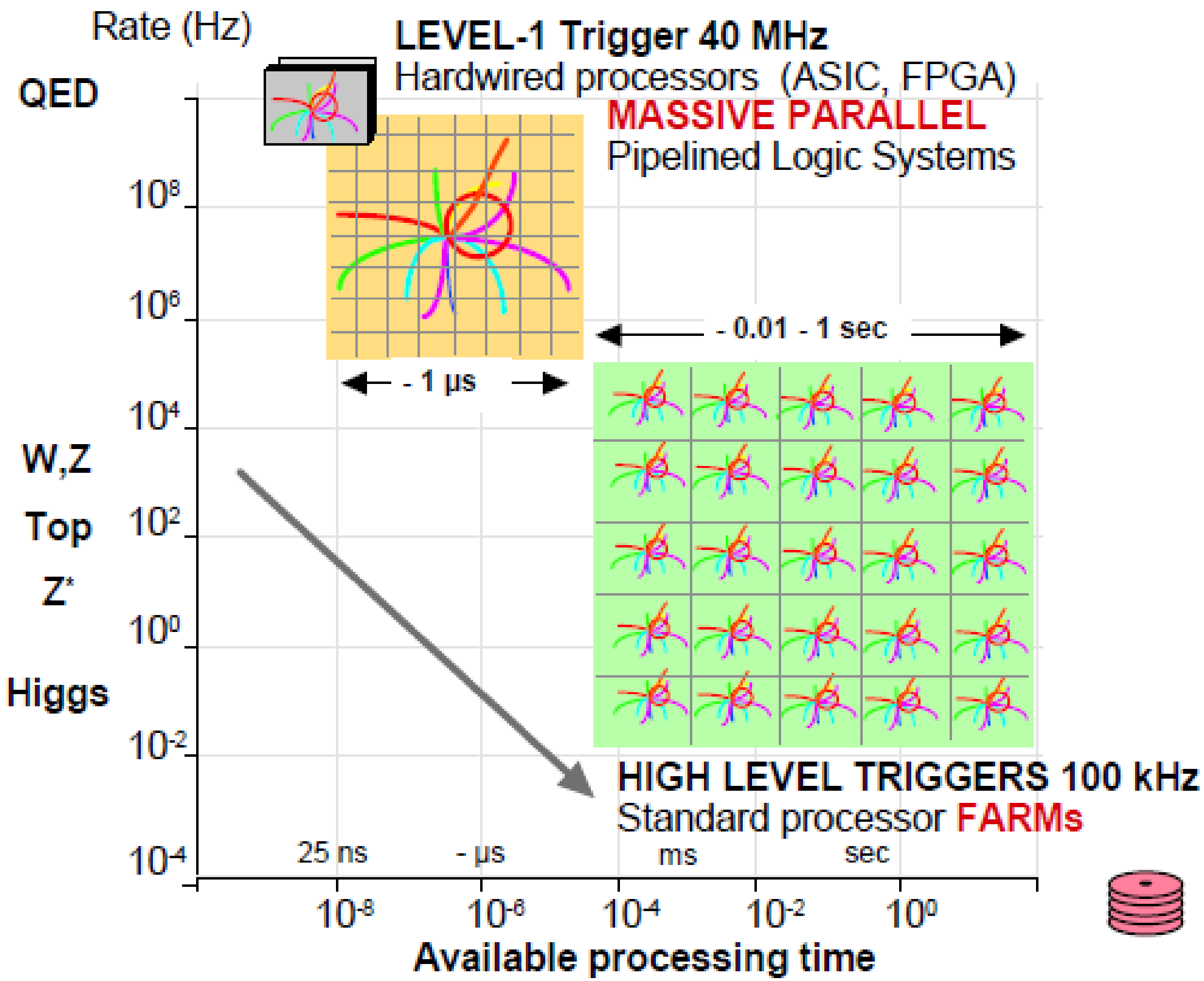
Conflict between:

"fast decision" / short latency

and

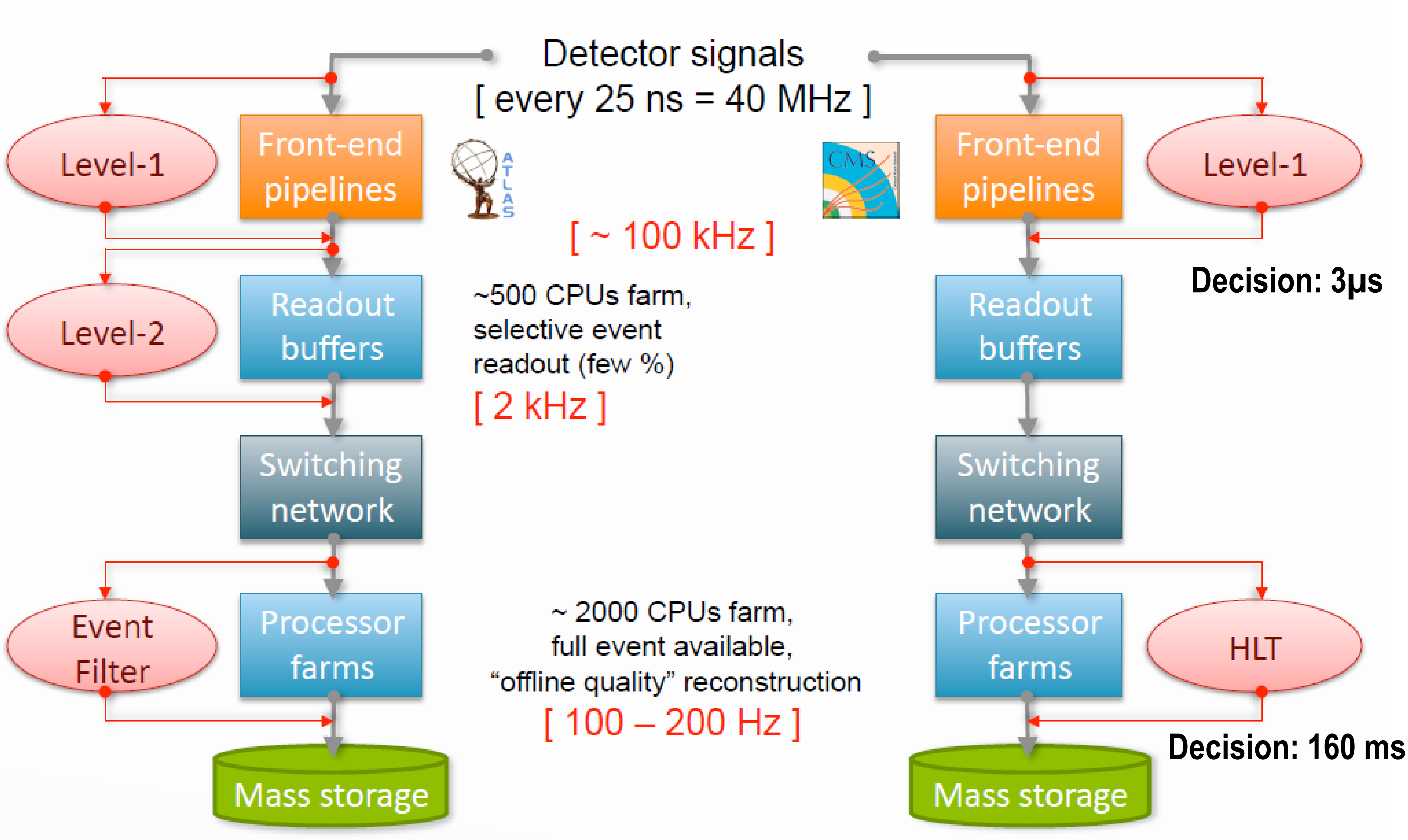
"high signal efficiency / high rejection of background"

Necessity to introduce a multi-stage trigger



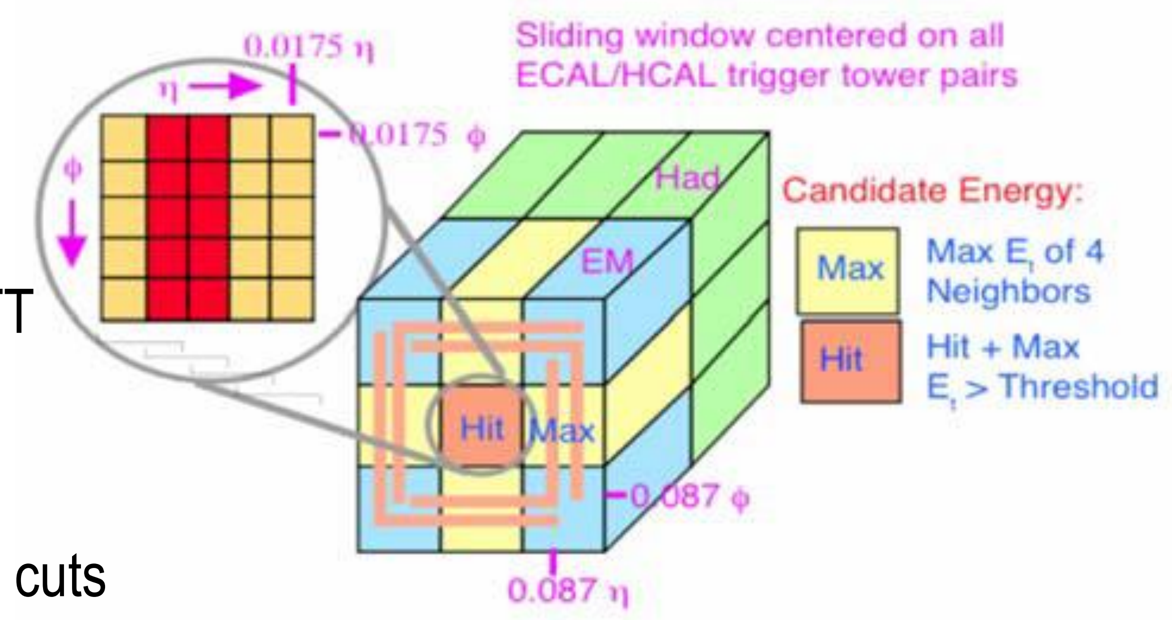
ATLAS & CMS Concepts

- **Level 1:** reduced granularity, reduced resolution, simplified algorithms.
- **High Level Trigger:** CPU's farms. As close as possible as offline.

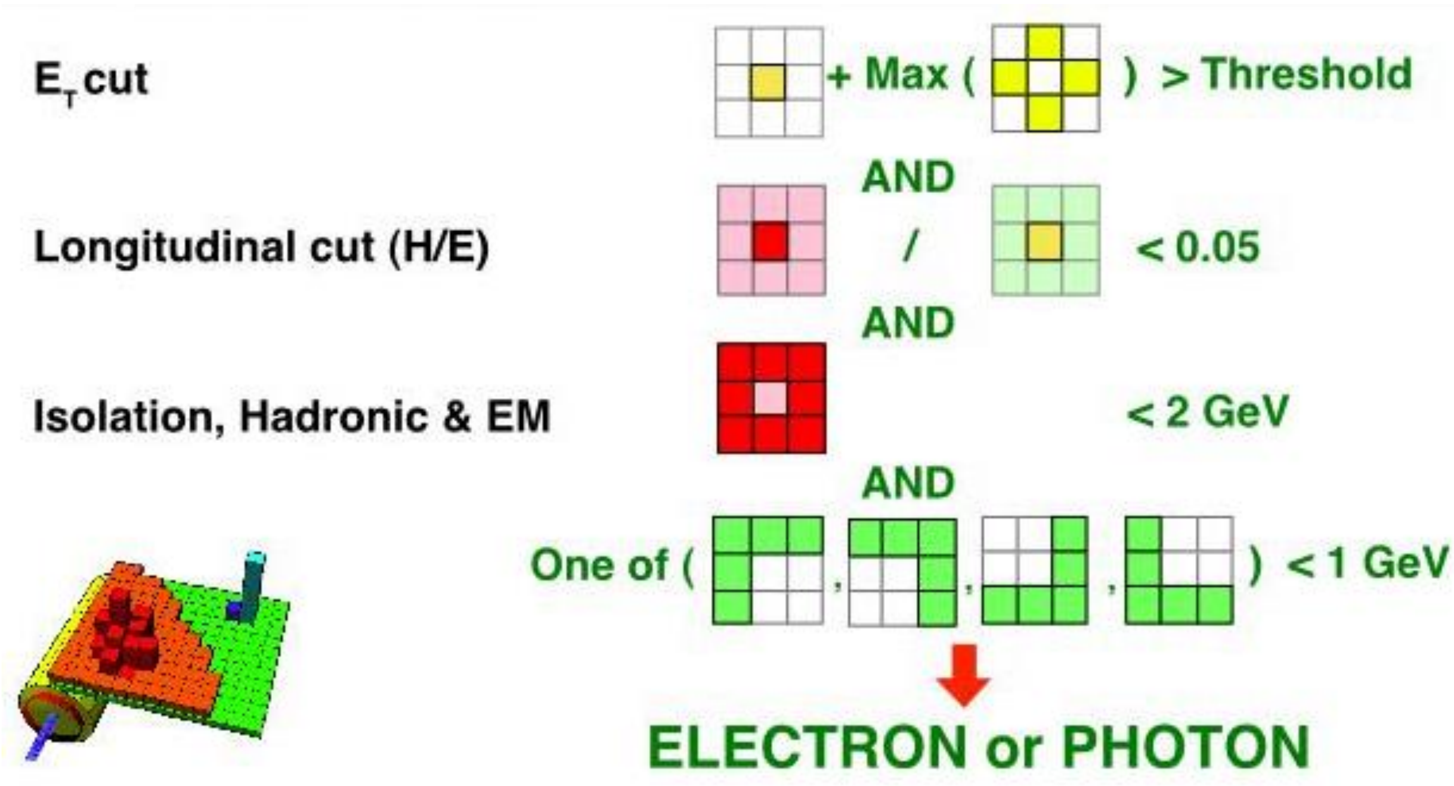


Level 1 Calorimeter Objects & Algorithms (CMS Run I example)

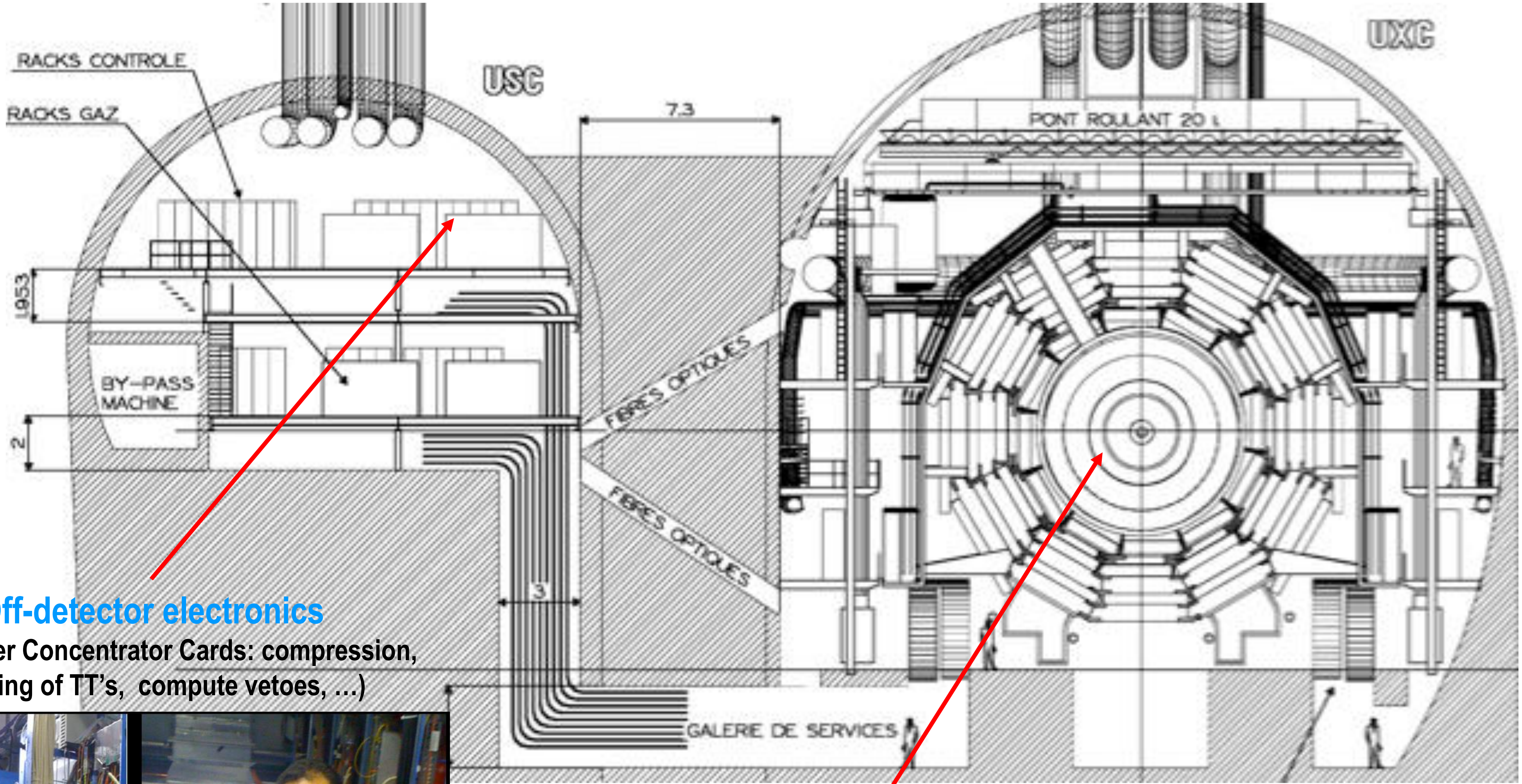
- Trigger Tower: 5x5 array of ECAL crystal
- Electron/Photon Candidates: 2 adjacent TT



+ additional cuts

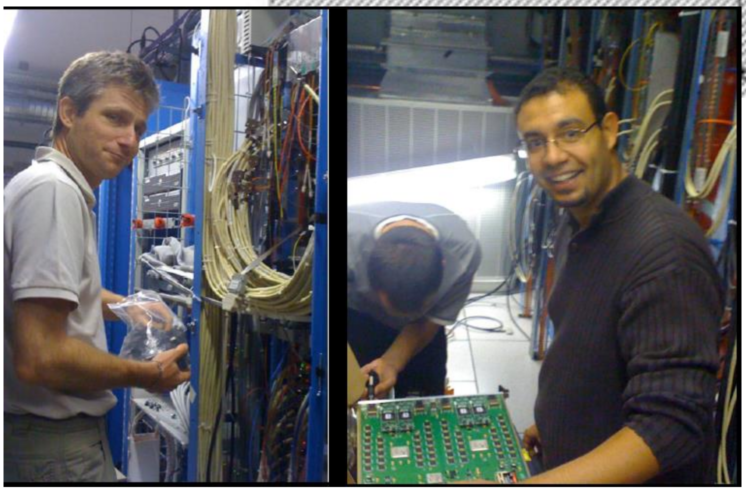


L1 Triggers: where in the detector ?

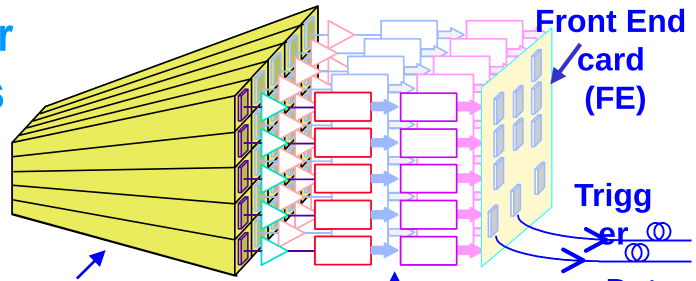


Off-detector electronics

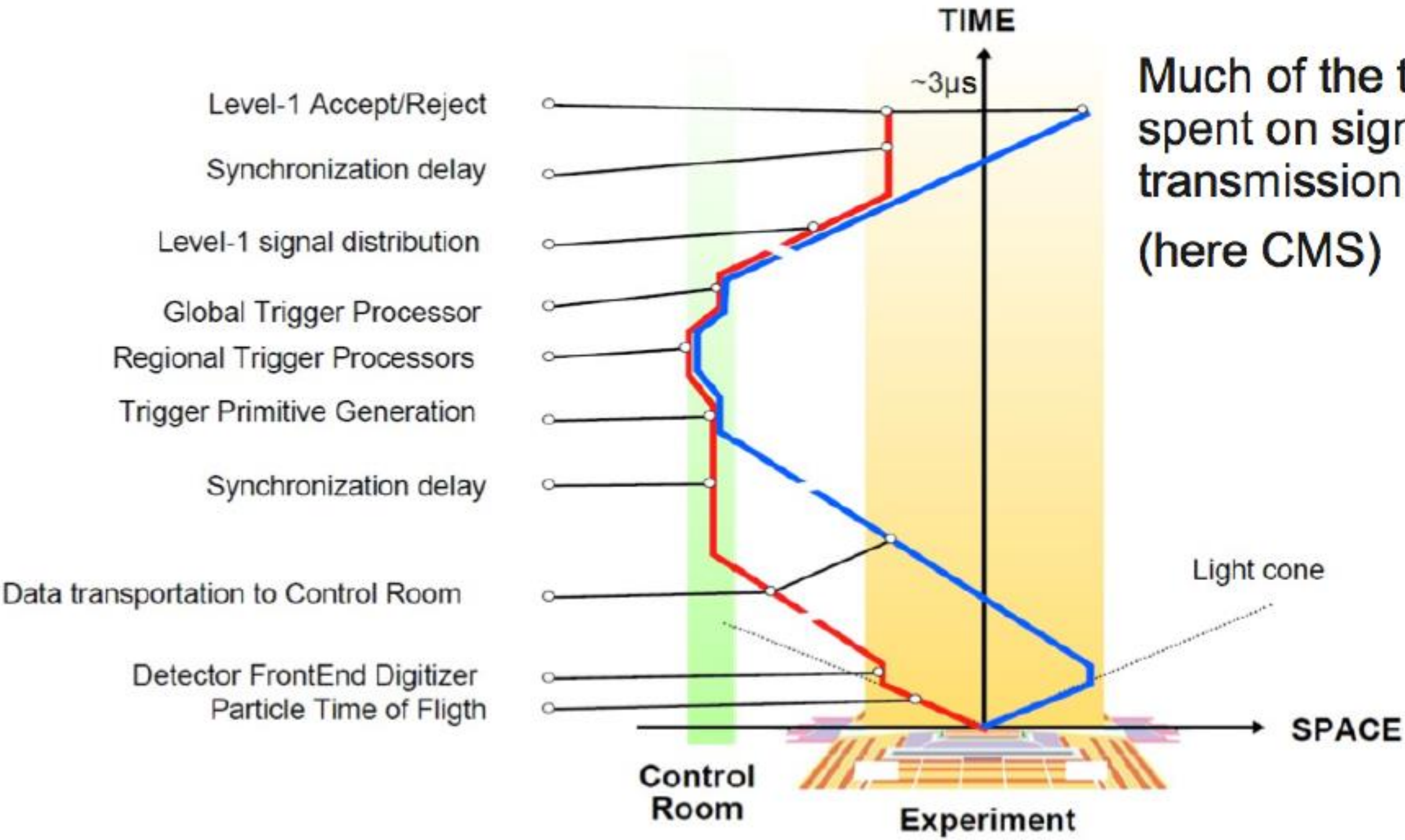
(ex: Trigger Concentrator Cards: compression, ordering of TT's, compute vetoes, ...)



On-detector electronics



Level 1 Latency



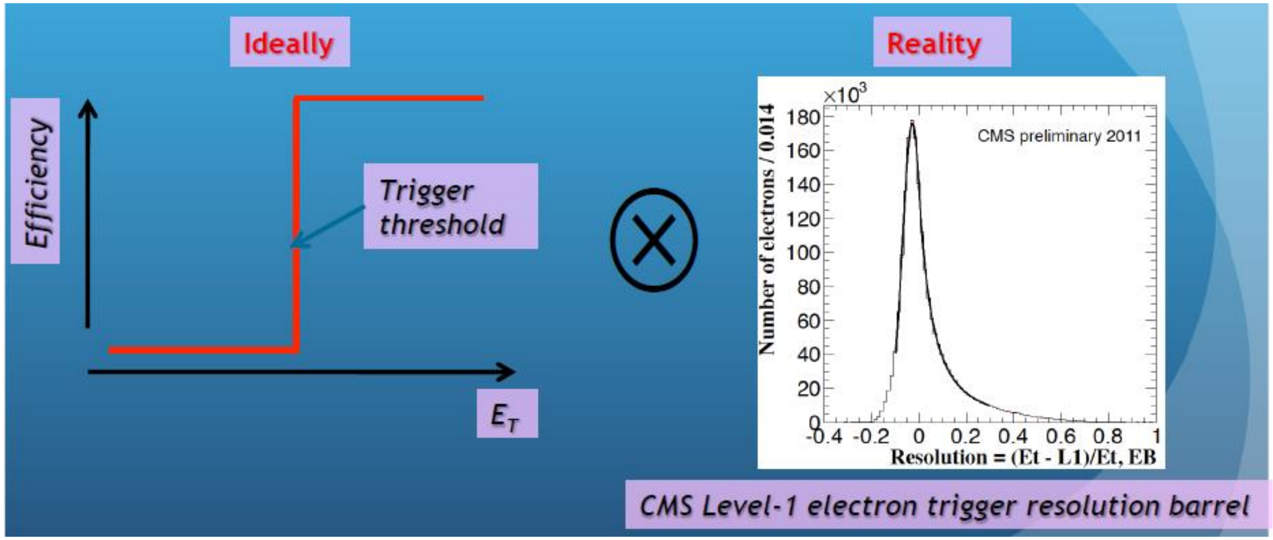
Much of the time spent on signal transmission

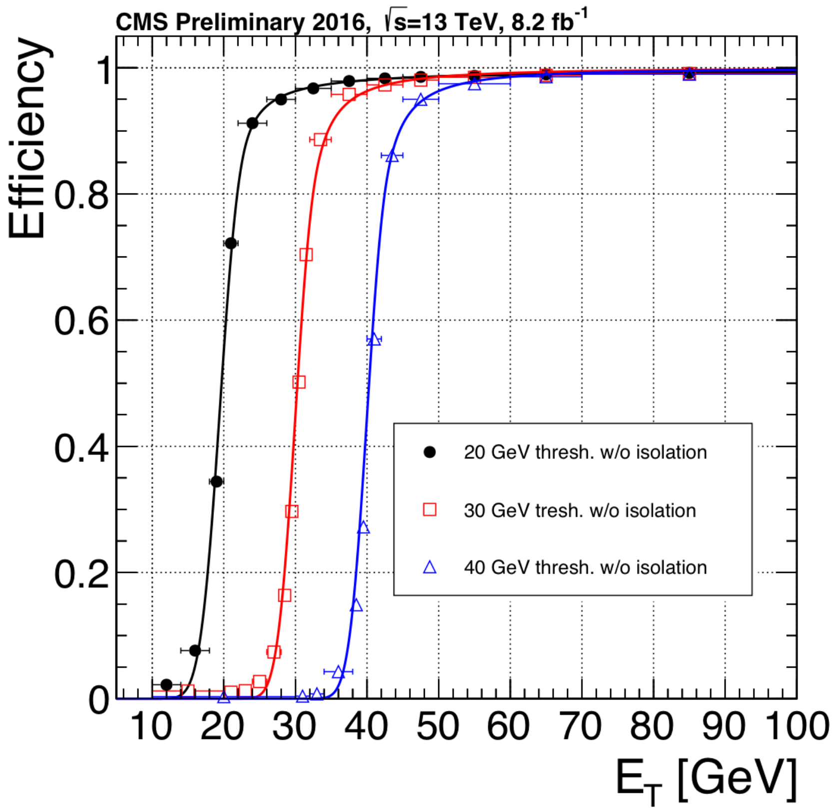
(here CMS)

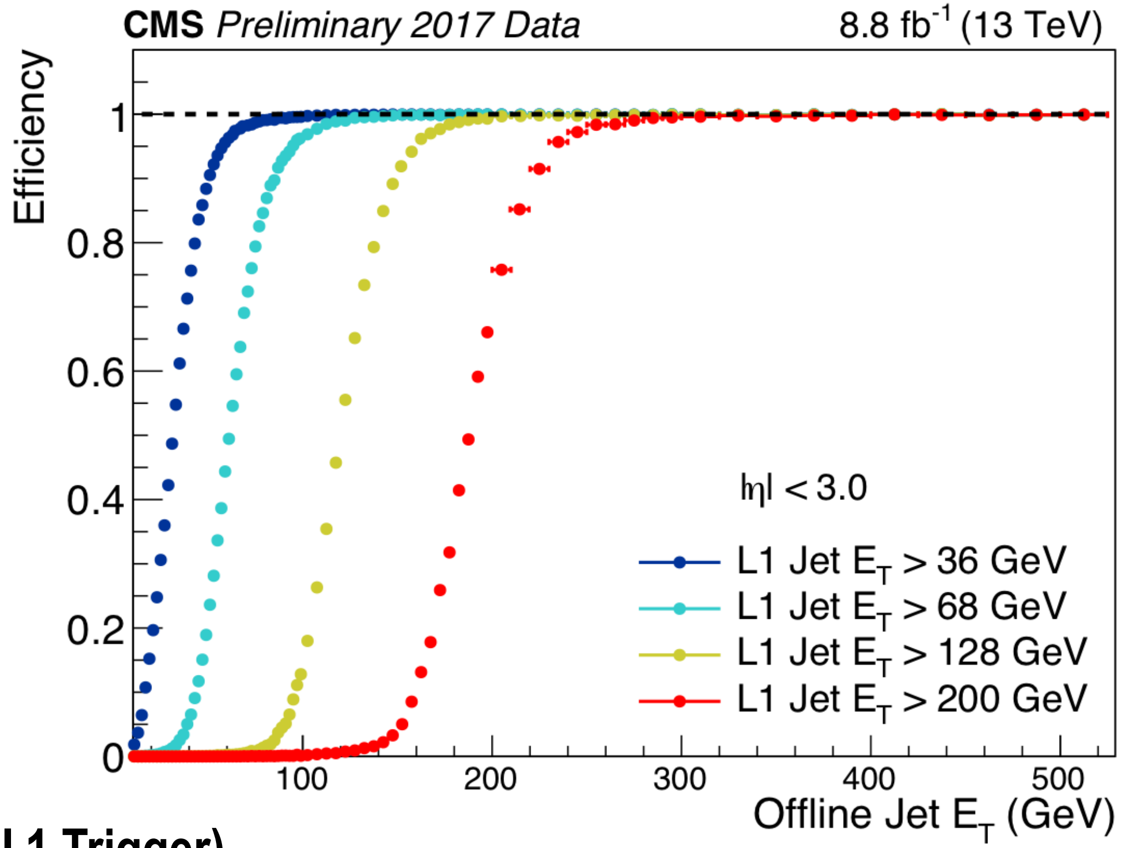
- Readout+processing: ~1μs
- Signal Collection & distribution: ~2μs

(stolen from A. David: “LHC Physics 2013”)

Performance of Calorimeter Triggers with real data





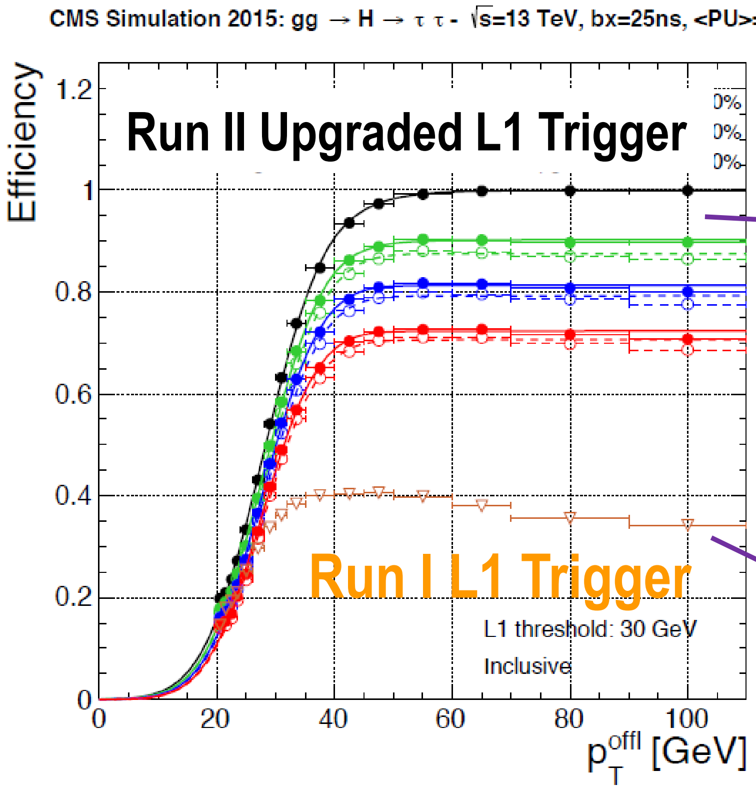


(Level 1 Trigger)

Impact of Calorimeter Trigger

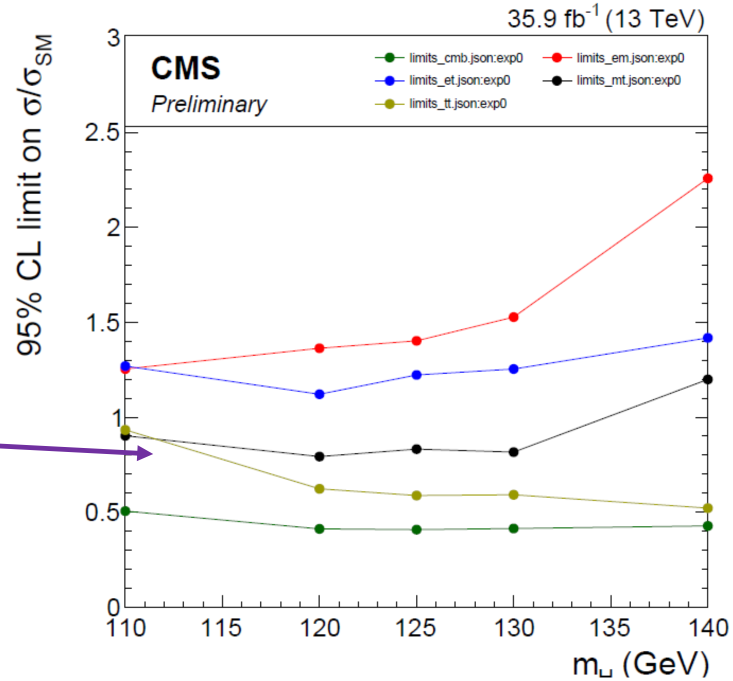
Calorimeter Trigger is essential for discovery !!!

Efficiency of Tau Trigger

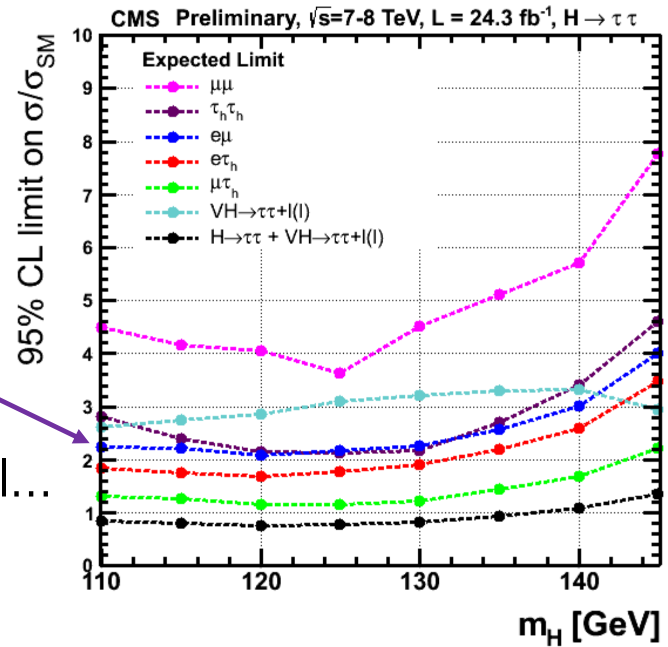


RunII: $H \rightarrow \tau_h \tau_h$ most sensitive channel !

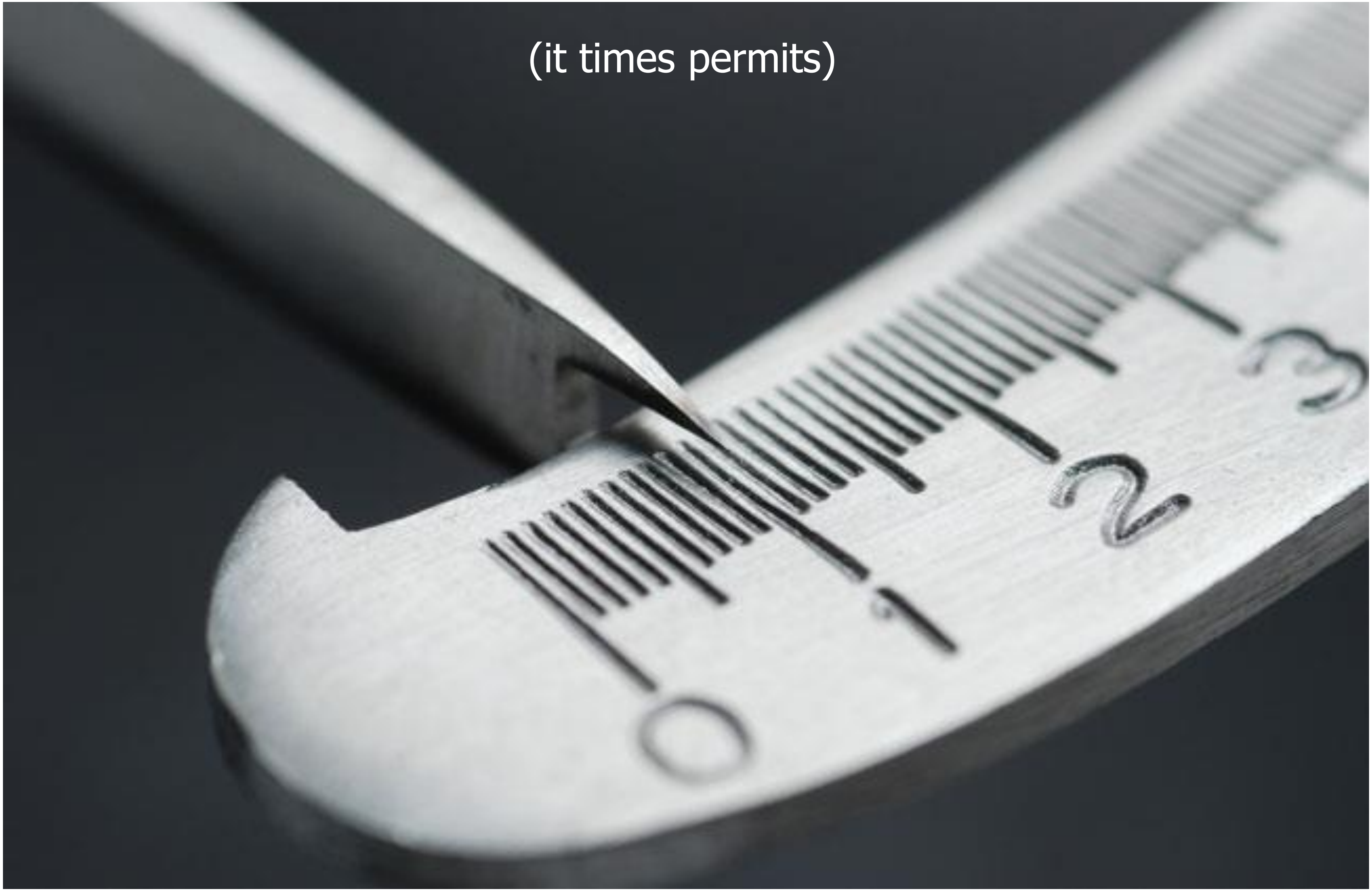
Observation of $H \rightarrow \tau\tau$!



Run I: $H \rightarrow \tau_h \tau_h$ 3rd most sensitive channel…



Calibration



Reconstructing Energy With ECAL

Laser Monitoring

Intercalibration

Global Scale

Cluster Corrections

Energy reconstruction for photons and electrons

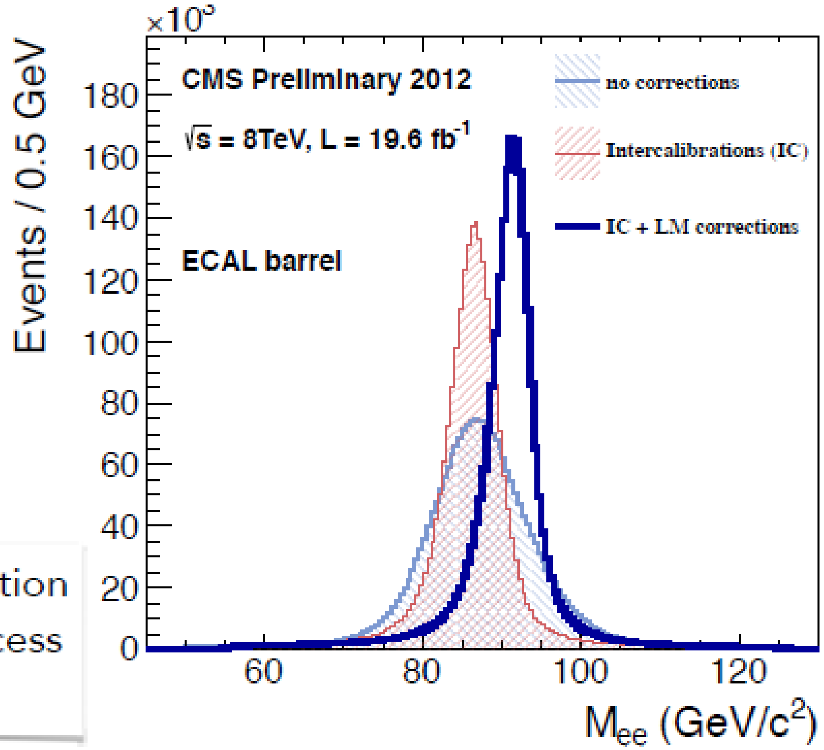
$$E_{e,\gamma} = \sum_i [S_i(t) \times c_i \times A_i] \times G(\eta) \times F_{e,\gamma}$$

Pulse Amplitude

CMS ECAL Energy Resolution

- **Uniformity and stability resolution** (intercalibration and monitoring) required < 0.5%
- For barrel photons, **1% energy inclusive resolution achieved in 2012** for unconverted/ late-converting photons (from H→γγ)

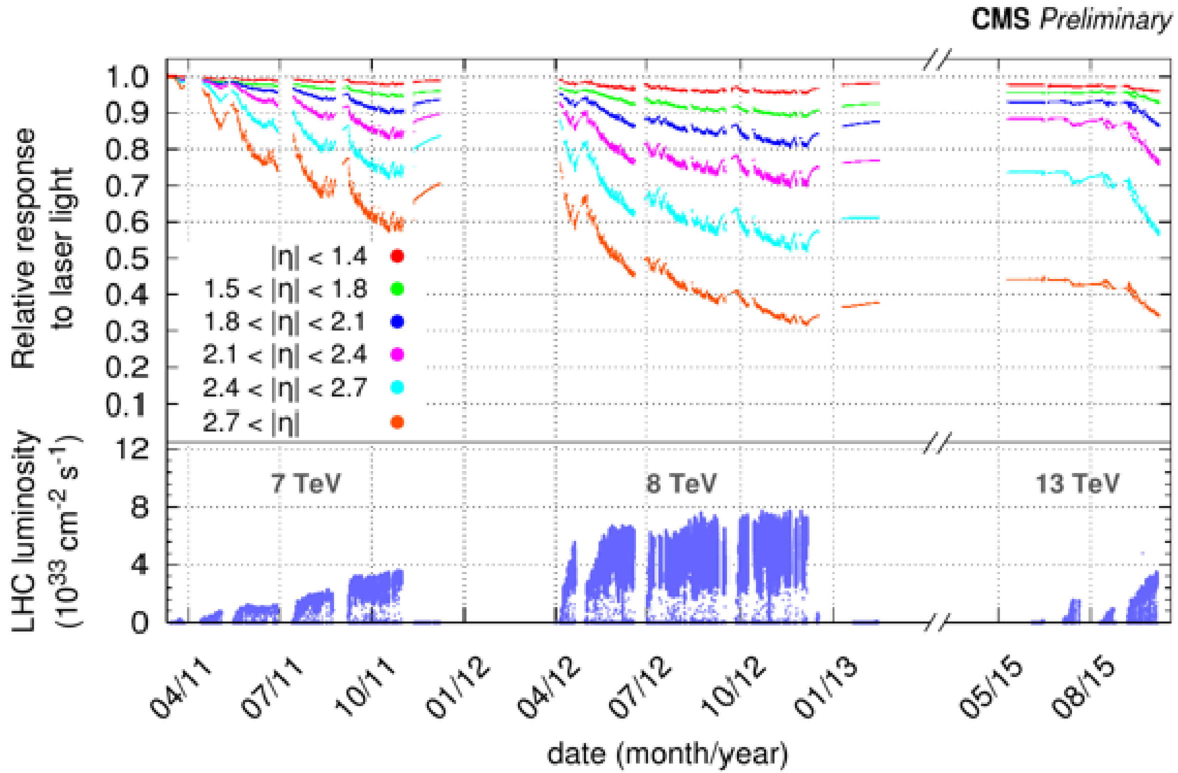
Effect of laser monitoring (LM) and intercalibration (IC) corrections on the width of the Z→ee process with 2012 data and calibration procedure



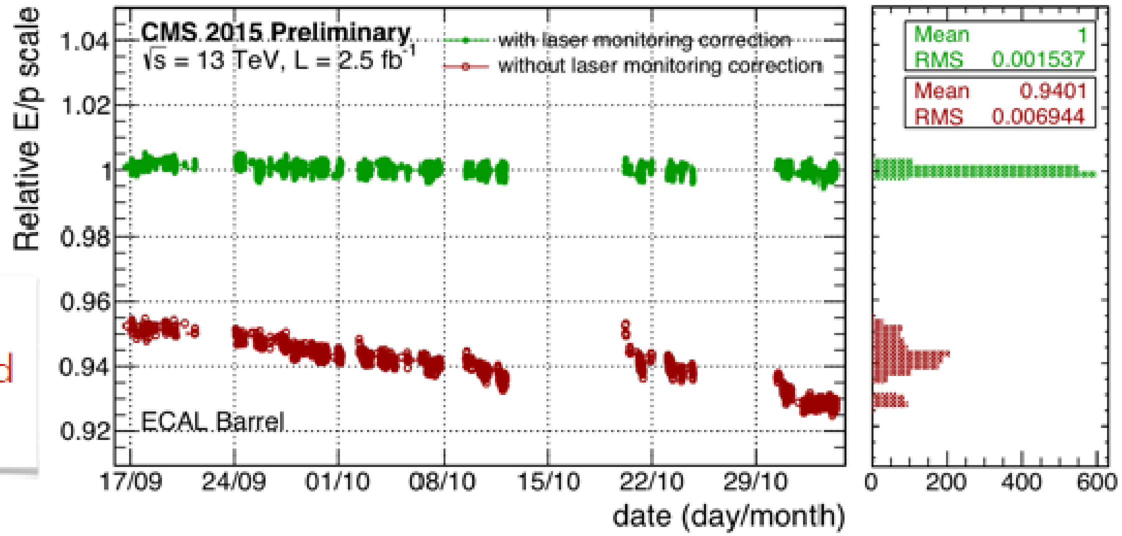
ECAL Crystal Response Monitoring

Laser Monitoring

- **ECAL crystals change response** due to radiation exposure (time dependent): change in crystal transparency and VPT response in endcaps
- Response is **monitored with a laser system** injecting light in every ECAL crystal
- $PbWO_4$ **crystals partially recover** during periods with no exposure
- Monitoring **corrections obtained/ applied promptly** (~48h)
- **Stability:** interpolate 2nd of 3 consecutive readings **<< required 0.2%**



Effect of monitoring corrections by comparing energy of electron reconstructed by ECAL (E) and tracker (p)

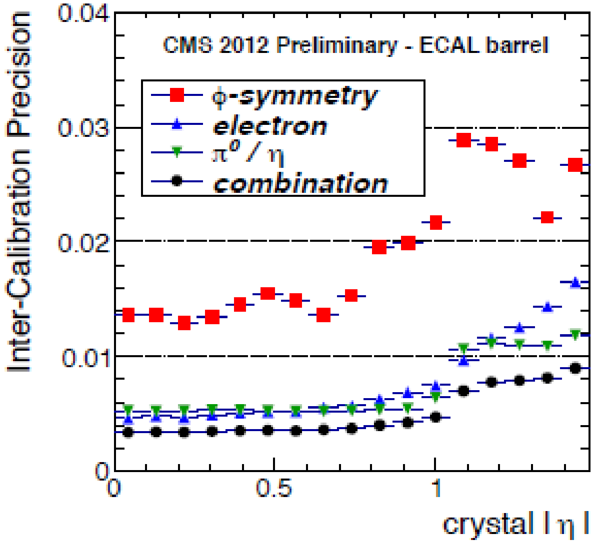


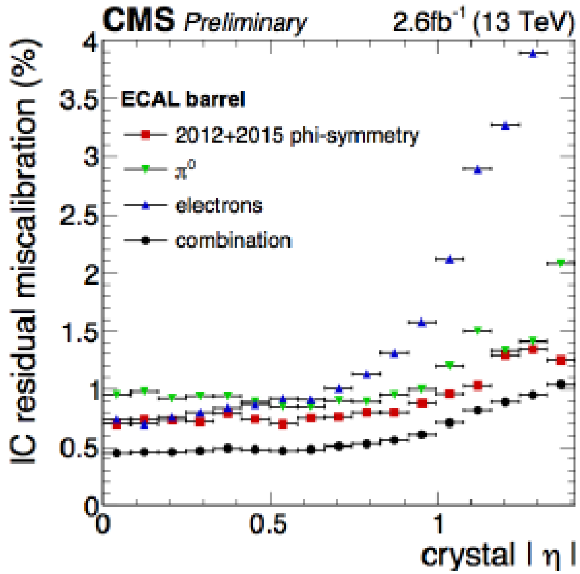
Relative Calibration of Single Channel Response

Intercalibration (IC)

- **Equalizes the response of each single crystal** to the deposited energy
  - Constants are normalized not to interfere with absolute scale

Intercalibration strategy same as in Run I



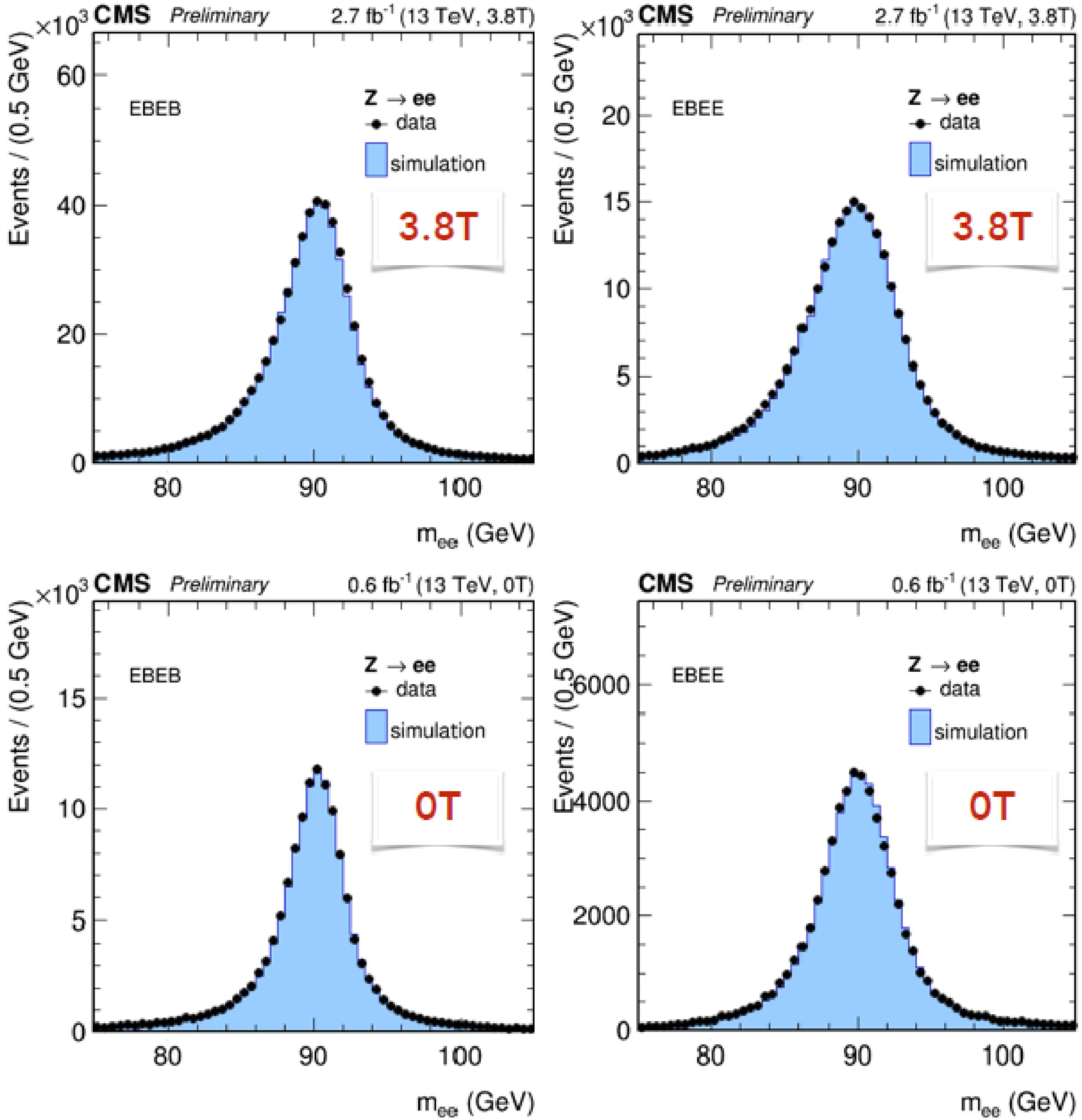


Method	Description	Timescale	Run I Precision (20 fb^{-1})
ϕ-symmetry	Energy flux around ϕ rings (constant η) should be uniform - IC corrects for non-uniformity	~days	Barrel: <3% Endcap: < 10%
$\pi^0/\eta \to \gamma\gamma$	In a ϕ ring, use IC to improve M(γγ) resolution for π^0 and η resonances	~months	Barrel: <1.5% Endcap: < 10%
E/p	Compare isolated electron energy from ECAL and Tracker, calculate IC to correct discrepancies	statistically limited	Barrel: <2% Endcap: < 10%

Absolute Calibration and η Scale

Calibration with Z→ee

- **Electrons from Z→ee** events are used to calibrate the **η dependence** of the energy reconstruction and its **absolute scale**
- The **Z peak is used to fix the overall absolute calibration (ADC to GeV)**, matching data to a detailed simulation of the detector
- Z peaks reconstructed with **electrons in a single ϕ ring** are used to **correct the relative scale** between different η regions

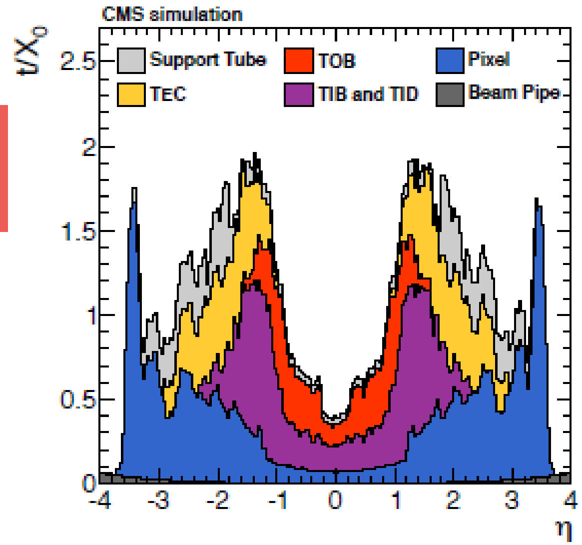


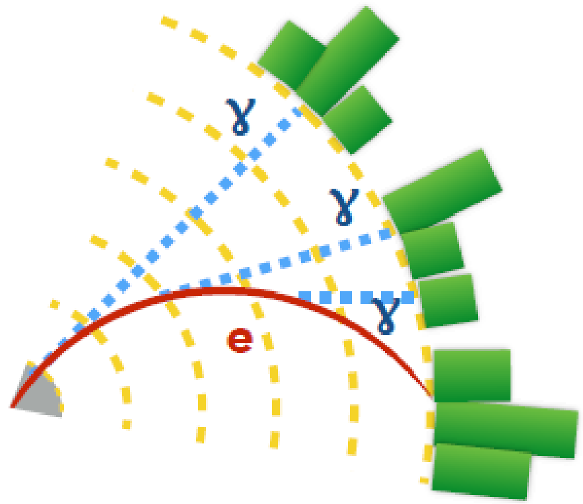
0T: no energy loss in reconstruction due to bremsstrahlung → better resolution

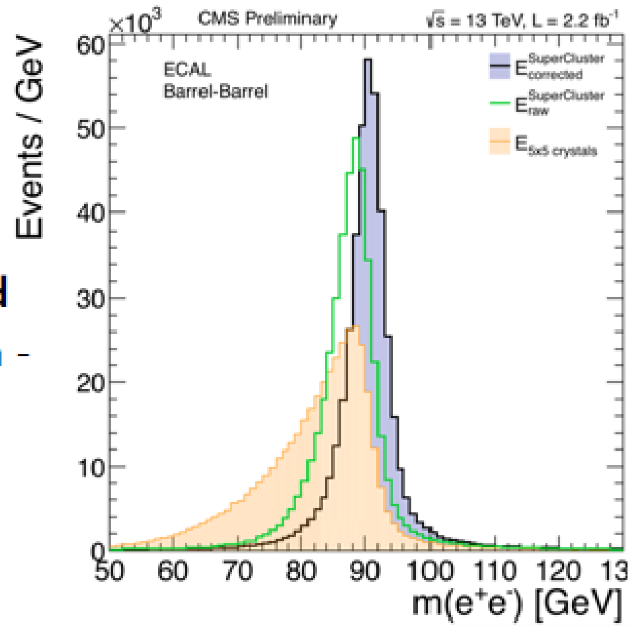
Clustering Reconstruction and Corrections

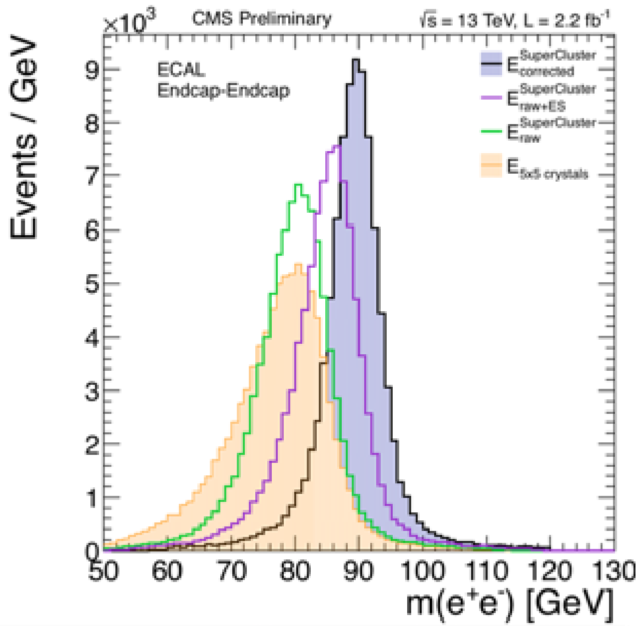
Cluster Corrections

- Large amount of **material before ECAL** - high **probability of bremsstrahlung** emission for electrons **and conversion** for photons
- **Clustering algorithm gathers clusters** of energy deposit **into superclusters** to recover that information
- **Supercluster's energy is corrected following a multivariate approach** - see J. Bendavid's talk







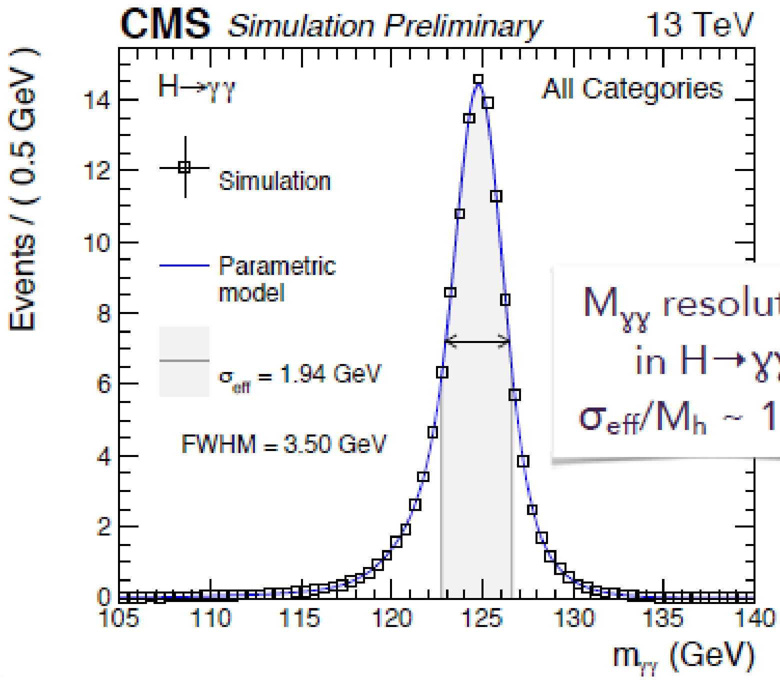


For endcap e/ɣ, energy deposited in the preshower is added to the supercluster

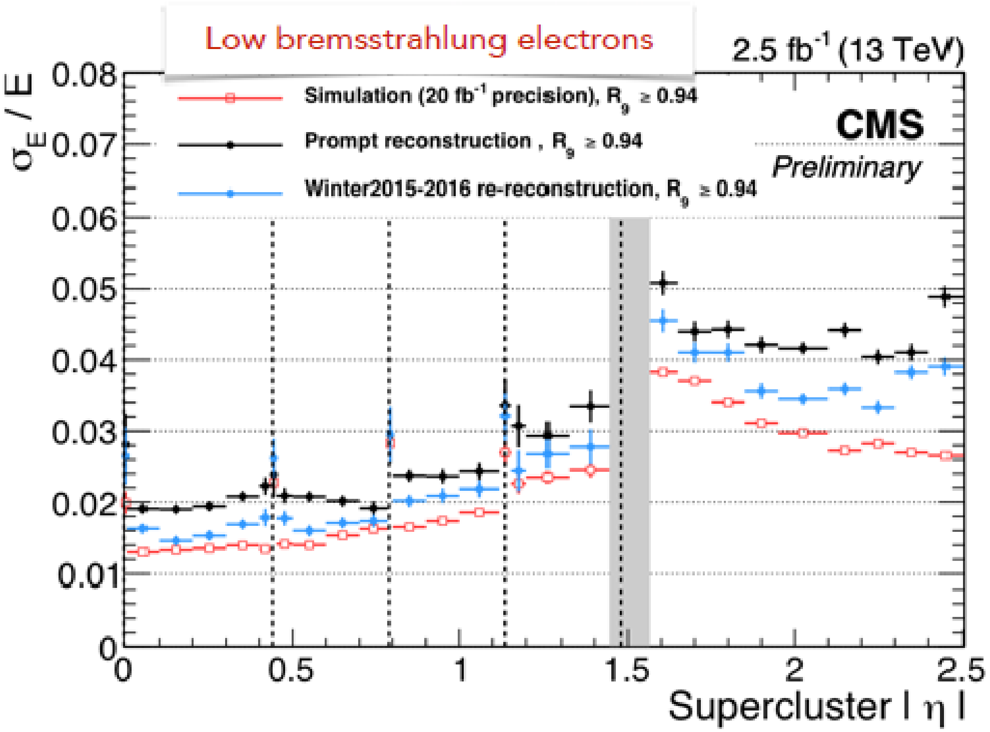
ECAL Energy Resolution with 2015 Data@3.8T

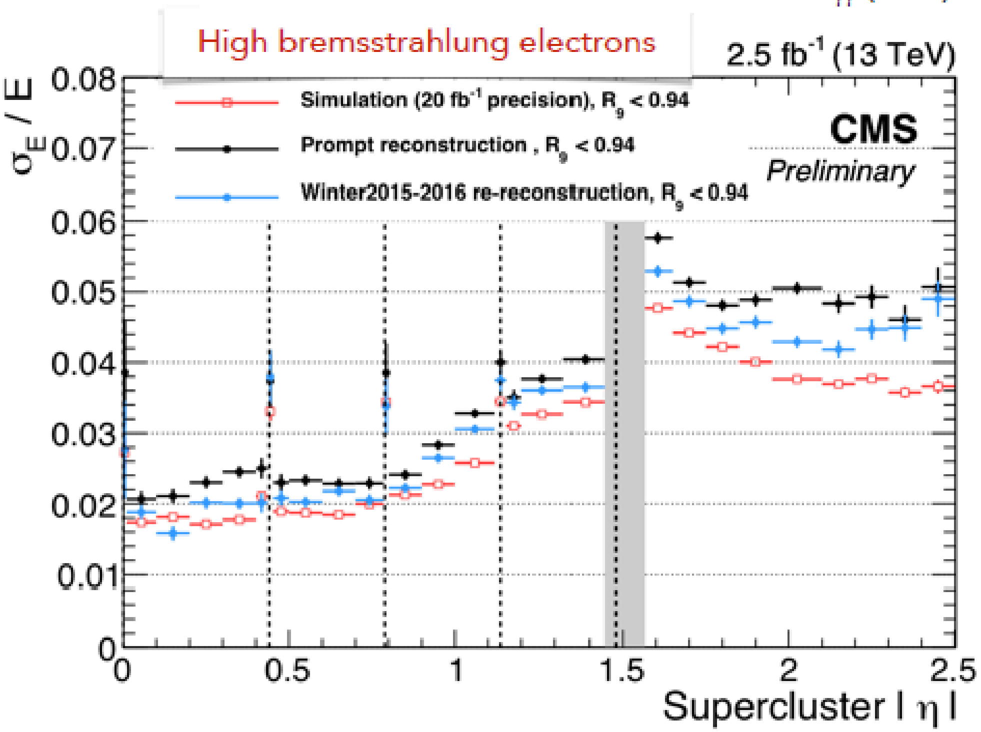
- The relative **resolution is extracted from an unbinned likelihood fit to Z→ee events**, using a Breit-Wigner function convoluted with a Gaussian as the signal model
- Large **improvement by recalculating calibration with 2015 data** (winter re-reconstruction) with respect to initial calibration (prompt) with Run I values for intercalibration/calibration constants

Current resolution is close to what is expected after calibration with 20 fb^{-1} of data



$M_{\gamma\gamma}$ resolution in H→γγ
σ_{eff}/M_h ~ 1.5%





BACK UP SLIDES

CMS ECAL: collecting the light

- Cannot use PMT (affected by magnetic field) or PIN photodiodes (no internal amplification, too sensitive to charged particles)

Barrel crystals read by
Avalanche Photo Diode

Endcap crystals read by
Vacuum Photo Triode

CMS Electronics chain

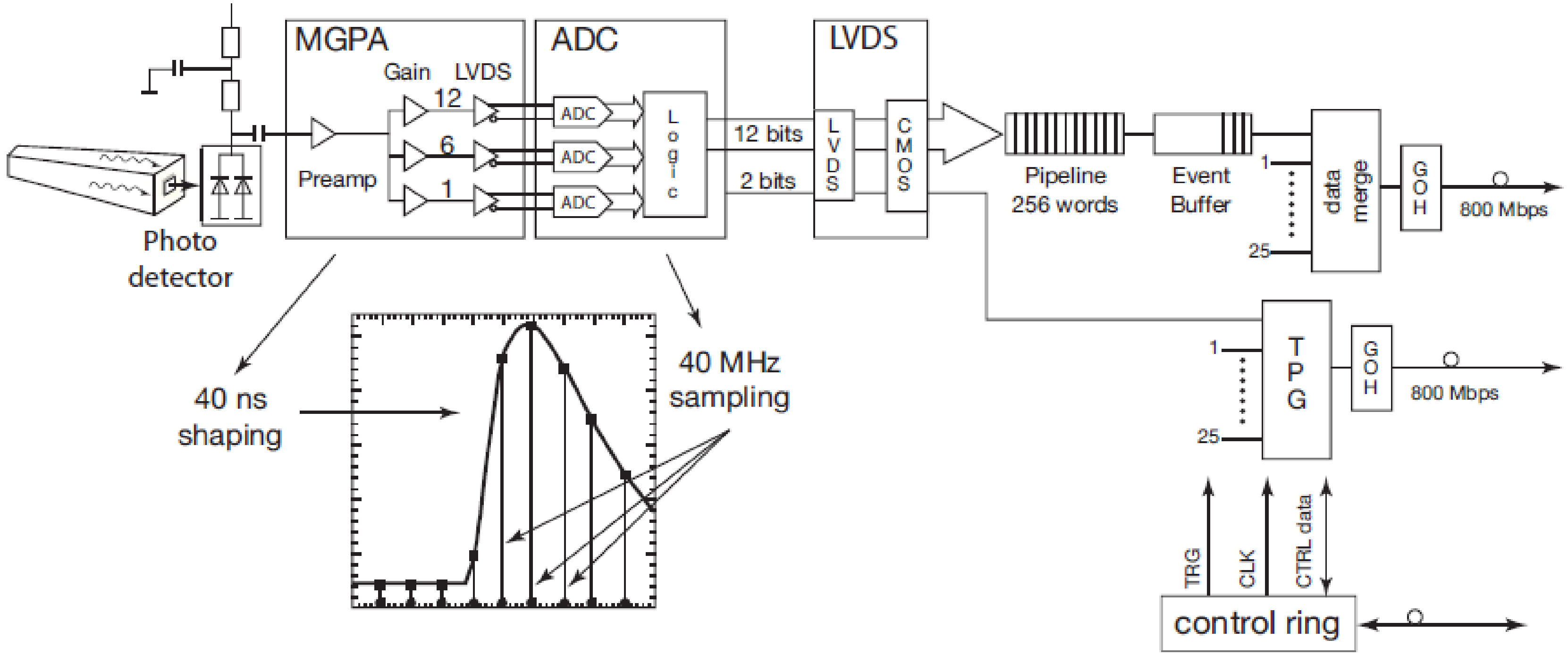


FIG. 3.2: Électronique de lecture du ECAL, en partant d'un cristal et son photodétecteur à gauche. Une carte VFE contient un pré-amplificateur à multi-gain (MGPA) et un convertisseur Analogue vers Digital (ADC) par cristal. La carte FE, qui contrôle 5 cartes VFE, enregistre les signaux provenant des cristaux individuel sur une mémoire tampon (buffer) en attendant un signal d'acceptation L1A. Chaque carte FE produit des primitives (pré-primitives dans les bouchons) de déclenchement (TPG) et les transmet à une carte TCC via des liens optiques GOH.

CMS L1 Trigger Chain

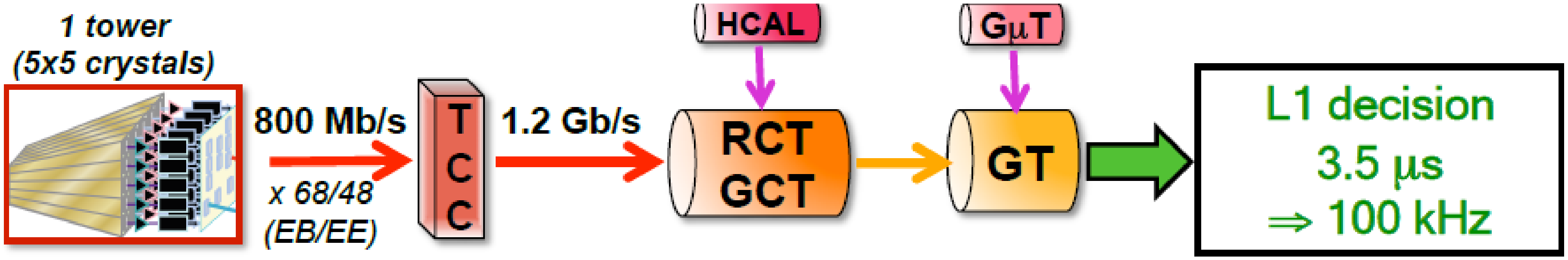


FIG. 3.5: *Système de déclenchement de niveau 1. Chaque carte FE calcule des primitives (pré-primitives dans les bouchons) de déclenchement, encodant l'énergie transverse totale déposée dans chaque tour (resp. pseudo-bande) dans le tonneau (resp. les bouchons). La carte TCC finalise les primitives de déclenchement et compresse les données. Le déclenchement calorimétrique régional (RCT) construit, dans plusieurs régions du détecteur, des candidats L1 EG (resp. Jets, Tau) à partir de primitives provenant du ECAL (resp. HCAL). Le déclenchement calorimétrique global (GCT) transmet les quatre candidats L1 EG d'énergie transverse maximale au GT. Le GT reçoit les candidats L1 EG, Jets, Tau et Muons et prend la décision finale en appliquant les algorithmes de sélection L1.*

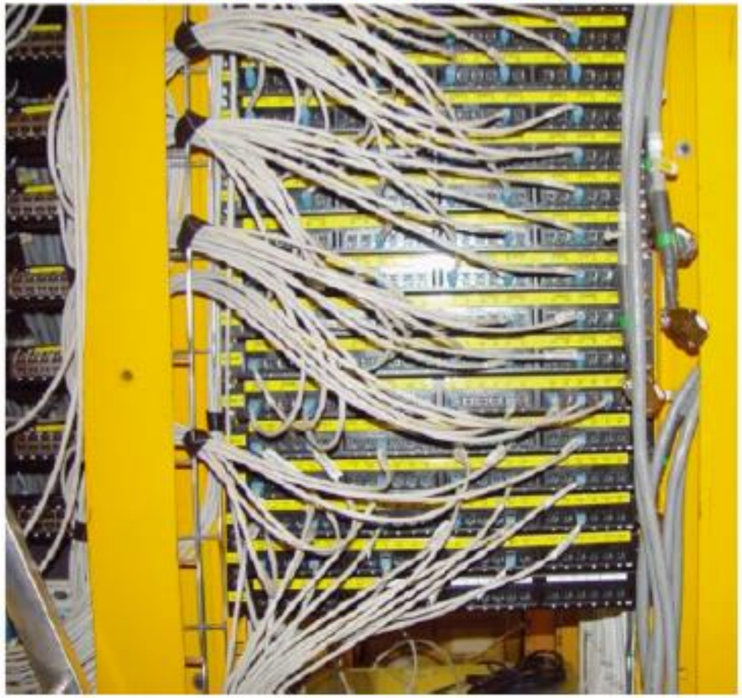
High-level trigger

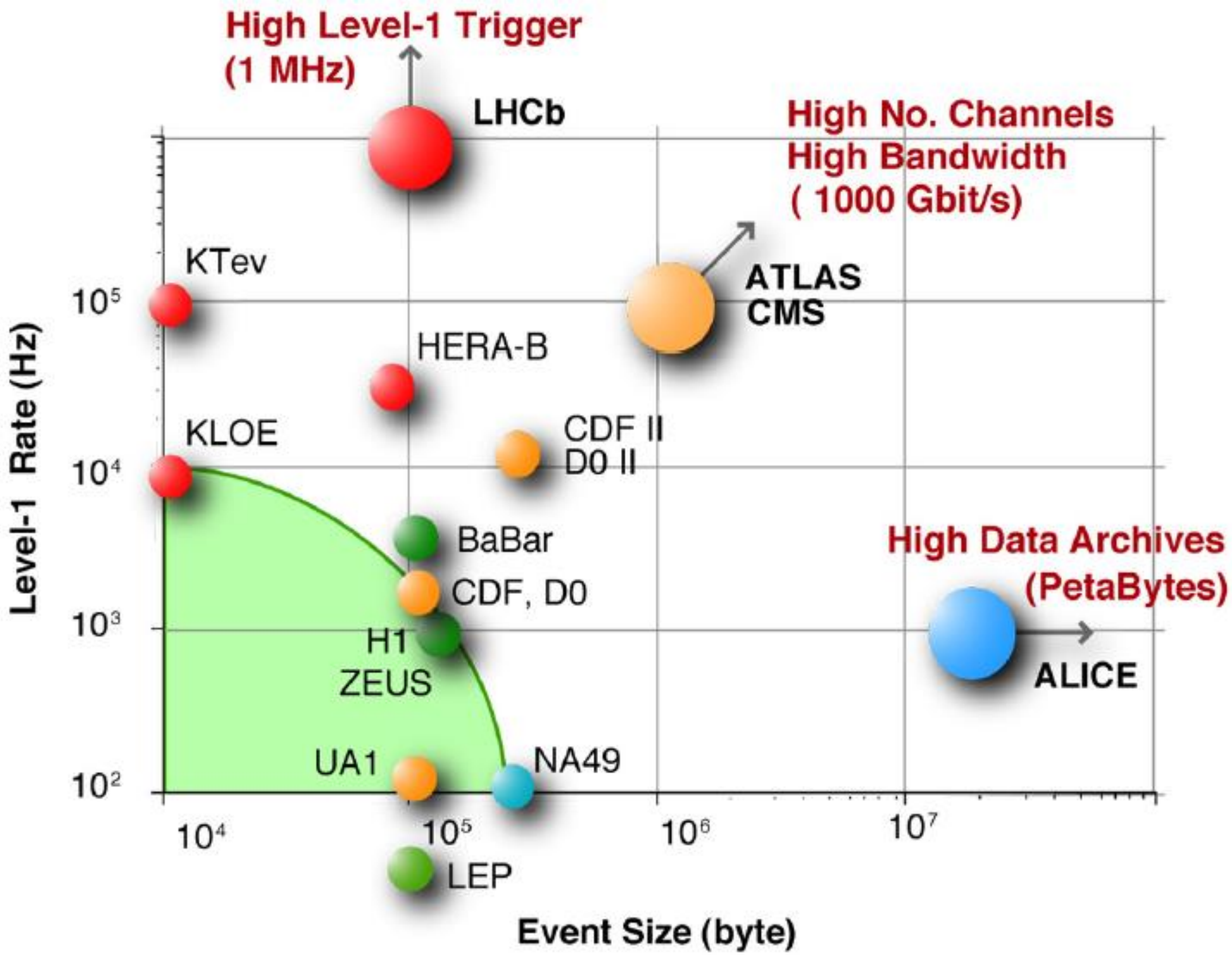
Final selection in software triggers using large commercial PC farms
- acces to full granularity and offline reconstruction-like algorithms
- extremely flexible
- slow (1-100+ ms latency), so use many PCs at the same time

Events are independent, so trivially parallelizable on PC cluster

ATLAS HLT farm:

LHCb readout switch:




High Level-1 Trigger
(1 MHz)
LHCb
High No. Channels
High Bandwidth
(1000 Gbit/s)
KTev
ATLAS
CMS
HERA-B
KLOE
CDF II
D0 II
BaBar
High Data Archives
(PetaBytes)
CDF, D0
H1
ZEUS
ALICE
UA1
NA49
LEP
Level-1 Rate (Hz)
Event Size (byte)
10^5
10^4
10^3
10^2
10^6
10^7

Future

More powerful FPGA => closer and closer to offline

“triggerless” => LHCb