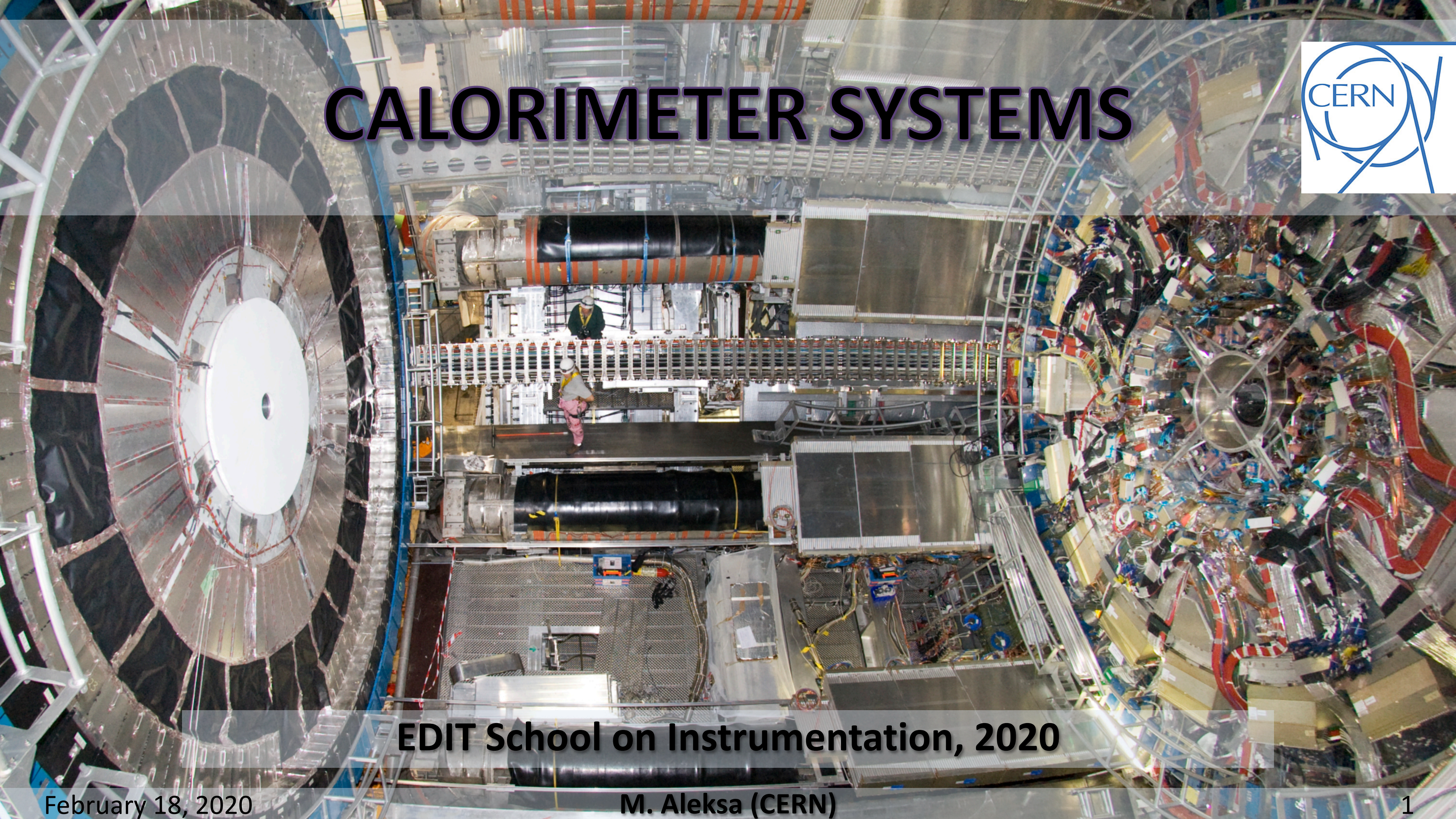
CALORIMETER SYSTEMS



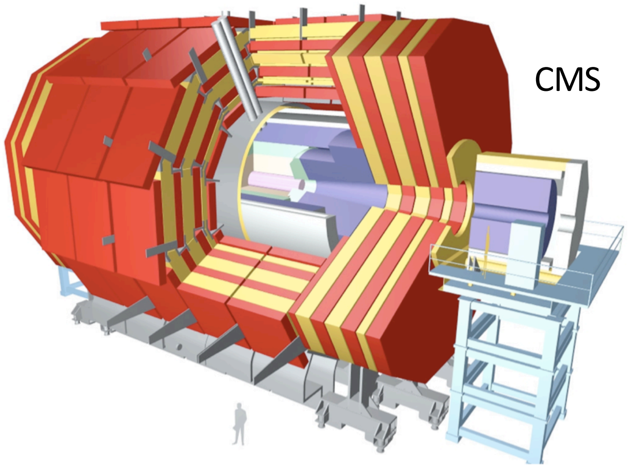
EDIT School on Instrumentation, 2020

Outline

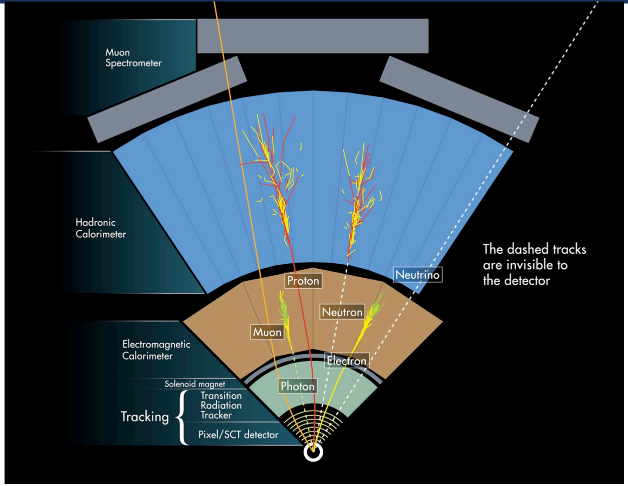
- Introduction – Why Calorimetry?
- Reminder: Physics of Electromagnetic Showers – EM Calorimeters
- Reminder: The Hadronic Cascade – Hadron Calorimeters
- Calorimeter Systems
- Examples in High Energy Physics (LHC)
- Examples of HL-LHC Upgrades and Future Colliders
- Design Exercise – FCC-hh Calorimetry
- Examples Outside Collider Physics
- Summary
- References

INTRODUCTION

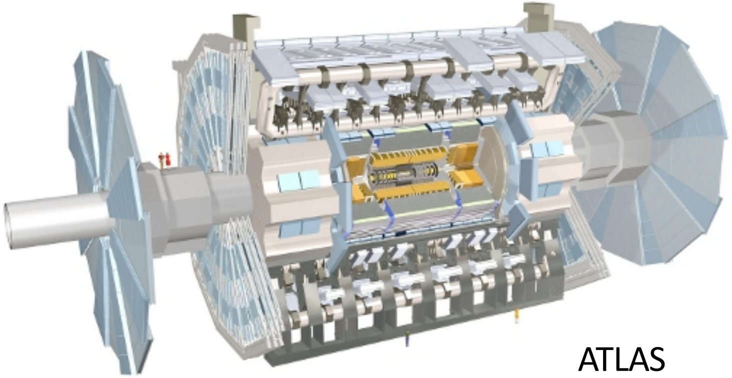
Particle Detection in High Energy Physics



CMS

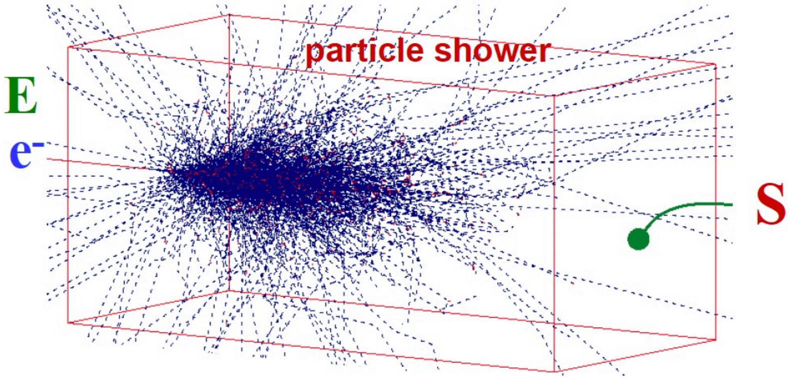


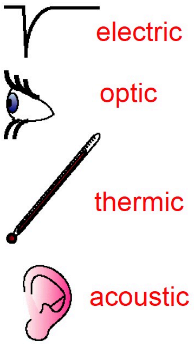
- The characteristics of particles are measured by different types of detectors and identified thanks to their different interactions with matter
- Calorimeters detect: photons (γ), electrons (e), protons, neutrons, jets (q, g), missing energy (e.g. ν)
- Calorimeters measure charged and un-charged particles!



ATLAS

Calorimetry: Basic Concept Very Simple





- **Energy measurement** via **total absorption** of the incoming particles
- **Principle of operation:**
  - Incoming particle interacts with calorimeter material → particle shower
    - Shower composition and dimension depend on particle type and detector material
  - Energy deposited in form of heat, ionization, excitation of atoms (e.g. scintillation), Cherenkov light…
    - Different calorimeter types use different kinds of these signals to measure total energy.
- **Important: Signal (S) is proportional to total deposited energy (E)**
  - Scale factor obtained by calibration

Why Calorimetry?

- Calorimeters measure **charged** and **neutral** particles
- Obtain information on **energy flow**: Total (missing) transverse energy, jets, …
- Dimensions necessary to contain the particle showers proportional to lnE → **compactness**
  - Calorimeter: $L \propto \ln E$
- Calorimeters have a **high rate capability** and are **fast** and can therefore recognize and select interesting events in real time → **Trigger**
- Longitudinal and lateral segmentation → Measurement of **position and direction**. Also **particle ID** on topological basis
- Detection based on stochastic processes → **precision increases with energy** $\frac{\sigma_E}{E} \propto \frac{1}{\sqrt{E}}$

Compare with spectrometer:

Only charged particles

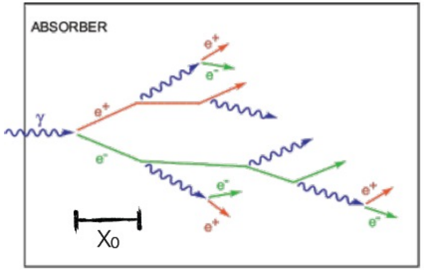
To keep same resolution $L \propto \sqrt{p_T}$

Tracking reconstruction needs more computing resources (usually possible in higher level trigger only)

$$\frac{\sigma_p}{p} \propto \frac{p_T \sigma_x}{L^2 B}$$

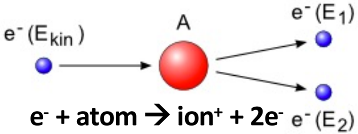
REMINDER – PHYSICS OF ELECTROMAGNETIC SHOWERS – EM CALORIMETERS

Electromagnetic Showers

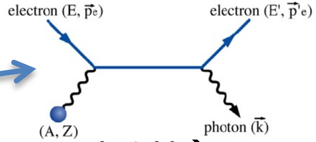


… let's start with **electrons** and **photons** – how do they loose energy due to their **interactions** with **nuclei and atomic electrons**?

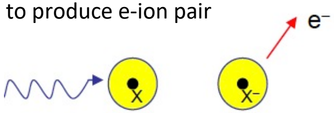
- **Electrons**:
  - Ionization (atomic electrons)
  - Bremsstrahlung (nuclear)
    - dominant at high energies
- **Photons**:
  - Photoelectric effect (atomic electrons)
  - Compton scattering (atomic electrons)
  - Pair production (nuclear)
    - dominant at high energies



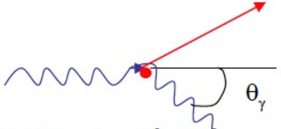
e^- + atom → ion$^+$ + 2e^-
need energy W (1—100 eV)
to produce e-ion pair



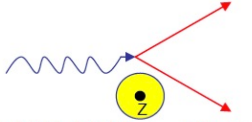
e^- + Coul. Field → e^- + γ



γ + atom → ion$^+$ + e^-



γ + e → γ' + e'



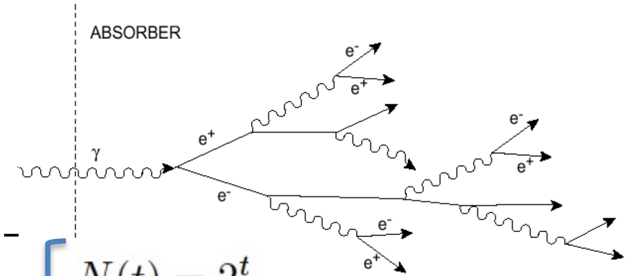
γ + Coul. Field → e^+ + e^-

Electromagnetic Showers Characteristics

- For E > E_C **two dominant interactions**:
  - **Pair production and Bremsstrahlung**
  - Shower development **governed by radiation length X_0**

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

    - After distance X_0 electrons remain with 1/e of their primary energy (rest lost by Bremsstrahlung)
    - Those Bremsstrahlungs photons produce e^+e^--pair after $9/7\ X_0 \approx X_0$.
  - In 0^{th} approximation after $1X_0$ number of shower particles N(t) has doubled ($t=x/X_0$)



$$N(t) = 2^t$$

Energy per particle:

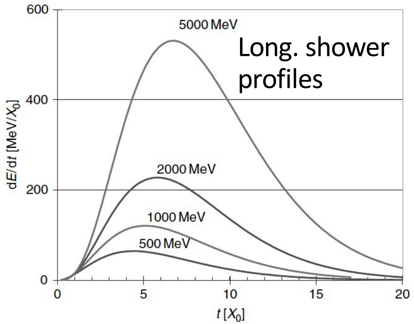
$$E = \frac{E_0}{N(t)} = E_0 \cdot 2^{-t}$$

Shower maximum:

$$t_{\max} \propto \ln(E_0/E_c)$$

- **Transverse shower development**:
  - Dominated by multiple scattering but also contribution due to Bremsstrahlung and Compton scattering
  - **Molière radius R_M** characterizes lateral shower spread (90% E_0 within cylinder with $1R_M$)

$$R_M = \langle\theta\rangle_{x=X_0} \cdot X_0 \approx \frac{21\mathrm{MeV}}{E_C} X_0$$



- **Longitudinal shower development** (reasonably well described by: Longo-Sestili NIM 128)

$$\frac{dE}{dt} = E_0\ t^{\alpha} e^{-\beta t}$$

Some Material Examples

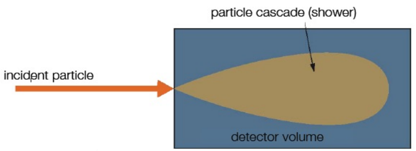
Typical values for X_0, E_C, R_M, λ_{int} and dE/dx of materials used in calorimeters

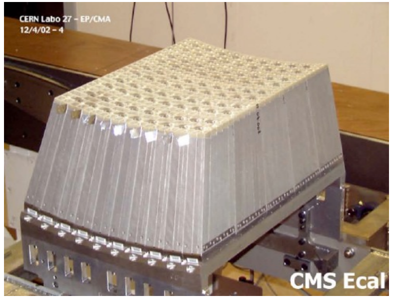
Material	Z	Density	E_C	X_0	R_M	λ_{int}	$(dE/dx)_{mip}$
		(g cm^{-3})	(MeV)	(mm)	(mm)	(mm)	(MeV cm^{-1})
C	6	2.27	83	188	48	381	3.95
Al	13	2.70	43	89	44	390	4.36
Fe	26	7.87	22	17.6	16.9	168	11.4
Cu	29	8.96	20	14.3	15.2	151	12.6
Sn	50	7.31	12	12.1	21.6	223	9.24
W	74	19.3	8.0	3.5	9.3	96	22.1
Pb	82	11.3	7.4	5.6	16.0	170	12.7
^{238}U	92	18.95	6.8	3.2	10.0	105	20.5
Concrete	-	2.5	55	107	41	400	4.28
Glass	-	2.23	51	127	53	438	3.78
Marble	-	2.93	56	96	36	362	4.77
Si	14	2.33	41	93.6	48	455	3.88
Ge	32	5.32	17	23	29	264	7.29
Ar (liquid)	18	1.40	37	140	80	837	2.13
Kr (liquid)	36	2.41	18	47	55	607	3.23
Polystyrene	-	1.032	94	424	96	795	2.00
Plexiglas	-	1.18	86	344	85	708	2.28
Quartz	-	2.32	51	117	49	428	3.94
Lead-glass	-	4.06	15	25.1	35	330	5.45
Air 20°, 1 atm	-	0.0012	87	304 m	74 m	747 m	0.0022
Water	-	1.00	83	361	92	849	1.99

Courtesy calorimetry lecture D. Fournier

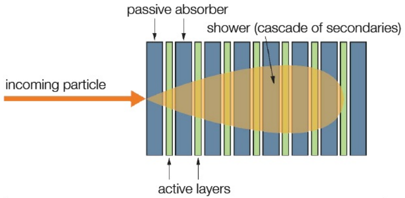
Homogeneous and Sampling Calorimeters

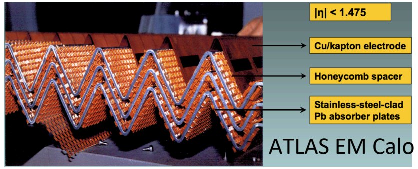
- In a **homogeneous calorimeter** all the energy is deposited in the active medium (**absorber = active medium**)
  - Excellent energy resolution (stochastic term down to 1% possible)
  - Used exclusively for EM calorimeters
  - Difficult to segment in 3 dimensions → often no information on longitudinal shower shape
  - Radiation damage is a problem
  - Signal:
    - Scintillation light: high density crystals e.g. $PbWO_4$ (8.3 g/cm^3, X_0 = 8.9mm, R_M=2.2cm), e.g. BGO, BaF_2, CeF_3, CsI, NaI(Tl)
    - Cherenkov light: e.g. lead glass
    - Ionization signal: e.g. liquid nobel gases (Ar, Kr, Xe)





- **Sampling calorimeter: stack of passive and active layers**
  - Limited energy resolution (stochastic (sampling) term >8%)
    - Only part of the energy is actually deposited in the active layer (typically a few %) → **sampling fraction f_s**.
    - Sampling fluctuations deteriorate energy resolution
  - Compact calorimeters possible (high density absorber material), also hadron calorimeters
  - Detailed shower shape information
  - Absorber: e.g. Fe, Cu, Pb, W, U
  - Active material: plastic scintillators, silicon detectors, liquid nobel gases, gases





EM Calorimeter Energy Resolution

- **Stochastic term *a***: accounts for any kind of **Poisson-like fluctuation**
  - Additional contribution to this term if only part of the energy is deposited in the active material (e.g. sampling calorimeters)
- **Noise term *b***: responsible for degradation of low-energy resolution
  - Main contribution is the energy equivalent of the **electronics noise**
  - In high luminosity environment also the **pile-up** contributes to this term: Pile-up noise comes from fluctuations of energy entering the measurement area from sources other than the primary particle (e.g. additional particles from other collisions in the same bunch crossing or in the bunch crossings before).
- **Constant term *c***: dominates at high energy
  - Main contribution is the uniformity and stability of the energy response (excellent calibration necessary to keep this term low).
  - Contributions from energy leakage, non-uniformity of signal generation and/or collection (construction!), loss of energy in dead materials,…

Paremetrization of resolution:

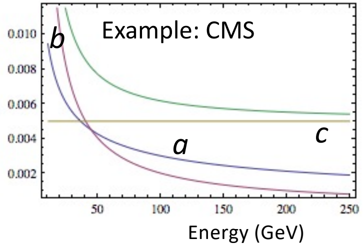
$$\frac{\sigma_E(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

stochastic/sampling term

noise term

constant term

$$x \oplus y \equiv \sqrt{x^2 + y^2}$$



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

Homogeneous

Sampling

Summary – EM Calorimeters

Homogeneous calorimeters: All energy is deposited in active material

Sampling calorimeters: Stack of active and passive layers

Resolution: Governed by

- **stochastic/sampling term (fluctuations)**
- **noise term (electronics and pile-up noise)**
- **constant term (stability, precision, dead material).**
  - **Determines resolution at high energies**

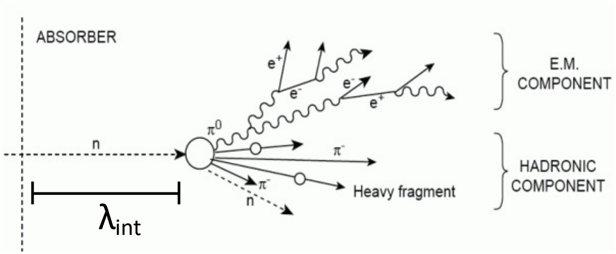
REMINDER – THE HADRONIC CASCADE – HADRON CALORIMETERS

Physics of the Hadronic Cascade

- Energy loss of **high-energy hadrons** in an absorber material is mostly due to **strong interactions**
- Two classes of effects:
  - Production of **energetic hadrons**, typically mesons (e.g. $\pi^{\pm}$, π^0, K, …) with momenta of typically a fair fraction of the primary hadron momentum (i.e. at the GeV scale) → in turn interact with further nuclei
    - **⅓ of pions produced will be π^0** which will decay into two photons ($\pi^0 \rightarrow \gamma\gamma$) → **electromagnetic cascade** (will not contribute further to hadronic processes) → **EM fraction F_{EM}**
    - After each "generation" EM fraction will increase → the higher the incident energy, the higher the EM fraction
  - A significant part of the primary energy is diverted to **nuclear processes** such as excitation, nucleon evaporation, spallation, etc., resulting in particles with characteristic nuclear energies at the MeV scale → high number of low-energy neutrons (~20-40 n/GeV in Pb) which will be captured leading to delayed (μs timescale) nuclear photon emission → in general not detected ("invisible", ~ ⅓ of non-EM fraction)

Nuclear interaction length

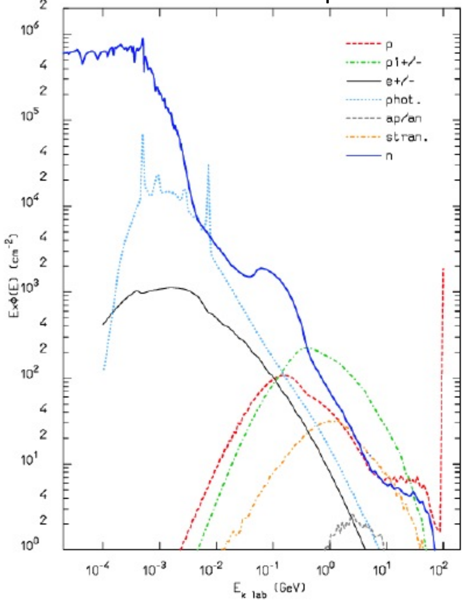
$\lambda_{int} = A/(N_A \sigma_{int}) = A/(N_A R^2 \pi) \propto A^{1/3}/\rho$



Fluctuations of EM fraction!

Fluctuations of "invisible" energy!

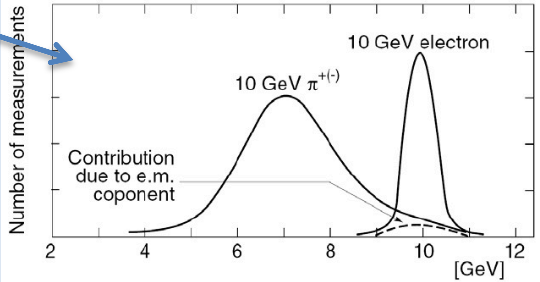
FLUKA simulations of 100GeV proton in Pb



Hadron Calorimeter Energy Resolution

- **Electromagnetic** (EM) component and **non-EM** component usually have **different response** (e.g. e/h > 1)
- If e/h ≠ 1 the fluctuations in the em-fraction F_{EM} lead to additional degradation of energy resolution and to a non-linearity in energy response (since F_{EM} increases with higher energy)
  - If possible identifying EM and non-EM part of the hadronic cascade with help of fine segmentation, classification according to energy density

→ a ~ 50% - 100%



Signal (in energy units) obtained for a 10 GeV energy deposit

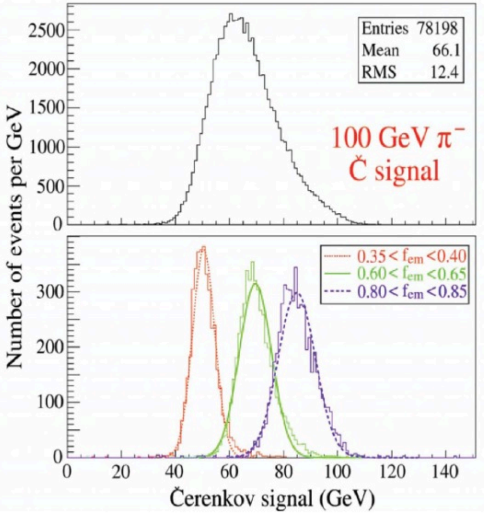
- How to obtain e/h = 1 (**compensation**)?

→ a ~ 35%

  - Suppress EM component (e.g. high Z absorber)
  - Enhance response to neutrons by using hydrogen close to active material (n-p scatter → recoil proton has a range of e.g. 20µm in scintillator)
  - Enhance neutron production by fission (U absorbers, e.g. ZEUS)

- Other ideas to improve energy resolution: **Dual readout** (e.g. Dream)
  - Difficult (impossible?) in collider environment
  - e.g. in quartz fiber calorimeter (e/h ~ 5)
  - Read-out of **Cerenkov light** (threshold β>1/n, i.e. 200keV of electrons, 400MeV for protons) → mainly EM component.
  - Read-out **scintillation light** → all components.
  - **→ Combine information to get F_{EM} and E.**

→ a ~ 15%



Summary – Hadron Calorimeters

Hadronic cascades: Energy loss of hadrons governed by strong interaction

- Showers have EM component and hadronic component (part of hadronic component is in general "invisible")

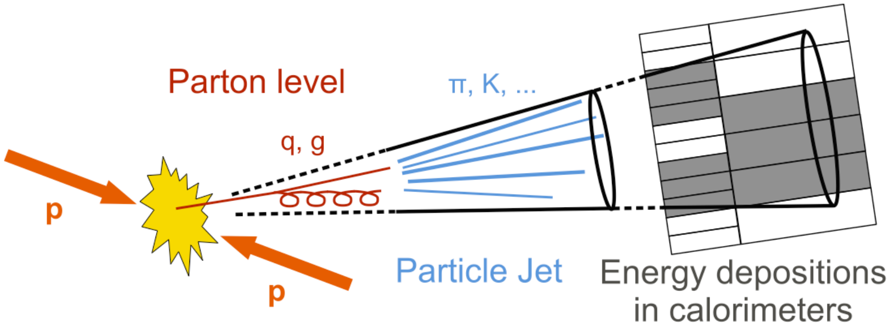
Typical length: Interaction length λ_{int}.

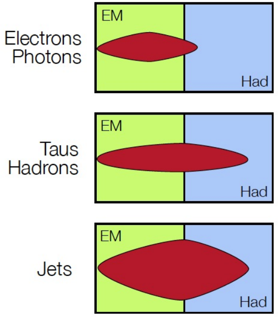
Resolution of hadron calorimeters:

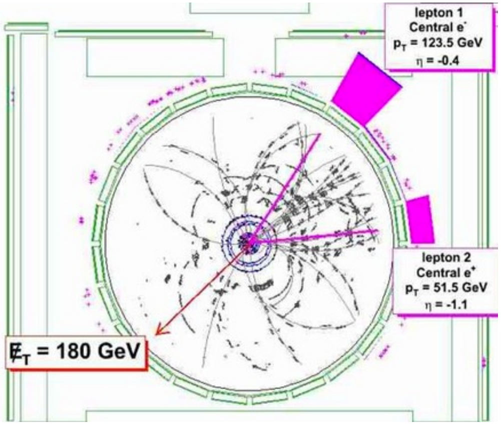
- Fluctuations of "invisible" energy and of EM component
- Difference in response between EM and hadronic component (e/h>1)
- Can be improved by compensation (e/h=1) or other ideas (e.g. dual readout)

CALORIMETER SYSTEMS

Measurement of Physics Objects in HEP

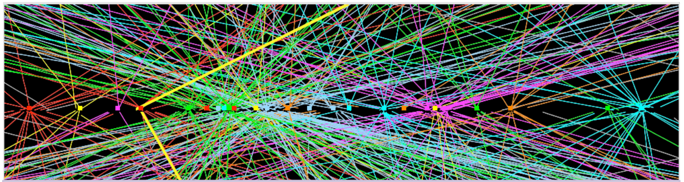






- In high energy physics (HEP) we **don't just measure leptons, photons and single hadrons**!
- Quarks and gluons produced in the p-p collisions have a colour charge and hence cannot exist freely (colour confinement) → they hadronize into colour neutral hadrons and form **particle jets**

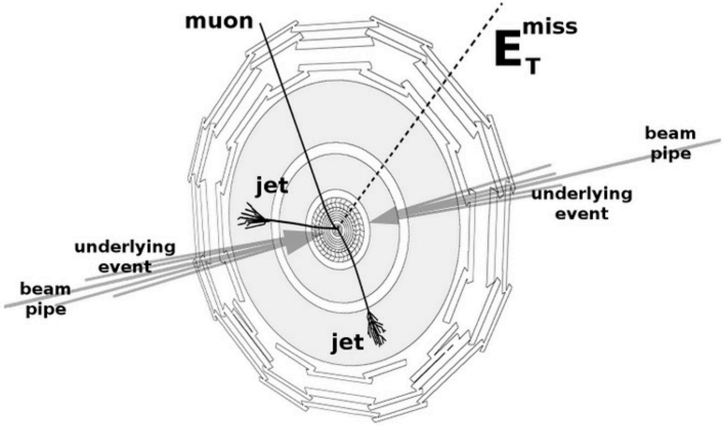
  → Measurement of quarks means measurement of many particles inside a cone
- Measurement of undetectable particles (e.g. neutrinos ν) → **missing E_T** (obtained by the negative vector sum of E_T)
- On top each event there is an **underlying event** (other particles from same p-p collision) and min. bias events from other simultaneous p-p collisions (**pile-up**)

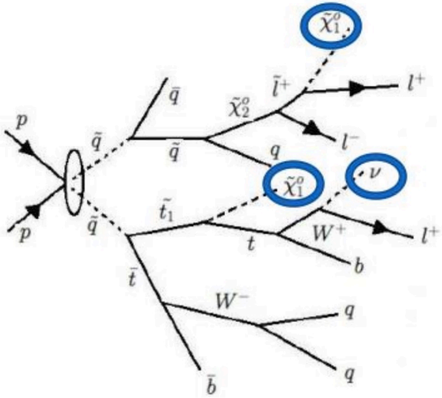


ATLAS: Z→μμ event from 2012 with 25 reconstructed vertices

What Is Missing Transverse Energy?

- Some particles don't interact via electromagnetic force nor strong force
  - e.g. neutrinos, SUSY particles, DM candidates
  - → no or very little energy deposit, no shower
- Momentum conservation:
  - $\sum p_T = 0$
  - → $E_T^{miss}/c = \mathbf{p}_T^{miss} = - \sum \mathbf{p}_T^{visible}$
    - if particles are assumed massless ($E >> m_0c^2$)



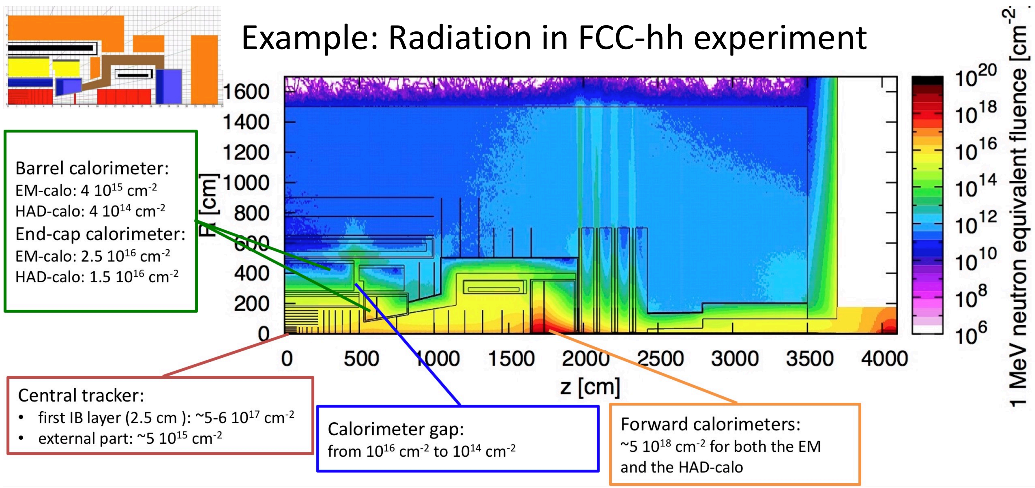


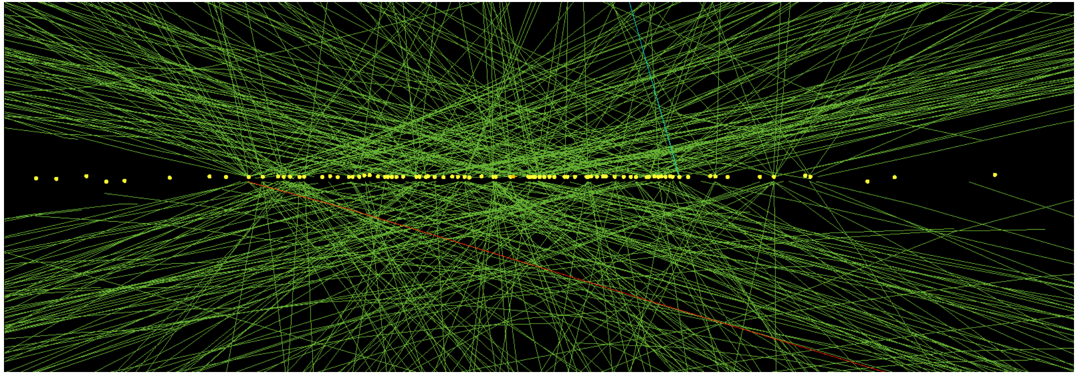
- → Large acceptance!
- → Good hermeticity!

Which Requirements – Which Constraints?

Which environment?

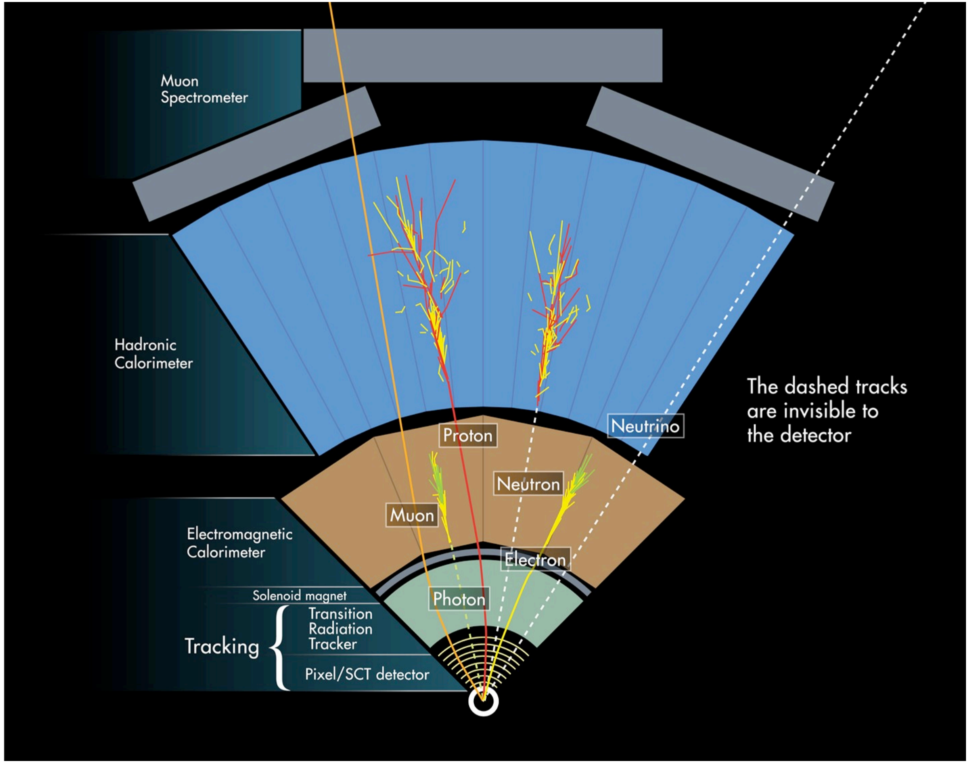
- Radiation environment
- Pile-up
  - = collisions per bunch crossing
  - Only at hadron colliders
- Magnetic field





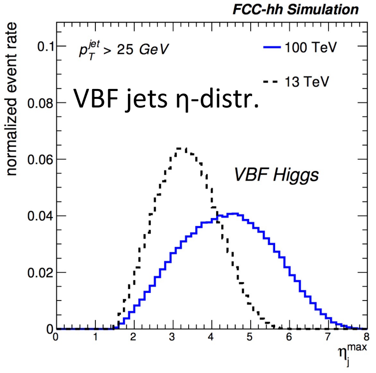
Which Requirements – Which Constraints?

- **What do I want to measure?**
  - Energy
  - Position (pointing?)
  - Particle type (PID)
  - Time
  - Shower image (3D, 4D, 5D?)
- **Which particles?**
  - $e^{\pm}$, γ, π^0, $\pi^{\pm}$, n, jets, …
  - Weakly interacting particles:
    - Neutrinos, SUSY particles, …
    - → missing transverse energy (E_T^{miss})
- **Do I need to trigger?**

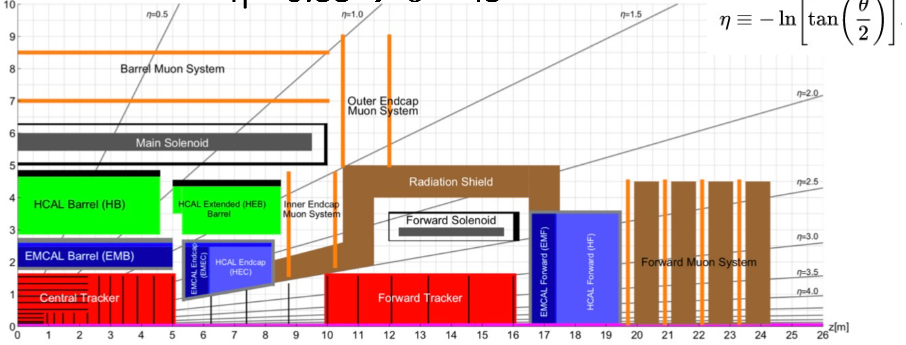


Which Requirements – Which Constraints?

- **Acceptance**
- **Hermeticity**
- **Granularity**
  - Combine measurement with tracker (e.g. particle flow)
  - Resolve boosted objects
  - Jet mass

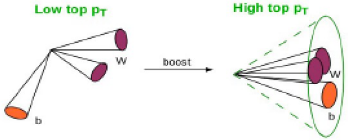


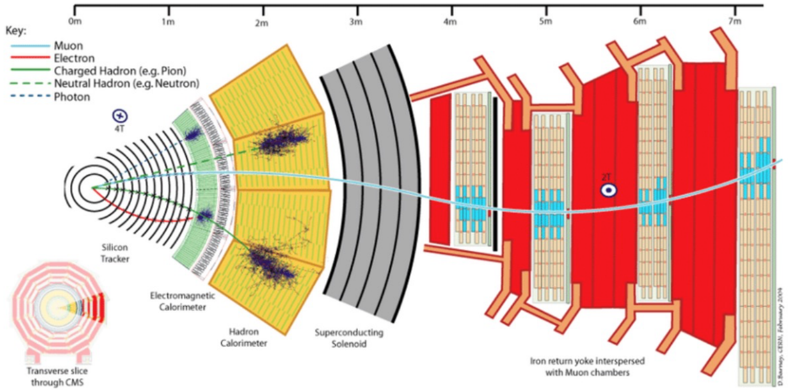
$\eta = 0.88 \rightarrow \theta = 45^o$



$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

$\eta = 4 \rightarrow \theta = 2^o$

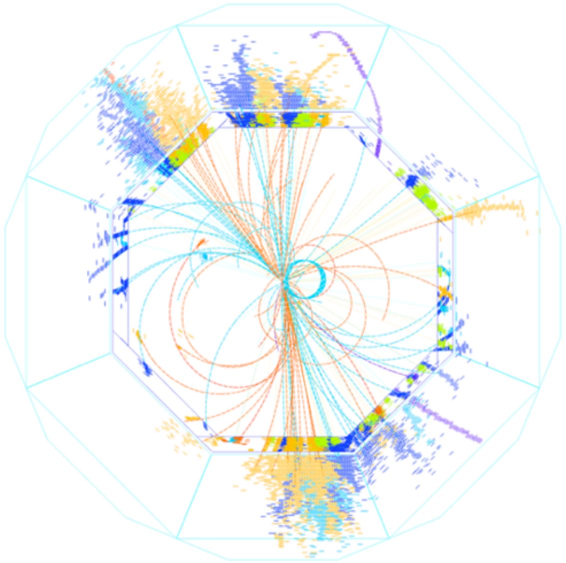




- **Space constraints**
  - E.g. size of tracker, solenoid coil
  - High magnetic field ↔ coil thickness
    - ATLAS: B=2T, coil relatively thin → inside calorimeter → additional dead material
    - CMS: B=4T, coil very thick → outside calorimeter → space constraints

Particle Flow

Component	Detector	Fraction	Part. resolution	Jet Energy Res.
Charged ($X^{\pm}$)	Tracker	60%	$10^{-4}\ E_X$	negligible
Photons (γ)	ECAL	30%	$0.1/\sqrt{E_\gamma}$	$.06/\sqrt{E_{jet}}$
Neutral Hadrons (h)	E/HCAL	10%	$0.5/\sqrt{E_{had}}$	$.16/\sqrt{E_{jet}}$



Choose **detector best suited** for particular **particle type**

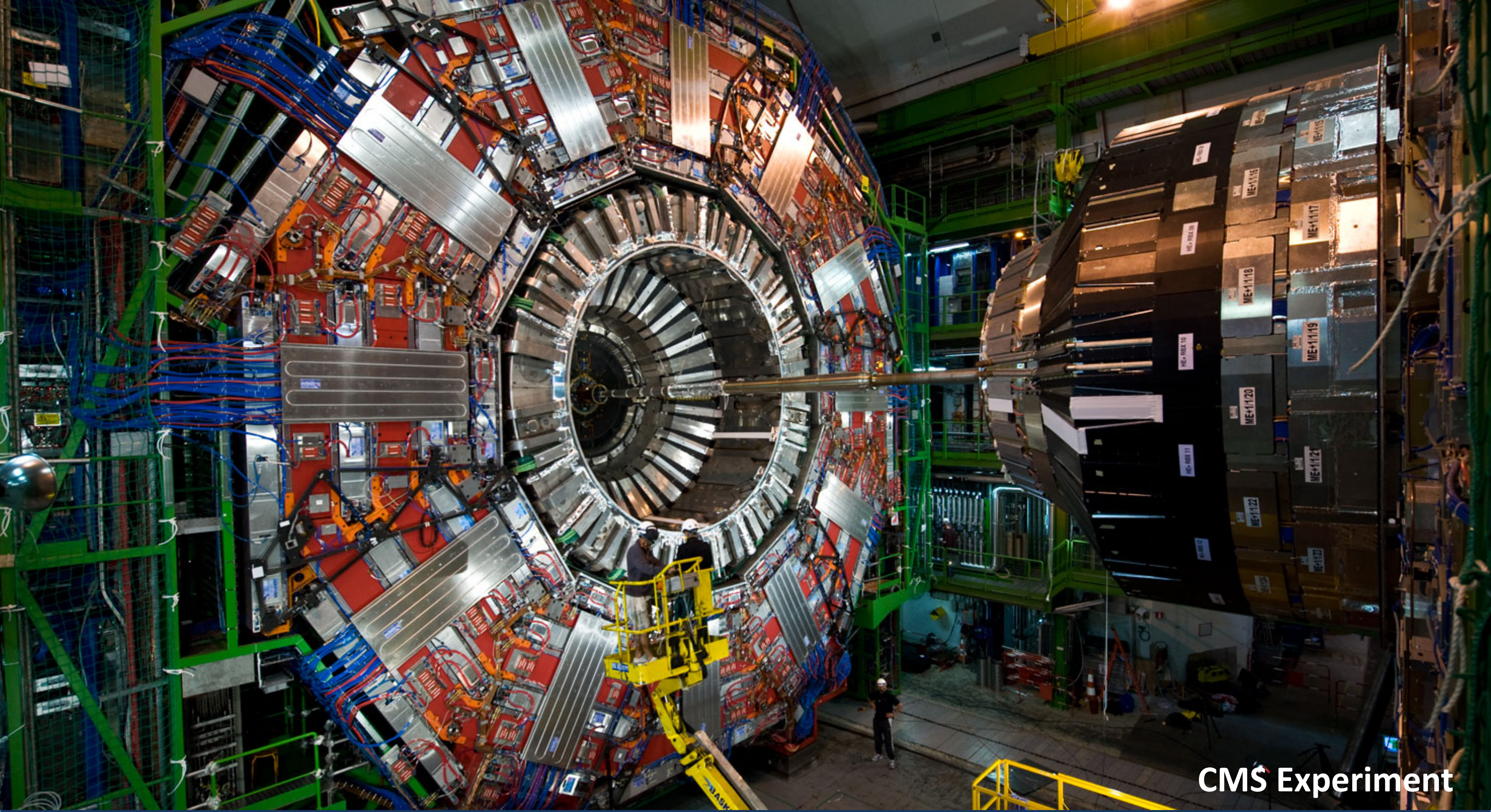
- Use tracks and distinguish "charged" from "neutral" energy to avoid double counting
- Distinguish electromagnetic and hadronic energy deposits in the calorimeter for software compensation

$$\sigma_{jet}^2 = \underbrace{\sigma_X^2 + \sigma_\gamma^2 + \sigma_h^2}_{\approx \frac{0.17}{\sqrt{E_{jet}}}} + \underbrace{\sigma_{confusion}^2}_{\approx \frac{0.25}{\sqrt{E_{jet}}}} + \ldots$$

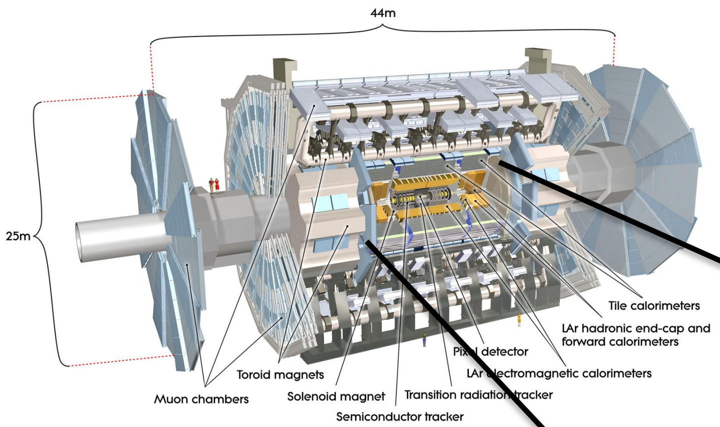
→ **Granularity more important than energy resolution!?**

EXAMPLES IN HIGH ENERGY PHYSICS


ATLAS Barrel Calorimeter


CMS Experiment

The ATLAS Calorimeter System



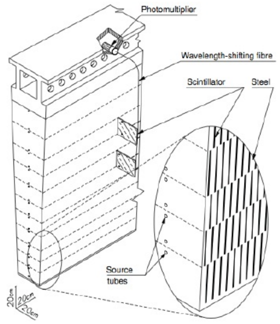
The Liquid Argon (LAr) calorimeter:

EM calorimeter: (|η|<3.2)

- Pb-LAr sampling calorimeter
- Presampler, fine segmentation first layer, 3 layers in total in central reg.
- Design EM resol.: $\frac{\sigma(E)}{E} = \frac{10\%}{\sqrt{E}} \oplus \frac{0.2}{E} \oplus 0.7\%$

Hadronic end-caps: 1.5<|η|<3.2: Cu-LAr

Forward: 3.1<|η|<4.9: Cu,W-LAr



The Tile calorimeter:

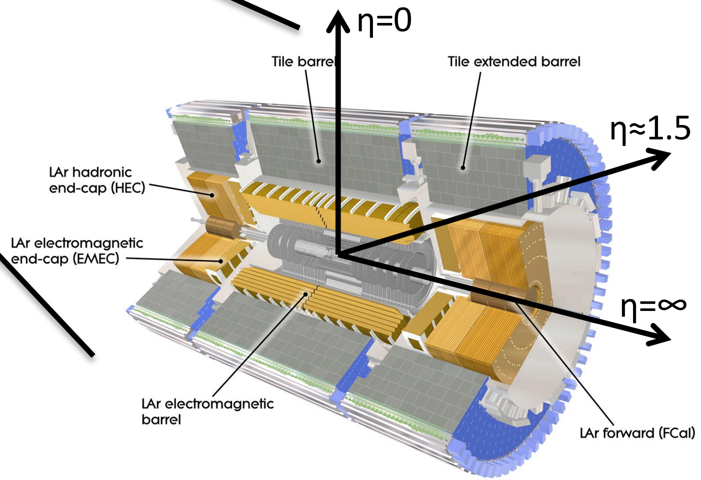
Hadronic calorimeter

Steel absorber plates and plastic scintillator tiles

- Coverage:|η| < 1.7
- Three longitudinal layers, total thickness of about 7λ

Design jet resolution (LAr+Tile):

$$\frac{\sigma(E)}{E} = \frac{50\%}{\sqrt{E}} \oplus 3\%$$



The ATLAS EM Calorimeter

Sampling calorimeter

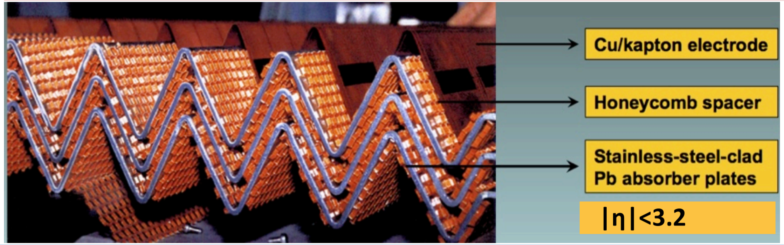
- with Pb absorbers and active LAr gaps (2mm in barrel, 1.2 – 2.7mm in endcap)

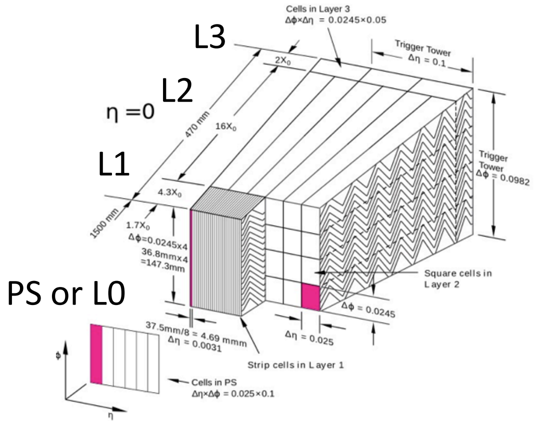
Advantages of **liquid argon (LAr) as active material**

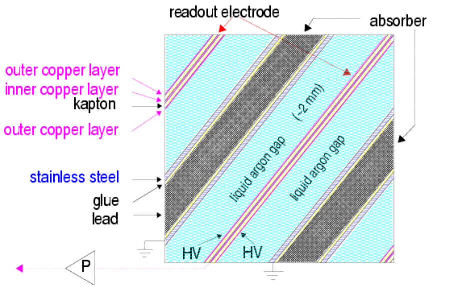
- linear behavior
- stability of the response over time
- radiation tolerance

Advantages of **accordion geometry**

- it allows **a very high η-ϕ granularity** and **longitudinal segmentation** (PS, L1, L2, L3)
- it allows for very **good hermeticity** since HV and signal cables run only at the front and back faces of the detector
- it allows for **a very high uniformity** in ϕ



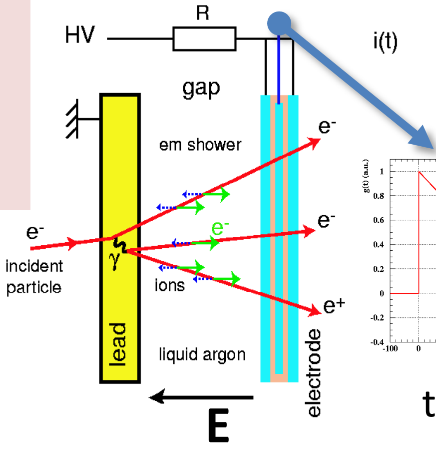


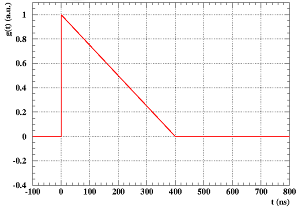


Incident electrons create **EM showers** in Pb (X_0=0.56cm) and LAr gaps (X_0=14.2cm)

secondary e^+ and e^- create e^-–ion pairs in LAr (W=23.3eV)

Ionized electrons and ions drift in electric field (2kV for 2mm gaps in barrel) and **induce triangular signal** (≈450ns e^- drift time)





$t_{drift} \approx 450$ ns

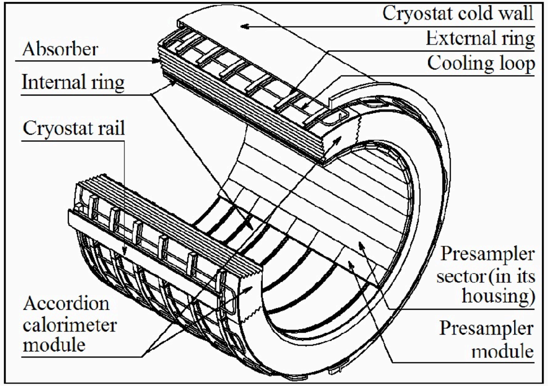
Design resolution:

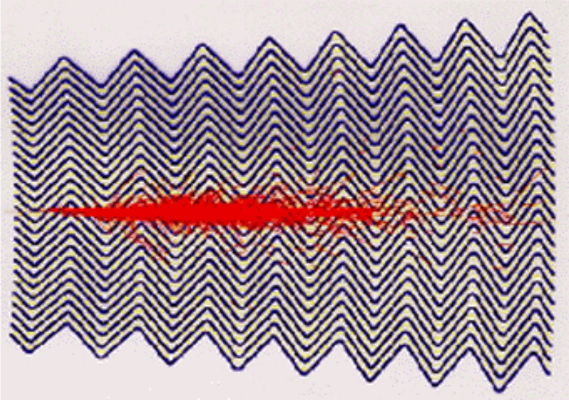
$$\frac{\sigma(E)}{E} = \frac{10\%}{\sqrt{E}} \oplus \frac{0.2}{E} \oplus 0.2\%$$

ATLAS LAr Calorimeter Accordion

- **Advantages:**
  - Hermeticity (no cracks in ϕ)
  - Uniformity in ϕ
  - Constant sampling fraction over depth
  - High segmentation in η and ϕ, 3 layers in depth

- **Complicated geometry →** difficult to achieve high precision during construction!
  - → Constant term!!





The CMS EM Calorimeter

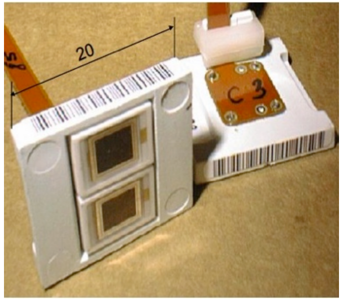
Homogenous $PbWO_4$ (PWO) ECAL:

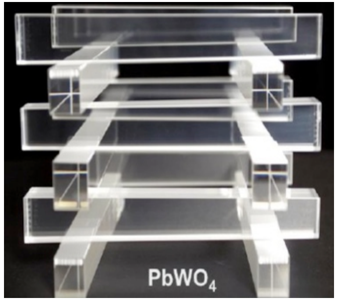
- **very low stochastic term**, excellent energy resolution, but response impacted by radiation (laser correction necessary)
- $PbWO_4$: $8.3 g/cm^3$, X_0=8.9mm, R_M=22mm, Refr. index: 2.3, light yield: 100γ/MeV.
- Readout via Avalanche photodiodes (APD) in the barrel and Vacuum phototriodes (VPT) in the endcaps

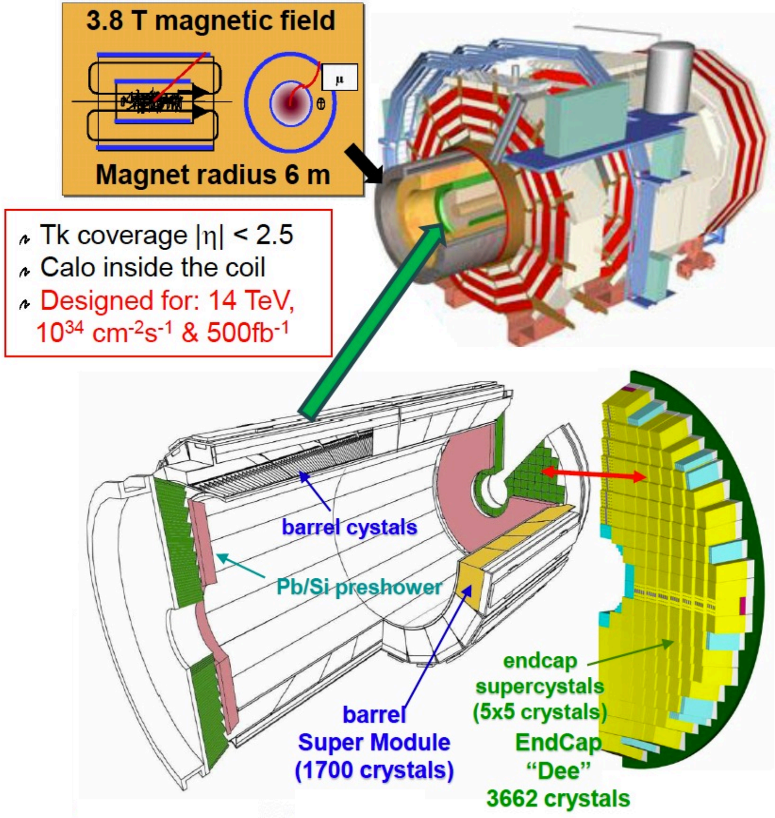
No longitudinal segmentation

Coverage: $|\eta|<3.0$, Preshower (ES) $1.65<|\eta|<2.6$

Design resolution: $\frac{\sigma(E)}{E} = \frac{3\%}{\sqrt{E}} \oplus \frac{0.2}{E} \oplus 0.3\%$







ATLAS – CMS Comparison (EM)

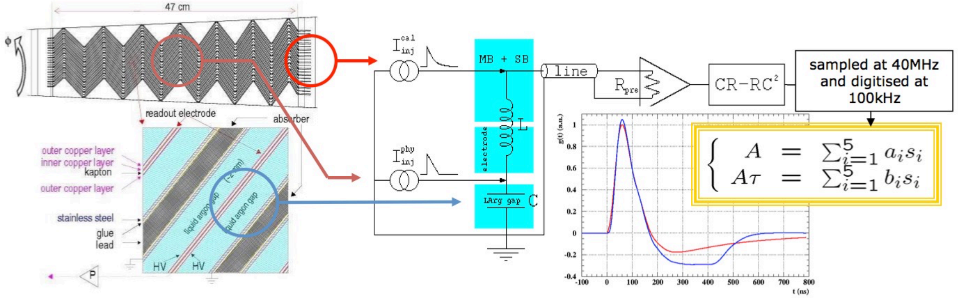
ATLAS

- Sampling calorimeter (LAr-Pb), 3 longitudinal layers + presampler, 173000 channels), E range MIP – TeV
- High lateral granularity
  - $\Delta\eta=0.0031$, $\Delta\phi=0.025$
- Radiation resistance
- Good energy resolution
- Very stable response in time
  - rms in time ≈$3\text{x}10^{-4}$
- Outside solenoid field (behind the coil) → 3 – 6 X_0 in front
- Main correction: dead material correction using presampler
- Strength: background rejection (e.g. π^0), stability, photon vertex measurement (pointing)

CMS

- Homogeneous calorimeter (75000 $PbWO_4$ crystals + PS in forward direction), E range MIP – TeV
- High lateral granularity
  - $\Delta\eta=\Delta\phi=0.0175$
- Radiation resistance
- Excellent energy resolution
- Response impacted by radiation
  - after laser correction rms ≈$2\text{x}10^{-3}$
- Inside strong solenoid field → only 0.4 – 1.9 X_0 in front
- Main correction: Laser correction to compensate impact of radiation
- Strength: little material in front, energy resolution

The Calibration Challenge ATLAS – Cell Response



- Concept of **LAr calorimeter electronics calibration** is to **inject a well known exponential pulse** as close as possible to the point where the ionization pulse is created → **extract gain R and pulse shapes, update DB every month**.
- **Noise runs** to measure **pedestal P**
- **In addition baseline shift** in presence of **pile-up** for finite bunch trains → Correction derived from measured pulse-shapes

$F_{\mu A \to MeV}$: current to energy conversion including sampling fraction, initial value from Test-Beam

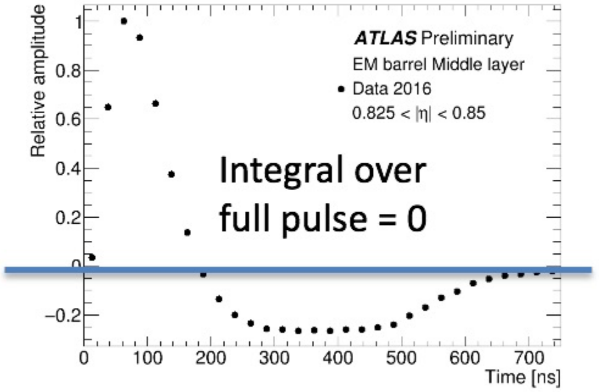
R electronics gain ($ADC \to \mu A$)

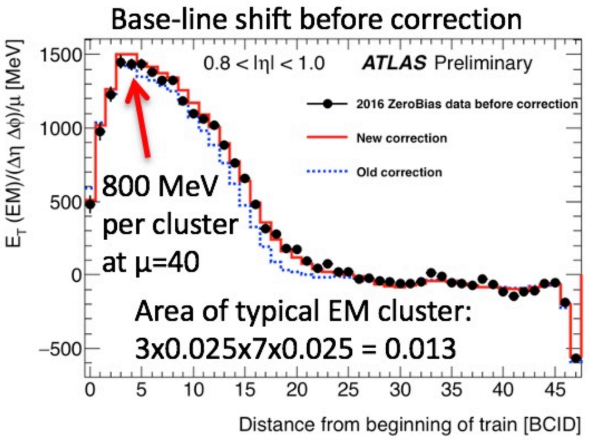
P pedestal

$$E_{cell} = F_{\mu A \to MeV} \,.\, M_{cal}/M_{phys} \,.\, R \,.\, \Sigma\, a_i\, (ADC_i - P)$$

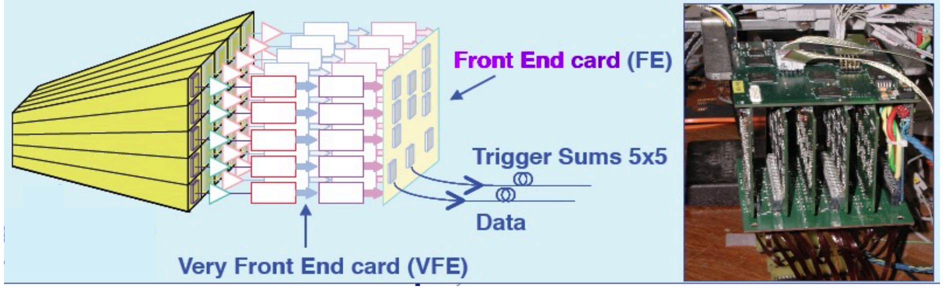
M_{cal}/M_{phys} : correct bias from calibration / physics difference

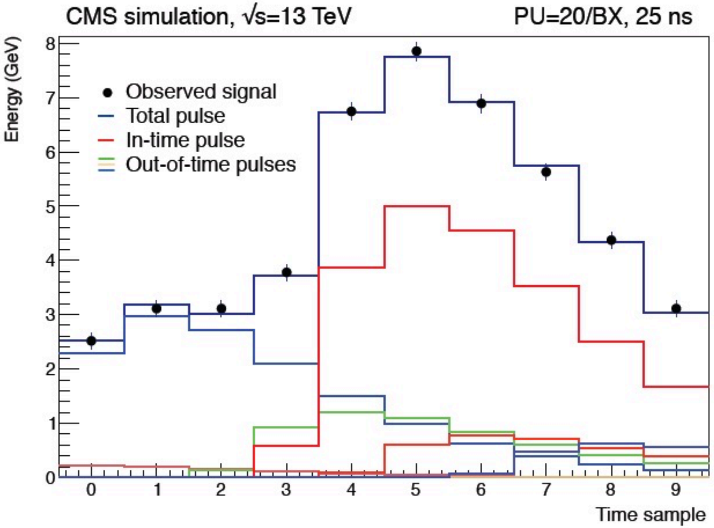
a_i : Optimal Filter Coefficient to estimate pulse amplitude





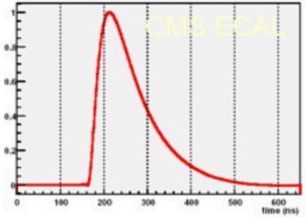
The Calibration Challenge CMS – Cell Response

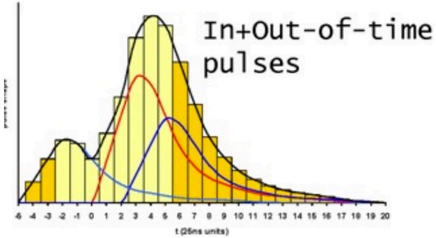




For Run-2 use out-of-time pile-up resistant multifit algorithm

- **Pulse shape** is modeled as a sum of one **in-time pulse plus** up to **9 out-of-time pulses**
- **Minimize χ^2 distribution** for best description of the in-time amplitude
- **Pulse shapes** (binned templates) extracted periodically from **LHC isolated bunches**
- Baseline and electronics noise from calibration runs



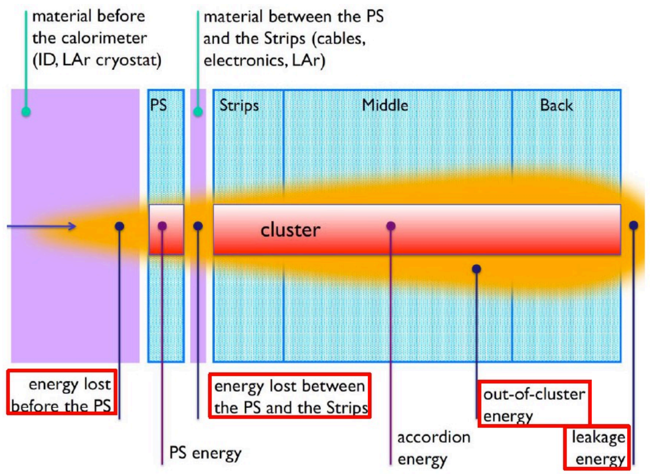


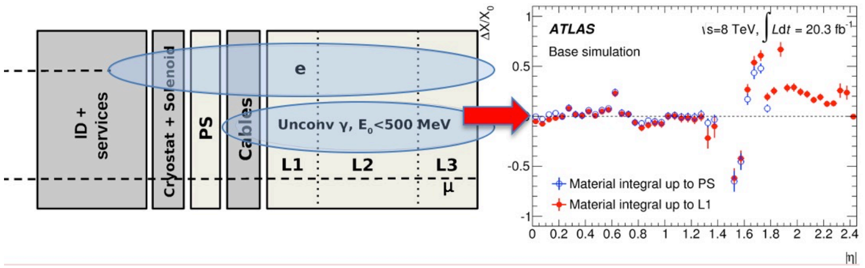
Time samples   Max 10 pulses

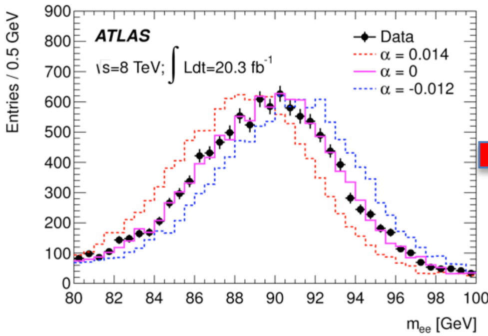
$$\chi^2 = \sum_{i=1}^{10} \frac{\left(S_i - \sum_{j=1}^{M} A_j \times p_{ij}\right)^2}{\sigma_{S_i}^2}$$

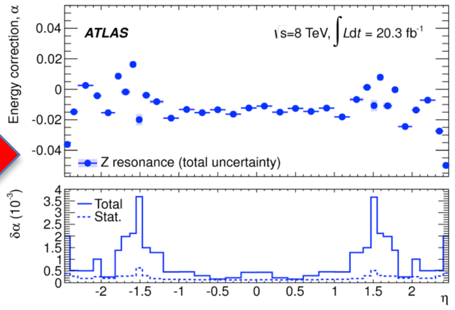
The Calibration Challenge ATLAS – Corrections

- Between **5% and 15%** of the particle energy is not reconstructed in the the cluster and needs to be corrected for.
- MVA based calibration based on MC:
  - Target: E_{true}/E_{meas}.
  - Inputs: E_{acc}, E_0, η, ϕ, shower-depth, shower-width (and extra variables for converted photons)
- On top of that data driven correction of PS scale, L1/L2 and Material in front of the calorimeter
  - $e^{\pm}$ → material up to L1,
  - unconverted γ for material between PS(L0) and L1
- Absolute scale calibration from Z-peak



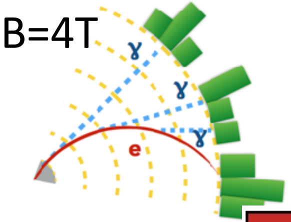


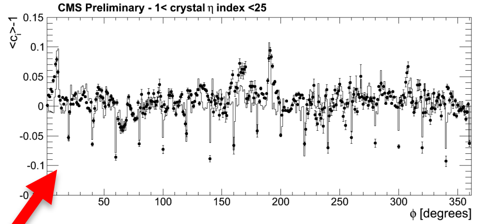




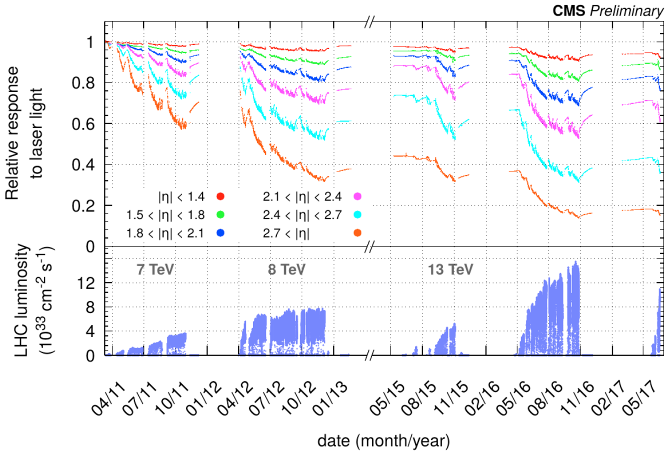
The Calibration Challenge CMS – Corrections

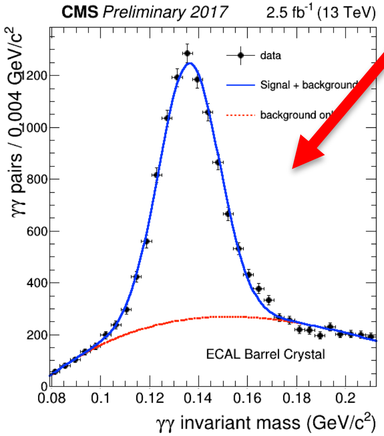
- **Sources of response variations under irradiation**:
  - **crystal transparency** (time dependent), **$PbWO_4$ crystals** partially **recover** during periods with no exposure
  - VPT conditioning in the endcaps
- Response **monitored with a laser system** injecting light in every ECAL crystal
- Several **data driven** methods used to **equalize the response** of **each single crystal** to the deposited energy.
- **Dynamic clustering** to recover energy radiated upstream of ECAL via **Bremsstrahlung** or conversions

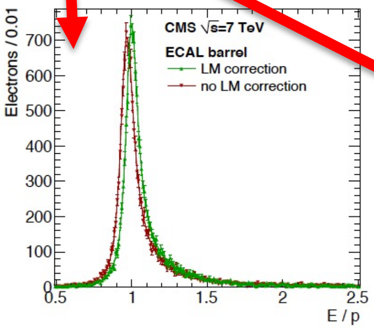


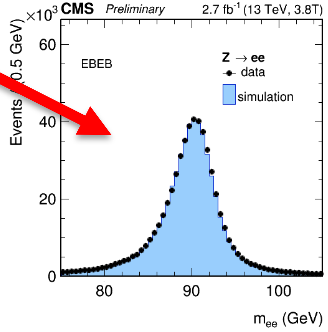


method	time needed	Run I precision
ϕ-symmetry	few days	1-3% in EB 3-5% in EE
$\pi^0/\eta \rightarrow \gamma\gamma$	1 month	0.5% in EB 3% in EE (|η|<2)
electron E/p	20 fb^{-1}	0.5% in EB 2% in EE
Z→ee mass	20 fb^{-1}	equalise the scale vs η in EE



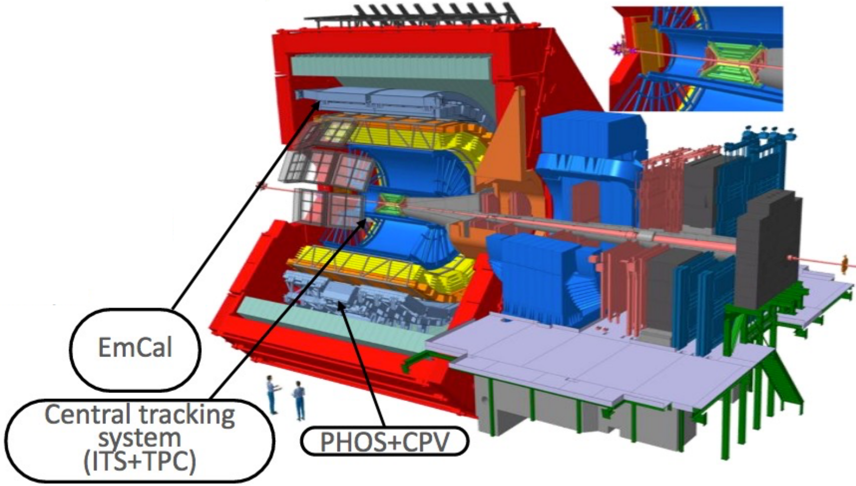


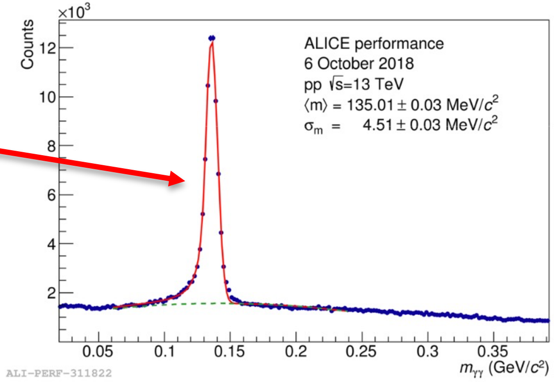




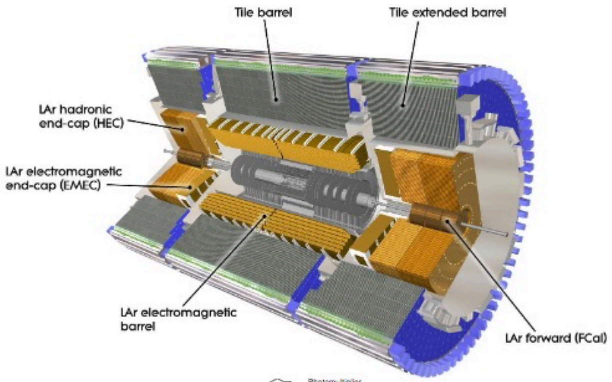
ALICE EMCal & PHOS

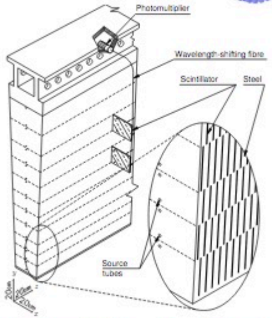
	EMCal/DCal	PHOS
Active element	Sampling 77 layers (1.44 mm Pb, 1.6 mm Sc) with WSF light collection	Homogeneous crystals $PbWO_4$
Molière radius	3.2 cm	2.0 cm
Photodetector	APD 5×5 mm^2	APD 5×5 mm^2
Depth	20 X_0	20 X_0
Acceptance	Run 1: EMCal: $\lvert\eta\rvert<0.7$, $80 < \varphi < 180°$ Run 2: EMCal: $\lvert\eta\rvert<0.7$, $80 < \varphi < 187°$ DCal: $0.22<\lvert\eta\rvert<0.7$, $260 < \varphi < 320°$, $\lvert\eta\rvert<0.7$, $320 < \varphi < 327°$	Run 1: $\lvert\eta\rvert<0.12$, $260 < \varphi < 320°$ Run 2: $\lvert\eta\rvert<0.12$, $250 < \varphi < 320°$
Granularity	Cell 6×6 cm^2 $\Delta\varphi\cdot\Delta\eta = 0.0143\cdot0.0143$ rad	Cell 2×2 cm^2 $\Delta\varphi\cdot\Delta\eta = 0.0048\cdot0.0048$ rad
Modularity	EMCal: 10+2(1/3) modules DCal: 6(2/3) + 2(1/3) modules 17664 cells	3+1/2 modules 12544 cells
Dynamic range	0-250 GeV	0-100 GeV
Energy resolution	$\sigma_E/E = 4.8\%/E \oplus 11.3\%/\sqrt{E} \oplus 1.7\%$	$\sigma_E/E = 1.8\%/E \oplus 3.3\%/\sqrt{E} \oplus 1.1\%$
Distance from IP	428 cm, 0.7-0.9 X_0	460 cm, 0.2 X_0

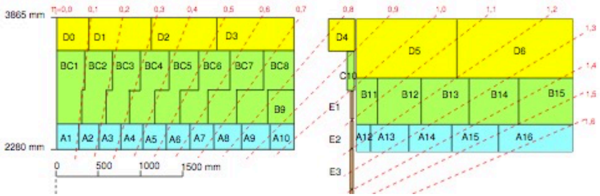




The ATLAS Hadronic Barrel Calorimeter







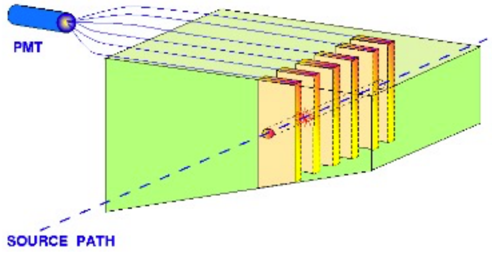
The Tile Calorimeter

- Central hadronic calorimeter($|\eta|$<1.7) in ATLAS detector
- Used to measure the 4-vectors of the jets and the missing transverse energy and in the ATLAS Level-1 trigger
- Sampling calorimeter: steel and scintillating plastic tiles
- Double photomultiplier readout using wave length shifting fibers
- 9892 PMTs
- 10 interaction lengths at eta=0 (EM+HCAL)
- Achieved single $\pi^{\pm}$ resolution (TB):

$$\frac{\sigma(E)}{E} = \frac{52.9\%}{\sqrt{E}} \oplus 5.7\%$$

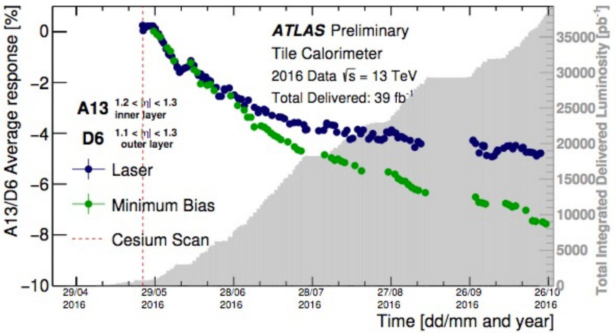
The Calibration Challenge – ATLAS TileCal

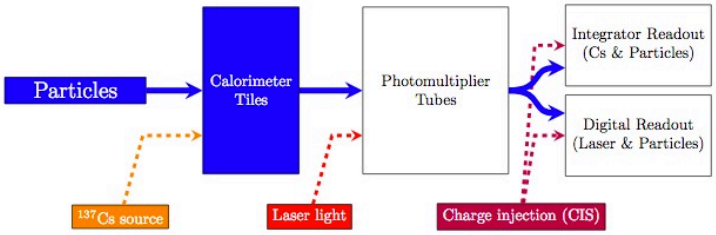
$$E\ [\mathrm{GeV}] = A\ [\mathrm{ADC}] \cdot C_{\mathrm{ADC}\to\mathrm{pC}} \cdot C_{\mathrm{pC}\to\mathrm{GeV}} \cdot C_{\mathrm{TileSize}} \cdot C_{\mathrm{Cs}} \cdot C_{\mathrm{Las}}$$



- Systems used for calibration in Tile calorimeter
  - Charge Injection System (CIS): Calibrates the response of ADCs: $C_{\mathrm{ADC}\to\mathrm{pC}}$
  - Cesium system: Calibrates optical components and PMT gains: C_{Cs}
  - Laser System: Calibrates variations due to electronics and PMTs: C_{Las}
  - Minimum Bias System (MB): Calibrates optical components and PMT gains
- $C_{\mathrm{pC}\to\mathrm{GeV}}$ EM scale constant measured during test beam campaigns
- C_{TileSize} correction addressing the different size of tiles in different layers

- Cell response is not constant in time due to the PMT gain variation and scintillator degradation due to the exposure to beam





In addition calibration with physics events:

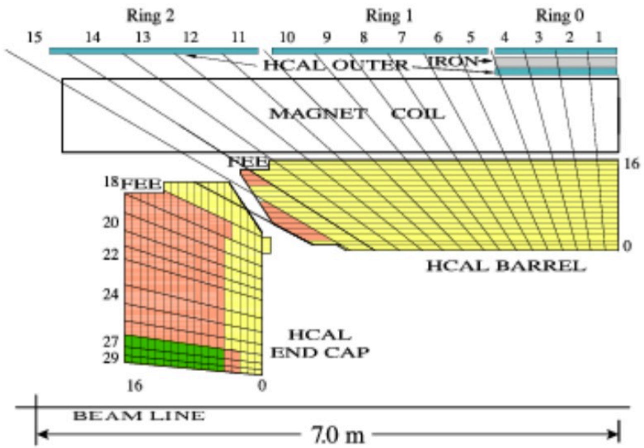
- Low p_T: Balance of Z→ll and a jet,
- Medium p_T: Balance of a photon γ and a jet
- High p_T: Multi-jet balance

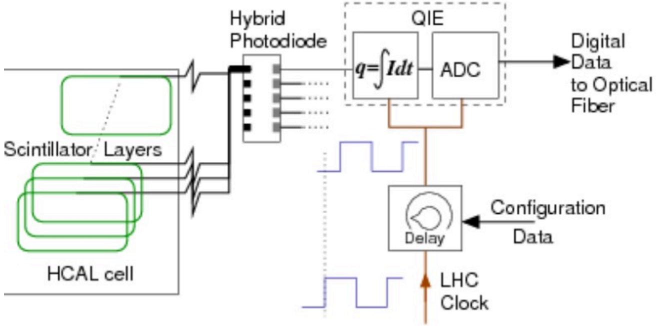
The CMS Hadronic Barrel Calorimeter

The CMS hadronic calorimeter (HCAL)

- Sampling calorimeter made of brass and plastic scintillator tiles.
- The tiles are arranged parallel to the beam axis in the barrel.
- The scintillation light is shifted in the visible region via wave-length shifting fibers and detected with HPD (hybridphotodiodes). One HPD can read multiple channels.
- 7 interaction lengths at eta=0 (EM+HCAL) → leakage
- Achieved single $\pi^{\pm}$ resolution:

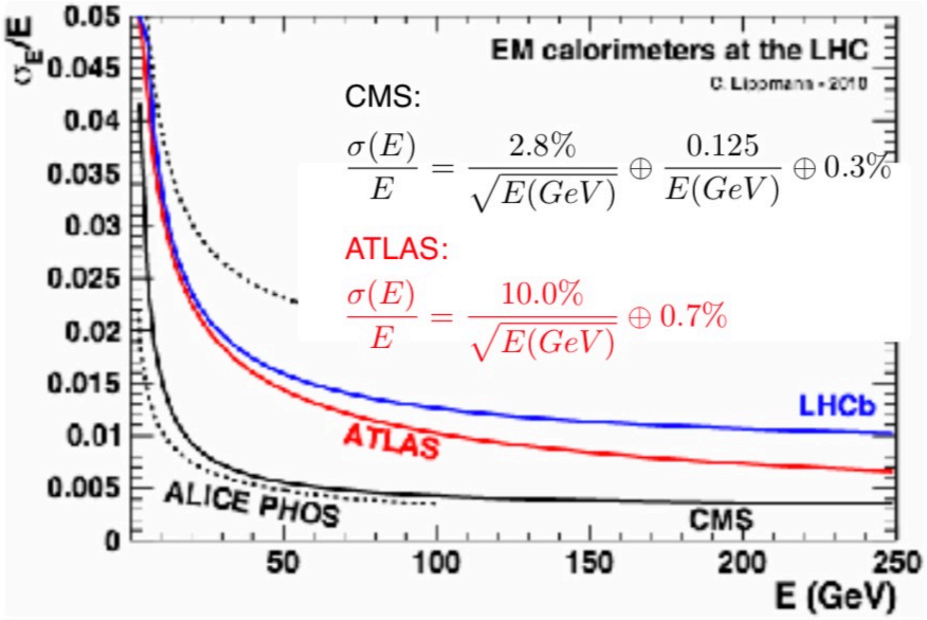
$$\frac{\sigma(E)}{E} = \frac{84.7\%}{\sqrt{E}} \oplus 7.4\%$$



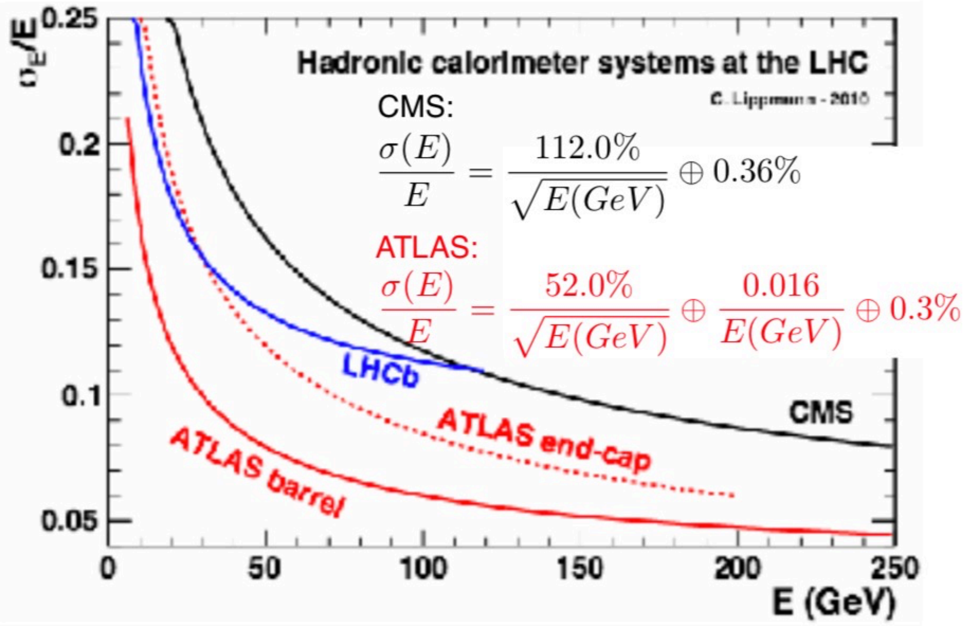


Resolution Comparison (Testbeams)

electrons



pions



EXAMPLES OF HL-LHC UPGRADES AND FUTURE COLLIDERS

HL-LHC Upgrade – CMS HGCal

CMS High Granularity CALorimeter

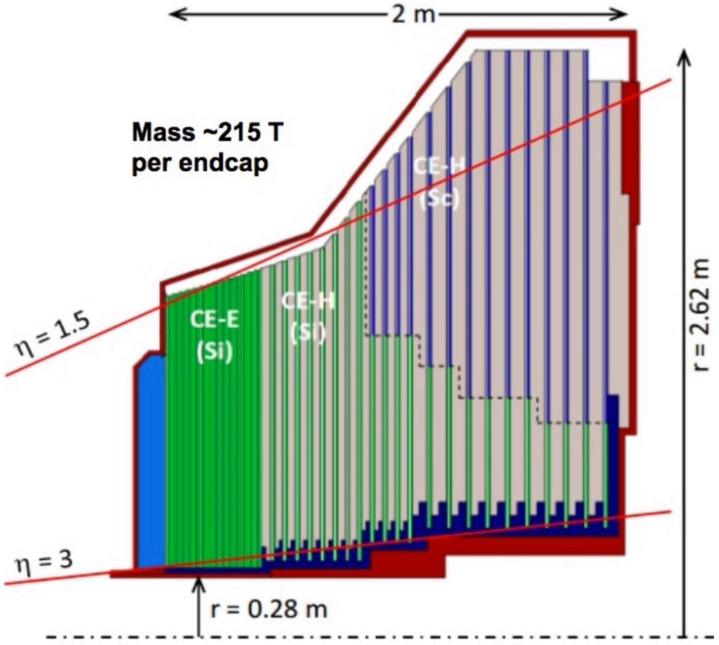
To sustain the harsh environment of HL-LHC run, forward region of CMS will be replaced by High Granularity Calorimeter (HGCAL).

Active Elements:

- Electromagnetic part of HGCAL:
  - **CE-E** : **Si** sensors as active layers, Cu/CuW/ Pb absorber
  - **28 layers, 25 X_0 & ~1.3 λ**
- Hadronic part of HGCAL:
  - **CE-H** : **Si** & **SiPM-on-scintillator** as active layers, steel absorbers
  - **22 layers, ~7.2 λ**

Key-parameters:

- HGCAL covers 1.5 < |η| < 3.0
- Full system maintained at -30°C
- **~640 m² ** of Si sensors & **~370 m²** of scintillators
- **6.1M Si channels**

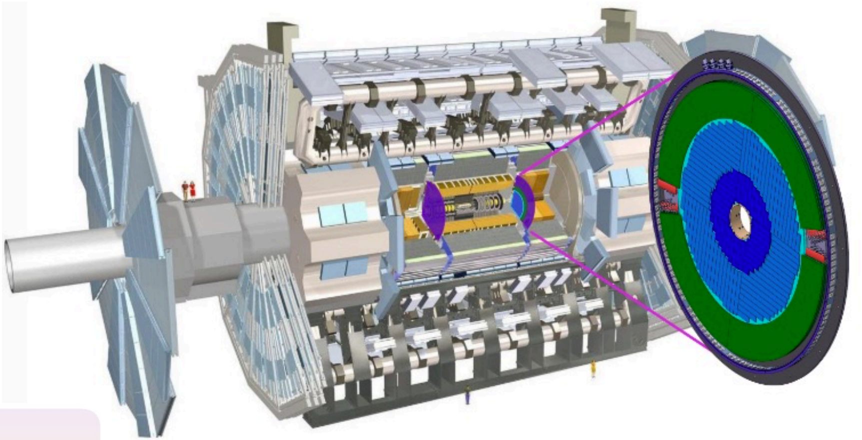


For more details, see the talk Status and plans for the CMS HGCAL upgrade project by Felix Sefkow

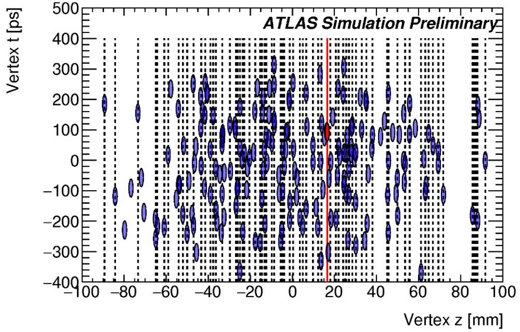
See 3rd calorimetry lecture by. K. Krüger (26.2.2020)

HL-LHC Upgrades – MIP Timing Detectors

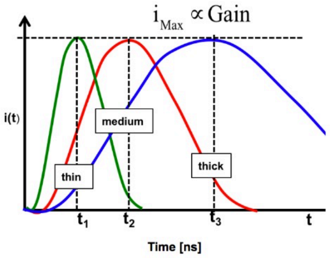
- Planned for HL-LHC in front of EM calorimeters to help mitigate pile-up
- ATLAS HGTD
  - Si LGAD
- CMS BTL
  - LYSO+SiPM
- CMS ETL
  - Si LGAD

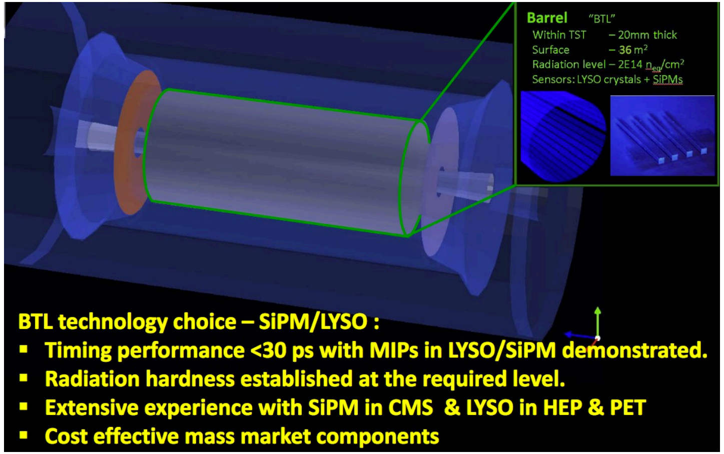


$$\sigma_t^2 = \sigma_{LandauNoise}^2 + \sigma_{TimeWalk}^2 + \sigma_{Jitter}^2 + \sigma_{TDC}^2$$



$$\sigma_{Jitter}^2 = \left(\frac{t_{rise}}{S/N}\right)^2$$

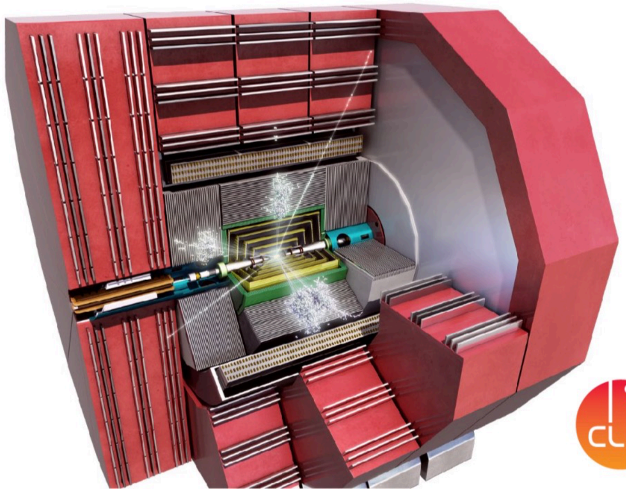


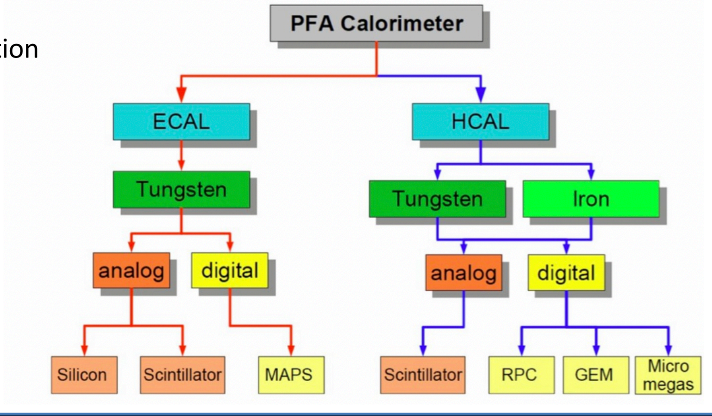


CLIC/ILC – CALICE

See 3rd calorimetry lecture by. K. Krüger (26.2.2020)

- **CALICE Collaboration** (https://twiki.cern.ch/twiki/bin/view/CALICE/CalicePapers)
- **CLIC/ILC calorimeters optimized for Particle Flow (PF)**
  - Radiation tolerance and bandwidth requirements benign compared to LHC
  - But ***higher precision requirements***! (2x for jet energies, 10x for track momenta)
  - High jet energy resolution (3-4% → ~30%/√E)! Separate W and Z decays!
  - Reconstruct each particle individually and use optimal detector (PF)
    - 60% charged, 20% photons, 10% neutral hadrons
  - Requires ***fine 3D segmentation*** (and sophisticated reconstruction software)
  - ECAL few 10 mm^2, HCAL 1-10 cm^2 - millions of channels
  - Granularity and timing (sub-ns accuracy) also essential for pile-up rejection
    - Dominant background from $\gamma\gamma \rightarrow$ hadrons
- **Technologies considered:**
  - Large area silicon arrays
  - New segmented gas amplification structures (RPC, GEM, Micromegas)
  - Silicon photomultipliers on scintillator tiles or strips
- **Large prototypes** exist and have been **tested in testbeams**





DESIGN EXERCISE

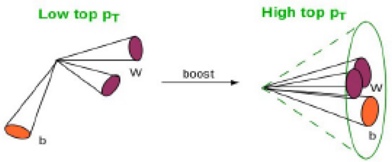
FCC-hh Calorimeter System – A Design Exersize

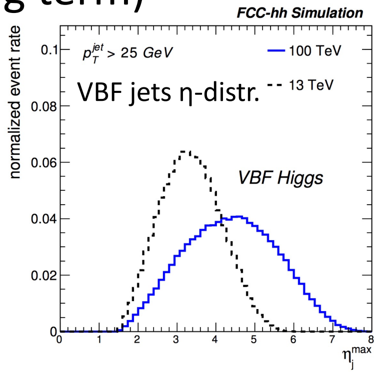
- **Hadron collider (pp)**
  - Up to 1000 collisions per bunch crossing
  - Centre of mass energy: 100TeV
- **Radiation in the barrel calorimeter:**
  - up to 100 kGy and
  - 1 MeV n eq. fluence of $5 \times 10^{15} cm^{-2}$
- **Which active material** for EM calo and HCAL?
- **Which general lay-out?**

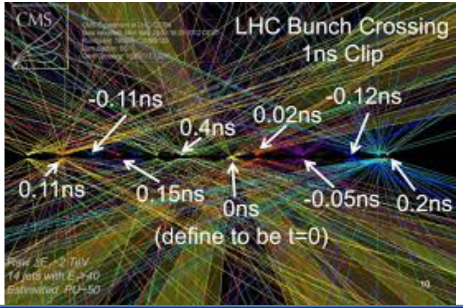
Requirements for FCC-hh Detector

Used in Delphes physics simulations

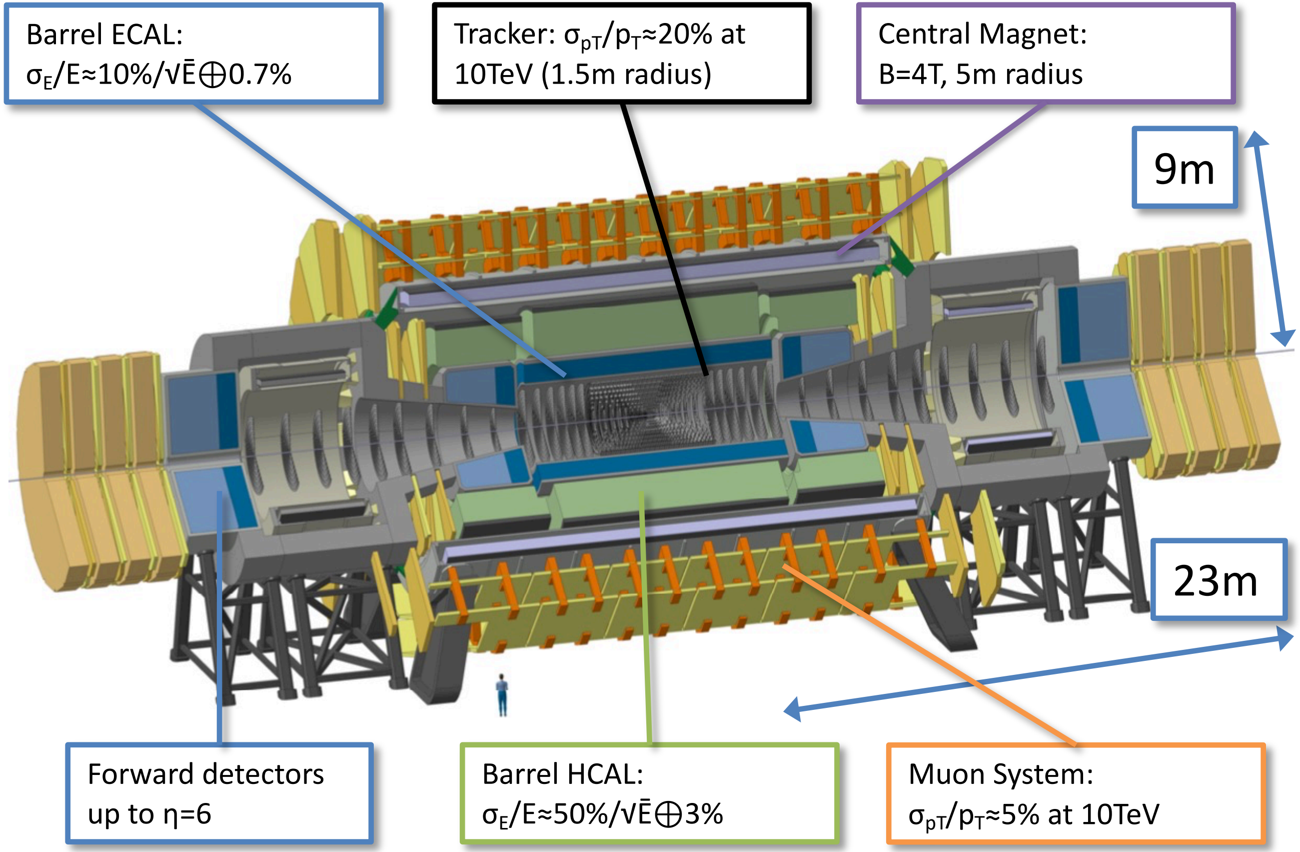
- **ID Tracking target**: achieve σ_{p_T} / p_T = 10-20% @ 10 TeV
- **Muons target**: σ_{p_T} / p_T = 5% @ 10 TeV
- Keep **calorimeter constant** term as small as possible (and good sampling term)
  - Constant term of <1% for the EM calorimeter and <2-3% for the HCAL
- **High efficiency b-tagging, τ-tagging, particle ID**!
- **High granularity** in tracker and calos
- **Pseudorapidity (η) coverage**:
  - Precision muon measurement up to |η|<4
  - Precision calorimetry up to |η|<6
- **→ Achieve all that at a pile-up of 1000! → Granularity & Timing!**
- **On top of that radiation hardness and stability!**





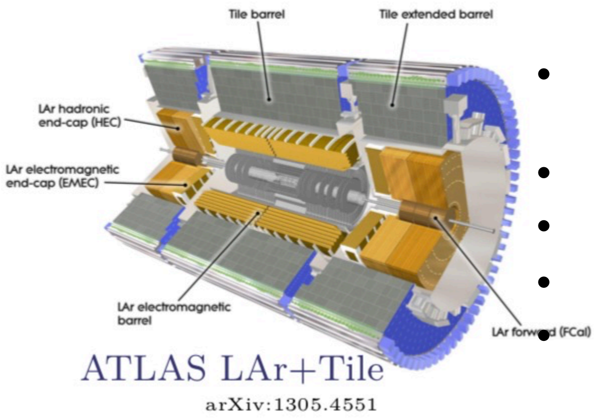


A Possible FCC-hh Detector – Reference Design for CDR



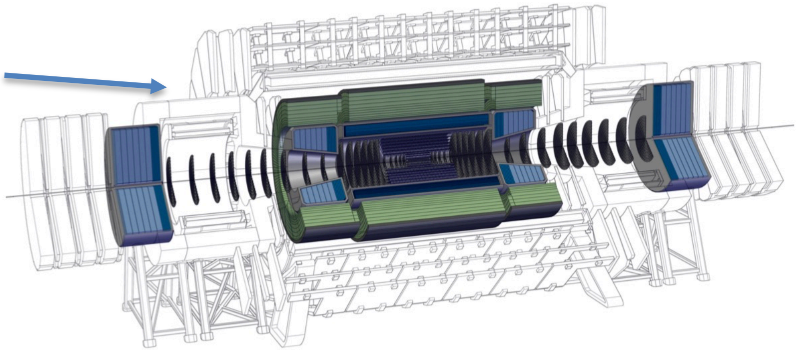
- **Reference design for an FCC-hh experiment developed to demonstrate feasibility of an experiment exploiting full physics potential**
- **→ Input for radiation simulations**
- **→ Input for Delphes physics simulations**
- Room for other ideas, other concepts and different technologies

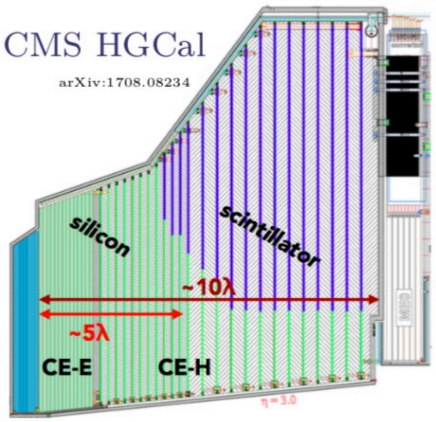
FCC-hh Calorimetry



- Good instrinsic energy resolution
- Radiation hardness
- High stability
- Linearity and uniformity
- Easy to calibrate

FCC-hh Calorimetry



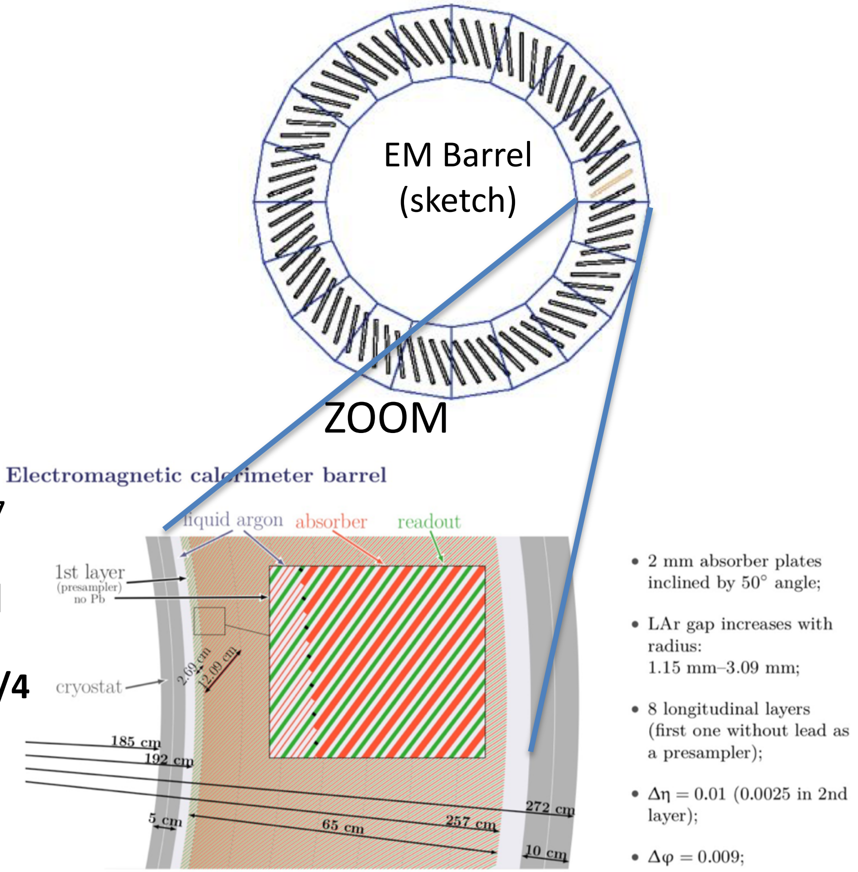


- High granularity
  - → Pile-up rejection
  - → Particle flow
  - → 3D/4D/5D imaging

Reference Detector, Calorimetry:
ECAL, Hadronic EndCap and Forward (≥30X_0):
LAr / Pb (Cu) (see next slide)
HCAL Barrel and Extended Barrel (≥10λ):
Scintillating tiles / Fe(+Pb) with SiPM

FCC-hh Electromagnetic Calorimeter (ECAL)

- Compared to ATLAS, **FCC-hh Calo** needs **finer longitudinal and lateral granularity**
  - **Optimized for particle flow**
  - **8 longitudinal compartments**, fine lateral granularity
  - **Granularity:** $\Delta\eta \times \Delta\phi \approx 0.01 \times 0.01$; first layer $\Delta\eta \times \Delta\phi \approx 0.0025 \times 0.02$ → ~2.5M channels
- **Noble liquid (LAr) as active material**
  - Radiation hardness, linearity, uniformity, stability
- **Possible only with straight multilayer electrodes**
  - Straight absorbers (Pb + stainless steel sheets in EM section) → no accordion!
  - Readout and HV on straight multilayer electrodes (PCBs, 7 layers, 1.2mm thick)
- **EM Barrel:** Absorbers 50° inclined with respect to radial direction
  - **→ Sampling fraction changes with depth $f_{sampl} \approx 1/7$ to $1/4$**
  - **→ LAr gap 2 x 1.15mm to 2 x 3.09mm**
  - **→ Longitudinal segmentation essential to be able to correct!**

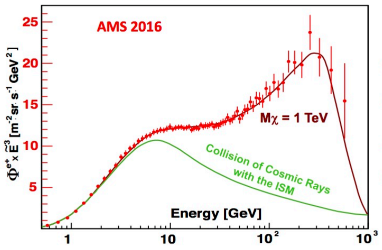


EXAMPLES OUTSIDE COLLIDER PHYSICS

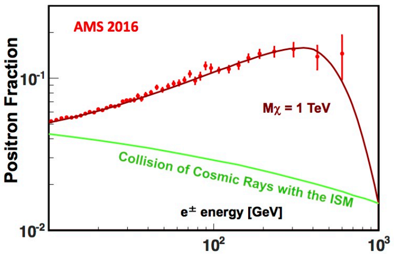
AMS

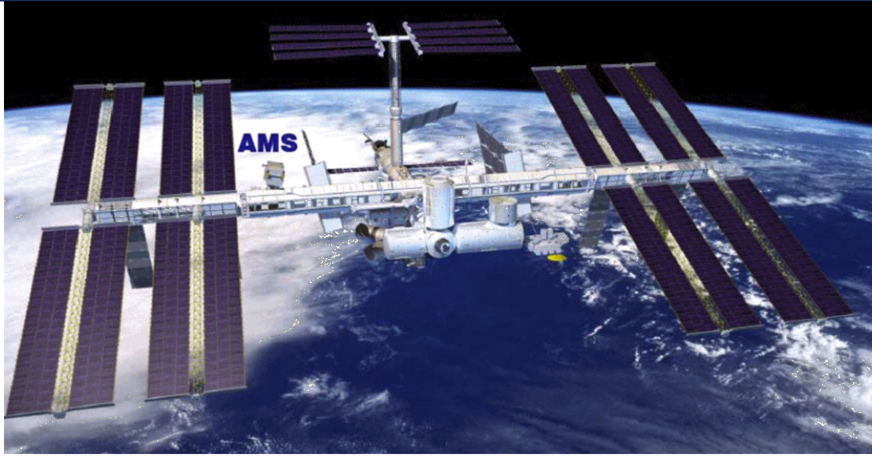
AMS-02 was installed on ISS on May 2011 and is expected to operate for 10-20 years collecting about 160-320 billions of events.

Positron Spectrum



Positron Fraction

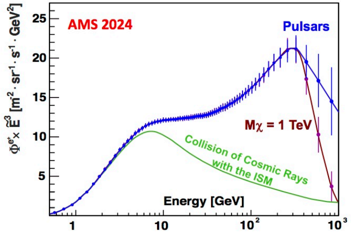


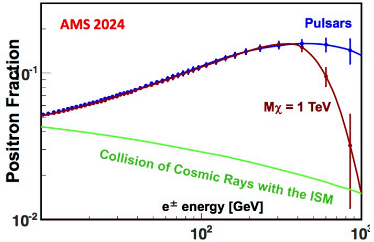


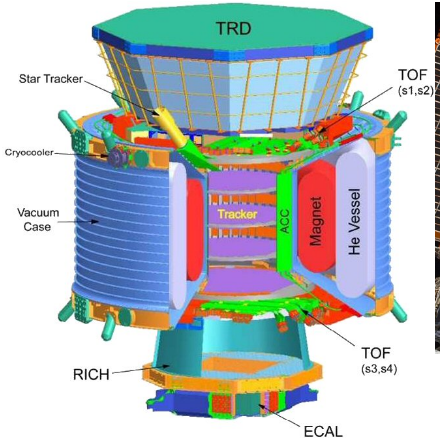
Positron Spectrum

Positron Fraction

By 2024 we will should be able understand the origin of this unexpected data.

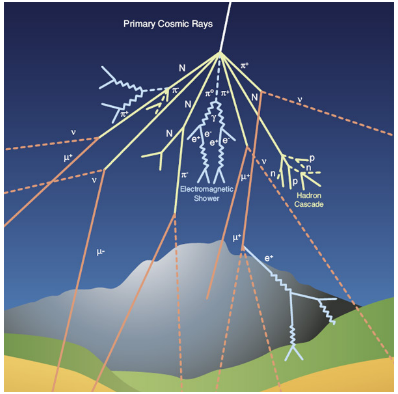






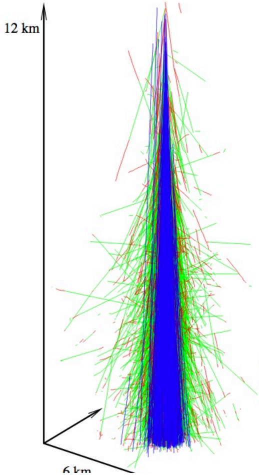
ECAL is a lead-scintillating fibre sandwich with an active area of 648x648 mm^2 and a thickness of 166mm for a weight of ~500 kg (17X_0). Fibres read out with PMTs

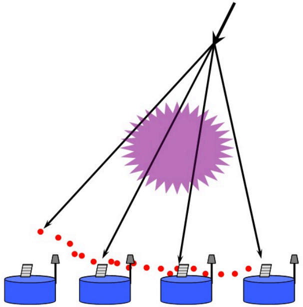
Auger Observatory

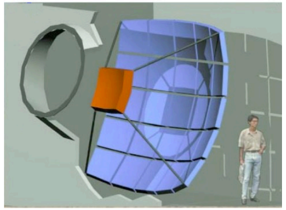


Hybrid Detection Technique

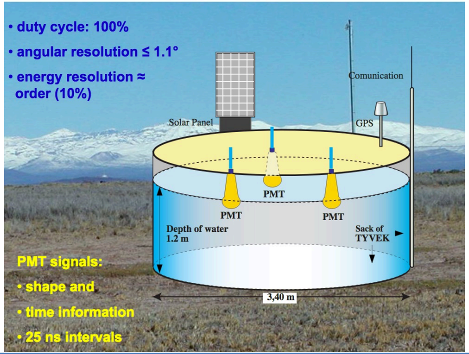
- longitudinal shower profiles by fluorescence light in atmosphere
- lateral particle distribution at ground



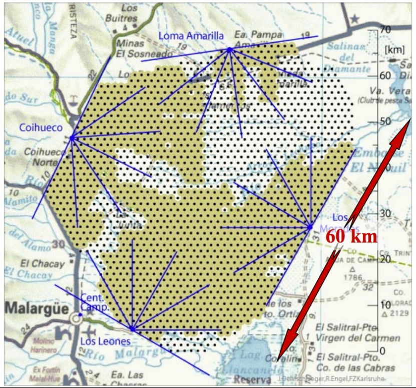


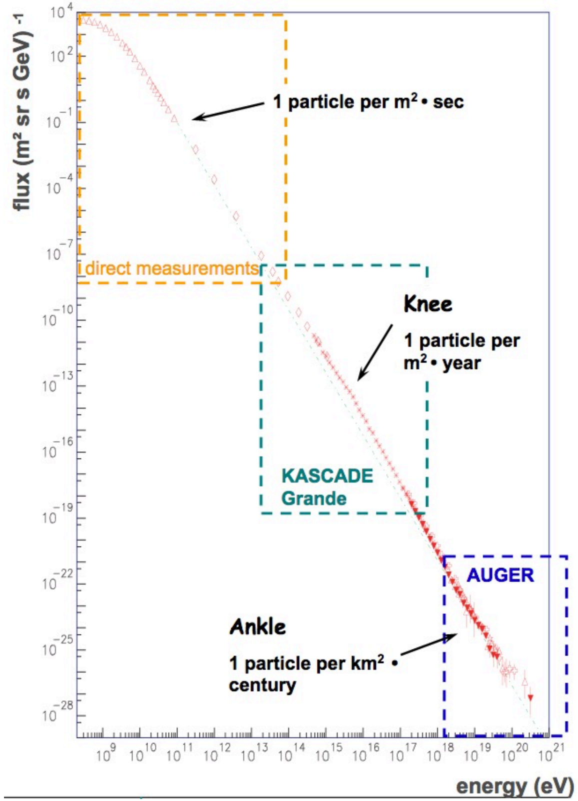


Water Cherenkov Tanks



Layout of Southern Observatory





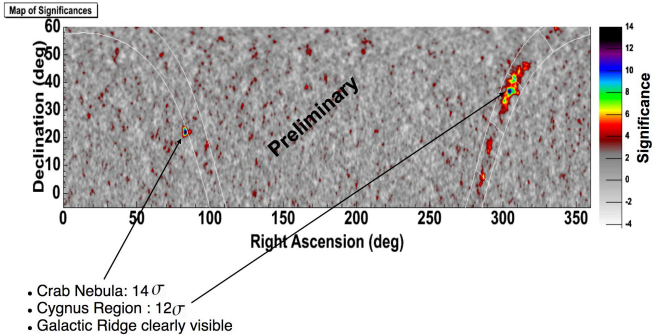
- Auger observatory to measure cosmic ray spectrum (esp. $E > 5\ 10^{18}$eV
- Use athmosphere as absorber
- Detection:
  - Water Cherenkov tanks
  - Fluorescence light detectors

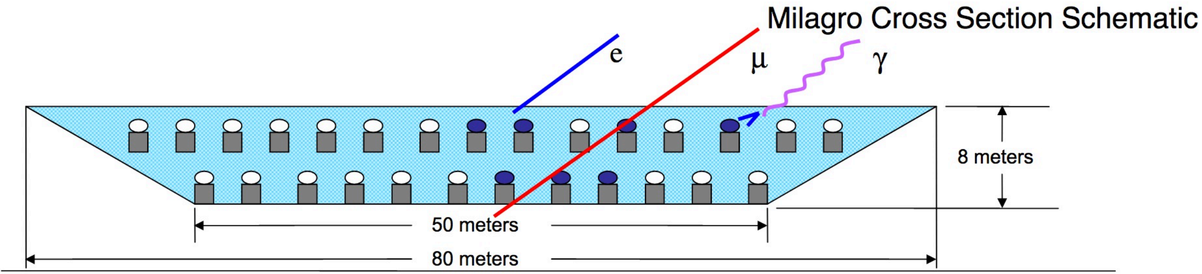
MILAGRO

The Milagro TeV γ-ray Detector:

- Water Cherenkov detector Located in Jemez Mountains near Los Alamos
- Central pond: 80m x 60m x 8m (depth) (5000 m^2)
  - Top layer: 450 PMTs under 1.4 m
  - Muon layer: 273 PMTs under 6 m
- 0.1 – 100 TeV energy range
- Atmosphere acts as an absorber:
  - 750 g/cm^2 overburden (73% of Atmosphere, 2630m altitude)
  - 20.5 X_0 for gamma-ray showers and 8.3 λ for hadronic showers
  - Milagro is thus a " Tail catcher Calorimeter"

TeV Sky Map Survey 2006





Summary

- **Calorimeter systems are an essential part of all High Energy Physics Experiments**
  - They do not only measure energy
  - Particle Identification, position and time measurement are as important
  - They are fast (trigger capability)
  - Performance usually improves with energy (statistical processes)
- **Benchmarks for the performance** are coming from **physics requirements** – very different for each experiment → there is **nothing such the "ideal" calorimeter**
- **Exact and constant calibration** of such systems is crucial (systematic errors!)
- **Huge calorimeter systems in operation in LHC Experiments**, need ~50FTEs for operation and calibration

Few References and Further Literature

- R. Wigmans, “Calorimetry, Energy Measurements in Particle Physics”, Oxford science publications
- ATLAS & CMS Calorimeter TDRs
- ATLAS & CMS Detector Paper J. Instrum., 3 S08003 and 3 S08004 (2008)
- PDG (http://pdg.lbl.gov/)
- H.-C. Schultz-Coulon and J. Stachel The Physics of Particle Detectors http://www.kip.uni-heidelberg.de/~coulon/Lectures/Detectors/
- CALOR Conference Series, e.g. http://www.hep.anl.gov/CALOR06/
- CHEF Conference Series, e.g. https://indico.cern.ch/event/818783/

BACK-UP SLIDES

Ionization Energy Loss

- **Bethe-Bloch Formula** (energy loss for heavy charged particles → not for electrons!)
  - Interaction dominated by elastic collisions with electrons

PDG 2010

$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

$K = 4\pi N_A r_e^2 m_e c^2 = 0.307$ MeV g^{-1} cm^2

$T_{max} = 2 m_e c^2 \beta^2 \gamma^2 / (1 + 2\gamma\, m_e/M + (m_e/M)^2)$

[Max. energy transfer in single collision]

z : Charge of incident particle
M : Mass of incident particle

Z : Charge number of medium
A : Atomic mass of medium

I : Mean excitation energy of medium
δ : Density correction [transv. extension of electric field]

$N_A = 6.022 \cdot 10^{23}$
[Avogardo's number]

$r_e = e^2/4\pi\varepsilon_0 m_e c^2 = 2.8$ fm
[Classical electron radius]

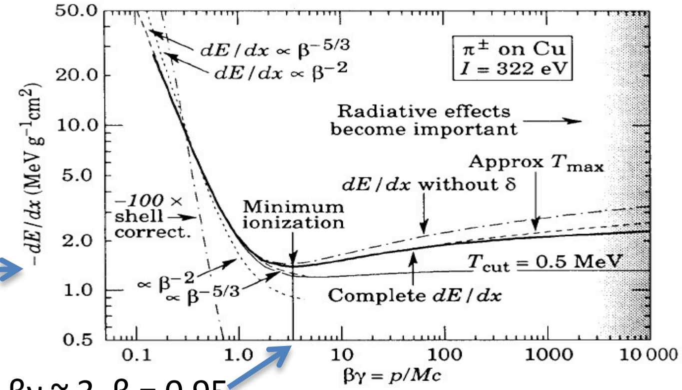
$m_e = 511$ keV
[Electron mass]

$\beta = v/c$
[Velocity]

$\gamma = (1-\beta^2)^{-2}$ - ½
[Lorentz factor]

Validity:
$.05 < \beta\gamma < 500$
$M > m_\mu$

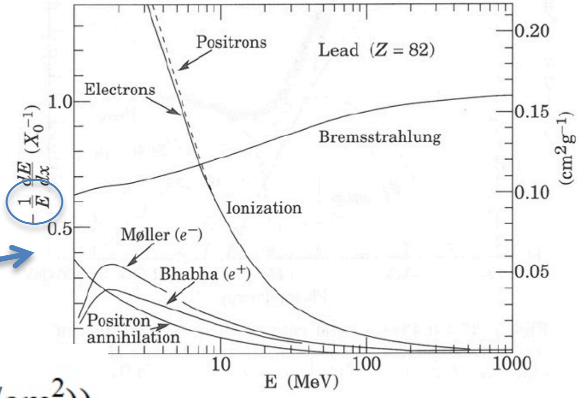
Courtesy calorimetry lecture H.-C. Schultz-Coulon



βγ ~ 3, β = 0.95

- **Ionization for electrons** is more complicated:

$$-\frac{dE}{dx} = k \frac{Z}{A} \frac{1}{\beta^2} \left\{ \ln \frac{\gamma m_e c^2 \beta \sqrt{\gamma - 1}}{I\sqrt{2}} + \frac{1}{2}(1-\beta^2) - \frac{2\gamma - 1}{2\gamma^2} \ln 2 + \frac{1}{16} \left(\frac{\gamma - 1}{\gamma} \right)^2 \right\} \text{ (MeV/ (g/cm}^2\text{))}$$



Relative energy loss of e±

Bremsstrahlung - Electrons

Bremsstrahlung

Arises if particles are accelerated in Coulomb field of nucleus

$$\frac{dE}{dx} = 4\alpha N_A \frac{z^2 Z^2}{A}\left(\frac{1}{4\pi\epsilon_0}\frac{e^2}{mc^2}\right)^2 E \ln\frac{183}{Z^{\frac{1}{3}}} \propto \frac{E}{m^2}$$

→ energy loss proportional to $(Z^2/A)(E/m^2)$

$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 \cdot E \ln\frac{183}{Z^{\frac{1}{3}}}$$

$$-\frac{dE}{dx} = \frac{E}{X_0} \quad \text{with} \quad X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln\frac{183}{Z^{\frac{1}{3}}}} \quad \Rightarrow \quad E = E_0 e^{-x/X_0}$$

[Radiation length in g/cm^2]

Radiation length X_0 is the thickness of material that reduces the mean energy of a beam of high energy electrons by a factor e.
Approx.: $X_0 \cong 180A/Z^2$ g cm^{-2}

Critical Energy - Electrons

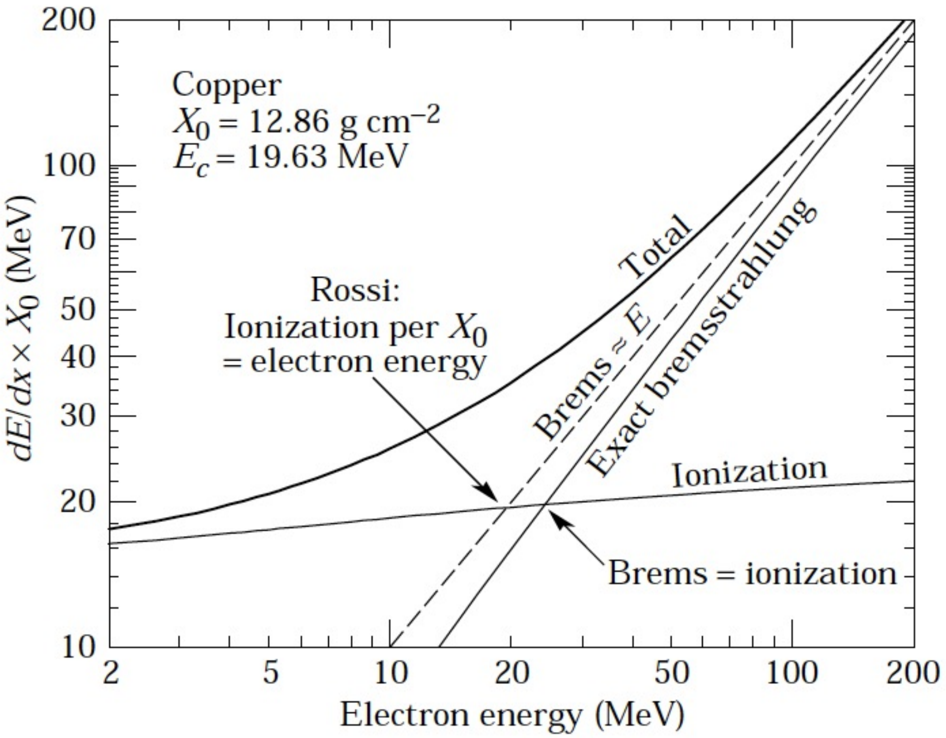
- **Critical energy** E_C:

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

$$E_c = \frac{610\ \text{MeV}}{Z + 1.24}$$

parameterization for solids and liquids

- **Electrons irradiate photons** until their energy becomes **less than E_C** (z.B. $E_C \cong 7$MeV for Pb).



Photons

- Photo-electric effect:

$$\sigma_{pe} \approx Z^5 \alpha^4 \left(\frac{m_e c^2}{E_\gamma}\right)^{\frac{7}{2}}$$ → $\sigma \approx Z^5, E^{-3.5}$

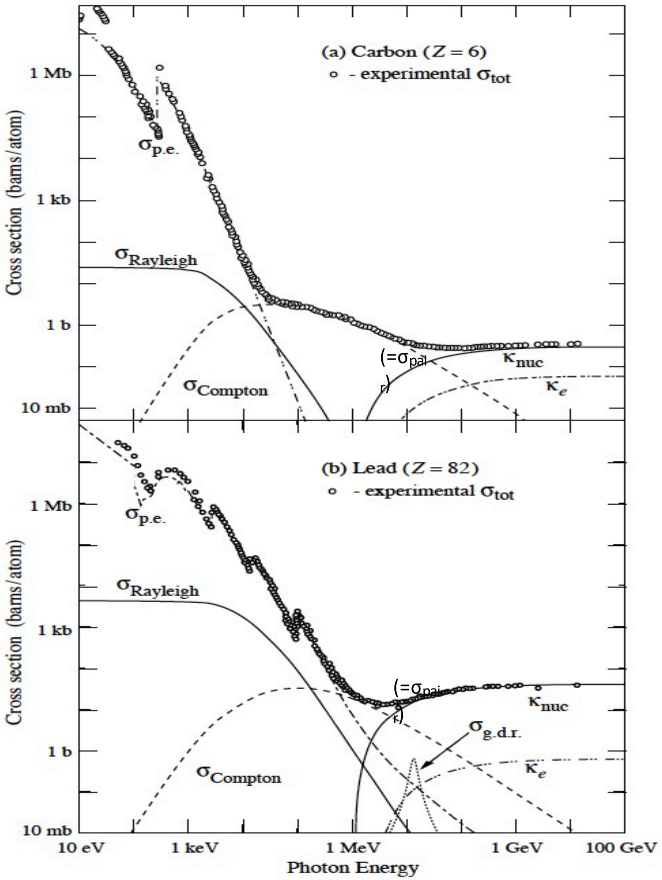
- Compton scattering:

$$\sigma_{Compton} \approx Z \frac{\ln E_\gamma}{E_\gamma}$$ → $\sigma \approx Z, E^{-1}$

- Pair-production
  - if $E_\gamma > 2m_e c^2 = 1.022\text{MeV}$

$$\sigma_{pair} \approx \frac{7}{9} \frac{A}{N_A} \frac{1}{X_0}$$ → $\sigma \approx Z(Z+1)$, $\ln E/m_e$ (<1GeV), then constant (>1GeV)

  - Probability of conversion in 9/7 X_0 is (1-1/e) (mean free path)



Summary – EM Showers

Electromagnetic showers are showers of Electrons and Photons

The most important processes at high energies are

- **Electrons/Positrons: Bremsstrahlung**
- **Photons: Pair production**

The typical length for these processes is the radiation length X_0.

All charged particles (here electrons and positrons) loose energy by ionization. For $E < E_C$ ionization dominates

EM Calorimeter Energy Resolution

- **Simple shower model**: The detectable signal is proportional to the total number of produced signal quanta *N* (e.g. e^--ion pair, scintillation photon)
- An estimation of the **energy resolution** is given by the **fluctuations of** the number ***N*** of produced signal quanta in the active medium (*N*: Poisson distributed). Need **average energy *W*** to produce 1 signal quantum.

$$N \approx \frac{E}{W}$$

Silicon detectors:	$W \approx$ 3.6eV
Gas detectors:	$W \approx$ 30eV
Plastic scintillators:	$W \approx$ 100eV
Liquid Ar:	$W \approx$ 23.3eV
Scint. crystal NaI:	$W \approx$ 25eV
Scint. crystal $PbWO_4$:	$W \approx$ 10keV

$$\frac{\sigma(E)}{E} \propto \frac{\sigma_N}{N} \approx \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}$$

Paremetrization of resolution:

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

stochastic/sampling term

noise term

constant term

$$\frac{\sigma_E}{E} \propto \sqrt{\frac{W}{E}}$$

Relative resolution improves with $1/E^{1/2}$

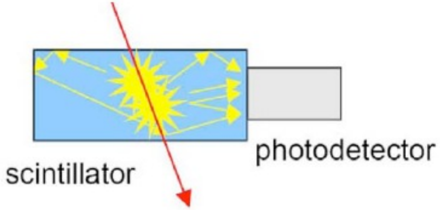
- Very simple model, reality is more complicated since the fluctuations are not independent (e.g. sum of deposit is *E* → Fano factor *F*<1)

$$\frac{\sigma_E}{E} \propto \sqrt{\frac{FW}{E}}$$

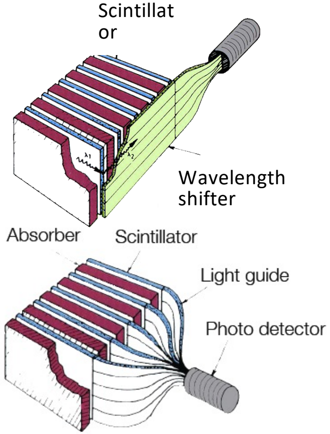
ACTIVE MATERIAL – SIGNAL DETECTION

Scintillation and Čerenkov Light

- **Čerenkov light**: Emitted by relativistic particles (e.g. $e^{\pm}$) $\beta>1/n$ (e.g. quartz n=1.45). Light is emitted at well defined angle
- **Scintillation light**: Some materials emit light when traversed by ionizing particles. Scintillation is caused by excited molecules falling back to ground state.
  - Organic scintillators
    - up to 10000 photons/MeV
    - decay time O(ns)
    - low Z, relatively low density
    - doped, large choice of emission wavelength, cheap, easy to manufacture, scintillation is single molecular process
  - Inorganic scintillators (crystals) – e.g. homogeneous calorimeters
    - High light yield, up to 40000 photons/MeV (NaI)
    - decay time O(ns to µs)
    - high Z, large variety of Z and density
    - difficult to grow, expensive. Require crystal latice to scintillate
- **Photodetectors** (used to detect scintillation light and also Čerenkov light):
  - Photocathode + secondary emission multiplication
    - e.g. photomultiplier (PMT)
  - Solid-state devices
    - Photodiodes (no gain), avalanche photodiodes APD (gain 10 – 100), solid state photomultipliers (e.g. SiPM)

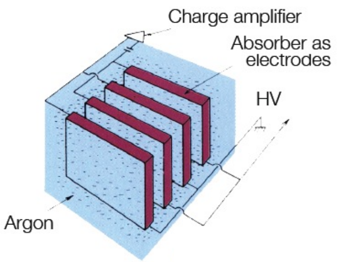


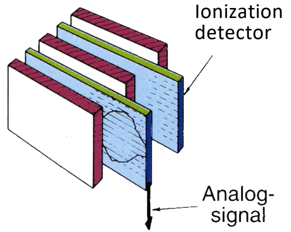
Light is guided out of the detector using light guides and wavelength shifters.



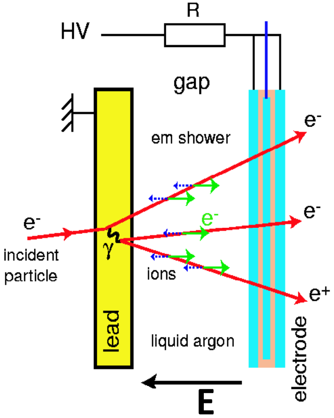
Ionization Detectors

- **Different types** depending on active material:
  - Liquids (noble liquids) - Cryogenic system! (~ 80K)
  - Solid materials (semiconductors)
  - Gaseous detectors (less used in sampling calorimeters for high energy physics, low density → small f_s)
- Typically **no charge amplification** (ionization mode)

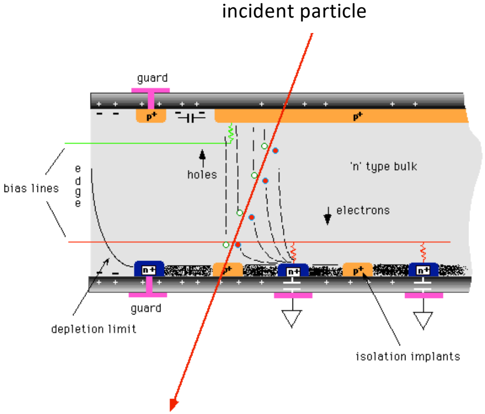




Liquids: Liquid Argon (LAr), liquid Krypton, liquid Xenon



Semiconductors: Silicon (strips, pixels), GaAs, Diamond



Summary – Signal Detection

Either detect light signal with photo-detectors

- **Čerenkov light**
- **Scintillation light**

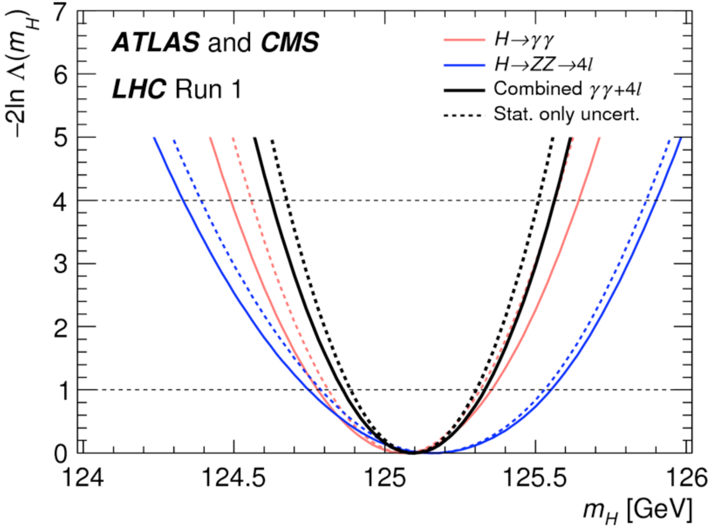
… or ionization signal with ionization detectors

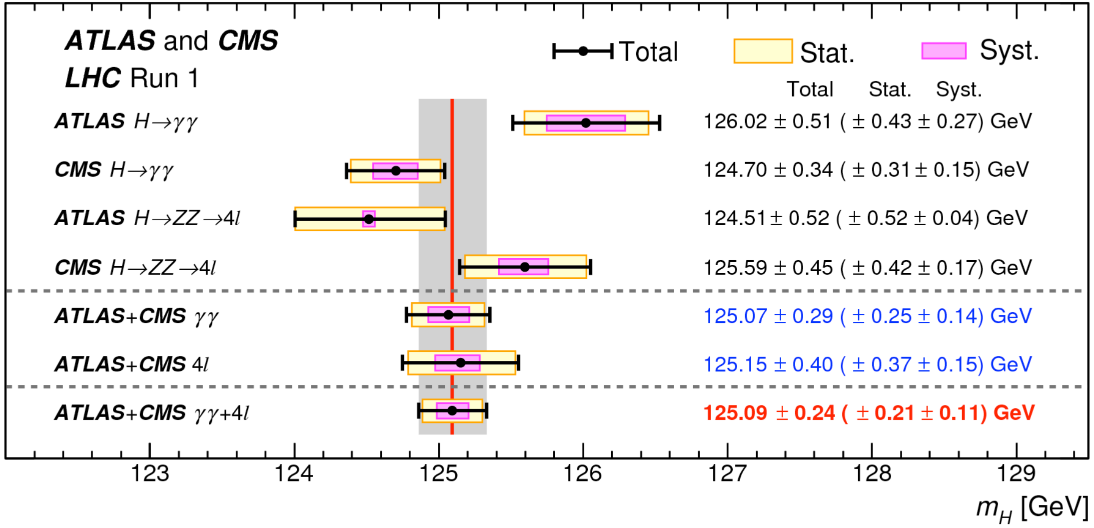
- **Nobel liquids as active material**
- **Semiconductors**

COMPARING ATLAS AND CMS – H-MASS AND W-MASS

Comparison Higgs Mass

- **Higgs discovery** in 2012 by ATLAS and CMS with basically **equal significance** – for both dominated by H→γγ channel (→ ECAL).
- **Higgs mass measurement** is a perfect benchmark measurement to compare the two experiments.



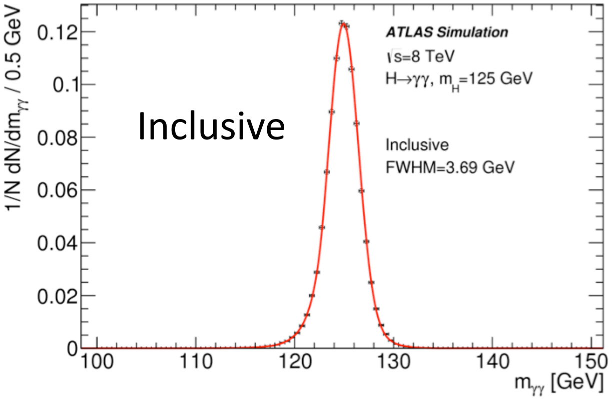


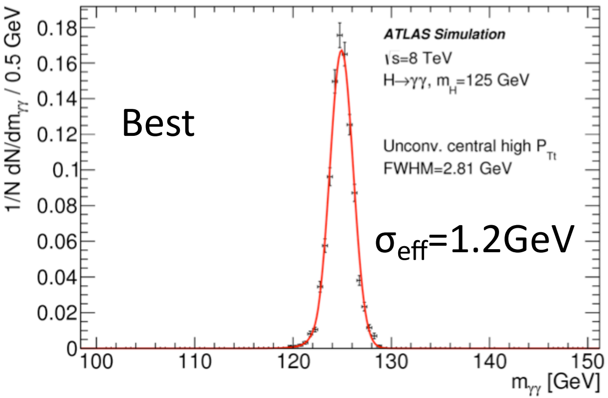
Comparison Higgs Mass Systematic Uncertainties

- **Systematic uncertainties** in both experiments dominated by energy and **momentum scale terms**.
- ATLAS has **larger uncertainties for material**, longitudinal response and lateral shower shape (data/MC agreement!)
  - **ATLAS** in general **more conservative**, but some differences can be explained
  - **Material uncertainty**: Due to more material in front of calorimeter 2x higher sensitivity on ID material

	Uncertainty in ATLAS results [GeV]: observed (expected)		Uncertainty in CMS results [GeV]: observed (expected)	
	$H \to \gamma\gamma$	$H \to ZZ \to 4\ell$	$H \to \gamma\gamma$	$H \to ZZ \to 4\ell$
Scale uncertainties:				
ATLAS ECAL non-linearity / CMS photon non-linearity	0.14 (0.16)	–	0.10 (0.13)	–
Material in front of ECAL	0.15 (0.13)	–	0.07 (0.07)	–
ECAL longitudinal response	0.12 (0.13)	–	0.02 (0.01)	–
ECAL lateral shower shape	0.09 (0.08)	–	0.06 (0.06)	–
Photon energy resolution	0.03 (0.01)	–	0.01 (<0.01)	–
ATLAS $H \to \gamma\gamma$ vertex & conversion reconstruction	0.05 (0.05)	–	–	–
$Z \to ee$ calibration	0.05 (0.04)	0.03 (0.02)	0.05 (0.05)	–
CMS electron energy scale & resolution	–	–	–	0.12 (0.09)
Muon momentum scale & resolution	–	0.03 (0.04)	–	0.11 (0.10)
Other uncertainties:				
ATLAS $H \to \gamma\gamma$ background modeling	0.04 (0.03)	–	–	–
Integrated luminosity	0.01 (<0.01)	<0.01 (<0.01)	0.01 (<0.01)	<0.01 (<0.01)
Additional experimental systematic uncertainties	0.03 (<0.01)	<0.01 (<0.01)	0.02 (<0.01)	0.01 (<0.01)
Theory uncertainties	<0.01 (<0.01)	<0.01 (<0.01)	0.02 (<0.01)	<0.01 (<0.01)
Systematic uncertainty (sum in quadrature)	0.27 (0.27)	0.04 (0.04)	0.15 (0.17)	0.16 (0.13)
Systematic uncertainty (nominal)	0.27 (0.27)	0.04 (0.05)	0.15 (0.17)	0.17 (0.14)
Statistical uncertainty	0.43 (0.45)	0.52 (0.66)	0.31 (0.32)	0.42 (0.57)
Total uncertainty	0.51 (0.52)	0.52 (0.66)	0.34 (0.36)	0.45 (0.59)
Analysis weights	19% (22%)	18% (14%)	40% (46%)	23% (17%)

H→γγ Mass-Peak Resolution

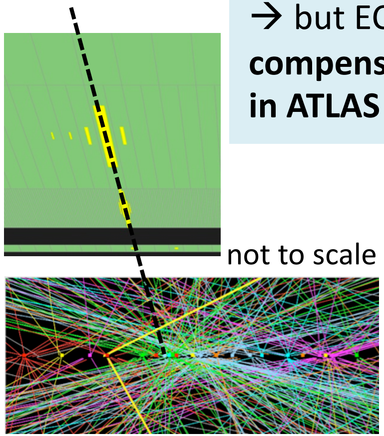




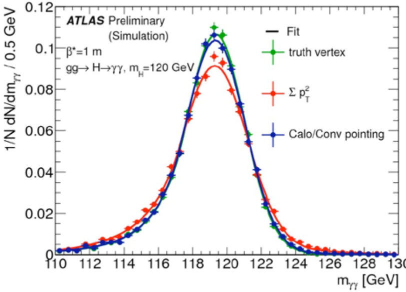
- **Statistical uncertainty bit better in CMS** (ECAL resolution!)
  - 0.43 GeV ATLAS
  - 0.31 GeV CMS
- Inclusive mass peak resolution slightly better in CMS, but higher tails

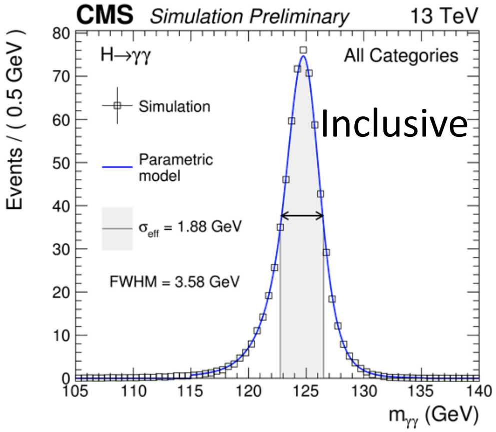
Statistical uncertainty driven by best photon categories – slight advantage of CMS

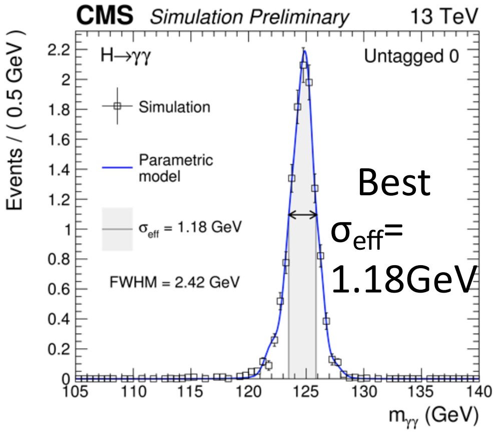
→ but ECAL resolution almost **compensated by photon pointing in ATLAS**



not to scale

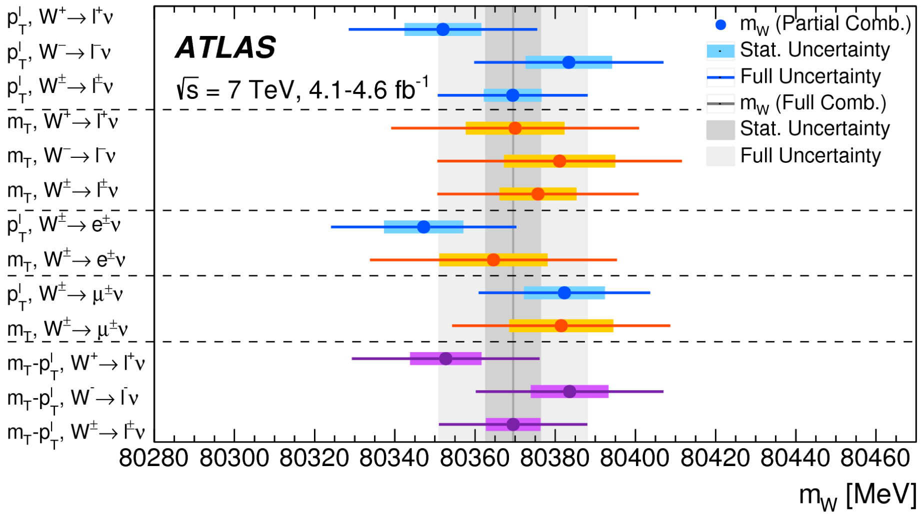






W-Mass

- **ATLAS published W-mass** measurement in 2017
  - arXiv:1701.07240
    - $\mathbf{m_W}$ = 80370±7(stat.)±11(exp. syst.)±14(mod. syst.)MeV = **80370±19MeV**
  - Measurement in $e^\pm$ and $\mu^\pm$ channel (equally contributing to result)
- **CMS: No measurement yet**, working on measurement with $\mu^\pm$-channel only



- → **Stability of the ATLAS EM calorimeter** clearly an advantage. Could use full statistics to **reduce systematic errors**.