Electromagnetic calorimeters in ATLAS and CMS

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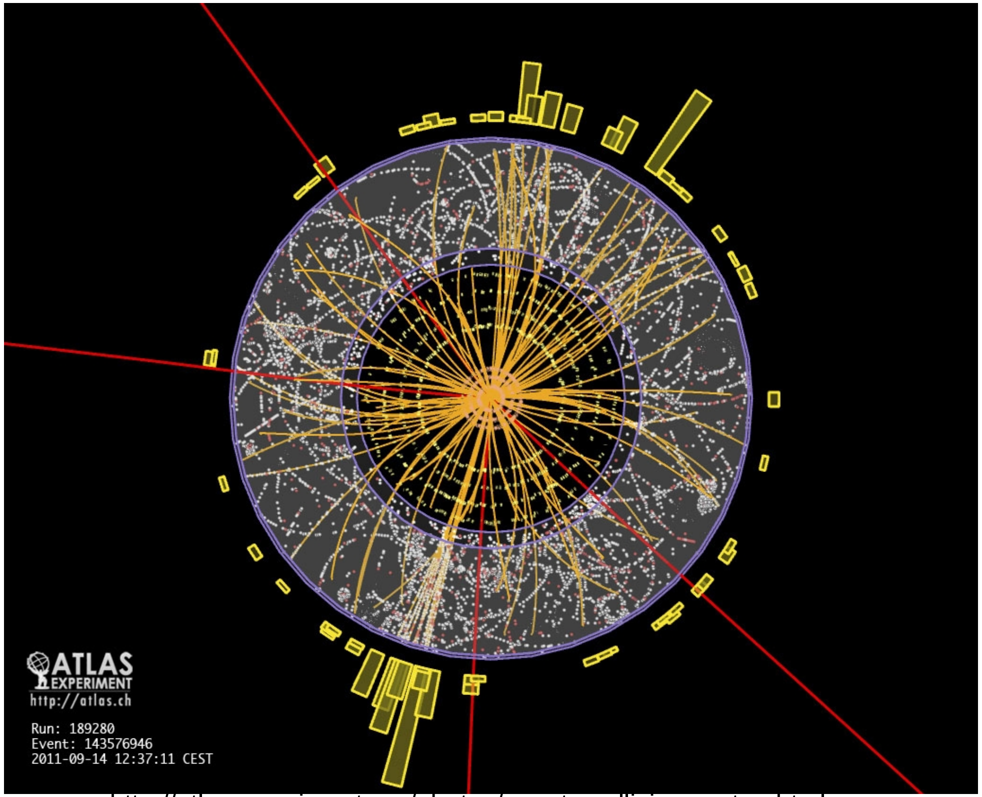
290 E Spring 2018

Outline

- Introduction
- Calorimeters
- Design of ATLAS vs. CMS
- Calibration and performance studies
- H→ $\gamma\gamma$ discovery
- Future

High energy collision

- A hot mess!!



http://atlasexperiment.org/photos/events-collision-proton.html

Particle detection

- Out of hundreds of particles produced most are short-lived that we will never see them directly
- Can identify particles through their decay products

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  - Photons, electrons, muons, hadrons and infer neutrinos
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  - All charged particles → Ionization, Cerenkov radiation
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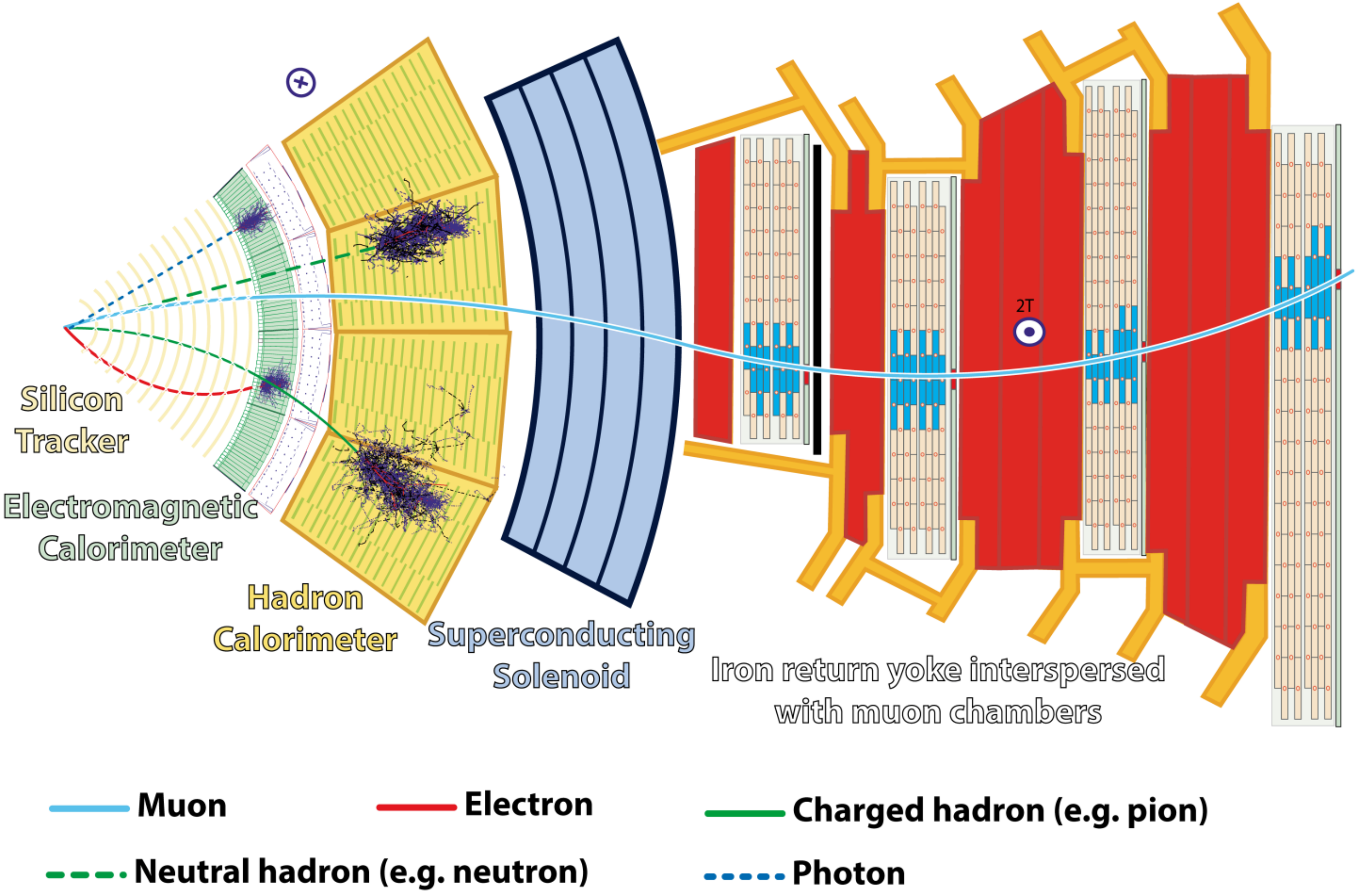
Ideal particle detector

- Should
  - Provide coverage of full solid angle
  - Measure momentum and/or energy
  - Detect and identify all particles
  - Have fast response time
- Limitations:
  - Technology, Space, $$$

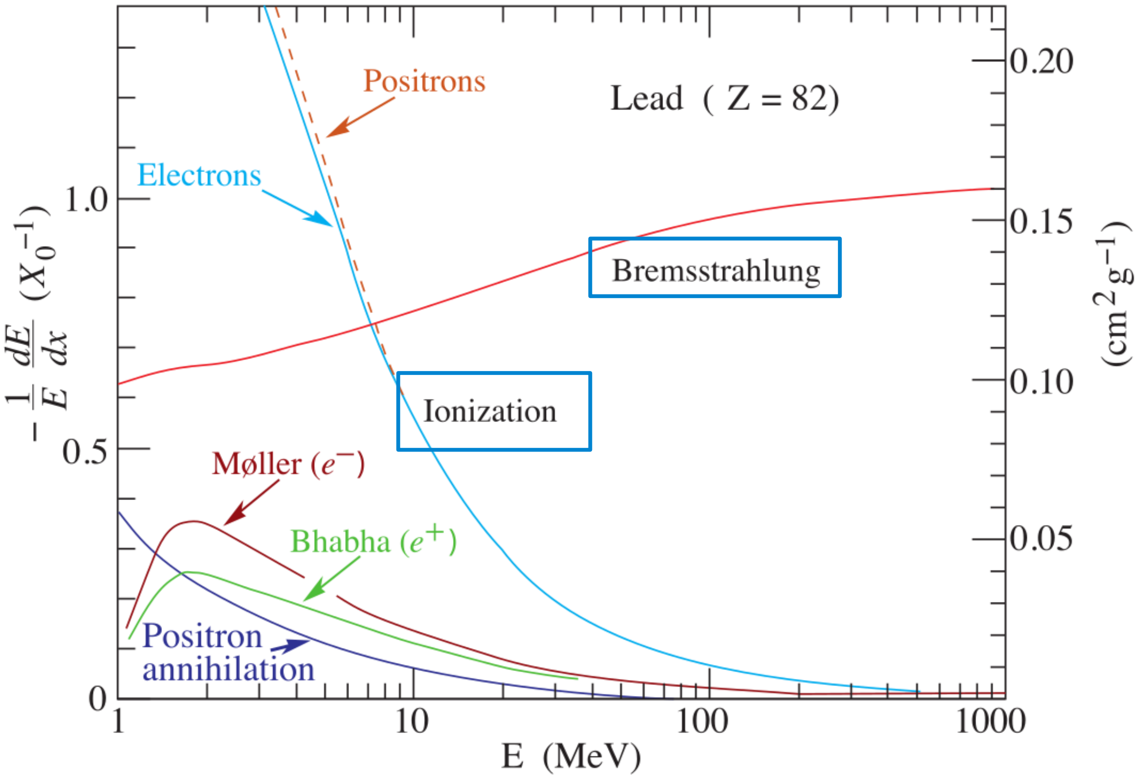
Generic detector design



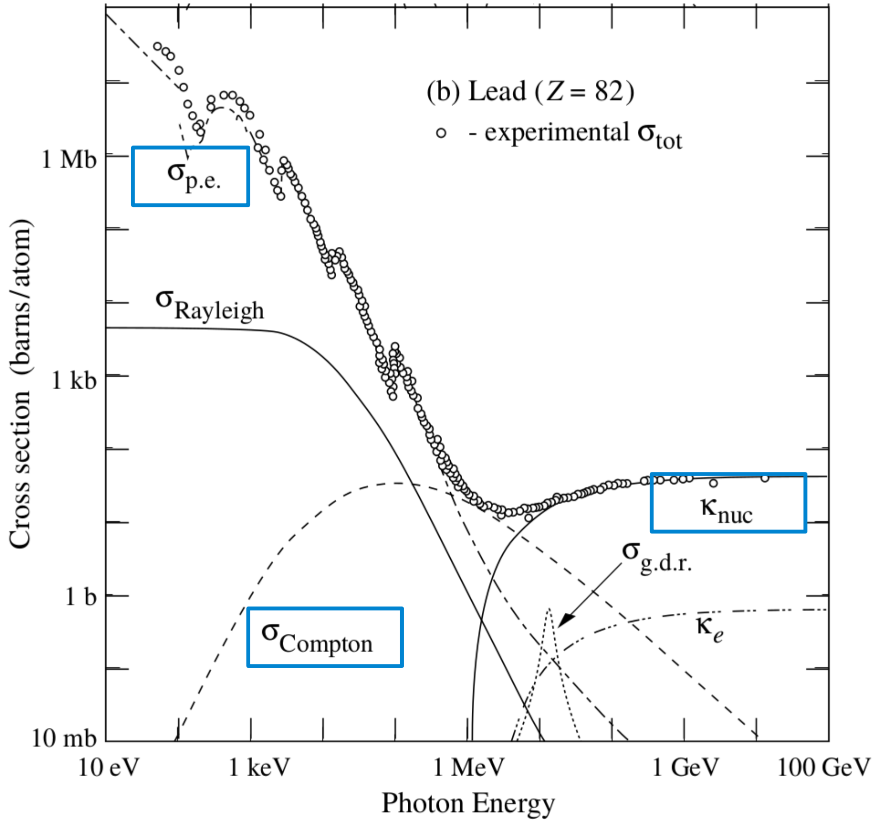
https://cds.cern.ch/record/2120661

Reminder – e/γ interaction with matter

electrons



Photons



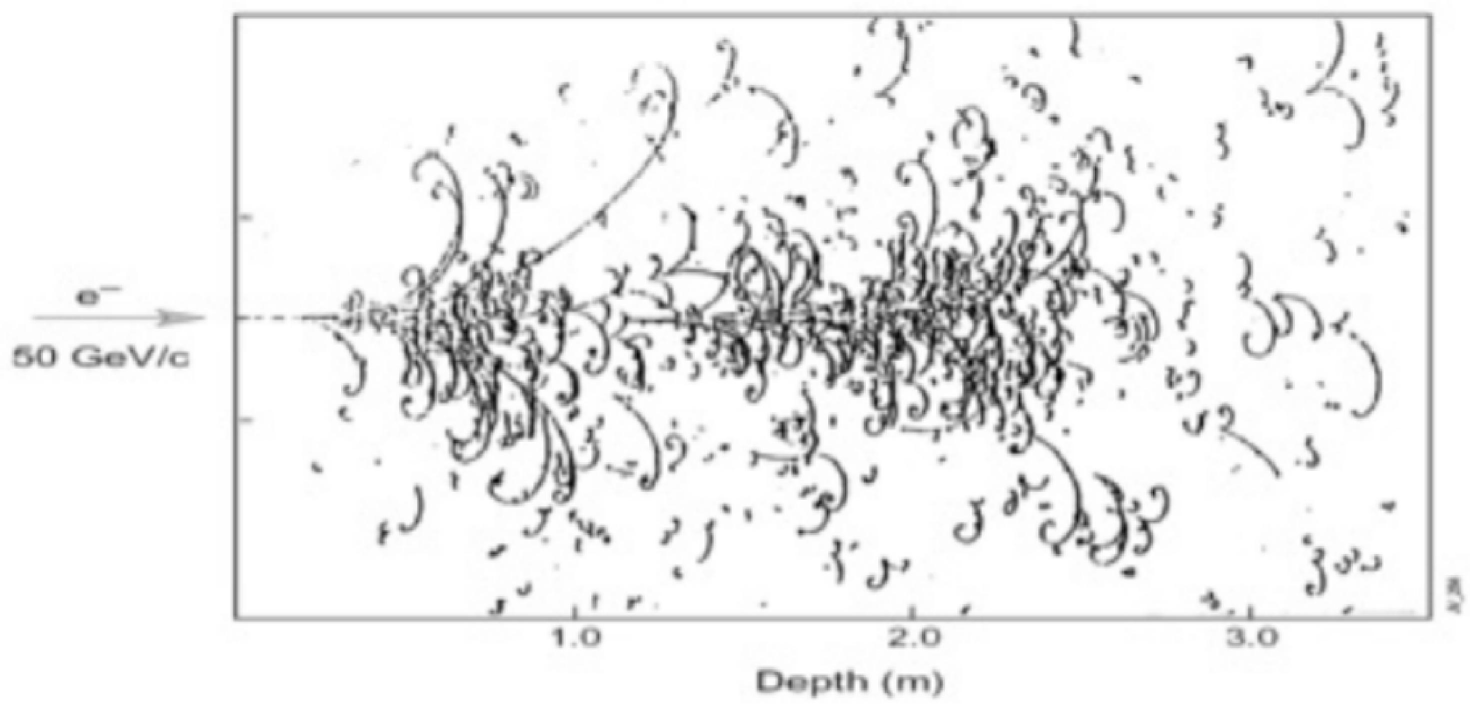
http://pdg.lbl.gov/2017/mobile/reviews/pdf/rpp2016-rev-passage-particles-matter-m.pdf

Calorimeters

- Principle: Measure energy loss as the particle traverses the medium
- At high energies, the dominant process:
  - Electrons: Bremsstrahlung
  - Photons: Pair production
- This results in a cascade of particles → Electromagnetic shower

EM shower

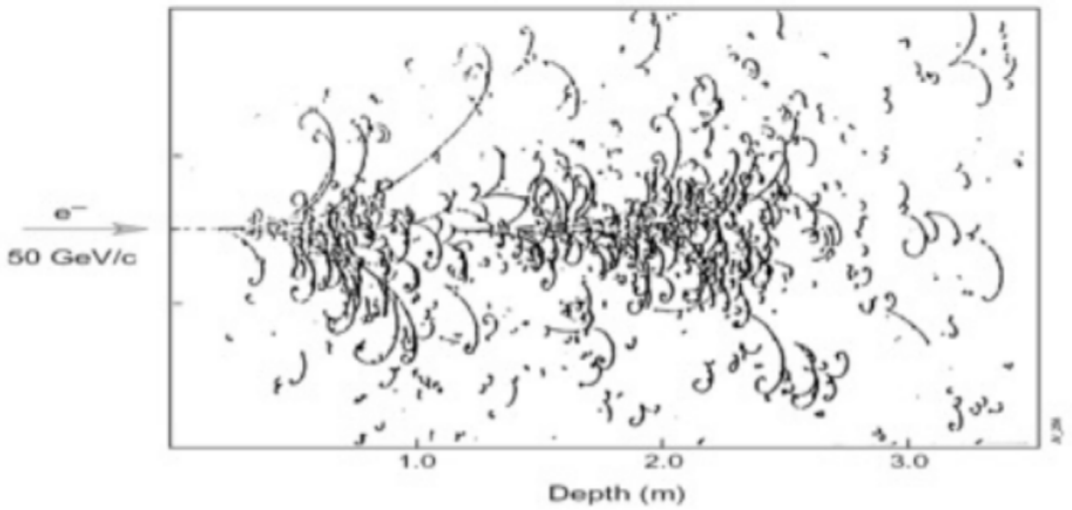
Big European Bubble Chamber filled with Ne:H_2 = 70%:30%,
3T Field, L=3.5 m, X_0=34 cm, 50 GeV incident electron



EM shower

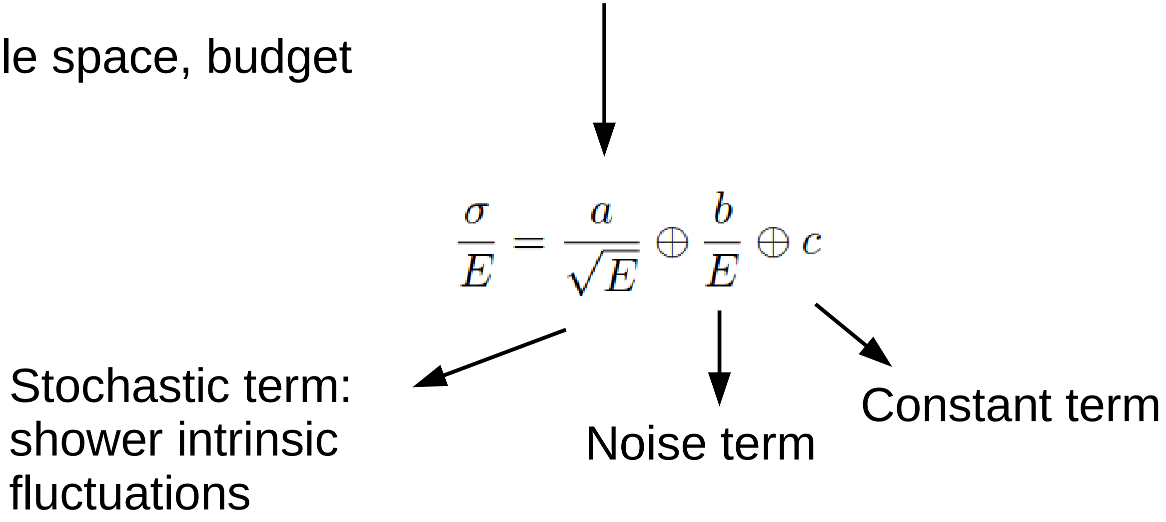
- Longitudinal characteristic
  - Radiation length(X_o): Mean distance after which an electron looses 1/e of its initial energy by radiiation
- Transverse profile
  - Moliere radius (ρ_M): Approximately 87% of the shower energy is contained in a cylinder of this radius

Big European Bubble Chamber filled with Ne:H_2 = 70%:30%, 3T Field, L=3.5 m, X_0≈34 cm, 50 GeV incident electron



Calorimeter design

- Longitudinal shower containment at 95% needs $25X_0$
- Lateral shower containment at 95% needs cylinder of radius $2\rho_M$
- Design needs to consider:
  - Energy range of particles to be detected
  - Performance requirements → Resolution, read out time, etc
  - Available space, budget



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

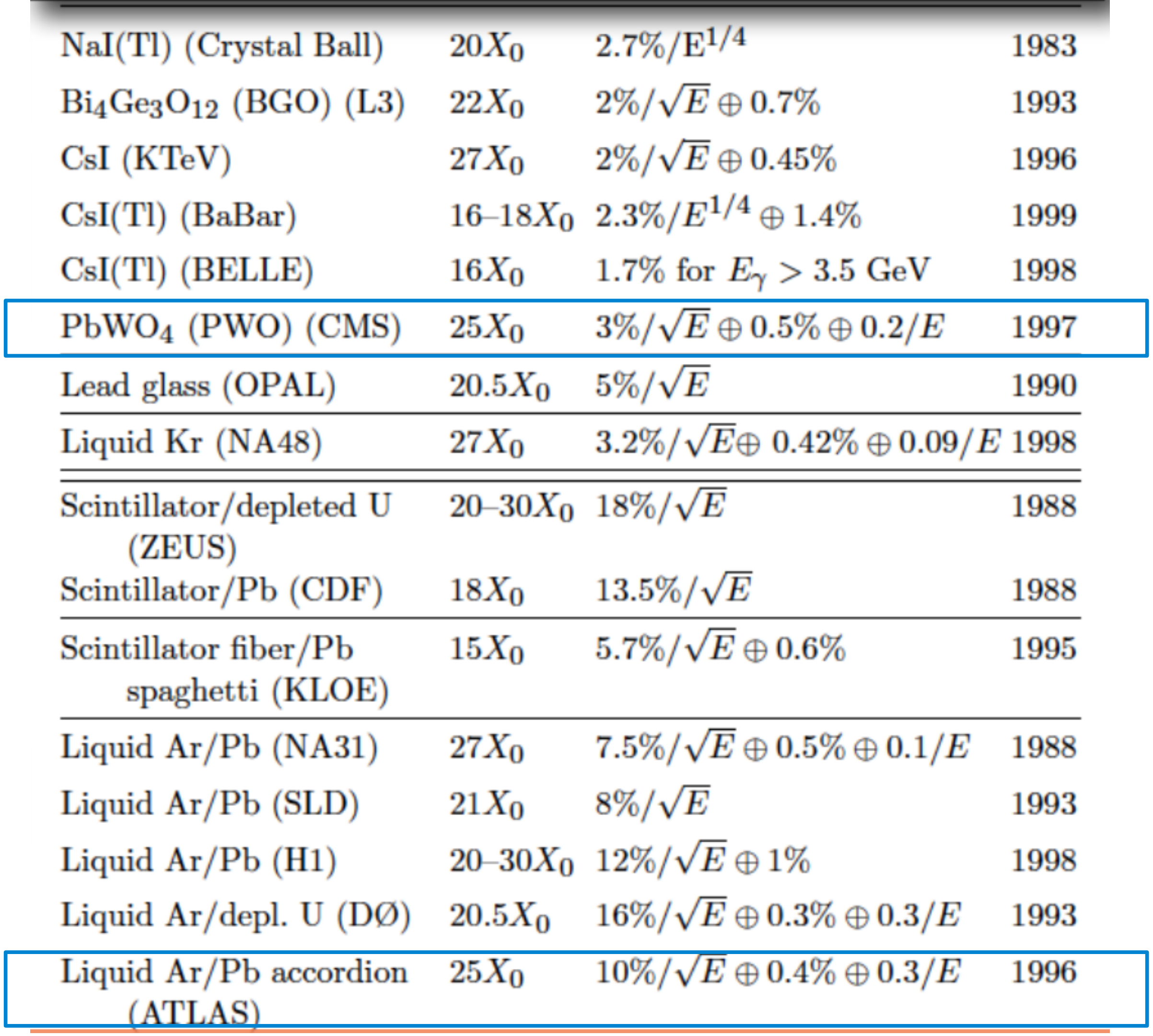
Calorimeter types

- Homogenous:
  - Full absorption detectors (active medium only)
  - Scintillation/Crystal, Semiconductor, Cerenkov, Ionization
  - Intrinsic fluctuations are small
- Sampling:
  - Alternate layers of absorber material with active media
  - Scintillation, Gas, Solid state, Liquids
  - Common absorbers: Pb, Fe, Cu, etc.

ATLAS and CMS calorimeters

- Physics goals: Discovery of Higgs (particularly $\gamma\gamma$, ZZ*,WW* channels) and/or beyond SM physics
- Energy range of e/γ of interest: 5 GeV to 5 TeV
- High resolution over the entire range

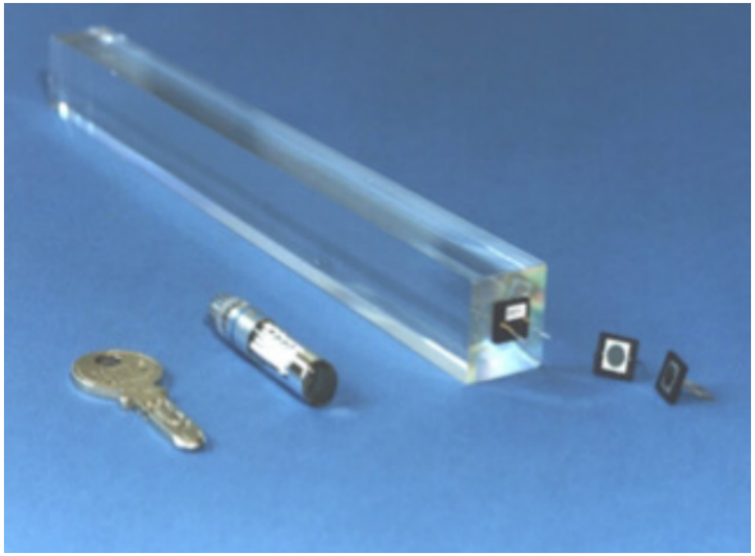
Existing Electromagnetic Calorimeters



Technology/Experiment	Depth	Resolution	Year
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/\mathrm{E}^{1/4}$	1983
$\mathrm{Bi_4Ge_3O_{12}}$ (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
$\mathrm{PbWO_4}$ (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

CMS calorimeter

- Homogeneous $PbWO_4$ crystal (2.2x2.2x23 cm^3)
- Radiation hard
- Fast scintillator
- Inside the CMS solenoid
- Material traversed before ECAL ~ 0.4 to 1.9 X_0
- Energy resolution of 1% @ 30 GeV



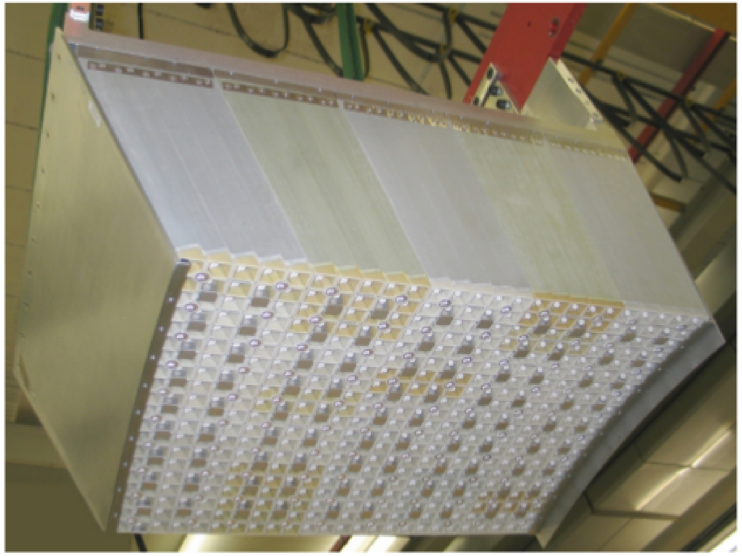
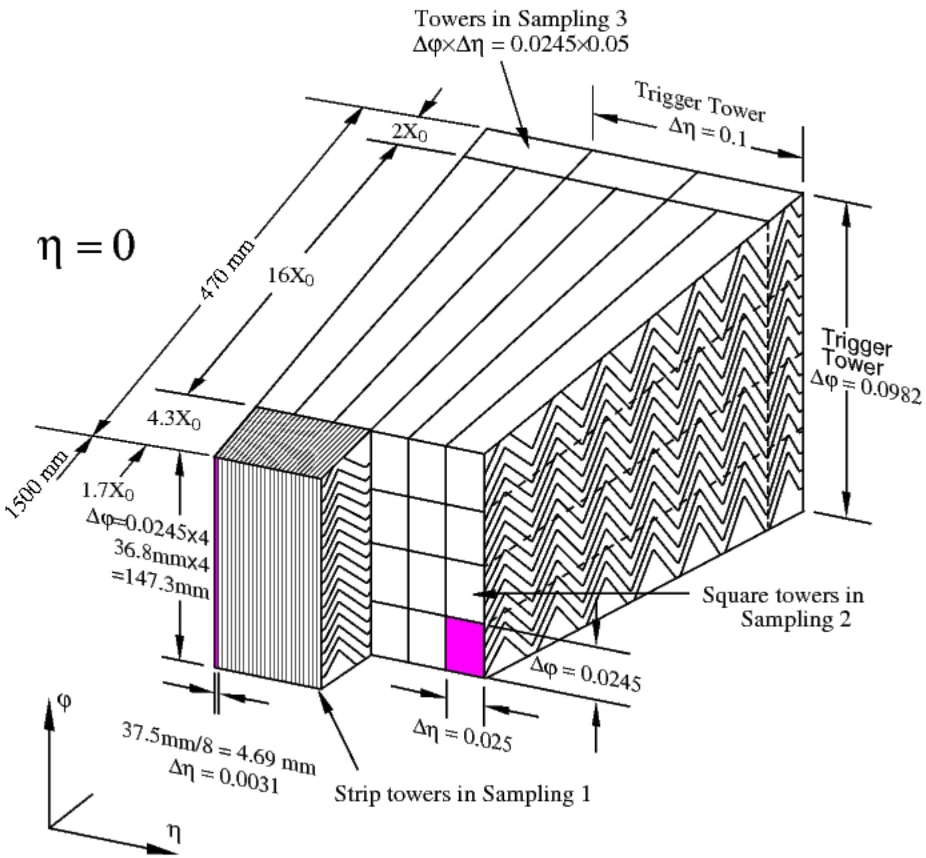
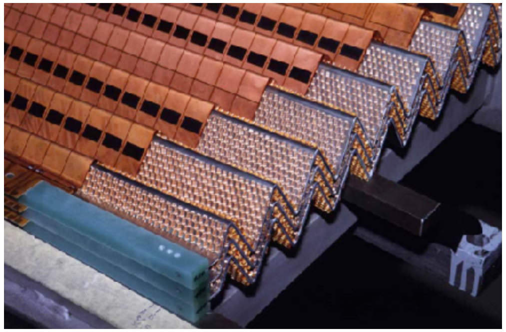


Figure 4.4: Front view of a module equipped with the crystals.

ATLAS calorimeter





- Sampling calorimeter
- Accordion design
- Absorber: Lead
- Active material: Liquid argon
- Divided into 3 layers
  - Gives depth and pointing information
- Central solenoid coil before ECAL
- Thin presampler layer
  - Correct for energy loss upstream
  - Amount of material traversed before reaching ECAL~ 3 to 6 X_o
- Energy rersolution ~ 1.8% @ 30 GeV

Calibration and performance studies

- Initially calibrated using single particle guns
- Then moved on to simulation of $Z \rightarrow ee$ events
- Simulated $H \rightarrow \gamma\gamma$ samples at different m_H
- Background rejection - studied the γ/π^0 separation
- Also studied performance for non-pointing photons
- Perform beam test measurements to make sure the built detector is in agreement with the expectations from simulations

Z → e^+e^- for calibration

- Simple, well-known process → ideal for benchmark performance studies
- Simulated 50000 events using PYTHIA and PHOTOS
- Studied energy resolution
- Checked the performance for complete physics event as opposed to single particle incidence
- Extract different correction factors, resolution, etc
- Will show results from ATLAS Technical Design Report (TDR)
- Similar results are presented for CMS in their TDR (Check references)

Energy comparison

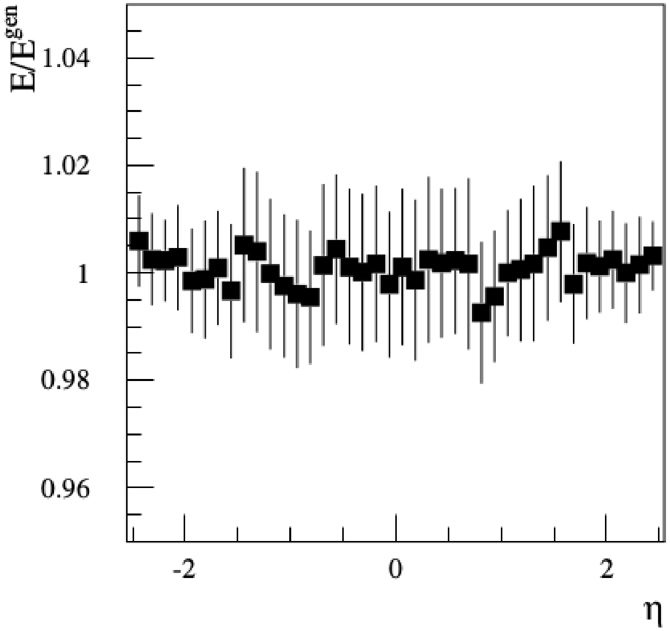


Figure 4-46 Reconstructed energy in the calorimeter, divided by the true energy, for electrons from Z decays as a function of pseudorapidity. The error bars give the rms spread on the reconstructed energy.

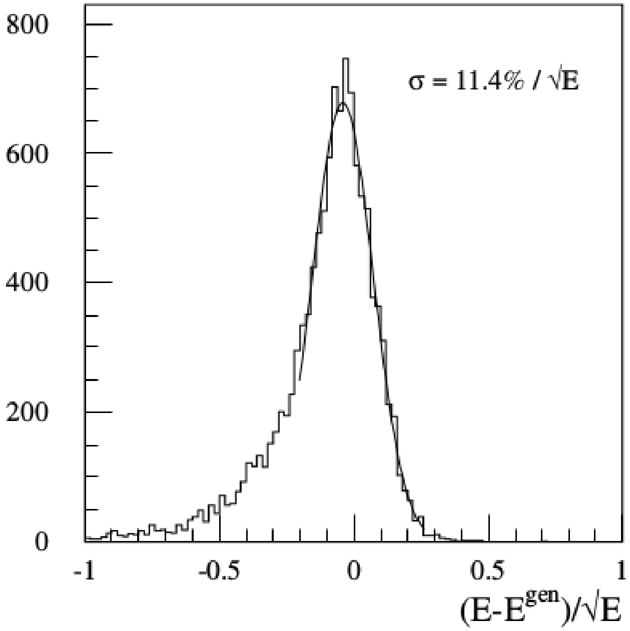


Figure 4-47 Difference between the reconstructed energy in the calorimeter and the true energy, divided by the square root of the true energy, as obtained for electrons from Z decays. The best fit is superimposed.

Z mass spectrum

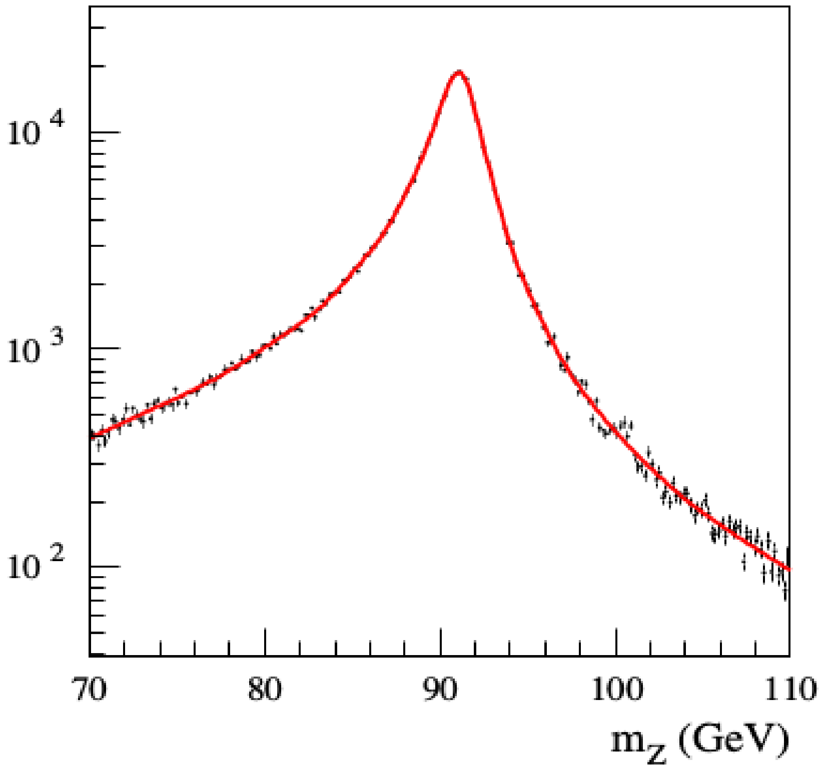


Figure 4-51 The *Z* lineshape as obtained from PYTHIA and PHOTOS.

H → $\gamma\gamma$ simulation

- Need to measure direction of both photons very precisely
- m_H was unknown → performance needs to be optimized for wide energy range

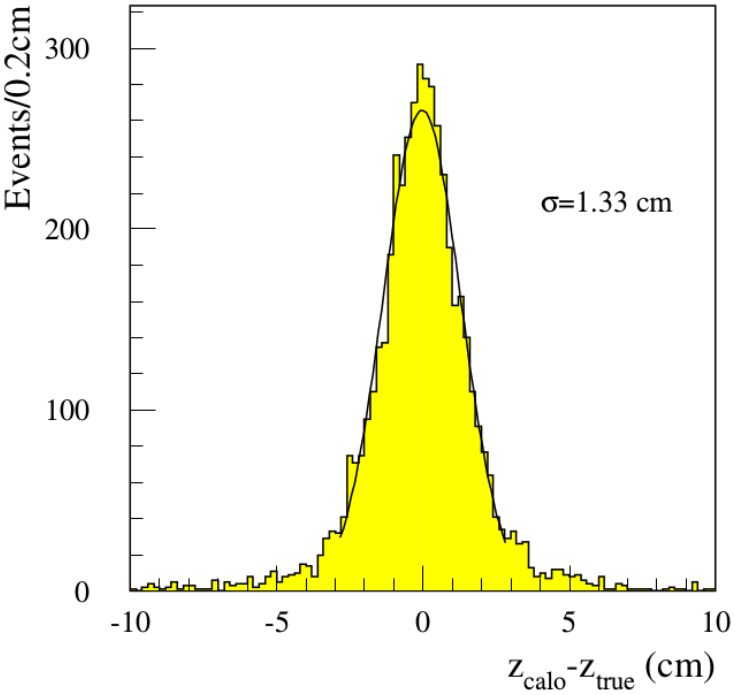
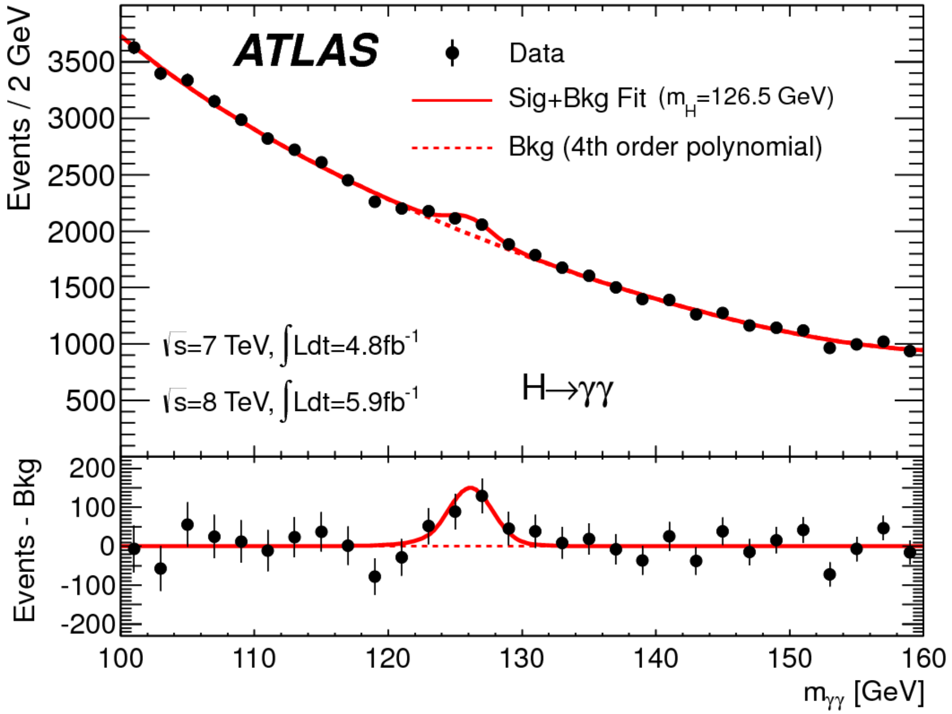
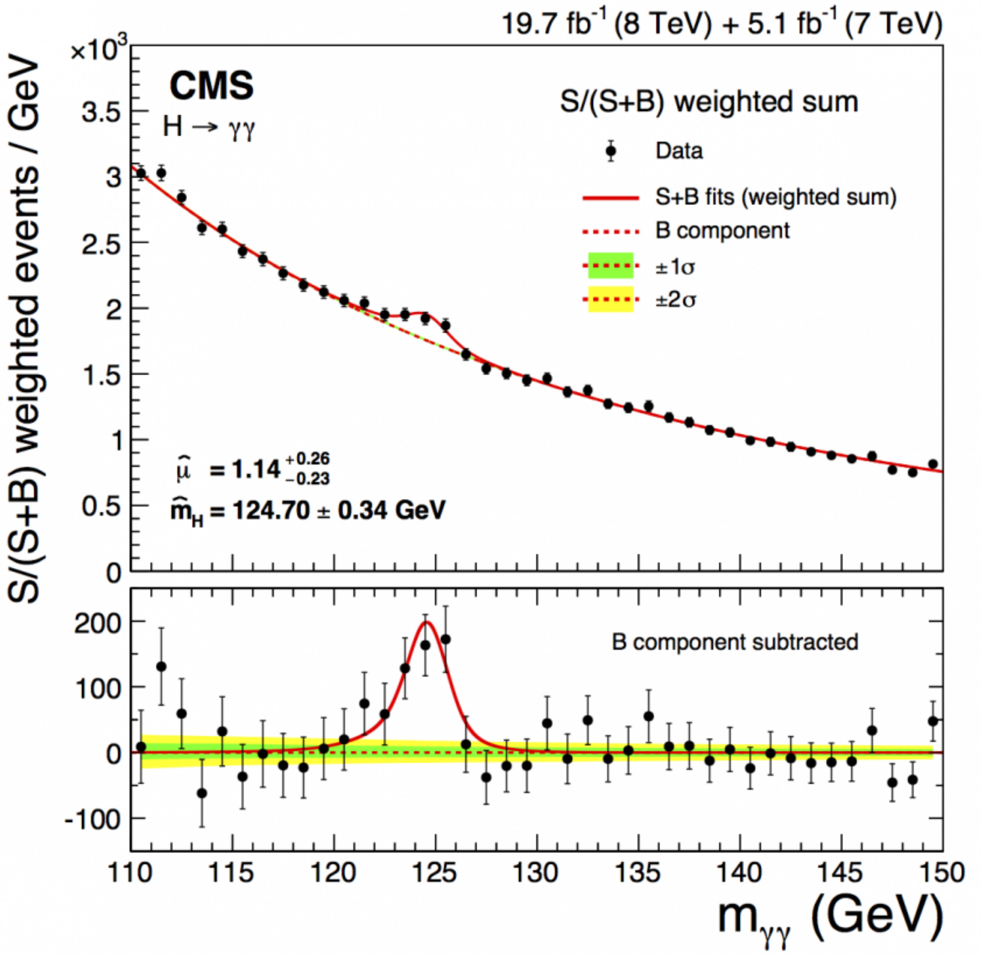


Figure 4-40 The difference between the reconstructed vertex, provided by the EM Calorimeter alone, and the generated vertex, as obtained for $H \rightarrow \gamma\gamma$ events with m_H = 100 GeV.

H → γγ discovery



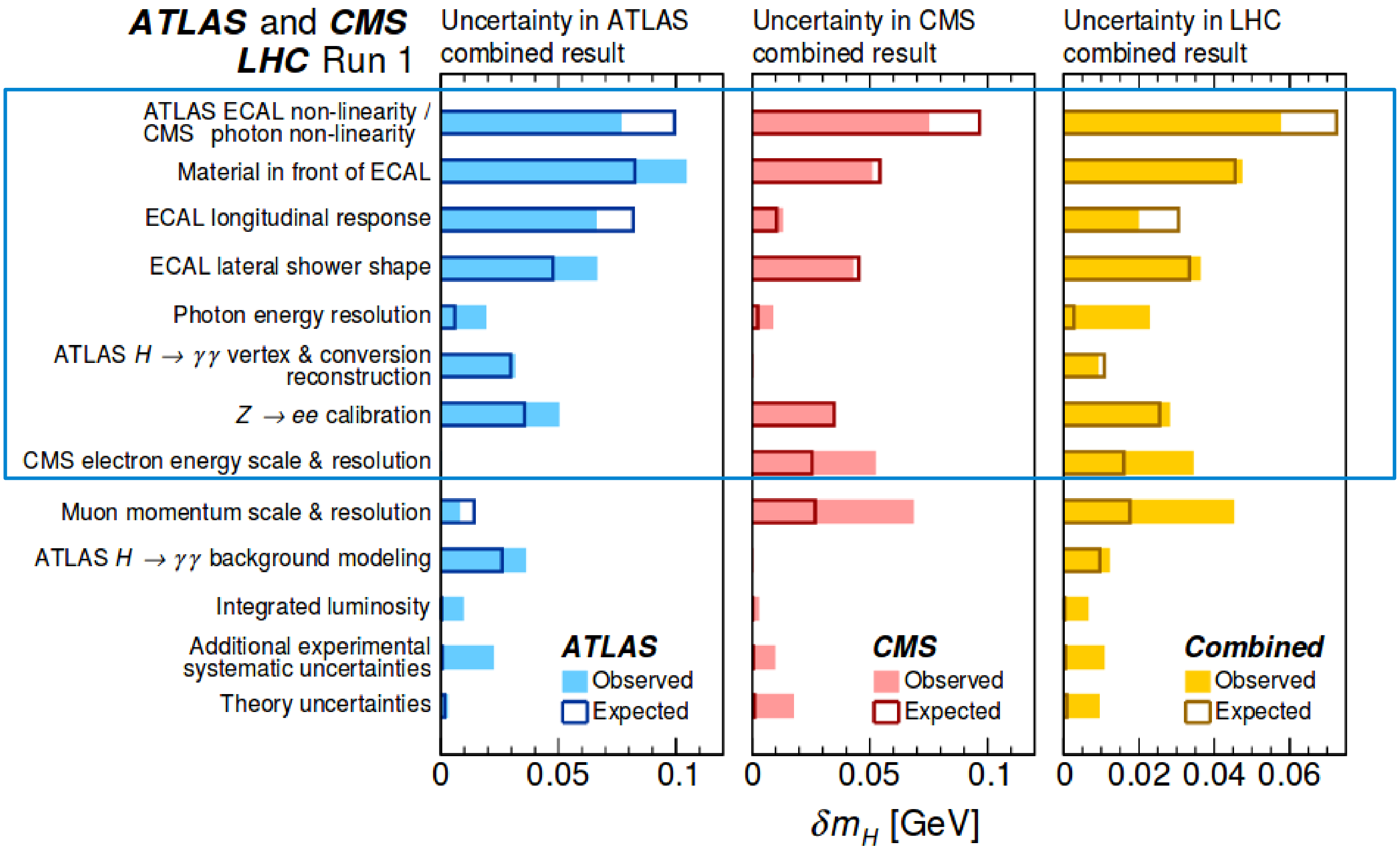


H→ $\gamma\gamma$ discovery

- Dominant uncertainties:
  - Photon reconstruction and identification efficiencies→ 8 to 11%

    Measured using Z → $l^+l^-\gamma$ events in data
  - Minor: Photon isolation → 0.4%

H → $\gamma\gamma$ discovery



$H \rightarrow \gamma\gamma$ result (Run 1)

- ATLAS: m_H = 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV
- CMS: m_H = 125.3 ± 0.4 (stat) ± 0.5 (syst) GeV
- Combined: m_H = 125.09 ± 0.21 (stat) ± 0.11 (syst) GeV

Summary

- Discussed ATLAS and CMS calorimeters → Design, performance and calibration
- Used H → $\gamma\gamma$ as a benchmark discovery to compare the calorimeter performance in the experiments and impact on the result
- Calorimeters from both experiments perform as expected despite increasing luminosity at LHC
- EM calorimeters play a critical role in precision measurements and searches for beyond Standard Model phyisics

References

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- Particle Data Group - http://pdg.lbl.gov/2017/
- ATLAS Technical Design Report - https://cds.cern.ch/record/391176/files/cer-0317330.pdf
- CMS Technical Design Report - https://cdsweb.cern.ch/record/922757/files/lhcc-2006-001.pdf
- XII ICFA school lectures - https://fisindico.uniandes.edu.co/indico/conferenceTimeTable.py?confId=61#20131125
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- http://lappweb.in2p3.fr/~chefdevi/Detector_reports/Calorimetry/Fabjan.pdf
- ATLAS collaboration, Phys.Lett. B716 (2012) 1-29
- CMS collaboration, Phys. Lett. B 716 (2012) 30
- ATLAS and CMS collaboration, Phys. Rev. Lett. 114, 191803 (2015)

Back up

ATLAS single particle calibration (γ)

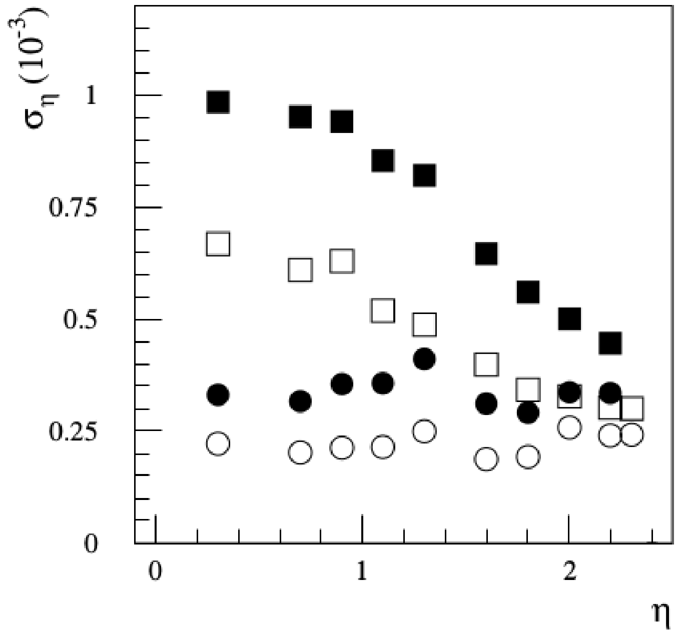

Figure 4-37 Position resolution in the η–direction, as measured in the strips (dots) and in the middle compartment (squares), as a function of pseudorapidity, for photons of E_T = 20 GeV (closed symbols) and E_T = 50 GeV (open symbols).

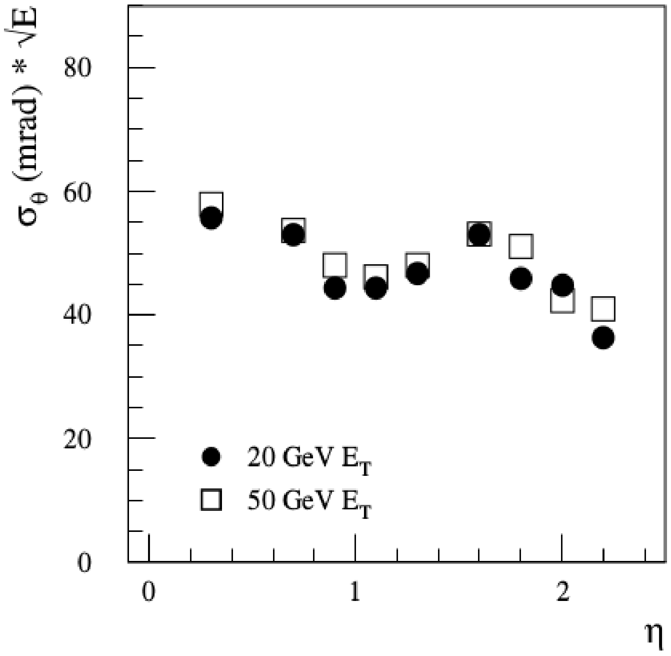

Figure 4-38 Calorimeter angular resolution in θ, as a function of pseudorapidity, for photons of E_T = 20 GeV and E_T = 50 GeV.

ATLAS γ/π^0 separation

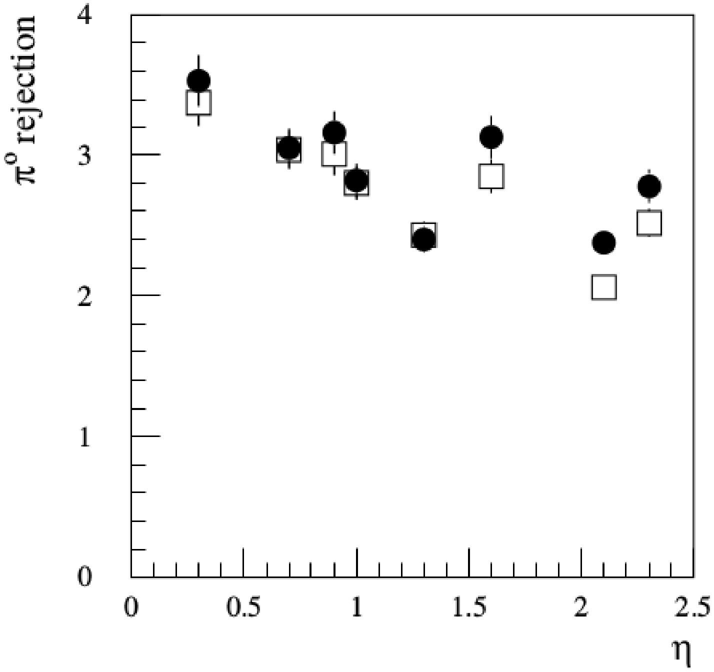

Figure 4-44 Rejection of π^0 of E_T = 50 GeV for 90% photon efficiency, as a function of pseudorapidity, with (open squares) and without (dots) including the electronic and pile-up noise expected at high luminosity.

ATLAS non-pointing photon study

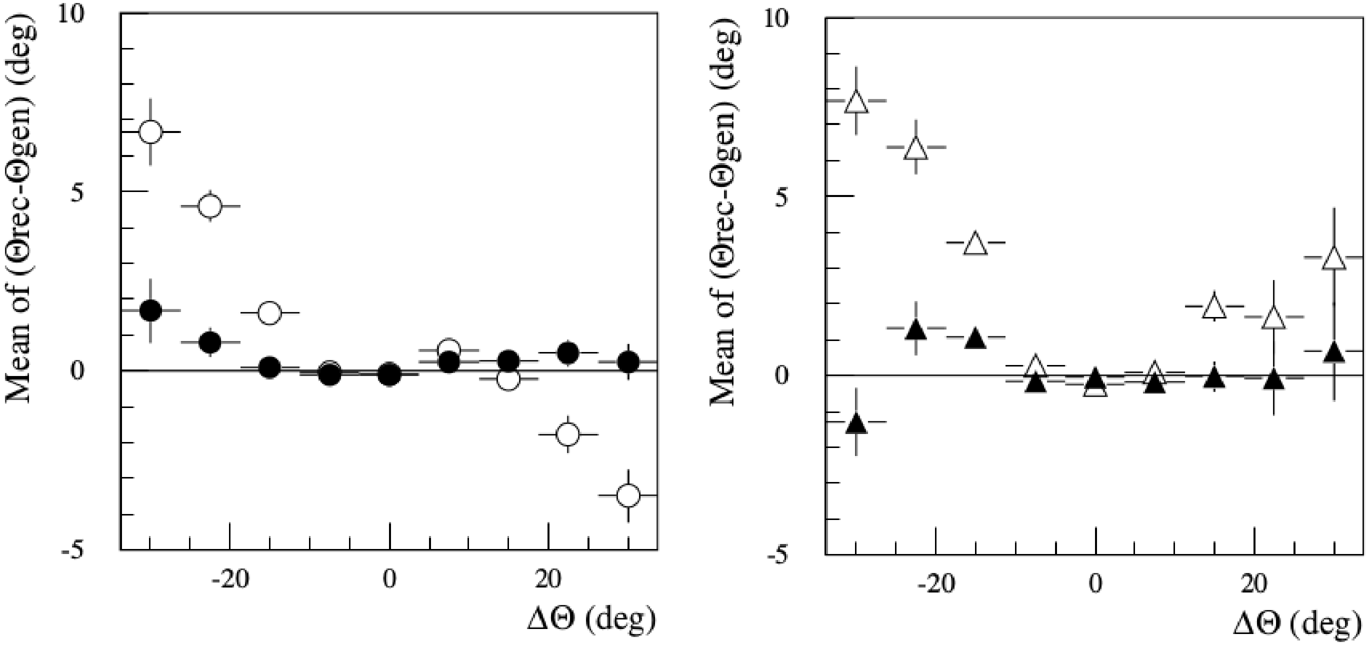

Figure 4-42 Mean of the deviation of the reconstructed value of θ from the generated value, as a function of Δθ, for GMSB photons with $0 < \eta < 0.6$ (left) and $0.6 < \eta < 1.2$ (right), as obtained with the standard reconstruction (open symbols) and with a neural network (closed symbols).