

Calorimetry

Margar Simonyan

Niels Bohr Institute

PhD course in detector technology for particle physics
Niels Bohr Institute, Copenhagen, Denmark

Outline

- Introduction
- Electromagnetic calorimeters
 - Shower development
 - Performance
- Hadronic calorimeters
 - Shower development
 - Performance
- ATLAS jet calibration
- Particle flow and dual readout

Introduction

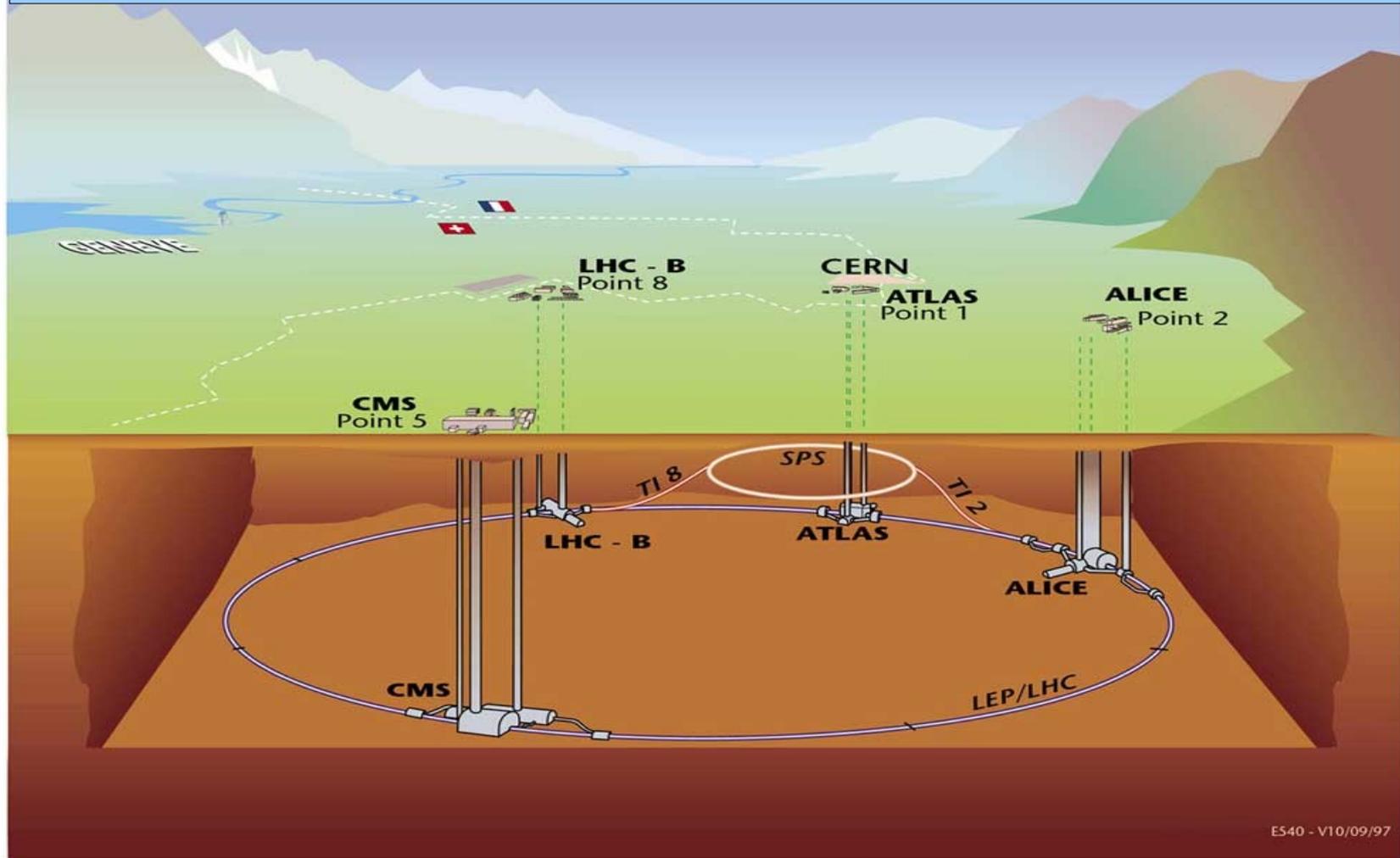
- The term “calorimeter” finds its origin in thermodynamics.
- In particle physics the term “calorimeter” is used to describe a device that absorbs a substantial fraction of the energy of an incident particle and produces a signal proportional to that energy.
- In the absorption process, almost all the particle’s energy is eventually converted into heat, hence the name calorimeter.
- Different types of calorimeters:
 - Electromagnetic (EM) and hadronic
 - Homogeneous and sampling calorimeters
- Common feature:
 - The measurements are destructive, except for muons.

Usage

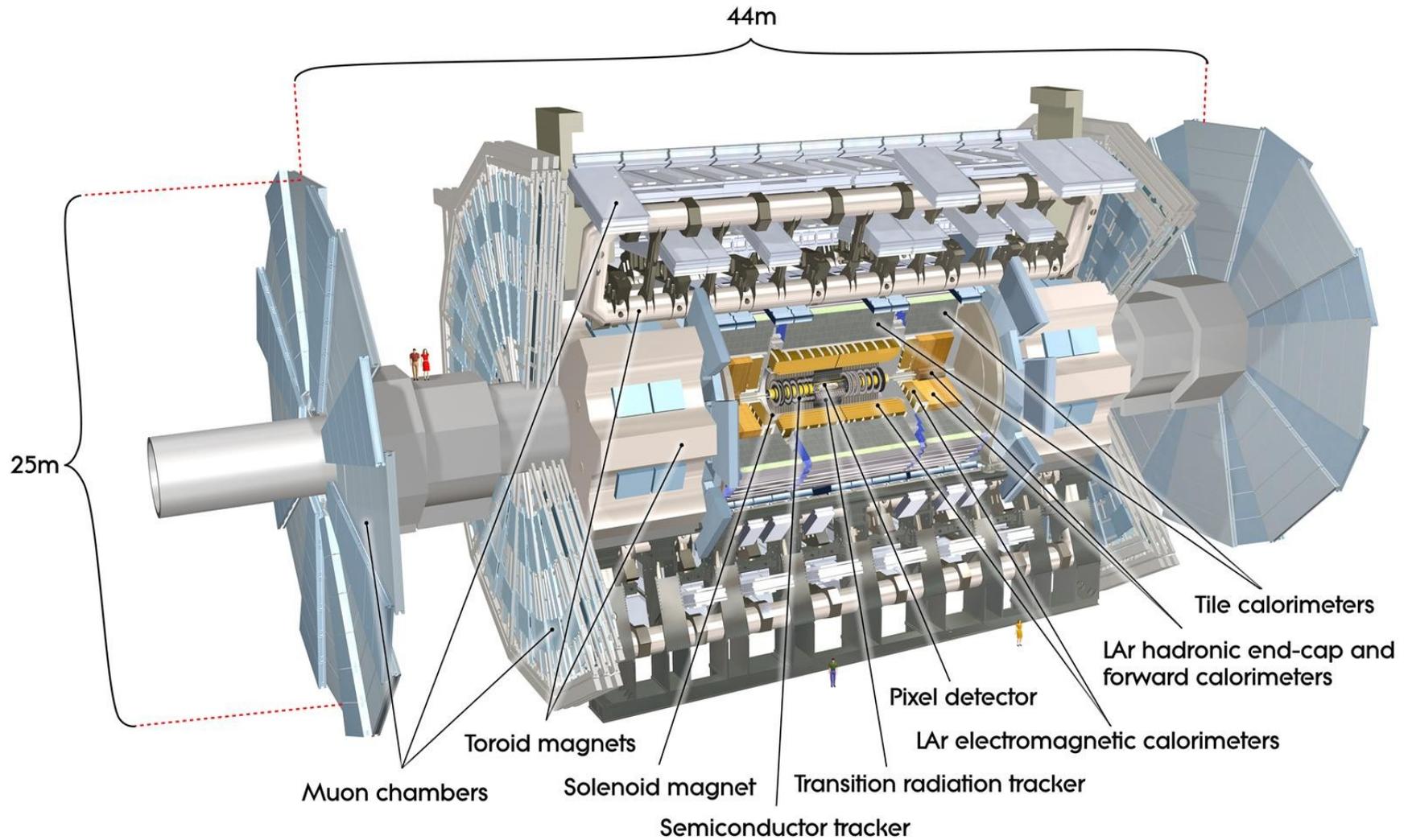
- Calorimeters are important part of modern high energy physics detectors.
- They are used for energy measurement of electrons, photons and jets as well as particle identification.
- With the increase of energy of particle accelerators calorimeters become more important:
 - Calorimeter relative energy resolution improves with the increase of energy.
 - The depth required to contain the shower grows only logarithmically with energy. In contrast, the length of a magnetic spectrometer would need to increase linearly with the momentum to keep relative momentum resolution constant.
- For electrically neutral particles calorimeters are the only detectors able to measure their energies.

LHC

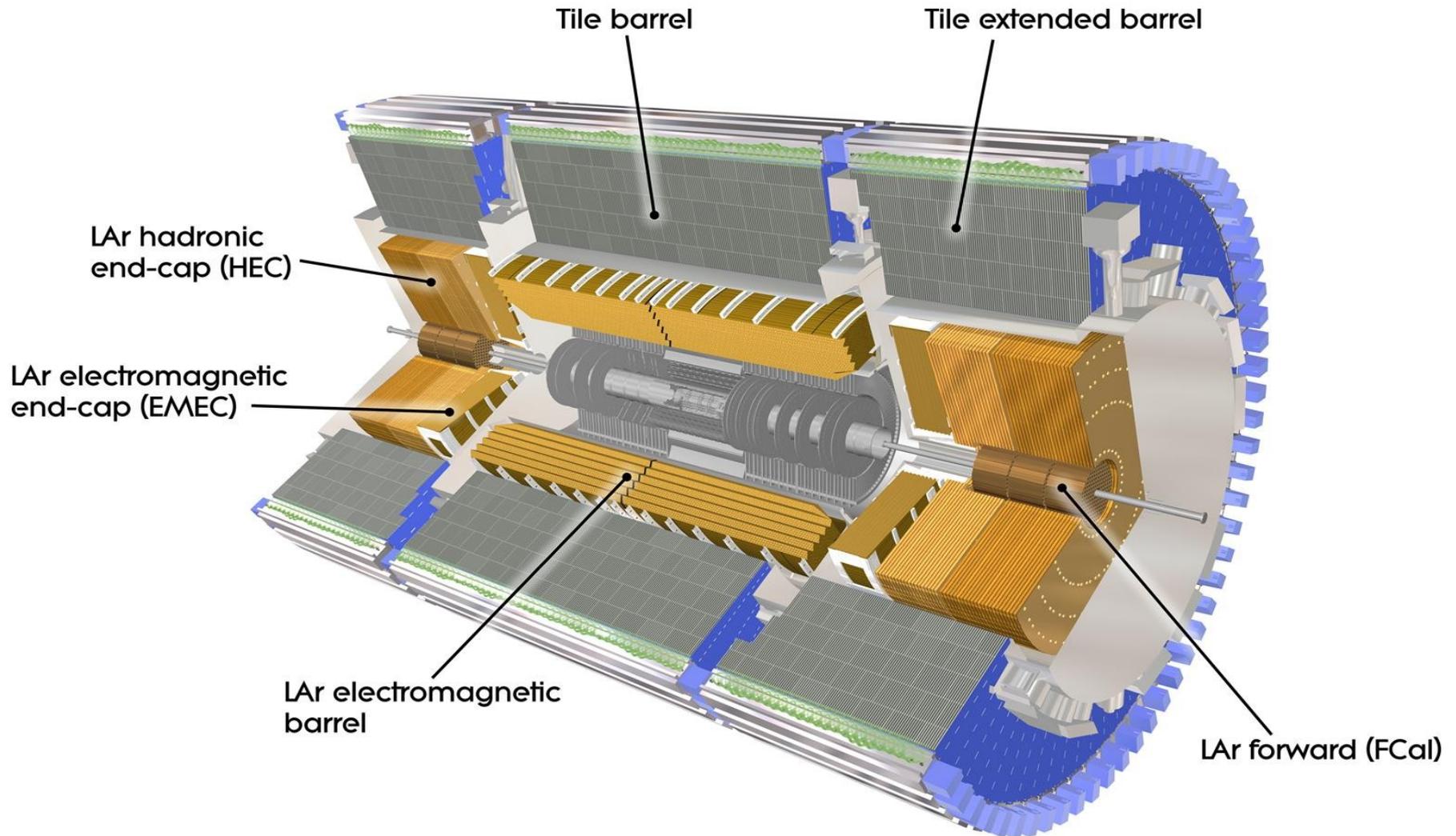
Proton-proton collider currently running at 8 TeV center-of-mass energy



ATLAS

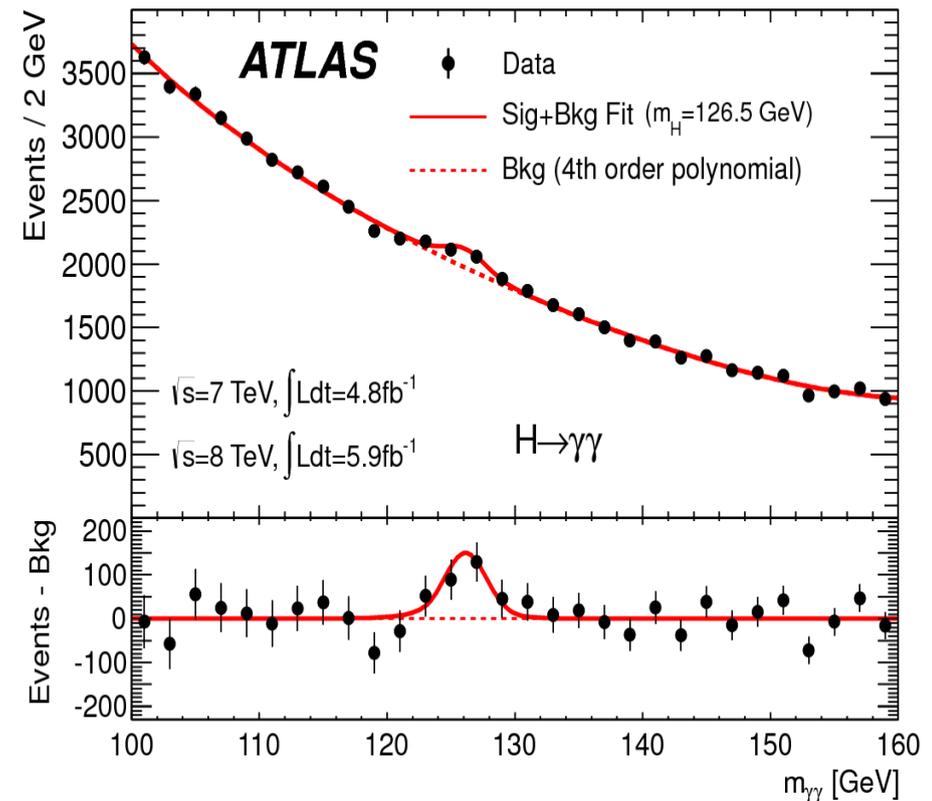


ATLAS Calorimeters



Requirements

- Excellent energy resolution to electrons and photons.
- Good jet energy resolution.
- Hermeticity for accurate determination of missing E_T .
- Fine granularity for particle identification.
- Fast detector response.
- Radiation tolerant.

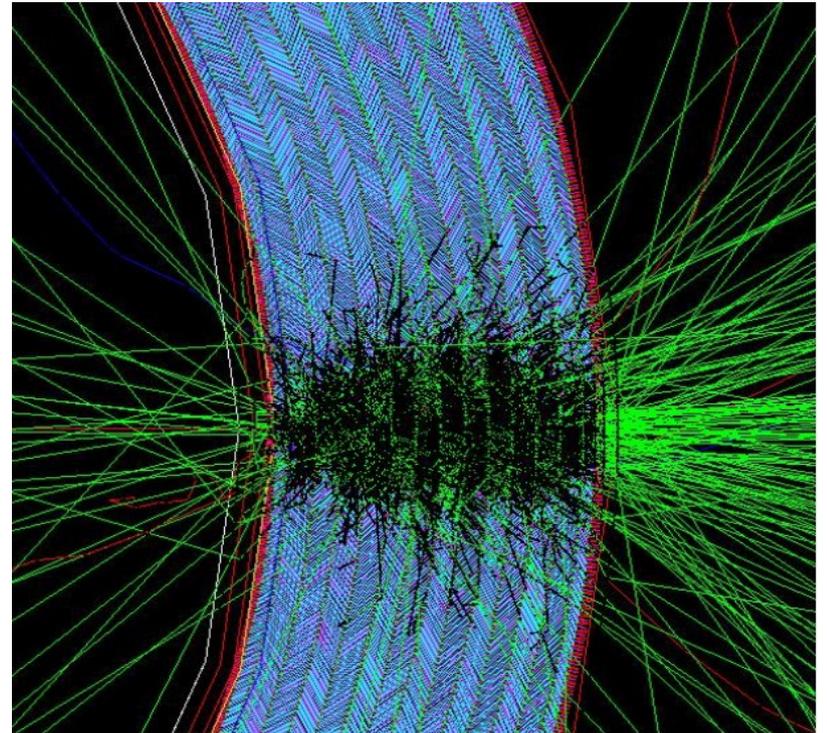


EM and Hadronic Calorimeters

- The electromagnetic calorimeters are used to measure energies of electrons and photons.
- In ATLAS jets will deposit significant fraction of their energy in the EM calorimeter.
- Electromagnetic and hadronic showers have different characteristics.
- The response of the calorimeters to electrons and hadrons is different. Calibration of the calorimeters is a non-trivial task.

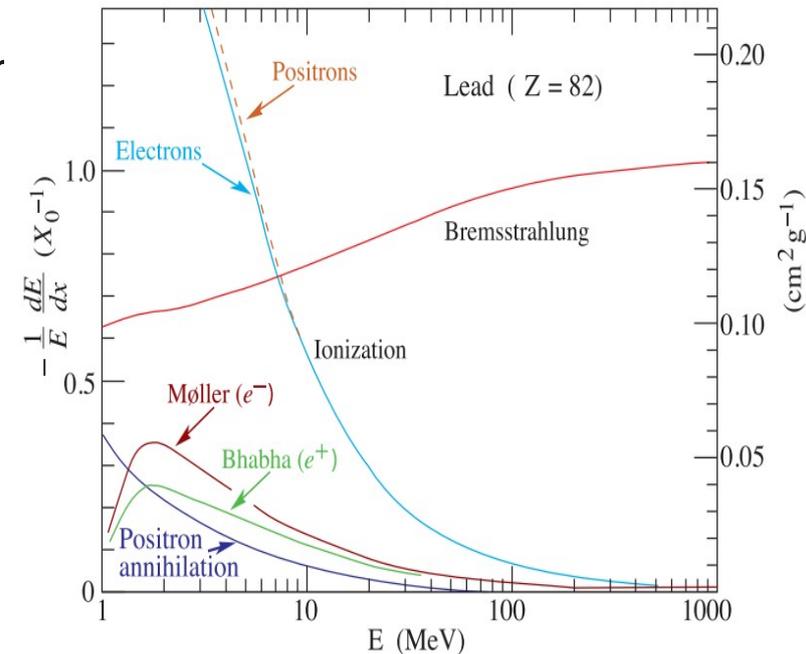
Simulation

- Detector simulation is widely used in the design and calibration of calorimeters.
- Geant4 is a software toolkit for the simulation of the passage of particles through matter.
- ATLAS calorimeter calibration relies on accurate simulation electromagnetic and hadronic showers.



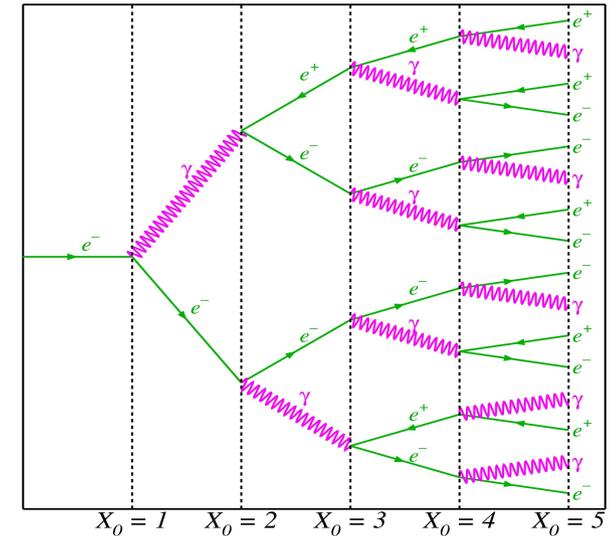
EM shower

- High energy electrons predominantly lose energy in matter by bremsstrahlung.
- For energetic photons the primary mechanism for energy loss is e^+e^- pair production.
- The radiation length X_0 is defined as the mean distance over which high energy electron energy decreases e times by bremsstrahlung.
- X_0 is equal to $7/9$ of mean free path for pair production by energetic photon.
- X_0 is the appropriate scale length for describing electromagnetic shower.



EM Shower Development

- In the initial stage of shower development bremsstrahlung and pair production create more electrons and photons with lower energies.
- Critical energy E_c is the energy at which the rate of energy loss through ionization and bremsstrahlung is equal. A good approximation is $E_c = 550/Z$ (MeV)
- Electron energies fall below the critical energy and dissipate their energy by ionization.
- At low energies ionization, Compton scattering and the photoelectric effect make the dominant contributions to energy loss.



EM Shower Development

- The following relationships are widely used:
 - Shower maximum in X_0 units $t_{\max} = \ln(E/E_c) + c_i$ where
 - $c_i = -0.5$ for electrons
 - $c_i = +0.5$ for photons.
 - $\langle L_{98} \rangle = 2.5t_{\max}$ or $\langle L_{98} \rangle = t_{\max} + 4\lambda_{\text{att}}$ where λ_{att} is related low energy photon attenuation, which dominates the tail of the shower. Experimentally it was found $\lambda_{\text{att}} = 3.5X_0$.
 - On average, laterally 95% of the shower is contained in cone with radius twice the Moliere radius $R_M = (21/E_c [\text{MeV}])X_0$ [gcm^{-2}]

Energy Resolution

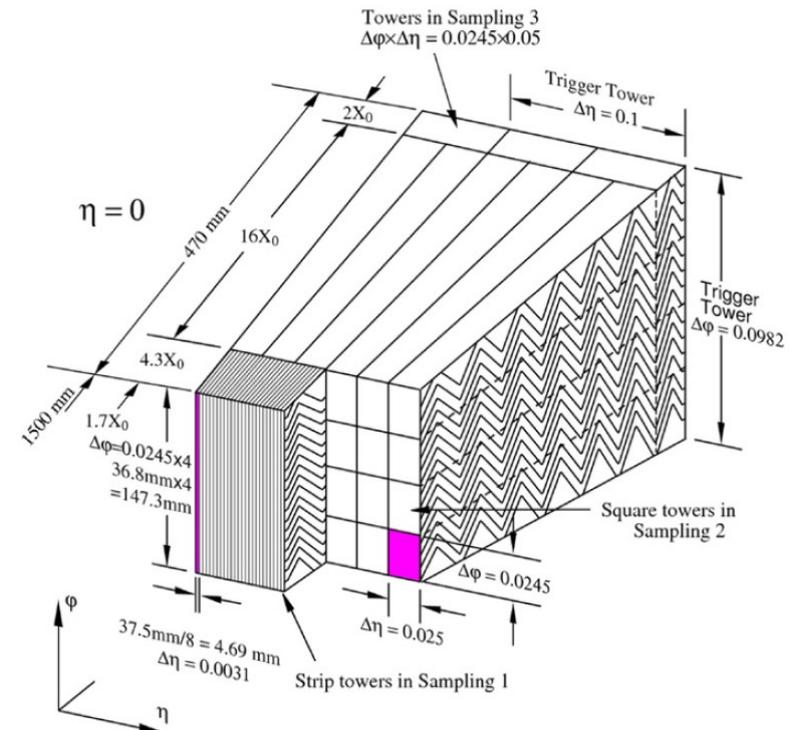
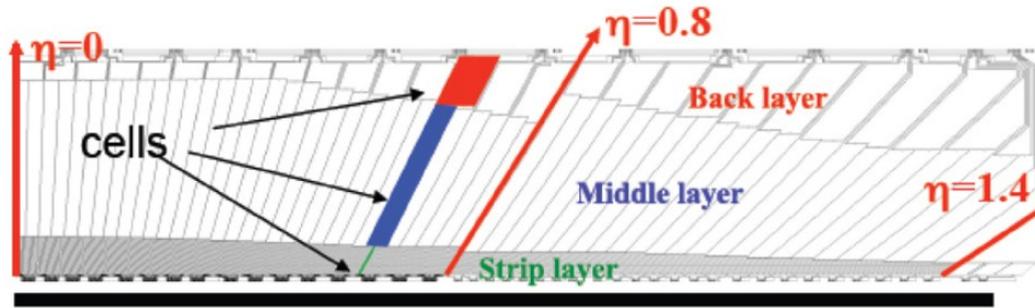
- The number of secondary particles in the cascade is proportional to incident energy $\langle n \rangle \sim E$.
- An important factor governing the energy resolution arises from fluctuations on the detected signal which is proportional to $\sqrt{\langle n \rangle}$.
- Therefore $\sigma_E/E \sim 1/\sqrt{\langle n \rangle} \sim 1/\sqrt{E}$, the relative resolution improves with the increase of energy.
- In practice there are various effects contributing to the energy resolution which is often parameterized by
 - $\sigma_E/E = a/\sqrt{E} \oplus b/E \oplus c$ where
 - the first term is called stochastic and arises from the fluctuations in number of detected signal quanta
 - the second term is referred to as noise term originating from electronics, pile-up ...
 - the third term is called constant term and comes from channel-to-channel response variations, non-uniformity of the response within single channel etc.

Sampling Calorimeter

- Detector composed of layers of active and passive medium.
- Advantages:
 - Fine granularity
 - Compactness due to use of high Z materials with small X_0
 - Cost effective
- Disadvantage:
 - Worse resolution due to sampling fluctuations
- State of the art example is ATLAS EM calorimeter. Liquid argon (LAr) is used as an active medium. The passive materials are lead, in the forward region copper or tungsten are used.

ATLAS LAr Calorimeter

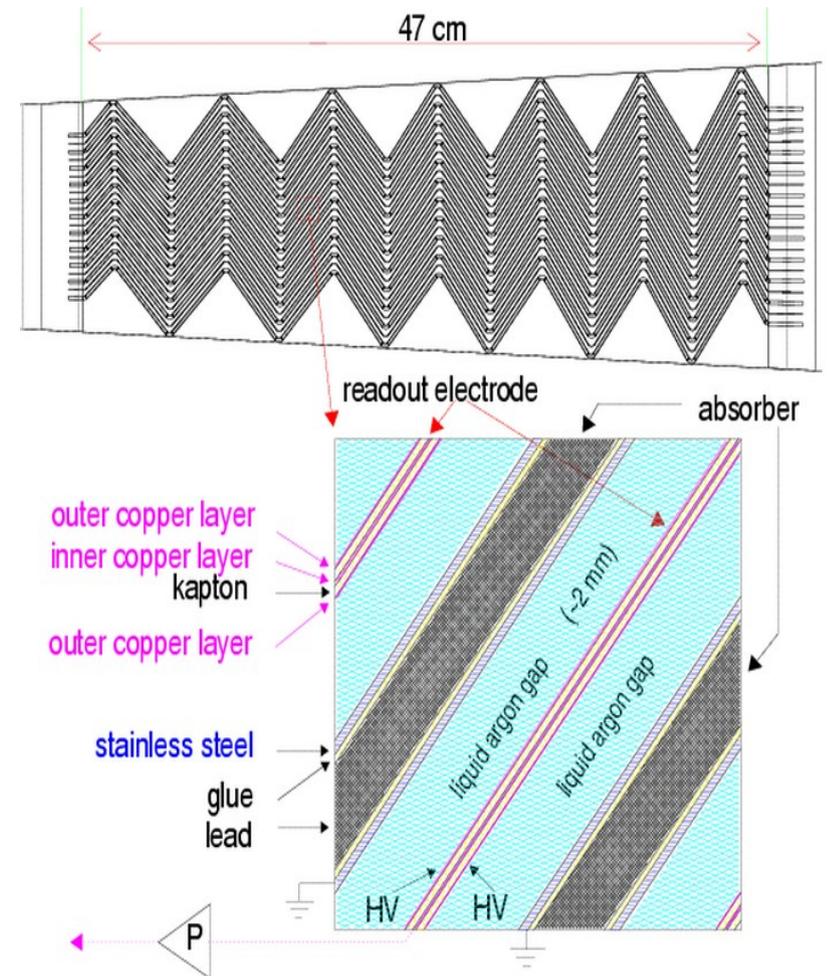
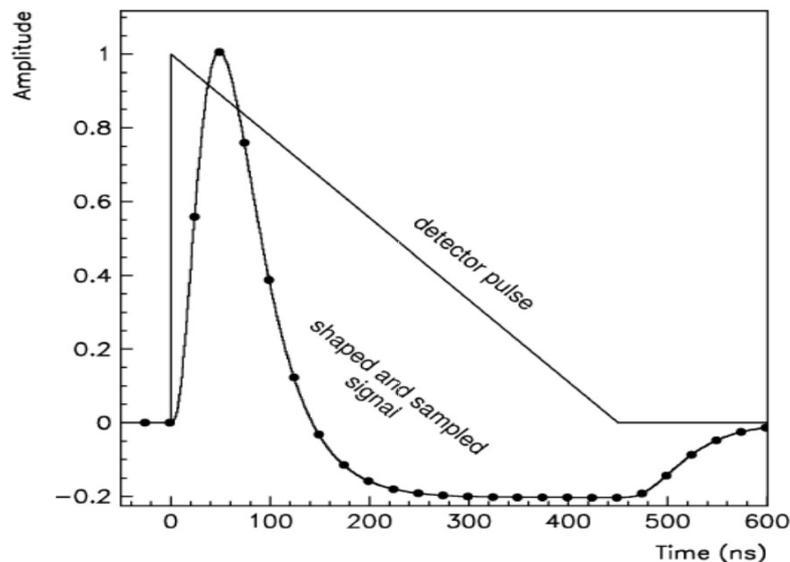
- Accordion geometry for hermeticity and high granularity.
- ~170K channels.
- Longitudinal segmentations.



Layer	Function	Size ($\Delta\eta \times \Delta\phi$)
0 = Presampler	Estimates energy loss before calorimeter	0.025 x 0.1
1 = Strips	High granularity for π^0/γ discrimination	0.003 x 0.1 ($\eta < 1.4$)
2 = Middle	Contains bulk of em shower energy	0.025 x 0.025
3 = Back	Tail of em shower, hadron shower rejection	0.05 x 0.025

Cell Energy Reconstruction

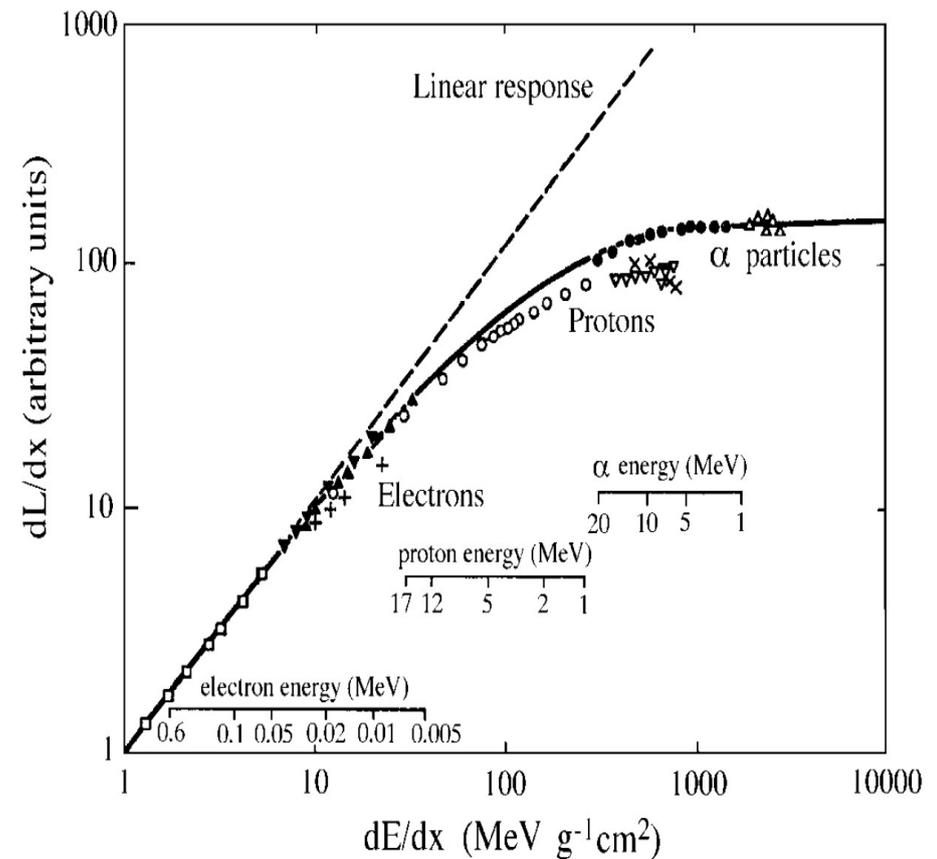
- Charged particles ionize the medium.
- Electrons drift in the electrical field.
- The drift time is 450 ns at 2000 V. This is too slow compared to 25 ns LHC bunch spacing.
- Use bipolar shaper to minimize the time need to collect the signal and reduce the impact of pileup.
- Digitize the pulse each 25 ns and use 5 samples to reconstruct energy and time as linear combination of samples.



Birks Law

- Saturation effects occur in scintillators quenching of primary excitations.
- In liquid argon recombination of electrons and ions lead to similar decrease of signal for high ionization particles.

$$\frac{dL}{dx} = S \frac{dE/dx}{1 + k_B \cdot dE/dx}$$



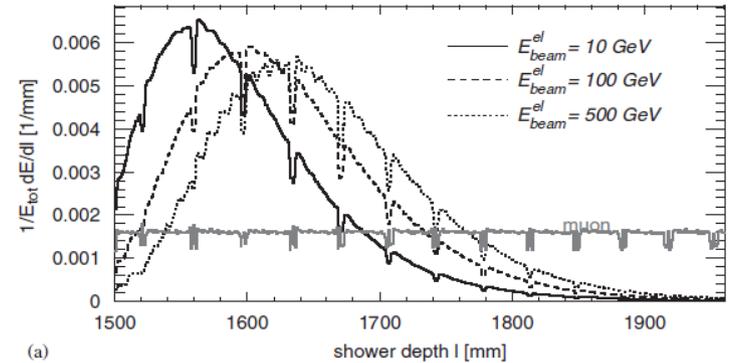
Clustering

- Calorimeter cells need to be grouped together for measurement of electron, photon and jet energies.
- Clustering provides noise suppression mechanism. Absolutely crucial for the measurement of global event level quantities like missing transverse energy or scalar sum of all energy.
- Two clustering algorithms are used in ATLAS:
 - Sliding window
 - Topological clustering
- In sliding window the size of clusters is fixed. The clusters are rectangular in $\eta \times \phi$ space and include all layers of (EM) calorimeter. Suitable for electron and photon measurements which have small fluctuations in shower lateral and longitudinal development.
- Topological clusters can have arbitrary size and shape. Topo-clusters are used for jet and missing transverse energy measurements and provide efficient noise suppression.

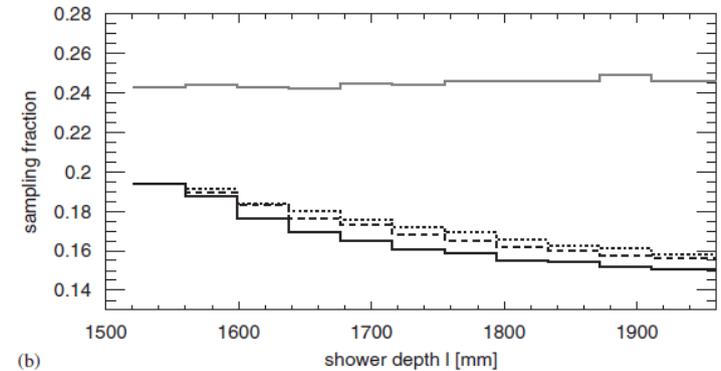
Electron Calibration

- Correct for:
 - Upstream energy loss
 - Presampler and strips
 - Downstream loss
 - Impact position

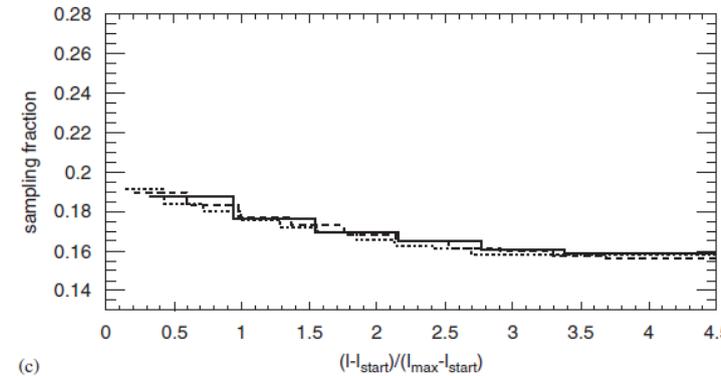
$$E^{\text{rec}} = \left(a(E) + b(E) E_0^{\text{vis}} + c(E)(E_0^{\text{vis}} \cdot E_1^{\text{vis}})^{0.5} + \frac{1}{d(E)f_{\text{samp}}} \sum_{i=1,3} E_i^{\text{vis}} \right) \cdot f_{\text{cell impact}}(\Delta\Phi) \cdot (1 + f_{\text{leakage}}(E))$$



(a)



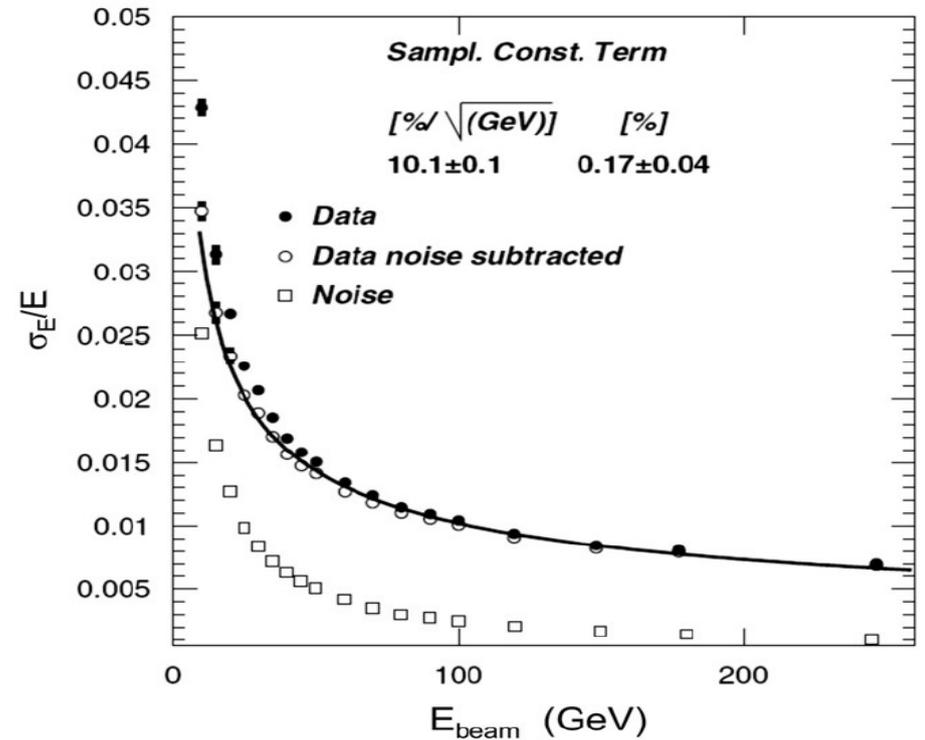
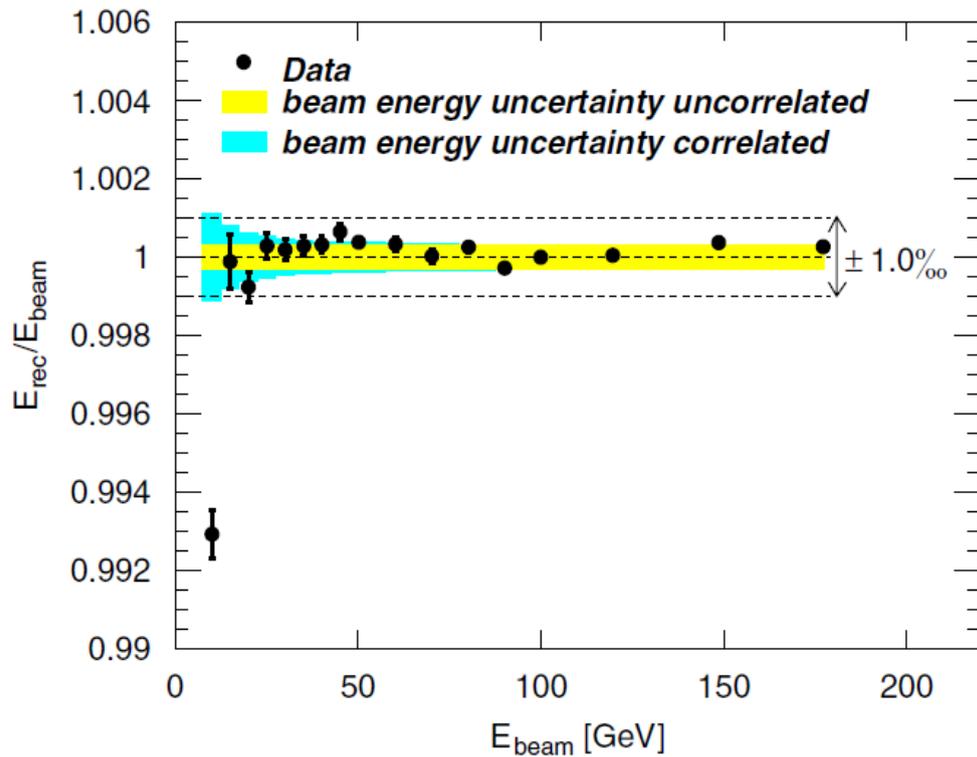
(b)



(c)

Response and Resolution

- Performance demonstrated at test beam.

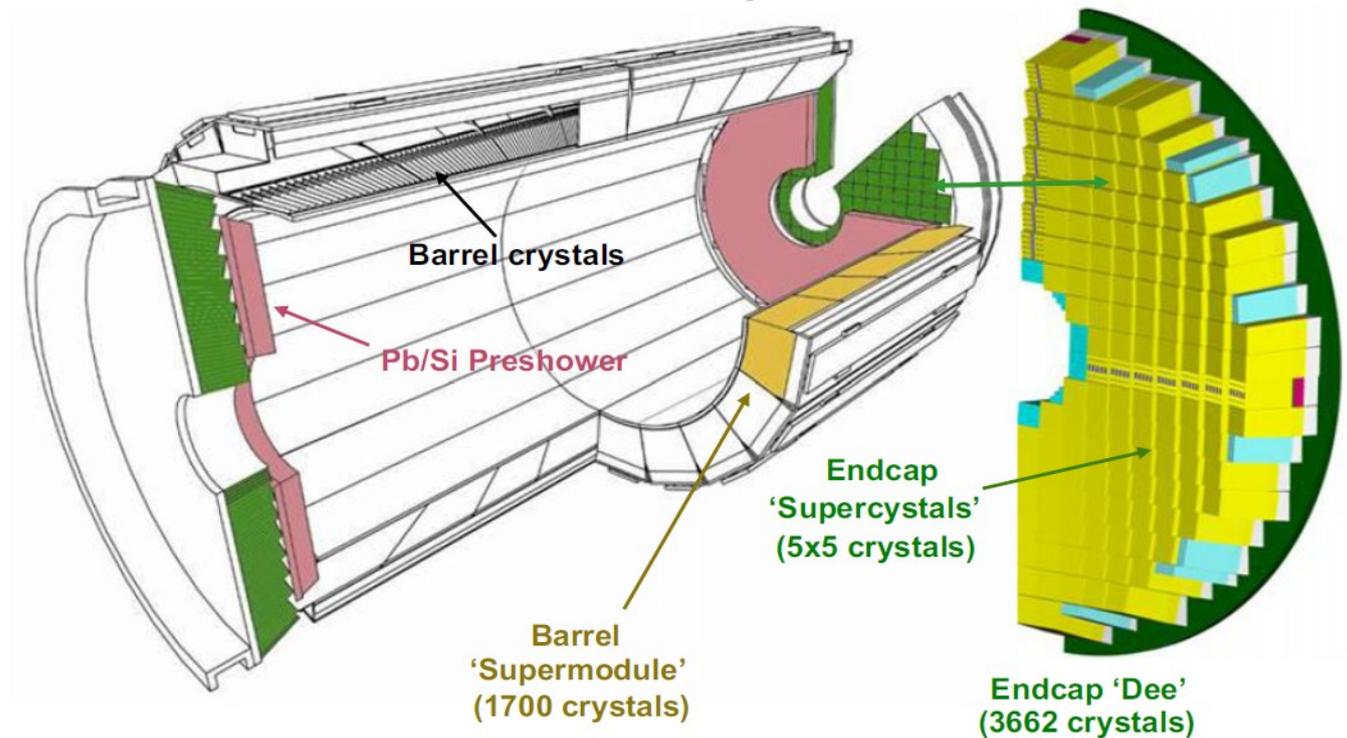


Homogeneous Calorimeters

- The absorber and the detection mediums are the same.
- CMS EM calorimeter is state-of-the-art example of such a detector. 76K lead tungstate (PbWO_4) crystals are used.
- In addition to excellent energy resolution other requirements are radiation resistance, fast response and high granularity.

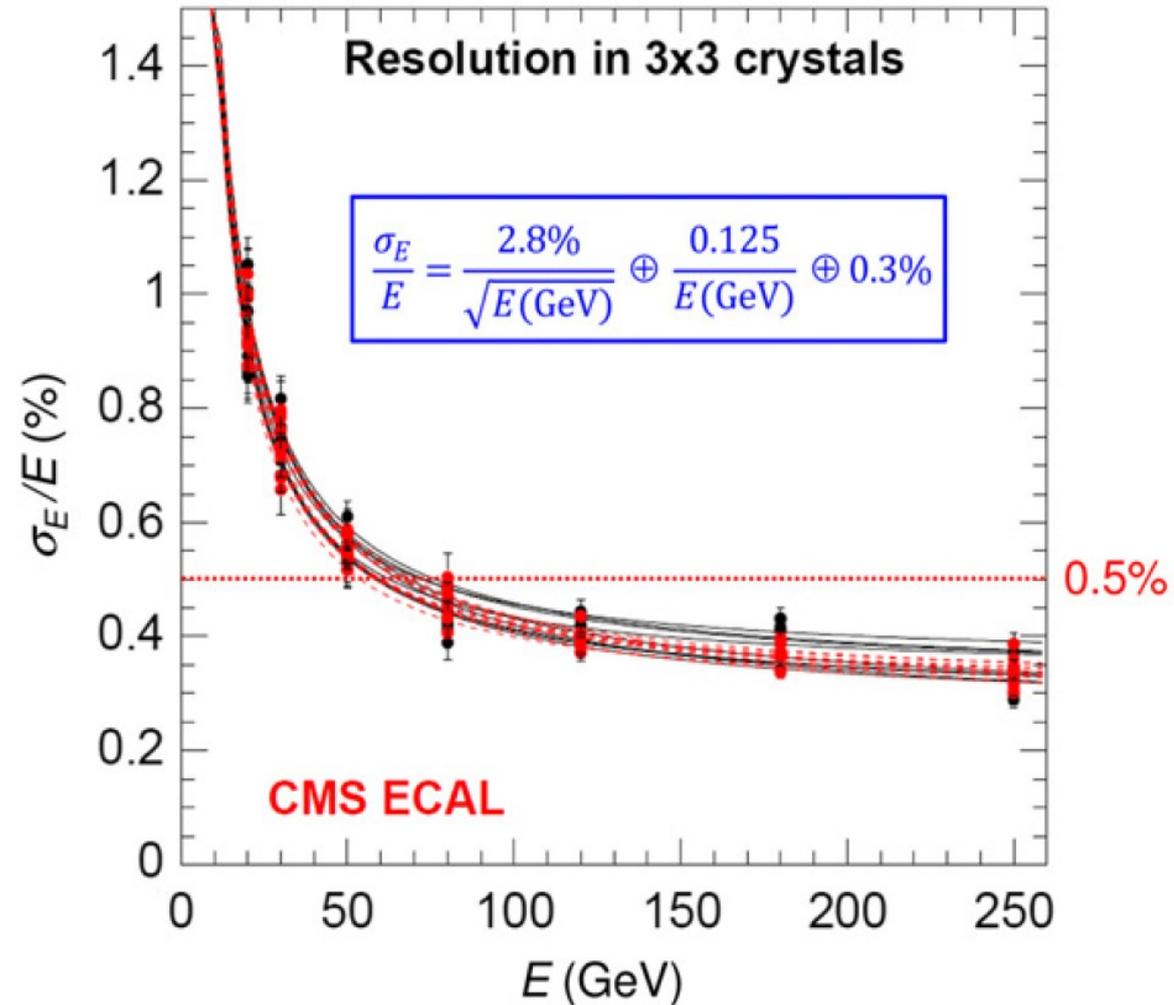
CMS ECAL

- In barrel the crystals are $25 \times 25 \text{ mm}^2$ in cross-section and 230 mm long corresponding to $\sim 25X_0$.
- Avalanche Photodiodes are used to for signal measurement.



Energy Resolution

- Performance from the test beam.
- Very good energy resolution is achieved.
- Various curves correspond to different impact points in the test beam setup.
- CMS ECAL has significantly better energy resolution than ATLAS LAr. However the sensitivities to $H \rightarrow gg$ in both experimenters are similar.
- Fine granularity in the first layer allows better γ/π^0 separation and longitudinal separation makes it possible to determine photon direction from the calorimeter measurements.



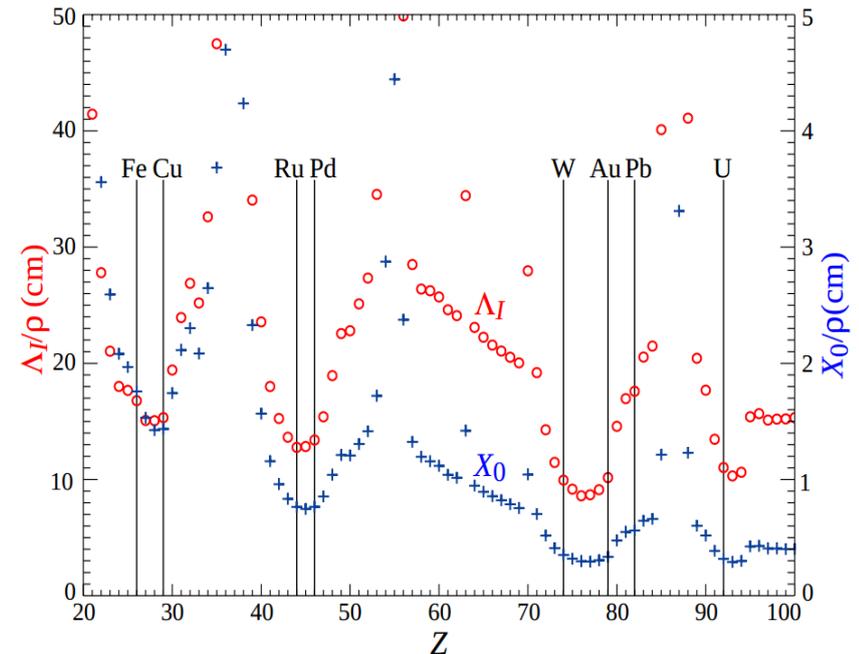
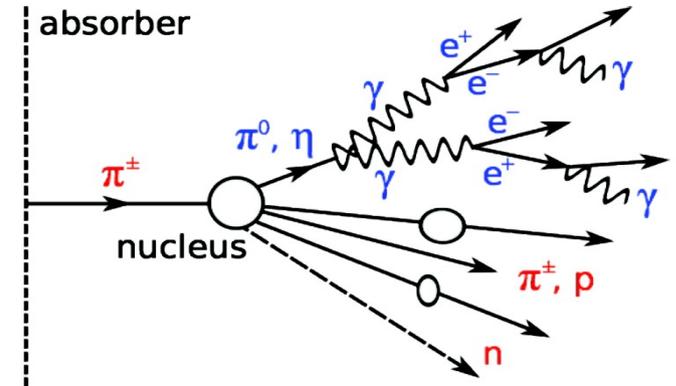
Hadron Calorimetry

Hadron Calorimetry

- The hadronic showers are much more complex than the electromagnetic ones.
- Calibration of hadronic calorimeters is a difficult task due to non-linearities of the response.
- Experimentally it is challenging to achieve good energy resolution for jets and determine the energy scale precisely.
- Large fluctuations in hadronic showers compared to EM ones due to lower multiplicity.
- For fairness one should note that the requirements are also different:
 - Resolution
 - Electron/photon $10\%/ \sqrt{E}$ vs. $50\%/ \sqrt{E}$ for jets
 - Energy scale uncertainty
 - Electron/photon 0.1% vs. 1% for jets

Hadronic Shower

- Incident hadron interacts with nuclei of absorber and creates secondary particles.
- Electromagnetically decaying particles initiate EM shower.
- Other hadrons interact further and induce hadronic shower.
- The scale of the shower is determined by the nuclear interaction length λ which is significantly larger than X_0 in typical materials used in calorimeters.
- λ is the average distance that high energy hadron travels before nuclear interaction occurs. λ is inverse proportional to hadron-nuclei nuclear interaction total cross-section, therefore different for pions and protons.



Hadronic Interactions

- The first stage is hard interactions.
- The second stage is nuclear de-excitation in which soft particles are emitted.
- The response of the detector to the hadronic part of shower is usually smaller compared to the electromagnetic part ($e/h > 1$) due to:
 - Energy lost in nuclei breakup which does not produce any signal, called invisible energy.
 - Short range of spallation nucleons
 - Saturation effect due to slow, high ionizing particles

Electromagnetic Fraction

- Energy transfer to the EM component is a one way street. π^0 s decay electromagnetically quickly without undergoing further hadronic interactions.
- With the increase of incident energy the number of generations increase. So does the EM energy fraction.
- Consider very simplified model:
 - Only pions are produced in hadronic interactions
 - 1/3 of pions are neutral
 - At low energies only one generation is possible $f_{EM} = 1/3$
 - For two generations $f_{EM} = 1/3 + 2/3 \times 1/3 = 5/9 > 1/3$
 - After n generation $f_{EM} = 1 - (1-1/3)^n$
- Widely used parameterization is $f_{EM} = 1 - (E/E_0)^{m-1}$ $E_0 \sim 1$ GeV, $m \sim 0.82$
- In proton induced shower f_{EM} is smaller compared to pion induced ones due to baryon number conservation.

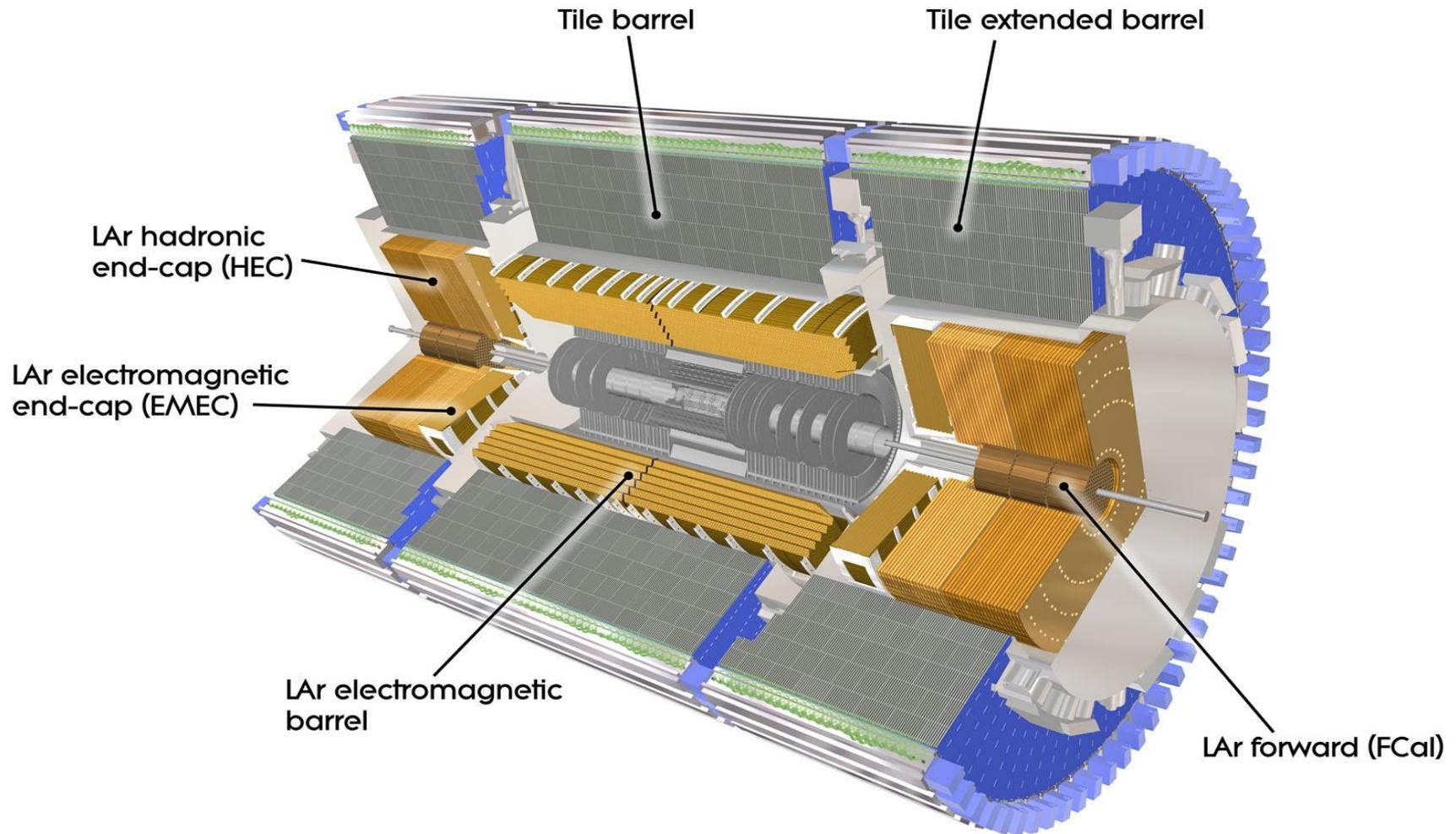
Energy Response

- The response of the detector to
 - electrons/photons $R_e = eE_0$
 - hadrons $R_h = ef_{EM}E_0 + h(1-f_{EM})E_0$
- Detectors with $e/h = 1$ are called compensating calorimeters.
- Most of the calorimeters are non-compensating due to invisible energy.
- Since f_{EM} depends on incident energy the response of non-compensating calorimeters to hadrons is non-linear.

Compensation

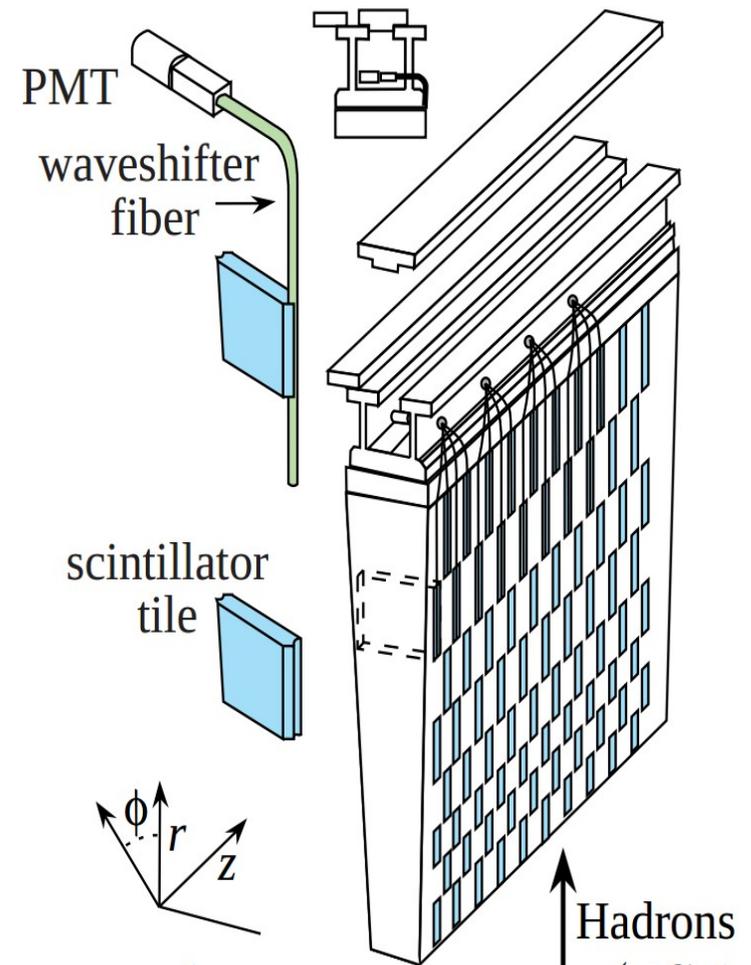
- Event-by-event fluctuations of EM energy fraction worsens the resolution of non-compensating calorimeters.
- To achieve compensations one can:
 - Decrease the response of the detector to EM component, for instance by using thick high Z absorber. This has negative consequence for electron/photon resolution. In LHC experiments EM calorimeters are used both for electron and jet measurements.
 - Increase the response to hadronic component by using uranium as an absorber which leads to an amplification of neutron component. Response time might be a limiting factor.
- Software or “hardware” compensations are other options discussed later.
- Homogeneous calorimeters are always non-compensating due to invisible energy.
- e/h cannot be determined experimentally without making assumption on f_{EM} dependence on incident energy.

Reminder: ATLAS Calorimeters



ATLAS Tile Calorimeter

- Iron-scintillator sampling detector located in the central region of the ATLAS detector.
- Scintillating tiles are read out by wave length shifting fibers connected to photomultipliers.
- Tiles are placed in planes perpendicular to the colliding beams. This allowed to build hermetic calorimeter and obtain high resolution with the need to bend the fiber which leads to light losses.



ATLAS Tile Calorimeter

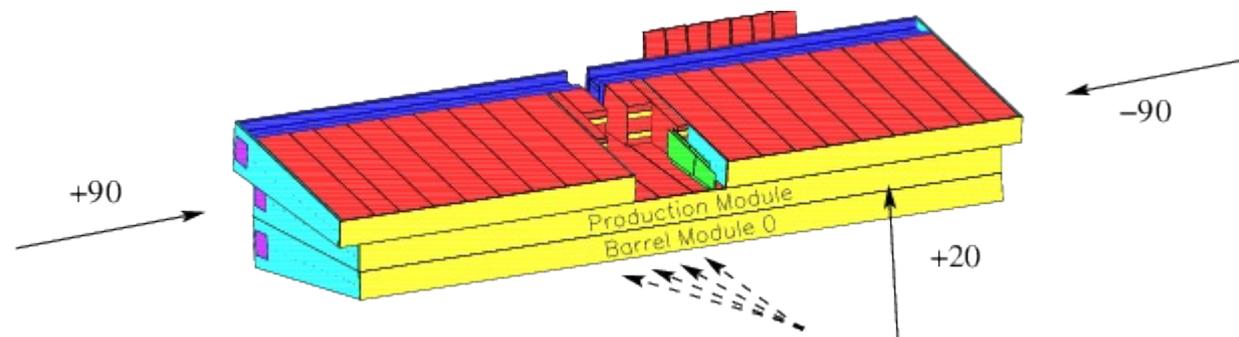
- TileCal covers pseudorapidity region $|\eta| < 1.7$
- The cell granularity is 0.1×0.1 in $\eta \times \phi$ space except the last layer. Each cell has two channels, in total $\sim 10\text{K}$ channels.
- The depth at $\eta = 0$ is 7.4 nuclear interaction lengths (λ). Combined with EM calorimeter the depth is 10λ .
- The response is faster compared to LAr calorimeters.

Monitoring

- Monitor detector response variations over time.
- Equalize the response of all cells.
- Three different systems:
 - Cesium source
 - Test tiles, fibers, PMTs using gammas from ^{137}Cs to equalize the response of cells by adjusting PMT voltage.
 - Laser
 - Test PMTs using light pulse.
 - Charge injection
 - Monitor charge to ADC conversion of both gains using reference charge.

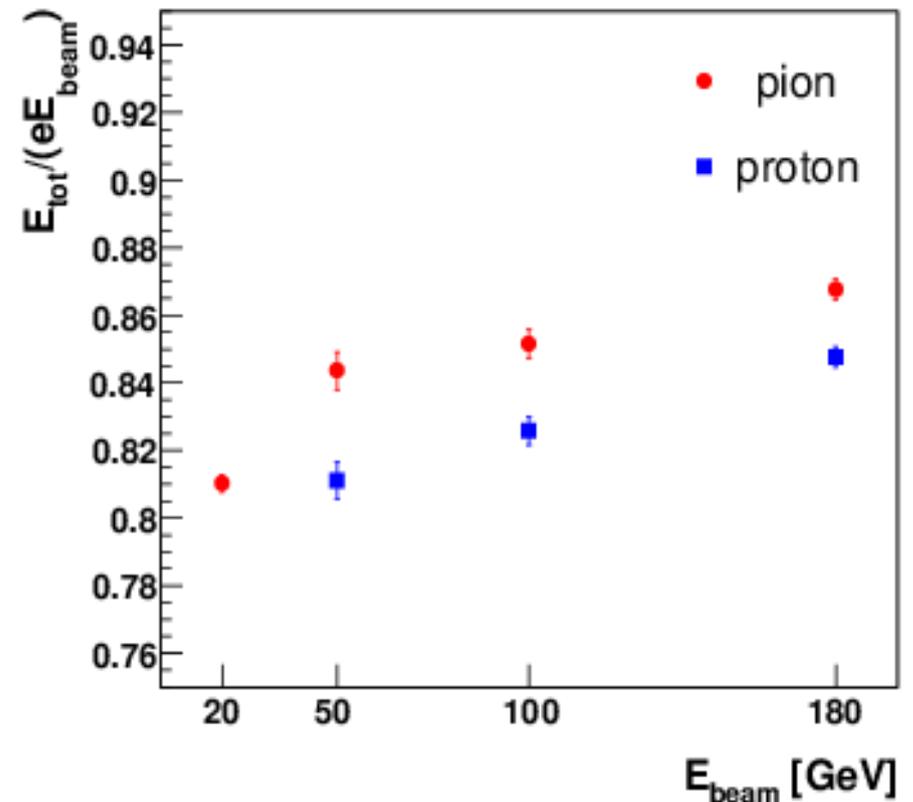
Test Beam

- Test beam studies provide valuable data for full understanding of the detectors in a simple environment. Very useful for validation of simulation.
- Some results from TileCal test beam measurements will be shown. Special runs, in which the beam impinging the detector from the side, the calorimeter has more than 20λ depth. This allowed to study the shower development, the impact of leakage on response and resolution in a unique environment.



Response

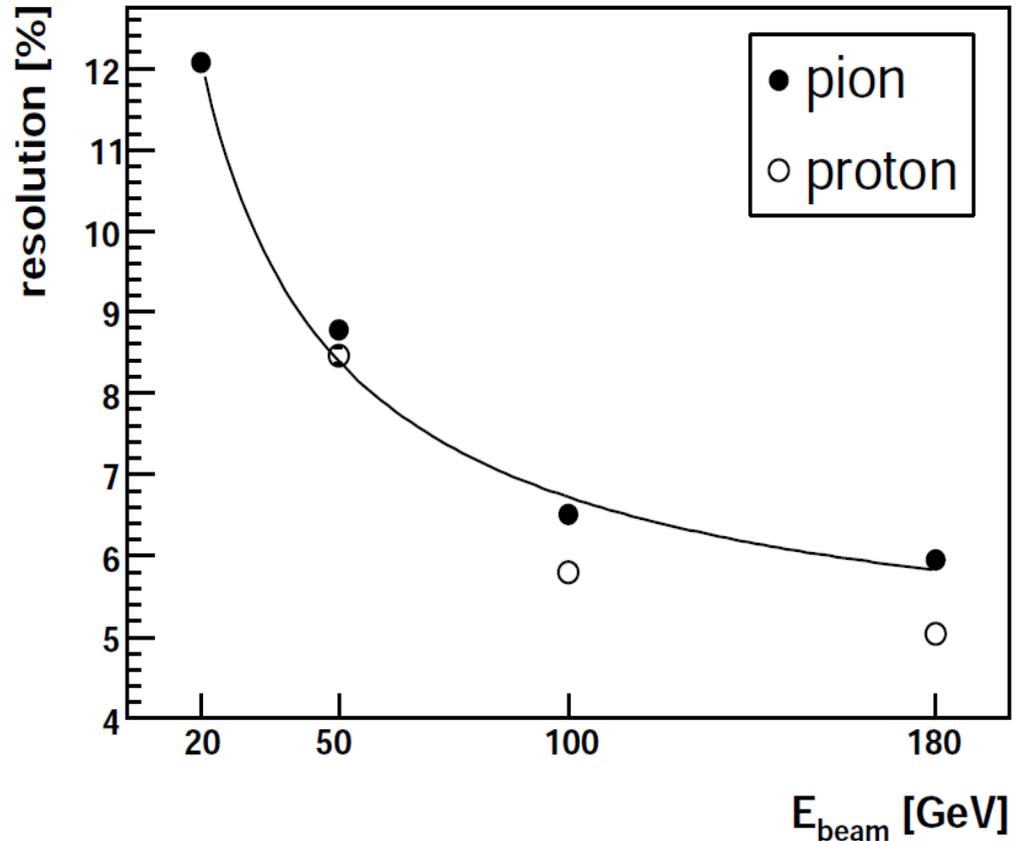
- Response to pions and protons divided by beam energy. The response is at electromagnetic energy scale, in other words, relative to electron response.
- Observations about hadron response:
 - 15-20% smaller compared to electrons.
 - Non-linear as function of incident energy.
 - pions have higher response compared to protons.
- Explanations:
 - Invisible energy, $e/h > 1$
 - EM energy fraction depends on incident energy
 - Smaller EM fraction in proton induced showers due to baryon number conservation.



$$e/h = 1.44$$

Resolution

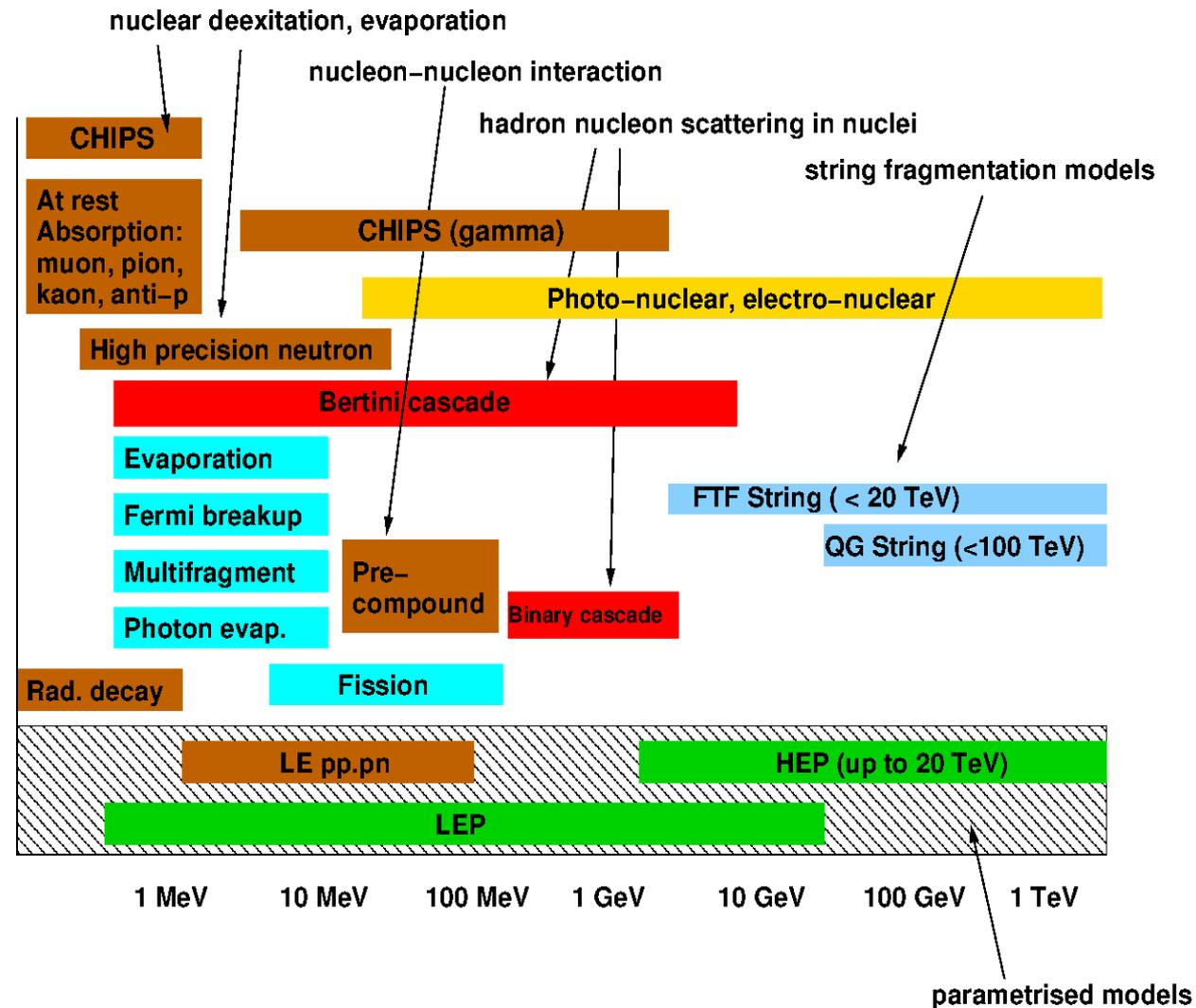
- Energy resolution defined as RMS of total energy distribution divided by its mean value.
- Pions have higher response but worse resolution.
- Large fluctuations in EM energy fraction in pion induced showers. For example, if charge exchange reaction $\pi^+ + n \rightarrow p + \pi^0$ occurs in the beginning of shower development almost pure EM shower will be generated.
- Baryon number conservation and leading particle effects in proton induced shower lead to reduction of EM energy fraction fluctuations.



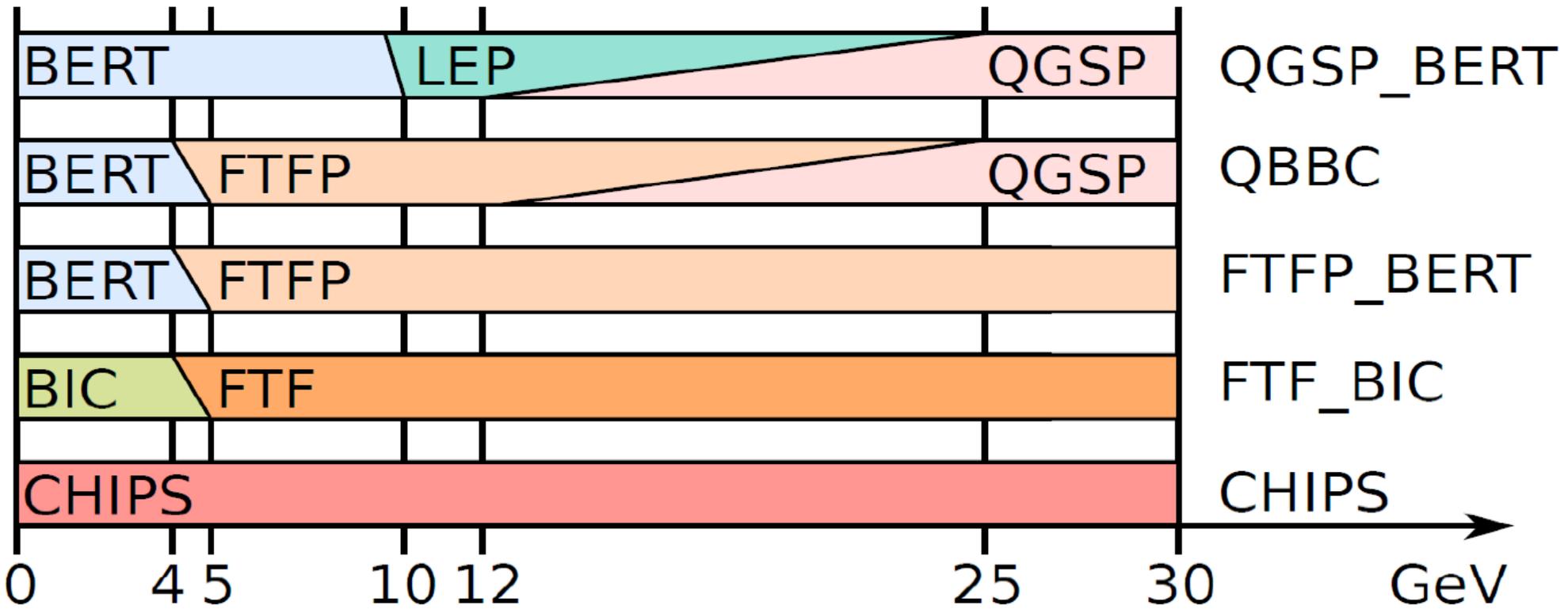
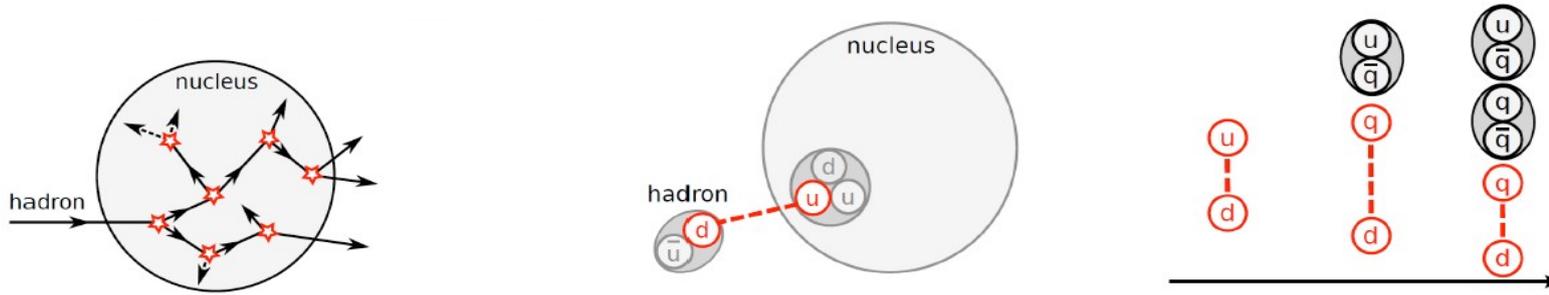
- For pions
 $\text{RMS}/E = a/\sqrt{E} \oplus b$
 $a = 50.3 \text{ GeV}^{-1/2}$, $b = 4.4\%$

Hadronic Shower Simulation

- Due to variety and complicated nature of nuclear interactions it is extremely difficult to obtain accurate description of hadronic shower in wide energy range and for all hadrons.
- Physics list is a collection of models covering interactions of all hadrons at all energies.

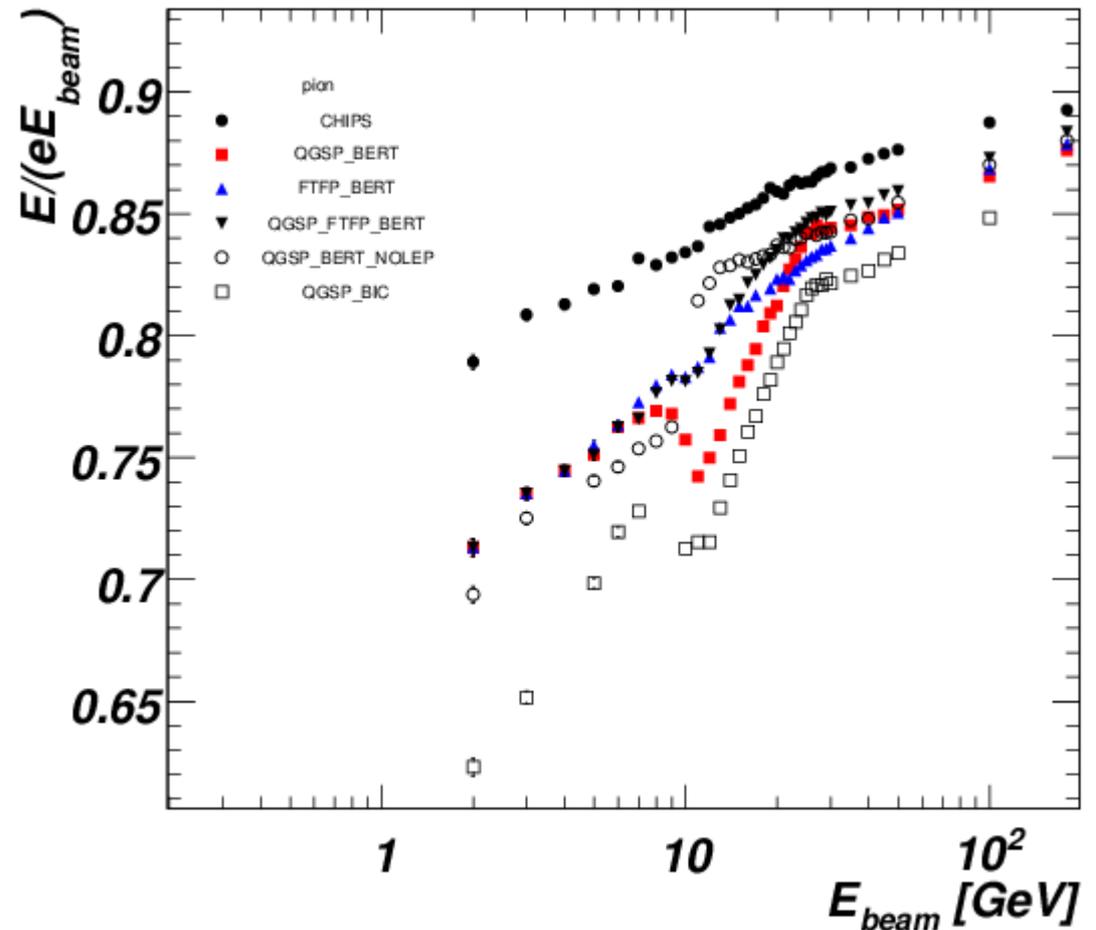


Physics List



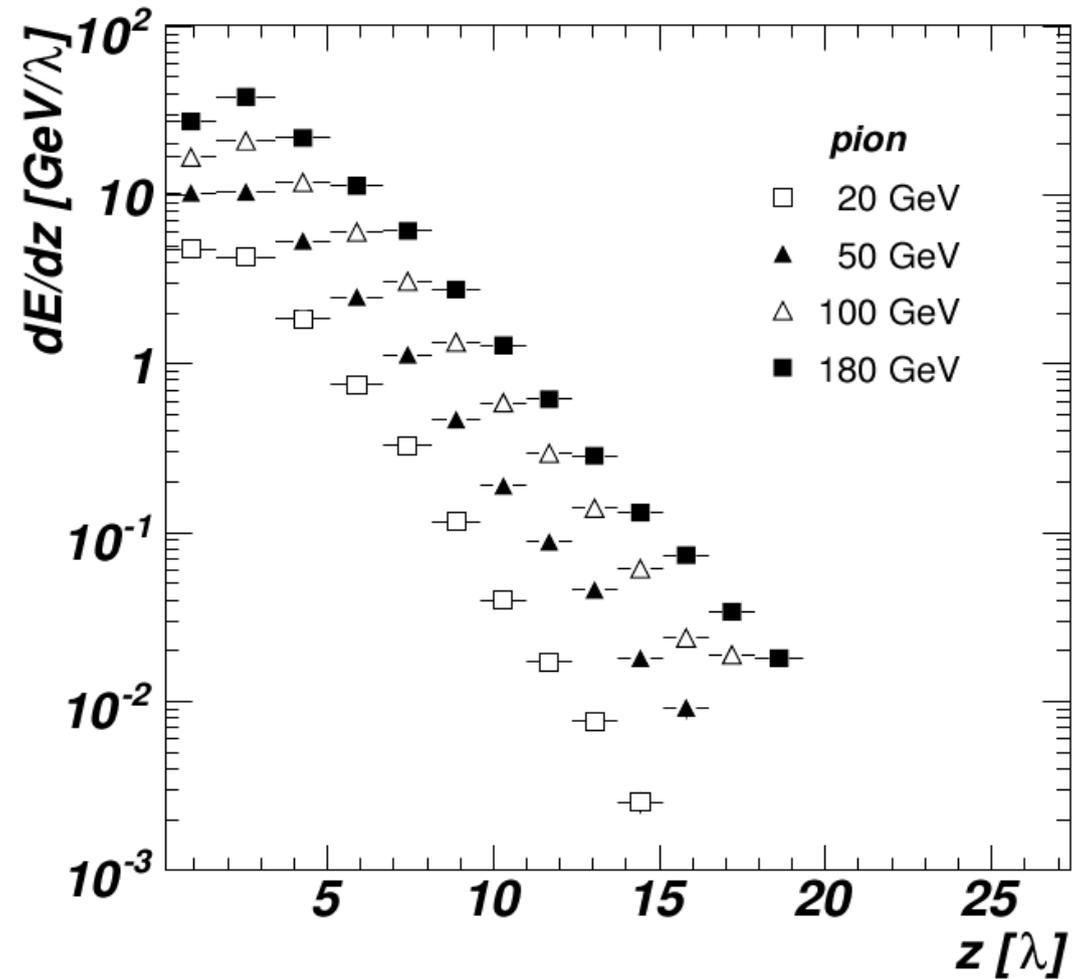
Response Simulation

- Large variation of the response between physics list.
- Unphysical energy dependence of the response on incident energy. The transitions between models are clearly visible.
- In recent years noticeable progress has been made in Geant4 to improve the description of hadronic interactions thanks to feedback from test-beam programs.



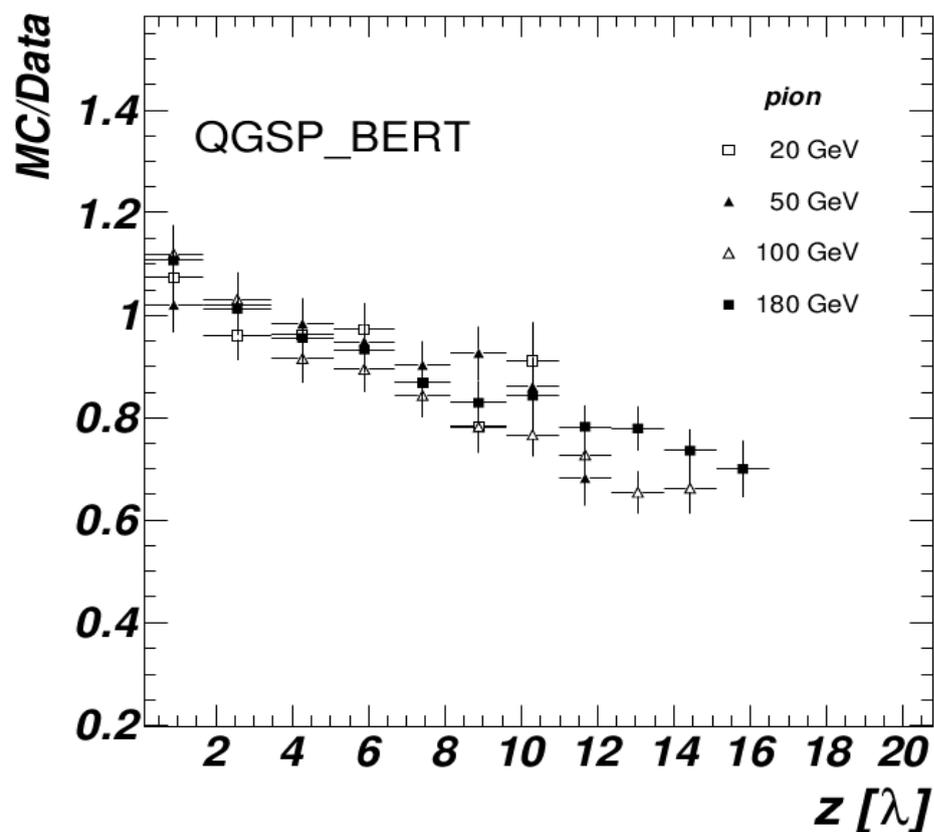
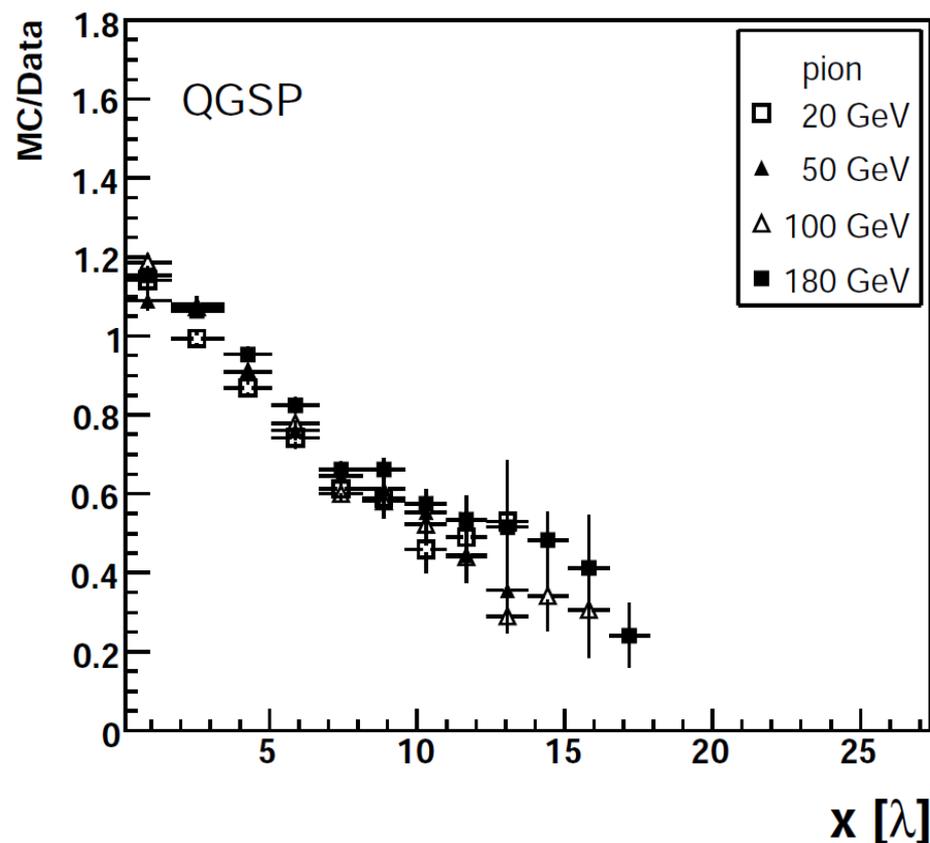
Longitudinal Profile

- Showers reach maximum quickly and decrease exponentially with the depth.
- First measurement up to 20λ .



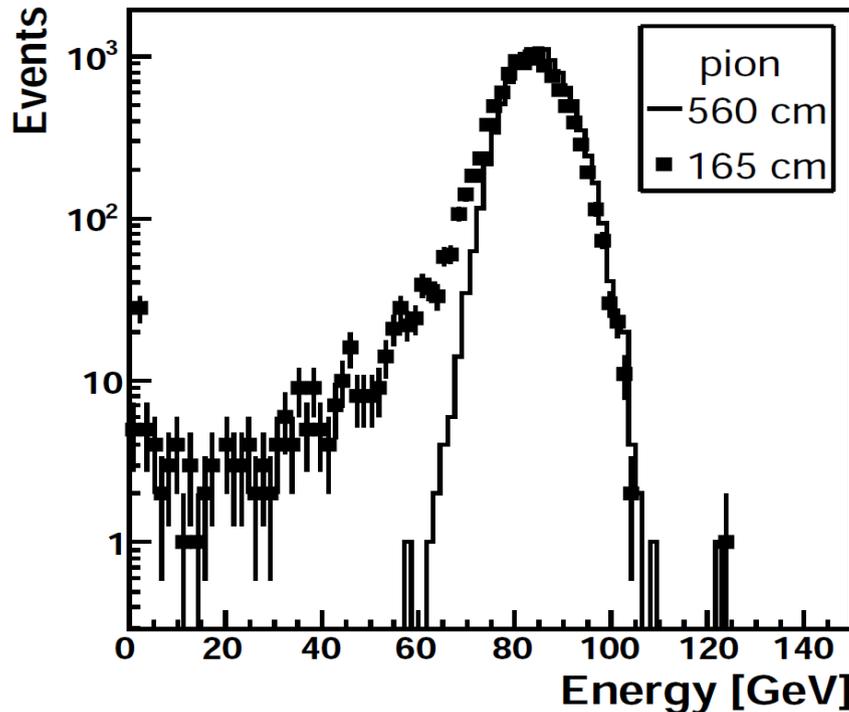
Longitudinal Profile Description

- Significant mis-modeling of shower longitudinal development.

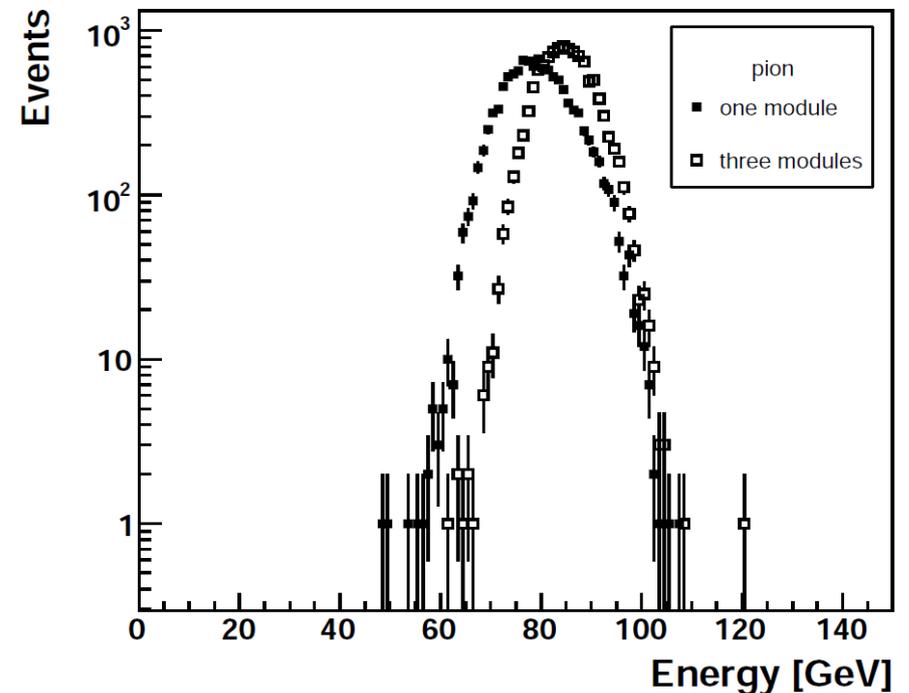


Limited Containment

- Longitudinal leakage



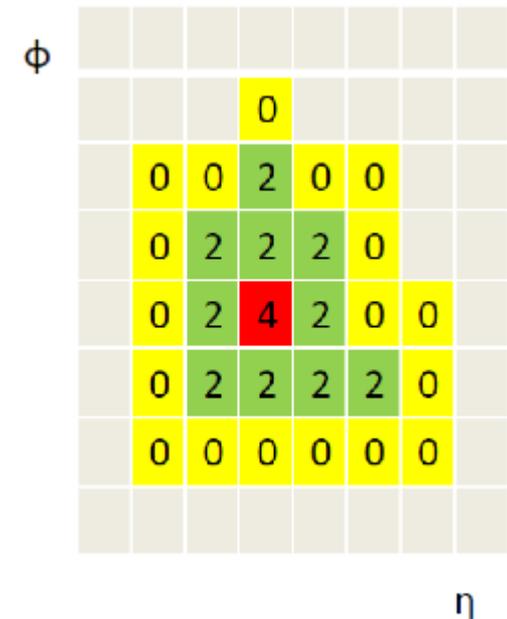
- Lateral leakage



- Longitudinal leakage has large fluctuations around its average value and creates low energy tail. Depends on the incident particle interactions, therefore large fluctuations.
- Lateral leakage shifts the entire distribution without creating tails. Depends on many soft particles, therefore small fluctuations.

Topological Clustering

- Cluster cells based on the significance of the energy and topology.
- Each cell has a certain noise (σ) determined from random trigger events. This can be electronic noise or include pile-up as well. Typical range is $\sigma \sim 20 - 200$ MeV, but pile-up has huge impact on the forward region.
- Find cells $|E| > 4\sigma$.
- Add neighboring cells with $|E| > 2\sigma$.
- Finally add all cells surrounding the selected cells.
- Clusters can have arbitrary size and shape.
- Efficient noise suppression.
- At the end clusters are split around local maxima.



Local Hadron Calibration

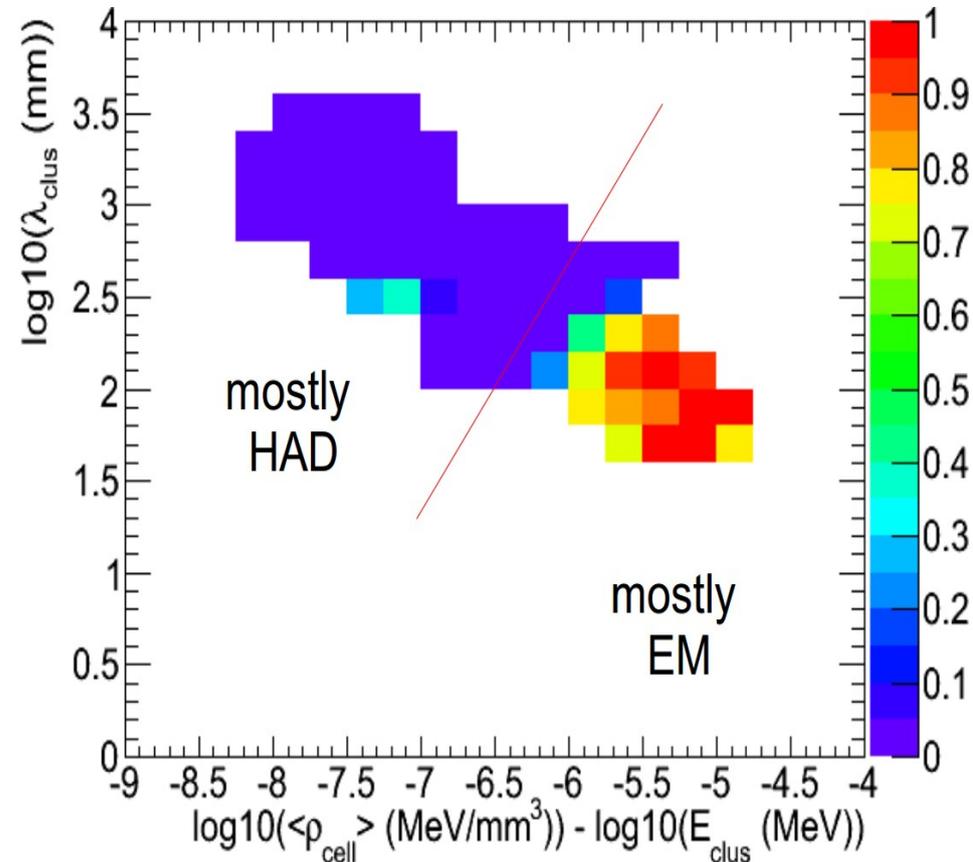
- ATLAS calorimeters are non-compensating detectors.
- Fluctuations of EM energy fraction in hadronic showers lead to degradation of energy resolution.
- Use local topology of energy deposition in the calorimeters to account for non-compensation and other effects and improve the energy resolution.
- Relies heavily on detailed simulation of hadronic shower, software compensation based on statistical methods.
- Inspired by "H1" weighting but provides calibration without the need to define a jet context.

Local Hadron Calibration

- Derive calibration constants from single pion simulation.
- Use observables discriminating EM and hadronic energy depositions.
- Build a PDF and classify the clusters as EM or hadronic using the observables.
- Each cell in clusters classified as hadronic receives a weight

$$w = \langle E_{\text{true}} / E_{\text{reco}} \rangle$$

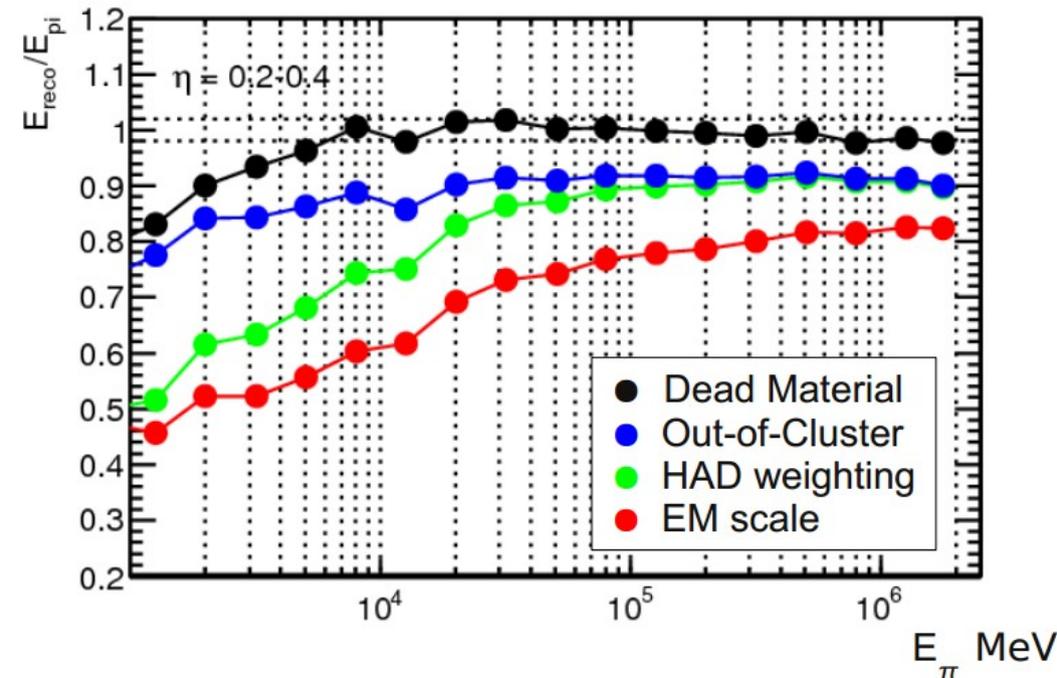
- The weights depend on cluster energy and η , sampling, cell energy density.



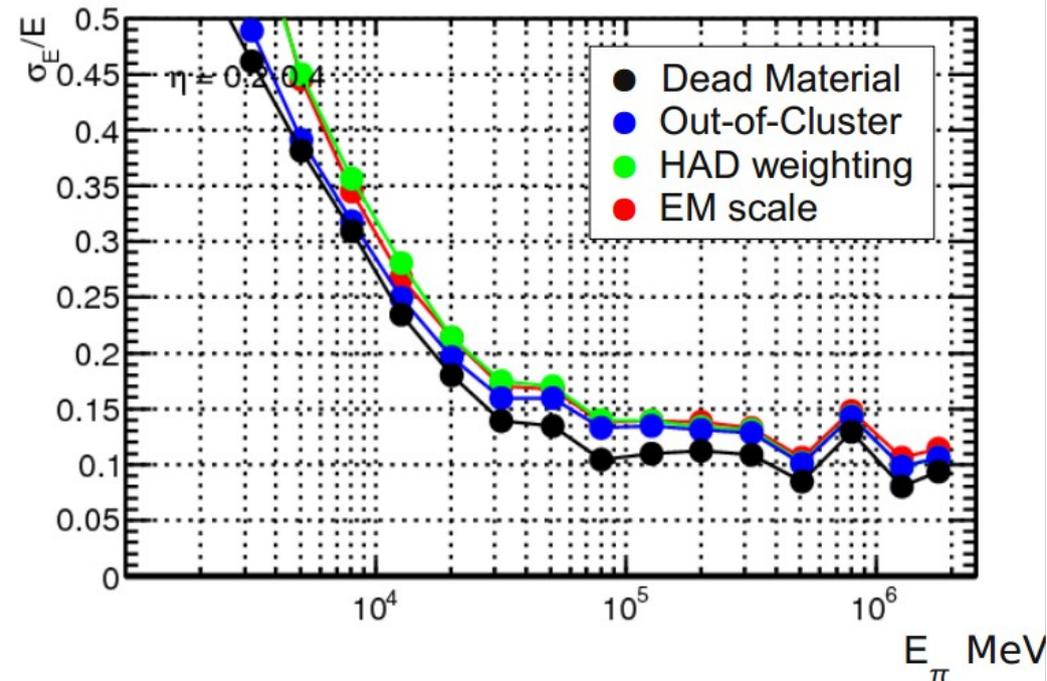
Local Hadron Calibration

- Additional correction for energy deposited:
 - Outside clusters (noise thresholds)
 - Dead material

Linearity E_{reco}/E_{π} vs. E_{π}



Energy resolution



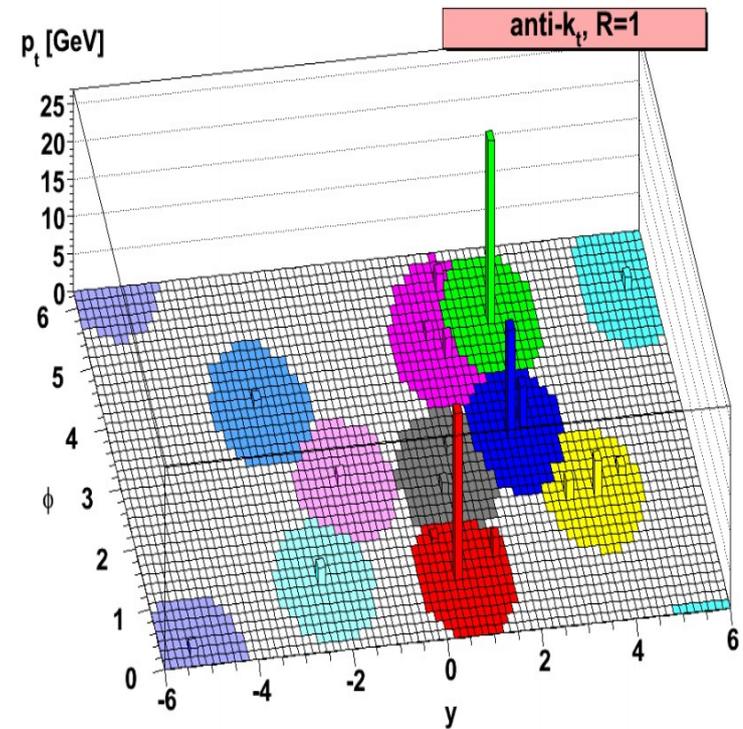
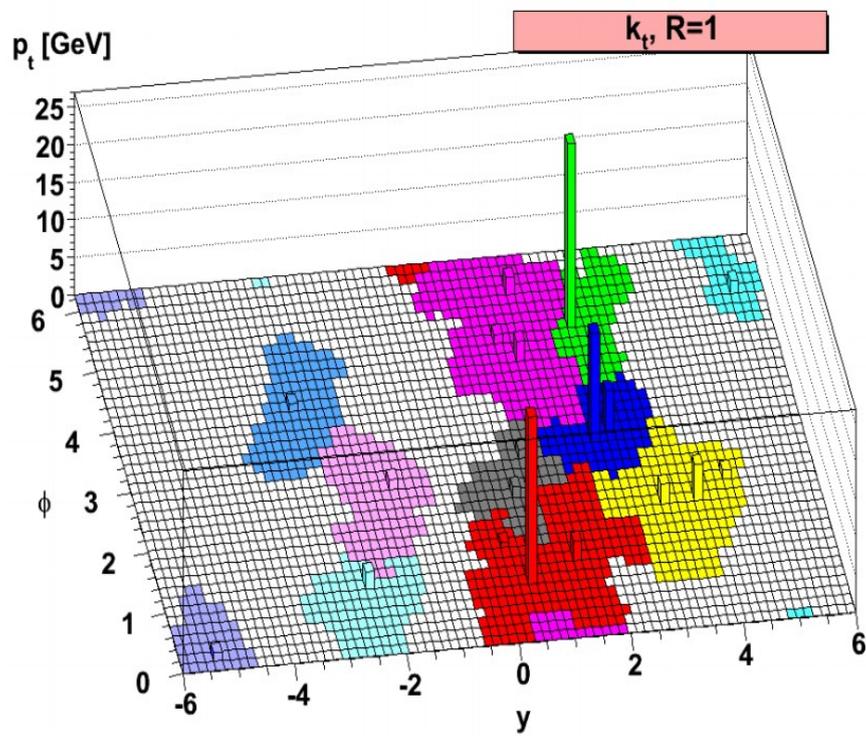
Jets

- Jets are collimated sprays of hadrons that result from the fragmentation of a high energy quark or gluon.
- Jet is defined by the jet algorithm and its parameters. Input is a list of momenta vectors, can be parton, particles, track, calorimeter clusters and towers etc.
- Combine two object closest in some distance measure until some stopping criterion is reached or stable cone is formed.
- Define distance between:
 - two constituents $d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \Delta R_{ij}^2 / R^2$
 - constituent i a beam $d_{iB} = p_{ti}^{2p}$

R is jet radius parameter, $\Delta R_{ij}^2 = (y_i - y_j)^2 + (\Delta\phi_{ij})^2$, $y_i = 0.5 \ln([E_i + p_{zi}]/[E_i - p_{zi}])$
- If $d_{ij} < d_{iB}$ recombine i and j by adding Lorentz vectors
else constituent i is a jet
- $p = 1$ k_t algorithm
- $p = -1$ anti- k_t algorithm
- $p = 0$ Cambridge/Aachen algorithm

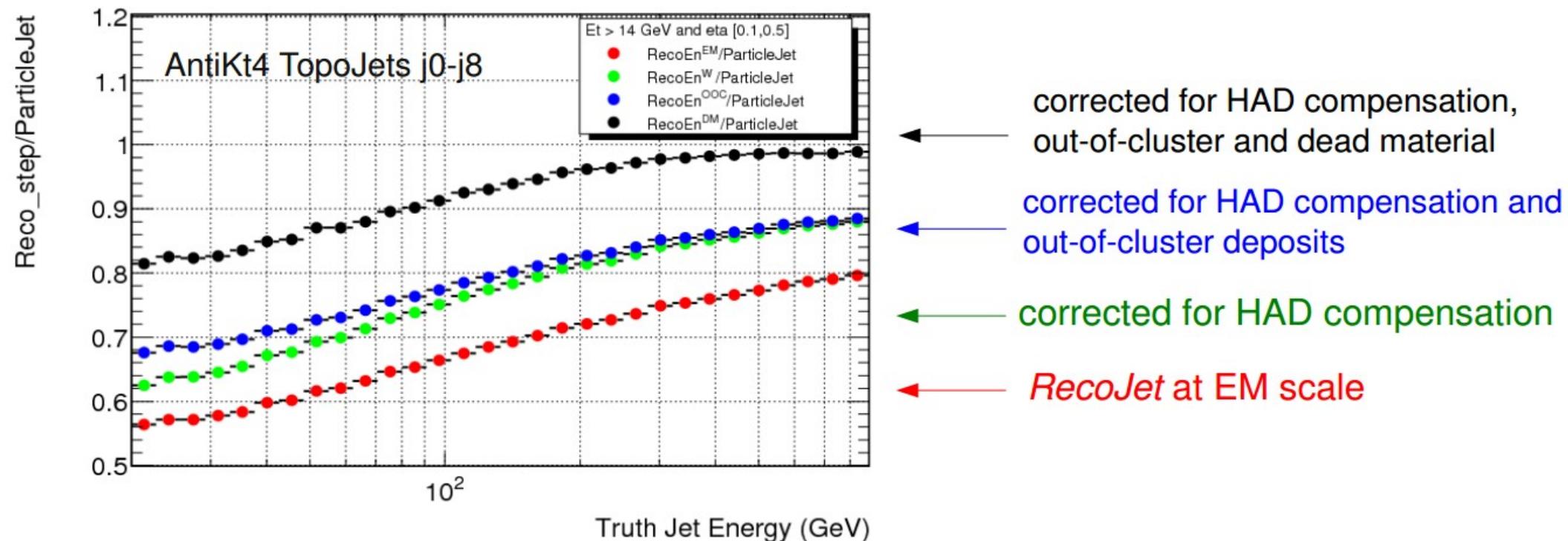
Jets

- Preferred properties of jet algorithms are infra-red and collinear safety.
- Irregular jet shapes, difficult to calibrate at LHC in high pile-up environment.
- Hard or isolated jets have fixed cone shape. Used by ATLAS and CMS.



Jet Calibration

- Topological clusters are inputs of jet algorithm in ALTAS.
- Clusters can be calibrated using Local Hadron Calibration or can be used at electromagnetic energy scale.
- Even after Local Calibration additional residual corrections are needed to bring the reconstructed calorimeter jets to the correct energy scale.

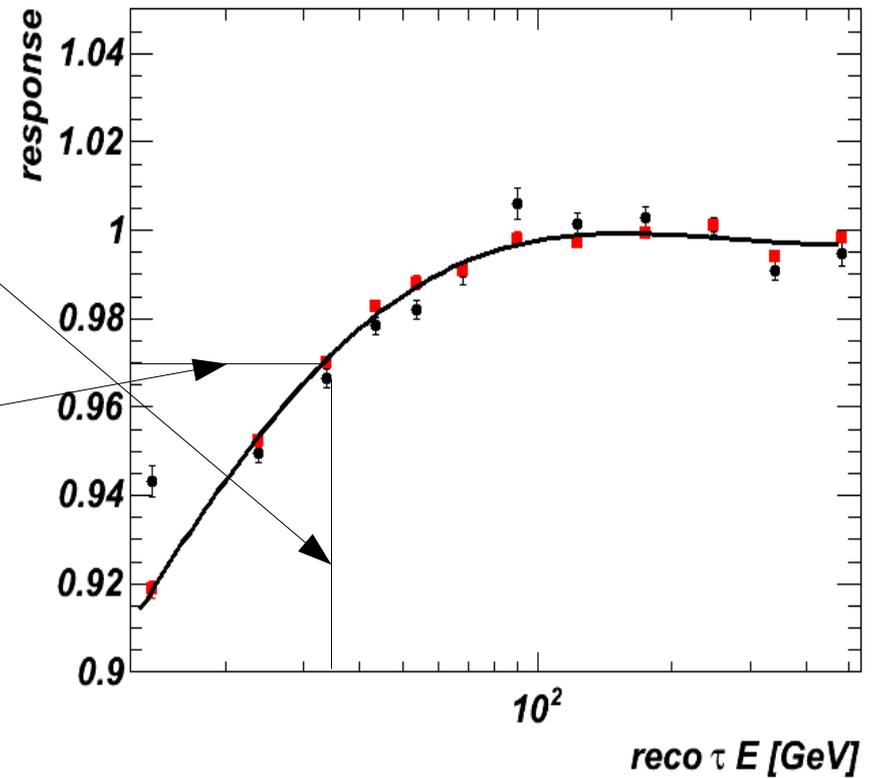
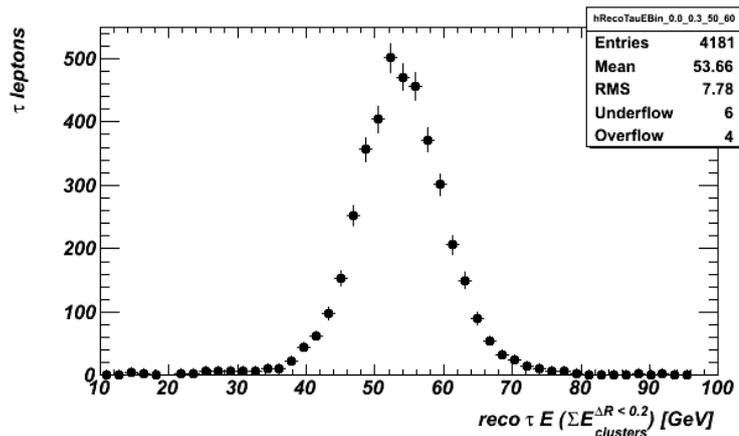
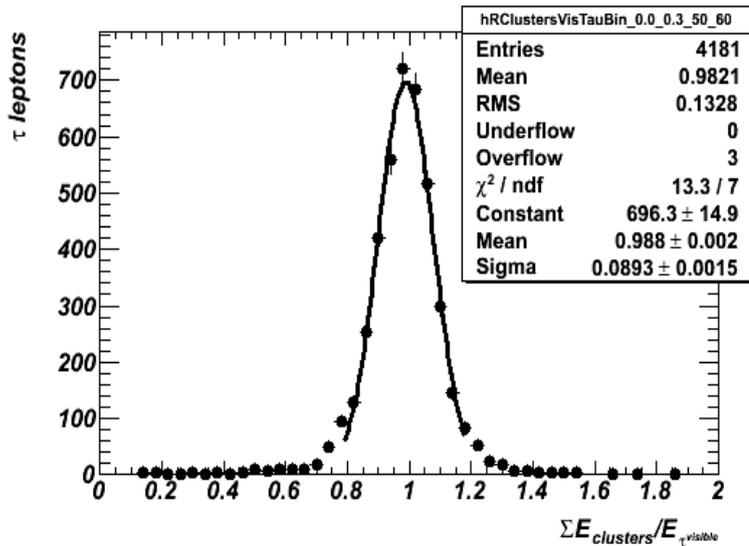


Jet Calibration

- Derive the residual corrections from simulation.
- Match the reconstructed and true jets, bin in true jet p_t or E to avoid bias due to exponentially falling jet p_t distribution.
- Various Corrections:
 - Pile-up
 - Vertex
 - Pseudorapidity bias

Jet Calibration

- Example from hadronic tau calibration.

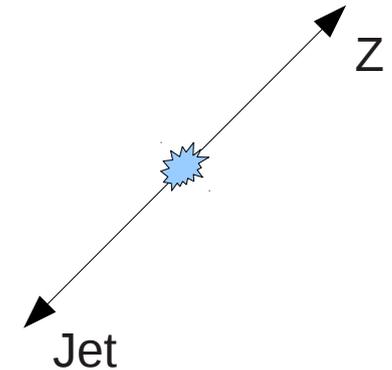


Pileup

- High luminosity of LHC creates challenging environment for jet reconstruction. 40 simultaneous proton-proton collisions in same bunch crossing or collisions in neighboring bunch crossings affect the reconstructed jets.
- In time pile-up can be estimated using the number of reconstructed primary vertex candidates (N_{PV}).
- Out of time pileup is estimated using the average number of additional interactions per crossing (μ).
- Using simulations derive average offset corrections for jets and subtract it from jet p_t or energy.
 - $p_t^{corr} = p_t - \text{Offset}(N_{PV}, \mu)$, $\text{Offset} = a(\eta)N_{PV} + b(\eta)\mu$

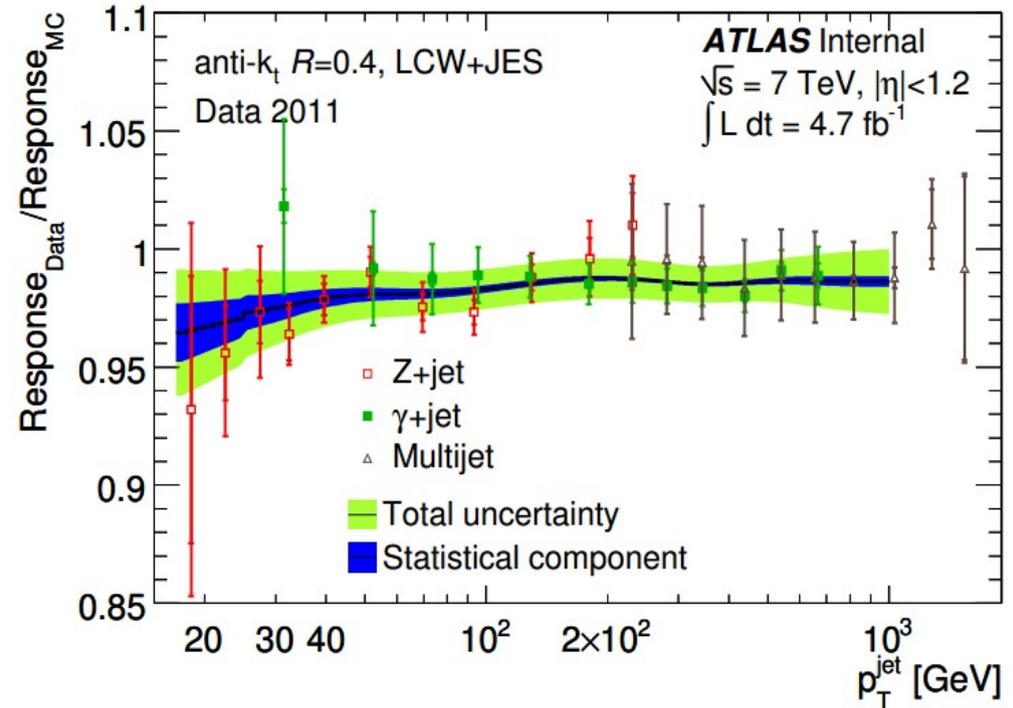
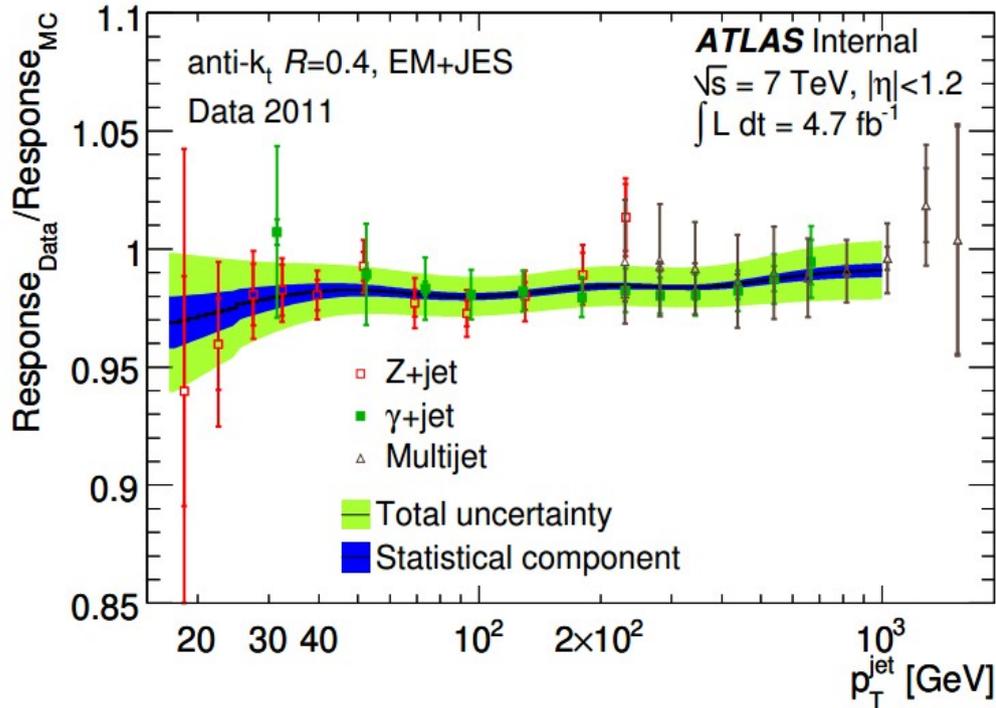
In situ Corrections

- Jet calibration constants derived from simulation are refined using data.
- Use well measured objects recoiling against jets
 - Z + jet
 - Gamma + jet
 - Missing ET projection fraction
 - Multi-jet balance
 - Track – jet comparison
- These corrections are applied to data only.



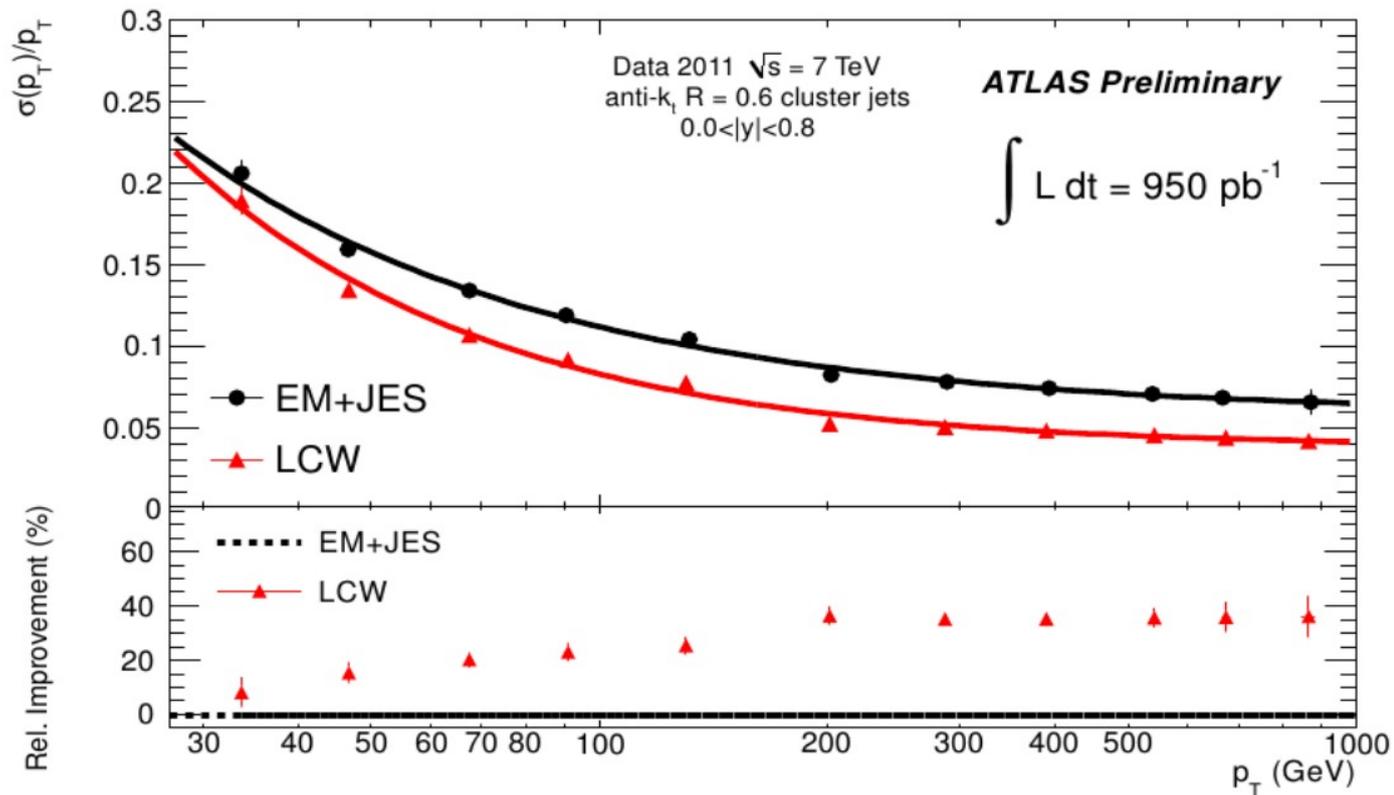
In situ Corrections

- Jets in data require $\sim 2\%$ increase of p_T .



Resolution

- Local calibration improves the resolution by 30%.

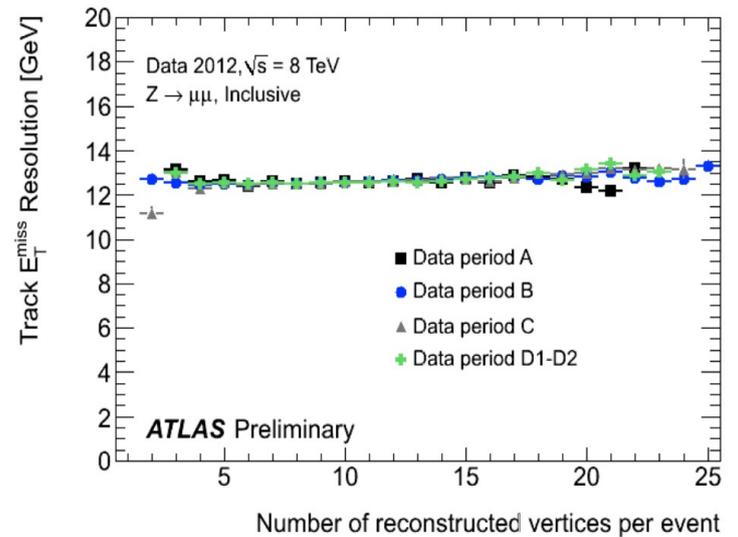
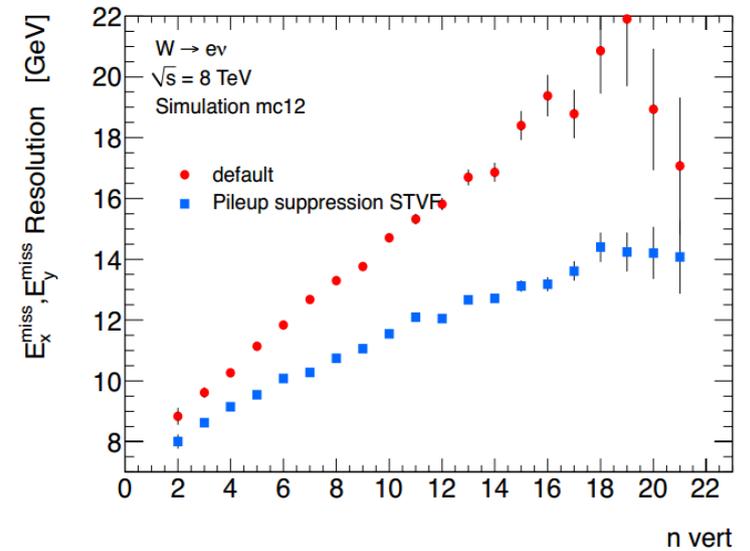


Missing E_T

- Neutrinos do not leave signal in ATLAS.
- Estimate transverse energy of neutrinos using imbalance in the transverse plane. At hadron colliders longitudinal component of neutrino momentum is not reconstructed.
- Vectorial sum of all measured objects with negative sign

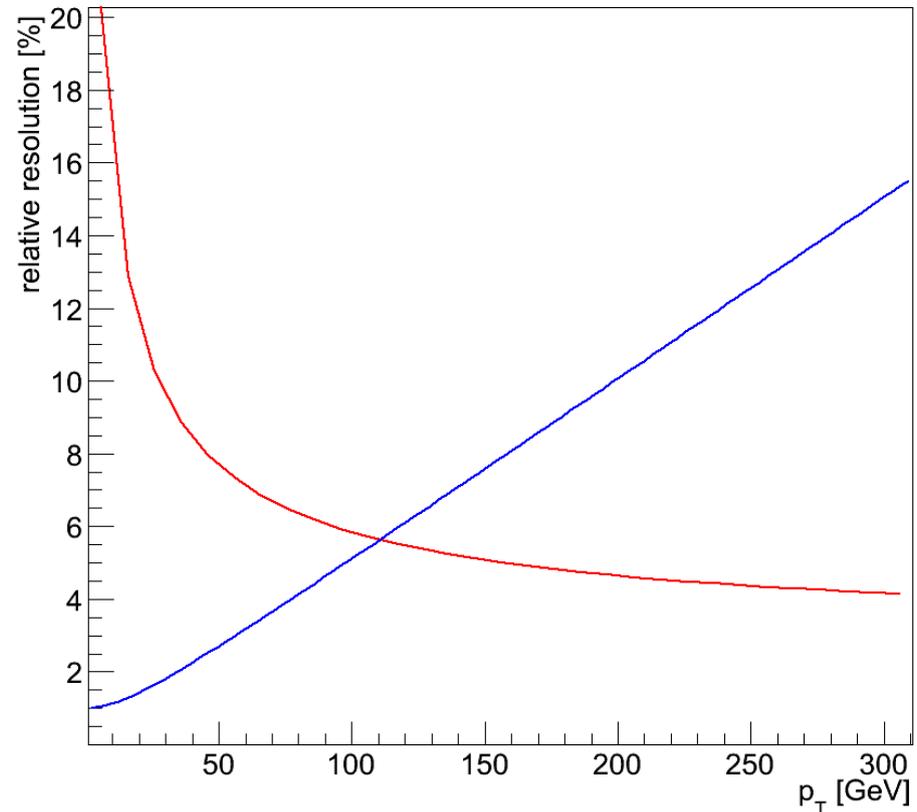
$$\mathbf{p}_T^{\text{miss}} = -\sum \mathbf{p}_T \quad E_T^{\text{miss}} = |\mathbf{p}_T^{\text{miss}}|$$

- Calorimeters are crucial for missing E_T measurement due to limited coverage of tracking detectors and neutral particles.
- Tails in track based missing E_T due to fake high p_T tracks.



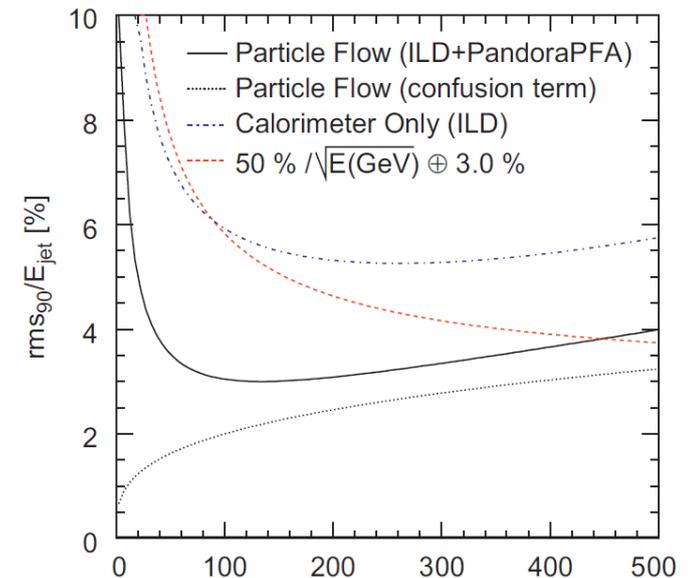
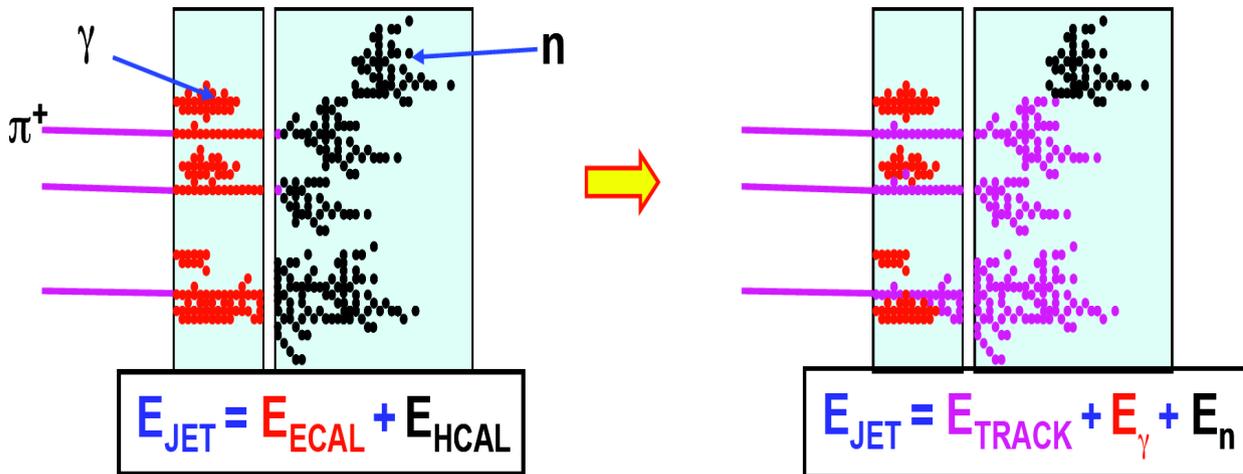
Particle Flow

- **Calorimeter**
 - $\sigma/p_t = 50\%/ \sqrt{p_t} \oplus 3\%$
- **Tracking**
 - $\sigma/p_t = 0.5\% p_t \oplus 1\%$
- Low momentum hadrons are measured with much better precision in the tracking detectors compared to calorimeters.



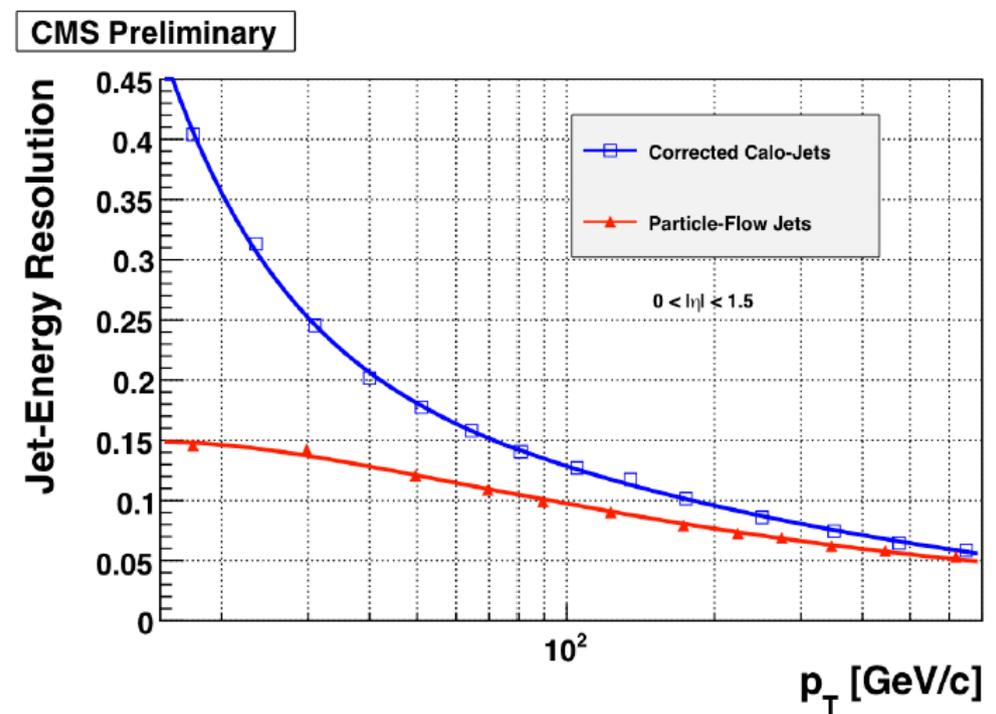
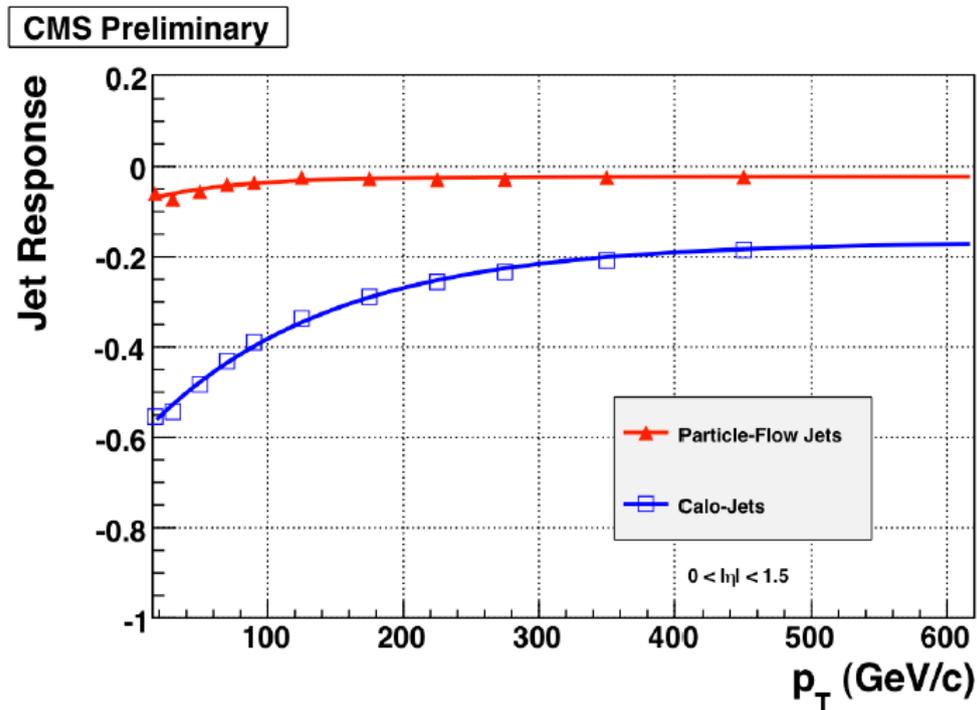
Particle Flow

- In typical jet:
 - 65% of jet energy is carried by charged hadrons
 - 25% by photons
 - 10% by neutral hadrons
- Use tracking to measure charged hadrons and the rest in calorimeters. The problem is to find “the rest”, confusion term.

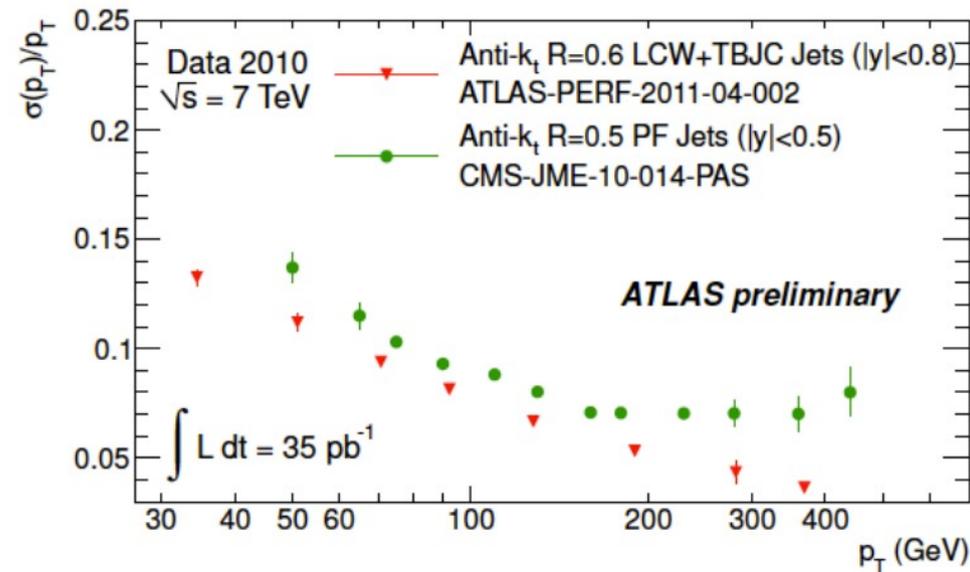
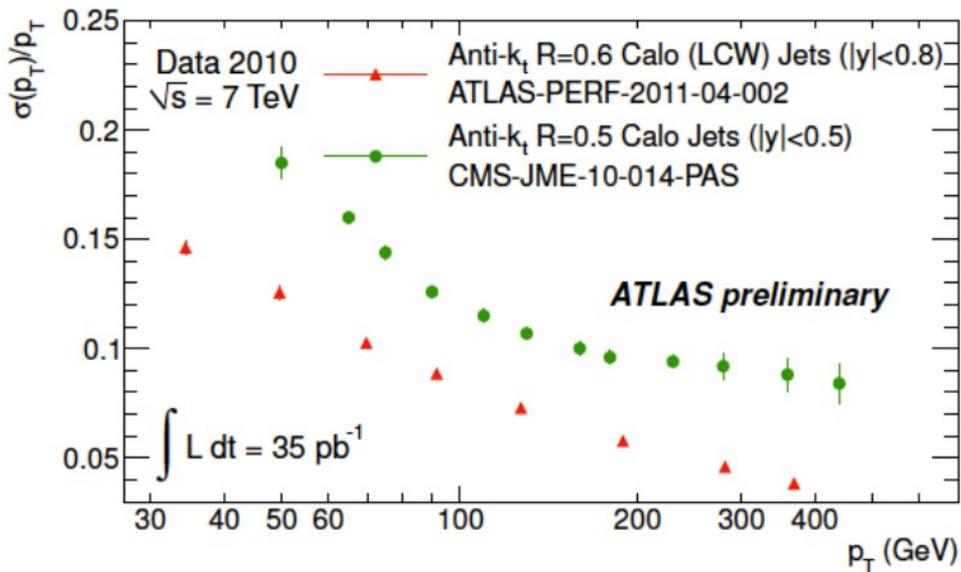


Particle Flow

- Future calorimeters will have very fine granularity which is necessary for particle flow.
- From the current experiments at LHC CMS is using particle flow.



ATLAS vs CMS



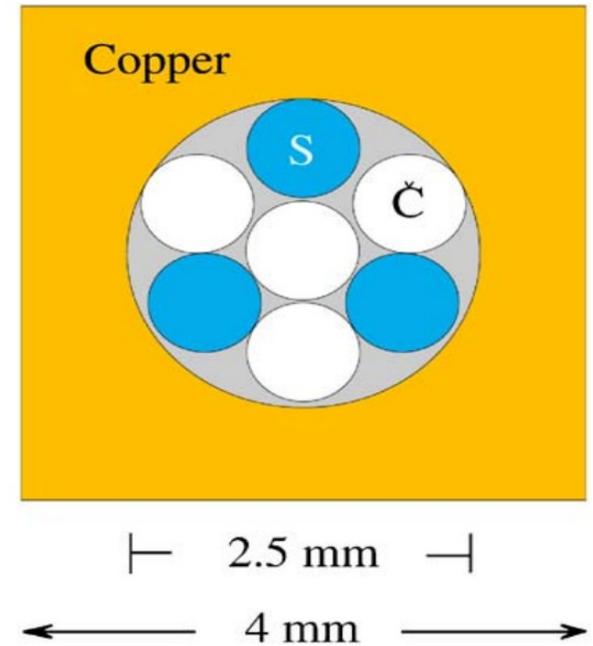
(a) ATLAS (LCW+JES) and CMS (Calo Jets) JER

(b) ATLAS (LCW+JES) and CMS (PF Jets) JER

- ATLAS calorimeters are better than CMS for jet measurements.
- CMS has larger magnetic field therefore better tracking resolution.
- Particle flow improves CMS jet energy resolution significantly, in ATLAS improvements were small.
- ATLAS still has better jet energy resolution, the performance in high pileup environment remains to be demonstrated.

Dual REAdout Module

- Use two different active media, scintillator and quartz to register scintillation and Cherenkov light.
- EM shower consists of relativistic particles which produce Cherenkov radiation.
- Hadronic shower is mainly non-relativistic, no Cherenkov light.
- Two calorimeters:
 - $(e/h)_Q = 5$
 - $(e/h)_S = 1.4$

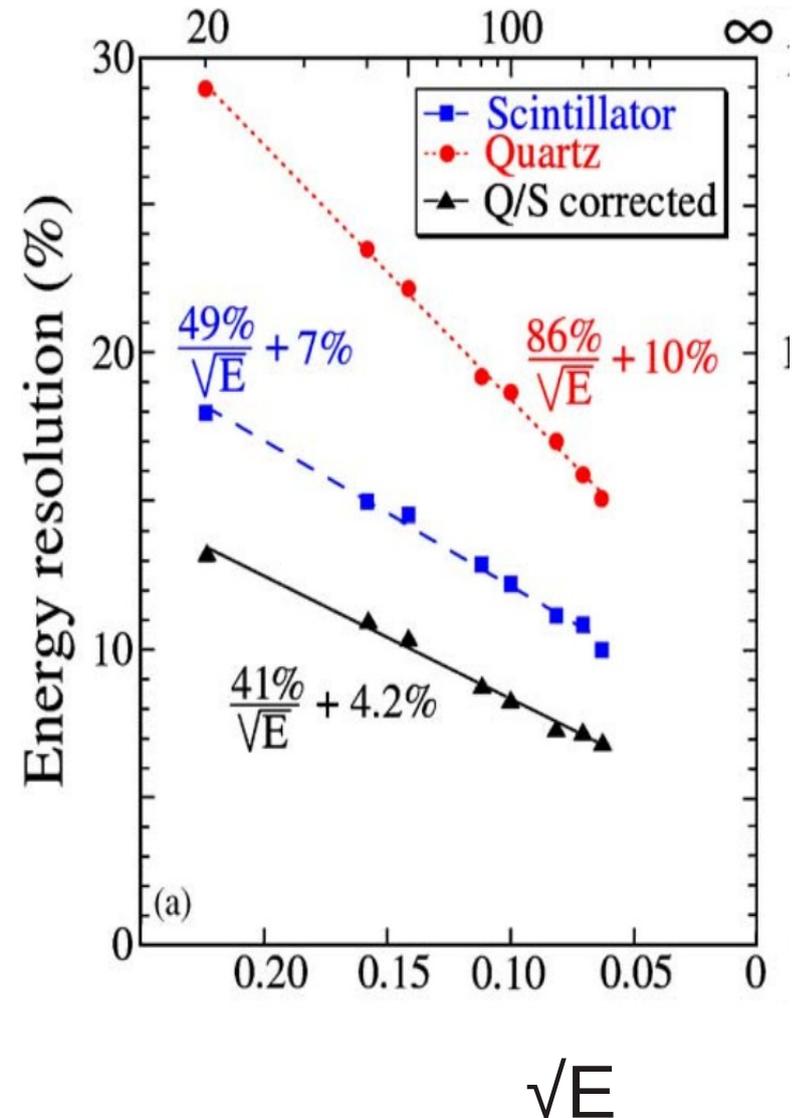


$$Q = [f_{em} + (h/e)_Q(1 - f_{em})]E$$

$$S = [f_{em} + (h/e)_S(1 - f_{em})]E$$

DREAM Results

- Significant improvement of the energy resolution.
- Feasibility of building large detector, performance at collider environment needs to be demonstrated.



Summary

- Calorimeters are important detectors at LHC providing vital measurements.
- Calibration is a huge effort, especially for hadronic objects.
- Various methods are used to improve the energy resolution.
- Many new ideas for future experiments.

Further Reading

- R.M Brown, D.J.A Cockerill “Electromagnetic calorimetry” NIM A 666 (2012) 47-79
- N. Akchurin, R. Wigmans “Hadron Calorimetry” NIM A 666 (2012) 80-97
- R. Wigmans “Calorimetry, Energy Measurement in Particle Physics” Oxford University Press 2000
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- M. Aharrouche et al. “Energy linearity and resolution of the ATLAS electromagnetic barrel calorimeter in an electron test-beam” NIM A 568 (2006) 601-623
- ATLAS Collaboration “Jet energy measurement with the ATLAS detector in proton-proton collisions at $\sqrt{s} = 7$ TeV” arXiv:1112.6426 [hep-ex]