XIII MEXICAN SCHOOL OF PARTICLES AND FIELDS

UNIVERSITY OF SONORA & SAN CARLOS, SONORA, MEXICO.

OCTOBER 2008 2-11

The Mexican School of Particles and Fields is a biennial conference organized by the Division of Particles and Fields of the Mexican Physical Society, designed to gather specialists in different areas of high energy physics to discuss the latest developments in the field. The format of the conference will consist of morning sessions devoted to theoretical and experimental reviews and afternoon thematic sessions.

Jet Reconstruction at the LHC (Lecture 1)

Peter Loch

University of Arizona

Tucson, Arizona, USA

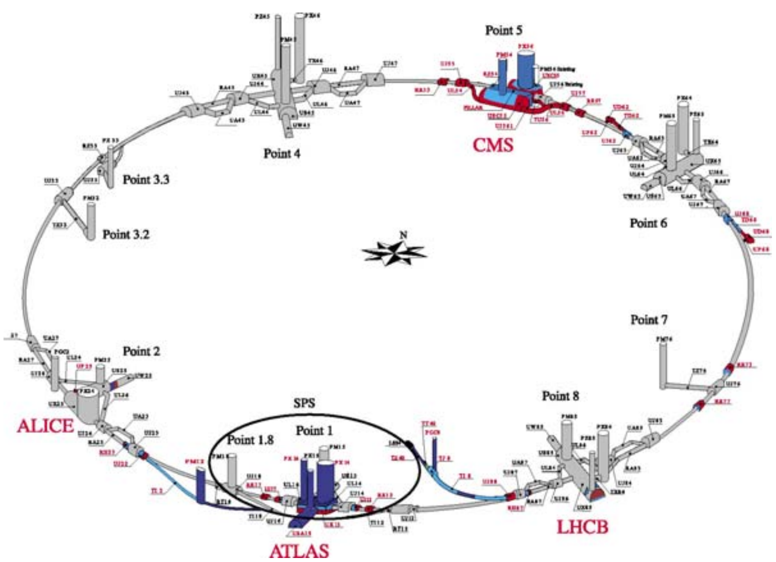
(loch@physics.arizona.edu)

ATLAS

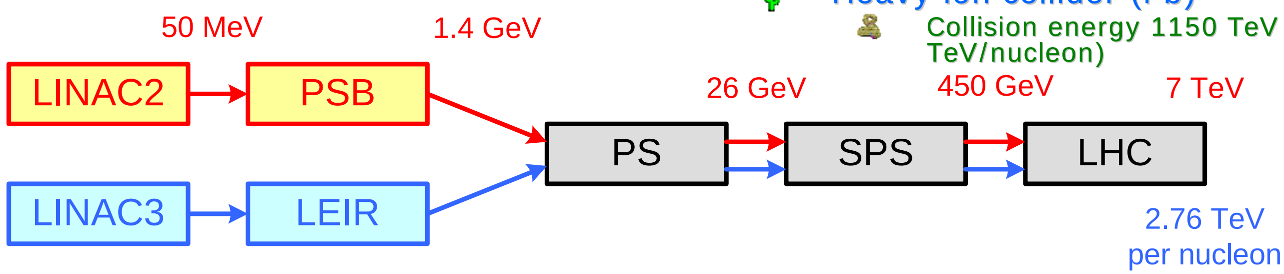
THE UNIVERSITY OF ARIZONA. Arizona's First University.

UAPhysics THE UNIVERSITY OF ARIZONA College of Science

The Large Hadron Collider (LHC)



- **Machine**
  - Occupies old LEP tunnel at CERN, Geneva, Switzerland & France
  - About 27 km long
  - 50-100m underground
  - 1232 bending magnets
  - 392 focusing magnets
  - All superconducting
    - ~96 tons of He for ~1600 magnets
- **Beams (design)**
  - pp collider
    - 7 TeV on 7 TeV (14 TeV collision energy)
    - Luminosity 10^{34} $cm^{-2}s^{-1}$
    - 2808 x 2808 bunches
    - Bunch crossing time 25 ns (40 MHz)
    - ~23 pp collisions/bunch crossing
  - Heavy ion collider (Pb)
    - Collision energy 1150 TeV (2.76 TeV/nucleon)



Proton acceleration chain:

LINAC→Proton Synchrotron Booster (PSB)→Proton Synchrotron (PS)→Super Proton Synchrotron (SPS)→LHC

Pb ion acceleration chain:

LINAC→Low Energy Ion Injector Ring (LEIR)→Proton Synchrotron (PS)→Super Proton Synchrotron (SPS)→LHC

Overview

- **Lecture 1 (Saturday, October 4th, 2008, 12:30-13:30): Signals from particle jets**
  - Experimentalist's view on jets
  - Jet response of a non-compensating calorimeter
  - Brief view at the ATLAS & CMS detectors
  - Calorimeter signal reconstruction: cells, towers, clusters
- **Lecture 2 (Sunday, October 5th, 2008, 12:30-13:30): Jet algorithms and reconstruction**
  - Physics environment for jet reconstruction at LHC
  - Jet algorithms and reconstruction guidelines
  - Jet calibration strategies
  - Jet Reconstruction Performance
- **Lecture 3 (Sunday, October 5th, 2008, 17:00-18:00): Refinement of jet reconstruction at LHC**
  - Refined calibration using other detectors
  - Tagging jets from pile-up
  - The origin of jets: masses and shapes
  - AOB

Experimentalist's View On Jets

“Jetology 101”

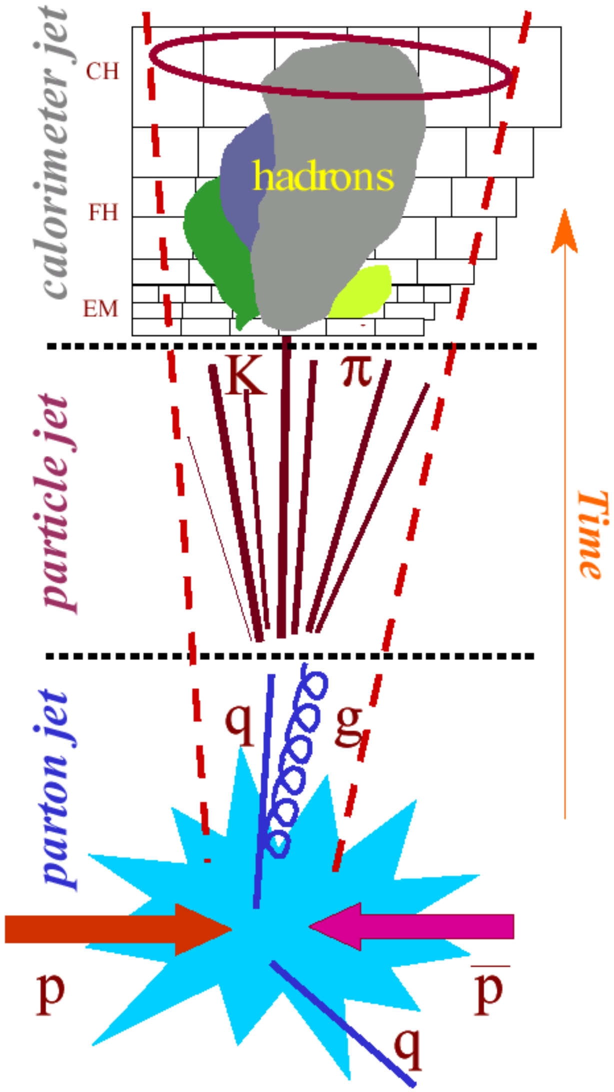
What are jets for experimentalists?

- A bunch of particles generated by hadronization of a common source
  - Quark, gluon fragmenation
- As a consequence, the particles in this bunch have correlated kinematic properties
- The **interacting** particles in this bunch generated an observable signal in a detector
  - Protons, neutrons, pions, photons, electrons, muons, other particles with laboratory lifetimes >~10ps, and the corresponding anti-particles
- The **non-interacting** particles do not generate a directly observable signal
  - Neutrinos, mostly
- The real answer was of course given in Michael Peskin’s lecture, of course!

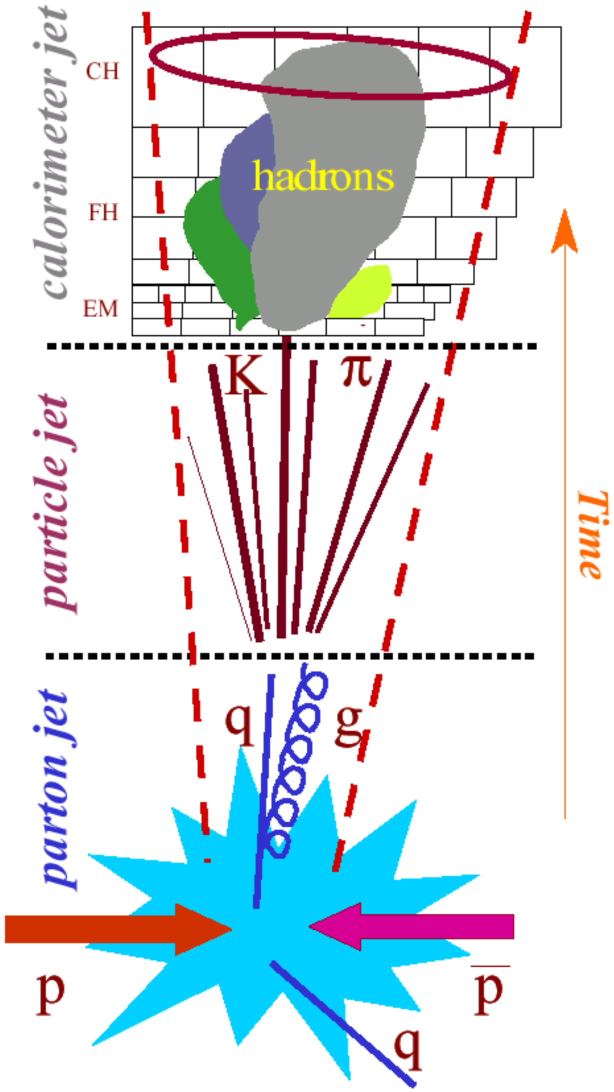
What is jet reconstruction, then?

- Model: attempt to collect the final state particles described above into objects (jets) representing the original parton kinematic
  - Re-establishing the correlations
- Experiment: attempt to collect the detector signals from these particles to measure their original kinematics
  - Usually not the parton!

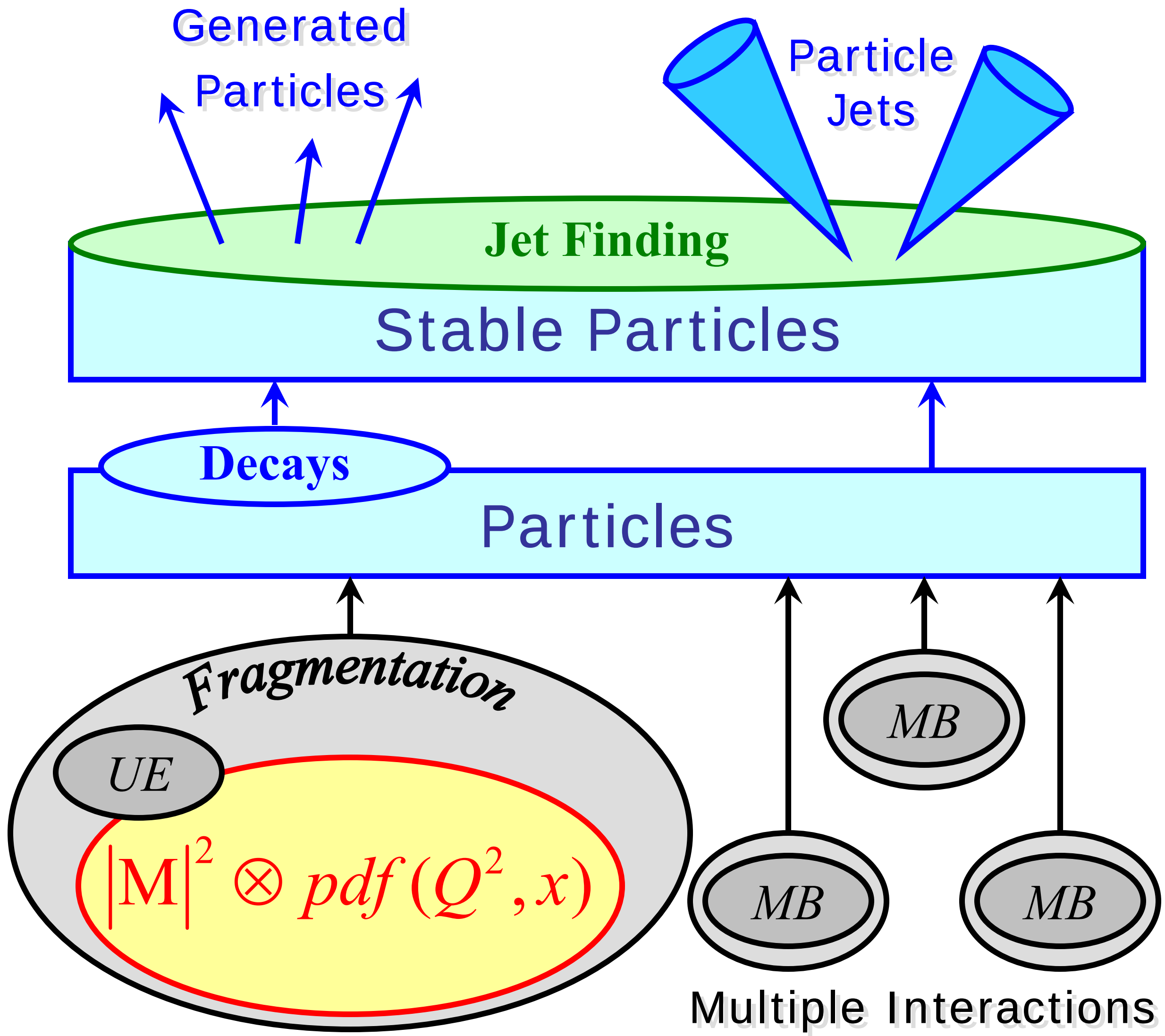
Experiment ("Nature")



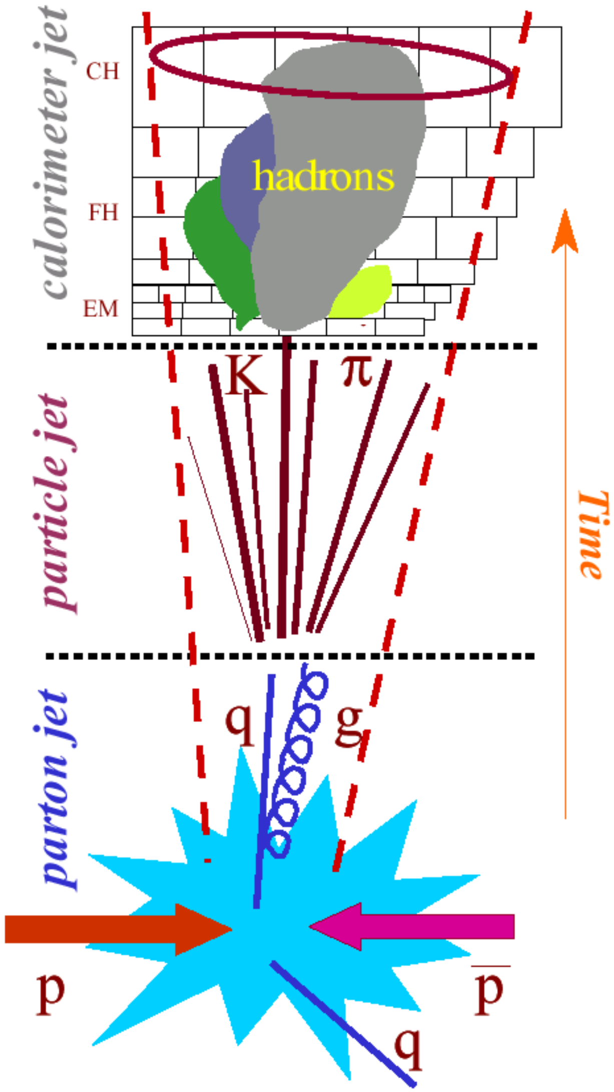
Experiment (“Nature”)



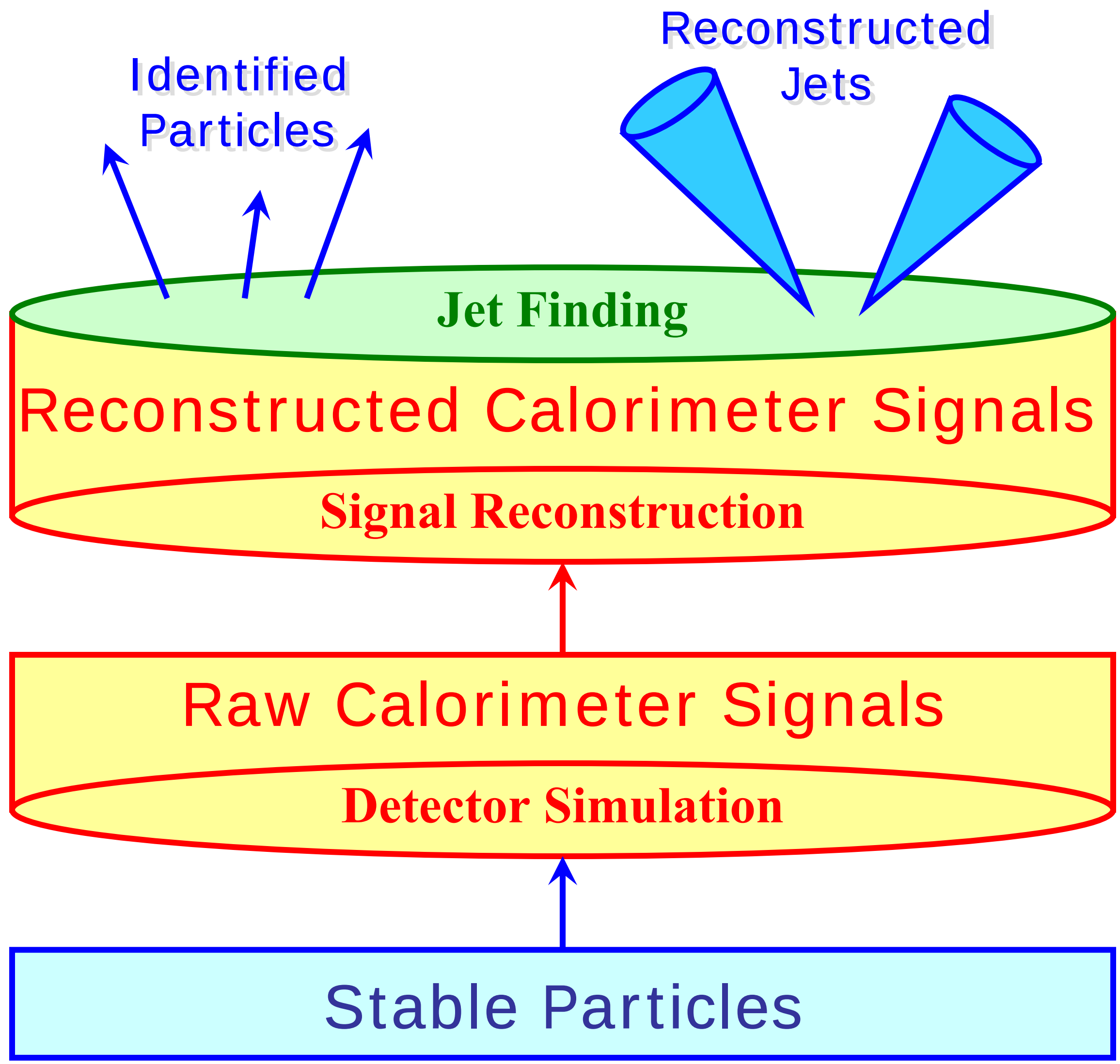
Modeling Particle Jets



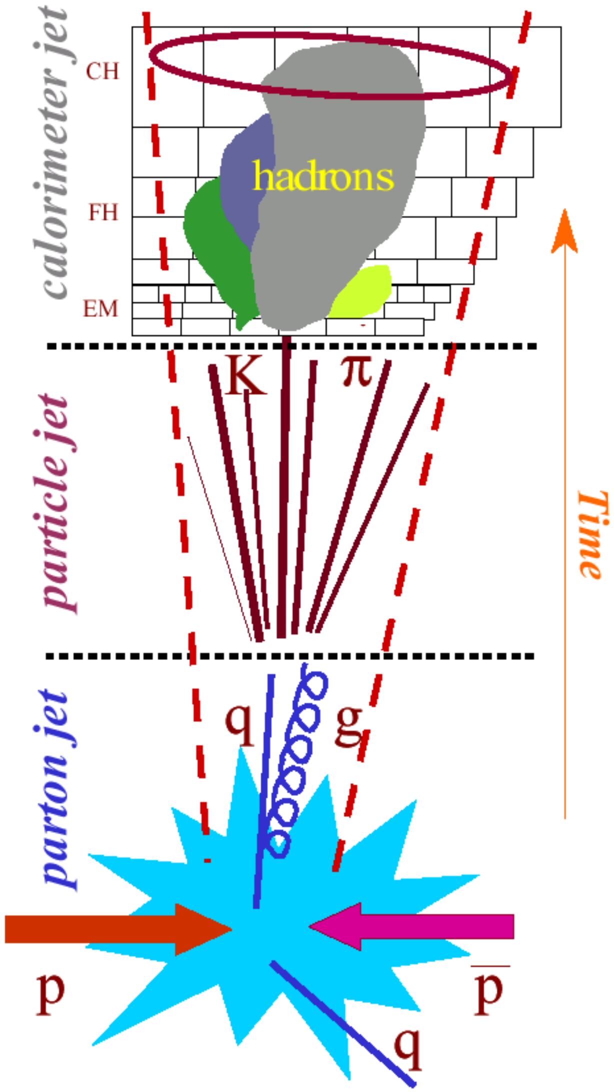
Experiment (“Nature”)



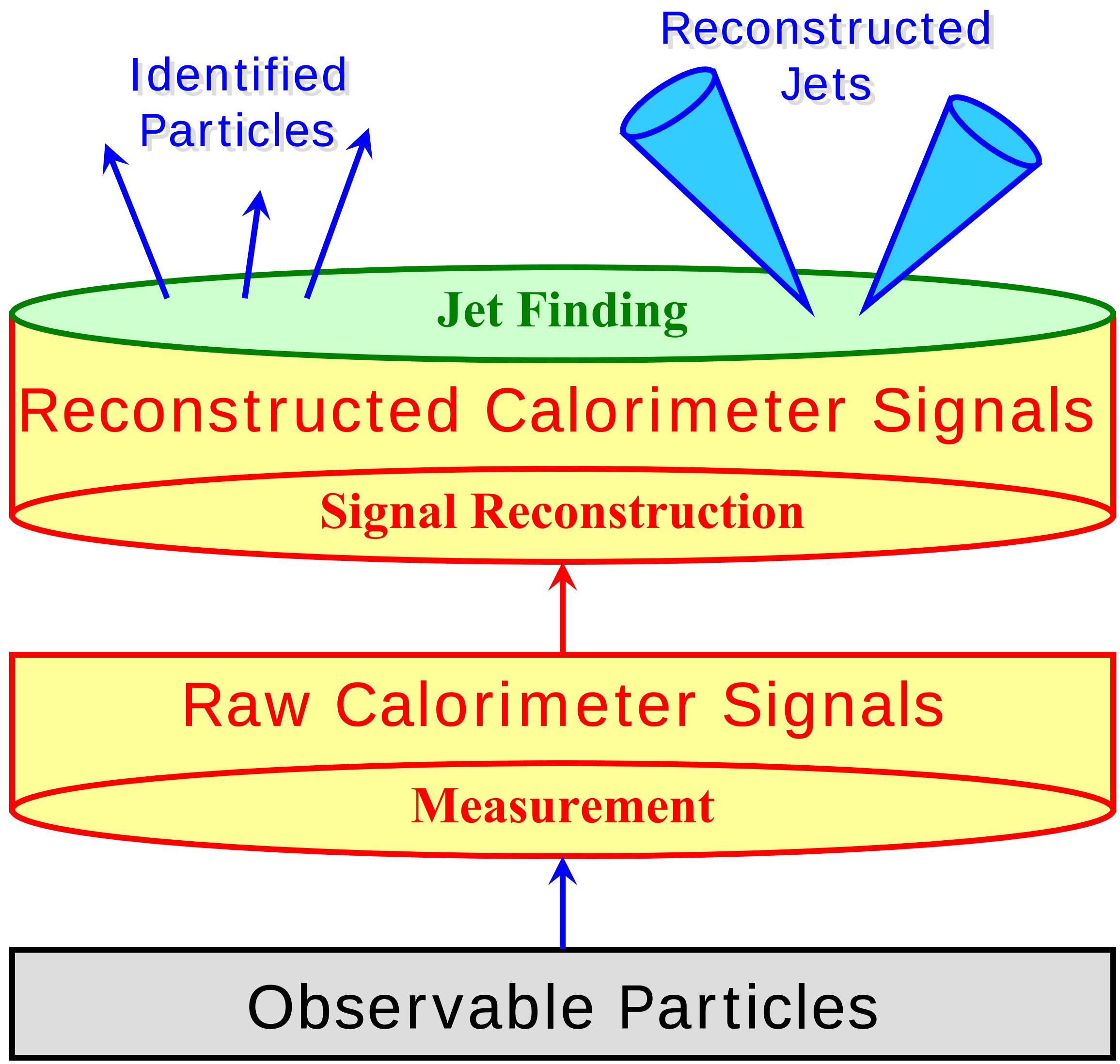
Modeling Calorimeter Jets



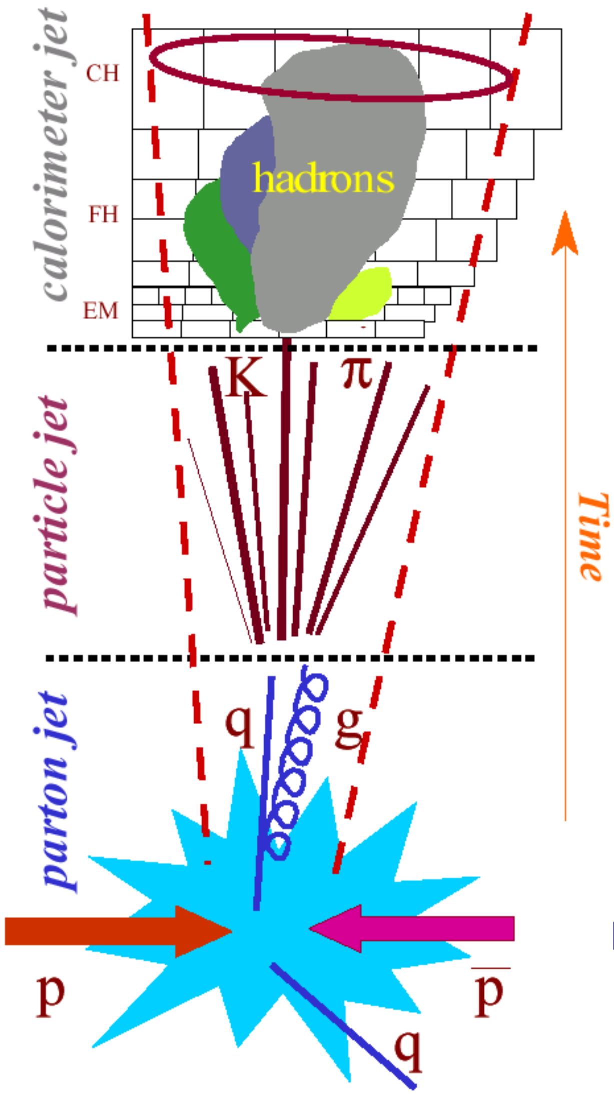
Experiment (“Nature”)



Measuring Calorimeter Jets



Experiment ("Nature")



Jet Reconstruction Challenges

longitudinal energy leakage
detector signal inefficiencies (dead channels, HV…)
pile-up noise from (off- and in-time) bunch crossings
electronic noise
calo signal definition (clustering, noise suppression…)
dead material losses (front, cracks, transitions…)
detector response characteristics (e/h ≠ 1)
jet reconstruction algorithm efficiency
lost soft tracks due to magnetic field

added tracks from underlying event
added tracks from in-time (same trigger) pile-up event
jet reconstruction algorithm efficiency

physics reaction of interest (interaction or parton level)

Jet Reconstruction

- **Experimental goal**
  - Find the best "picture" of the final state representing the collision dynamics behind a given event
    - Best reconstruction of fragmented hard scattered parton and general event energy flow
    - "Resolution" requirements for this picture depend on physics question asked
    - Reconstruct source of jet
- **Sequential process**
  - Input signal selection
    - Get the best signals out of your detector on a given scale
  - Preparation for jet finding
    - Suppression/cancellation of "unphysical" signal objects with E<0 (due to noise)
    - Possibly event ambiguity resolution (remove reconstructed electrons, photons, taus,… from detector signal)
    - Pre-clustering to speed up reconstruction (not needed as much anymore)
  - Jet finding
    - Apply your jet finder of choice
  - Jet calibration
    - Depending on detector, jet finder choices, references…
  - Jet selection
    - Apply cuts on kinematics etc. to select jets of interest or significance
- **Objective**
  - Reconstruct particle level features
    - Test models and extract physics

Jet Signal Detection

- **Calorimeters are the detectors of choice**
  - Generate signals from charged and neutral particles in jets
    - Tracking devices only sensitive to charged particles
  - Full absorption detectors
    - All energy of the original particle deposited within calorimeter
    - Generate signals proportional to energy deposit
  - Segmented readout
    - Collection energy in (small) volumes allows reconstruction of the particle direction
    - Spatial energy distribution hints at incoming particle nature
- **Overall detector contributes to detection efficiency**
  - Magnetic field
    - Often solenoid field in inner detector cavity in front of calorimeters
    - Leads to jet energy losses due to bending of charged particles away from the calorimeter (low pT, no calorimeter signal at all) or away from the jet
  - Inactive materials
    - Energy losses in inner detector and its services and support (from point of calorimetry)
    - Energy losses in mechanical structures insides (support beams, internal transition regions etc.) and outside the calorimeter (cryostat walls etc.)

Jet Response Of Non-compensating Calorimeters

Calorimeter Basics (1)

Full absorption detector

- Idea is to convert incoming particle energy into detectable signals
  - Light or electric current
  - Should work for charged and neutral particles
- Exploits the fact that particles entering matter deposit their energy in particle cascades
  - Electrons/photons in electromagnetic showers
  - Charged pions, protons, neutrons in hadronic showers
  - Muons do not shower at all in general

Principal design challenges

- Need dense matter to absorb particles within a small detector volume
  - Lead for electrons and photons, copper or iron for hadrons
- Need "light" material to collect signals with least losses
  - Scintillator plastic, nobel gases and liquids
- Solution I: combination of both features
  - Crystal calorimetry, BGO
- Solution II: sampling calorimetry

Calorimeter Basics (2)

Sampling calorimeters

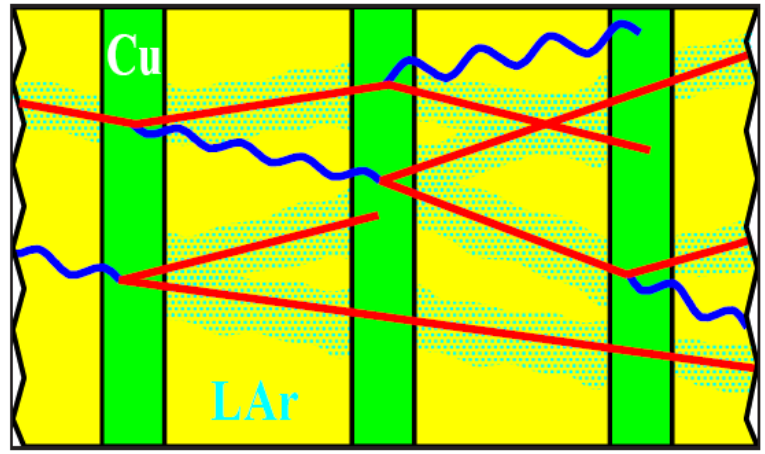
- Use dense material for absorption power…
  - No direct signal
- …in combination with highly efficient active material
  - Generates signal
- Consequence: only a certain fraction of the incoming energy is directly converted into a signal
  - Typically 1-10%
- Signal is therefore subjected to sampling statistics
  - The same energy loss by a given particle type may generate different signals
  - Limit of precision in measurements

Need to understand particle response

- Electromagnetic and hadronic showers

Electromagnetic Calorimeter Signals

- **Electromagnetic showers**
  - Particle cascade generated by electrons/positrons and photons in matter
  - Developed by brems-strahlung & pair-production
- **Compact signal**
  - Regular shower shapes
    - Small shower-to-shower fluctuations
  - Strong correlation between longitudinal and lateral shower spread
- **Well measured in sampling calorimeters**
  - Signal directly proportional to deposited energy
  - Signal resolution nearly completely due to sampling fluctuations



$$T_c = \frac{2}{3}T,\ \text{with } N_\times = \frac{T_c}{d} \propto E_{in}$$

$$E_{vis} \propto N_\times \frac{dE}{dx} d \approx N_\times \Delta E$$

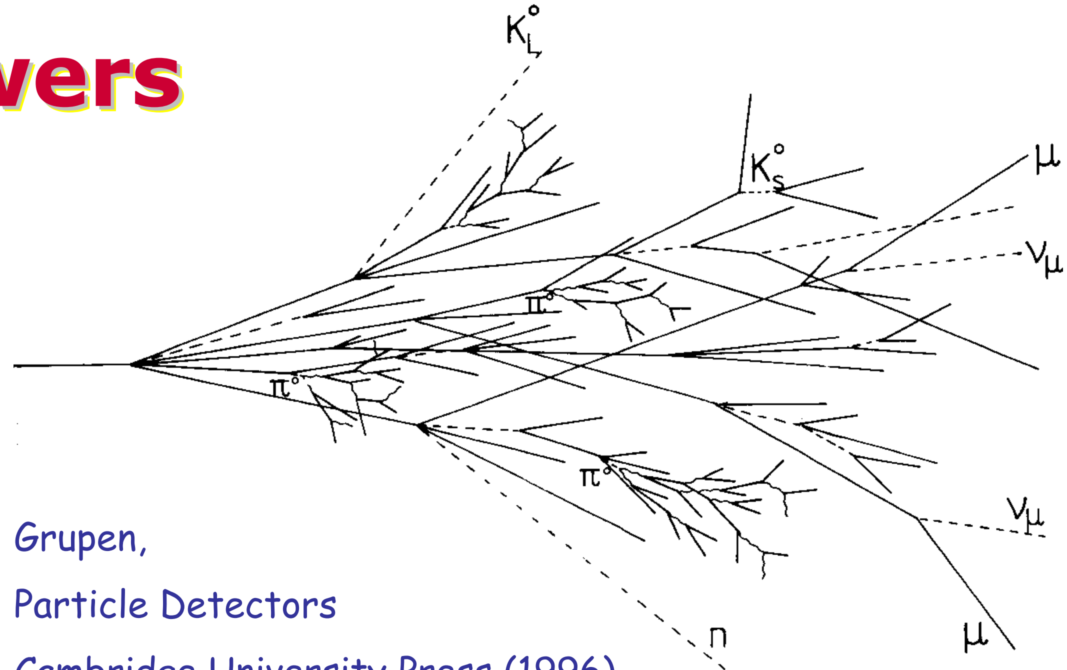
$$\sigma(N_\times) = \sqrt{N_\times}$$

$$\Rightarrow \sigma(E_{vis}) \propto \sqrt{N_\times \Delta E} \propto \sqrt{E_{in}}$$

Hadronic Showers

Hadronic cascades

- Particle cascade generated in matter by hadron-nucleon collisions in nucleus
- Driving force for shower development is strong interaction
  - ~200 possible processes with <1% probability each!
- Intrinsic electromagnetic showers from π^0 production in inelastic hadronic interaction



Grupen,

Particle Detectors

Cambridge University Press (1996)

Hadron-nucleus interaction:

(1) Fast component from internal hadron-nucleon cascades produce more hadrons continues shower development

(2) Energy in slow nuclear phase with nuclear fission or break-up, and evaporation (de-excitation) lost for shower developement

Hadronic Shower Characteristics

Hadronic signals

- Signal only from ionization by charged particles and intrinsic electromagnetic showers
- Large energy losses without signal generation
  - Binding energy losses
  - Escaping energy/slow particles (neutrinos/neutrons)
- Signal depends on size of electromagnetic component
  - Energy invested in neutral pions lost for further hadronic shower developement
  - Fluctuating significantly shower-by-shower
  - Weakly depending on incoming hadron energy

Consequence: non-compensation

- Hadrons generate less signal than electrons depositing the same energy

Shower Parameters

Electromagnetic

- Compact
  - Growths in depth ~log(E)
- Longitudinal extension scale is radiation length X_0
  - Distance in matter in which ~50% of electron energy is radiated off
  - Photons $9/7\ X_0$
- Strong correlation between lateral and longitudinal shower development
- Small shower-to-shower fluctuations
  - Very regular development
- Can be simulated with high precision
  - 1% or better, depending on features

Hadronic

- Scattered, significantly bigger
  - Growths in depth ~log(E)
- Longitudinal extension scale is interaction length λ
  - Average distance between two inelastic interactions in matter
  - Varies significantly for pions, protons, neutrons
- Weak correlation between longitudinal and lateral shower development
- Large shower-to-shower fluctuations
  - Very irregular development
- Can be simulated with reasonable precision
  - ~2-5% depending on feature

Hadronic Signal Composition (1)

Single hadron response:

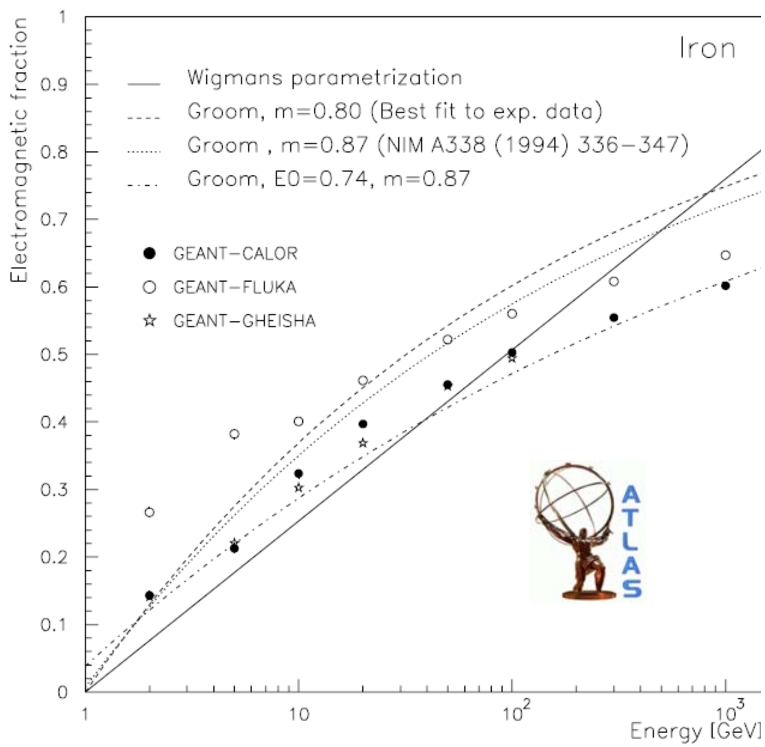
$$\pi(E) = \left(1 - f_{em}(E)\right) \cdot h + f_{em}(E) \cdot e$$

$$= \left(\left(1 - f_{em}(E)\right)\frac{h}{e} + f_{em}\right) \cdot e$$

with intrinsic electromagnetic energy fraction in hadronic showers parametrized as*:

$$f_{em}(E) = 1 - \left(\frac{E}{E_0}\right)^{m-1}$$

$$m = 0.8 - 0.85, E \simeq \begin{cases} 1 \text{ GeV} & \text{for } \pi^{\pm} \\ 2.6 \text{ GeV} & \text{for } p \end{cases}$$



*D.Groom et al., NIM A338, 336-347 (1994)

Hadron Signal Composition (2)

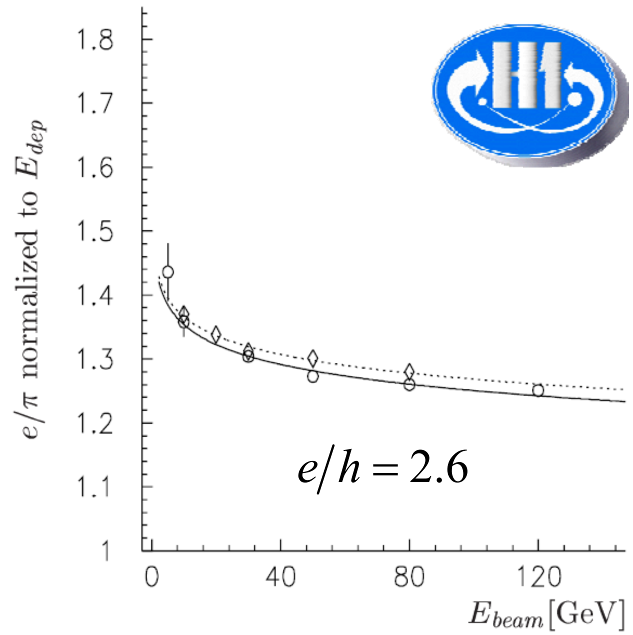
Observable

$$e/\pi \approx \frac{e}{\left(E/E_0\right)^{m-1} h + \left(1-\left(E/E_0\right)^{m-1}\right) e} = \frac{1}{1-\left(1-\frac{h}{e}\right)\left(E/E_0\right)^{m-1}}$$

provides experimental access to characteristic calorimeter variables in pion testbeams, like *e/h*, by fitting the energy dependence of the pion signal in testbeams:

$$e/\pi = E_{rec}/E_{dep}\text{, with } e/h = const$$

e/h is often constant, example: in both H1 and ATLAS about 50% of the energy in the hadronic branch generates a signal independent of the energy itself



Jet Signal Composition

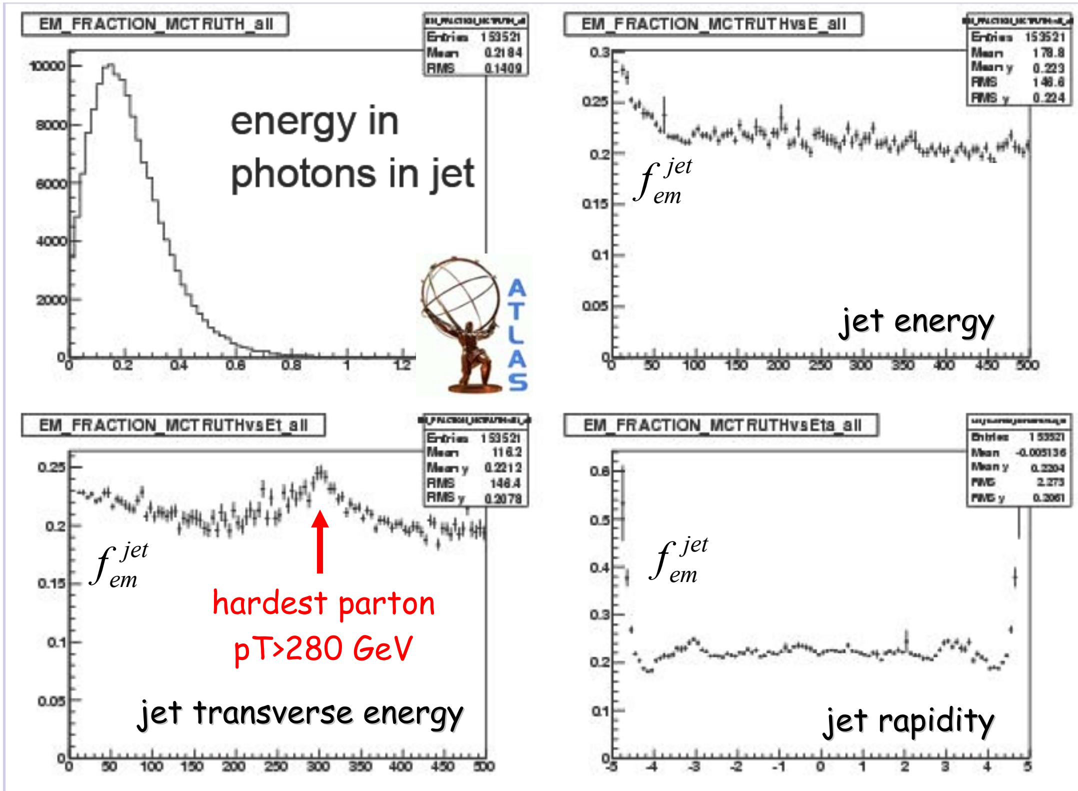
Jet response with perfect acceptance (all particles detected):

$$j(E) = f_{em}^{jet} \cdot e + \left(1 - f_{em}^{jet}\right) \cdot \pi = \left(f_{em}^{jet} + \left(1 - f_{em}^{jet}\right) \cdot \left(f_{em} + \left(1 - f_{em}\right) \frac{h}{e} \right) \right) \cdot e$$

Jet energy fractions from fragmentation functions:

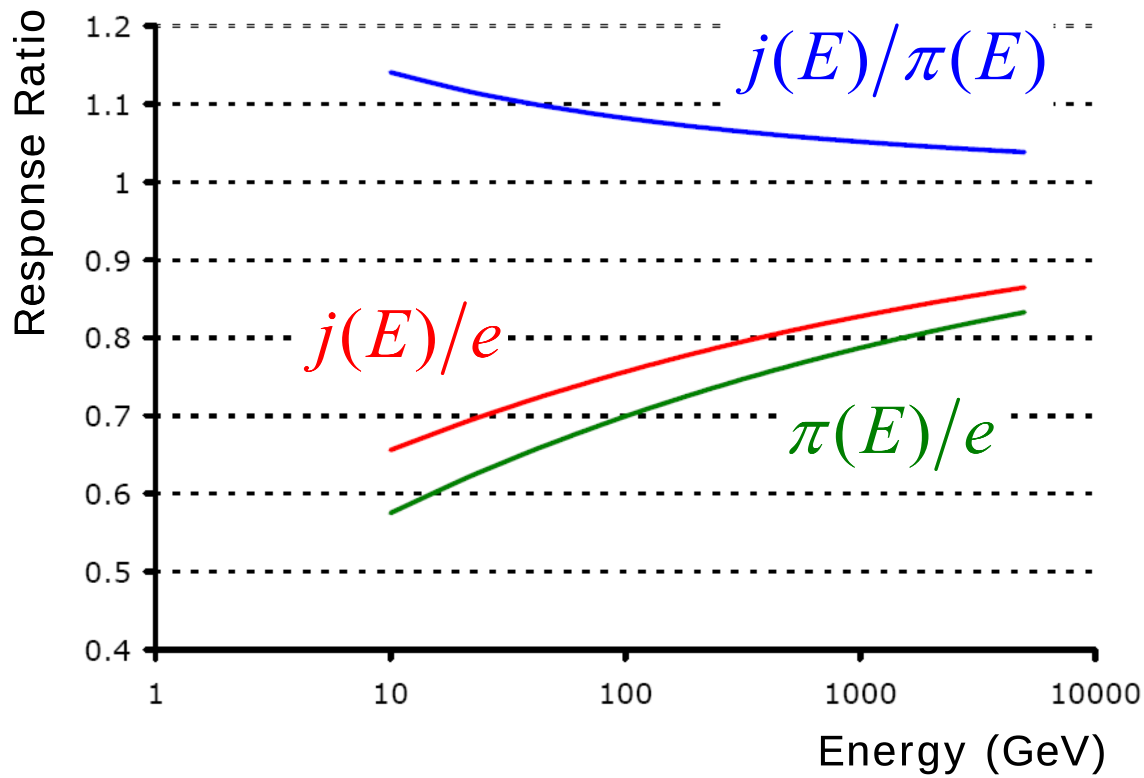
$$f_{em}^{jet} = \frac{1}{E} \sum_{i=1}^{N_\gamma} E_i^\gamma$$

Fragmentation well measured at LEP – extrapolation to much higher energy jets not obvious



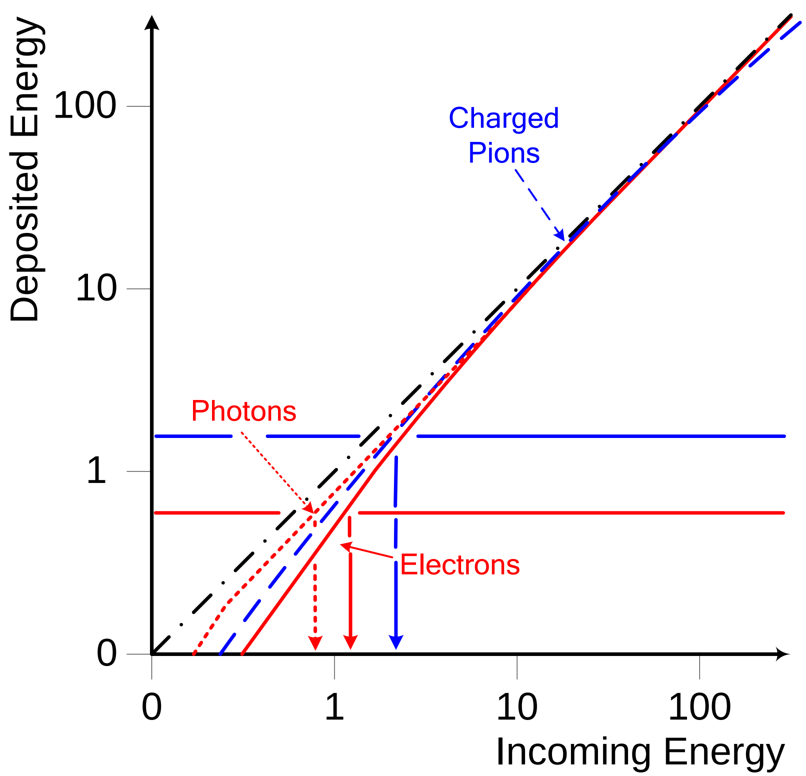
Ideal Jet Response

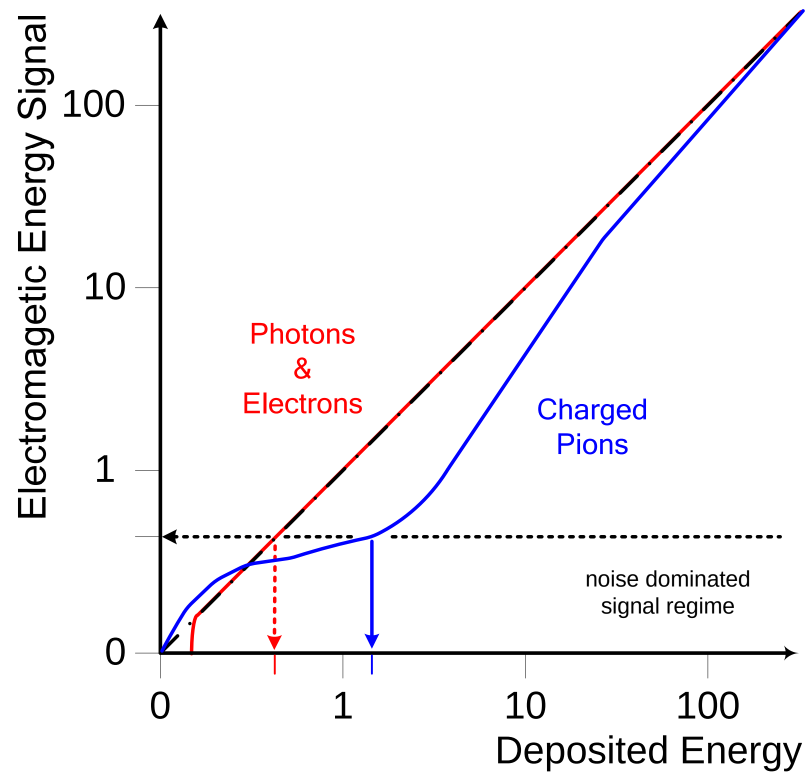
- **Assume all particles in jet contribute to signal**
  - Not really true, see later
  - Expect primary photon content to increase jet signal compared to pion signal



- **Expectation too naïve**
  - low energetic particles may not reach calorimeter at all
  - Realistic response evaluation needs acceptance folded in!

Calorimeter Acceptance





Not all incoming energy deposited in calorimeter due to upstream material losses (depend on the particle type and material)

Detection thresholds on incoming particle energy – no precision measurement possible below this!

Basic energy scale signal depends on particle type, deposited energy and signal characteristics of calorimeter (noise etc.);

Jet Response To Jet Energy Reconstruction

- **Jets are bundles of particles**
  - ~25% initial photons
  - Hadronic particles include mostly pions, kaons, protons and their anti-particles
    - Different response!
- **Jet response in non-compensating calorimeters**
  - Jet signal depends on fragmentation/particle content
    - Significant jet-to-jet response variations due to more or less photons

$$E_{true}^{jet} = E_{dep}^{calo} + E_{mag}^{loss} + E_{low}^{loss} + E_{leak}^{loss} + E_{out}^{loss} - E_{UE\otimes PU}^{gain} - E_{env}^{gain}$$

E_{dep}^{calo}	energy deposited in the calorimeter within signal definition
E_{mag}^{loss}	charged particle energy lost in solenoid field
E_{low}^{loss}	particle energy lost in dead material
E_{leak}^{loss}	energy lost due to longitudinal leakage
E_{out}^{loss}	energy lost due to jet algorithm/calorimeter signal definition
$E_{UE\otimes PU}^{gain}$	energy added by underlying event and/or pile-up
E_{env}^{gain}	energy added by response from other nearby particles/jets

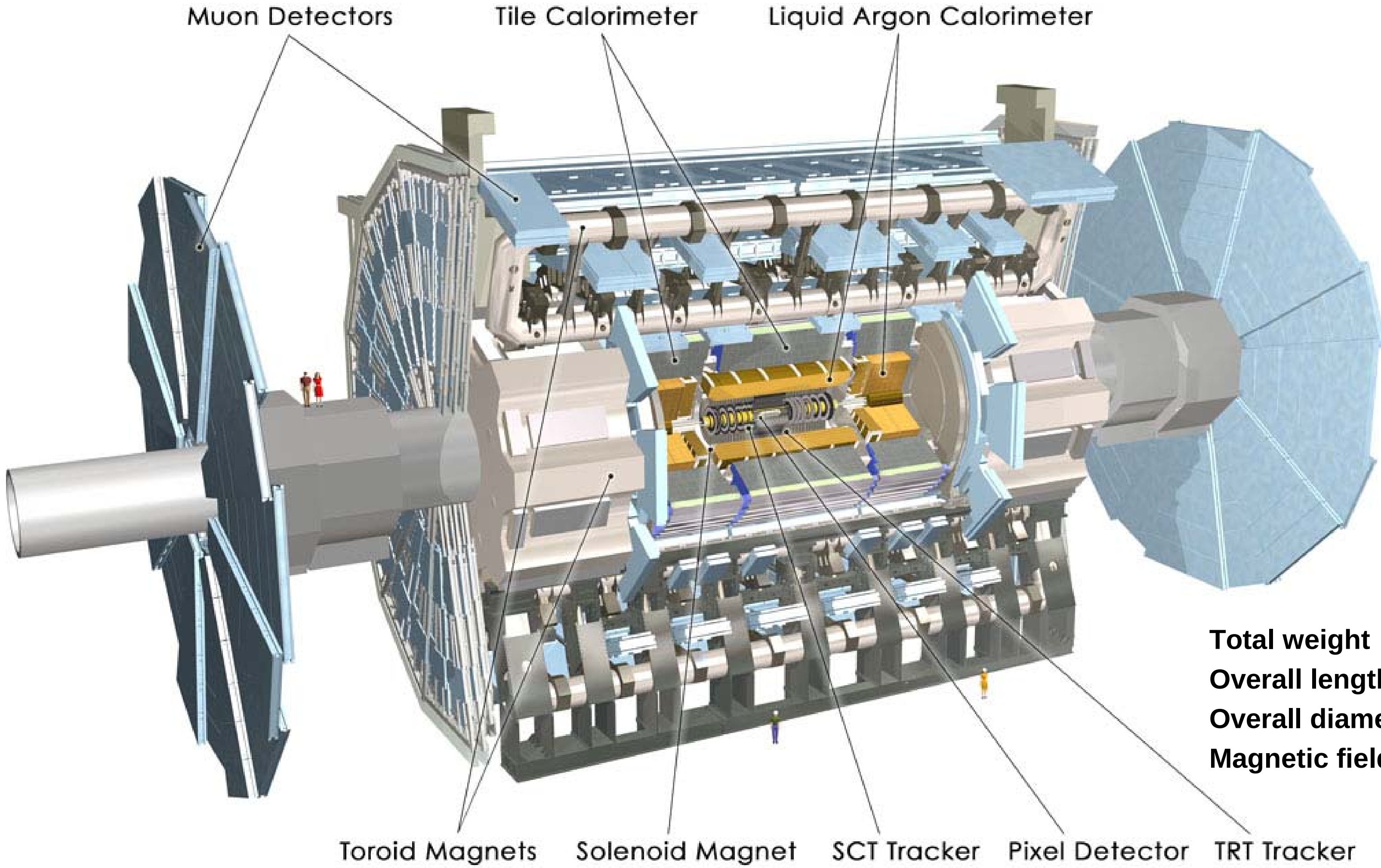
only source of signal!

Limitations Of Simple Models

- **Jet response is complex**
  - Need to understand electron/photon and hadron response of calorimeter
  - Also need to understand acceptance for each particle type
    - Signal thresholds
    - Overlapping showers in jets may enhance acceptance for low energetic particles if compared to isolated particles
  - Jet particle content/fragmentation not easily accessible in hadron colliders
    - Cannot analytically fold single particle response with fragmentation to understand experimental signals
    - Large fluctuations in particle composition
  - Large shower signal fluctuations for hadrons
    - Net effect on jets depends on fragmentation!
- **Need physics and detector simulation to understand jet response!!**

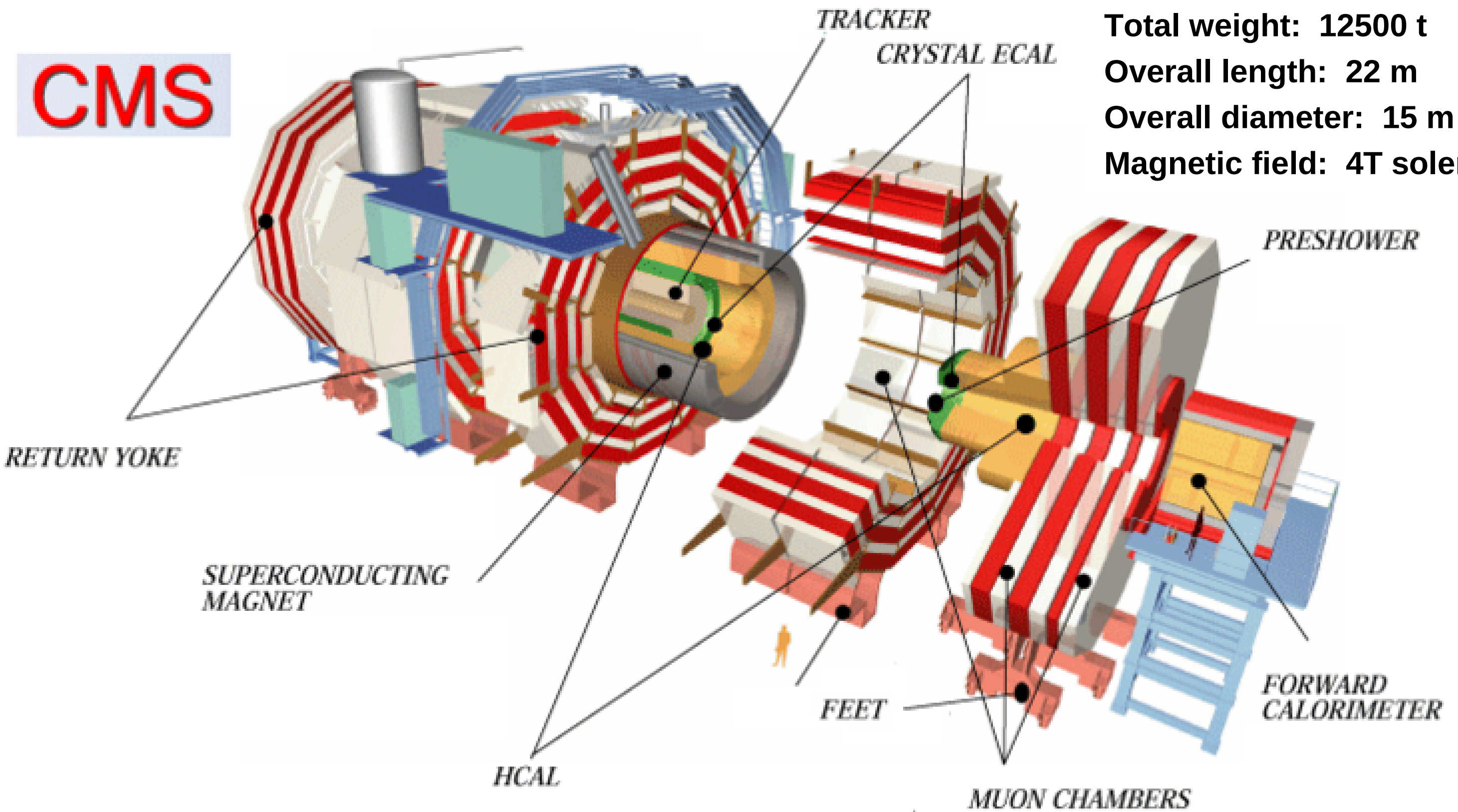
ATLAS & CMS Detectors

ATLAS: A General Purpose Detector For LHC



Total weight : 7000 t
Overall length: 46 m
Overall diameter: 23 m
Magnetic field: 2T solenoid + toroid

CMS: A General Purpose Detector For LHC



Total weight: 12500 t
Overall length: 22 m
Overall diameter: 15 m
Magnetic field: 4T solenoid

Typical Detector Features

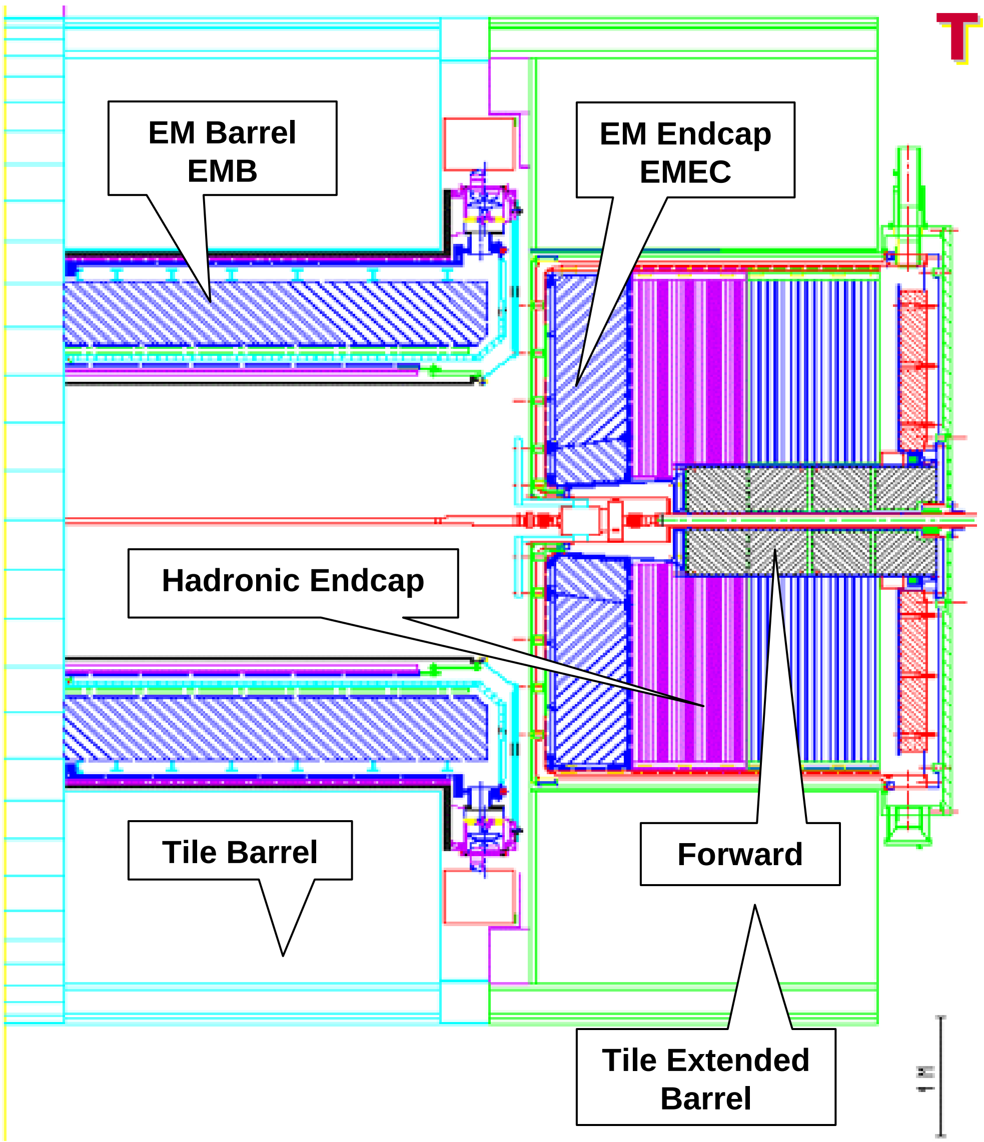
- **Hermetic coverage over a wide angular range**
  - Efficient missing transverse energy reconstruction due to large coverage in pseudo-rapidity

$$|\eta| = \left|\frac{1}{2}\ln\left(\frac{p+p_z}{p-p_z}\right)\right| = \left|\ln\left(\tan\frac{\theta}{2}\right)\right| \leq 5$$

  - Very forward detection of particles and jets produced in pp collisions
- **High particle reconstruction efficiency**
  - Important for final state reconstruction and classification
- **Relative energy resolution for electrons, photons and muons is 2-4%**

Particles	Efficiency	Jet Rejection
muon	~90%	10^5
$e^\pm$	~80%	10^5
photon	~80%	10^3
b-jet	~60%	100
tau	~50%	100

The ATLAS Calorimeters



Electromagnetic Barrel

$|\eta| < 1.4$

Electromagnetic EndCap

$1.375 < |\eta| < 3.2$

Hadronic Tile

$|\eta| < 1.7$

Hadronic EndCap

$1.5 < |\eta| < 3.2$

Forward Calorimeter

$3.2 < |\eta| < 4.9$

Varied granularity
Varied technologies
Overlap/crack regions

~200,000 readout cells

Electromagnetic Calorimetry

- **Highly segmented lead/liquid argon accordion**
  - No azimuthal cracks
  - 3 depth segments
    - + pre-sampler (limited coverage)
- **Strip cells in 1st layer**
  - Very high granularity in pseudo-rapidity

$$\Delta\eta \times \Delta\varphi \approx 0.003 \times 0.1$$

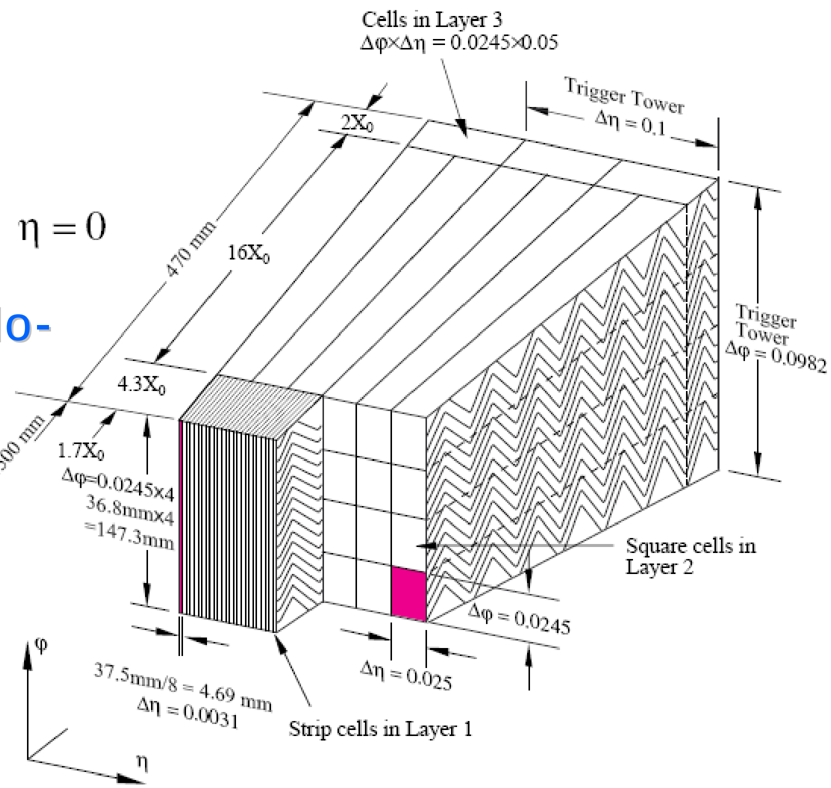
- **Deep cells in 2nd layer**
  - High granularity in both directions

$$\Delta\eta \times \Delta\varphi \approx 0.025 \times 0.025$$

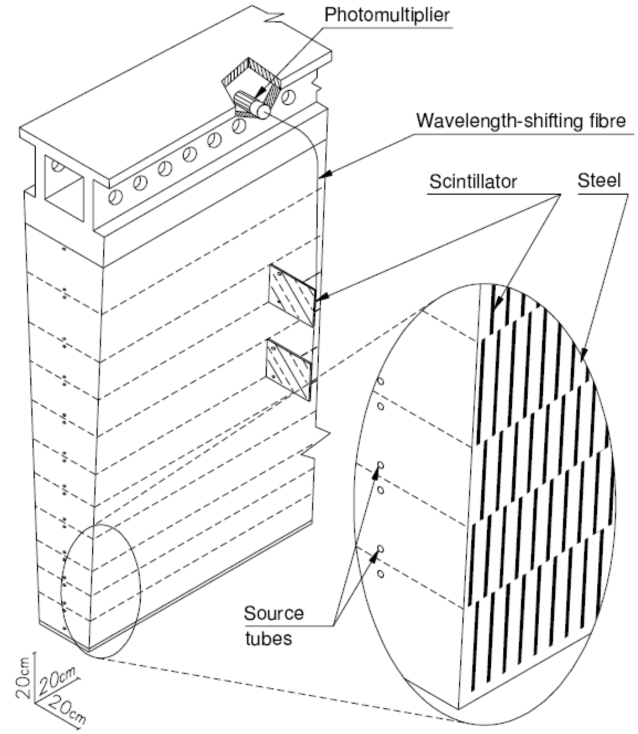
- **Shallow cells in 3rd layer**

$$\Delta\eta \times \Delta\varphi \approx 0.05 \times 0.025$$

Electromagnetic Barrel



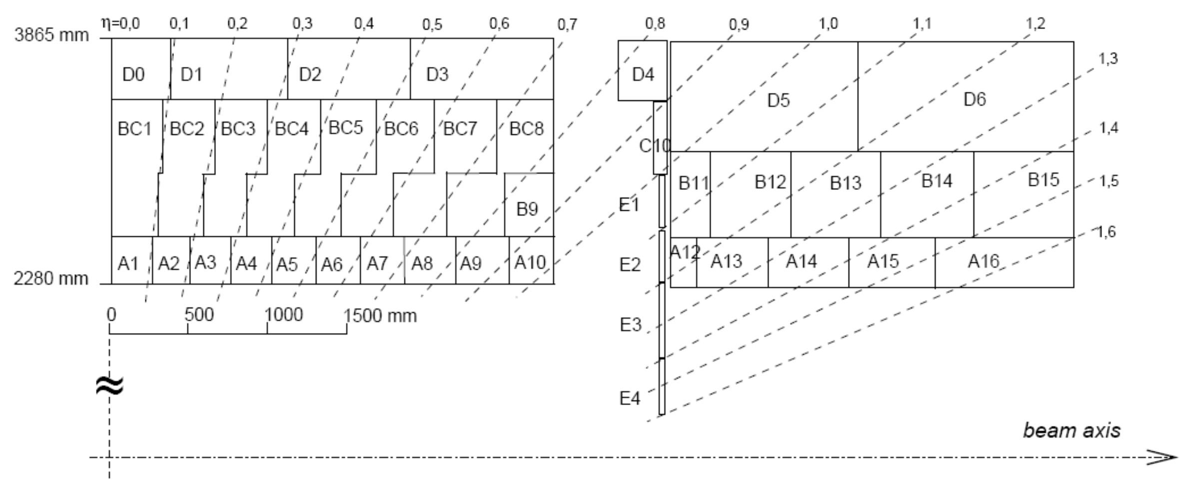
Hadronic Calorimetry



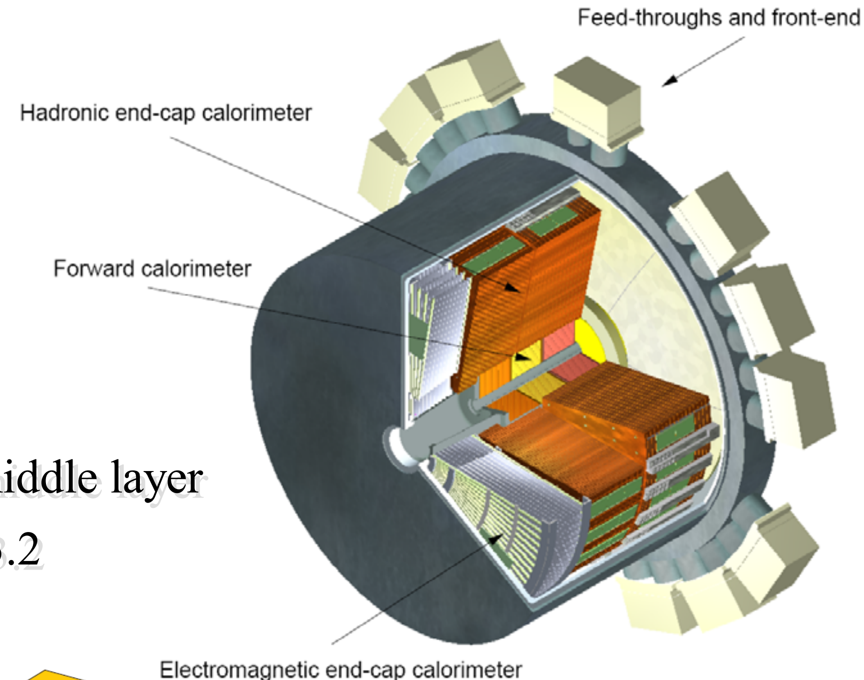
- **Tile calorimeter**
  - Iron/scintillator tiled readout
  - 3 depth segments
- **Quasi-projective readout cells**
  - First two layers:

    $\Delta\eta \times \Delta\varphi \approx 0.1 \times 0.1$
  - Third layer

    $\Delta\eta \times \Delta\varphi \approx 0.2 \times 0.1$
- **Very fast light collection**
  - ~50 ns
  - Dual fiber readout for each channel



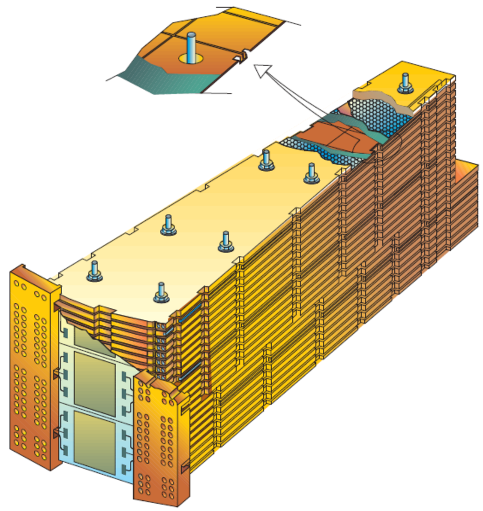
EndCap Calorimeters

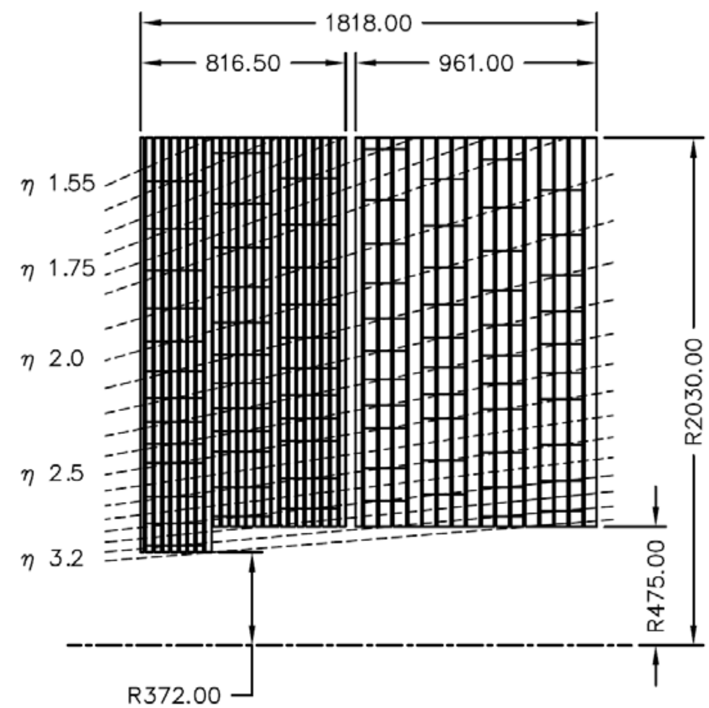


- **Electromagnetic "Spanish Fan" accordion**
  - Highly segmented with up to three longitudinal segments

$$\Delta\eta\times\Delta\varphi\approx\begin{cases}0.025\times0.025 & |\eta|<2.5,\ \text{middle layer}\\ 0.1\times0.1 & 2.5<|\eta|<3.2\end{cases}$$

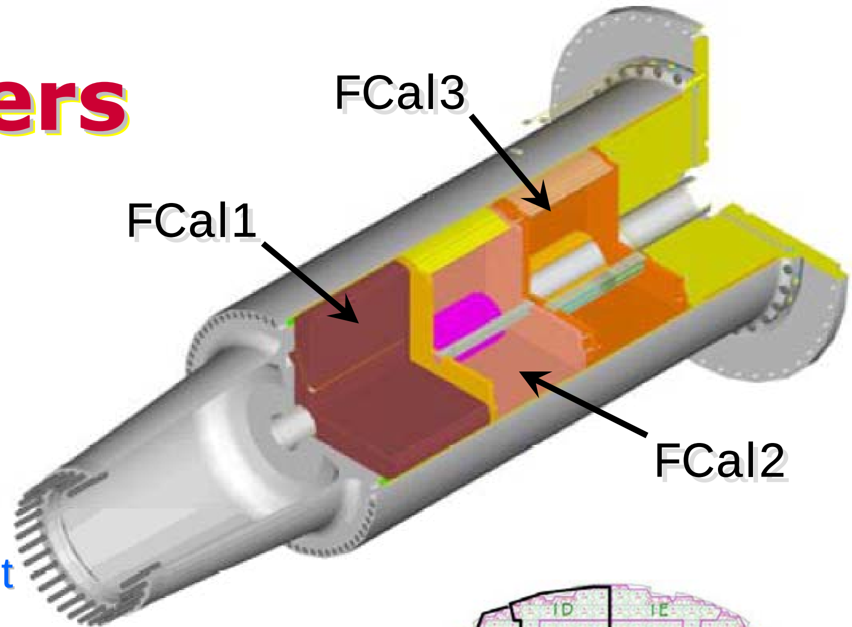
- **Hadronic liquid argon/copper calorimeter**
  - Parallel plate design
  - Four longitudinal segments
  - Quasi-projective cells





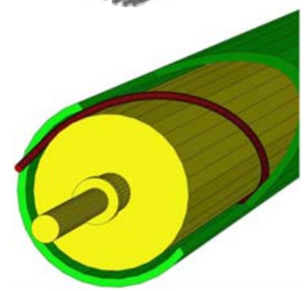
$$\Delta\eta\times\Delta\varphi\approx\begin{cases}0.1\times0.1 & |\eta|<2.5\\ 0.2\times0.2 & 2.5<|\eta|<3.2\end{cases}$$

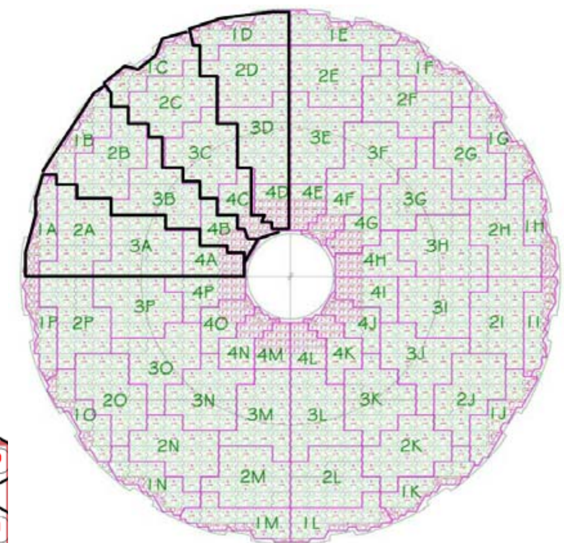
Forward Calorimeters



- **Design features**
  - Compact absorbers
    - Small showers
  - Tubular thin gap electrodes
    - Suppress positive charge build-up (Ar+) in high ionization rate environment
    - Stable calibration
  - Rectangular non-projective readout cells

$$\Delta\eta \times \Delta\varphi \approx 0.2 \times 0.2$$

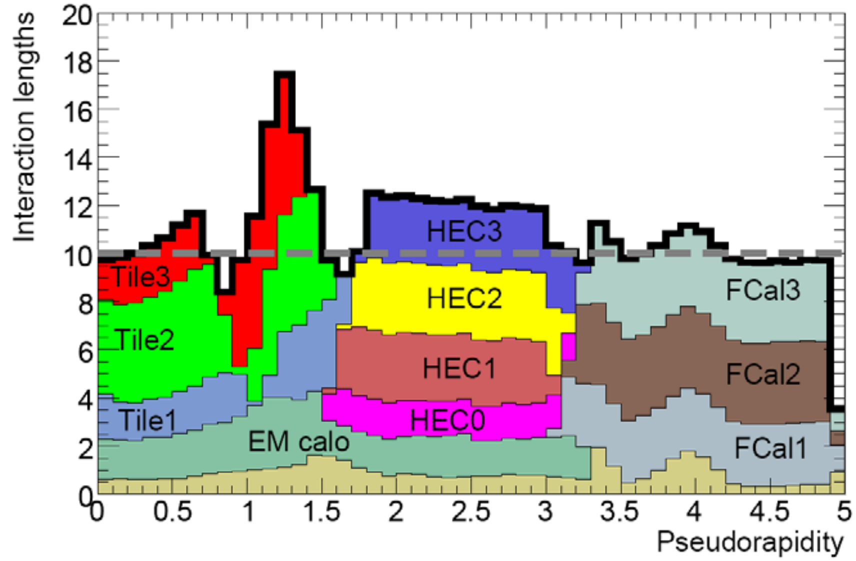




- **Electromagnetic FCal1**
  - Liquid argon/copper
    - Gap ~260 μm
- **Hadronic FCal2**
  - Liquid argon/tungsten
    - Gap ~375 μm
- **Hadronic FCal3**
  - Liquid argon/tungsten
    - Gap ~500 μm

ATLAS Calorimeter Summary

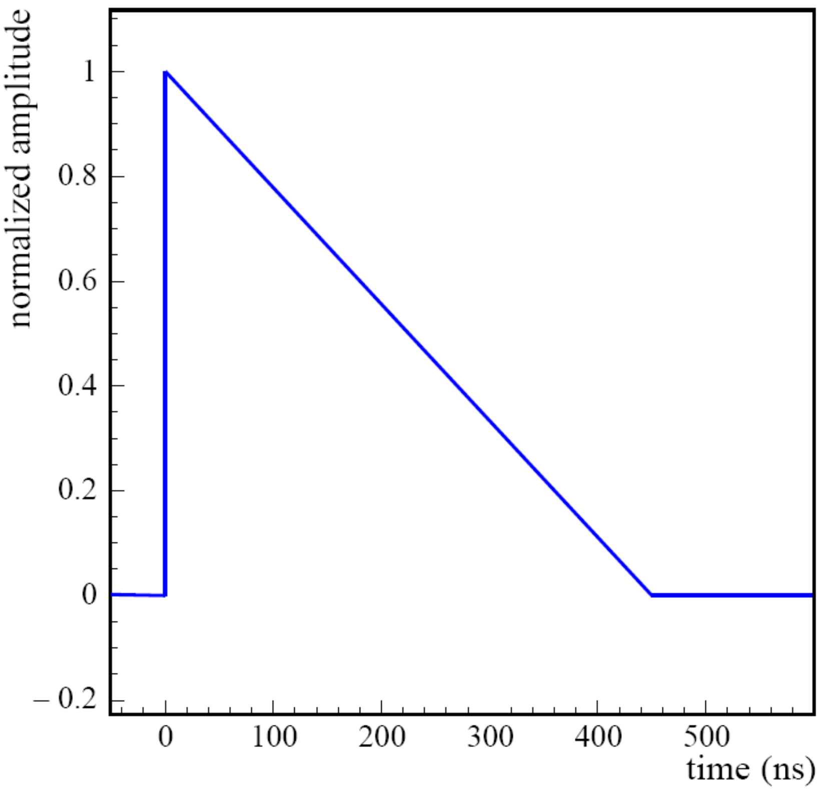
- **Non-compensating calorimeters**
  - Electrons generate larger signal than pions depositing the same energy
    - Typically $e/\pi \approx 1.3$
- **High particle stopping power over whole detector acceptance $|\eta|<4.9$**
  - $\sim$26-35 X_0 electromagnetic calorimetry
  - $\sim 10\,\lambda$ total for hadrons
- **Hermetic coverage**
  - No significant cracks in azimuth
  - Non-pointing transition between barrel, endcap and forward
    - Small performance penalty for hadrons/jets

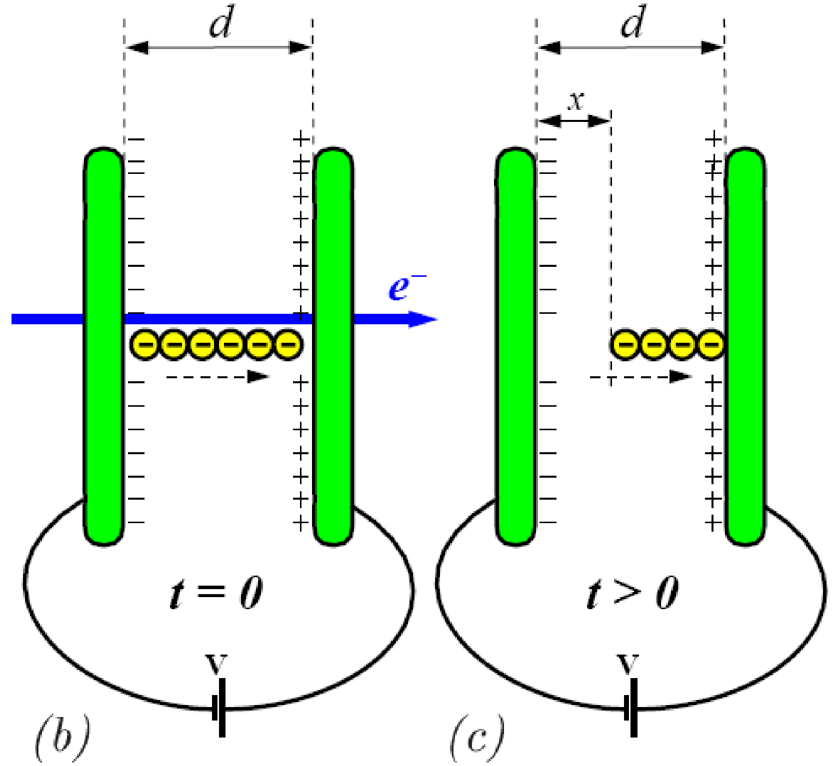


Calorimeter Signal Reconstruction

Signal Collection

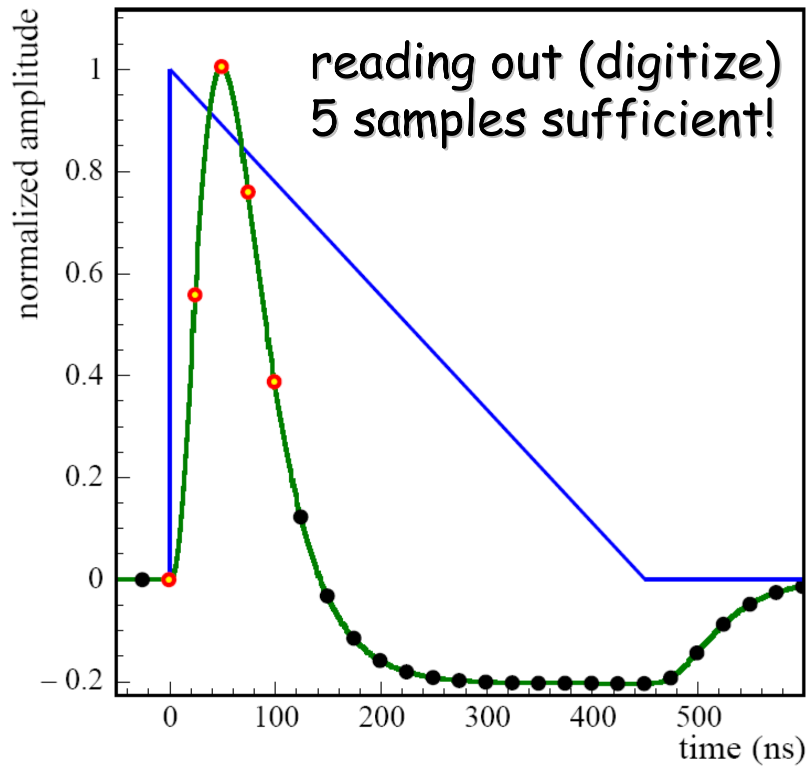
$$I(t) = I_0\left(1 - \frac{t}{t_d}\right) \text{ for } t \le t_d\text{, and } I_0 \propto E_{in}$$



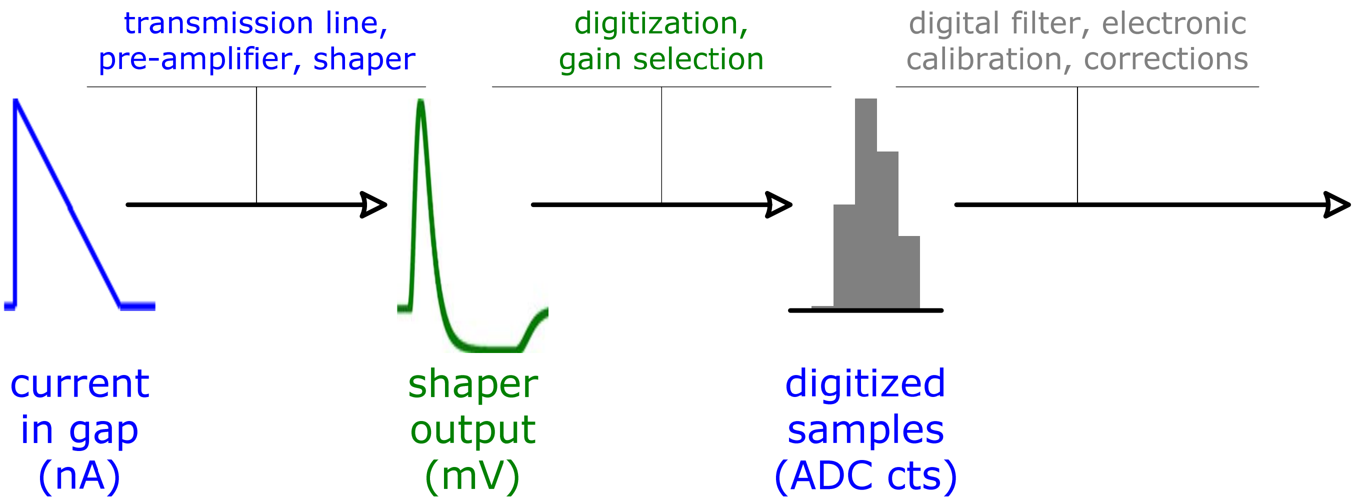


Signal Formation in ATLAS (Example)

- **Slow signal formation**
  - ~450 ns drift time @ 1 kV/mm electric field
  - High bunch crossing (collision) frequency at LHC
    - 40 MHz/every 25 ns
- **Shape signal electronically**
  - Make time integrated average of all signals 0
    - Suppresses signal history, no signal pile-up
  - Bi-polar shaping with fast rising edge
    - Peak of shaped pulse is measure of initial current



Online Signal Channel Processing



Raw Channel Data

- energy E_{raw} (MeV)
- time t (ns)
- quality Q
- selected gain g
- online id id_{online}

$$E_{raw} = A_{peak} \times \underbrace{\left[\mathrm{ADC} \rightarrow \mathrm{nA}\right]}_{\text{current calibration}}$$

$$\times \underbrace{\left(\left[\mathrm{HV}\right] \times \left[\text{cross-talk}\right] \times \left[\text{purity}\right]\right)}_{\text{electronic and efficiency corrections}}$$

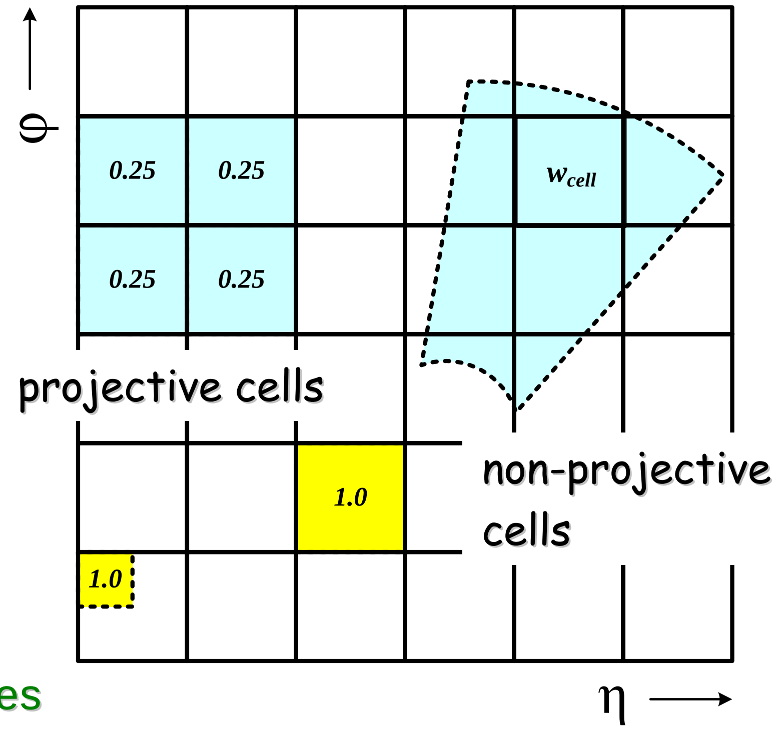
$$\times \underbrace{\left[\mathrm{nA} \rightarrow \mathrm{MeV}\right]}_{\text{energy calibration}}$$

Correction & calibration sequence is ***example only***! Order and applicable factors depend on calorimeter sub-system (electrode structure, readout organization...)

Calorimeter Cells

- **Smallest signal collection volume**
  - Defines resolution of spatial structures
  - Each is read out independently
- **Individual cell signals**
  - Sensitive to noise
    - Fluctuations in electronics gain and shaping
    - Time jitters
    - Physics sources like multiple interactions
  - Hard to calibrate
    - No measure to determine if electromagnetic or hadronic, i.e. no handle to estimate e/h from single cell alone
    - Need signal neighbourhood to calibrate
  - Basic energy scale
    - Use electron calibration to establish basic energy scale for cell signals
- **Cell geometry**
  - Often pointing to the nominal collision vertex
    - Lateral sizes scale with pseudo-rapidity and azimuthal angular opening

Collecting Cells: Towers



- **Imposes regular grid view on event ($\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$)**
  - Motivated by event ET flow
  - Natural for trigger!
- **Calorimeter cell signals are summed up in tower bins**
  - Default: no cell selection, all cells are included
    - Indiscriminatory signal sum includes cells without any true signal at all
  - Sum typically includes geometrical weight
- **Towers have fixed direction**
  - Massless four-momentum representation on electro-magnetic energy scale

$$E_{\eta\varphi} = \sum_{\left(A_{cell}^{\eta\varphi} \cap A_{\eta\varphi}\right) \neq 0} w_{cell} E_{0,cell}$$

$$w_{cell} = \begin{cases} 1 & \text{if } A_{cell}^{\eta\varphi} \leq \Delta\eta \times \Delta\varphi \\ <1 & \text{if } A_{cell}^{\eta\varphi} > \Delta\eta \times \Delta\varphi \end{cases}$$

$$\left(E_{\eta\varphi}, \eta, \varphi\right) \mapsto \left(E_{\eta\varphi}, p_x, p_y, p_z\right) \text{ with } p = E_{\eta\varphi} = \sqrt{p_x^2 + p_y^2 + p_z^2}$$

Topological Cell Clusters

Motivation

- Attempt reconstruction of individual particle showers
  - Reconstruct 3-dim clusters of cells with correlated signals
- Use shape of these clusters to locally calibrate them
  - Explore differences between electromagnetic and hadronic shower development and select best suited calibration
- Supress noise with least bias on physics signals
  - Often less than 50% of all cells in an event with "real" signal

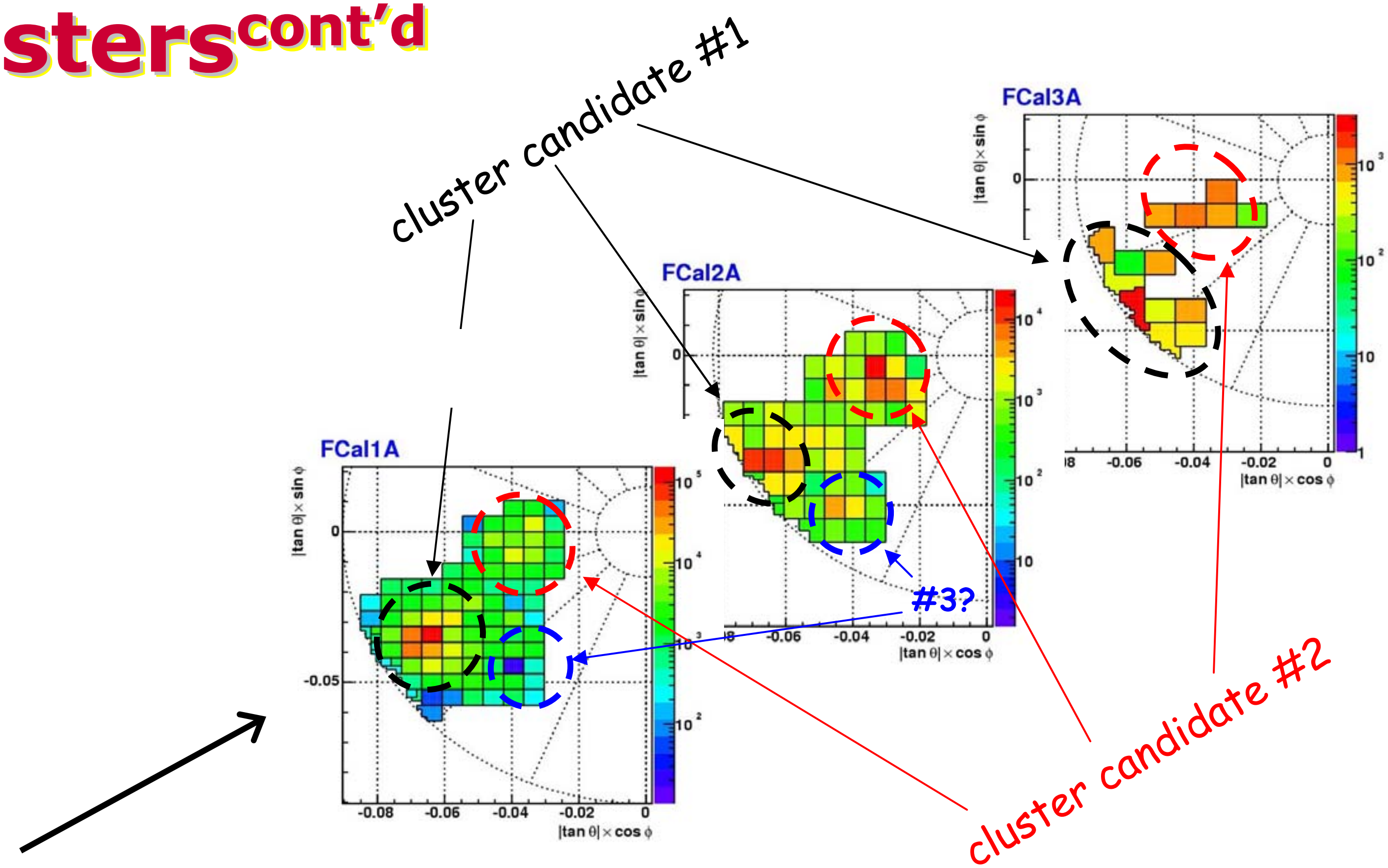
Implementation

- Find seed with significant signal above primary seed threshold S
  - Signal significance is signal-over-noise (absolute)

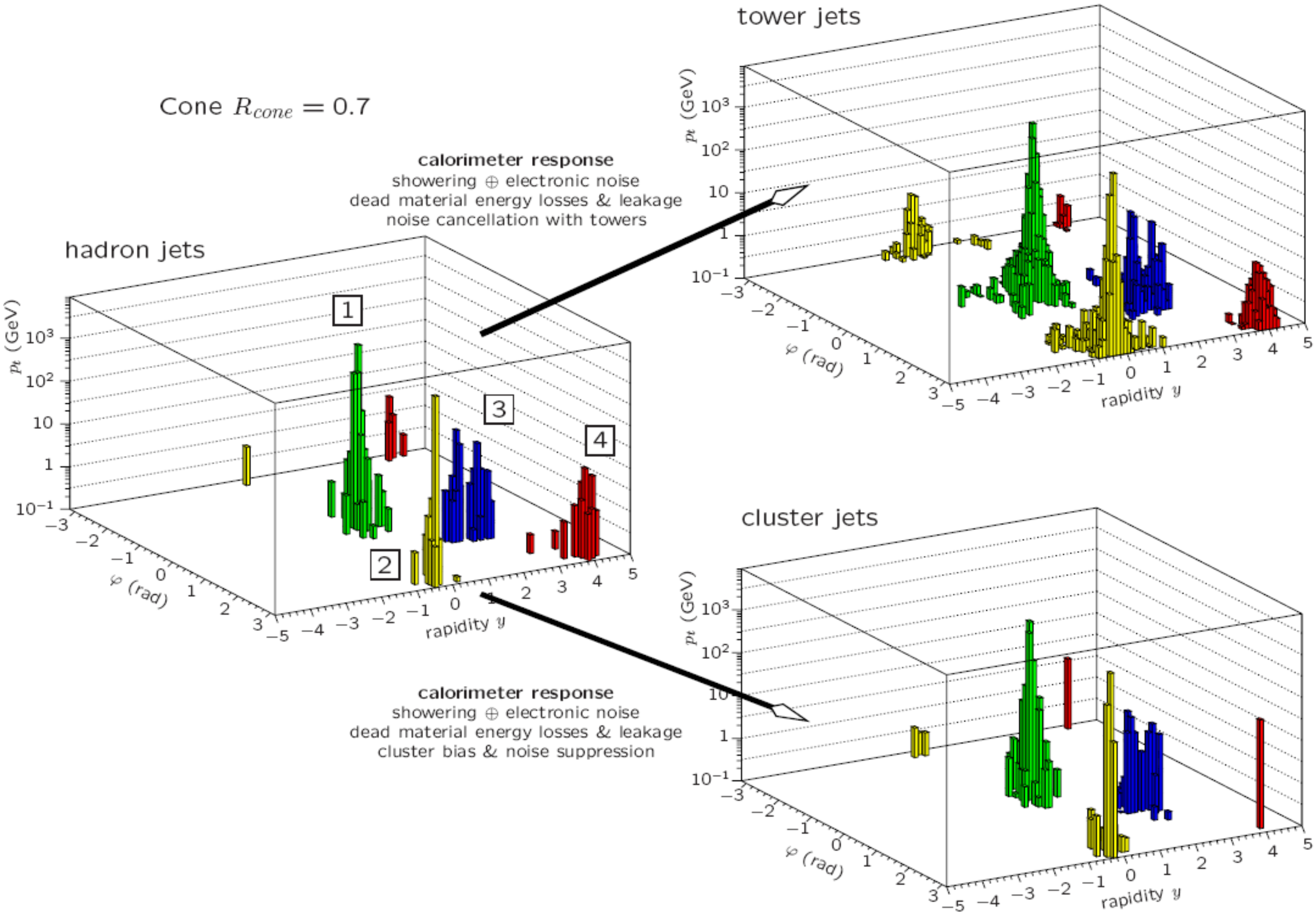
$$|E_0|/\sigma_{noise}$$

- Collect all neighbouring cells (in 3-d) with signals with significance above basic threshold P
- If neighbouring cells have signal above secondary seed N, collect neighbours of neighbours if they have significance above P
- Analyze clusters for local signal maxima and split if more than one found
  - In 3-d, again
- Note that very low signal cells can survive "effective" cell signal significance selection with this algorithm if larger signal in vicinity

Topological Cell Clusters$^{cont'd}$



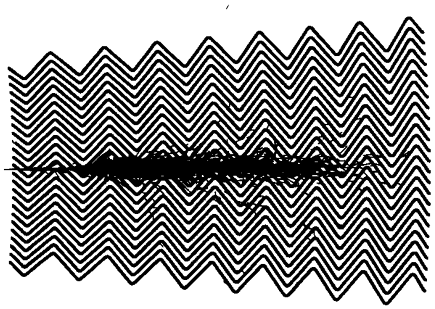
Calorimeter Jet Signals: It's All In The Pictures…



Hadronic Cluster Calibration

Local approach (cluster context)

- Calibrate calorimeter signal first
  - Provides calibration for all signals without need for jet context
- Separate electromagnetic from hadronic signals
  - Topological clustering/energy blob reconstruction
  - Cluster shape analysis explores differences between electromagnetic and hadronic shower development
    - Compactness of electromagnetic shower



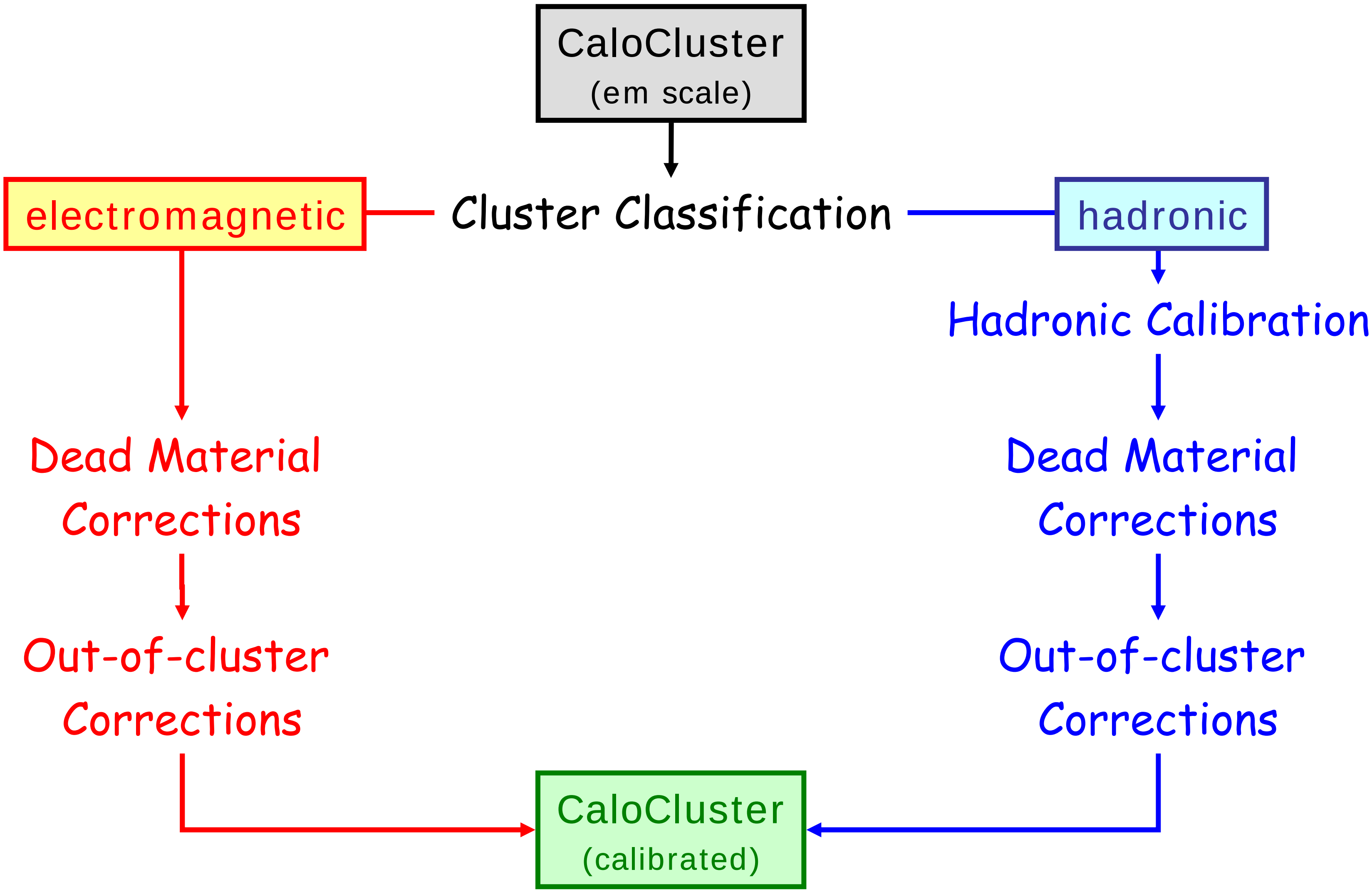
RD3 note 41, 28 Jan 1993

- Attempt to only calibrate hadronic clusters
  - Non-compensation only issue for hadronic showers
- Absorb particle or jet signal variations due to algorithms, size, physics environment into corrections
  - Factorization possible
  - Jet context corrections not applied to other hadronic objects

Cannot completely factorize calibration and corrections

- Correlation between inactive material energy losses and effective e/h in calorimeters, for example

Local Hadronic Calibration



Cell Signal Weighting In ATLAS

- **Weights are extracted from simulations**
  - Signals and deposited energies from single charged pion MC

$$w = \left\langle \left(E_{cell}^{Em} + E_{cell}^{nonEm_{vis}} + E_{cell}^{nonEm_{invis}} + E_{cell}^{escaped} \right) \Big/ E_{cell} \right\rangle$$

$$c^{em} \cdot A\left(\left[E_{cell}^{Em} \oplus E_{cell}^{nonEm_{vis}} \right]_{active}, t, \vec{\varepsilon}, \ldots \right)$$

Reconstructed em scale signal

Escaped energy (no signal contribution)

Invisible energy (no signal contribution)

Ionization energy (charged hadron & muon signal contribution)

Electromagnetic energy (electron,positron,photon signal contribution)

Electromagnetic shower branch

Purely hadronic shower branch

- **Weights are calculated as function of cluster & cell variables**
  - Signal environment used as additional indicator of hadronic character

Local Hadronic Calibration Summary

- **Attempt to calibrate hadronic calorimeter signals in smallest possible signal context**
  - Topological clustering implements noise suppression with least bias signal feature extraction
  - No bias towards a certain physics analysis
  - Good common signal base for all hadronic final state objects
    - Jets, missing Et, taus
- **Factorization of cluster calibration**
  - Cluster classification largely avoids application of hadronic calibration to electromagnetic signal objects
    - Low energy regime challenging
  - Signal weights for hadronic calibration are functions of cluster and cell parameters and variables
    - Cluster energy and direction
    - Cell signal density and location (sampling layer)
  - Dead material and out of cluster corrections are independently applied

From This Lecture:

- **Calorimeters are signal processors for incoming particles**
  - They generate an image of particles they are sensitive to in the collision event
  - The image is distorted due to environment (physics and detector)
- **Calorimeter signal reconstruction is the attempt to improve the resolution of this image**
  - Attempt to unfold the distortions by signal definition, possibly including identification of significant objects
  - Best choice for unfolding strategy may depend on physics question
  - Two signal definitions (e.g., towers and clusters) allow evaluation of systematic uncertainties
- **We will explore this further in the 2nd lecture on Sunday!**

Backup Slides

Digital (Optimal) Filtering

- **Determines signal amplitude and timing**
  - Minimizes noise contributions
    - Note: noise depends on the luminosity
  - Requires explicit knowledge of pulse shape
    - Folds triangular pulse with transmission line characteristics and active electronic signal shaping
    - Characterized by signal transfer functions depending on *R*, *L*, *C* of readout electronics, transmission lines
- **Filter coefficients from calibration system**
  - Pulse “ramps” for response
  - Noise for auto-correlation
    - Pile-up dependence

Signal Amplitude (~Energy):

$$A_{peak} = \sum_{i=1}^{N_s} a_i \left(S_i - P \right)$$

Signal Peak Time:

$$A_{peak} t_{peak} = \sum_{i=1}^{N_s} b_i \left(S_i - P \right)$$

S_i .... signal amplitude in sample i

P .... analog-to-digital converter pedestal

N_s .... number of digital samples (def. 5)

a_i .... digital filter coefficient

R_{ij} .... noise auto-correlation

g_i .... normalized physics pulse shape:

Filter Coefficients

Determined by:

- Known pulse shape
- Minimizing noise

to 1st order independent of time jitter!

$$\sum_{i=1}^{N_s} a_i g_i = 1$$

$$\sum_{i=1}^{N_s} a_i \frac{\partial g_i}{\partial t} = \sum_{i=1}^{N_s} a_i g_i' = 0$$

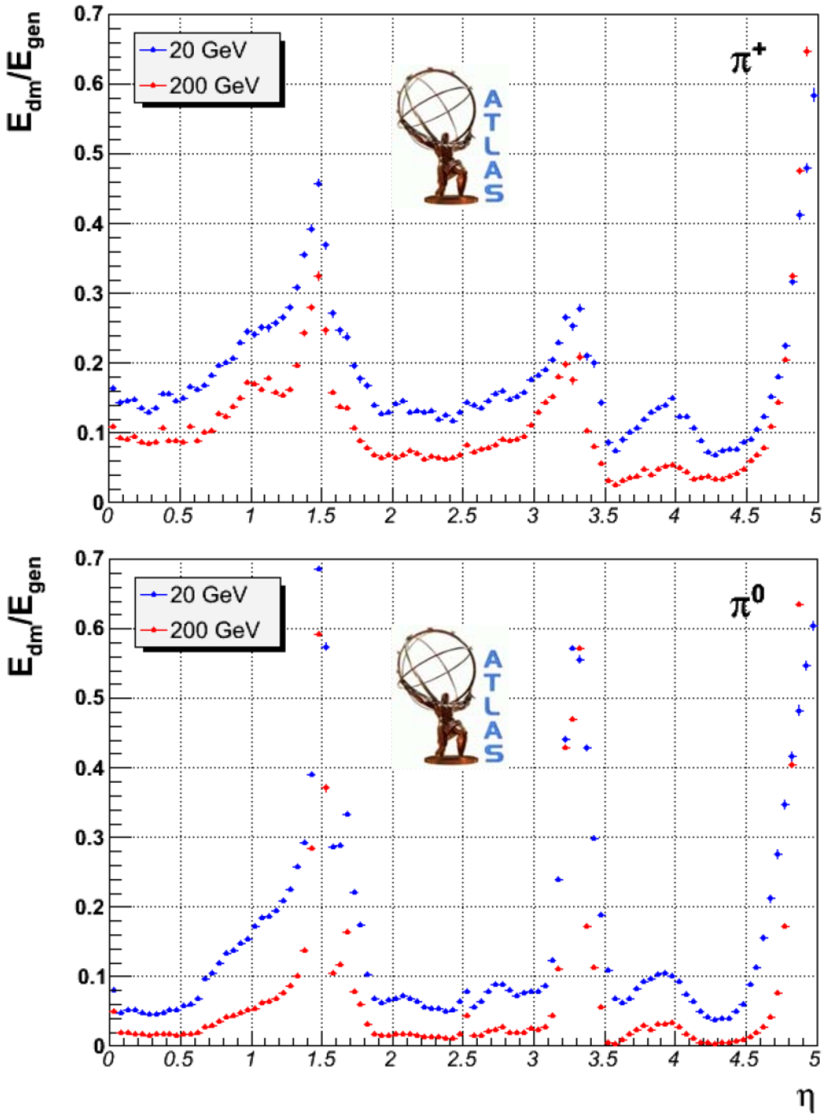
$$\sum_{i=1}^{N_s} \sum_{j=1}^{N_s} a_i a_j \sigma_i \sigma_j R_{ij} \rightarrow \min$$

Lagrange Multipliers

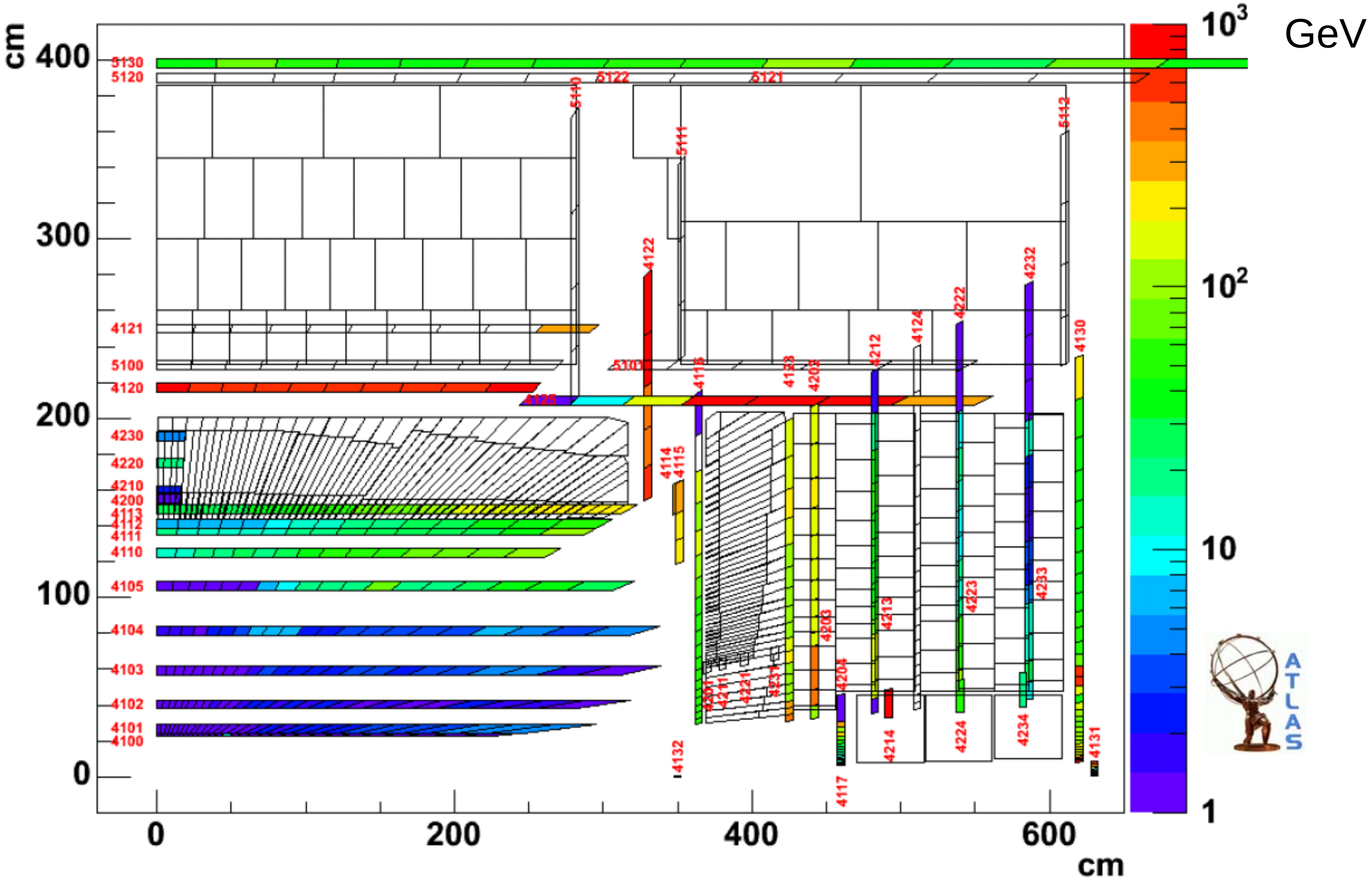
$$a_i = \sum_{j=1}^{N_s} R_{ij}^{-1} \left(\lambda g_j - \mu g_j' \right) \quad \begin{cases} \lambda = \dfrac{1}{\Delta} \sum_{i=1}^{N_s} \sum_{j=1}^{N_s} R_{ij}^{-1} g_i' g_j' \\ \mu = \dfrac{1}{\Delta} \sum_{i=1}^{N_s} \sum_{j=1}^{N_s} R_{ij}^{-1} g_i g_j' \\ \Delta = \left(\sum_{i=1}^{N_s} \sum_{j=1}^{N_s} R_{ij}^{-1} g_i' g_j' \right) \cdot \left(\sum_{i=1}^{N_s} \sum_{j=1}^{N_s} R_{ij}^{-1} g_i g_j \right) - \left(\sum_{i=1}^{N_s} \sum_{j=1}^{N_s} R_{ij}^{-1} g_i g_j' \right)^2 \end{cases}$$

Dead Material Energy Losses

- **Tracking device in front of a calorimeter**
  - And maybe even a cryostat wall
- **Try to use the cluster signal to correct for the losses**
  - In front
  - Inbetween
    - Central ATLAS!
  - Between
    - Endcap and forward cracks
- **Approach:**
  - Correlate cluster signal with nearby dead material energy loss in simulations
  - Do this for each dead material region separately



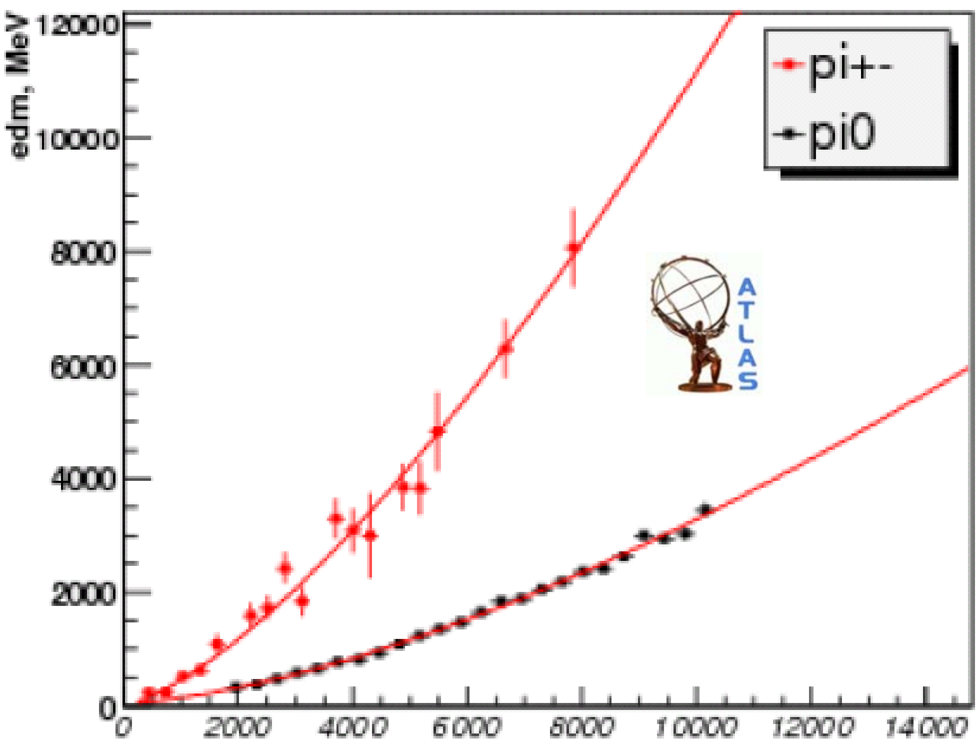
Dead Material Energy Losses in ATLAS



Dead Material Corrections

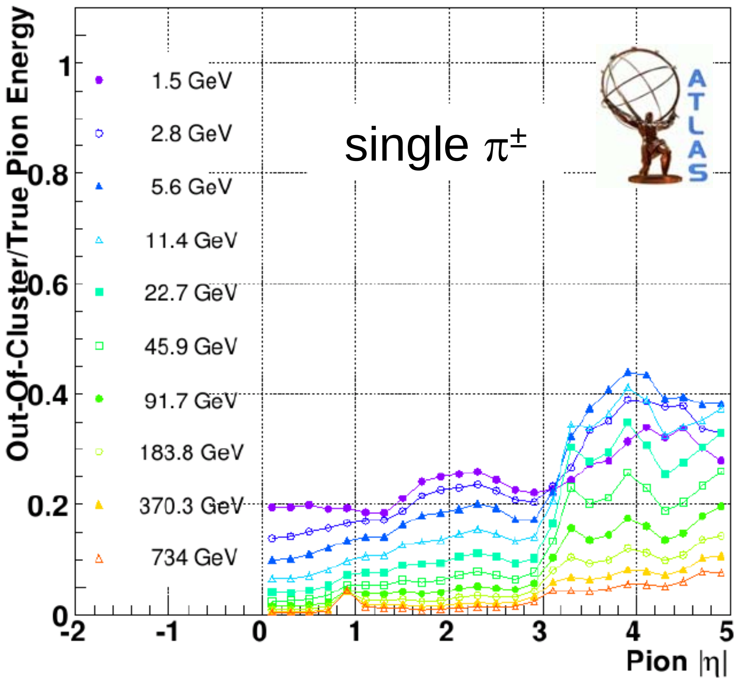
Example: central region

- Dead material between pre-sampler and first sampling in central ATLAS calorimeter
- Use geometrical mean of presampler energy and first sampling energy as variable

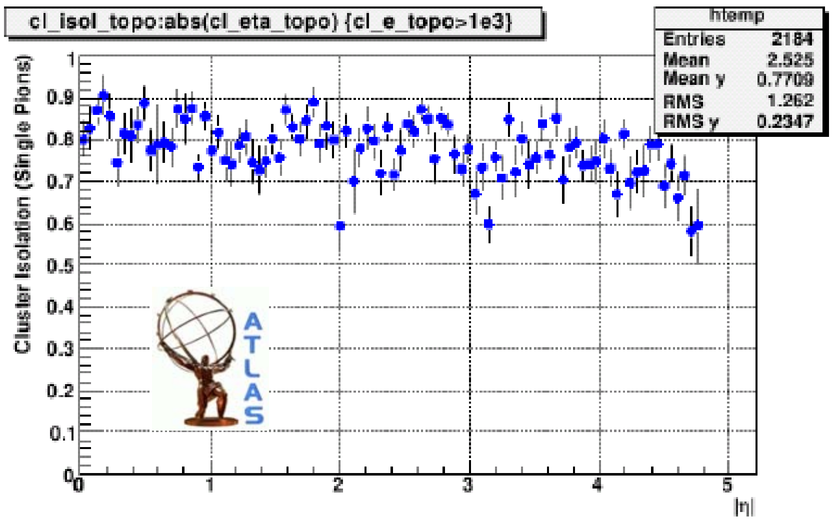


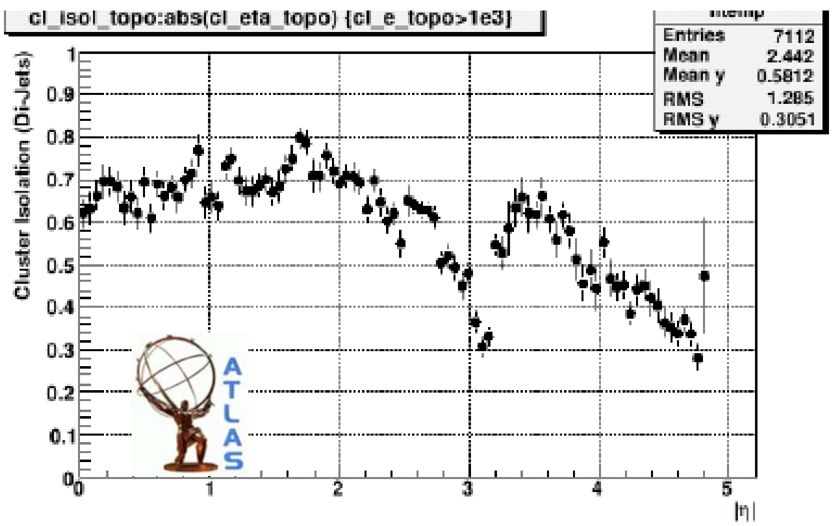
Out-of-cluster Corrections

- **Consider a cluster produced by a single pion**
  - Some energy deposited outside of cluster
    - Clustering algorithm inefficiency
    - Signal way below all thresholds
- **Integrated effect can be large**
  - Especially in forward calorimeter
    - E.g, large noise
- **Corrections have been developed for single pions**
  - Again using detailed shower simulations
- **Need to avoid over correcting for jets**
  - out-of-cluster energy for one cluster could actually be deposited in another cluster in jets
- **Isolation moment**
  - The fraction of calorimeter cells neighbouring a given cluster but are not part of any other clusters is determined and used as a scale for isolation



Out-of-cluster Corrections: Isolation





- **Out-of-cluster correction estimate is the product of**
  - out-of-cluster correction from single pions
  - isolation moment
- **This correction is applied as a multiplicative factor to all the cells in the cluster**
  - Lost energy is equally shared
    - Mostly because we don't know better!
- **Clear dependence on signal context**
  - single pions
    - most clusters isolated
  - di-jets
    - less isolation