Calorimetry

in particle physics experiments

6. Calorimeter Design

a.k.a. design principles, or “why did experiments make the choices they did?”

Course roadmap

- **Week 1 (Foundations)**
  - ✓ Lecture 1: Why calorimetry?
  - ✓ Lecture 2: EM shower physics
- **Week 2 (Physics depth)**
  - ✓ Lecture 3: Hadronic shower physics
  - ✓ Lecture 4: Energy resolution from first principles
- **Week 3 (Technology)**
  - ✓ Lecture 5: Calorimeter Technologies (real-life EM and Hadronic calorimeters)
  - ✓ Lecture 6: Calorimeter Design
- **Week 4 (Systems & Future)**
  - ✓ Lecture 7: Signal chain, readout, calibration
  - ✓ Lecture 8: Future calorimetry

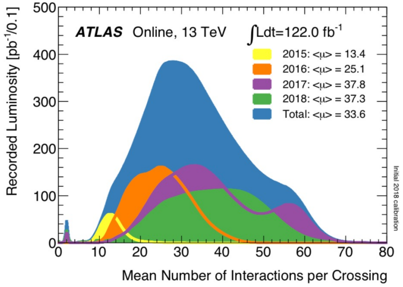
Today's Lecture

- **Week 3 (Technology)**
  - ✓ Lecture 5: Calorimeter Technologies (real-life EM and Hadronic calorimeters)
  - ✓ Lecture 6: Calorimeter Design
    - *a.k.a. design principles, or "why did experiments make the choices they did?"*
    - *6.1 Physics requirements for LHC calorimetry*
    - *6.2 LHC calorimeter implementation deep-dives*
      - *6.2.1 ATLAS LAr Accordion: Deep-Dive*
      - *6.2.2 CMS ECAL: Deep-Dive*
      - *6.2.3 ATLAS TileCal & CMS HCAL: Design Choices*
    - *6.3 Design Principles & Considerations*
    - *6.4 Beyond hardware compensation: Dual Readout & Particle Flow*

6.1

Physics requirements for LHC calorimetry

Physics requirement on calorimetry: the LHC example



- LHC calorimeters must have a ***fast*** response
  - ✓ Otherwise, signal will "integrate" over many bunch crossings → large "pile-up" bias
  - ✓ Ideal response time : 20-50 ns
    - Even so, integrate over 1-2 bunch crossings → pile-up of 25-100 minimum-bias events
    - Very challenging readout electronics

- LHC calorimeters must be highly ***granular***
  - ✓ Minimize probability that pile-up particles be in the same readout element as interesting object (e.g. γ from H $\rightarrow \gamma\gamma$ decays)
    - Large number of electronic channels
    - High cost

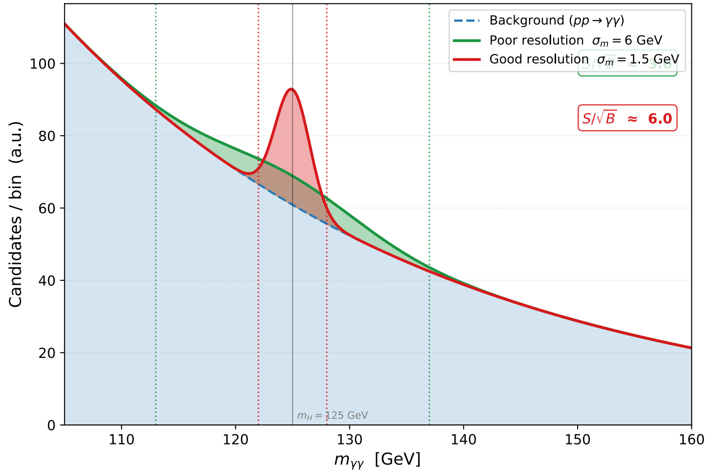
- LHC calorimeters must be ***radiation resistant***
  - ✓ High flux of particles from pp collisions → high radiation environment e.g. in forward calorimeters
    - Up to 10^{17} n/cm^2 in 10 years of LHC operation
    - Up to 10^7 Gy (1 Gy = unit of absorbed energy = 1 Joule/Kg)

H → γγ requirements on LHC EM calorimeters

- Two handles to distinguish a small resonance peak over a large background:
  - ✓ **“Squeeze” the signal peak**
    - **Improve energy resolution of the calorimeters**
    - Example: H → γγ for “low” mass Higgs:
      - – Higgs natural width very narrow (~4 MeV), signal significance directly proportional to mass resolution:

$$S = \frac{N_S}{\sqrt{N_B}} = \frac{\sqrt{\mathcal{L}}}{\sqrt{\sigma_{m_{\gamma\gamma}}}}$$

      - – Before the LHC data taking m_H not know, but H → γγ only relevant at low mass (e.g. m_H ~ 120 GeV)
      - – L=30 fb^{-1} σ_m/m~1% for m_H=120 GeV → S ~ 5



    - **Improve the measurements precision of the shower direction**
      - – calo standalone σ_θ ~ 50 mrad/√(E/GeV)
  - ✓ **Reject background, especially high energy π^0** [jet rejections factor ~10^{3-4}]
    - Fine detector granularity to resolve the maxima of the showers from pion decay and isolation

Physics requirement on calorimetry: the LHC example

- EM calorimeters
  - ✓ Benchmarks
    - $H \to \gamma\gamma$, $H \to ZZ^* \to eeee$
      - excellent energy resolution and linearity in 5-100 GeV range
    - $Z' \to ee$ with mass up to few TeV range
    - b-physics
      - electrons down to ~ 1 GeV range
  - ✓ Calorimeter TDR goals ($|\eta| < 2.5$)
    - Stochastic term a<10% (ATLAS); <3% (CMS)
      - $H \to \gamma\gamma$, $H \to ZZ^* \to eeee$
    - Constant term c<0.7% (ATLAS); <0.5% (CMS)
      - Dominates at high E: driven by top mass, W mass measurements
    - Energy scale ~0.1%
      - required for W mass precision at the 10 MeV level
    - Linearity better than 0.5%
      - required for high-E_T electrons/photons in SUSY searches.

- HAD and FWD calorimeters
  - ✓ Benchmarks
    - W → in from top decays, $H \to bb$
    - SUSY events with many high p_T jets and missing energy
      - jet resolution, linearity, hermeticity, forward coverage
    - VBF Higgs, forward physics
      - forward jet tagging
  - ✓ Calorimeter TDR goals
    - $\sigma_E/E < 3\%$ for $E_T > 1$ TeV jets ($|\eta| < 3$)
      - Required by new physics searches at high mass.
    - $\sigma_E/E < 10\%$ for $3 < |\eta| < 5$ (few % in FCAL)
    - full coverage to $|\eta| \sim 5$
      - jet energy scale and missing-ET resolution requirements
    - Energy scale ~1%
    - Linearity ~2% up to ~4 TeV

EM calorimetry at LHC: two coherent design answers

Homogeneous calorimeter made of 75848 $PbW0_4$ scintillating crystals

- Compact
- Excellent energy resolution
- Fast
- High granularity
- Radiation resistance
- E range MIP → TeV

Sampling LAr-Pb, 3 Longitudinal layers + presampler

- Good energy resolution
- Fast
- High granularity
- Longitudinally segmented
- Radiation resistance
- E range MIP → TeV

- .. but *opposite* choices!
  - ✓ CMS decided to rely on vertex reconstruction from tracking and pointed to homogenous calorimeter with very low stochastic term aiming for excellent energy resolution
  - ✓ ATLAS require segmented calorimeter to have redundant measurement of γ angle

EM calorimetry at LHC: two “opposite” bets…

Homogeneous calorimeter made of 75,848 PbW0$_4$ scintillating crystals

- No longitudinal segmentation; APD readout inside 3.8 T solenoid
- Bet: intrinsic crystal resolution (no sampling fluctuations) gives best sigma/E
- Trade-off: no **γ** direction from ECAL alone (relies on tracker for vertex)
- Trade-off: APD radiation sensitivity
  - laser monitoring every 40 min (entire run history)
- Trade-off: HCAL barrel thin (constrained by solenoid)
  - needed outer HCAL (HO)
- *A posteriori* trade-off: crystal opacity vs lumi
  - Very complex time-dependent calibration

Sampling LAr-Pb, 3 Longitudinal layers + presampler

- ~170 000 channels; 3 longitudinal samplings; accordion geometry for phi uniformity
- Bet: strip layer (~4 mm eta granularity) gives π^0 rejection AND **γ** direction independently of tracker
- Trade-off: solenoid material before ECAL
  - Presampler required
- Trade-off: inherently larger stochastic term (~10%/sqrt(E)) compared to crystal (~3%)
- Trade-off: cryogenics (cost, complexity) but: stable calibration (no gain drift)
- *A posteriori* trade-off: electronic calibration significantly more complext than foreseen because of longitudinal segmentation

- Neither was wrong: both achieved physics goals (H→**γγ** discovery, W mass, SUSY limits, …)
- Same physics requirements can be satisfied by multiple coherent engineering philosophies!

6.2

LHC calorimeter implementation deep-dives

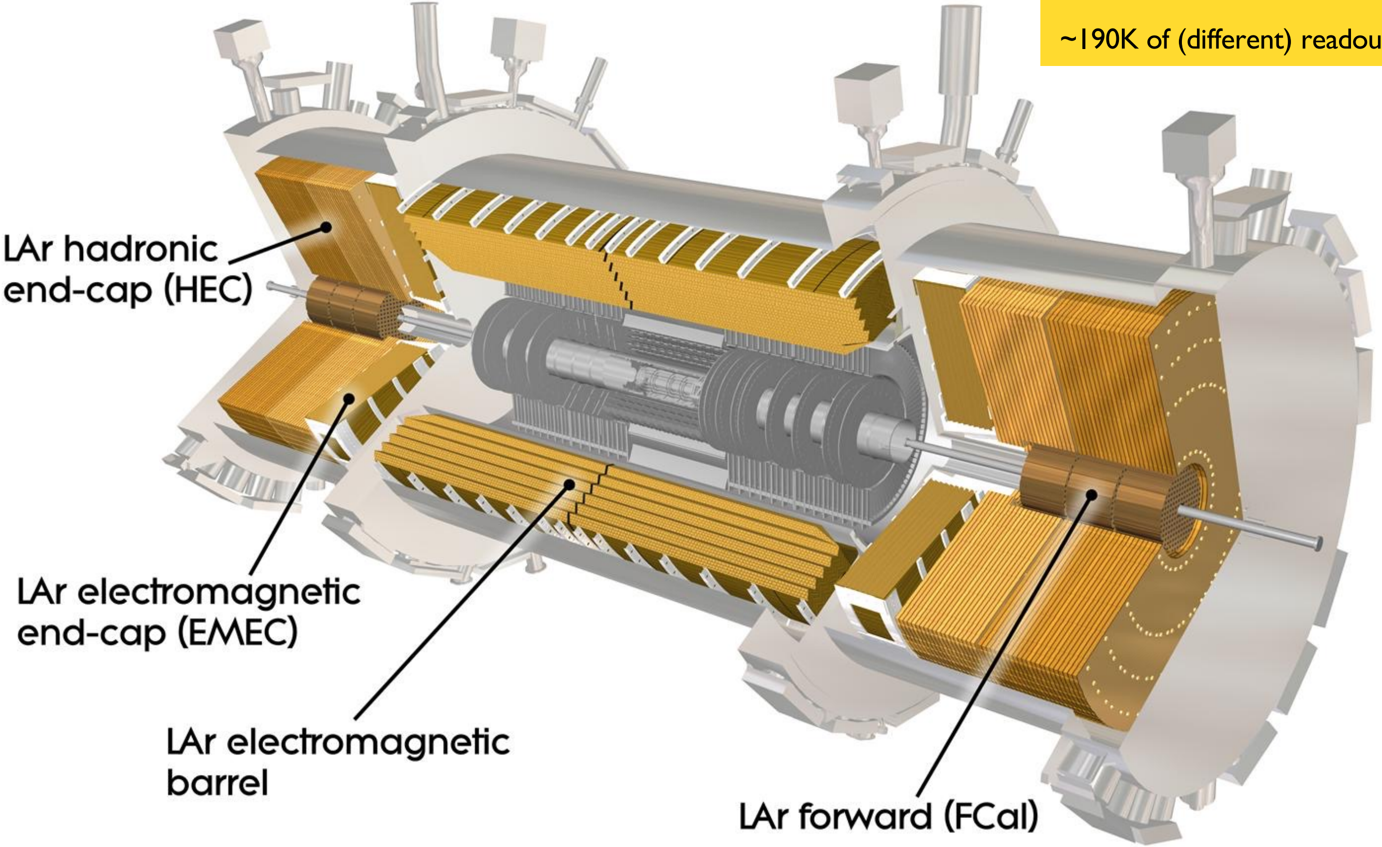
6.2.1

ATLAS LAr Accordion: Deep-Dive

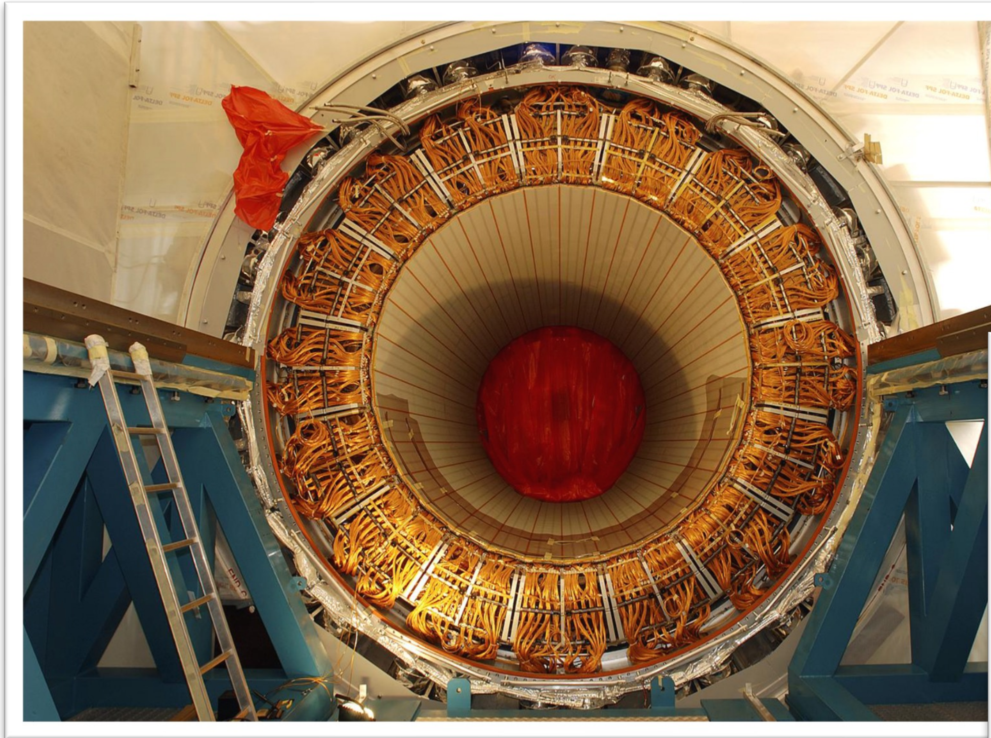
ATLAS LAr calorimeters

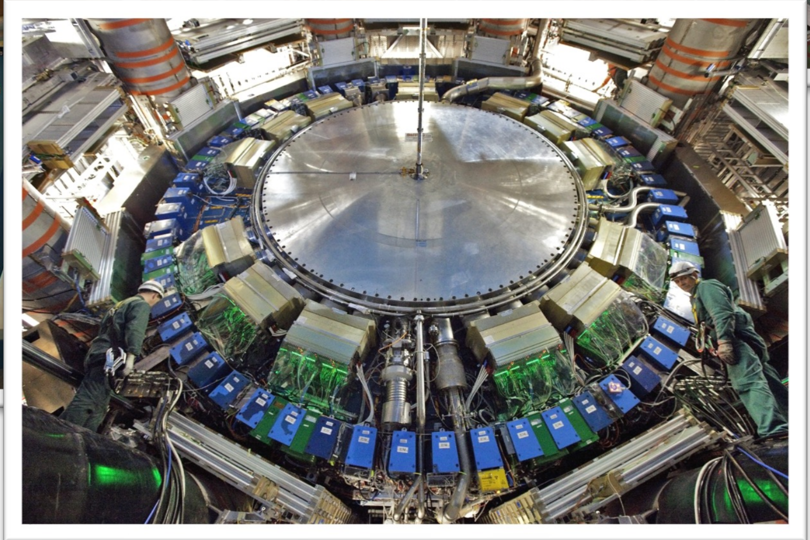
- ✓ EM Barrel : ($|\eta|<1.475$) [Pb-LAr]
- ✓ EM End-caps : $1.4<|\eta|<3.2$ [Pb-LAr]
- ✓ Hadronic End-cap: $1.5<|\eta|<3.2$ [Cu-LAr]
- ✓ Forward Calorimeter: $3.2<|\eta|<4.9$ [Cu,W-LAr]

~190K of (different) readout channels

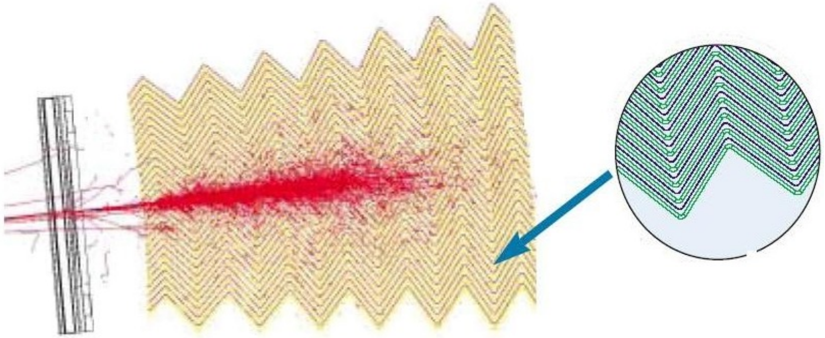


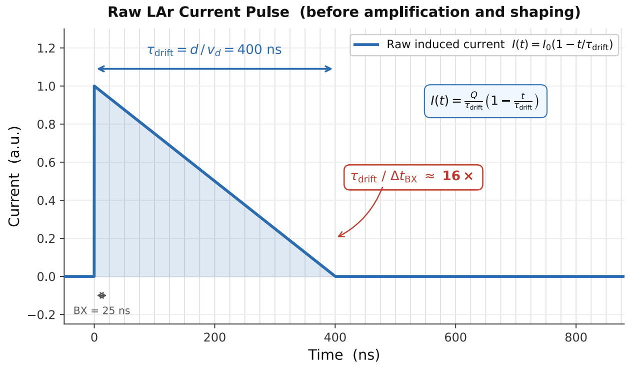
ATLAS LAr EM calorimeter



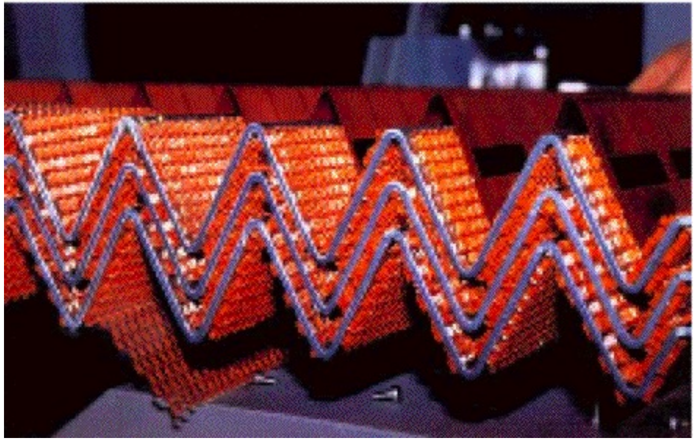


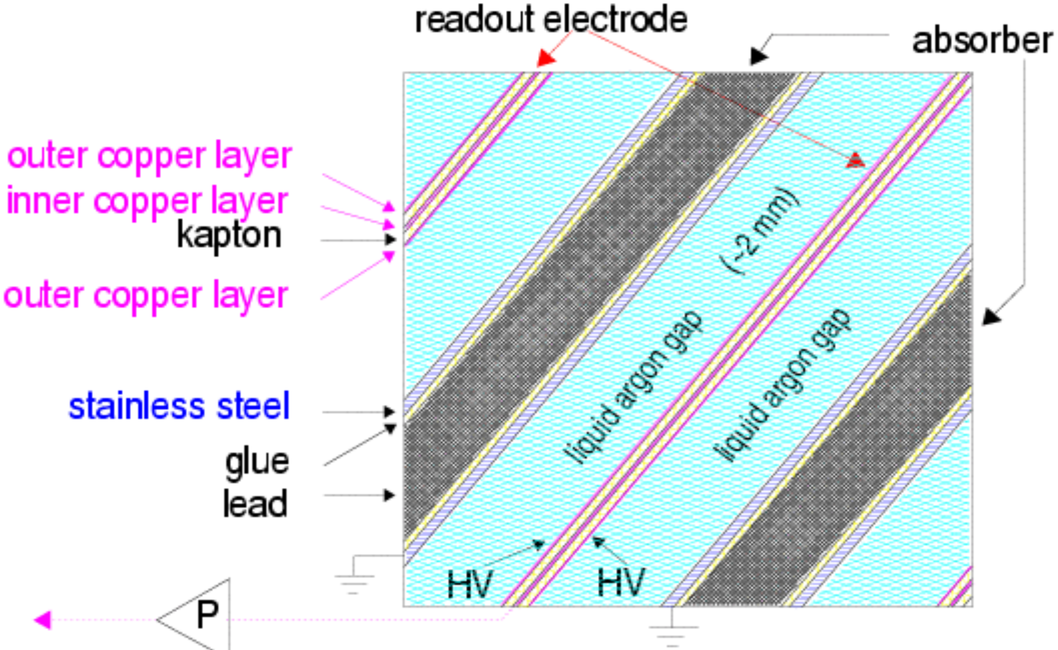
ATLAS LAr EM calorimeter



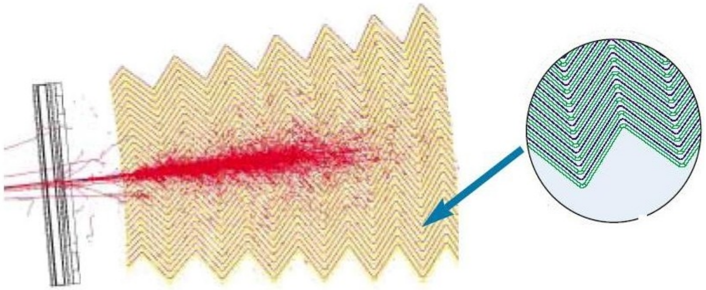


Raw LAr Current Pulse (before amplification and shaping)

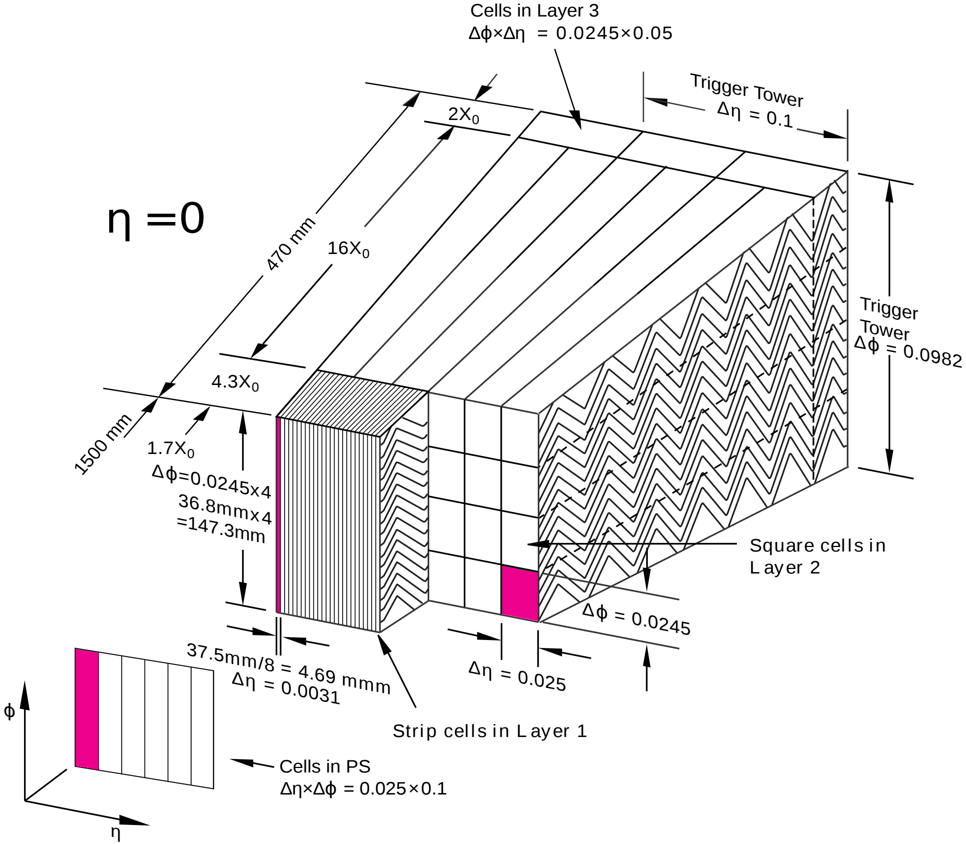




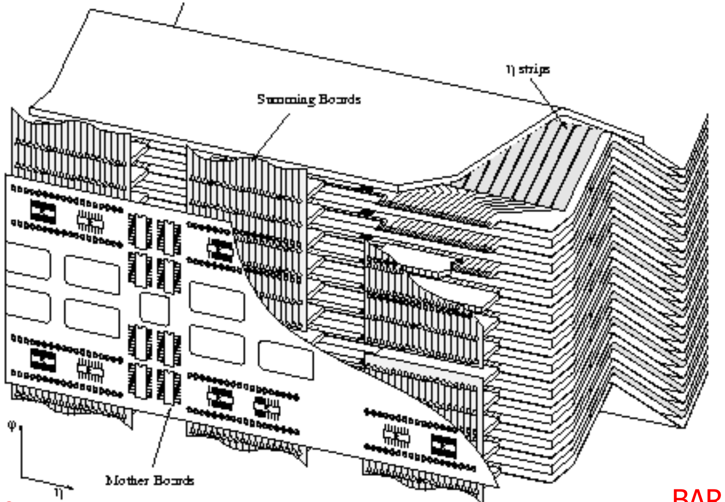
ATLAS LAr EM calorimeter



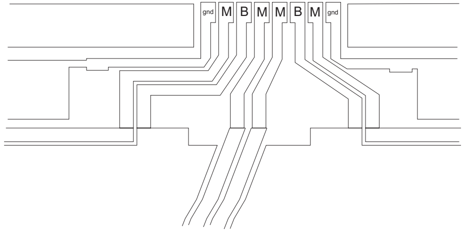
- Longitudinal dimension: 47 cm ~ 25 X_0 (CMS 22 cm)
  - ✓ Pseudorapidity coverage $0 < |\eta| < 3.2$
- Longitudinal segmentation
  - ✓ Strips (~4 X_0): very fine grain in η for π^0 rejections (separation of 2 decay photons)
  - ✓ Middle : ~16 X_0 for shower core containment
  - ✓ Back : ~2 X_0 shower profile, leakage correction
  - ✓ Presampler: ~2 X_0recover energy lost in the upstream material
- High granularity: ~170,000 readout channels
- Electronic calibration only

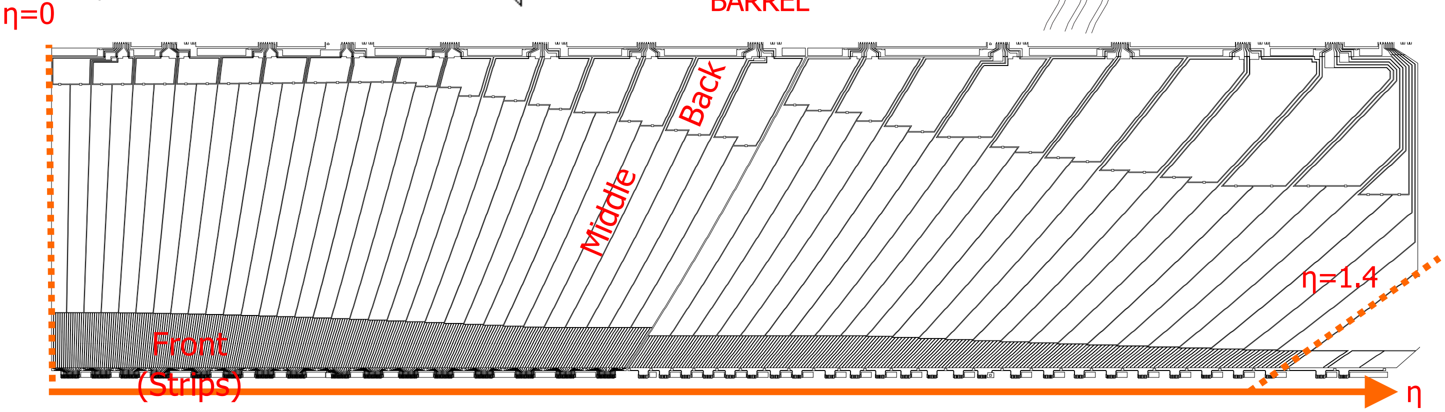


How is ATLAS LAr granularity achieved?



- η: etching of readout electrode
- φ: electrode connection via “summing boards”
- Signal from summing boards collected ”mother board”, where also calibration resistors are located
  - ✓ Signal path: partly on electrode, then SB+MB, then cables





- Readout on front and back minimizes signal path on electrode, adds material in front (cables)
- Accordion structure in ϕ guarantees perfect hermeticity
- Etching on electrodes and readout lines introduce cross-talk and (unexpected) response modulation, to be corrected offline

LAr readout electronics in a nutshell

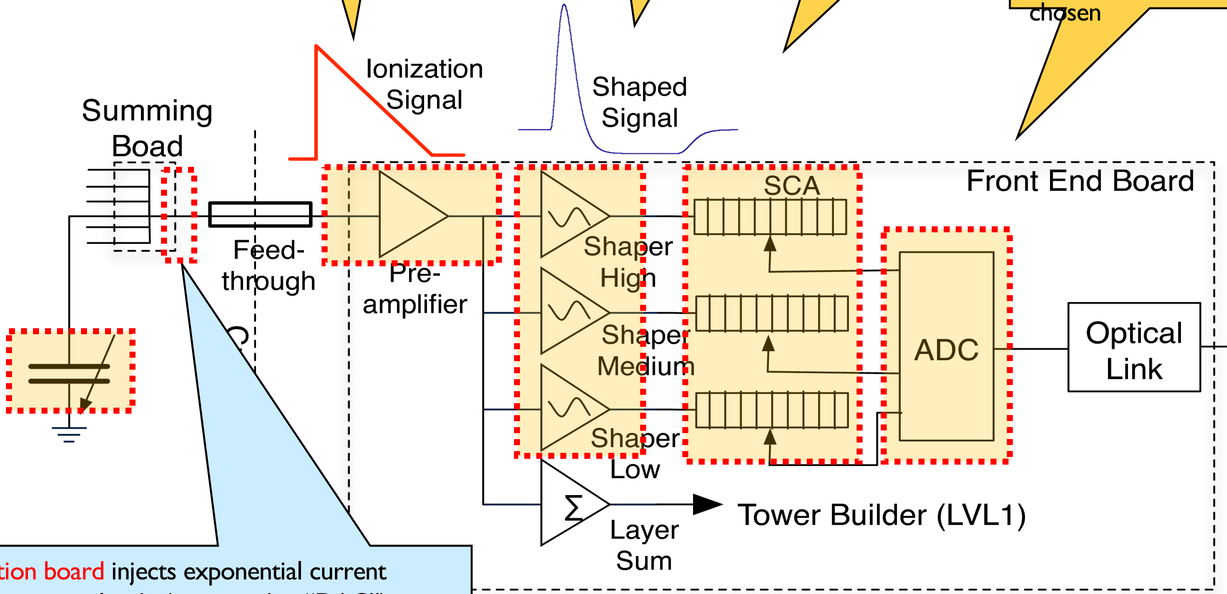
The LAr cell electrodes collect the LAr ionization electrons (that drift in the LAr gap in the electrical field generated by the HV)

The preamplifier amplifies (and integrates) the current signal

The CR-RC2 shaping filter shapes the amplified signal in 3 gains (HIGH, MEDIUM, LOW)

The SCA stores in analogue format the signal samples in 3 gains, waiting for the trigger

Once a trigger accept signal is received, the selected samples are digitized by the 12 bit ADC, then transmitted to the BE electronics. If in "Free" gain (physics), the correct gain is chosen



The calibration board injects exponential current pulses of known amplitude (measured in "DAC") on the detector cell, at the MB level, in order to probe the actual electronic response

- Why CR-RC2 shaper?
  - ✓ Ionization signal too long…
- Why 3 gains 3-gain system (x64, x8, x1)?
  - ✓ Covers MeV to TeV dynamic range
- Why calibration injection only?
  - ✓ LAr response very stable, only electronic potentially drifting

Pros and cons of LAr technology

- Pros
  - ✓ High number of electron-ion pair produced
  - ✓ No strong signal amplification needed, thus lower fluctuations
  - ✓ Liquid → very uniform response
    - But purification needed
  - ✓ Stability with time
  - ✓ Intrinsically radiation hard
  - ✓ Cheap

- Cons
  - ✓ Slow time response ~400 ns
    - Needs signal shaping
  - ✓ Sampling calorimeter
    - Sampling fluctuations
    - Sampling fraction
  - ✓ LAr boiling temperature 87K
    - Cryogenic system needed
  - ✓ Temperature sensitivity
    - -2% signal drop for $\Delta T = 1K$
    - Temperature control

ATLAS LAr EM resolution

JINST 3 (2008) S08003

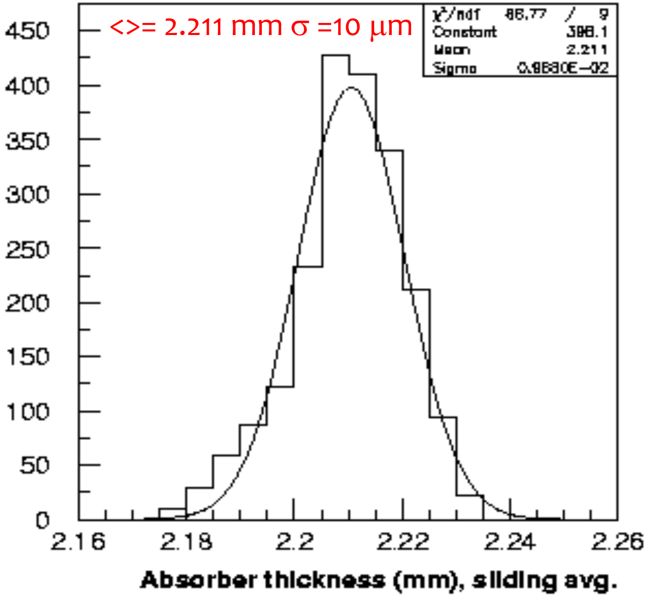
$$\frac{\sigma_E}{E} \simeq \frac{10\%}{\sqrt{E}} \oplus \frac{170\ \mathrm{MeV}}{E} \oplus 0.7\%$$

- Challenge: keep constant term as low as possible
  - ✓ Compromise between technological and physics requirements: c ~ 0.7%
  - ✓ Total constant term $c = c_{local} \oplus c_{LR}$
    - c_{local} = Local contribution to constant term < 0.5% : variation in $\Delta\eta \times \Delta\phi = 0.2 \times 0.4$ (16 x 8= 128 Middle cells), measured in test-beam
      - Absorber and gap thickness variations
      - Modulation of the response in h/f (electrode etching)
      - Accuracy of readout electronic calibration
      - Technological challenge!
    - c_{LR} = Long range variations between sectors
      - Signal dependence on LAr purity, temperature, mechanical deformations…
      - Can be corrected *in-situ* with physics events: intercalibrate with electrons from Z→ee events : 250 electrons in each unit of $\Delta\eta \times \Delta\phi = 0.2 \times 0.4$, 440 such regions in ATLAS. 10^5 Z→ee events (few days @ 1Hz) to achieve $c_{LR} < 0.4\%$

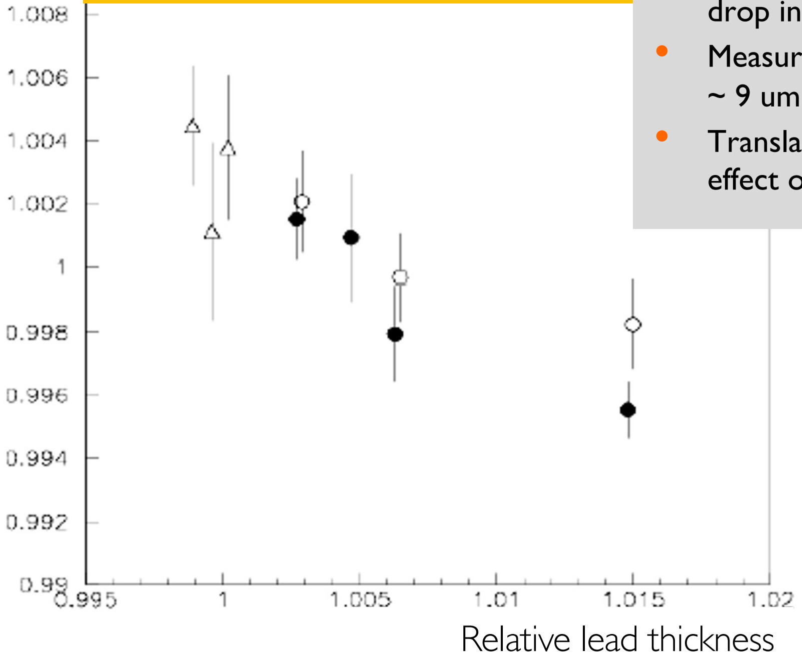
An example of the technological challenge: absorber thickness

- Efforts during construction to produce calorimeter modules as similar as possible: fewer corrections, as small as possible…

Lead thickness distribution

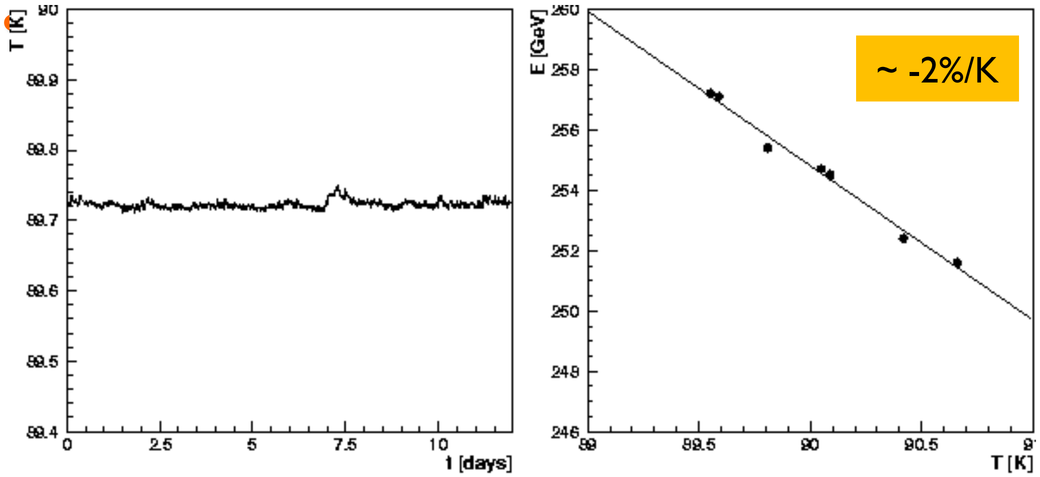

<>= 2.211 mm σ =10 μm

Effect of variation in lead thickness

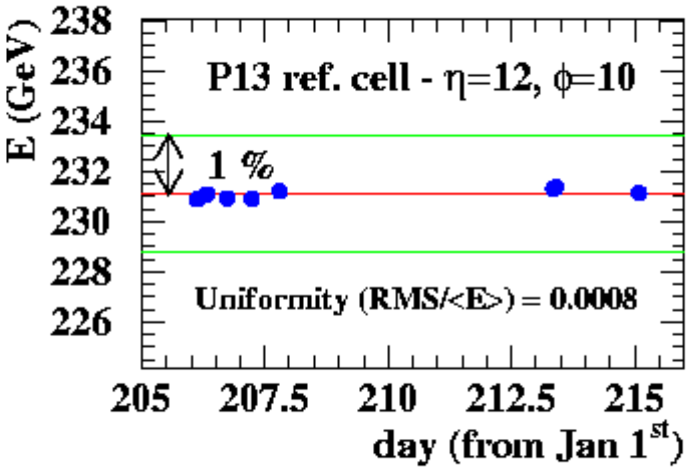


- 1% Pb variation ~ 0.6% drop in response
- Measured dispersion σ ~ 9 um
- Translates to < 2 ‰ effect on constant term

An example of the technological challenge: temperature



~ -2%/K

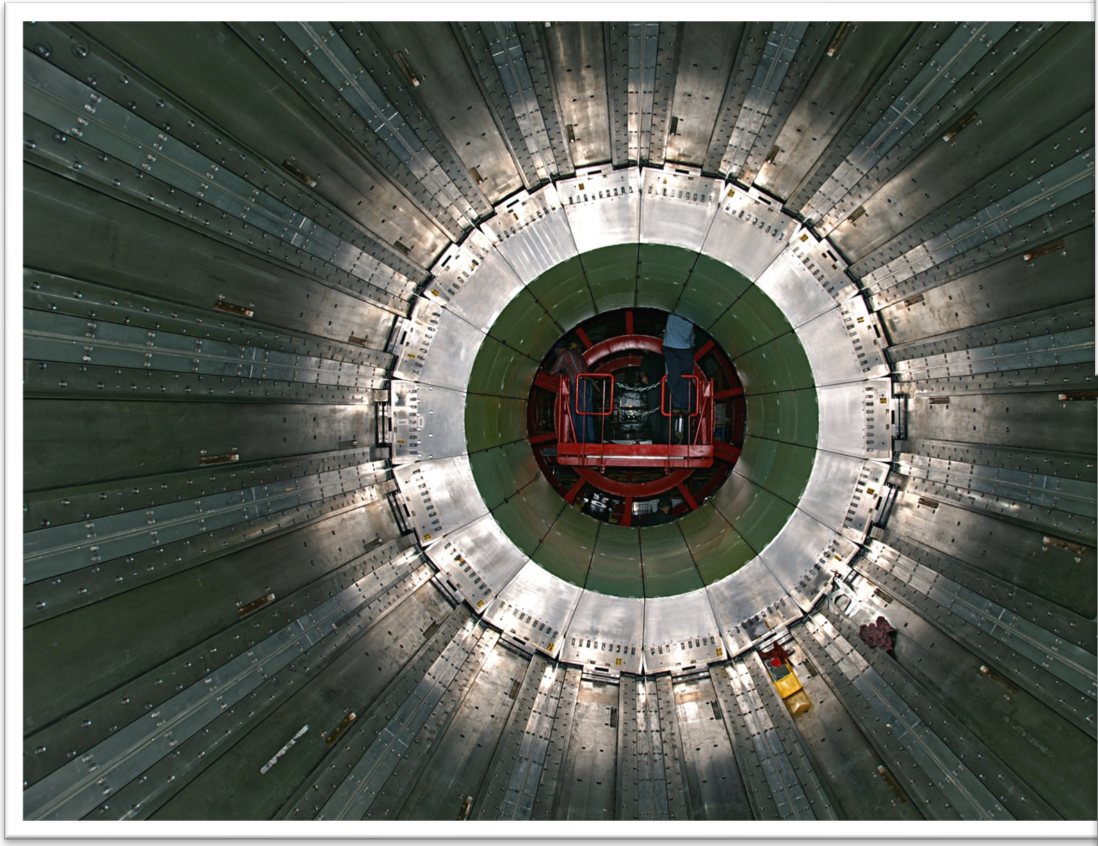


- Measurement of response stability during test-beam to verify cryogenic and purity system
  - ✓ At test-beam, Stability over 10 days ~ 0.08 %

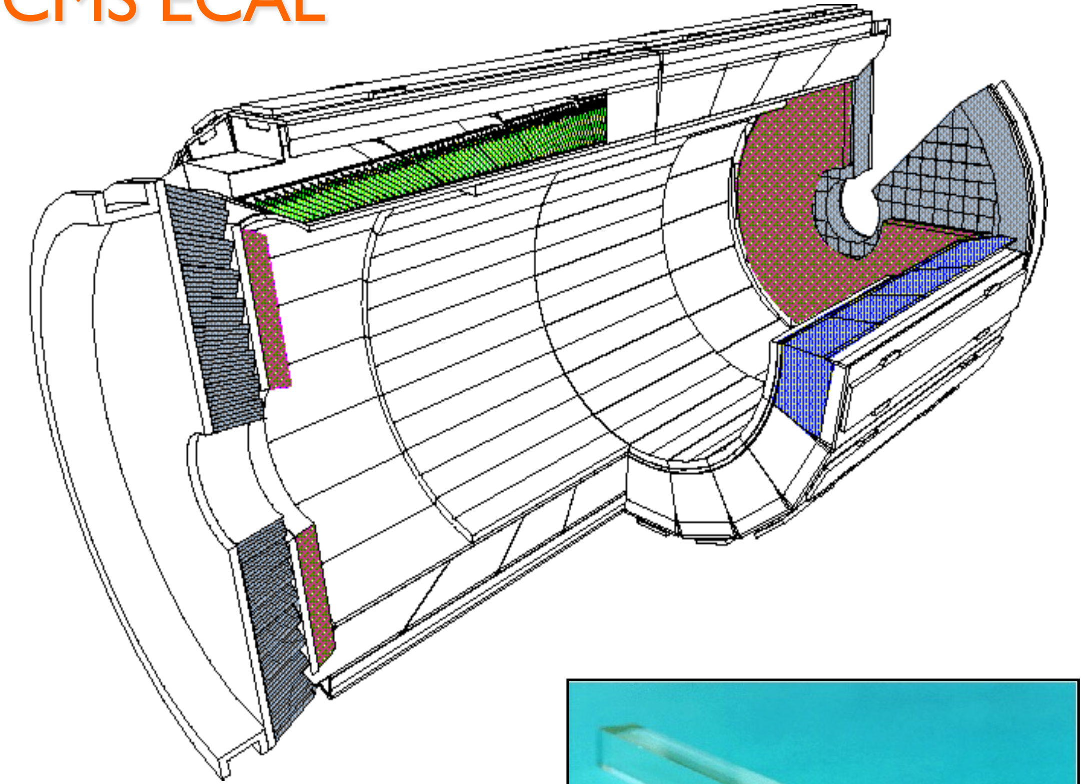
6.2.2

CMS ECAL:
Deep-Dive

CMS ECAL



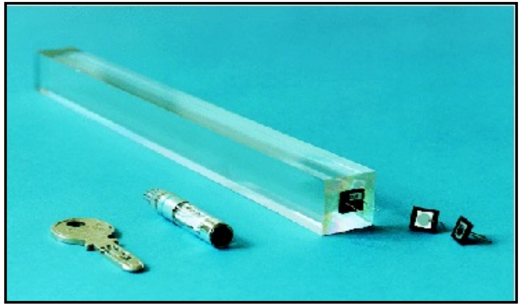
CMS ECAL

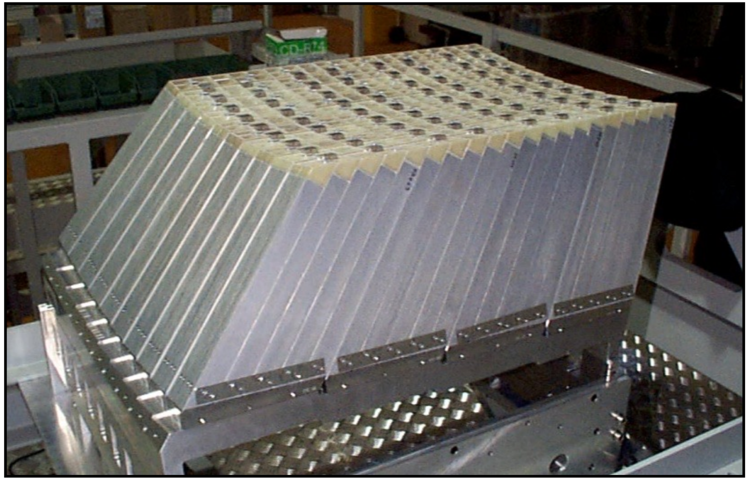


- Depth 25 X_0 = 22.2 cm (compact)
- 1 R_M = 2.2 cm → 95% in 2 R_M

Material	X_0/cm	Ec/MeV	R_M/cm
Fe	1.8	22	1.7
Lead	0.56	7.4	1.6
$PbWO_4$	0.89	8.5	2.2

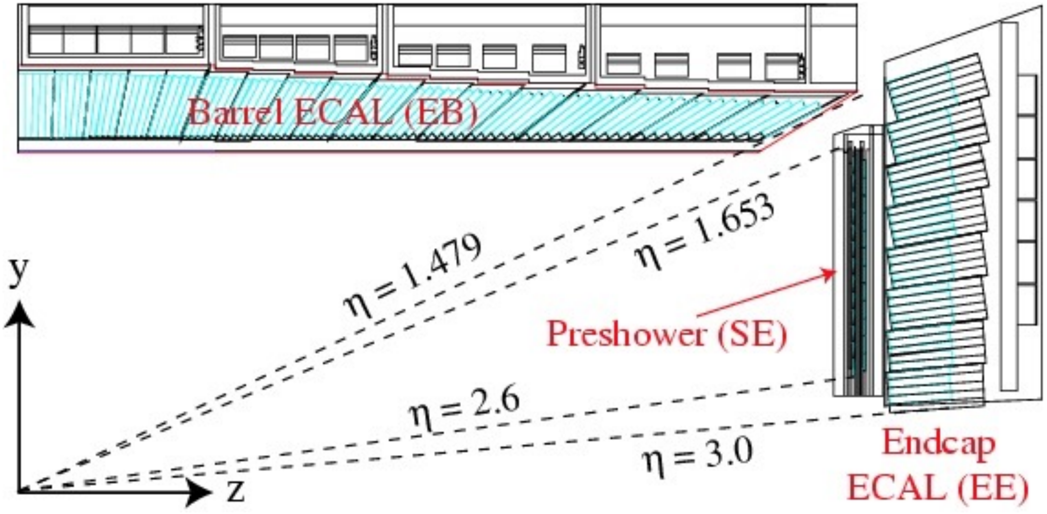
75,848 crystals total
61,200 barrel (EB, |η|<1.48)
14,648 endcap (EE, 1.48<| η |<3.0)

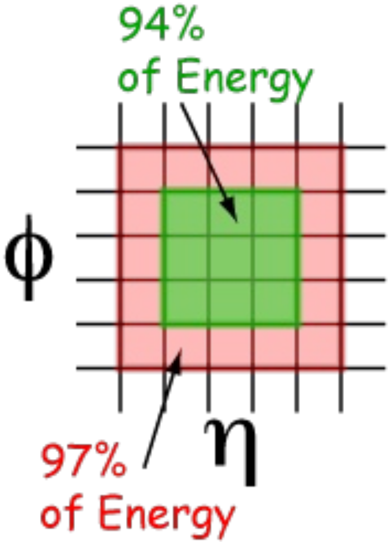


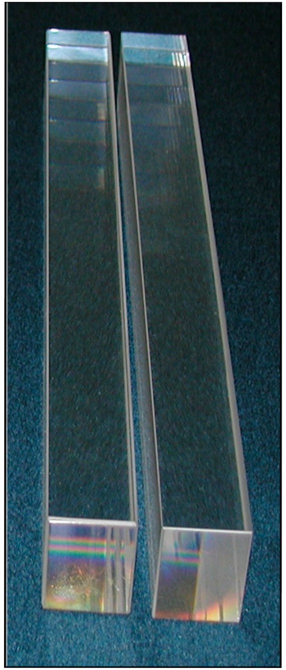


CMS ECAL

- Where ATLAS approaches hermeticity with accordion folds and projectivity with electrode etching, CMS solves both with homogeneous crystal + off-pointing tilt

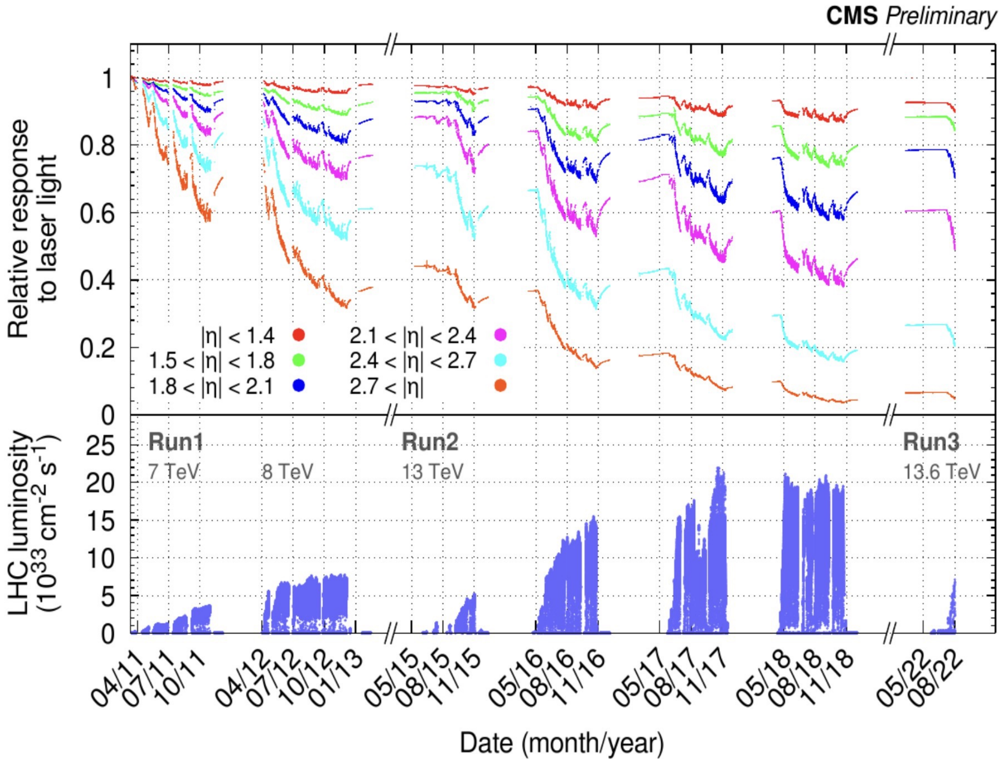




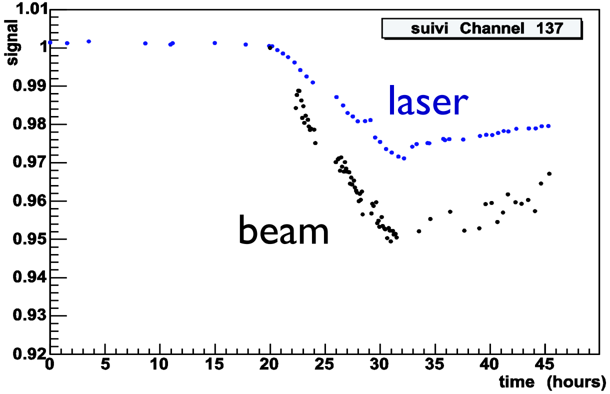


CMS ECAL APD readout and laser monitoring

- APD readout in EB (higher B field), VPT readout in EC (lower B field, higher radiation)
- Laser monitoring needed because of crystal transparency loss vs radiation and response drift in time



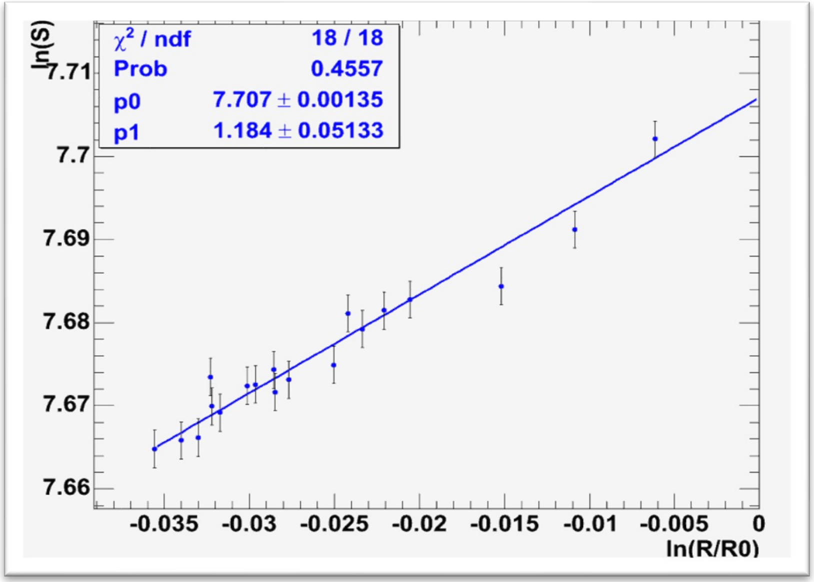
- ✓ PbWO4 crystal transparency reduced by radiation damage
- ✓ Damage level reaches equilibrium after a small administered dose
- ✓ Partial damage recovery in few hours
- ✓ Loss in extracted light of few % is tolerable and can be followed at the level of better <0.5% by a laser monitor system between two adjacent calibration with physics

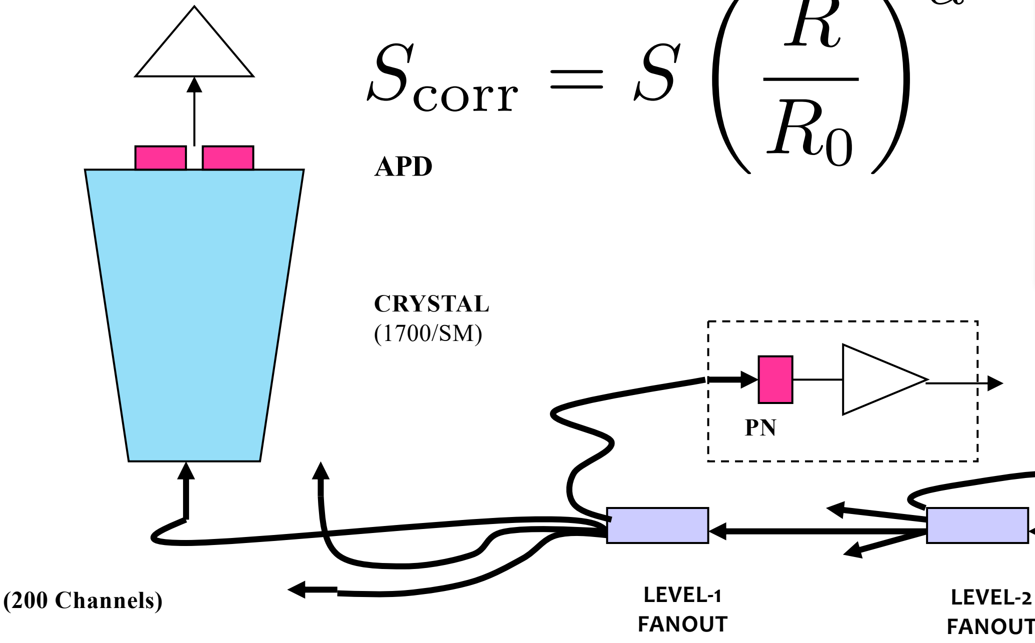


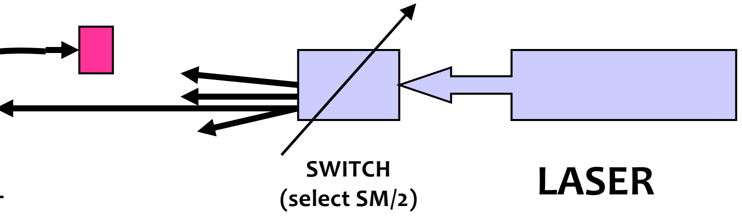
CMS ECAL laser monitoring

- Relation expected between S (beam signal) and R (laser signal): laser monitor provides good compensation
  - ✓ Laser light injection: λ = 440 nm and 500 nm
  - ✓ 1/140 (80 Hz) beam gaps on 850 crystals → Full ECAL barrel pulsed in ~15’

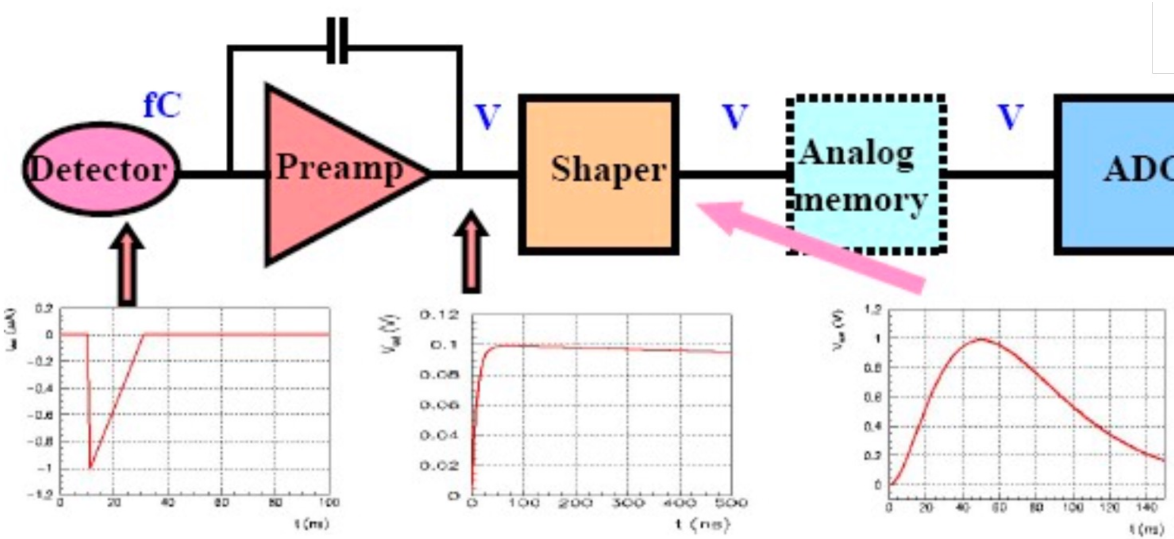
$$S_{\mathrm{corr}} = S\left(\frac{R}{R_0}\right)^{\alpha}$$

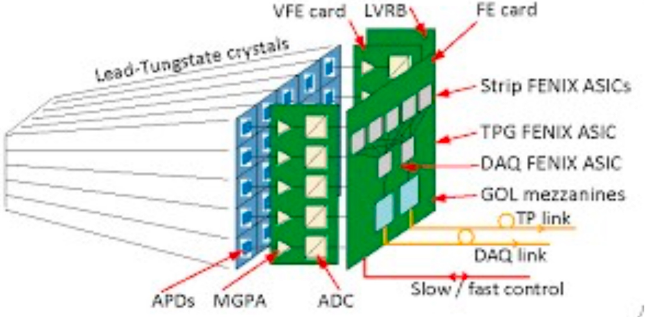






CMS ECAL readout electronics in a nutshell





- Located as close as possible to the detector
  - ✓ Contrary to ATLAS, where ECAL electronics is outside cryostat
- Signal chain: APD current → MGPA (Multi-Gain Pre-Amplifier, 3 parallel gain channels x12/x6/x1) → 12-bit ADC per channel → effective ~16-bit dynamic range.
  - ✓ Identical philosophy to ATLAS 3-gain LAr readout: cover low-energy electrons up to 2 TeV jets with single front-end

Pro and cons of $PbWO_4$ technology

- Pros
  - ✓ Shortest X_0 (0.89 cm) and R_M (2.2 cm) of any practical scintillator
    - Full 25.8 X_0 containment within the tight CMS solenoid radial budget
  - ✓ Fast scintillation (~25 ns) compatible with 25 ns LHC bunch spacing
    - Reduced out-of-time pileup impact
  - ✓ Overall Excellent energy resolution

- Cons
  - ✓ Very low light yield
    - ~100 photons/MeV at room temperature
  - ✓ Radiation damage
    - Mechanism: hadronic irradiation creates colour centres (F-centres, impurity complexes) in PbWO4 lattice that absorb scintillation photons before they reach APD (optical transmission loss)
  - ✓ Temperature dependence
    - Crystal light yield has dLY/dT ~-2%/C
    - APD gain has dM/dT ~-2.4%/C
    - Combined: -4%/C total response drift
    - Cooling must stabilise T to +/-0.05 C

CMS ECAL EM resolution

JINST 8 (2013) P09009

$$\frac{\sigma_E}{E} \simeq \frac{3\%}{\sqrt{E}} \oplus \frac{120\,\mathrm{MeV}}{E} \oplus 0.3\% \text{ @ test-beam}$$

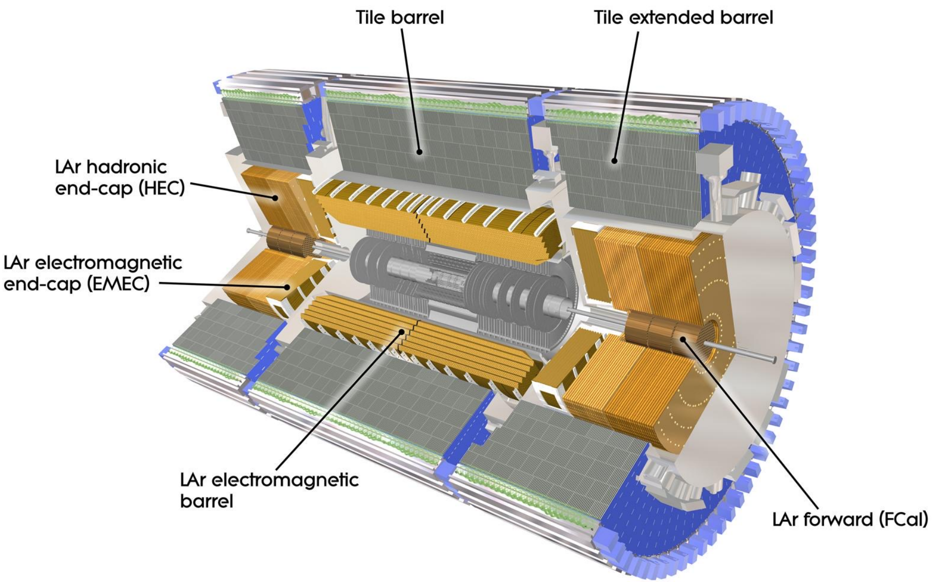
- Challenge: replicate test-beam performance (no B filed, no radiation) in LHC conditions…
  - ✓ c_{local} = 0.3%
  - ✓ Additional contributions → back of the envelope sum c_{total} ~ 0.56-0.7% in Barrel
    - Barrel
      - Intercalibration Uncertainty: ~ 0.3% in central region (|η|<1.0) ~ 0.5% rest of barrel (1.0<|η|<1.48)
      - Laser Monitoring ~ 0.3% to the resolution.
      - Residual Instabilities: ~ 0.12%
    - Endcaps
      - Intercalibration Uncertainty: 1-1.5% depending on |η| region
      - Laser Monitoring: ~1.5% on average (0.5% at |η|~1.6 tp 2.5% at |η|~2.5)
      - Residual Instabilities: ~ 0.35%
    - Temperature and High Voltage: < 0.2%

6.2.3

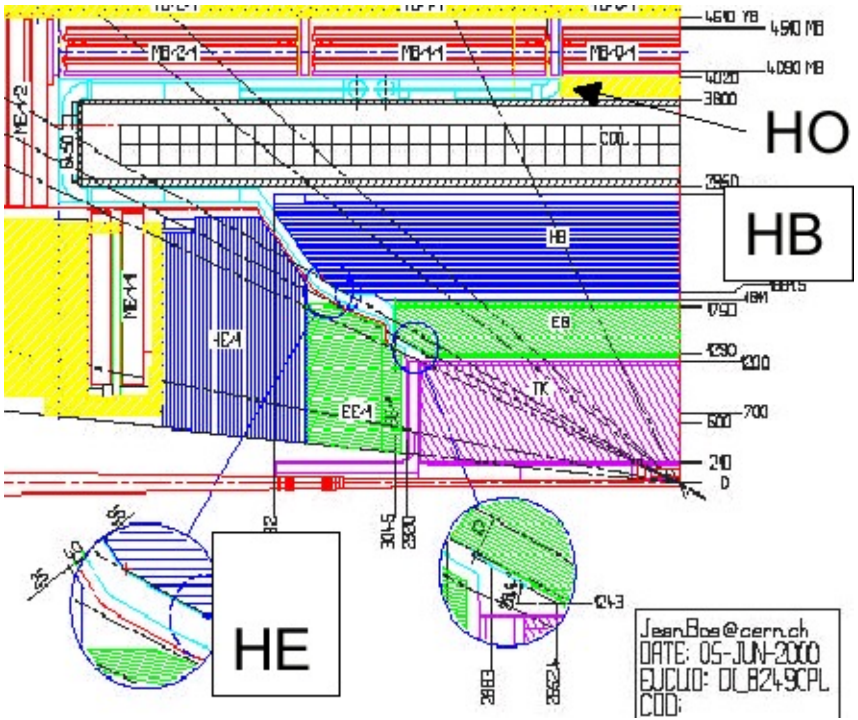
ATLAS TileCal & CMS HCAL: Design Choices

ATLAS TileCal & CMS HCAL: absorber choices

- Why iron for ATLAS TileCal?
  - ✓ HCAL sits outside solenoid

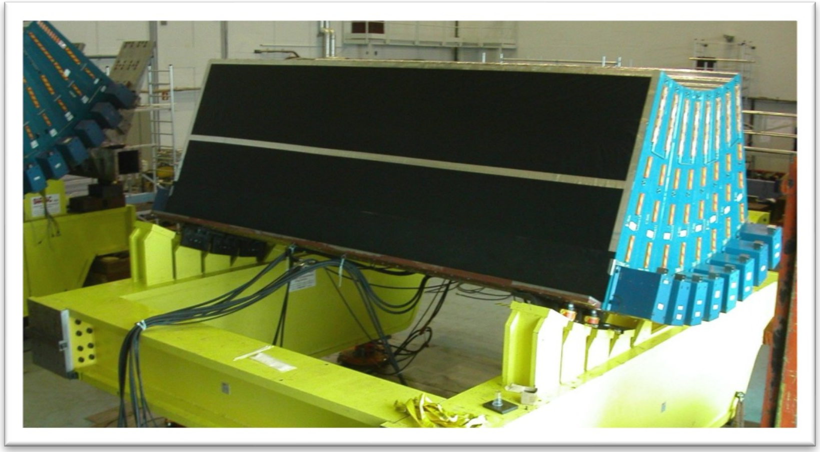


- Why brass for CMS HB?
  - ✓ Solenoid encloses ECAL+HCAL → fixed radial budget

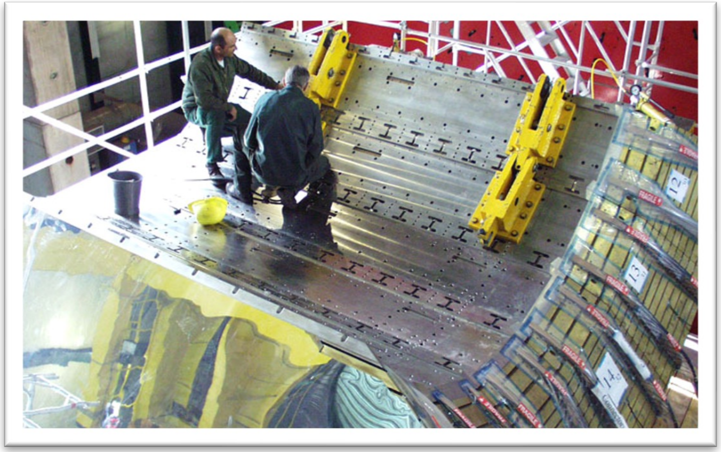


ATLAS TileCal & CMS HCAL: absorber choices

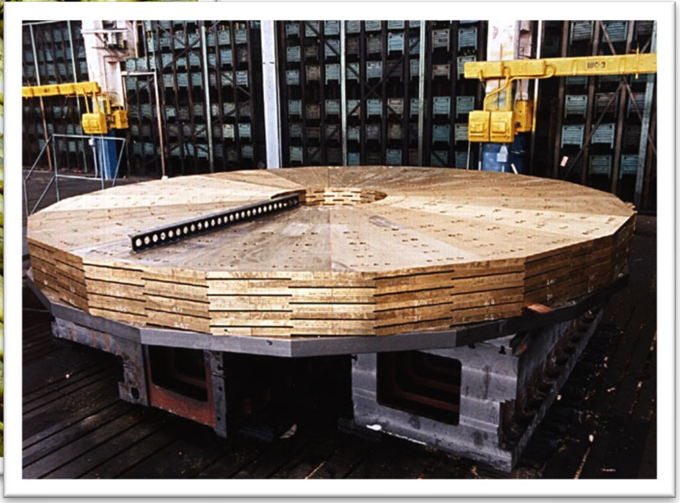
- Why iron for ATLAS TileCal?
  - ✓ HCAL sits outside solenoid
    - No B-field constraint
    - Leaves enough room for full HCAL without needing "tail-catcher" (additional HCAL layer after material)
  - ✓ Iron
    - Cheap, non-magnetic, easy to machine
    - λ_{int} ~ 16.8 cm
  - ✓ Cost and scale dominate absorber choice



- Why brass for CMS HB?
  - ✓ Solenoid encloses ECAL+HCAL → fixed radial budget
  - ✓ Brass (70% Cu + 30% Zn)
    - Denser than Fe, non-magnetic, machinable
  - ✓ But… HB alone reaches only ~5.8 λ_{int} (insufficient for full hadronic containment)
    - Consequence: CMS needed to add outer "tail-catcher" (HO) outside solenoid using iron return yoke, reaching ~11 λ_{int} total

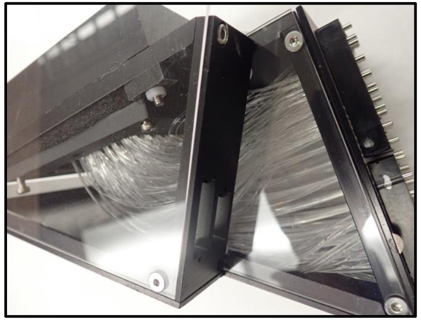


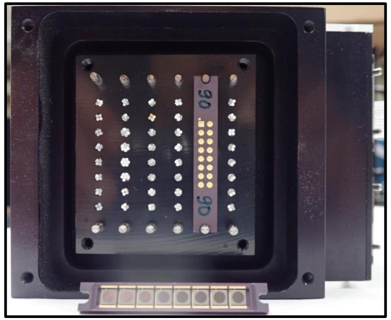
CMS HE brass absorbers

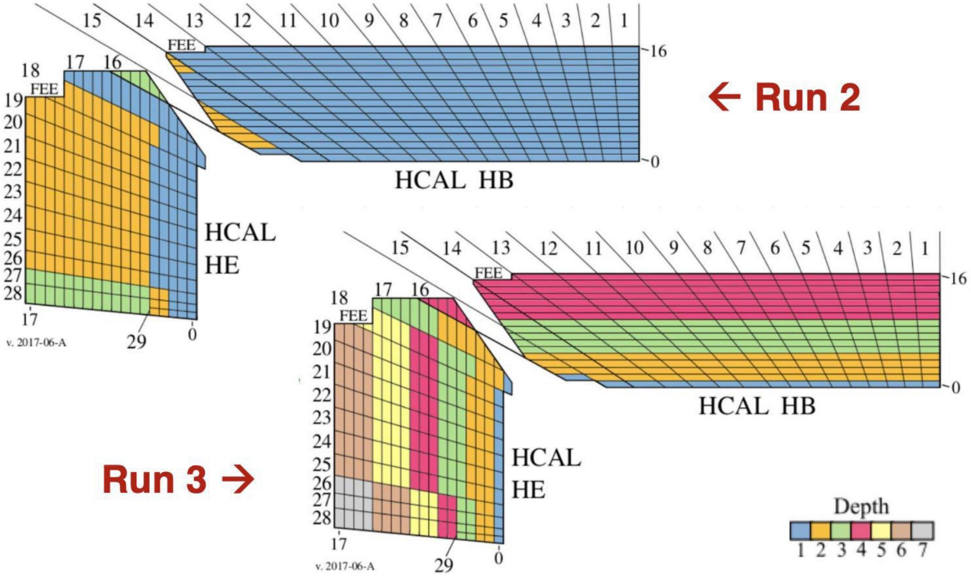


Other consequences of HCAL positioning

- Solenoid enclosing CMS ECAL+HCAL led to CMS HCAL SiPM upgrade
  - ✓ Original HPD readout was best choice in 2000
    - PDE ~12%, gain ~2000, fast, large dynamic range, low radiation sensitivity
  - ✓ But…
    - HPD B-field-sensitive, saturated at high occupancy, internal discharge noise, gain per PDE too small for thin layers of scintillator, device size limited channel count (depth segmentation)
- Replaced with SiPMs in ~2020 (Phase I upgrade)
  - ✓ SiPMs are B-field immune
  - ✓ ~16k pixels/device, single-γ sensitive → better granularity, trigger
  - ✓ HL-LHC ready







← Run 2

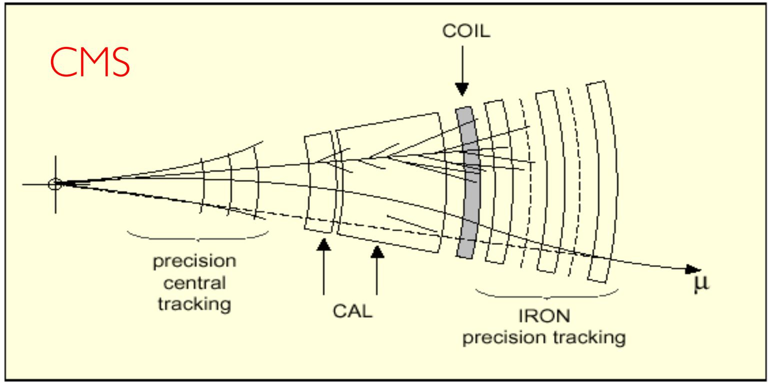
Run 3 →

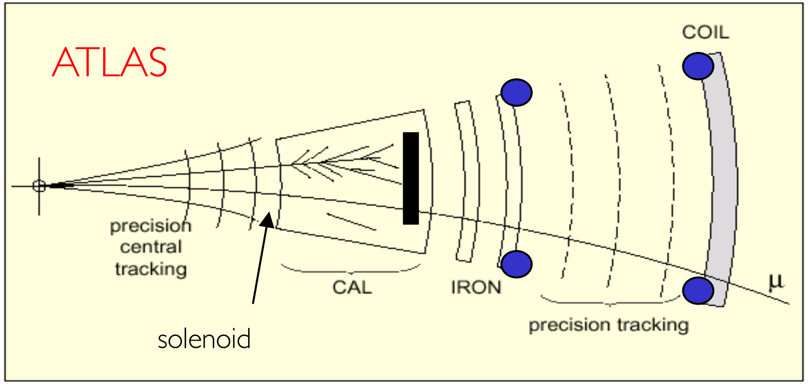
6.3

Design Principles & Considerations

Solenoid placement: a fundamental design choice

	EM calo INSIDE solenoid (CMS)	**EM calo OUTSIDE solenoid (ATLAS)**
	Solenoid encloses tracker + ECAL + HCAL barrel	**solenoid (2 T) surrounds only tracker; LAr EM calorimeter is outside the solenoid.**
Advantages	Optimal EM energy resolution (no material before ECAL) μ spectrometer uses solenoid return flux: only 1 (big) magnet	Same cryostat for solenoid and ECAL HCAL has more radial room (TileCal ~9.7 λ_{int}) PMT readout feasible for TileCal Air toroid for μ spectrometer: optimal μ momentum resolution
Constraints	strong solenoid (3.8 T) must be large and heavy HCAL barrel is thin (only ~5.8 λ_{int} for HB alone → needs HO outside coil) APD readout required because ECAL inside B field.	solenoid material before ECAL → dead material → presampler limited EM energy resolution lower B field → softer p_T threshold four magnets in total!





Main design ideas for a EM calorimeter

- **ECAL should stop electrons and photons BUT NOT hadrons**
  - ✓ Small radiation length X_0 to reduce ECAL size
  - ✓ Large interaction length λ_{int} to reduce probability of hadron interaction in ECAL
  - ✓ Ratio between λ_{int} and X_0 can be up to ~30 for high-Z materials
    - Can be fruitfully used to distinguish between EM and Hadronic showers

- **Get good sampling of particles in shower to get good statistical sampling of energy**
  - ✓ Ideally homogeneous calorimeter
  - ✓ If sampling calorimeter, optimize f_{samp} and active layer depth to get best possible resolution sampling term

EM calorimeter size and granularity

- **Size**
  - ✓ dictated by dominant X_0
  - ✓ driven by the required resolution (% of longitudinal leakage at target energy range)

- **Cell lateral dimension**
  - ✓ Defines as 70-80% of energy of a centrally incoming particle is deposited in a single cell, while having energy in the neighboring cells large enough to measure the center of gravity coordinates

- **Granularity**
  - ✓ Needed to separate showers induced by nearby particles
  - ✓ Achievable angular separation limited by the lateral size of the shower (R_M) and by distance of the calorimeter from the interaction point
  - ✓ Lateral segmentation determines possibility to correlate calorimeter information with charged tracks measured by tracker

Detector hermeticity and η coverage

- **Hermeticity**
  - ✓ Calorimeter system is hermetic if it captures essentially all energy from the hard scatter, leaving no uninstrumented "holes"
- **Coverage requirements: |η| ~ 5 for LHC**
  - ✓ Requires dedicated forward calorimeters (ATLAS FCal, CMS HF) operating in extremely high radiation and particle flux.
  - ✓ Forward region also dominates total cross-section (~80% of pp inelastic activity in |η| > 3)
- **Projective geometry**
  - ✓ Cells are organized in η-ϕ towers projecting back to the IP, so that energy can be summed coherently across depth layers
  - ✓ Sets the tower granularity and the cell aspect ratio throughout the detector.
- **Crack regions**
  - ✓ Unavoidable gaps between barrel and endcap, and between different sub-systems
  - ✓ ATLAS and CMS both have known "crack" regions at η ~ 1.4-1.6 where resolution degrades
    - Excluded in precision physics analyses, corrected with dedicated MC modelling

Signal collection

- **“Light” calorimeters**
  - ✓ Optimize light collection chain
  - ✓ Length of sensitive material needs be compatible with light transmission properties and light attenuation length
  - ✓ Light output should be uniform along the length of the crystal

- **“Charge” calorimeters**
  - ✓ Signal length determined by gap thickness: compromise between impact on f_{samp}, Landau fluctuations and impact on resolution
  - ✓ Increasing HV can shorten signal, at the cost of possible discharges and instability
  - ✓ Signal will anyway be O(100 ns) in any practical configuration, require shaping
  - ✓ Location of readout electronics: can be close to signal generation (cold, low noise, reduce service, but difficult to maintain) or farer (thus cables, reflection and attenuation, …)

Properties of active layer in sampling calorimeters

- In absorption processes dominating in EM and HAD shower **most of energy deposited by very soft shower particles, yielding isotropic angular distribution of the shower particles**
  - ✓ **Orientation of active layers in sampling calorimeters does not matter much!**

- **Typical EM shower particle = ~1 MeV electron**
  - ✓ **Range very short (<1 mm in typical absorber materials)**
  - ✓ Such range set scale for useful sampling frequency of EM showers

- **Typical HAD shower particles = 50-100 MeV spallation protons + 3 MeV neutrons**
  - ✓ **Range of protons ~1 cm**
  - ✓ This set the scale for useful sampling frequency in hadron calorimeters
  - ✓ Neutrons travel several cm → Important when active medium has a high probability of interaction (Hydrogen for compensating calorimeter)

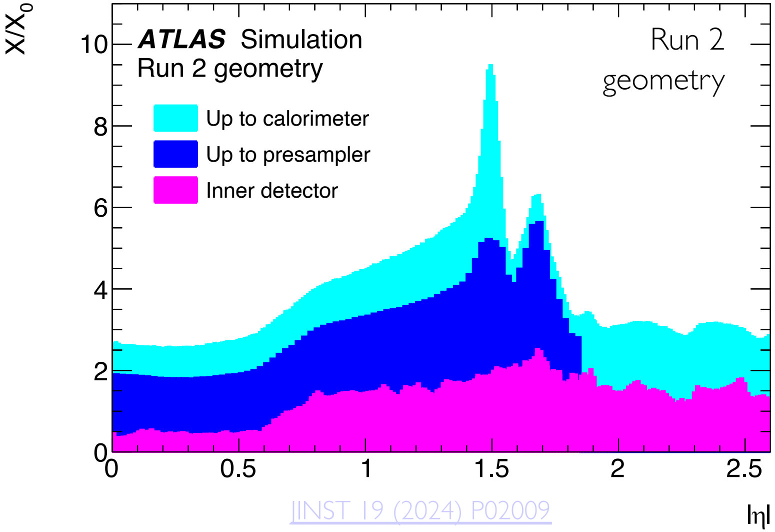
Fluctuations

- A variety of fluctuation sources contribute to the energy resolution
  - ✓ **However, usually one of these sources dominates!**
  - ✓ In the design of a calorimeter one should not waste money reducing fluctuation sources that do not dominate!
  - ✓ **It is very important to understand which contribution is dominant in the energy range of interest, to come out with the optimal calorimeter design**
  - ✓ *Example*
    - *Light yield of quartz-fiber detectors typically so small that signal fluctuations (photoelectron statistics) are dominant*
    - *In this case, no much gain in increasing sampling frequency by using more thinner fibers instead of fewer thick ones*

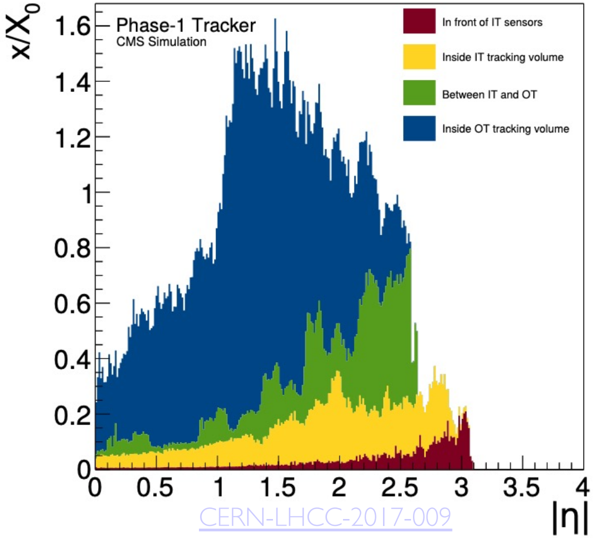
- Position of the supporting structure has big impact on the calorimeter performance
  - ✓ Performance is least affected when structural elements are placed directly upstream of the sensitive detector volume, perpendicular to the direction of the incoming particles (same traversed material regardless of the incoming direction)

“Dead” (upstream) material vs. energy resolution

- Particles traverse material (e.g. from tracking devices) before reaching active part calorimeter: **energy losses most important for electrons and photons**
- Ideally, minimum material budget in front of ECAL
  - ✓ Material: Inner detectors + solenoid coil (if before calo) + calo support structures + services
  - ✓ ATLAS and CMS material ~ 0.1-0.5 X_0 at η=0, up to 1-2 X_0 at |η|~2
- *Average* energy lost by electrons and photons in upstream material can be determined and corrected for, **event-by-event fluctuations cannot → Additional contribution to the energy resolution**



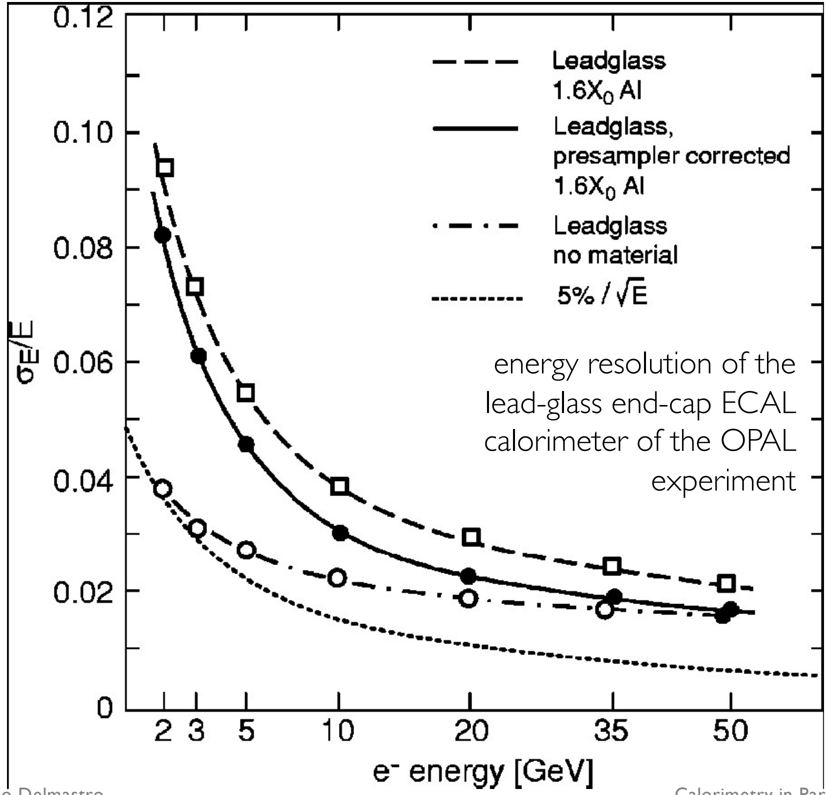
JINST 19 (2024) P02009



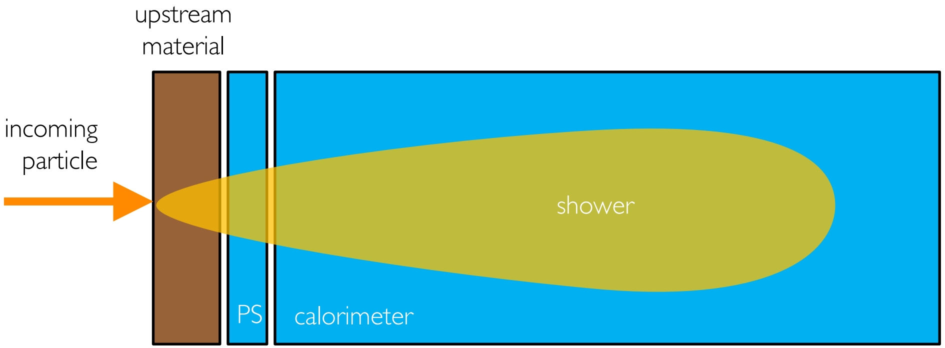
CERN-LHCC-2017-009

Pre-sampler strategy

- If upstream material <2.5-3 X_0 acceptable recovery of energy resolution due to dead material possible by using **massless gaps and pre-sampler detectors**



energy resolution of the lead-glass end-cap ECAL calorimeter of the OPAL experiment

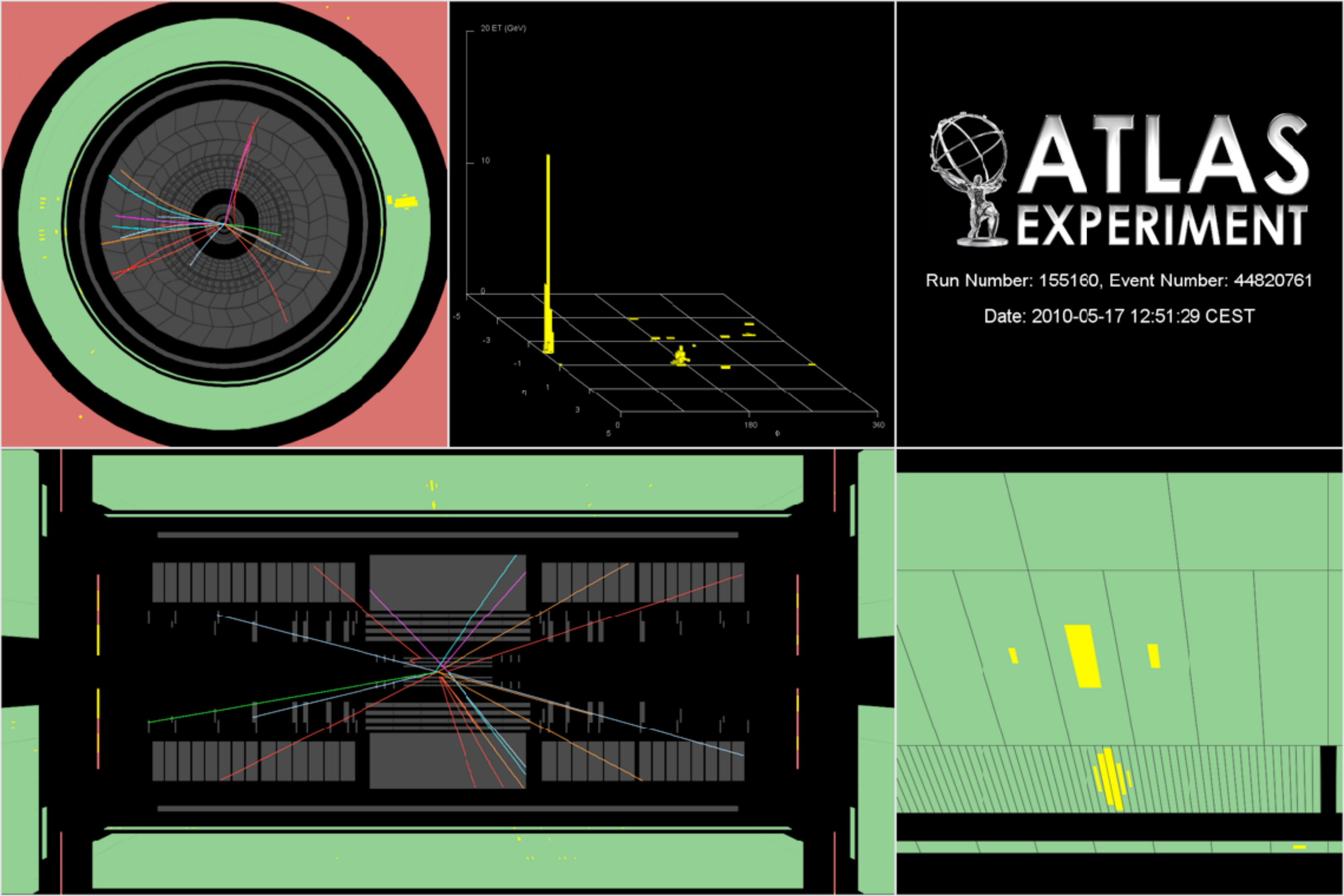


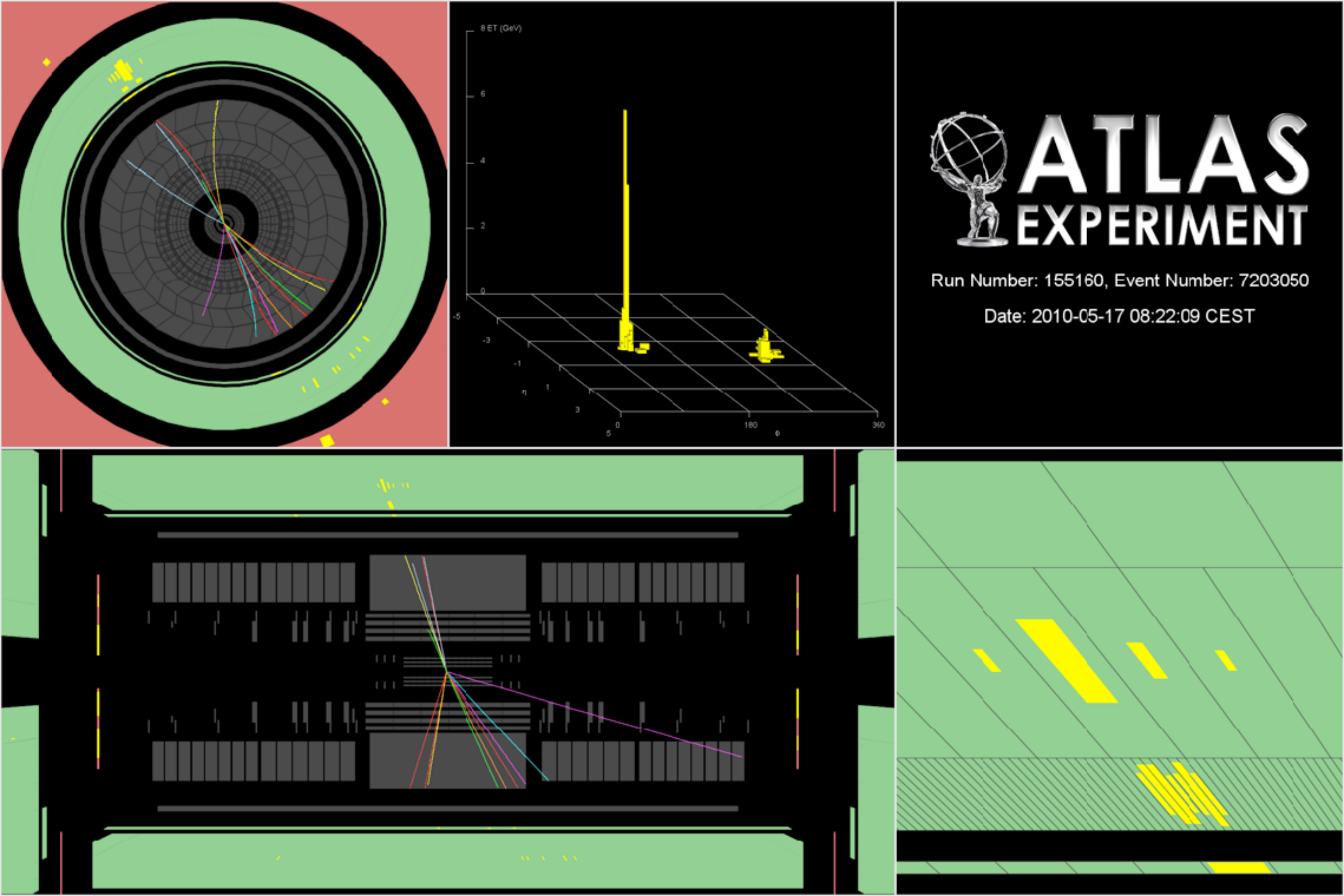
Energy released by incident particles in PS devices proportional to energy lost upstream
By adding the energy collected (suitably weighted) to energy measured in calorimeter, possible to recover energy losses event-by-event

Longitudinal segmentation and shower profile exploitation

- Longitudinal shower profiles differ between EM and HAD showers, and between electrons, photons, pions, and jets. Longitudinal sampling provides shape information needed for
  - ✓ e/γ identification: for relevant energies EM shower peaks near 6 X_0 and is completely contained by 25 X_0; HAD shower starts later and extends deeper → shower maximum depth distinguishes them
  - ✓ γ/**π**^{0} discrimination: two nearby photons from **π**^{0} can mimic single photon in first layer; fine transverse granularity in first sampling (e.g. ATLAS strip layer, 4 mm in η) designed to resolve these
  - ✓ HAD shower leakage estimation: last HCAL depth sampling flags punch-through; feeds into jet energy corrections.

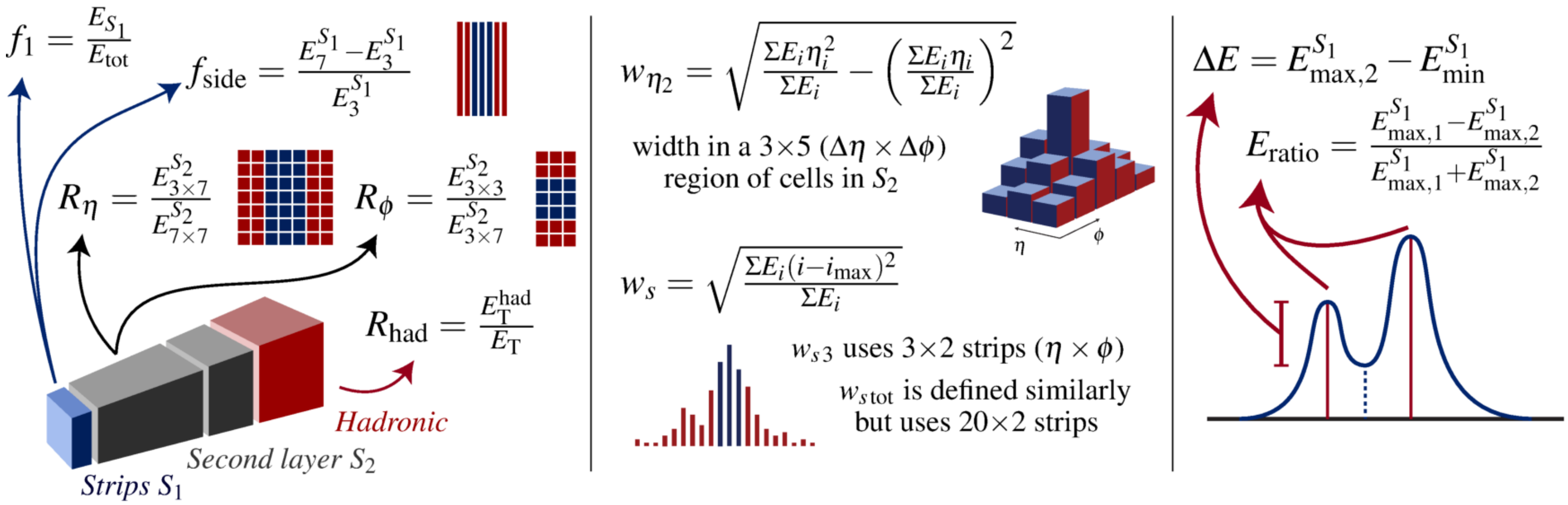
CMS	**ATLAS**
no longitudinal EM segmentation relies entirely on fine transverse granularity ($\Delta\eta \times \Delta\phi \sim 0.0174 \times 0.0174$) and tracker for EM/HAD separation, **π**^{0} rejection and photon direction measurement	3 EM samplings (strips / middle / back) + presampler 3 HAD samplings in TileCal EM Strips give ~4 mm η granularity for **π**^{0} rejection and photon direction measurement independent of tracker


20 ET (GeV)
10
0
-5
-3
-1
η
1
3
5
0
180
360
ϕ
ATLAS
EXPERIMENT
Run Number: 155160, Event Number: 44820761
Date: 2010-05-17 12:51:29 CEST



Run Number: 155160, Event Number: 7203050

Date: 2010-05-17 08:22:09 CEST



$$f_1 = \frac{E_{S_1}}{E_{\text{tot}}}$$

$$f_{\text{side}} = \frac{E_7^{S_1} - E_3^{S_1}}{E_3^{S_1}}$$

$$R_\eta = \frac{E_{3\times7}^{S_2}}{E_{7\times7}^{S_2}}$$

$$R_\phi = \frac{E_{3\times3}^{S_2}}{E_{3\times7}^{S_2}}$$

$$R_{\text{had}} = \frac{E_{\text{T}}^{\text{had}}}{E_{\text{T}}}$$

Hadronic

Second layer S_2

Strips S_1

$$w_{\eta_2} = \sqrt{\frac{\Sigma E_i \eta_i^2}{\Sigma E_i} - \left(\frac{\Sigma E_i \eta_i}{\Sigma E_i}\right)^2}$$

width in a 3×5 ($\Delta\eta \times \Delta\phi$)
region of cells in S_2

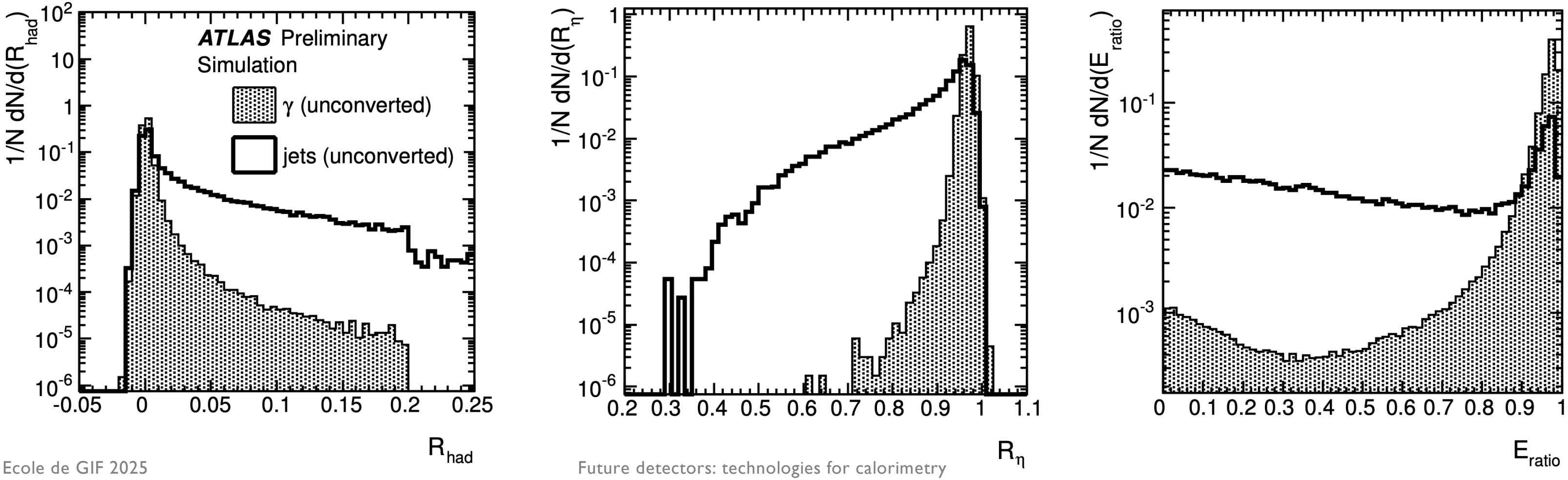
$$w_s = \sqrt{\frac{\Sigma E_i (i - i_{\max})^2}{\Sigma E_i}}$$

$w_{s\,3}$ uses 3×2 strips ($\eta \times \phi$)

$w_{s\,\text{tot}}$ is defined similarly
but uses 20×2 strips

$$\Delta E = E_{\max,2}^{S_1} - E_{\min}^{S_1}$$

$$E_{\text{ratio}} = \frac{E_{\max,1}^{S_1} - E_{\max,2}^{S_1}}{E_{\max,1}^{S_1} + E_{\max,2}^{S_1}}$$



ATL-PHYS-PUB-2011-007

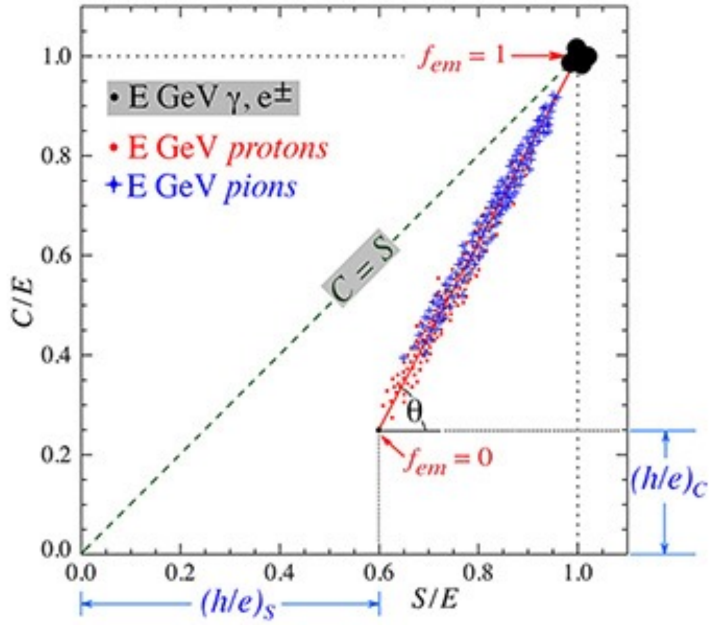
6.4

Beyond hardware compensation:

Dual Readout & Particle Flow

Beyond hardware compensation: dual readout calorimeter

- **Idea: measure f_{EM} directly exploiting**
  Cerenkov vs Scintillation light
  - ✓ Electrons in hadronic shower are relativistic down to 200 keV → Cerenkov
  - ✓ Most non-EM energy in hadronic shower from protons from nuclear reaction → Scintillation
- Advantages
  - ✓ No need for high Z absorber (e.g. Cu has e/mip ~0.86)
  - ✓ Can select any sampling fraction
  - ✓ Method does not rely on measuring neutrons (smaller volume, faster integration time)



$$S = E\left[f_{\rm em} + \frac{1}{(e/h)_S}(1 - f_{\rm em})\right]$$

$$C = E\left[f_{\rm em} + \frac{1}{(e/h)_C}(1 - f_{\rm em})\right]$$

$$f_{\rm em} = \frac{(h/e)_C - (C/S)(h/e)_S}{(C/S)[1-(h/e)_S] - [1-(h/e)_C]}$$

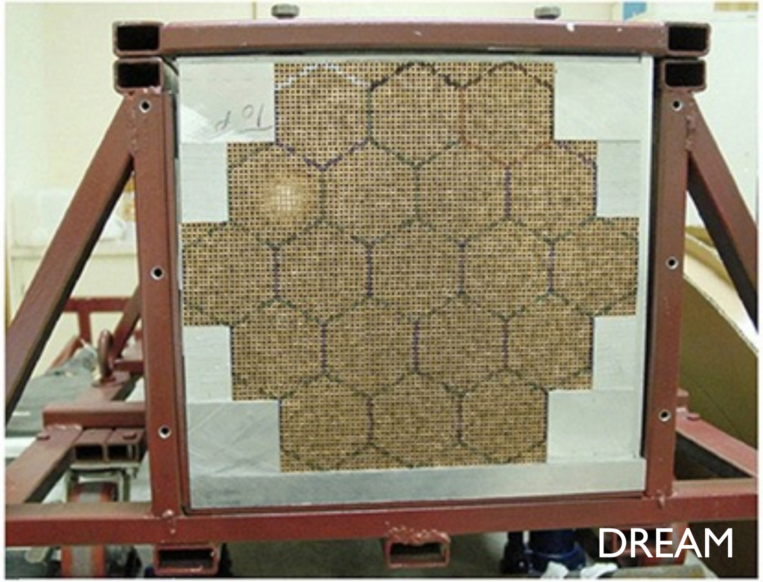
$$\cot\theta = \frac{1-(h/e)_S}{1-(h/e)_C} = \chi$$

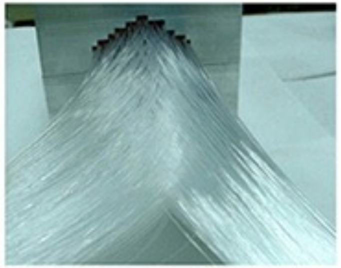
$(e/h)_S$ and $(e/h)_C$ need to be known

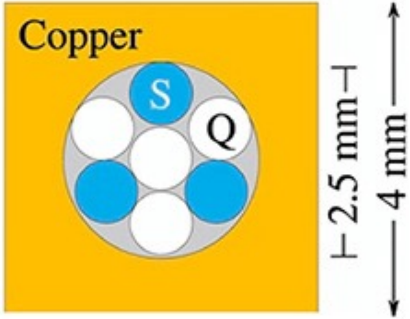
$$E = \frac{S - \chi C}{1-\chi}$$

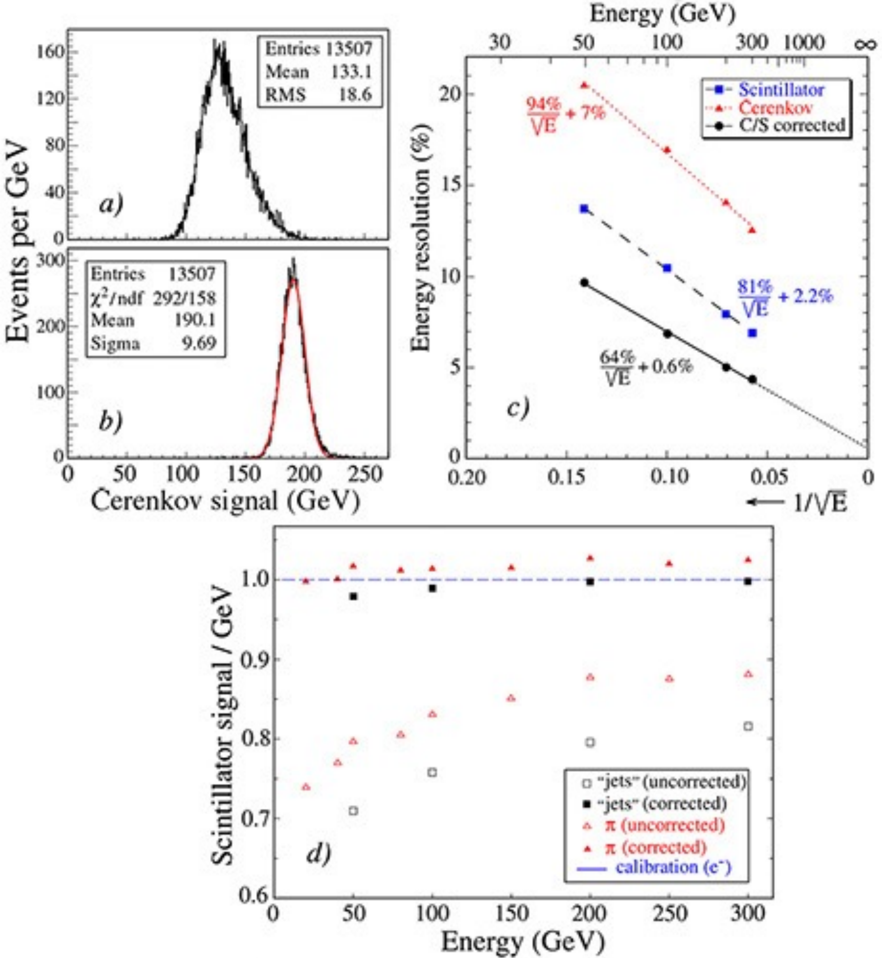
arXiv:1712.05494

How is a dual readout calorimeter realized? An example







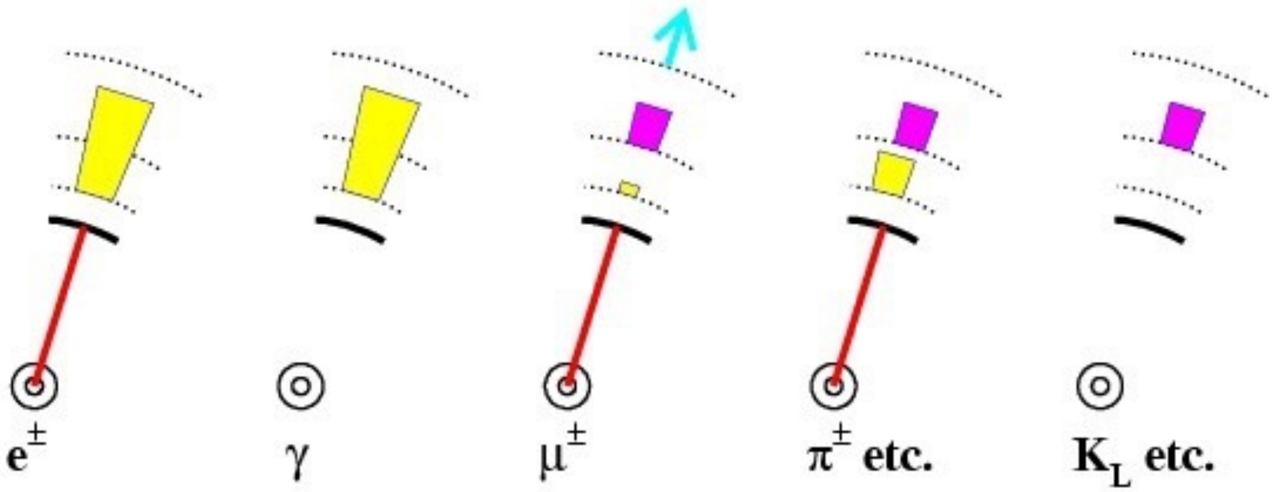


arXiv:1712.05494

Jet energy composition and impact on jet resolution

- Typical jet energy composition
  - ✓ ~62% carried by charged particles (mainly hadrons)
  - ✓ ~27 % carried by photons
  - ✓ ~10% by long-lived neutral hadrons
  - ✓ ~1.5 % by neutrinos.

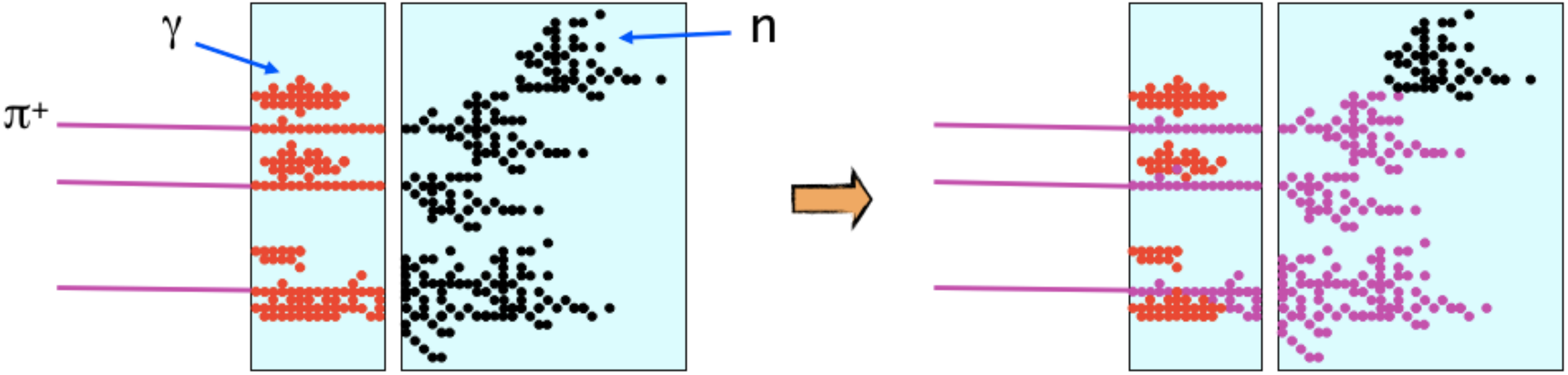
- Traditional approach to calorimetry
  - ✓ Measure all jet energy via energies deposited in the electromagnetic and hadronic calorimeters (ECAL and HCAL)
  - ✓ **>70 % energy measured by HCAL → ~50%/√E/GeV**



What are the only particles for which HCAL is irreplaceable for energy measurement?

Particle flow

- Particle flow calorimetry: trace paths of individual particles through detector, collecting energy deposits left in each subdetector system
  - ✓ Energy and momentum for each particle extracted from subdetector system most accurate in measuring that kind of particle
    - Charged hadrons → Tracker ($\sigma(p_T)/p_T \sim 1\%$)
    - Photons → ECAL (~3-10%/$\sqrt{E/\mathrm{GeV}}$)
    - **Long-lived hadrons (only 10% of jet energy) → HCAL**
  - ✓ **Significant improvement to jet energy measurements → 30-50% better than standalone HCAL!**
  - ✓ It relies on **accurate pattern recognition** and "precedence" techniques to collect energy deposits from individual particles
  - ✓ **Segmentation + resolution**



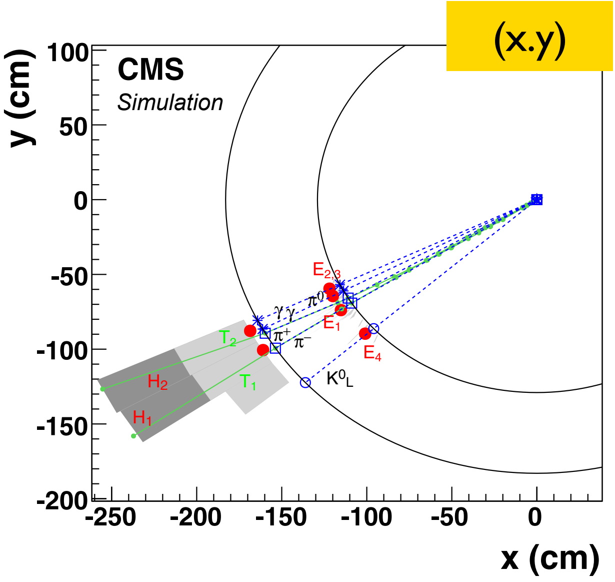
$$E_{JET} = E_{ECAL} + E_{HCAL}$$

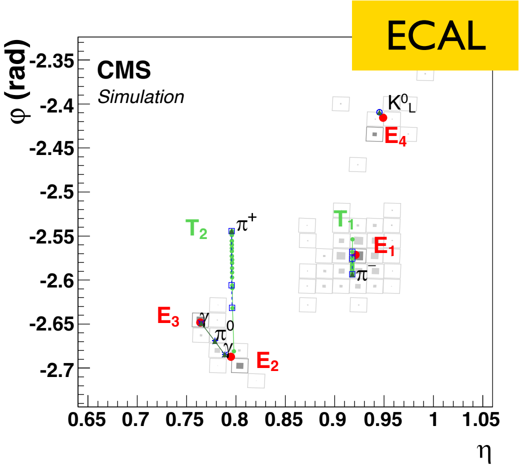
$$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$$

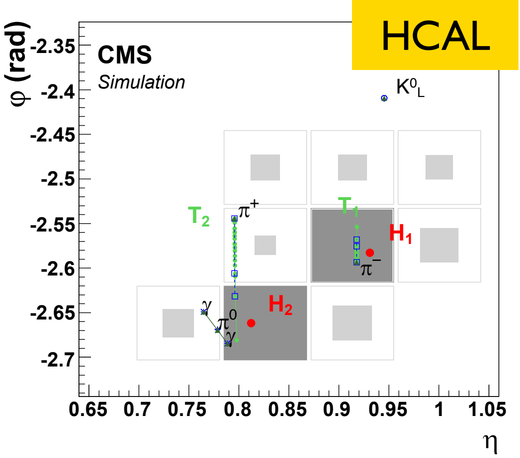
arXiv:1308.4537

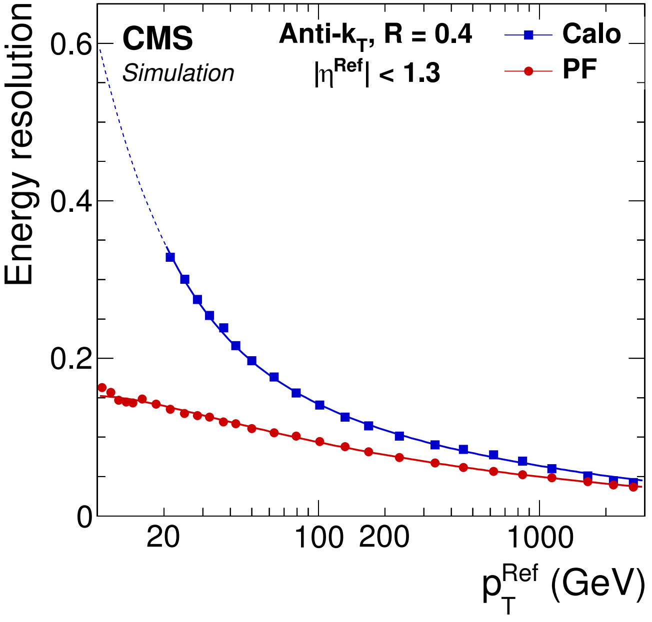
Example: CMS particle flow

arXiv:1706.04965





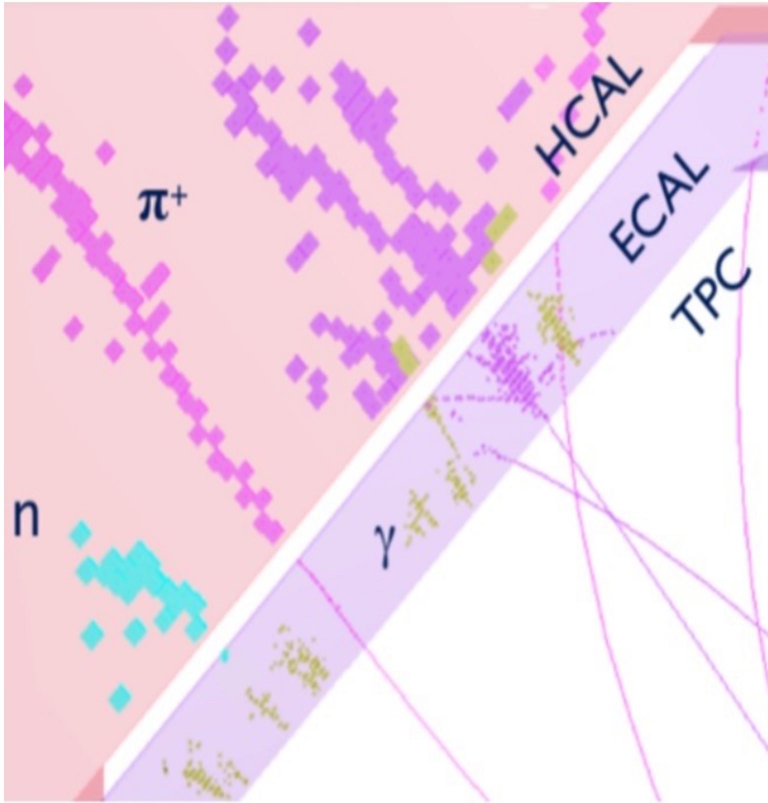




- True particles in blue; Reconstructed tracks and tracker hits (+extrapolation) in green;
- Cluster seeds in dark grey; Other cluster cells in light grey; Cluster position in red;
- Symbols indicate the positions of the true particles

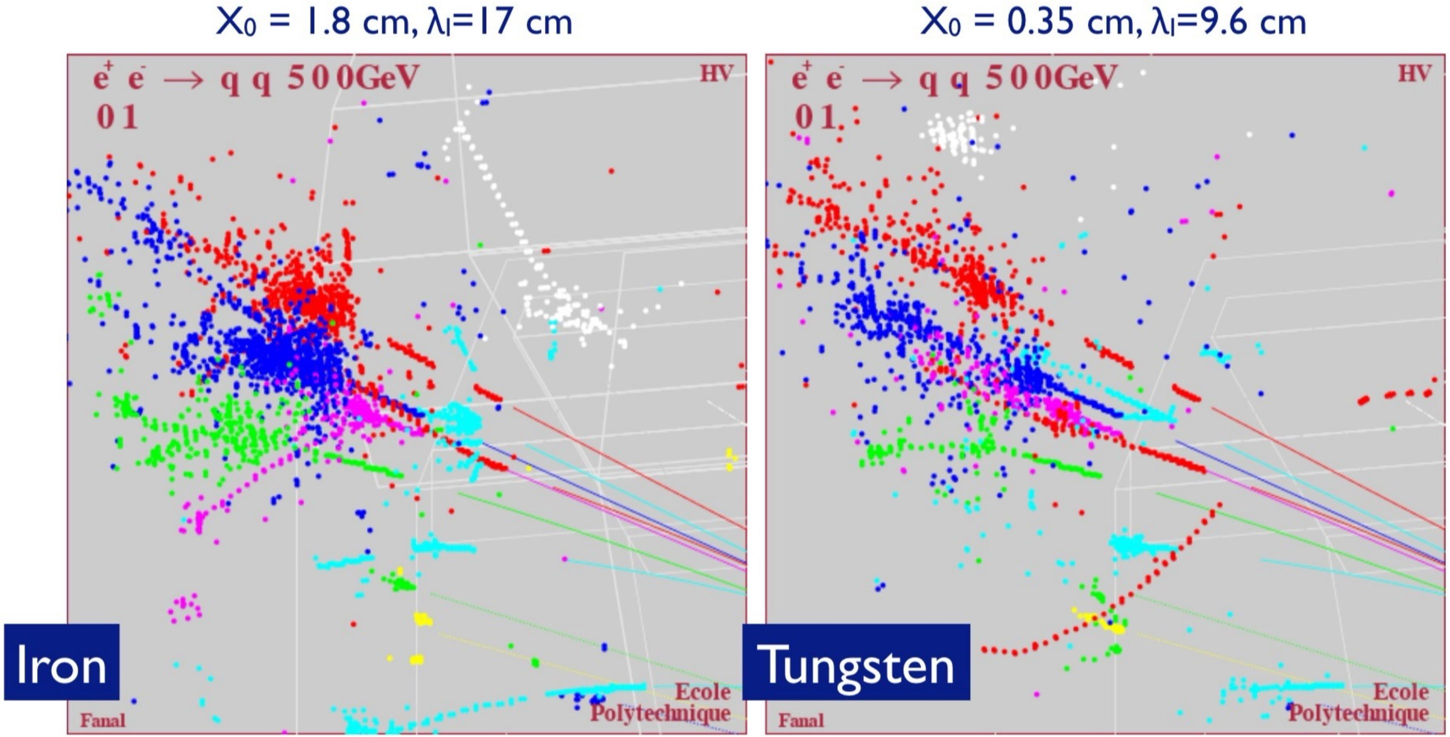
Main criteria for a particle-flow friendly *detector*

- 4π hermeticity
  - ✓ Every missing particle affects physics interpretation reliability
- **Fine 3D granularity of all sub-detectors**
- **Shower compactness in calorimeters**
  - ✓ Minimize overlapping tracks and showers from different particles in jets
  - ✓ Calor energy resolution is a valuable bonus, but granularity comes first
    - Too fine granularity may resolve secondary particles inside showers and defeat the purpose
    - Too many readout channels also increase the electronics noise accordingly (higher thresholds)
- Sufficiently large magnetic field (and/or tracking volume)
  - ✓ To separate showers from charged particles in jets
  - ✓ Too large B field would bend many particles towards the end-caps and defeat the purpose
- **Little material in front of the calorimeters**
  - ✓ e.g., light tracker, solenoid coil behind the calos
  - ✓ To avoid several tracks and showers for one particle due to secondary interactions
- Measurement redundancy (e.g., with pads and wires) in each sub-detector
  - ✓ Very instrumental for noise/fake identification, but not compulsory



An example of future calorimeter for particle-flow

- CALICE = “digital” calorimeters → SiECAL: 1×1 cm² cells; AHCAL: 3×3 cm² + SiPM
  - ✓ 40 layers, ~0.5 M readout channel per m^3 of active volume



X_0 = 1.8 cm, λ_I=17 cm

X_0 = 0.35 cm, λ_I=9.6 cm

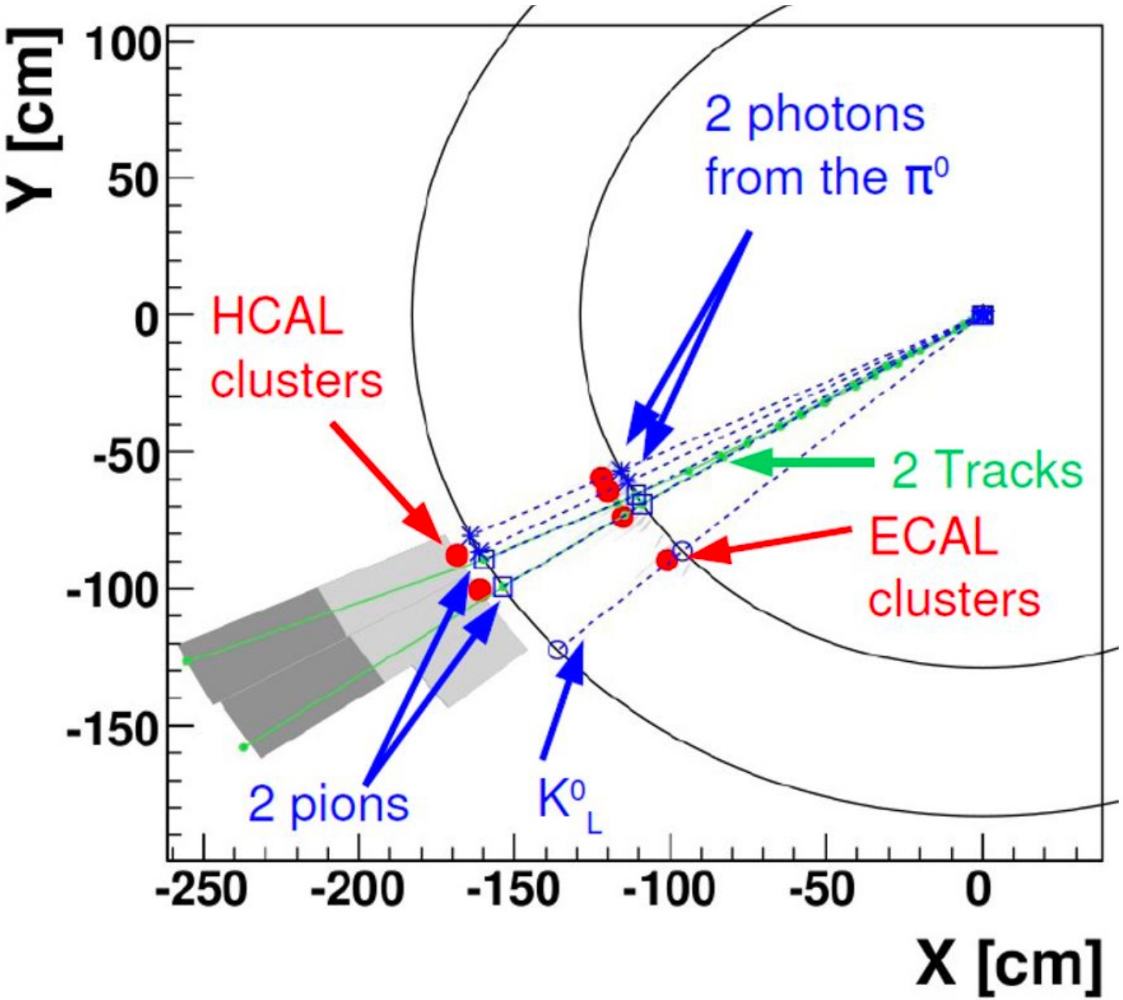
PF calorimetry baseline for all future lepton colliders

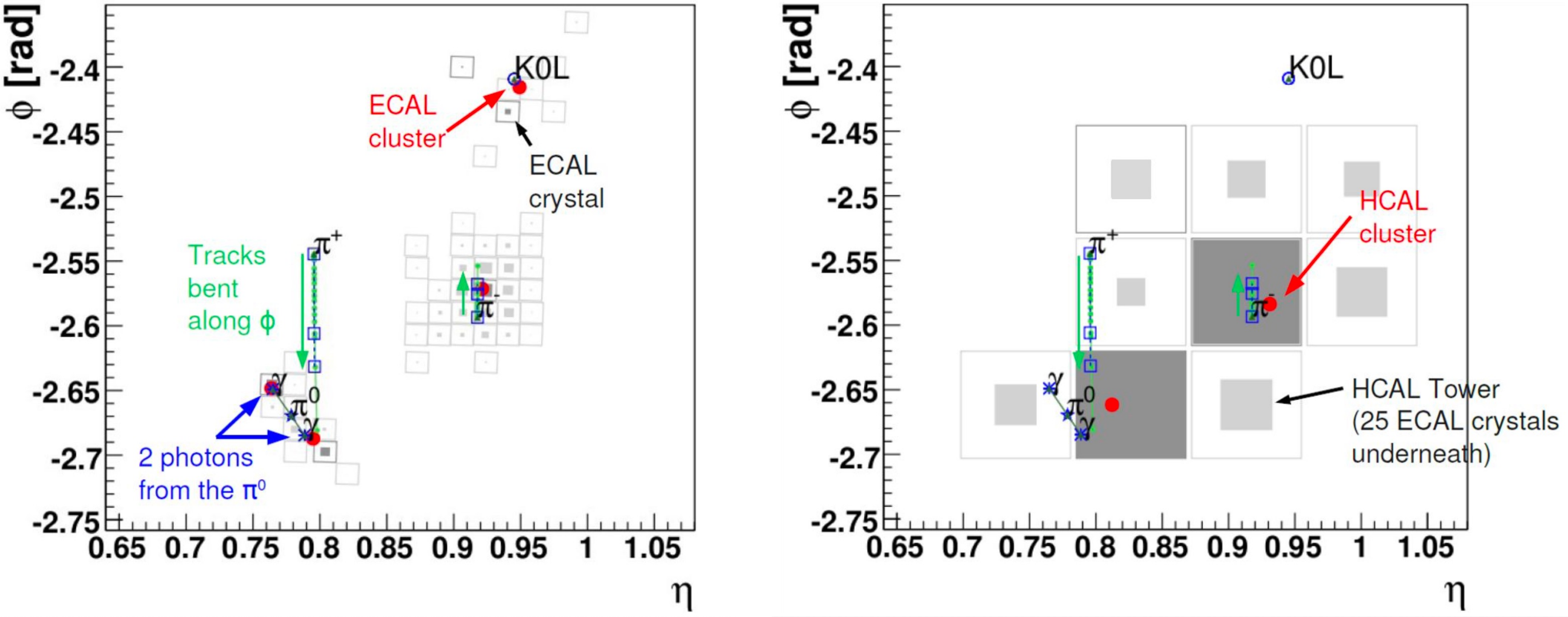
CMS HGCAL (Phase-2): silicon pad endcap, ~6 M channels → PF also baseline for HL-LHC

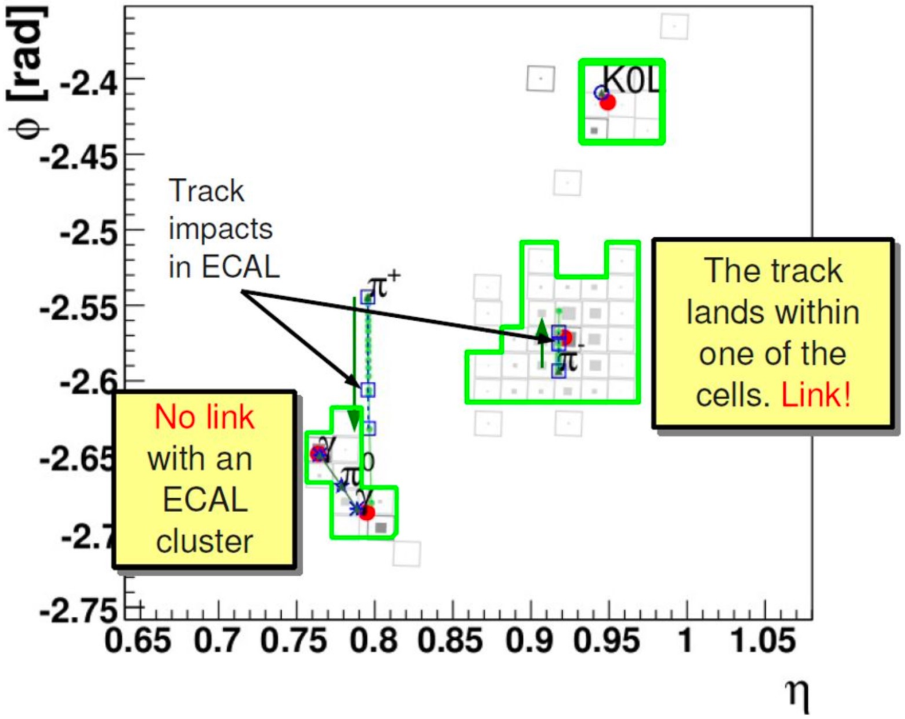
What did we learn today?

- **Week 3 (Technology)**
  - ✓ Lecture 6: Calorimeter Design
    - *6.1 Physics requirements for LHC calorimetry*
      - *LHC requirements drove design: 25 ns speed → only PbWO4/LAr/Cherenkov viable; 10^7 Gy radiation -→ rad-hard sensors/fibres/crystals mandatory; 10^5 channels -→ custom ASIC electronics.*
      - *H→$\gamma\gamma$ set the EM resolution benchmark: $\sigma_m/m \sim 1\%$ at 125 GeV → $c < 0.5\%$, $a < 10\%/\text{sqrt}(E)$.*
      - *Same requirements, two coherent answers: CMS bet on crystal homogeneity (no segmentation, best intrinsic resolution); ATLAS bet on sampling + longitudinal segmentation (π^0 rejection, γ direction from strip layer).*
    - *6.2 LHC calorimeter implementation deep-dives*
      - Both ATLAS (LAr accordion) and CMS ($PbWO_4$) achieve $c < 0.7\%$ constant term via opposite engineering bets — shared calibration challenges despite different technologies
    - *6.3 Design Principles & Considerations*
      - *The solenoid placement fork is the first, irreversible design decision: it determines material before ECAL, presampler need, HCAL depth budget, B-field readout constraints, …*
      - *Dead material mitigation: material between IP and calorimeter degrades resolution stochastically*
      - *Hermeticity is not optional: gaps in η coverage create fake MET, destroying sensitivity to new-physics signatures. Forward calorimeters (FCal, HF) are required*
    - *6.4 Beyond hardware compensation: Dual Readout & Particle Flow*
      - *Granularity is key!*

More on Particle Flow


Y [cm]
100
50
0
-50
-100
-150
-250
-200
-150
-100
-50
0
X [cm]
2 photons
from the π^0
HCAL
clusters
2 Tracks
ECAL
clusters
2 pions
K^0_L

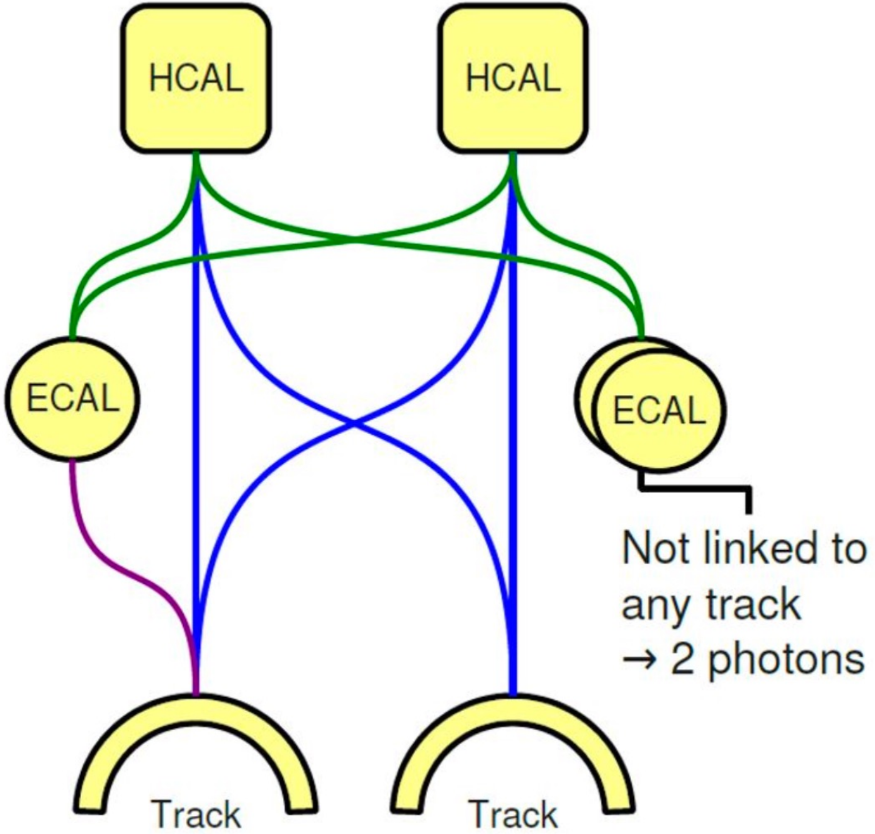

φ [rad]
-2.4
-2.45
-2.5
-2.55
-2.6
-2.65
-2.7
-2.75
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
1.05
η
K0L
ECAL cluster
ECAL crystal
π^+
π^-
π^0
γ
γ
Tracks bent along φ
2 photons from the π^0
φ [rad]
-2.4
-2.45
-2.5
-2.55
-2.6
-2.65
-2.7
-2.75
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
1.05
η
K0L
HCAL cluster
π^+
π^-
π^0
γ
γ
HCAL Tower (25 ECAL crystals underneath)



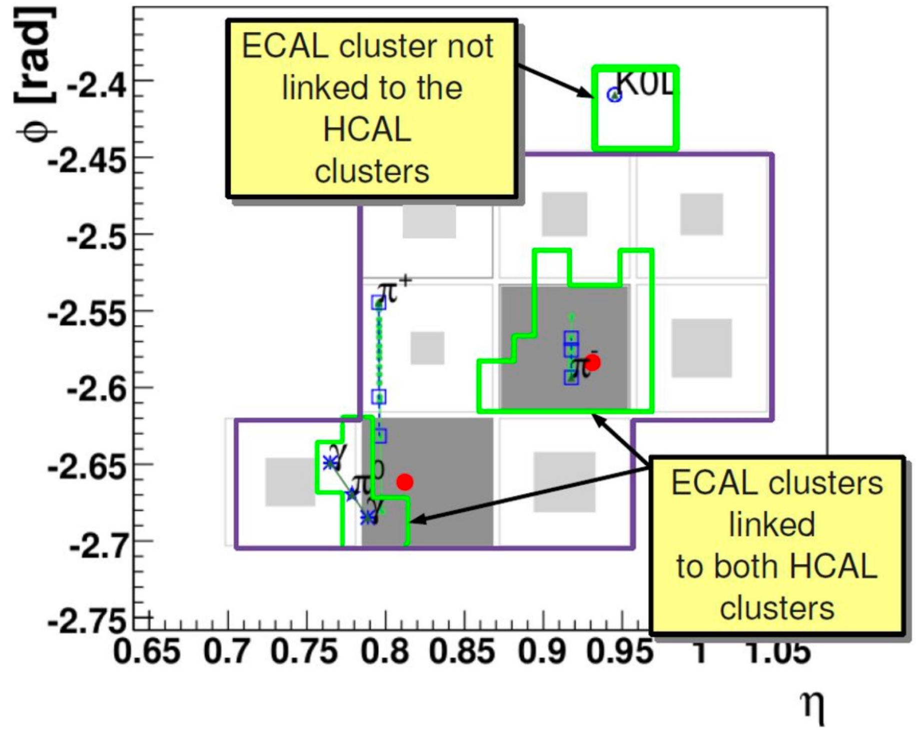
Track impacts in ECAL

The track lands within one of the cells. Link!

No link with an ECAL cluster

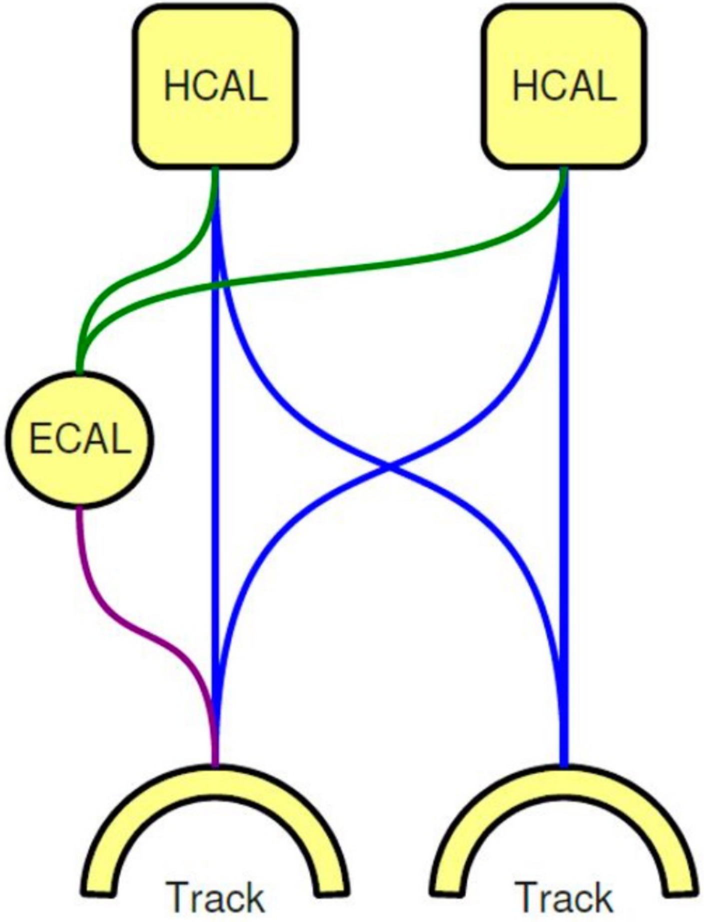


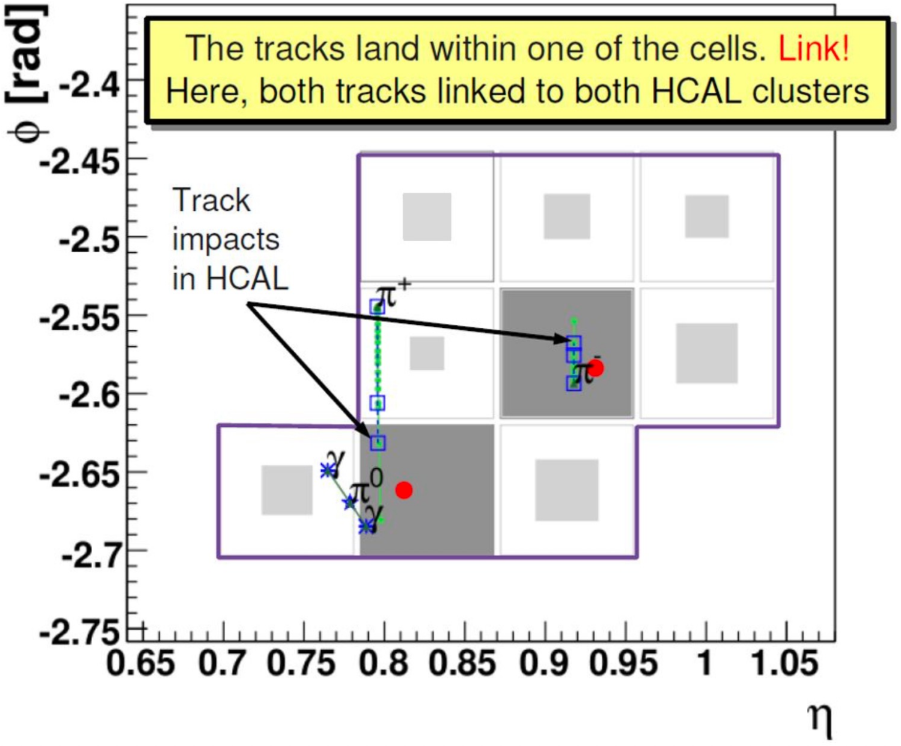
Not linked to any track → 2 photons



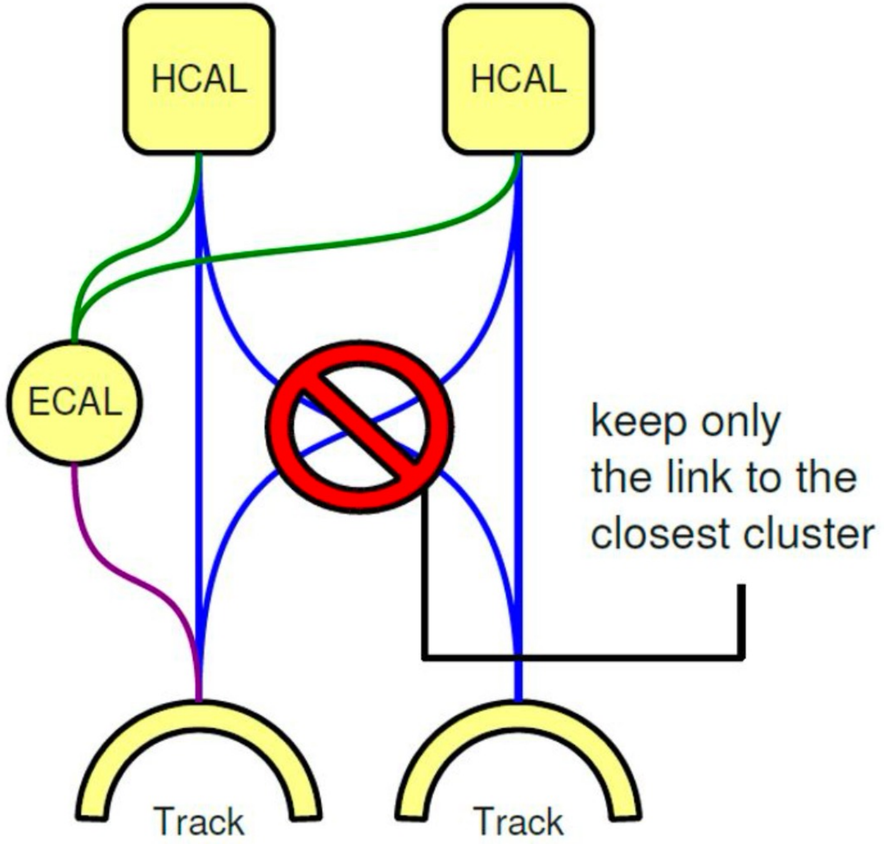
ECAL cluster not linked to the HCAL clusters

ECAL clusters linked to both HCAL clusters





The tracks land within one of the cells. Link!
Here, both tracks linked to both HCAL clusters



keep only
the link to the
closest cluster