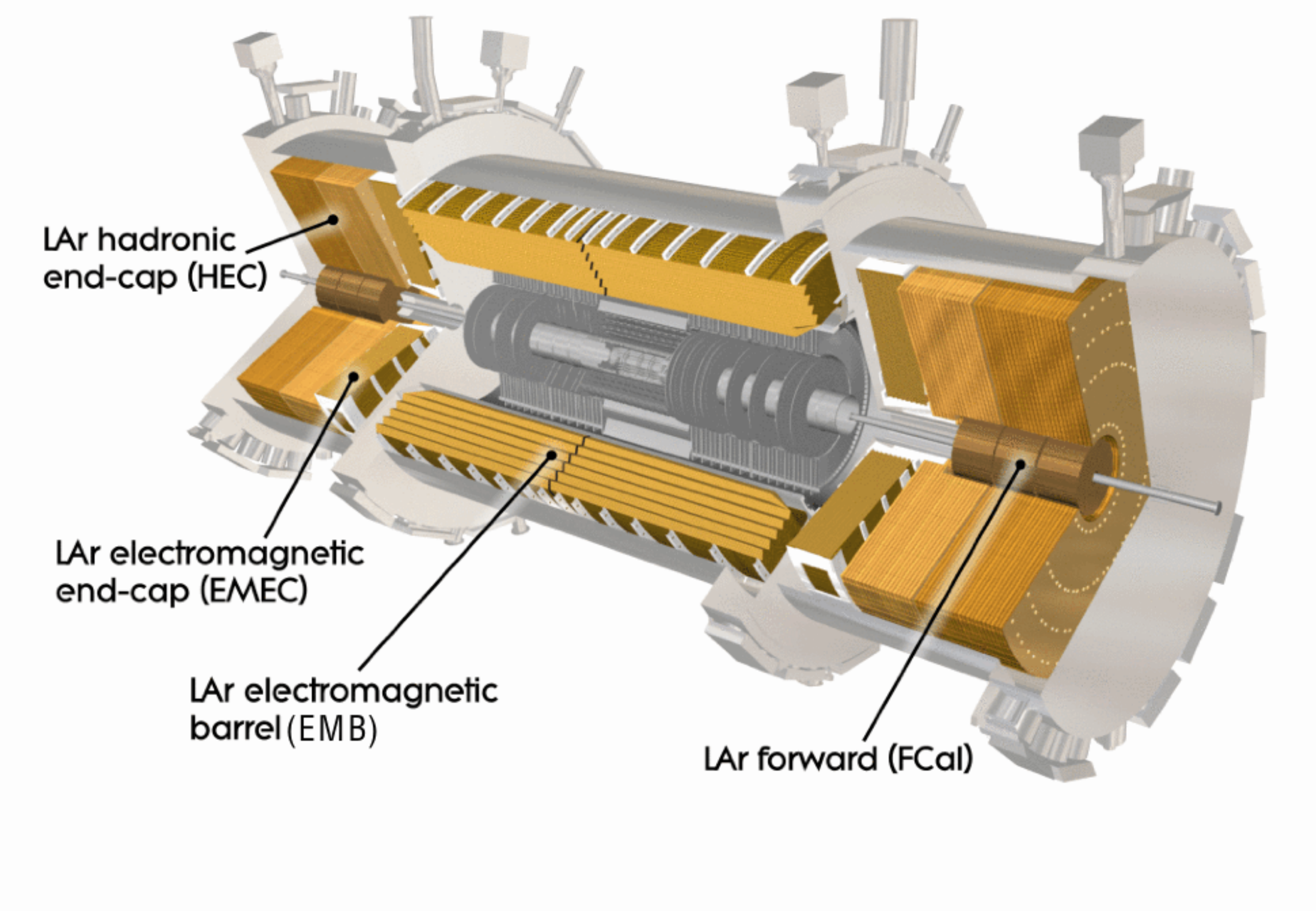
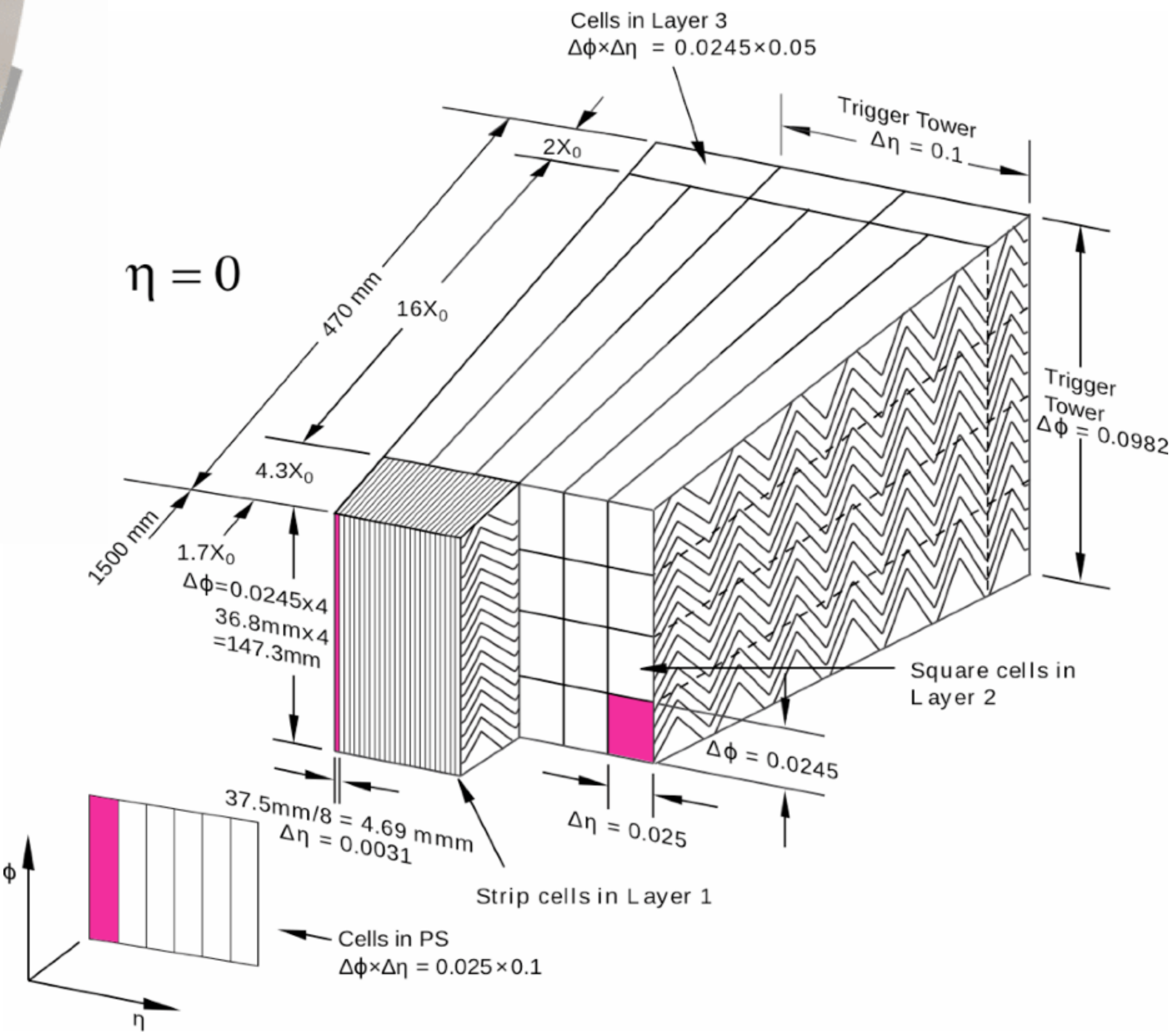
Simulation and digitization of the ATLAS calorimeter

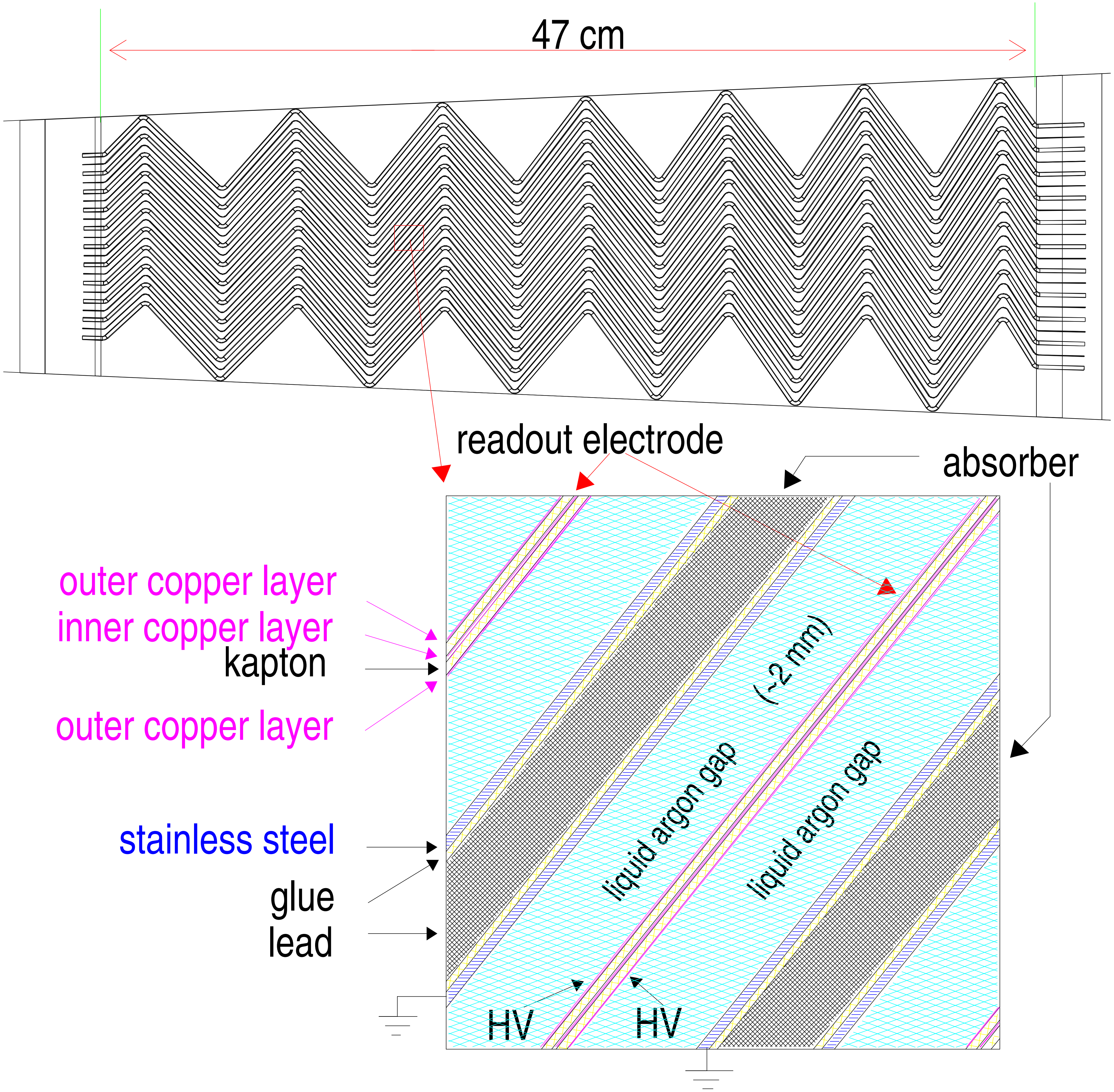
G.Unal (CERN)
GranuLAr workshop - 08/04/2022

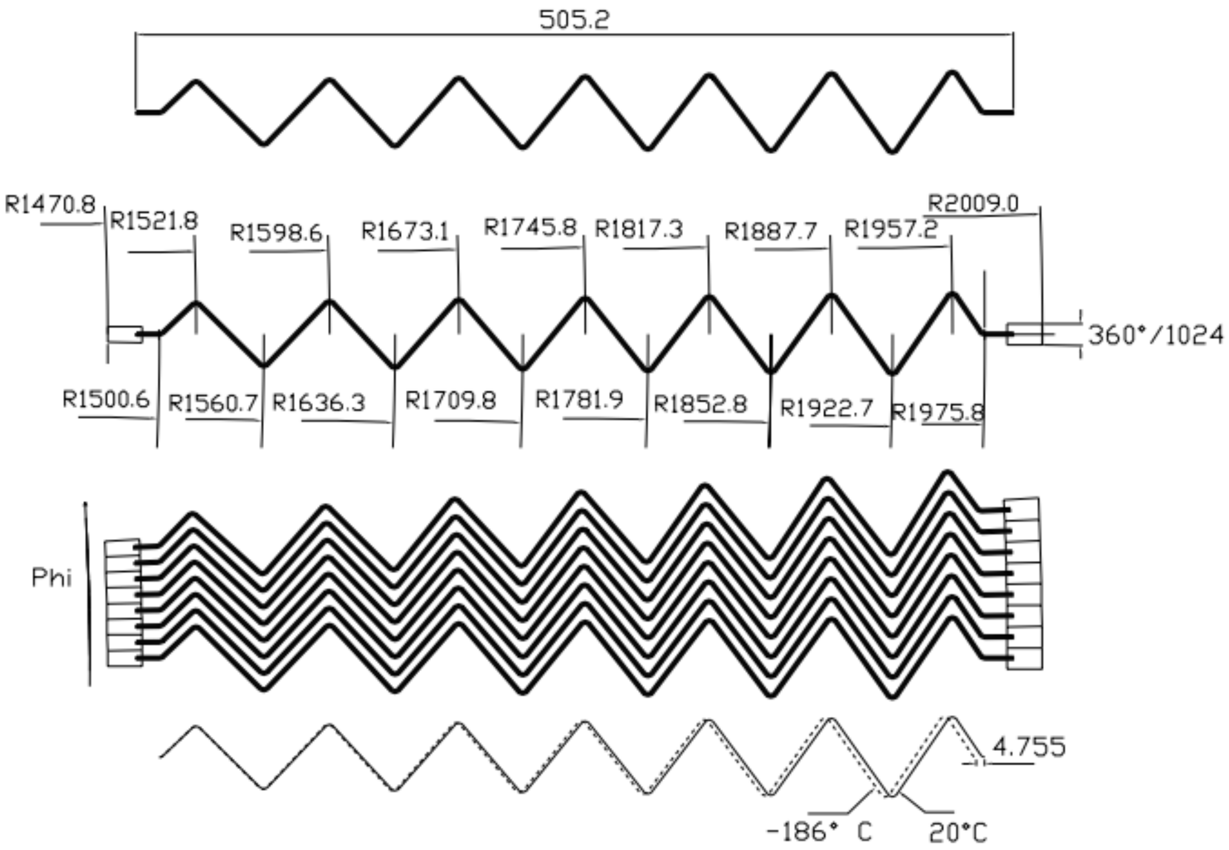
ATLAS LAr calorimeter



EM calo: Pb+LAr, accordion geometry
EM Barrel: +- 1.45 in eta
EM EndCap (1.37-3.2 in eta): 1.5-2.4 with high granularity in layer 1
182468 channels (173312 in EM calo, 0.2% non operational during data taking)




47 cm
readout electrode
absorber
outer copper layer
inner copper layer
kapton
outer copper layer
stainless steel
glue
lead
(~2 mm)
liquid argon gap
liquid argon gap
HV
HV



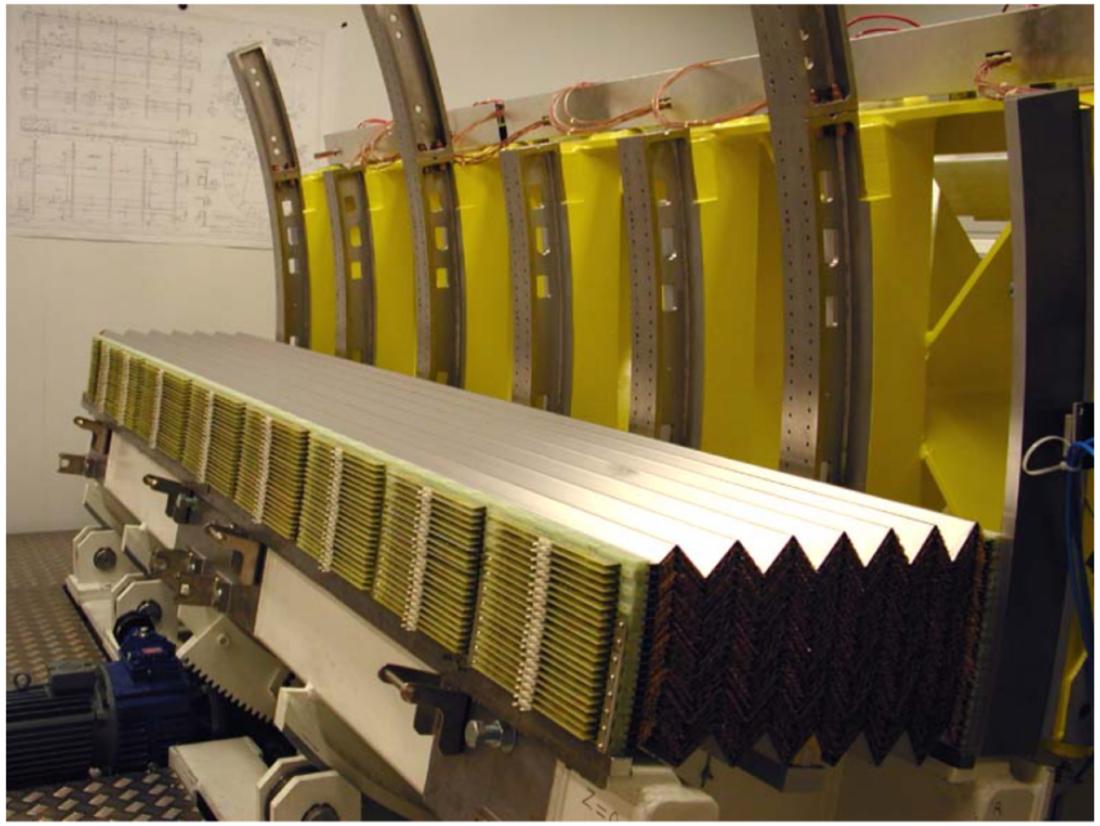
Absorbers and electrodes ~ parallel to direction of particles => "easy" to readout signal from electrodes, no crack.

Zig-Zag angle ("Accordion") to avoid particles travelling only in LAr or only in Pb

Varying angle to keep gap constant as function of radius in projective cylindrical geometry

No cold "active" electronics

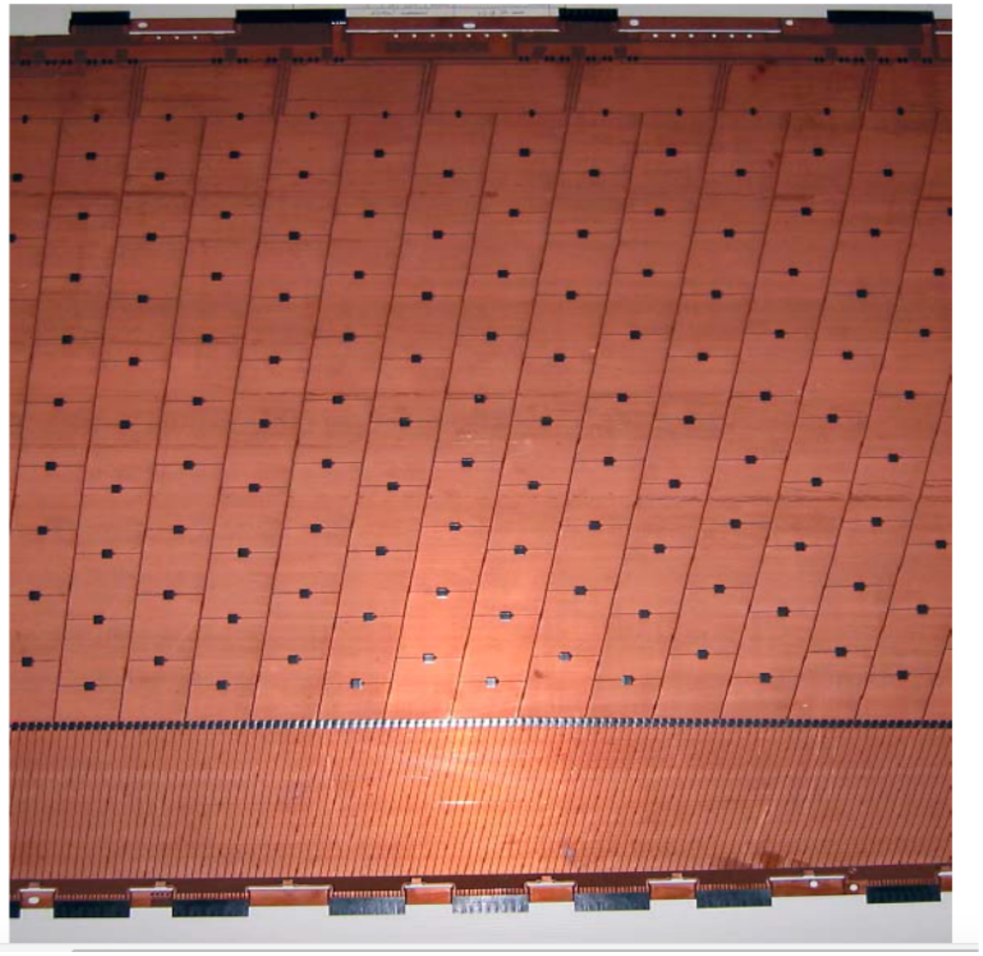
Gap size ~2mm
Sampling fraction~15-20%

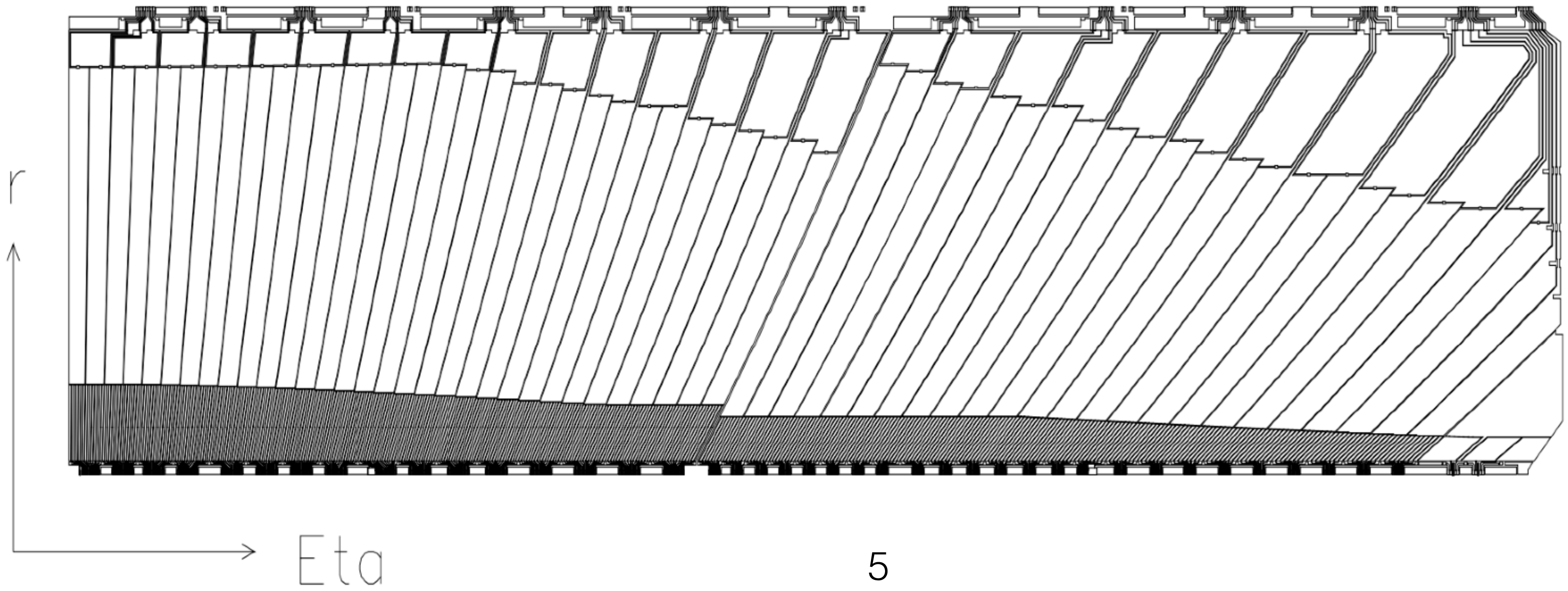


Granularity in eta (z) direction and in depth defined by drawing of readout cells on electrodes

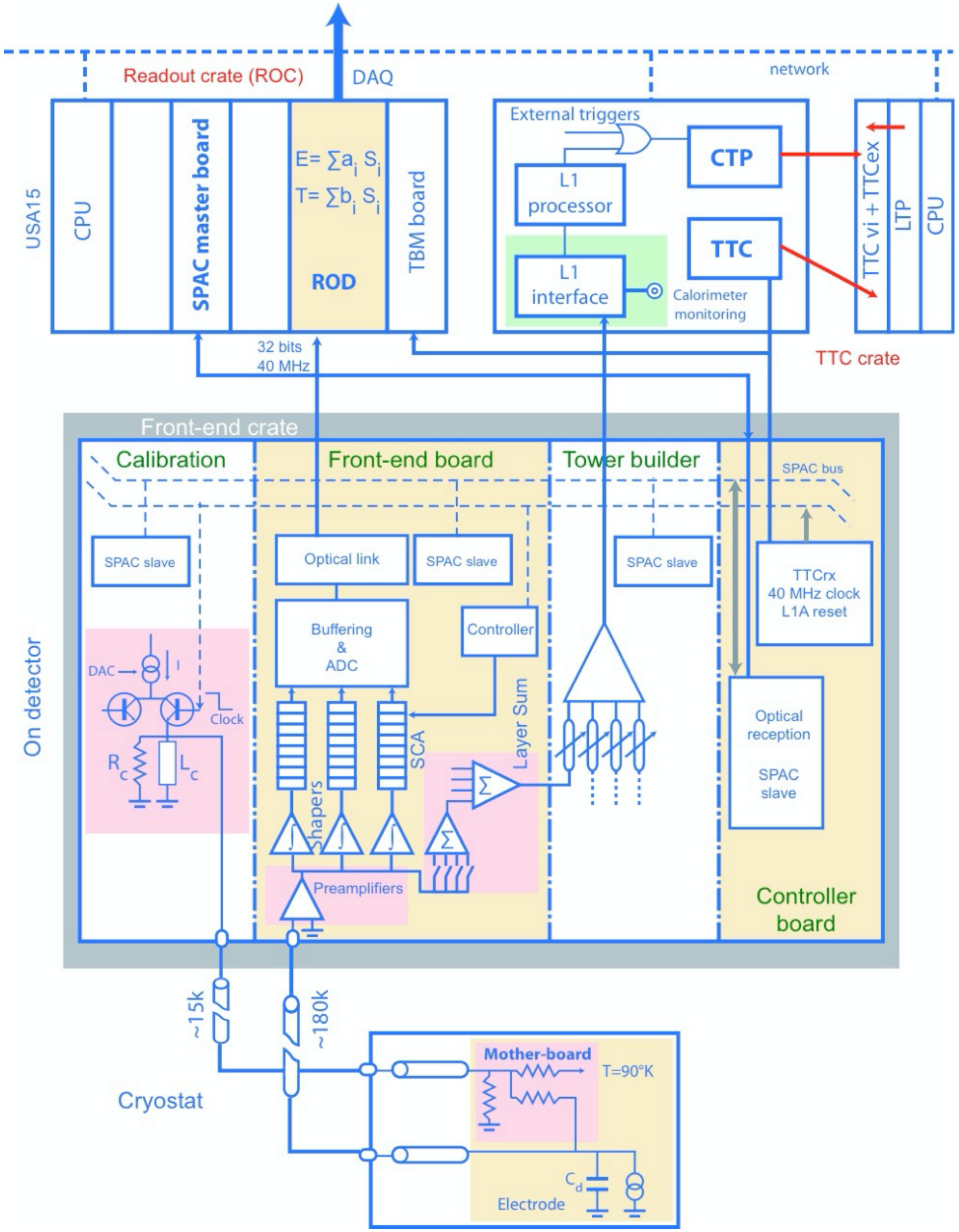
3 layers per electrode:
HV-readout-HV

Granularity along phi defined by grouping of electrodes
1024 electrodes, 4 electrodes per cell => 2pi/256 cells for 2nd layer





Readout

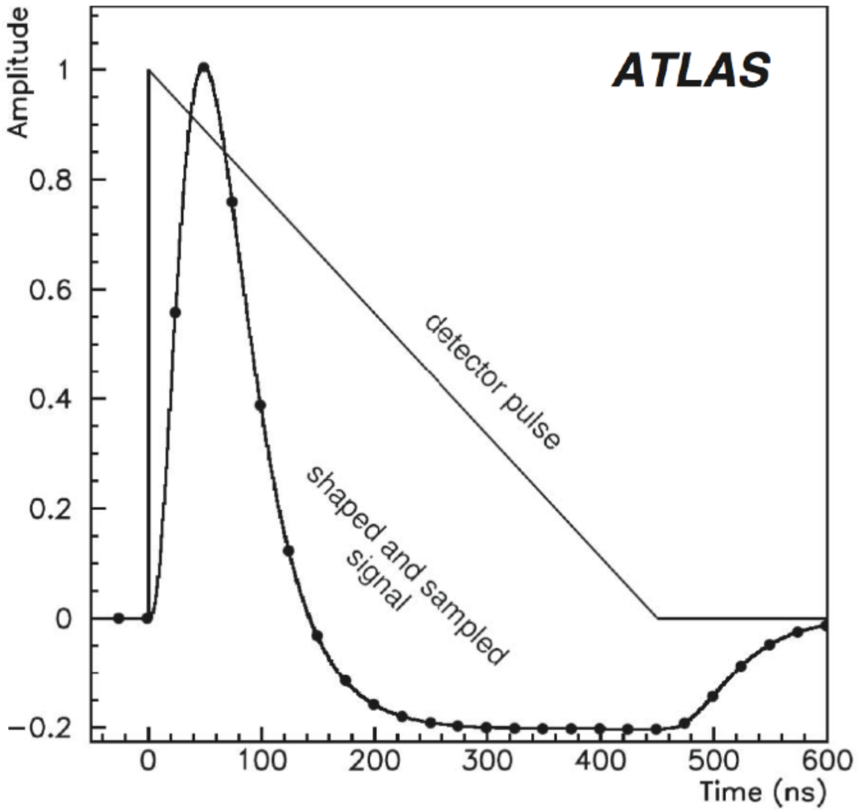


Low noise electronics on the feedthrough to amplify and shape the signal (*3 gains)
(Signal is ~15 μA / GeV)

Analog pipeline to wait for L1 trigger decision

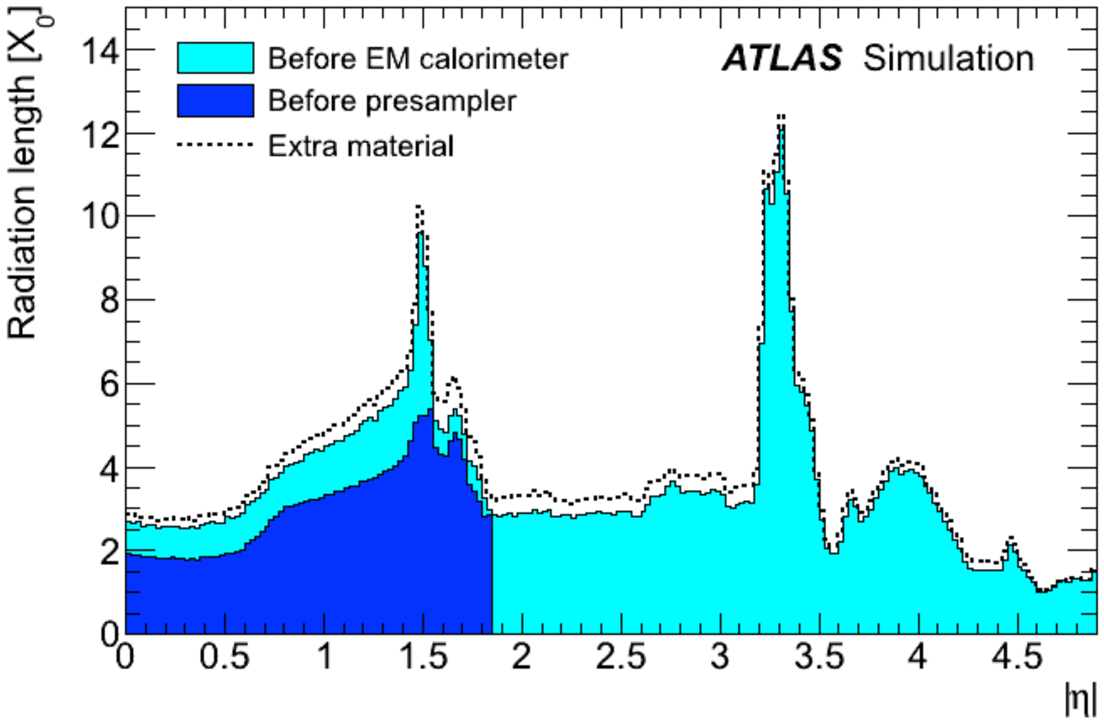
12-bits ADC

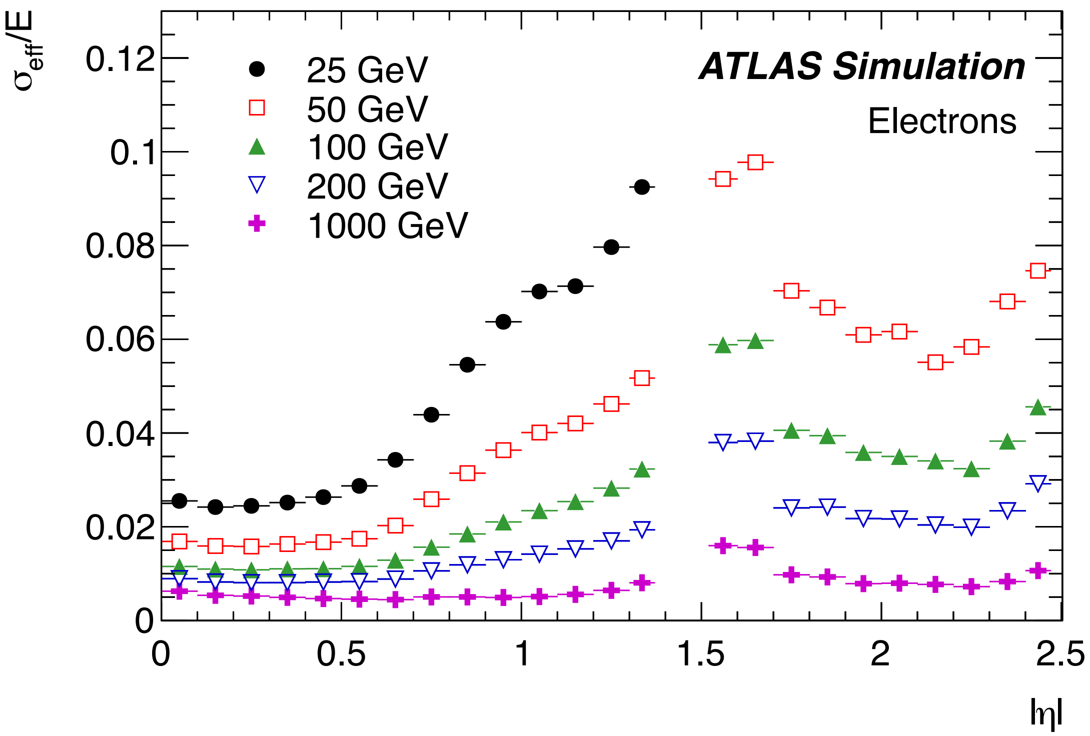
Data sent by optical link to back-end electronics for energy reconstruction and input to HLT and readout paths

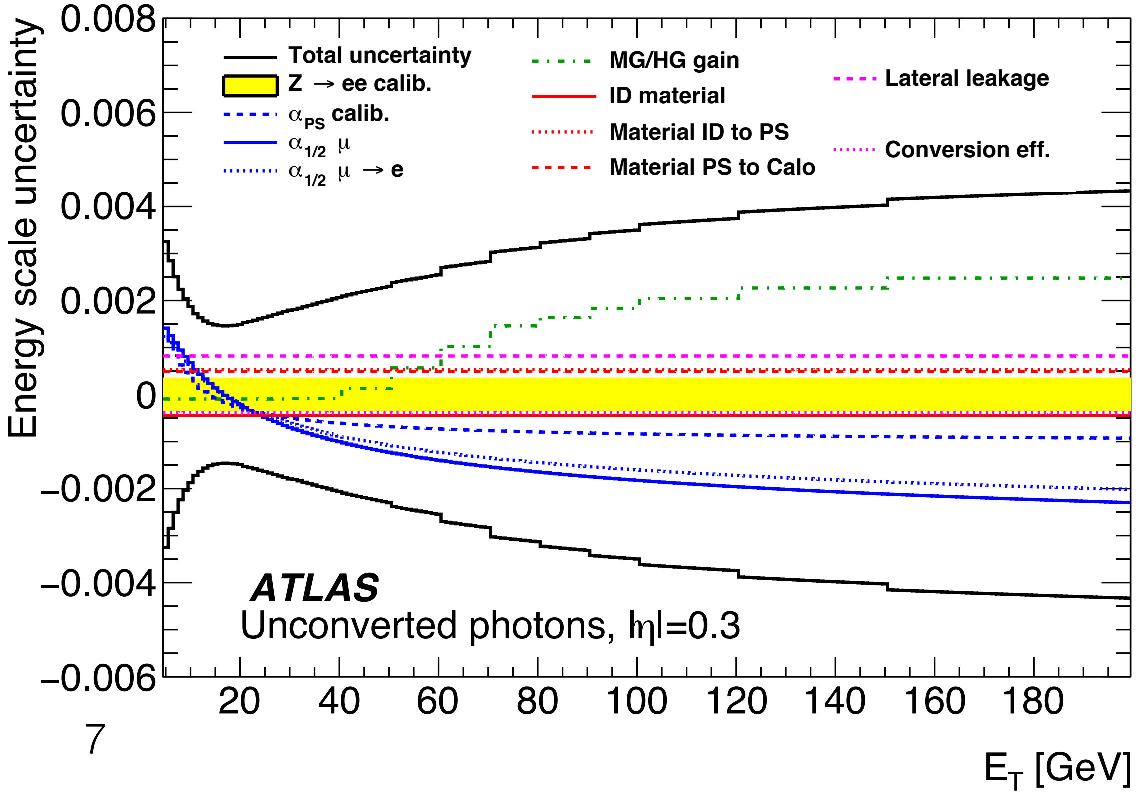


why do we care about detailed simulation ?

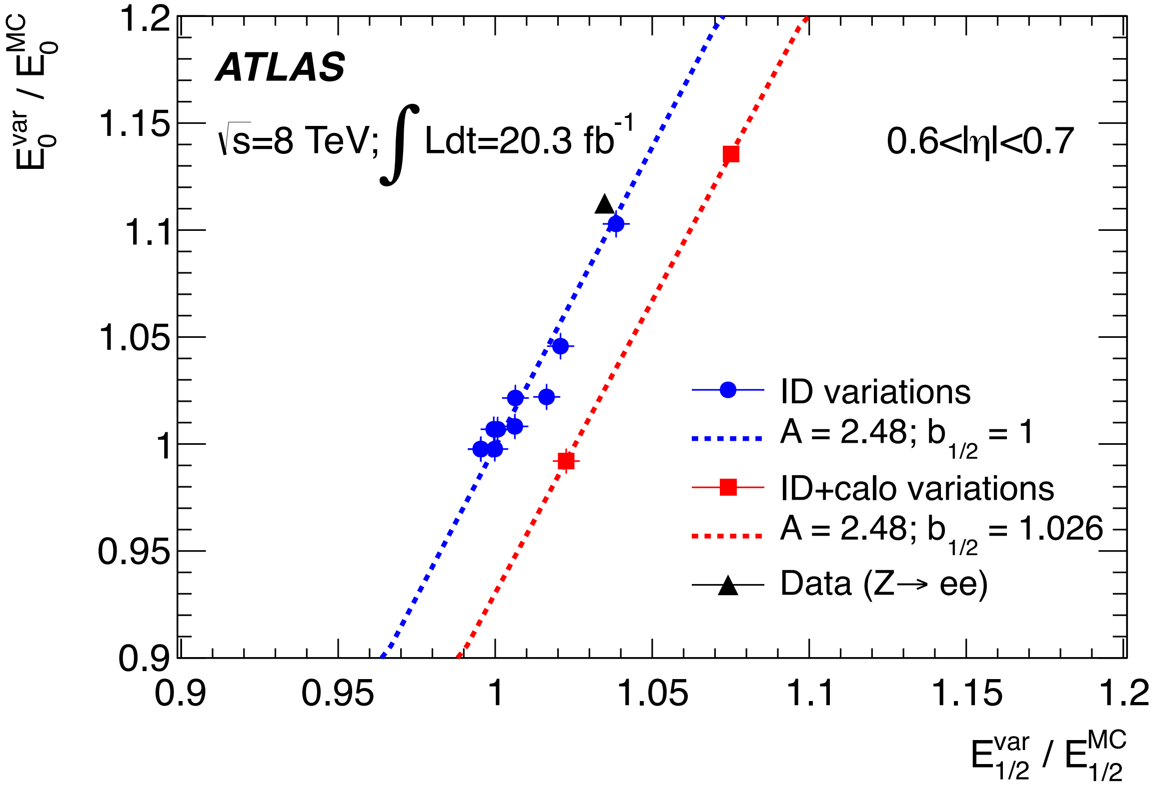
- Significant material before EM calorimeter
- To improve energy resolution, correct event-by-event using longitudinal shower development
- BDT regression trained on simulated events
- Rely on good modelling of longitudinal shower shape

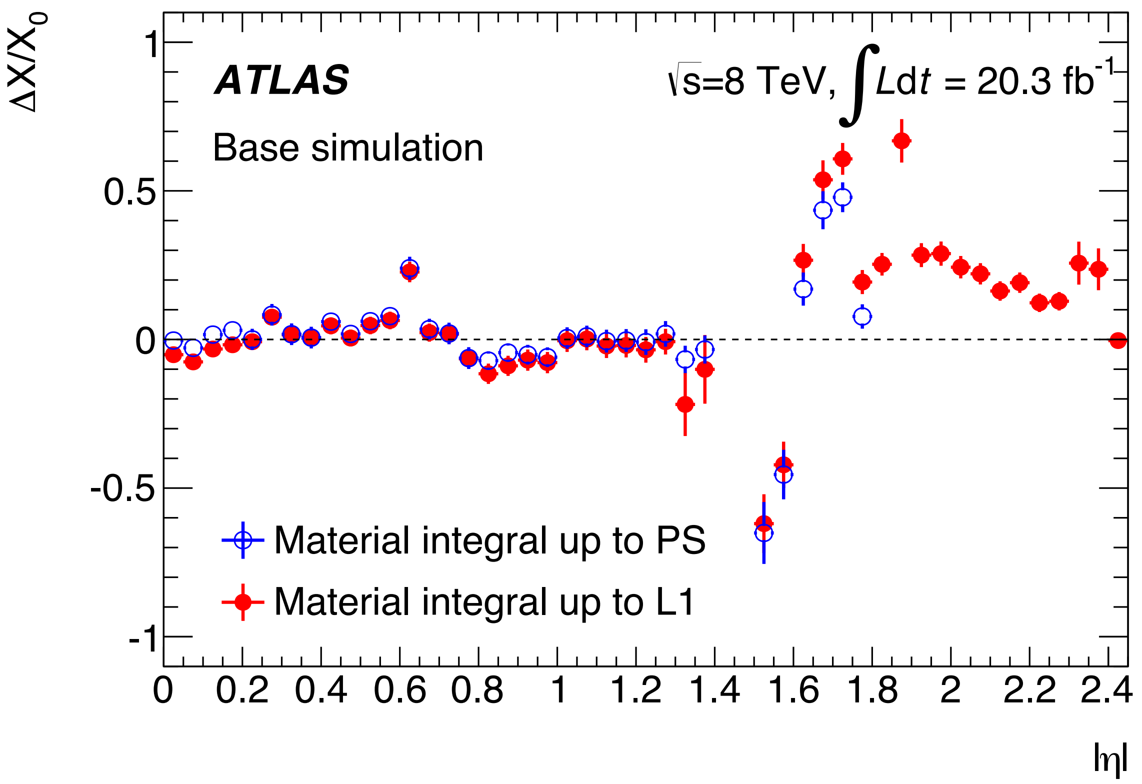


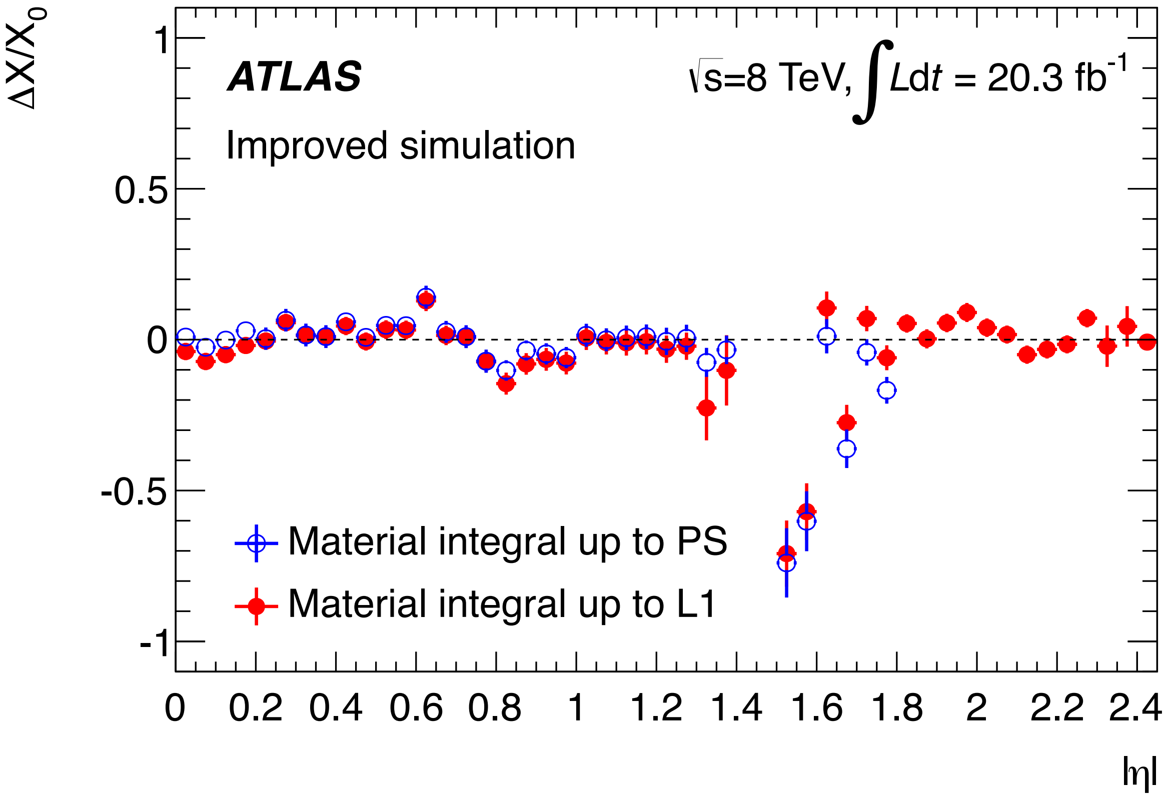




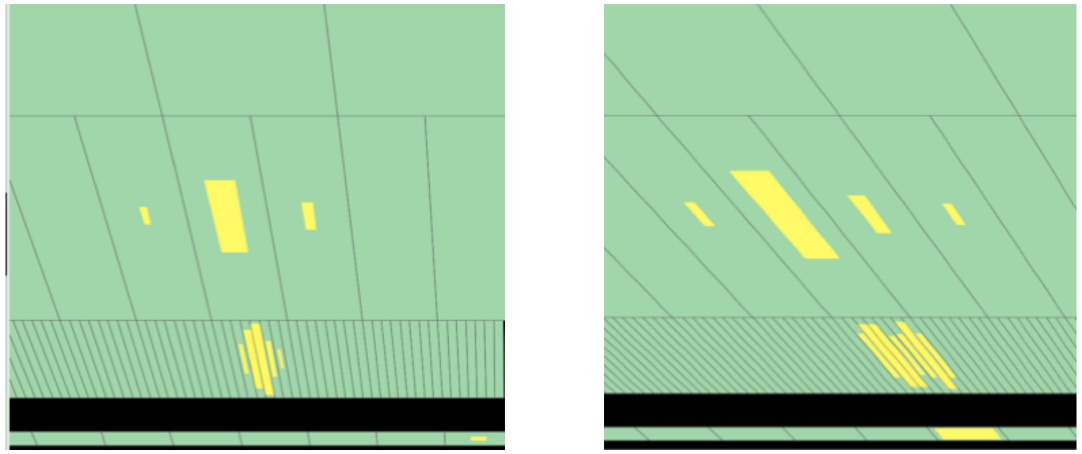
- Longitudinal shower profile (E1/E2) is a very sensitive probe of the material in front of the calorimeter
- Can be used to check / tune this material provided the other ingredients entering in E1/E2 modelling are under control



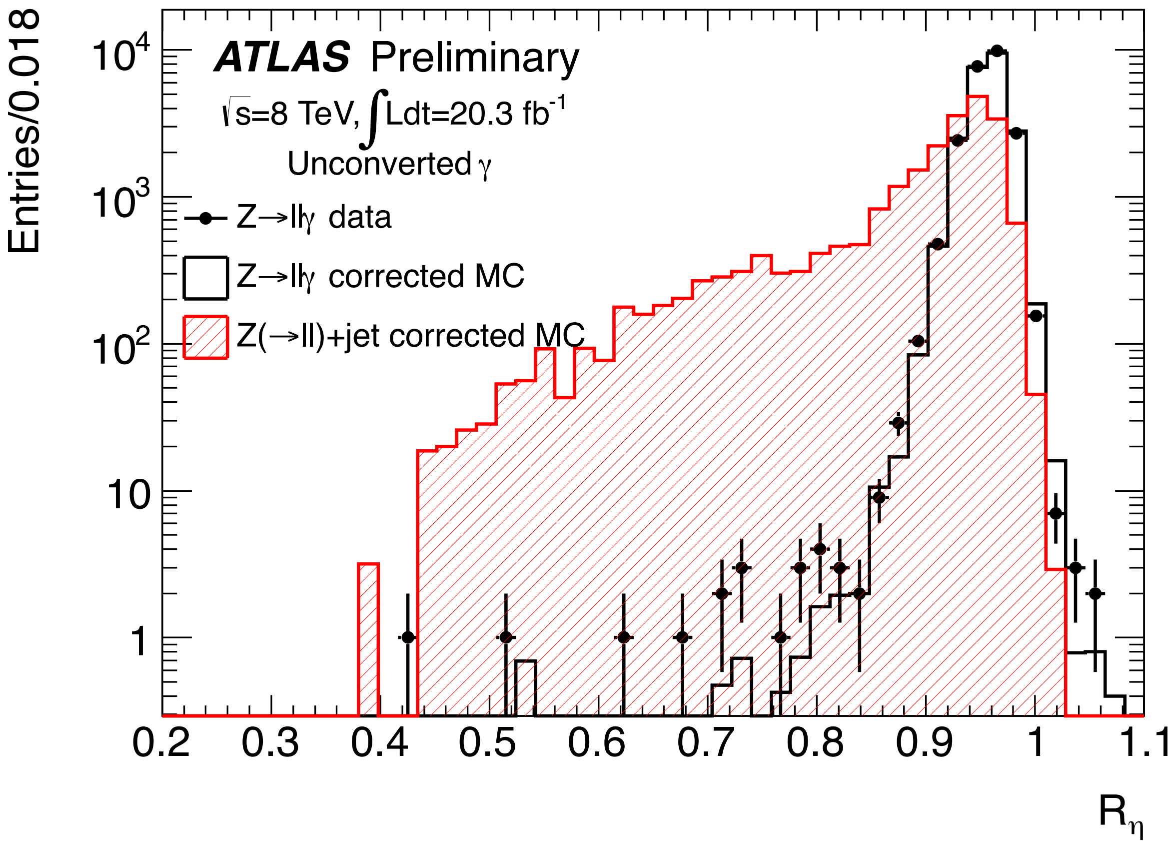




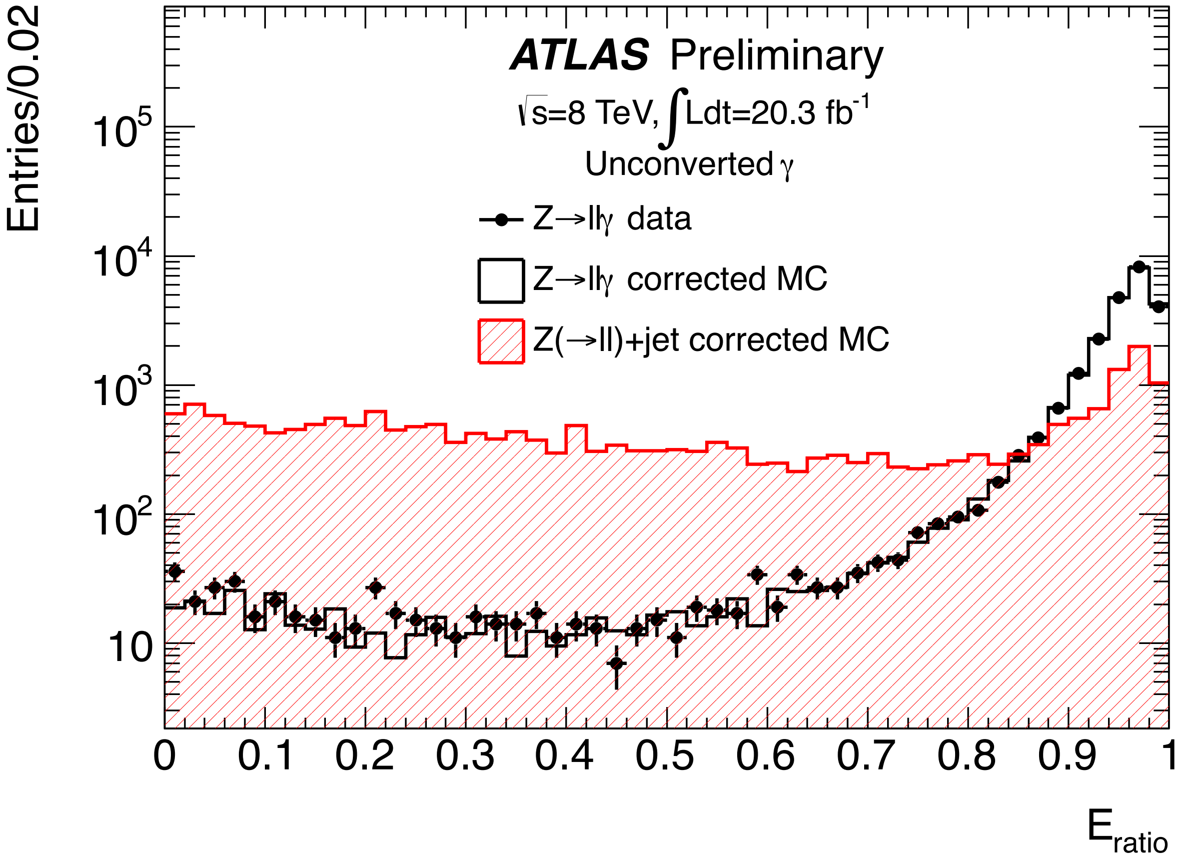
Electron and photon identification strongly rely on shower shape development in the calorimeter (mostly transverse variables)



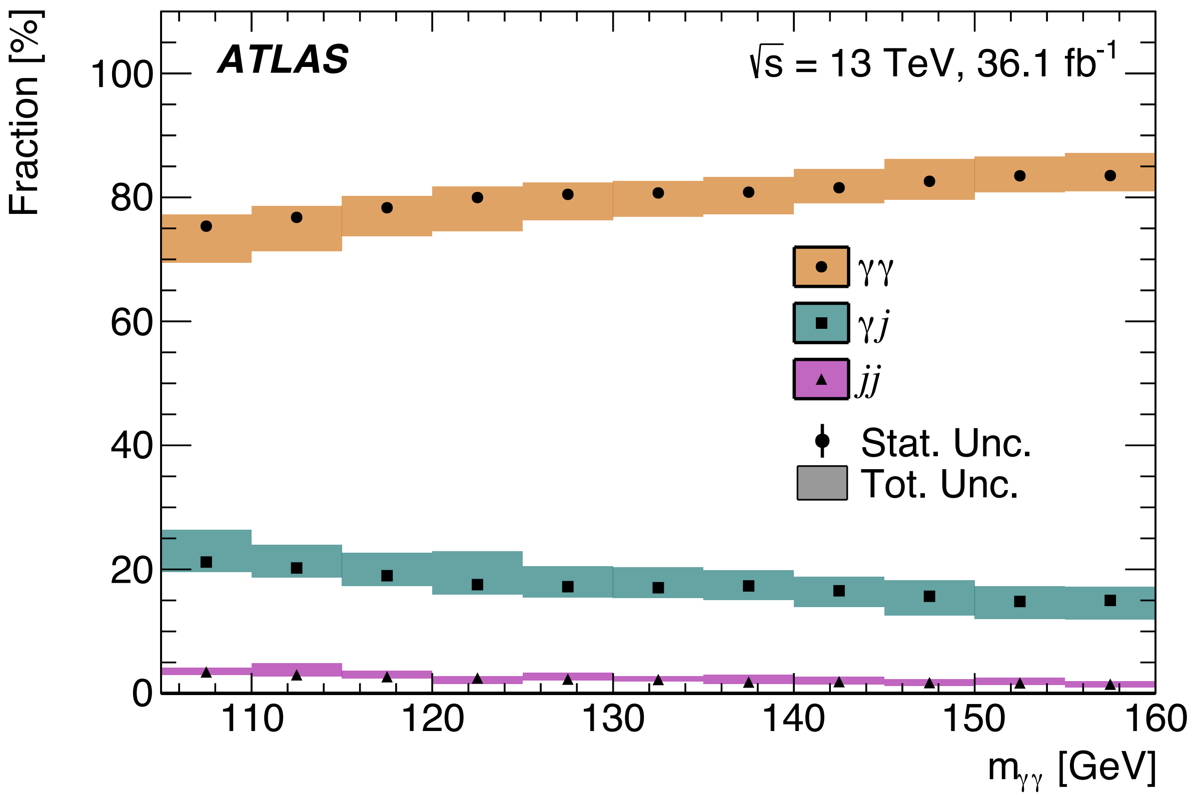
Shower shape in eta direction - 2nd layer

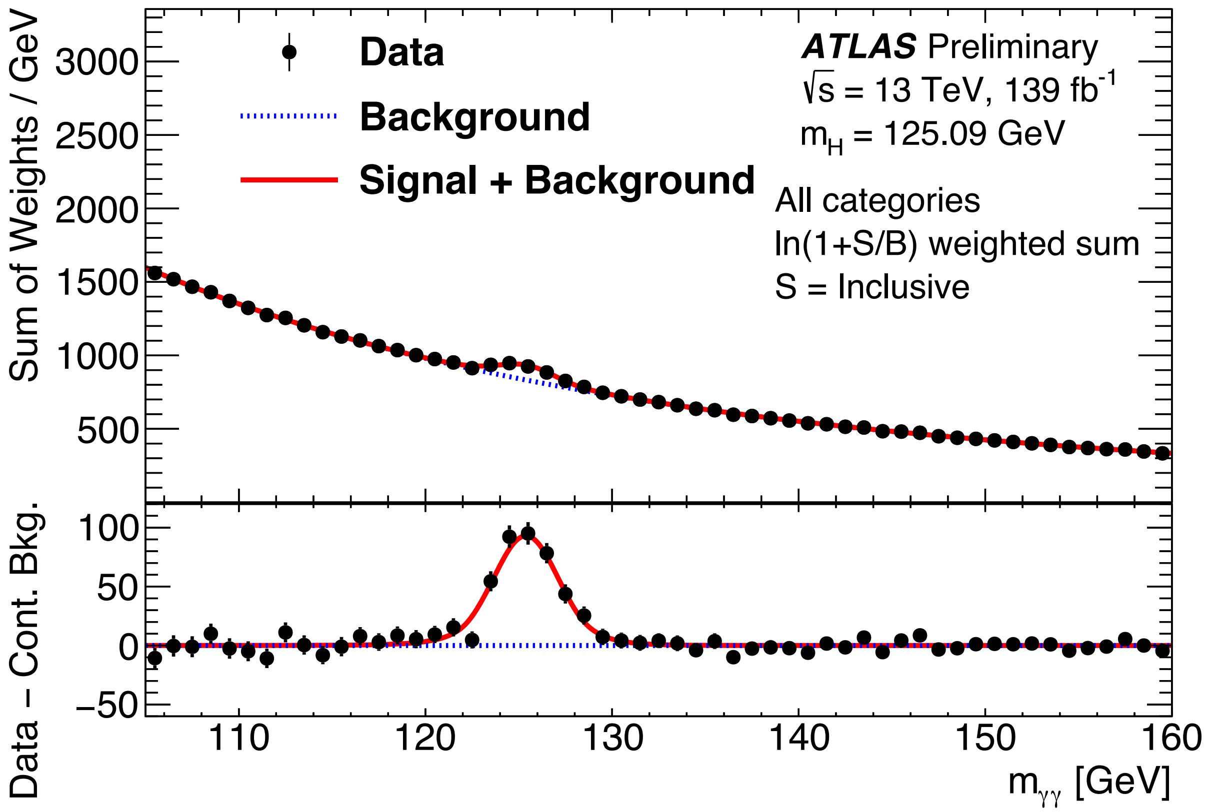


Search for second maximum in first layer



Photon identification plays a crucial role to enhance the purity of diphoton candidates and better observe H->gamma gamma





Steps for simulation

- Detailed description of the geometry with accurate material budget
- Geant4 tracking and physics modelling (not discussed here)
    - EM and hadronic physics
- Simulation of energy collection in LAr gaps and of cell boundaries
- Simulation of noise, cross-talk effects, pileup interactions

Stable particles

G4 simulation (tracking, physics, treatment of energy deposited in active LAr gap)

Effective energy deposit per cell

simulation of electronics readout (noise, cross-talk)
addition of pileup interactions
-> pulse Shape ADC vs time
emulation of energy reconstruction

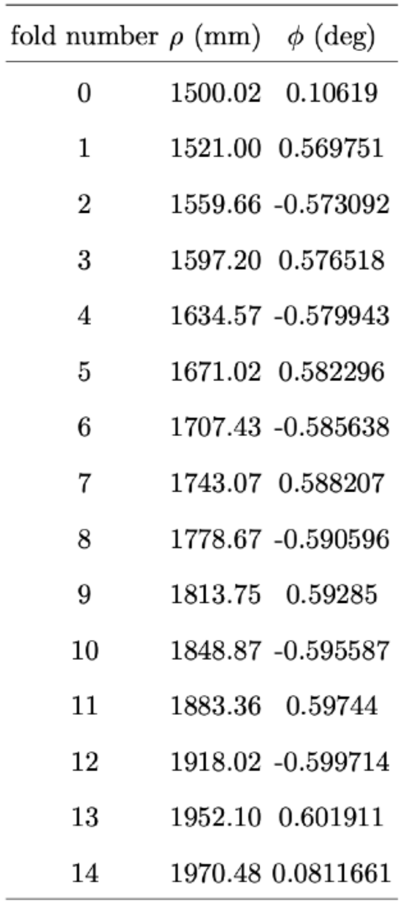
Cell energy in MeV (~same format as data)

Reconstruction

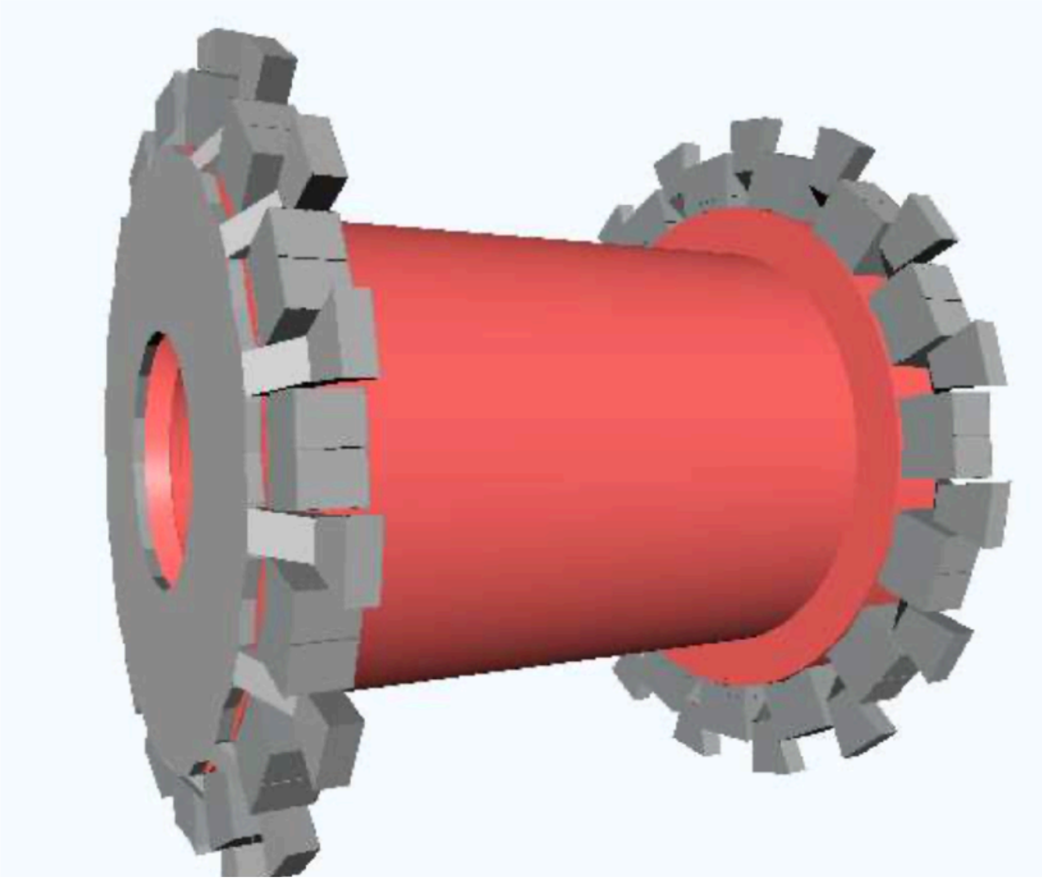
Description of geometry

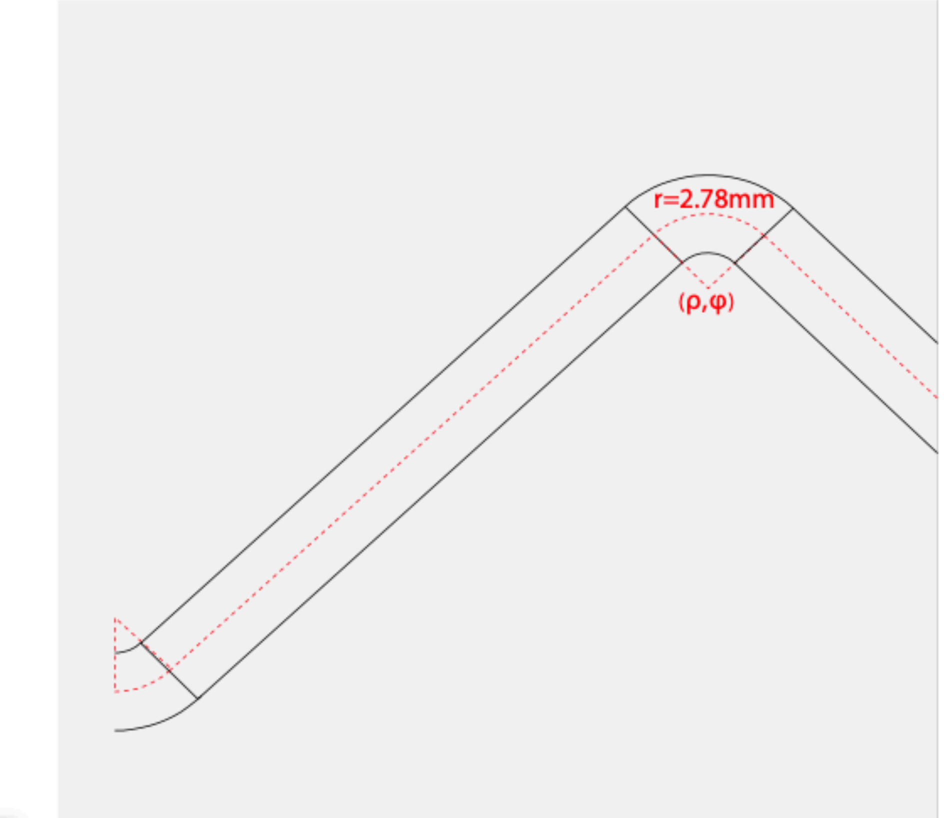
- Inputs taken from detector construction papers as much as possible

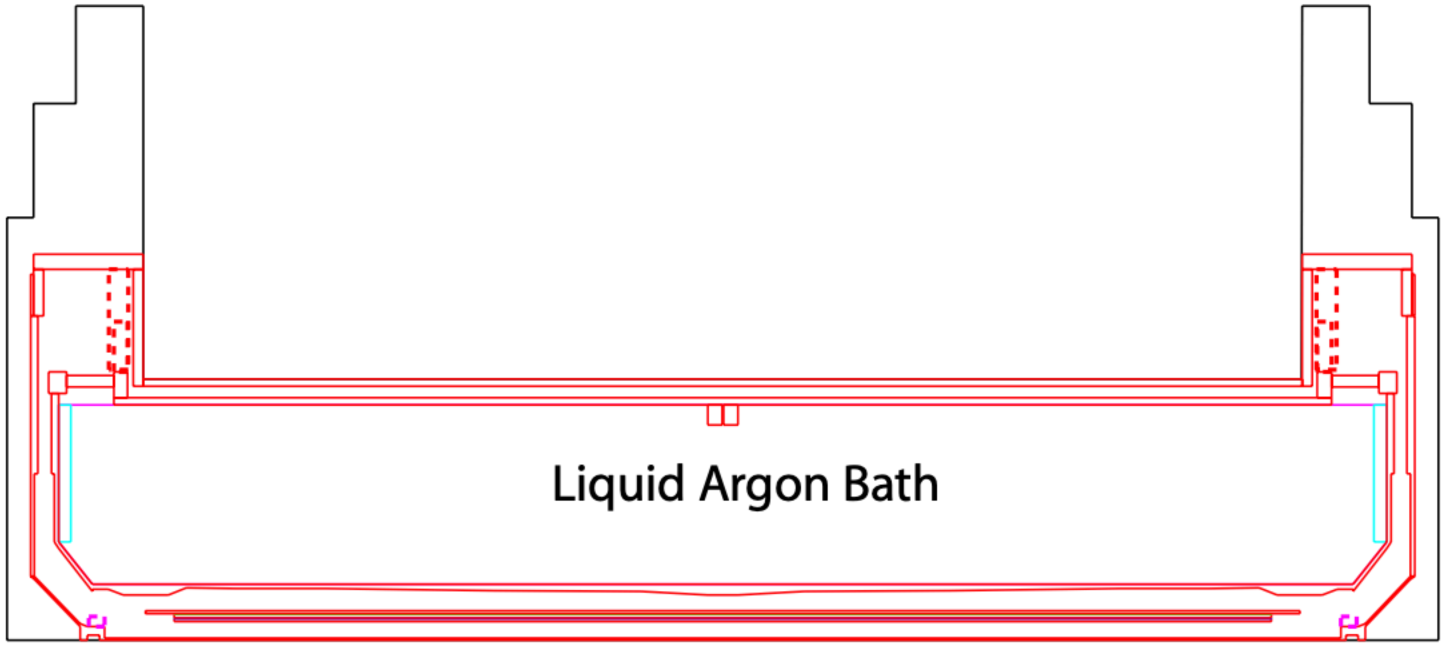
- Geometry numbers for cold LAr temperature (some uncertainty in contraction factor)

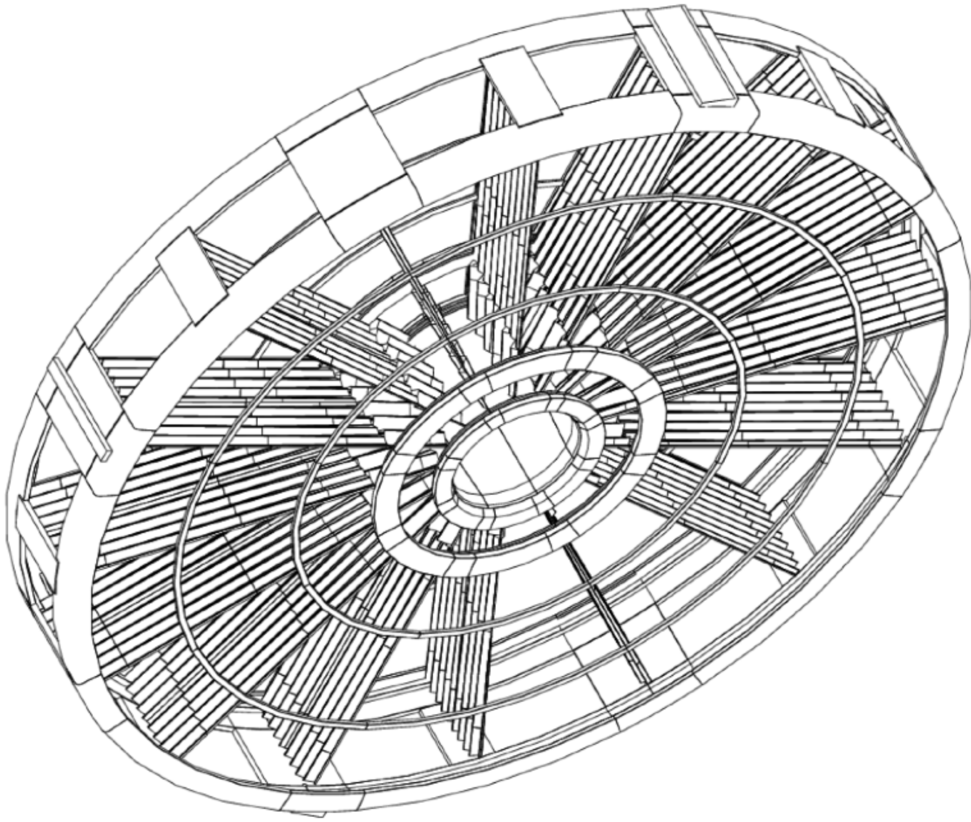


fold number	ρ (mm)	ϕ (deg)
0	1500.02	0.10619
1	1521.00	0.569751
2	1559.66	-0.573092
3	1597.20	0.576518
4	1634.57	-0.579943
5	1671.02	0.582296
6	1707.43	-0.585638
7	1743.07	0.588207
8	1778.67	-0.590596
9	1813.75	0.59285
10	1848.87	-0.595587
11	1883.36	0.59744
12	1918.02	-0.599714
13	1952.10	0.601911
14	1970.48	0.0811661

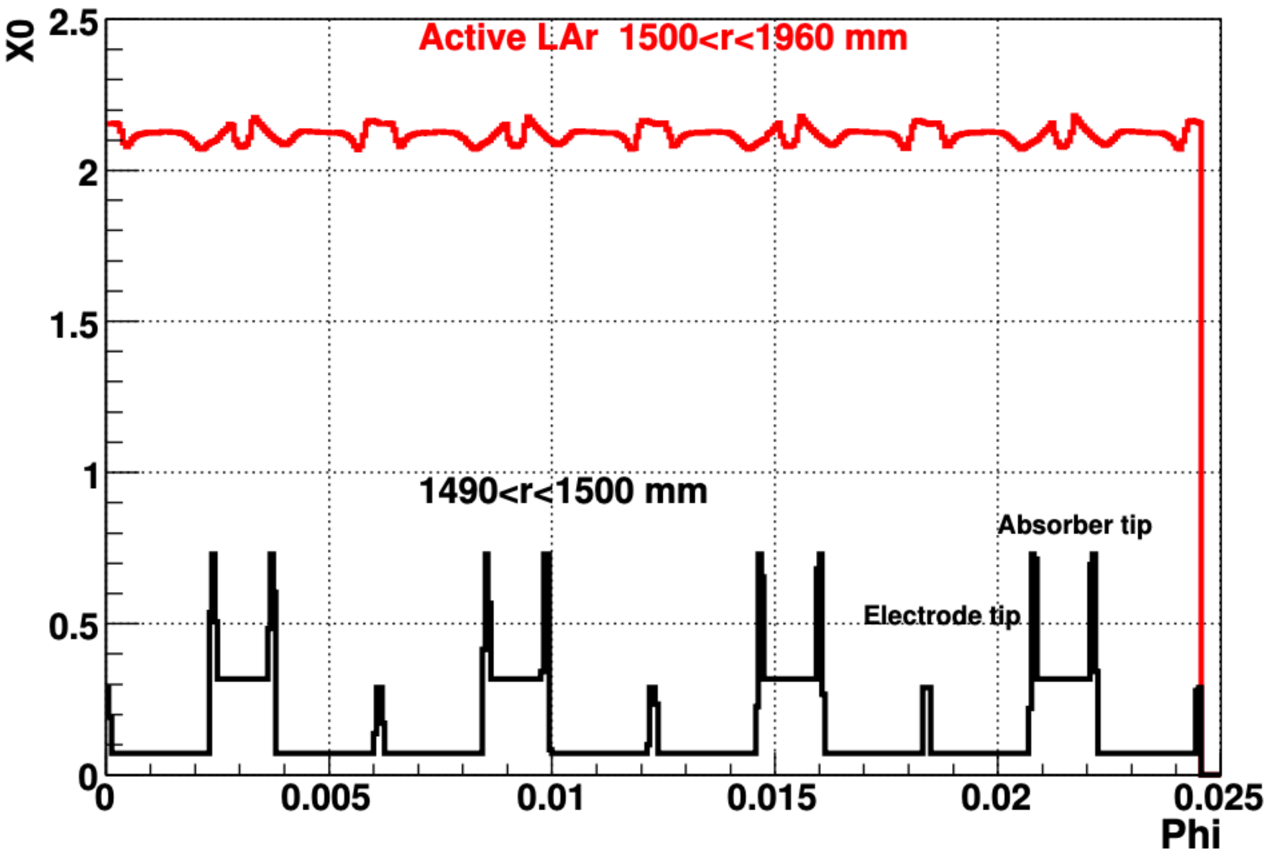


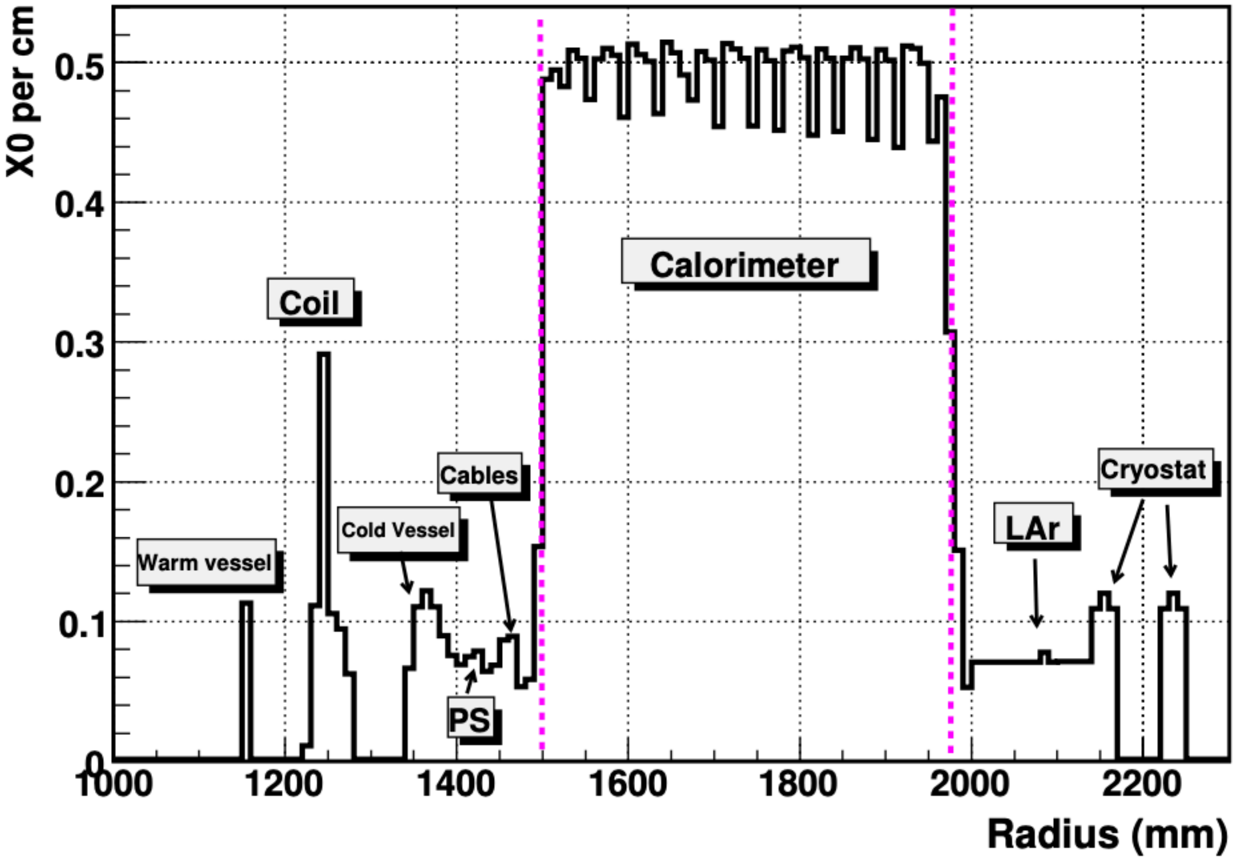

r=2.78mm
(ρ,φ)

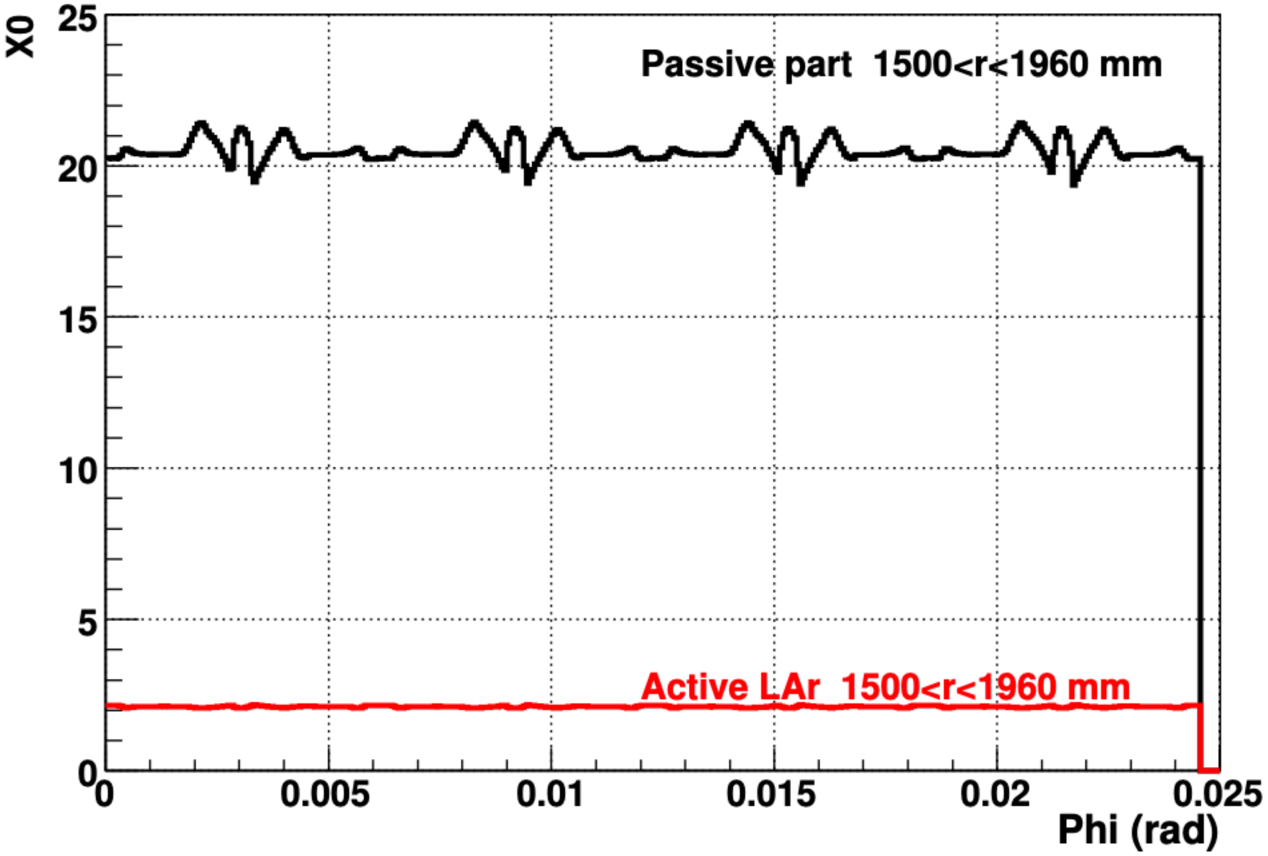

Liquid Argon Bath



Radiation length distributions: some residual structures vs phi affect slightly energy response (corrected in the BDT energy regression trained on simulation)



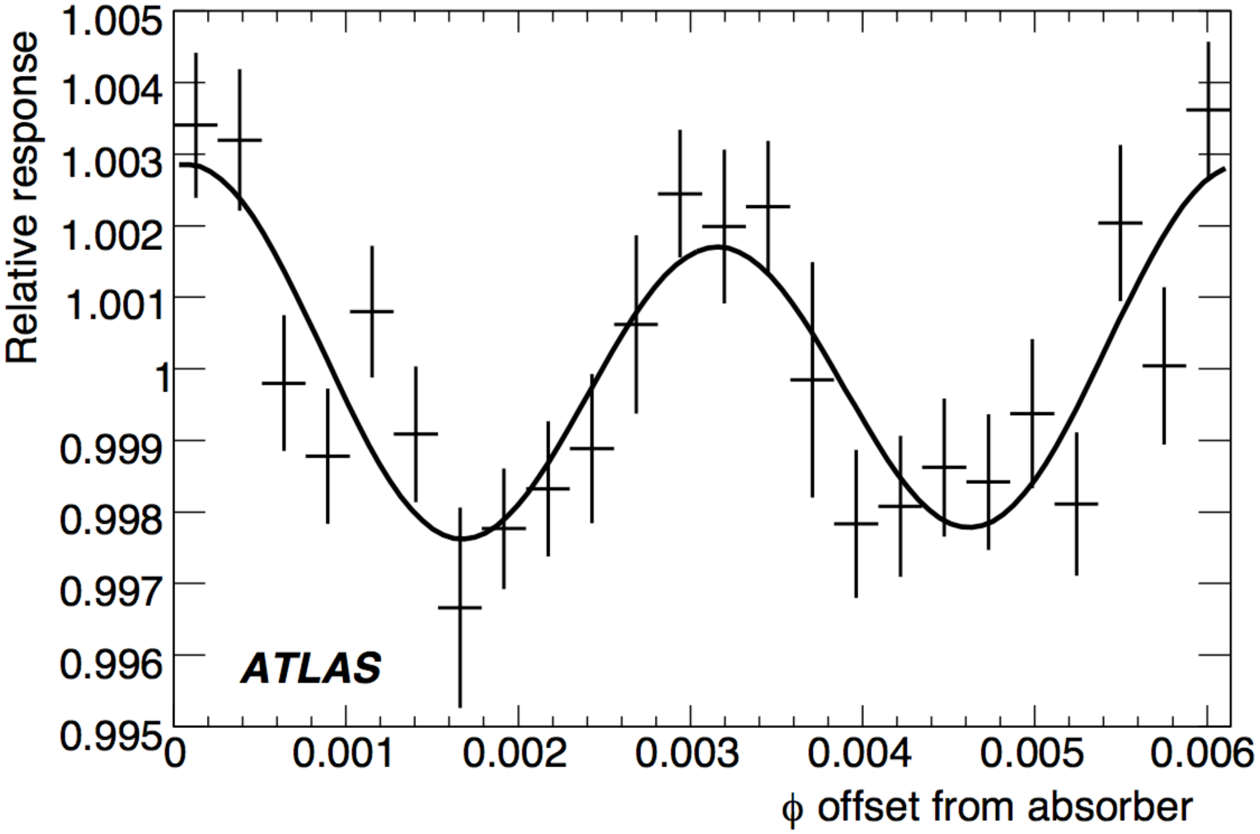




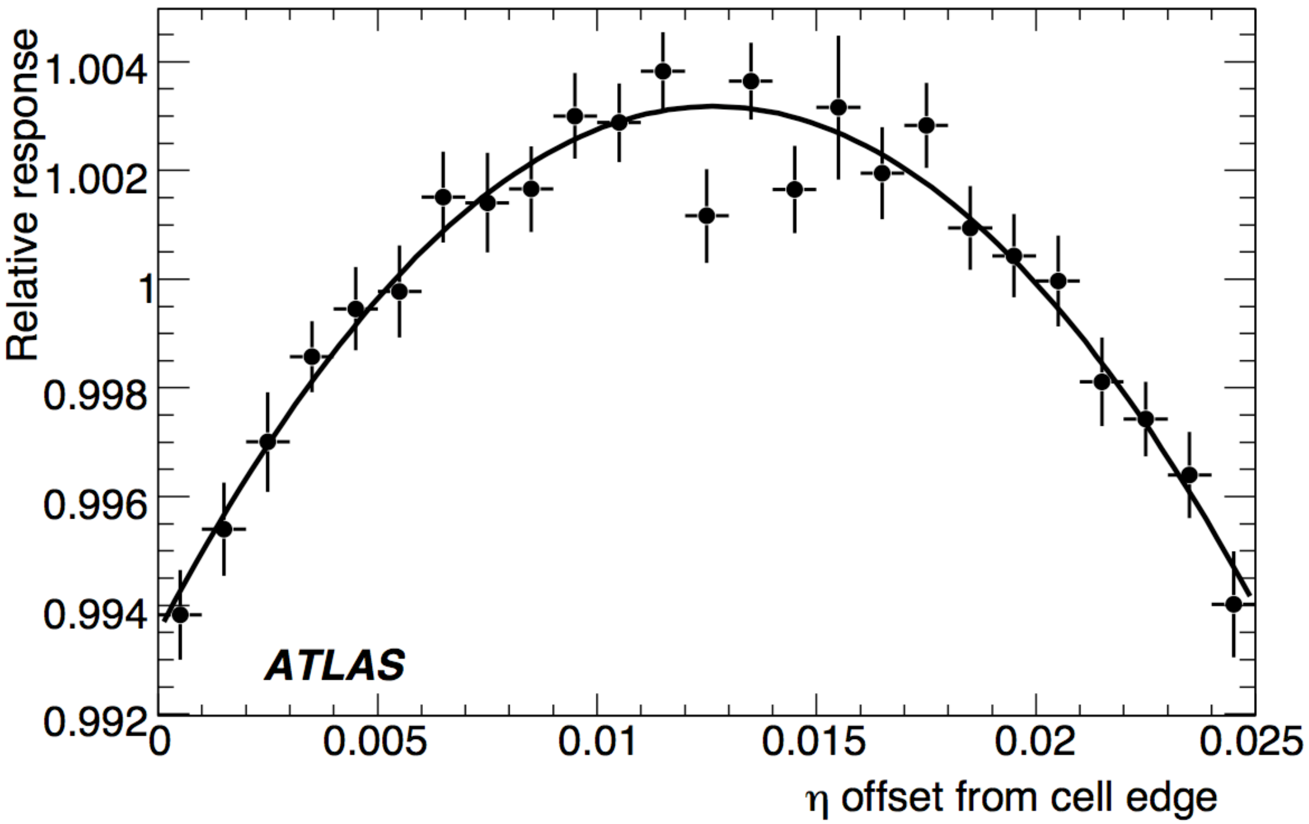
Relative energy variation vs impact position in cell

(in simulation)

Variation vs phi: related to accordion structure



Variation vs eta: mostly from out of cluster leakage



Description of material between presampler and calorimeter

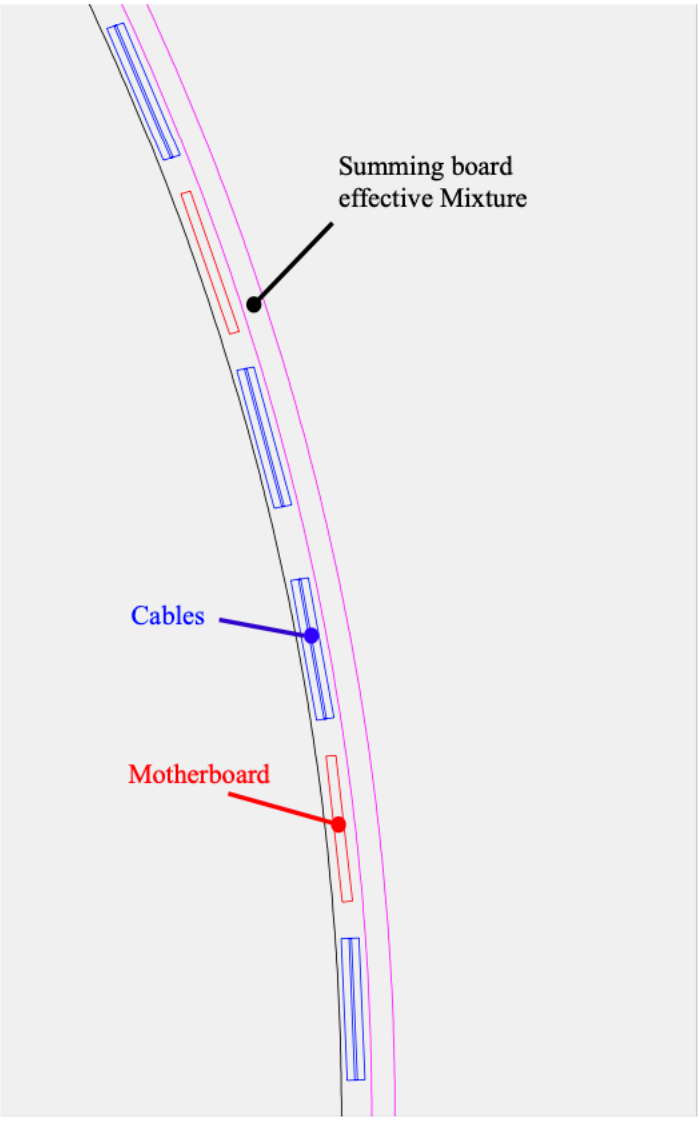
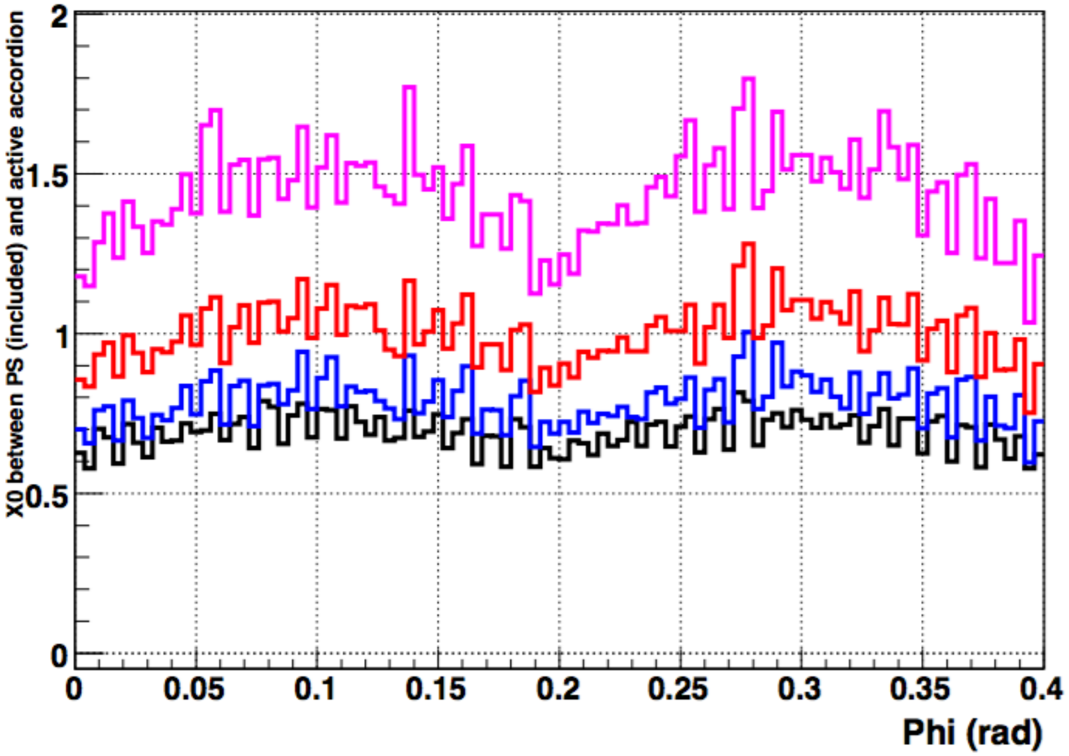
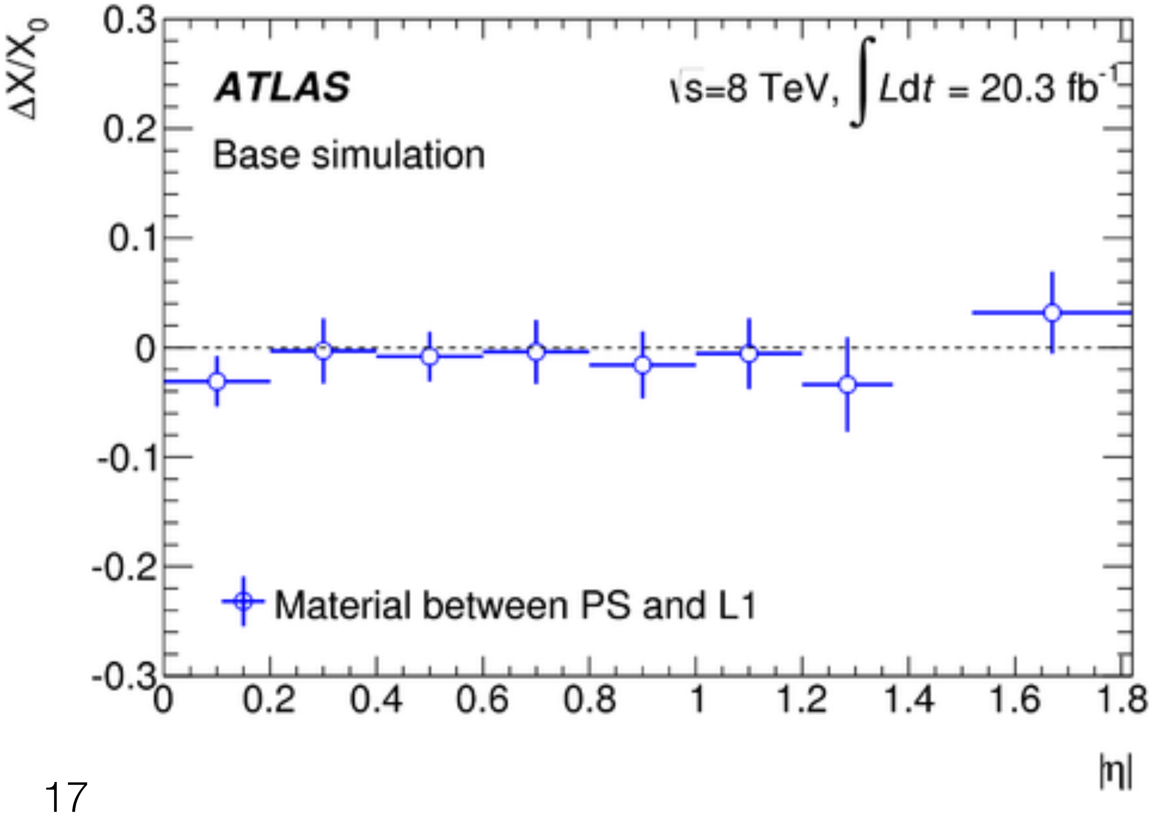


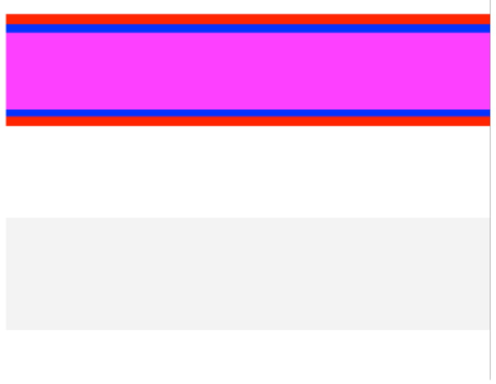
FIG. 17: *Cable and motherboard structure for one module in ϕ*

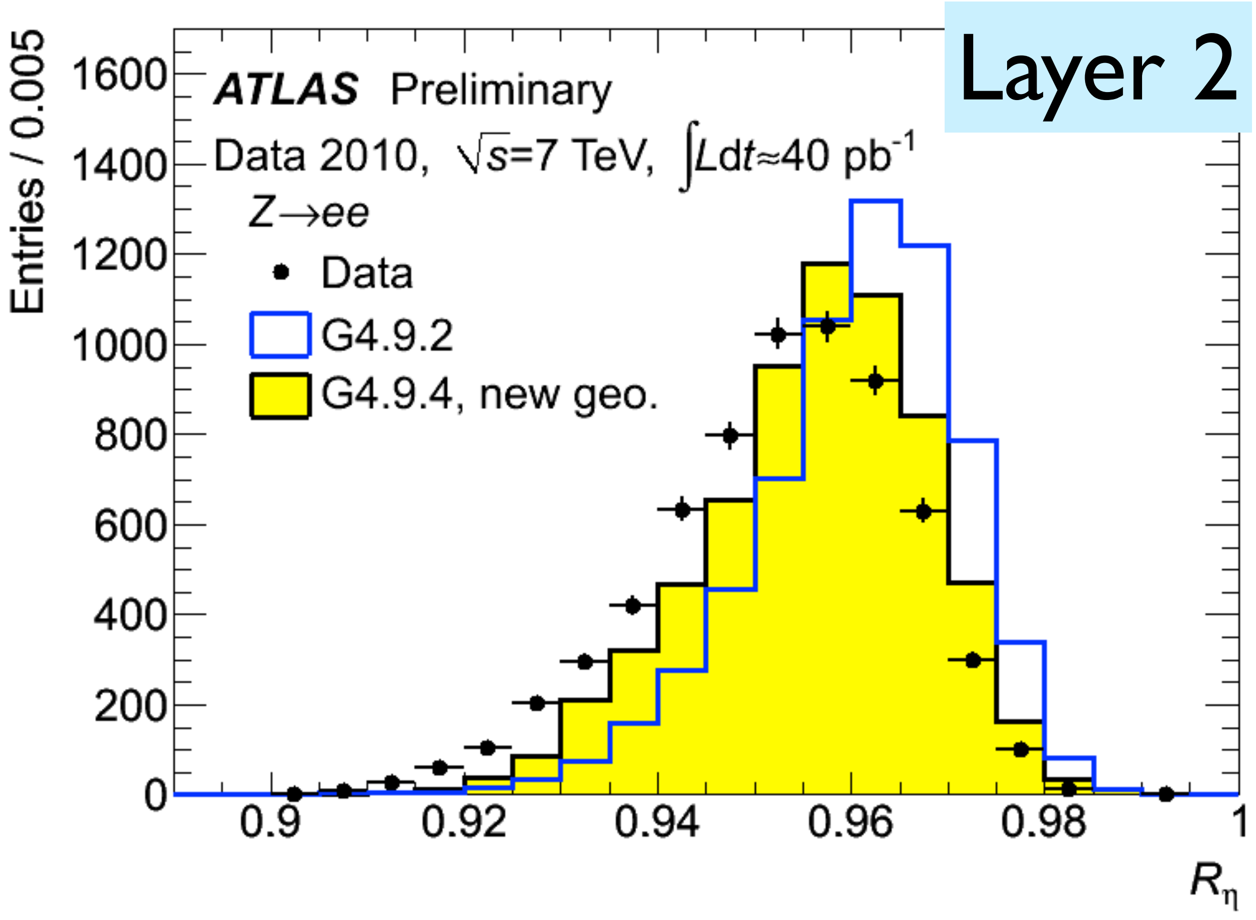


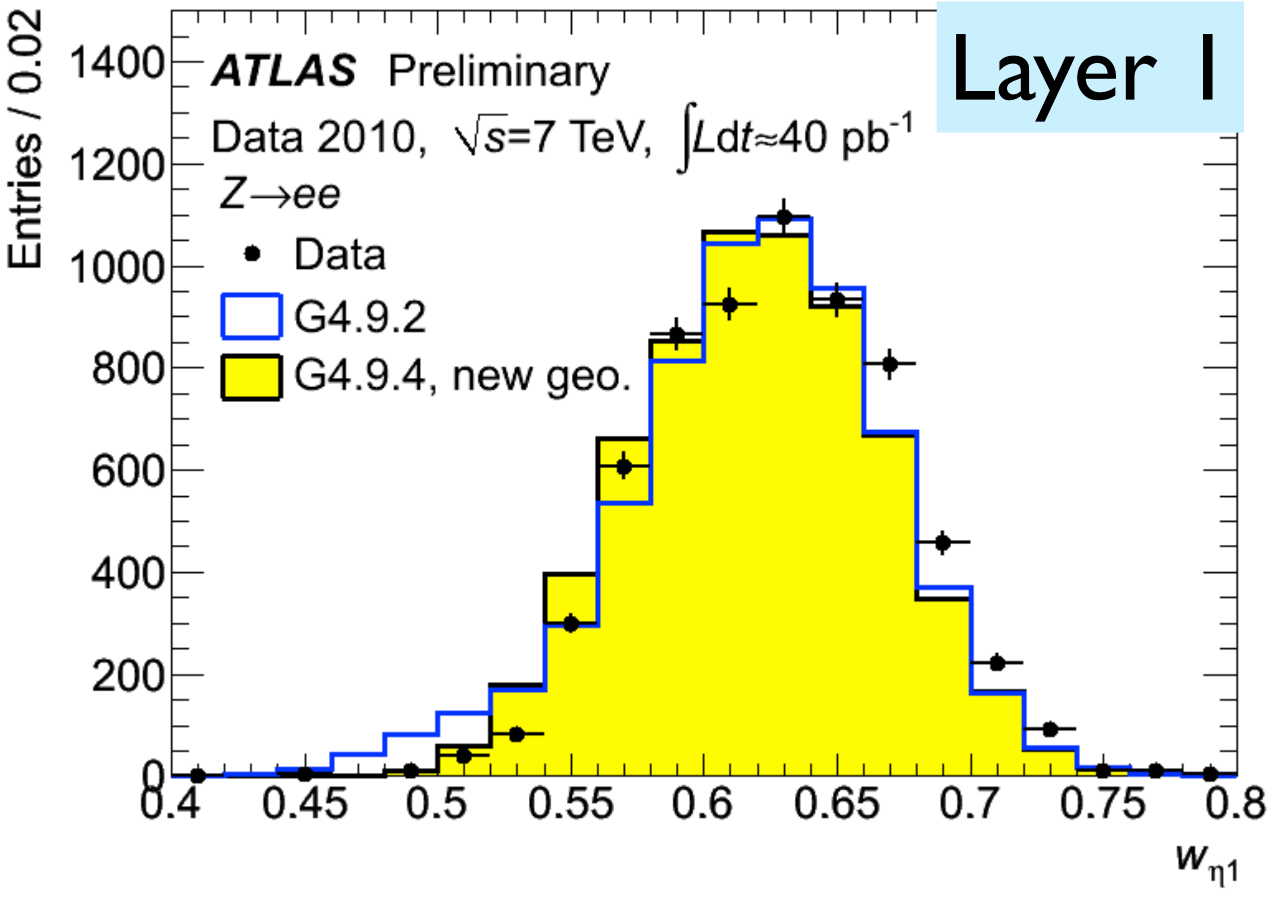


Material between presampler and calorimeter can be probed using E1/E2 of unconverted photons

Detailed description of absorber structure in geometry



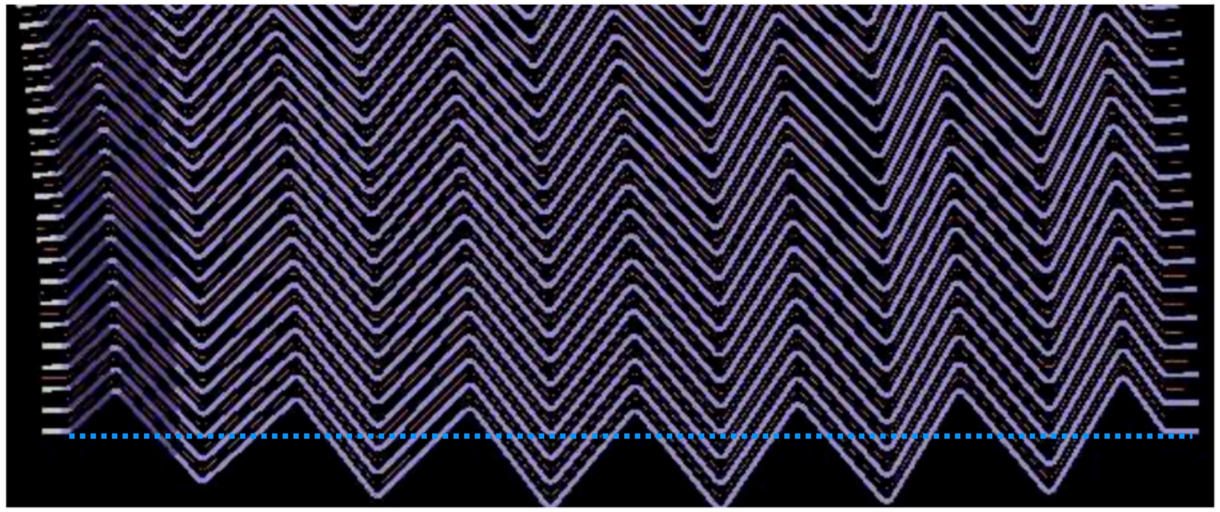




Residual difference not understood, apply "ad-hoc" correction
Identification efficiencies are measured directly on data to correct MC predictions

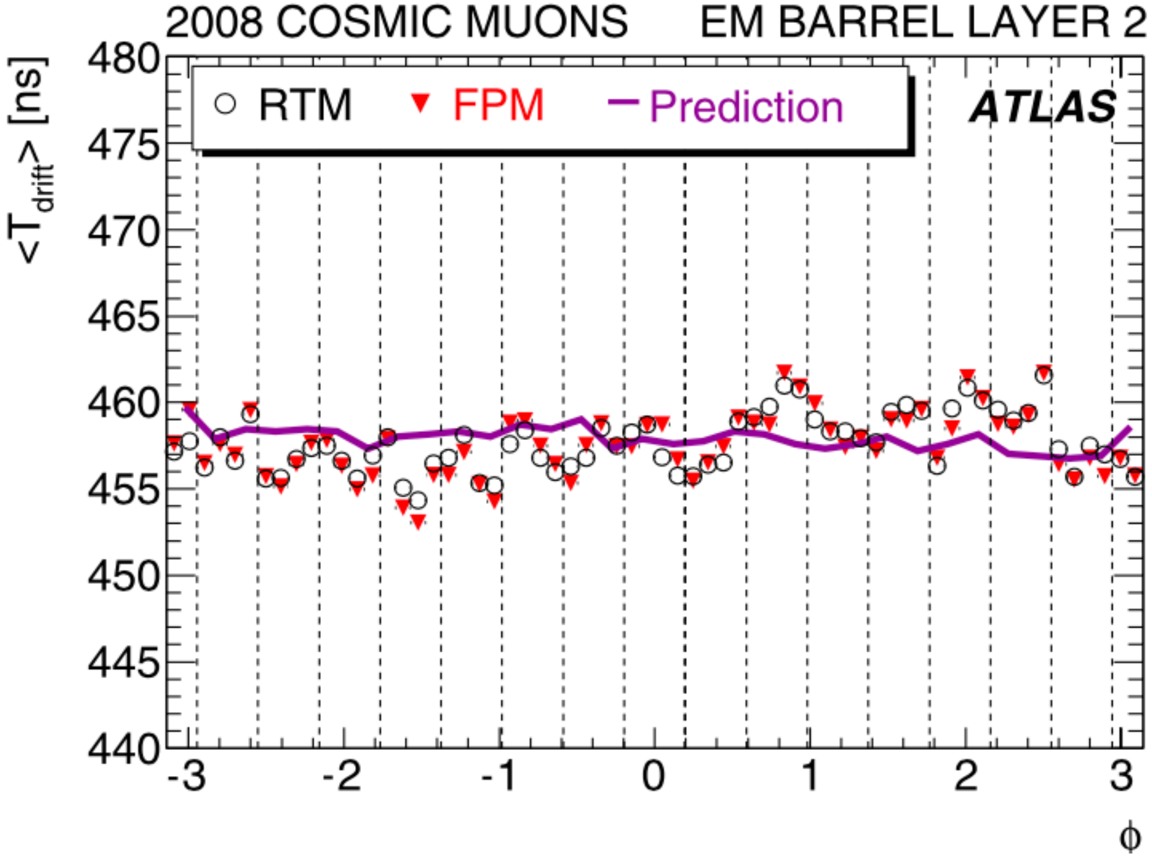
Some effects that are not included in baseline simulation

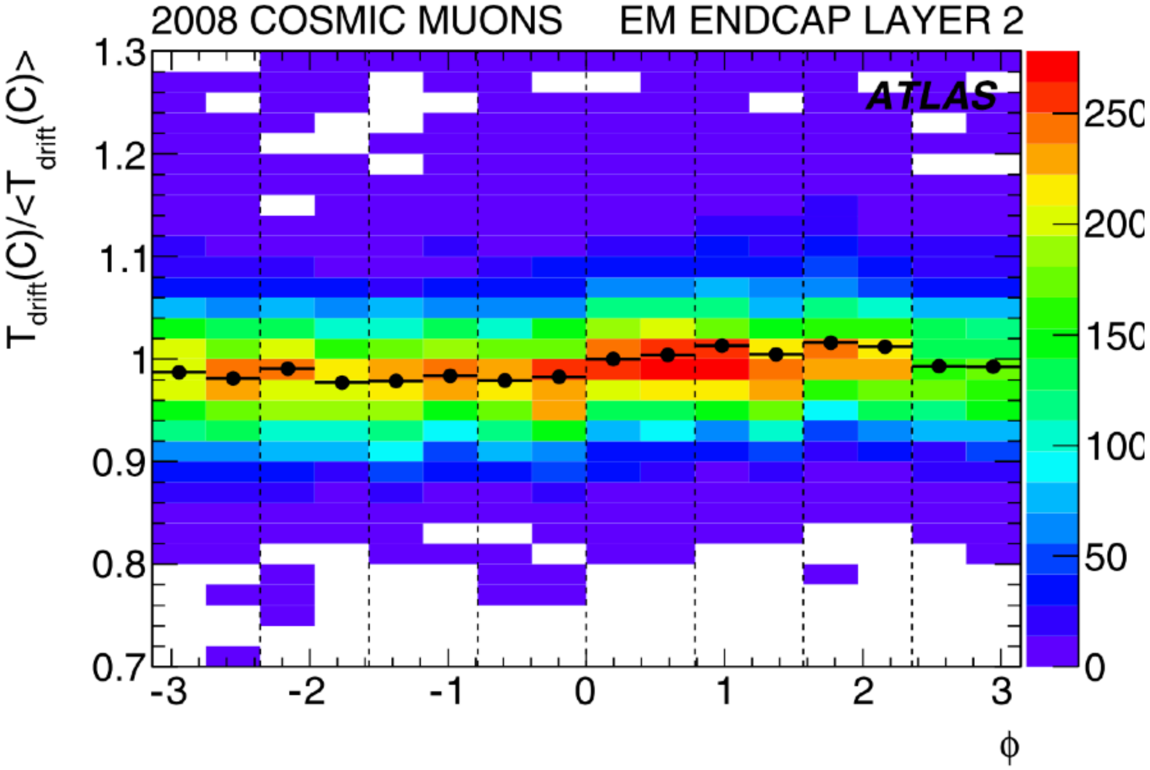
Sagging of absorber under gravity



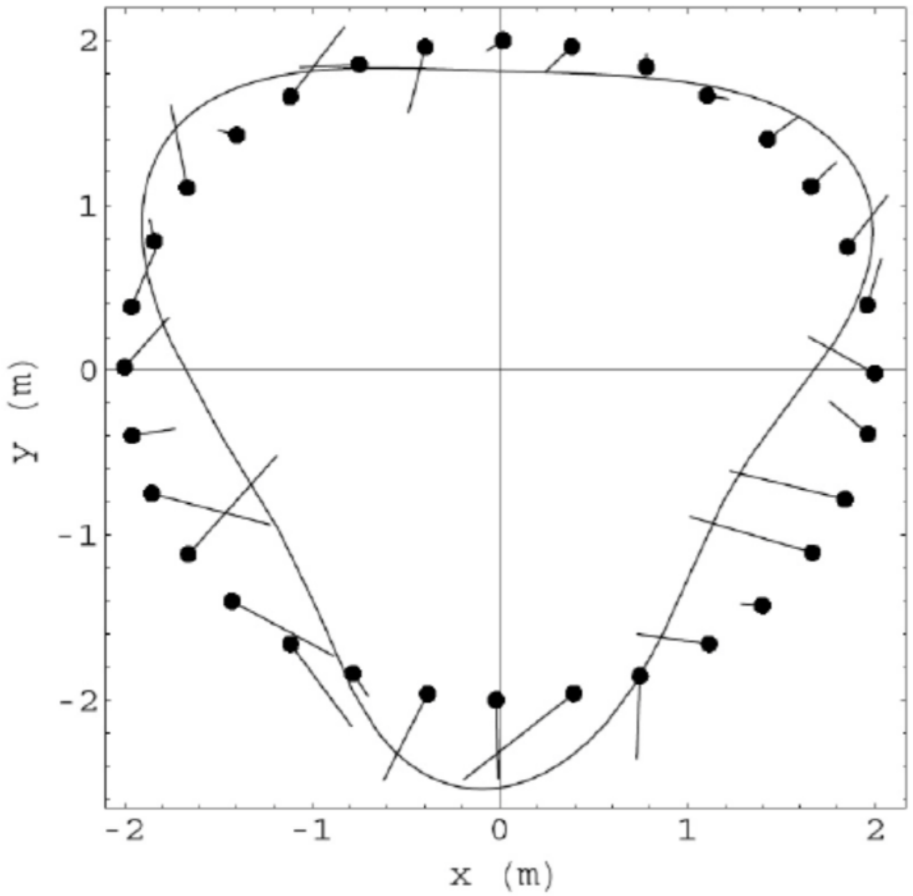
Impact on position measurement (corrected in data)
and energy measurement (mostly in endcap)

Can be checked with dedicated drift time measurements in situ

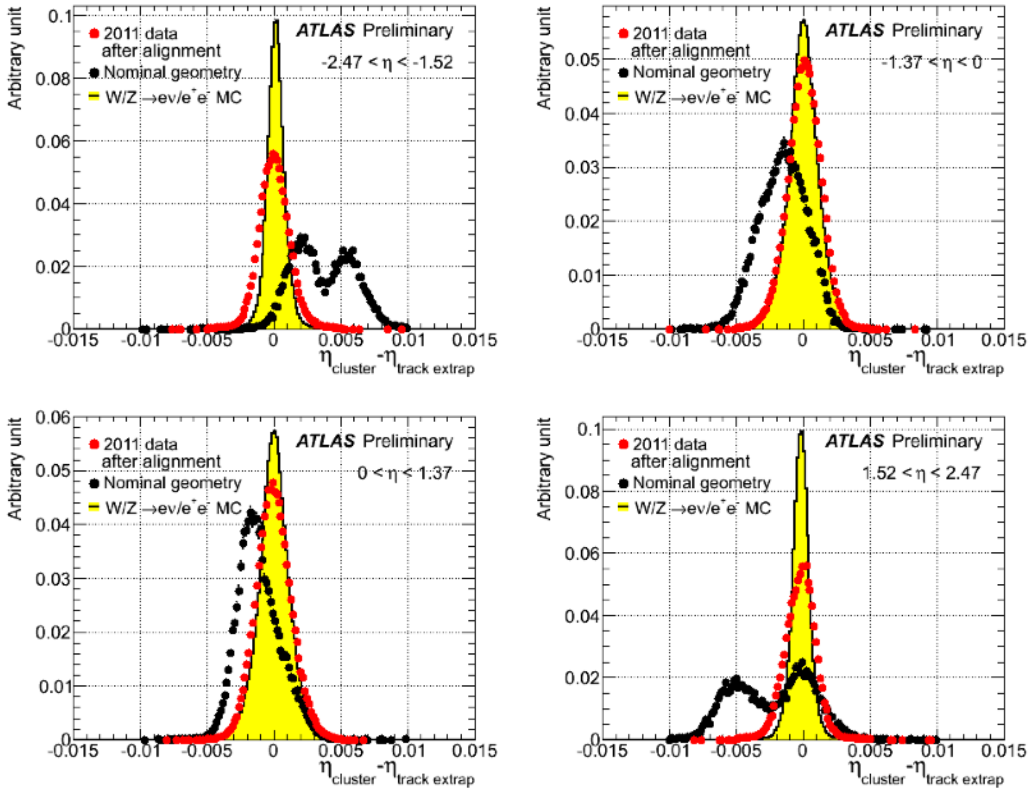




Deformation of calorimeter shape



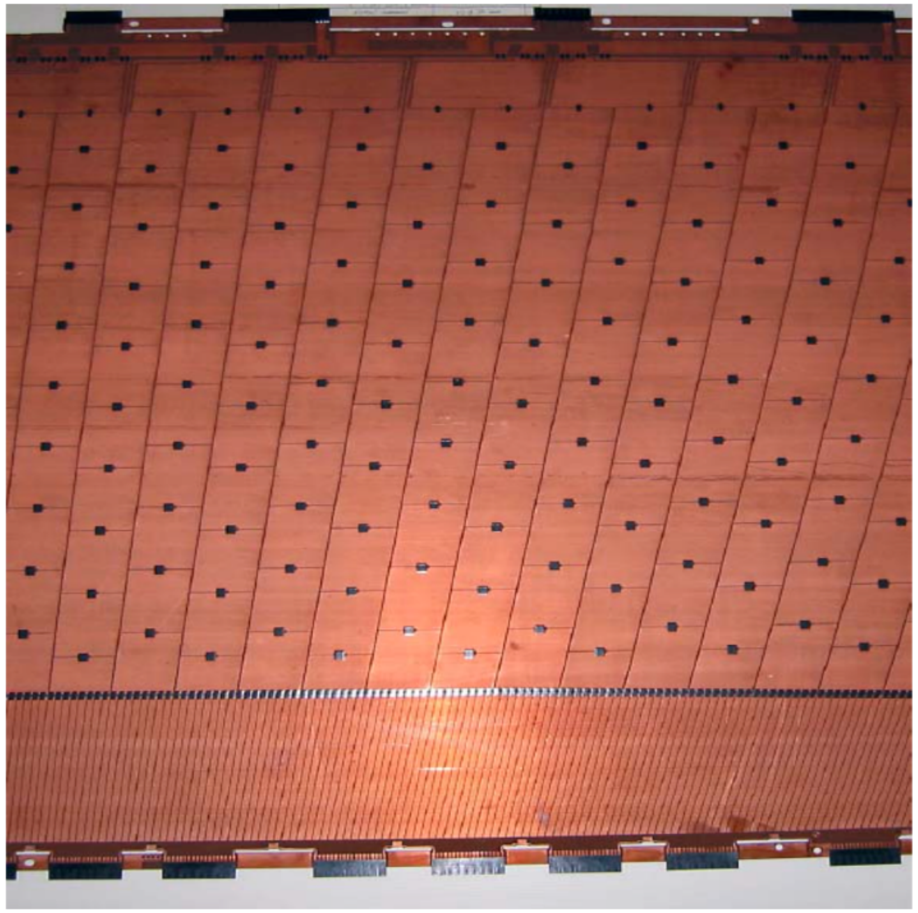
This affects mostly the position measurement-> corrected with effective alignment corrections derived from electro data

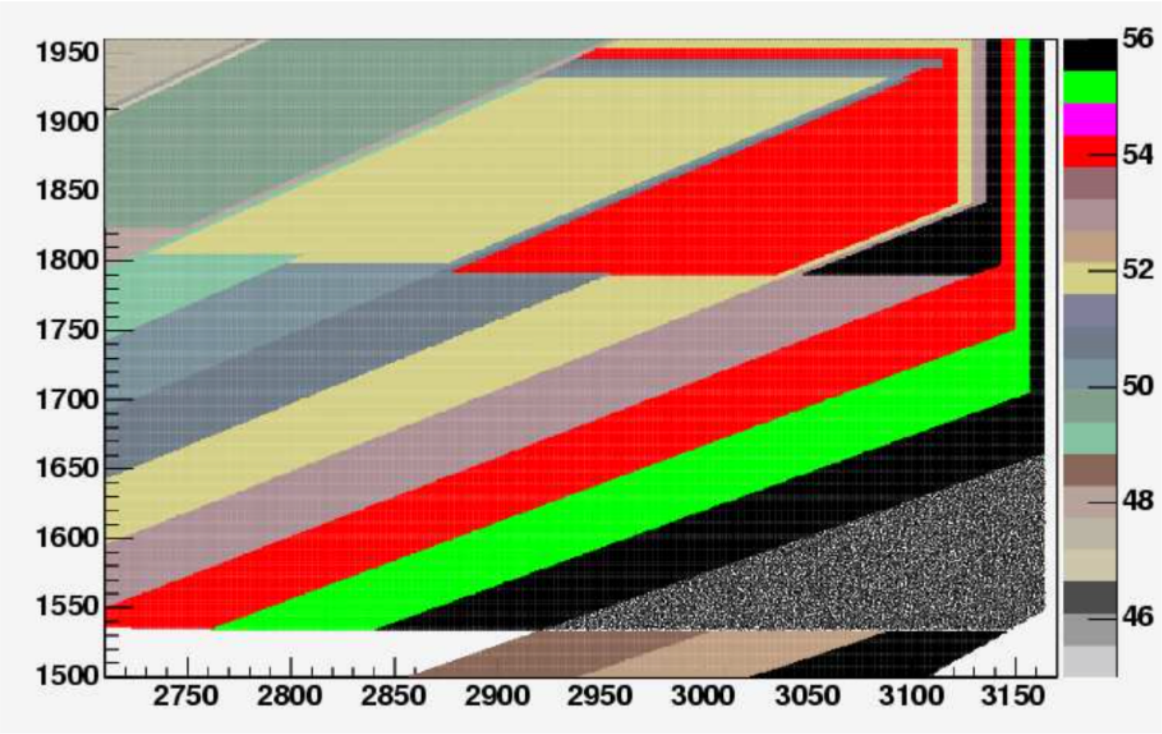


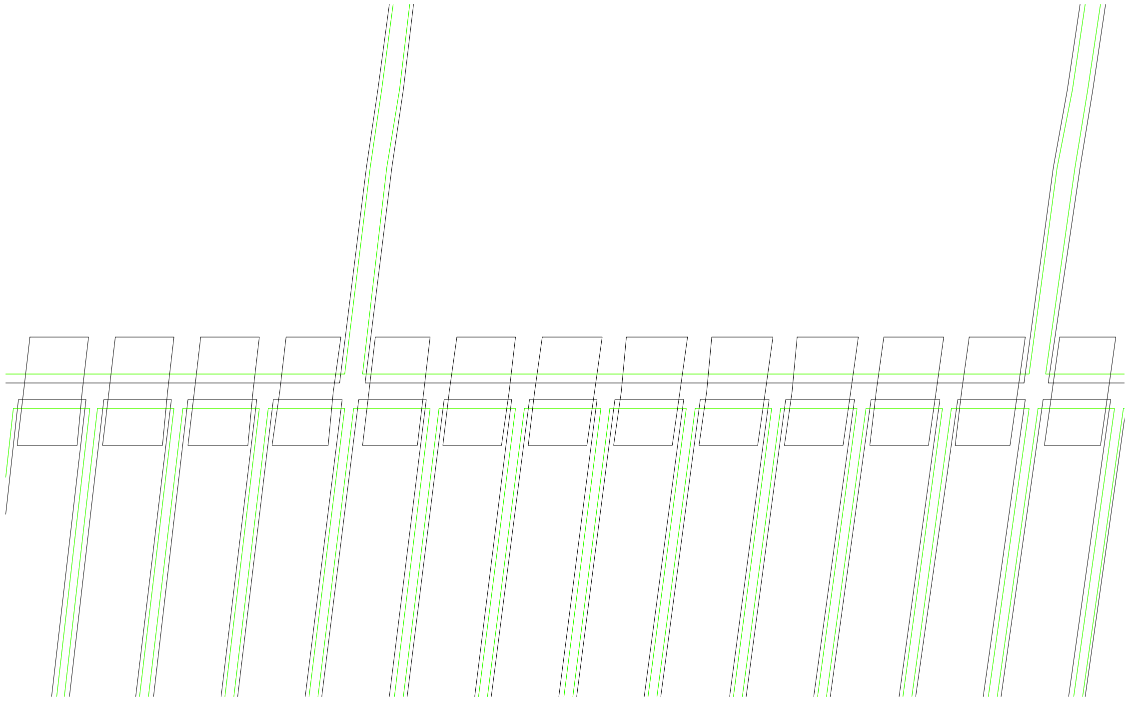
Simulation of energy collection

- For each Geant4 step
    - divide in smaller sub steps to probe properly field variation
    - compute the cell in which the step is
    - converted energy to "effective" energy
        - i = q. vd . E/V
        - based on pre-computed 2D maps in r-phi plane
        - don't attempt to estimate event-by-event fluctuation of the pulse shape, only record the effective energy (CPU, memory and disk usage)
    - take into account sharing of energy between different cells in eta (mostly relevant in the first layer where cell size is small)
    - Simulation is run by default assuming nominal HV over the full calorimeter but we could also run with reduced /no HV and some specific electrodes.

Modelling cell granularity in eta-depth
Can be probed using muon tracks



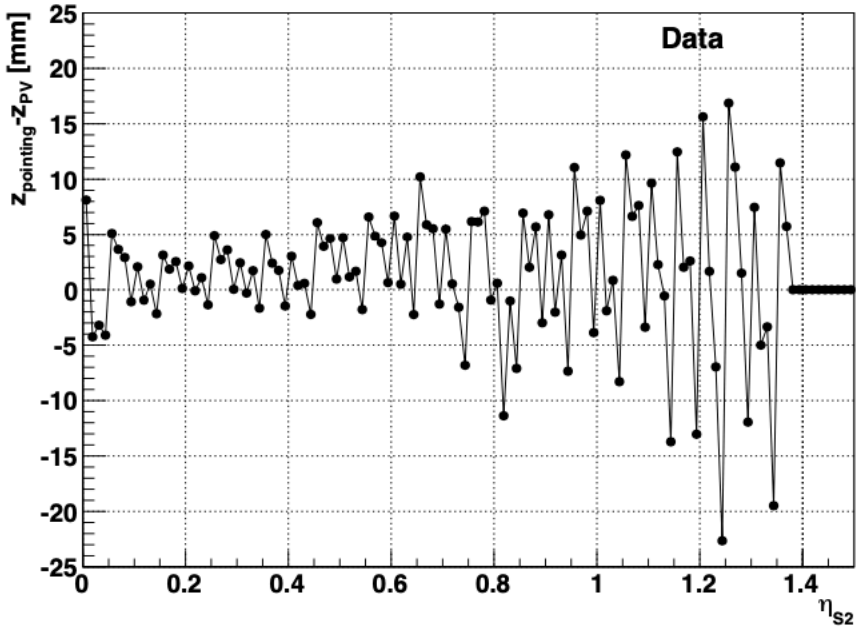




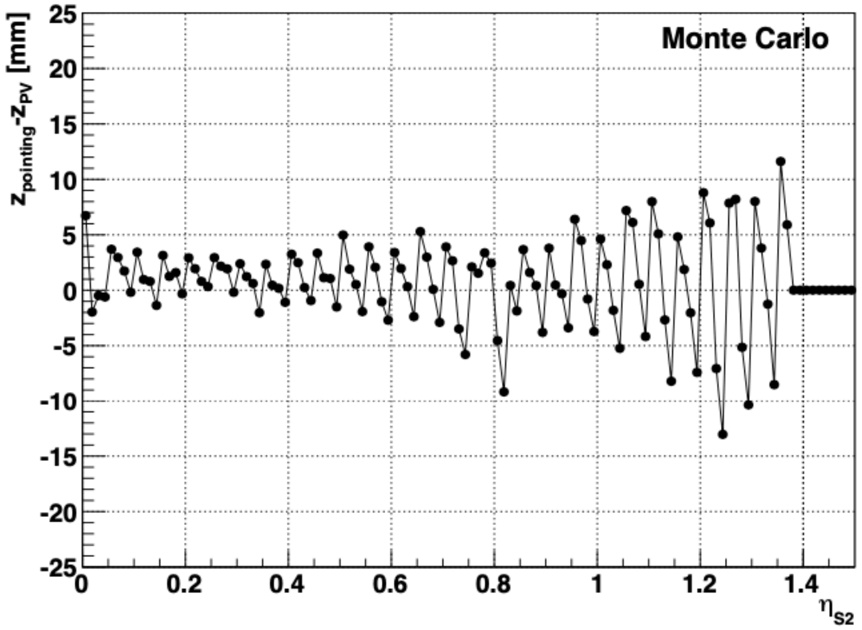
Possible small uncertainties in description of electrode geometry
-> ~1% uncertainty on E1/E2 when using muons to check the intercalibration (muon energy deposit proportional to path length)

Impact of readout strips on position measurement can be seen on data , ~reproduced by simulation in barrel

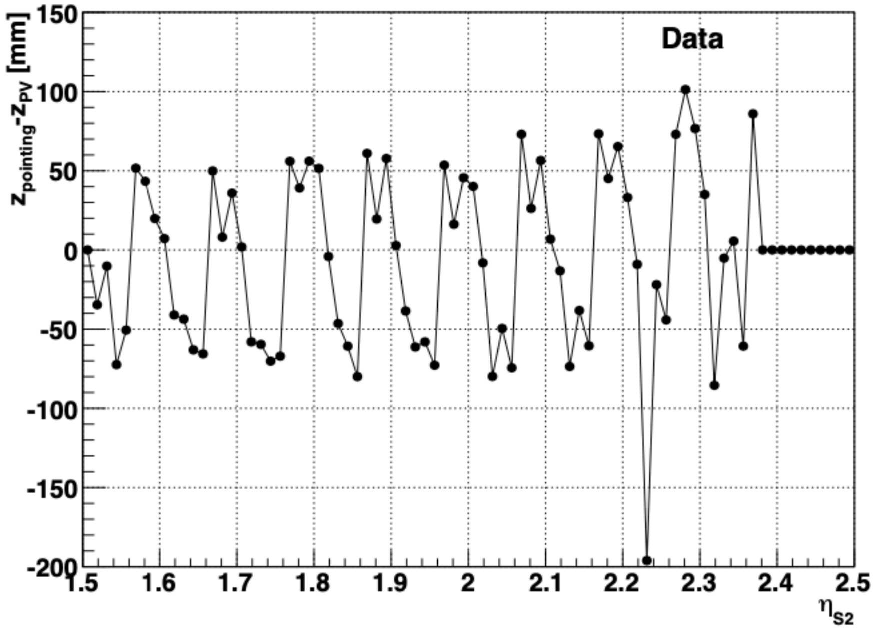
(Estelle Scifo thesis)



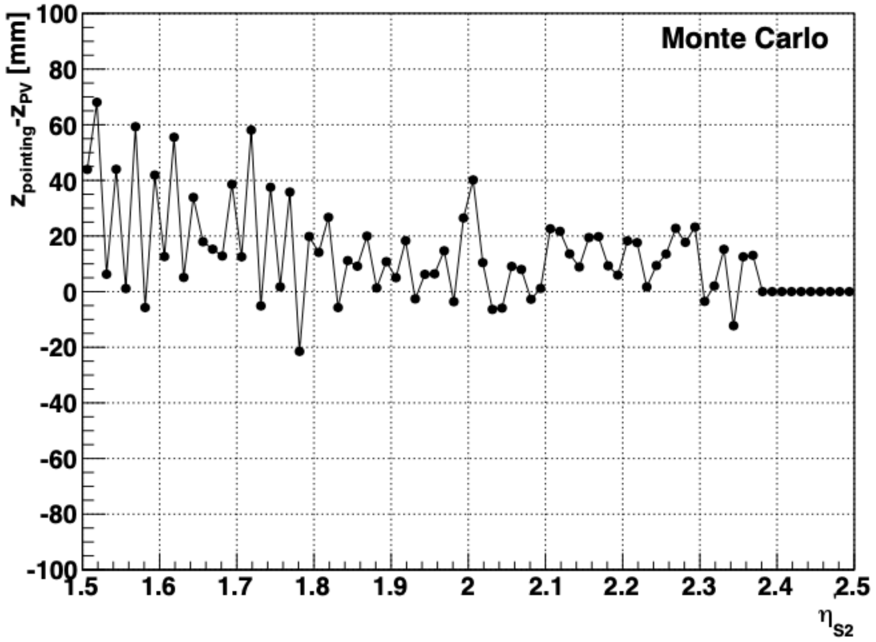
(b) Barrel A



(b) Barrel A



(d) End-cap A



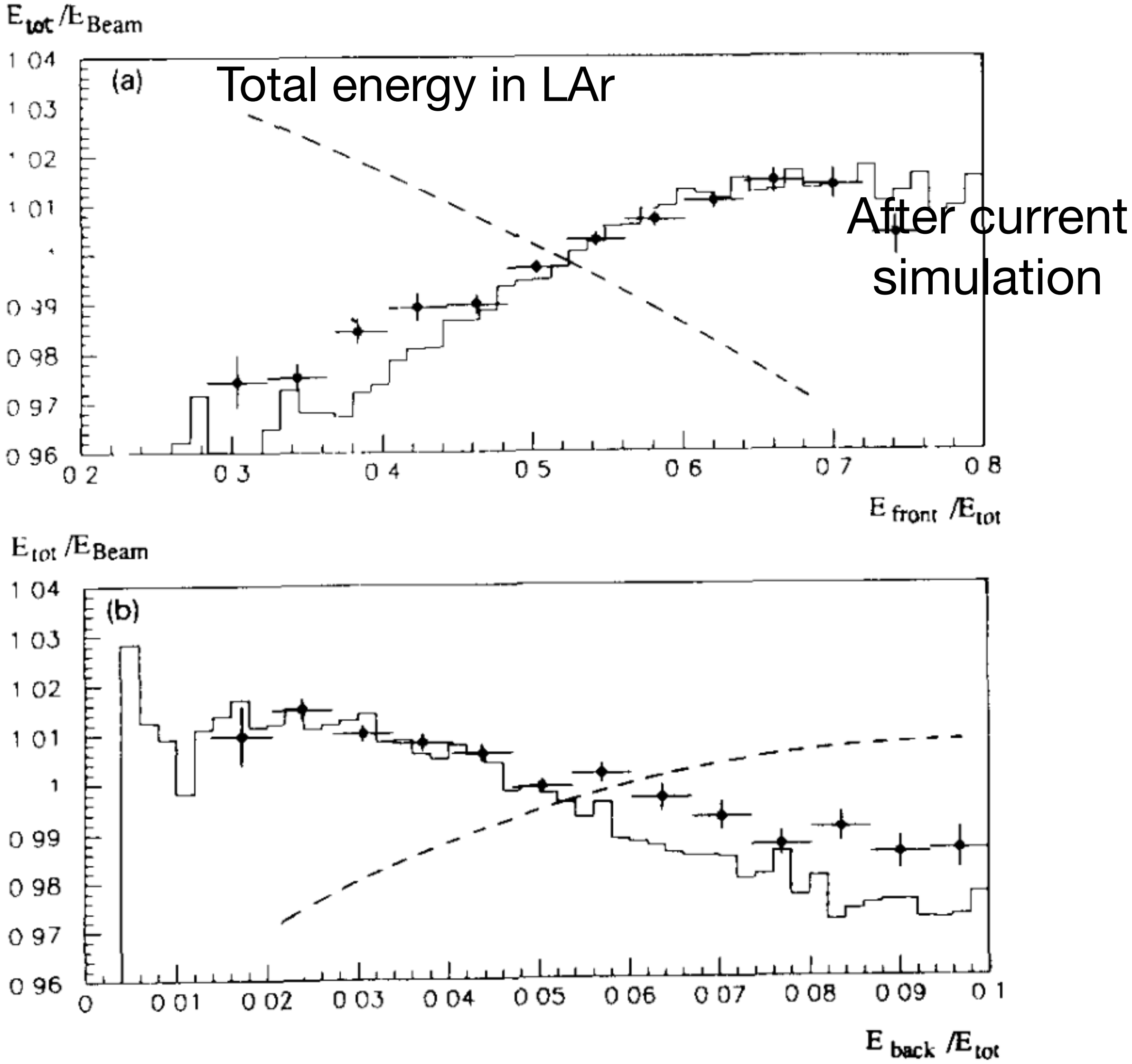
(d) End-cap A

Impact of varying gap size and charge collection modelling

If gap size varies along shower axis, response depends on position along shower depth

Example below from a 1991 prototype with opening gap geometry (constant accordion angle)

For ATLAS case: small gap variation in each accordion section taken into account

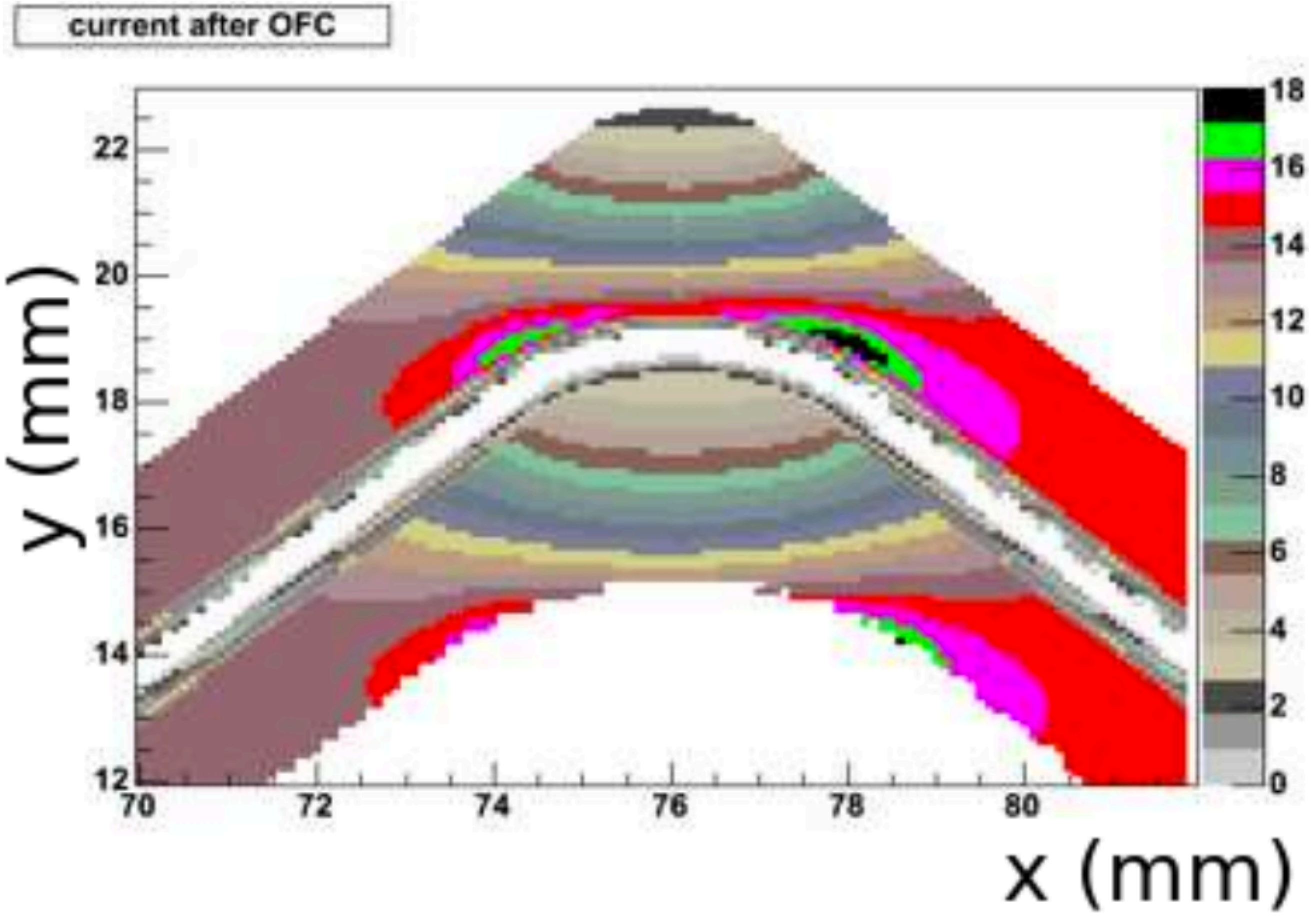


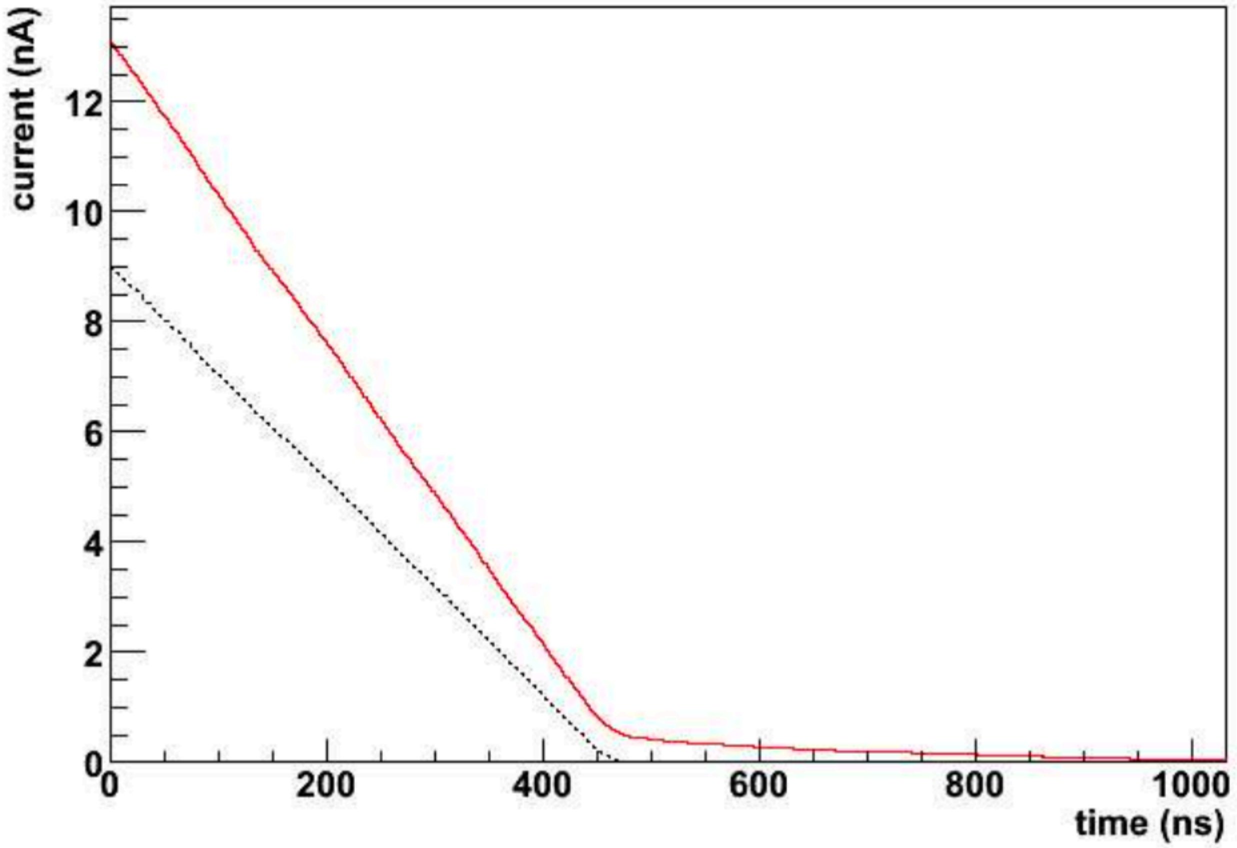
Total energy in LAr

After current simulation

Charge collection effect: Current maps

- one map per accordion fold
- produced from electric field map
- simulate at each point of the map the current from a single energy deposit, take into account drift velocity = f(E) and recombination effects
- convolve the current vs time with optimal filter coefficients to get the effective measured current
- store this value in the current maps that are accessed by the G4 simulation

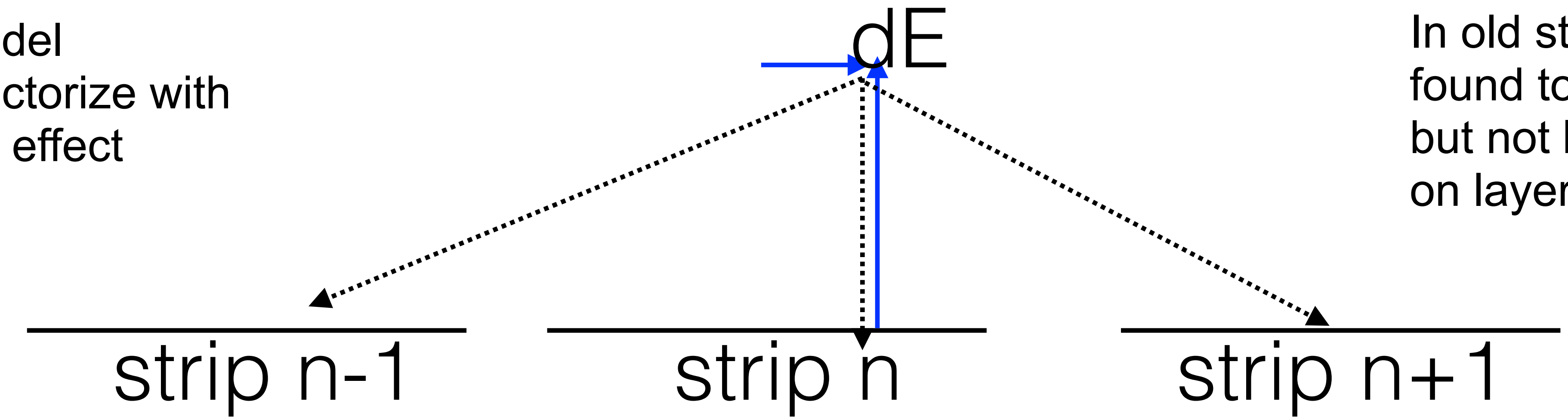


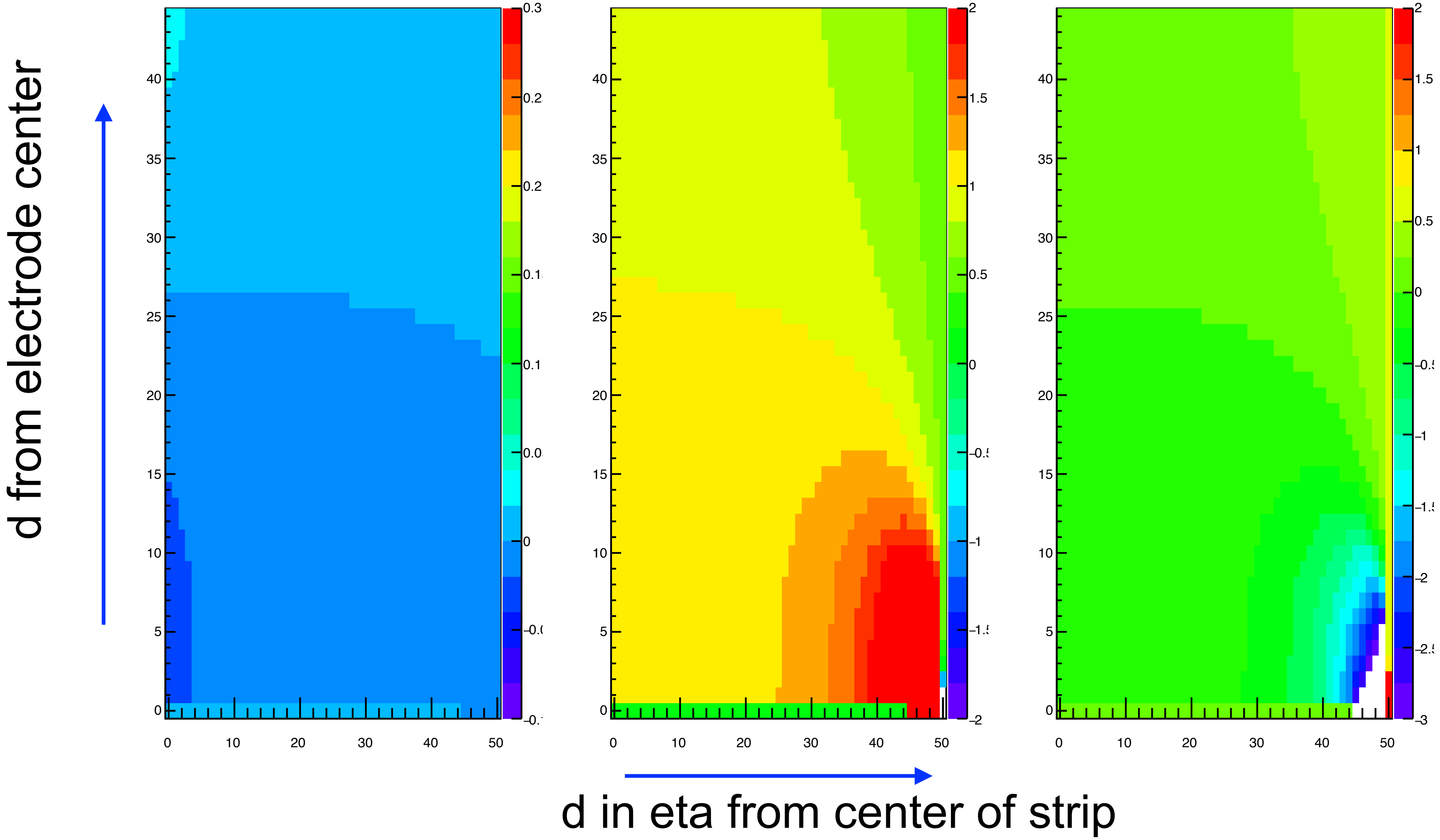


Charge collection effect: energy sharing

Simple 2D model
assumed to factorize with
accordion fold effect

In old studies was
found to have a non-zero
but not large impact
on layer 1 shower shapes



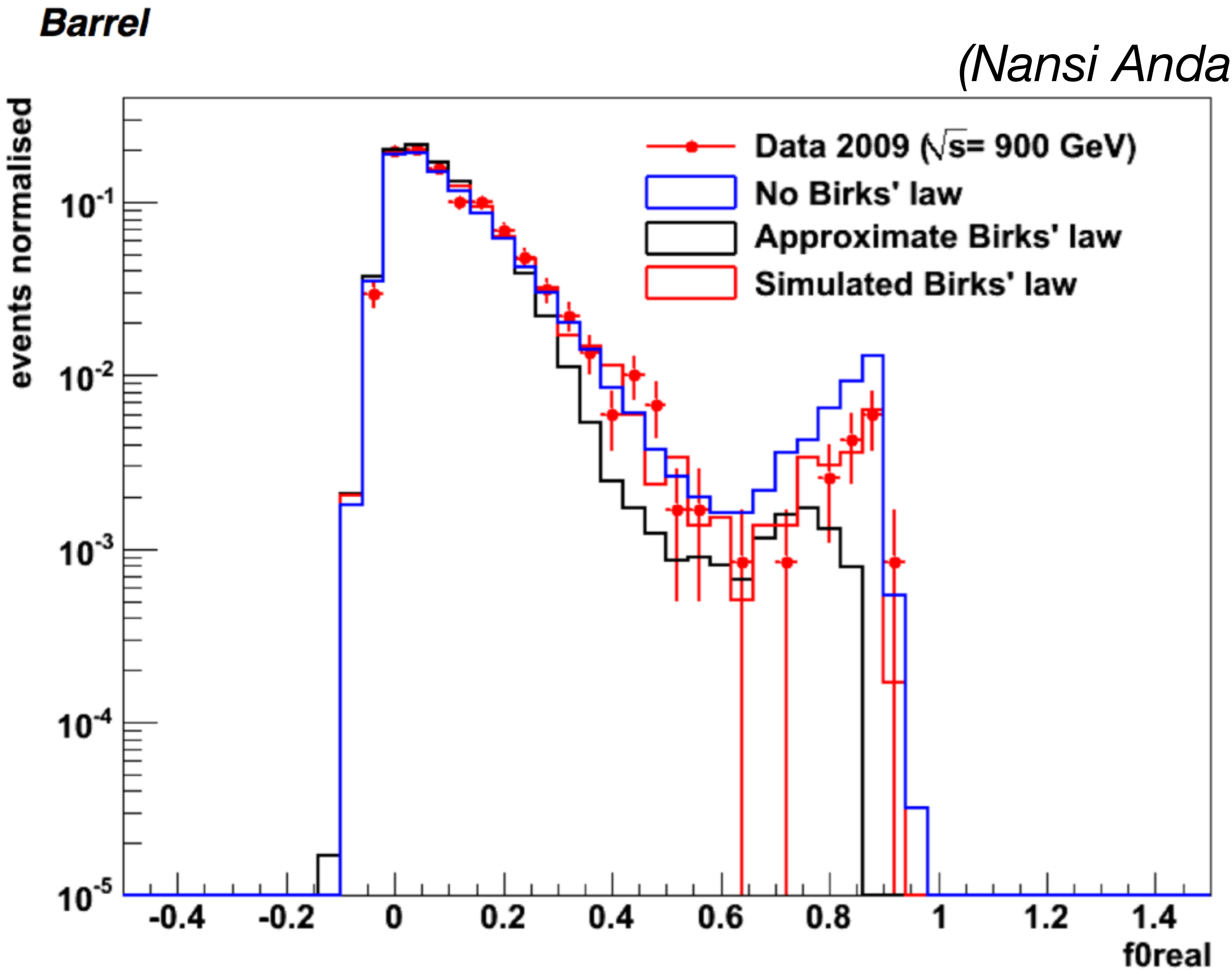


Birk law

Response ~ A / (1 + k/Efield *dEdx)

For large dEdx visible energy is reduced by recombination between electrons and ions (formula above was actually slightly improved for very large dEdx, relevant for exotics highly ionizing particles)

Small effect for EM showers (but was quite visible in low Et cluster from 2009 MinBias events (contribution from low Et hadrons, including pbar annihilation), mostly in the presampler.

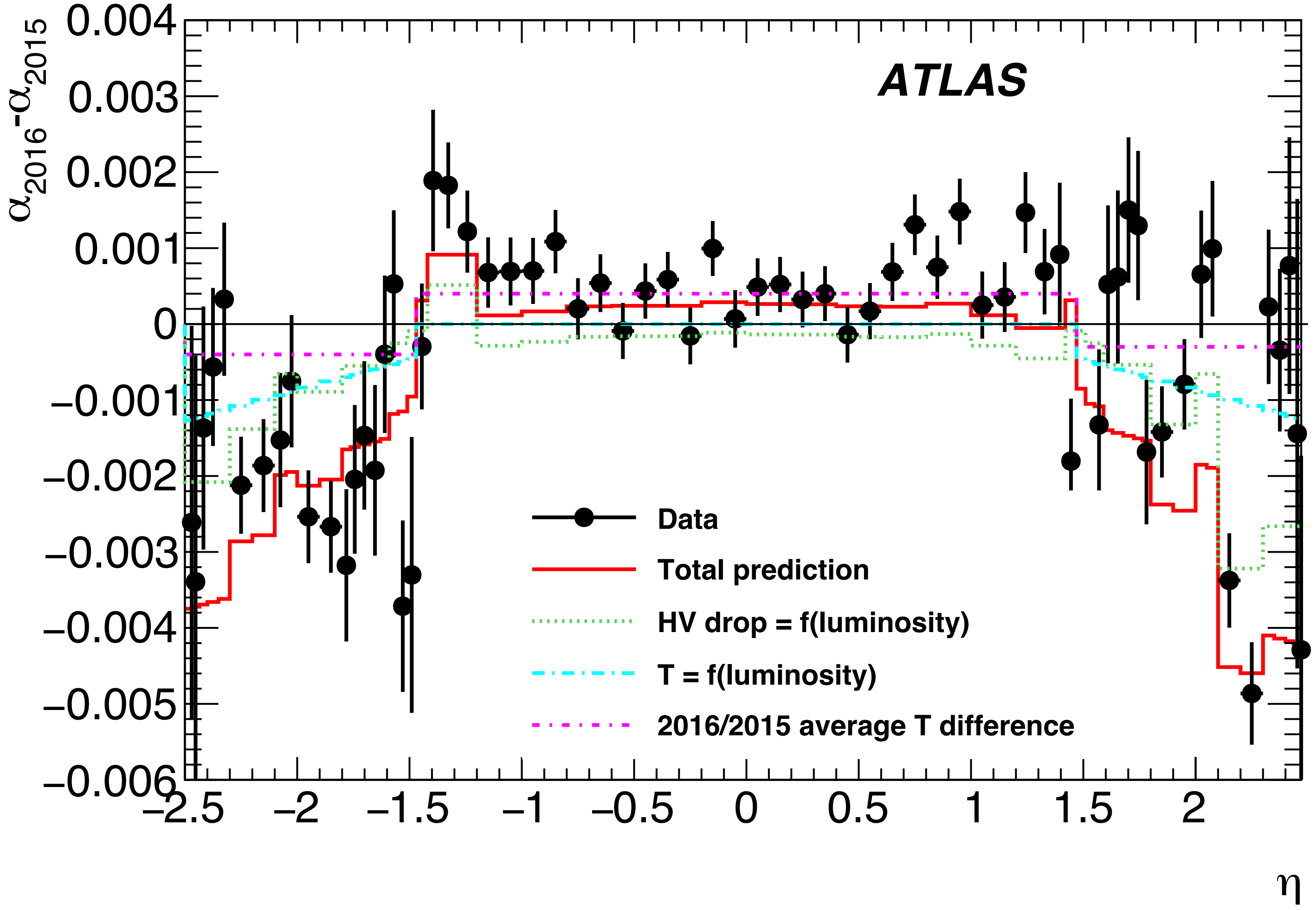


(Nansi Andari thesis)

Some effects not included in charge collection model

- space charge effects
- HV drop at high ionisation current
- increase of LAr temperature from energy deposited by collision (response change = -2%/K)

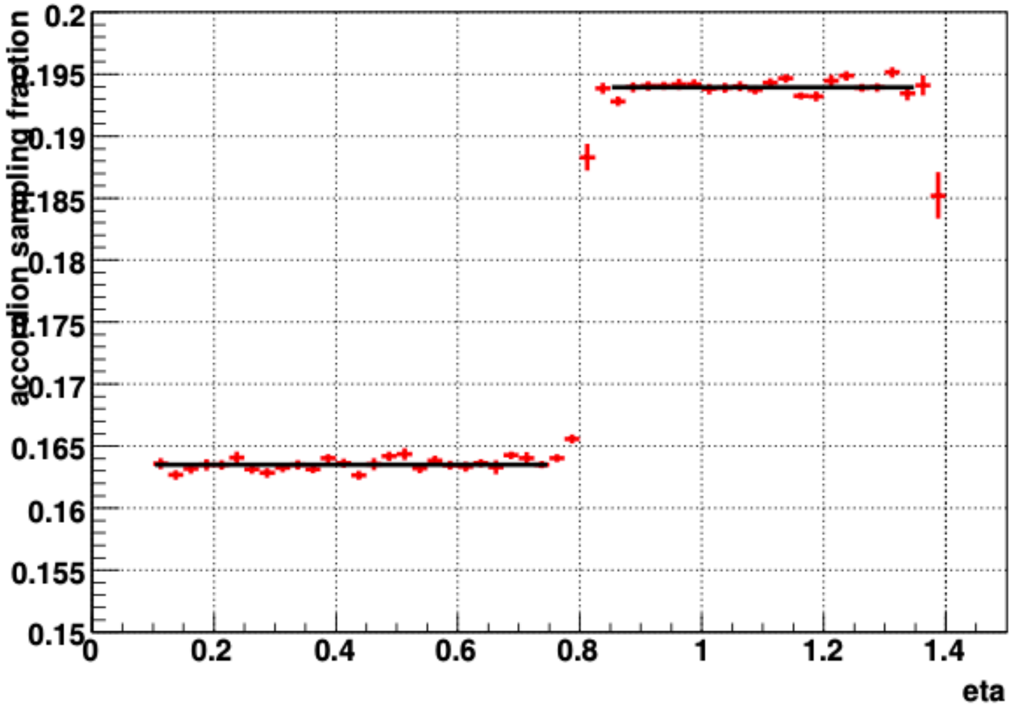
Effect from HV drop and LAr temperature change are noticeable but small enough that we don't need to simulate them

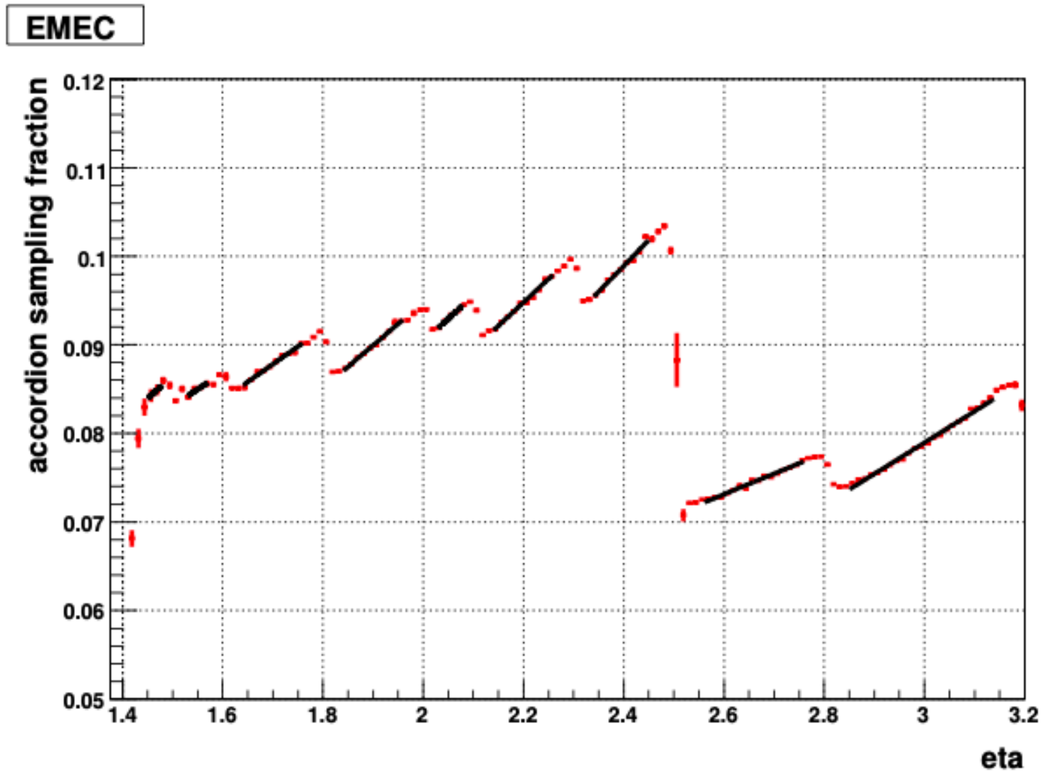


Digitization step

- Start from effective energy from simulation, correct by sampling fraction
- simulate cross-talk in readout electronics, sharing energy across neighbour cells (in layer or in eta)
- apply "average" pulse shape
- add pileup energy deposits to this pulse shape including effect of in-time and out-of-time pileup
- convert to ADC time samples
- add electronics noise
- apply energy reconstruction algorithm
  - E = C. Σai.(ADCi-Ped)
- emulate (small) fraction of dead cells, etc..

Sampling fraction examples
(in practice recomputed for each Geant4 version change)

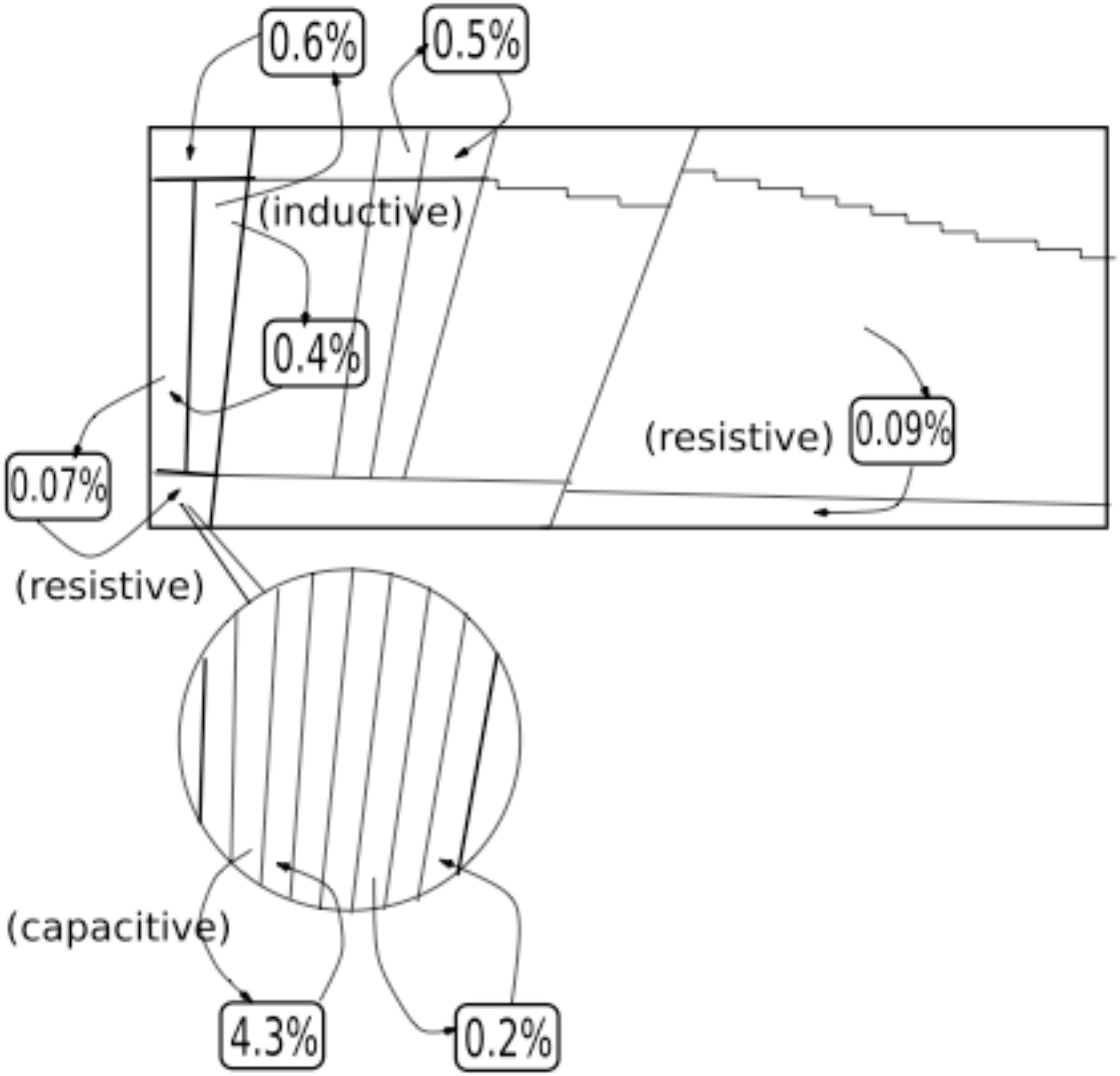




Largest cross-talk is L1-L1 in eta (capacitive)
Other cross-talks are O(0.5-1%), sometime more complicated

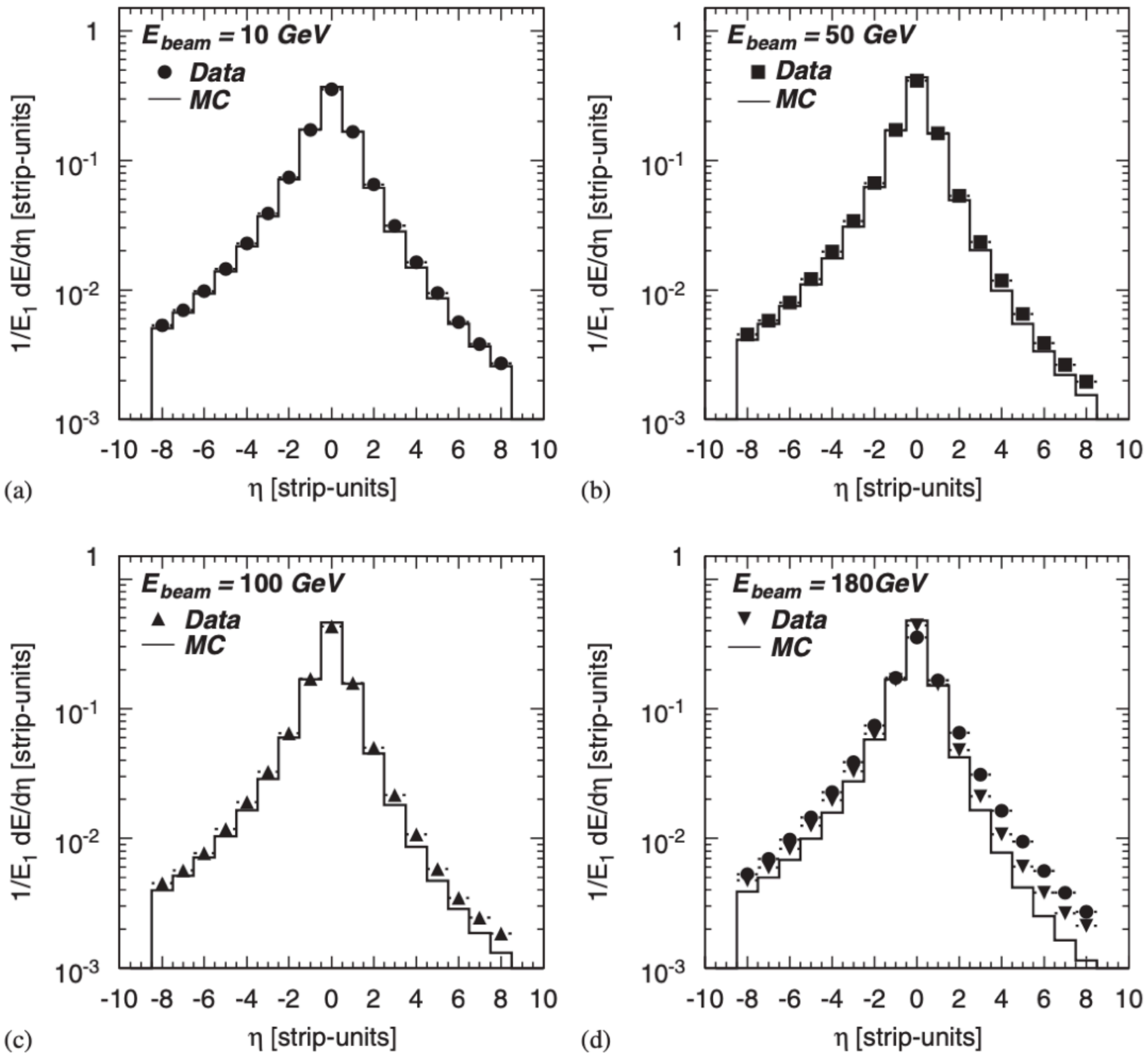
Measured in electronics calibration run and applied to MC simulation

Applied as effective energy, don't attempt to simulate the detailed shape of cross-talk pulses

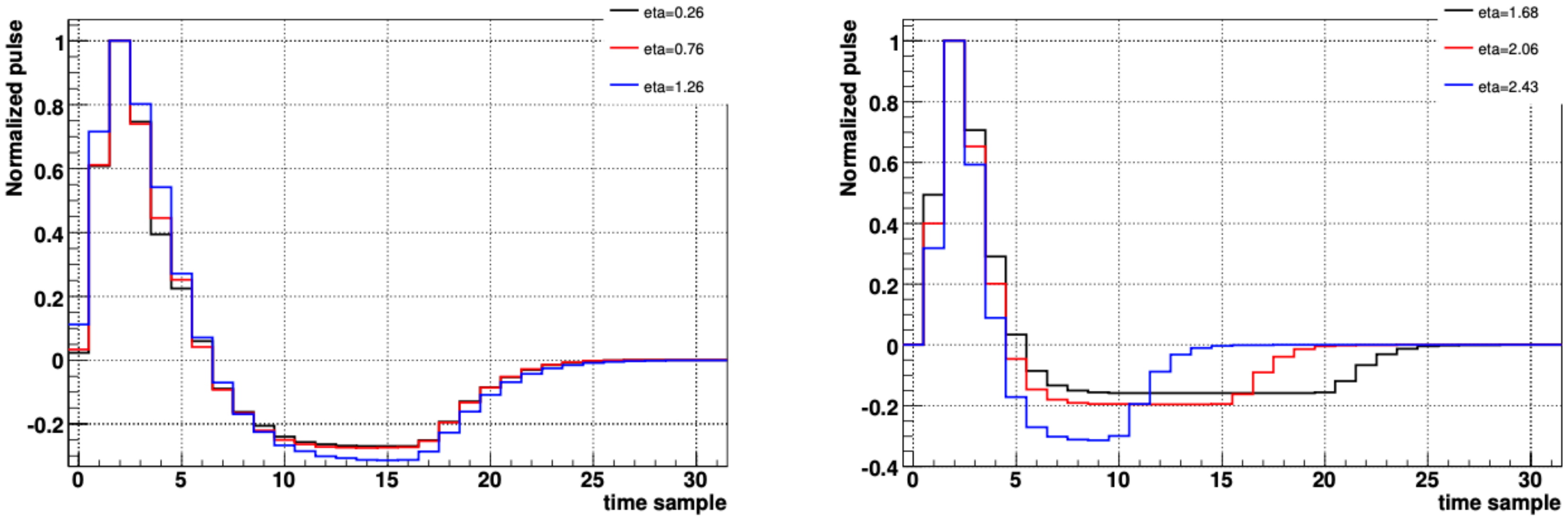


2002 test beam data

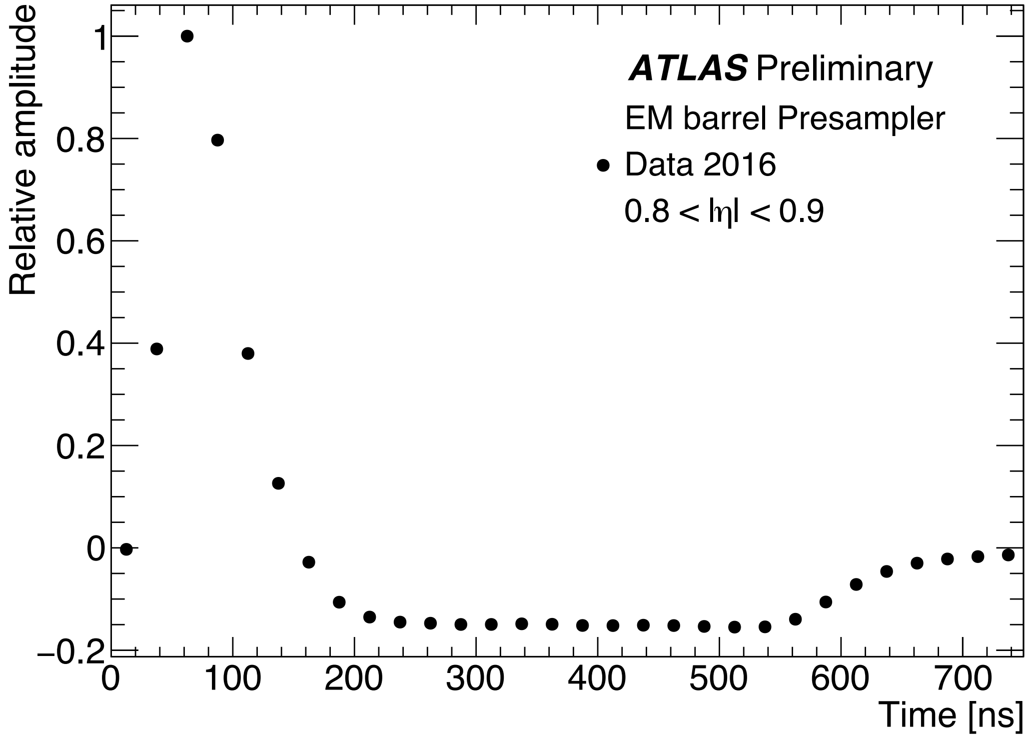
cross talk L2->L1 was not included in simulation at this time
visible impact at high energy since E1/E2 is intrinsically smaller
and cross-talk will give a flat addition of energy over 8 layer 1 cells (matching the layer 2 cell size)



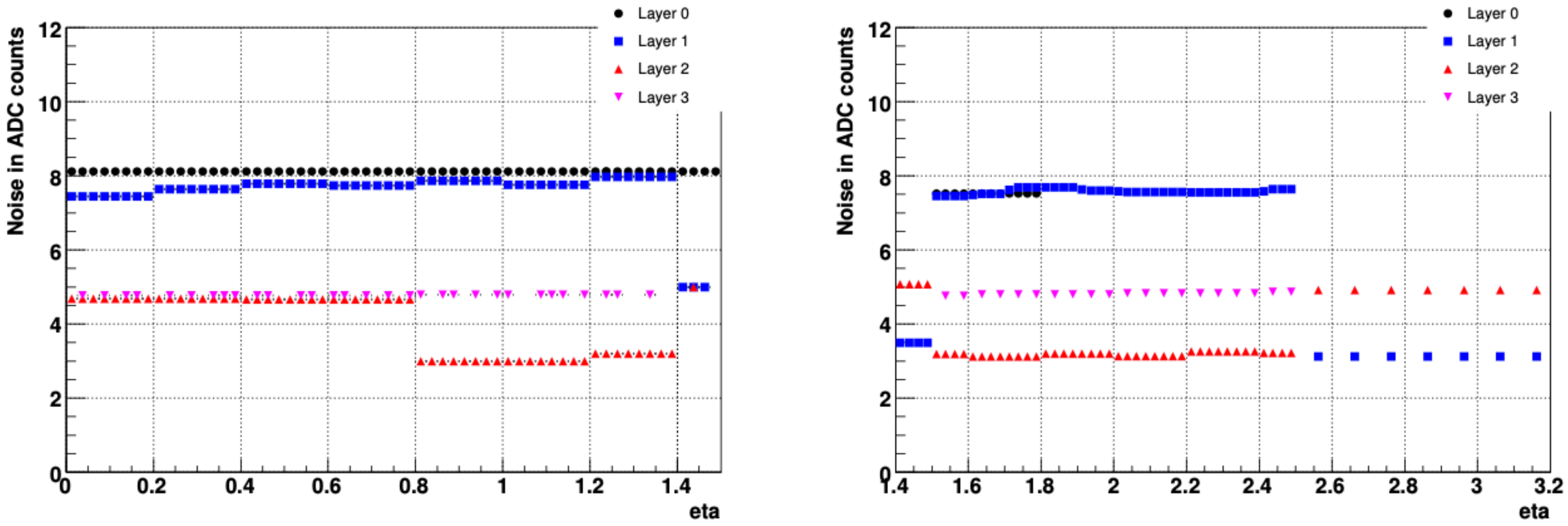
Pulse shapes used in initial digitization before data taking



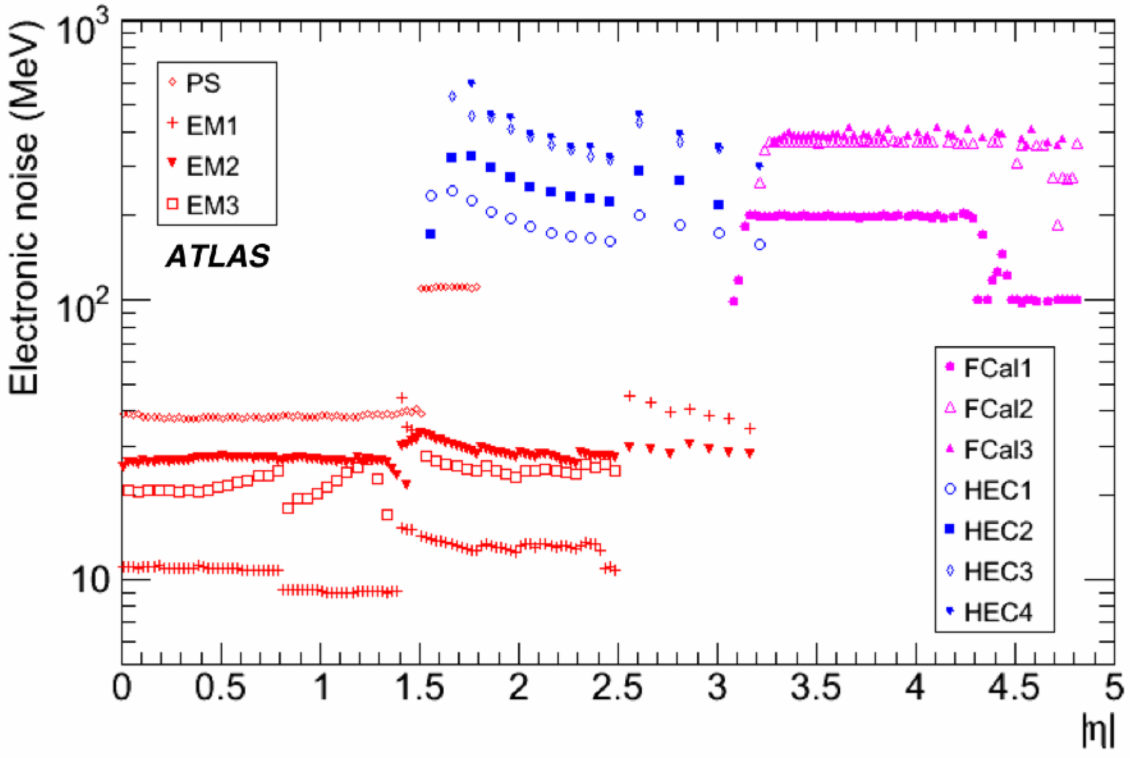
Some refinements done using pulse shape measured with special data



Inputs for noise simulation derived from commissioning data

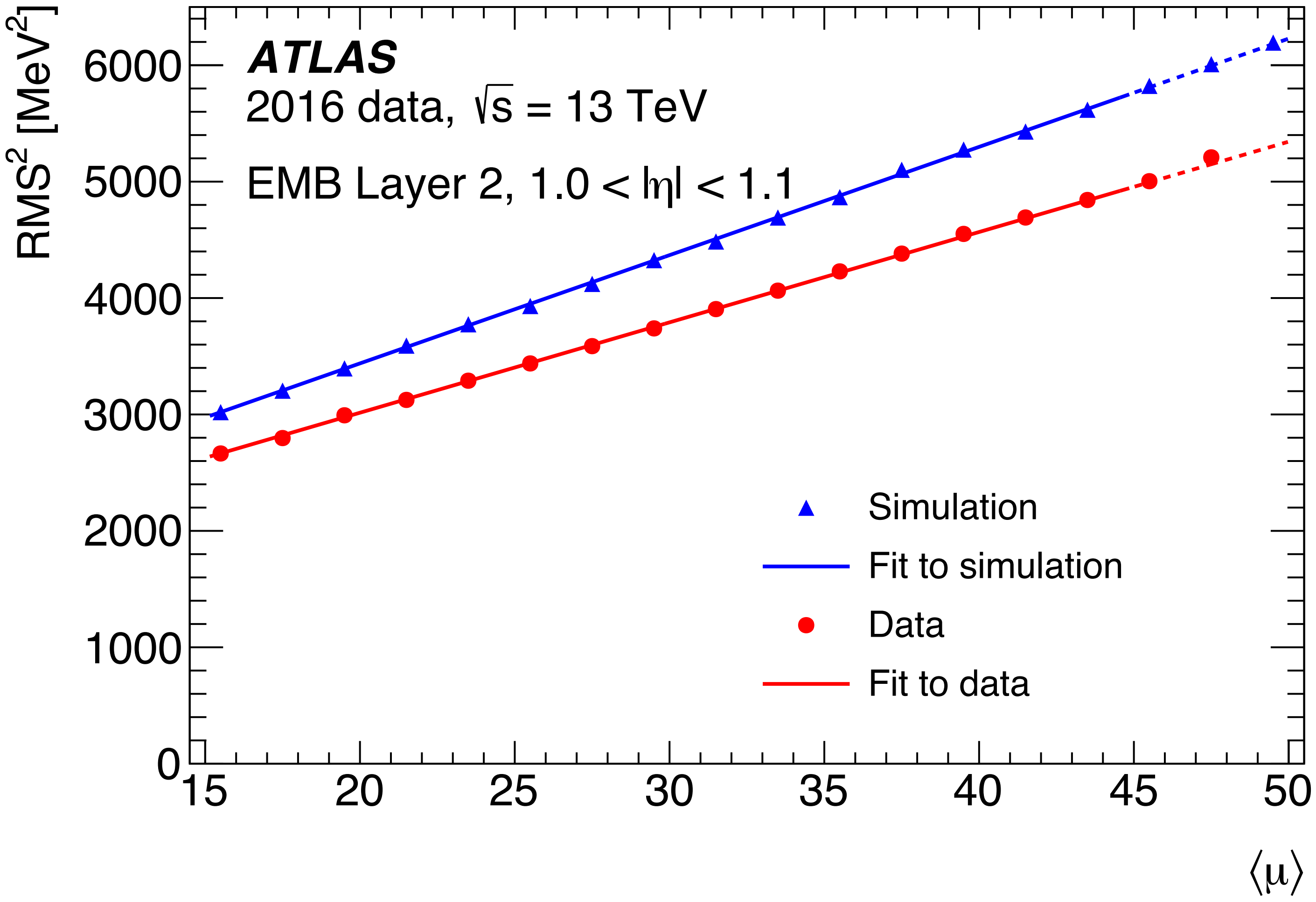


Electronics noise after the full cell energy reconstruction measured on data



Pileup:

add extra interactions over the full LAr drift time window
(Poisson fluctuations around average values)
After the bipolar shaping and the energy reconstruction, this is equivalent to another noise contribution which scales like sqrt(N interactions)
Pileup simulation depends on many ingredients: simulation of inelastic pp collisions, propagation and simulation of low energy particles in the detector, pulse shape, ...
With the latest ATLAS MC simulation ~10% agreement between data and simulation for pileup noise



- Detailed simulation and digitization of the ATLAS LAr calorimeter
    - as much "first principles" as possible
    - some approximations always needed as otherwise computing requirements would become excessive
- Does not reproduce perfectly the data (mostly lateral shower shape) but works well for many purposes