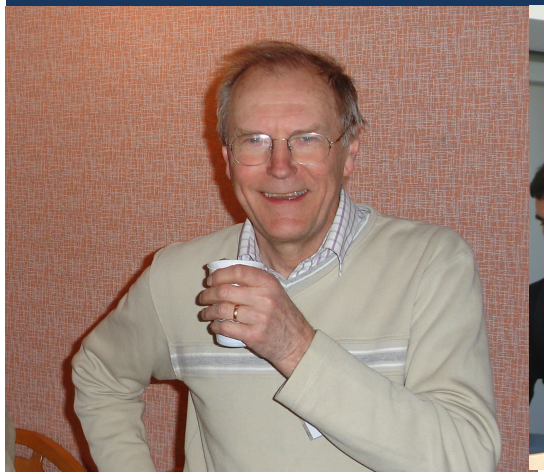
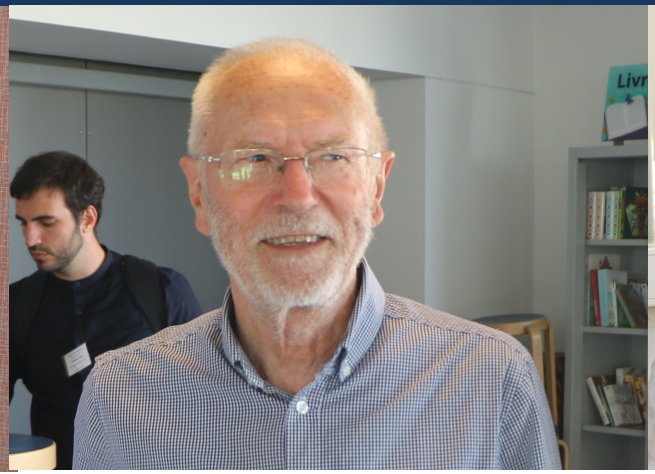
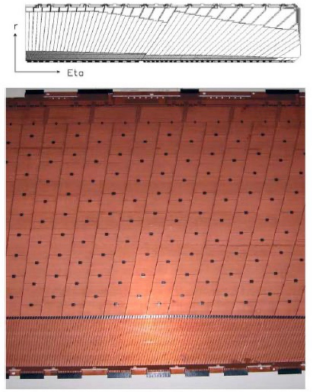
Daniel Fournier and the FCC





…When I Started in ATLAS LAr (2002)

- The accordion calorimeter was invented by Daniel more than 10 years before!
- The LAr TDR was written and approved
- Module production was in full swing, integration in B180 being prepared
- I joined the Barrel EM calorimeter group led by Daniel

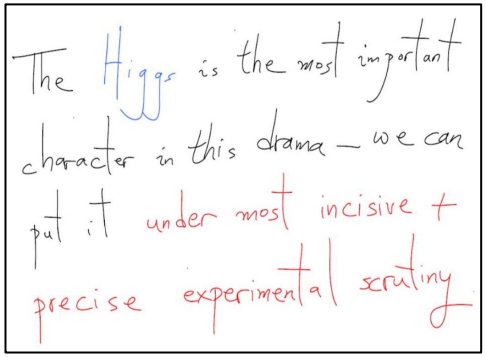


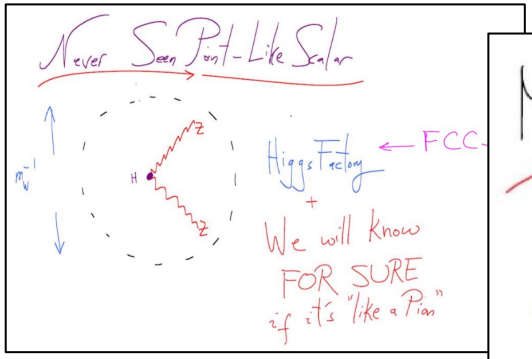
I was impressed by the incredible precision of Daniel and the whole group, the successful effort to control all parameters to utmost precision, deep understanding of full chain of signal creation and signal extraction! Incredibly high expertise of the full team!

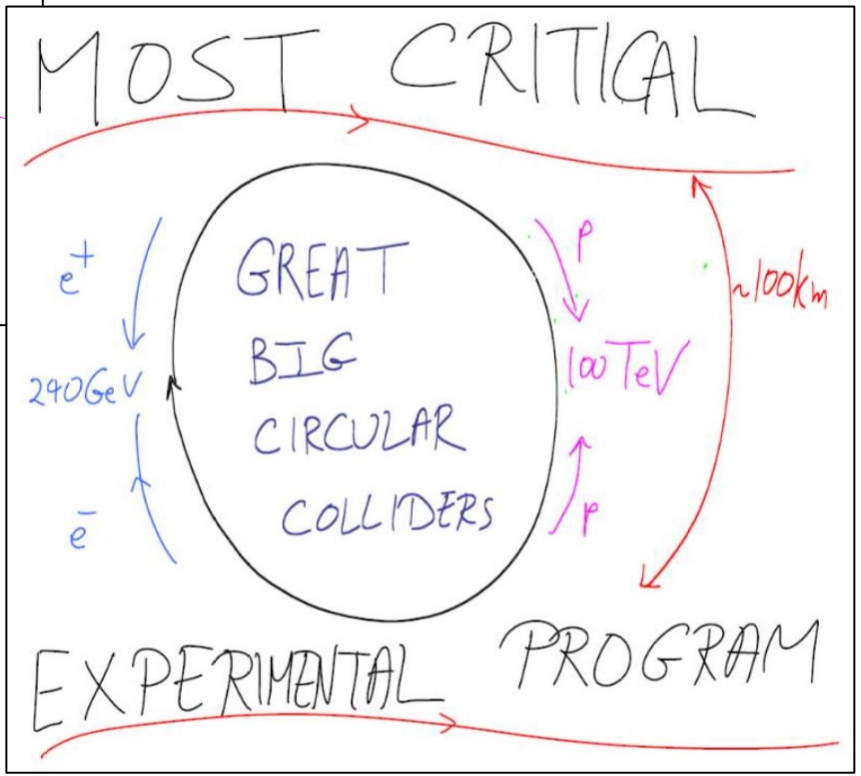
- → The place to be for a young physicist eager to learn!

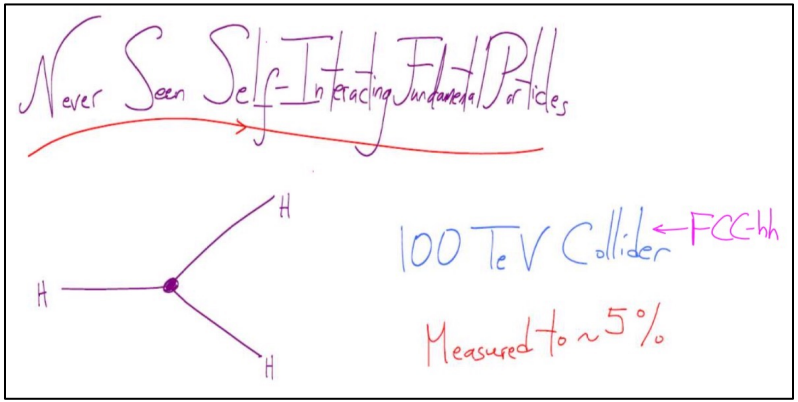
Why FCC? The Theorist's View…

LHC: SM rules the world – many open questions remain (dark matter, dark energy, neutrino masses, …)





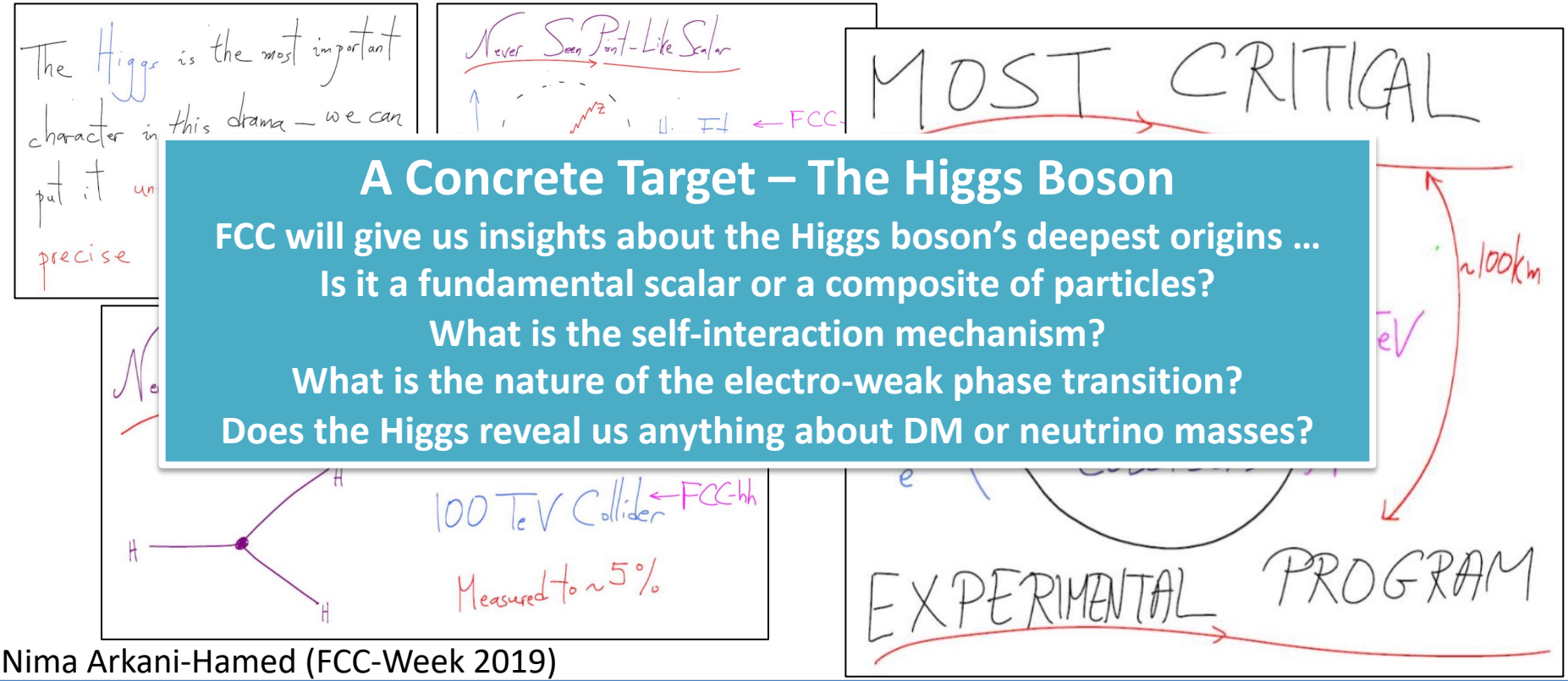




Nima Arkani-Hamed (FCC-Week 2019)

Why FCC? The Theorist's View…

LHC: SM rules the world – many open questions remain (dark matter, dark energy, neutrino masses, …)



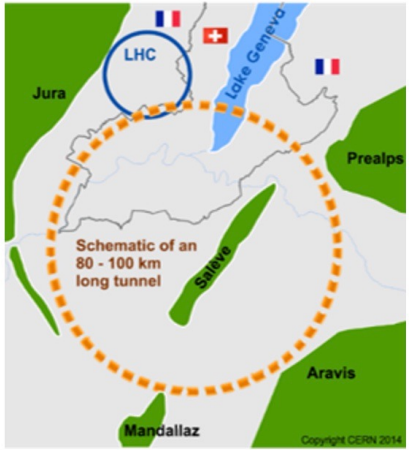
A Concrete Target – The Higgs Boson

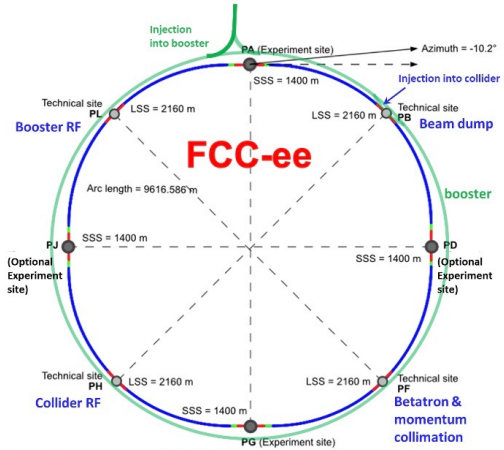
FCC will give us insights about the Higgs boson's deepest origins …
Is it a fundamental scalar or a composite of particles?
What is the self-interaction mechanism?
What is the nature of the electro-weak phase transition?
Does the Higgs reveal us anything about DM or neutrino masses?

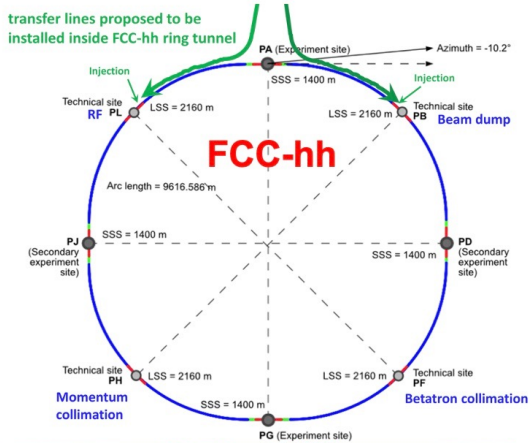
Nima Arkani-Hamed (FCC-Week 2019)

FCC

- **FCC: Long-term program maximizing physics opportunities:**
  - Stage 1: **FCC-ee** (Z, W, H, tt) as Higgs factory, electroweak & top factory at highest luminosities
  - Stage 2: **FCC-hh** (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option
- → New, major facility at CERN within a few years of the end of HL-LHC



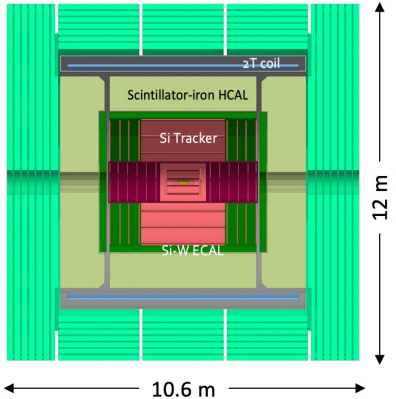




2020 - 2040 | 2045 - 2063 | 2070 - 2095

FCC-ee Proto Detectors – Overview

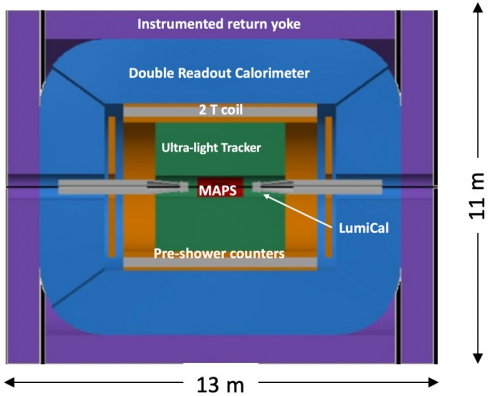
CLD



- Well established design
  - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker;
- CALICE-like calorimetry;
- Large coil, muon system
- Engineering still needed for operation with continuous beam (no power pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations
  - σ_p/p, σ_E/E
  - PID ($\mathcal{O}$(10 ps) timing and/or RICH)?
  - …

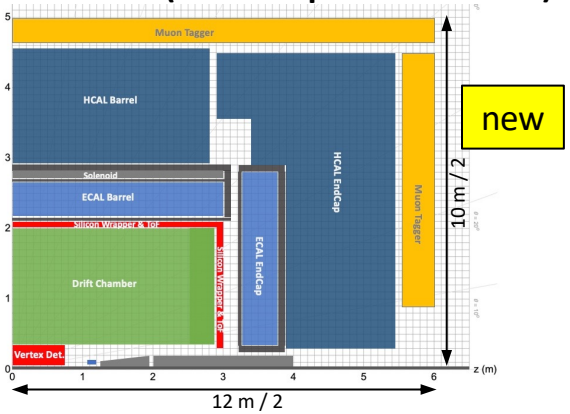
CDR

IDEA



- A bit less established design
  - But still ~15y history
- Si vtx detector; ultra light drift chamber w powerful PID; compact, light coil;
- Monolithic dual readout calorimeter;
  - Possibly augmented by crystal ECAL
- Muon system
- Very active community
  - Prototype designs, test beam campaigns, …

ALLEGRO (Noble Liquid ECAL based)



- A design in its infancy
- Si vtx det., ultra light drift chamber (or Si)
- High granularity Noble Liquid ECAL as core
  - Pb/W+LAr (or denser W+LKr)
- CALICE-like or TileCal-like HCAL;
- Coil inside same cryostat as LAr, outside ECAL
- Muon system.
- Very active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, …
  - Software & performance studies

FCC-ee CDR: https://link.springer.com/article/10.1140/epjst/e2019-900045-4

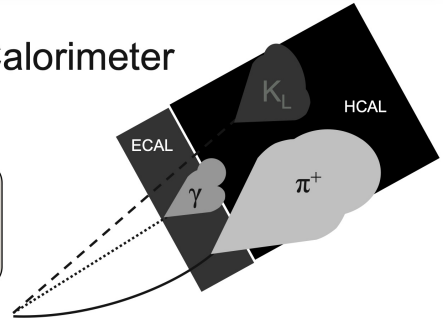
Calorimetry Evolves

- Linear collider experiments aim for jet resolution of 3.5% for 50 – 250 GeV (→ stochastic term of ~30%/√E)
- → High granularity to "follow" particle throughout the experiment and measure it where the resolution is best → particle flow (e.g. CALICE)
- Huge computing resources (Big Data) make it possible to improve resolution using Machine Learning and Neural Networks (AI) → "the more information about the showers the better"
- However we should not forget the physics behind: Many of these developments have very small sampling fraction, or sometimes only digital read-out → sub-optimal calorimeter resolution (e.g. for γ), only partly recovered by particle flow algorithms

Particle Flow Algorithms and Imaging Calorimeter

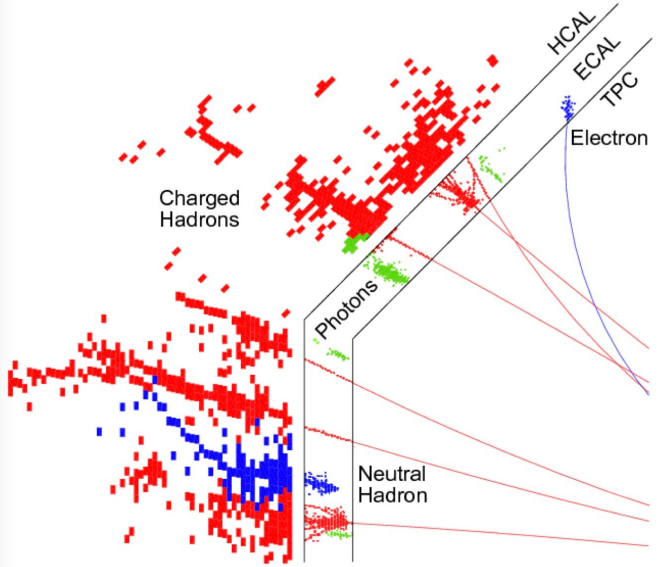
The idea…

Charged particles } measured with the { **Tracker**
Neutral particles } { **Calorimeter**

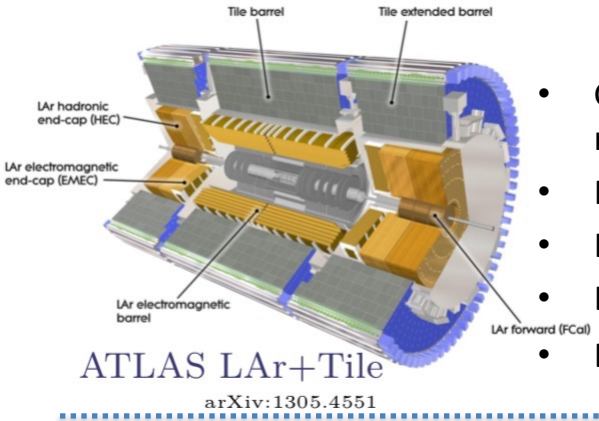


Particles in jets	Fraction of energy	Measured with	Resolution [σ^2]
Charged	65 %	Tracker	Negligible
Photons	25 %	ECAL with 15%/√E	$0.07^2\ E_{jet}$
Neutral Hadrons	10 %	ECAL + HCAL with 50%/√E	$0.16^2\ E_{jet}$
Confusion		Required for 30%/√E	$\leq 0.24^2\ E_{jet}$

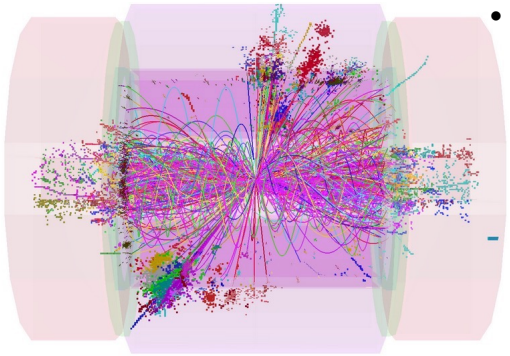
} 18%/√E



Noble-Liquid Calorimetry for FCC



- Good intrinsic energy resolution
- Radiation hardness
- High stability
- Linearity and uniformity
- Easy to calibrate

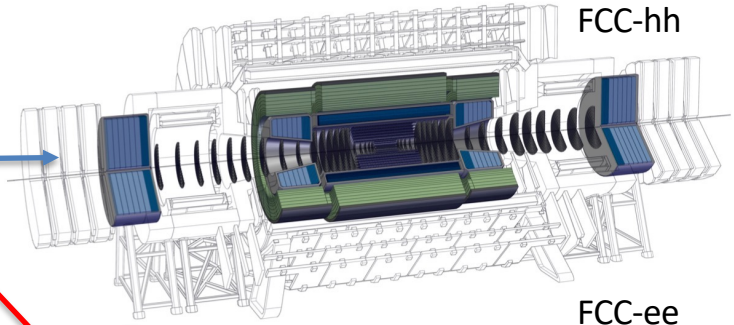


- High granularity
  - → Pile-up rejection
  - → Particle flow
  - → 3D/4D/5D imaging

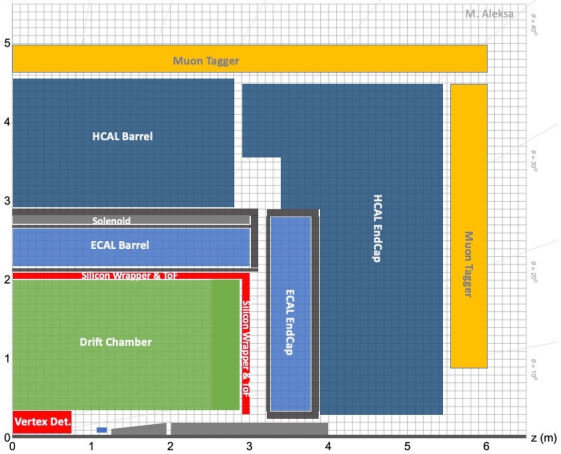
CLIC Detector (CALICE)

FCC Calorimetry

FCC-hh



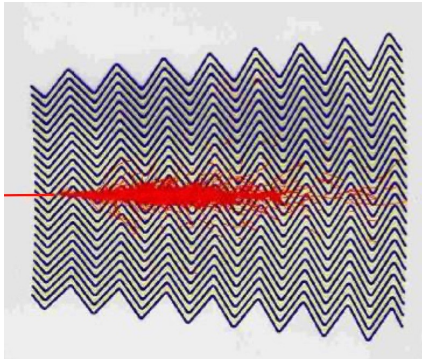
FCC-ee



FCC-hh Calorimetry studies have been published at https://arxiv.org/abs/1912.09962

ATLAS LAr Calorimeter

- ATLAS LAr Accordion with excellent EM resolution, uniformity and stability
- Together with TileCal HCAL: Not optimized for particle flow, jet resolution ~70%/√E (sufficient for LHC – but not optimal for e^+e^- colliders)
- Accordion → reading out barrel at inner and outer radius without any cracks for services (full 2π, excellent uniformity)
- Accordion → Constant sampling fraction → shower depth fluctuations don't matter (apart from leakage correction)



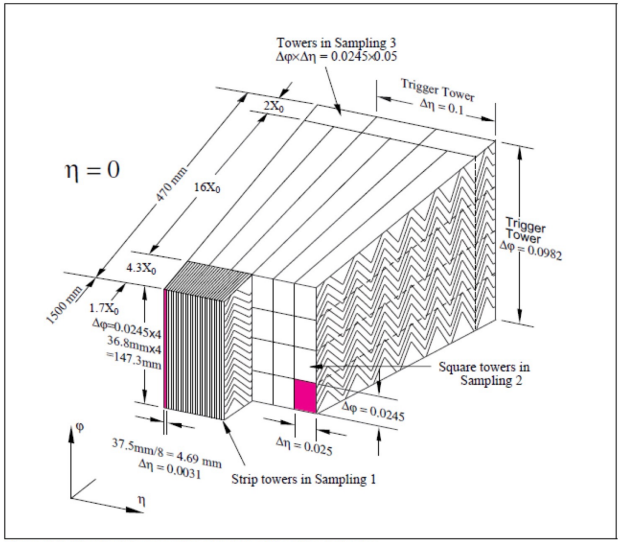
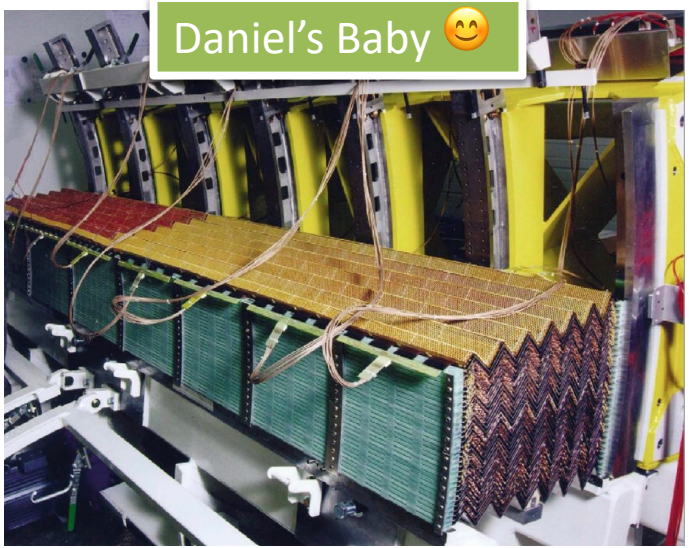
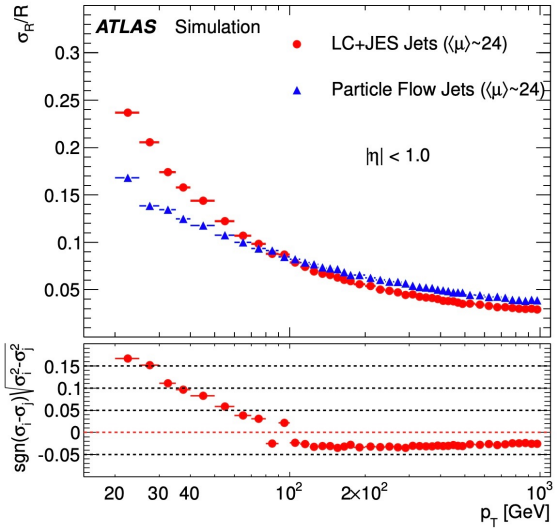


Figure 1-2 Sketch of the accordion structure of the EM calorimeter.





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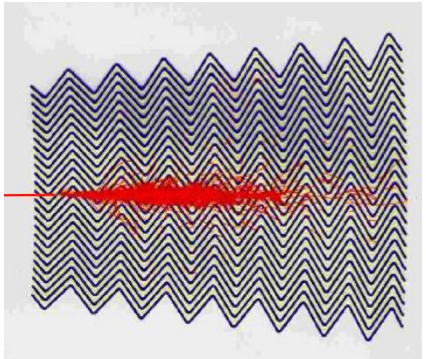


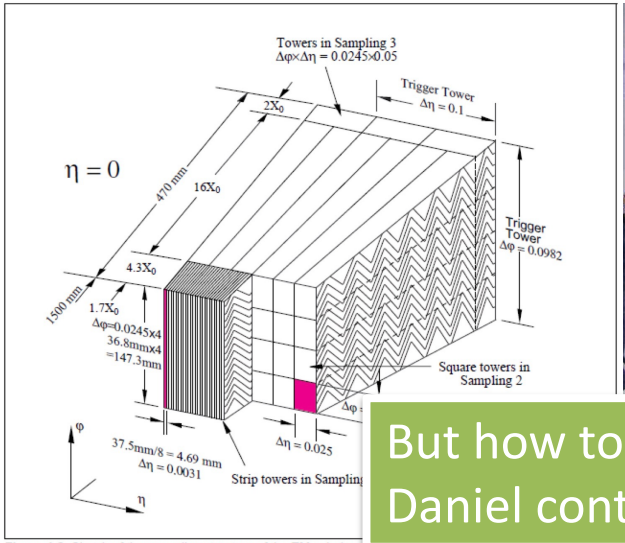
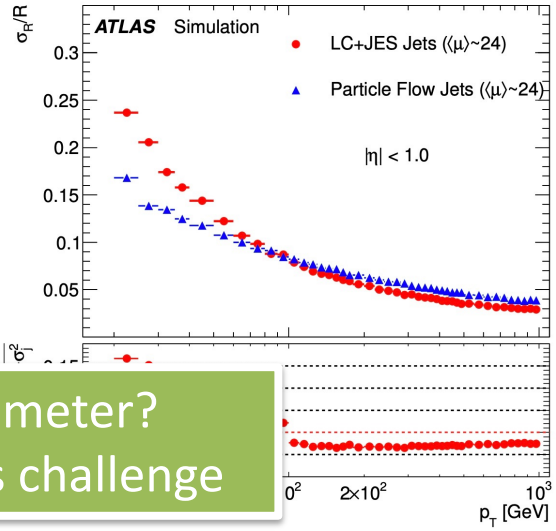


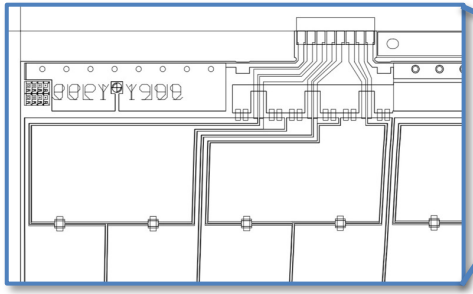
Figure 1-2 Sketch of the accordion structure of the EM calorimet

Daniel's Baby 😊

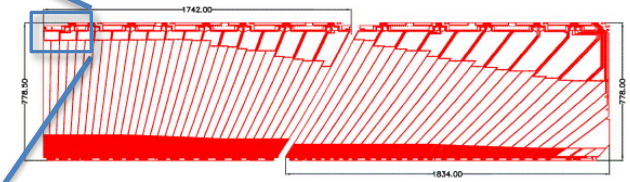


But how to increase granularity for FCC calorimeter?
Daniel contributed from the beginning to this challenge

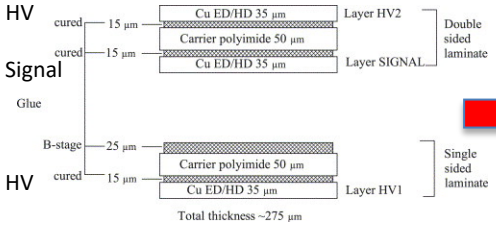
How to Increase Granularity?



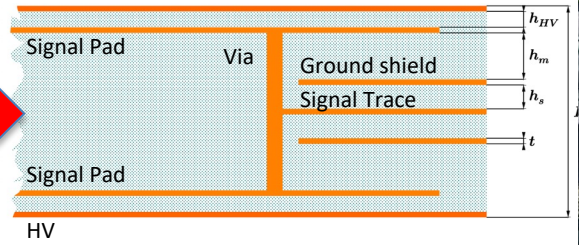
ATLAS segmentation → O(200k) cells



3-layer ATLAS electrode

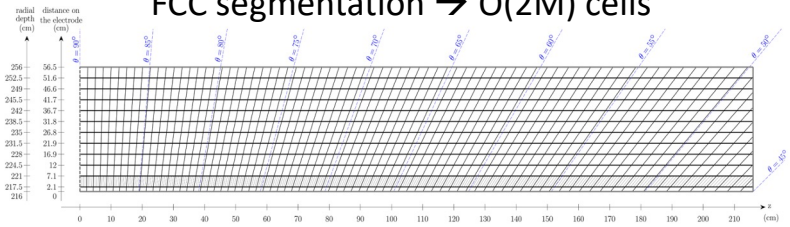


7-layer read-out electrode for FCC

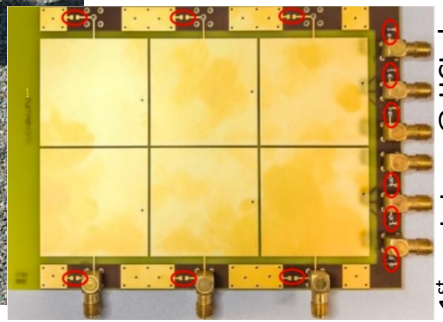


1st prototype @ CERN

FCC segmentation → O(2M) cells



Thank you for the numerous discussions, your inputs and ideas! ... they encouraged us to believe that this could actually work 😊



1st prototype @ IJCLab

High Granularity Noble-Liquid Calorimeter

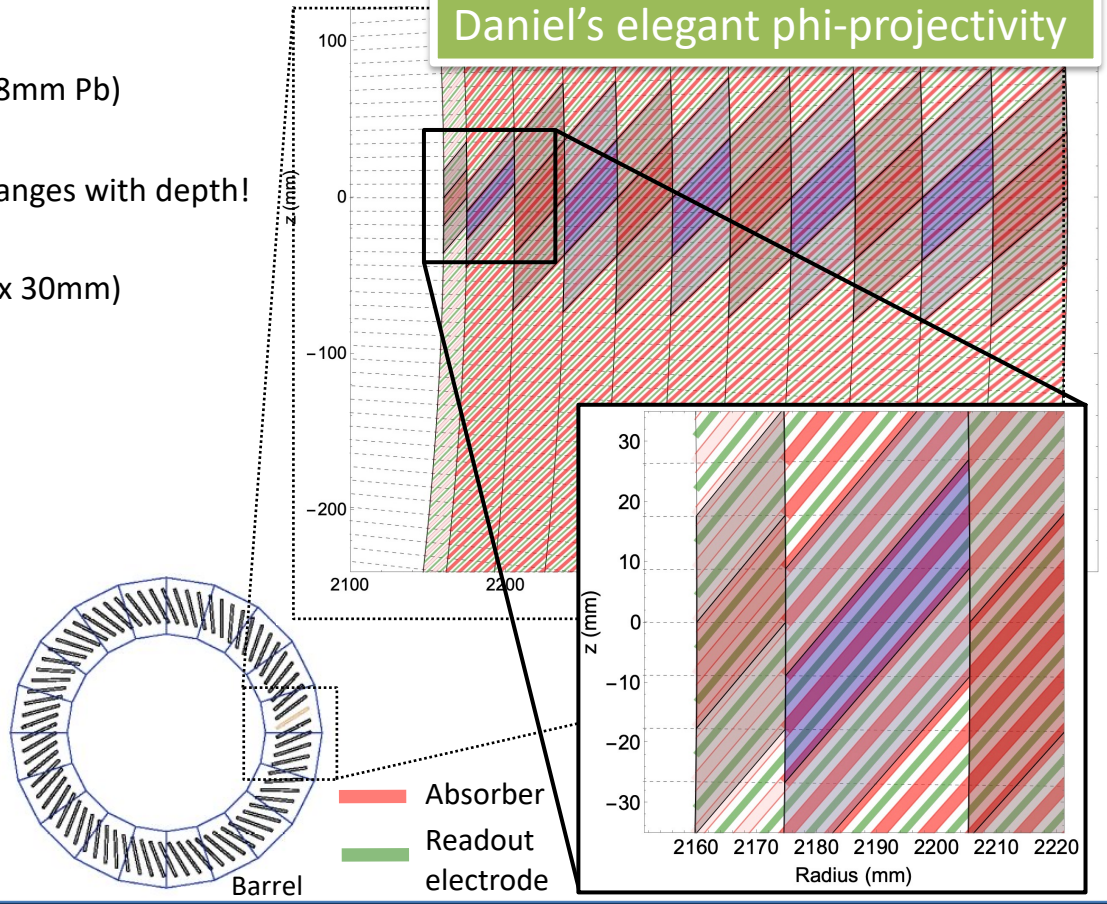
Baseline design

- 1536 straight inclined (50.4°) absorber plates (1.8mm Pb)
- Multi-layer PCBs as readout electrodes
- → 1.2 – 2.4mm LAr gaps → sampling fraction changes with depth!
- 40cm deep (≈ 22 X_0),
- fine segmentation (e.g. strips: 5.4mm x 17.8mm x 30mm)
- 11 longitudinal compartments

Possible Options

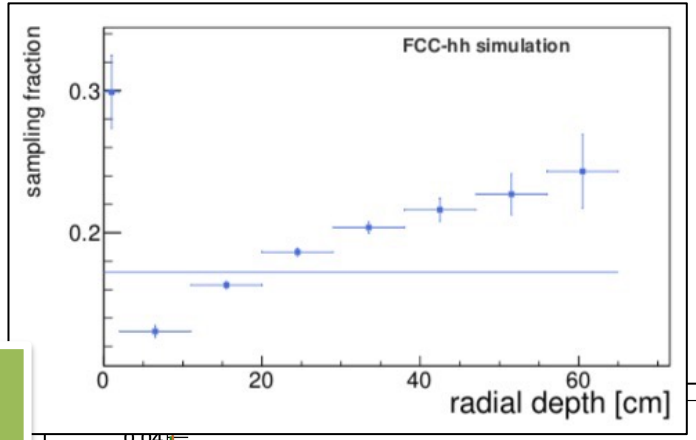
- LKr or LAr, W or Pb absorbers,
- absorbers with growing thickness,
- warm or cold electronics,
- carbon fibre cryostat

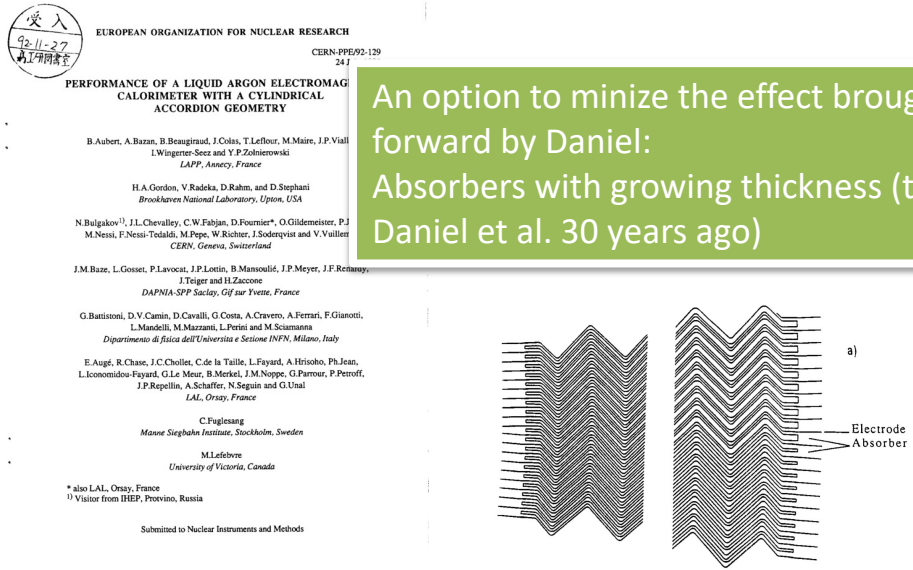
Daniel's elegant phi-projectivity



Changing Sampling Fraction with Depth

- Why is the changing sampling fraction with depth not an issue anymore?
- → Longitudinal segmentation → we know the depth of the energy deposits → during reconstruction take varying sampling fraction into account!
- → need minimum 8 longitudinal segments (“layers”)




EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-PPE/92-129

PERFORMANCE OF A LIQUID ARGON ELECTROMAG CALORIMETER WITH A CYLINDRICAL ACCORDION GEOMETRY

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H.A.Gordon, V.Radeka, D.Rahm, and D.Stephani
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N.Bulgakov[1], J.L.Chevalley, C.W.Fabjan, D.Fournier*, O.Gildemeister, P.J M.Nessi, F.Nessi-Tedaldi, M.Pepe, W.Richter, J.Soderqvist and V.Vuiller
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J.M.Baze, L.Gosset, P.Lavocat, J.P.Lottin, B.Mansoulié, J.P.Meyer, J.F.Renardy, J.Teiger and H.Zaccone
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G.Battistoni, D.V.Camin, D.Cavalli, G.Costa, A.Cravero, A.Ferrari, F.Gianotti, L.Mandelli, M.Mazzanti, L.Perini and M.Sciamanna
Dipartimento di fisica dell'Universita e Sezione INFN, Milano, Italy

E.Augé, R.Chase, J.C.Chollet, C.de la Taille, L.Fayard, A.Hrisoho, Ph.Jean, L.Iconomidou-Fayard, G.Le Meur, B.Merkel, J.M.Noppe, G.Parrour, P.Petroff, J.P.Repellin, A.Schaffer, N.Seguin and G.Unal
LAL, Orsay, France

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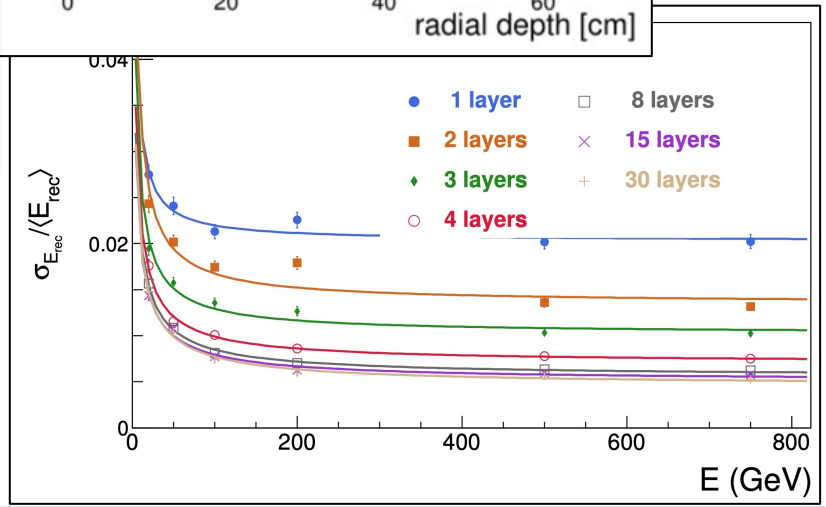
University of Victoria, Canada

* also LAL, Orsay, France
[1] Visitor from IHEP, Protvino, Russia

Submitted to Nuclear Instruments and Methods

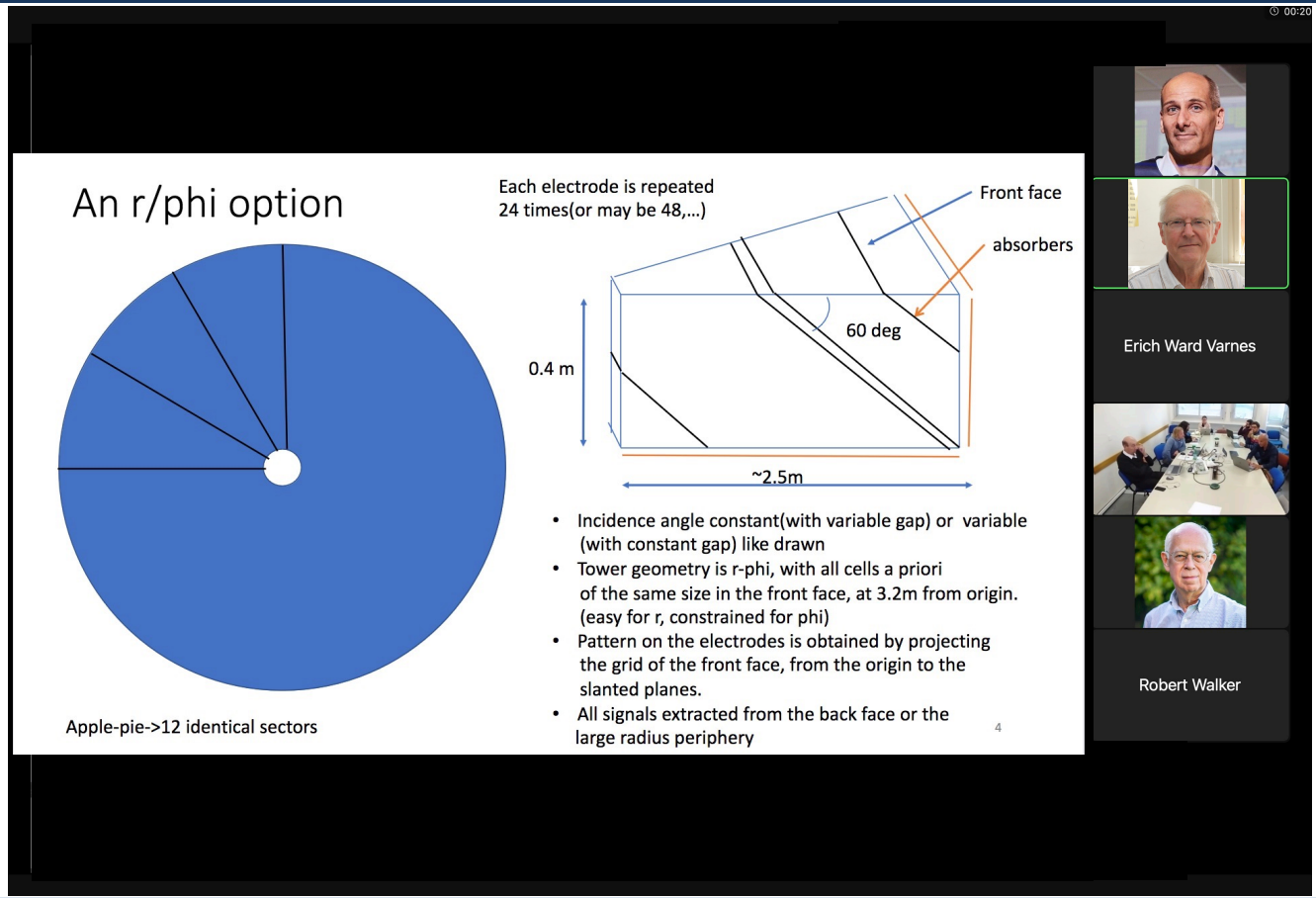
An option to minize the effect brought forward by Daniel:
Absorbers with growing thickness (tried by Daniel et al. 30 years ago)

Paper 1992: featured accordion absorbers with growing thickness



… Extremely Valuable Inputs and Suggestions

- Extremely supportive to the full FCC noble-liquid project!
- Many excellent ideas and inputs!
- Phi-projectivity of cells
- Absorbers growing with depth
- PCB design suggestions
- Input to measurements
- Cold electronics
- EndCap geometries
- Thinking out of the box and huge experience → too many ideas to test them all 😊



Congratulations!

- My warmest congratulations for the Lagarrigue Prize!
- Thank you for your lead in making ATLAS LAr the calorimeter that discovered the Higgs Boson!
- Thank you for your continuing ideas, your inspiration and your support for me and many young physicists!
- I wish you to continue in that way for many years to come and on many interesting projects!

… the Future

- We worked together (with others) on many serious projects 😀!
- I am looking forward to the next challenges … especially of that kind … but not only!