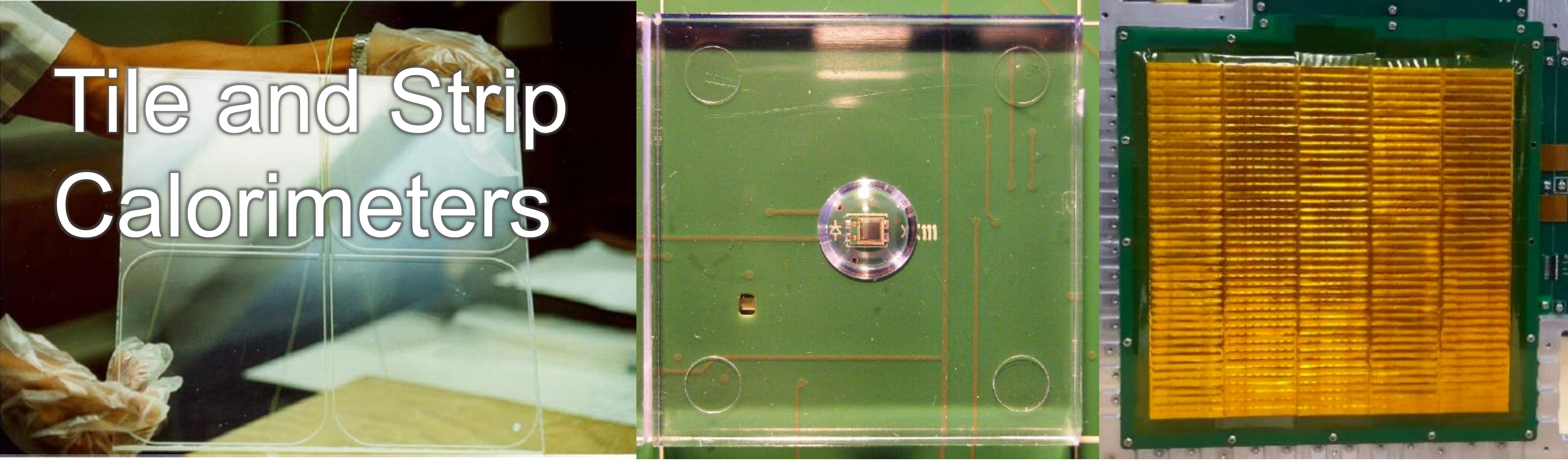
Tile and Strip Calorimeters



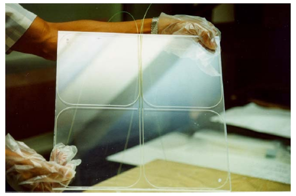
Katja Krüger (DESY)

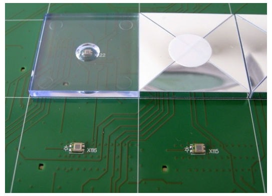
ECFA Detector R&D Roadmap Symposium of Task Force 6 Calorimetry
7 May 2021

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

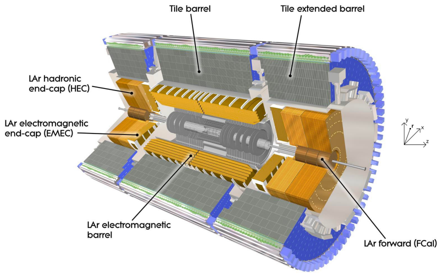
Overview

- Concepts: “Classic” vs “Integrated”

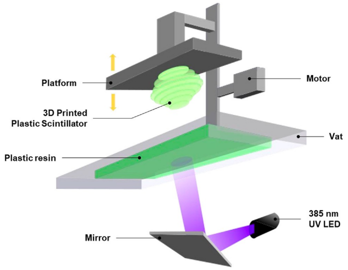




- State of the Art



- The Future

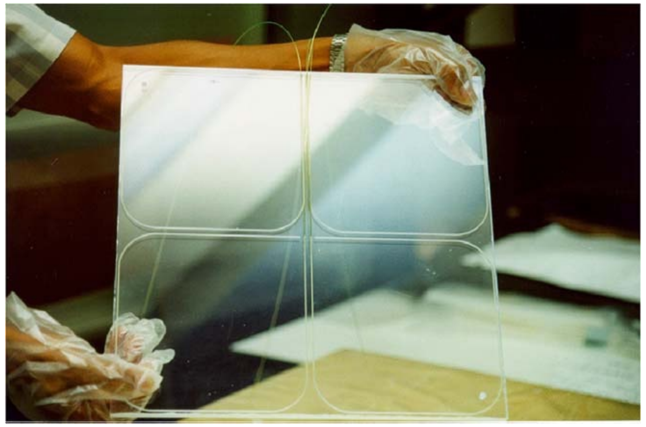


- Summary

Concepts

“Classical” scintillator tile calorimeters

Working horse for hadron calorimeters



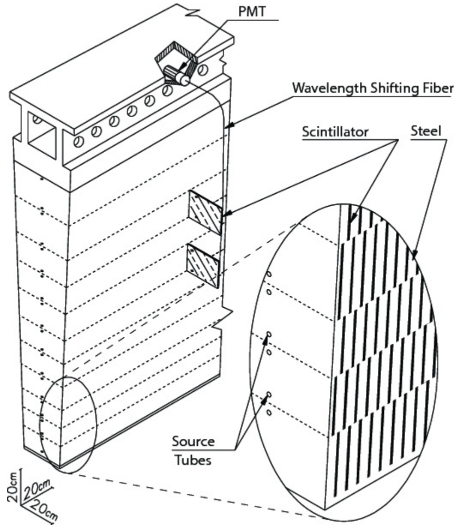
CMS HO tile

Characteristics:

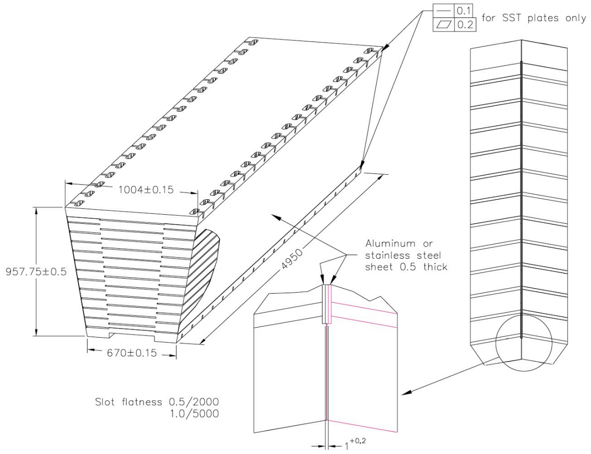
- Relatively large scintillator tiles (typically ~20*20 cm^2)
- Photodetector and readout electronics outside of active volume
  - Light transport via WLS fibre
  - Grouping of tiles into readout channels

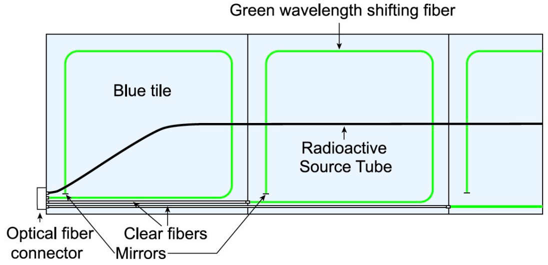
Examples:

- **ATLAS TileCal:** 500,000 plastic scintillator tiles, ~10,000 readout channels in Barrel + Extended Barrel
- **CMS HCAL:** 70,000 tiles (barrel) + 20,000 tiles (endcaps), 2592 readout channels each



ATLAS TileCal

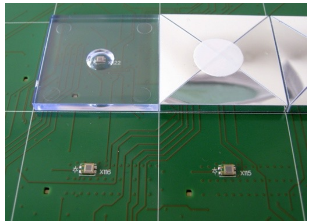




CMS HCAL

“Integrated” scintillator tile and strip calorimeters

Scintillator calorimeters going high granularity



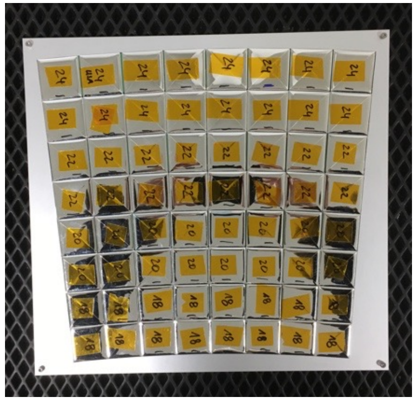
Characteristics

- Photodetector (SiPM) and frontend electronics integrated in active volume
- Small tiles and strips possible
- Individual readout of each tile (strip)

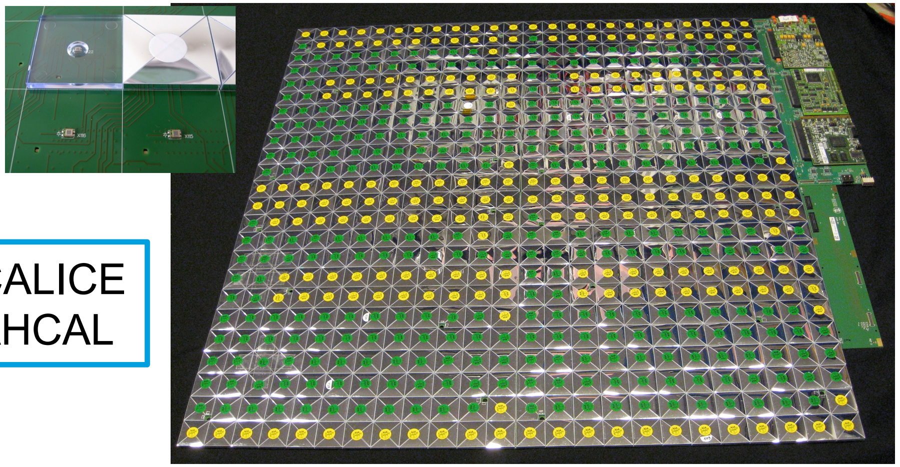
Examples

- Scintillator part of **CMS HGCAL** (endcap): 2.5*2.5 to 5.5*5.5 cm^2 tiles, ~240,000 tiles (= readout channels)
- **CALICE AHCAL**: 3*3 cm^2 tiles, ~24,000 tiles (prototype), ~8,000,000 tiles (ILC detector)
- **CALICE ScECAL**: 0.5*4.5 cm^2 strips, ~6,000 strips (prototype), ~10,000,000 strips (ILC detector)

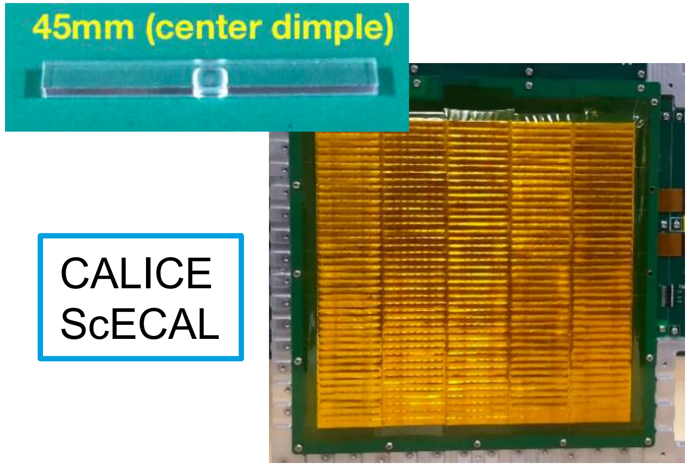
CMS HGCAL



CALICE AHCAL



CALICE ScECAL



Comparison of the two concepts

Pros and Cons

Classical	**Integrated**
+ Radiation hardness only determined by scintillator	– Also photodetector and electronics in radiation area
+ Photodetectors and electronics can be replaced	– Only complete detector units can be replaced
• Limited number of channels	• Large number of channels possible
+ Relatively cheap	– More expensive (but still moderate cost)
+ Customizable tile shape(s)	– Scalable production techniques needed
– Coarse information on shower shapes	+ Detailed information on shower shapes
– Very sensitive to single cell calibration	+ Only sensitive to global calibration shifts
– Pile-up rejection difficult	+ Pile-up separation possible
– Not optimal for Particle Flow	+ Optimisation for Particle Flow Algorithms

State of the Art

How to quantify “state of the art”?

What is important? What really depends on the tile/strip calorimeter?

Energy resolution

- **Single particle energy resolution** depends on several factors
  - Sampling fraction & frequency
  - Scintillator and absorber material
  - For hadrons: interplay of ECAL and HCAL
  - At higher energies: total absorber thickness
  - Reconstruction algorithm (software weighting algorithms)
- For physics analysis: **jet energy resolution** usually more important than single hadron energy resolution
  - Reconstruction algorithm (Particle Flow Algorithms, Jet Clustering Algorithms)
  - At (HL-)LHC and FCChh: pile-up removal
  - Interplay of tracker, ECAL and HCAL

  → Comparisons are difficult

Hadron energy performance still critical for particle flow

Time resolution: mostly covered in Nural’s talk

Robustness

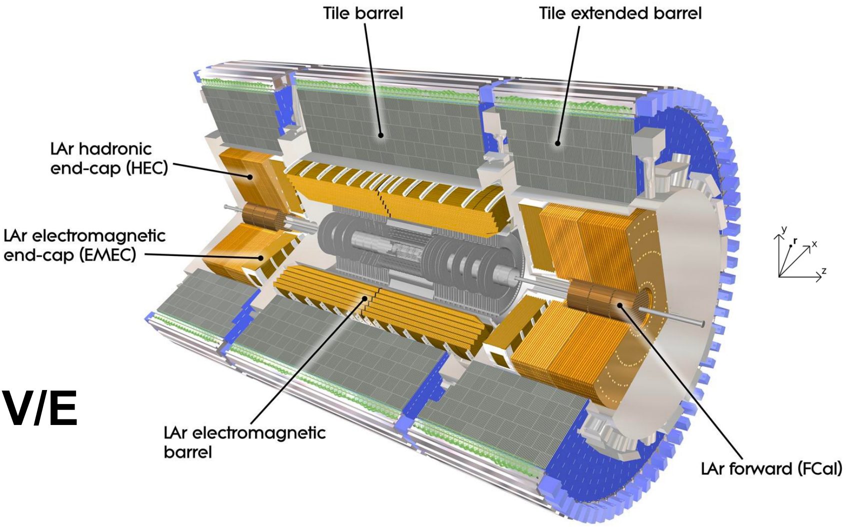
- in general hard to quantify, but **radiation hardness** is a clear criterion

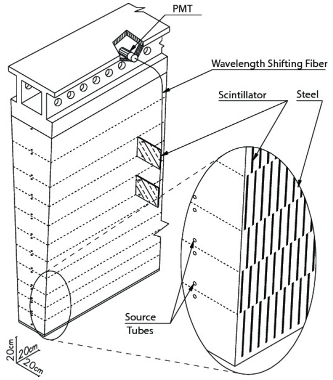
State of the Art: “Classical” tile calorimeters

Calorimeters at (HL-)LHC

ATLAS TileCal

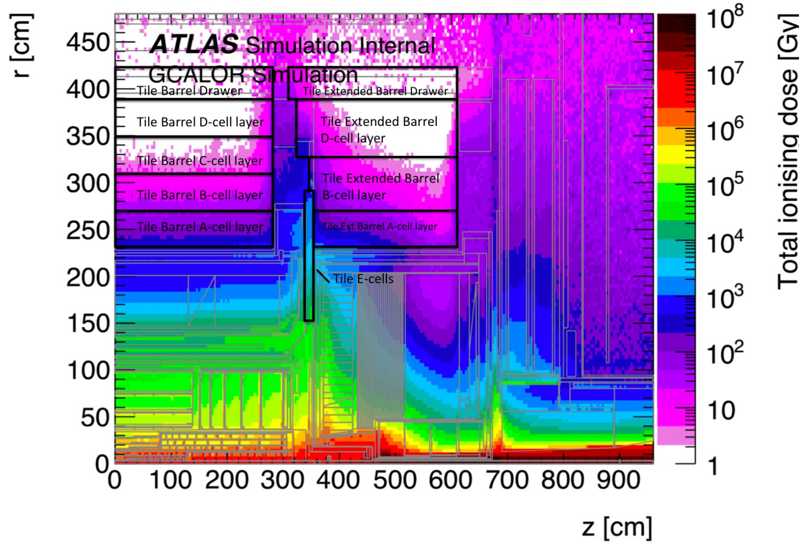
- Material composition: steel : plastic-tiles 4.7 : 1
- Thickness: >7.4 λ_I (>10 λ_I with ECAL)
- **Single hadron energy resolution (testbeam)**
  - TileCal stand-alone: ~56% √E ⊕ 5.5%
  - **LAr-ECAL+ TileCal: ~52% √E ⊕ 3% ⊕ 1.6 GeV/E**
- Maximum radiation (HL-LHC)
  - **tiles: TID up to ~2 kGy, ~10% light loss**
  - **electronics: up to ~20 Gy, ~2 * 10^12 neq/cm^2**





For comparison: CMS PbWO$_4$ ECAL + tile HCAL

- Single hadron energy resolution (testbeam)
  - ~110%/ √E ⊕ 7% (without weighting) (ECAL π/e=0.55 … 0.7)



ZEUS HCAL

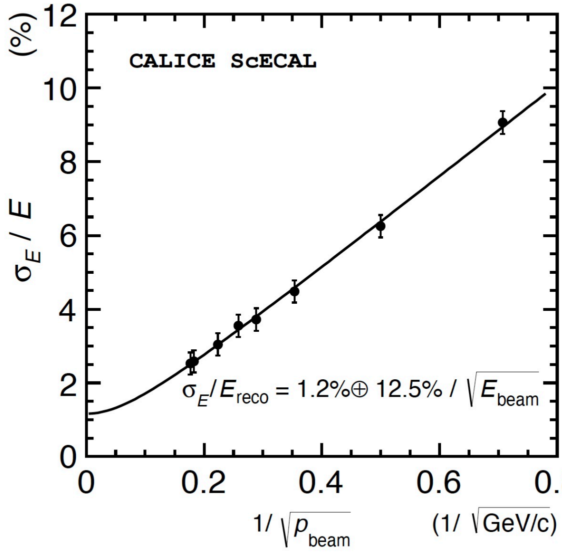
- Depleted Uranium absorber, optimised for **compensation**
- **Single hadron energy resolution: 35%/√E ⊕ 2%**

State of the Art: “Integrated” tile and strip calorimeters

High granularity ECAL and HCAL

CALICE AHCAL and ScECAL

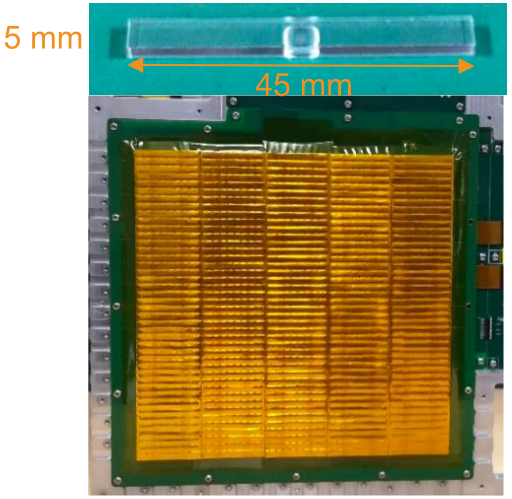
- Calorimeter concepts developed for linear e+e- colliders
  - Radiation hardness not very important
- High granularity, optimised for Particle Flow
  - Not optimised for single particle energy resolution
- Prototypes built and tested in beam tests
  - Performance determined with physics prototypes
  - Full integration in technological prototypes, expected performance similar or better

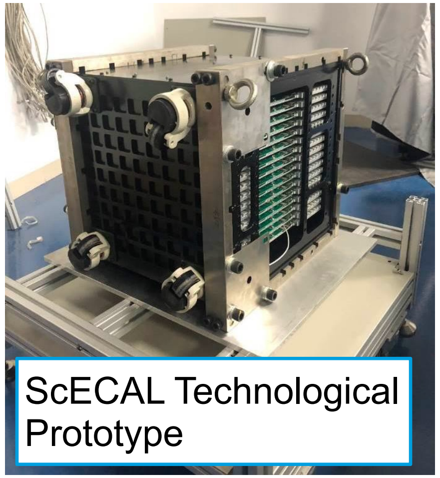


ScECAL Physics Prototype

Scintillator ECAL (ScECAL)

- Material composition: tungsten : scintillator 3.5 : 3 mm
- Thickness: 21.5 X0
- **Electron energy resolution 12.5% $\sqrt{E} \oplus 1.2\%$**
- **Granularity: 45 * 5 mm^2 strips**
  - **Alternating orientation: effective 5*5 mm^2**
- # of channels: ~6,000 (prototype), ~10,000,000 (ILD)





ScECAL Technological Prototype

State of the Art: “Integrated” tile and strip calorimeters

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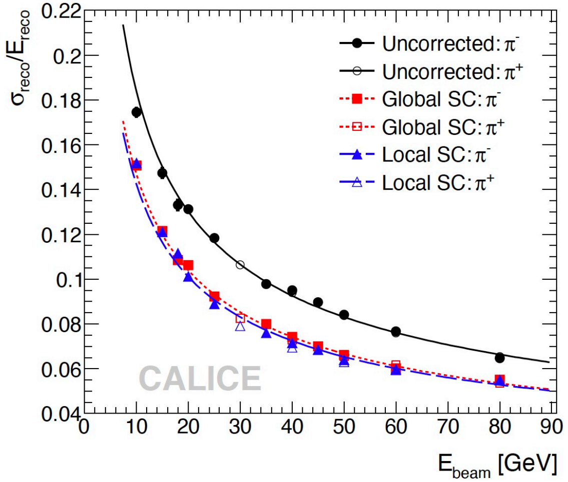
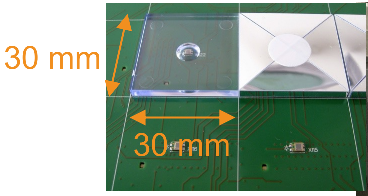
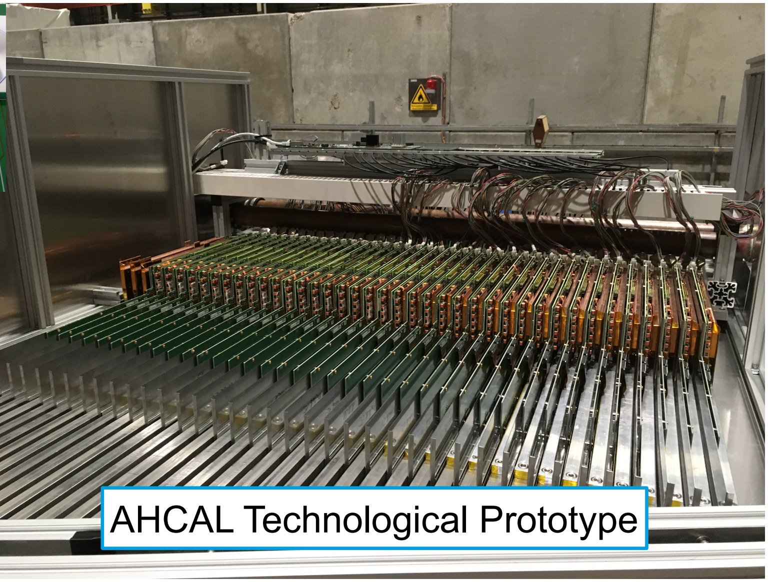


AHCAL Physics Prototype

AHCAL

- Material composition: steel : scintillator 21 : 5 mm
- Thickness: 5.3 λ_I
- **Single hadron energy resolution 58% $\sqrt{E} \oplus$ 1.6%**
  - **With software compensation 44% $\sqrt{E} \oplus$ 1.8%**
- **Granularity: 30 * 30 mm^2**
- # of channels: ~22,000 (prototype), ~8,000,000 (ILD)



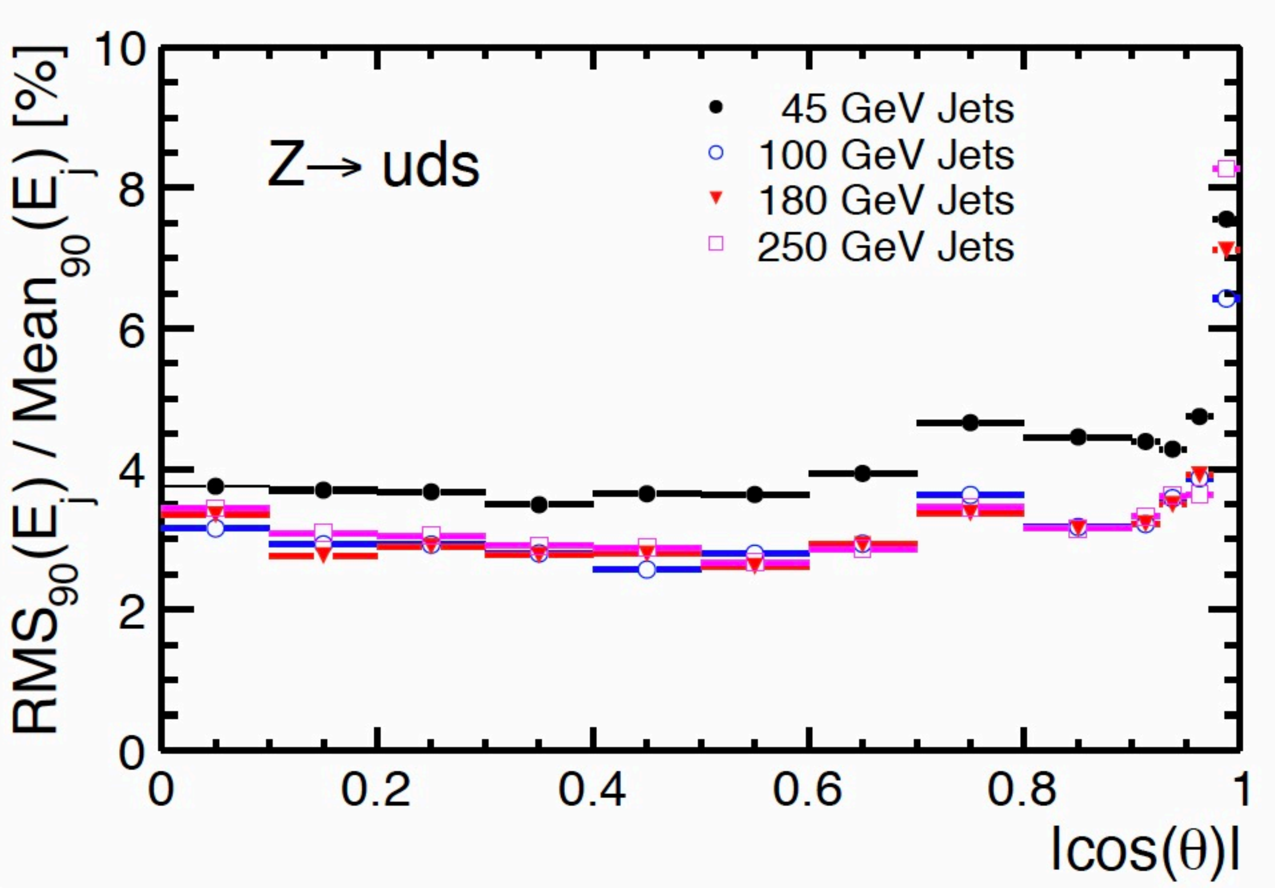


AHCAL Technological Prototype

State of the Art: “Integrated” tile and strip calorimeters

Jet Energy Resolution: the power of granularity

- “Jet” Energy resolution from hemispheres in Z(‘)-> jet jet



ILCTDR

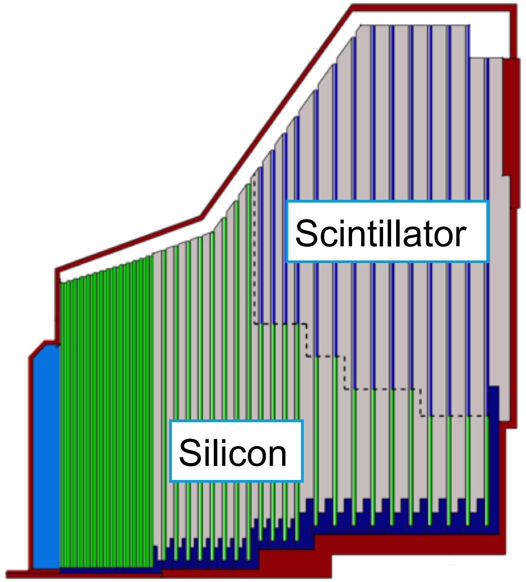
State of the Art: “Integrated” tile and strip calorimeters

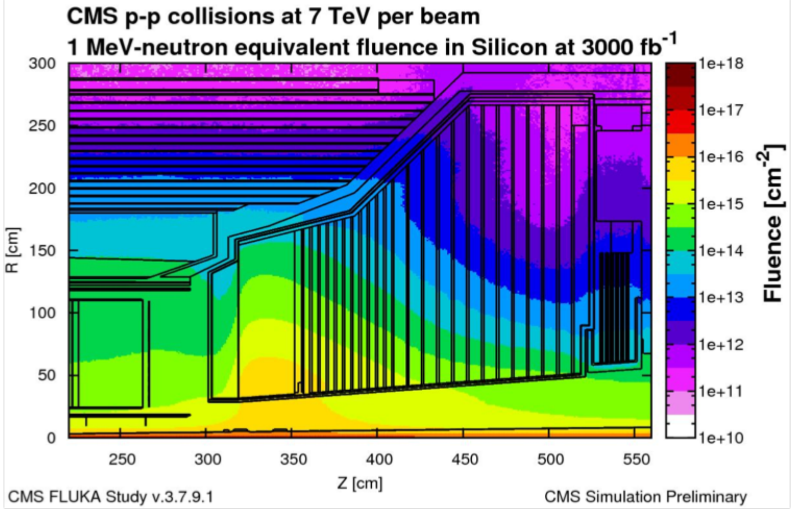
High granularity for HL-LHC

CMS HGCAL: scintillator part (for silicon → Dave’s and Vincent’s talks)

- CMS calorimeter endcap upgrade for HL-LHC
- Scintillator tiles where radiation levels allow, otherwise silicon
- Design inspired by CALICE AHCAL
- Material composition: steel : scintillator = 3.5 (6.6) : 0.3 cm
- Thickness: 10.7 λ_I (total HCGAL)
- Maximum radiation
  - up to ~2 kGy
  - **~5 * 10^13 neq/cm^2**
- **Granularity: 2.5 * 2.5 to 5.5 * 5.5 cm^2**
- # of channels: ~240,000
- Scintillator and silicon share the same (cold) volume
  - Operation at -30° C beneficial for SiPM noise
  - Limited possibility to warm up for annealing

The first high granularity calorimeter in a collider experiment!





State of the Art: “Integrated” tile and strip calorimeters

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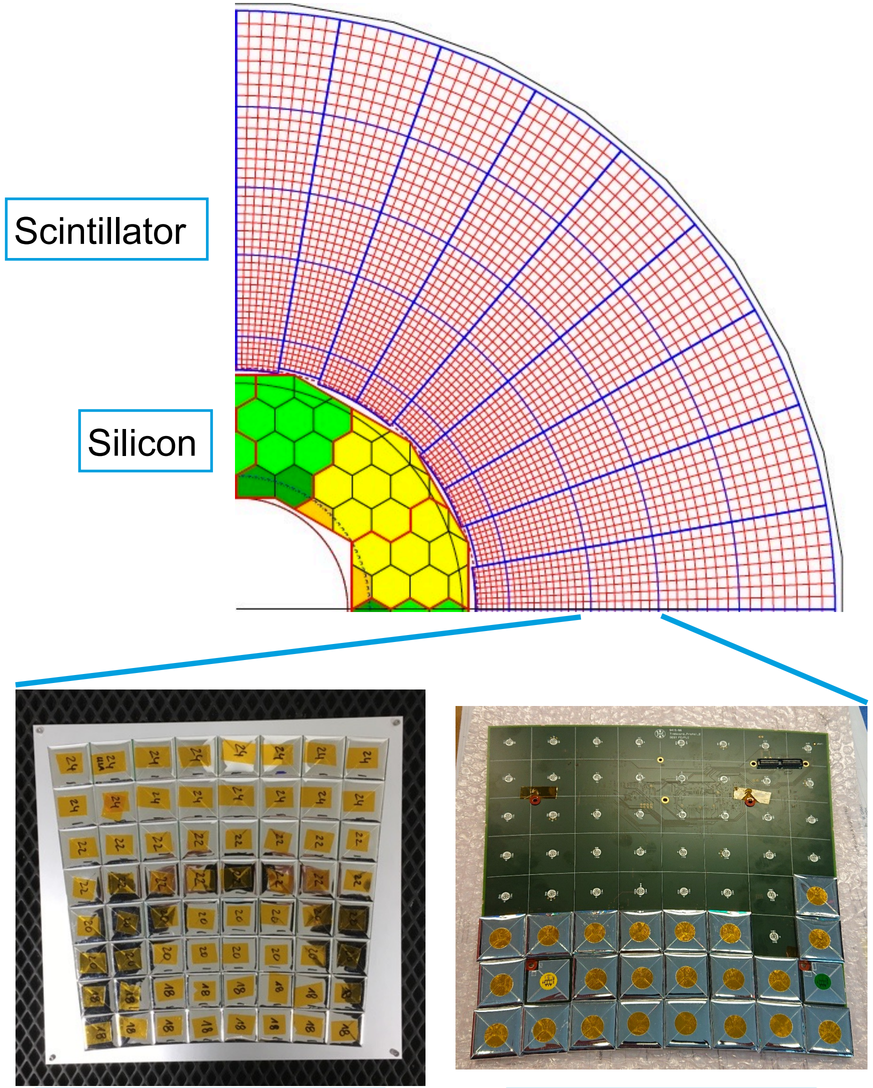


Mechanical dummy

Prototype module

Limitations: Radiation Hardness

Effects on active detector elements

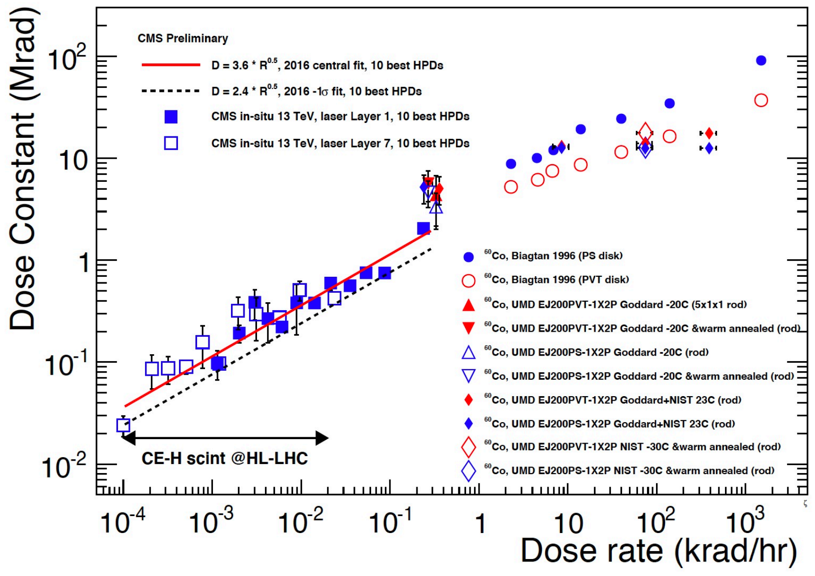
Radiation damage of plastic scintillator: TID

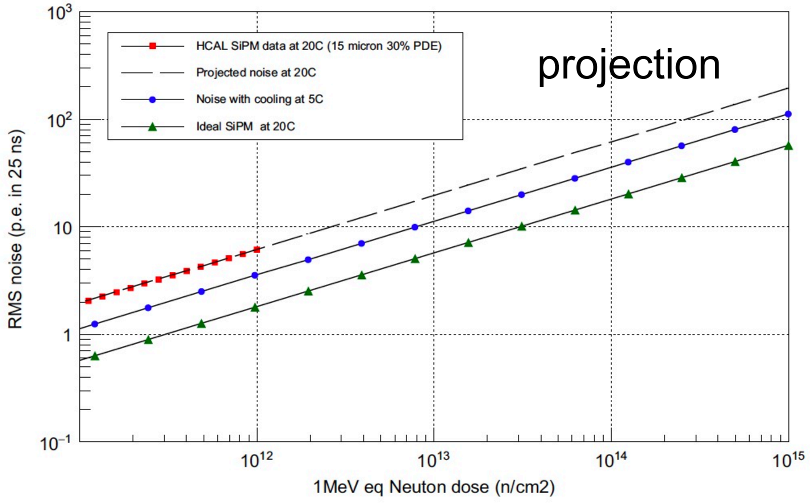
- Light loss depends not only on dose, but also on dose rate
- The lower the dose rate, the faster the damage!
  - Makes extrapolation from high-rate irradiations more difficult

Radiation damage of photodetector (SiPM): neutron fluence

- State of the art: CMS BTL plans use up to 3 * 10^14 neq/cm^2
- Effects:
  - Breakdown voltage increases
  - Dark count rate increases
    - Lose ability to see single pixel spectra → implications for calibration
    - Large leakage currents → electronics needs to cope
    - At some point: significant fraction of pixels occupied by noise
  - Effect smaller at lower temperature
  - Effects can be mitigated by annealing (higher T → more annealing)
  - Effects of the package: optical transparency, self-heating

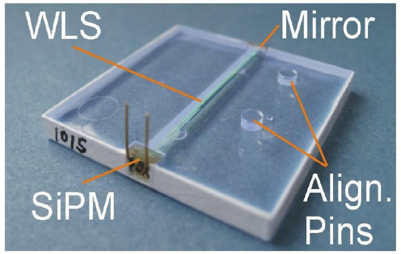
$$D_c = (3.6\,\mathrm{Mrad})\left(\frac{R}{1\,\mathrm{krad/hr}}\right)^{0.5}$$

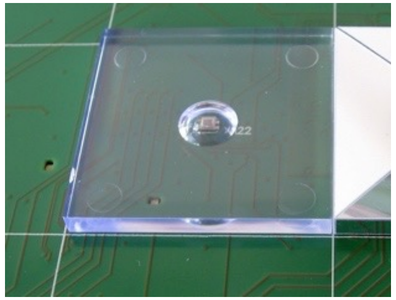




Limitations: Complexity and Integration

High granularity and Integration lead to new challenges



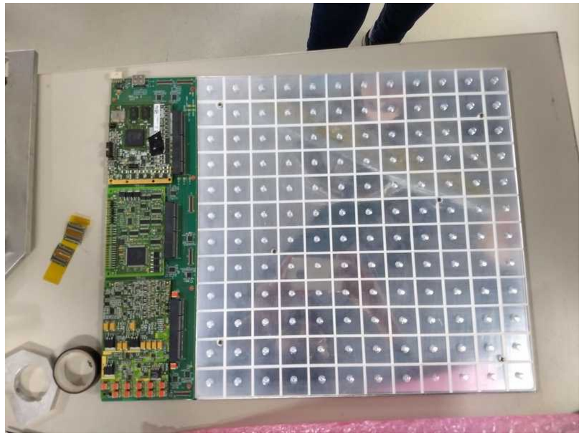


Large channel count → large number of components (tiles, strips)

- Several mitigation strategies to reduce handling effort
  - Simplification: SiPMs directly coupled to tiles/strips (no WLS)
  - Automatization
    - Moulded (instead of machined) tiles/strips
    - (semi-)automatic wrapping in reflector foil
    - SMD components, assembly with pick-and-place machines
  - Larger units (“Megatiles”)
    - not easy to reach good light yield and low channel-to-channel cross talk

Integrated electronics

- Couples electronics tightly to active elements
- No later upgrades possible
- Final electronics needs to be ready before production can start

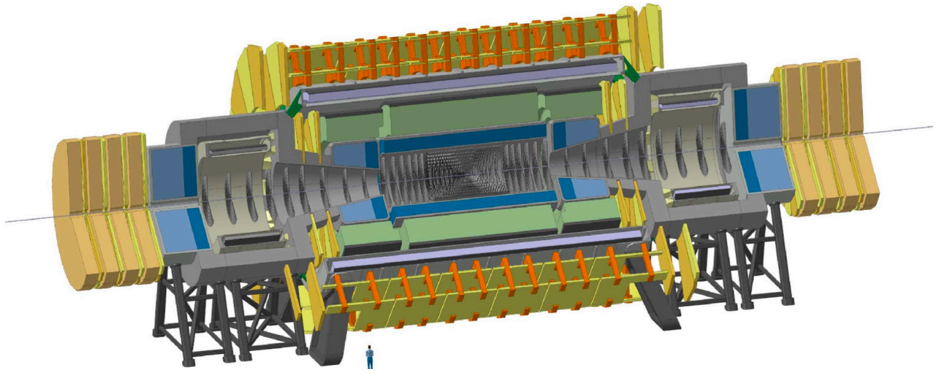


AHCAL Megatile

Application in Future Experiments

Future TileCal: FCChh detector

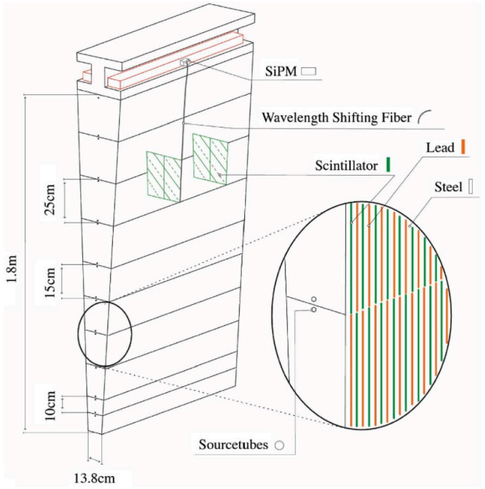
Tile calorimeter for future hadron collider

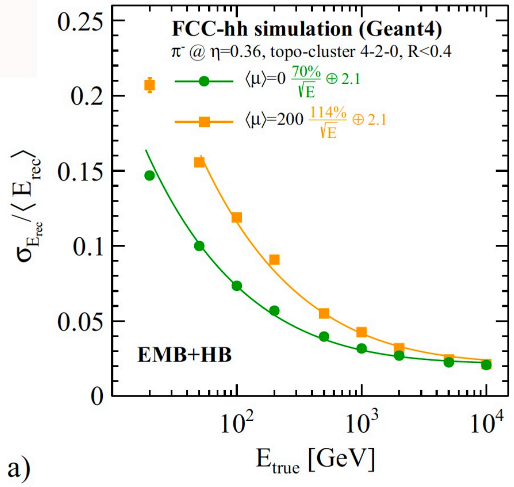


FCChh detector reference design inspired by ATLAS

- HCAL barrel and extended barrel: TileCal
  - Inner radius at 2.85 m → reduces radiation
- Radiation:
  - HCAL (extended) barrel: < 10 kGy, < 3*10^14 neq/cm^2
  - Allows use of organic scintillator
- Add lead to improve energy resolution (constant term)
  - Fe: Pb : Sci = 3:3 : 1.3 : 1
- Readout with SiPMs
  - Finer granularity than ATLAS (factor 2 in ϕ), 300,000 channels
- Goal for single hadron energy resolution
  - Calorimeter system: ~50% √E ⊕ 3%
  - Clustering needed for pile-up rejection → significant degradation

Similar HCAL barrel also foreseen for LHeC or FCCeh detector





Future Integrated Tile Calorimeters

Tile and strip calorimeters for future lepton colliders

Integrated scintillator tile (and strip) calorimeters foreseen for detectors at e+e- **Higgs factories**

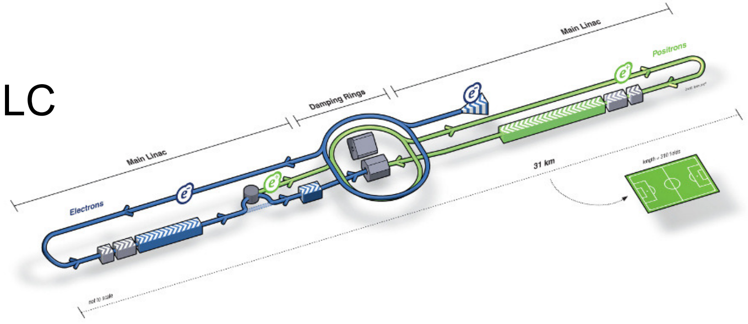
- ILD and SiD at ILC
- CLICdet at CLIC
- CLD at FCCee
- Detector at CEPC

CALICE concepts developed for this environment, but

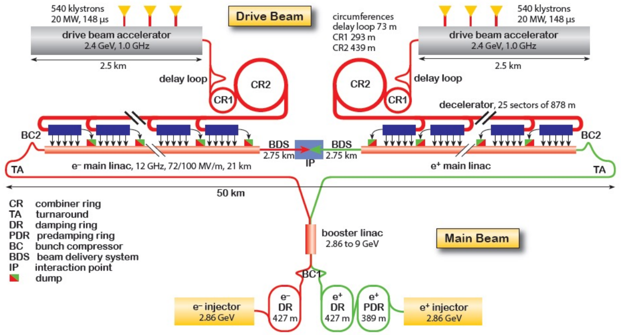
- Needs **engineering** for integration into collider detector
- For circular collider, adaptation of electronics, power and cooling for continuous operation necessary
- **Scaling up** from prototypes to collider detector by factor ~300 to ~1000 is a major effort

Similar HCAL is an option for a muon collider detector, but radiation might be an issue

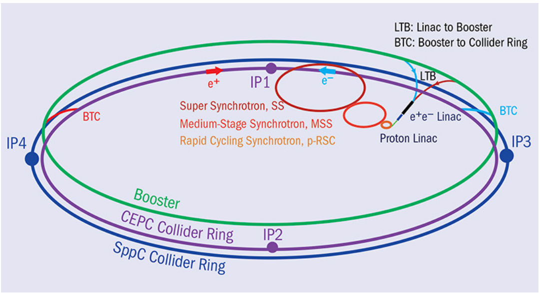
ILC



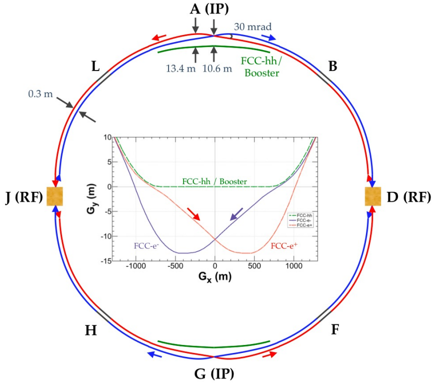
CLIC



CEPC

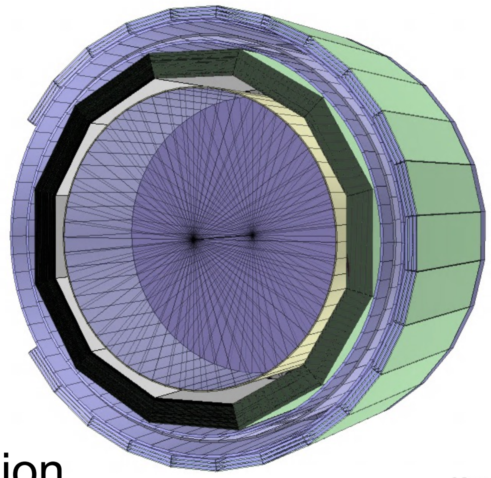


FCCee



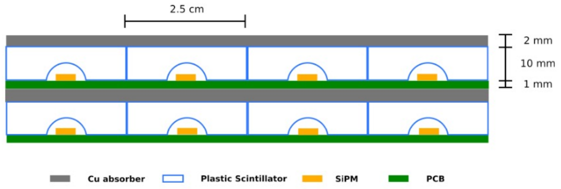
Future Integrated Tile Calorimeters: DUNE Near Detector

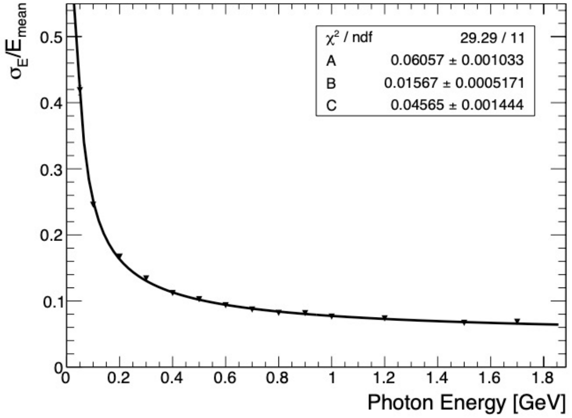
Tile calorimeter for a future neutrino experiment



ND-GAr

- Measure particles produced in neutrino interactions
  - **typical energies of a few 100 MeV**
- Gaseous Argon TPC surrounded by high performance calorimeter
- Requirements for the calorimeter:
  - Good energy resolution at very low energies
  - Identification of photons from NC events → position/angular resolution
  - Neutron id and energy measurement (ToF) → sub-ns time resolution
- Key designs
  - **Very thin absorber: 2 mm Copper** → mechanical challenge
  - **High granular layers** based on CALICE AHCAL design
    - 5 mm plastic scintillator tiles of 2.5*2.5 cm^2
  - Large strip layers in the back
  - Estimated number of channels: ~1 - 3M
  - Estimated performance
    - EM energy resolution 6%/√E + 4%
    - Angular resolution 8°/√E + 4°



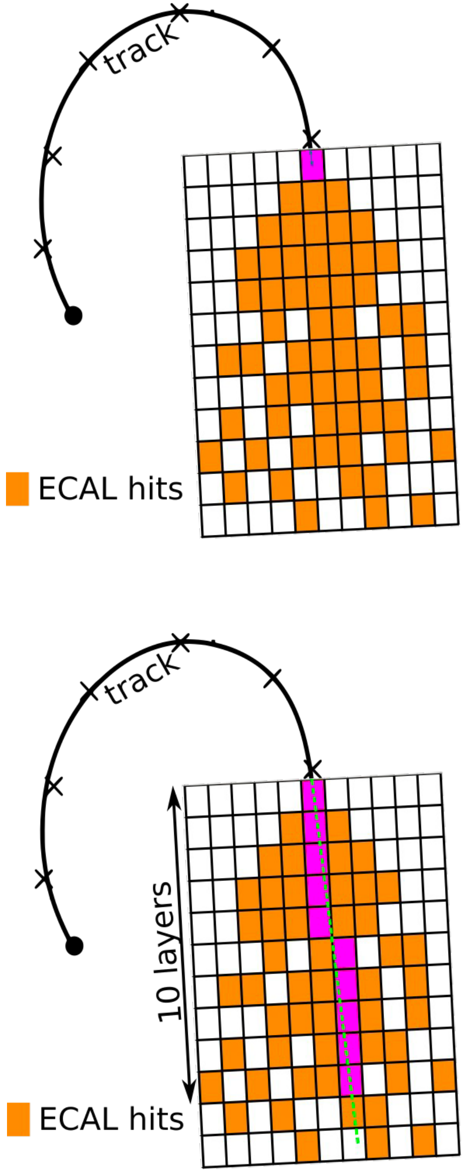


Future Ideas

Integration of Timing

Towards 5d calorimeters

- Possible uses of timing
  - In the energy reconstruction (weighting, dual read-out)
  - For particle flow: watch showers propagate in time
  - For ToF particle ID (→ TF4, Roger Forty)
- Good timing needs large signal size
  - Can be reached by many cells contributing to a shower time
  - Much harder for MIPs, need high light yield
    - In general crystals better than plastic scintillator (CMS barrel MIP timing detector uses LYSO)
- For high granularity calorimeters in general there are (at least) two options:
  - All layers provide precise time measurement
  - Dedicated timing layers (how many, where?)
- Interplay not obvious, might depend on
  - What can be reached technically
  - What is affordable
  - How is the information used in the reconstruction
- Many interesting aspects to explore!

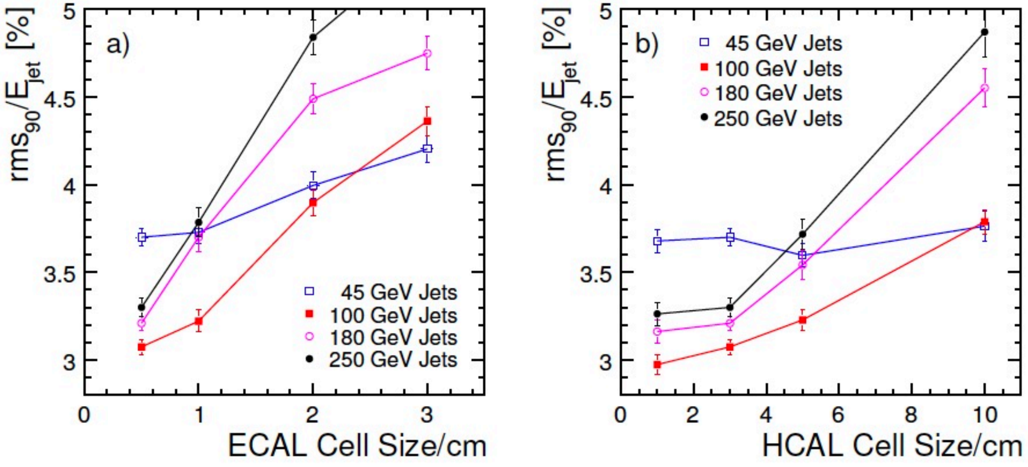


B. Dudar, LCWS2021

Ultimate Granularity

What makes sense?

- Tile and Strip size in CALICE concepts given by jet and shower properties
  - ScECAL strip size allows virtual 0.5*0.5 cm^2 cells, optimised to reach jet energy resolution < 3.8%
  - AHCAL tile size corresponds to Moliere radius to resolve EM sub-showers, optimised for jet energy resolution
- What can be gained by going smaller?
  - Better pile-up rejection
  - Better 2-particle separation (especially for ECAL)
  - Smaller tiles result in higher light output for MIPs
    - Better S/N
    - Better time resolution



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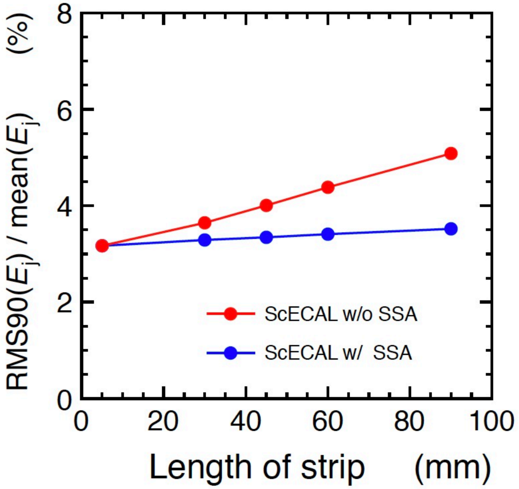
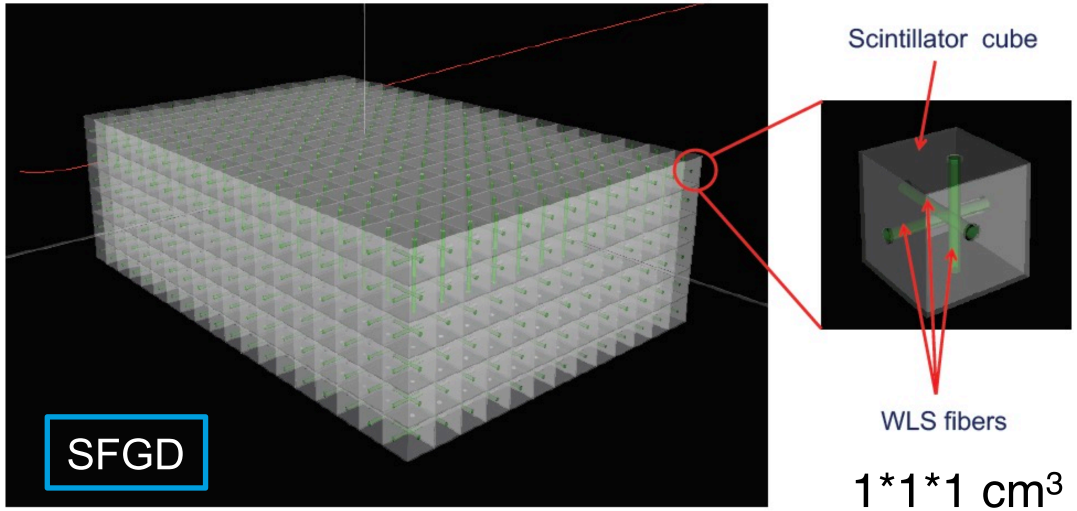


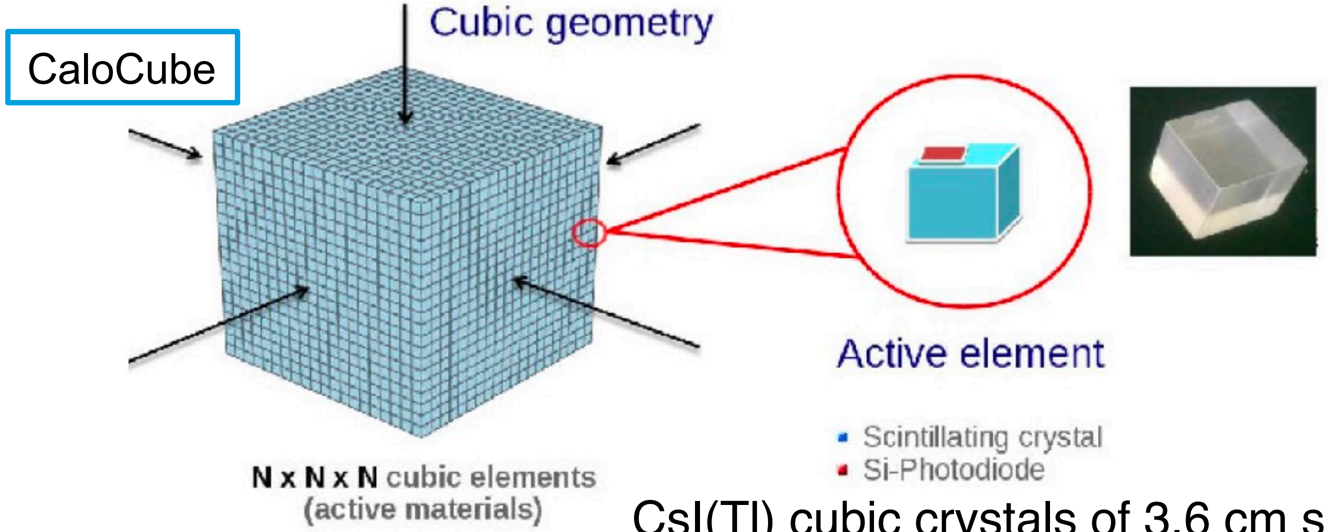
Ultimate Granularity

How far can we go?

- Some ideas are investigated already
  - CaloCube: EM calorimeter for satellite experiment with large angular acceptance
  - HyperK ND280 Super-Fine-Grained Detector: active target (and tracker) for neutrino interactions
  - Mu3e tile detector: time measurement with ~50 ps resolution for MIPs



$1*1*1$ cm^3



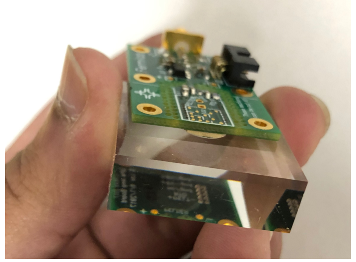
CsI(Tl) cubic crystals of 3.6 cm size

6.3 * 6.2 * 5.0 mm^3

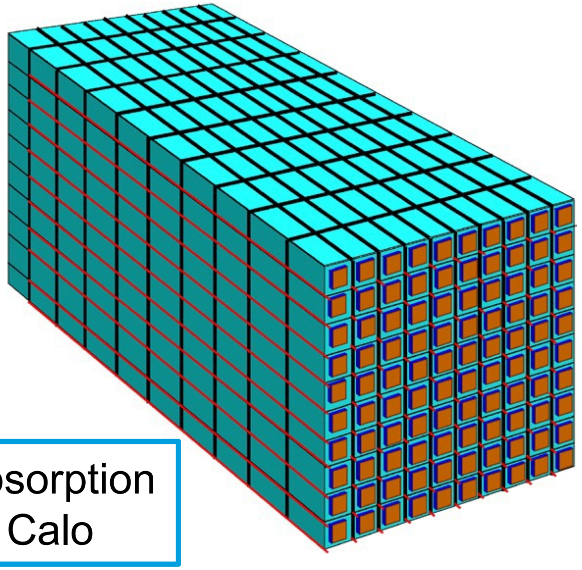
Tiles with Dual Readout

Combining advantages

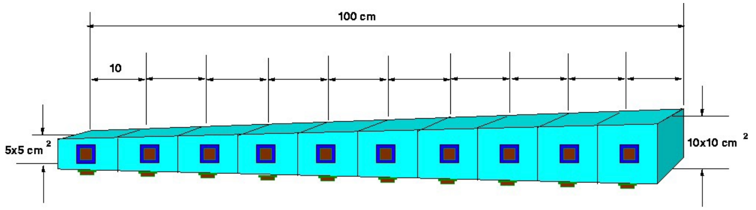
- Fundamental limit of hadron calorimeters: fluctuations in shower composition
  - Electro-magnetic fraction
  - Hadronic fraction
  - Invisible fraction
- Compensating calorimeters are insensitive to fluctuations of EM fraction, but usually have degraded EM resolution
- Fluctuations in EM fraction can be measured
  - Indirectly by energy density (used in software compensation)
  - Directly with dual readout (→ Gabriella's talk)
- Combination of Dual Readout and High Granularity
  - Dual readout tiles (ADRIANO2 concept)
  - Total absorption dual readout hadron calorimeter → removes also sampling fluctuations
    - Simulation promises stochastic term of 10-15 % (doi:10.1088/1742-6596/404/1/012049, doi:10.1088/1748-0221/6/10/P10012)
    - Requires high density materials producing scintillation light and Cerenkov radiation, and photon detection sensitive to either of the two
    - No experimental verification yet



ADRIANO2 Lead-Glass Tile



Total absorption Hadron Calo



Connection to Industry

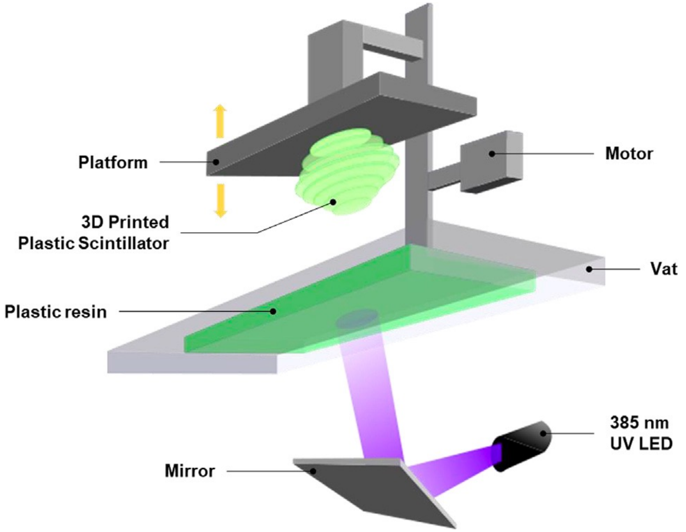
Possible areas of interest

Larger number of tiles/strips/channels calls for further automatization and/or simplification

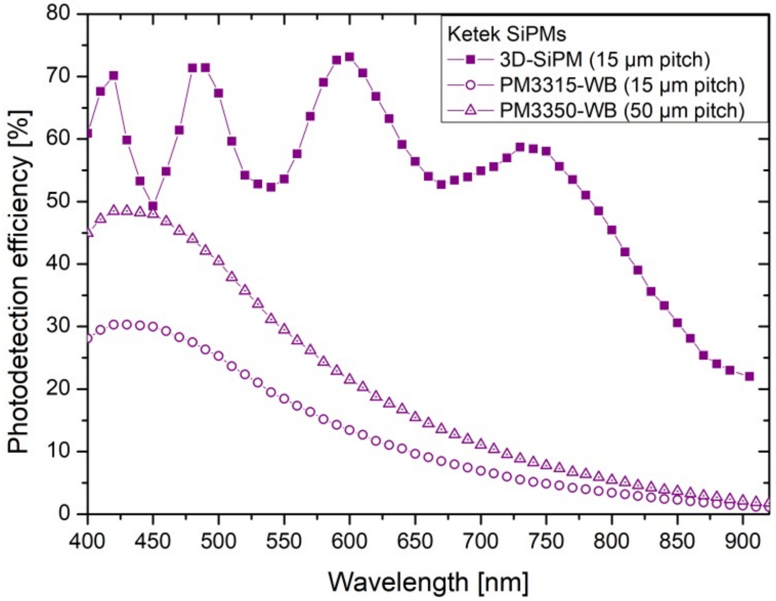
- Can **3d printing** of tiles/strips make a difference?
  - Would give large freedom for special shapes and on-demand production
  - How scalable is it? How expensive is it?

SiPMs are a dynamic field (→ TF 4)

- Ongoing developments towards more radiation hardness, less noise
- Applications in industry (e.g. automotive, medical)
  - We are not driving the field
  - But we might profit from developments
  - Example: SiPMs sensitive in other wave length ranges
    - Development of blue-sensitive SiPMs allowed to go from WLS fibres to direct coupling
    - New: (Infra-)Red sensitive 3D SiPMs → higher PDE



https://doi.org/10.1016/j.net.2020.05.030



arXiv:2010.10183

Software

Nothing works without simulation and reconstruction

Simulation

- Plastic scintillator material properties in general well known (e.g. Birks' law)
- Combination with neutron-rich absorber material (tungsten) for hadron showers less well known
  - Detailed description increasingly important for high granularity calorimeters
- High granularity requirements lead to slow simulation
  - Some efforts ongoing to use Machine Learning

Reconstruction

- Advantages of high granularity can only fully be exploited with appropriate reconstruction algorithms
  - What is appropriate depends on the environment! (e.g. PFAs developed for e+e- not directly applicable at LHC and vice versa)
- Timing adds a whole new dimension to this!

Summary

- Calorimeters based on scintillator tiles and strips have been and are core components of detectors at colliders (and beyond)
  - “Classic” approach allows decoupling scintillator and photodetector + electronics
  - “Integrated” approach allows high granularity
    - CMS HGCAL will be the first application in a collider detector

- Potential of tile and strip calorimeters by far not exhausted
  - Concepts for future experiments: Higgs Factories, DUNE ND-GAr, FCChh
  - Ideas for future developments: timing, spectral sensitivity, novel materials…

Thank you!