The IDEA detector for FCC-ee and overview on calorimetry

F. Bedeschi, INFN-Pisa,
Swiss FCC workshop,
Geneva, September 2021

Outline

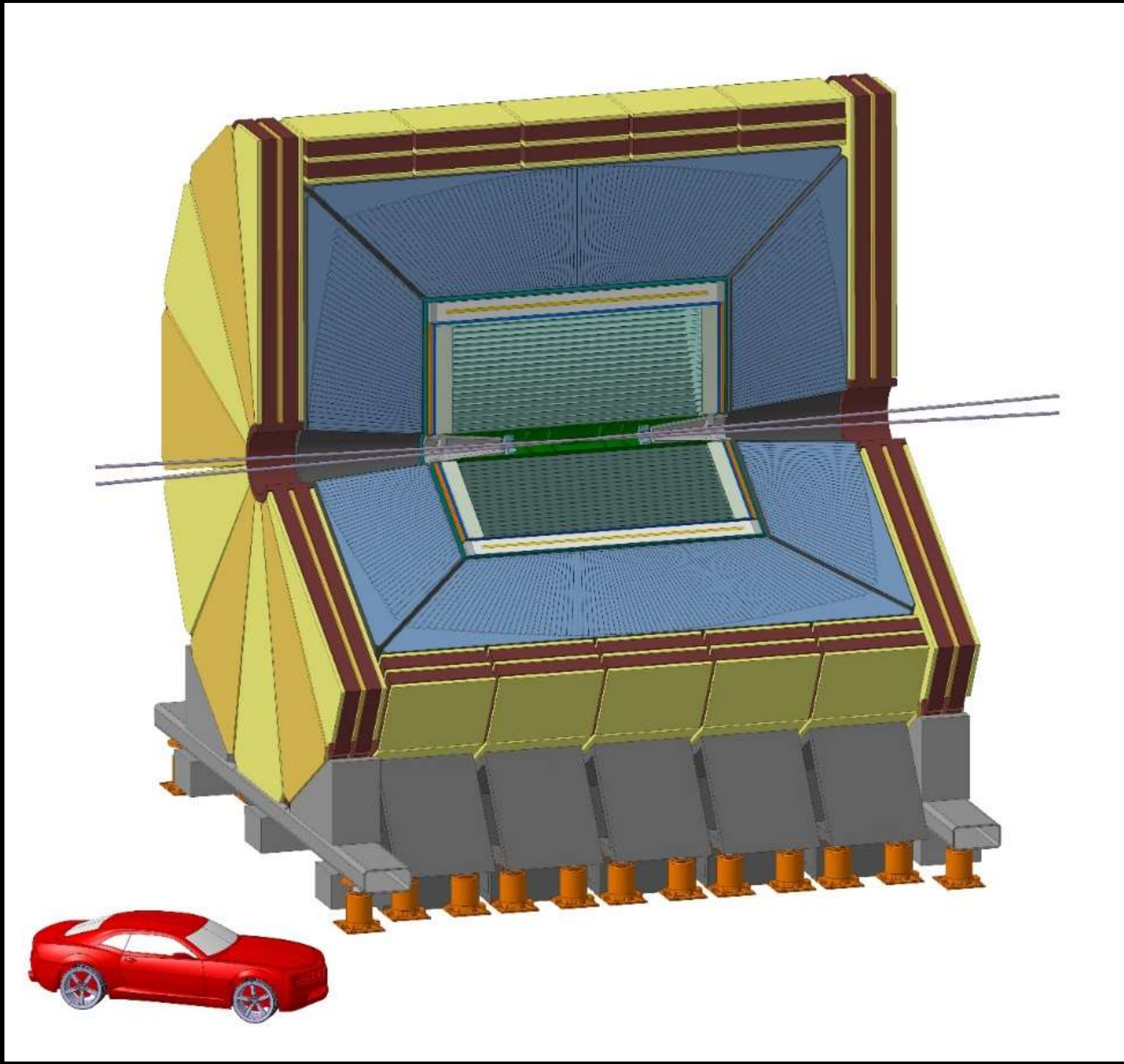
- Two flavors of IDEA detector concept
- Calorimetry R&D overview
- Dual readout support and collaboration
- Conclusions

IDEA detector concept

Innovative Detector for Electron-positron Accelerator

❖ Basic features

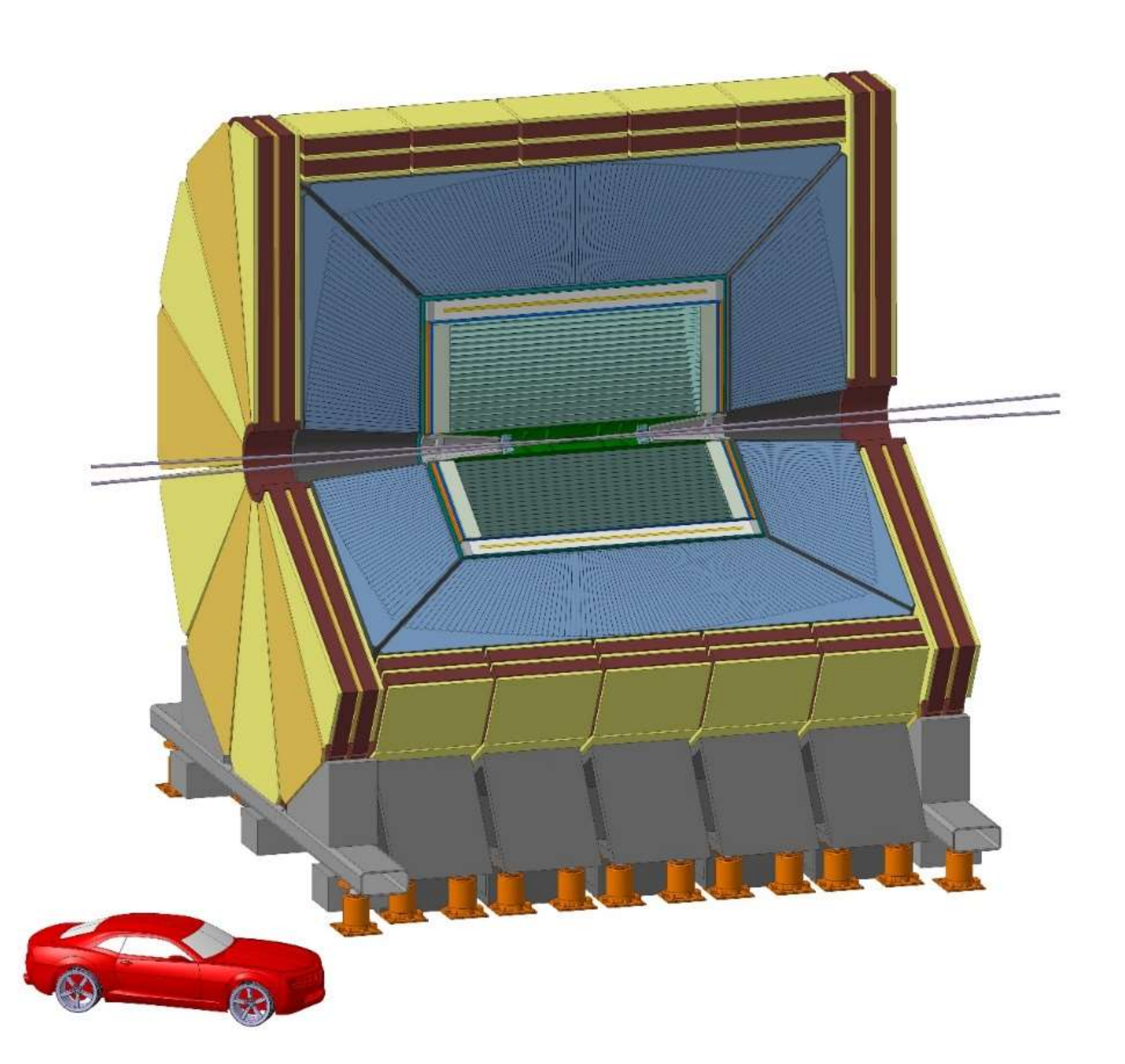
- ➢ Precise vertex detector
- ➢ Large tracking volume with good PID
- ➢ Thin solenoid wih calorimeter outside
- ➢ Dual Readout calorimeter EM/Had in single package
- ➢ Thin yoke instrumented with muon chambers



IDEA detector concept

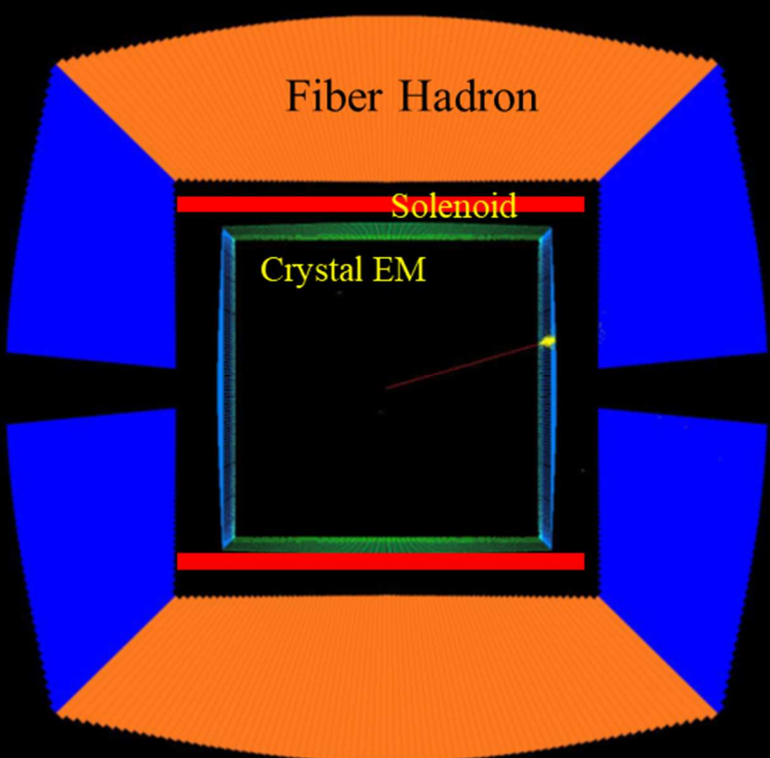
Innovative Detector for Electron-positron Accelerator

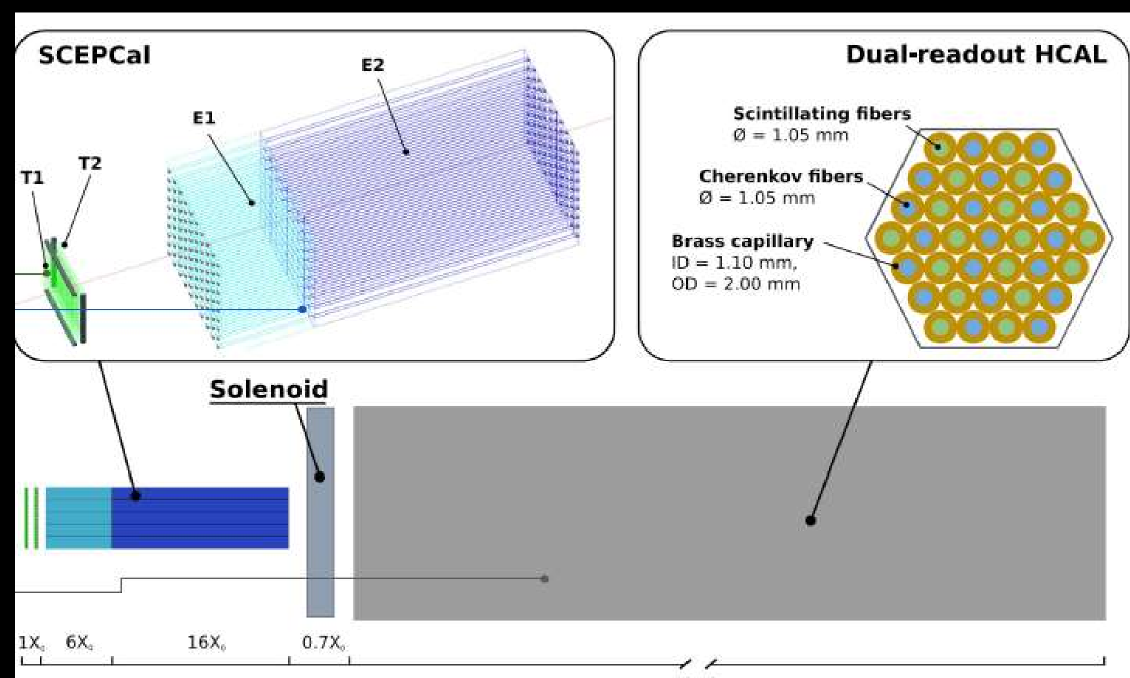
- R&D in progress
  - MAPS vertex detector
    - ARCADIA
  - Drift chamber
    - Cluster counting
  - Silicon wrapper
    - ATLASpix3
  - Dual Readout calorimeter
    - Also with crystals
  - μRwell muon chambers



IDEA with crystals

- More performant/expensive version w/ crystals
  - ~ 25cm inside solenoid – 22 X_0 – Dual Readout
  - 1x1 cm^2 $PbWO_4$ crystals – LYSO timing layer in front





Calorimetry requirements at FCC-ee

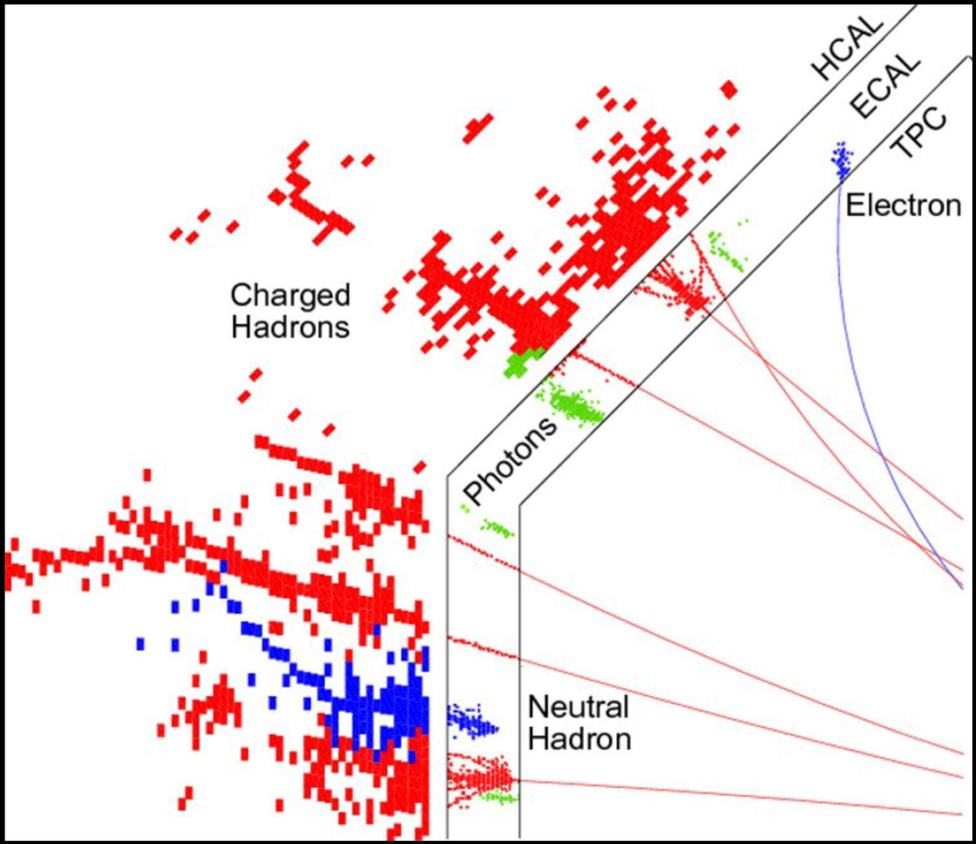
- ZH
  - Jet-jet invariant mass resolution to resolve W from Z (~ 3%)
    - Better jets for Z→jet jet recoil and ννH→ jet jet measurements
    - Both energy and angular resolutions matter
  - EM resolution ~15% sufficient to sustain jet resolution, but
    - Better resolution allows electron track energy recovery
    - Better resolution/granularity improves π^0 reconstruction
      - Both τ and jets are improved
- Z pole
  - HF and τ physics
    - Extreme EM energy resolution for great π^0 reconstruction

Modern calorimeters

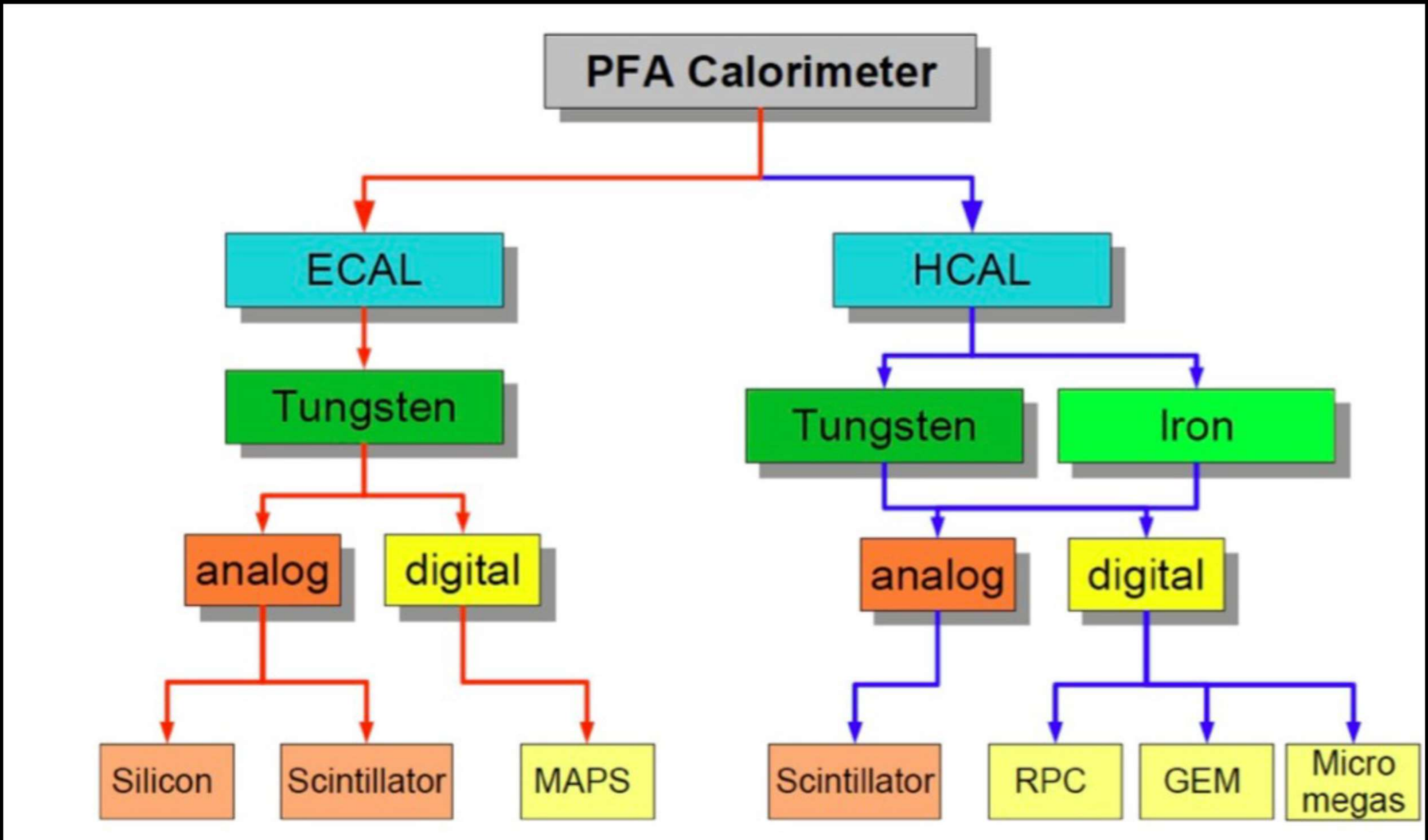
- Key technologies have been around for many years
  - Some already used in real experiments
    - Crystals and liquid noble gases (LNG)
  - Others have already done extensive R&D and prototyping
    - High granularity (HG), dual readout (DR)
- Crystals (and LNG) for good EM resolution
- HG and DR for good jet resolution
- Merging LNG or crystals with HG or DR requires changes to the standard implementations
- New technological developments push R&D forward
  - Mainly on SiPMs and readout electronics

High granularity (1)

- Principle:
  - Separate signal by neutral and charged particles
  - Use tracking for charged
  - Need high transverse and longitudinal segmentation



High granularity (1)



- Many technologies explored

High granularity (2)

❖ Large prototypes built and tested

Si ECAL – Physics prototype

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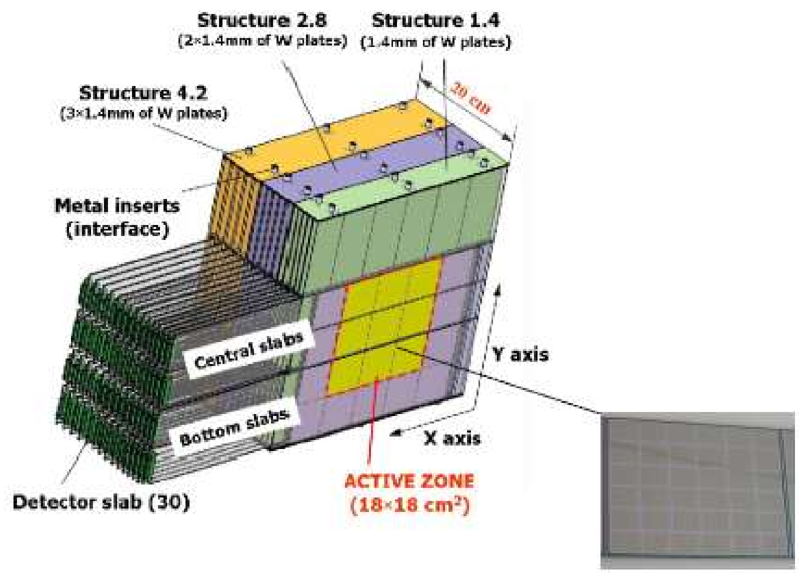
- Sampling calorimeter
- Absorber: Tungsten plates1.4-4.2mm:
- Active material: silicon P-I-N Diodes
  Thickness 525µm
- Granularity: 10x10mm^2



Three modules of with increasing W thickness
Total depth: 24 X_0, 1 λ_I
Active Zone 18x18 cm^2
Total: 9720 Pixels/Channels

High granularity (2)

❖ Large prototypes built and tested

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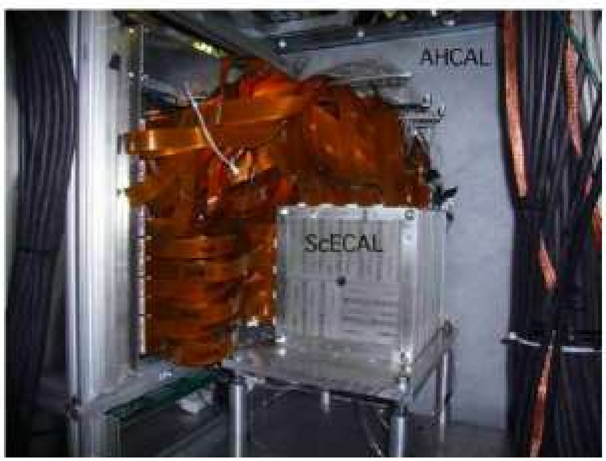
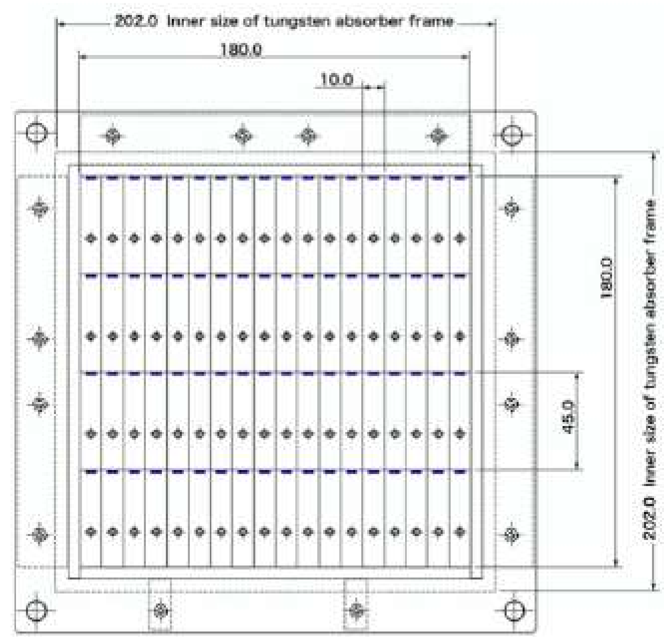
Sc ECAL – Physics prototype

- Sampling calorimeter
- Absorber: Tungsten plates 3.5mm:
- Active material: Scintillator strips 45x10x3 mm^3
  - Arranged in alternating xy-layers





Total depth: 21.5 X_0, 1.2 λ_I

Active Zone 18x18 cm^2

Total: 2160 Channels

High granularity (2)

❖ Large prototypes built and tested

AHCAL – Physics prototype

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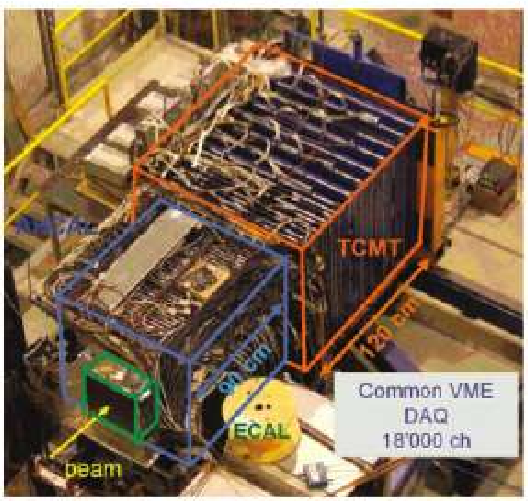
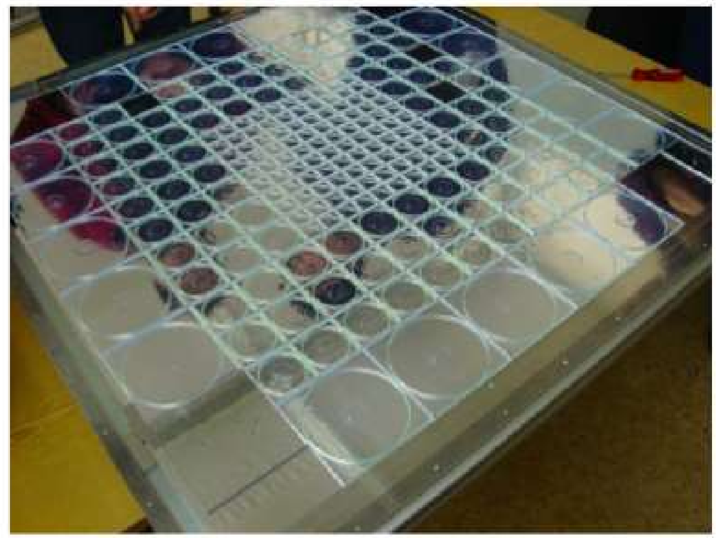
- Sampling calorimeter
- Absorber: Steel or tungsten plates 21,4 or 10 mm
- Active material: Scintillator tiles with different dimensions
  - 30x30x5 mm^3, 60x60x5 mm^3, 120x120x5 mm^3



Combined setup at CERN 2006



Total depth: 47.2 X_0, 5.3 λ_I

Active Zone ~90x90 cm^2

Total: 7608 Channels

High granularity (2)

❖ Large prototypes built and tested

(Semi-) Digital Hadron Calorimeters – DHCAL and SDHCAL

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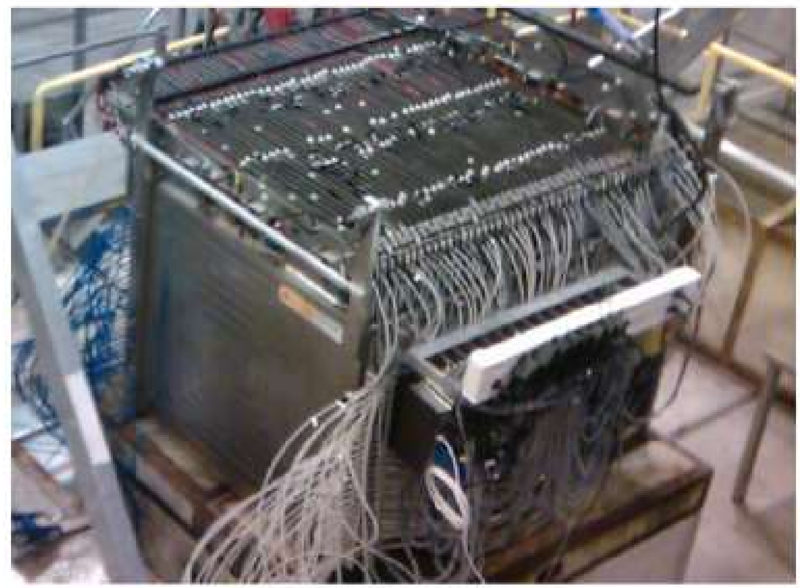
DHCAL (until 2014)

1bit resolution (i.e. 1 threshold)

SDHCAL (since 2011)



2bit resolution (i.e. 3 thresholds)

- Two 1 m^3 stacks with 40-50 layers
- About 500000 cells each

High granularity (3)

- Key technologies
  - Large area silicon detectors
  - SiPMs
  - Highly integrated FE electronics with timing

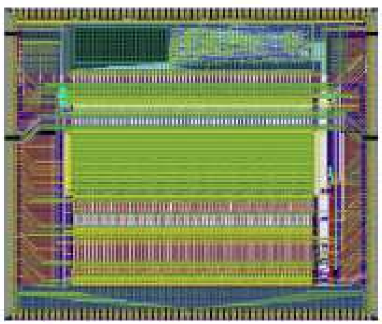
High granularity (3)

❖ Key technologies

Calorimeters for PFA – Technological premises

Highly integrated front end electronics

e.g. SKIROC (for SiW Ecal)

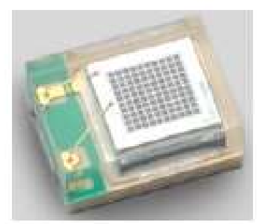


Size 7.5 mm x 8.7 mm, 64 channels

- Analogue measurement
- On-chip triggering
- Data buffering
- Digitisation

... all within one ASIC

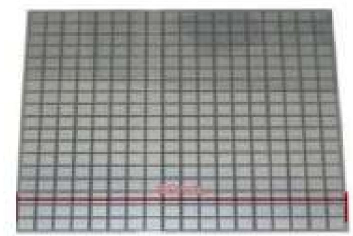
Miniaturisation of r/o devices



- Small scinitllating tiles
- (Low noise) SiPMs

Large surface detectors

Si Wafer



RPC layers

Many things that look familiar to you today were/are pioneered/driven by CALICE

High granularity (3)

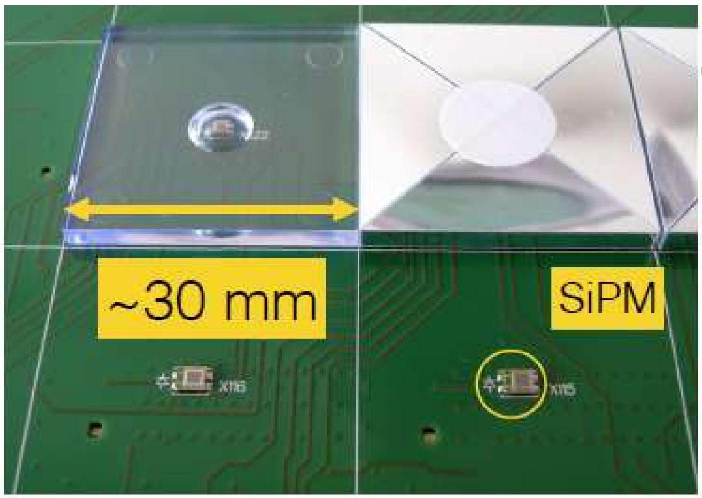
- Key technologies
  - Large area silicon detectors
  - SiPMs
  - Highly integrated FE electronics with timing
- System integration
  - Very large number of channels
    - Handling
    - Readout
    - Cooling
    - Services
    - Cost optimization

High granularity (3)

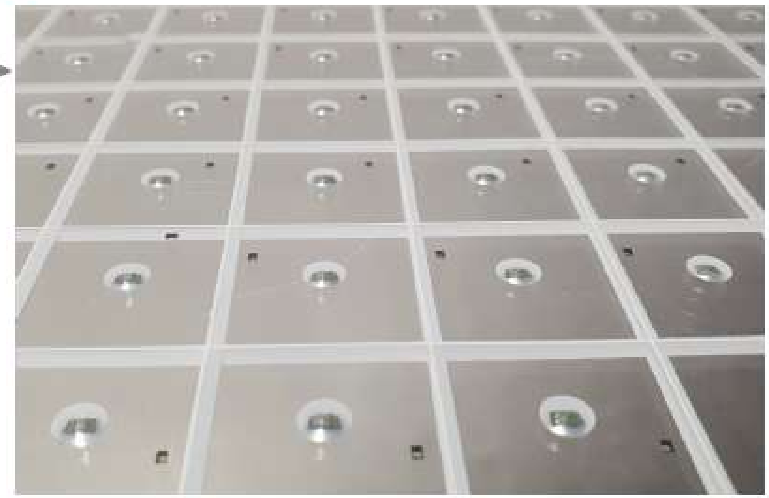
❖ Key technologies

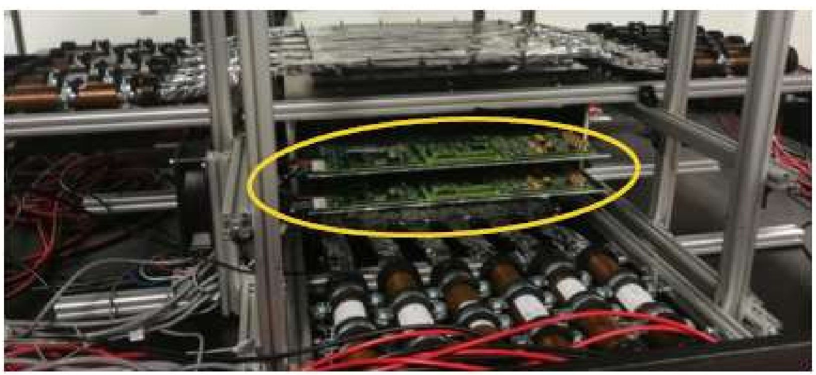
Large scintillator planes with optical separation instead of single tiles

Much easier assembly during production

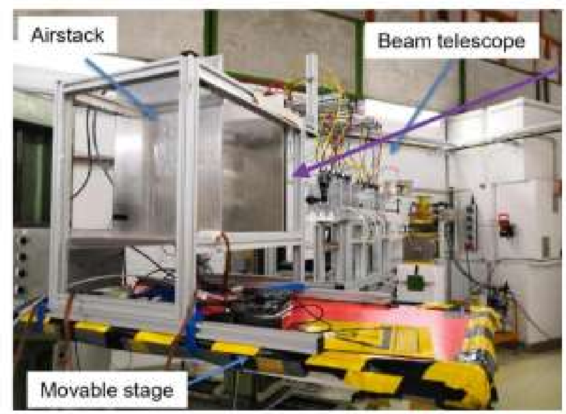


No wrapping, easier positioning and gluing





Under test with cosmic rays and beam to measure light yield, uniformity and optical cross talk



High granularity (4)

❖ Performance:

➢ Raw single particle resolution

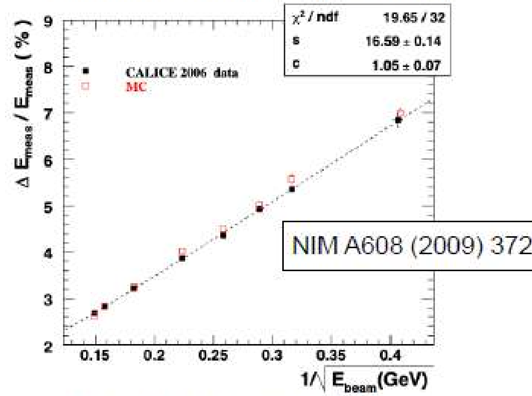
Single Particle Energy Resolution

Performance of CALICE Calorimeter Prototypes - Examples

- Achieved single particle (intrinsic) energy resolution of CALICE calorimeter prototypes remarkable - even if they are not explicitly optimised on this quantity alone
  - ➡ SiW ECAL physics prototype (EM): **~16.6% / $\sqrt{E(GeV)}$ ⊕ ~1.05%**
  - ➡ ScECAL physics prototype (EM): **~12.5% / $\sqrt{E(GeV)}$ ⊕ ~1.2%**
  - ➡ AHCAL physics prototype (HAD): **~58% / $\sqrt{E(GeV)}$ ⊕ ~1.6%** (before weighting)

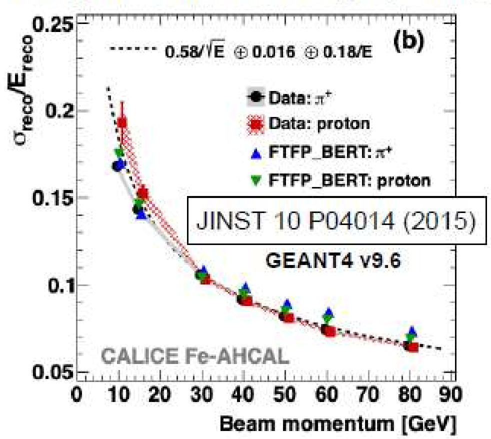
Recall: Particle Flow requires high granularity, and profits from good hadronic energy resolution

Energy Resolution SiW ECAL (e-)



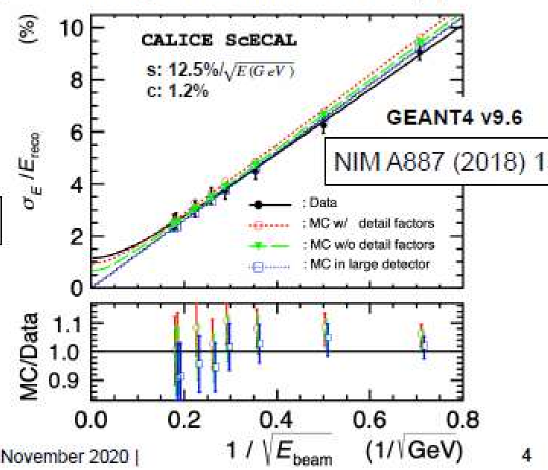
NIM A608 (2009) 372

Energy Resolution AHCAL (pi+/protons)



JINST 10 P04014 (2015)

Energy Resolution ScECAL (e-)

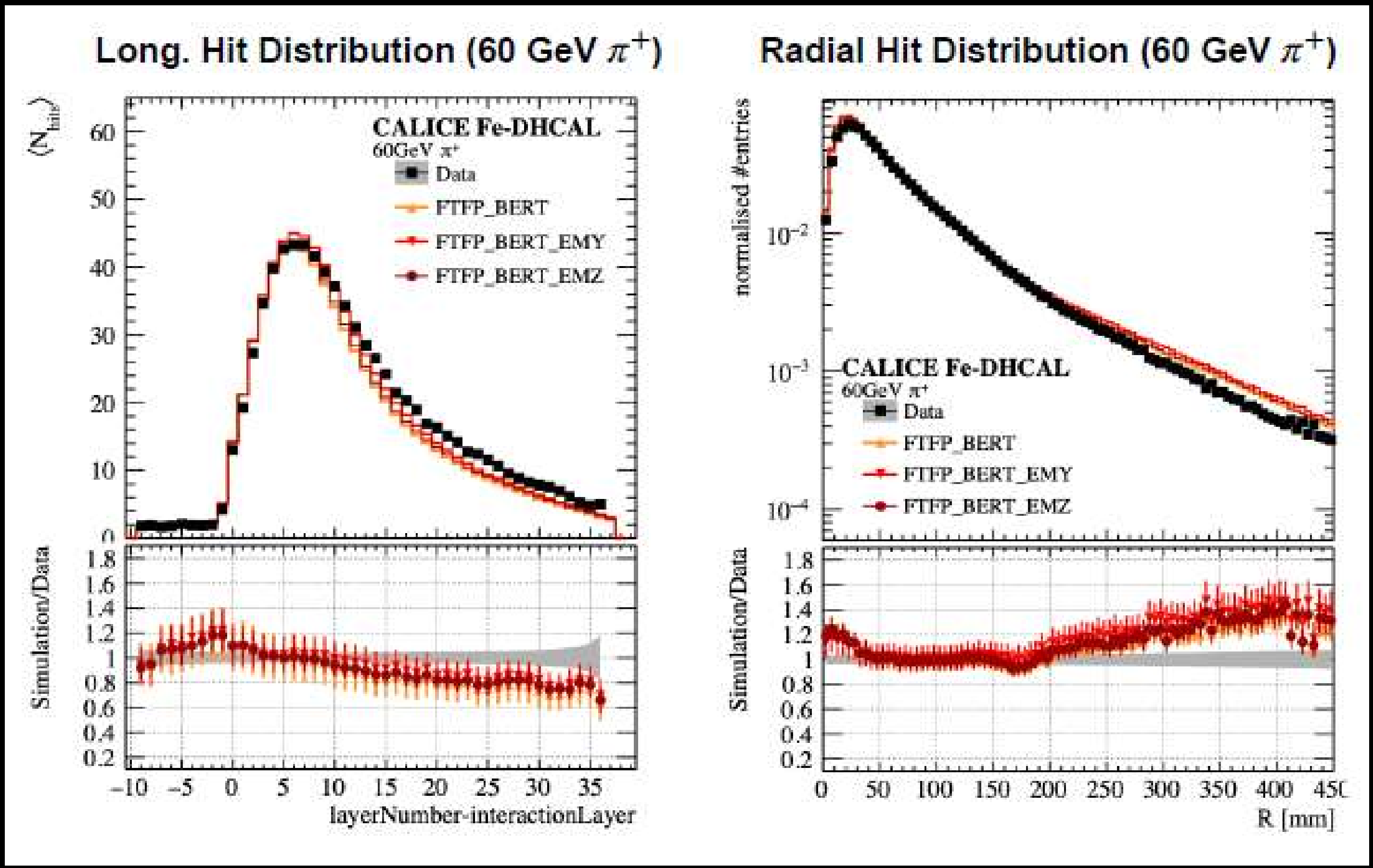


NIM A887 (2018) 15

DESY. | CALICE Results - Performance & Analysis Highlights | Daniel Heuchel | FCC Physics and Experiments Workshop | Virtual - 11th November 2020 | 4

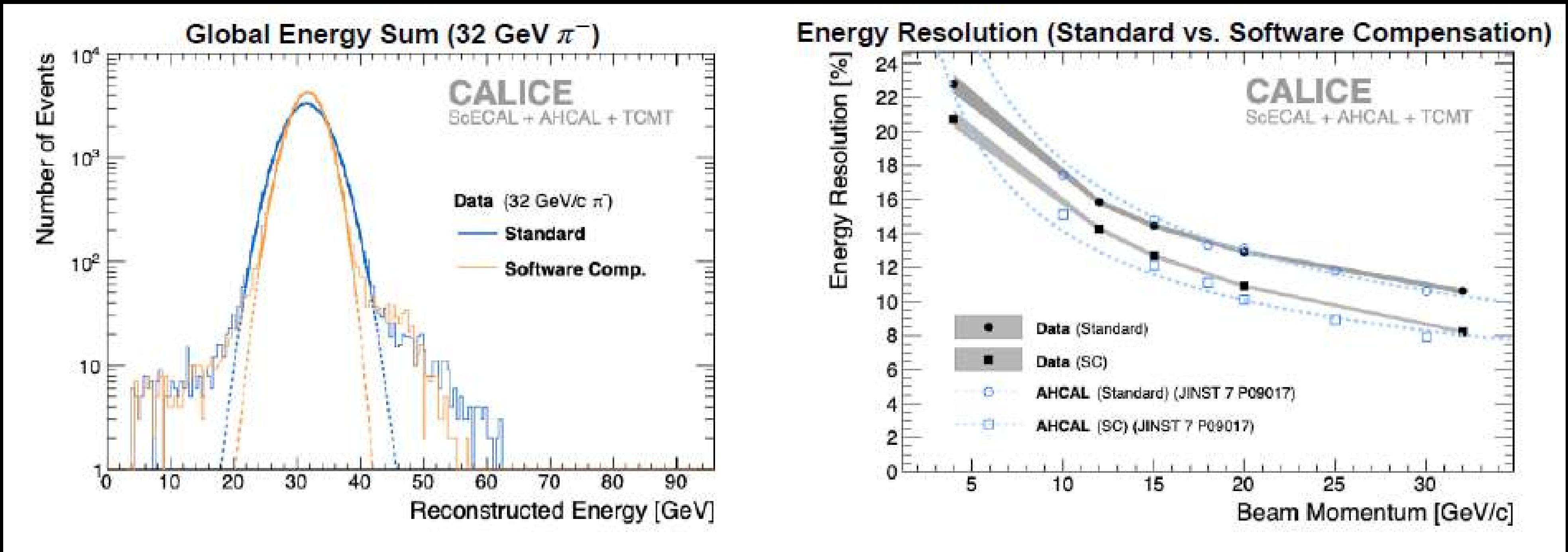
High granularity (4)

- Performance:
  - Raw single particle resolution
  - Study of shower profiles



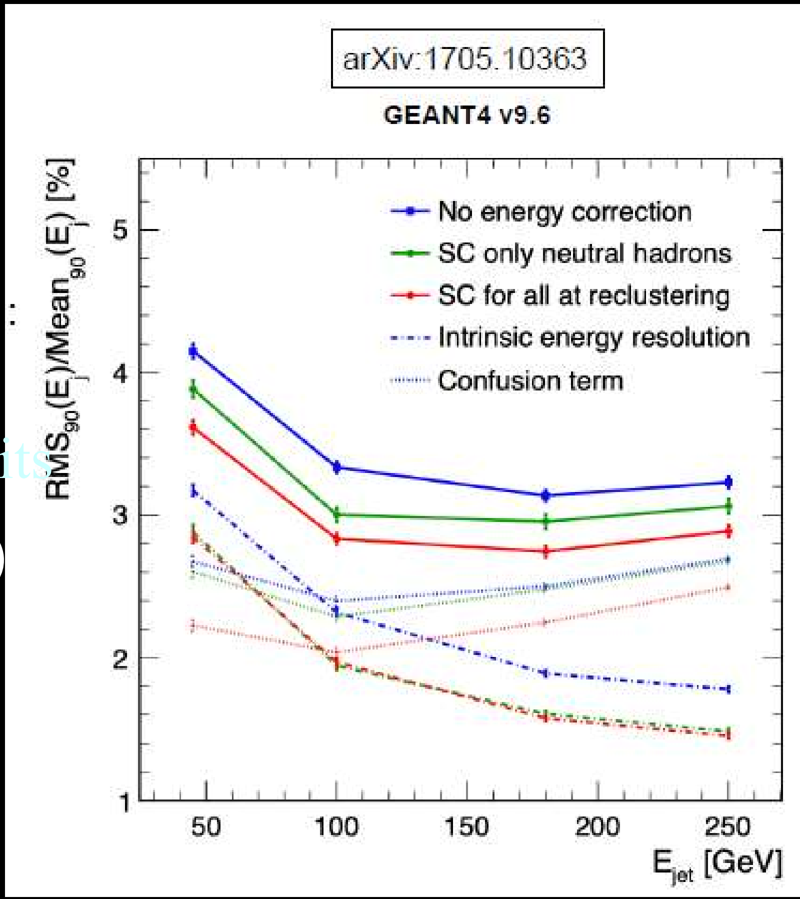
High granularity (4)

- Performance:
  - Raw single particle resolution
  - Study of shower profiles
  - Software compensation
    - Local energy density higher for EM deposits



High granularity (4)

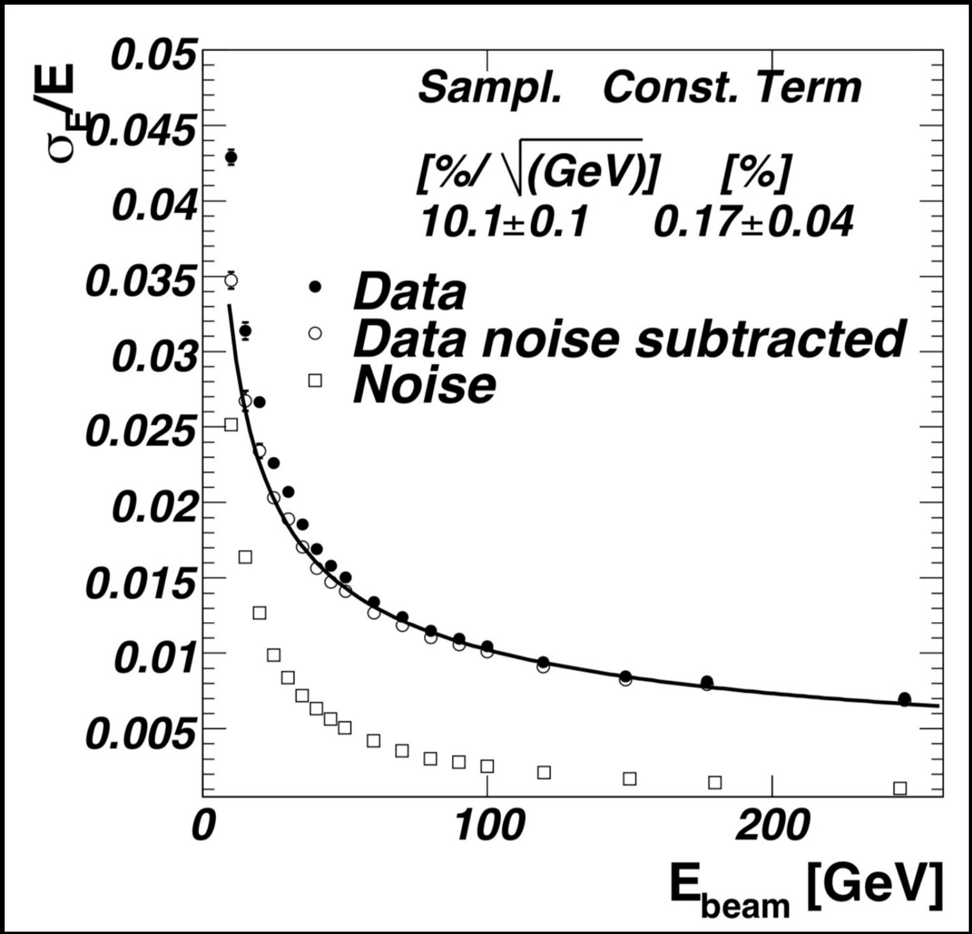
- Performance:
  - Raw single particle resolution
  - Study of shower profiles
  - Software compensation
    - Local energy density higher for EM deposits
  - Optimal jet resolution with PF (w/ SC)



Liquid noble gas (1)

- Tested technology in Atlas
  - $\approx 10\%/\sqrt{E}$ demonstrated

$$\frac{\sigma(E)}{E} = \frac{10\%}{\sqrt{E}} \oplus \frac{0.2}{E} \oplus 0.2\%$$



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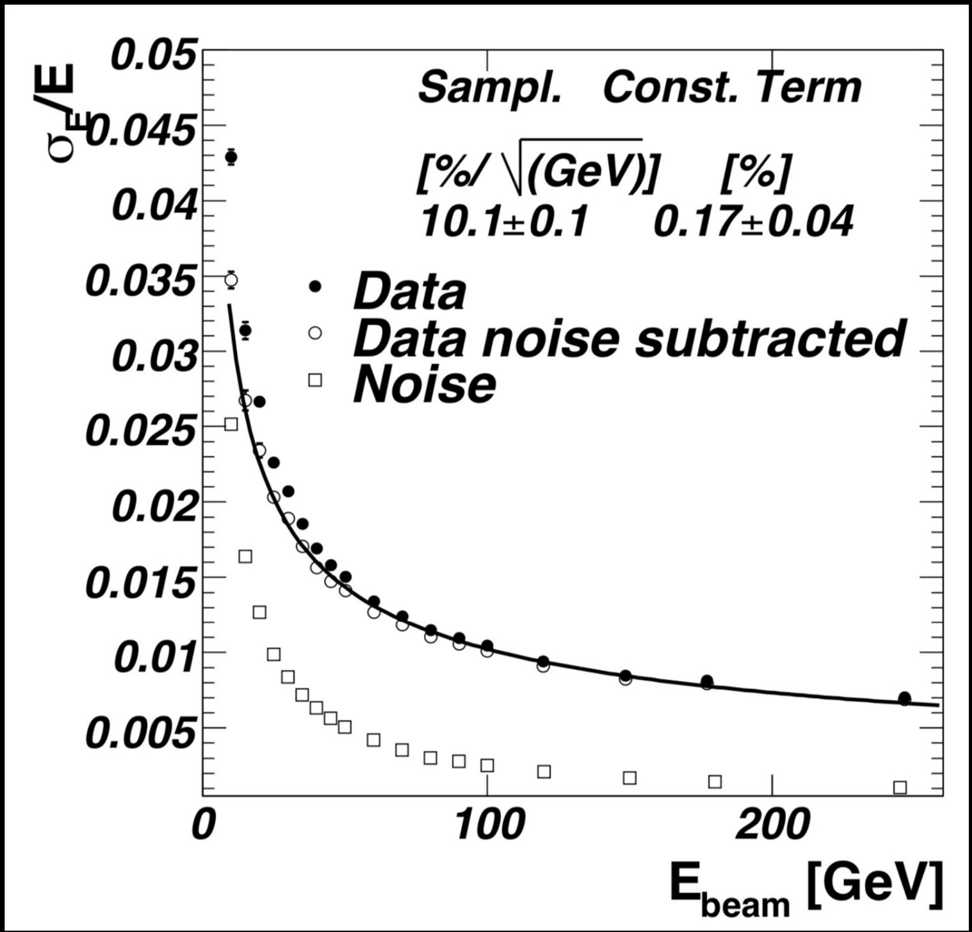

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  - HG friendly
    - Higher granularity
      - Transverse and depth
      - Many signal traces

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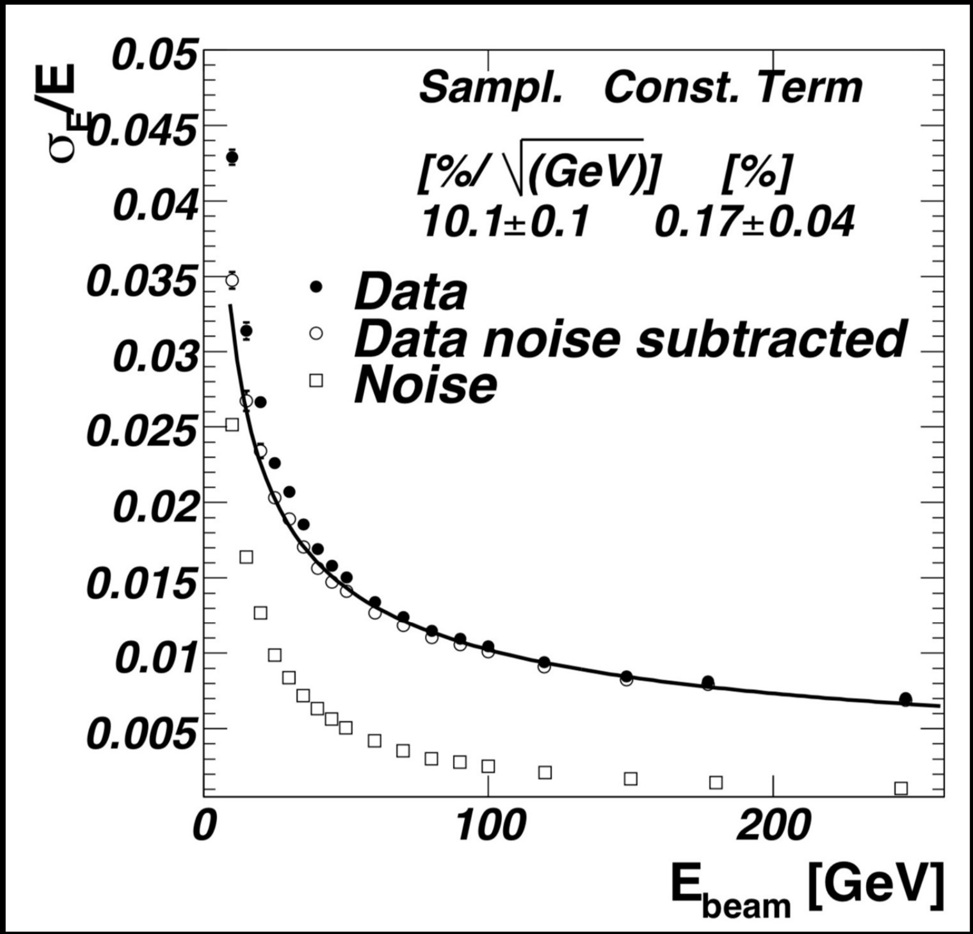

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    - Higher sampling fraction
      - Thicker detector

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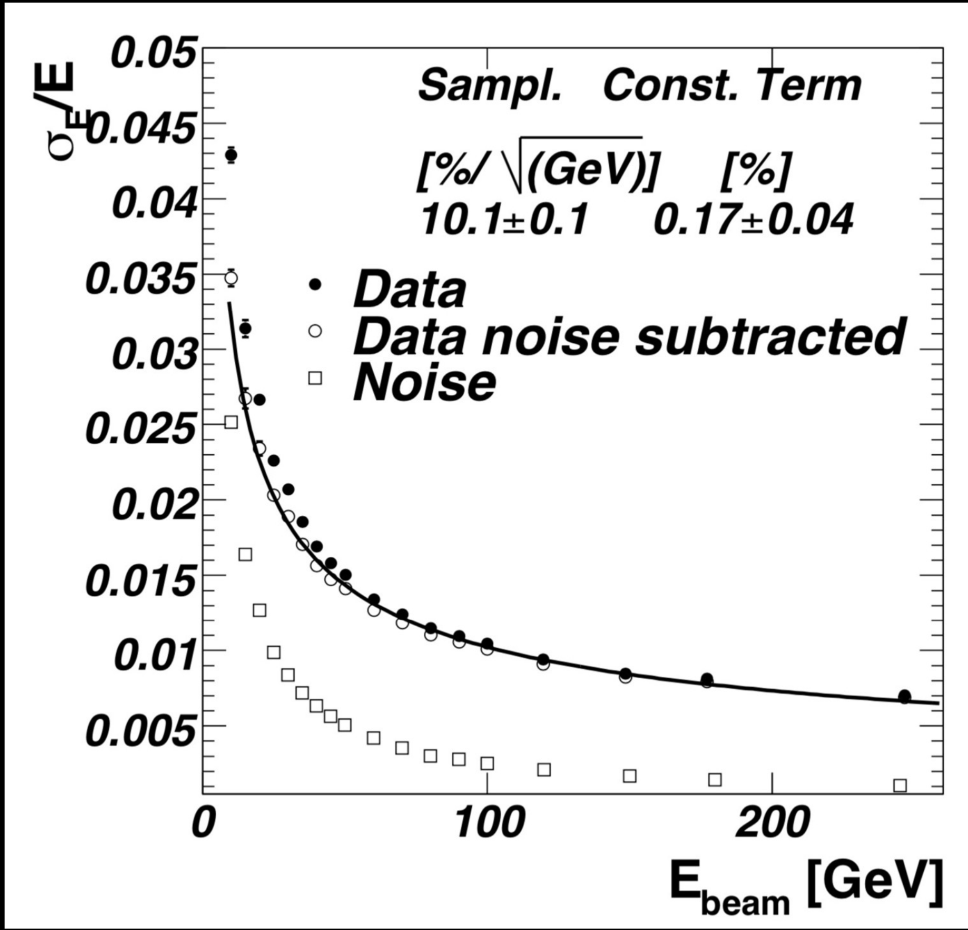

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  - HG friendly
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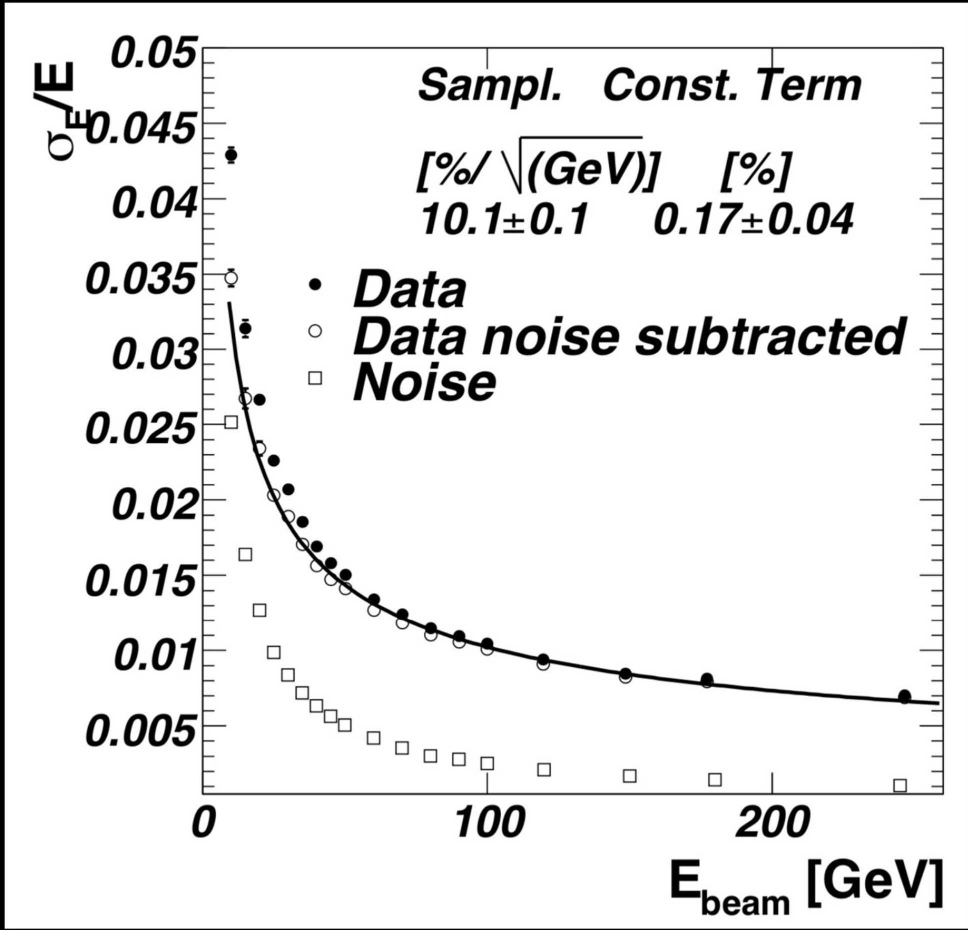
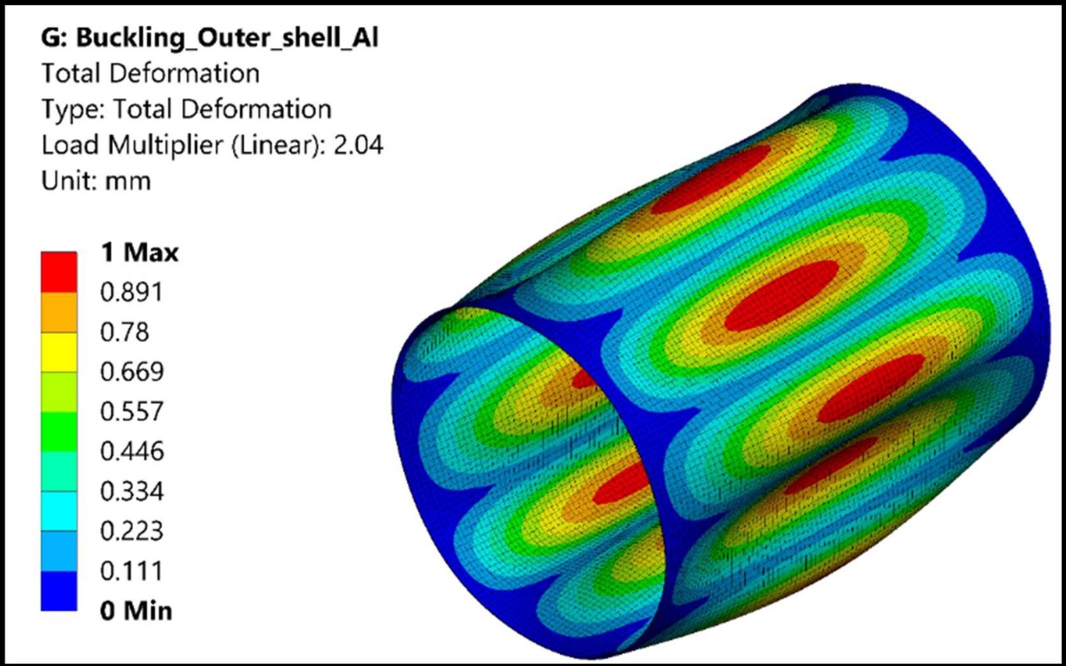
      - Transverse and depth
      - Many signal traces
  - Push EM resolution
    - Higher sampling fraction
      - Thicker detector
  - Low energy photons (300 MeV)
    - Low mass cryostat
    - Small noise term

$$\frac{\sigma(E)}{E} = \frac{10\%}{\sqrt{E}} \oplus \frac{0.2}{E} \oplus 0.2\%$$



Liquid Noble gas (2)

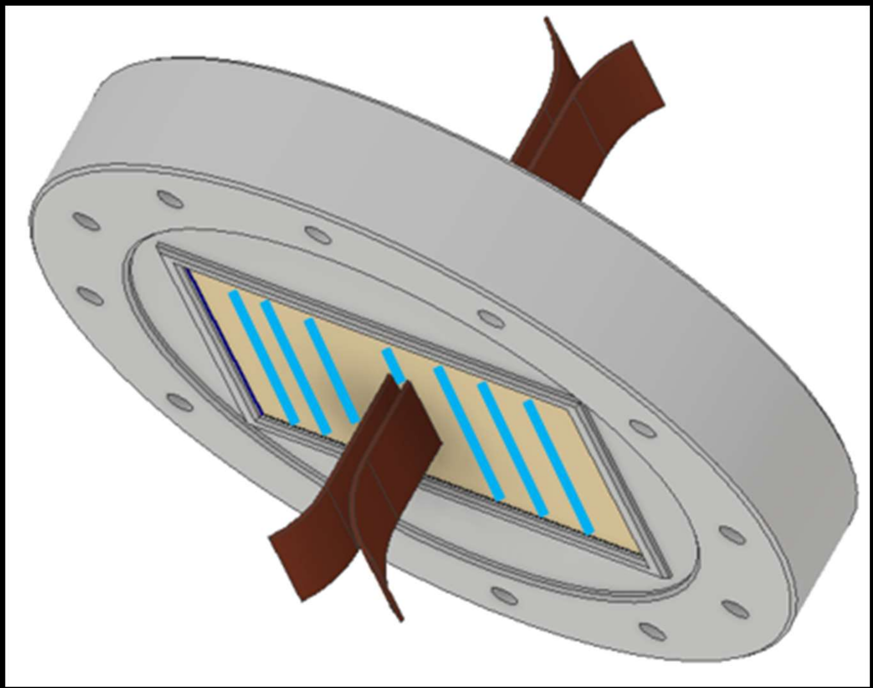
- Preliminary tests on carbon fiber cryostats
  - Numerical studies & tests

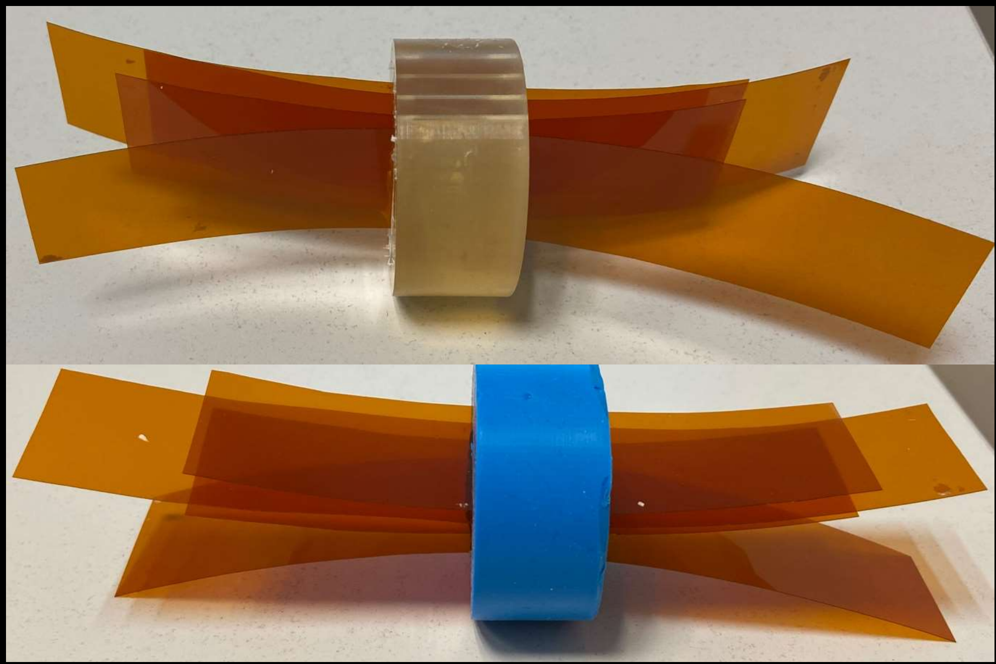


Out of Autoclave process

Liquid Noble gas (2)

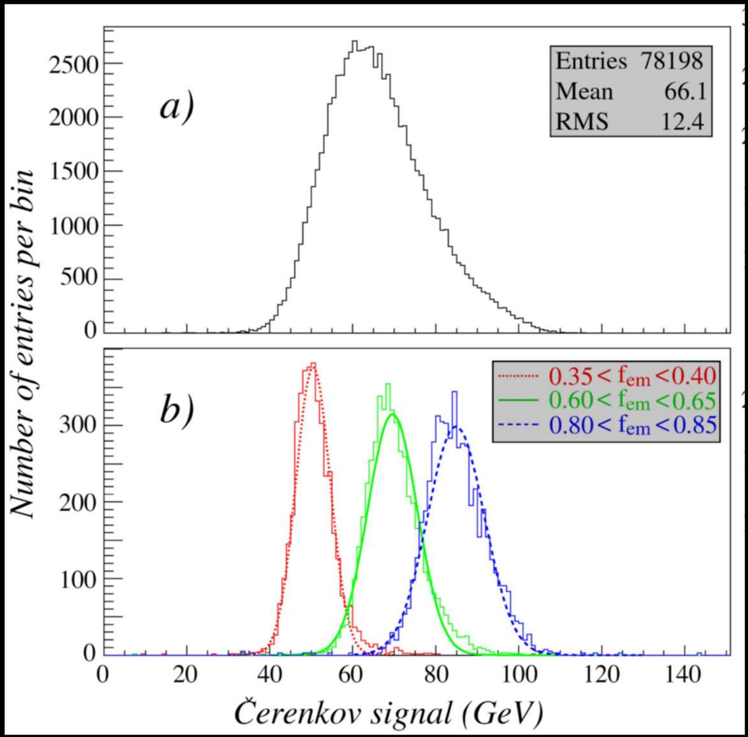
- Preliminary tests on carbon fiber cryostats
  - Numerical studies & tests
- High density feedthrough development

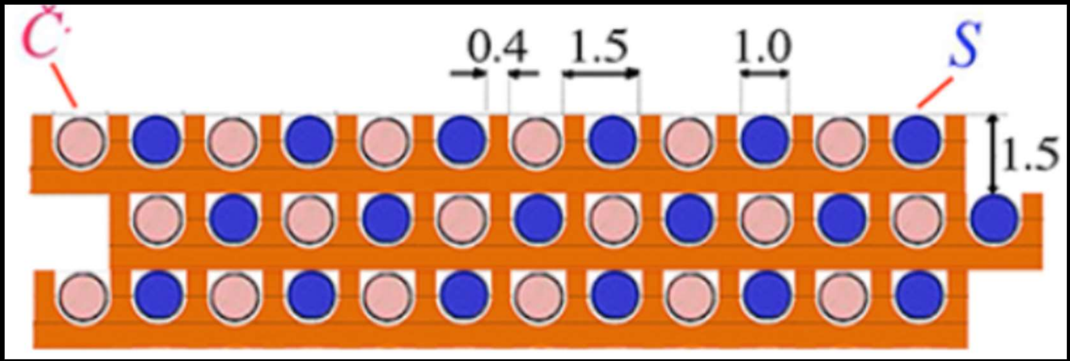




Dual Readout (1)

- Principle;
  - Correct f_{em} in every event
    - Main source of fluctuations
  - Fibers pointing toward IP
    - Scintillating:
      - sense charged
    - Clear:
      - sense Cherenkov, mostly electrons





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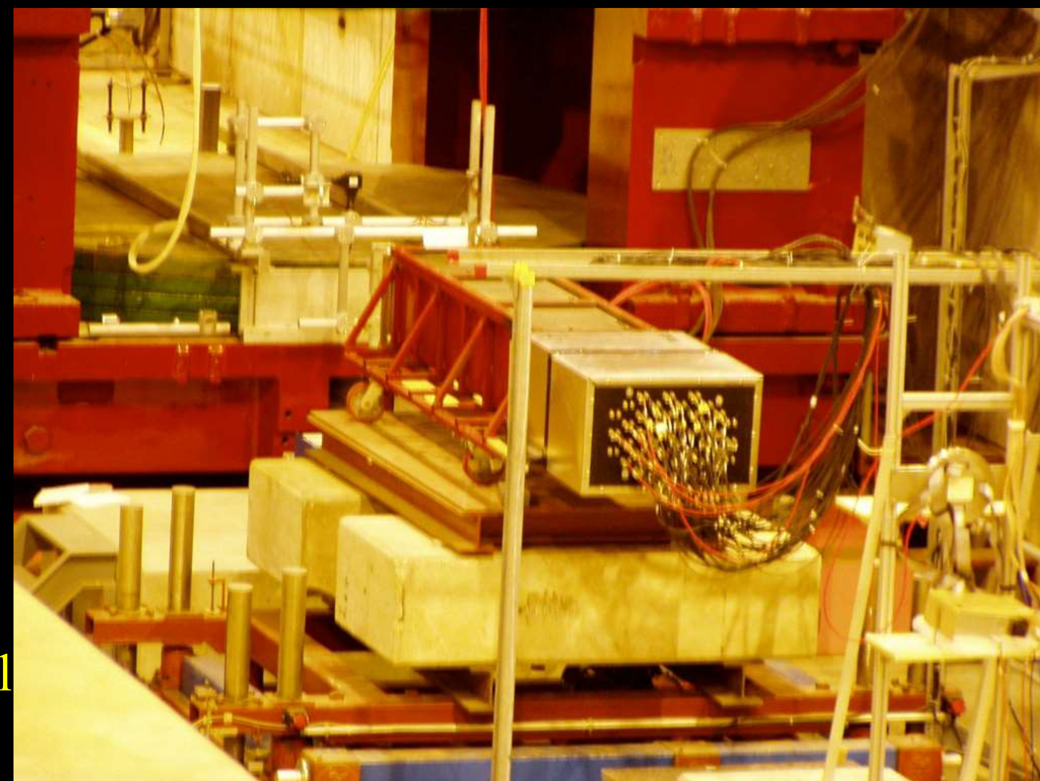
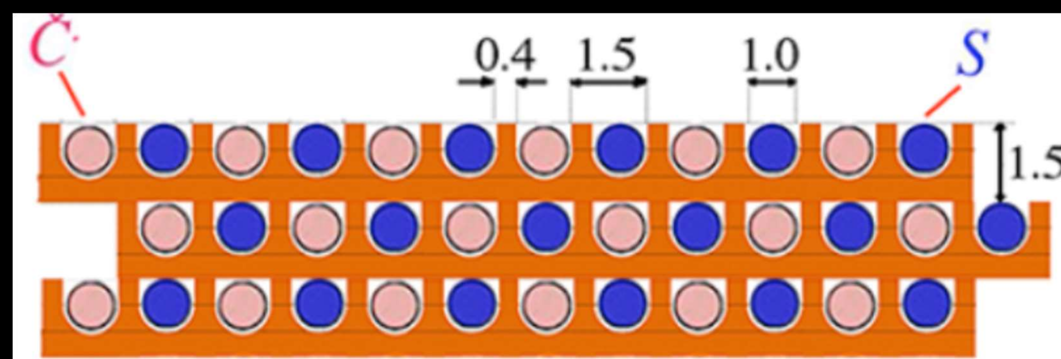
      - sense Cherenkov, mostly el
- Principle demonstrated:
  - Extensive tests by RD52
    - Partial containment
  - Hadronic-size by 2025





Dual Readout (2)

- New scalable technologies under test

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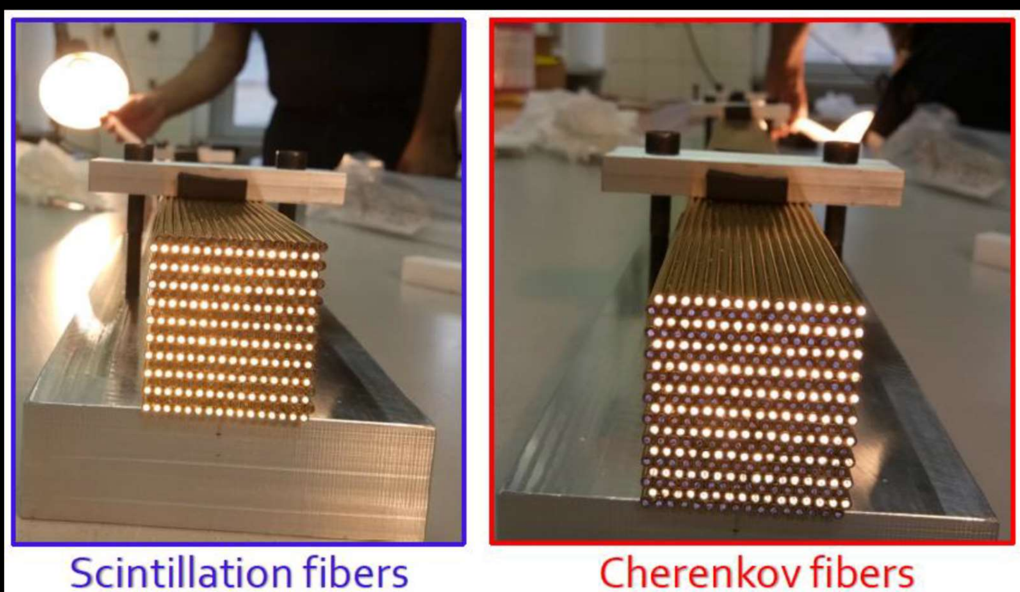
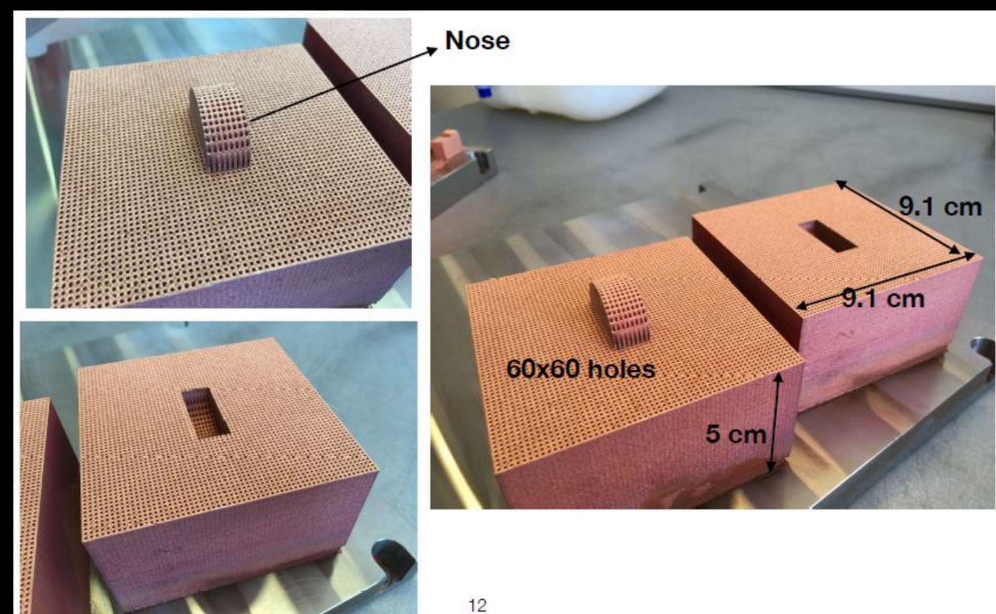
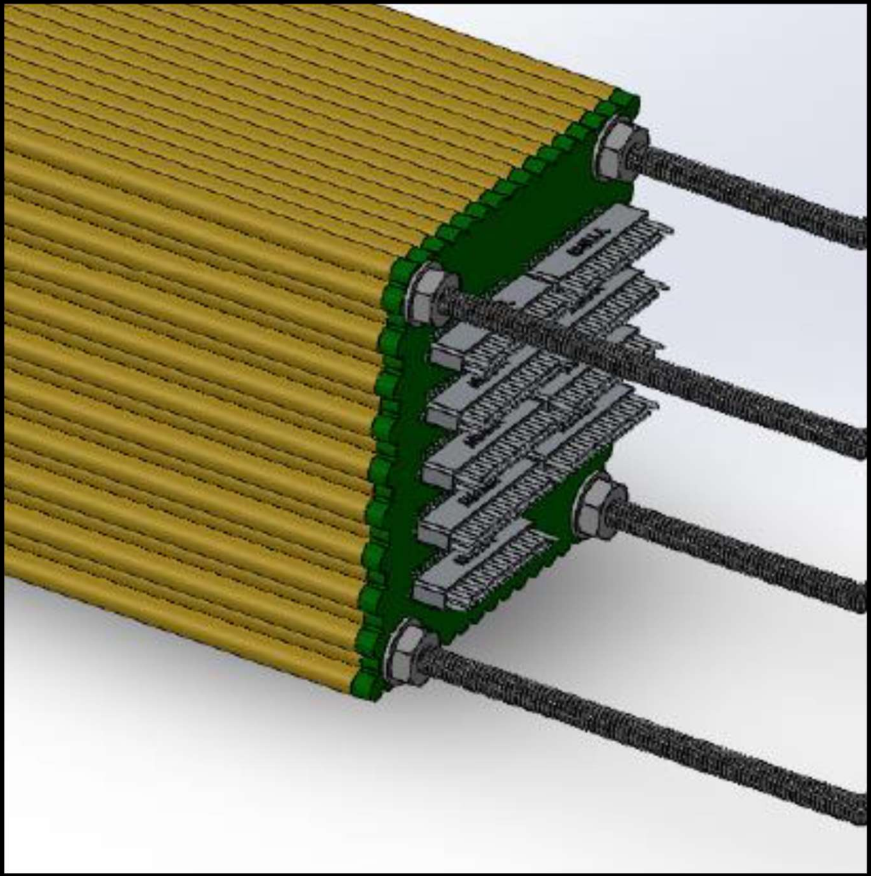
  - Mechanics: metal capillaries and 3D printing

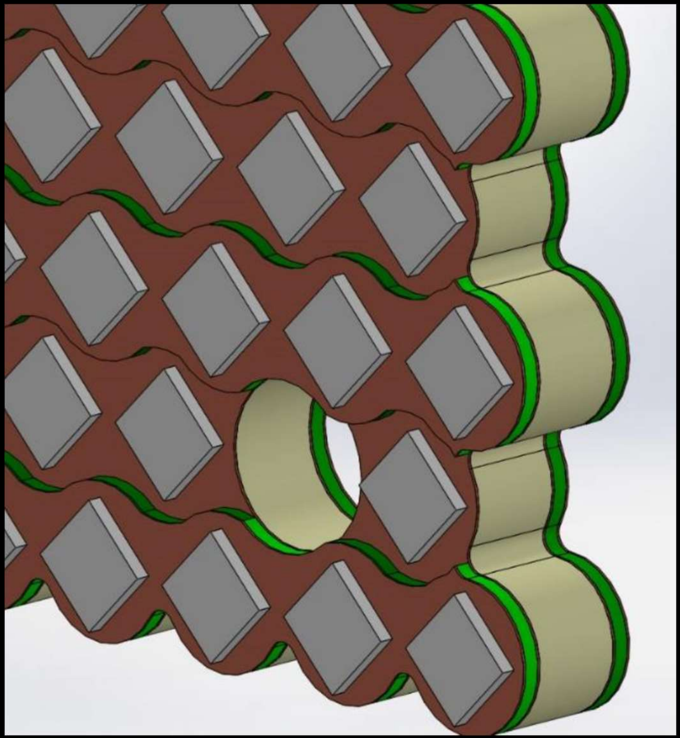




Dual Readout (2)

- New scalable technologies under test
  - Mechanics: metal capillaries and 3D printing
  - SiPM readout → maximize transverse granularity





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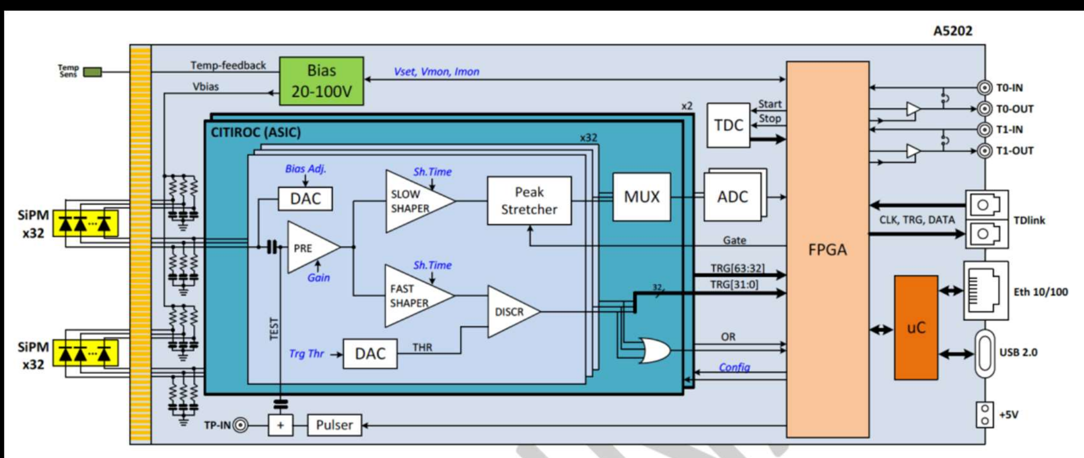
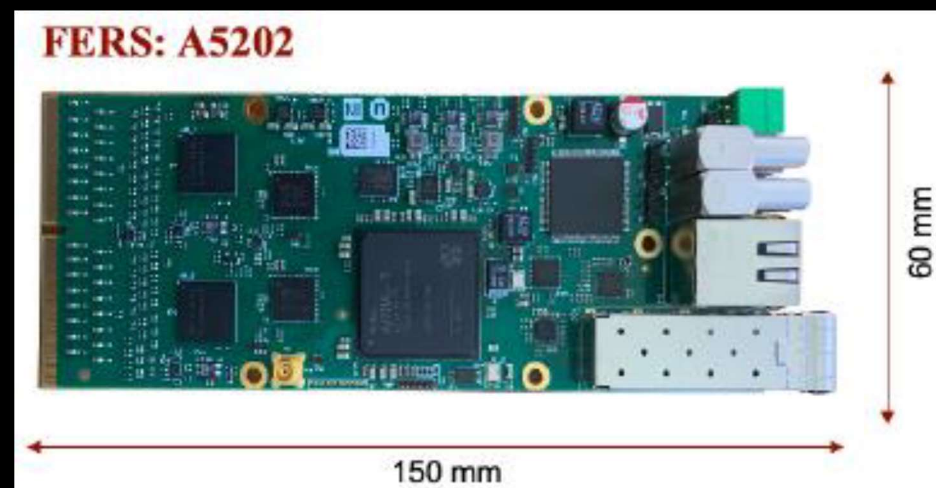
  - Readout: CAEN FERS system w/ Citiroc1A chip





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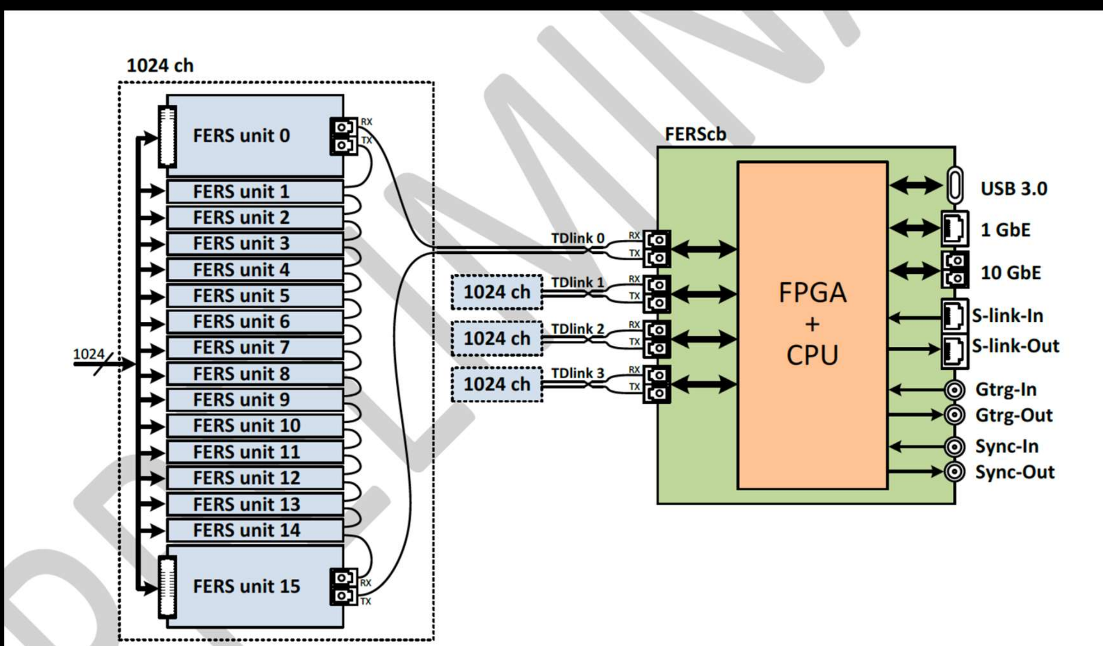
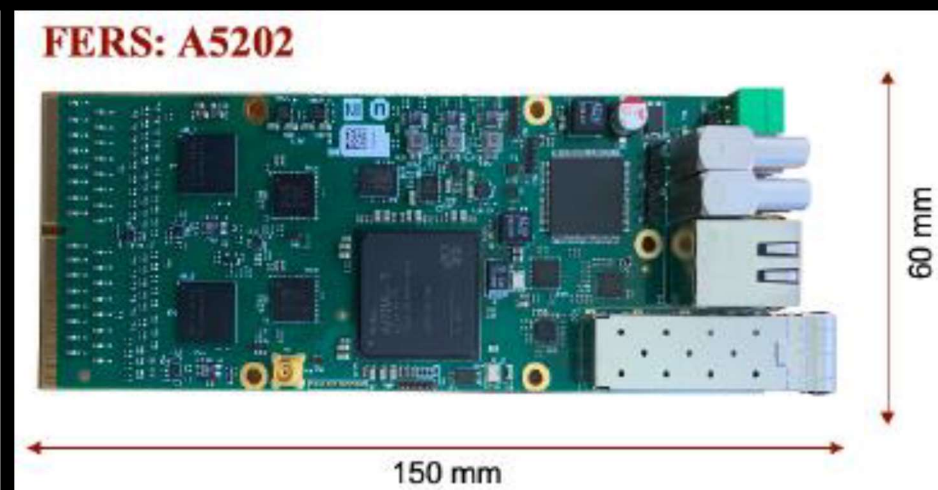


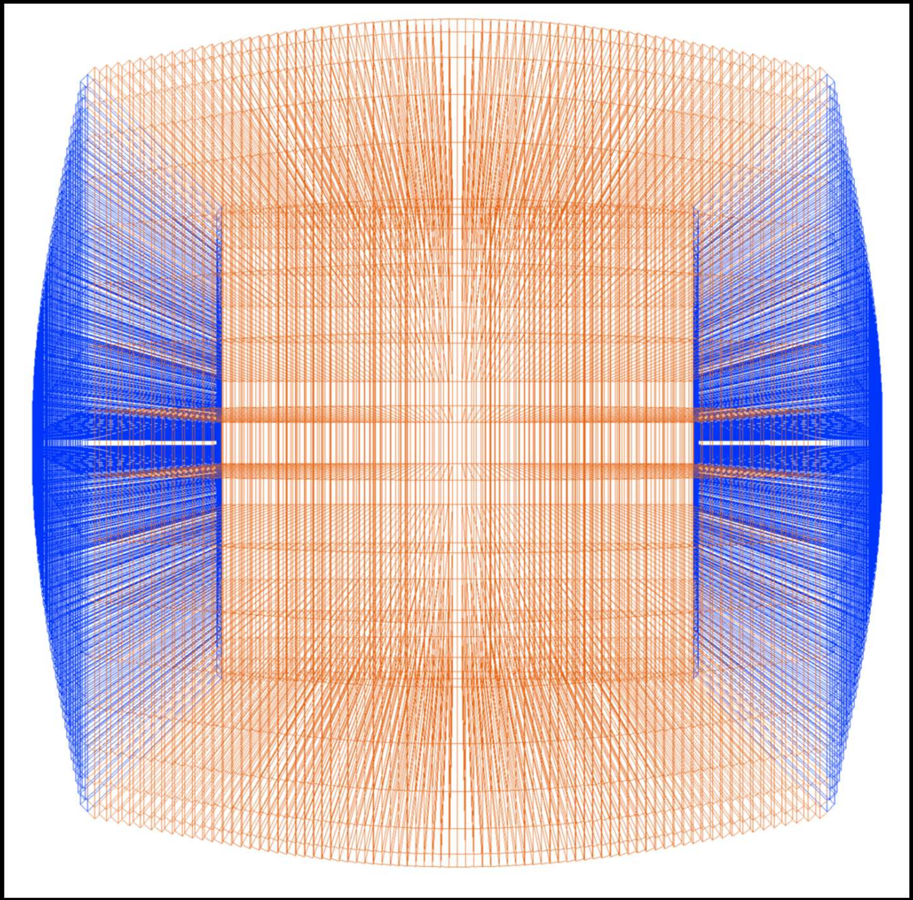


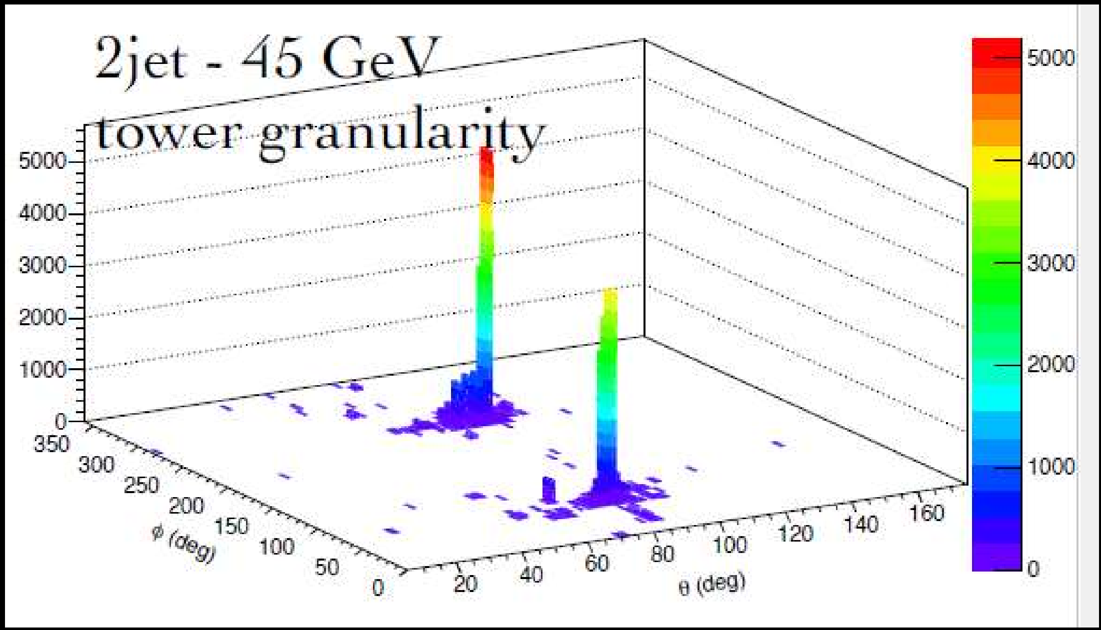
Dual Readout (3)

- EM prototype with FERS readout
  - Tested June 2021 at DESY (low energy electrons)
  - Tested August 2021 at CERN (high energy electrons)

Dual Readout (4)

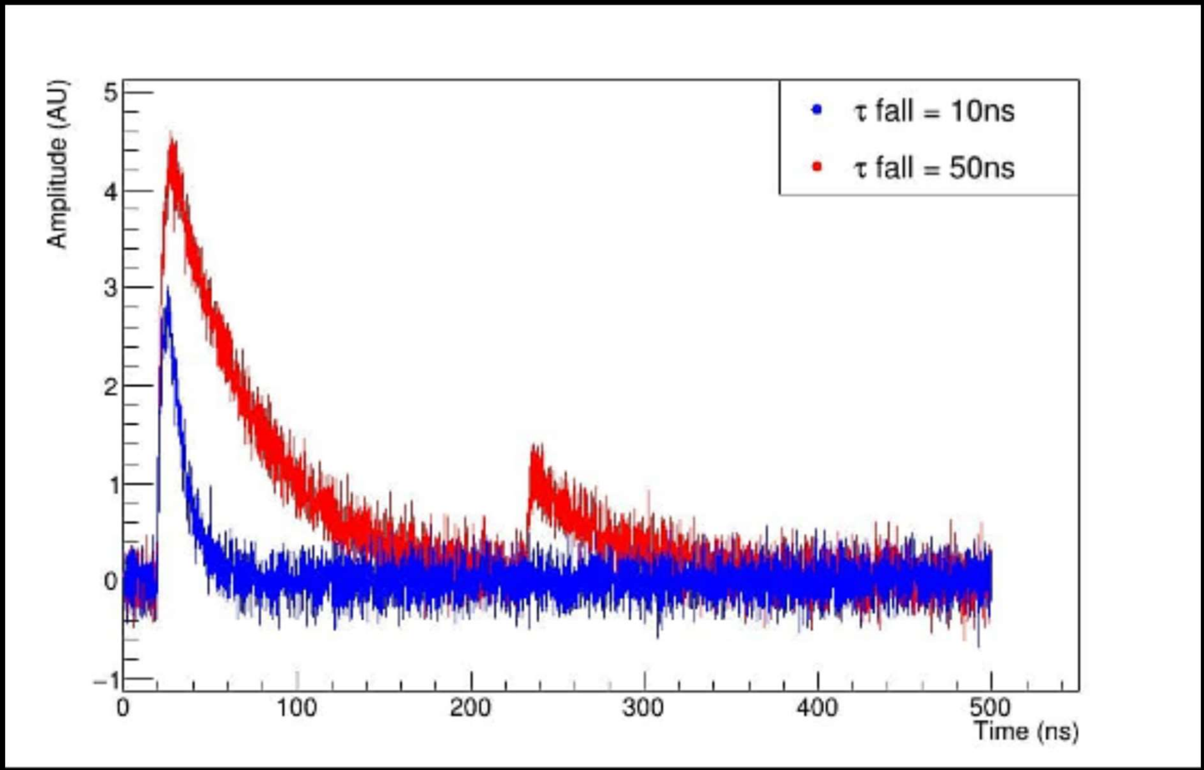
- Performance/SW integration
  - Full 4π calorimeter in GEANT4 → exporting to FCCSW
    - Migration to DD4hep/EDM4hep completed





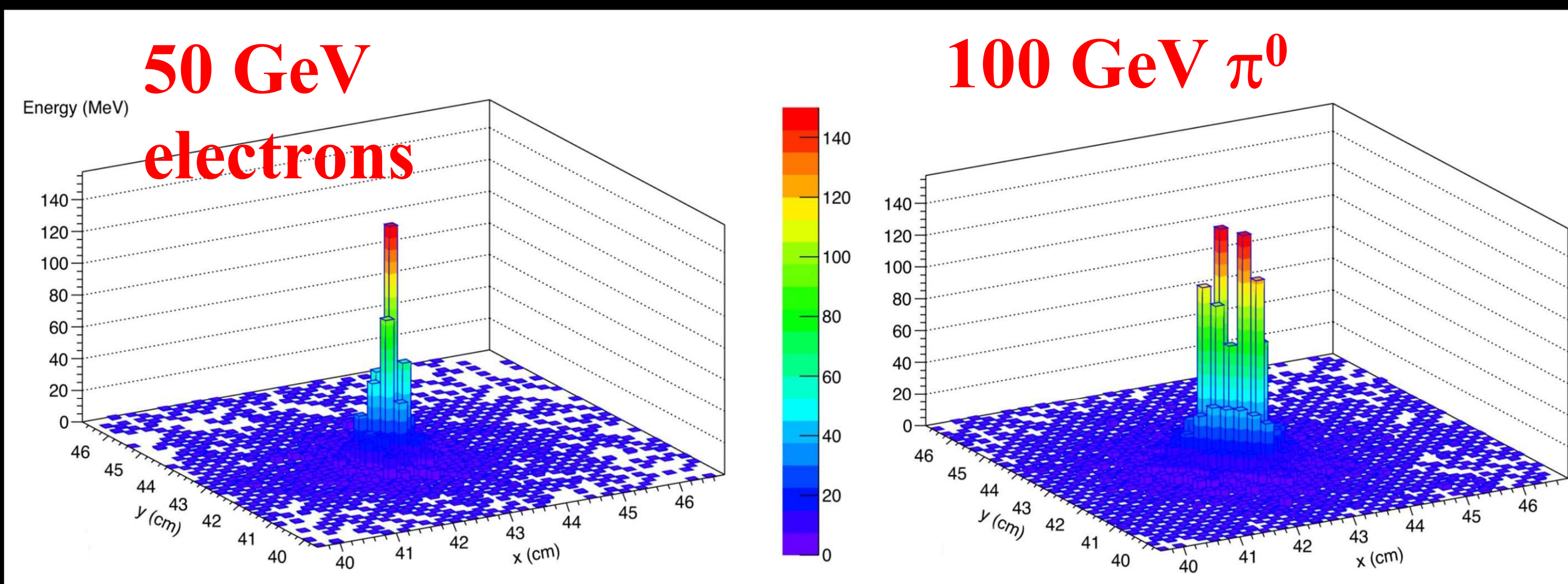
Dual Readout (4)

- Performance/SW integration
  - Full 4π calorimeter in GEANT4 → exporting to FCCSW
    - Migration to DD4hep/EDM4hep completed
  - Detailed SiPM digitization



Dual Readout (4)

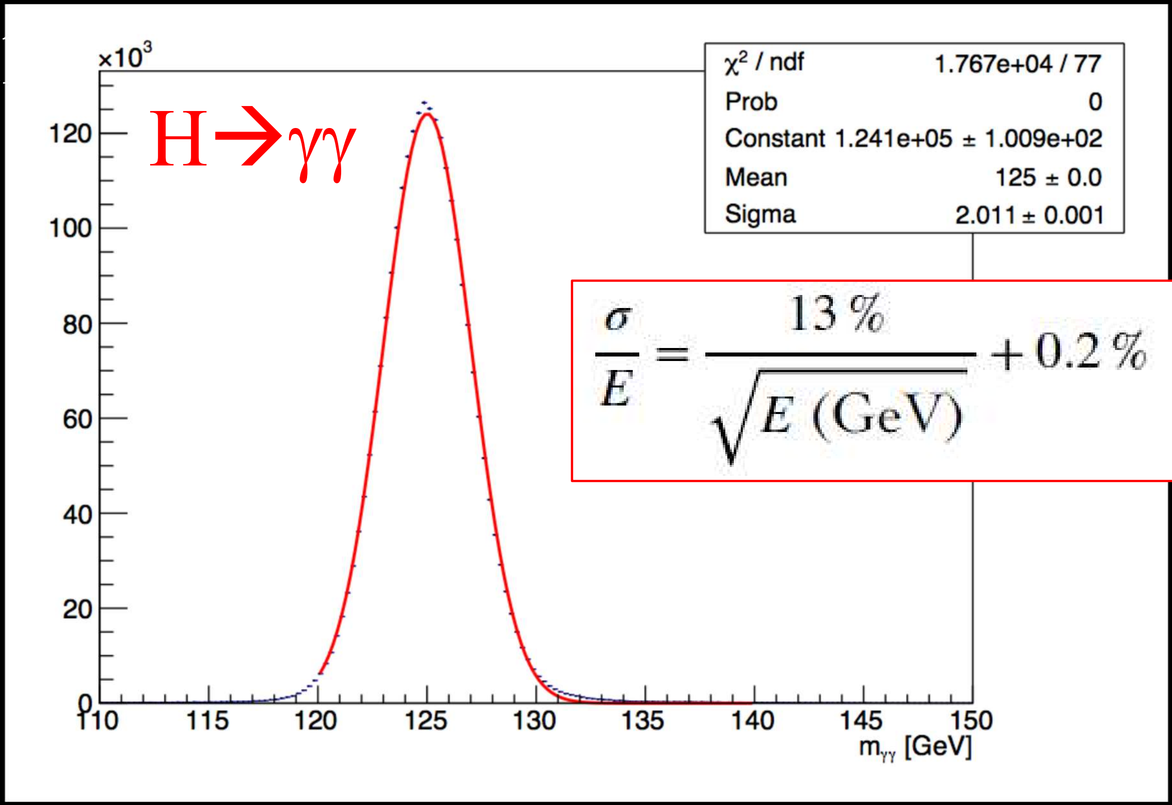
- Performance/SW integration
  - Full 4π calorimeter in GEANT4 → exporting to FCCSW
    - Migration to DD4hep/EDM4hep completed
  - Detailed SiPM digitization
  - Extreme transverse granularity (up to ~2mm)



Dual Readout (4)

Performance/SW integration

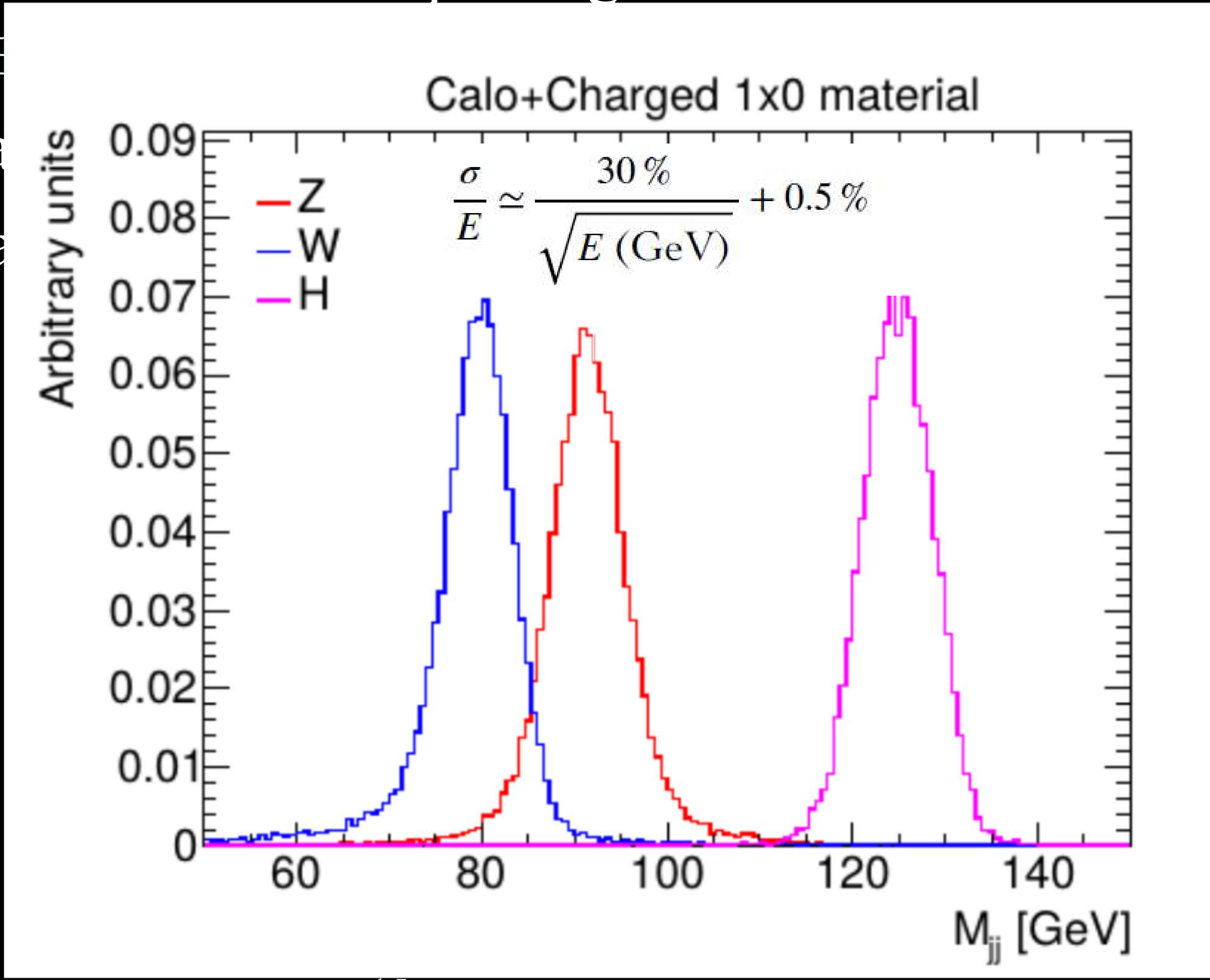
- Full 4π calorimeter in GEANT4 → exporting to FCCSW
  - Migration to DD4hep/EDM4hep completed
- Detailed SiPM digitization
- Extreme transverse granu
- EM performance



$$\frac{\sigma}{E} = \frac{13\,\%}{\sqrt{E\ (\mathrm{GeV})}} + 0.2\,\%$$

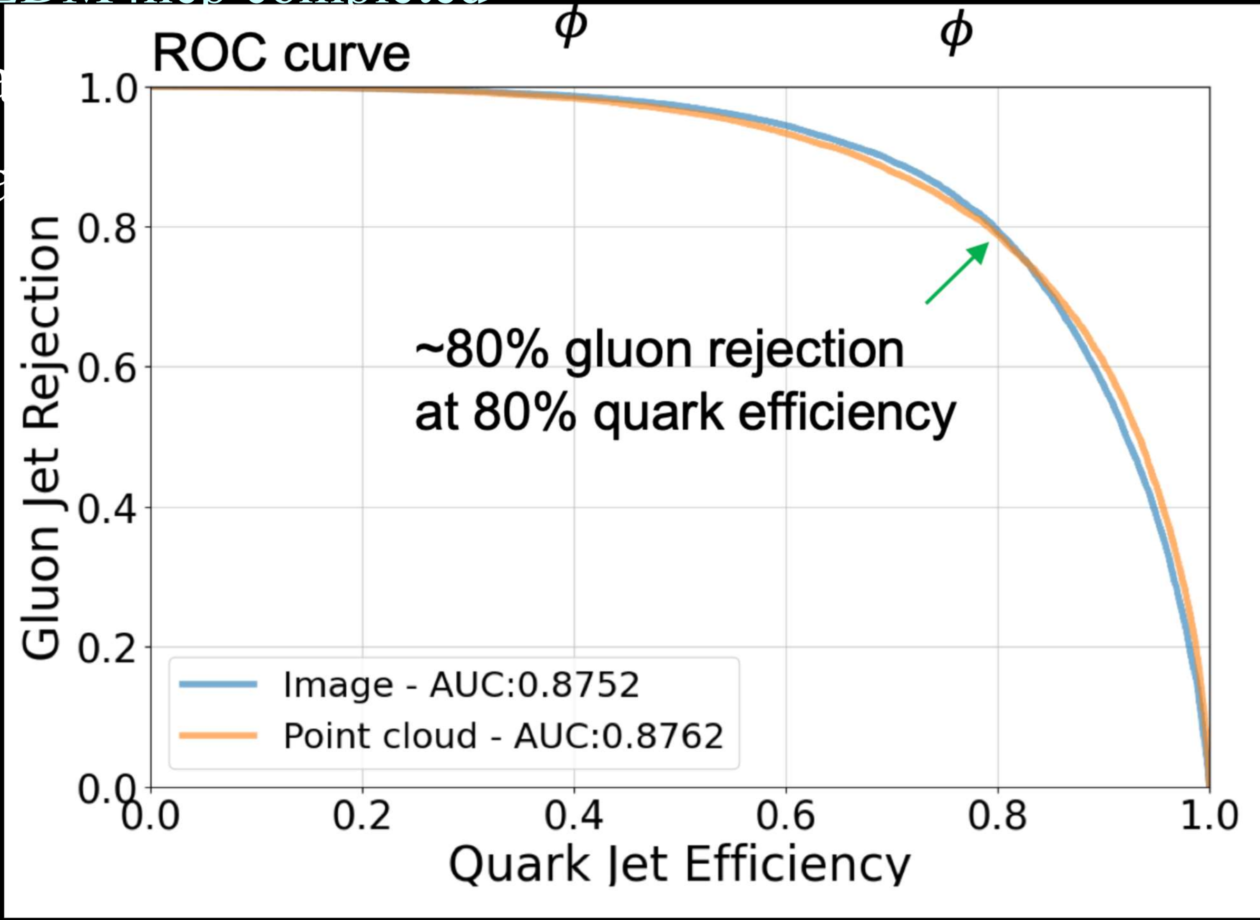
Dual Readout (4)

- Performance/SW integration
  - Full 4π calorimeter in GEANT4 → exporting to FCCSW
    - Migration to DD4hep/E
  - Detailed SiPM digitiza
  - Extreme transverse gra
  - EM performance
  - Jet performance



Dual Readout (4)

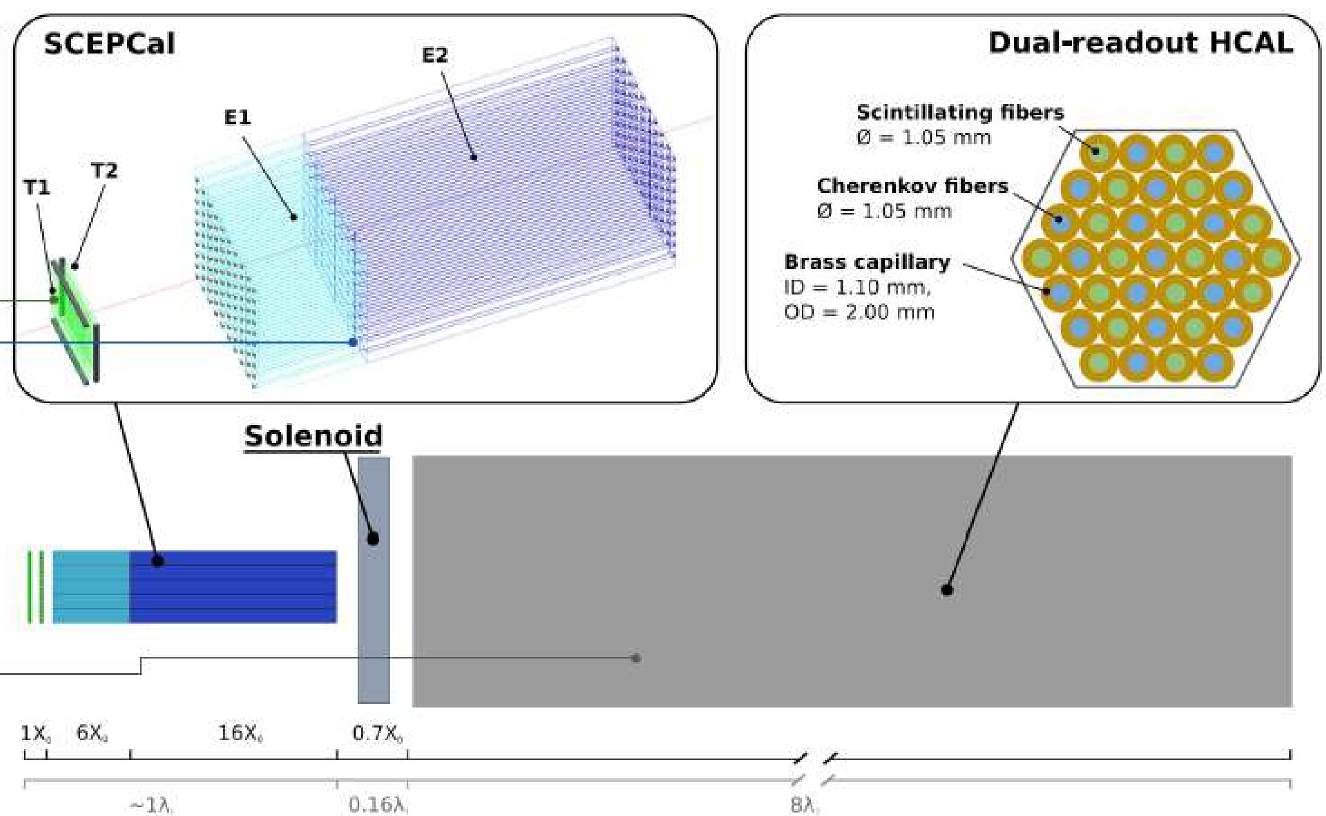
- Performance/SW integration
  - Full 4π calorimeter in GEANT4 → exporting to FCCSW
    - Migration to DD4hep/EDM4hep completed
  - Detailed SiPM digitiza
  - Extreme transverse gra
  - EM performance
  - Jet performance
  - Machine Learning



Dual Readout with crystals (1)

- Adding crystals inside solenoid
  - DR by readout with 2 SiPMs with different optical response/filters
  - 20 ps with LYSO layer

- **Timing layers** — $\sigma_t \sim 20$ ps
  - LYSO:Ce crystals (~$1X_0$)
  - 3x3x60 mm³ active cell
  - 3x3 mm² SiPMs (15-20 um)
- **ECAL layers** — $\sigma^{EM}_E/E \sim 3\%/\sqrt{E}$
  - PWO crystals
  - Front segment (~$6X_0$)
  - Rear segment (~$16X_0$)
  - 10x10x200 mm³ crystal
  - 5x5 mm² SiPMs (10-15 um)
- **Ultra-thin IDEA solenoid**
  - ~$0.7X_0$
- **HCAL layer** — $\sigma^{HAD}_E/E \sim 27\%/\sqrt{E}$
  - Scintillating and quartz fibers inserted in brass capillaries
  - (similar to prototypes in A.Karadzhinova-Ferrer slides)



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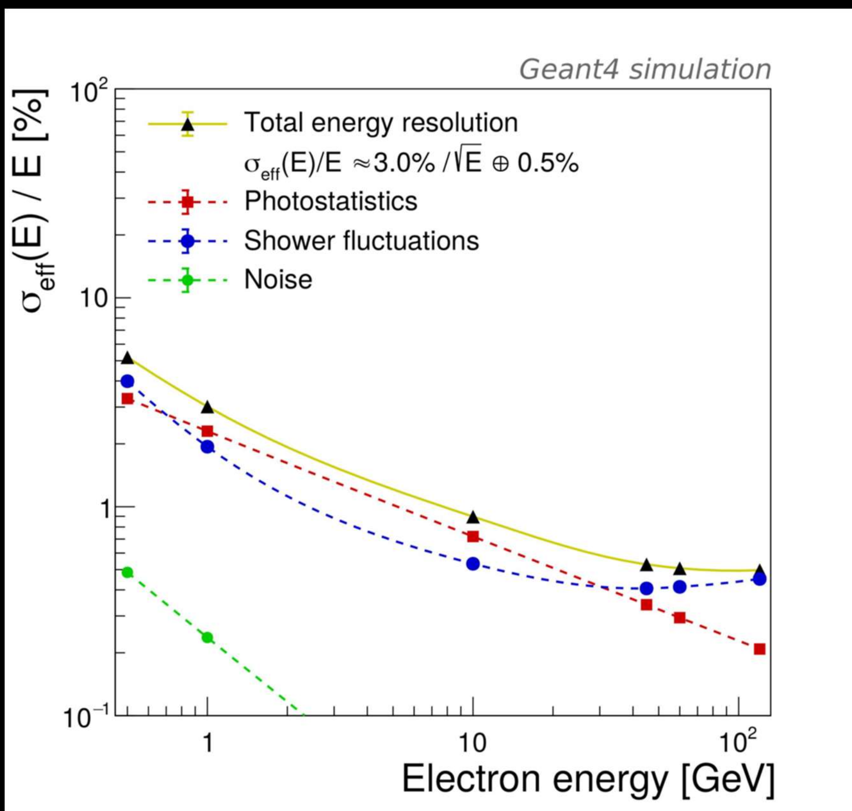
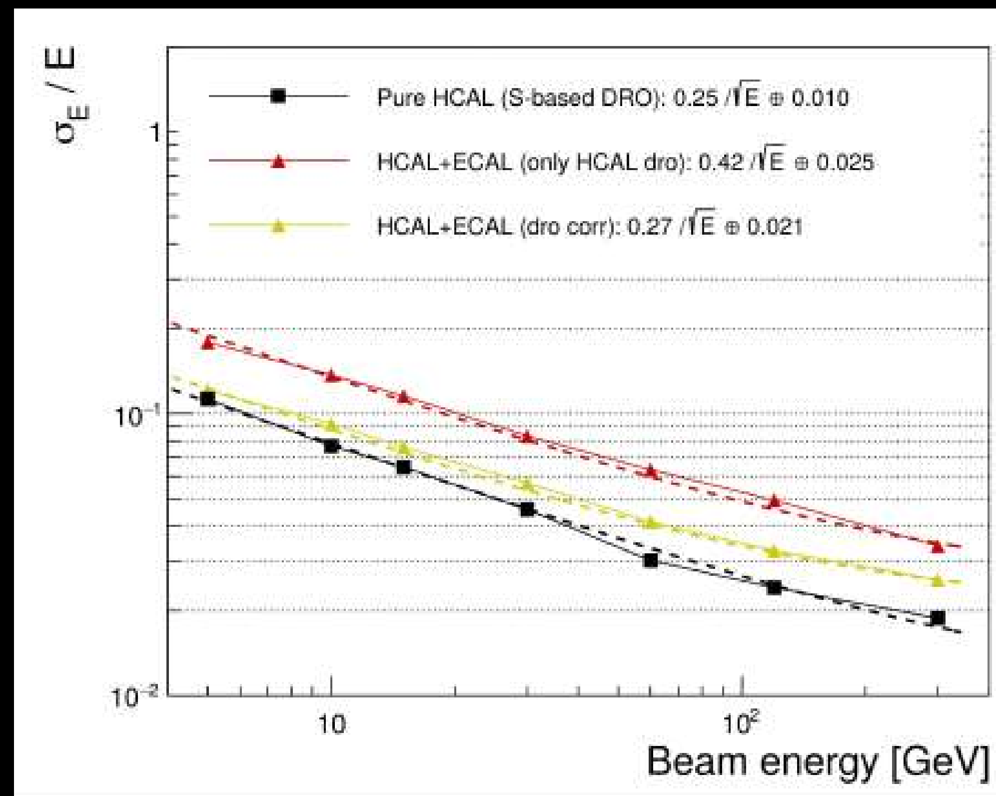
Dual Readout with crystals (1)

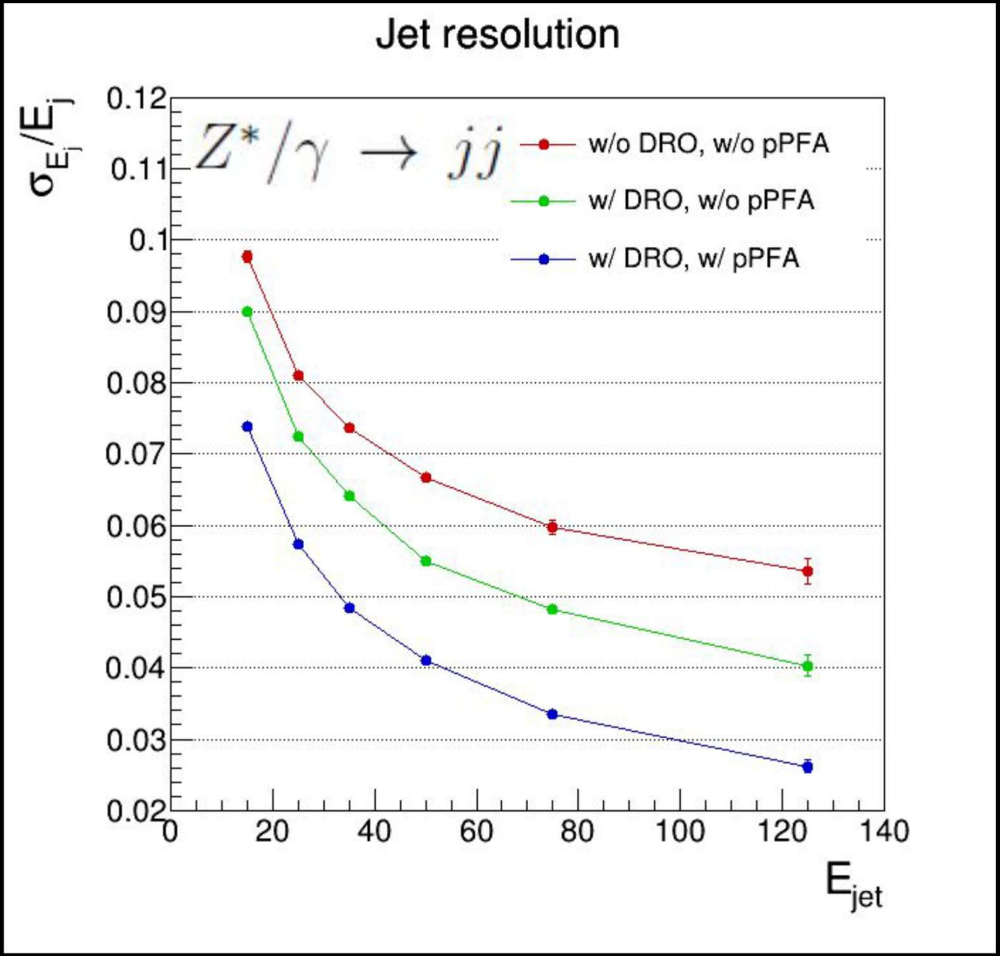
- Adding crystals inside solenoid
  - DR by readout with 2 SiPMs with different optical response/filters
  - 20 ps with LYSO layer
  - Great EM resolution w/ minor degradation of had. performance





Dual Readout with crystals (2)

- Simple Particle Flow improves energy resolution
  - More expected with timing in the HAD section



Summary table

Detector technology (ECAL & HCAL)	E.m. energy res. stochastic term	E.m. energy res. constant term	ECAL & HCAL had. energy resolution (stoch. term for single had.)	ECAL & HCAL had. energy resolution (for 50 GeV jets)	Ultimate hadronic energy res. incl. PFlow (for 50 GeV jets)
Highly granular Si/W based ECAL & Scintillator based HCAL	$15 - 17\,\%$ [12,20]	$1\,\%$ [12,20]	$45 - 50\,\%$ [45,20]	$\approx 6\,\%$?	$4\,\%$ [20]
Highly granular Noble liquid based ECAL & Scintillator based HCAL	$8 - 10\,\%$ [24,27,46]	$< 1\,\%$ [24,27,47]	$\approx 40\,\%$ [27,28]	$\approx 6\,\%$?	$3 - 4\,\%$?
Dual-readout Fibre calorimeter	$11\,\%$ [48]	$< 1\,\%$ [48]	$\approx 30\,\%$ [48]	$4 - 5\,\%$ [49]	$3 - 4\,\%$?
Hybrid crystal and Dual-readout calorimeter	$3\,\%$ [30]	$< 1\,\%$ [30]	$\approx 26\,\%$ [30]	$5 - 6\,\%$ [30,50]	$3 - 4\,\%$ [50]

Table 1. Summary table of the expected energy resolution for the different technologies. The values are measurements where available, otherwise obtained from simulation. Those values marked with "?" are estimates since neither measurement nor simulation exists.

M. Aleksa, F. Bedeschi, R. Ferrari, F. Sefkow, C. Tully:
"Calorimetry at FCC-ee", submitted to EPJ (2021)
http://arxiv.org/abs/2109.00391

AidaInnova WP8

- Tasks foster strong collaboration:
  - 8.1 Management (CNRS-IJCLab, INFN-PV, DESY)
  - 8.2 Towards next generation highly granular calorimeters
    - Integration aspects of highly granular calorimeters
      - DESY, CNRS-IJCLab, CNRS-LLR, CNRS-LPNHE, JGU, CERN, TAU, FZU
    - Future Liquid Noble Gas Calorimeters (CERN, CNRS-IJCLab, CNRS-LAPP, CUNI)
  - 8.3 Innovative calorimeters with optical readout
    - Crystal detectors (CERN, FZU, VU, INFN-PG, INFN-LNF, INFN-TO)
    - Large area scintillator detectors (MPP-MPG, DESY, INFN-BO, INFN-LNF, JGU)
  - 8.4 Innovative solid-state light sensors and highly granular dual-readout fibre-sampling calorimetry
    - Innovative SiPMs and future applications in PID detectors
      - JSI, INFN-PD, INFN-TO, CERN, FBK, UiB, FZU)
    - Development of highly-granular dual-readout fibre-sampling calorimeters
      - INFN-PV, INFN-MI, INFN-PI, INFN-BO, UOS, RBI, CAEN

ECFA roadmap

ECFA Detector R&D Roadmap Process

Organisation

May 2020
EPPSU mandate to ECFA to develop a roadmap for detector R&D efforts in Europe

Sep 2020
Structure in place with **Detector R&D Roadmap Panel**

Dec 2020
Task Forces active

Website:
https://indico.cern.ch/e/ECFADetectorRDRoadmap

Expert & Community Consultation

Feb 2021
Collection of requirements of future facilities & projects

Feb/March 2021
Questionnaires of Task Forces to national contacts

Task Forces liaise with experts in
- ECFA countries
- adjacent disciplines
- industry

March-May 2021
Open Symposia

Drafting Roadmap & Feedback

May 2021
Task Forces collate input from symposia

25-28 May 2021 **Drafting sessions**
- opening session with all experts involved
- plenary & parallel sessions with Task Force members
- final session of Roadmap Panel

2 July 2021
Near final draft shared with RECFA*

30 July 2021
Presentation at Joint ECFA-EPS session

Until Sep 2021
Collect final community feedback*

Oct 2021
Detector R&D Roadmap Document submission to RECFA and afterwards to PECFA and Council

*community feedback via RECFA delegates and National Contacts

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All calorimeter technologies related to FCC included in this process

RECFA approval November 2021
CERN council approval December 2021

*community feedback via RECFA delegates and National Contacts

DR calorimetry collaboration

- INFN, CERN, USA, UK, S. Korea, Chile
  - Current main funding:
    - INFN CSN1, S. Korea (2 M$ 5 yr grant)
    - Additional support from AIDAinnova
      - Including CAEN for readout R&D
    - Funding requests to Italian MUR and INFN-CSN5 ~ 1 M€
    - Grant approvals in progress in UK and USA
  - Synergy with ALICE-FoCal, LHCb upgrade, MuonE

- Manpower still limited
  - Open for additional collaborators!

Conclusion

- FCC has strong requirements on calorimeters
  - New life to calorimetry R&D
  - Many activities in progress on many technologies
- Good support from EU grants such as AidaInnova
- Good support from ECFA roadmap in preparation

- IDEA focuses on Dual Readout approach w/ or w/o crystals
  - Much activity in progress with seed funding
  - Major funding step expected soon
    - Lot of work! Need people!