Calorimeter Technologies

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Max-Planck-Institut für Physik

on behalf of the CLICdp collaboration

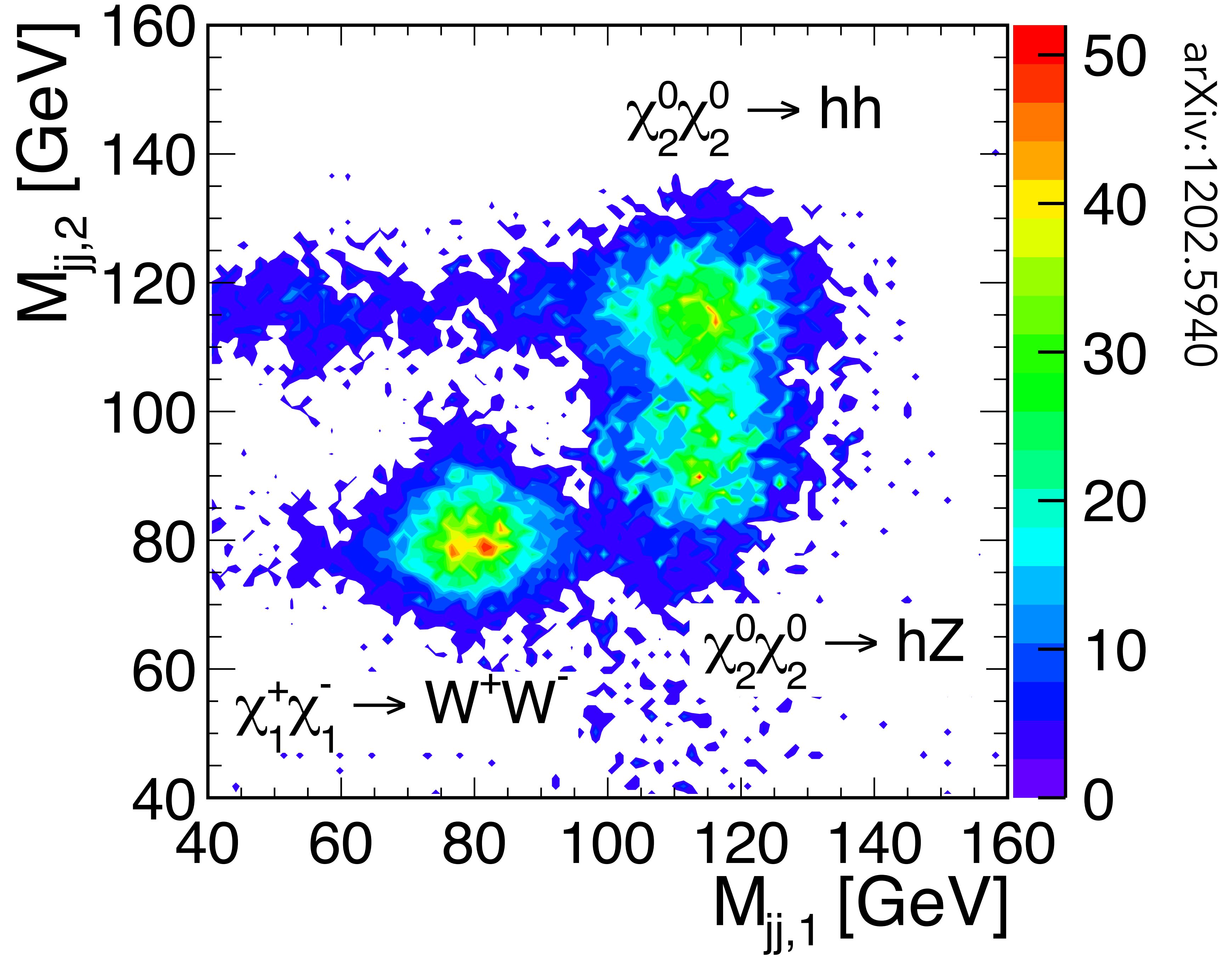
Outline

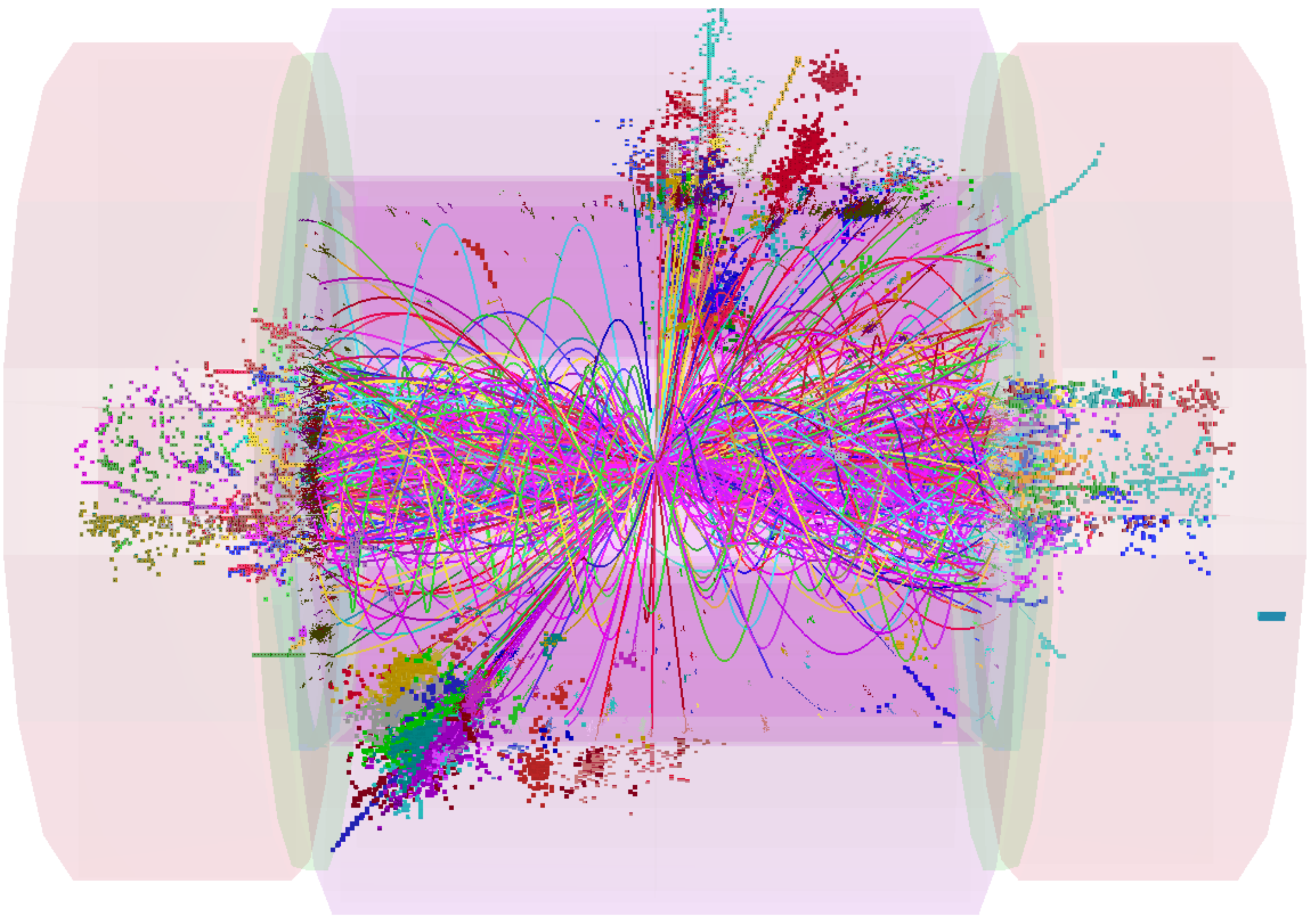
- Requirements for calorimetry at CLIC
- The CLICdet calorimeter system
- Calorimeter technologies
  - ECAL: Silicon, Scintillator + SiPMs
  - HCAL: Scintillator + SiPMs
  - Common items: Electronics
- Prototype performance in test beams
- Optimisation of the CLICdet calorimeter design

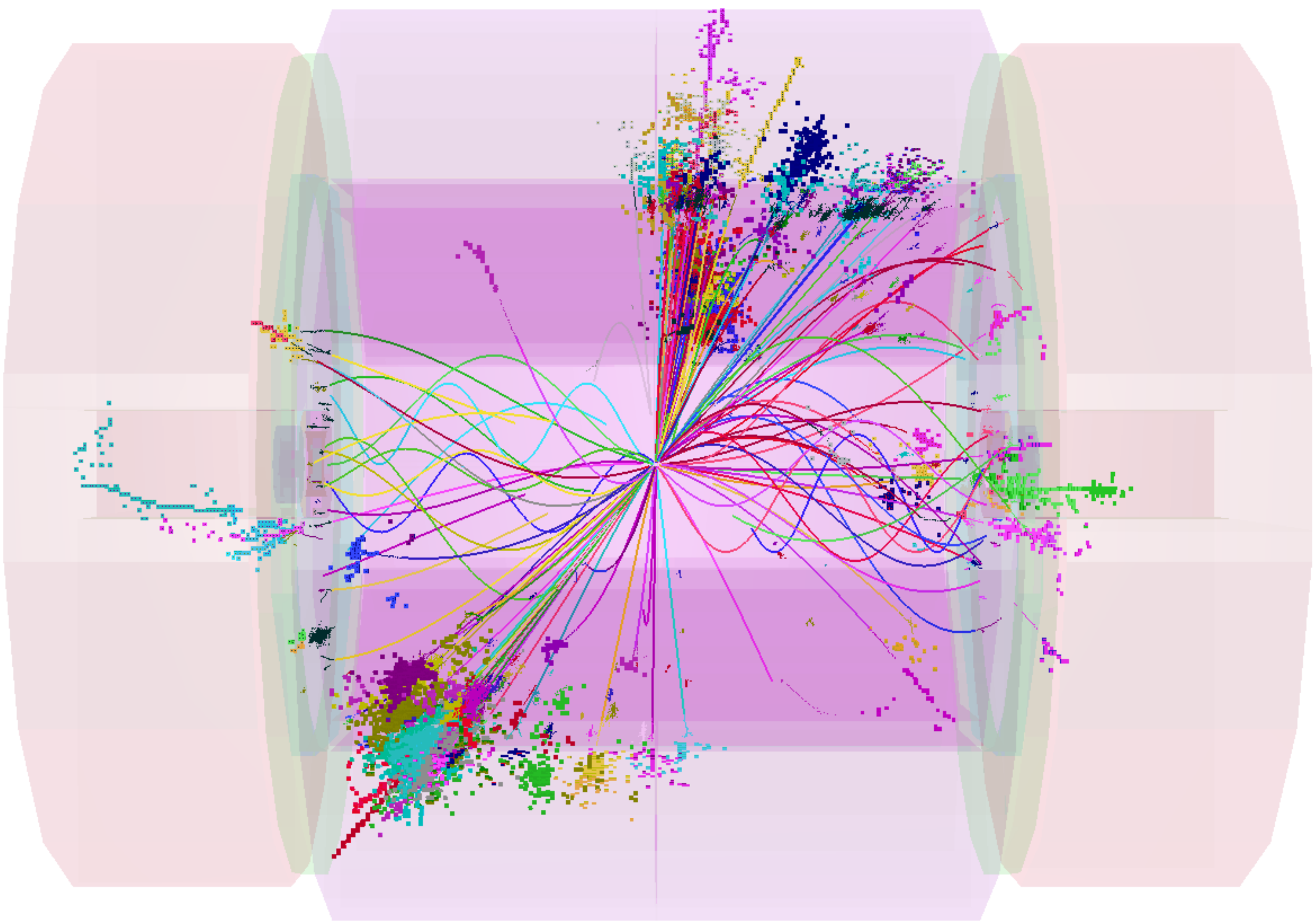
Requirements for Calorimetry at CLIC

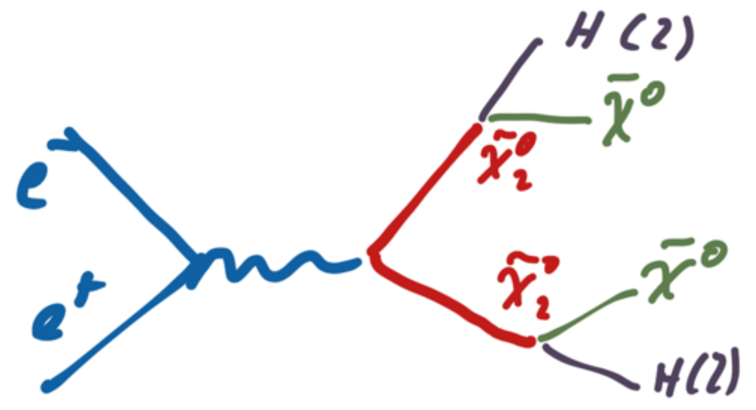
- Hadronic multi-jet final states prevalent in CLIC physics: Jet energy reconstruction and resolution of key importance
  - ➩ Event reconstruction using PFA in highly granular calorimeters
- Challenging environment: “pile-up” of γγ→hadrons needs to be reduced
  - ➩ high granularity and ns - level timing

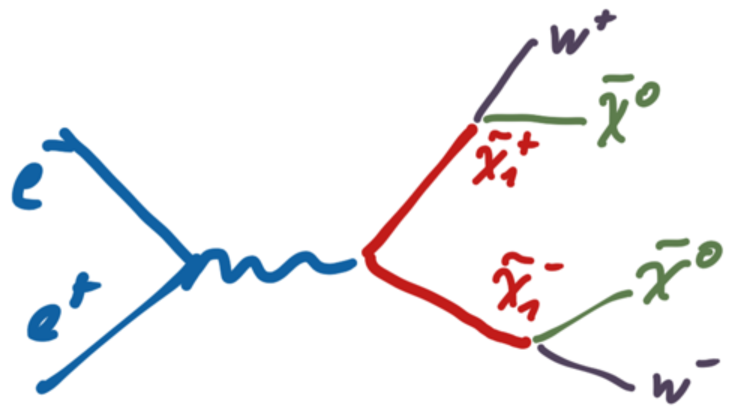
➩ A “CALICE - like” calorimeter system



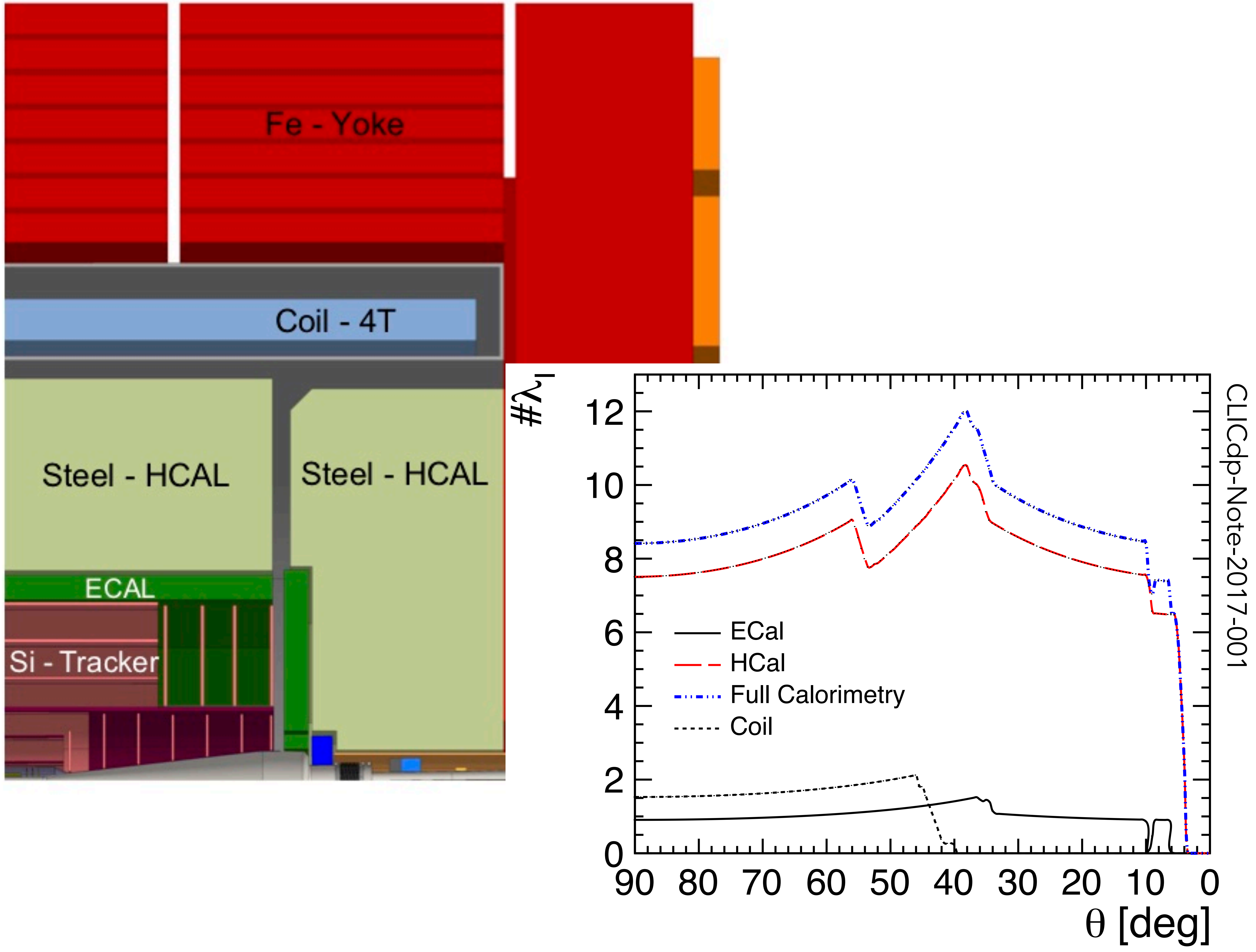








The CLICdet Calorimeter System

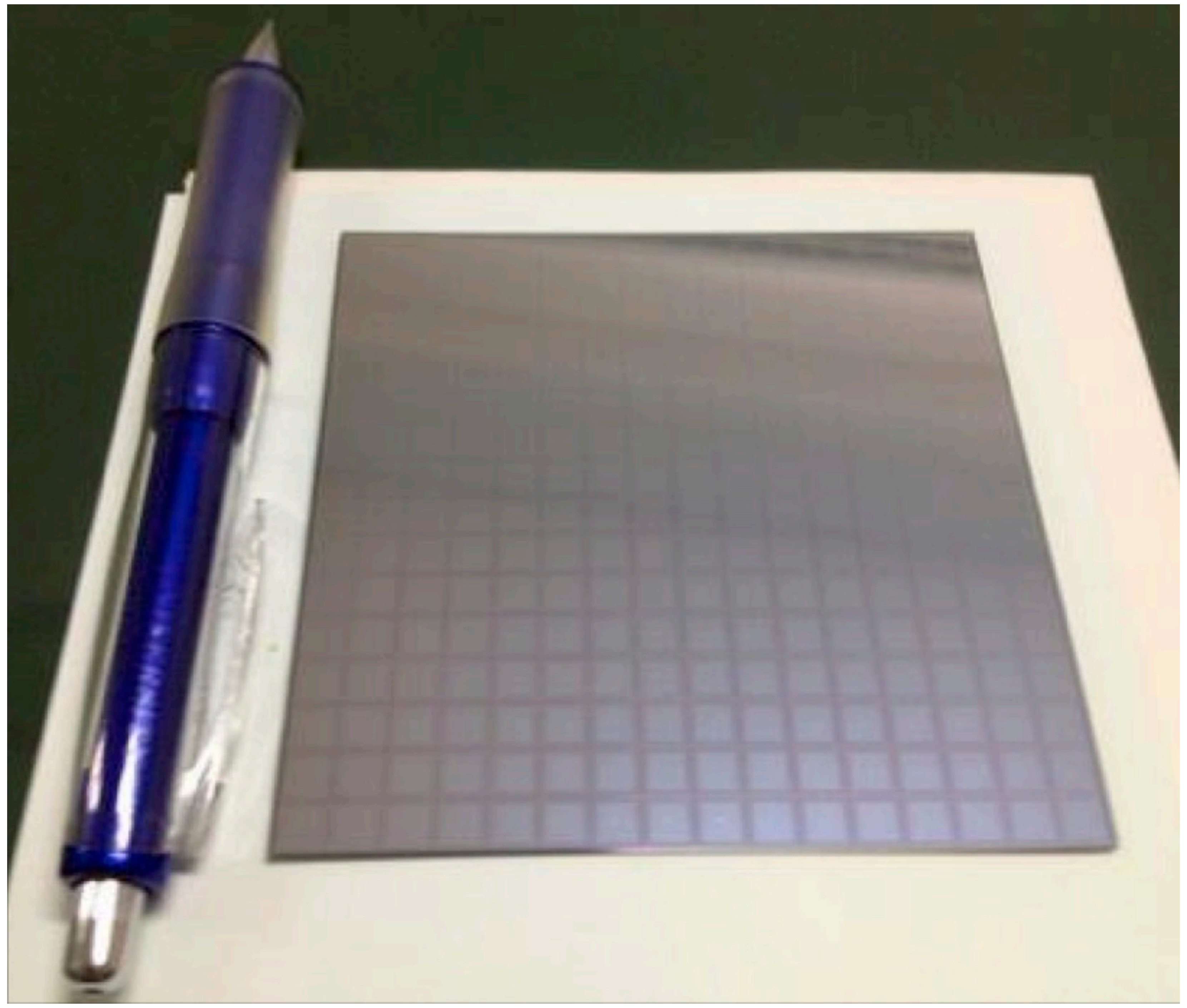


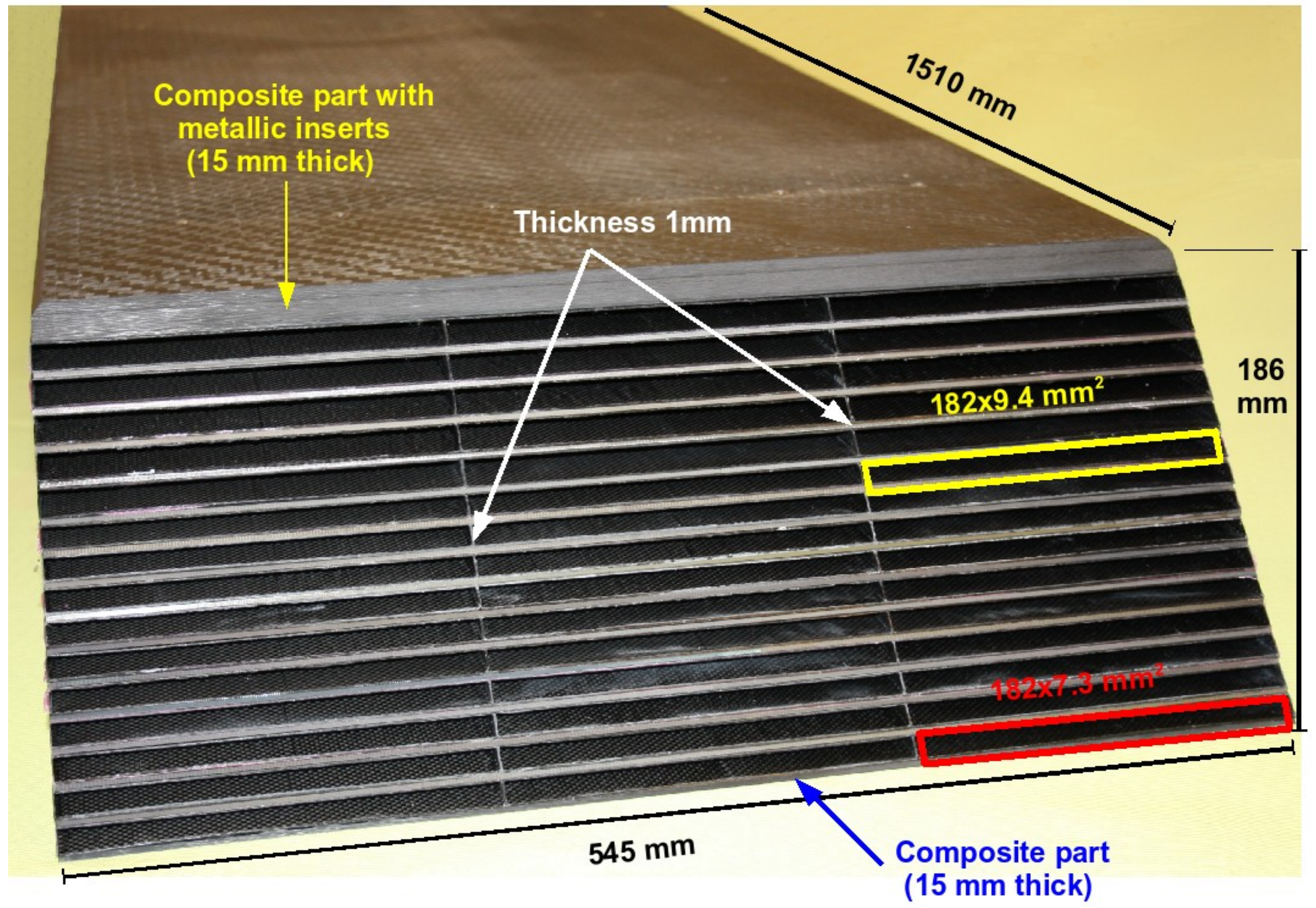
Key parameters:

- ECAL
  Depth: 40 layers, 22 X_0 (~ 1 λ_I)
  Absorber: W, 1.9 mm / layer
  Active elements: Silicon
  Granularity: 5 x 5 mm^2
- HCAL
  Depth: 60 layers, 7.5 λ_I
  Absorber: Stainless Steel, 20 mm / layer
  Active elements: Scintillator tiles / SiPMs
  Granularity: 30 x 30 mm^2

Technologies: ECAL

- Silicon / Tungsten calorimeter
  - Planar silicon pad sensors

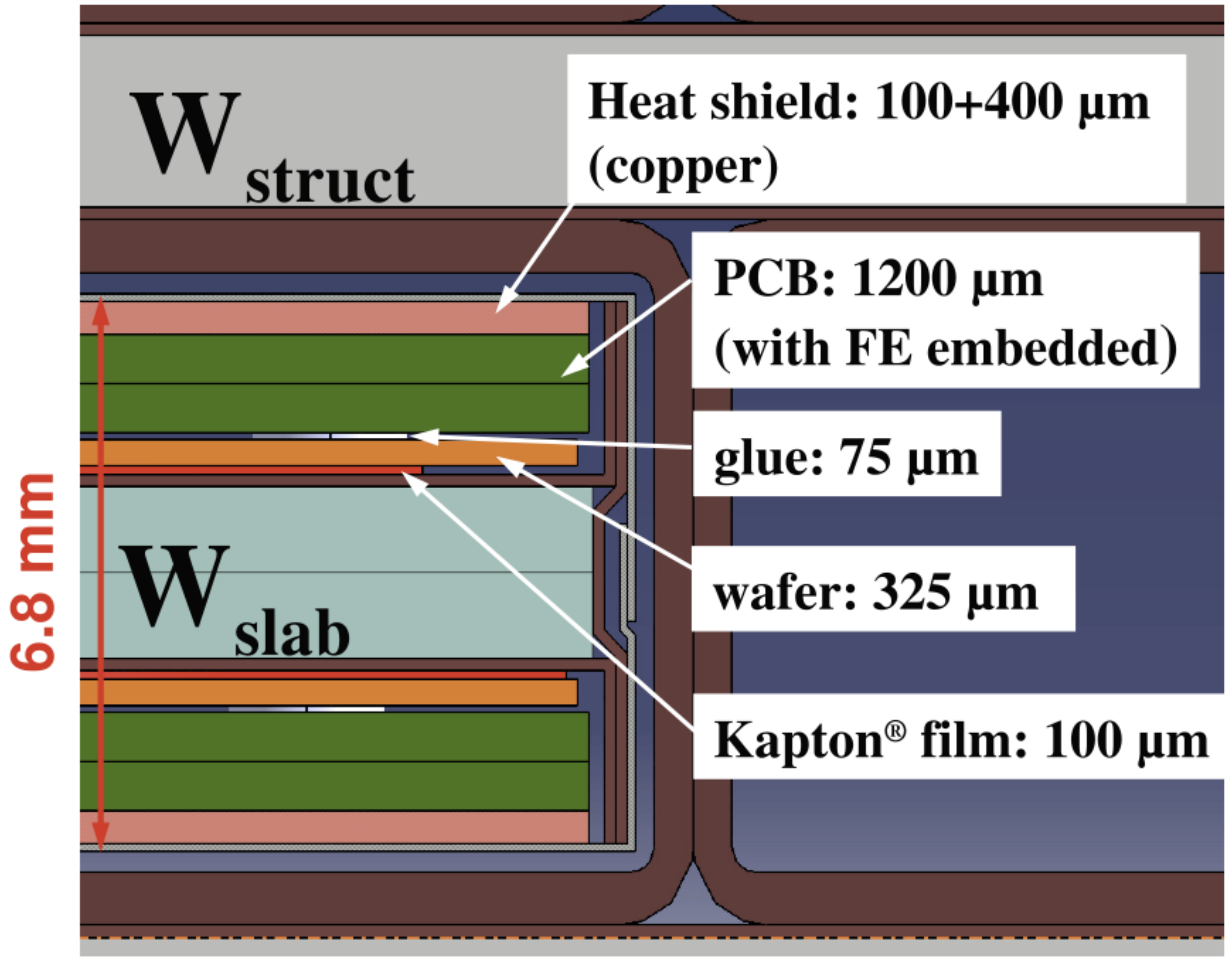




- Aggressive original ILD design made more realistic: Assume 3.15 mm space between W absorber layers
  - up from 2.2 mm

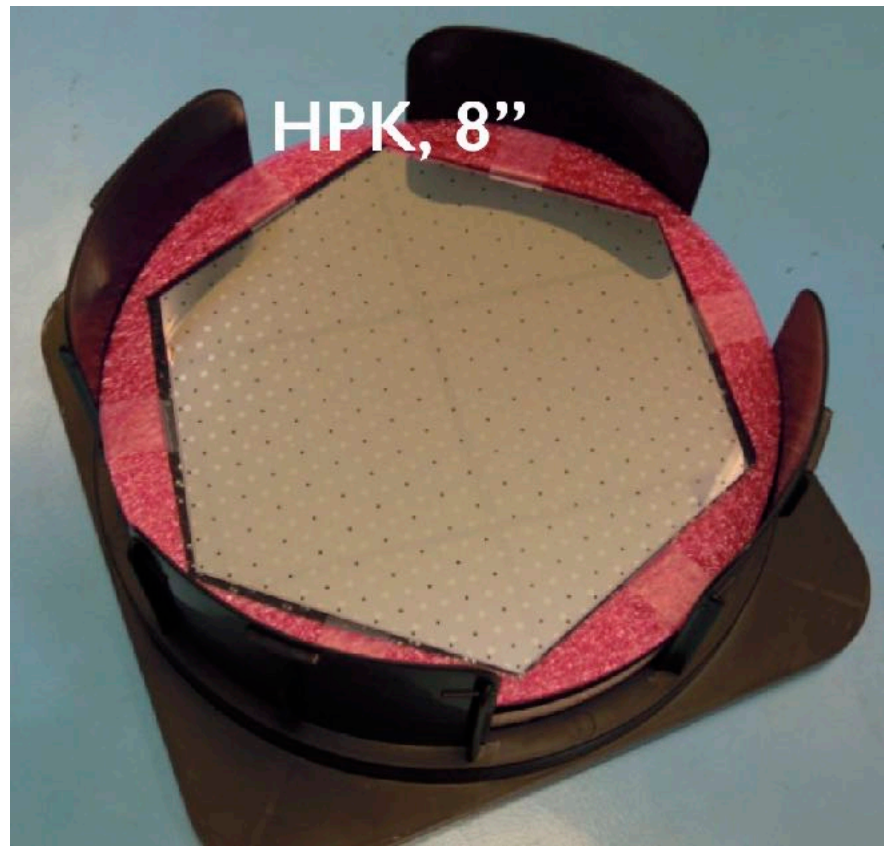
N.B. Similar changes also made in ILD

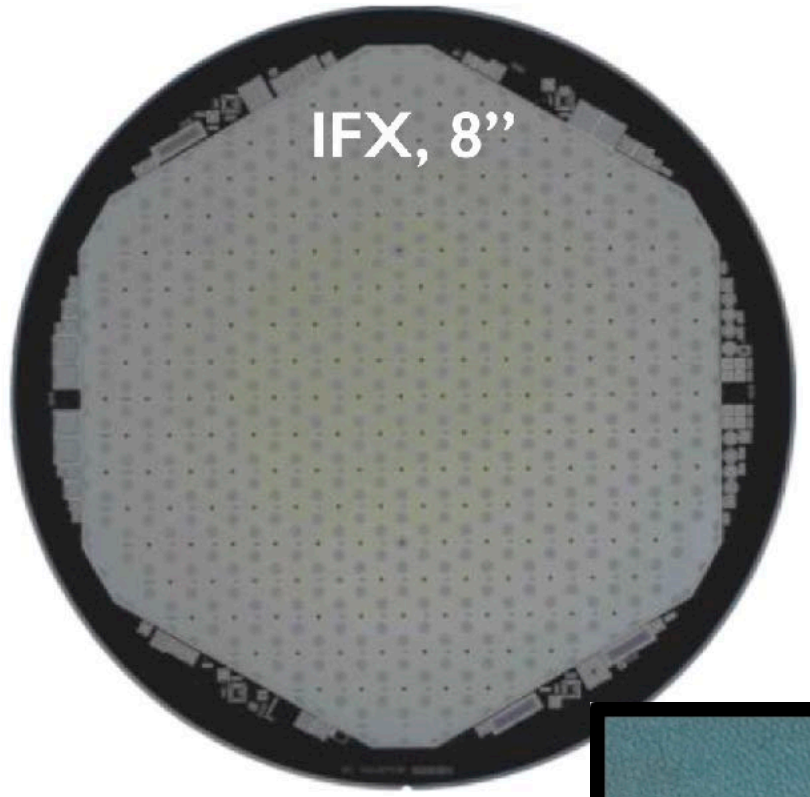
- Extensive experience in CALICE, including complex mechanical design

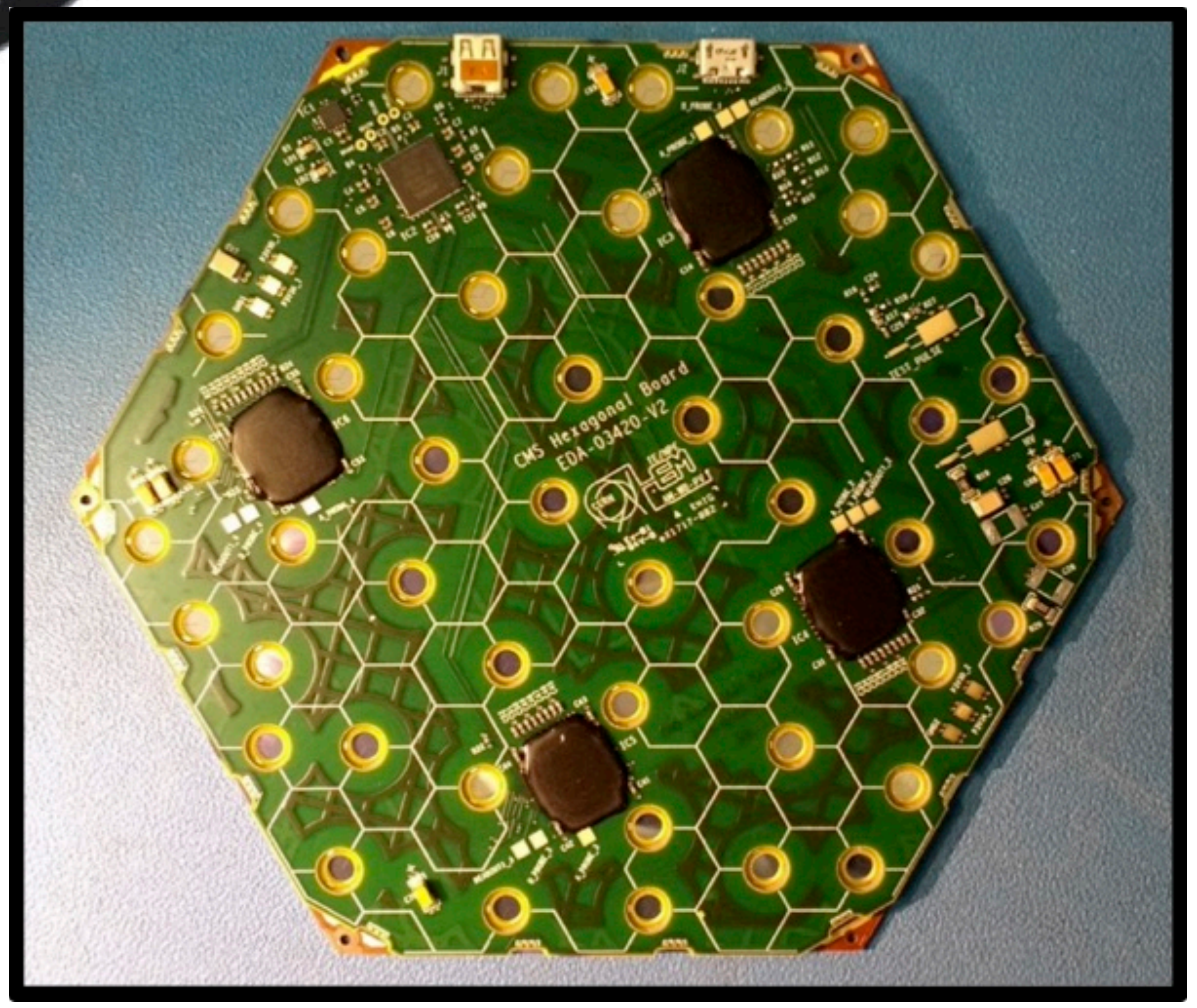


Technologies: ECAL

- Silicon activities profit enormously from CMS HGCAL project - CERN LCD group directly involved in sensor testing & test beam activities







➾ Acquiring experience with multiple vendors, large scale production and testing, electronics, …

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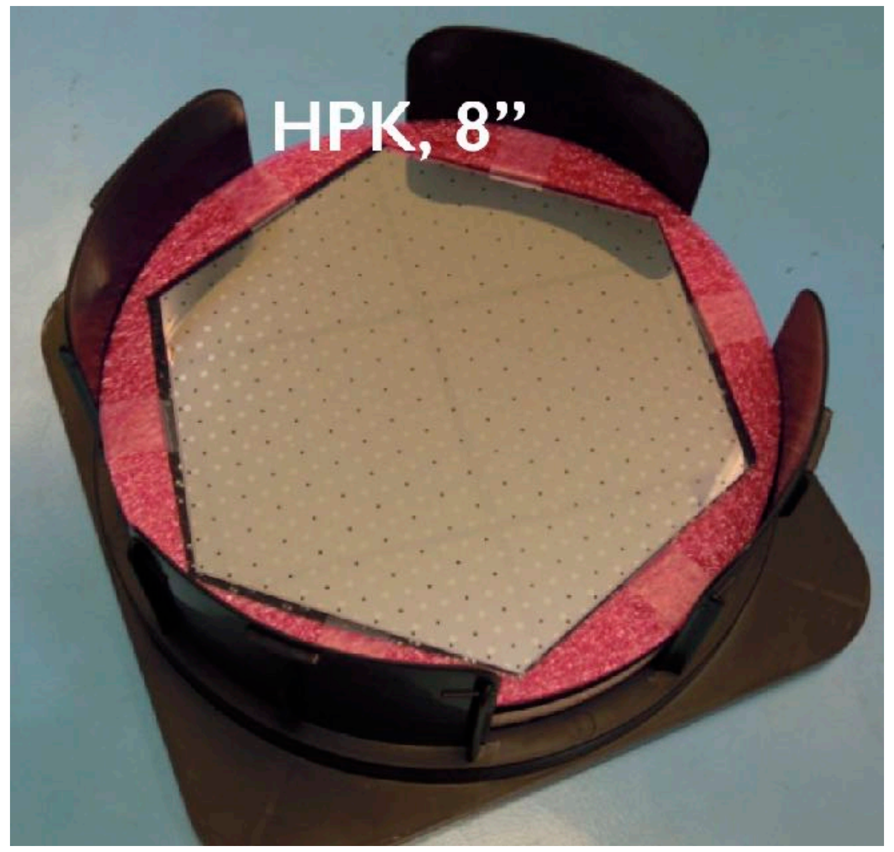

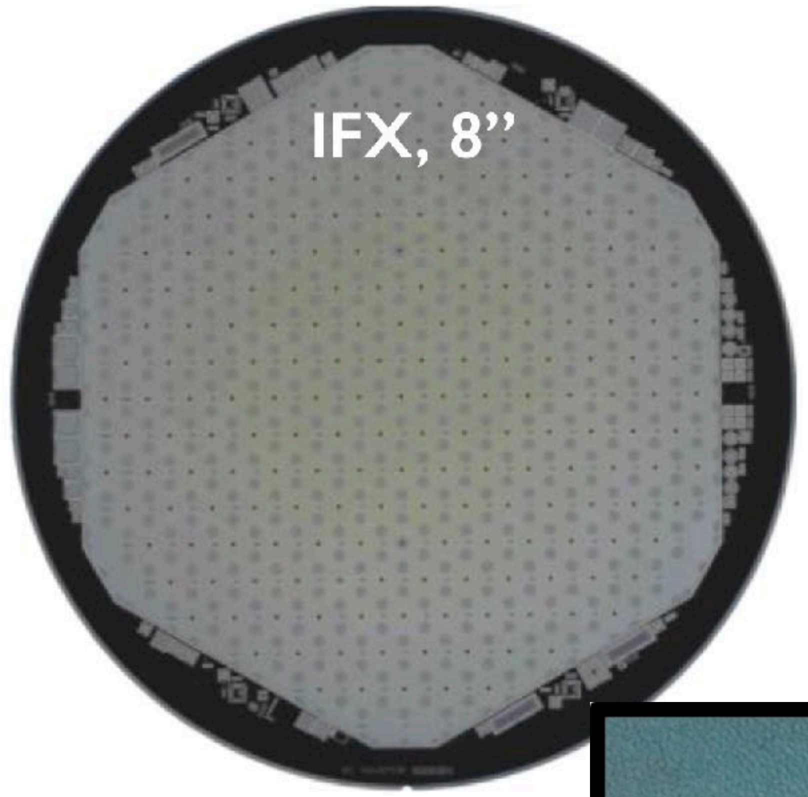

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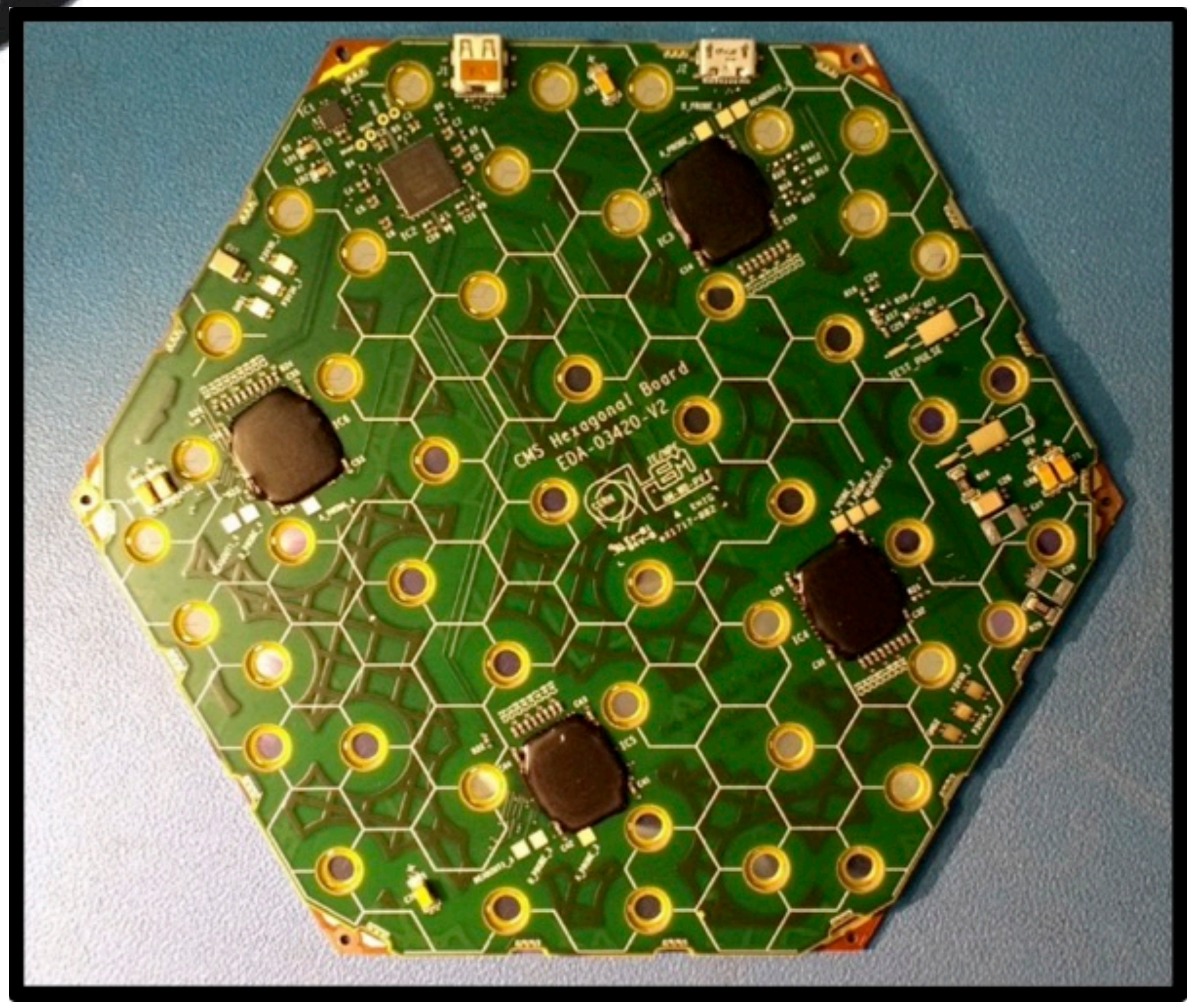
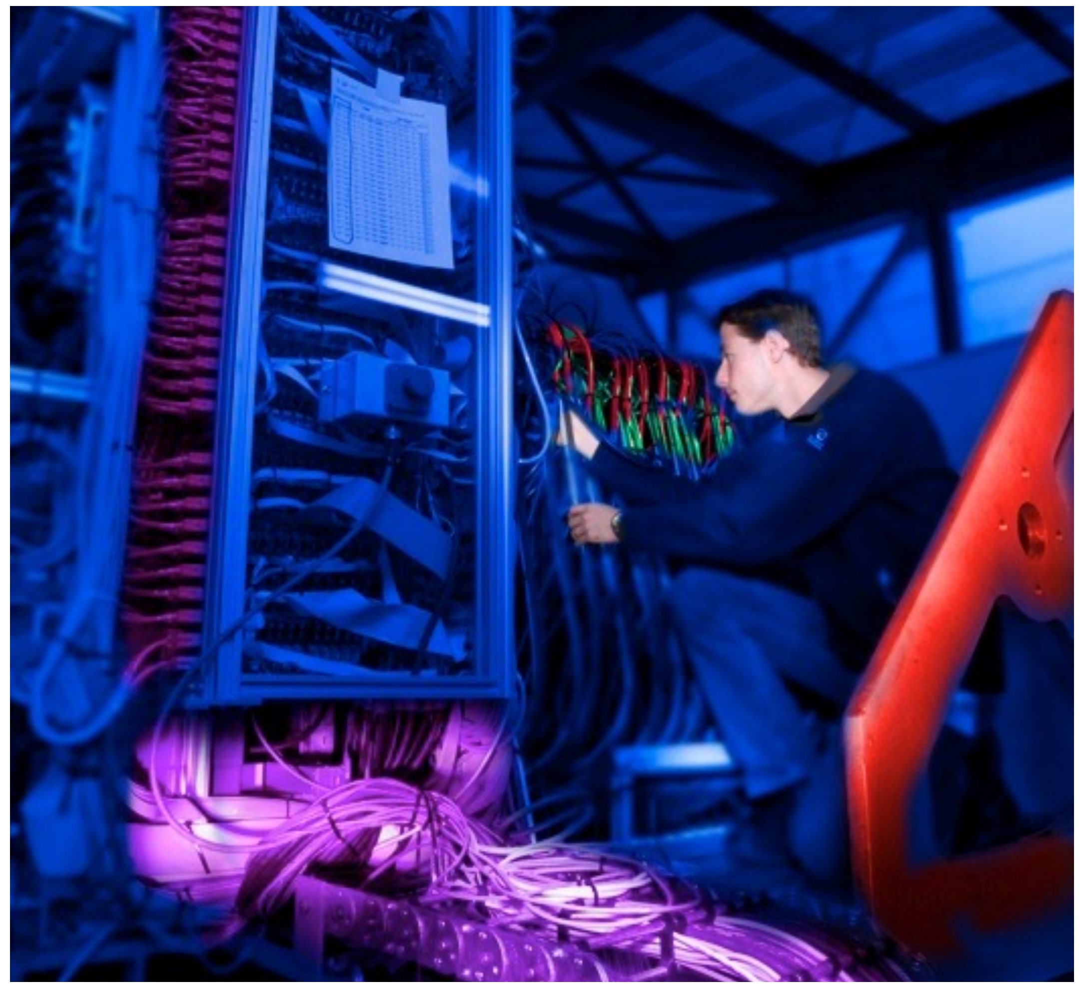


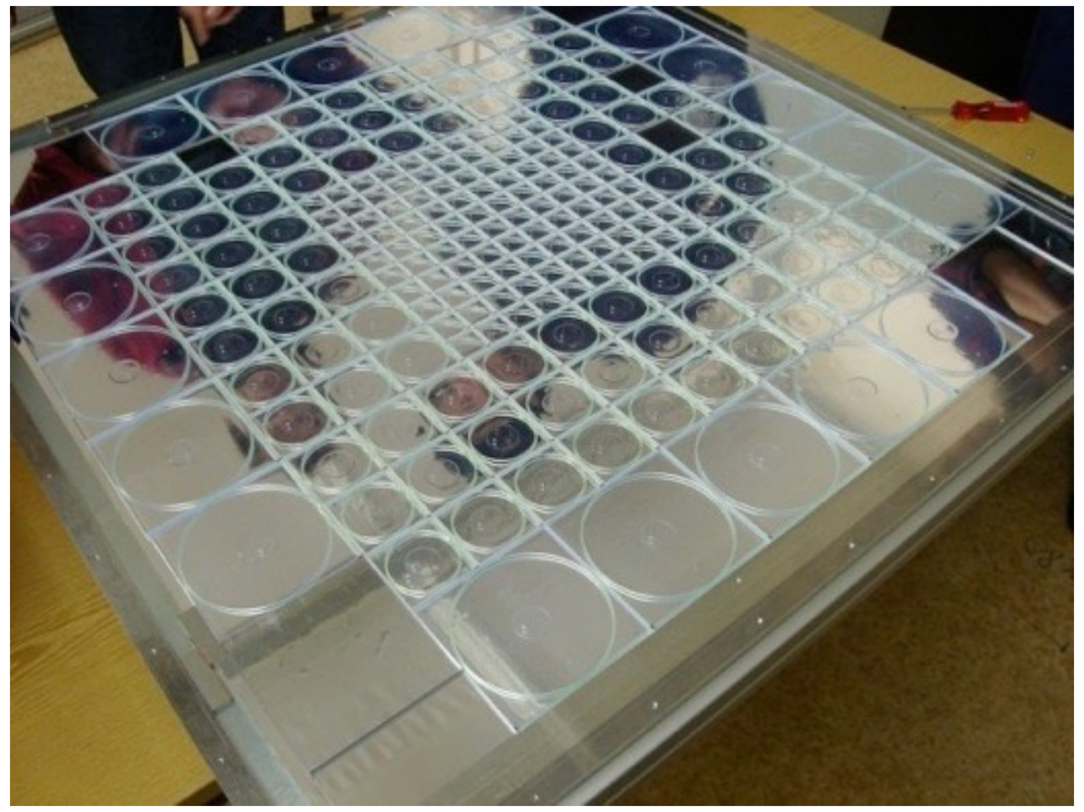
- Scintillator with SiPM readout also studied as an option for ECAL in CALICE
  - Small scintillator tiles (10 x 10 mm^2) tested in CERN LCD group, larger prototype so far only built with strips lead by Shinshu

  - Less compact than silicon, uniformity requirements still need to be fully understood

Technologies: HCAL

- Scintillator tile + SiPM readout: Established by CALICE
  - Technology proven with physics prototype (2006 - 2011)





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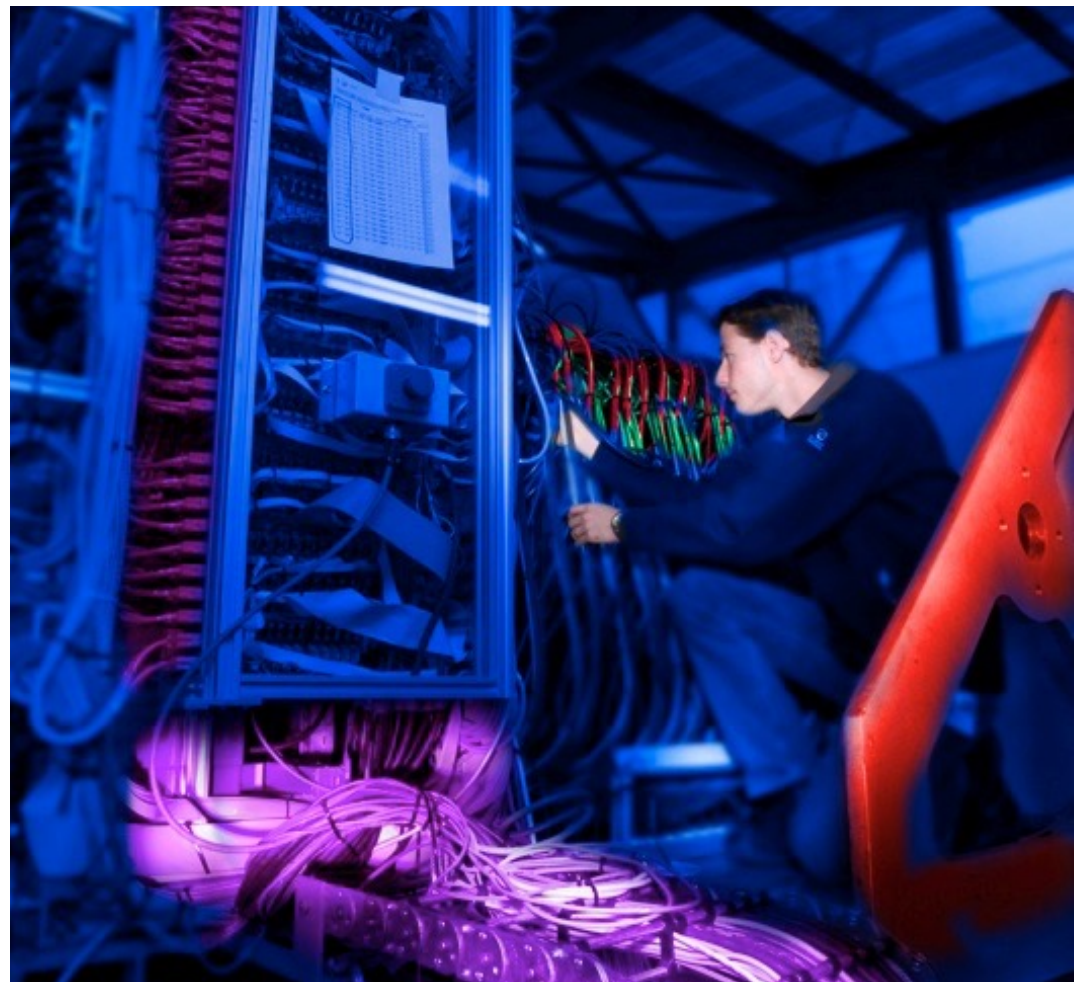
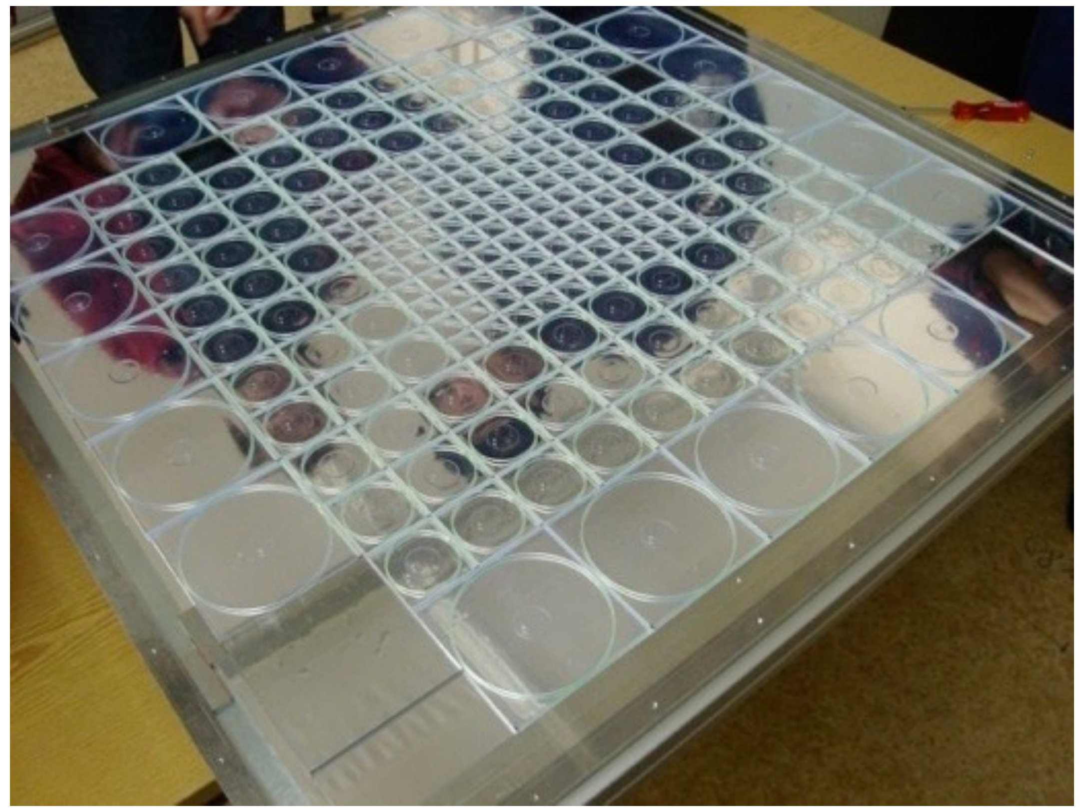
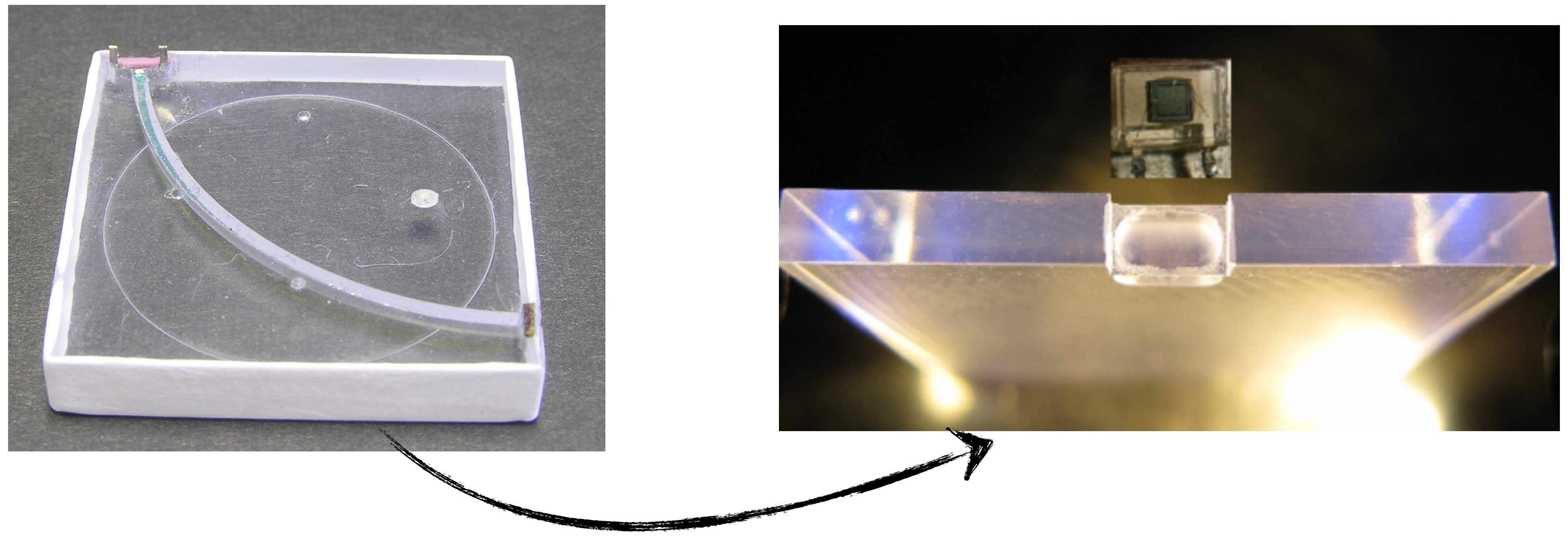




And the technology has since evolved to allow scaling to large systems:



A first simplification of the scintillator tiles: Blue-sensitivity of current SiPMs enables fiberless coupling, combined with specialized tile geometries

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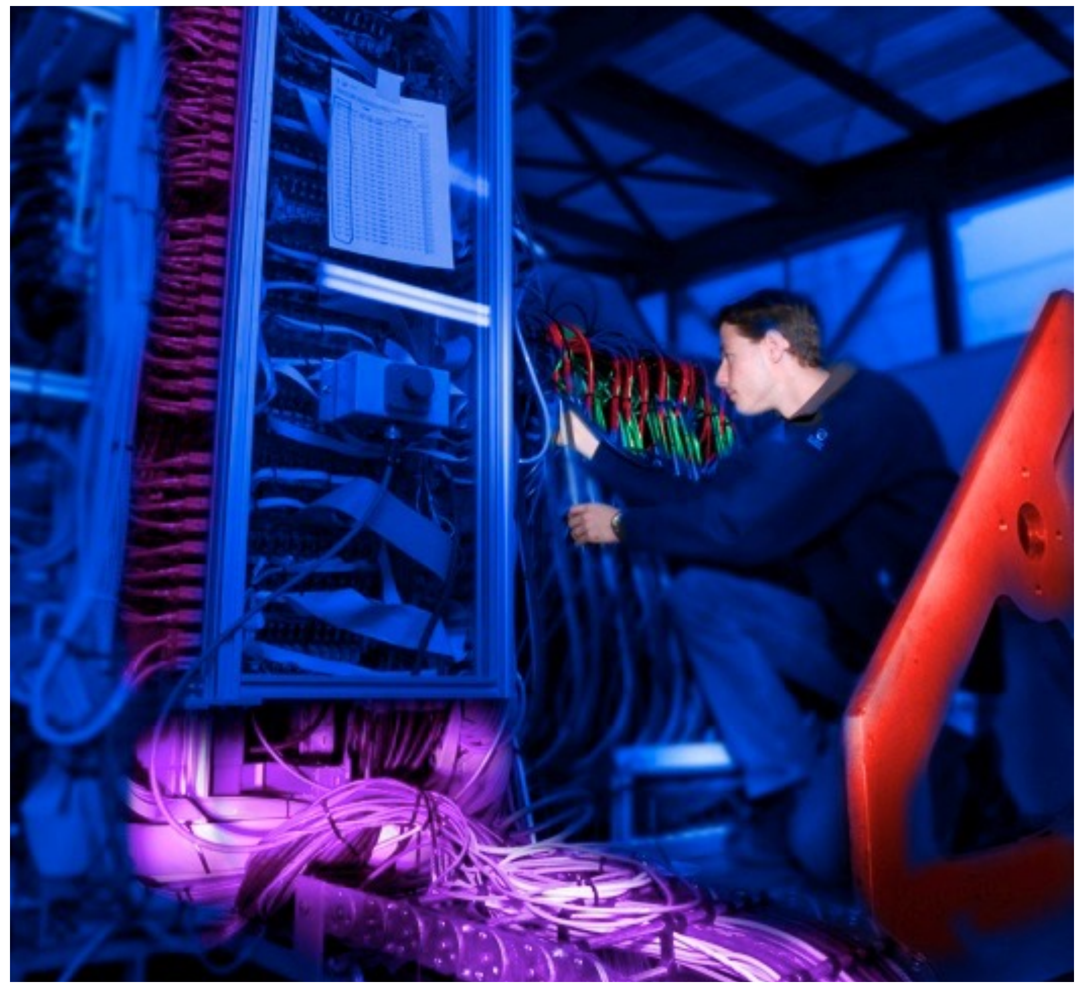

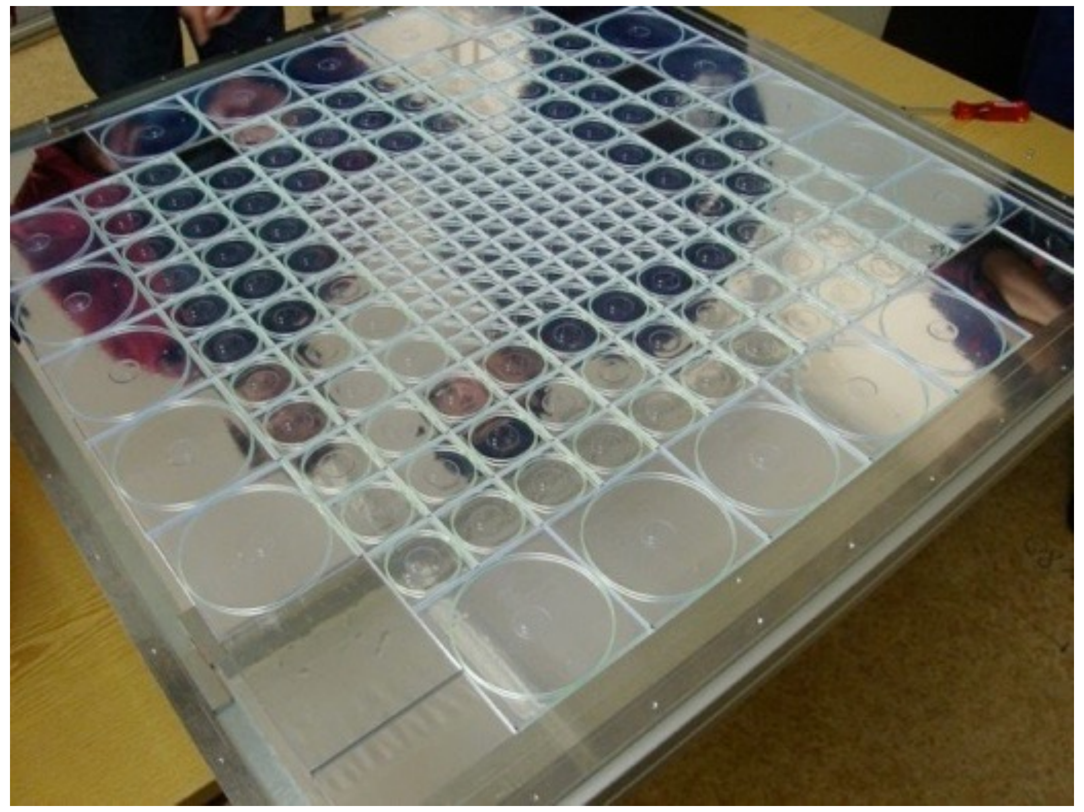

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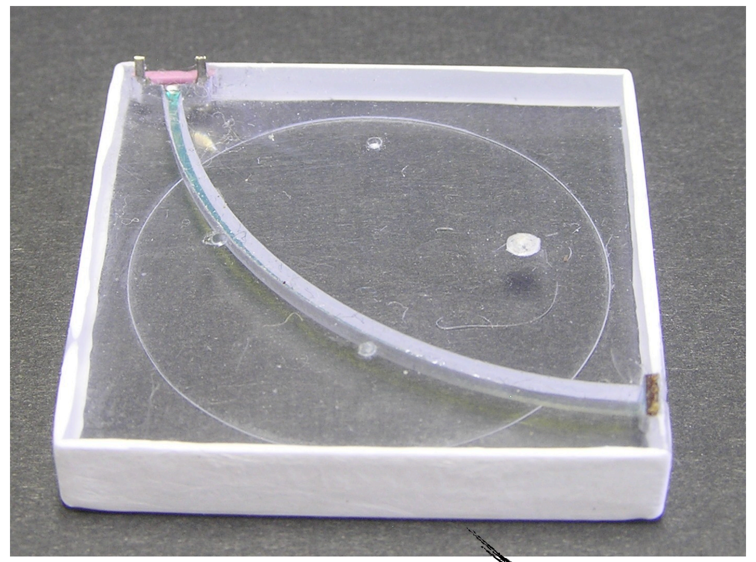

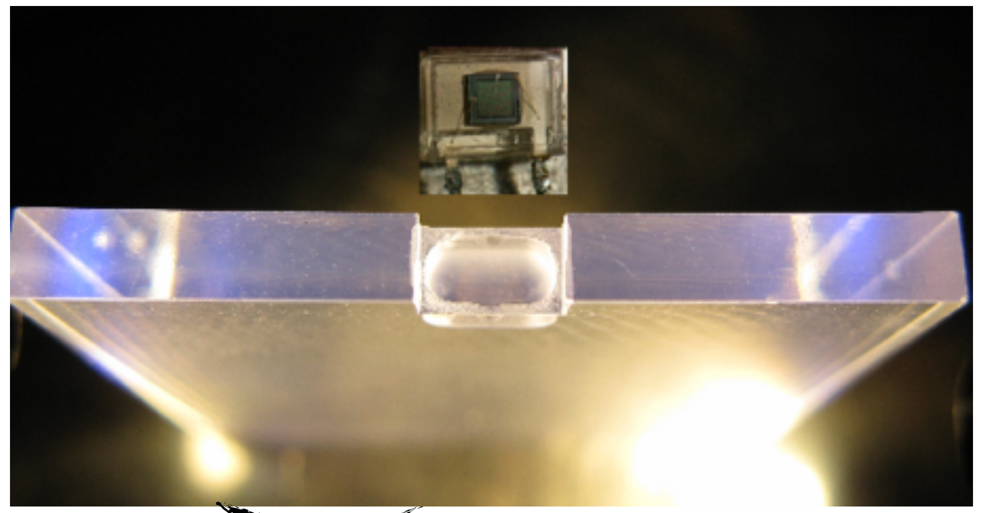

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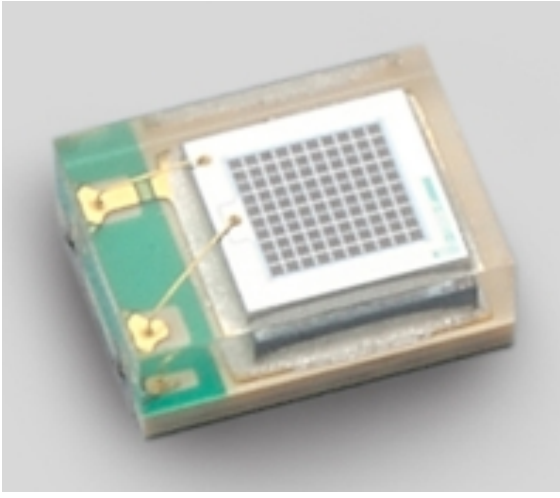

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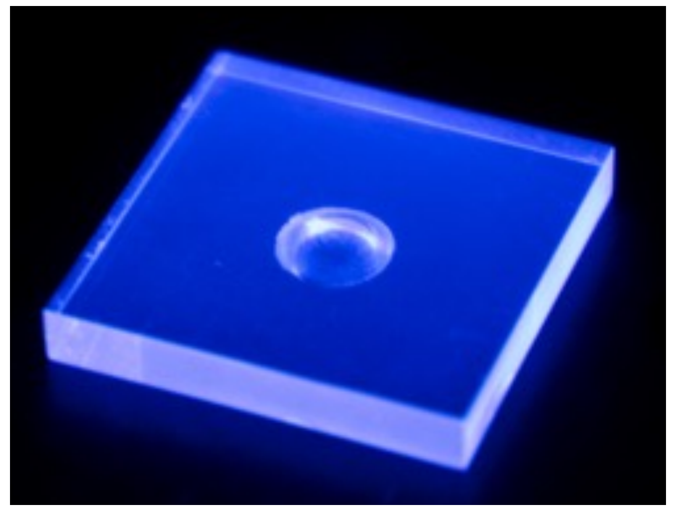
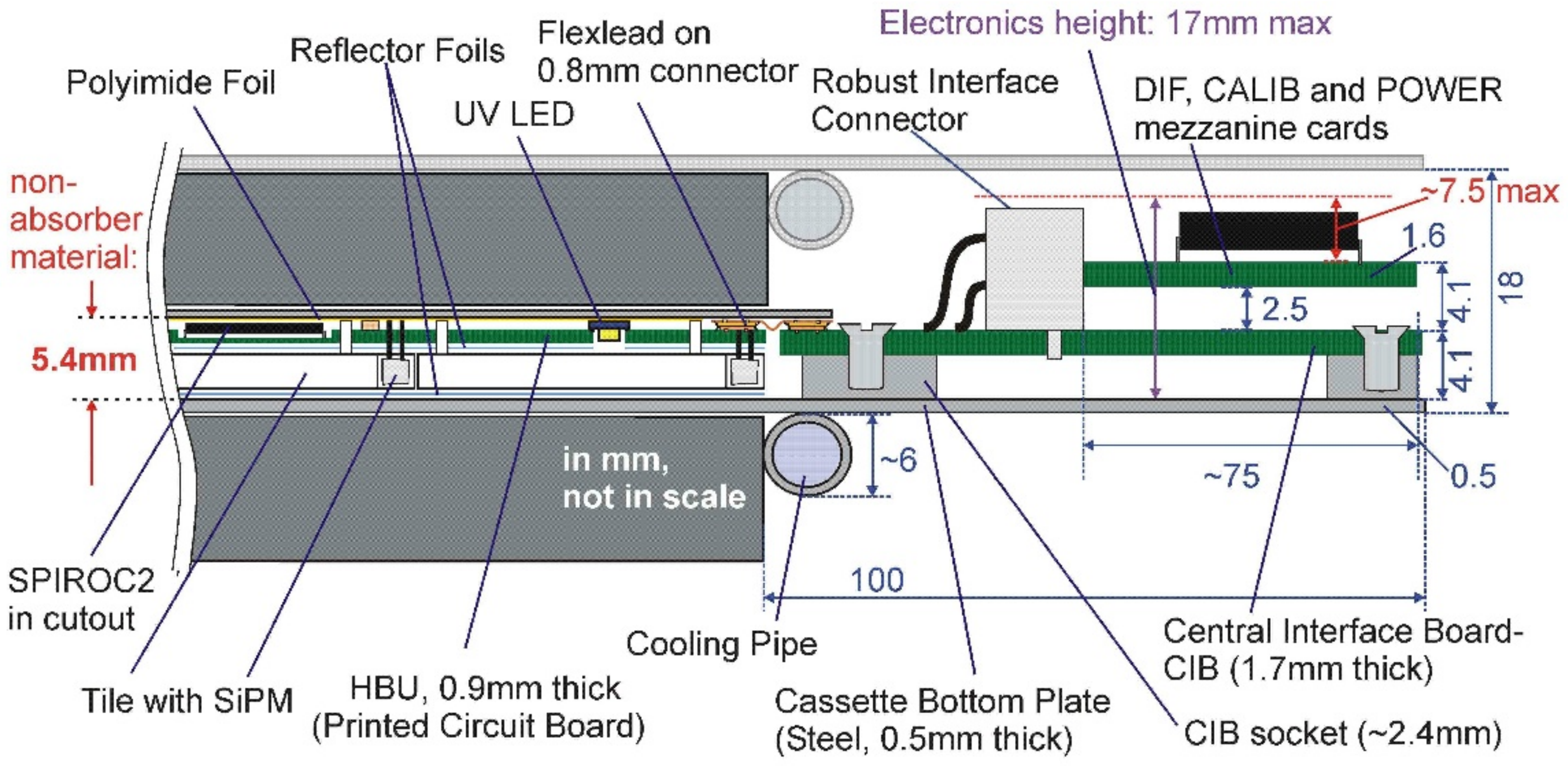


SiPMs in surface-mount packages for pick-and-place machines, together with fiberless tiles, pave the way towards automatic assembly of active layers

Substantial improvements in SiPM performance enable auto-triggering, essentially noise-less detector

Technologies: HCAL

- Compact design now being implemented in CALICE AHCAL technological prototype



- Cassette thickness ~ 6.5 mm, including 2 x 0.5 mm stainless steel in covers
  - 1 mm additional tolerance per layer: 7.5 mm space between absorbers

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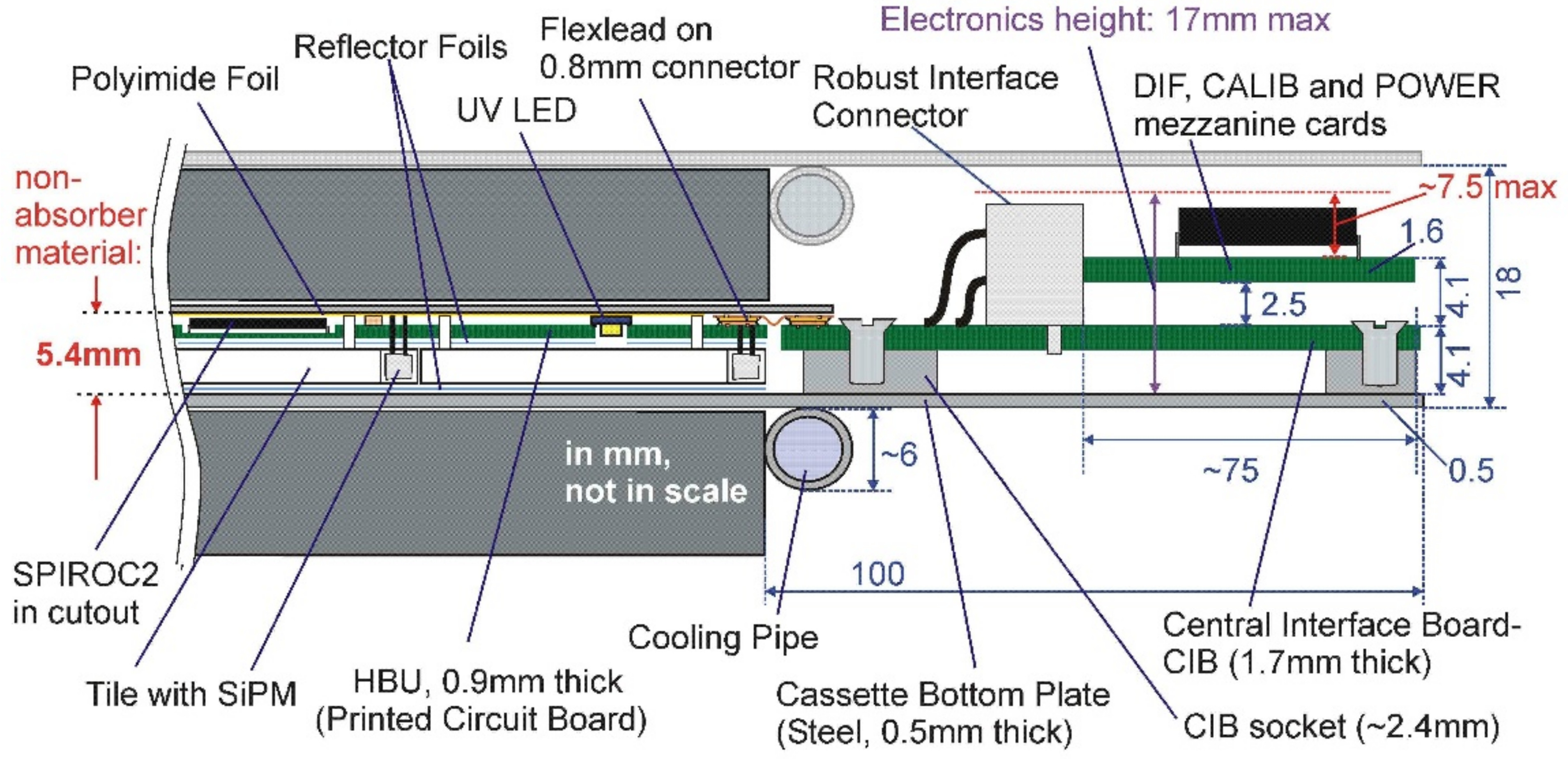

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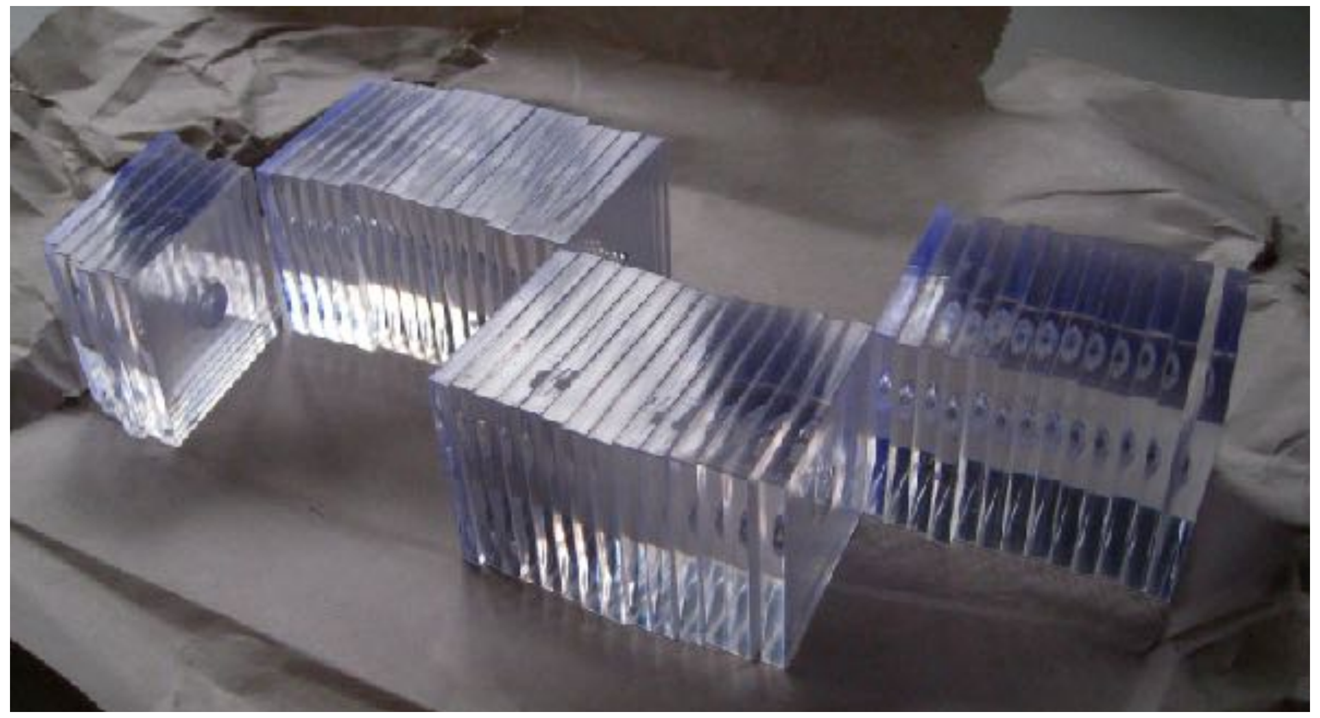
- Scalable technology:

injection-molded scintillator tiles



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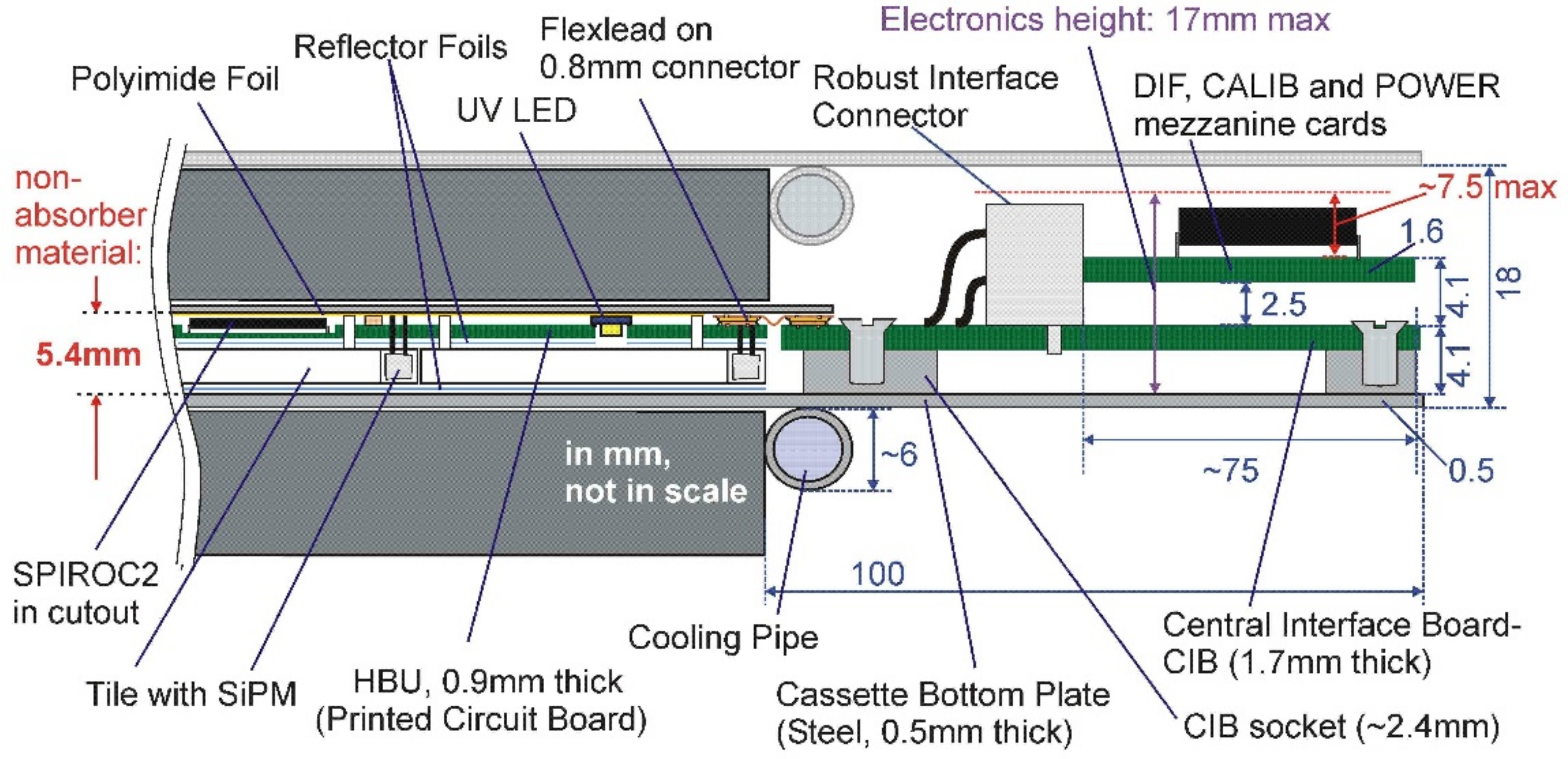

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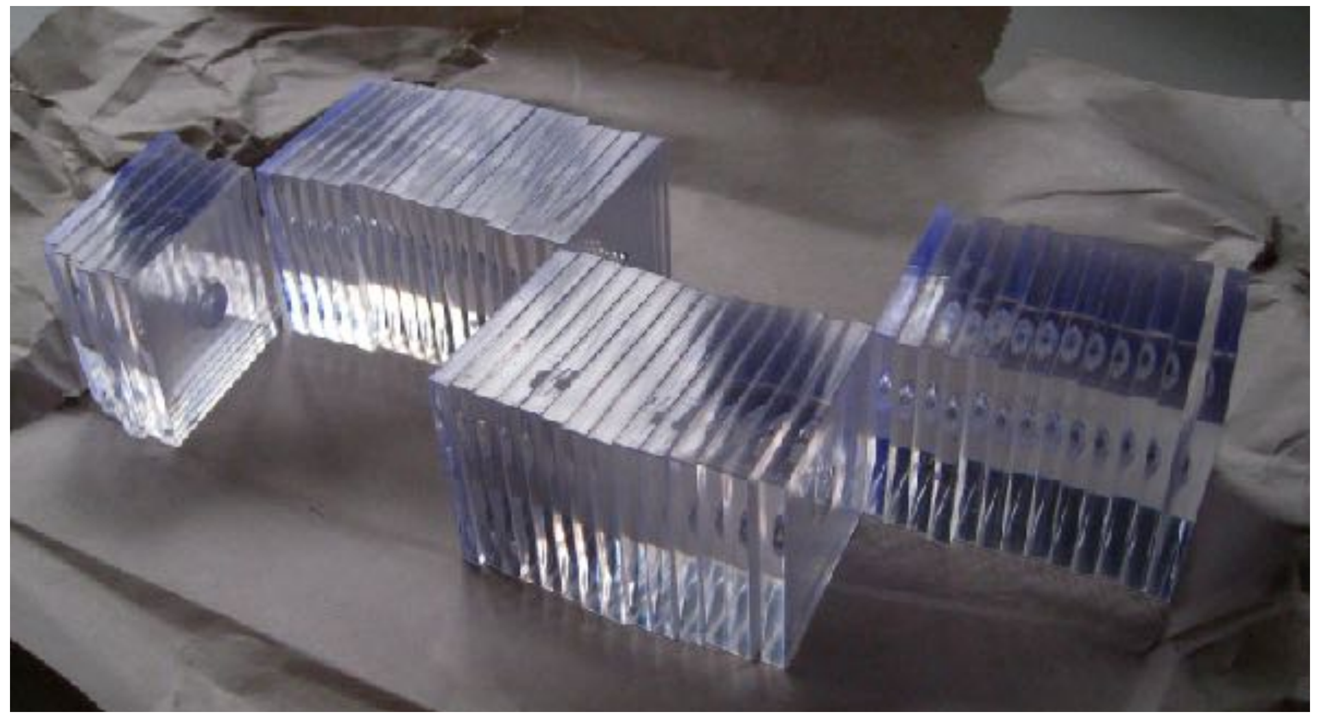
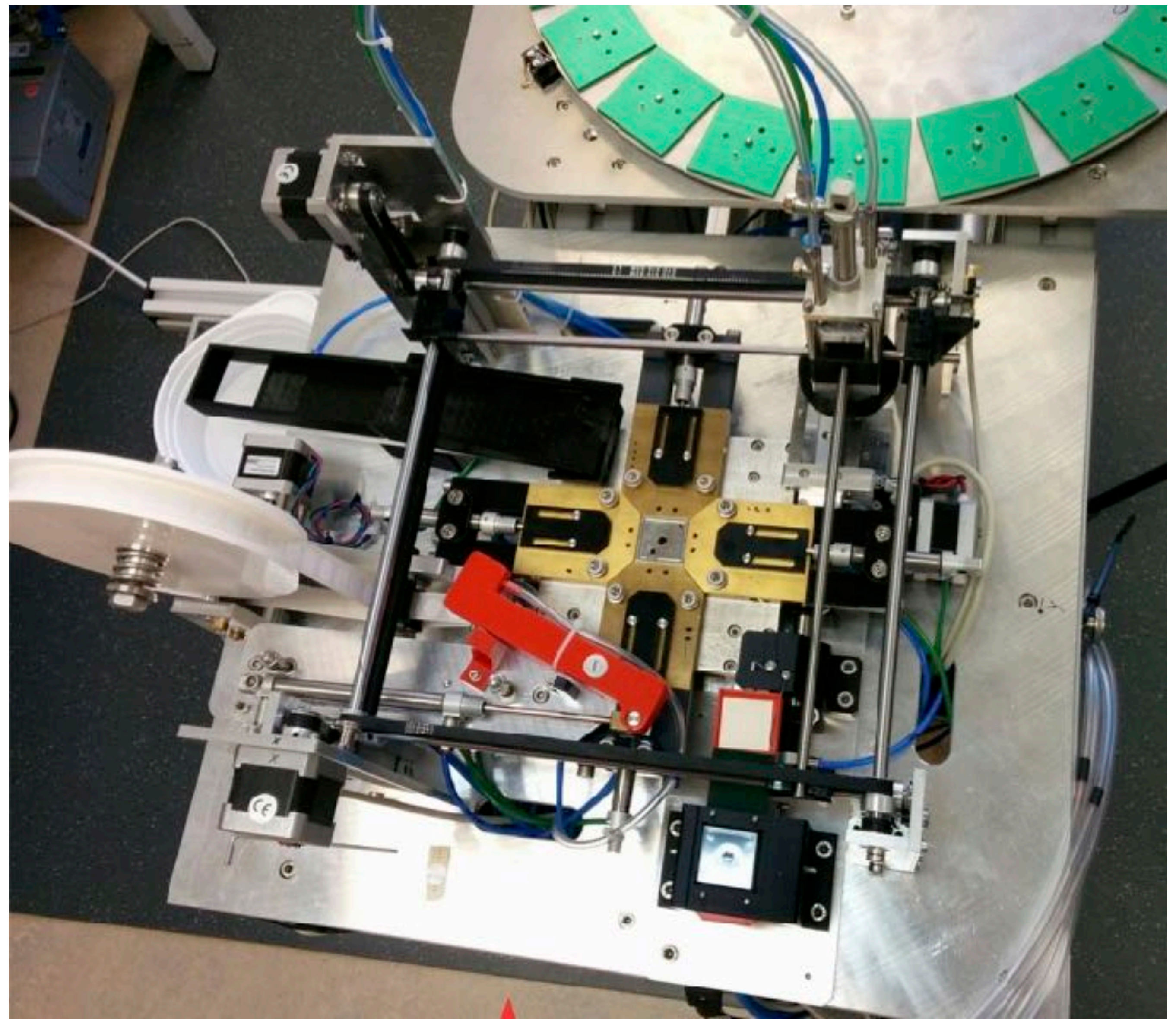
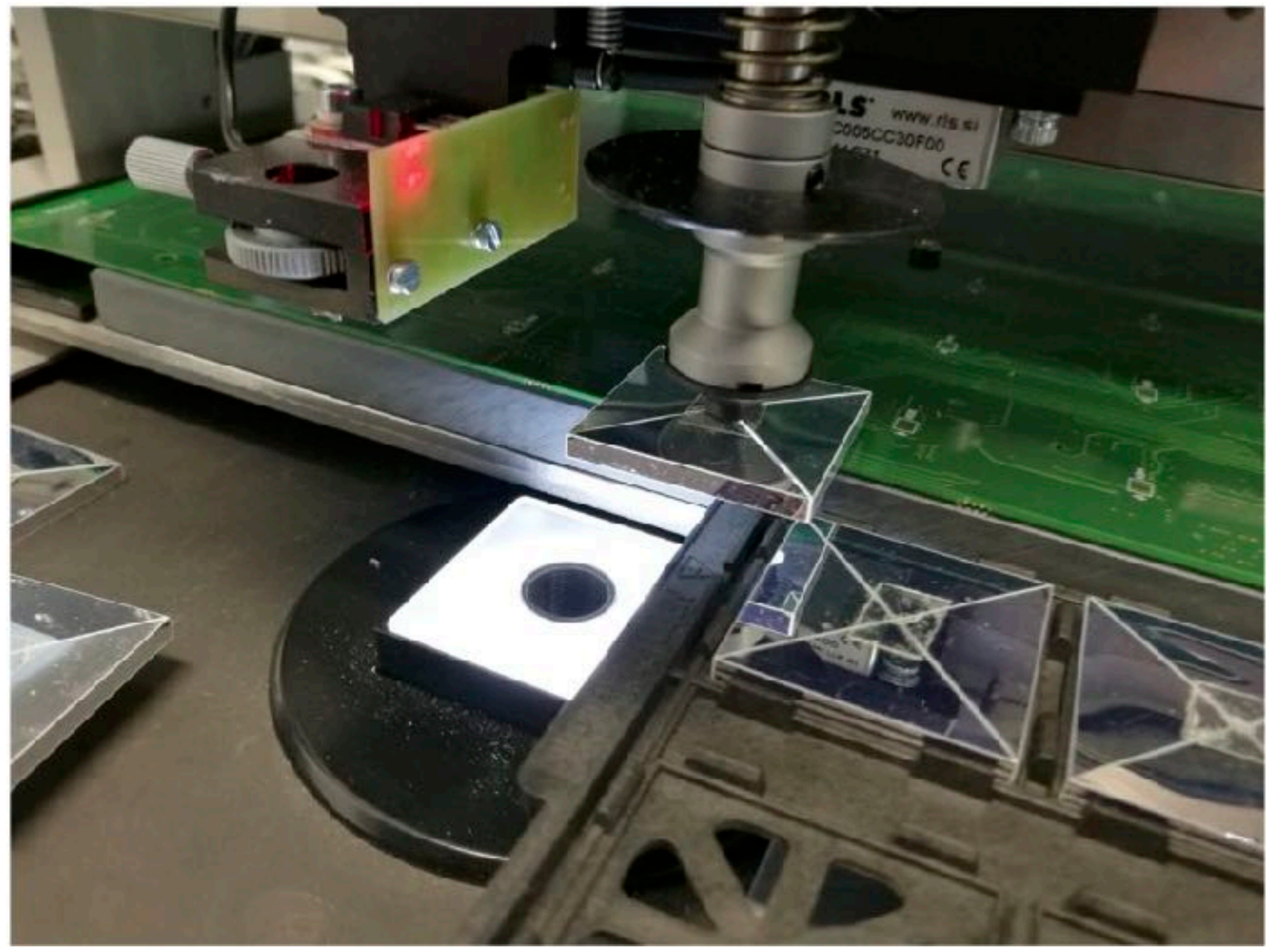




Semi- automatic wrapping of scintillator tiles in reflective foil

Technologies: HCAL

- Scalable technology:



Automatic placement
on electronics boards

Technologies: HCAL

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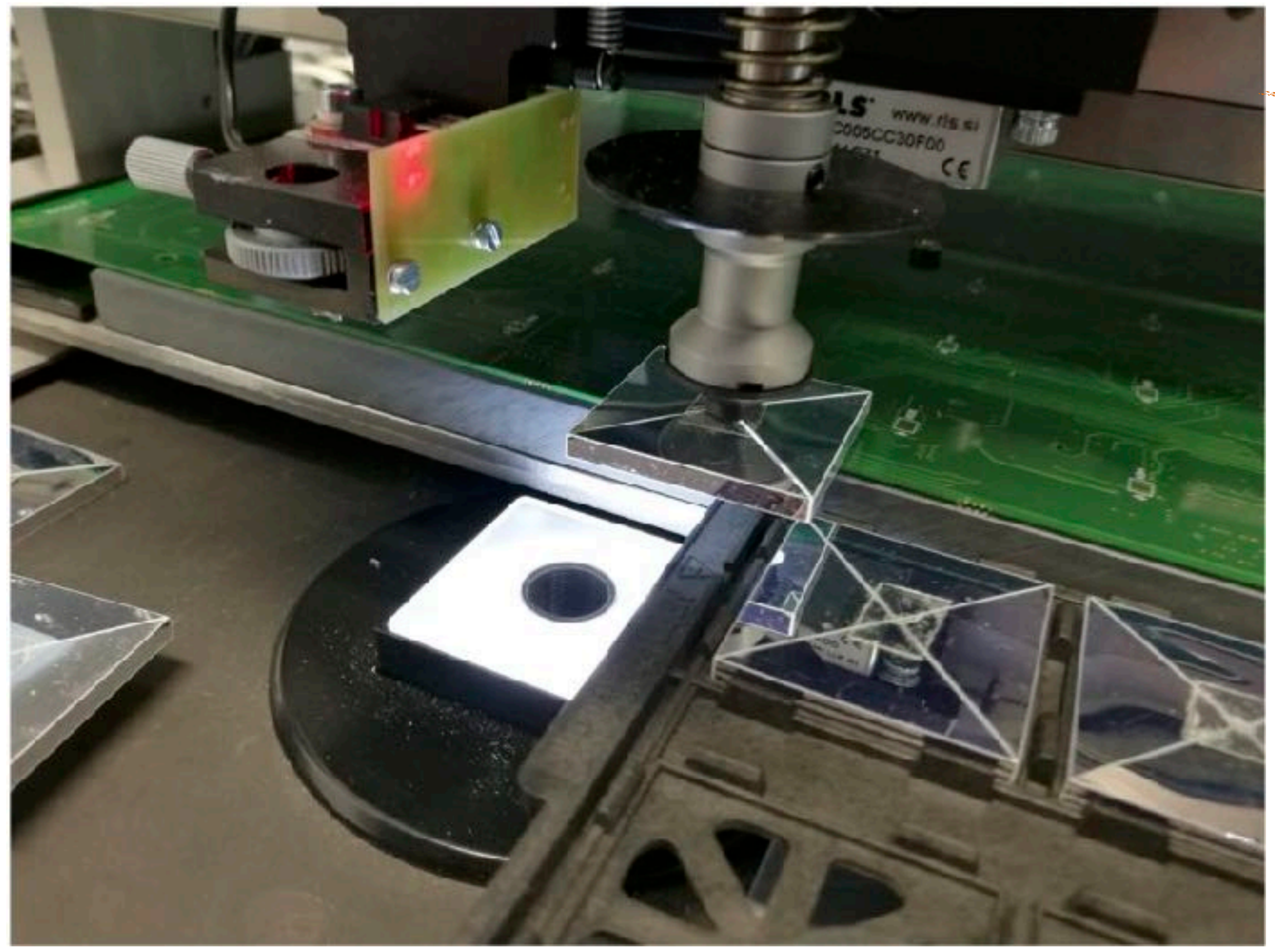

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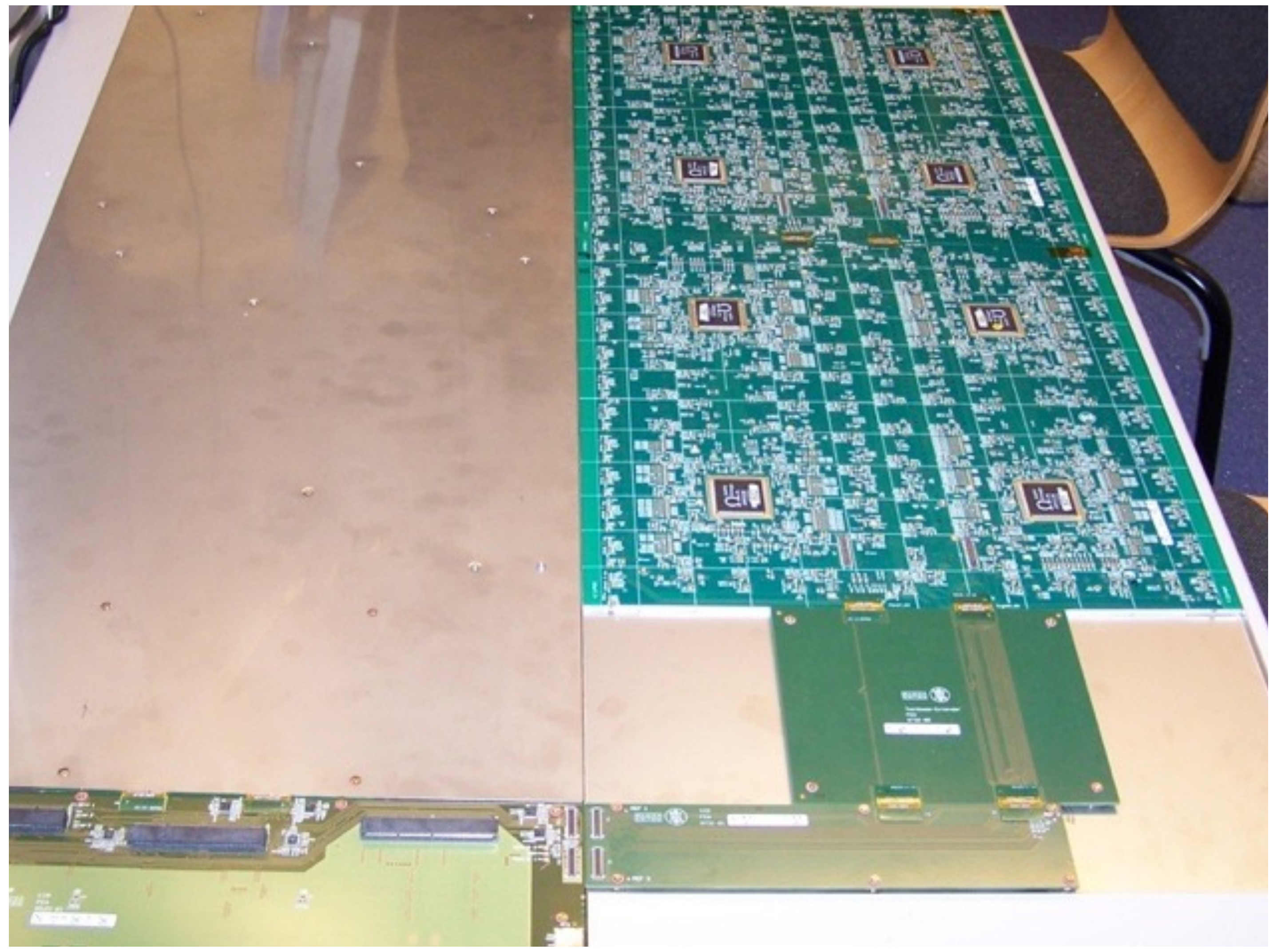

Precise cassette elements and absorber structures

Technologies: HCAL

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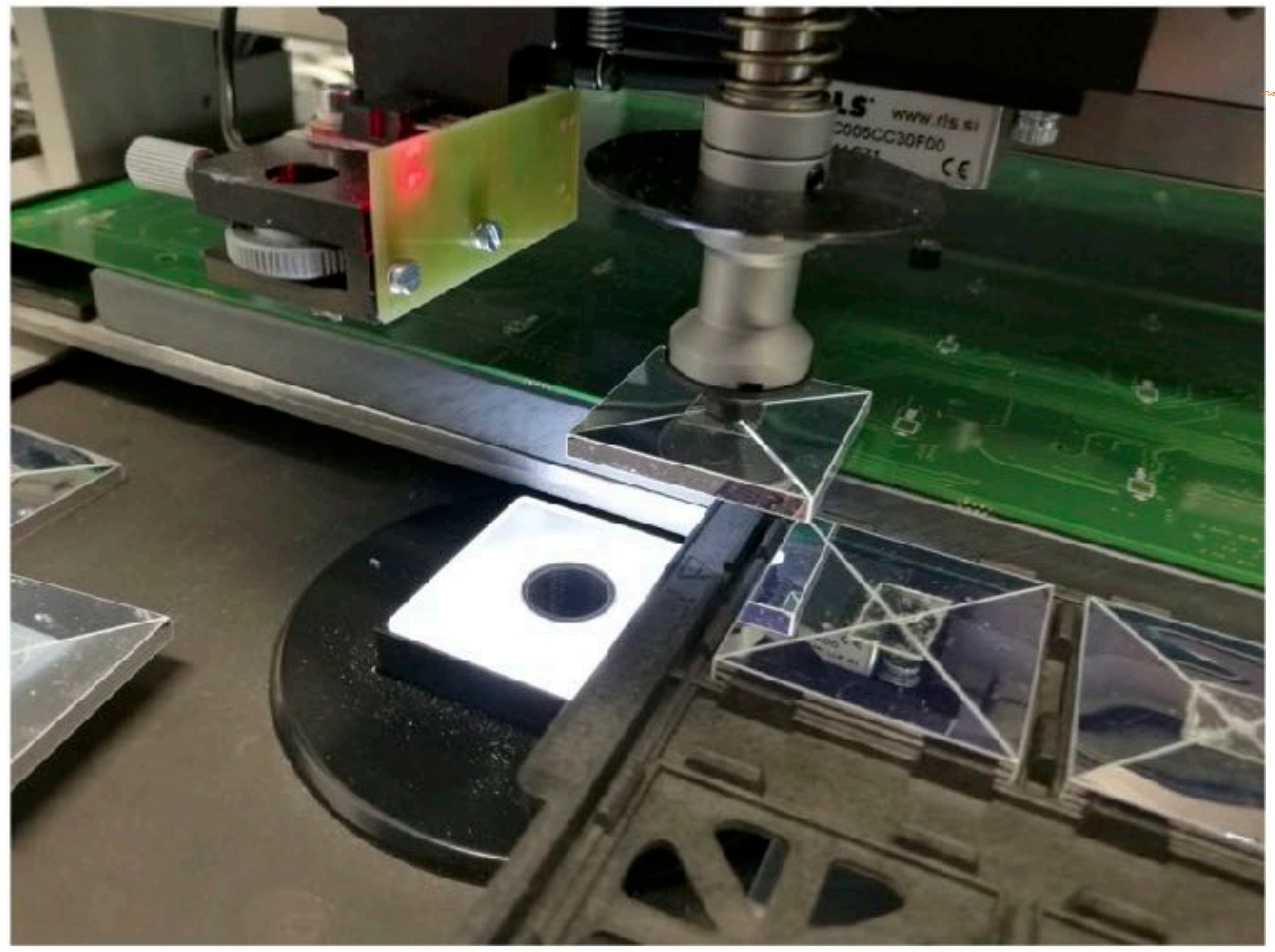

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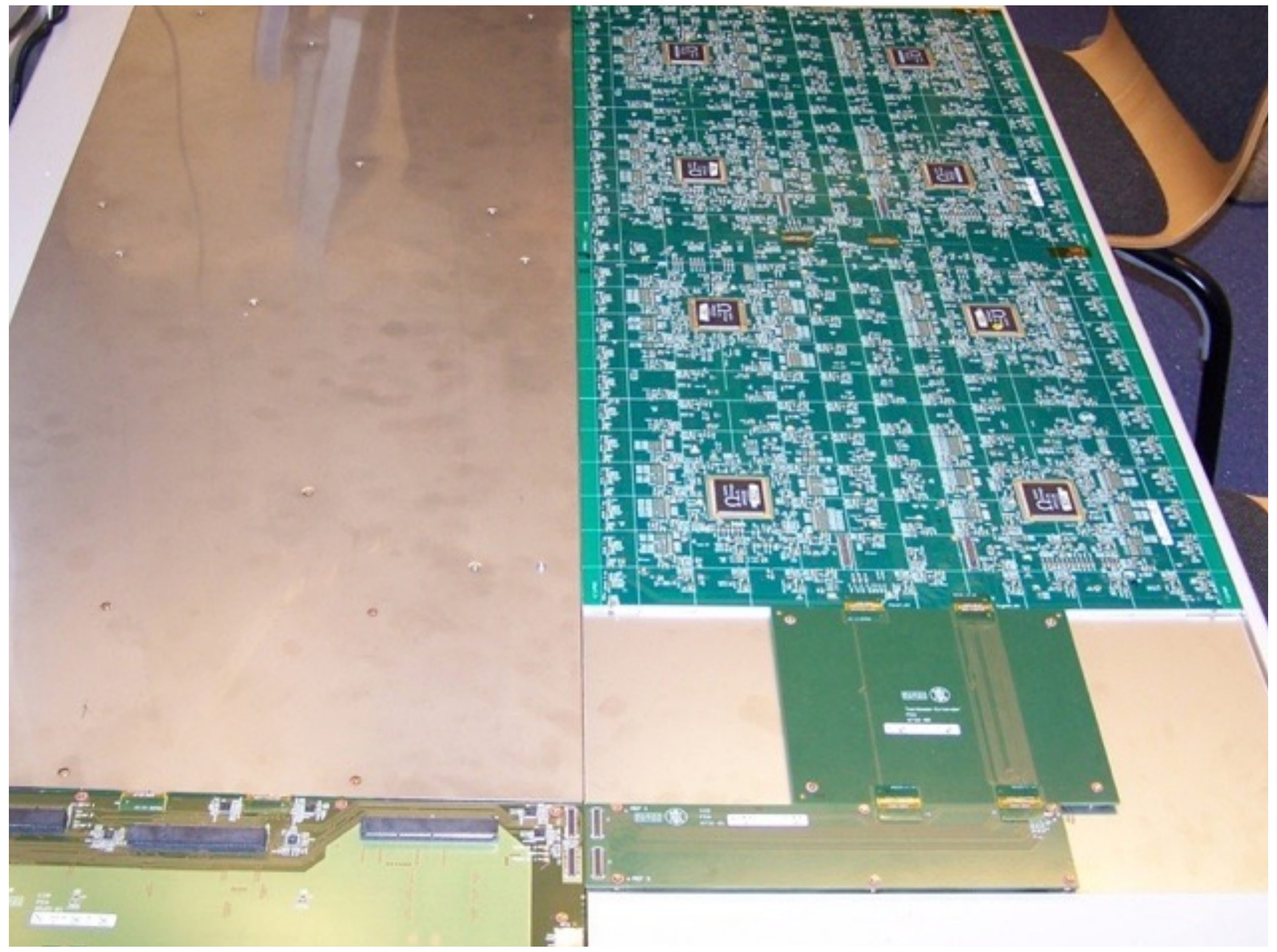


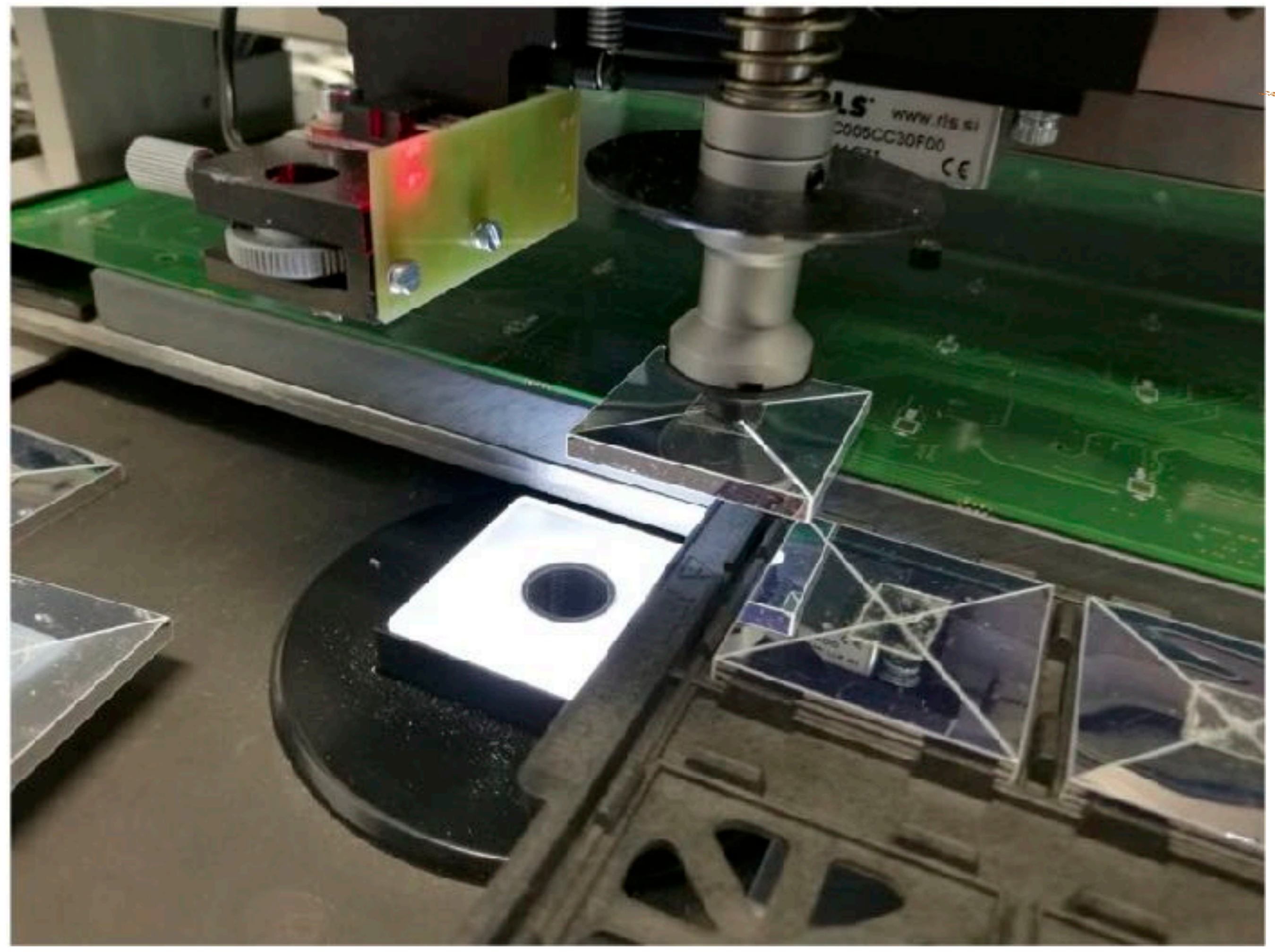
Precise cassette elements and absorber structures

Currently ongoing construction for a full hadronic prototype with 23k channels - in May 2018 in beam

Technologies: HCAL

- Scalable technology:

Technology also used in CMS HGCAL - closely follows CALICE design, with some changes imposed by LHC environment



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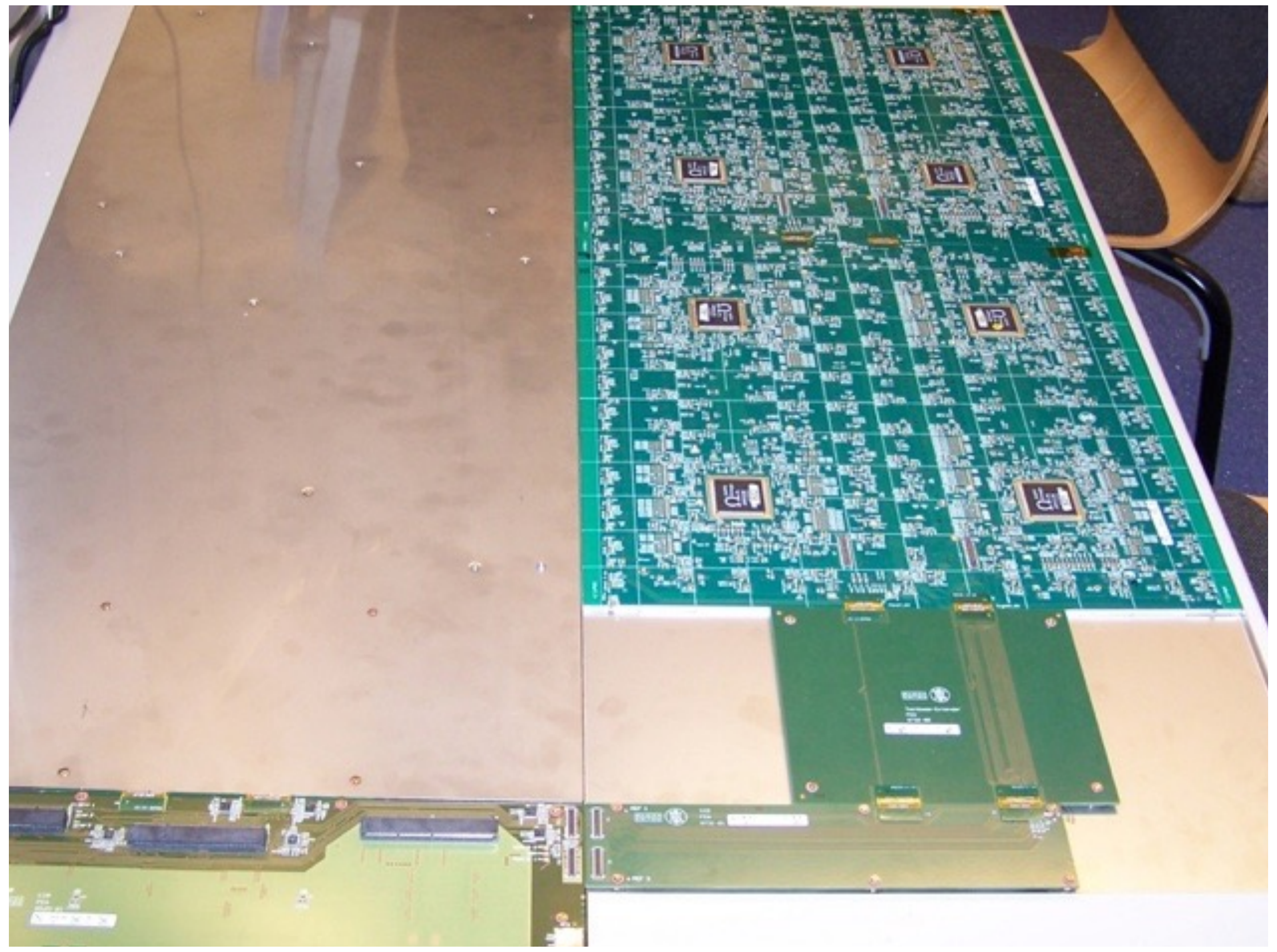

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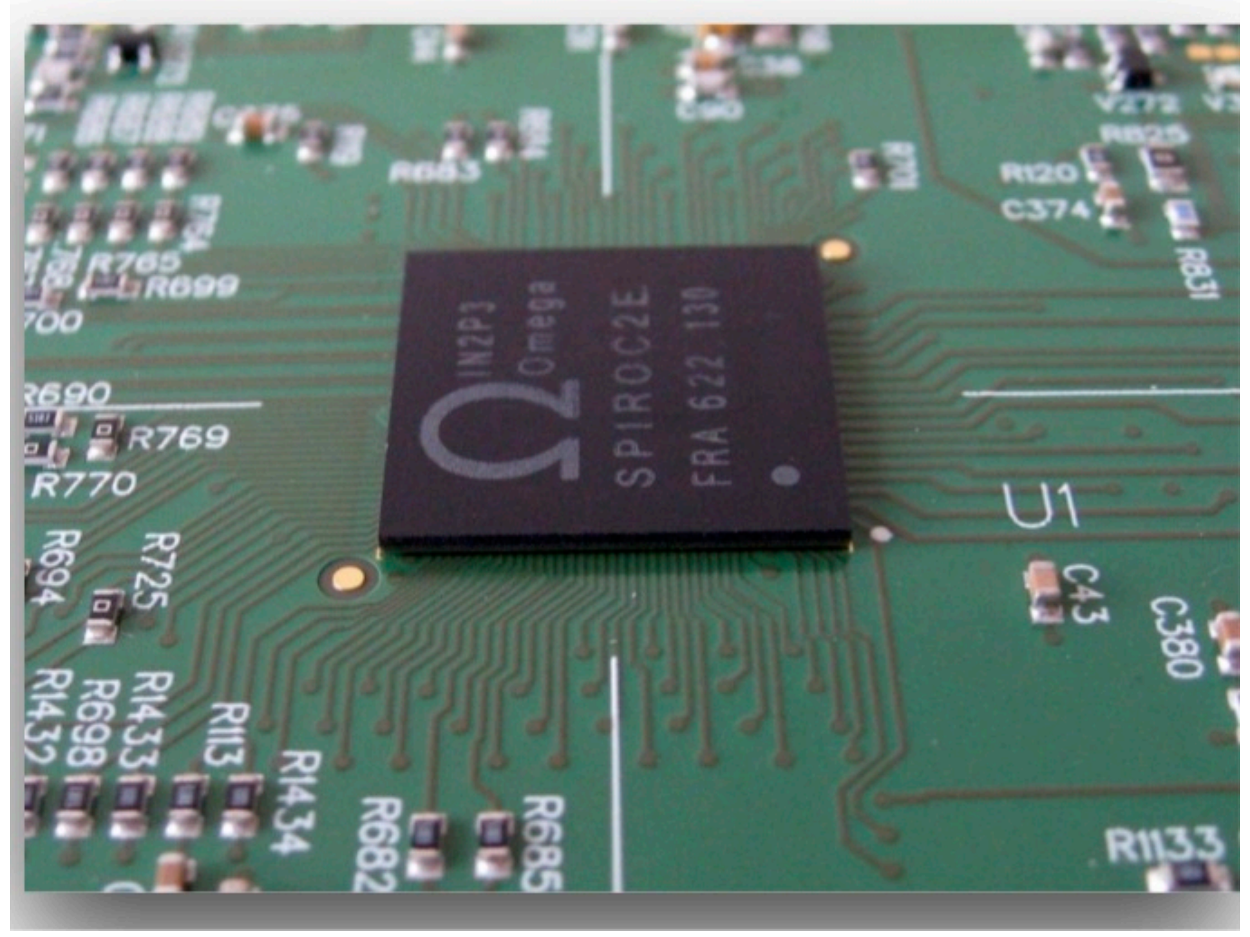
Common Features - Electronics



- Front-end electronics directly integrated into detector volume
  - CALICE and CMS make use of same ASIC family
- ASIC provides extended dynamic range by dual gain mode, 12 bit ADC
- Time stamping capability better than 1 ns for linear collider - optimised operation: Satisfies CLIC background rejection requirements
- Auto triggering: Enables triggerless operation of the calorimeter

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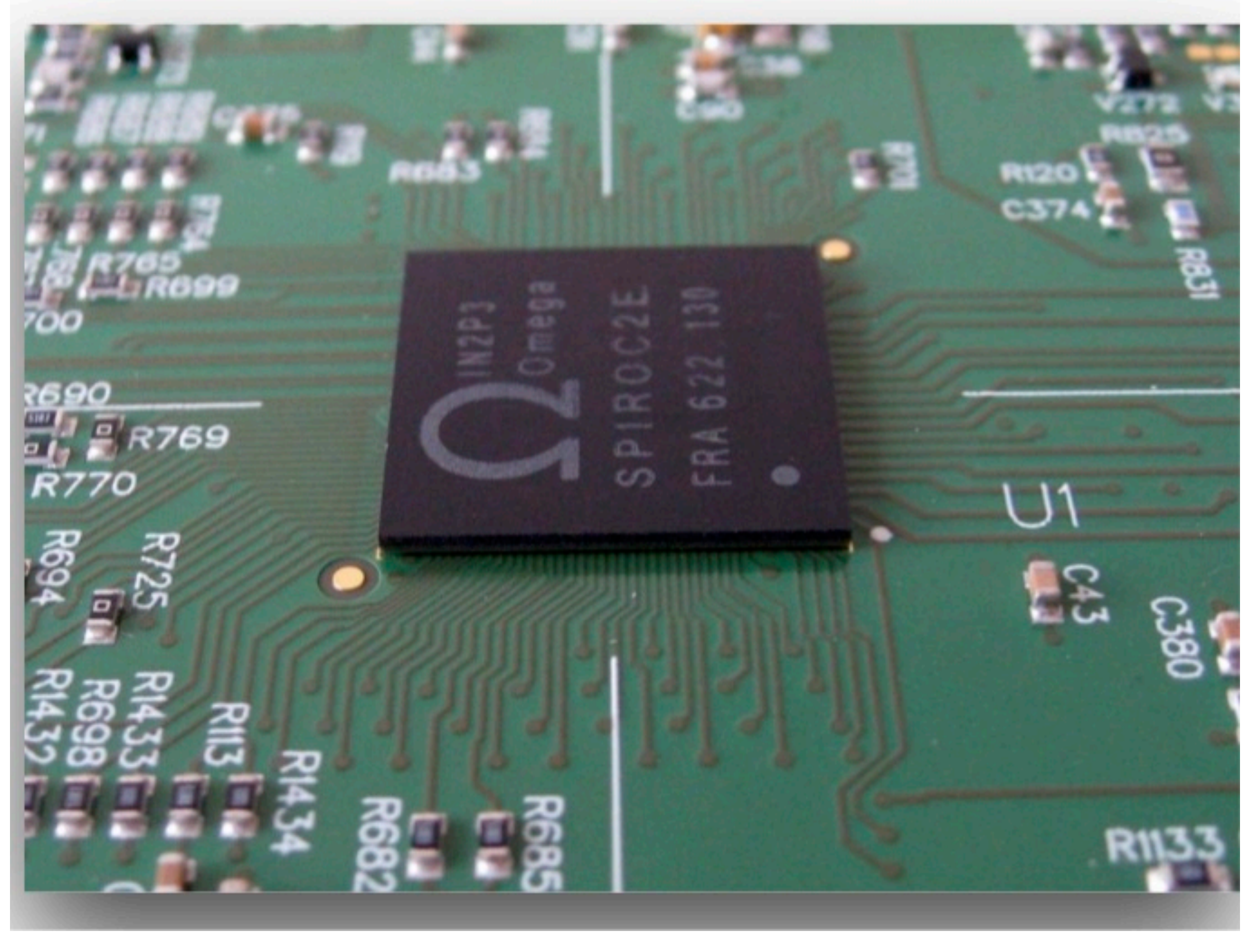

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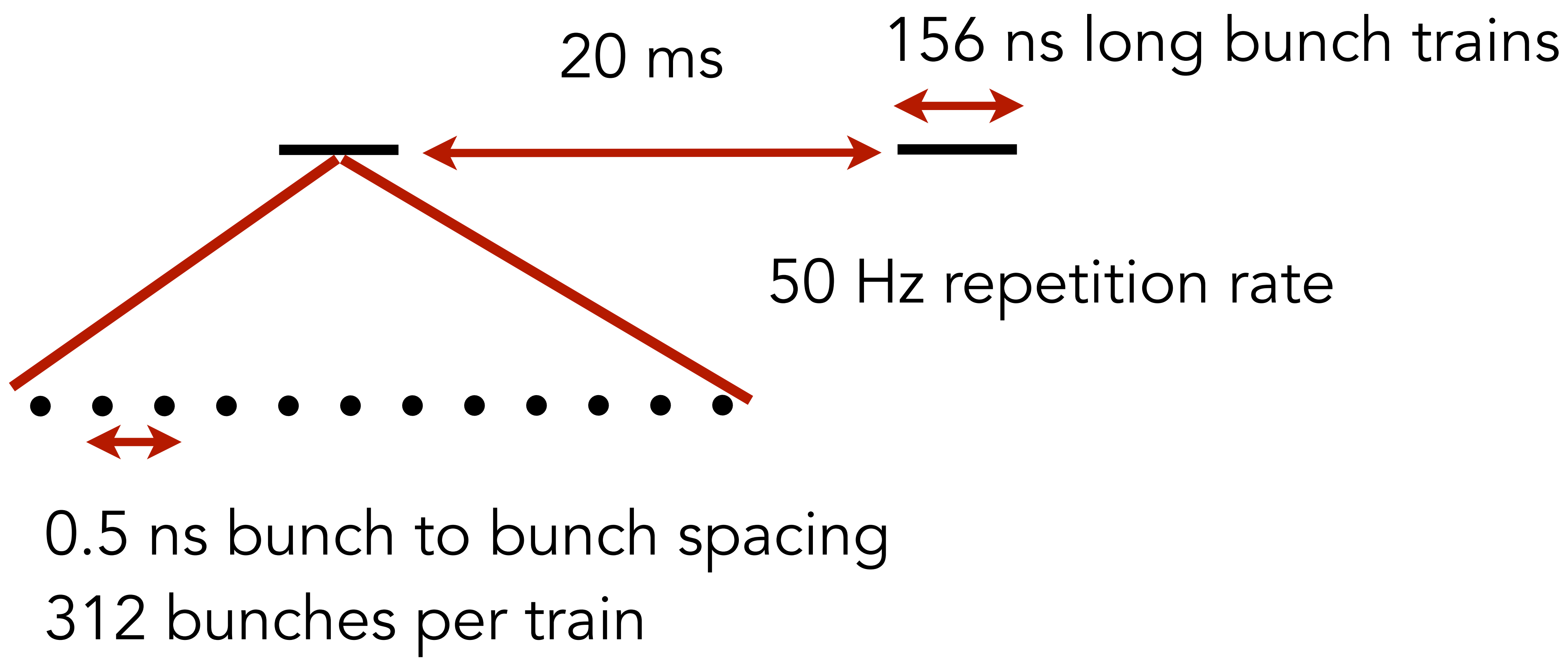
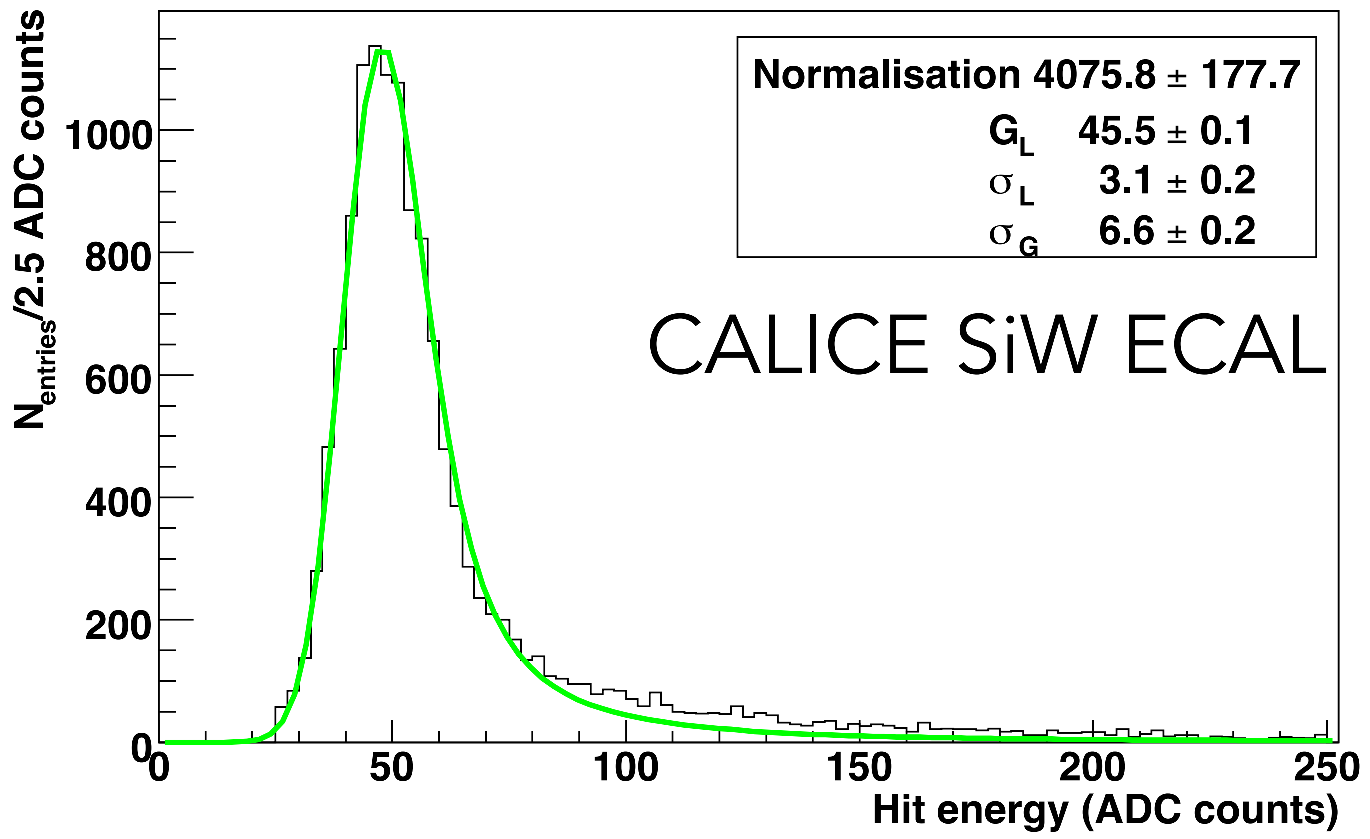


- A key requirement to achieve maximum compactness: No active cooling in detector volume: Low-power electronics!
- Power-pulsing allowed by bunch train structure of CLIC - allows a duty cycle of < 1% for front-end electronics
  - Capability integrated in current CALICE electronics

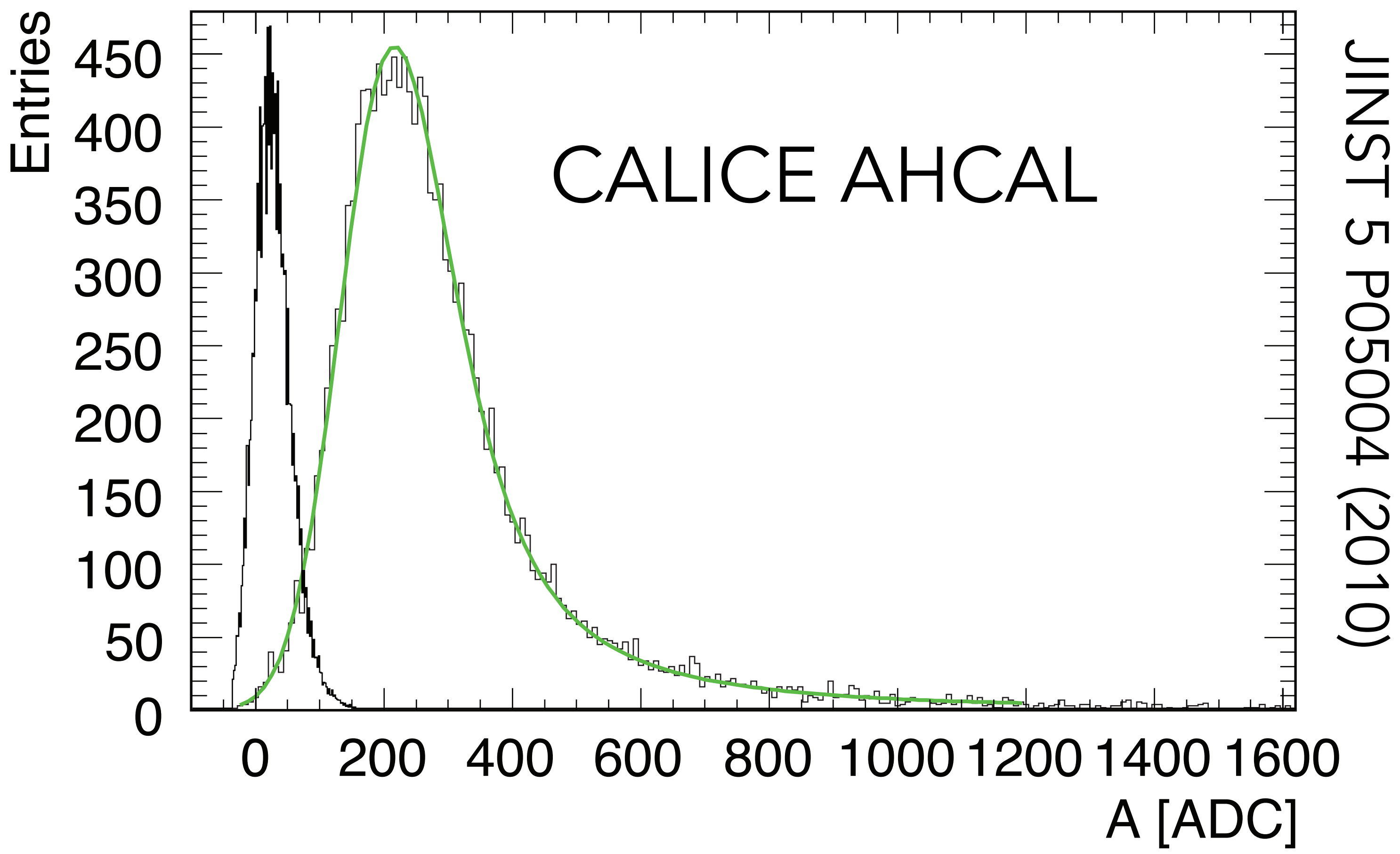
Calibration of Imaging Calorimeters

- The large number of cells requires a dedicated calibration strategy:
  - Each individual cell calibrated with muons “on the MIP scale”: provides cell-by-cell inter-calibration



JINST 3 P08001 (2008)

- Typical uncertainties of 0.4% in ECAL, 2% in HCAL (statistical) - for Si stable on the ~ % level, for SiPMs temperature correction key



JINST 5 P05004 (2010)

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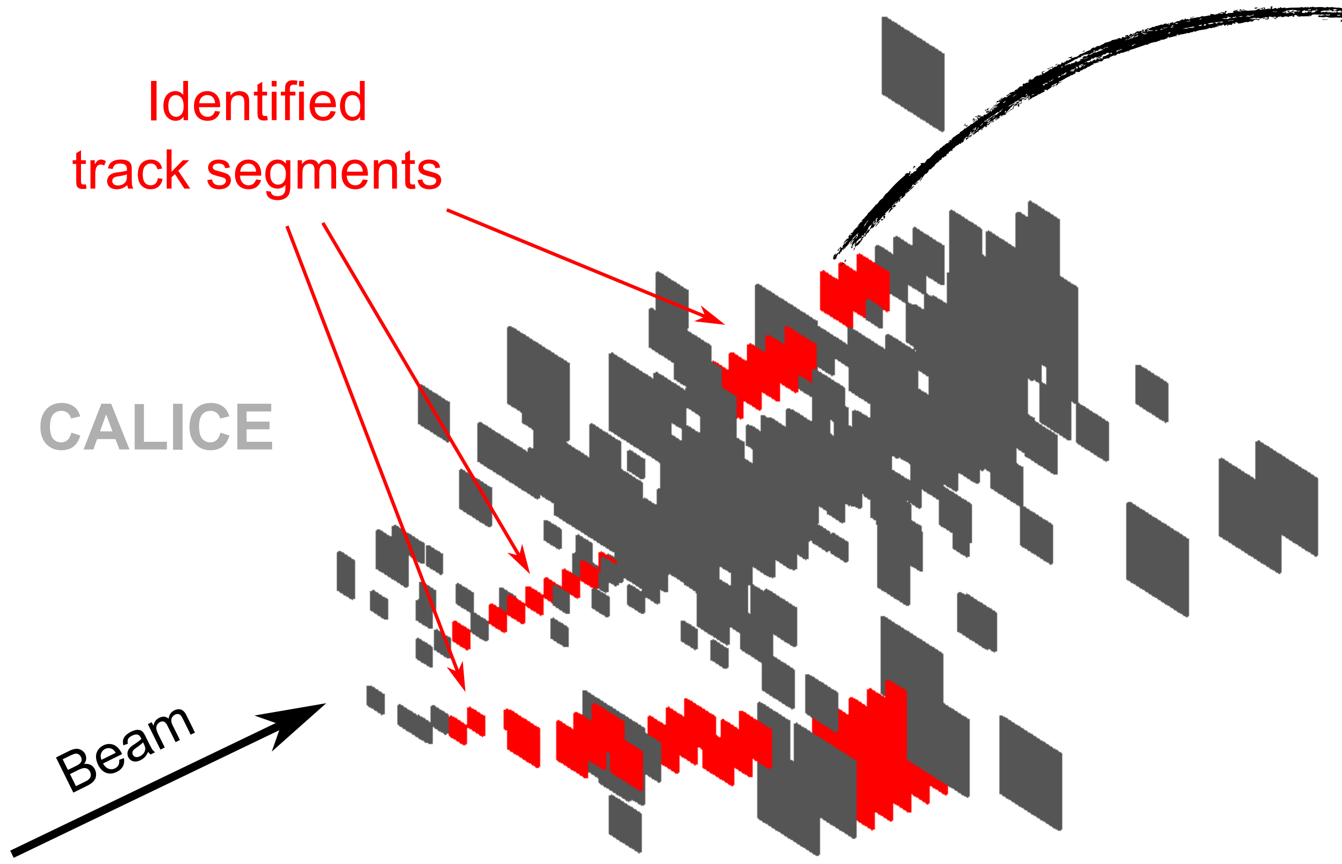
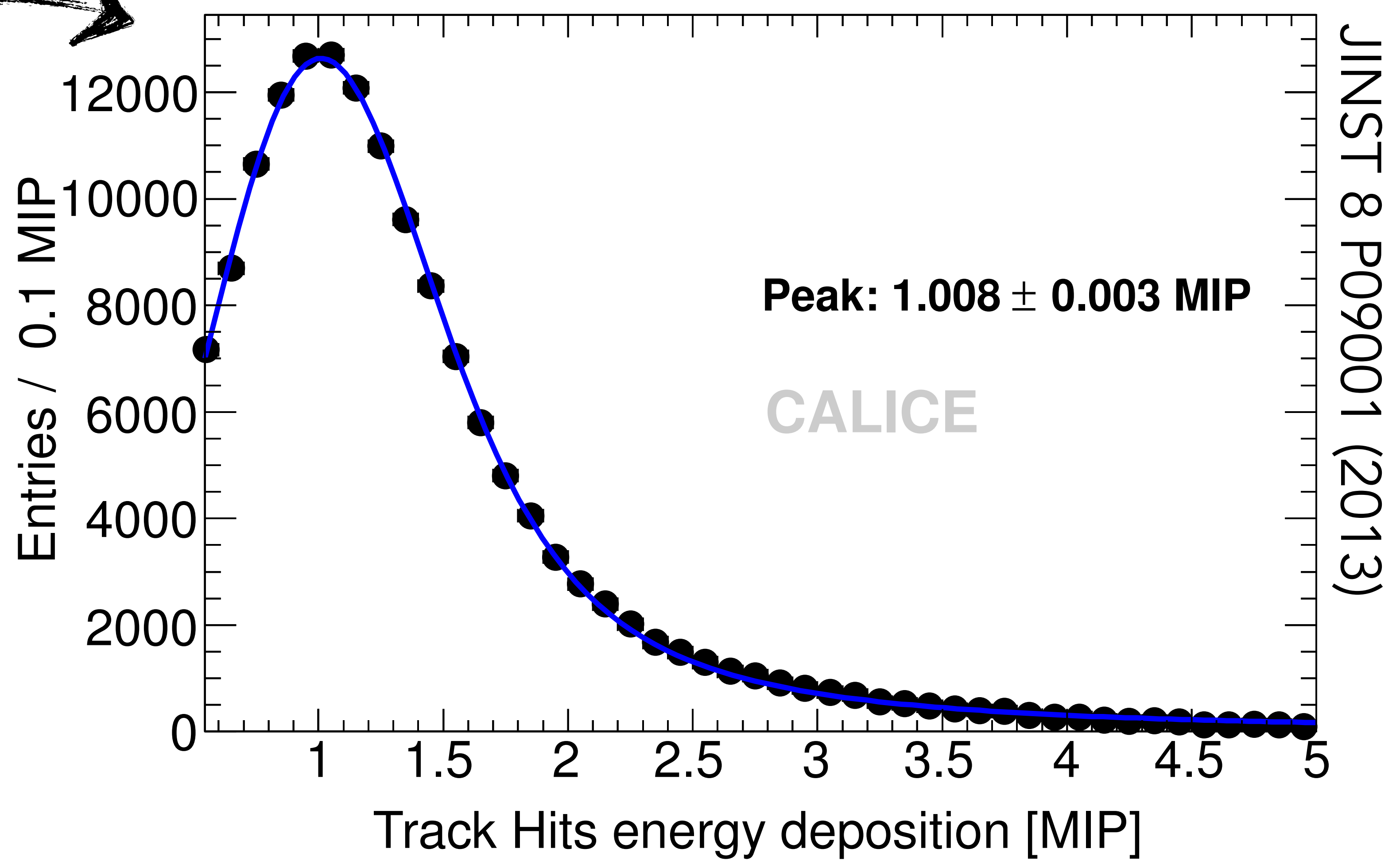
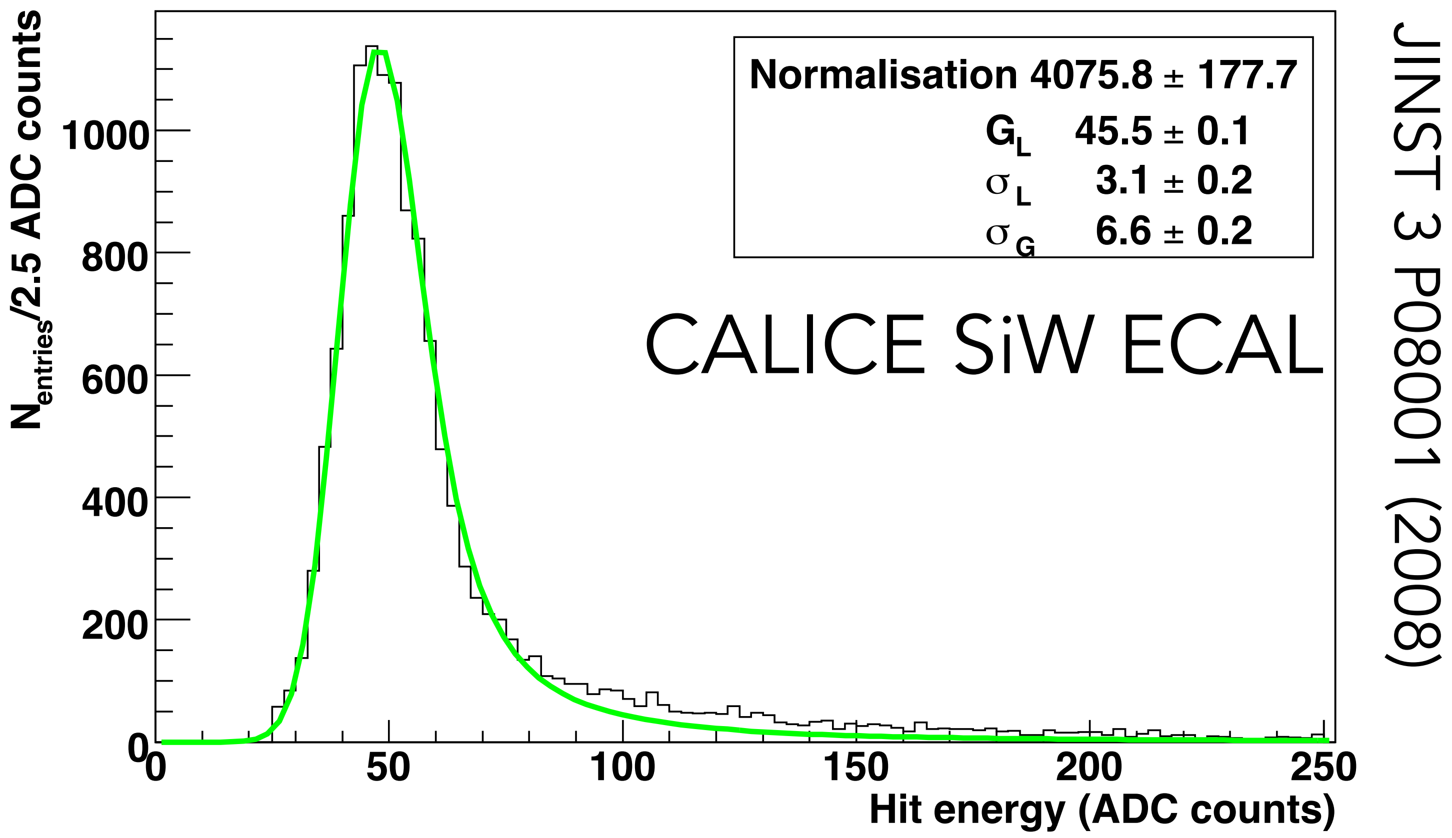
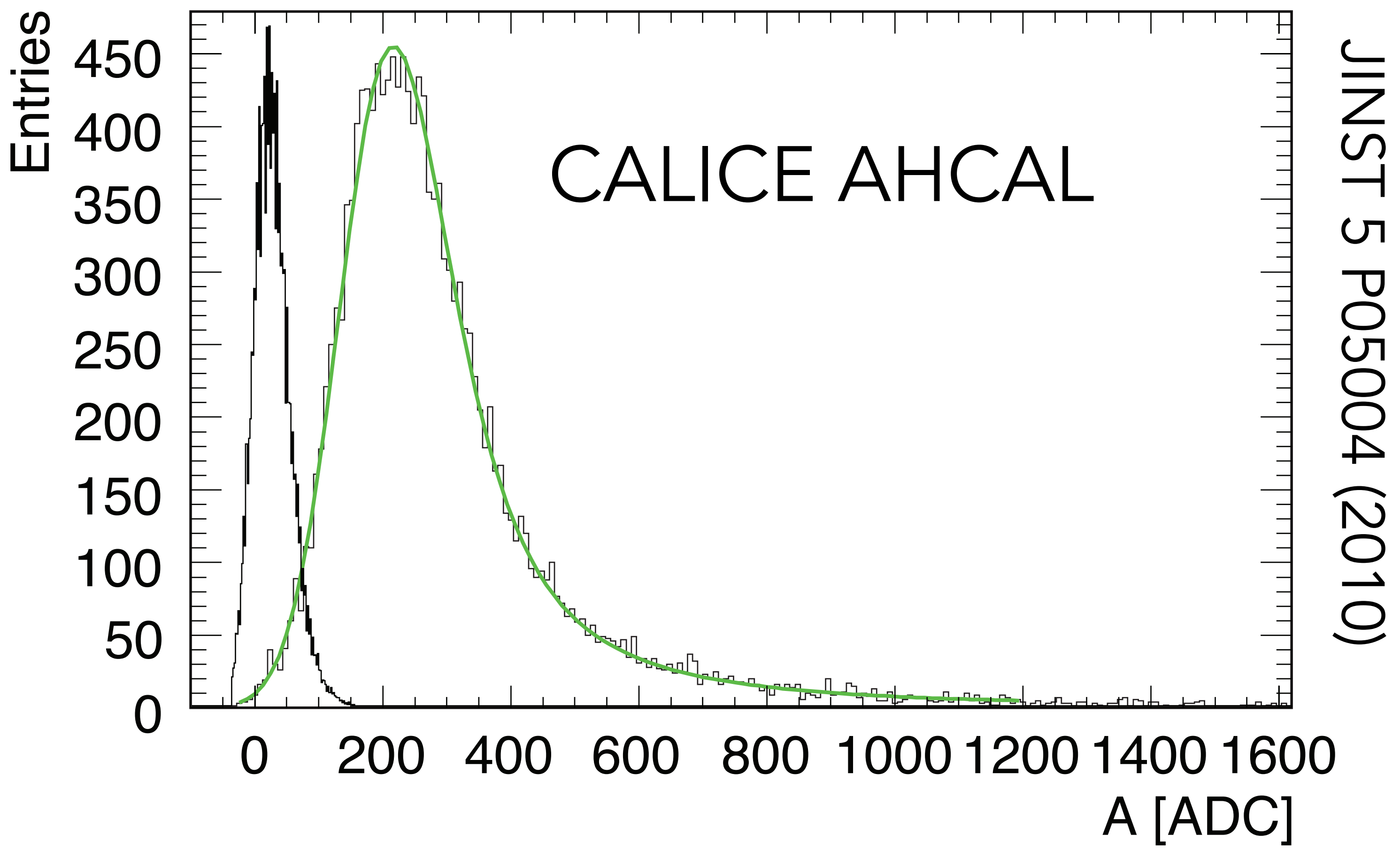






- Can be monitored on the electronics module level in-situ with track segments in hadronic showers



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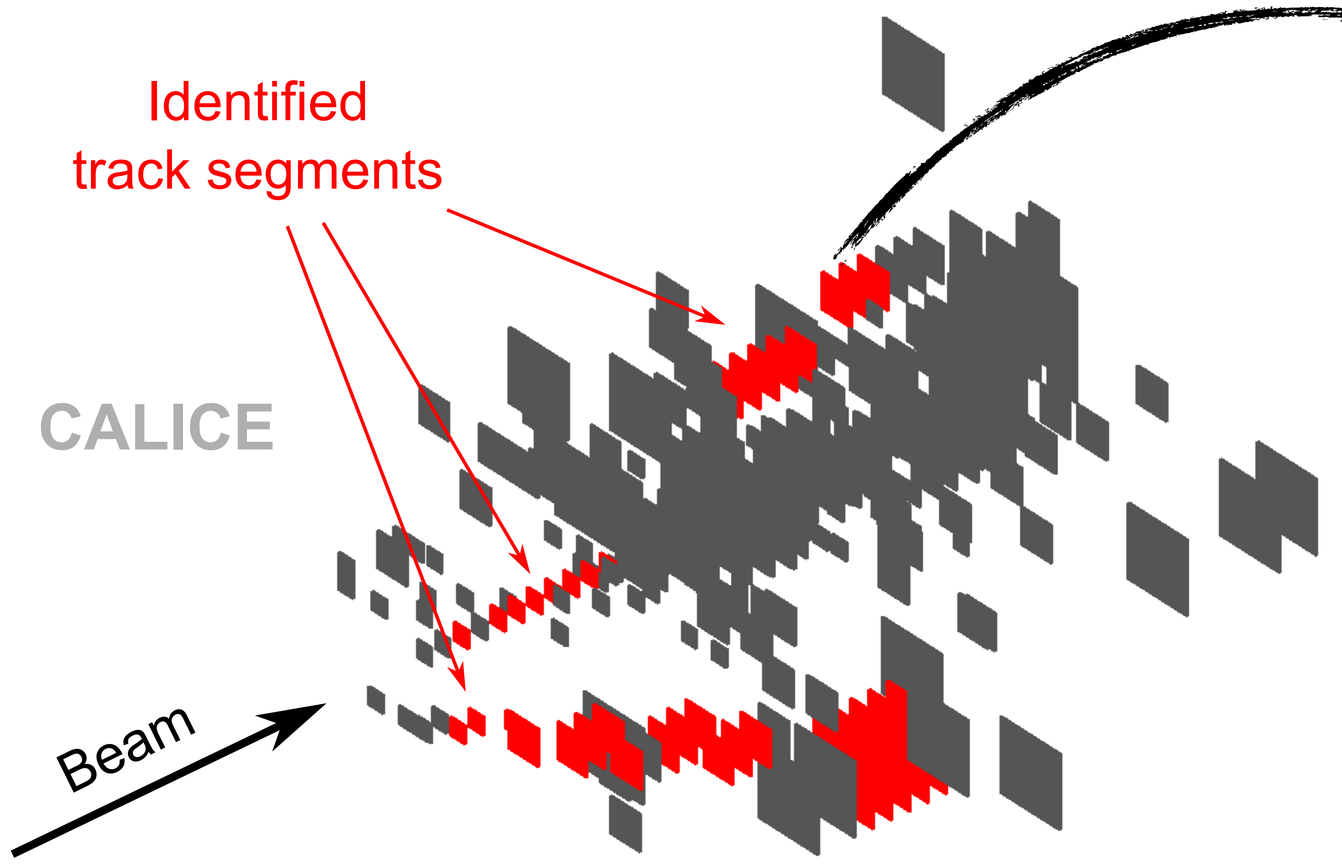

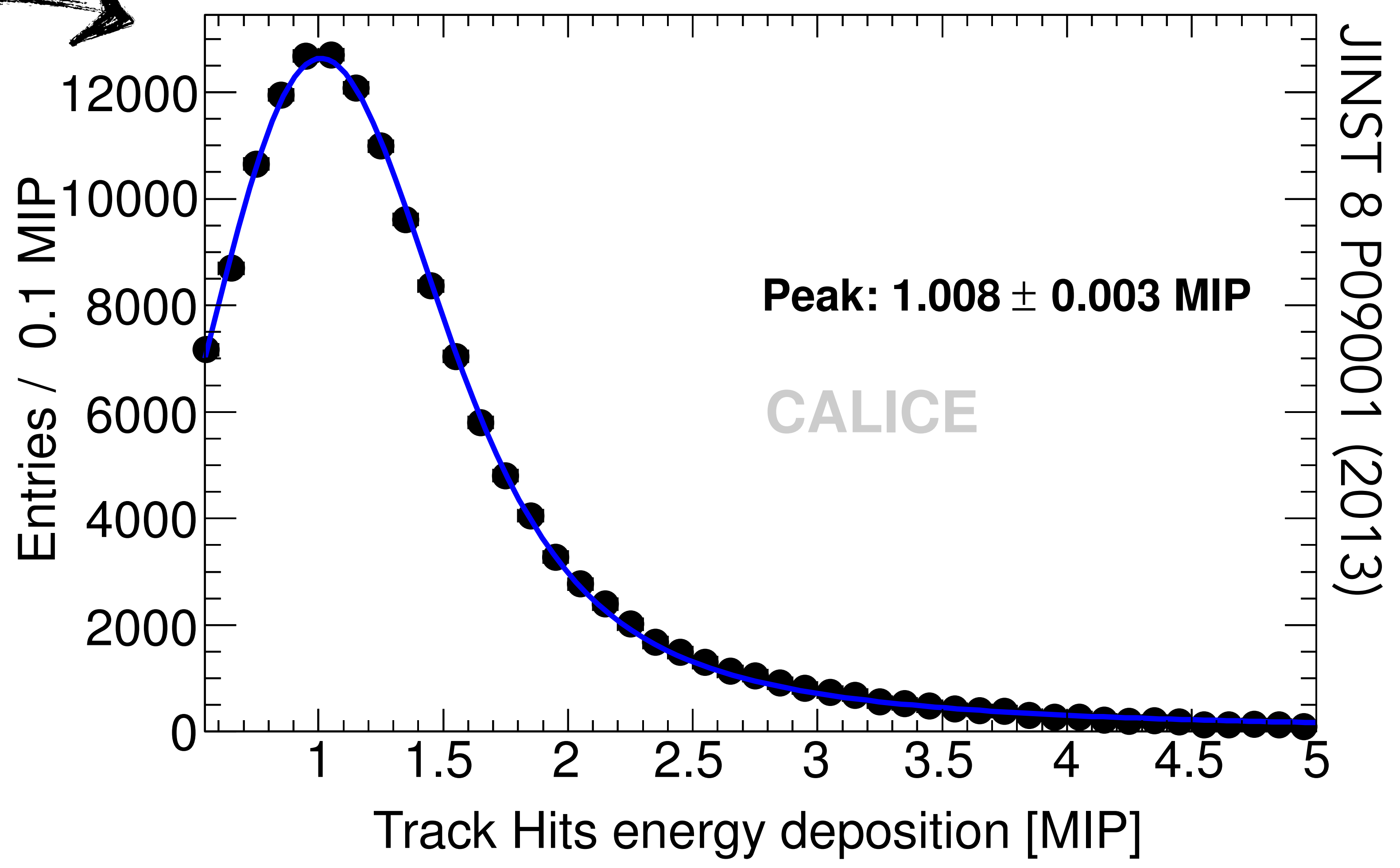

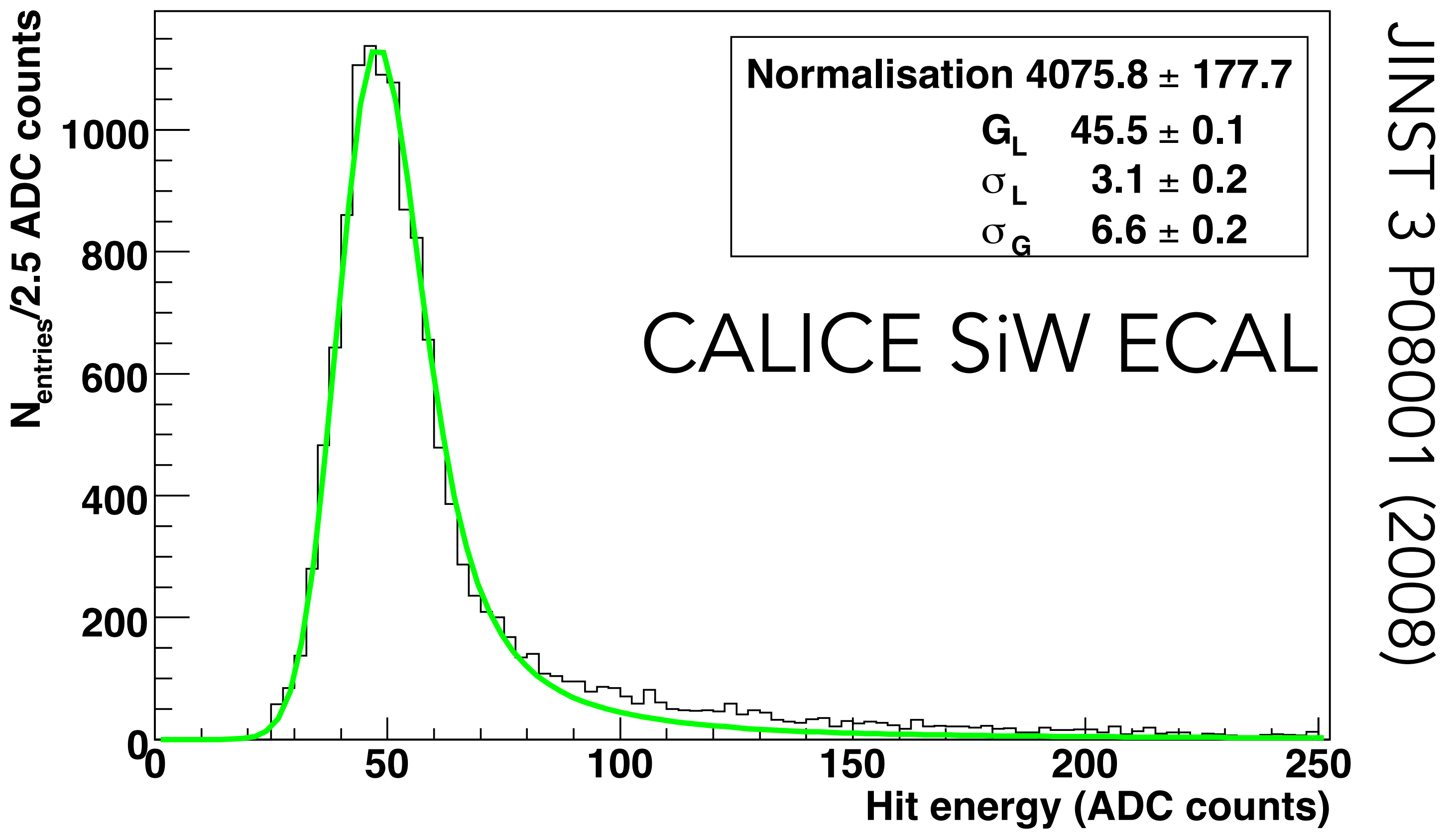

- Can be monitored on the electronics module level in-situ with track segments in hadronic showers

- SiPM based calorimeter require an additional saturation correction based on signal amplitude
- Energy calibration (MIP -> GeV) with showers - geometry dependent, stable

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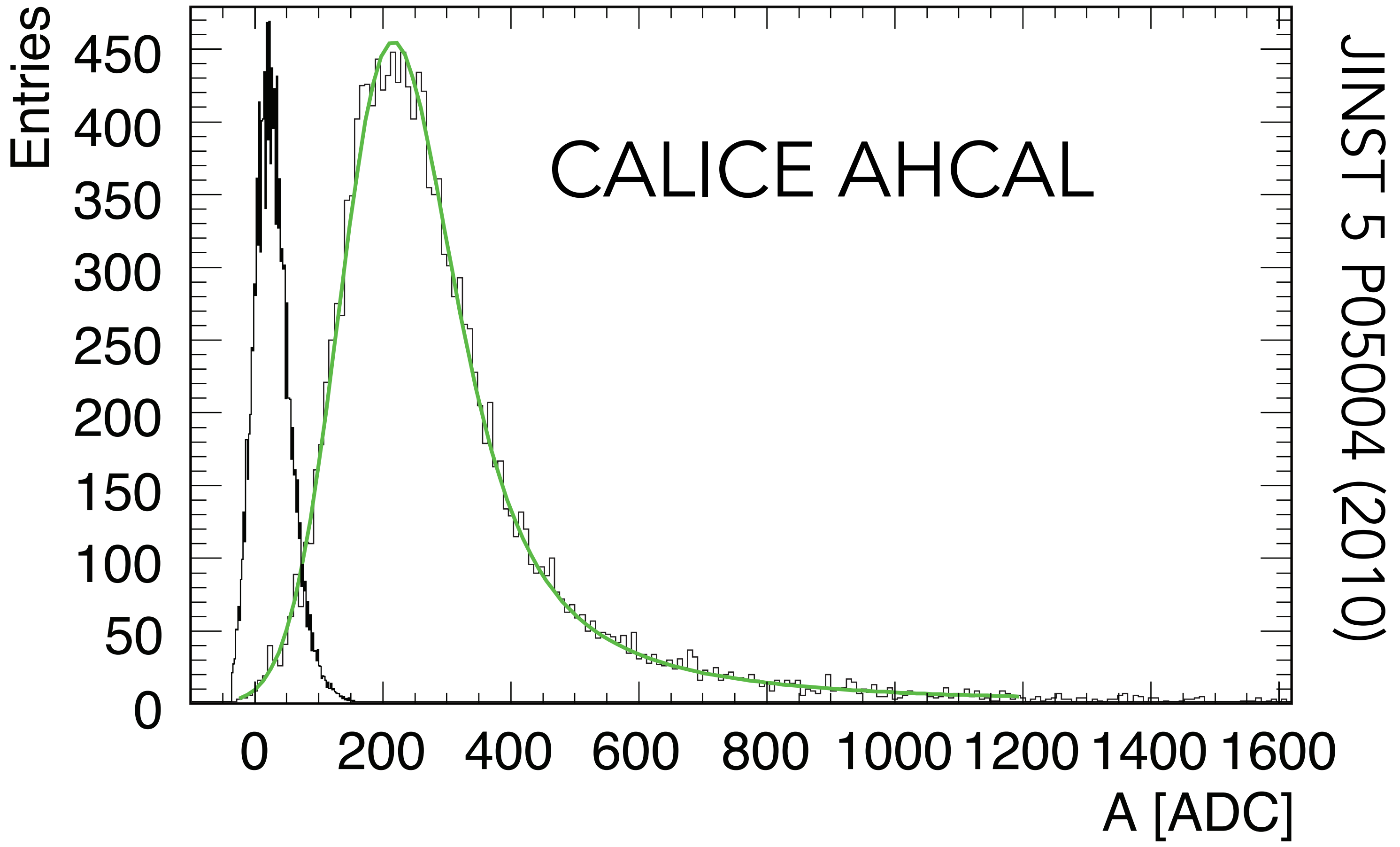
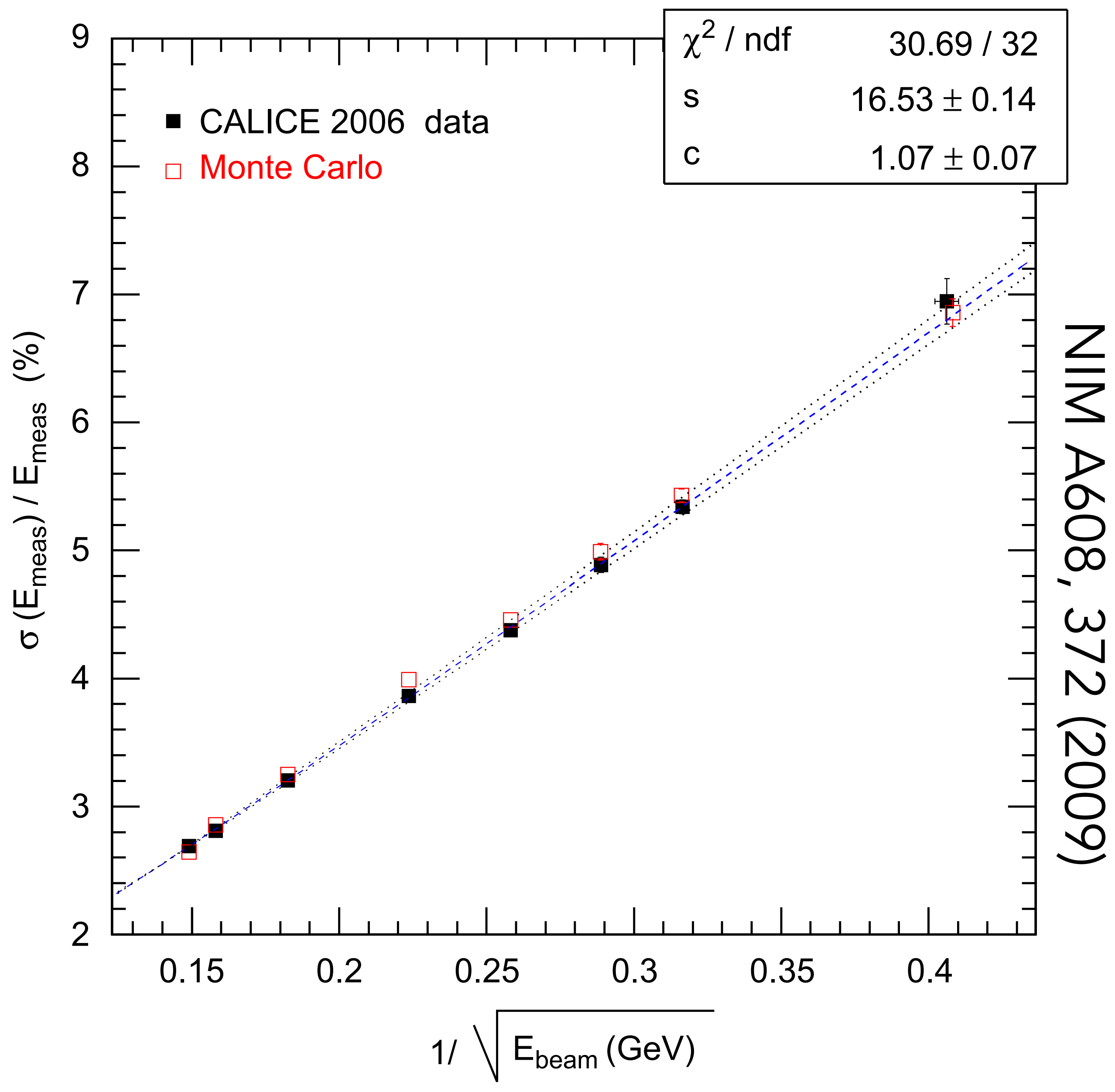


Total energy systematics on the 1% - 3% level, comparable to observed deviations from linearity

Technology Validated in Beams

- Electromagnetic performance of CALICE SiW ECAL



NIM A608, 372 (2009)

Technology Validated in Beams

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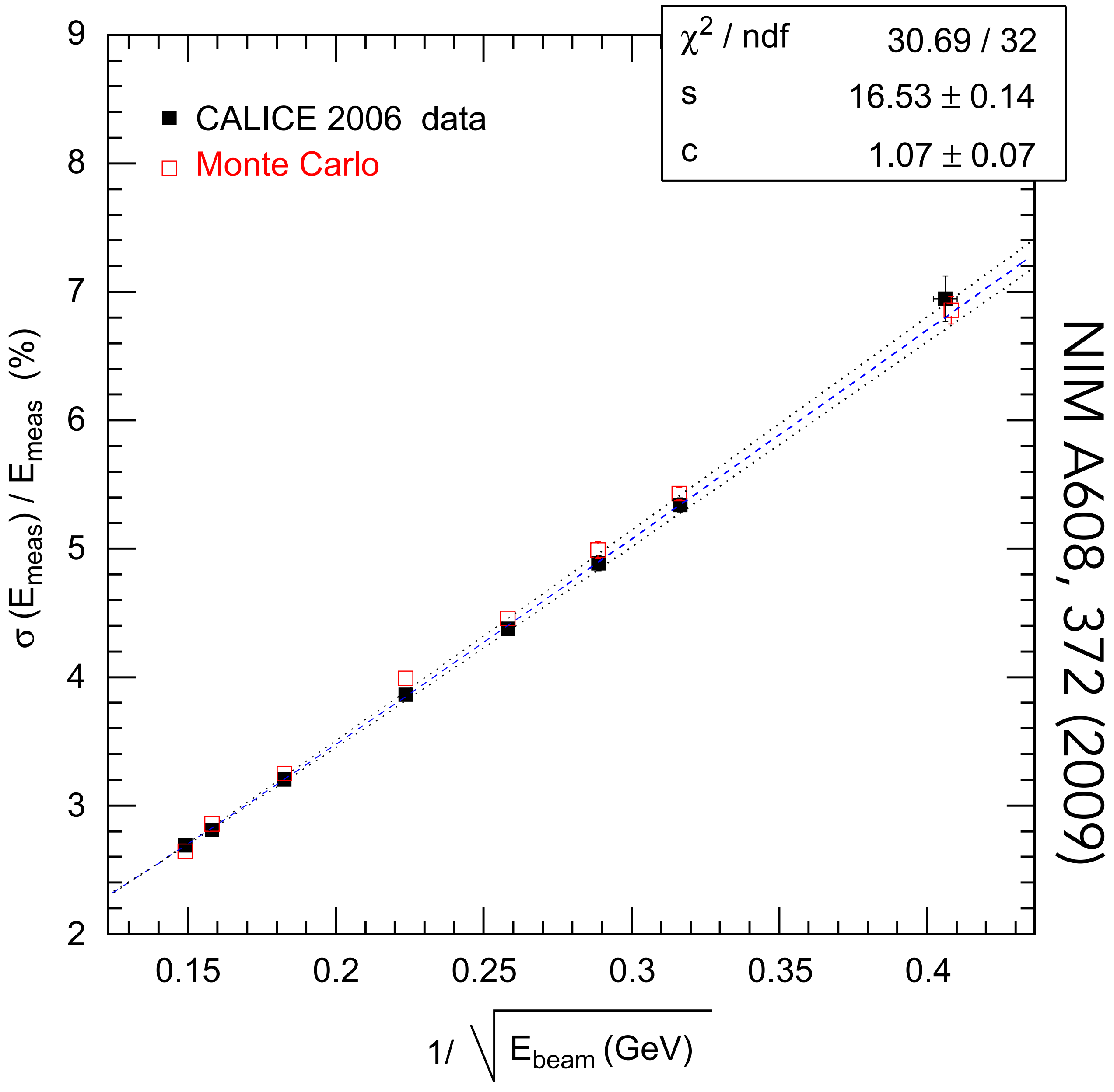
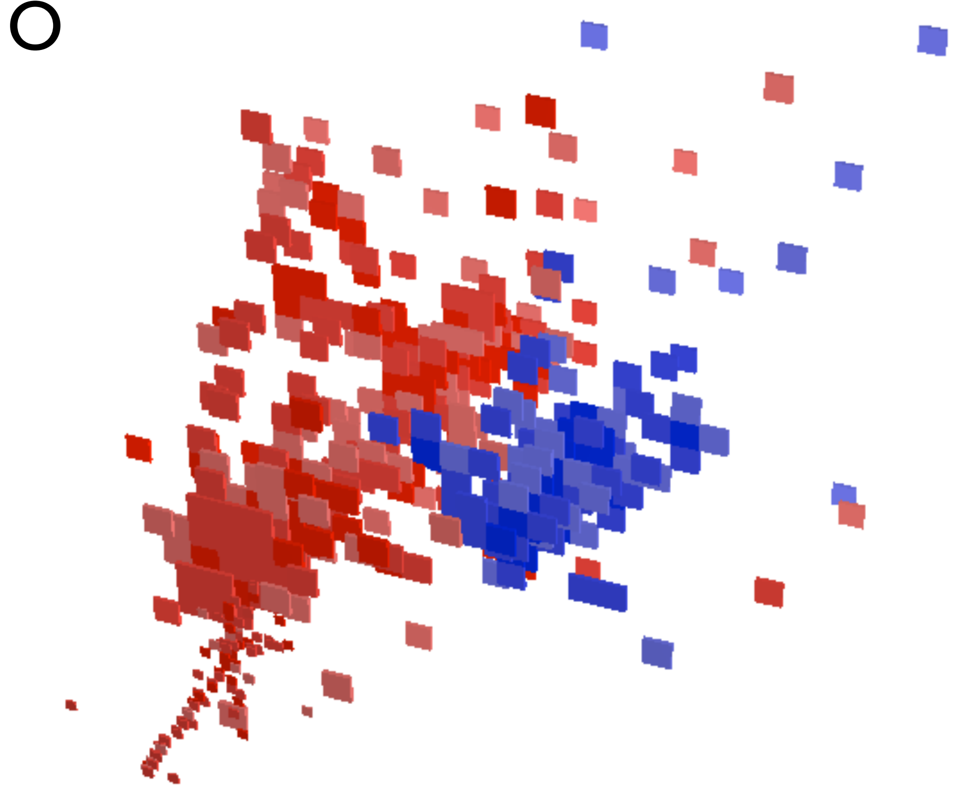
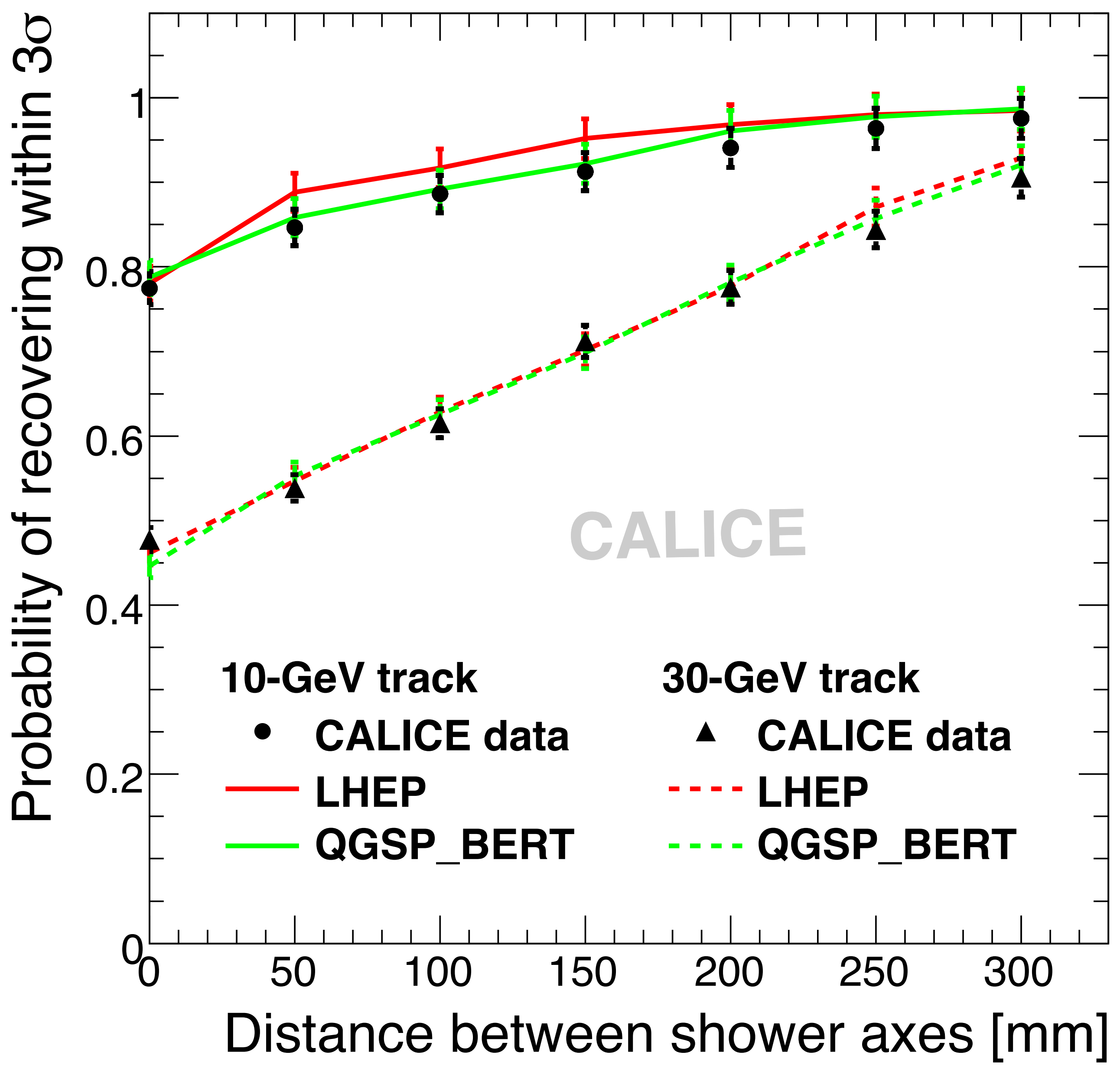


NIM A608, 372 (2009)

- Two-particle separation in the calorimeters using Pandora Algorithms





JINST 6 P07005 (2011)

Technology Validated in Beams

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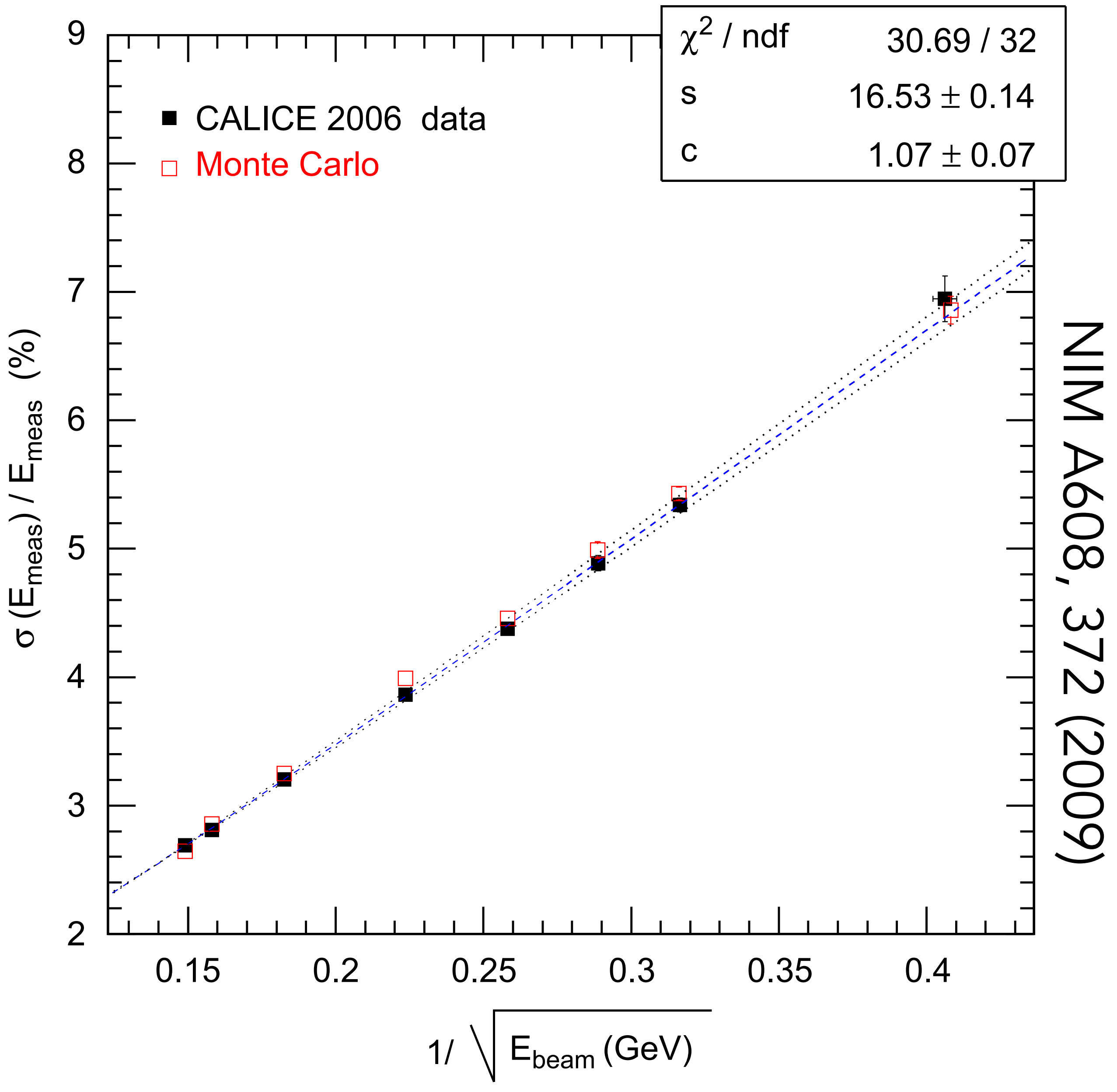
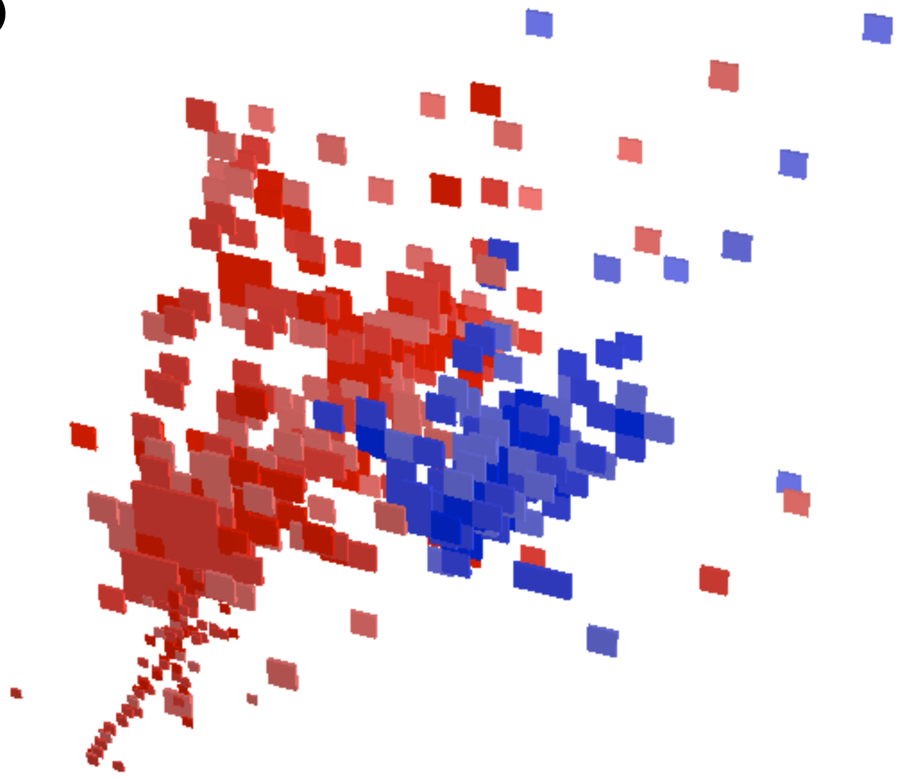
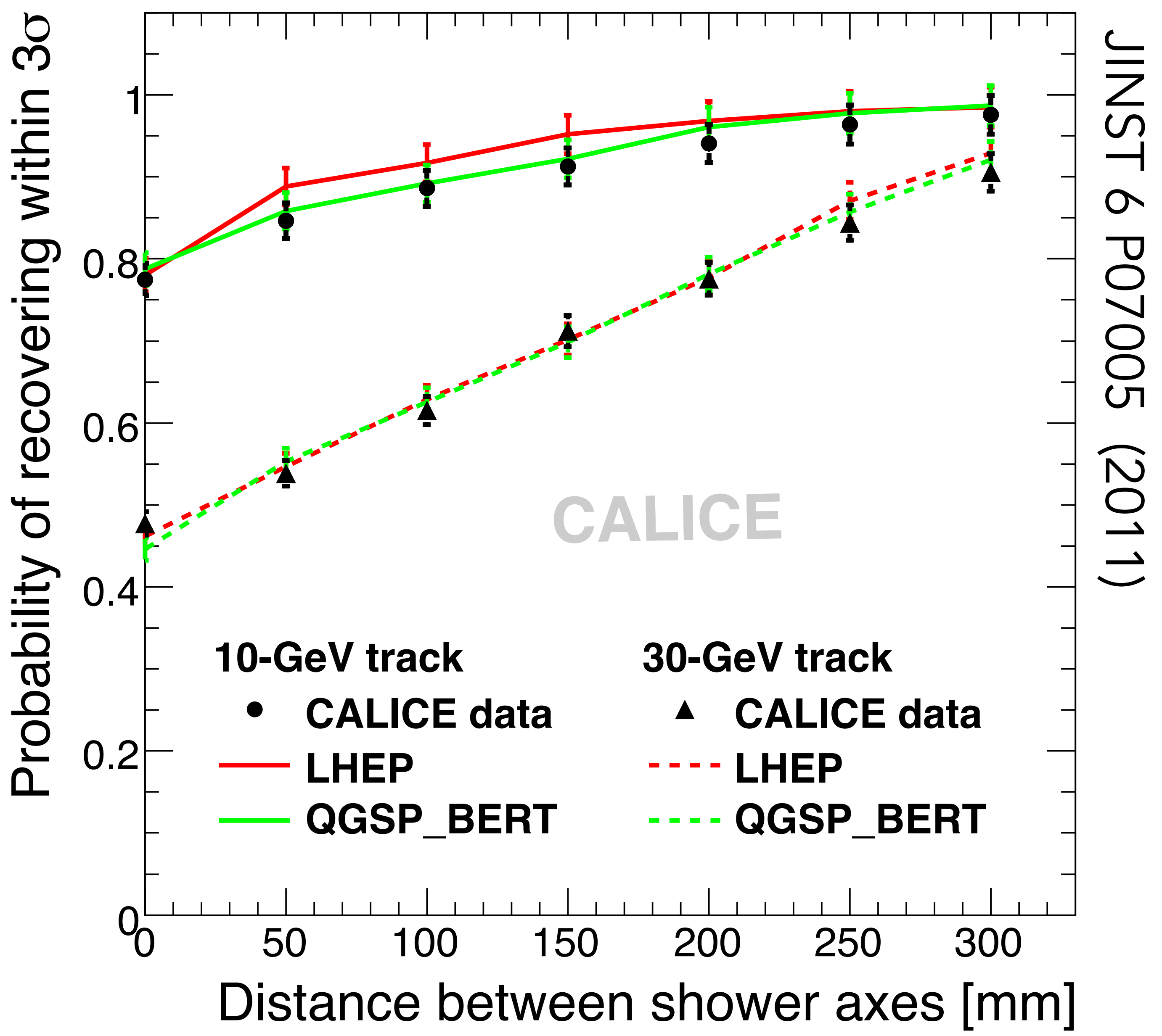
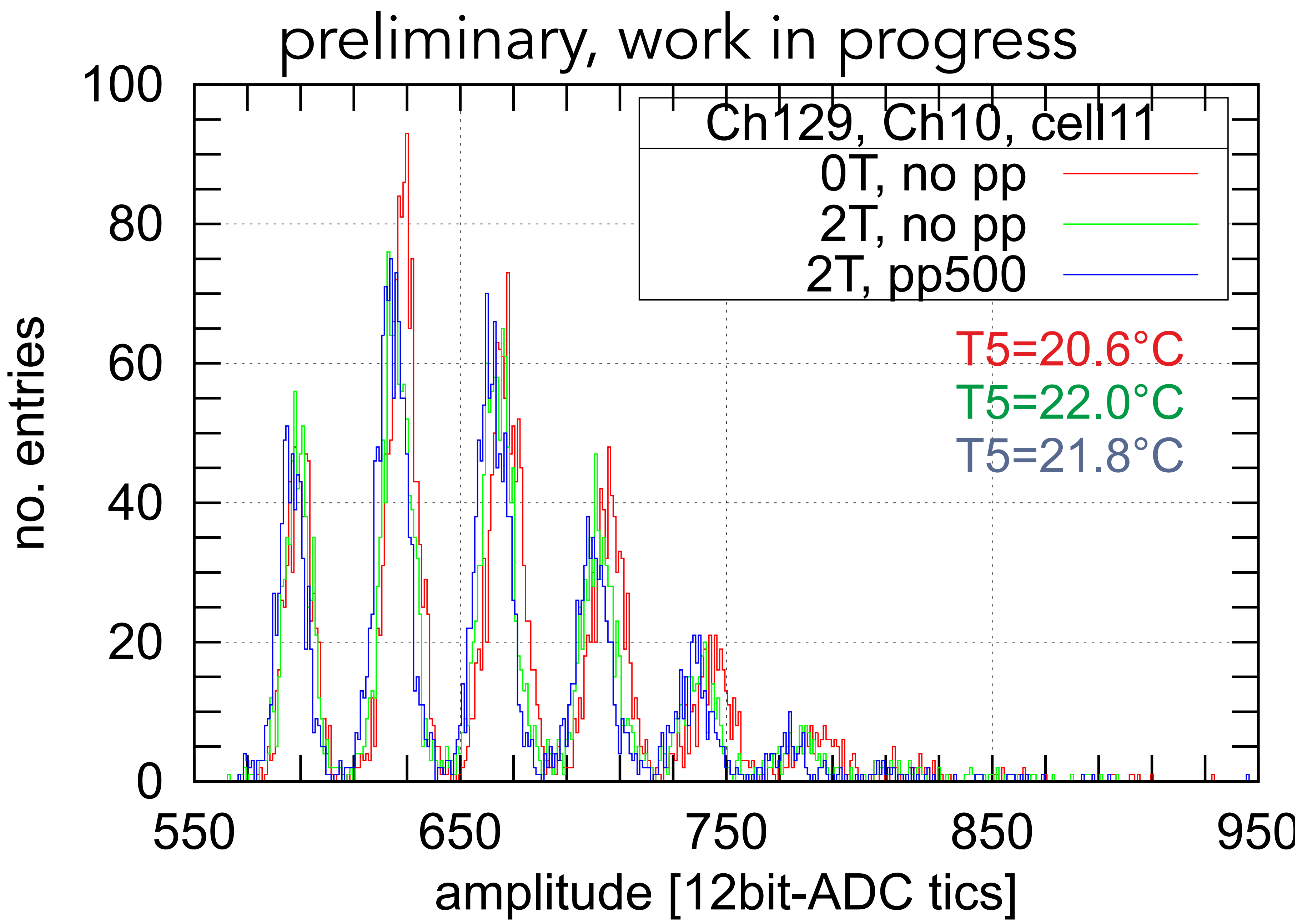




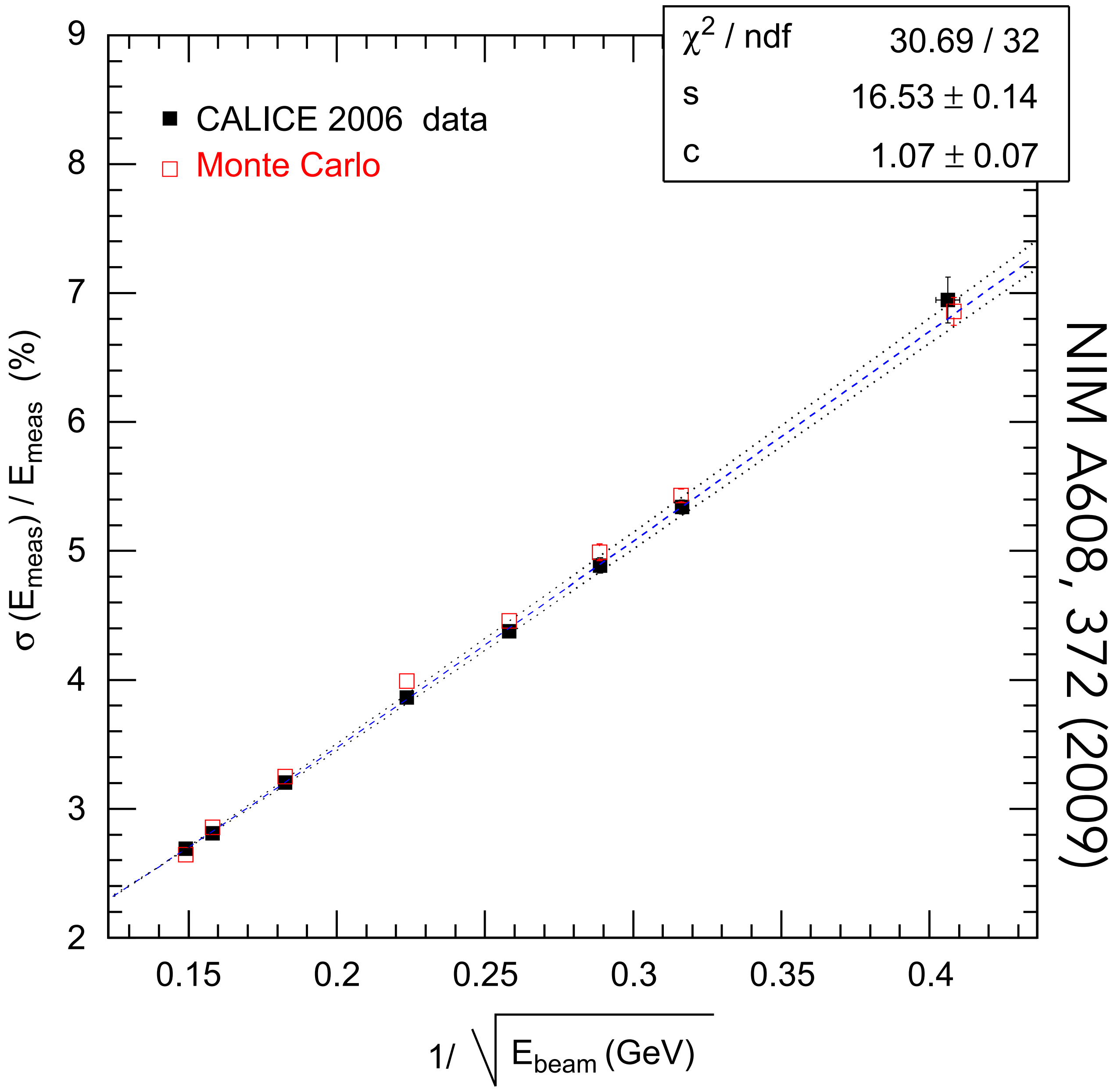


- Two-particle separation in the calorimeters using Pandora Algorithms
- Front-end electronics tested in 2T magnetic field with power pulsing

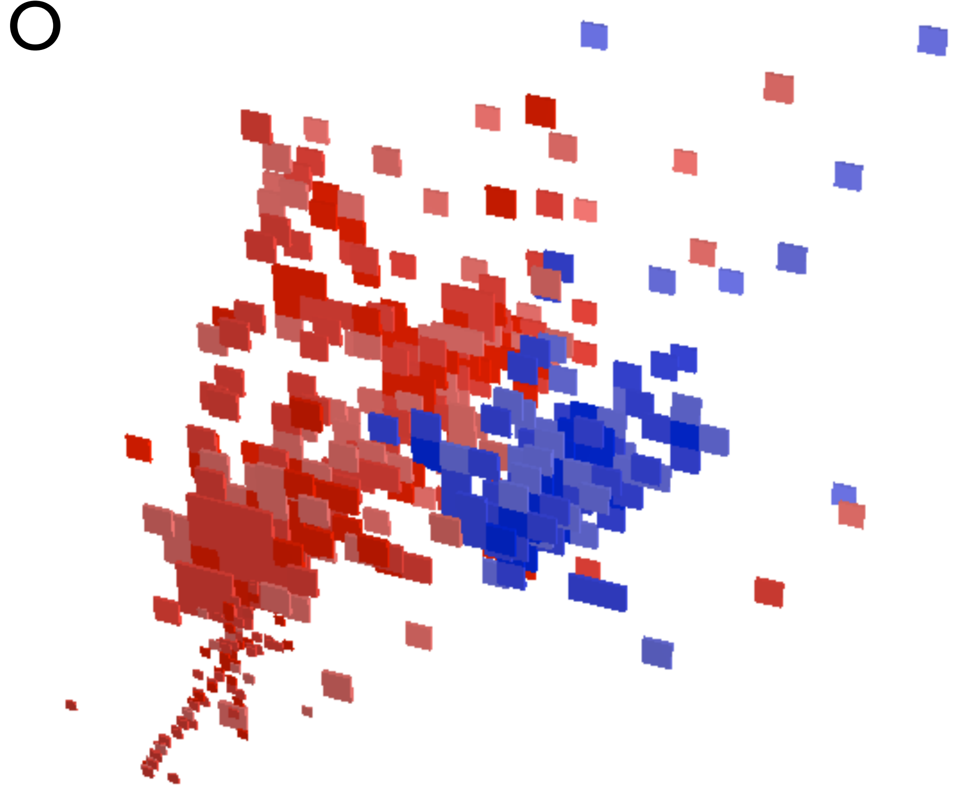


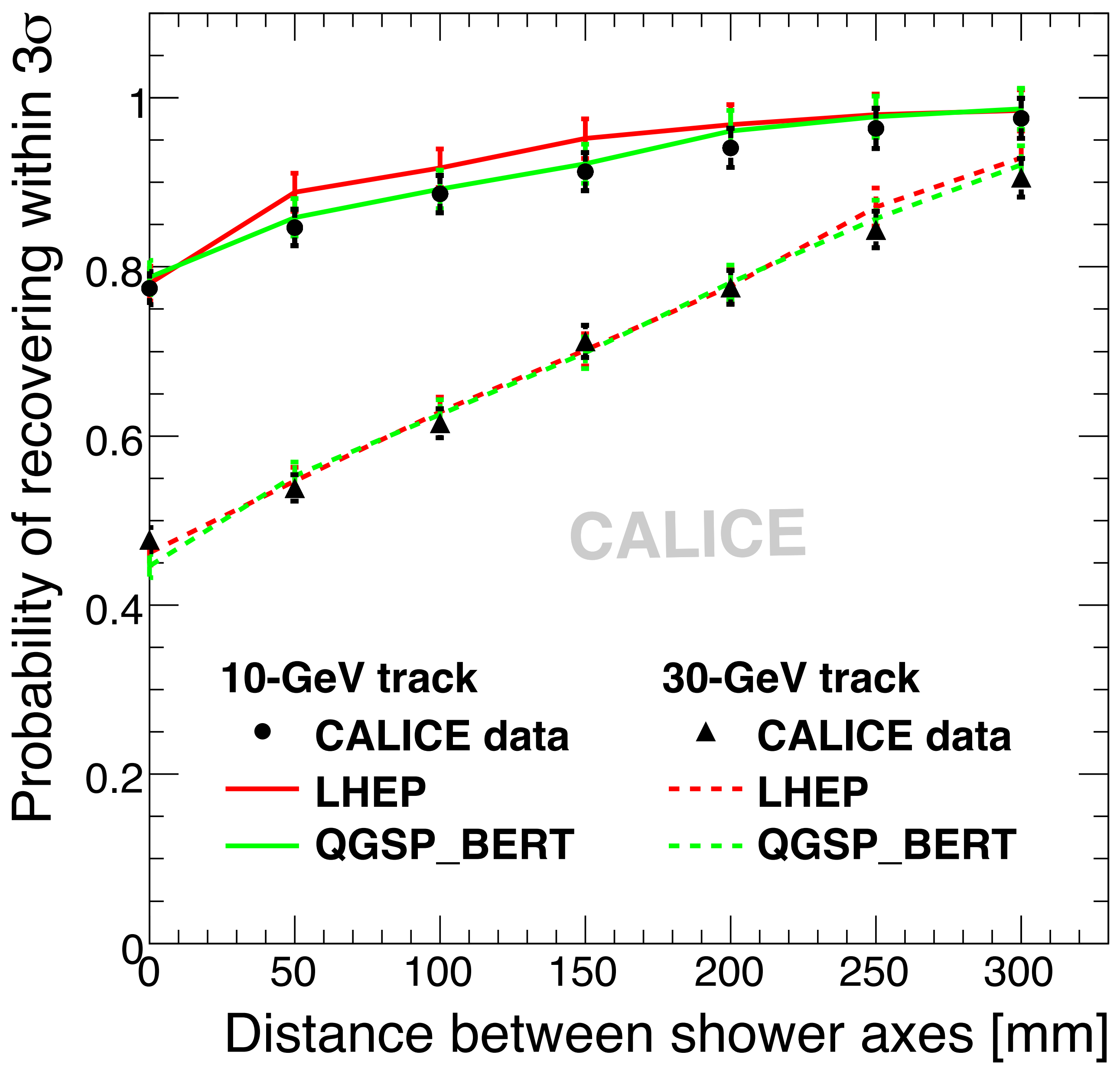
Technology Validated in Beams

- Electromagnetic performance of CALICE SiW ECAL



NIM A608, 372 (2009)



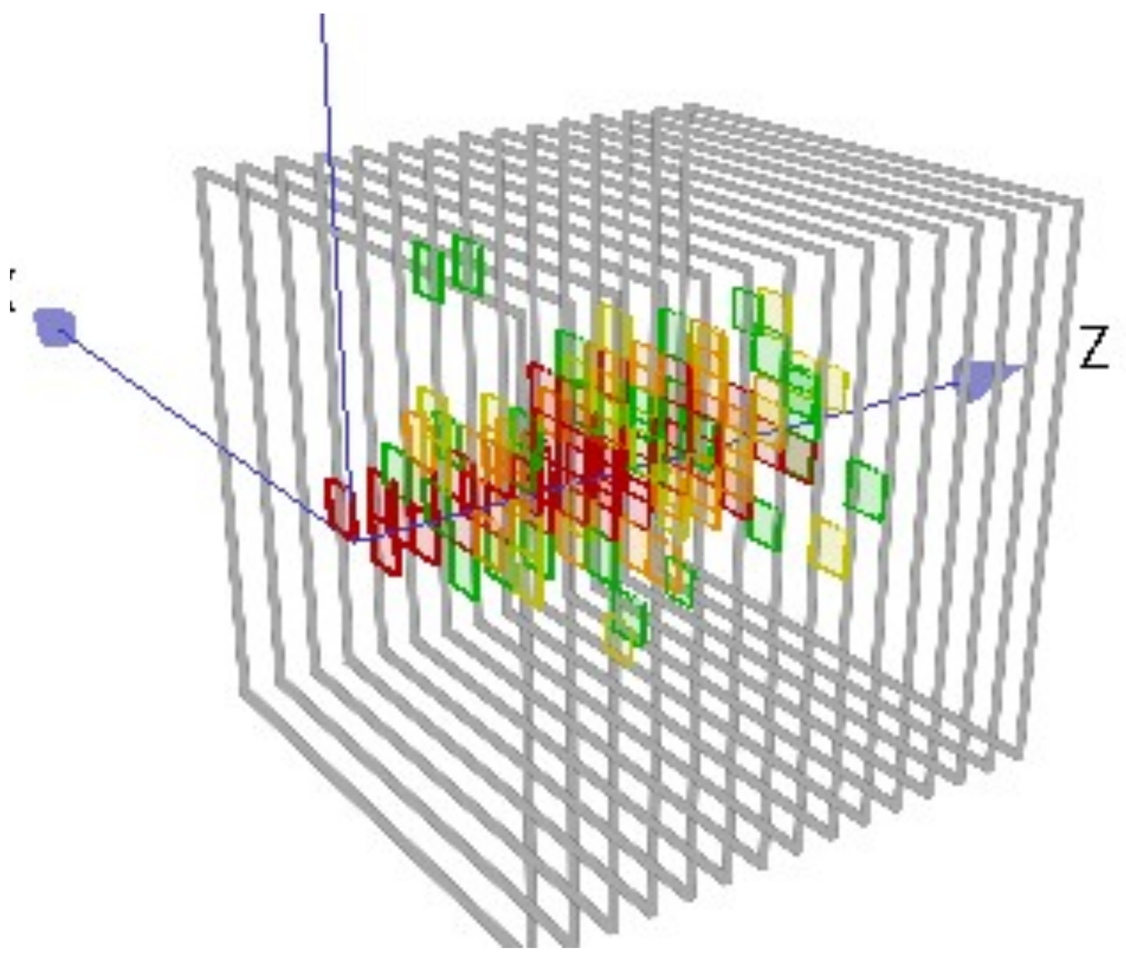


JINST 6 P07005 (2011)

- Two-particle separation in the calorimeters using Pandora Algorithms

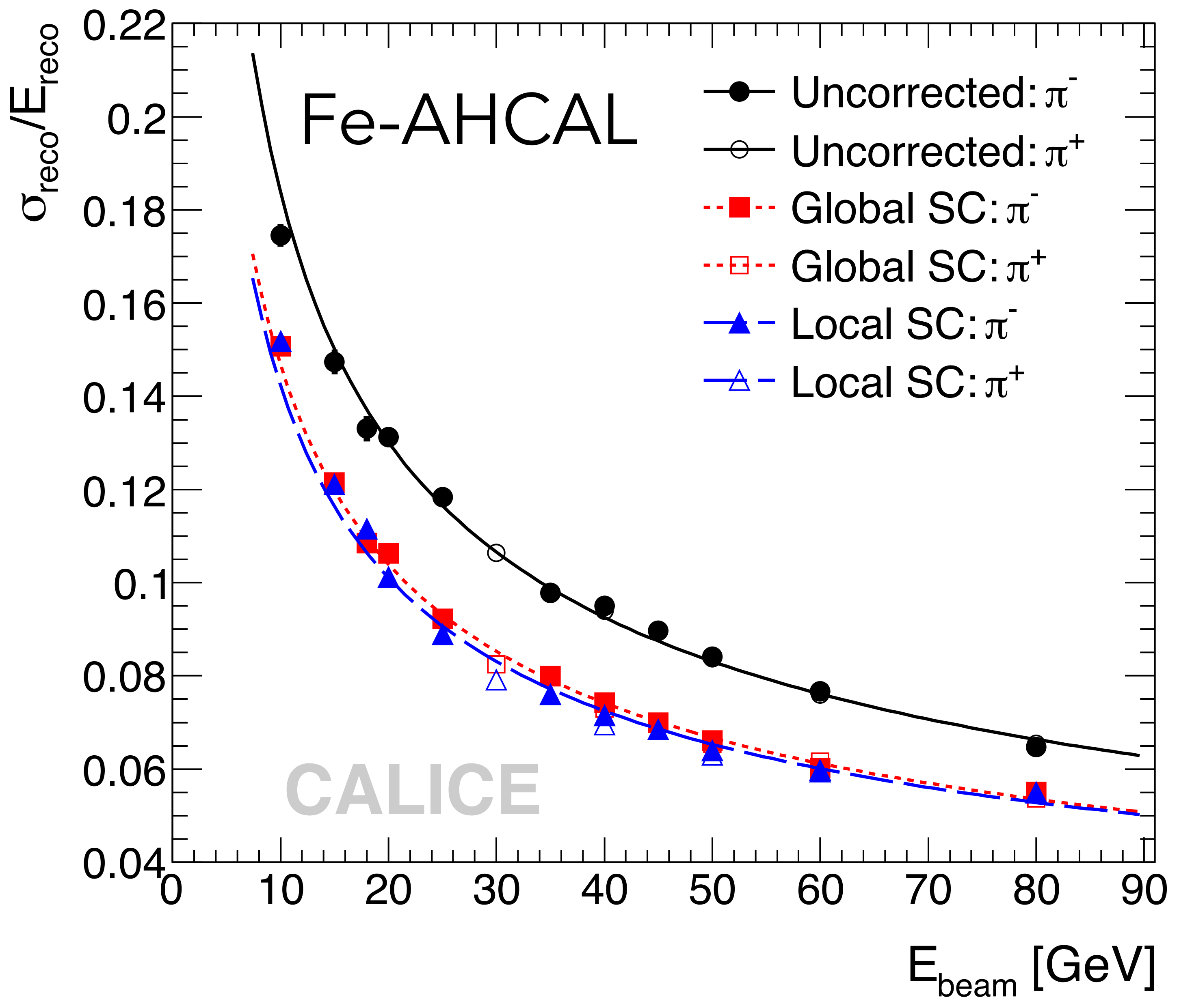
- Small "electromagnetic prototype" based on latest technological prototype elements tested in 1.5 T field with electron beam

60 GeV e^-, 1.5 T



Energy Resolution & Software Compensation

- Use local energy density information to adjust weight of each hit in energy sum
  - Corrects for non-compensating nature of calorimeters: Lower weight for electromagnetic subshowers
  - Also corrects for very high local energy deposits due to hadronic activity



JINST 7 P09017 (2012)

~ 25% improvement in hadronic energy resolution

stochastic term: 57.6%

constant term: 1.6%

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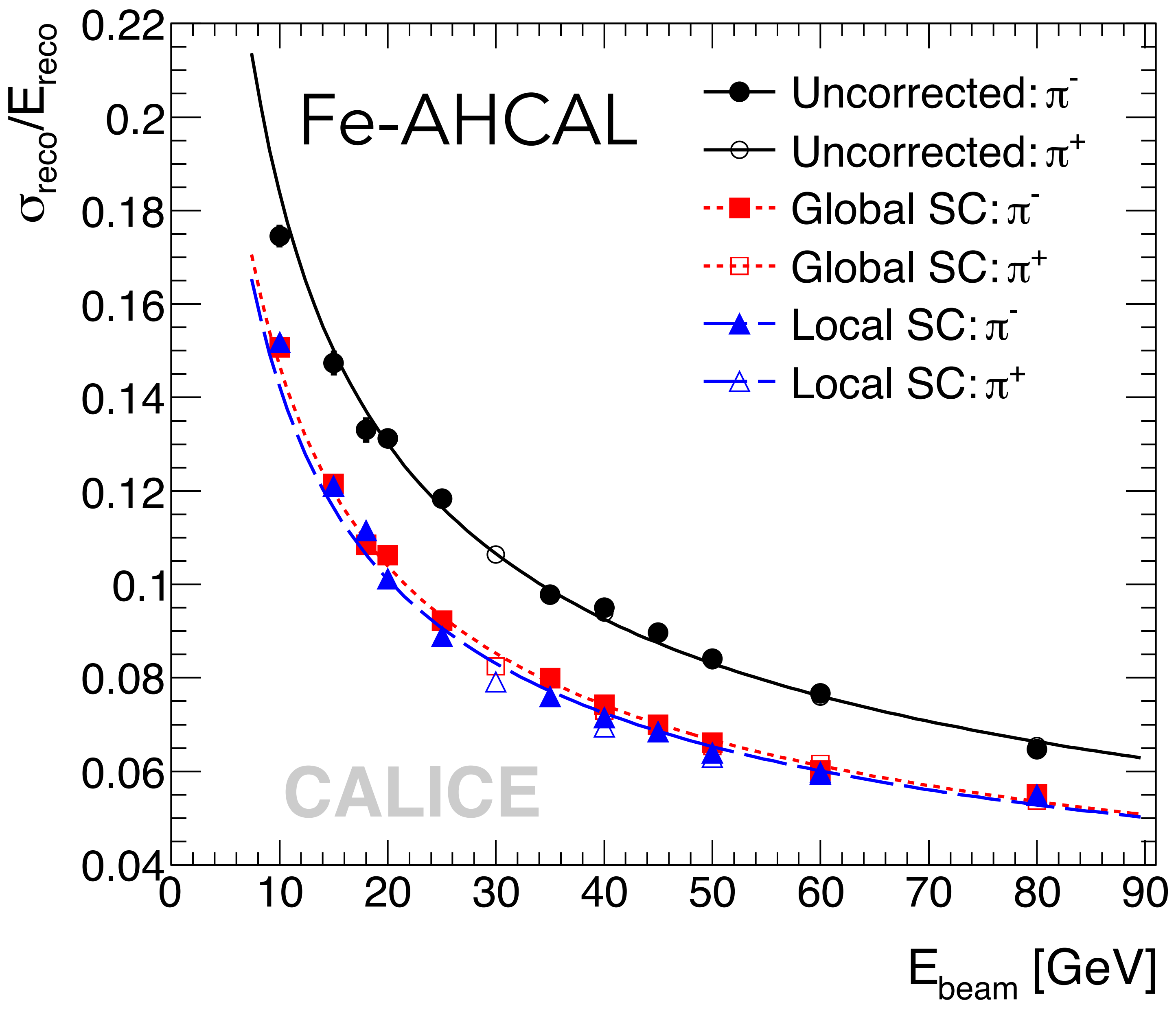

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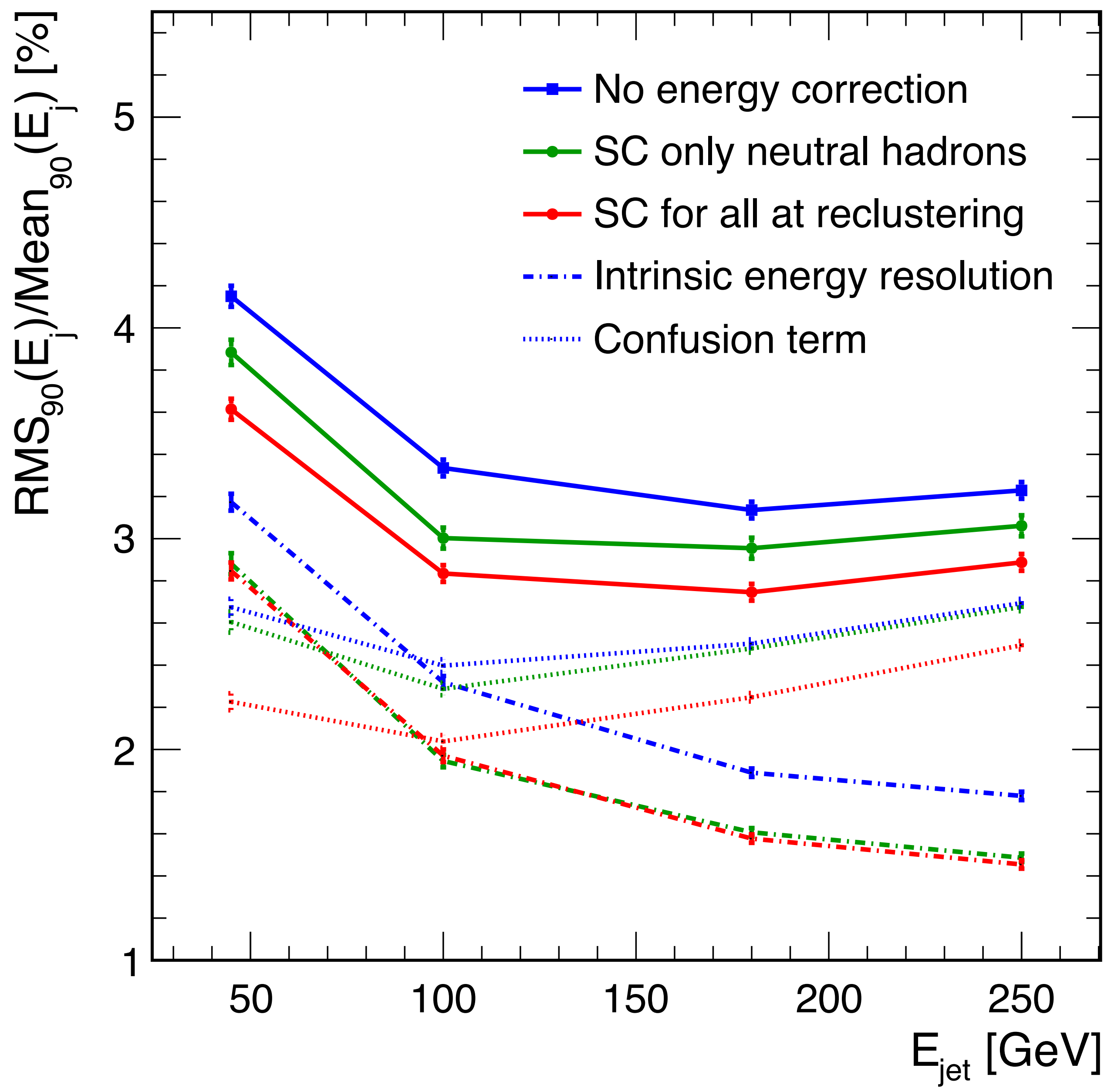
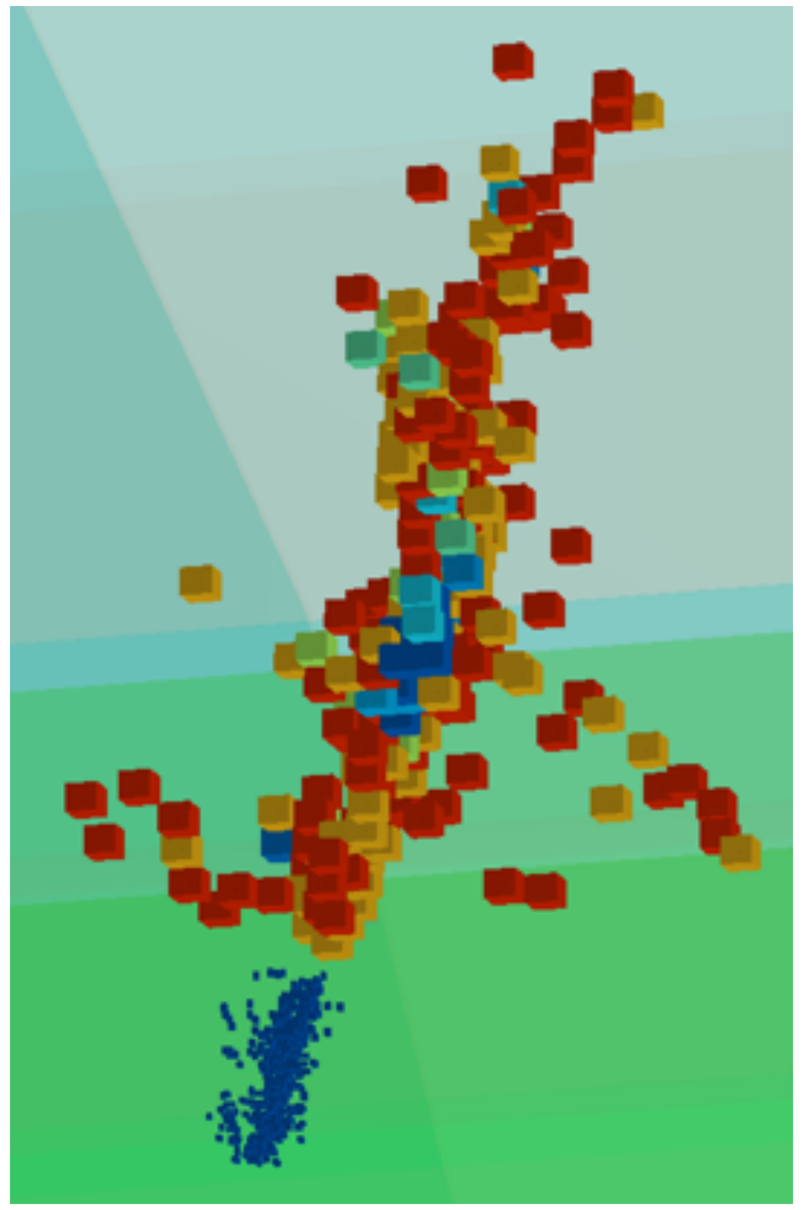


EPJ C77, 698 (2017)



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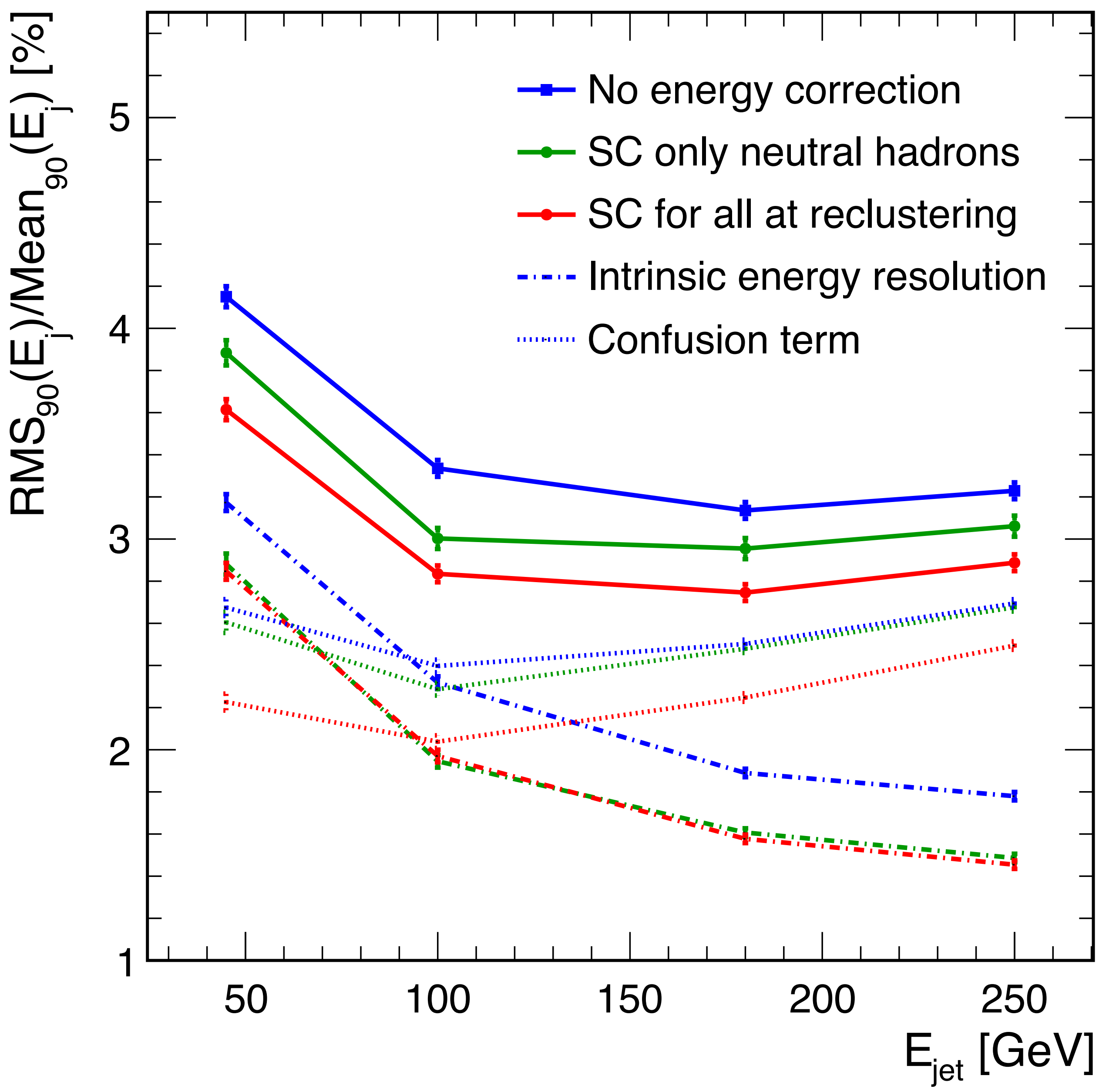

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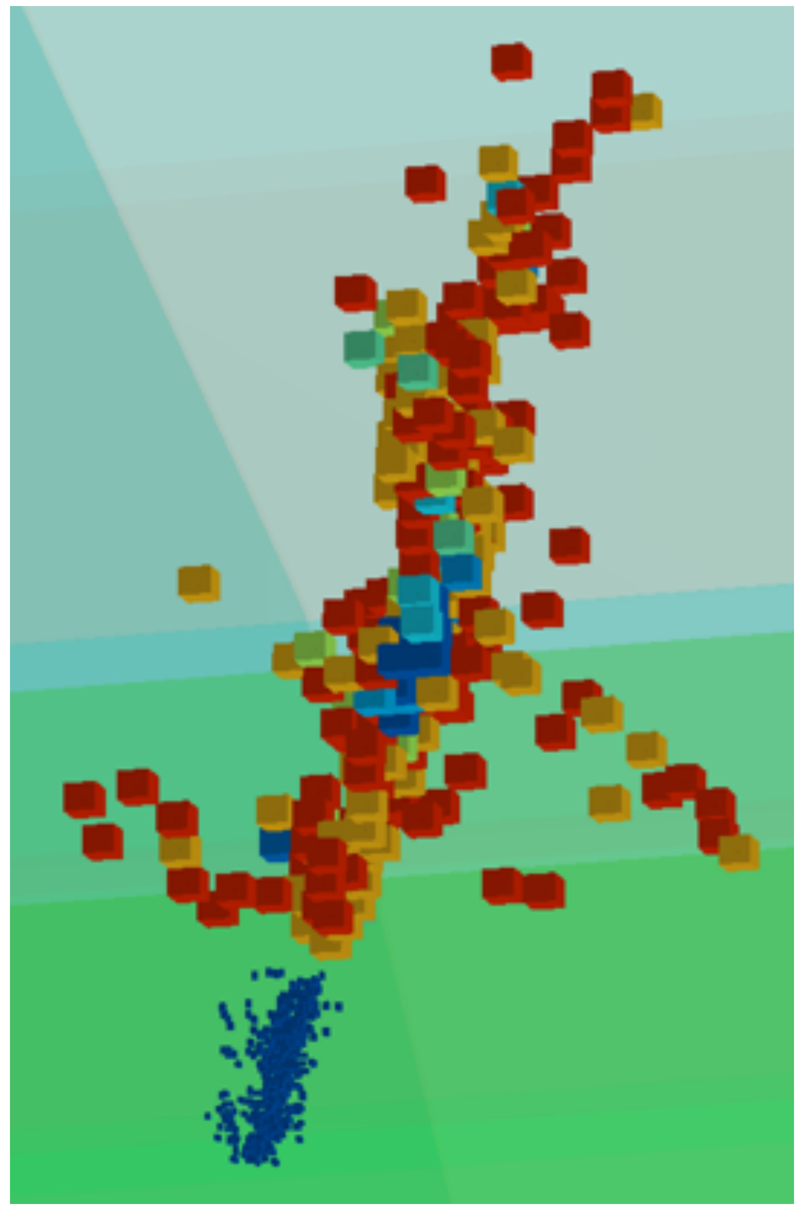
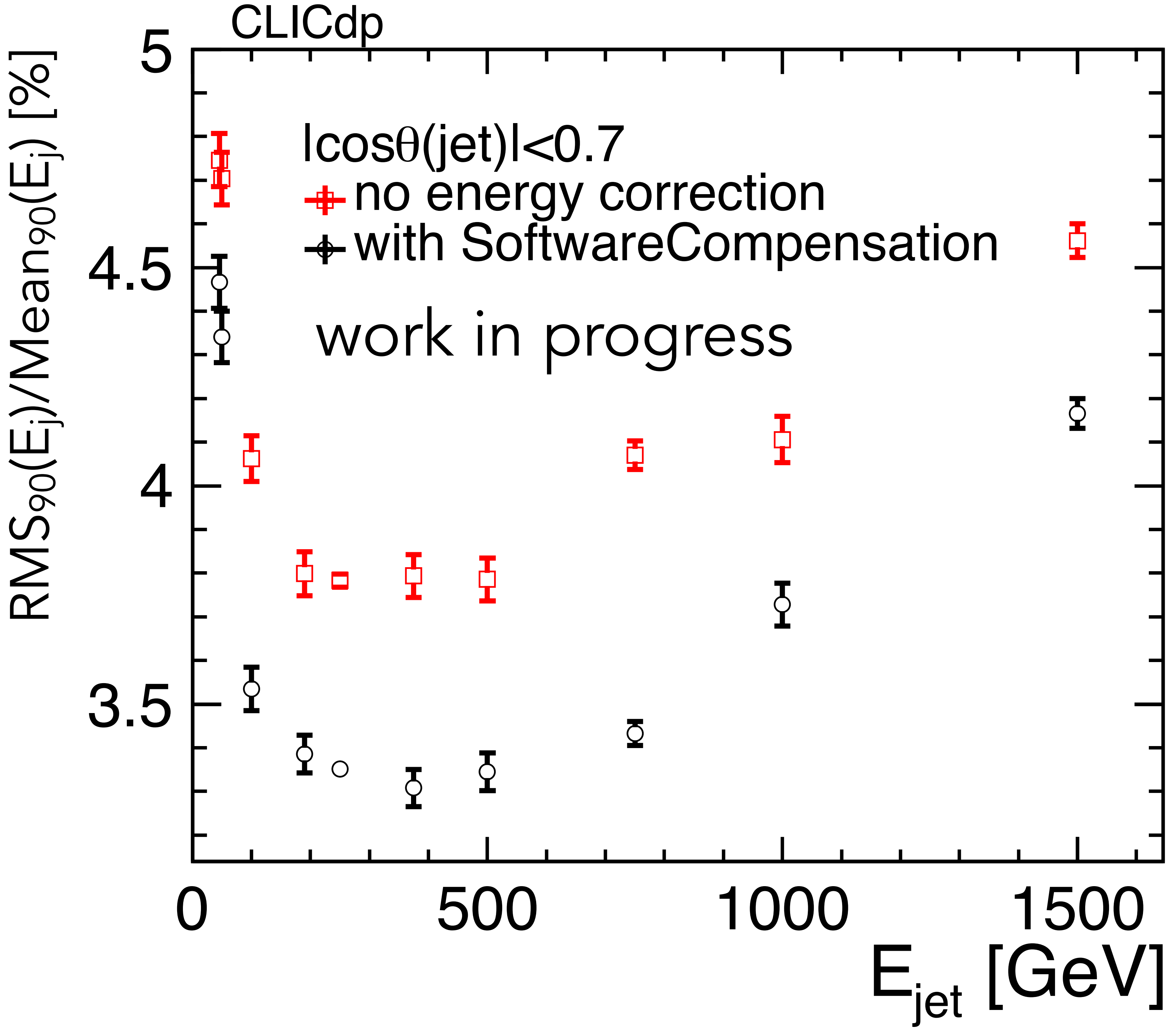
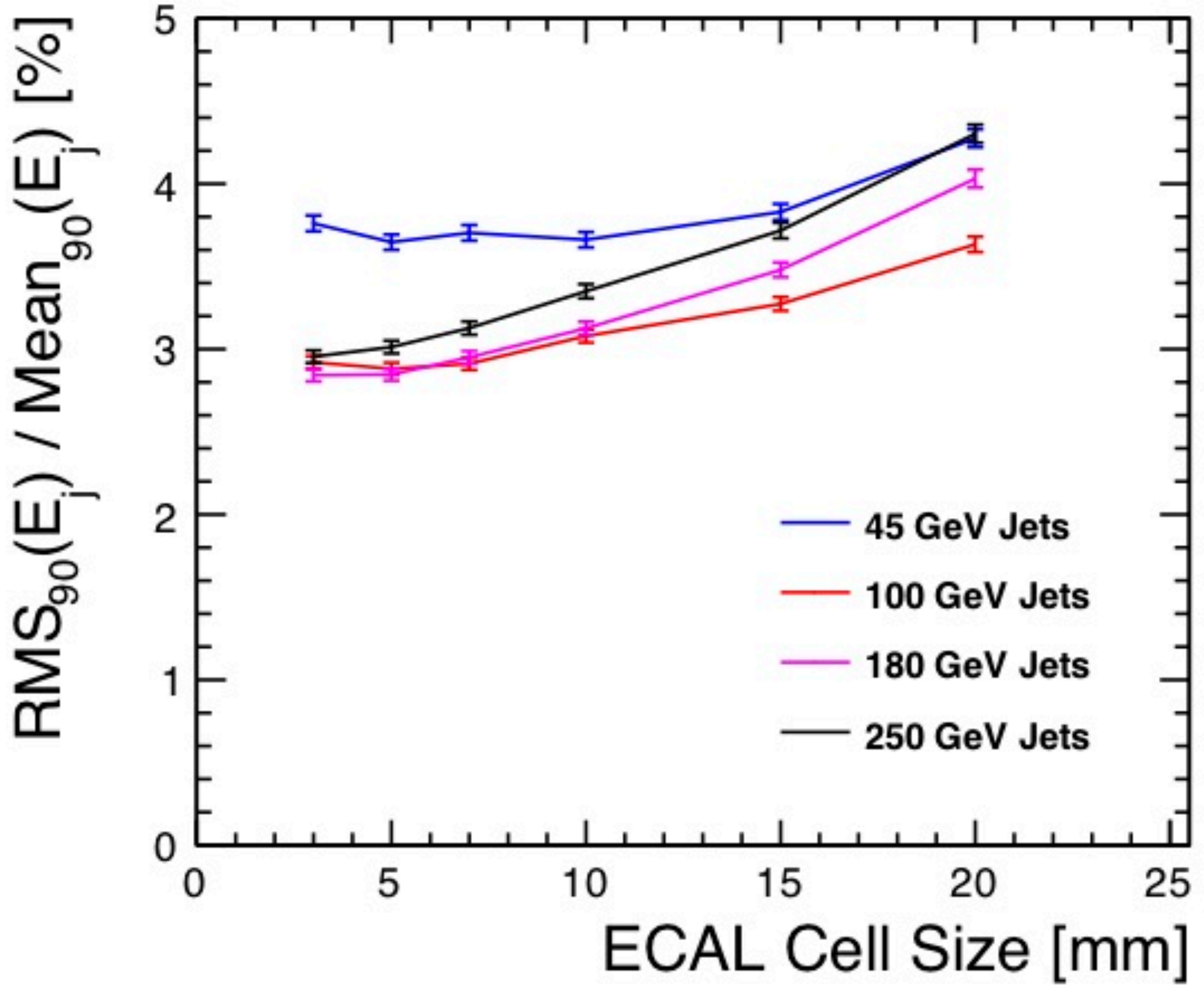




- Successfully transferred from ILD to CLIC
  - wider energy range: 1.5 TeV maximum energy, instead of 250
  - training with neutrons and K_L^0, wide energy range

Optimisation of Calorimeter Layout: ECAL

- The main driver: Jet energy resolution in CLIC environment
  - Jet energy resolution studied for different ECAL geometries and granularities



CLICdp-Note-2017-001

CLICdp-Note-2017-001

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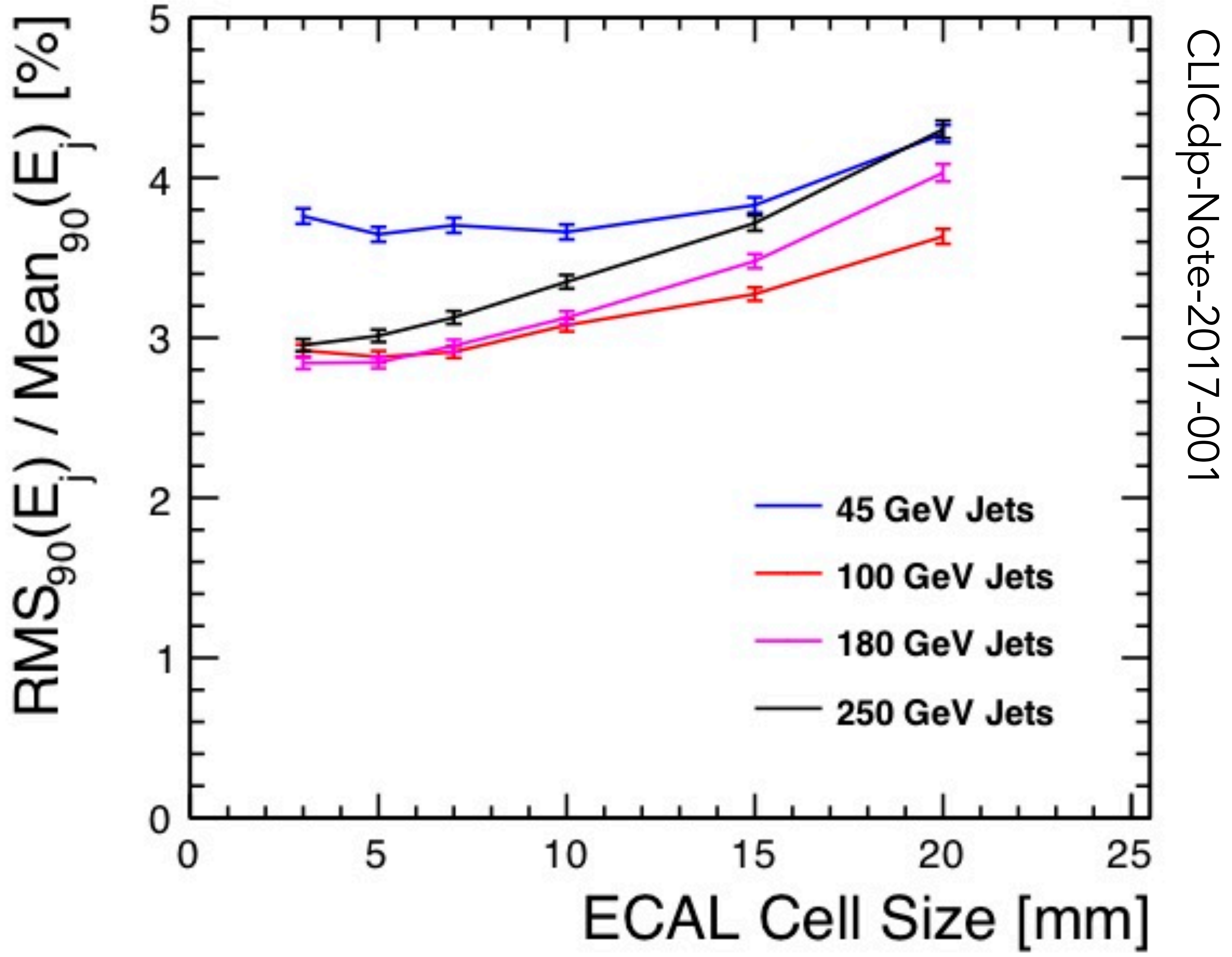
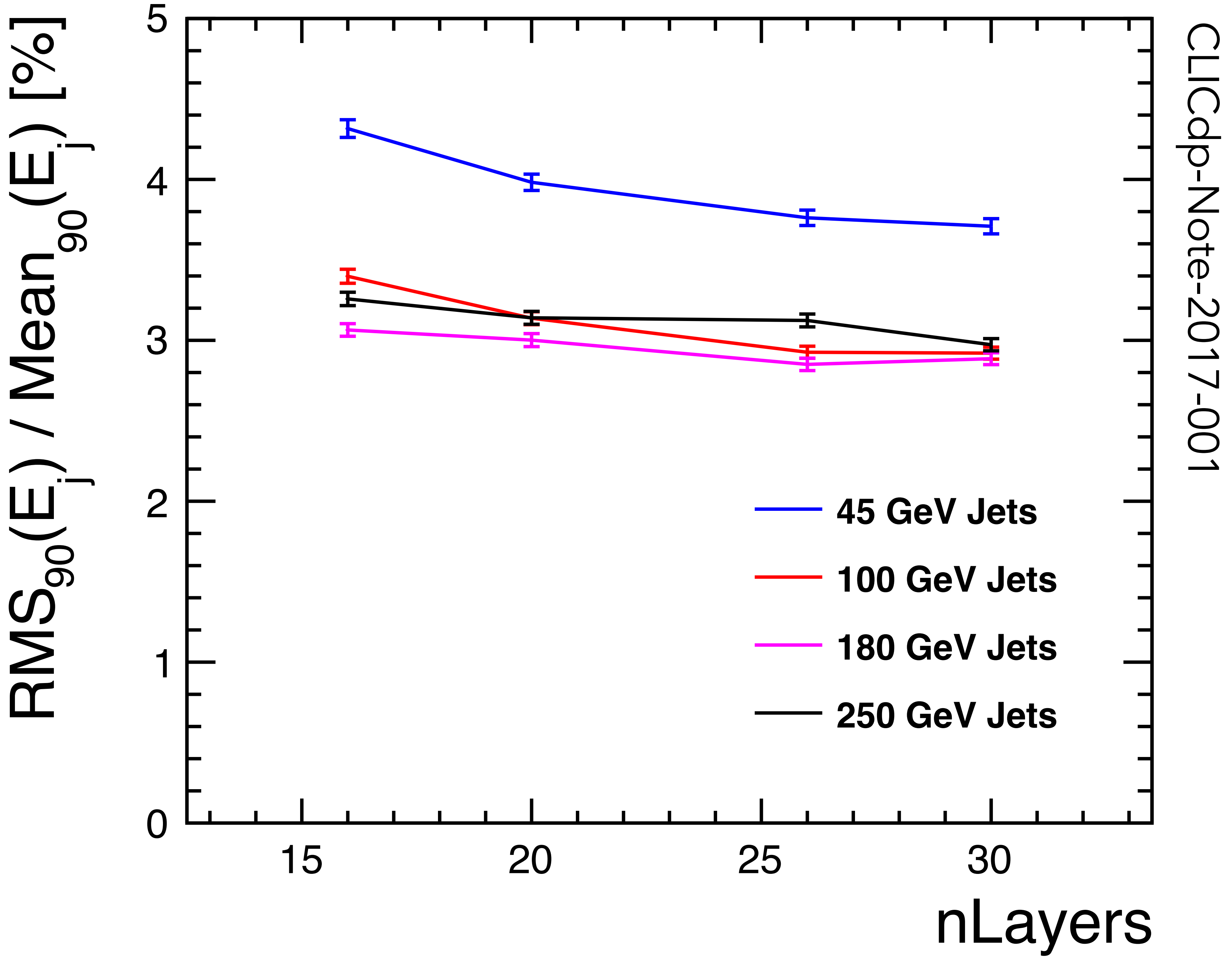
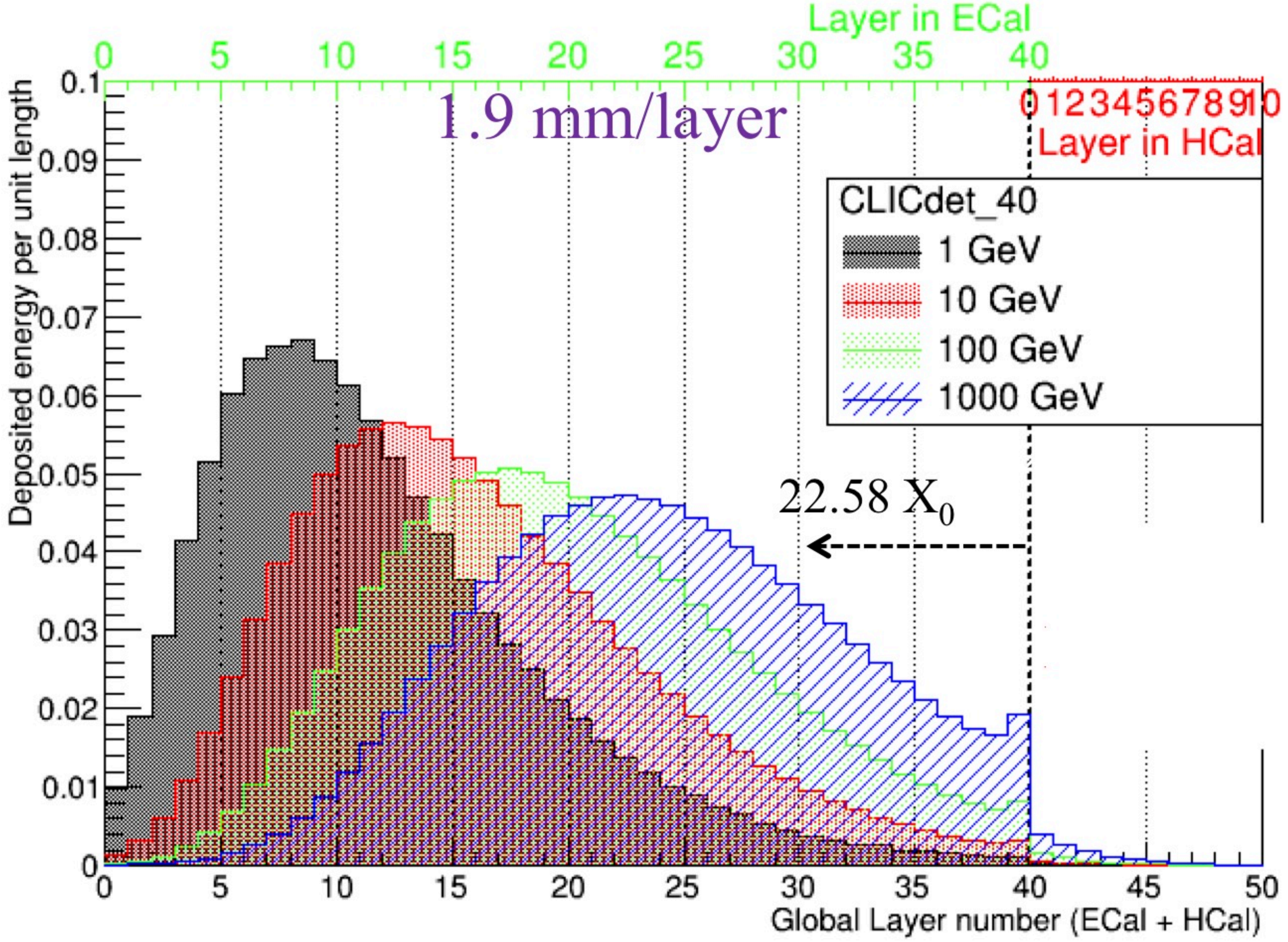




- 5 x 5 mm^2 cell size a good compromise, further improvement possible, but at the expense of significant increase in channel count
- From a jet energy resolution perspective, ~ 25 layers distributed over 23 X_0 appear sufficient, with 17 layers with finer sampling and 8 layers with thicker absorber

Optimisation of Calorimeter Layout: ECAL

- But: Optimisation purely on jet energy resolution neglects photon performance at high energy
  - May be crucial for high mass objects decaying to photons



CLICdp Det-Opt Meeting 15.11.2016

CLICdp-Note-2017-001

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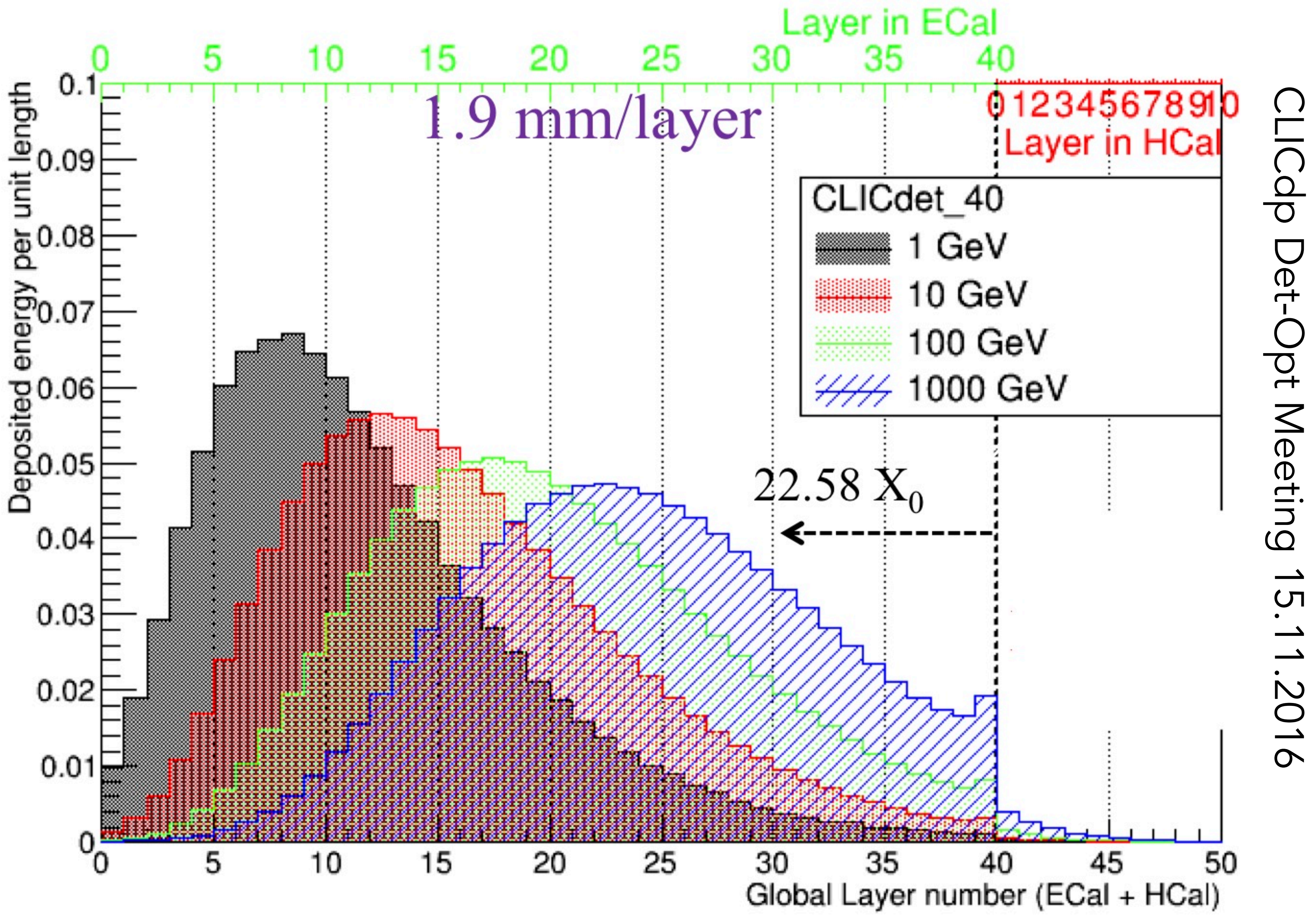
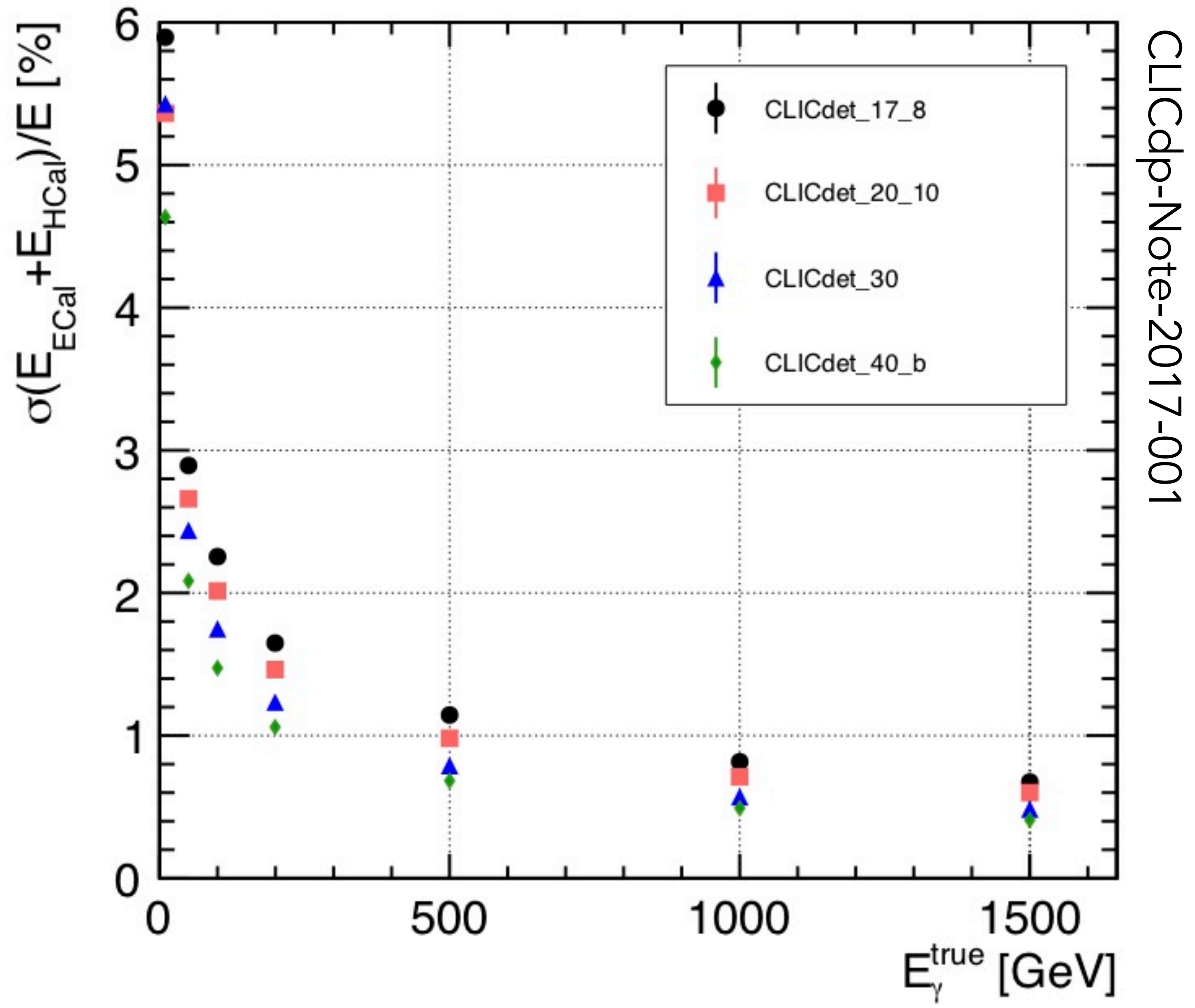
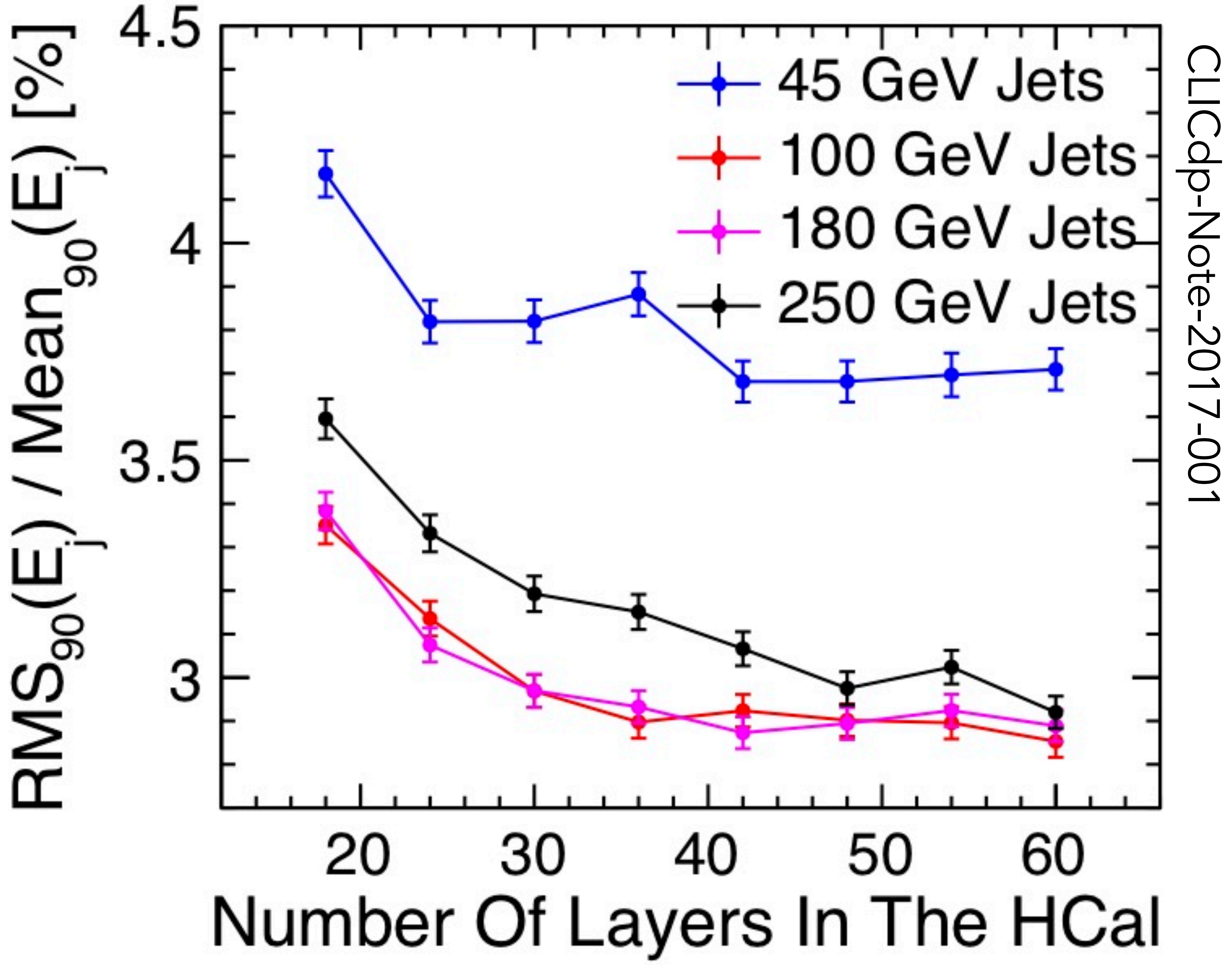




- Tricky optimisation: wide energy range of photons pushes for high sampling frequency throughout whole ECAL
- Best performance obtained for a 40 layer ECAL with 1.9 mm / layer, substantially better than 25 layer option with coarse layers in rear: Improvement at all energies, with up to ~40% for TeV photons

Optimisation of Calorimeter Layout: HCAL

- Jet energy resolution as a function of the number of layers (keeping calorimeter thickness constant): high sampling beneficial! (performed in ILD context)



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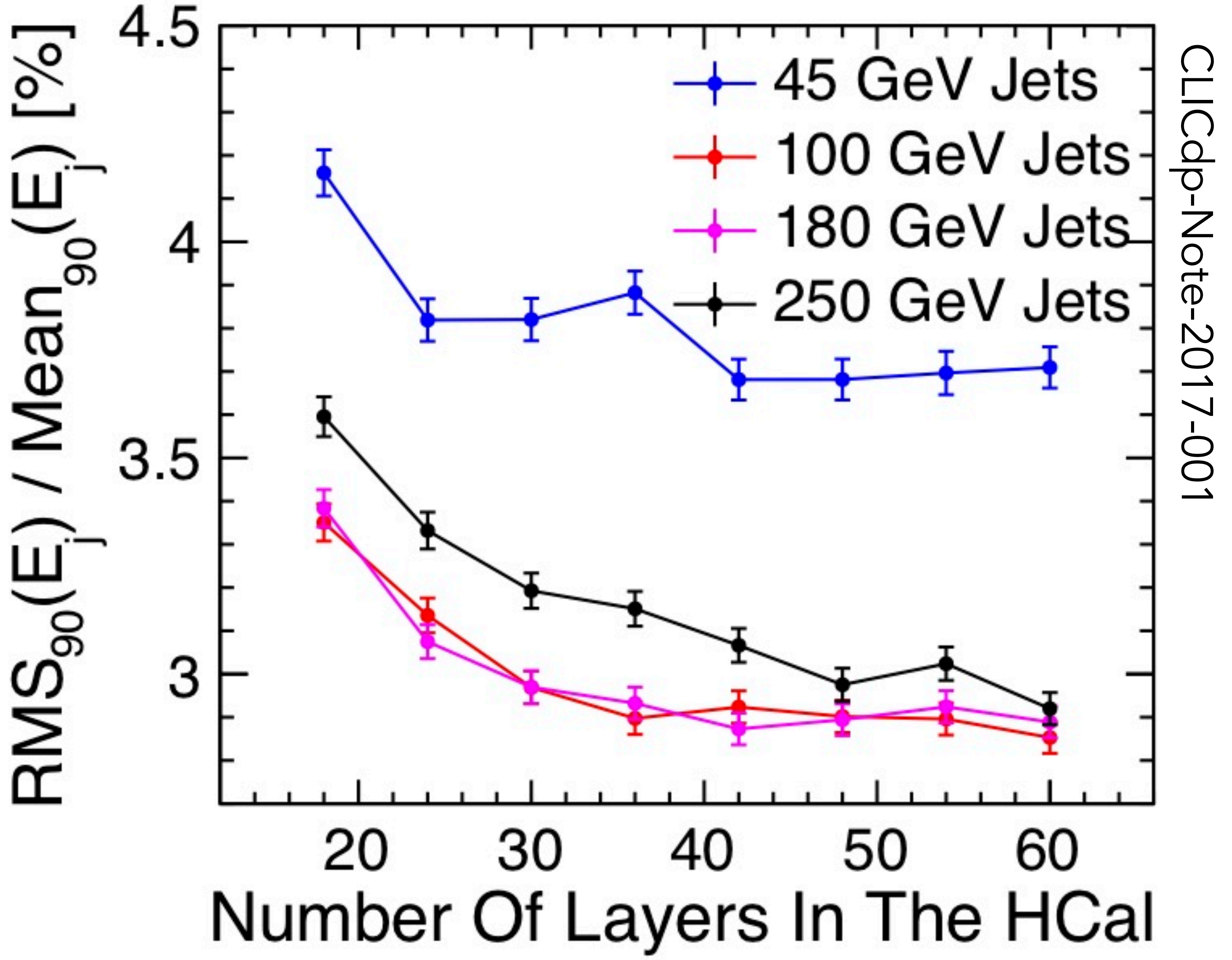

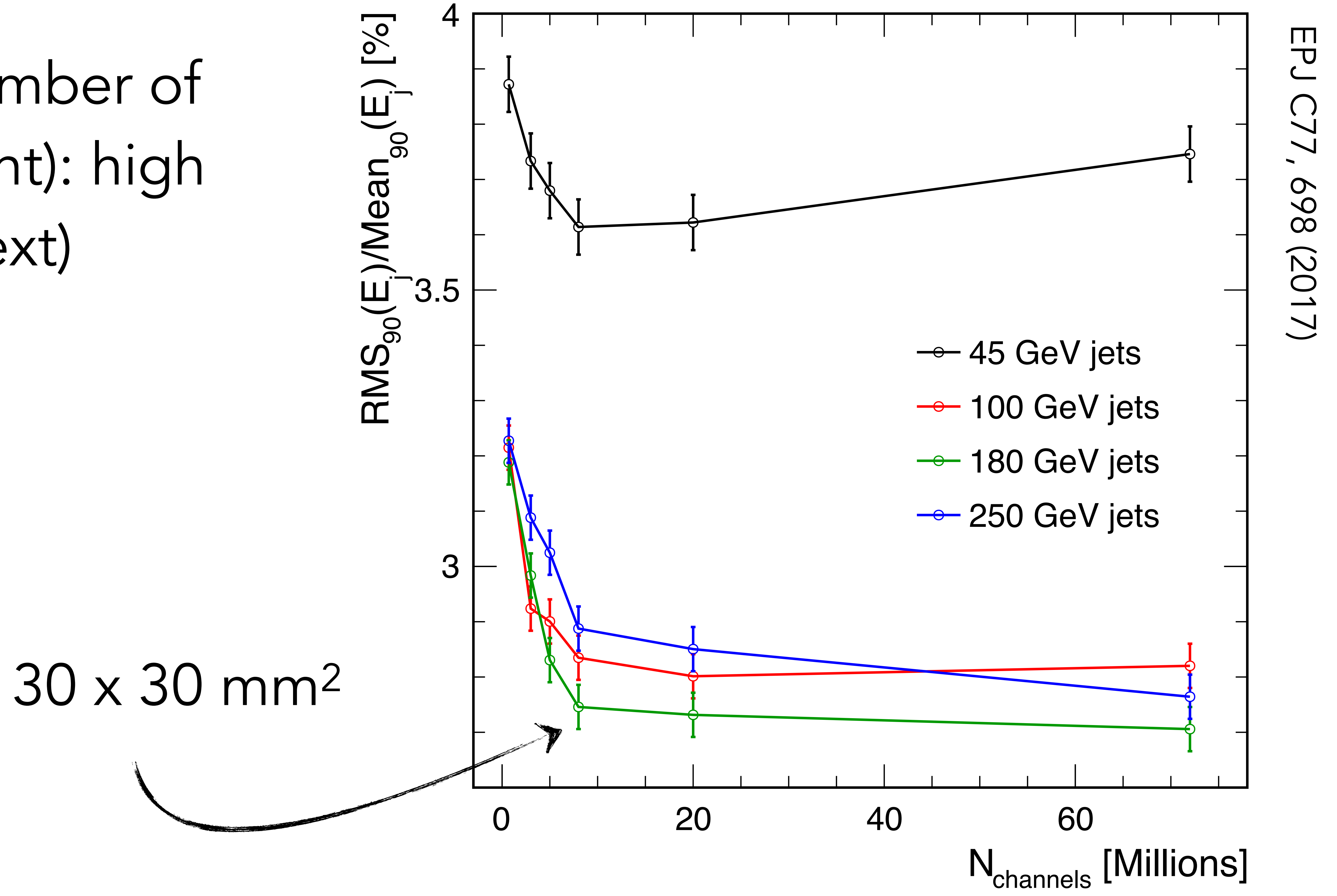

- Cell size optimisation with software compensation (separate training for each data point, binning range not optimal for low energies and small cells)

HCAL Absorber Material

- Tungsten was thoroughly scrutinized as a possible absorber material for the barrel HCAL
  - More compact: HCAL thickness reduced by 40 cm - reduced radius of solenoid: cost savings of ~ 40 MCHF
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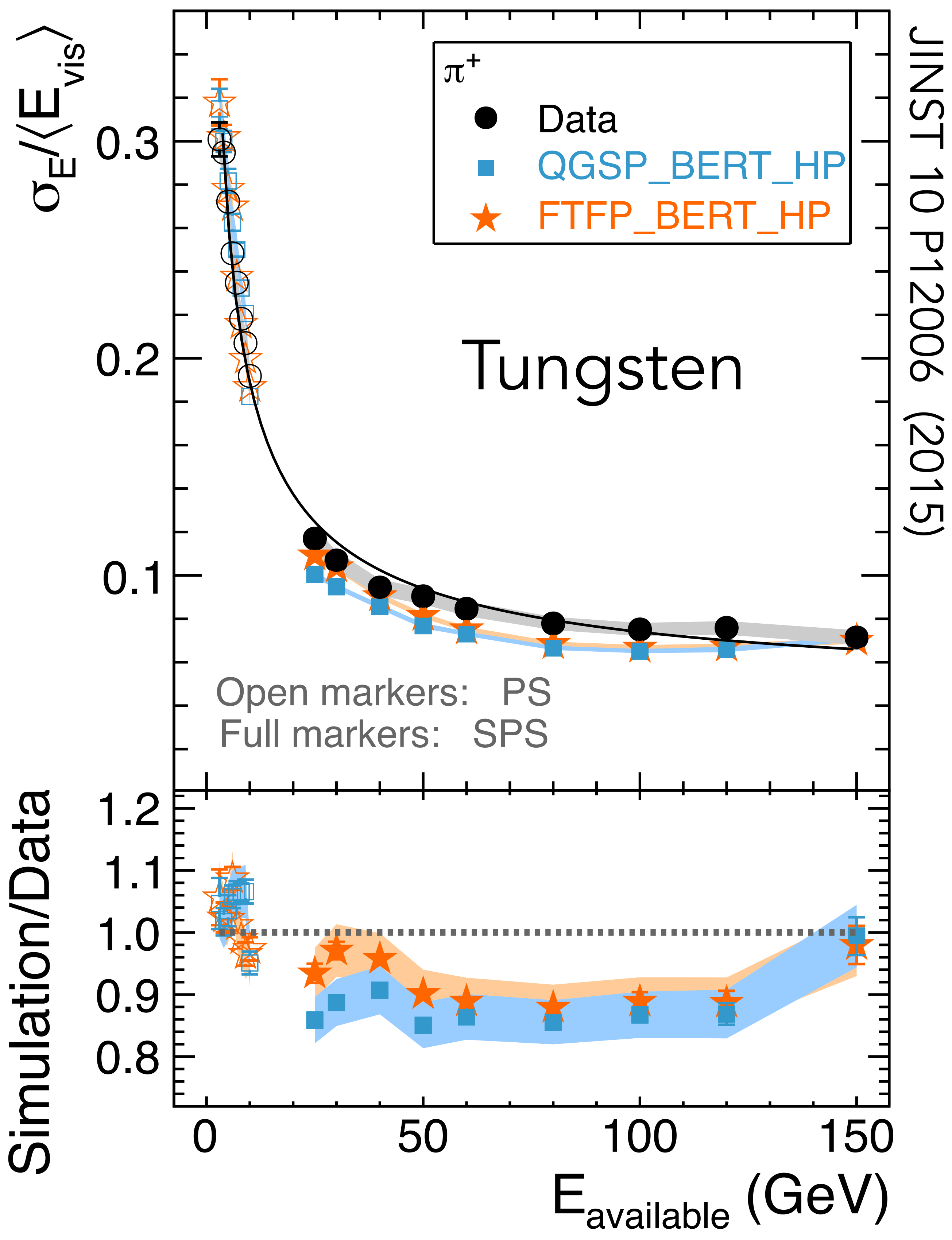
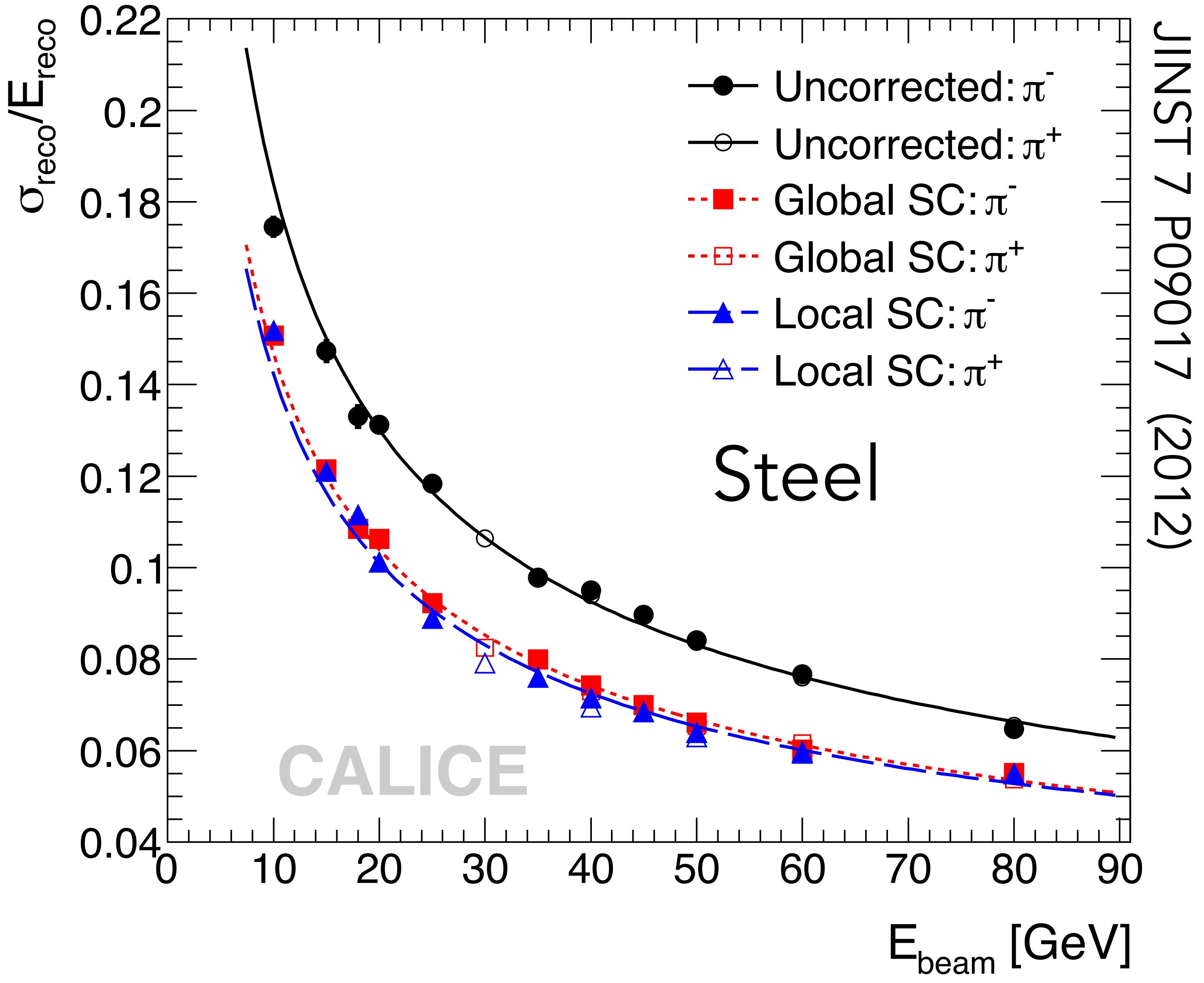


- Studied physics impact of absorber in extensive test beam program with CALICE W-AHCAL

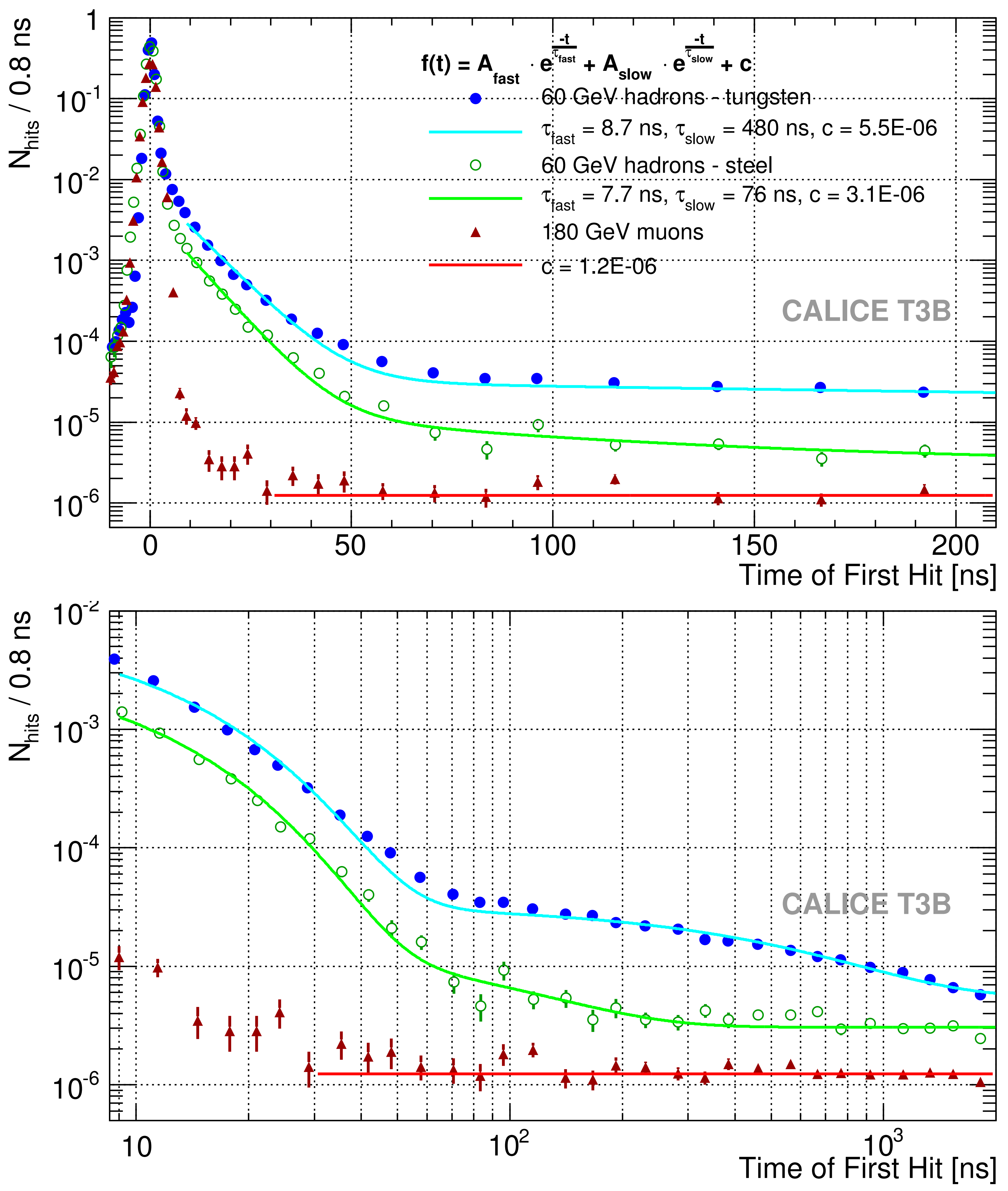


- Energy resolution of W-AHCAL and Fe-AHCAL without software compensation essentially identical: stochastic term of ~ 58%/√E
- But: No potential for software compensation in W-AHCAL: ~ compensating by construction
- Significant improvement in Fe-AHCAL with software compensation

⇨ Hadronic energy resolution in Steel ~ 20% - 25% better than in Tungsten

HCAL Absorber Material

- A critical issue in tungsten (in particular when combined with scintillator): Delayed signals from neutrons
  - Measured with a dedicated scintillator-based timing detector (T3B) behind W-AHCAL (very limited coverage)
  - ➩ Substantially more pronounced late shower activity in W, with ~ x5 more detector hits at times > 50 ns
  - ➩ Tungsten requires a longer integration time in HCAL: 100 ns vs 10 ns in Steel, larger impact of background



JINST 9 P07022 (2014)

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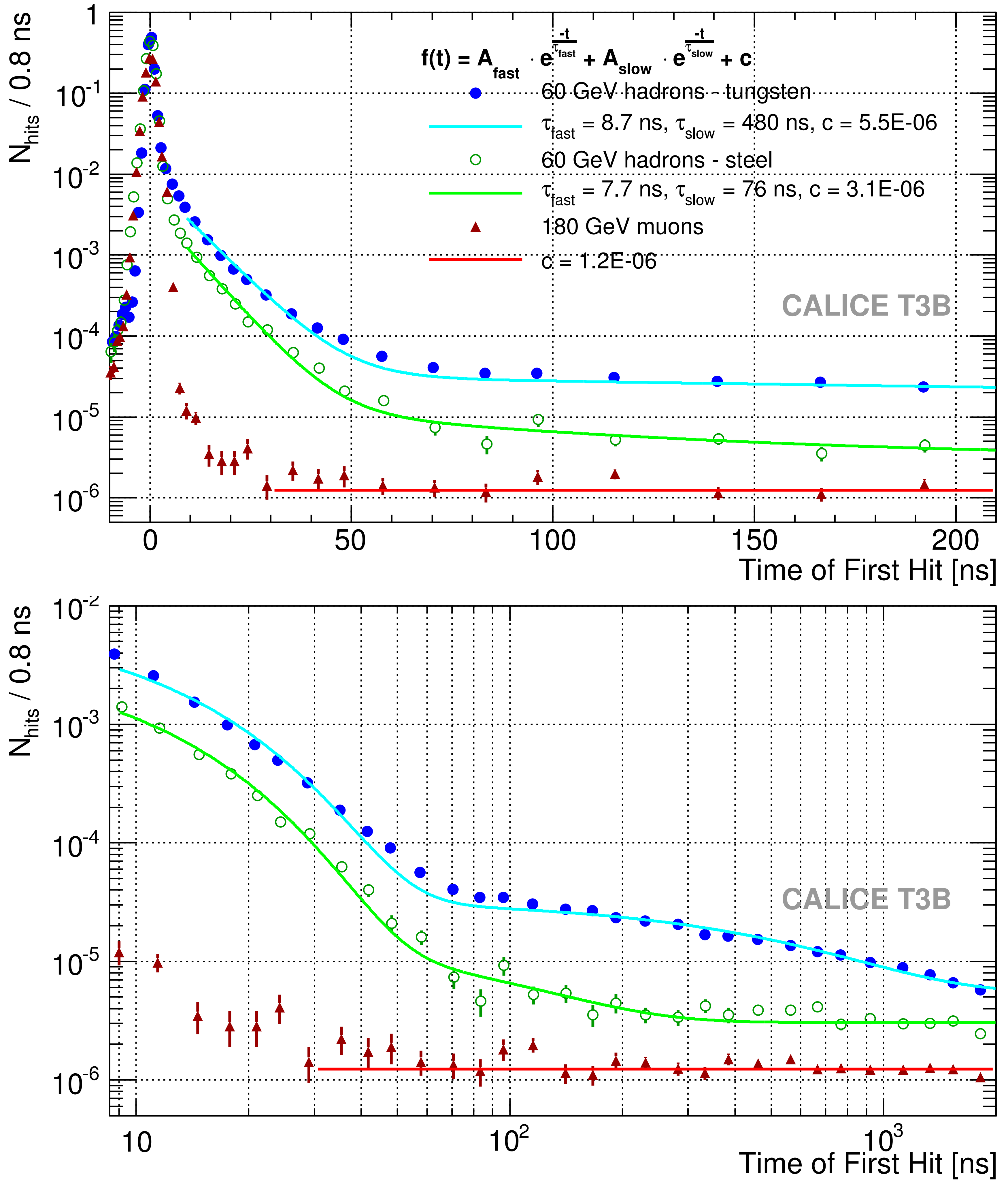
  (W resolution highly physics-list dependent, Fe stable)
- With background Fe is better in all scenarios



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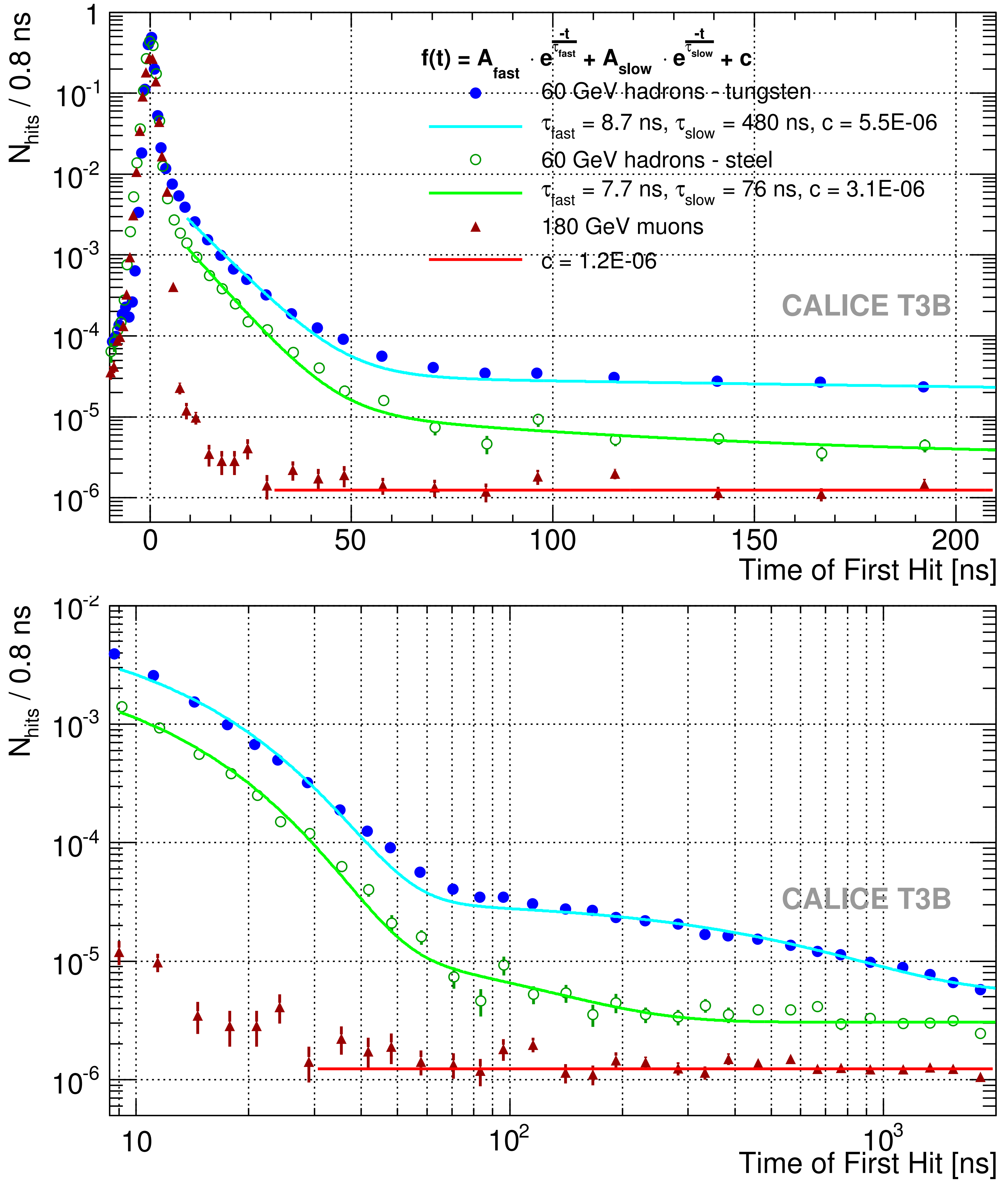


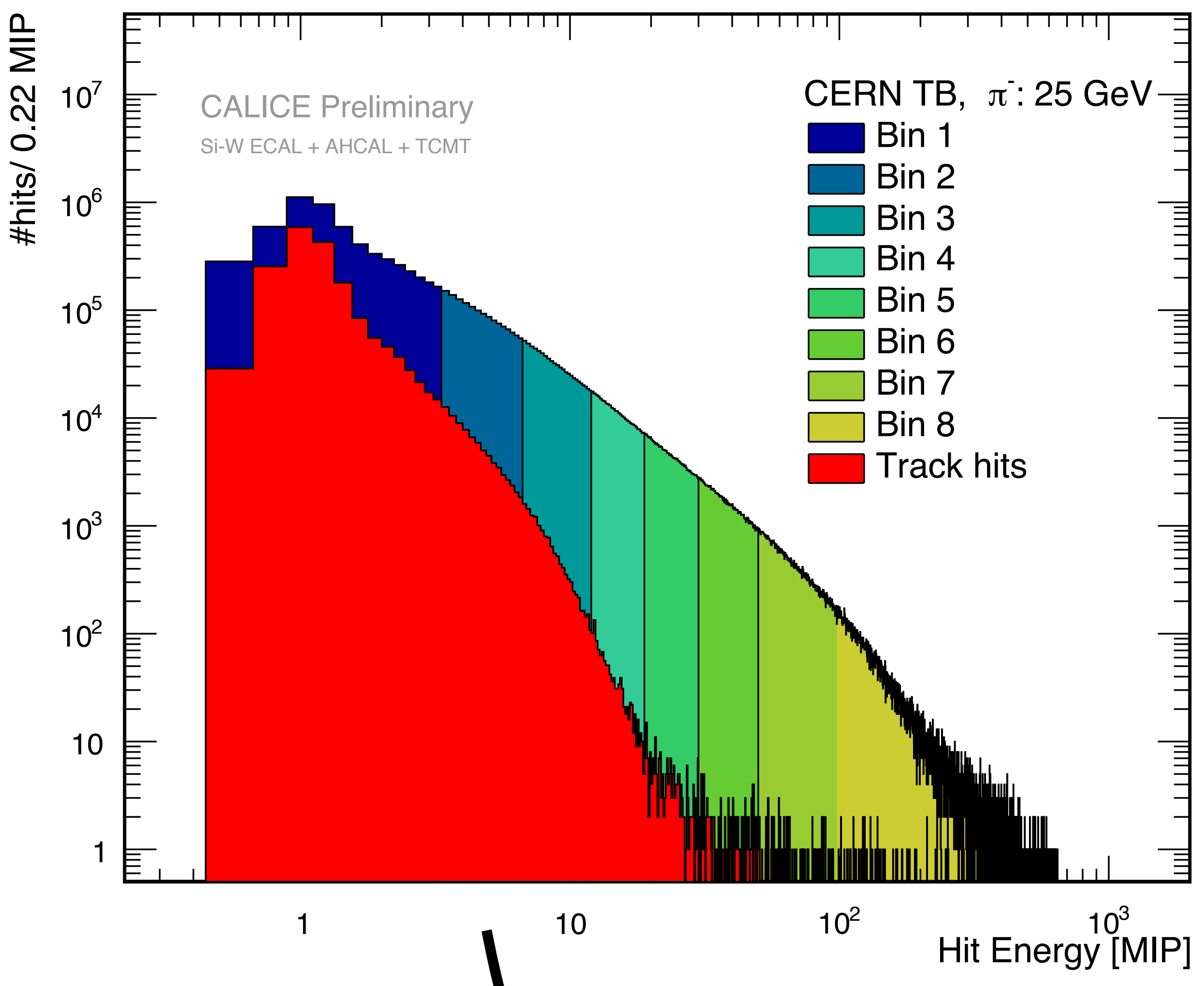
JINST 9 P07022 (2014)

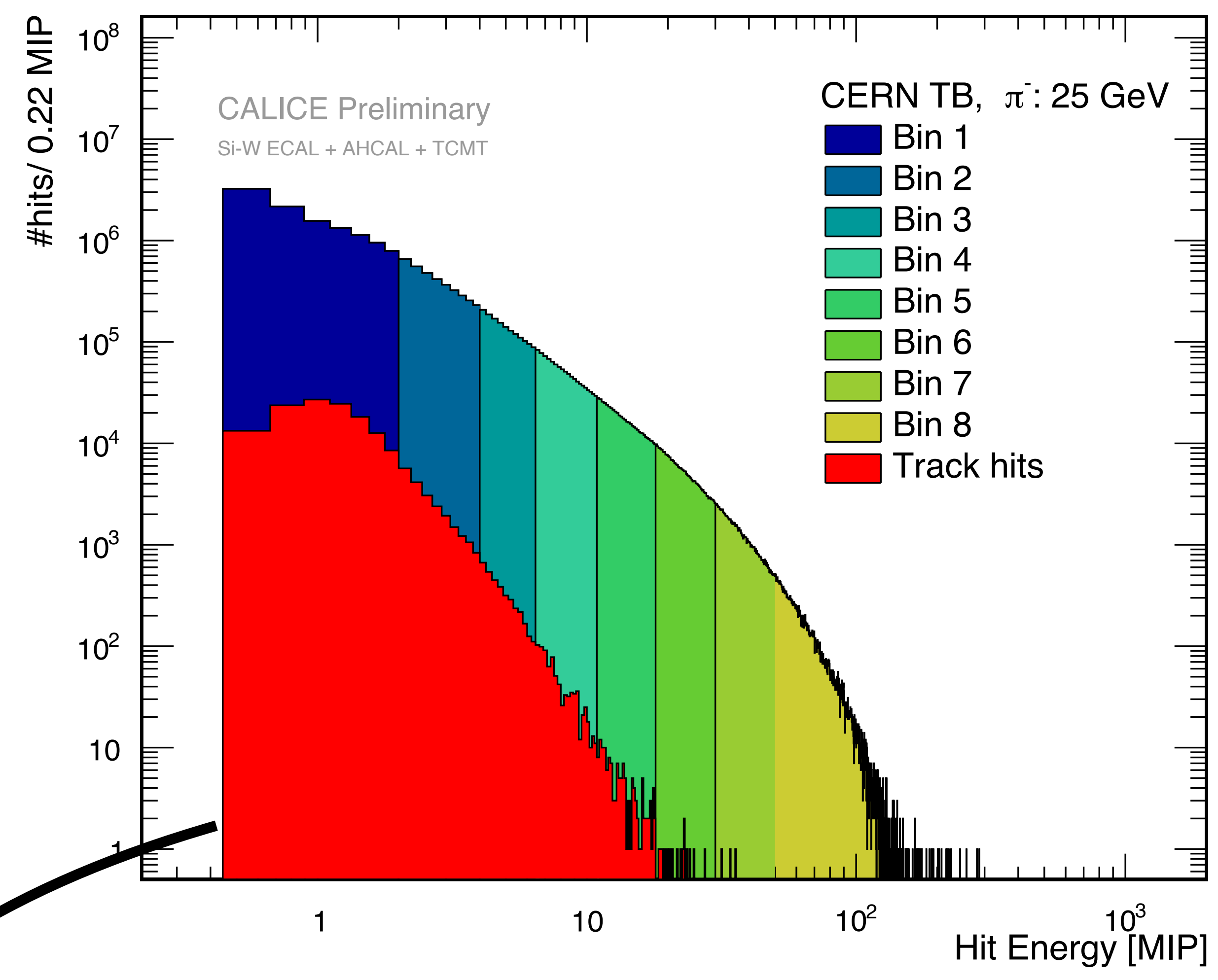
➩ Overall, the disadvantages of W outweigh the advantages: Use Stainless Steel as absorber

Summary

- Calorimetry for CLIC is very well developed and understood - based on technical developments by CALICE and, recently, also CMS
  - The technological concepts for sensors, electronics and mechanics used in CLICdet are demonstrated by large prototypes in test beams
- CLICdet uses highly granular calorimeter systems:
  - A 40 layer Silicon-Tungsten ECAL optimised for jet energy and photon resolution over a wide energy range up to the TeV region
  - A 60 layer Stainless Steel - Plastic Scintillator/ SiPM HCAL optimised for jet energy resolution and performance in the CLIC background environment
- Reconstruction techniques developed and demonstrated on test beam data, such as software compensation, are implemented in the full CLIC detector simulations

Extras


#hits/ 0.22 MIP
CALICE Preliminary
Si-W ECAL + AHCAL + TCMT
CERN TB, π⁻: 25 GeV
Bin 1
Bin 2
Bin 3
Bin 4
Bin 5
Bin 6
Bin 7
Bin 8
Track hits
Hit Energy [MIP]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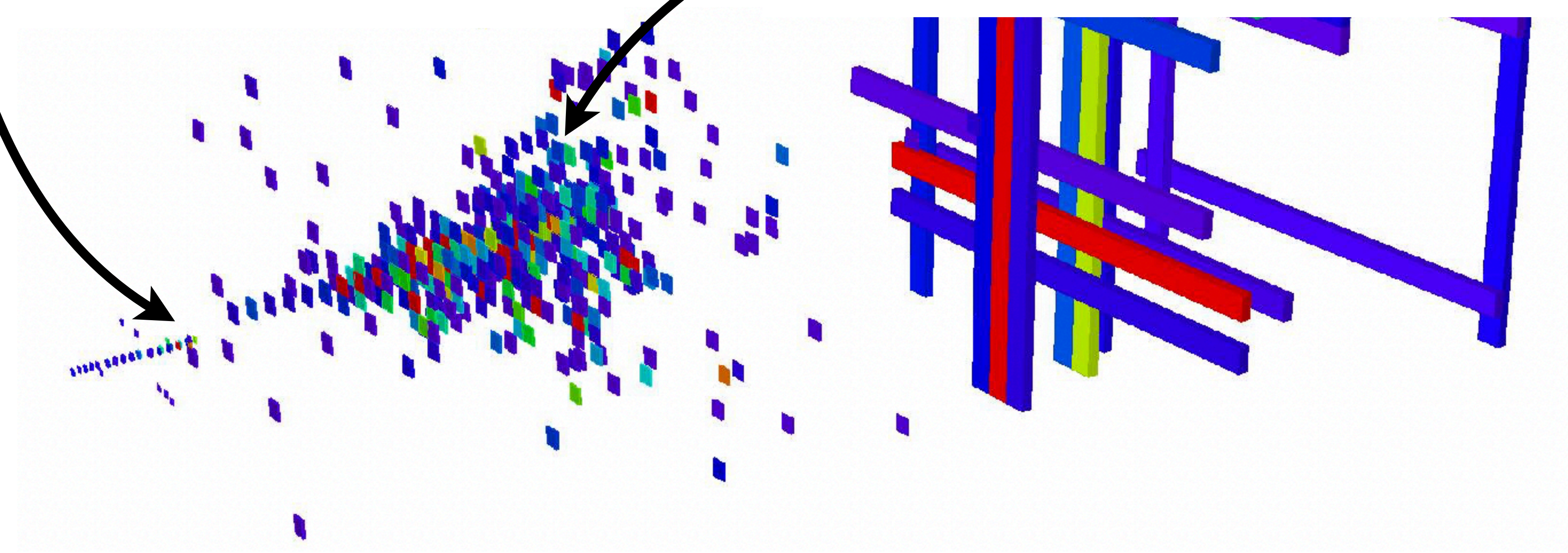

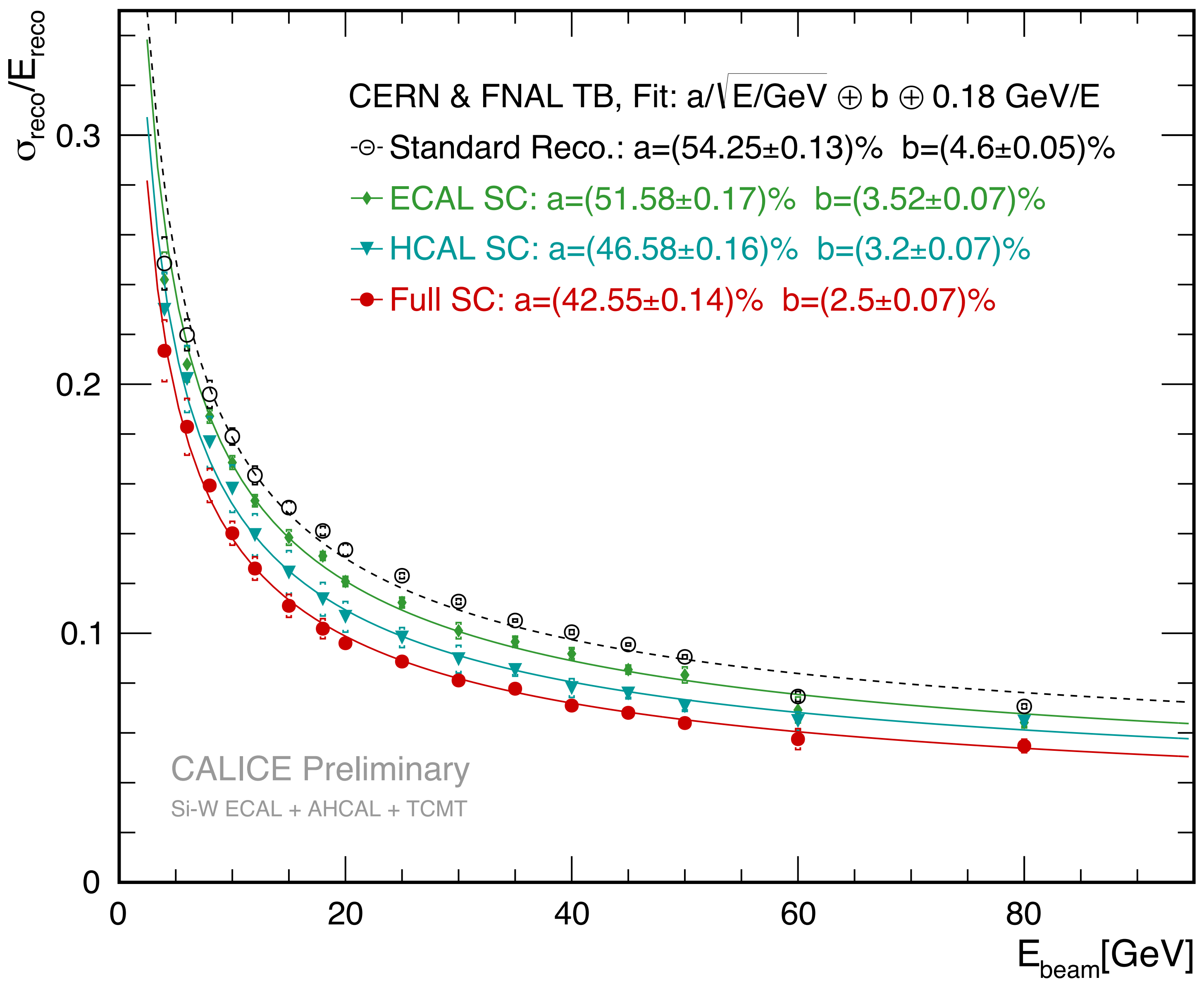
σreco/Ereco
CERN & FNAL TB, Fit: a/√E/GeV ⊕ b ⊕ 0.18 GeV/E
Standard Reco.: a=(54.25±0.13)% b=(4.6±0.05)%
ECAL SC: a=(51.58±0.17)% b=(3.52±0.07)%
HCAL SC: a=(46.58±0.16)% b=(3.2±0.07)%
Full SC: a=(42.55±0.14)% b=(2.5±0.07)%
CALICE Preliminary
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Ebeam[GeV]