FRI
11
JUN 2021

The CMS High Granularity Calorimeter upgrade for HL-LHC

Experimental Particle Physics seminar

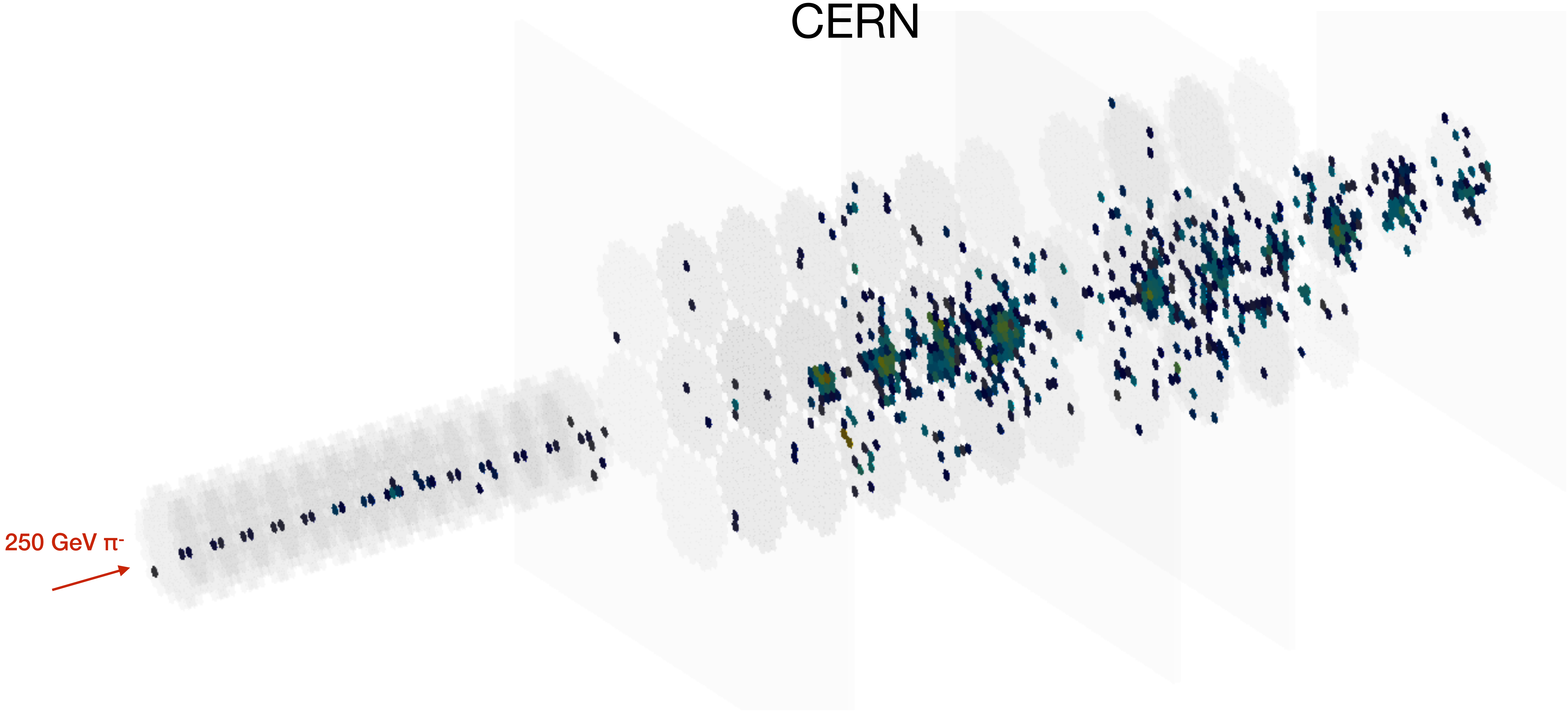
4:00pm until 5:00pm
11th June 2021
Dr Thorben Quast (CERN)
Zoom

THE UNIVERSITY of EDINBURGH

The CMS High Granularity Calorimeter (HGCAL) upgrade for HL-LHC

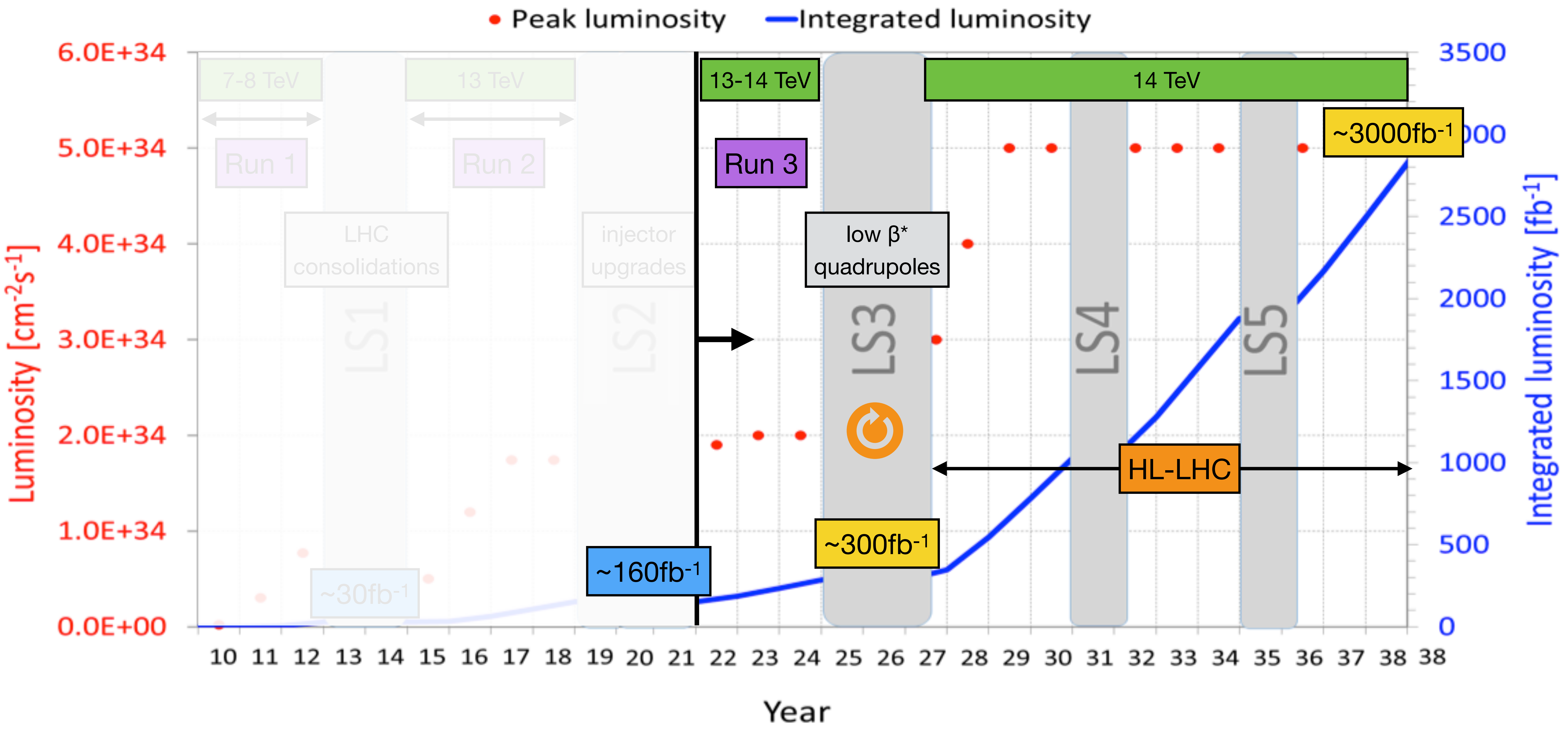
Thorben Quast

CERN



~~The medium-term future at CERN: High Luminosity LHC~~

Experimental testing of SM high-energy particle collisions: **Large Hadron Collider (LHC)** @ CERN.



LHC upgrade to ~5x design luminosity = HL-LHC

LHC —> HL-LHC: More activity in the CMS detector

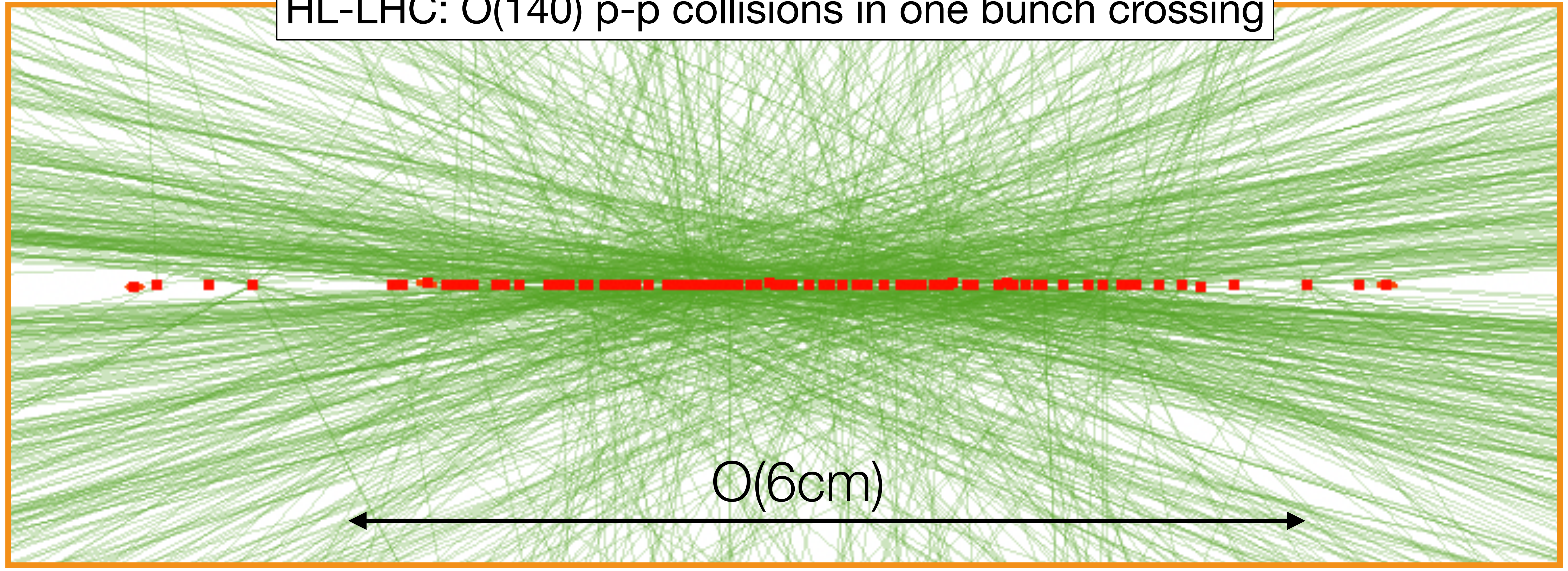
Nominal 5E34 $cm^{-2}s^{-1}$ luminosity

"Ultimate" 7.5E34 $cm^{-2}s^{-1}$ luminosity

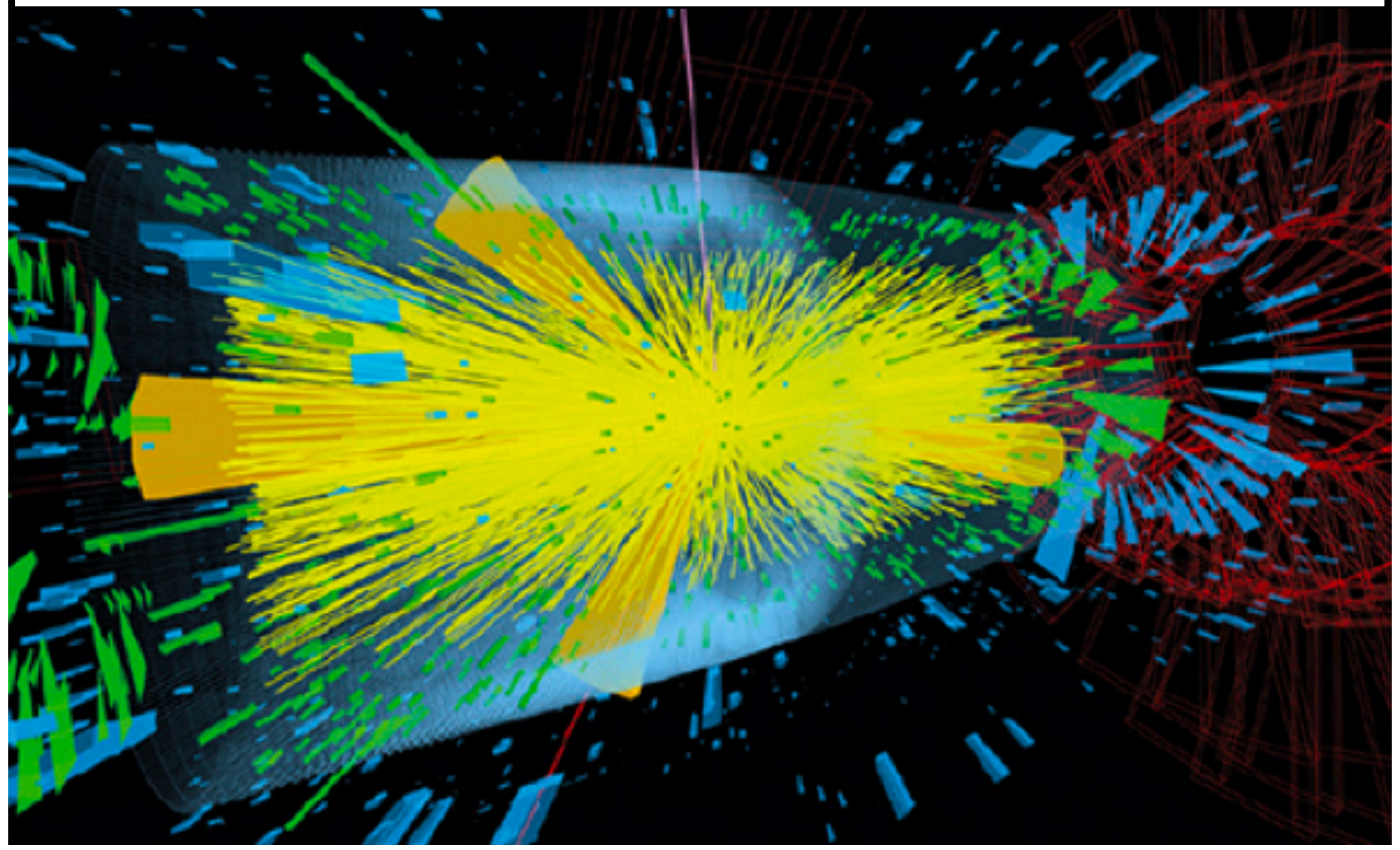
Increasing pile-up

- **140 - 200 collisions** per bunch crossing >> **3-4x** larger than in run 2.
  - spread over few centimetres
  - spread over O(200) ps

HL-LHC: O(140) p-p collisions in one bunch crossing

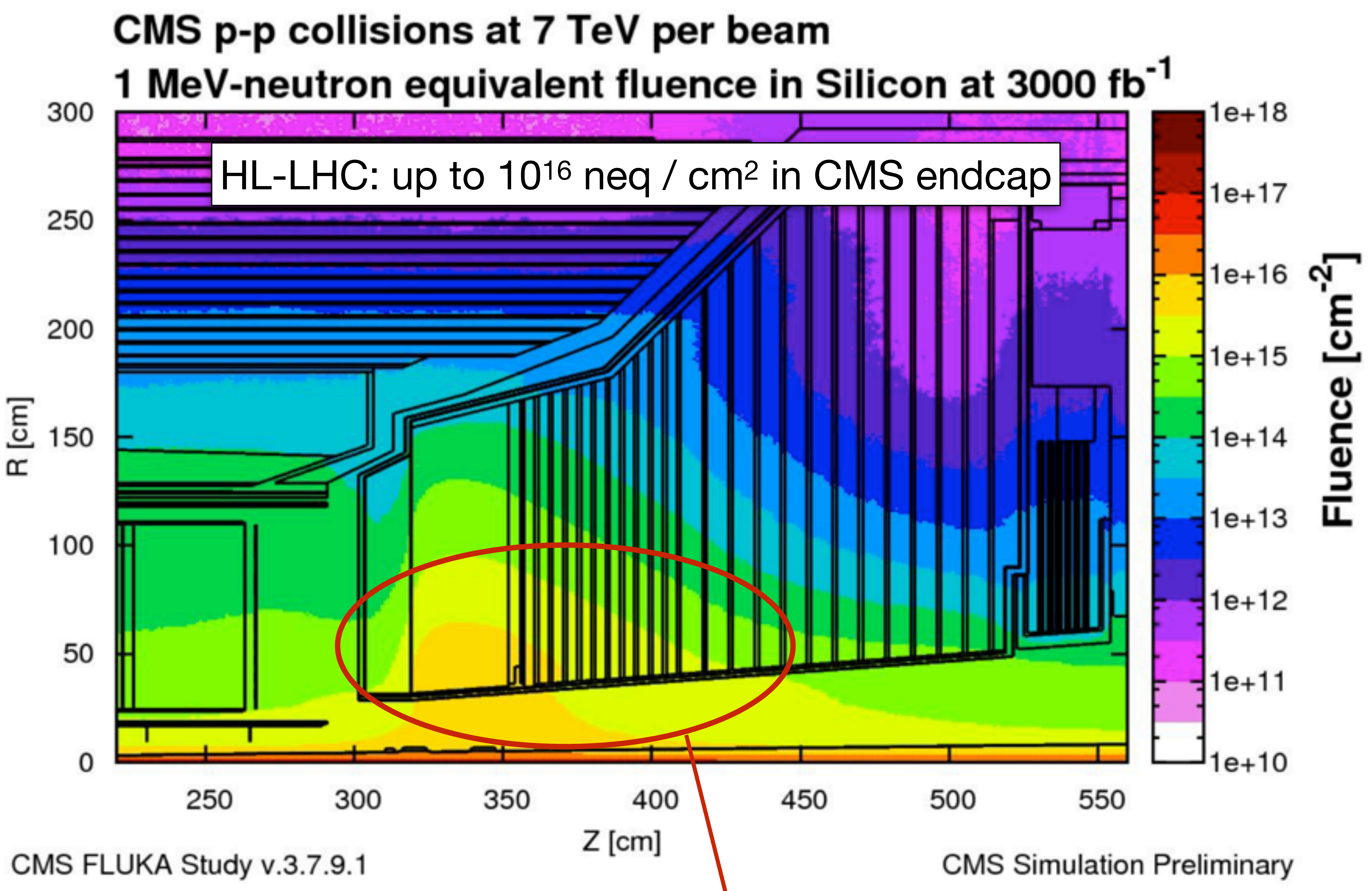


HL-LHC: A lot of activity in the CMS detector



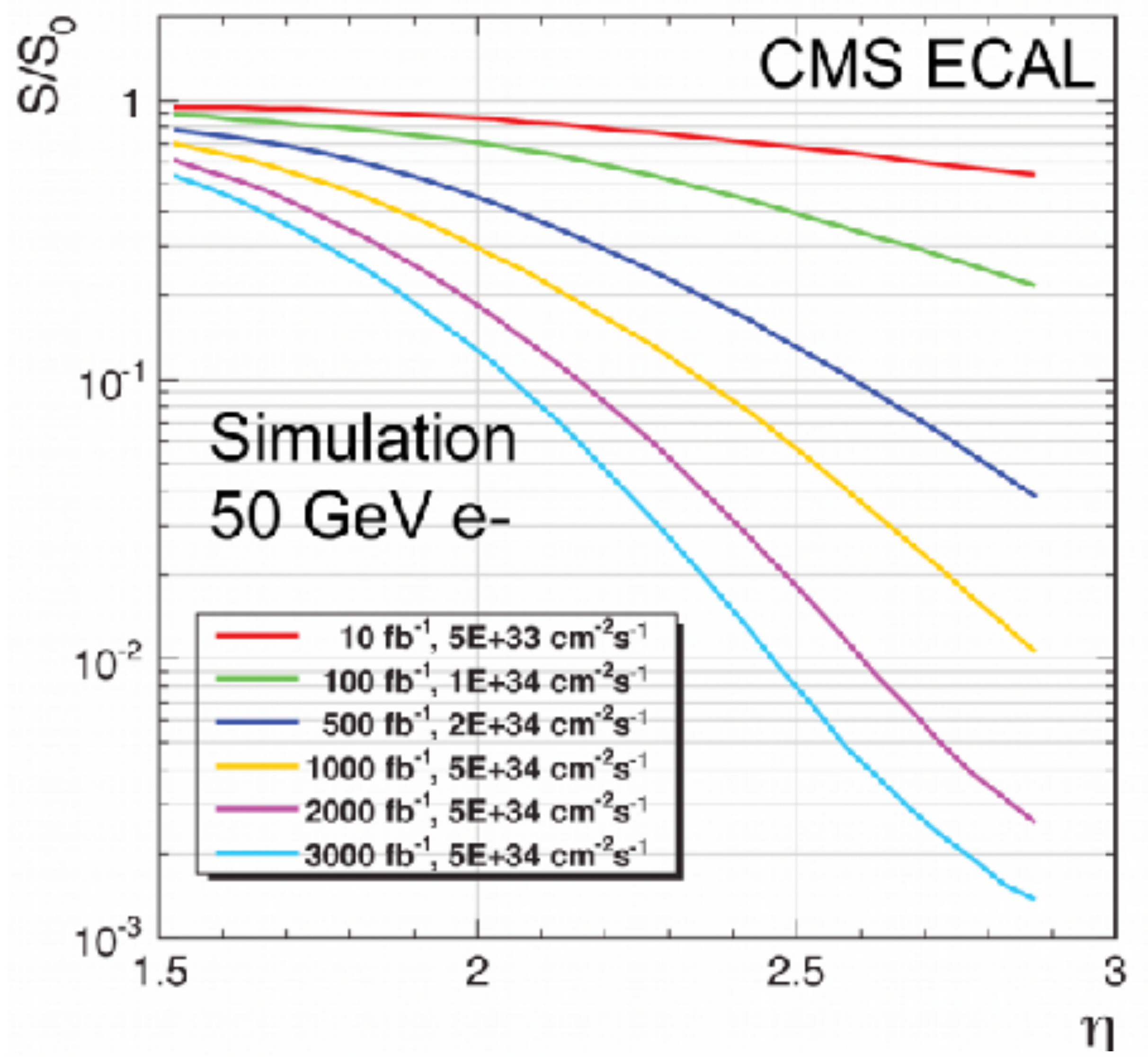
LHC —> HL-LHC: Increased radiation levels

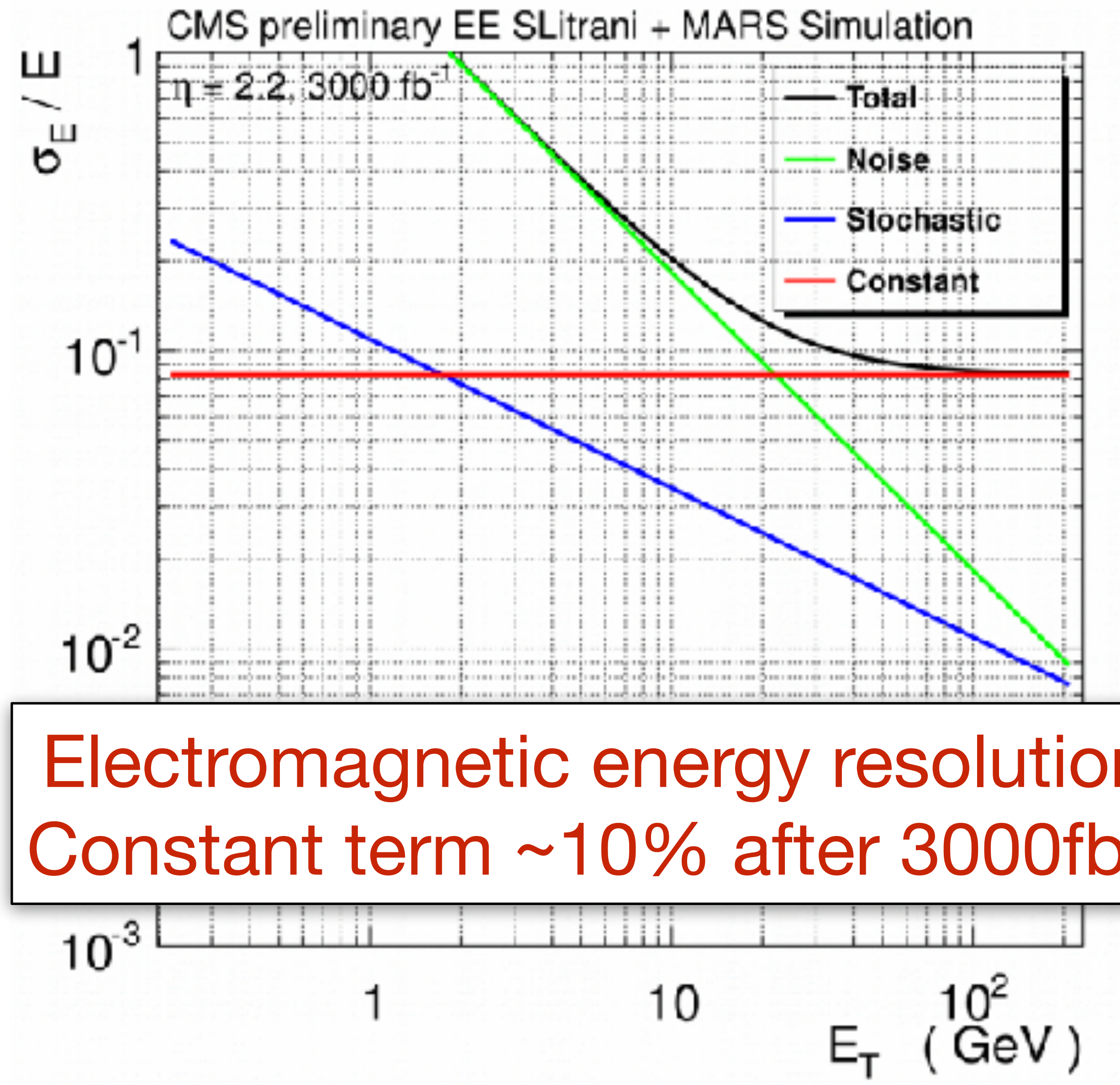
Current CMS detectors designed for end of Run 3 (300fb-1).



➡ECAL crystals & HCAL scintillators will suffer from irreparable radiation damage during HL-LHC.

Example: Current CMS ECAL





Electromagnetic energy resolution: Constant term ~10% after 3000fb-1.

HL-LHC necessitates detector upgrades

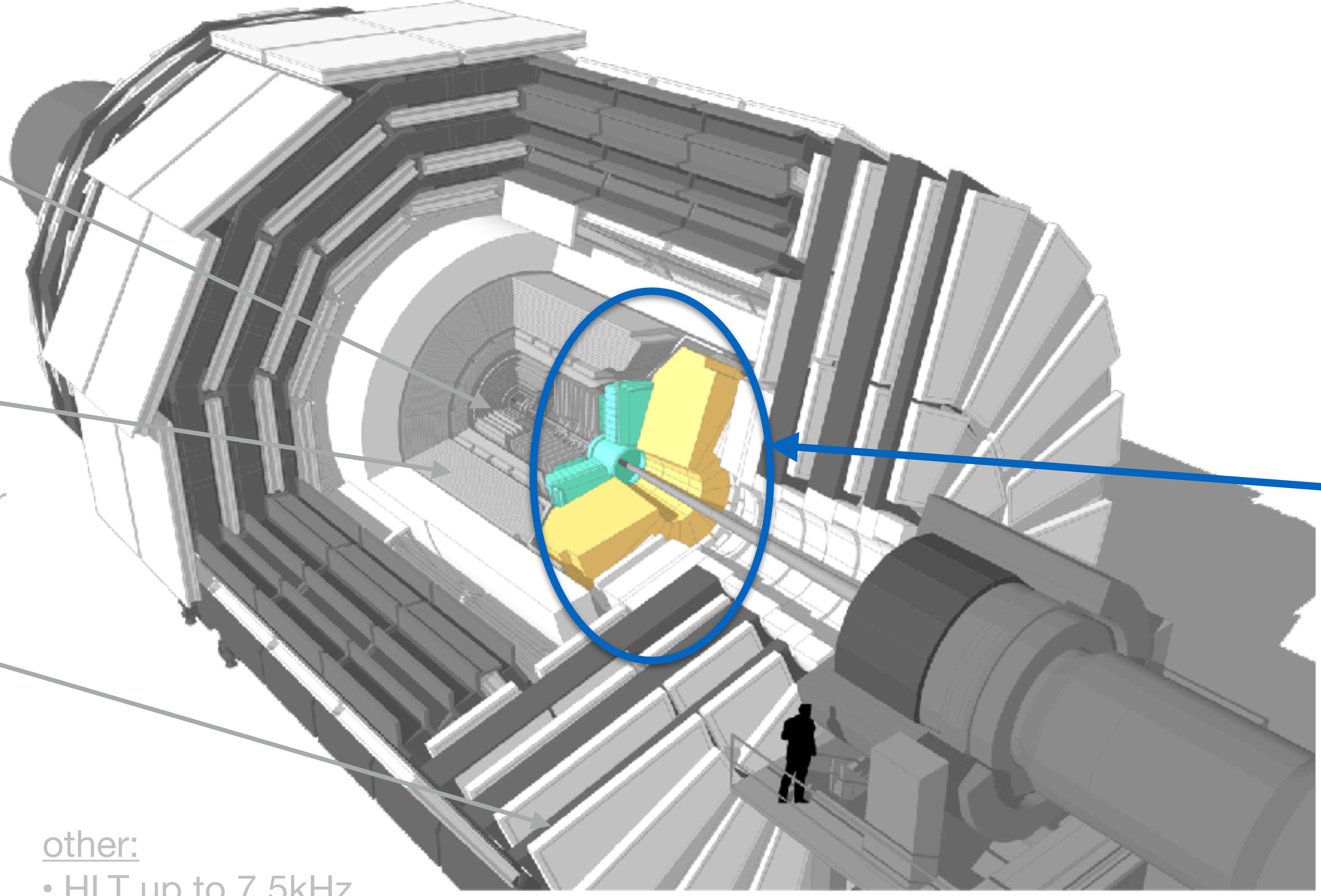
Experimental challenges	LHC		HL-LHC	General mitigation strategy
• inst. luminosity	$2 \times 10^{34}\ s^{-1}\ cm^{-2}$	→	up to $7.5 \times 10^{34}\ s^{-1}\ cm^{-2}$	‣ improved trigger & computing
• detector irradiation	$O(10^{14}\ neq/cm^2)$		$>O(10^{15}\ neq/cm^2)$	‣ radiation-tolerant sensors & electronics
• pile-up interactions	O(40)		140-200	‣ timing and increased granularity

Compact **M**uon **S**olenoid (CMS)
HL-LHC Upgrades

Tracker:
Radiation tolerant, high granularity, less materials, tracks in hardware trigger (L1), coverage up to |η| = 3.8

Barrel Calorimeter:
New BE/FE electronics,
ECAL: lower temp.,
HCAL: partially new scintillator

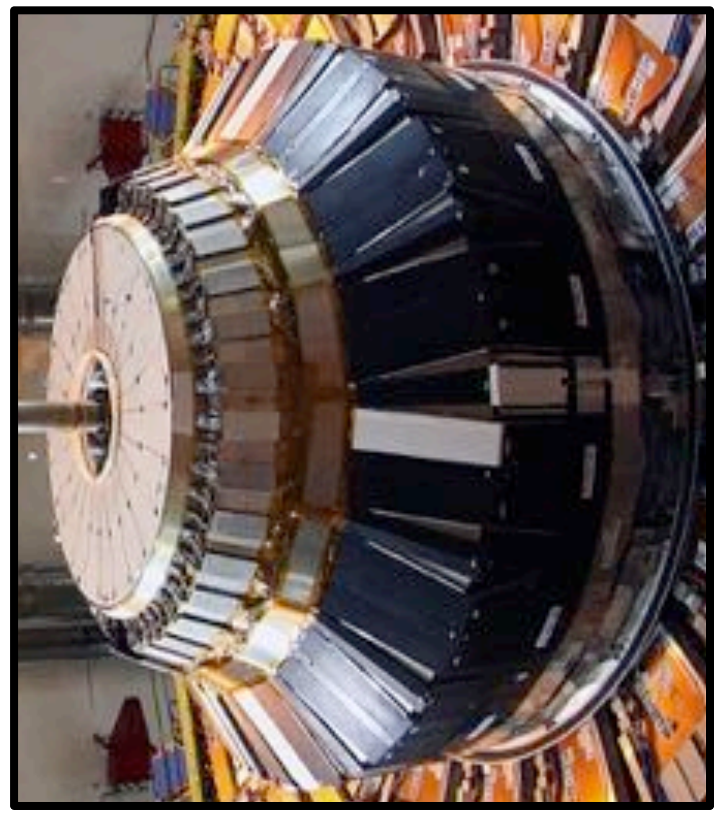
Muon system:
New electronics
GEM/RPC coverage in 1.5 < |η| < 2.4,
investigate muon tagging at higher η



other:
• HLT up to 7.5kHz
• MIP timing detector

To be replaced for HL-LHC

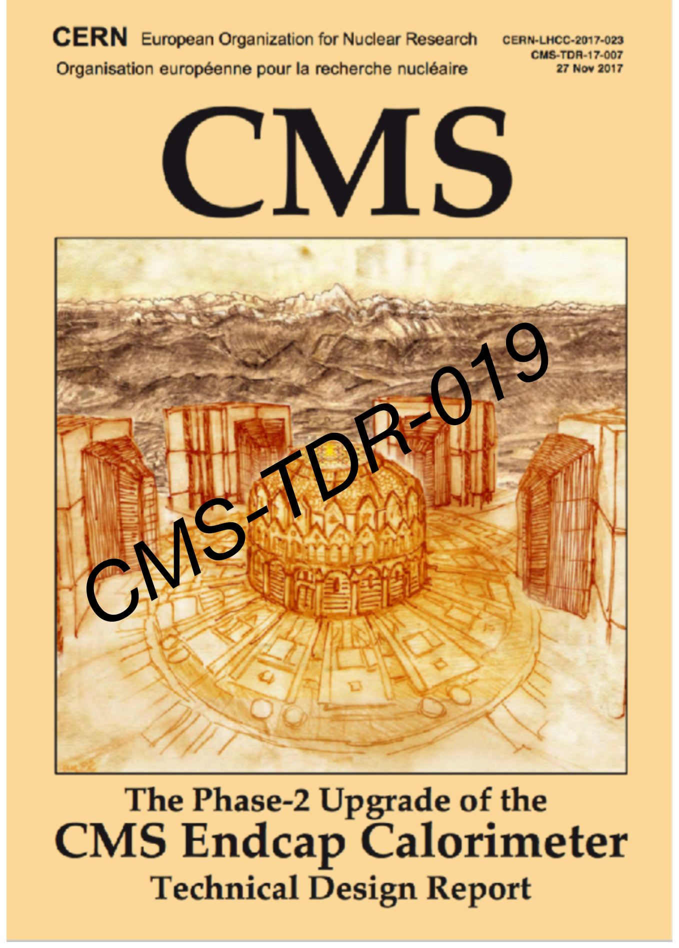
Endcap Calorimeters:
1.5 < |η| < 3.0



This presentation: The new CMS calorimeter endcap for HL-LHC

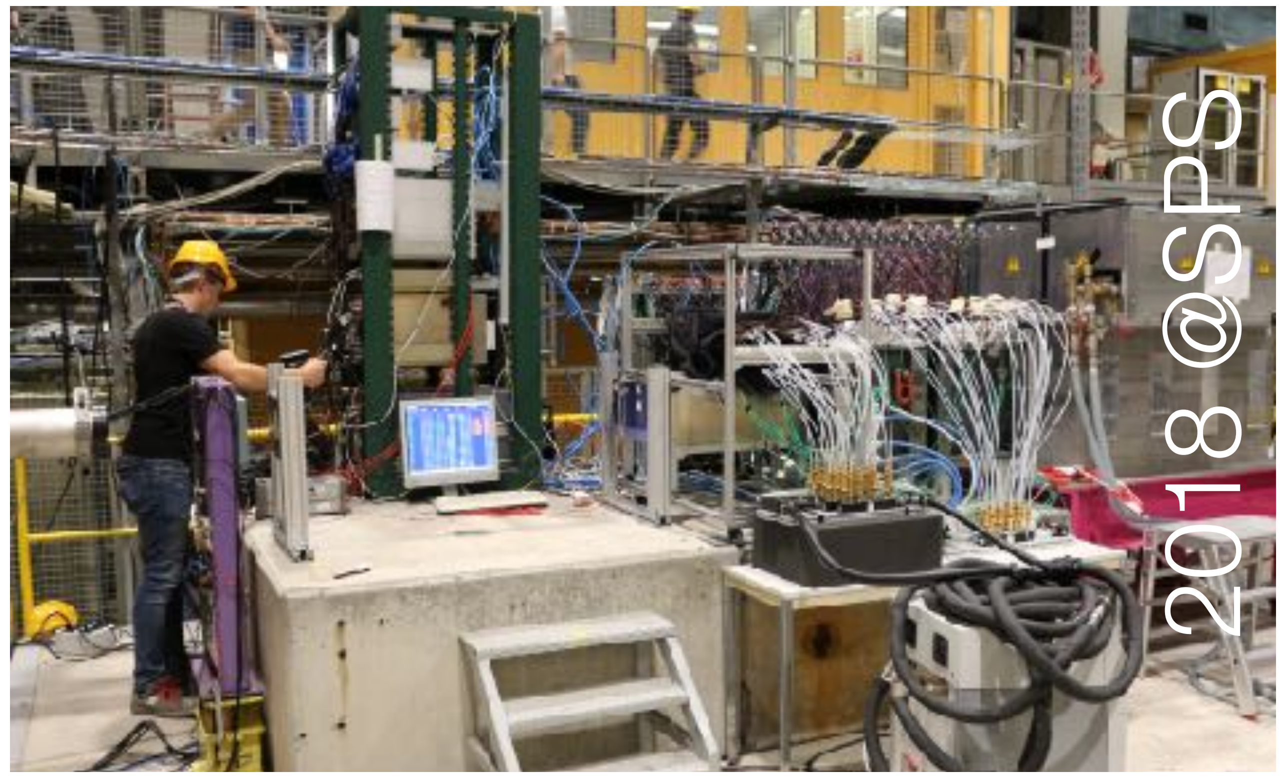
CMS High Granularity Calorimeter Endcap Upgrade

- Concept and design
- Components and prototyping



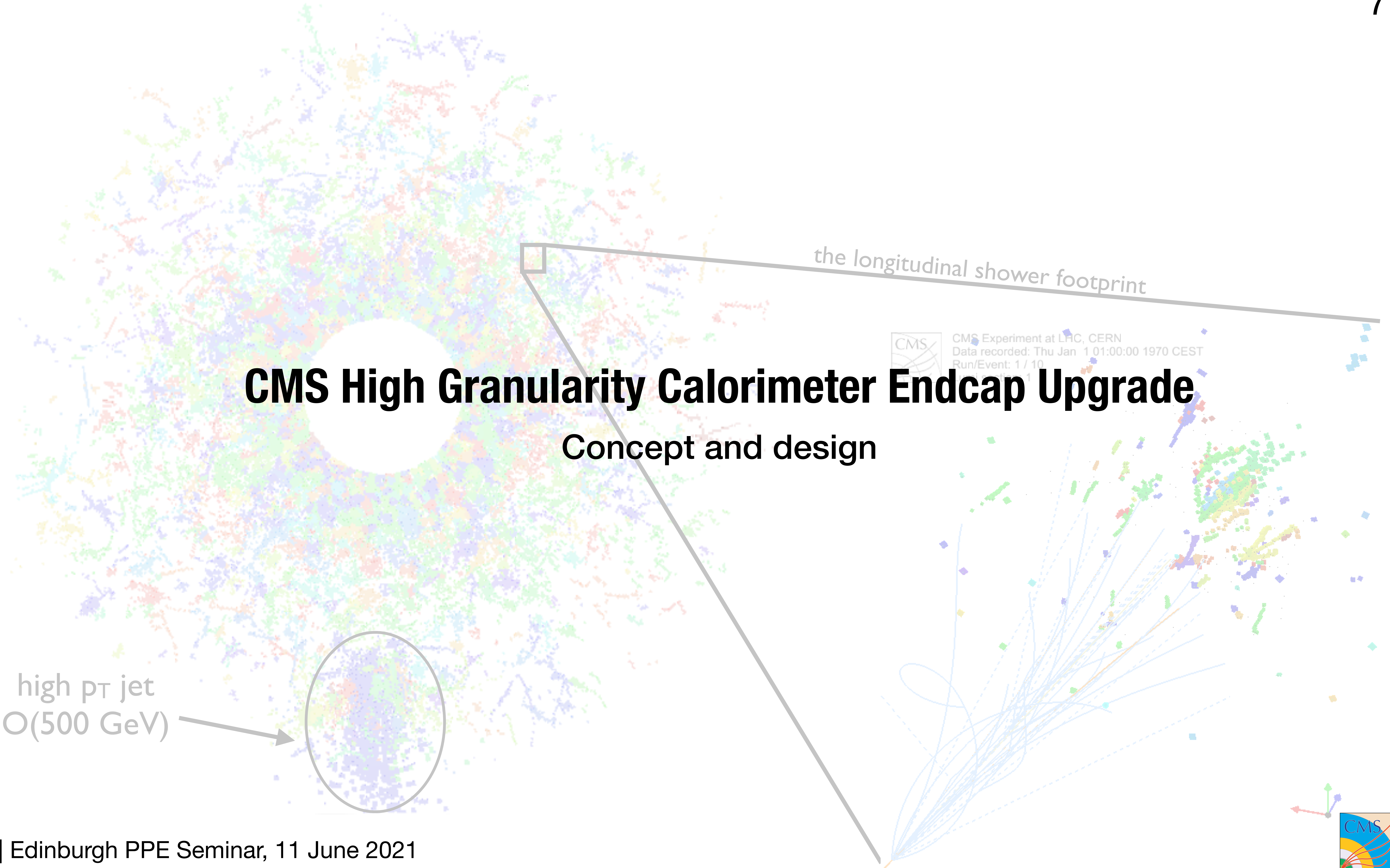
Proof-of-concept in test beam experiments

- HGCAL test beam prototype 2018
- Performance with positrons and charged pions



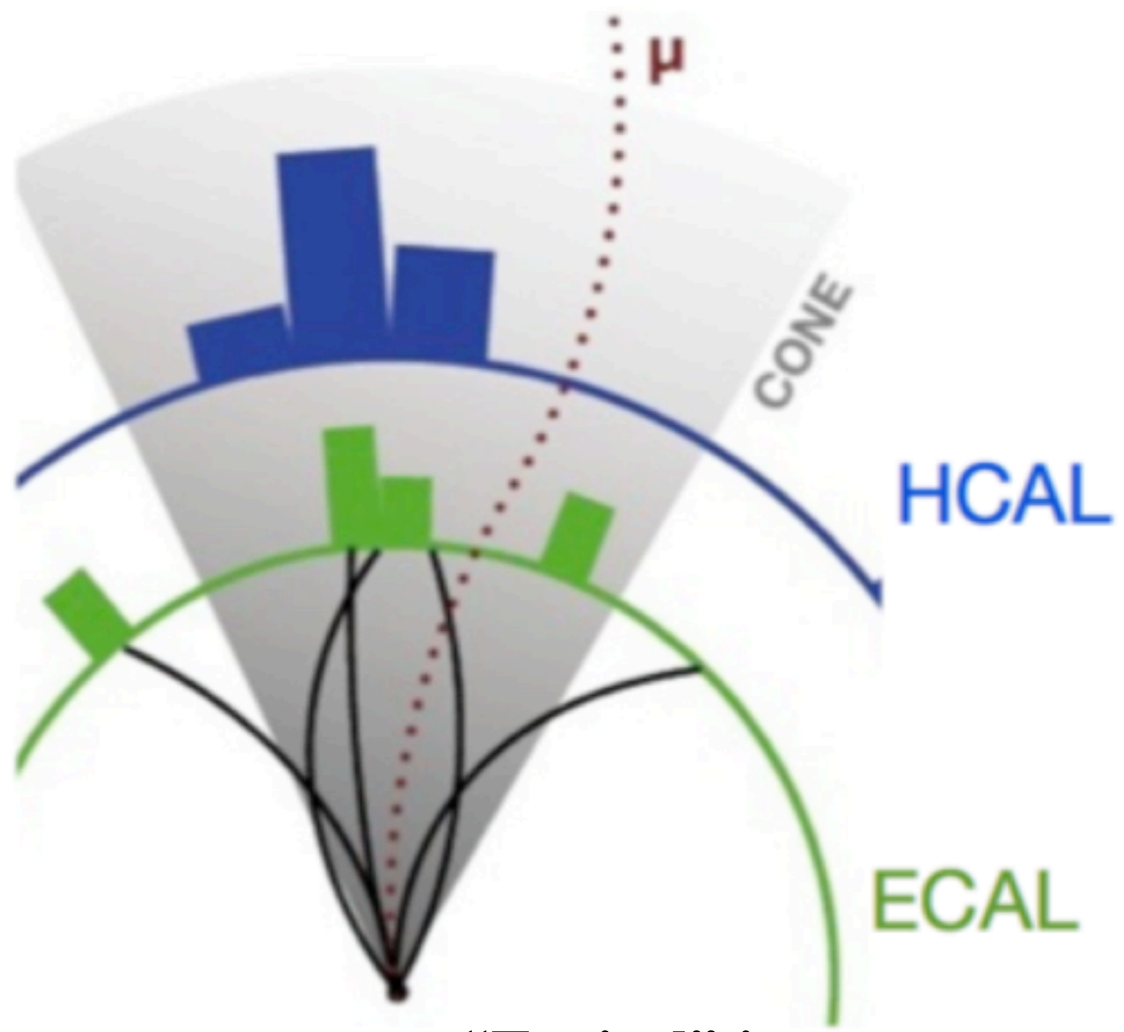
CMS High Granularity Calorimeter Endcap Upgrade

Concept and design



The case for high granularity

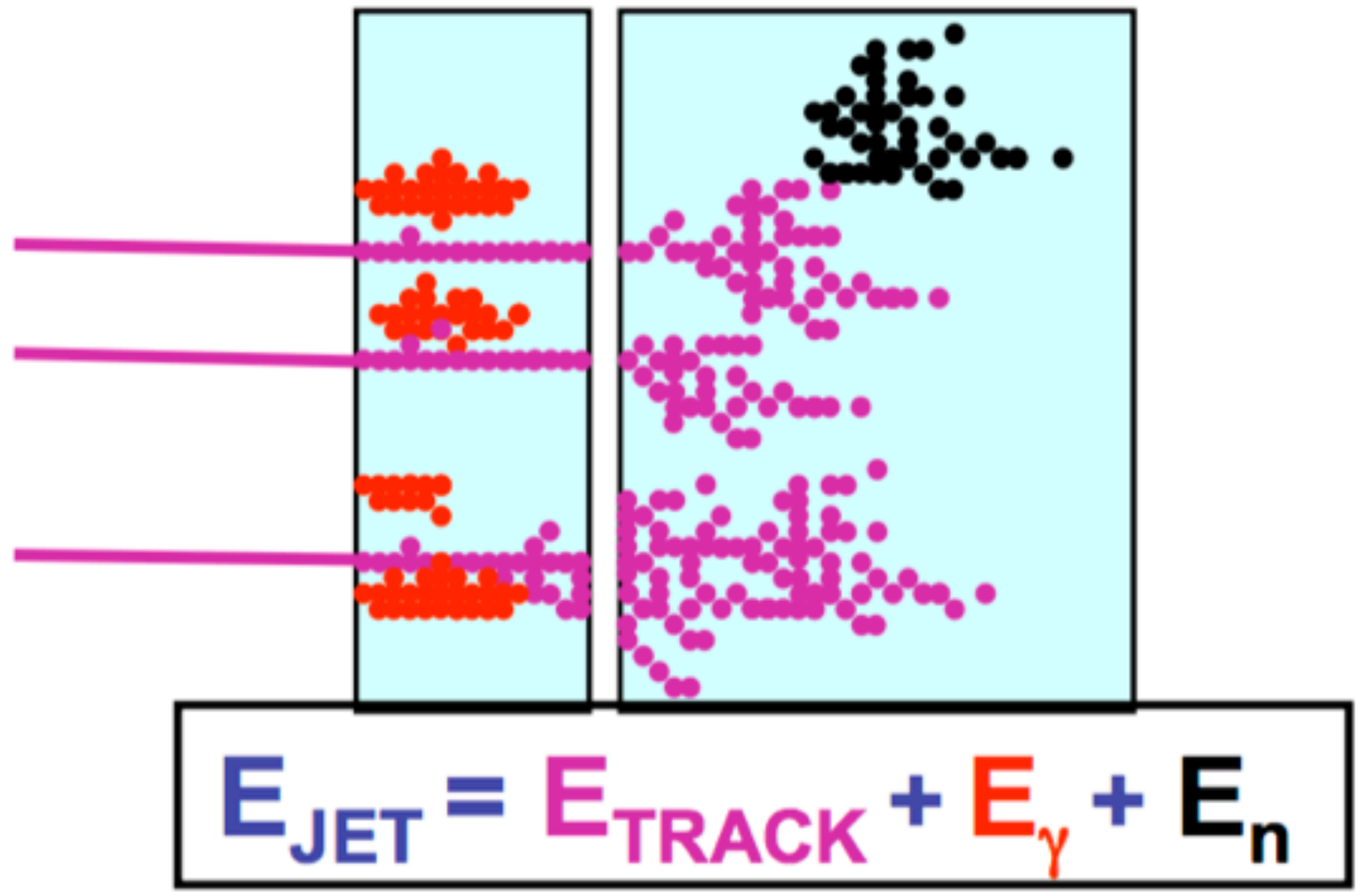
➡ Real need to improve ***jet energy resolution*** for the next generation of calorimeters @ HL-LHC



"Typical" jet:
~62% charged particles (mainly hadrons)
~27% photons
~10% neutral hadrons
~1% neutrinos

CMS follows the ***particle flow*** paradigm.

- Accurate reconstruction of ***each particle within a jet.***
- For each individual particle in a jet, use detector with best energy/ momentum resolution.
- Assignment of energy deposits to tracks: ***granularity* in the energy measurement.***
- ***Granularity*** is more important than energy resolution.



* Rule of thumb:

- Calorimeter can be considered granular if ***readout pitch*** is ***smaller*** than the ***Molière radius***.

Endcap calorimeter upgrade proposal

CALICE - inspired idea

An all-new 'imaging' calorimeter with unprecedented readout granularity that offers robustness and good performance through the full HL-LHC operational lifetime.

Requirements

Radiation tolerance

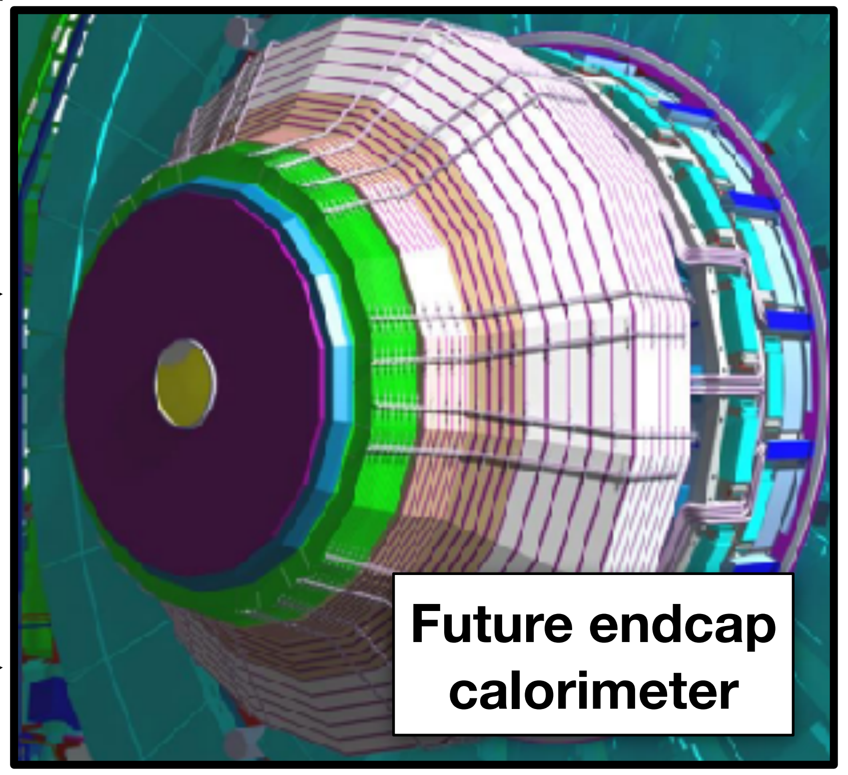
fully preserving the energy resolution after 3000 fb^{-1}

Dense calorimeter

preserve lateral compactness of showers

Fine lateral granularity

two shower separation + observation of narrow jets, minimise pileup contributions in energy & timing measurements



Fine longitudinal granularity

fine sampling of the shower: good energy resolution, pattern recognition, pile-up discrimination, …

Precision time measurement

high energy showers for pile-up rejection, primary vertex identification

Contribute to L1 (Hardware) trigger

New calorimeter endcap (CE): High-Granularity Calorimeter (HGCAL)

HGCAL = Sampling calorimeter

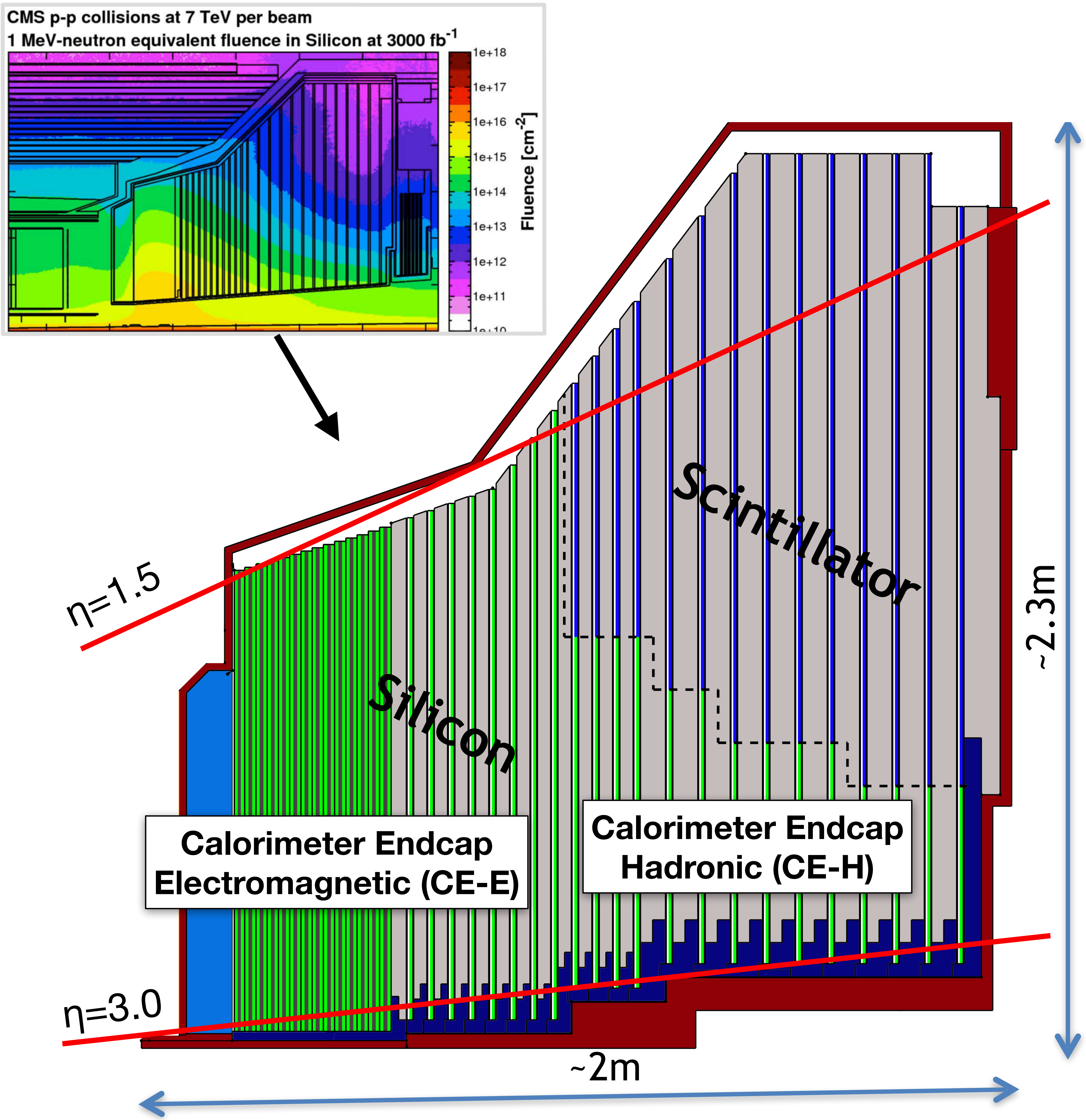
- Hexagonal **silicon sensor** based modules in CE-E and high radiation regions of CE-H.
- **Scintillating tiles** with on-tile SiPM readout in low-radiation regions of the CE-H.

Active material

Both endcaps	Silicon	Scintillators
Area	**~620m²**	~370m²
#Modules	~27000	~4000
Channel size	**0.5 - 1 cm²**	4-30 cm²
#Channels	**~6 M**	~240k
Op. temp.	-30 ° C	-30 ° C

Passive material

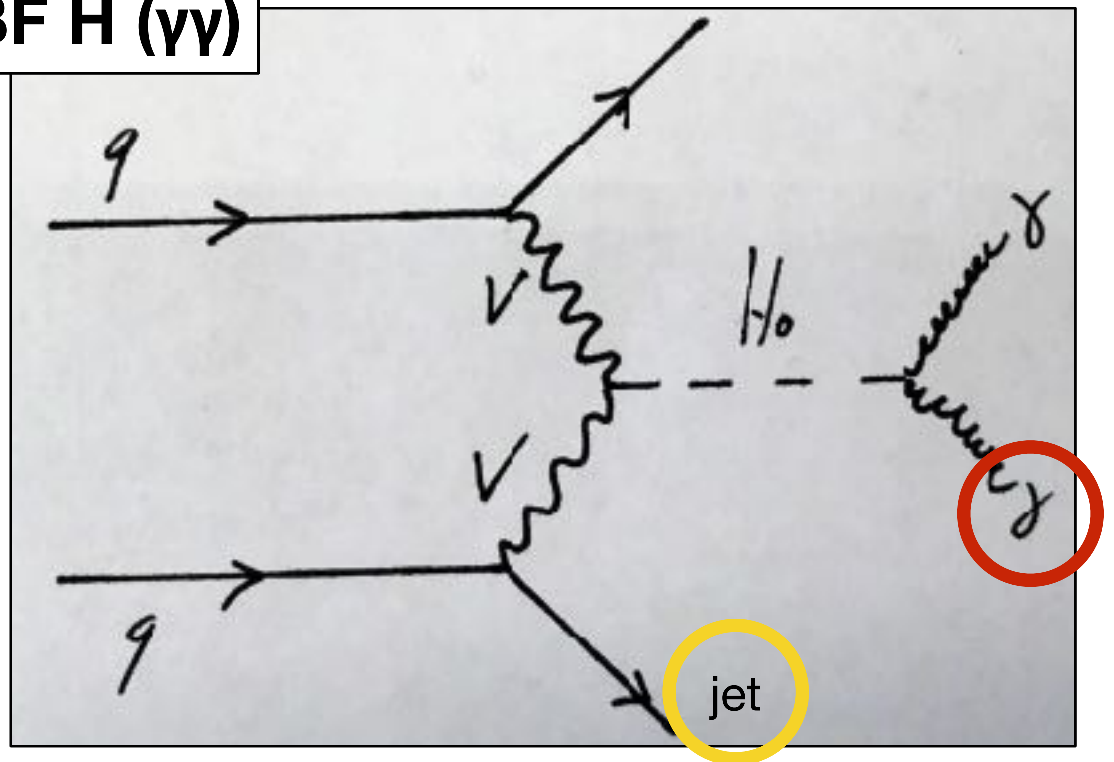
Per endcap	CE-E	CE-H (Si)	CE-H
Absorber	Pb, CuW, Cu	Stainless steel, Cu	
Depth	27.7 X_0	10.0 λ	
Layers	26	7	14
Weight	~230 t / endcap		



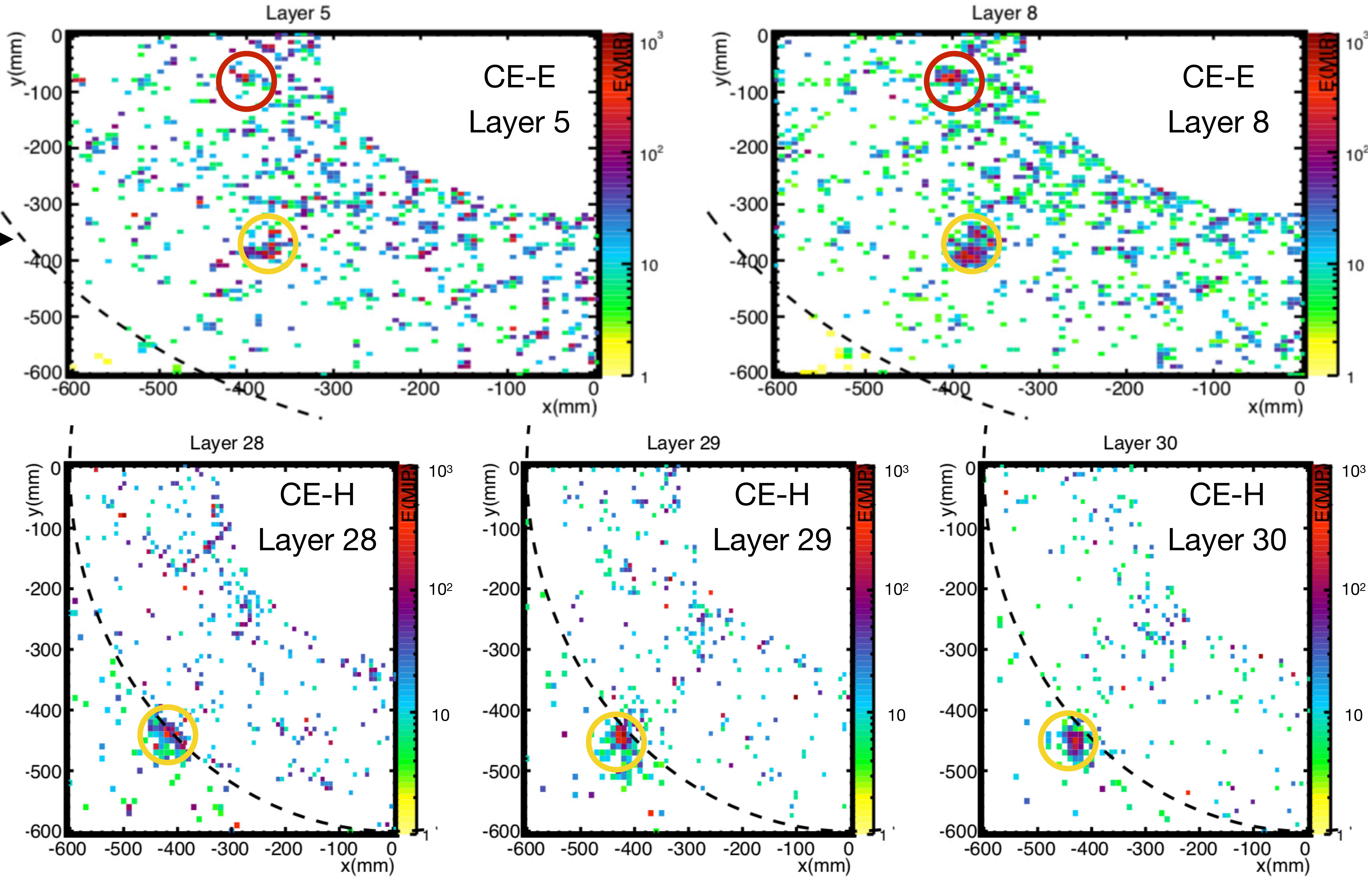
Idea: HGCAL will be 3D imaging calorimeter

Simulated VBF H (γγ) signatures in the granular endcap calorimeter

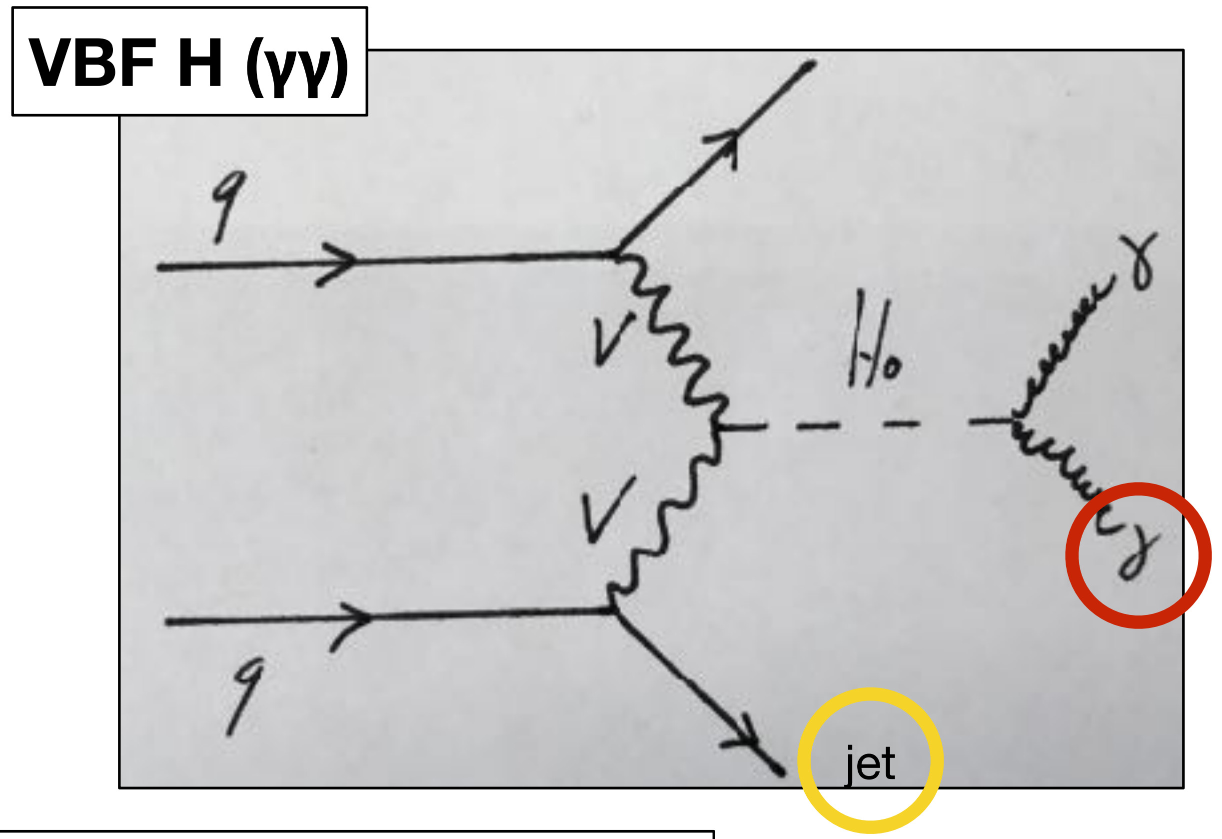
VBF H (γγ)



+ 200 PU

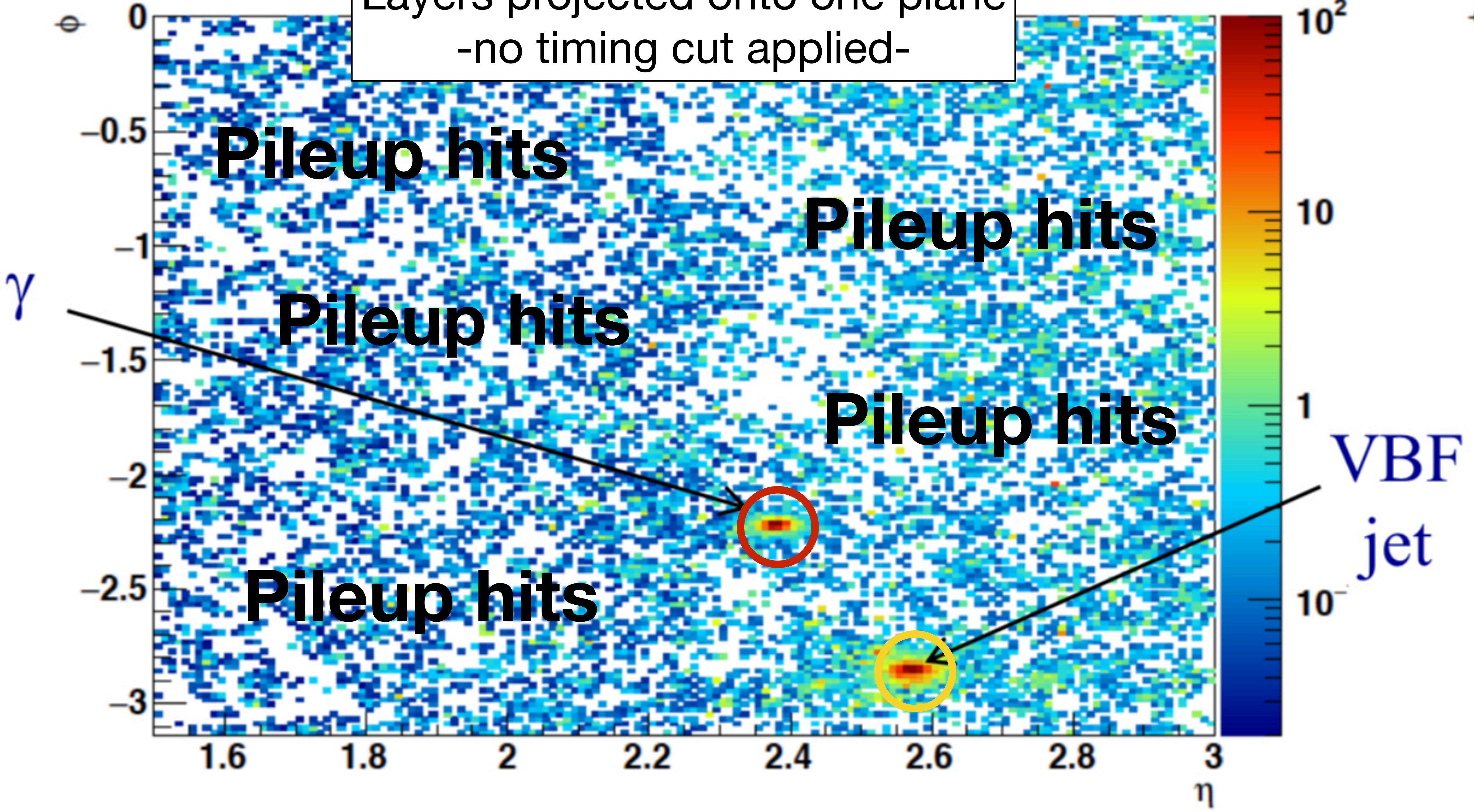


Idea: HGCAL will be 3D imaging calorimeter with timing capabilities

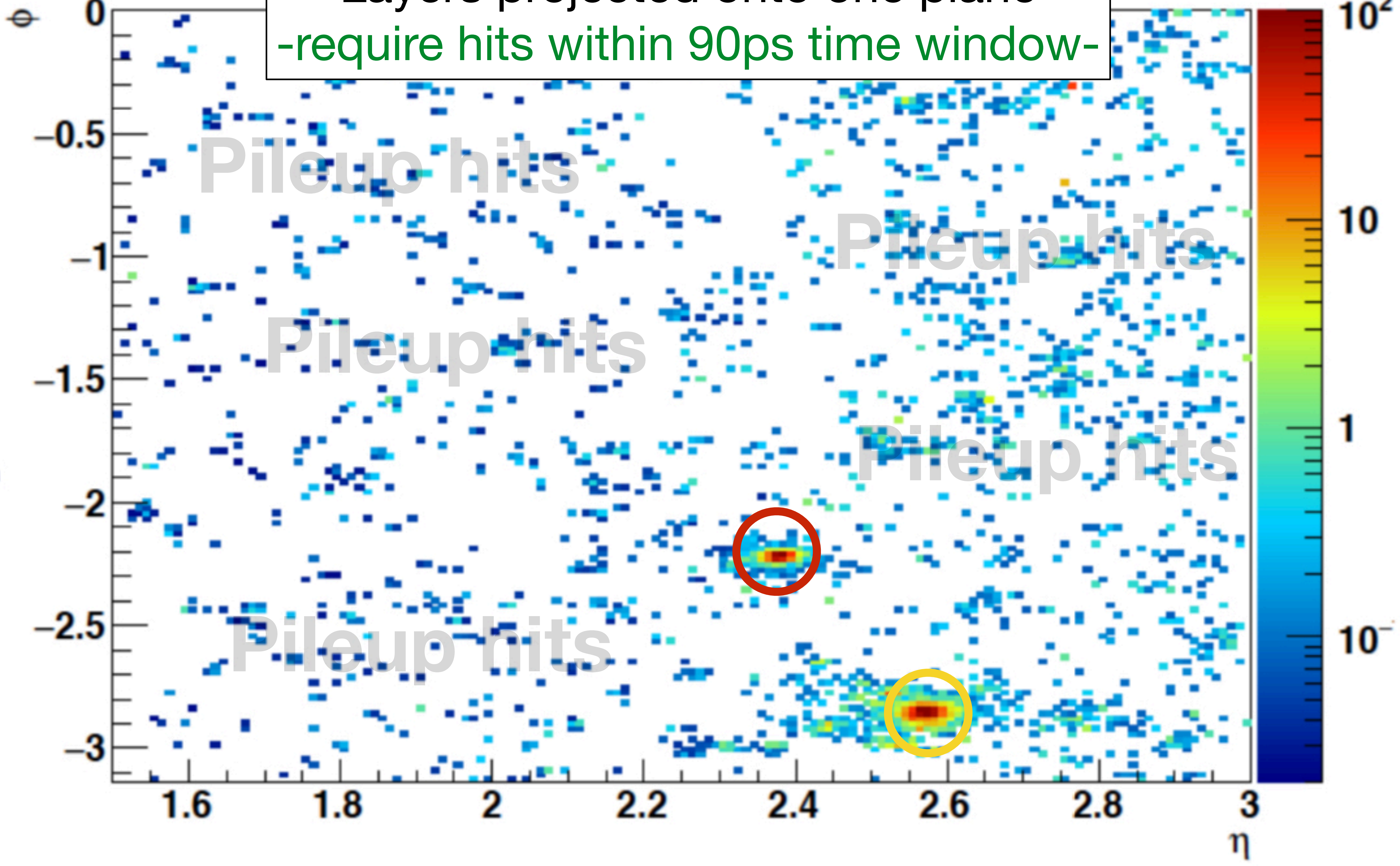


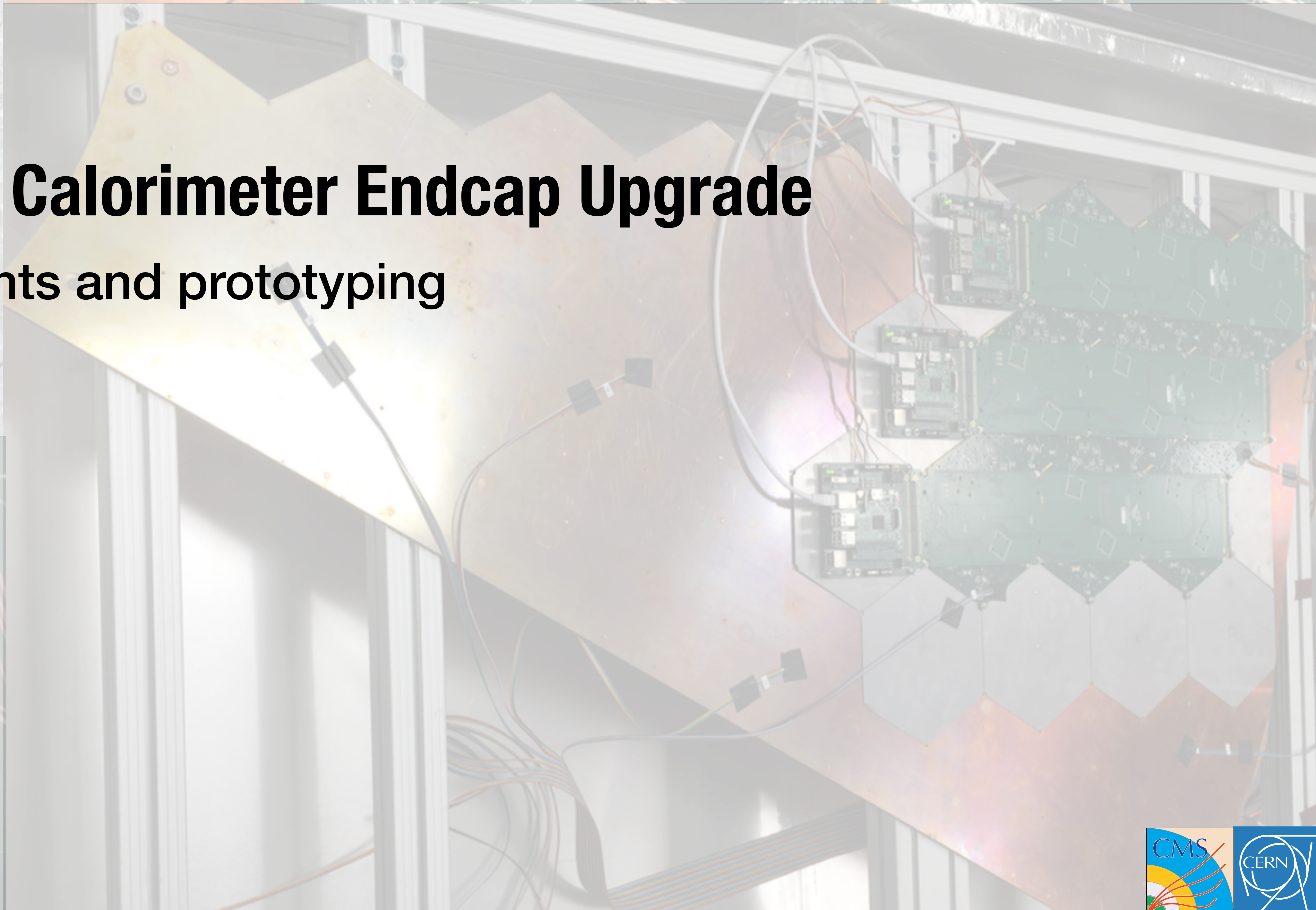
+ 200 PU

Layers projected onto one plane
-no timing cut applied-



Layers projected onto one plane
-require hits within 90ps time window-

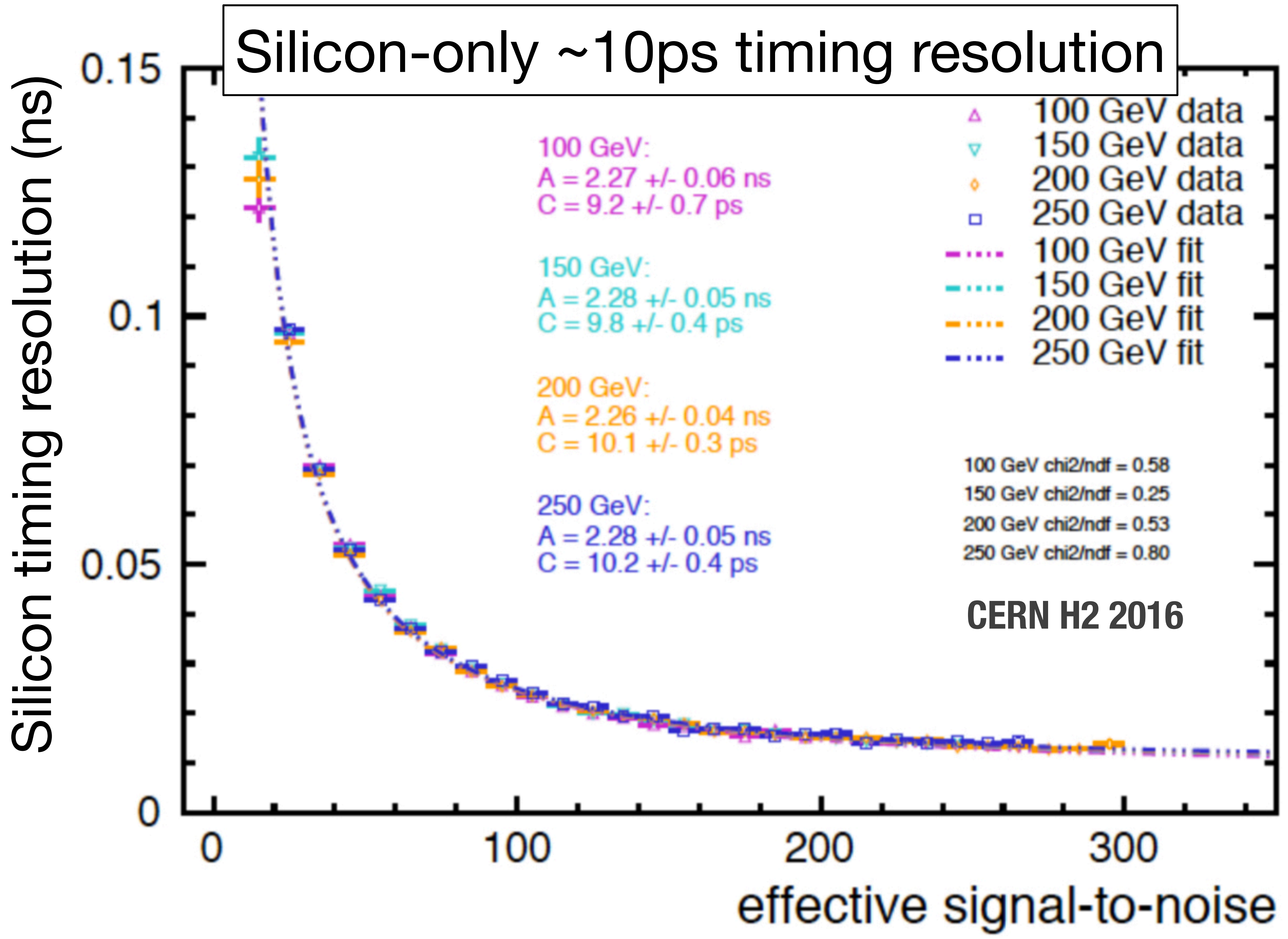


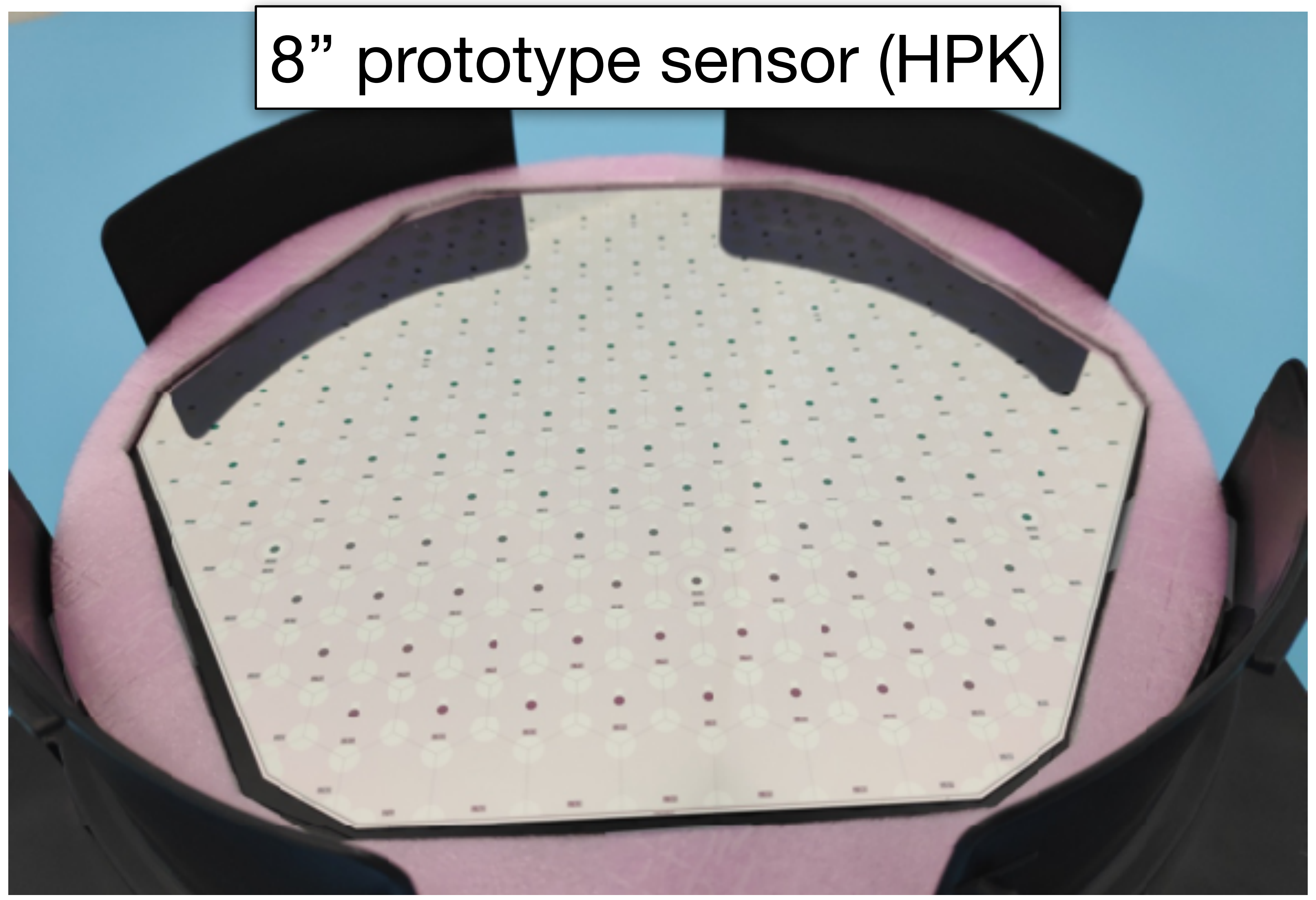


CMS High Granularity Calorimeter Endcap Upgrade

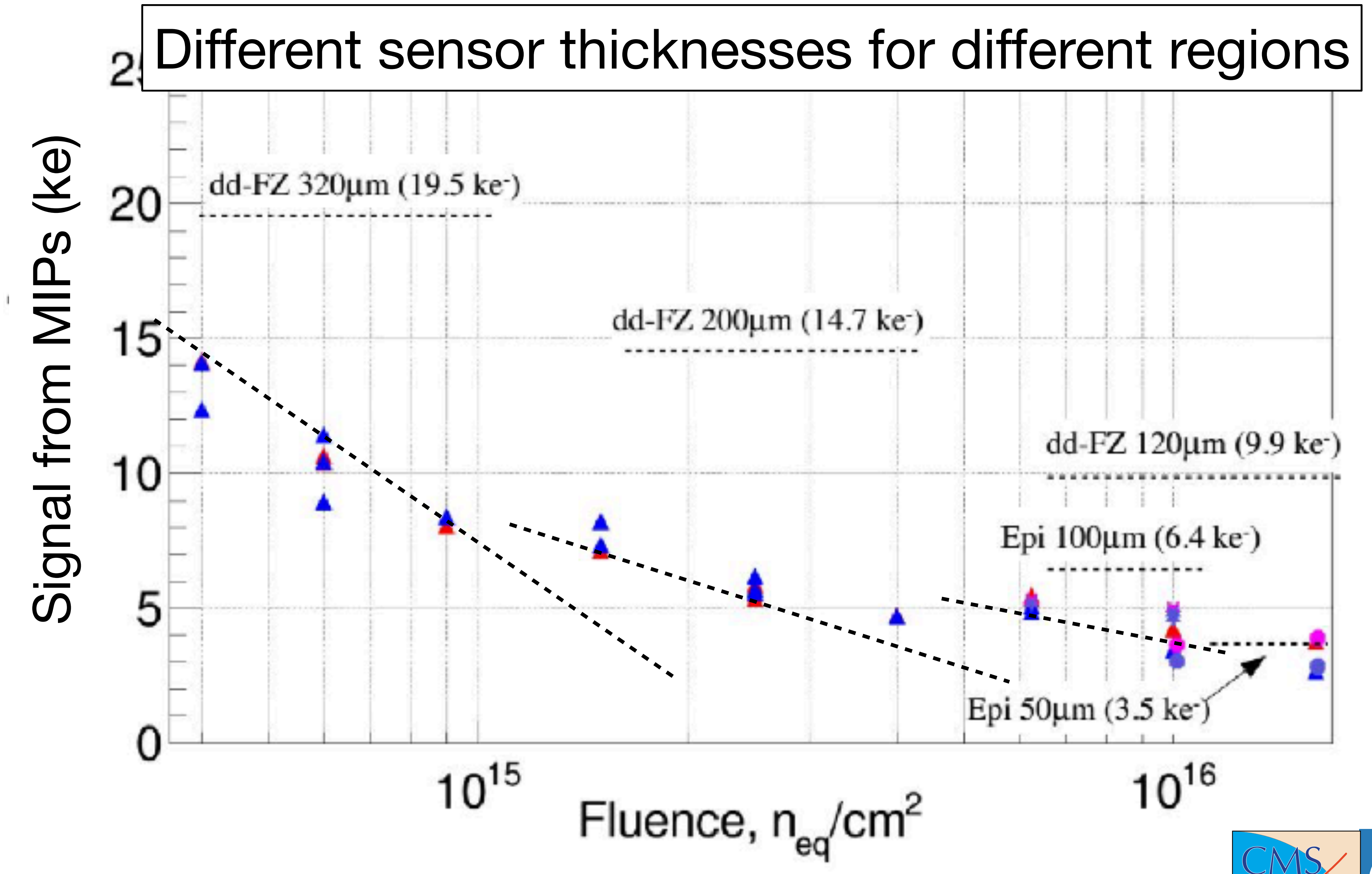
Components and prototyping

~620m² of 8” silicon sensors: Radiation hard and fast signals





- ***8” hexagonal geometry***: most efficient use of Si area.
- Bulk: p-type, found to be more irradiation-tolerant than n-type.
- ***Sensor thickness and cell size vary*** with radiation levels:
  - 120, 200, 300 μm thickness.
  - 0.5 and 1cm² cell size.



Minimising degradation

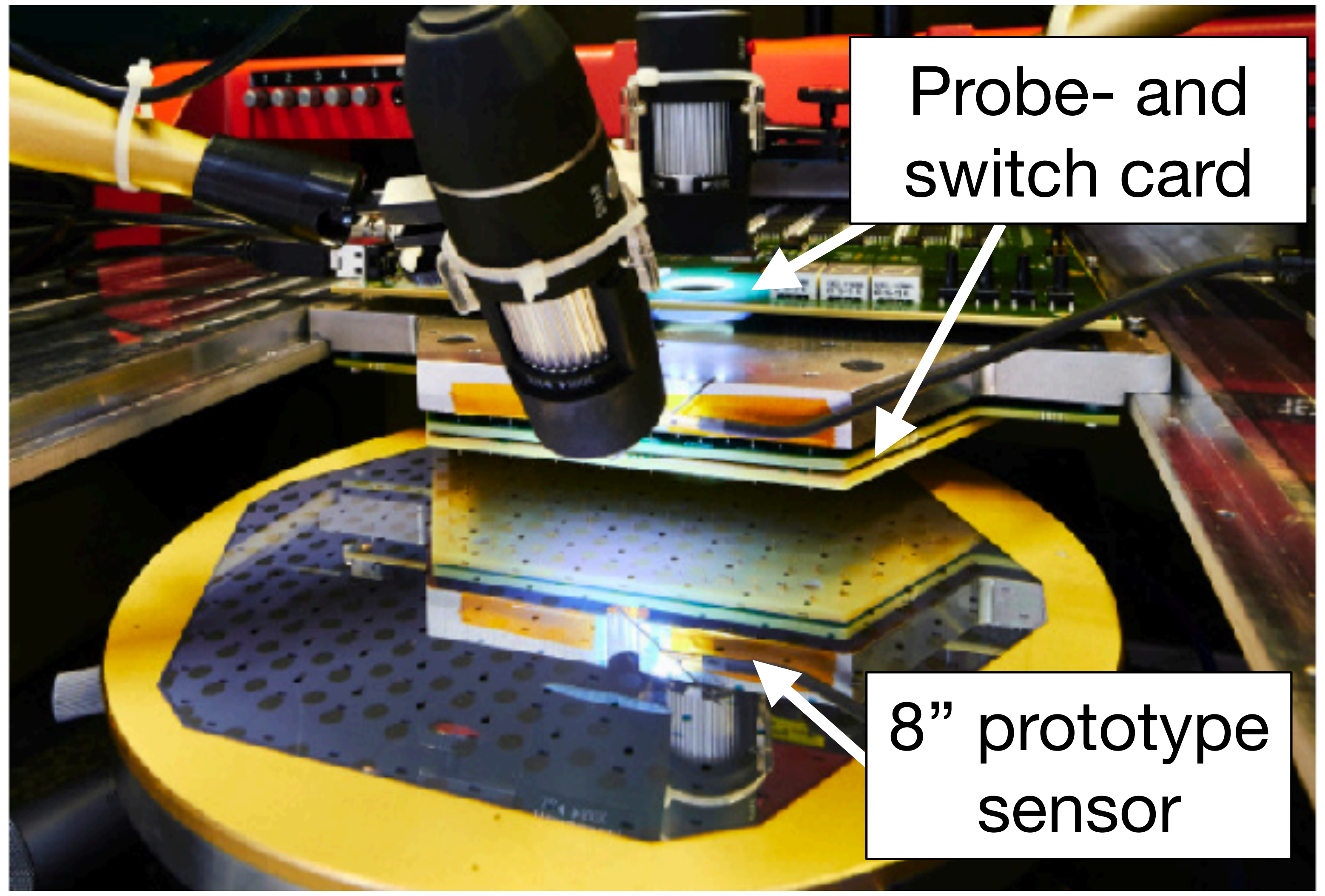
- Operation at -30° C: Reduce **increasing bulk leakage current**.
- Increasing the bias voltage up to -800V to reduce **signal loss**.

Electrical sensor characterisation is crucial

<u>Important:</u> leakage current = power dissipation, capacitance ~ noise

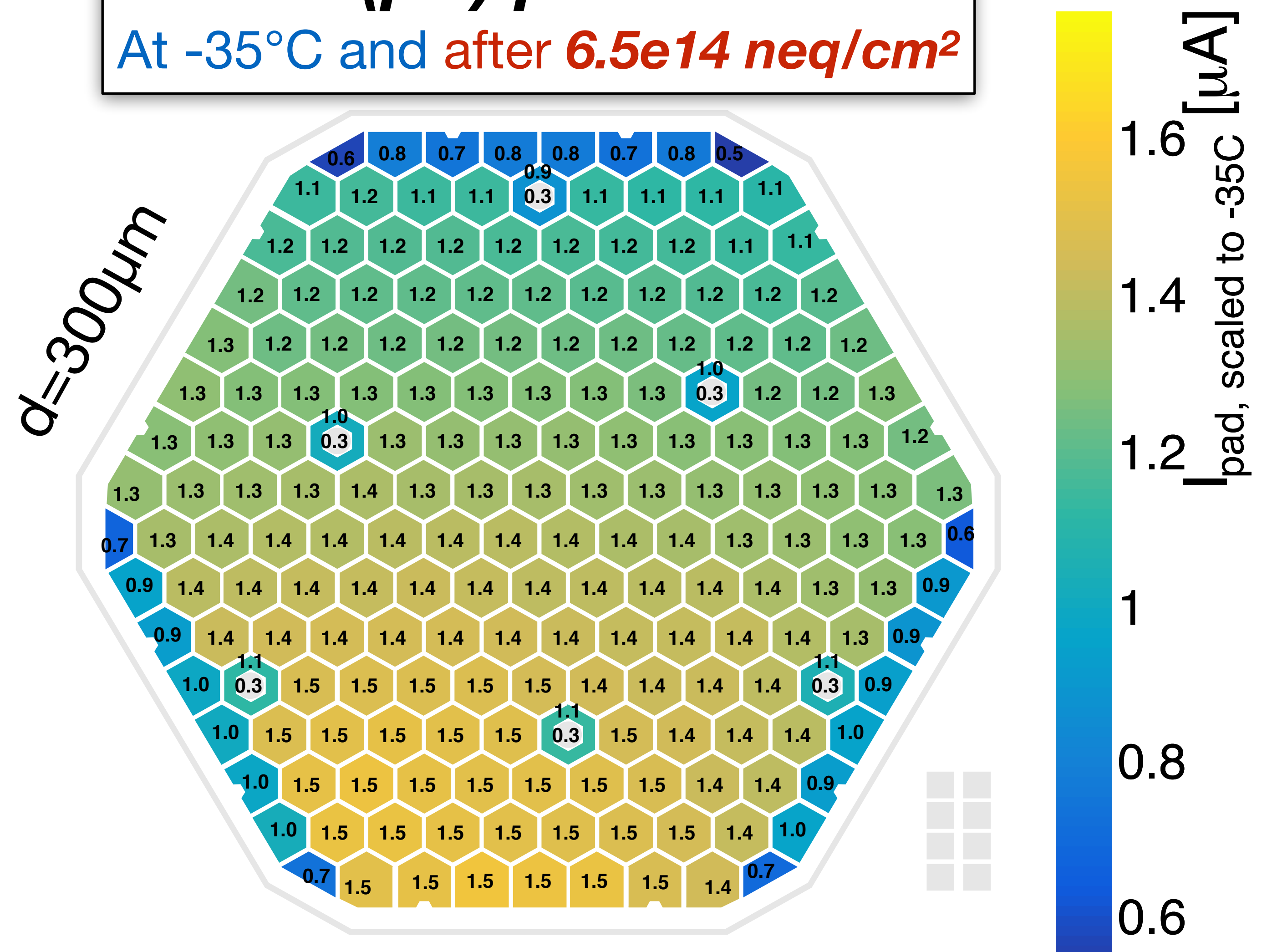
★ *Switching and probe-card setup*

- Contact all cells via pogo-pin card, all pads biased while one is tested.
- Switch between channels using switching card.
- **Temperature control of the sensor**, important after irradiation to O(e14-e16) neq/cm².



O(μA) per cell

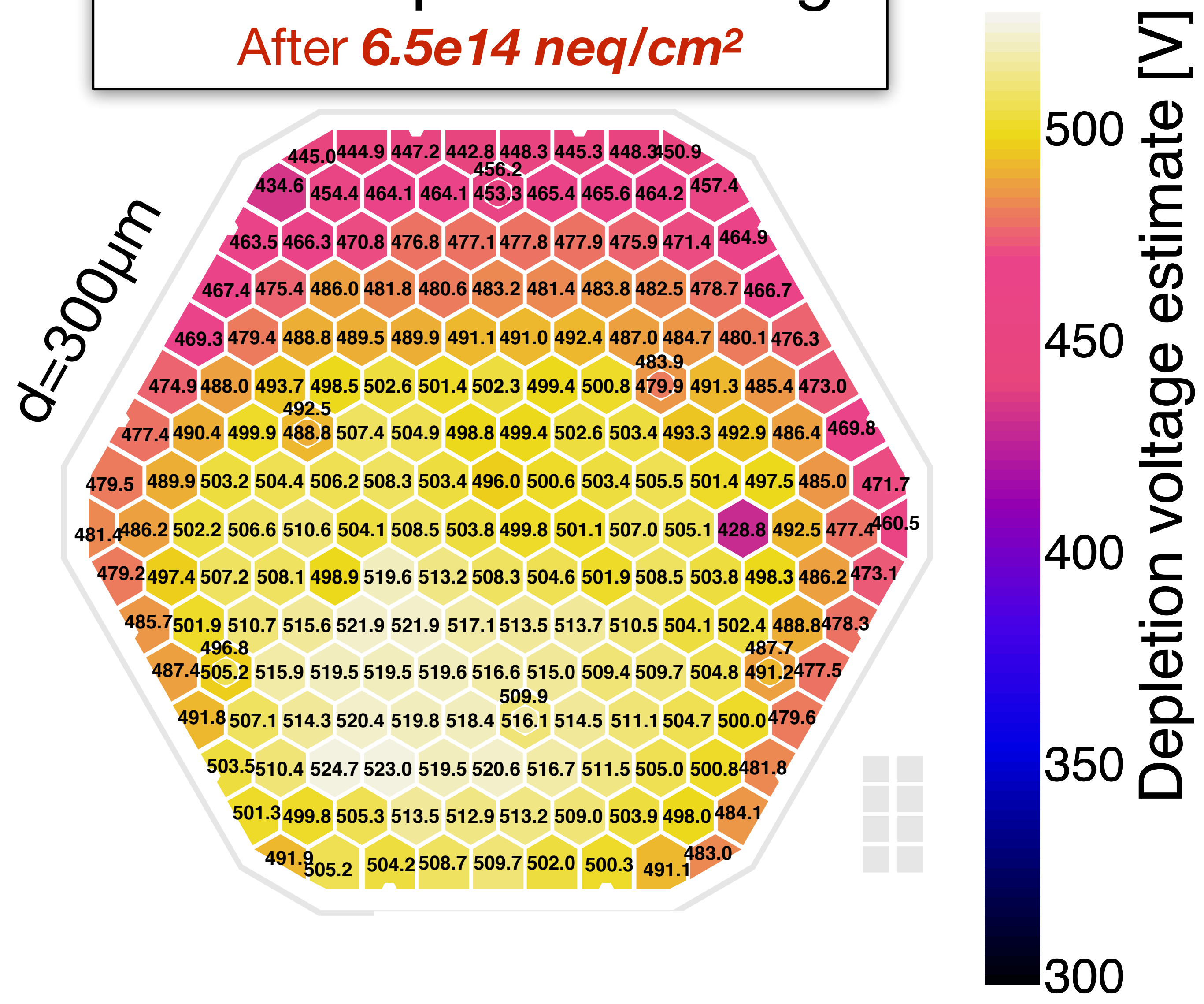
At -35°C and after ***6.5e14 neq/cm²***



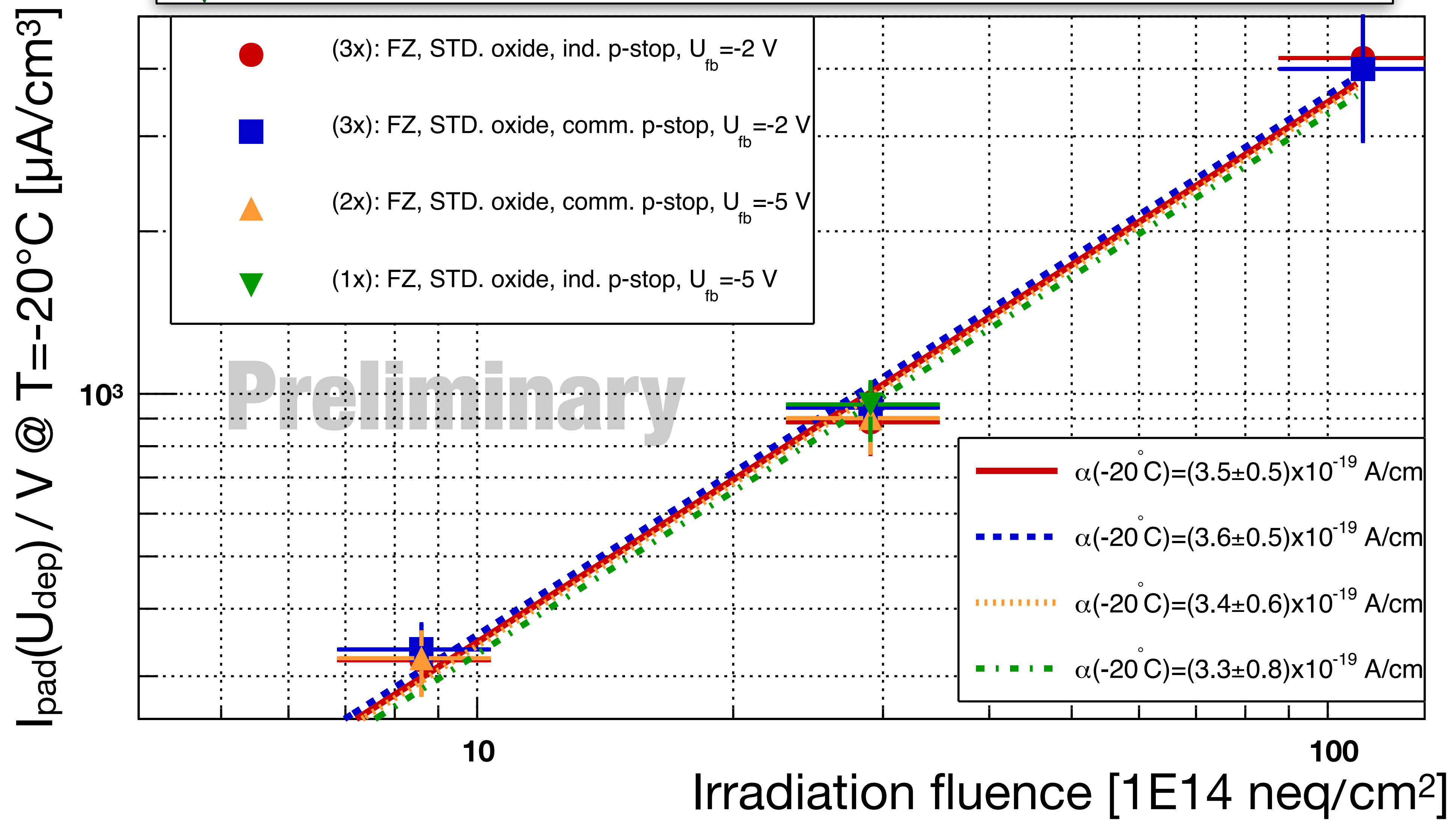
Values for U = 800.0 V

~500V depletion voltage

After ***6.5e14 neq/cm²***

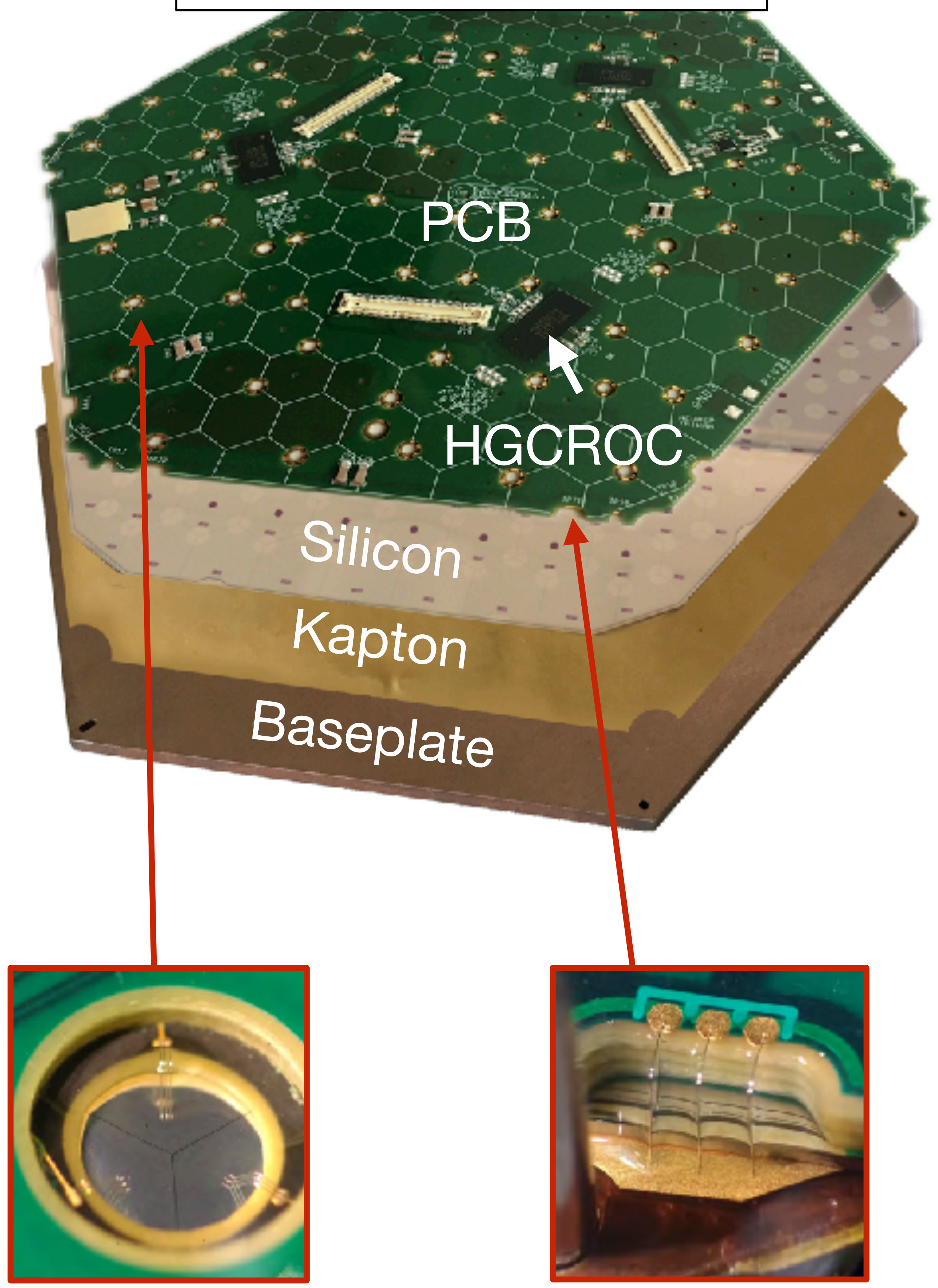


✓ As expected: ***Leakage current ~ fluence***



Silicon modules and cassettes

8” prototype module



Silicon modules

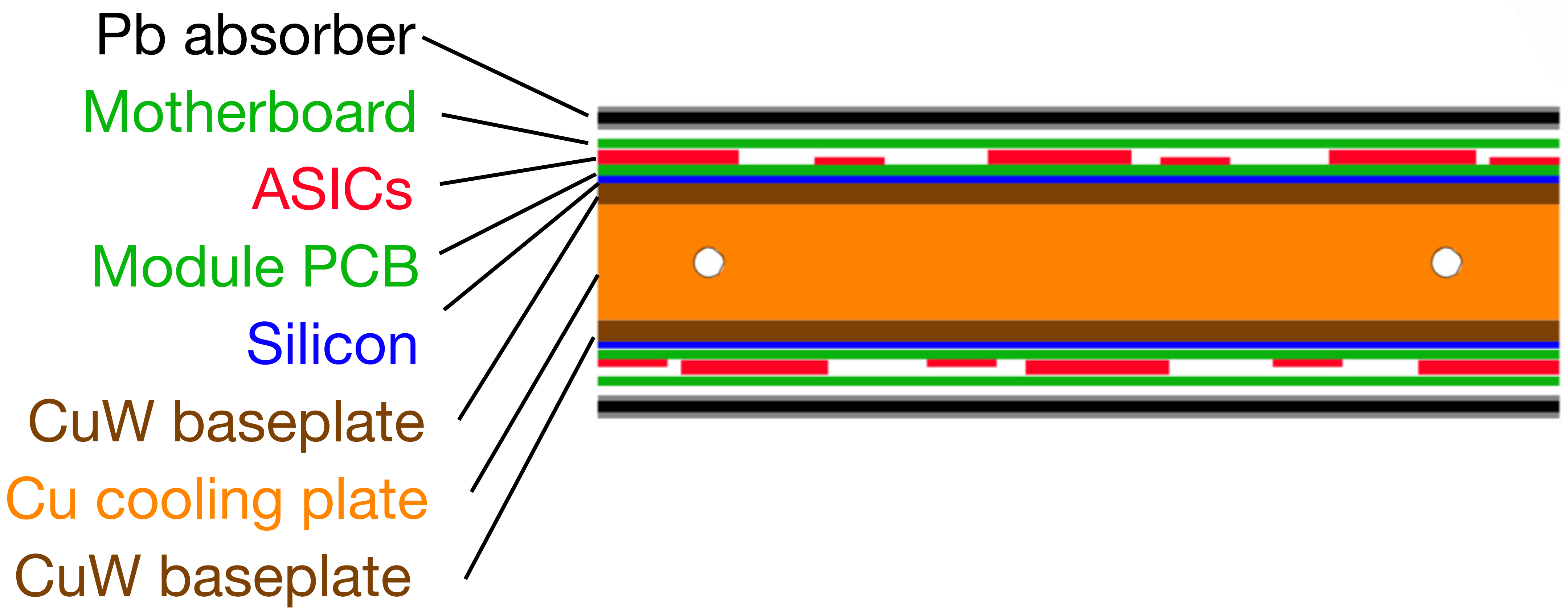
Sandwich of **PCB**, **sensor**, biasing/insulation layer and **baseplate** for rigidity/cooling.

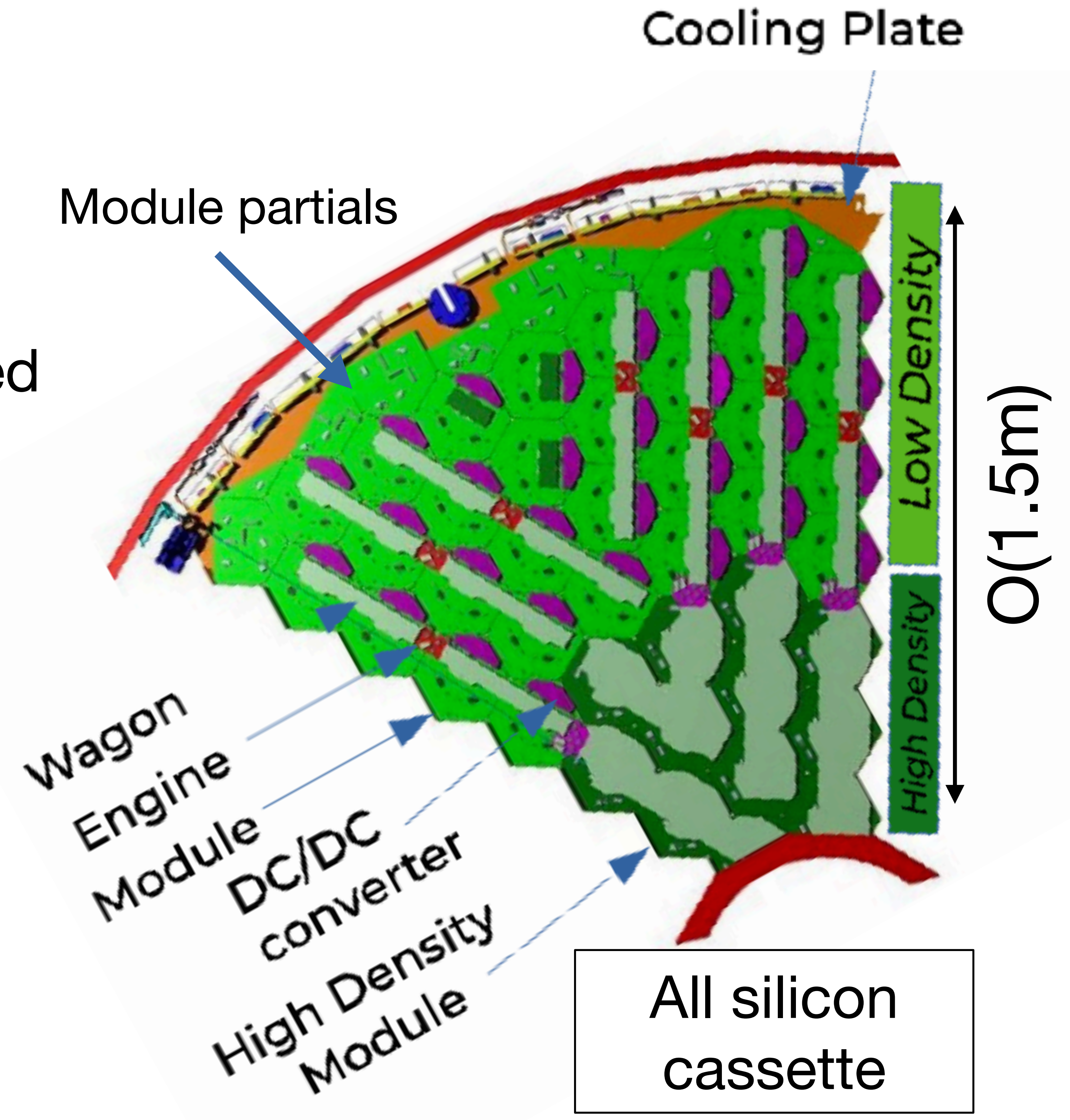
- Wire-bonding from PCB onto the silicon.
- CE-E: CuW baseplates act as absorbers.
- CE-H: PCB baseplates (good thermal properties and cheaper).

CE-E cassettes

Self-supporting sandwich structures (with absorbers).

- Modules placed on both sides of Cu cooling plate and closed with Pb plates.





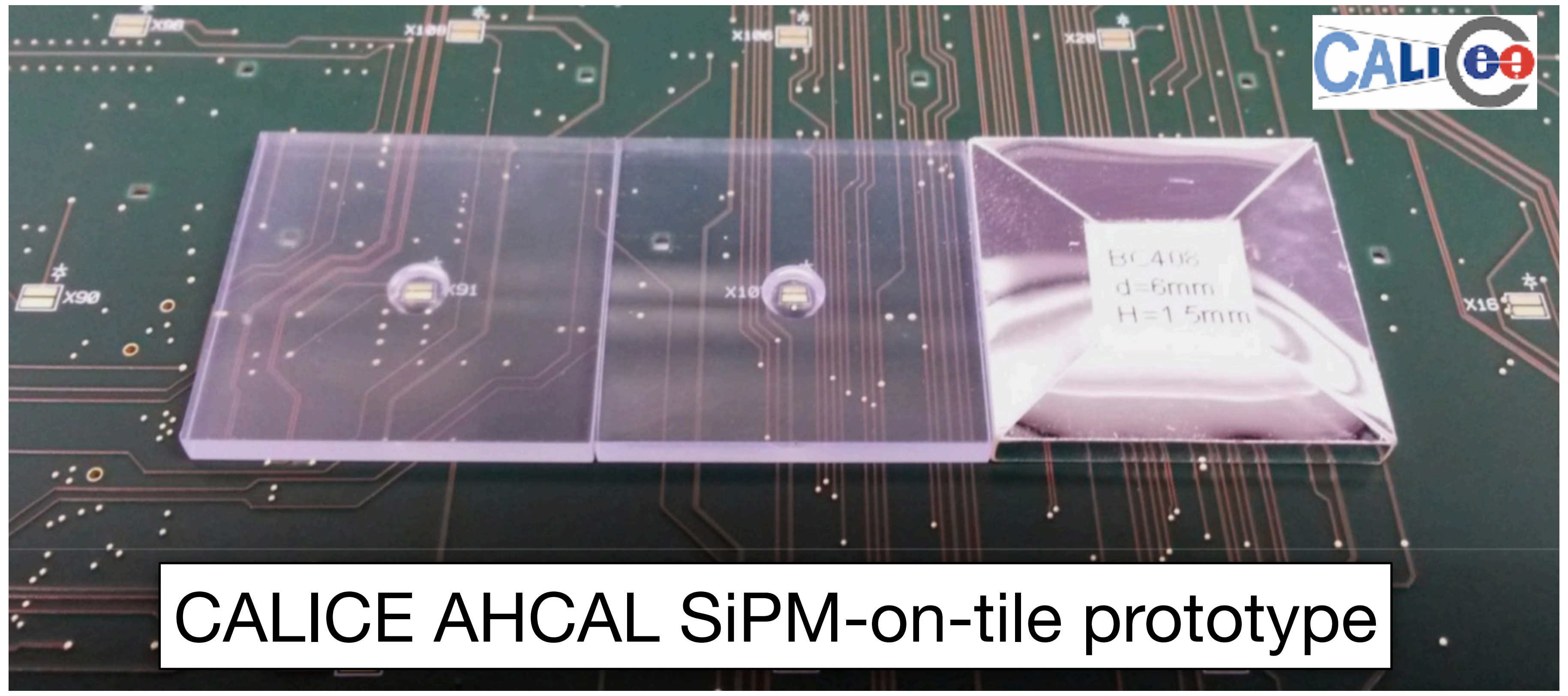
~370m² of scintillator for regions of lower radiation

- ***Cheaper*** than silicon.

- Rely on experience from CALICE and past CMS HCAL upgrade.

➡Radiation hardness of scintillators & Si-PMs well understood.

➡Overall ***S/N for MIP*** remains ***> 5*** after 3000 fb^{-1}.

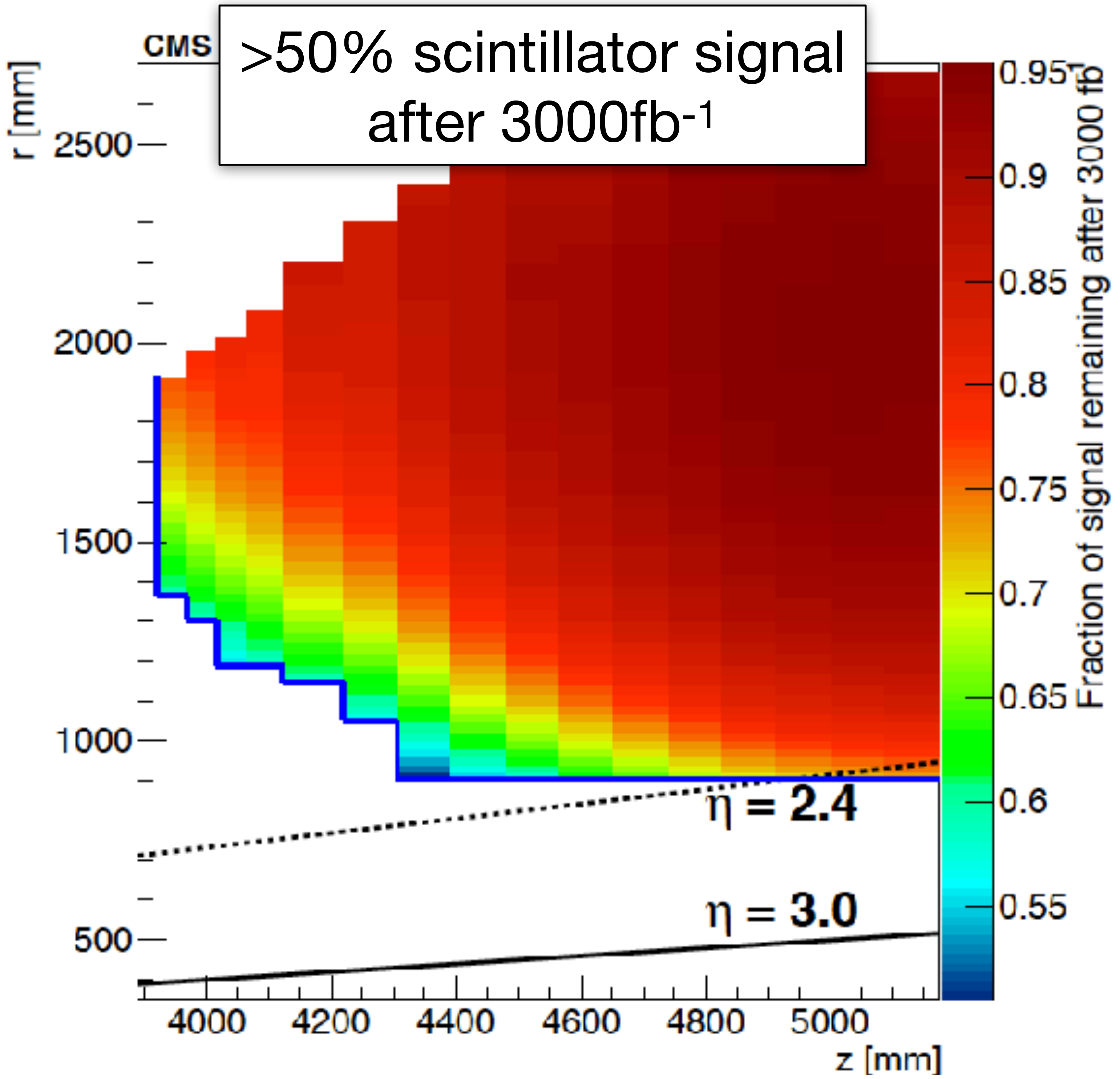


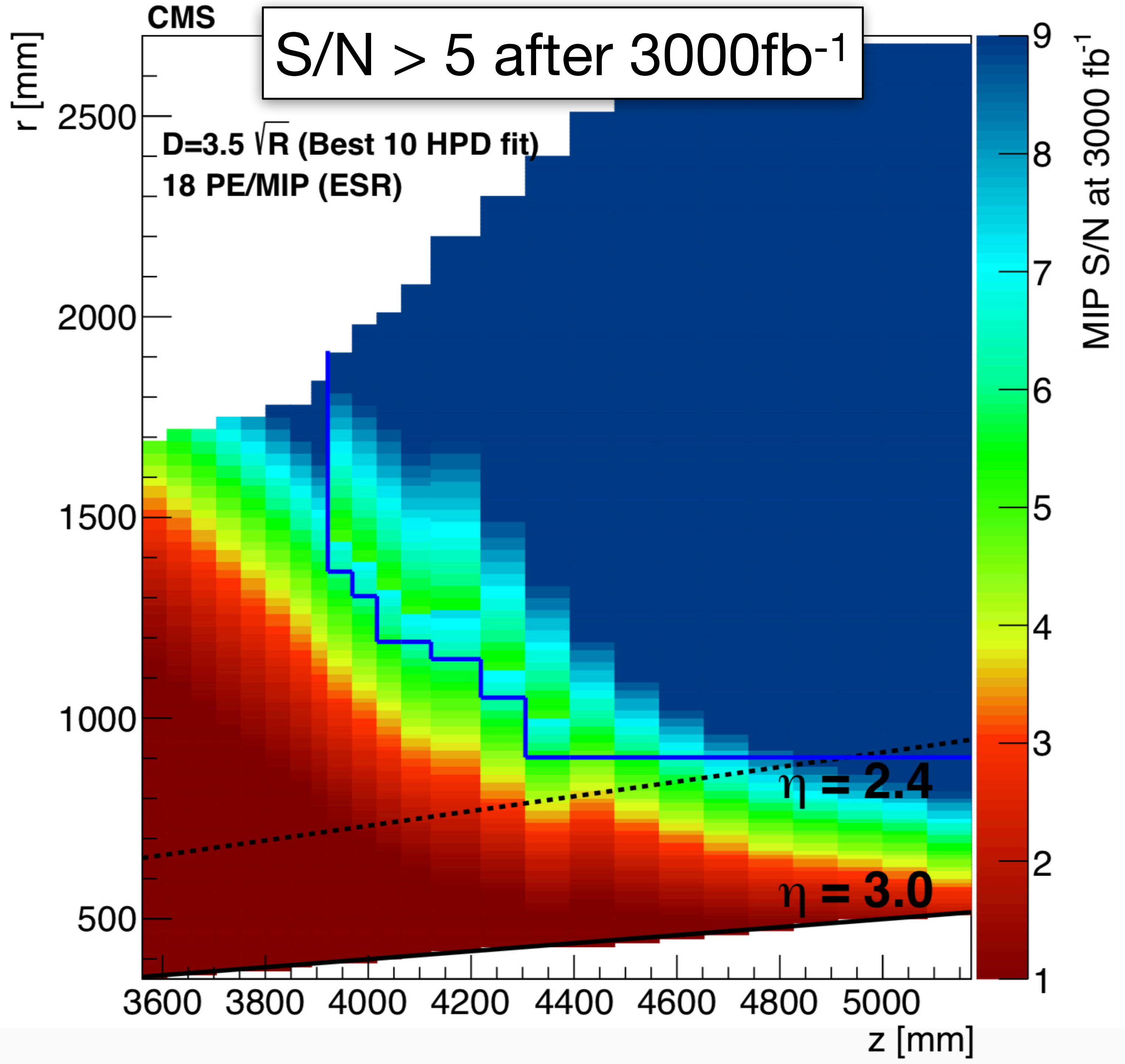
SiPM-on-tile design

- 240k SiPMs integrated into the PCB, need to be cooled.
- Light ***readout*** directly on ***detector***.
- More compact and cost-effective.

R&D from CALICE—>CMS

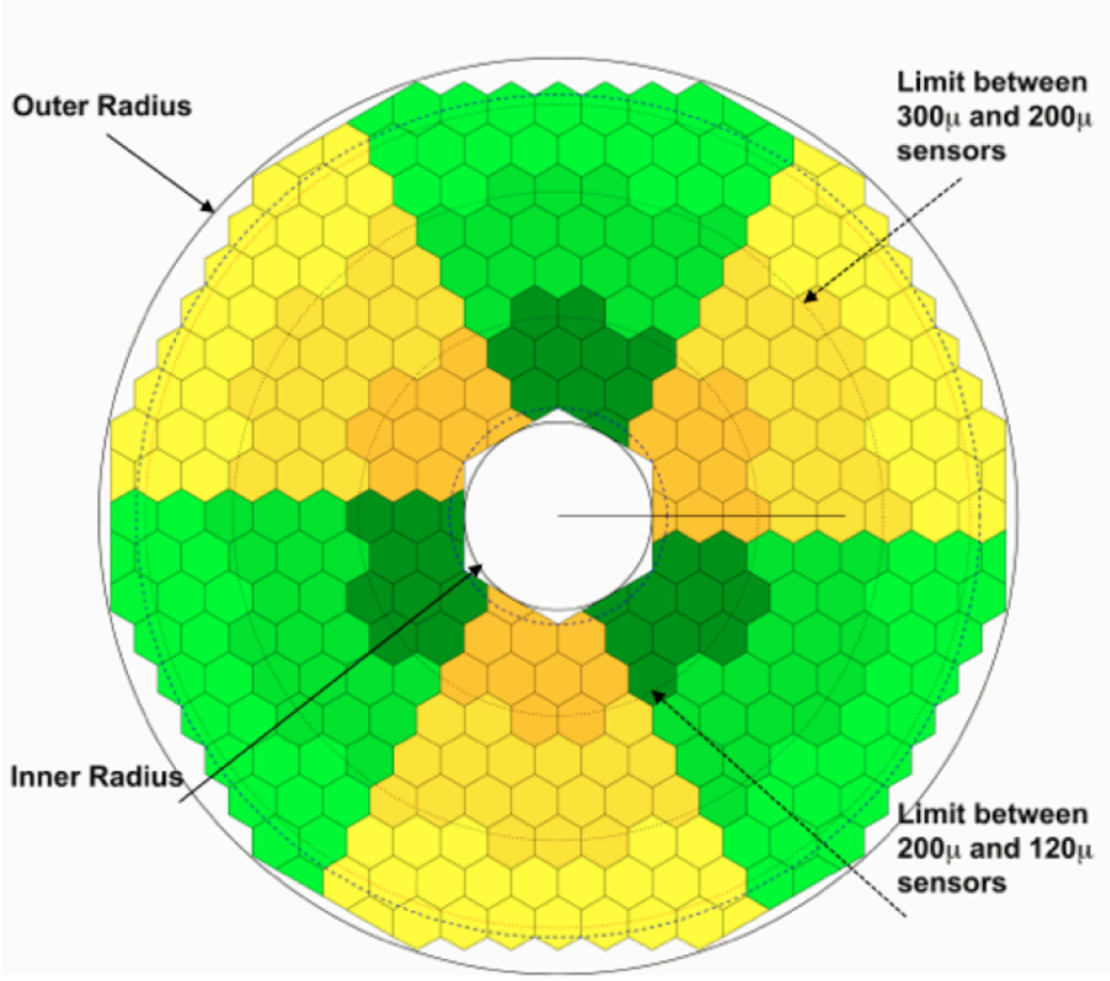
- e.g. validate interplay SiPM - ROC.
- e.g. tile geometry and wrapping optimisation.
- …

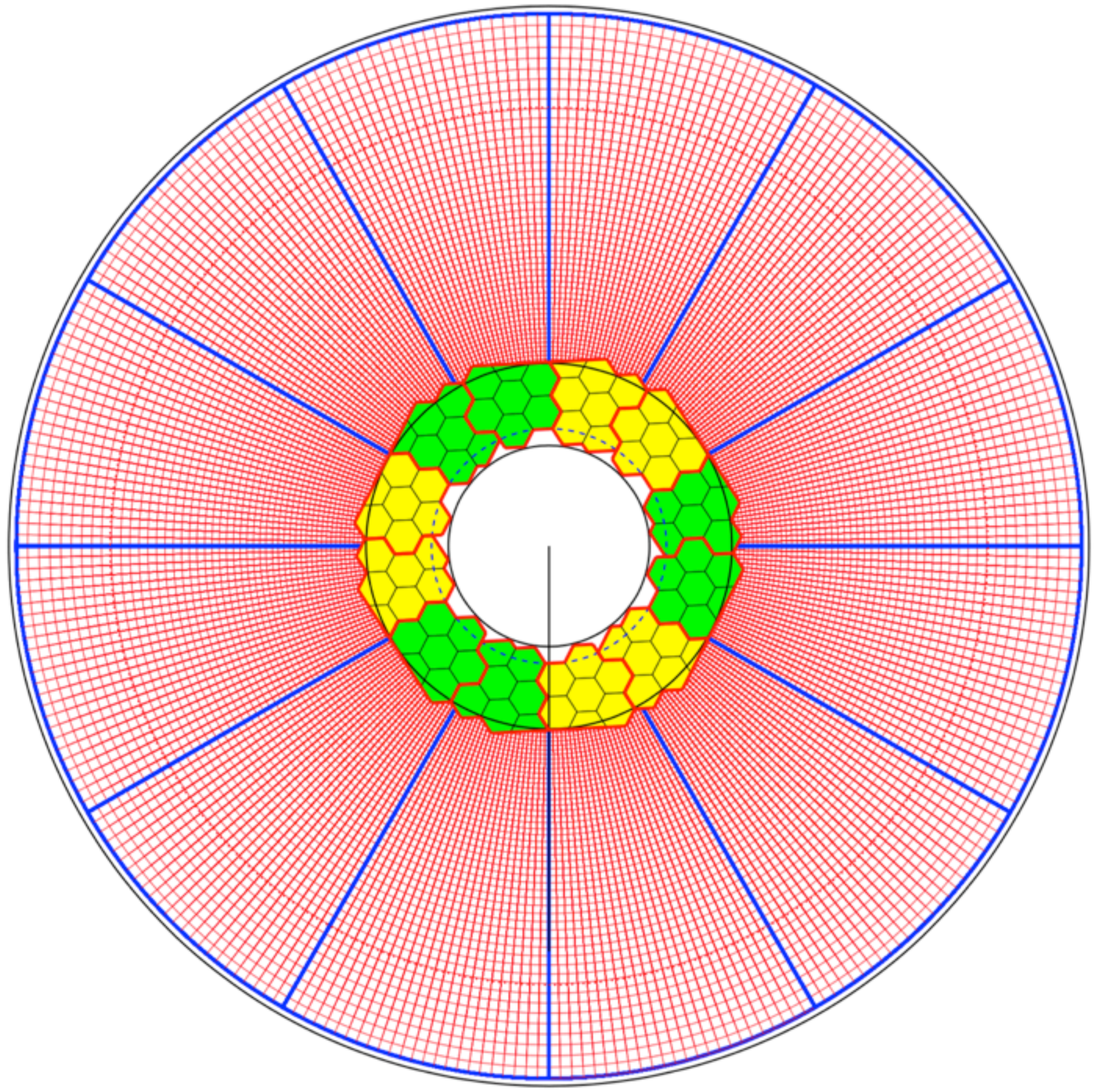




Arrangement of active modules

Silicon-only layer (in CE-E) showing “cassettes” and different sensor thicknesses.

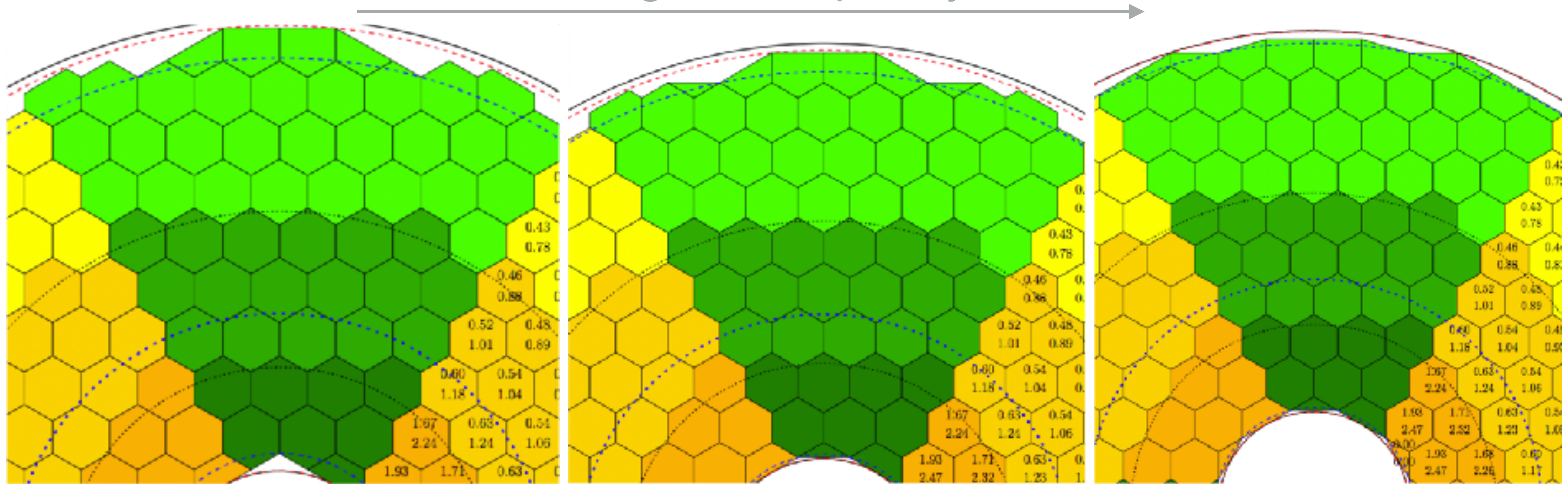




Mixed layer (in CE-H) with silicon at high η and scintillator+SiPM at low η.

coverage & complexity

Inner/Outer coverage:
Best coverage by O(10) variants of hexagonal modules.

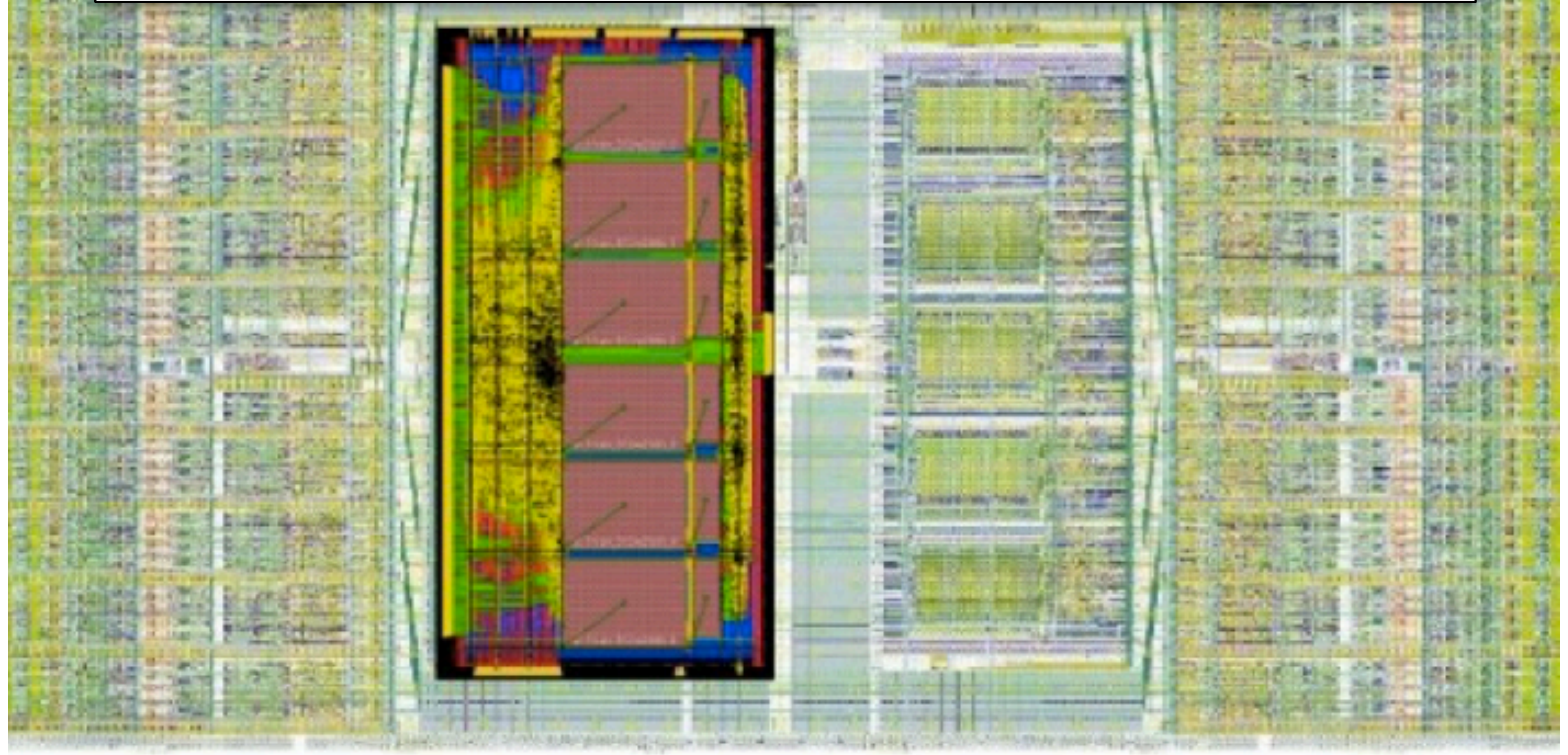


Front-end electronics are challenging

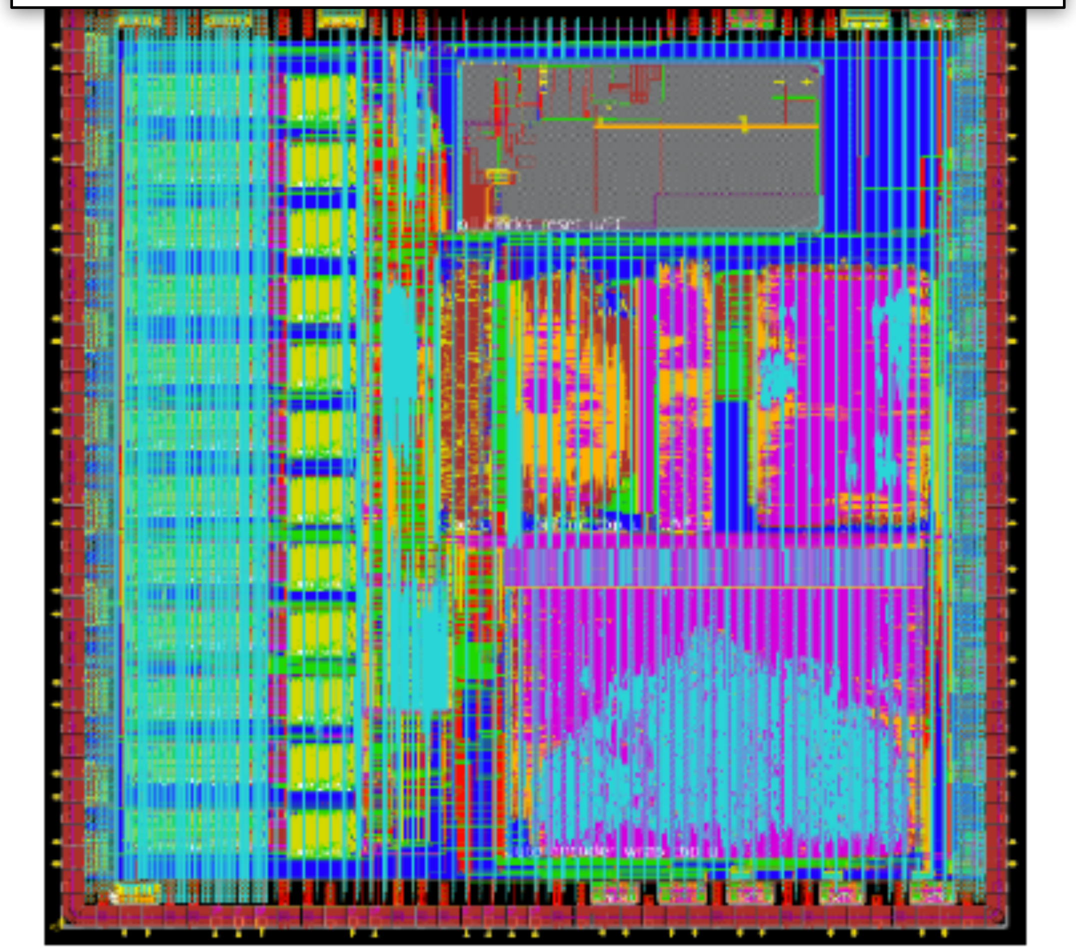
HGCAL FE electronics requirements:

- ***Low noise*** (<2500e) and ***high dynamic range*** (0.2fC -10pC).
- Timing information to ***tens of picoseconds***.
- ***Radiation tolerant.***
- ***<20mW*** per channel (cooling limitation).
- ***Zero-suppression*** of data to transmit to DAQ.
- Computation of ***trigger sums*** for L1 trigger.

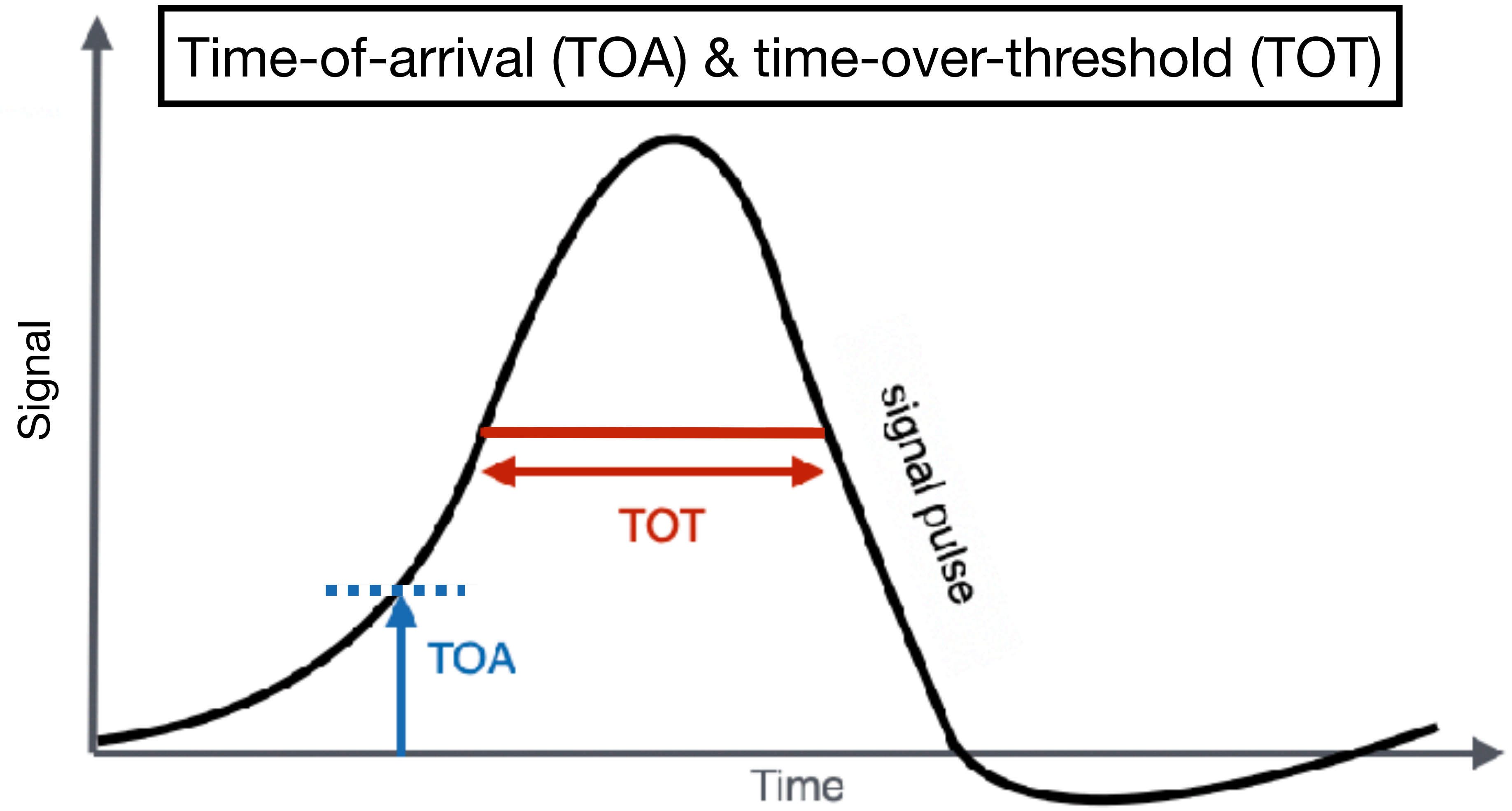
V3 ***HGCROC*** ASIC both for silicon and SiPMs

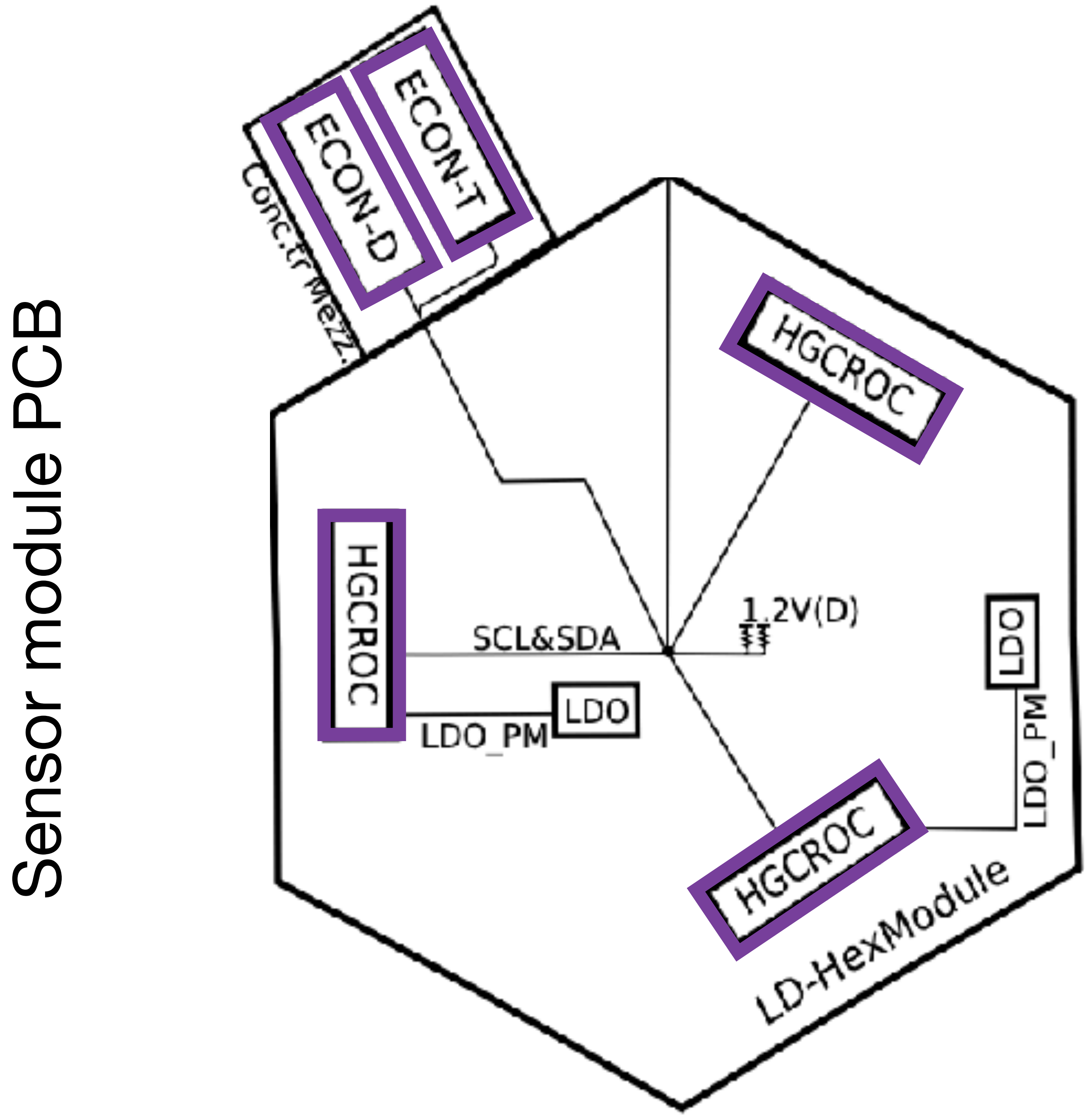


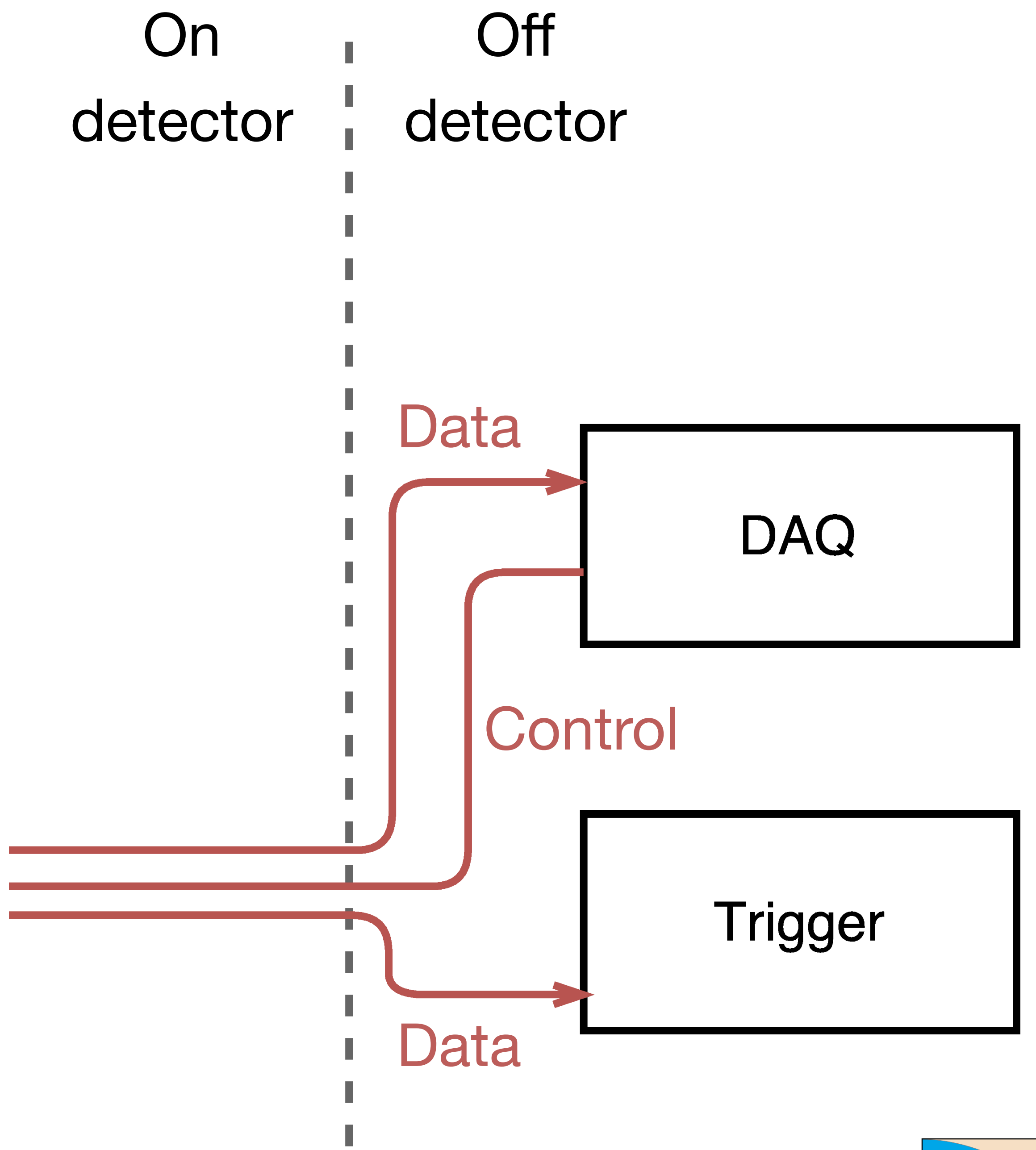
ECON as concentrator ASIC



Time-of-arrival (TOA) & time-over-threshold (TOT)







HGCAL trigger = 3D clustering

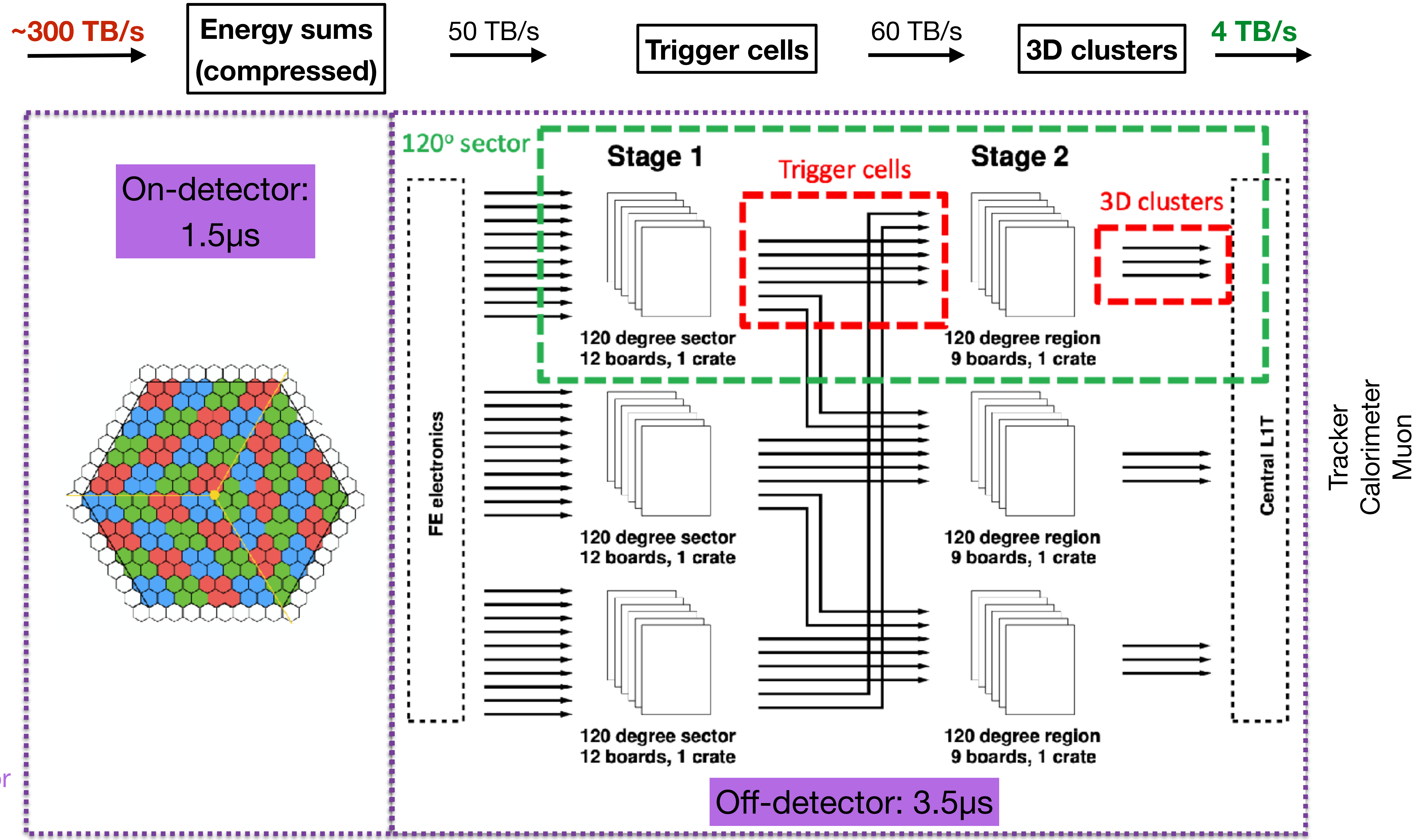


Diagram is for one endcap

Due to design: Requirements become features

✓ **Radiation tolerance**

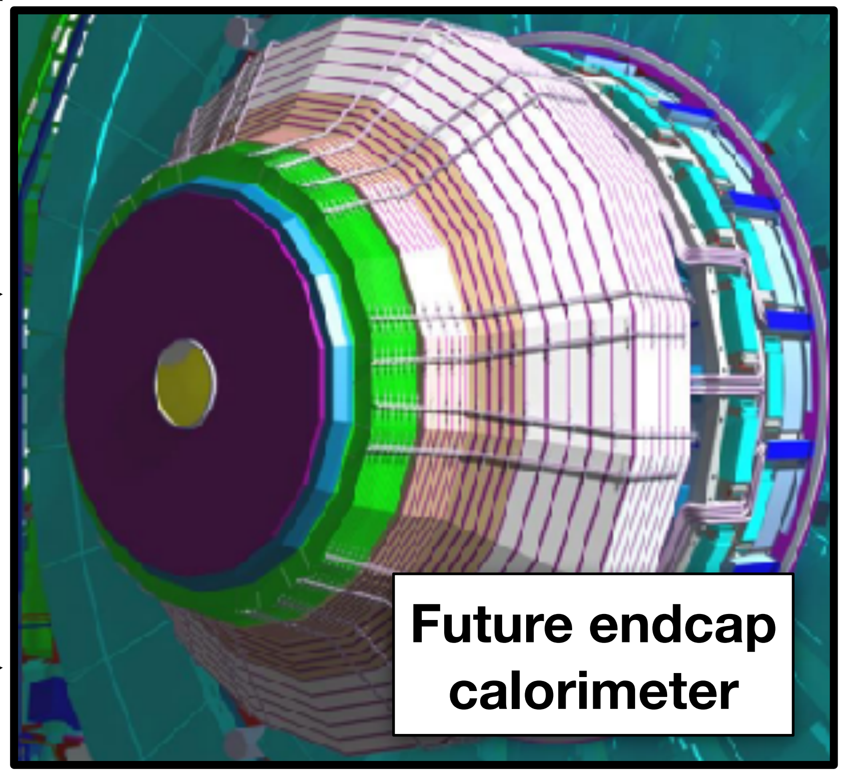
fully preserving the energy resolution after 3000 fb^{-1}

✓ **Dense calorimeter**

preserve lateral compactness of showers

✓ **Fine lateral granularity**

two shower separation + observation of narrow jets, minimise pileup contributions in energy & timing measurements



✓ **Fine longitudinal granularity**

fine sampling of the shower: good energy resolution, pattern recognition, pile-up discrimination, …

✓ **Precision time measurement**

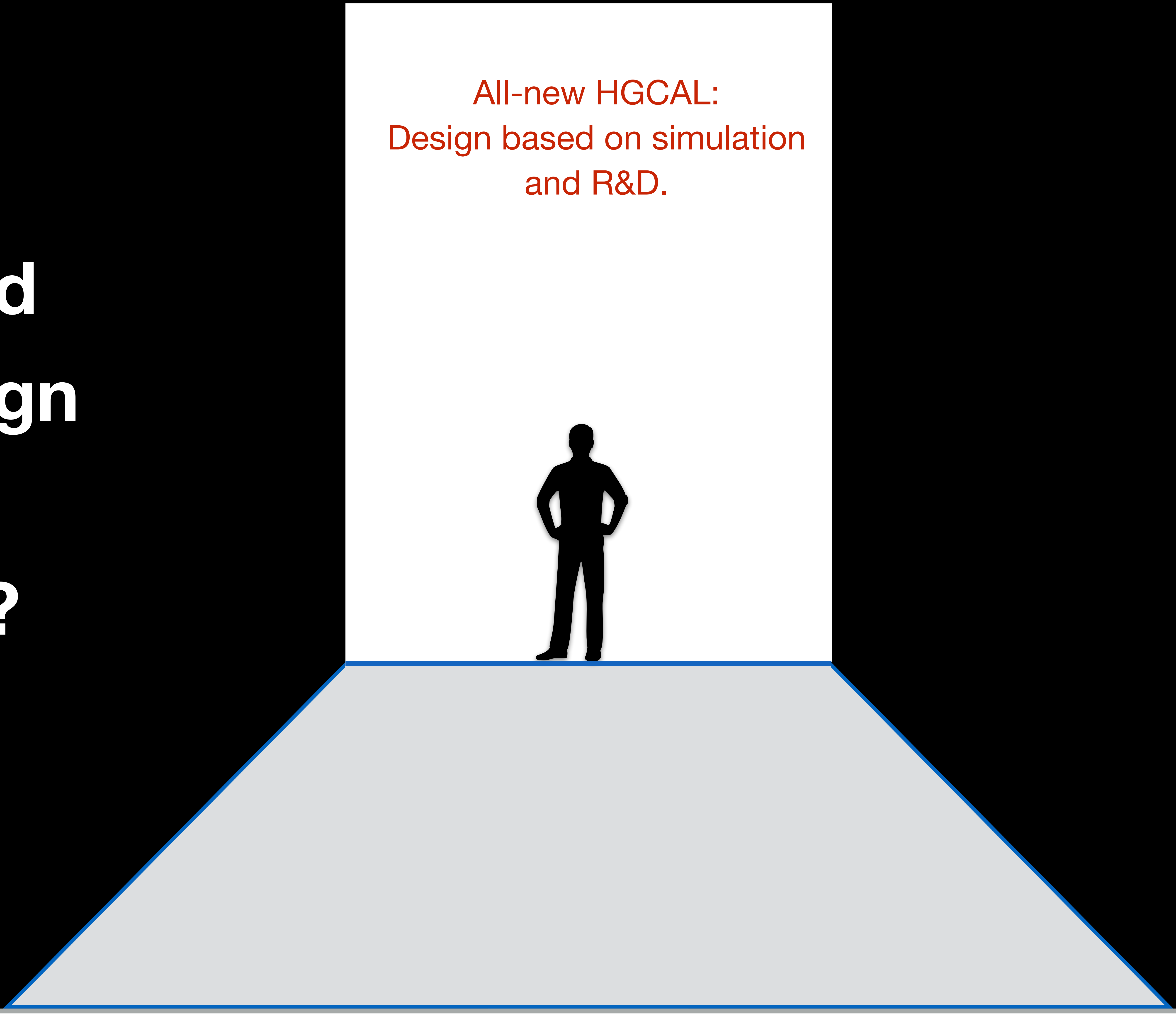
high energy showers for pile-up rejection, primary vertex identification

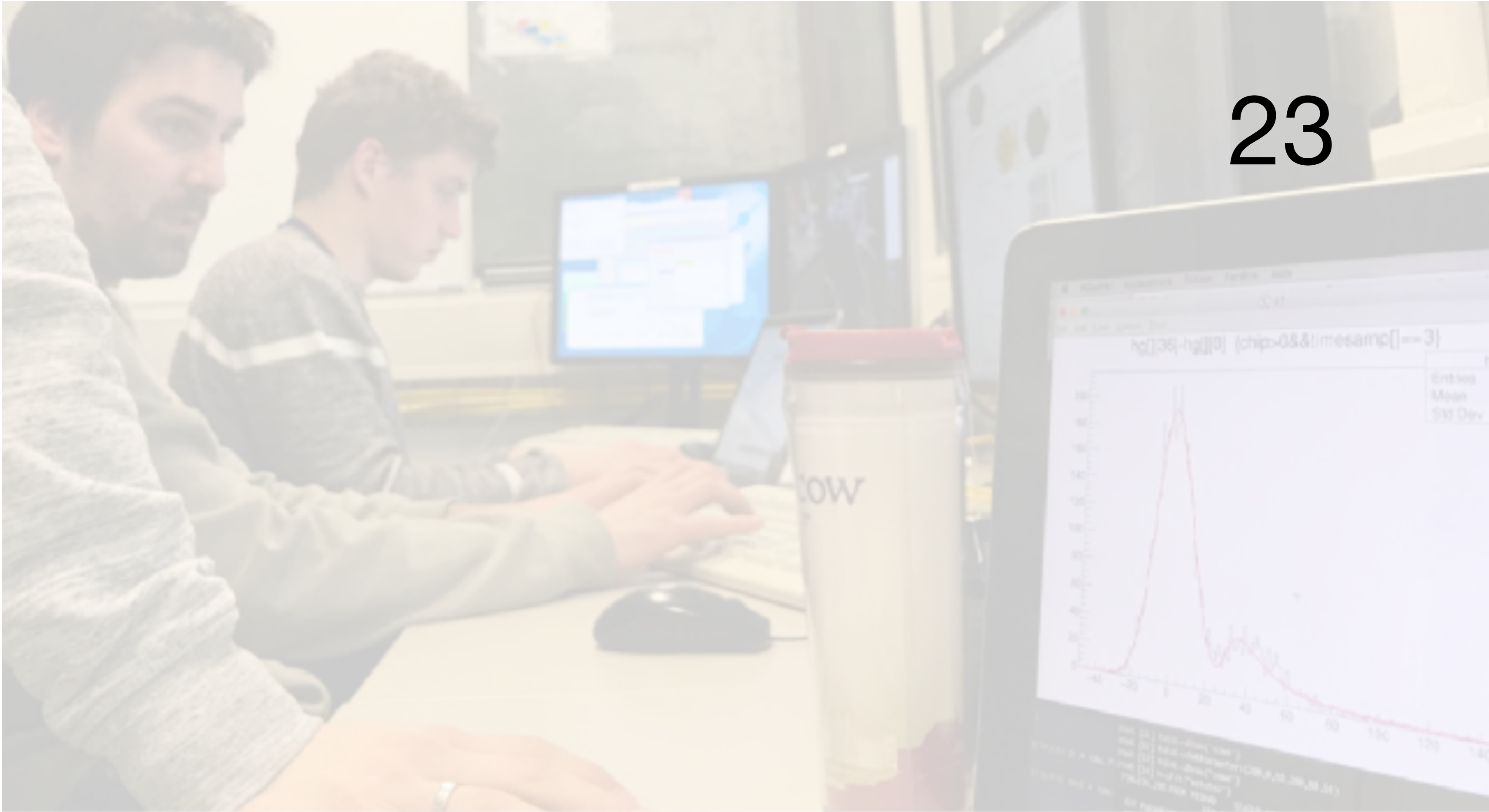
✓ **Contribute to L1 (Hardware) trigger**

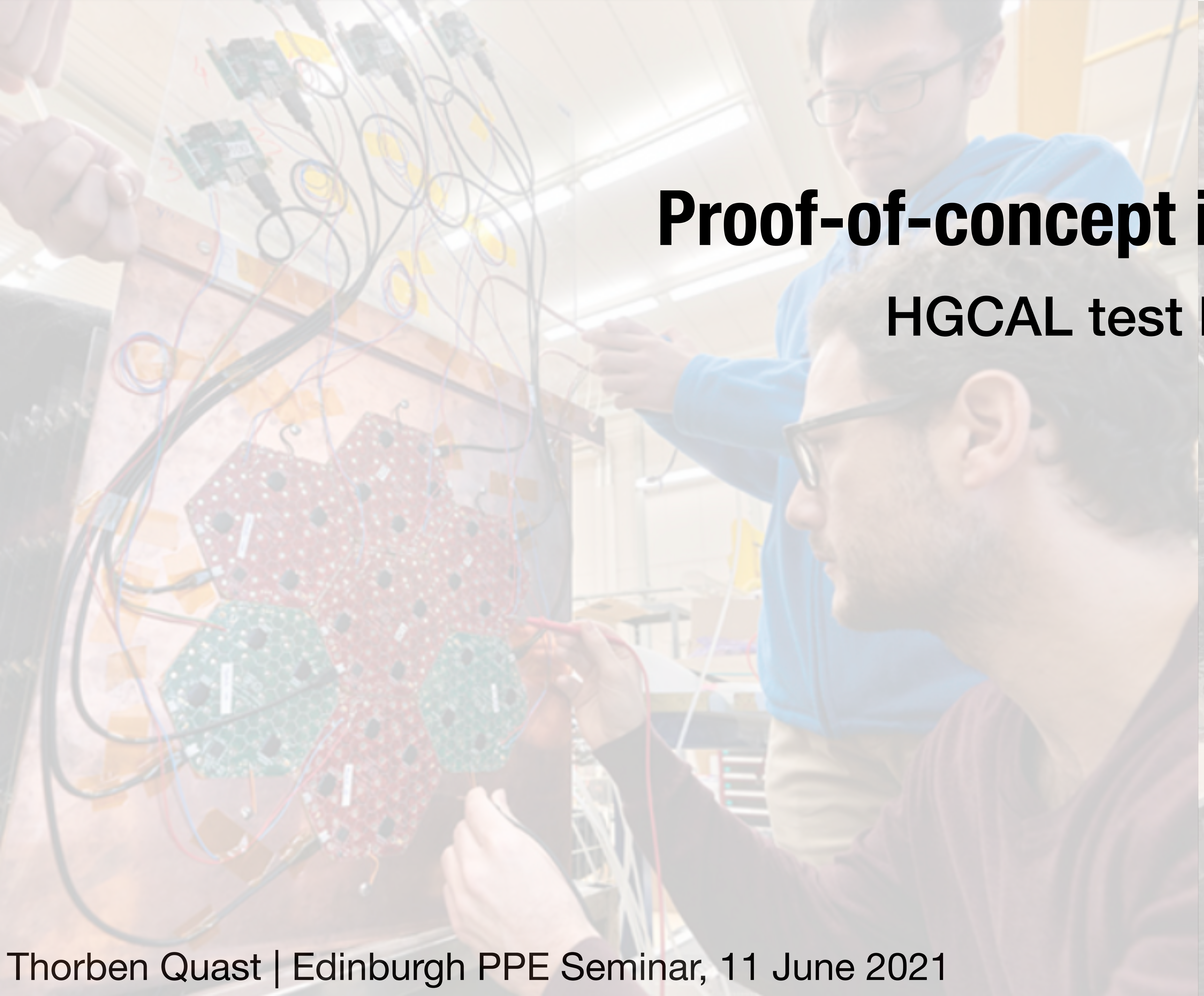
Many engineering challenges not mentioned:

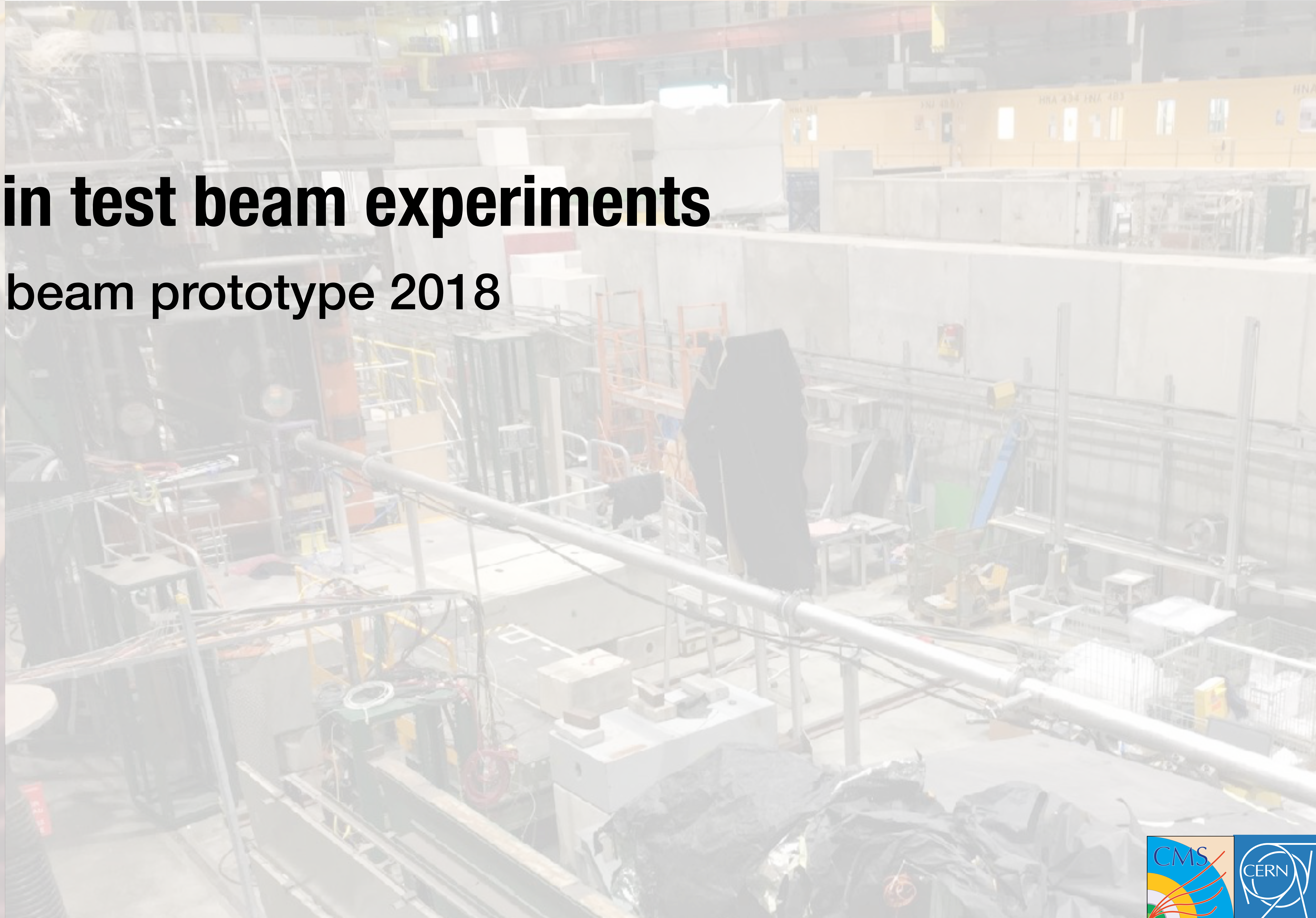
- 2x 200 t detector to assemble and install.
- Operation at -30°C will require two-phase CO_2 cooling system.
- …

Does the silicon-based HGCAL design meet the expectation?







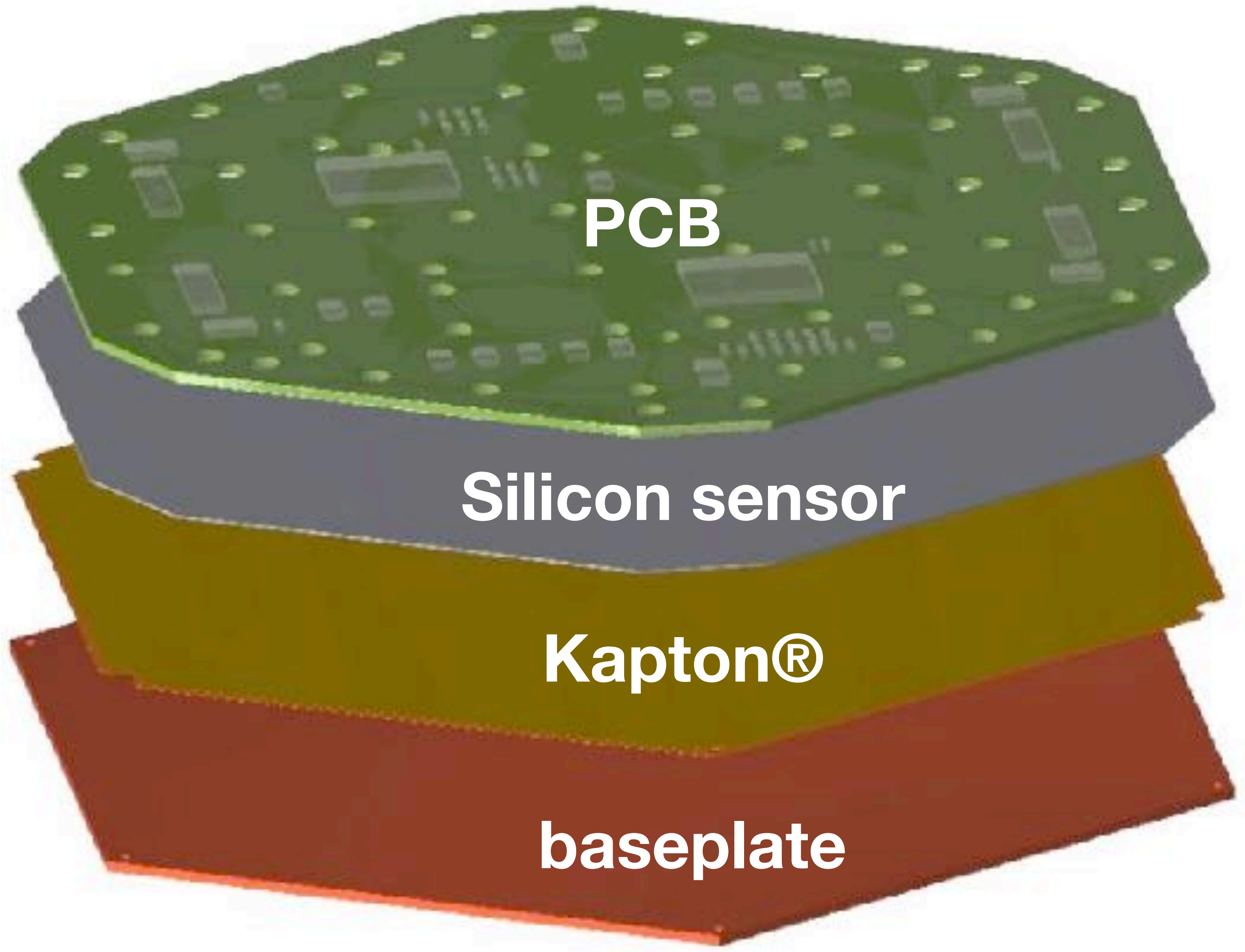


Proof-of-concept in test beam experiments

HGCAL test beam prototype 2018

HGCAL test beam prototype module assembly

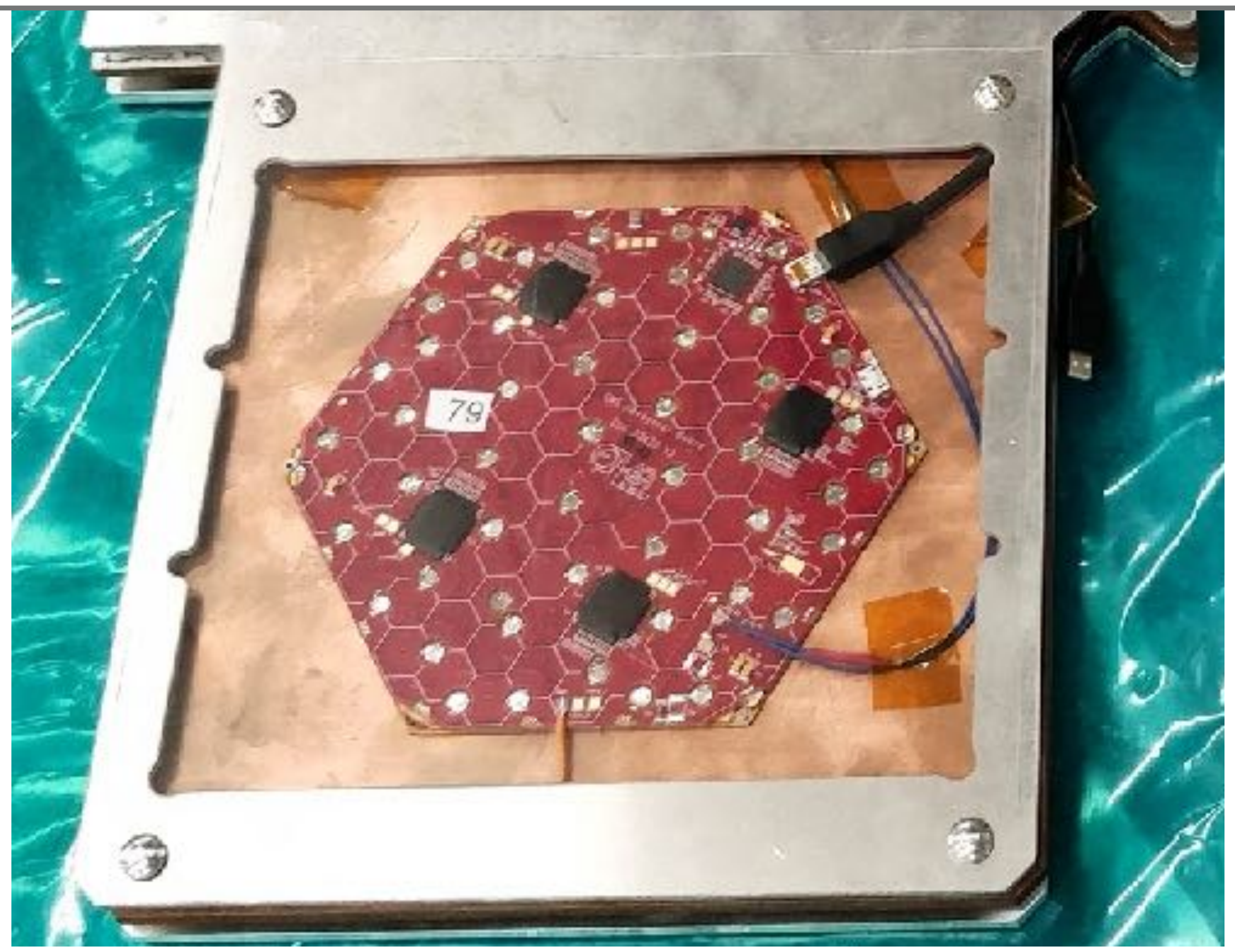
Modules assembled as glued stack
of **baseplate**, **Kapton®**, **Si sensor** and **PCB**:



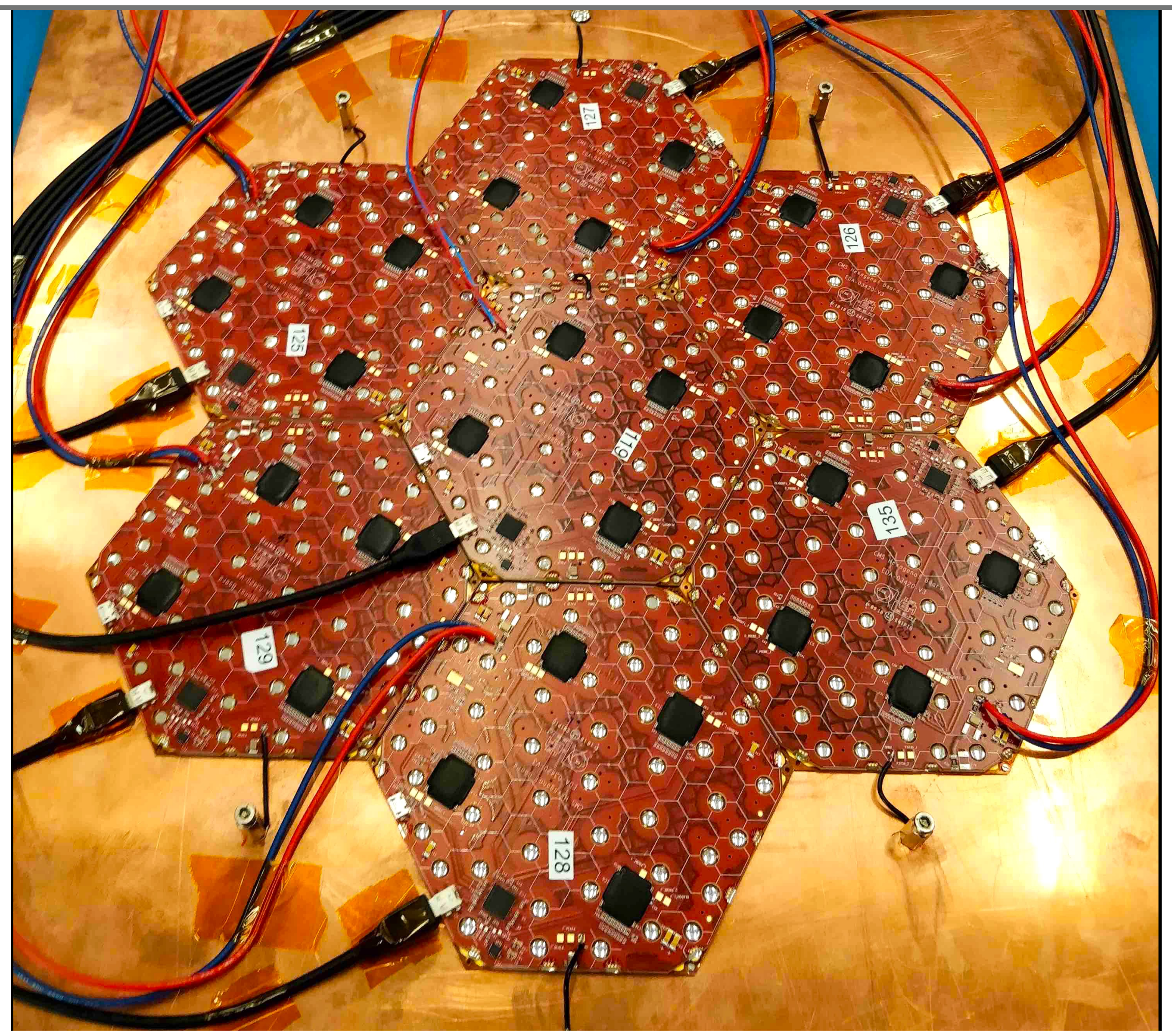
gluing

wire bonding

1-module cassettes in electromagnetic part

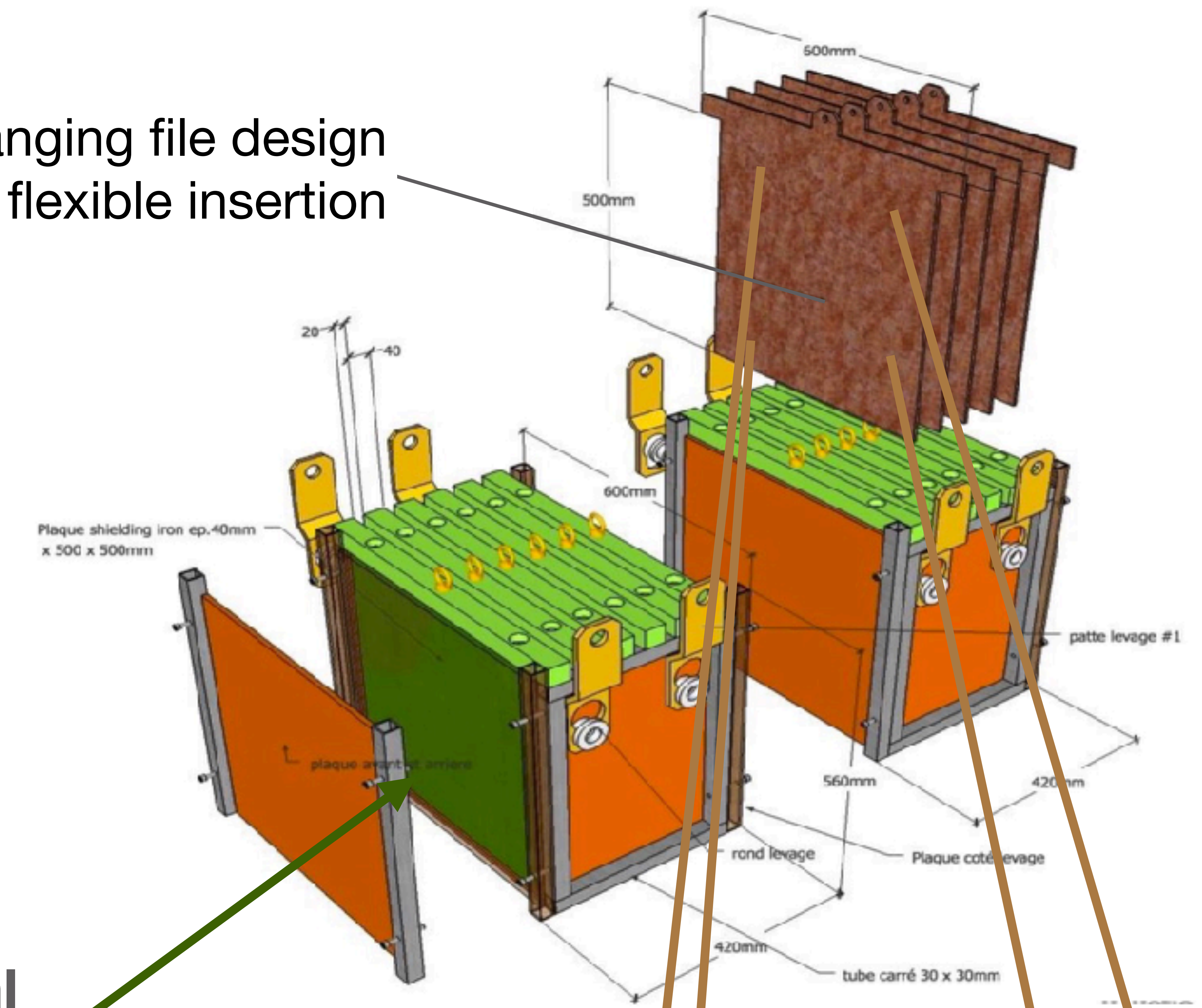


7-module “daisy” layer in hadronic part



HGCAL test beam prototype mechanics

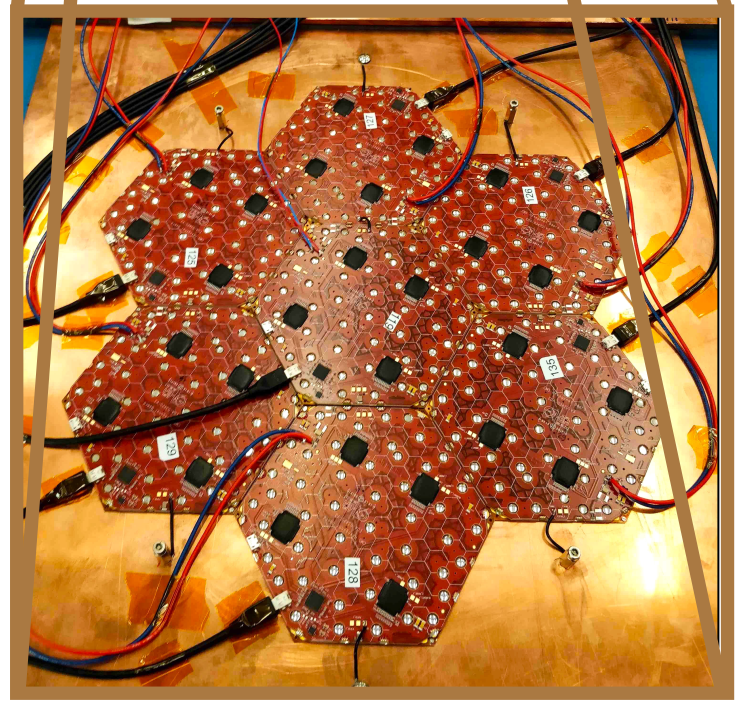
Hanging file design
for flexible insertion



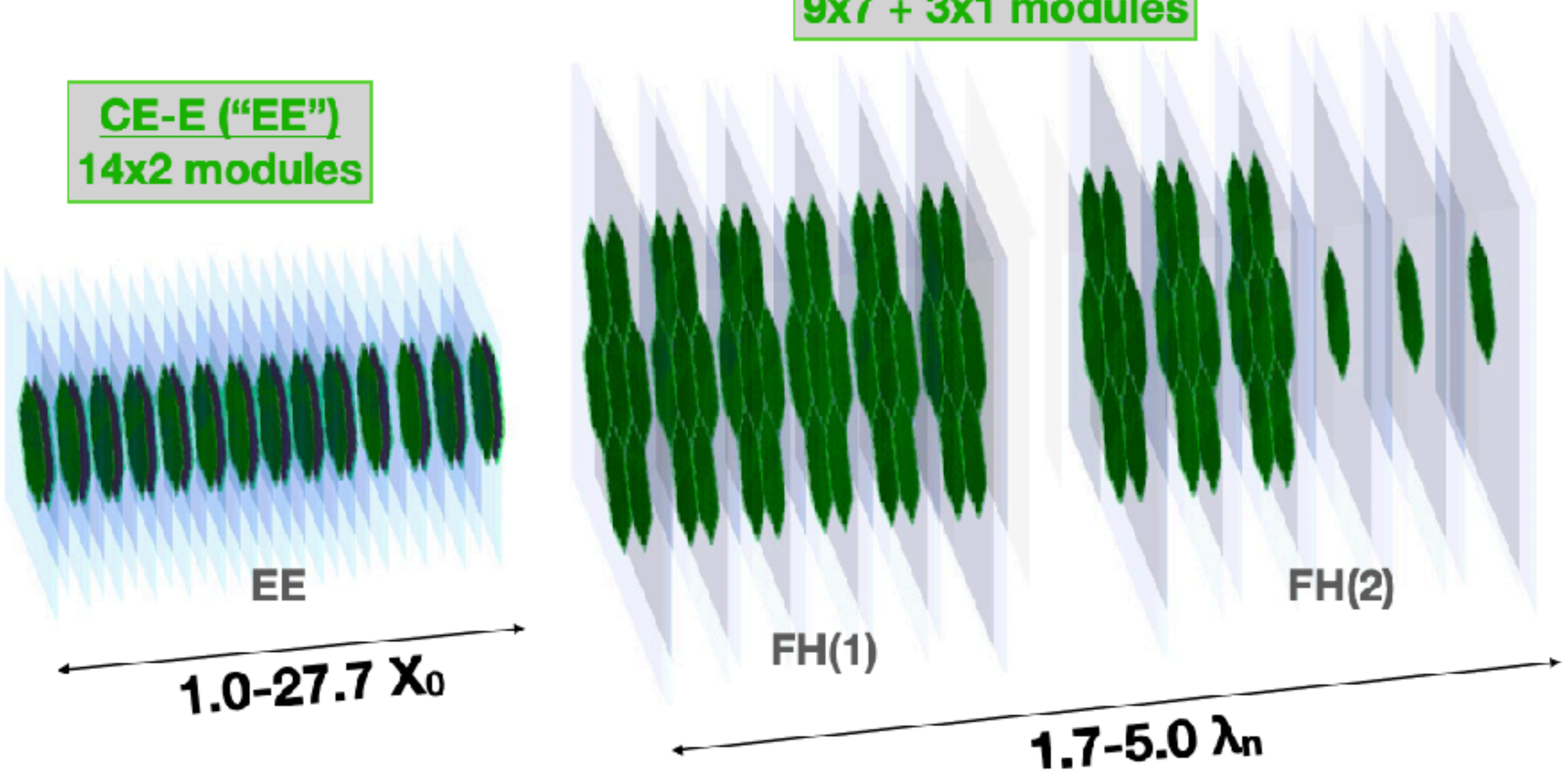
Passive material

- <u>CE-E:</u>
  material: Pb, W, Cu
  thickness: 5-6 mm
- <u>CE-H-Si:</u>
  material: Fe
  thickness: 4 cm
  weight: O(1000kg)

Active material



- 94 prototype modules assembled by October 2018.
- Full CE-E prototype with 28 layers.
- Half-equipped CE-H(Si) prototype with 12 layers.



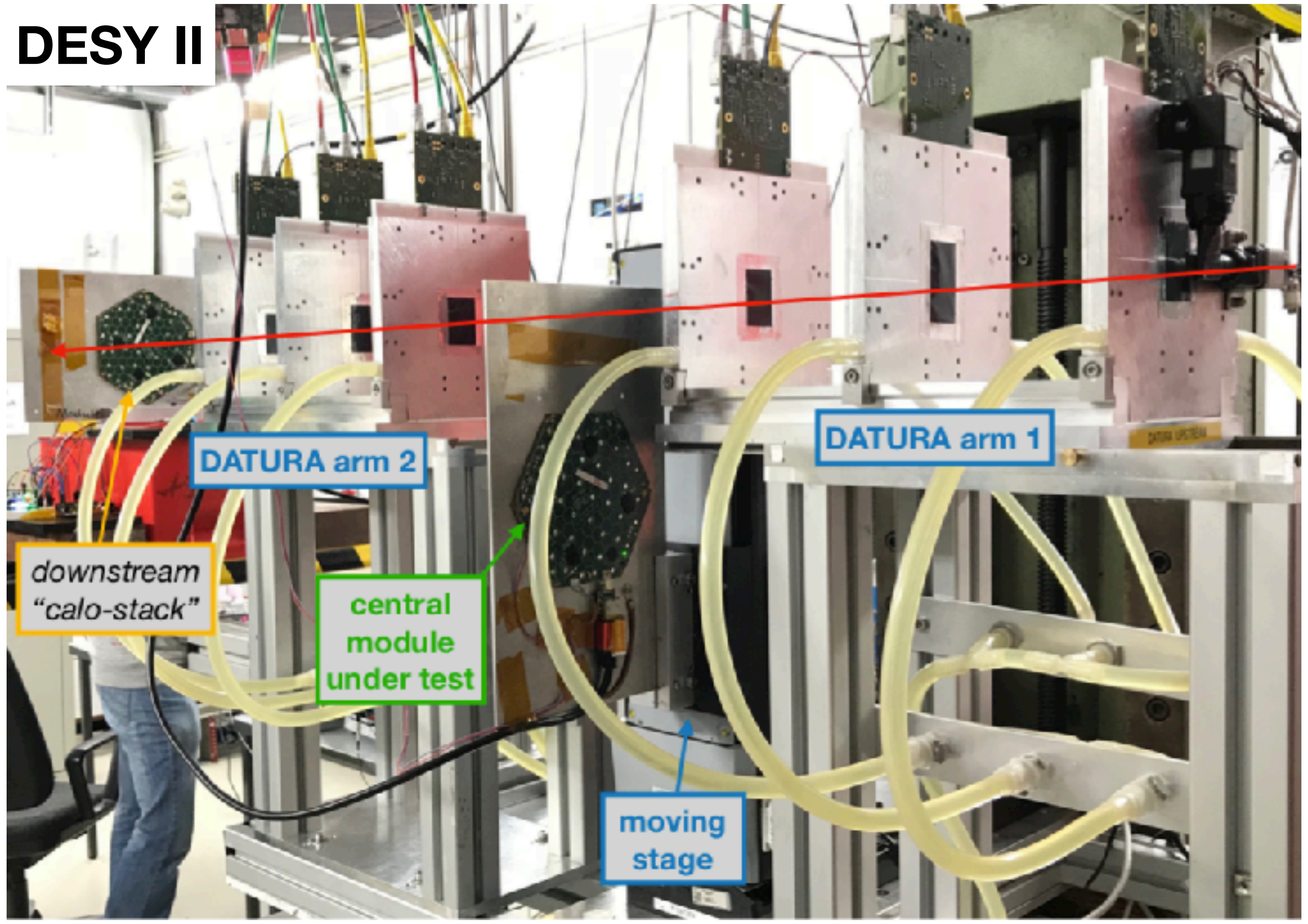
X_0 = electromagnetic radiation length

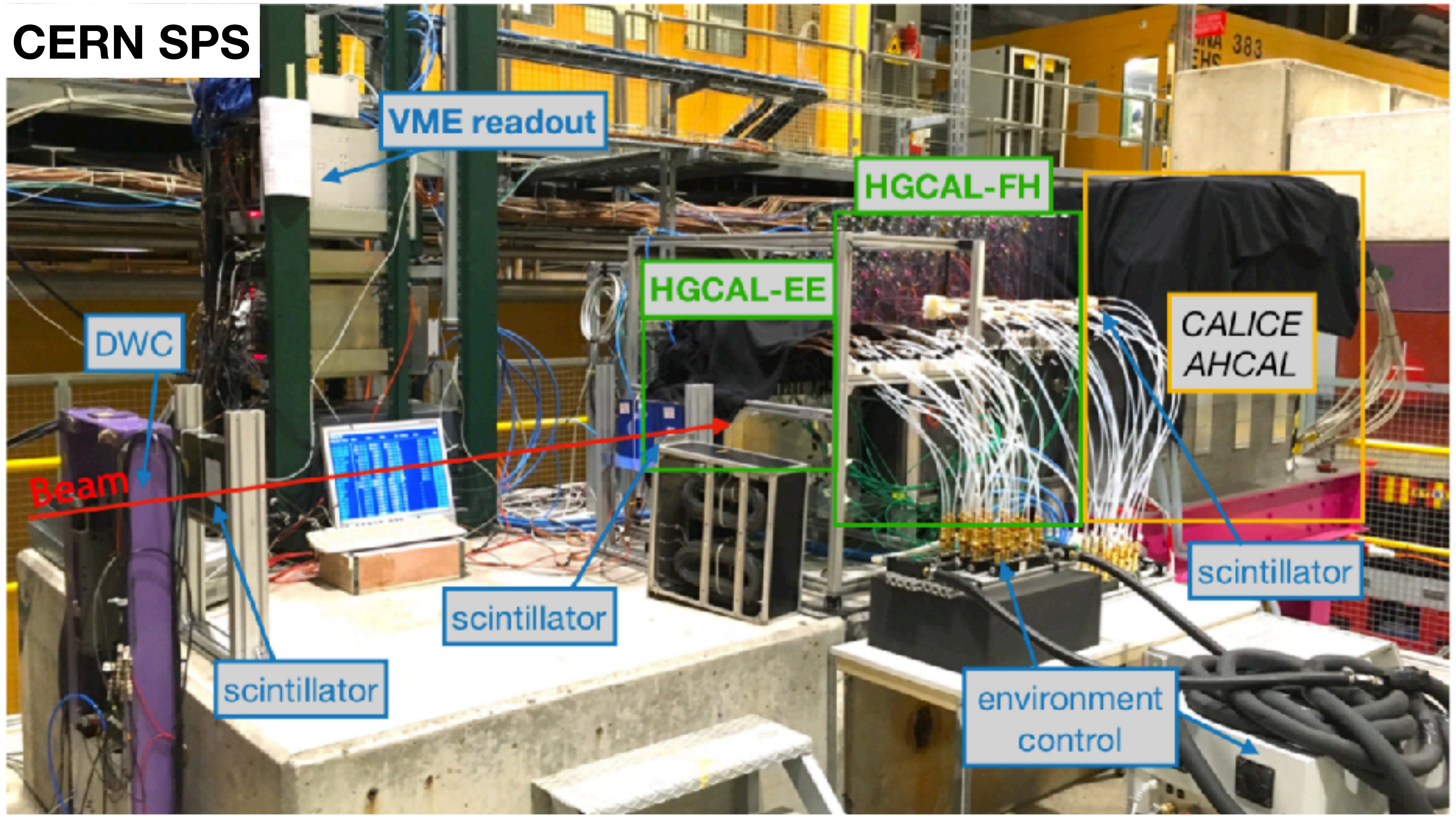
λ_n = nuclear interaction length

➡~12,000 readout channels.

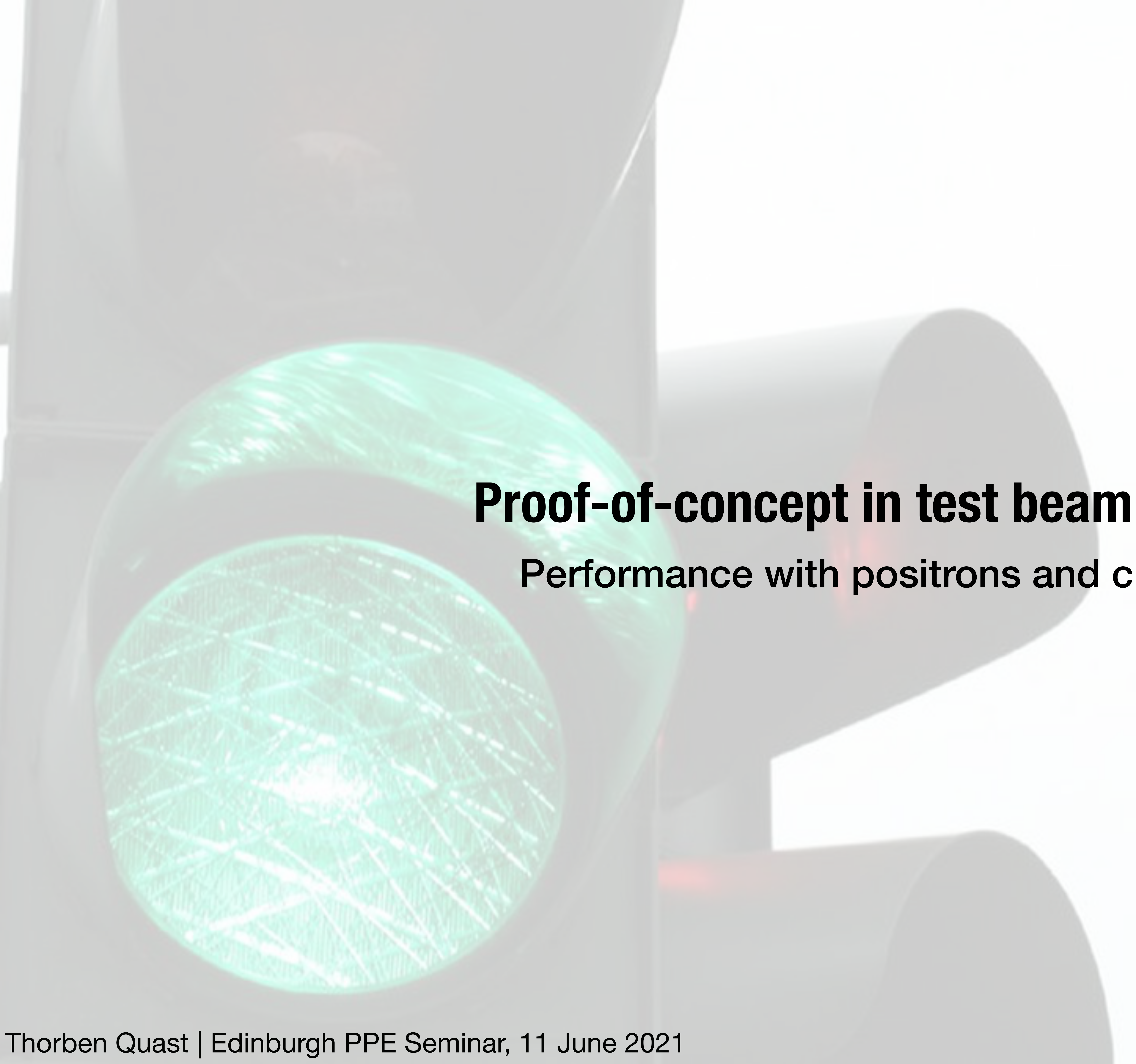
Test beam experiments at DESY II and at CERN's SPS

March 2018 @DESY II (T21)	→	October 2018 @CERN SPS (H2)
1 + 2 HGCAL modules: 1 module: mounted on moving stage	***Setup***	94 HGCAL modules: 28-layer EE setup + 12-layer FH setup
1.6 - 6 GeV/c e^-	***Particles***	e^+, μ^-, π^- up to 300 GeV/c
silicon module design qualification	***Goal***	full in-situ calibration, performance+comparison to simulation
DATURA beam telescope	***Aux. detectors***	delay wire chambers (DWC), microchannel plates, threshold Cherenkov detectors





HGCAL = Imaging calorimeter



Proof-of-concept in test beam experiments

Performance with positrons and charged pions

QUALIFICATION, PERFORMANCE VALIDATIO[N]
AND FAST GENERATIVE MODELLING
OF BEAM TEST CALORIMETER PROTOTYPES
FOR THE CMS CALORIMETER ENDCAP UPGRADE

Von der Fakultät für Mathematik, Informatik und Naturwissenschaften
der RWTH Aachen University zur Erlangung des akademischen Grades eines
Doktors der Naturwissenschaften genehmigte Dissertation

vorgelegt von

Thorben Quast
M. Sc. RWTH
aus Salzgitter

Berichter: Universitätsprofessor Dr. Martin Erdmann
Professor Dr. André David Tinoco Mendes

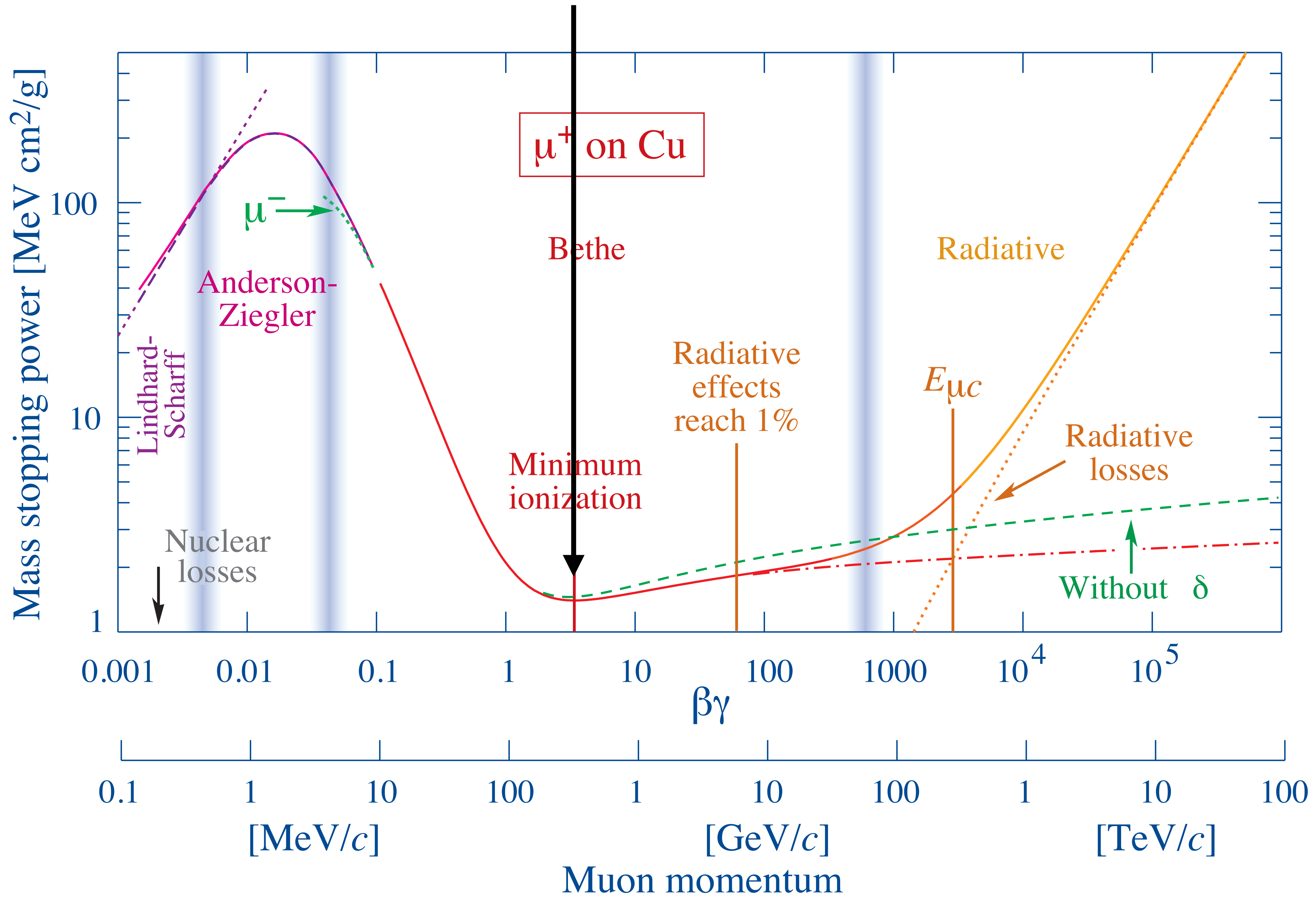
Tag der mündlichen Prüfung: 28 Mai 2020

Diese Dissertation ist auf den Internetseiten
der Universitätsbibliothek online verfügbar.

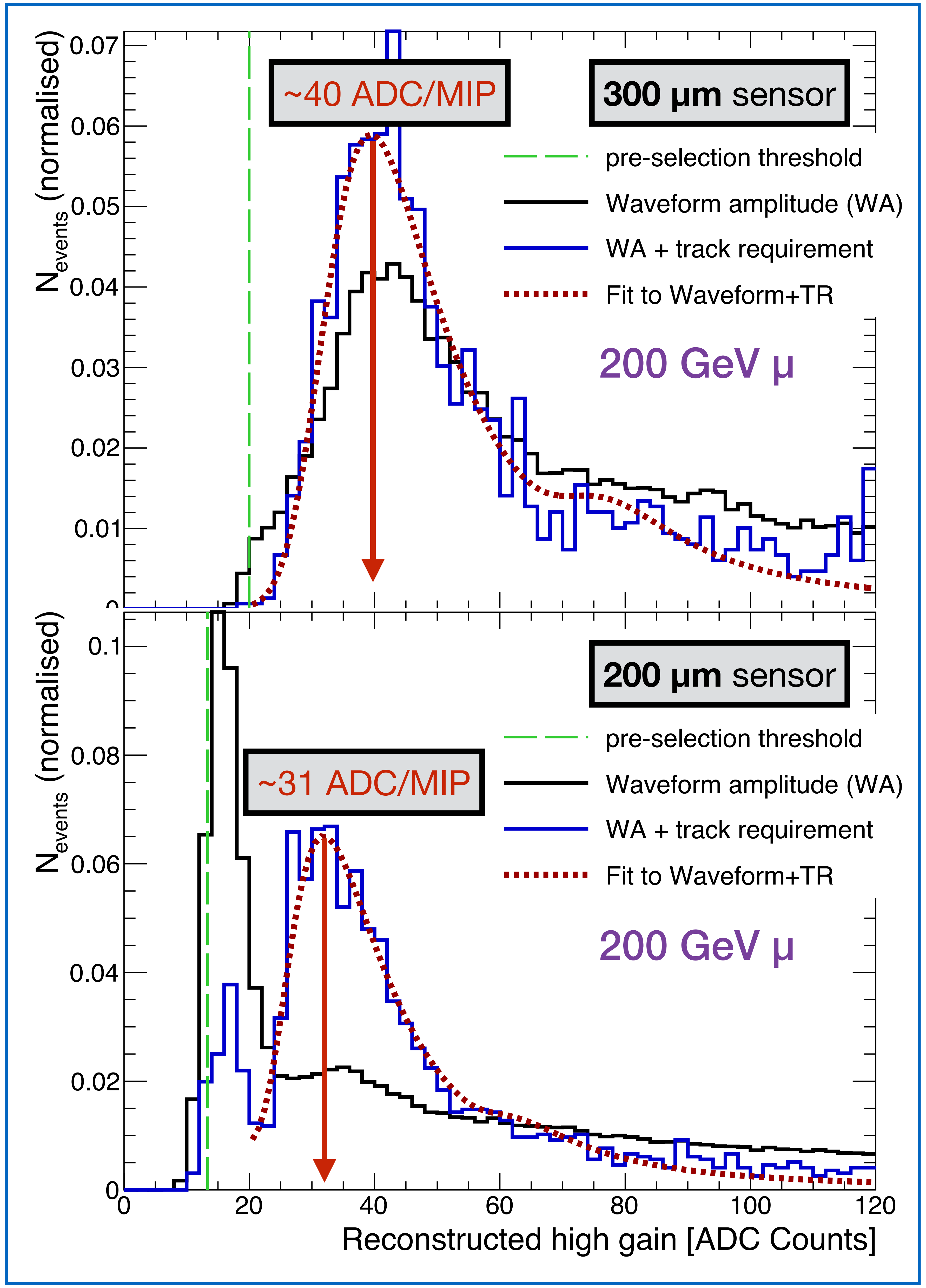
Energy scale calibration with minimum ionising particles (MIPs)

MIP calibration => Energy scale

- Reference energy = $\langle dE/dX \rangle_{min}$.



- Signal spectrum induced by MIPs:
  - Tracking of MIPs within HGCAL prototype: —> Signal purification.
  - Calibration = maximum of (Landau x Gaussian) model.



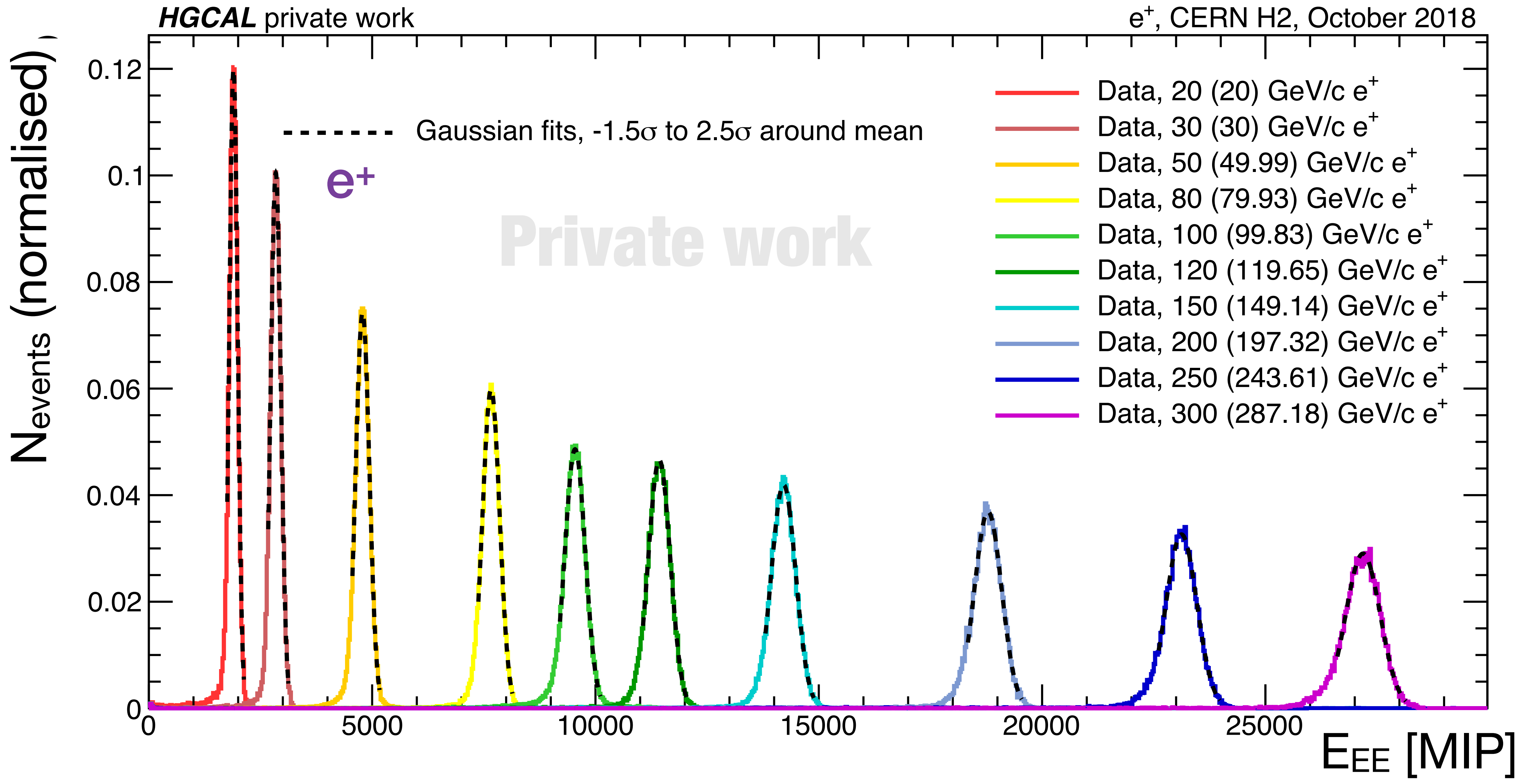
Energy linearity & resolution for electromagnetic (EM) showers

EM: Energy linearity and resolution

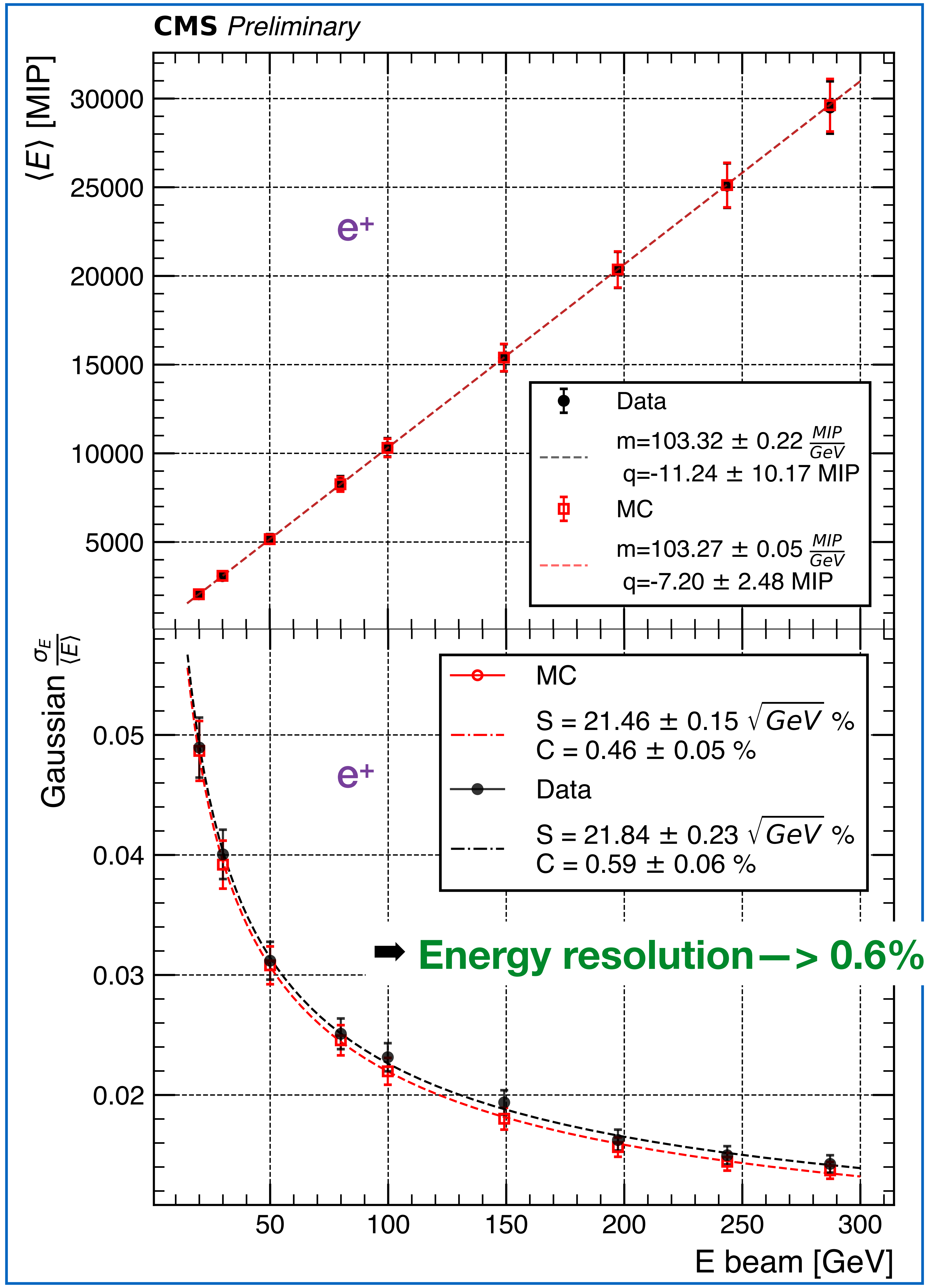
Most important calorimeter quantity!

Equal layer distancing —> **Energy ~ $E_{EE} := \Sigma_{EE} E_{hit}$.**

- Gaussian distribution of E_{EE}.



➡ **The HGCAL prototype is a calorimeter: Very good.**

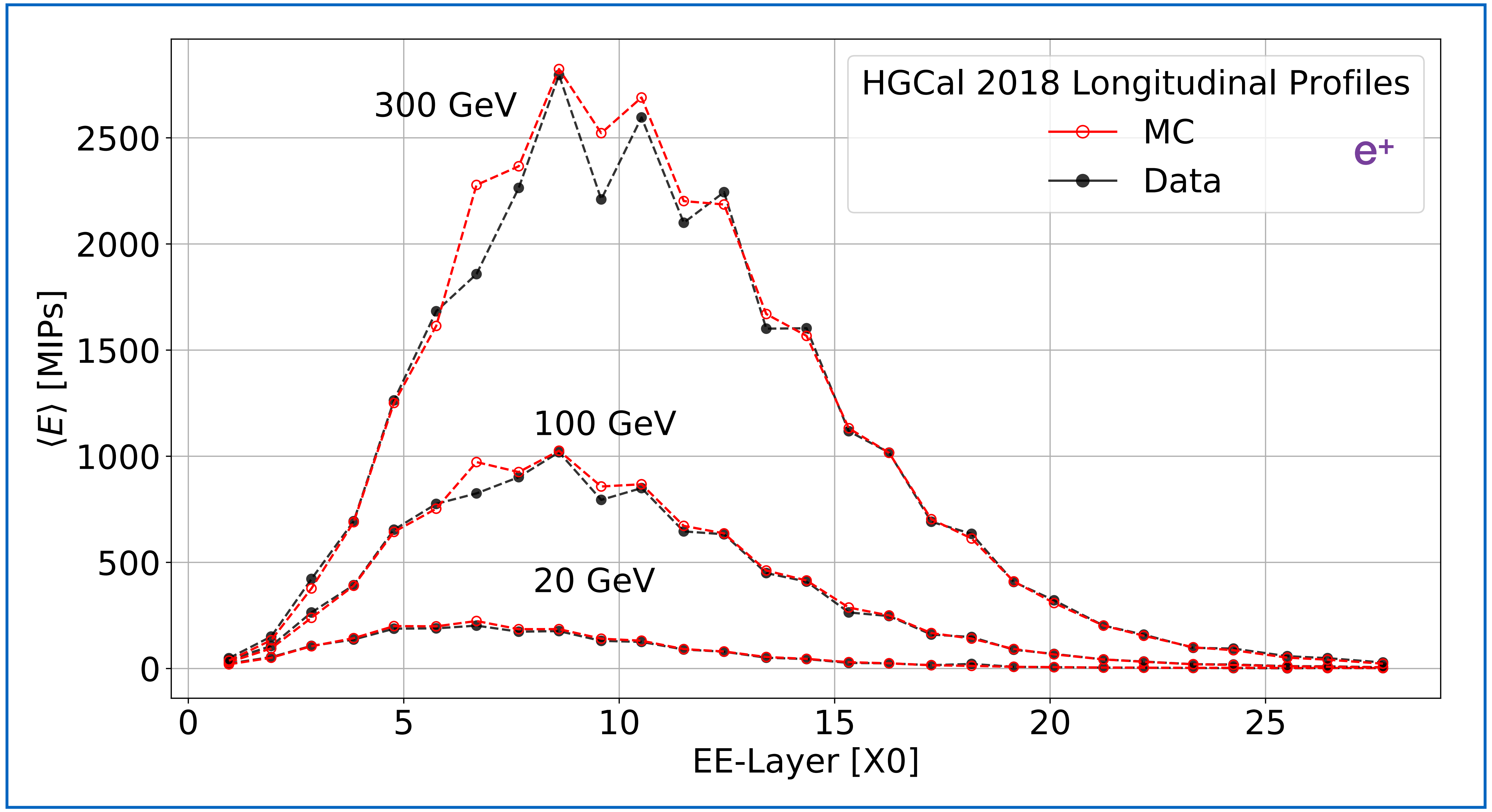


➡ **Energy resolution —> 0.6%.**

Longitudinal shower evolution for electromagnetic showers

EM: Longitudinal shower profile

:= mean energy deposit in a layer vs. depth.

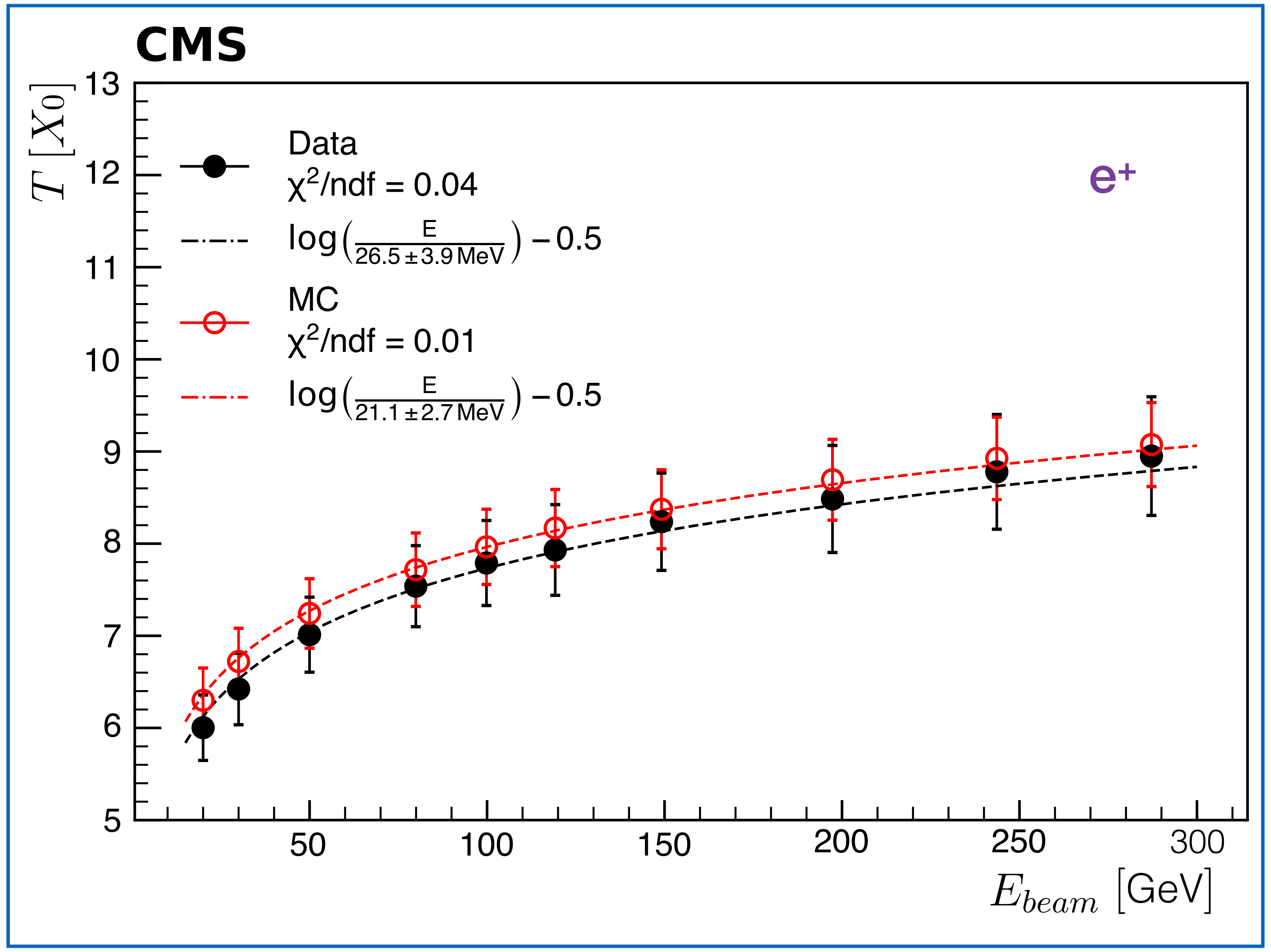


➡ **Longitudinal profile: Good.**

EM: Shower depth

:= Maximum of longitudinal profile ("T")
Expect: Depth ~ log(#particles) ~ log(E).

- Log-scaling.



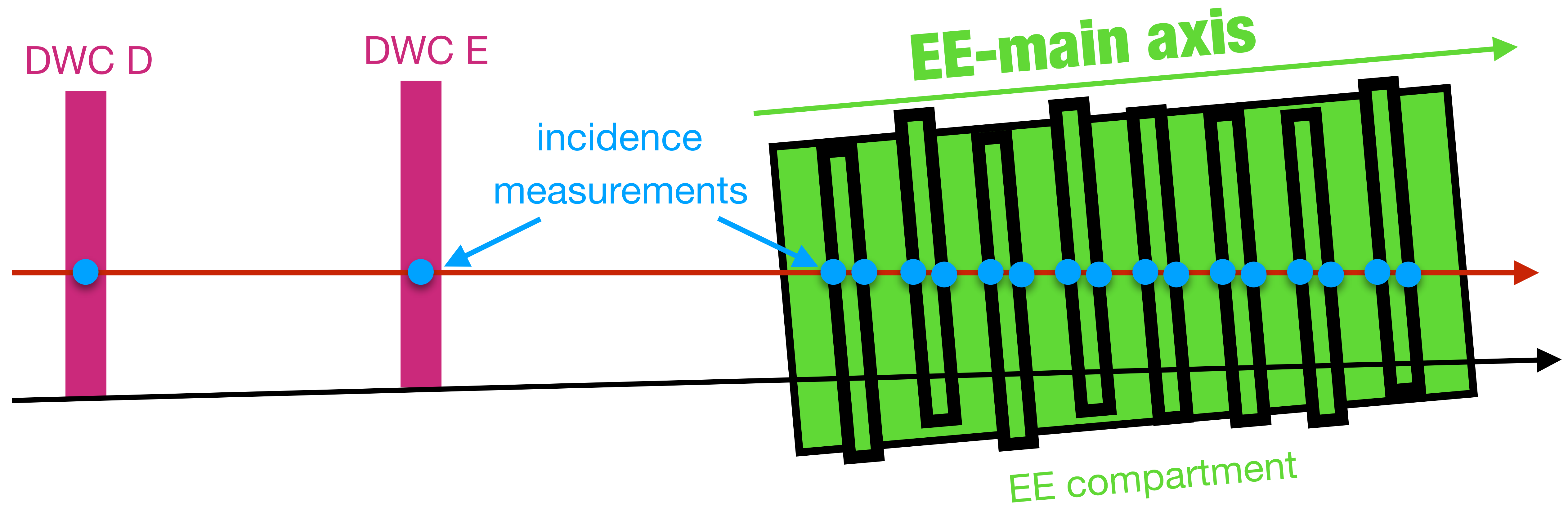
➡ **Depth scaling with energy: Good.**

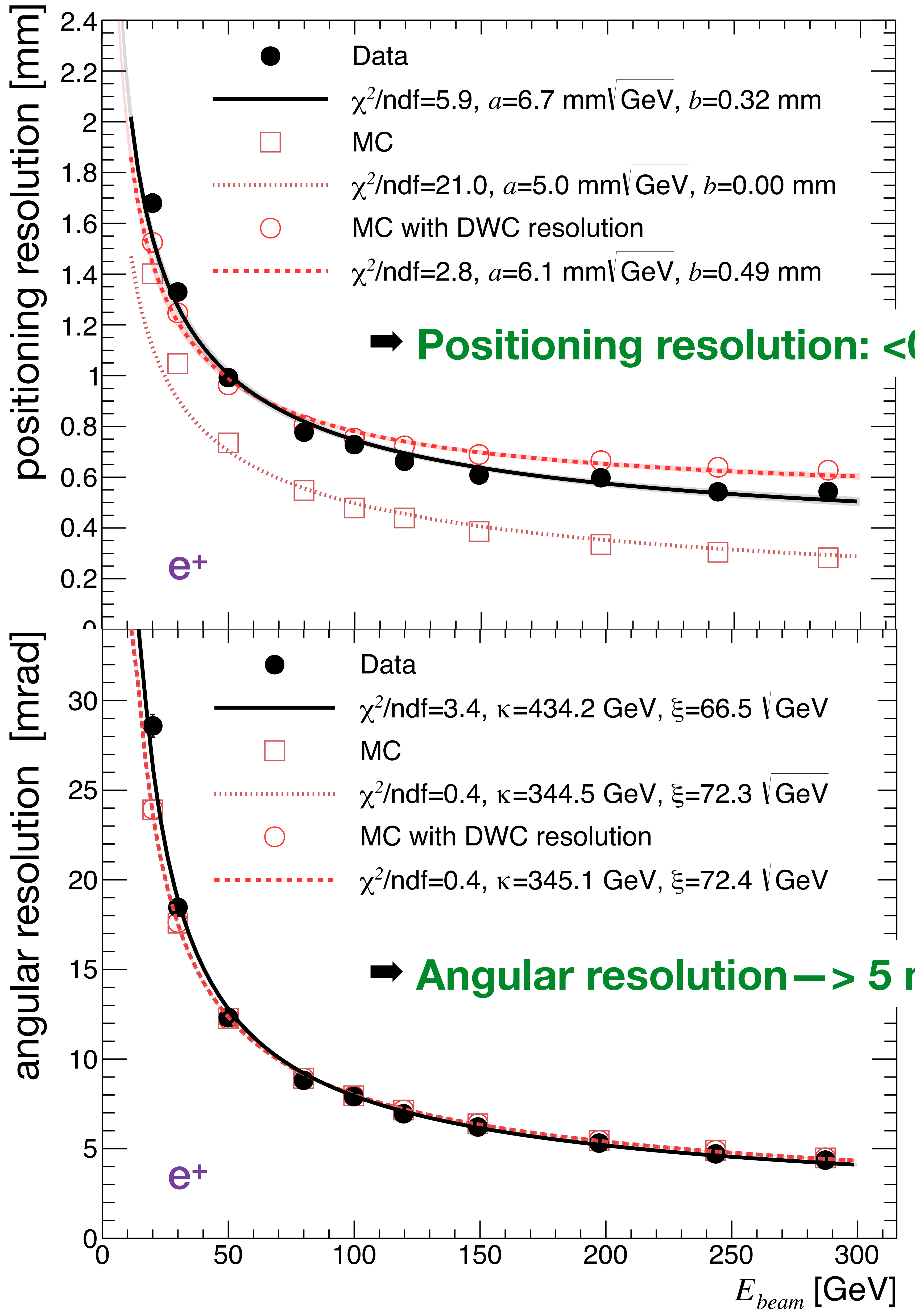
Positioning and angular resolution important for particle flow

EM: Shower axis positioning & angular resolution

3-step procedure:

1. Compute impact position at each EE layer using logarithmic weighting.
2. Combine EE layers to shower axis.
3. Compare position and angle to upstream wire chambers.





➡ **Positioning resolution: <0.6 mm.**

➡ **Angular resolution —> 5 mrad.**

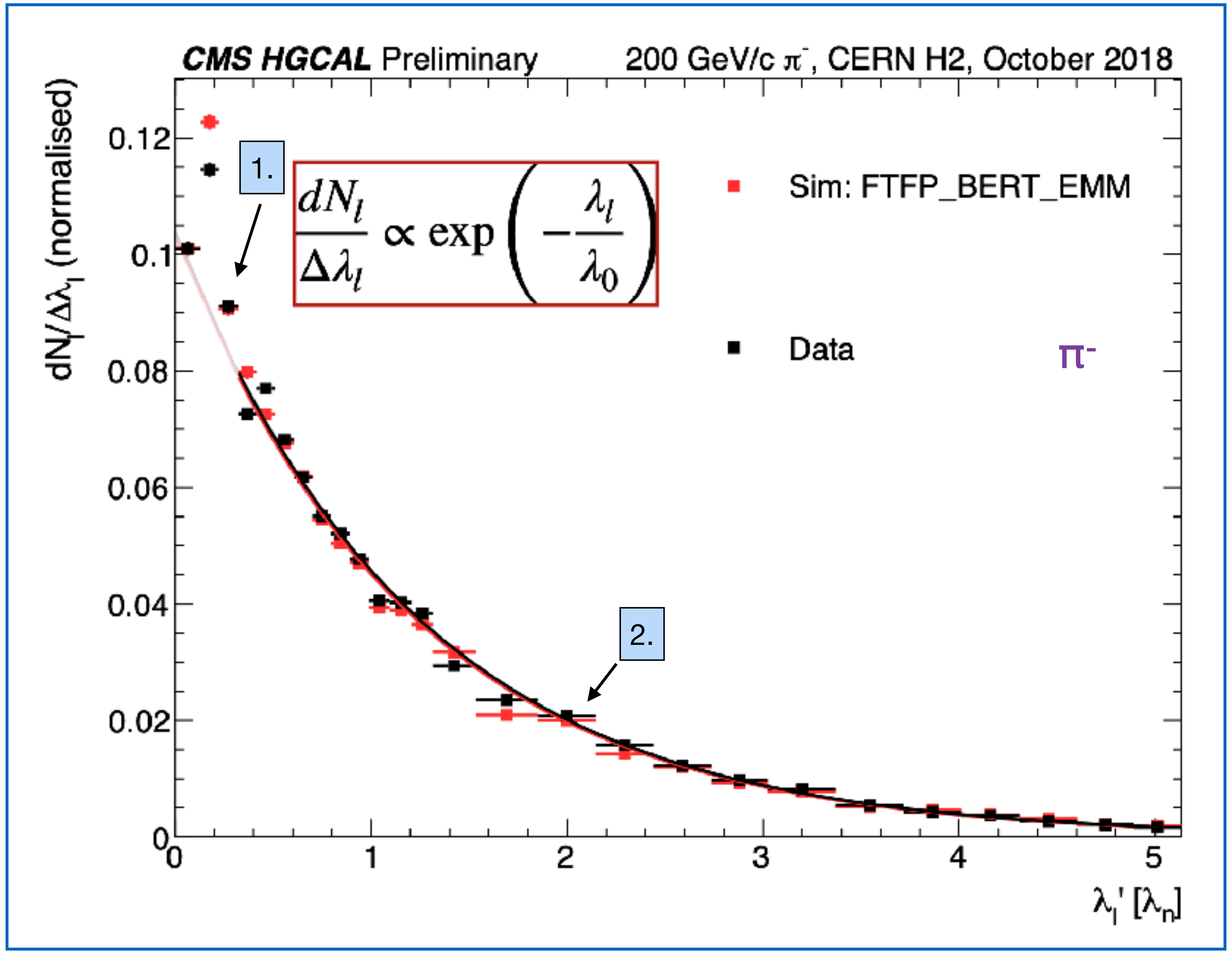
➡ **The HGCAL prototype is suitable for particle flow: Very good.**

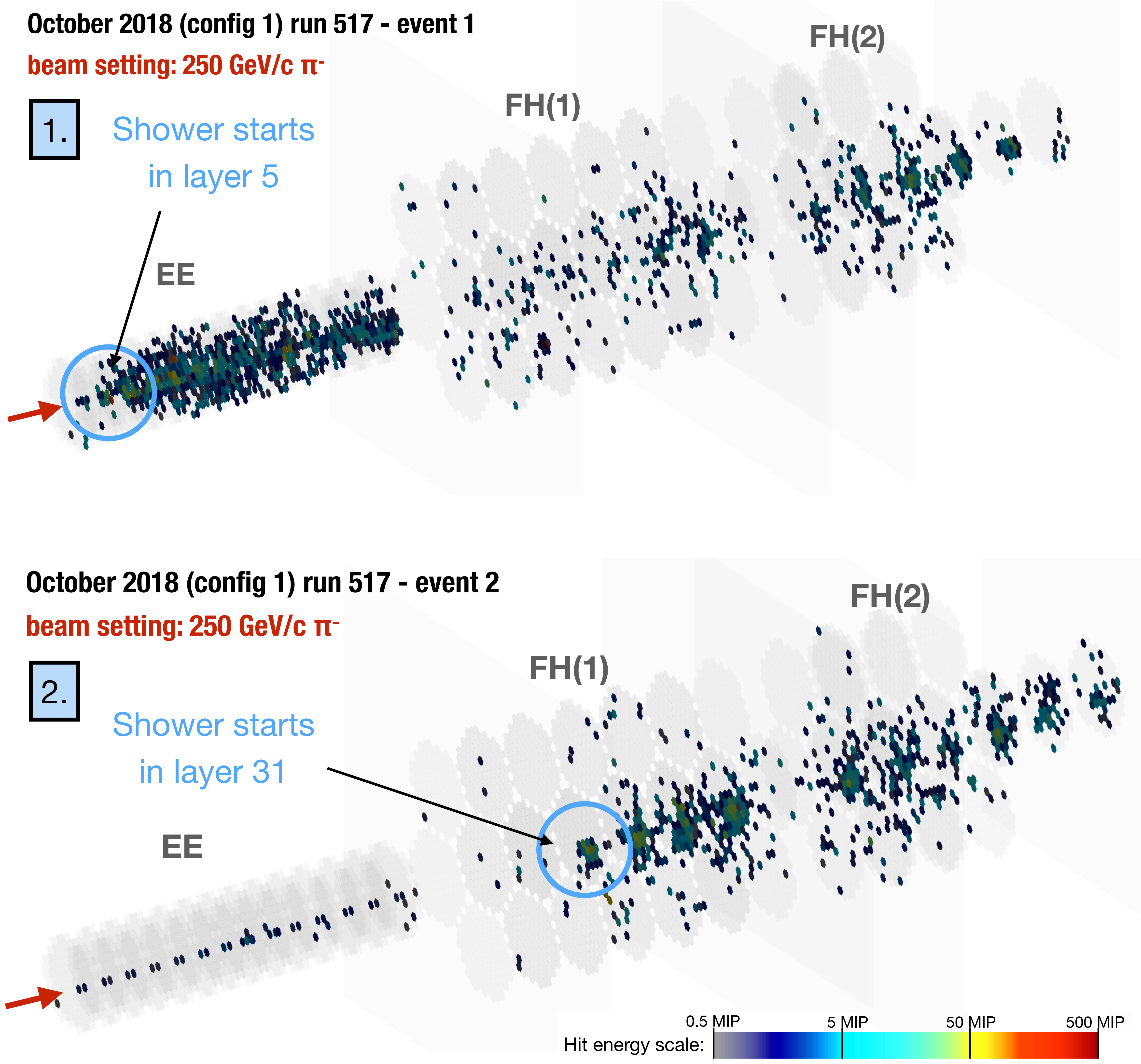
Hadronic showers start at random depths

Shower start identification for hadronic showers

Use longitudinal segmentation to identify shower start depth.
Shower start := significant increase in energy density.

- Exponential decay function.

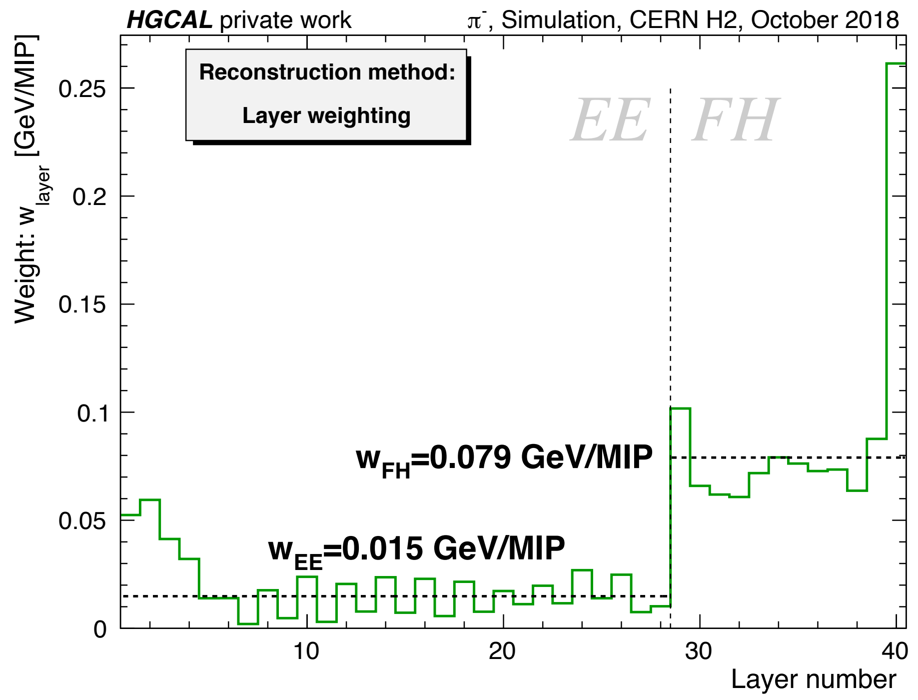




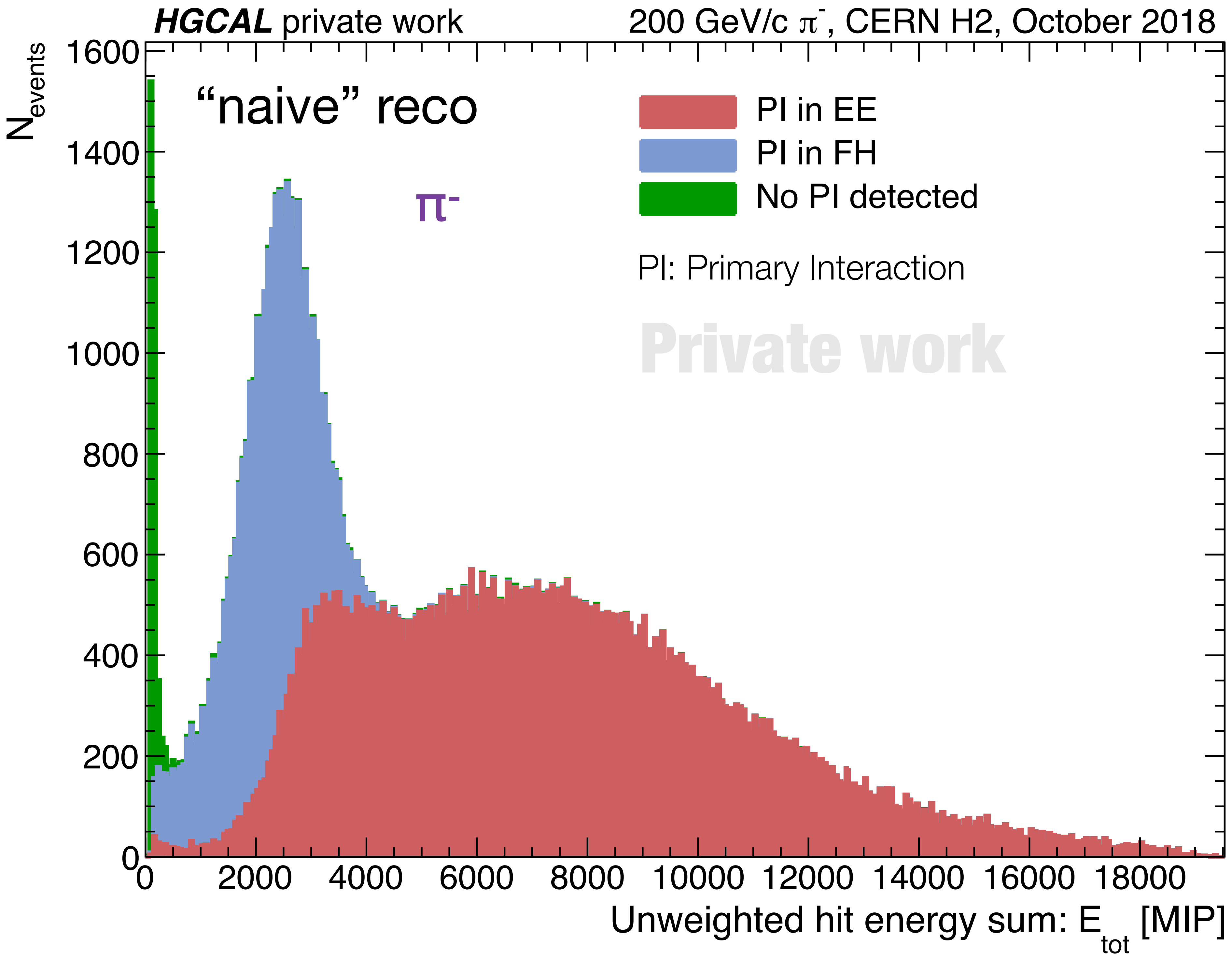
Signal sum for hadronic shower energy not sufficient

Advanced shower energy reconstruction

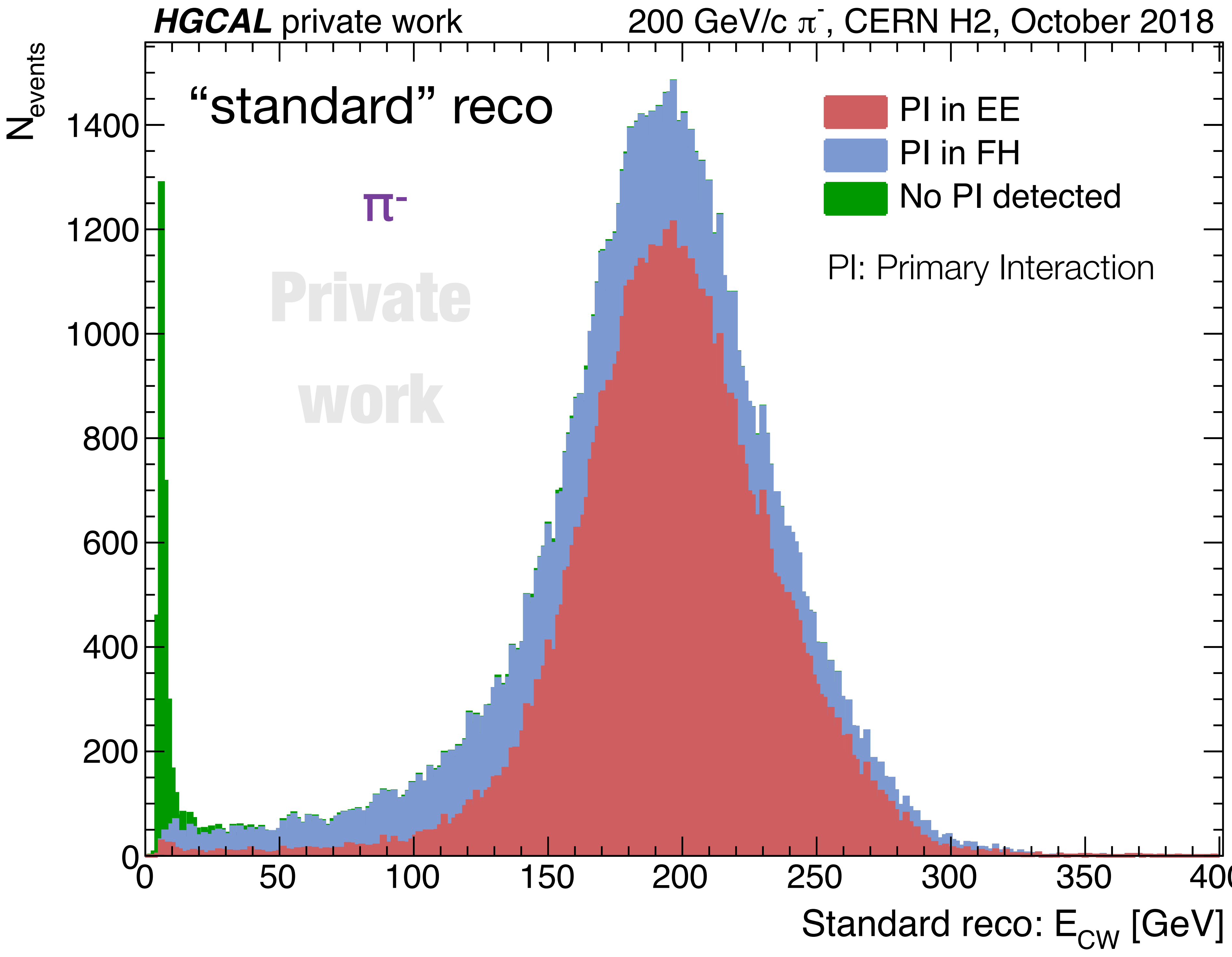
a) Different sampling configurations in EE and FH.
- Compartment weights w_{EE} and w_{FH}.



$E_{tot} := \Sigma_{EE,\,FH}\, E_i$



$E_{CW} := w_{EE} \times [\Sigma_{EE}\, E_i] + w_{FH} \times [\Sigma_{FH}\, E_i]$



Granularity allows for ~~software-based~~ response compensation

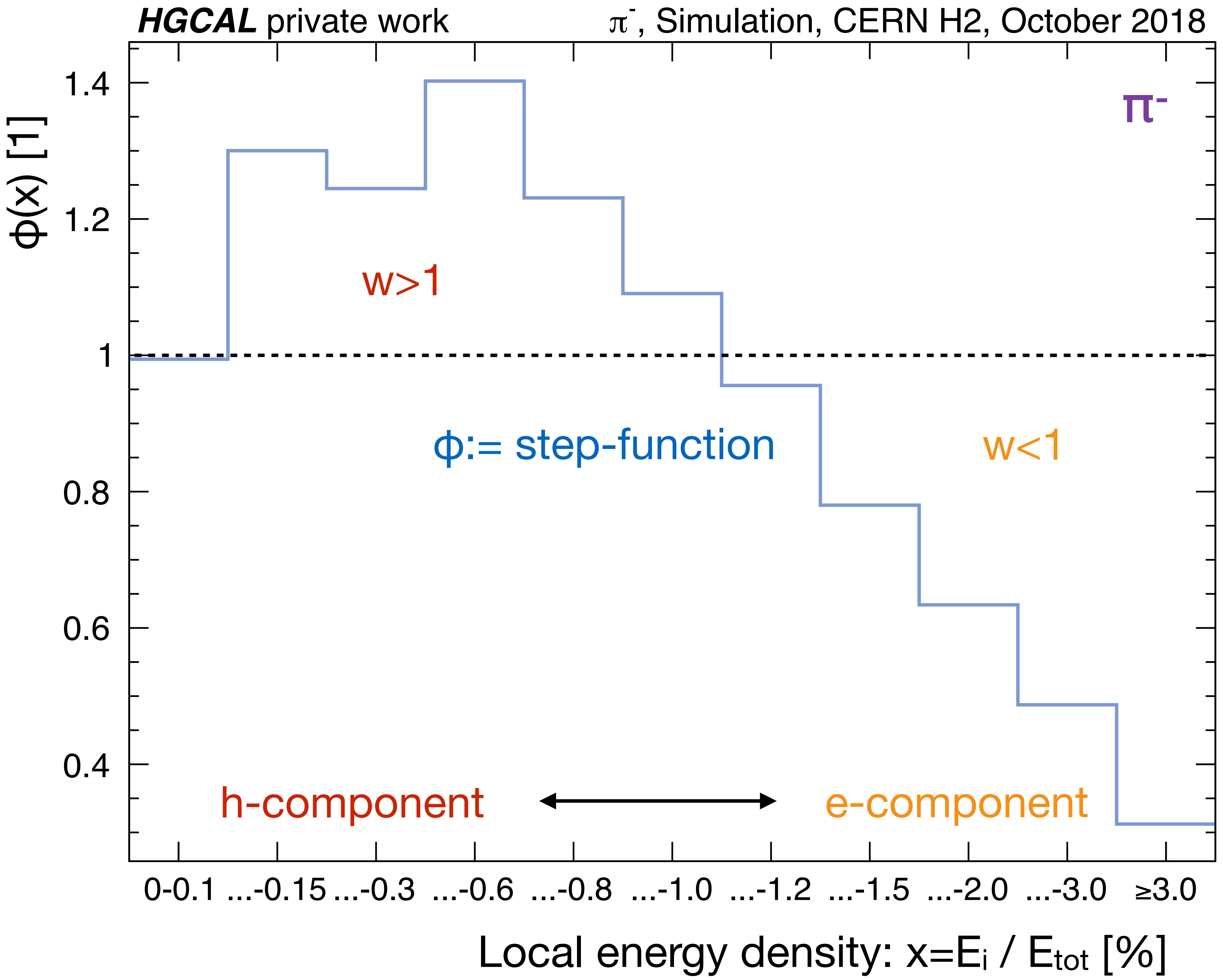
Advanced shower energy reconstruction

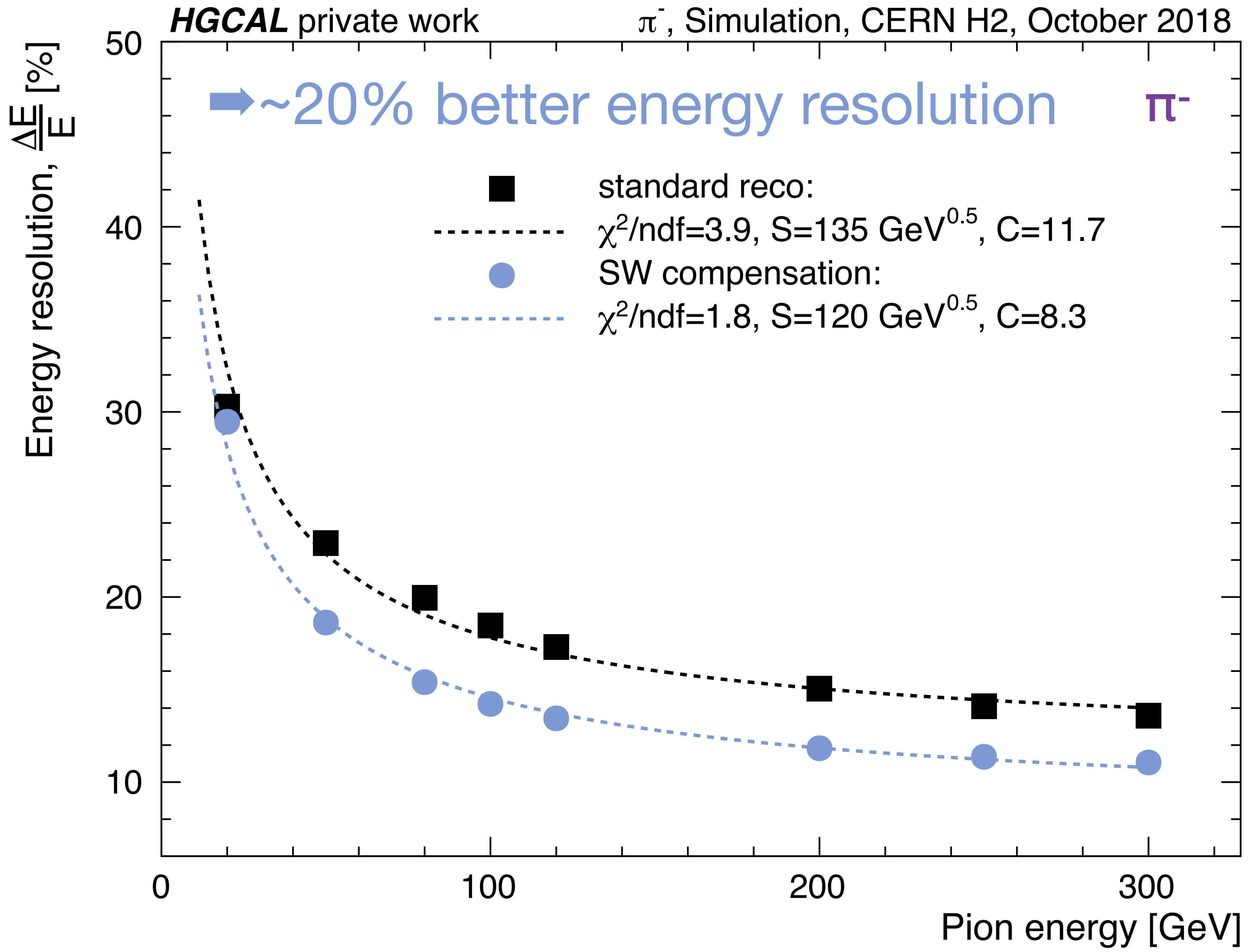
a) Different sampling configurations in EE and FH.
- Compartment weights w_{EE} and w_{FH}.

b) **Non-compensation: h/e < 1.**
- Treat hadronic and electromagnetic constituents differently: Weights $\phi(x)$.
- x := energy density as a proxy. **Relies on granularity.**

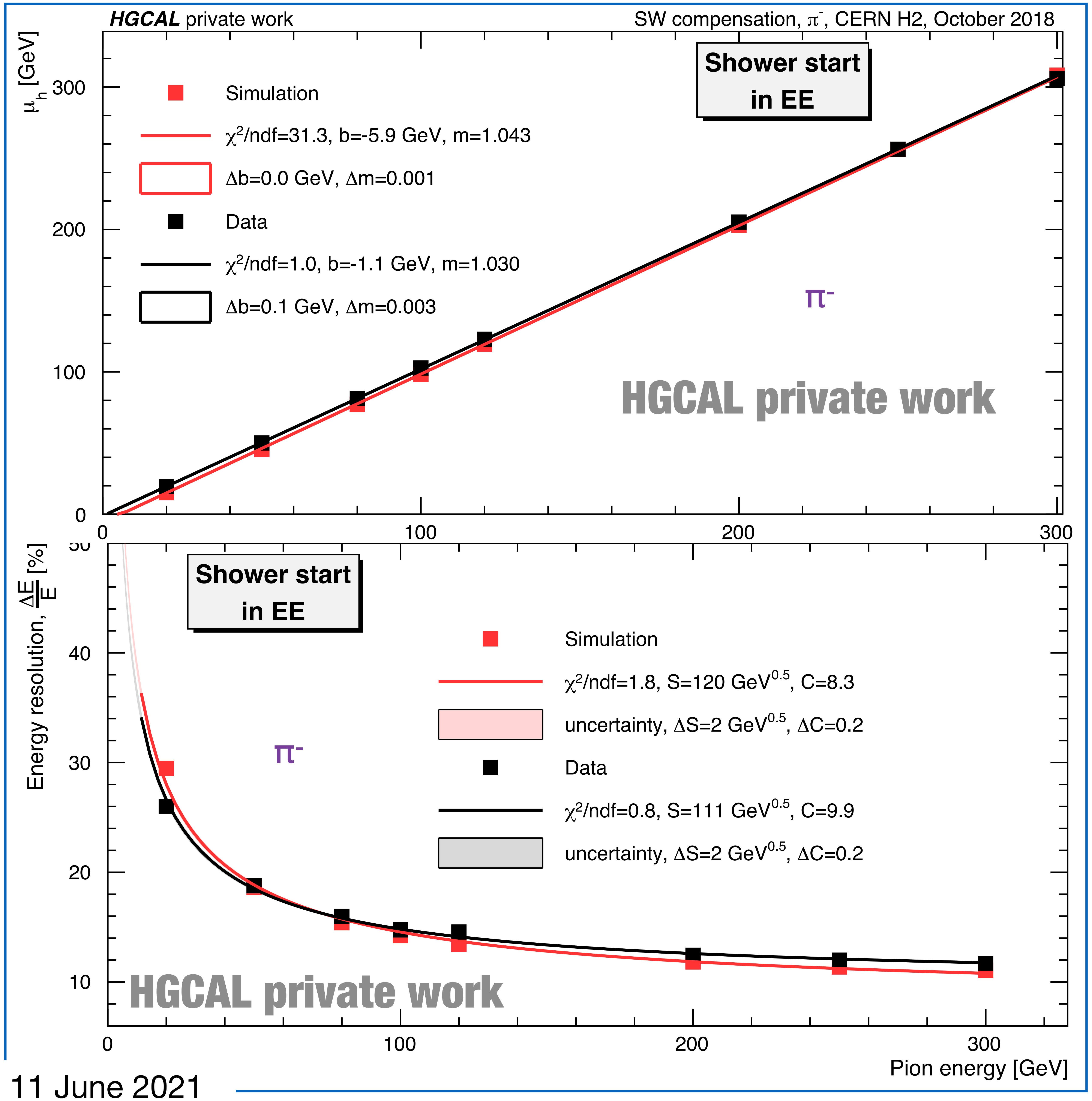
"Software compensation"

SW) $E_{SW} := w_{EE} \times [\Sigma_{EE} E_i \times \phi(E_i/E_{tot})] + w_{FH} \times [\Sigma_{FH} E_i \times \phi(E_i/E_{tot})]$





Energy linearity & resolution for hadronic showers



Machine learning-based e/π separation

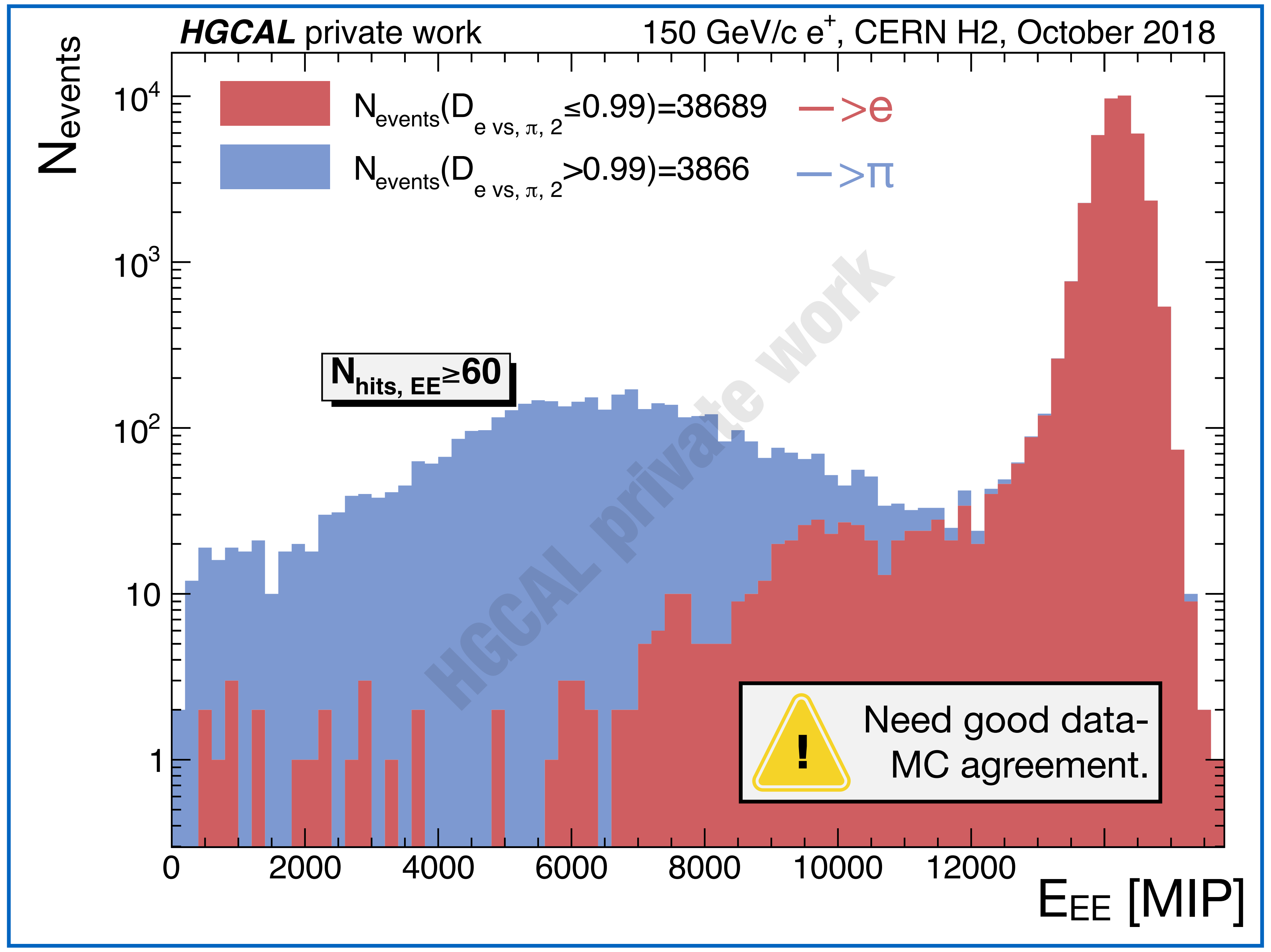
e/π separation

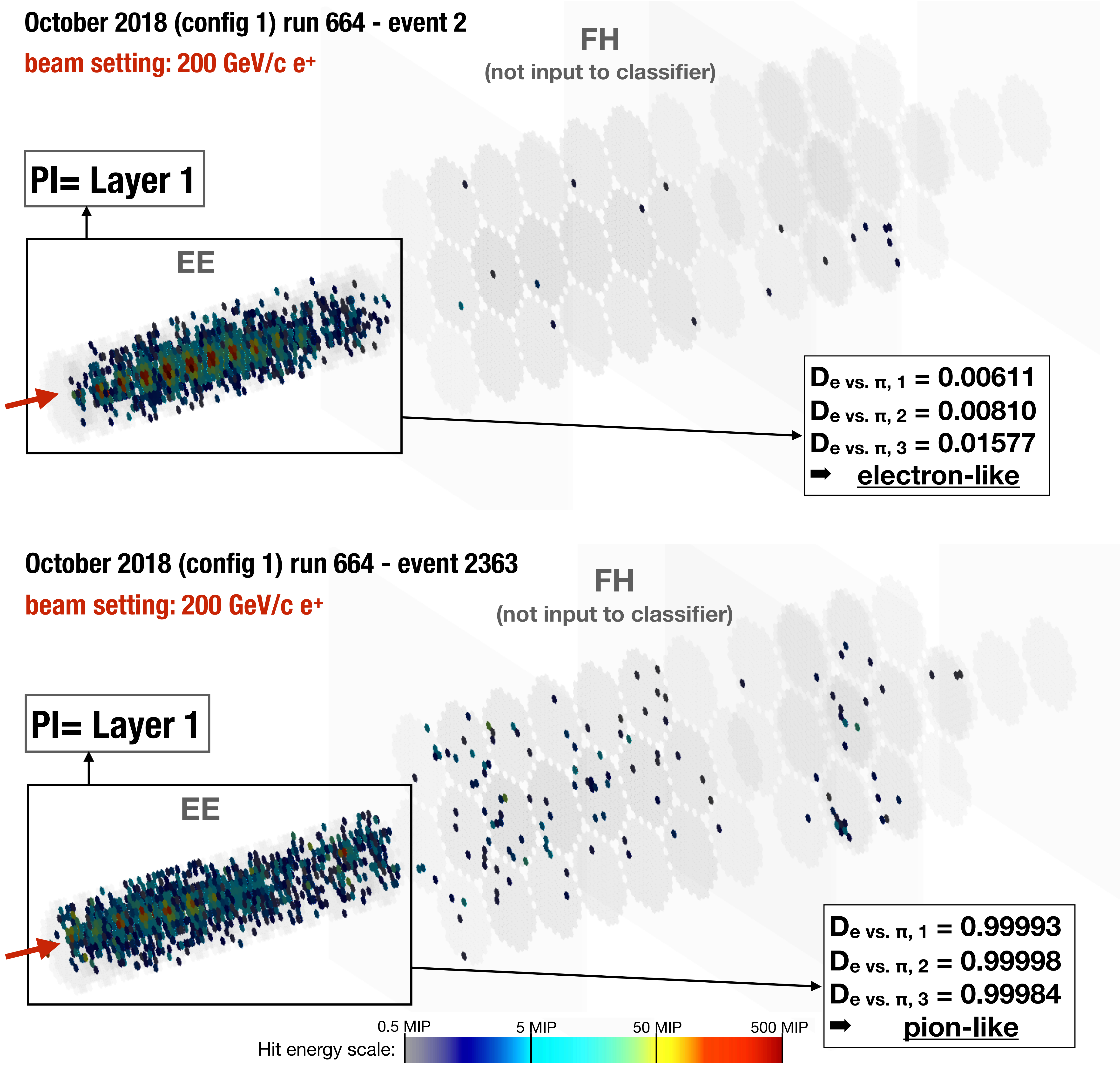
Granularity for sophisticated task beyond classic calorimetry?

Shower "image" = input to **CNN**.

- $D_{e\ vs\ \pi}(e) \longrightarrow 0$, $D_{e\ vs\ \pi}(\pi) \longrightarrow 1$. Training on simulated data.

‣ Proof-of-principle demonstrated on test beam data.





➡ **Granularity exploitable for e/π separation: Good.**

➡ **Machine learning a suitable tool.**

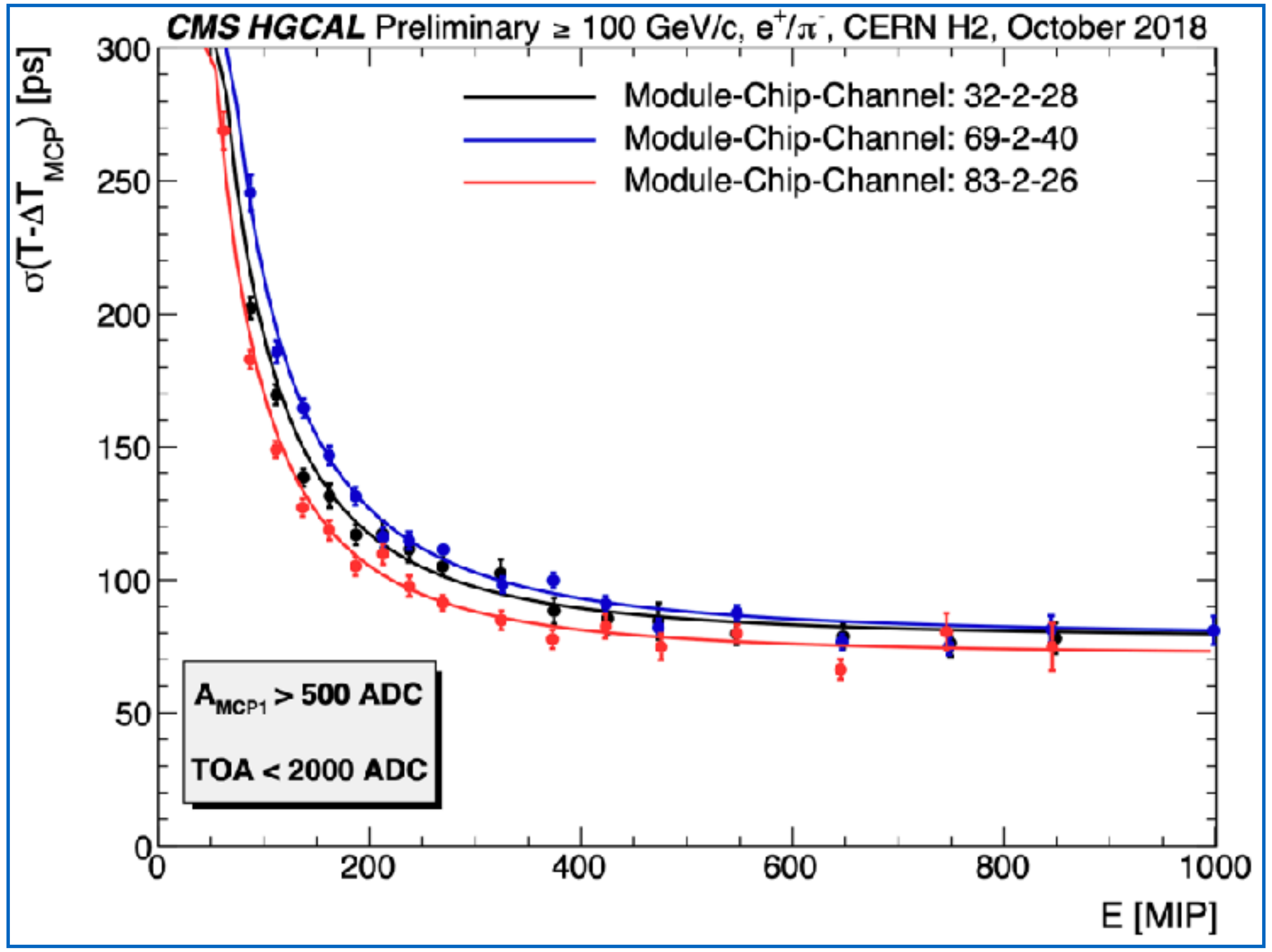
Last but not least: Timing performance

Per-channel timing performance

2 calibration ingredients:

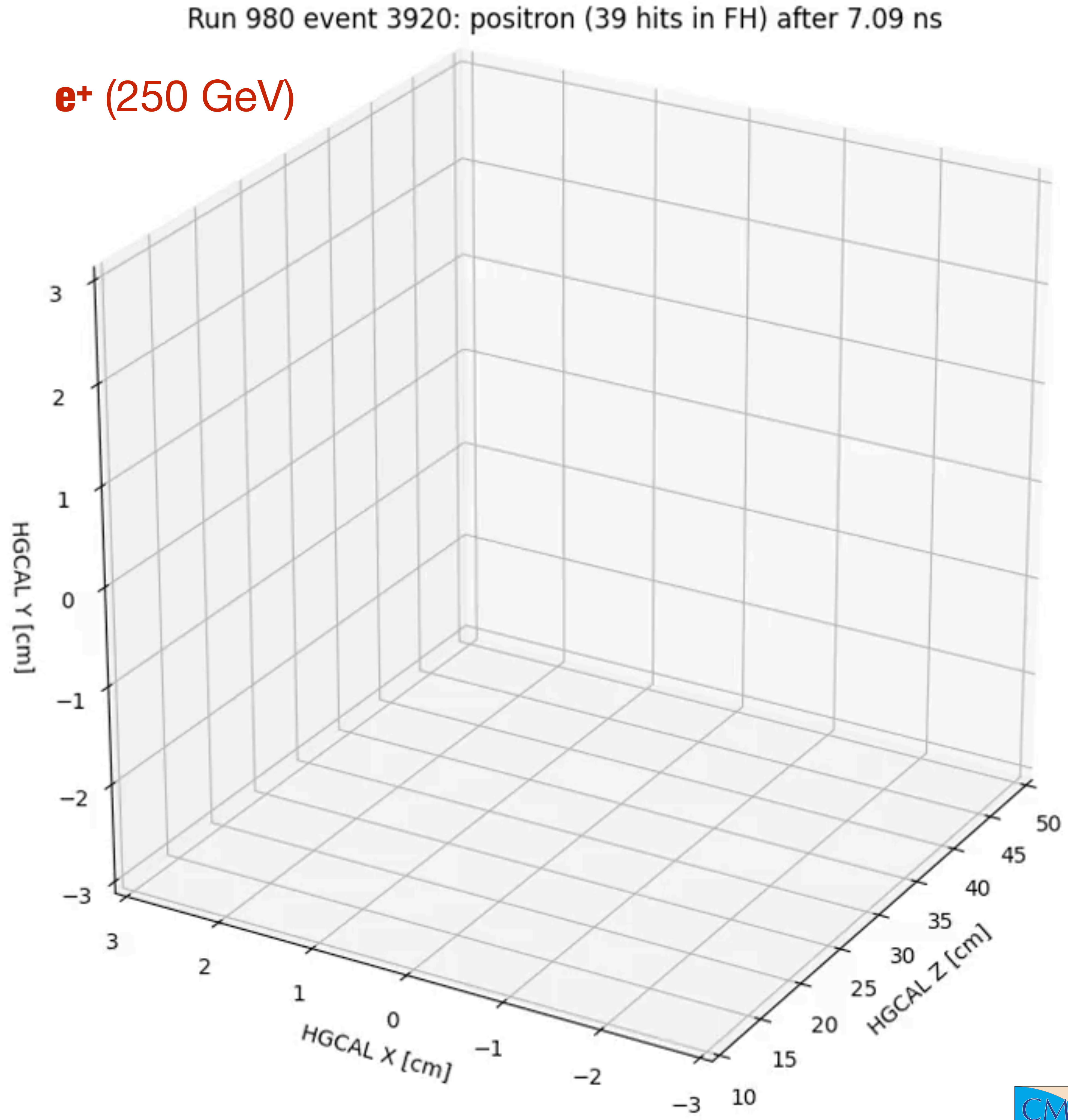
- TOA-nonlinearity.
- Time walk due to fixed threshold discriminator.

- Compare calibrated timestamp to reference time from MCP.
  - E-dependent resolution. Constant ~70-80ps.

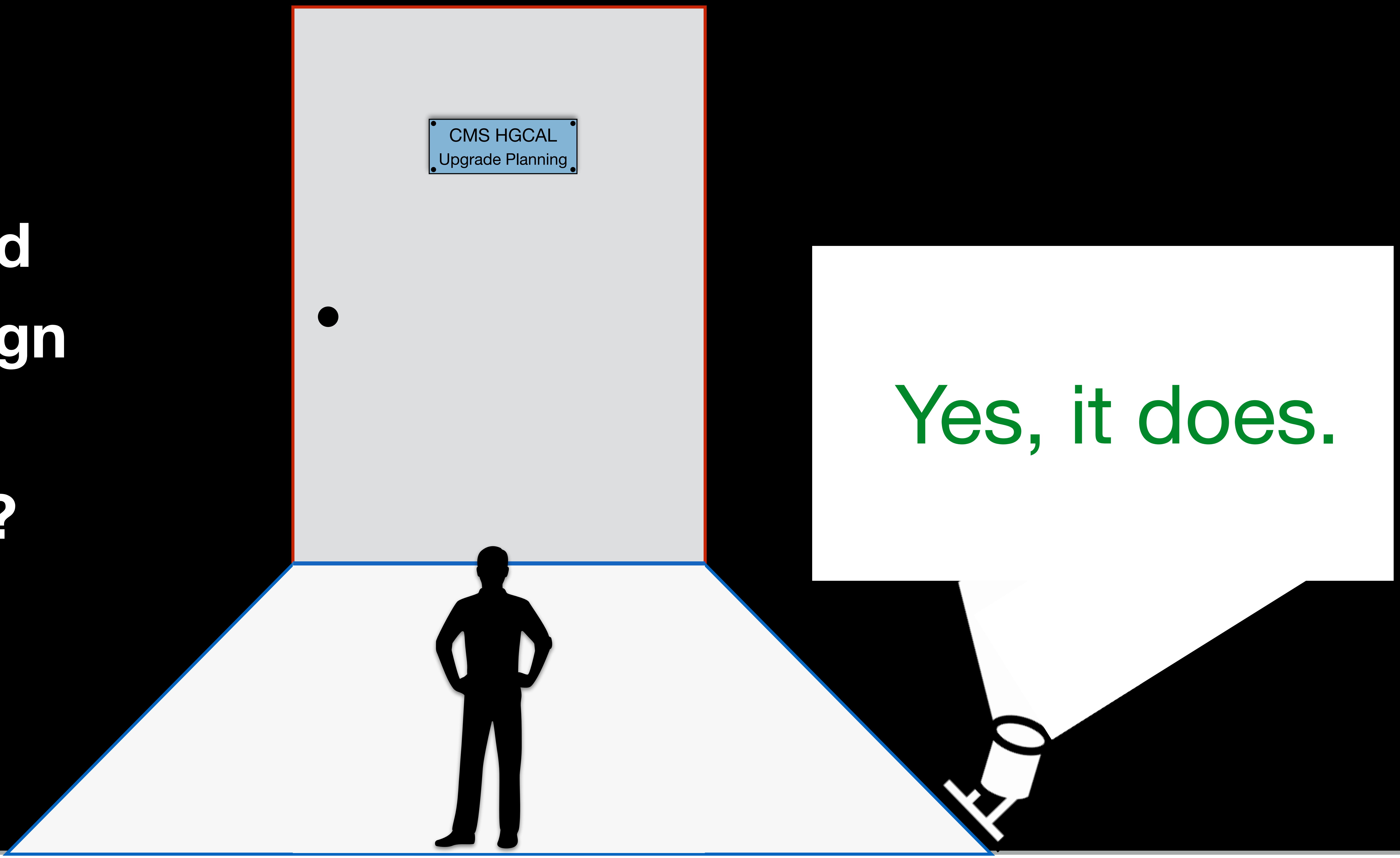


➡ σ_T close to 60-70 ps for high hit energies: Good.

➡Time evolution of particle showers!



Does the silicon-based HGCAL design meet the expectation?

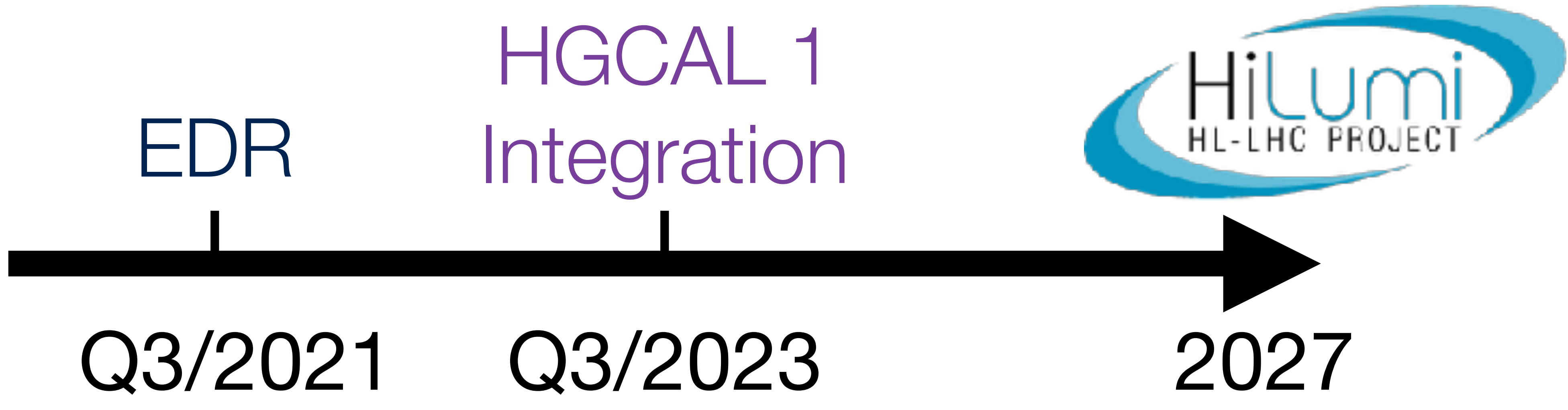


HGCAL upgrade project: Outlook

✓ Important progress since the Technical Proposal (2015) and ongoing developments since the Technical Design report (2018).

- <u>Currently, the focus is on:</u>
    - Finalisation of design, prototyping towards final systems.
    - Market surveys, orders.
    - Preproductions, qualification of final components.

- Next major step: <u>**Engineering Design Review due at the end of this year**</u>
    - Validation of silicon sensors and SiPMs.
    - Final version of very front-end ASIC.
    - Si modules and scintillator tileboards designed.
    - Cassettes and mechanics design ready.



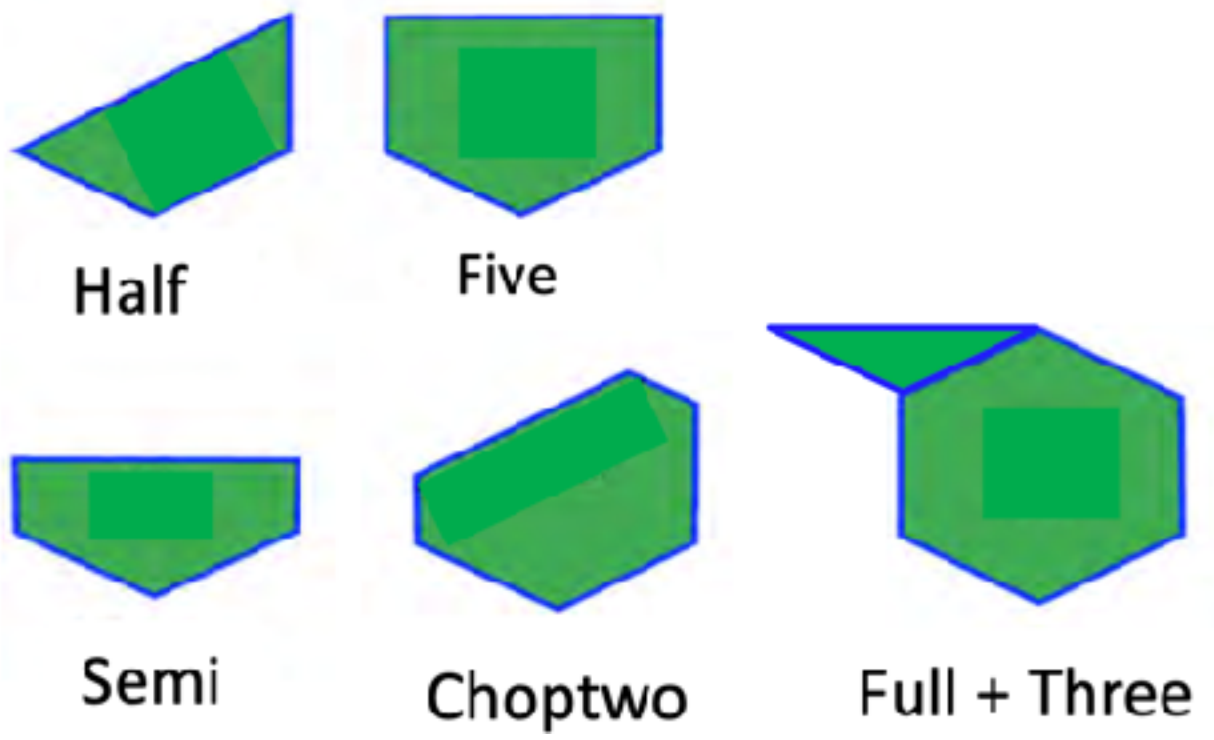
- **Production starting in 2022.**

Towards mass production of silicon modules around the world

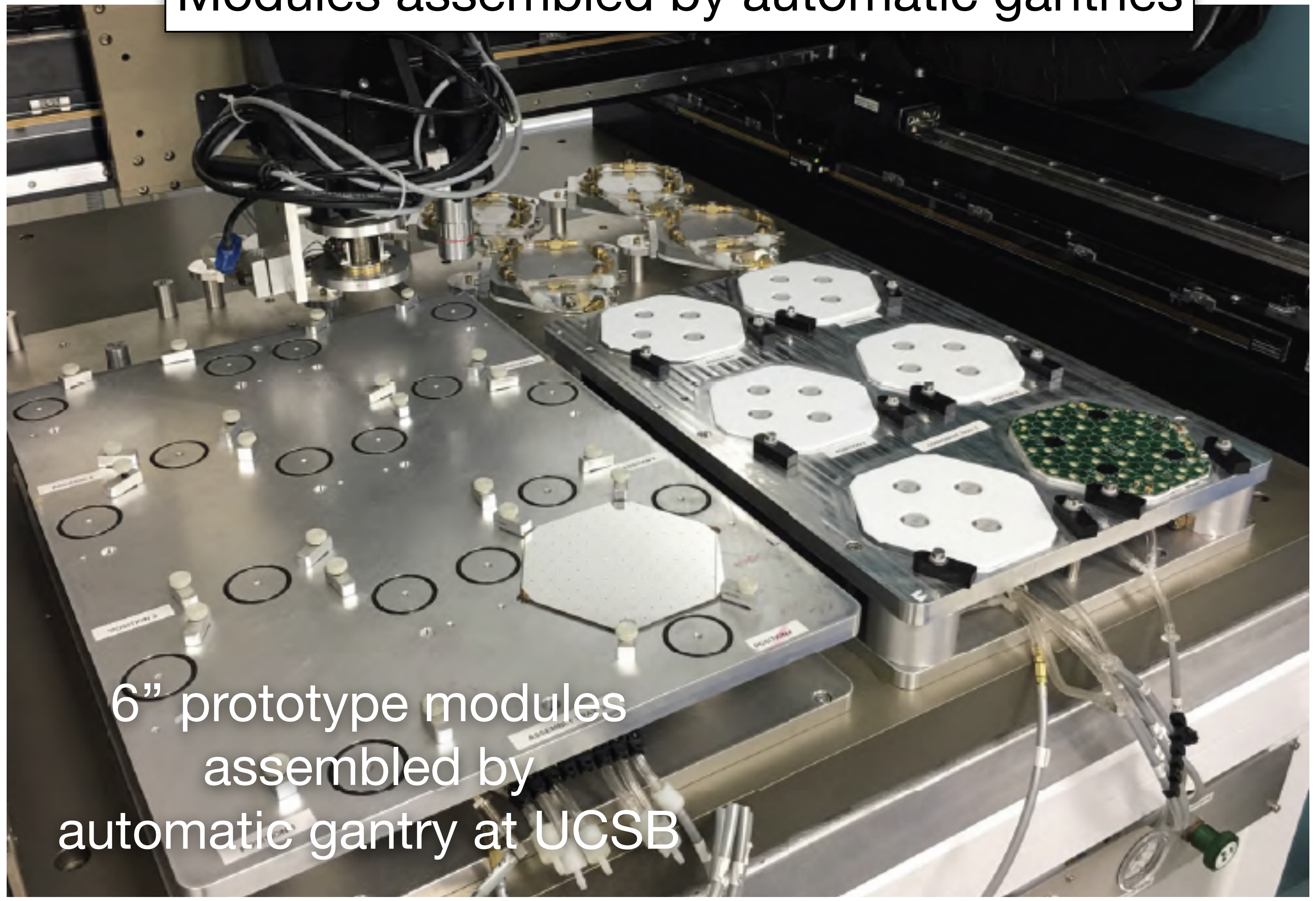
27k silicon modules to be produced

Module Type	300 µm	200 µm	120 µm	Sum
Full	8820	7740	4356	20916
Five	1158	144	0	1302
Choptwo	0	0	312	312
Semi	450	0	312	762
Half	1386	156	84	1626
Full+Three	1092	0	0	1092
Totals	13998	8040	5064	27102

Modules have different shapes



Modules assembled by automatic gantries



Tooling development and preparation for large scale production:

- ***Tooling*** for low density full modules ***ready***, soon also for high density full module.
- Design of gantry tooling for ***partial modules ramping up*** this year.

Module Assembly Centers (MACs) preparation is well advanced

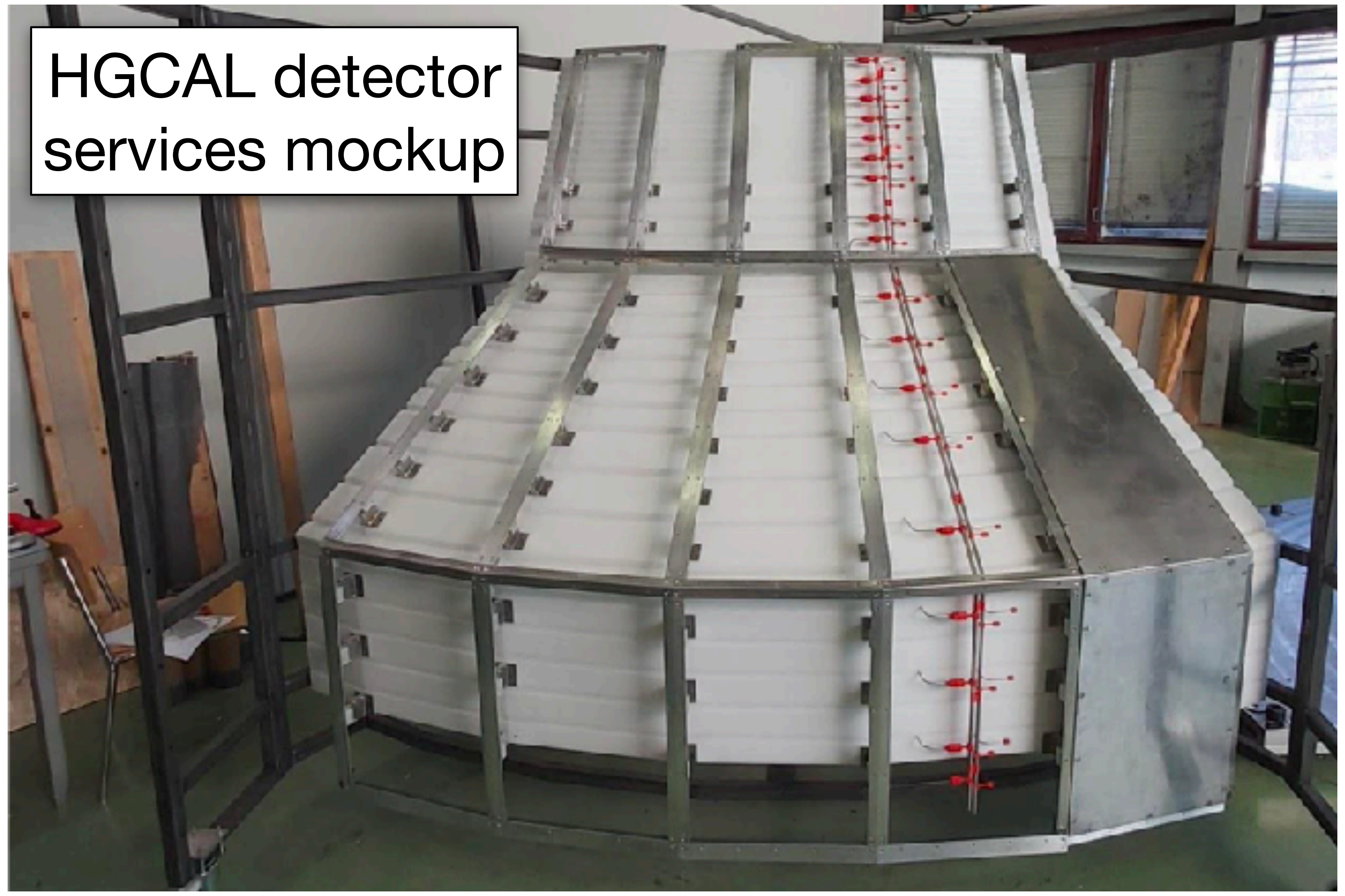
- All **6** sites progressing on qualification of various module production steps.
- ***5 sites fully equipped*** and on track to be qualified for assembly in 2021.

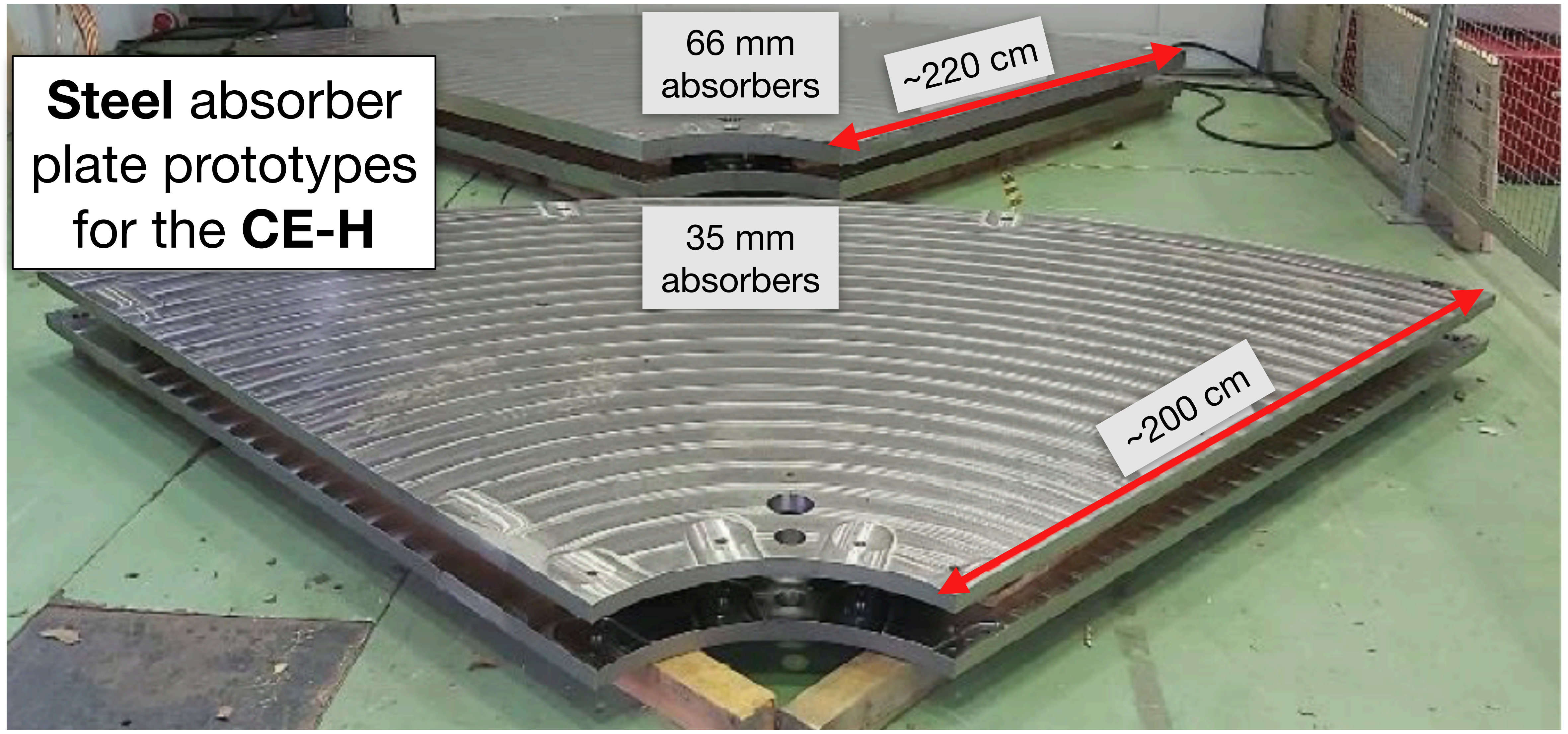
Production plan

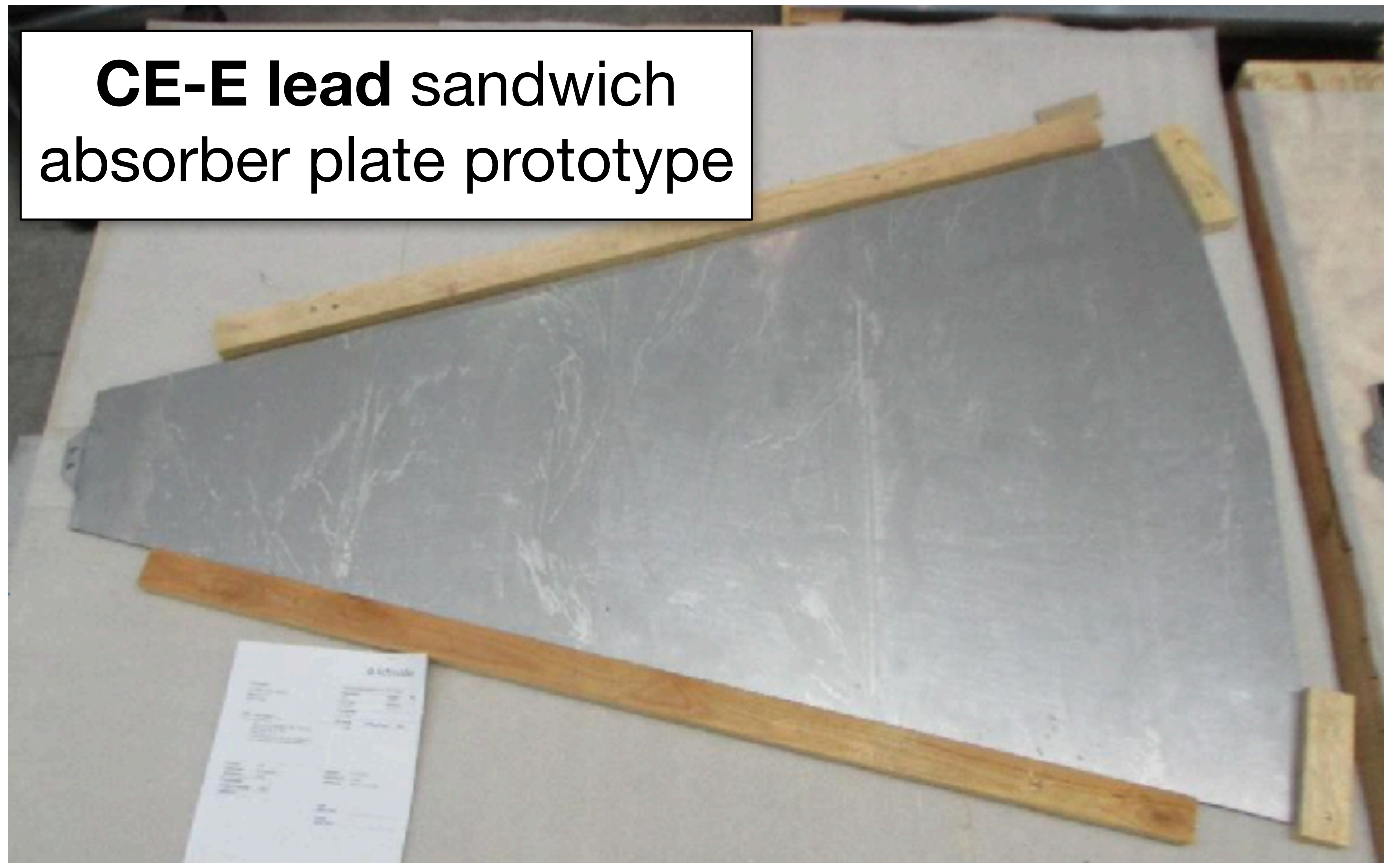
- 10 modules/day per MAC with 6 MACs.
- Could achieve up to 24 modules / day per MAC.

Prototyping of services and passive absorber plates advancing

- ***Mockup structures*** to study installation steps and on-detector services locations.
- Procurement process of ***600 tons of stainless steel*** started.
- Achieved ***1 mm flatness*** for CE-H steel absorber plates.
- Lead sandwich absorber development challenging due to relative weakness and low workability.







🏁 Summary 🏁

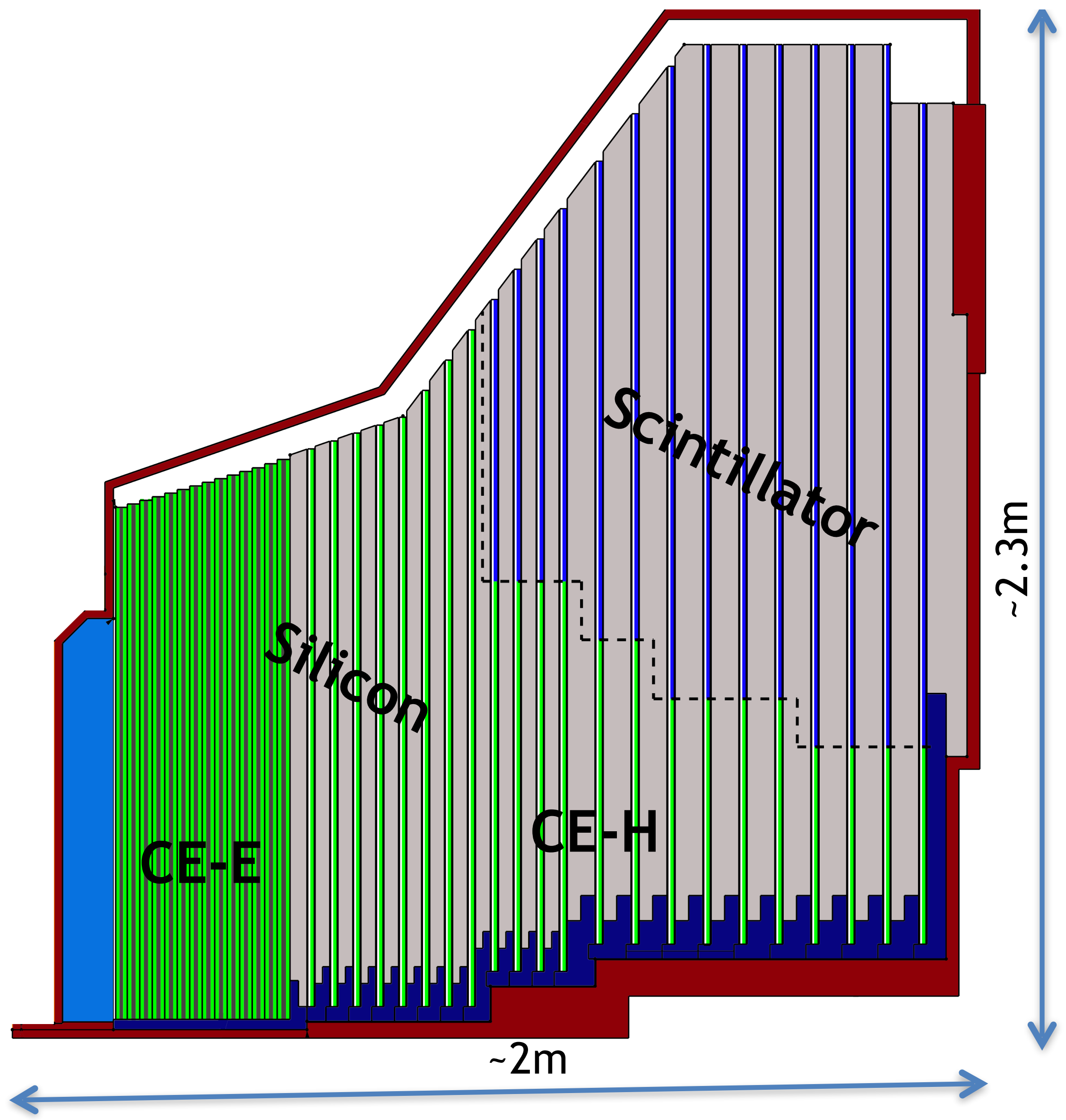
Take home messages

Detector upgrades necessary High Luminosity LHC.

- Able to properly operate in harsh radiation environment, high pileup & occupancy.

One of them: CMS High Granularity Calorimeter which is an imaging calorimeter.

- Silicon as sensitive material in high radiation region, scintillator+SiPMs elsewhere.
- 3D energy & time measurement of particle showers.



HGCAL test beam results: Silicon-based HGCAL design meets expectation.

- Silicon-based prototype modules are functional.
- Calorimetric performance as expected:
  - ✓Longitudinal shower evolution, energy linearity & resolution, positioning capabilities for particle flow.
  - ✓Granularity helpful, especially for hadronic showers.

HGCAL lab tour at CERN ?
thorben.quast@cern.ch

References / Additional reading

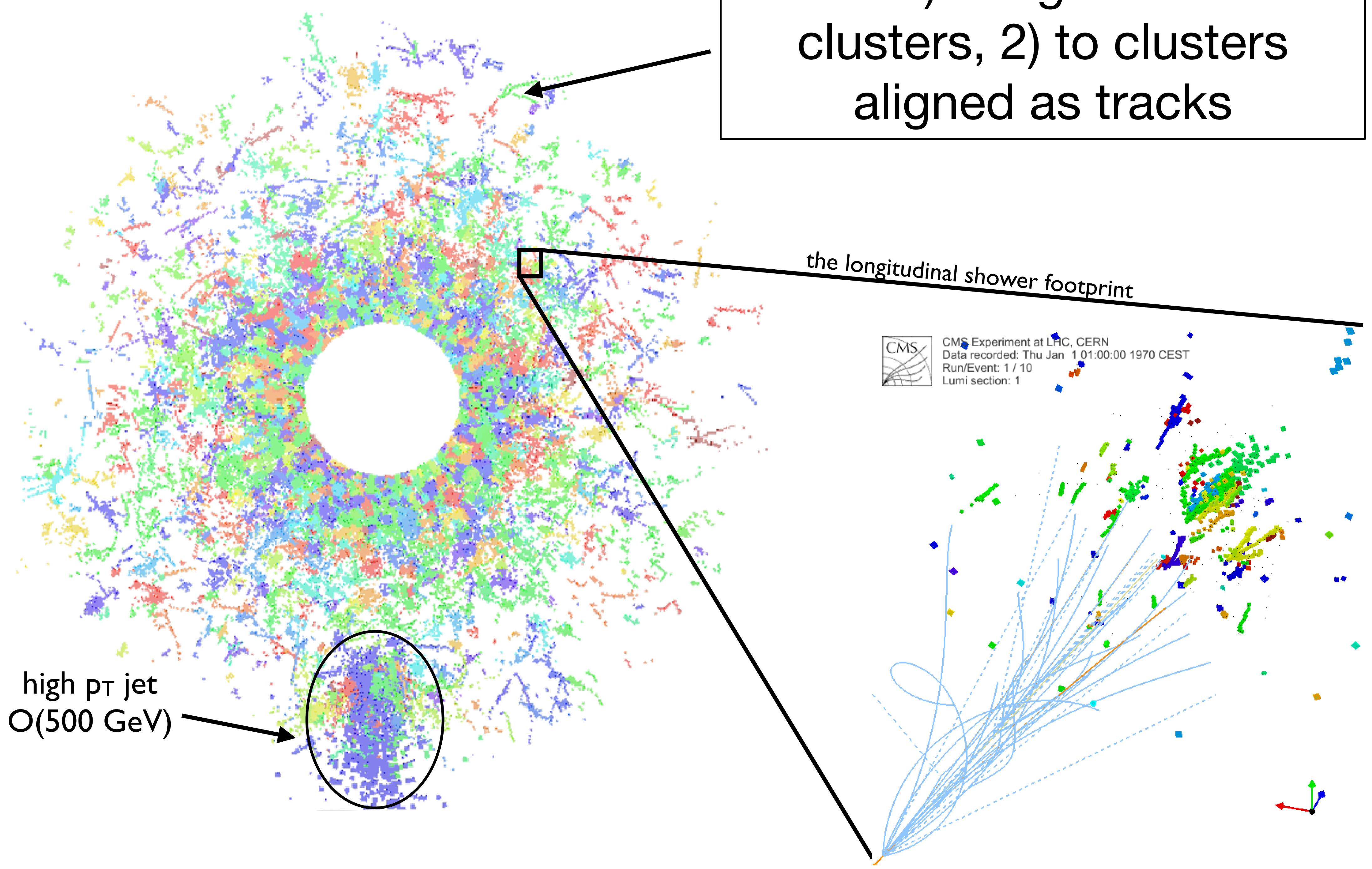
- The Phase-2 Upgrade of the CMS Endcap Calorimeter
- ARRAY: An open source, modular and probe-card based system with integrated switching matrix for characterisation of large area silicon pad sensors
- Software compensation in particle flow reconstruction
- First beam tests of prototype silicon modules for the CMS High Granularity Endcap Calorimeter
- Qualification, Performance Validation and Fast Generative Modelling of Beam Test Prototypes for the CMS Calorimeter Endcap Upgrade
- The DAQ system of the 12,000 Channel CMS High Granularity Calorimeter Prototype
- Construction and commissioning of CMS CE prototype silicon modules

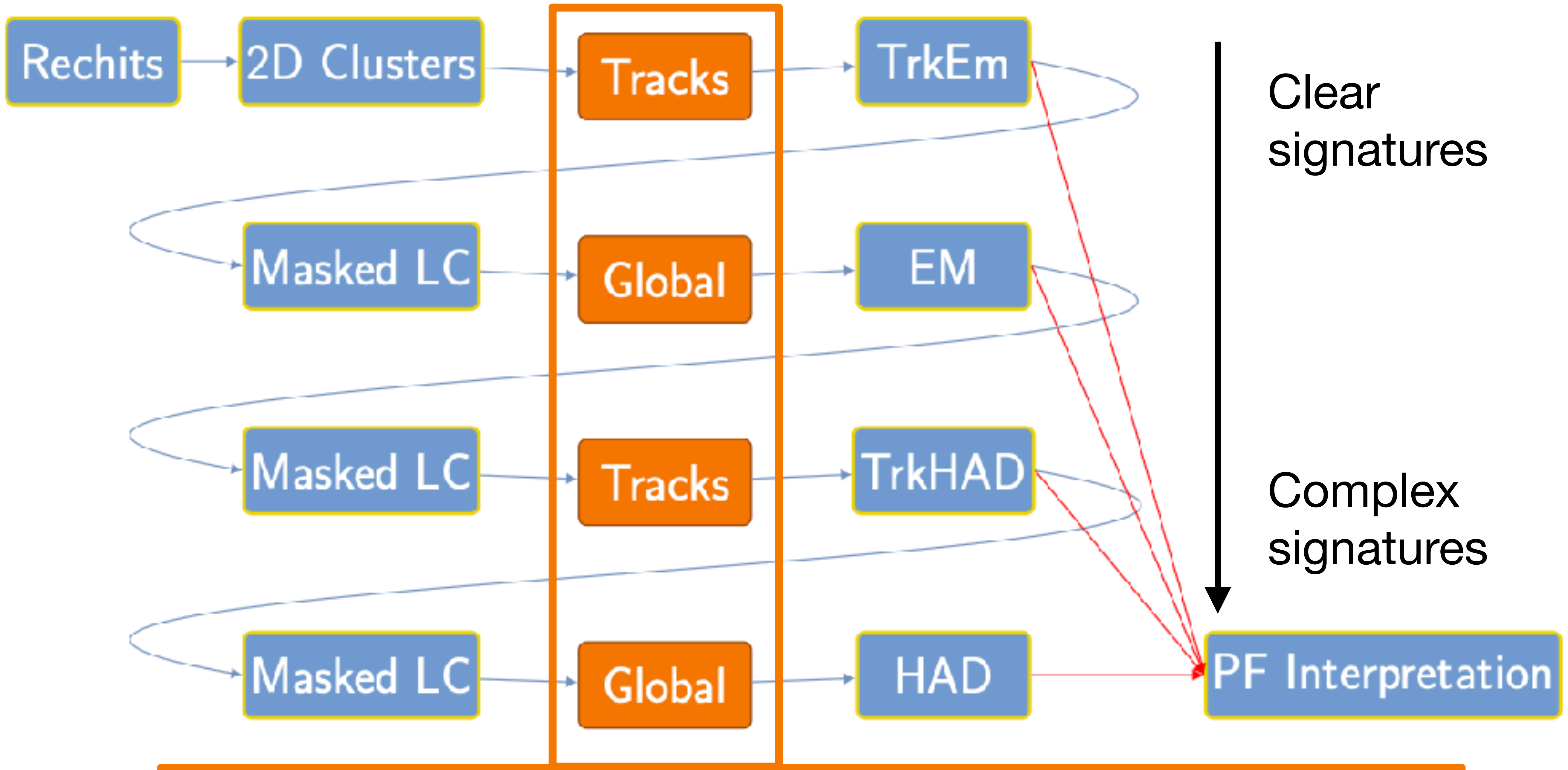
Backup

Sophisticated offline reconstruction = The Iterative CLustering

Goal: 1) merge hits to 2D clusters, 2) to clusters aligned as tracks

Iterative strategy: Reconstruct "easy stuff" first and work with what is left



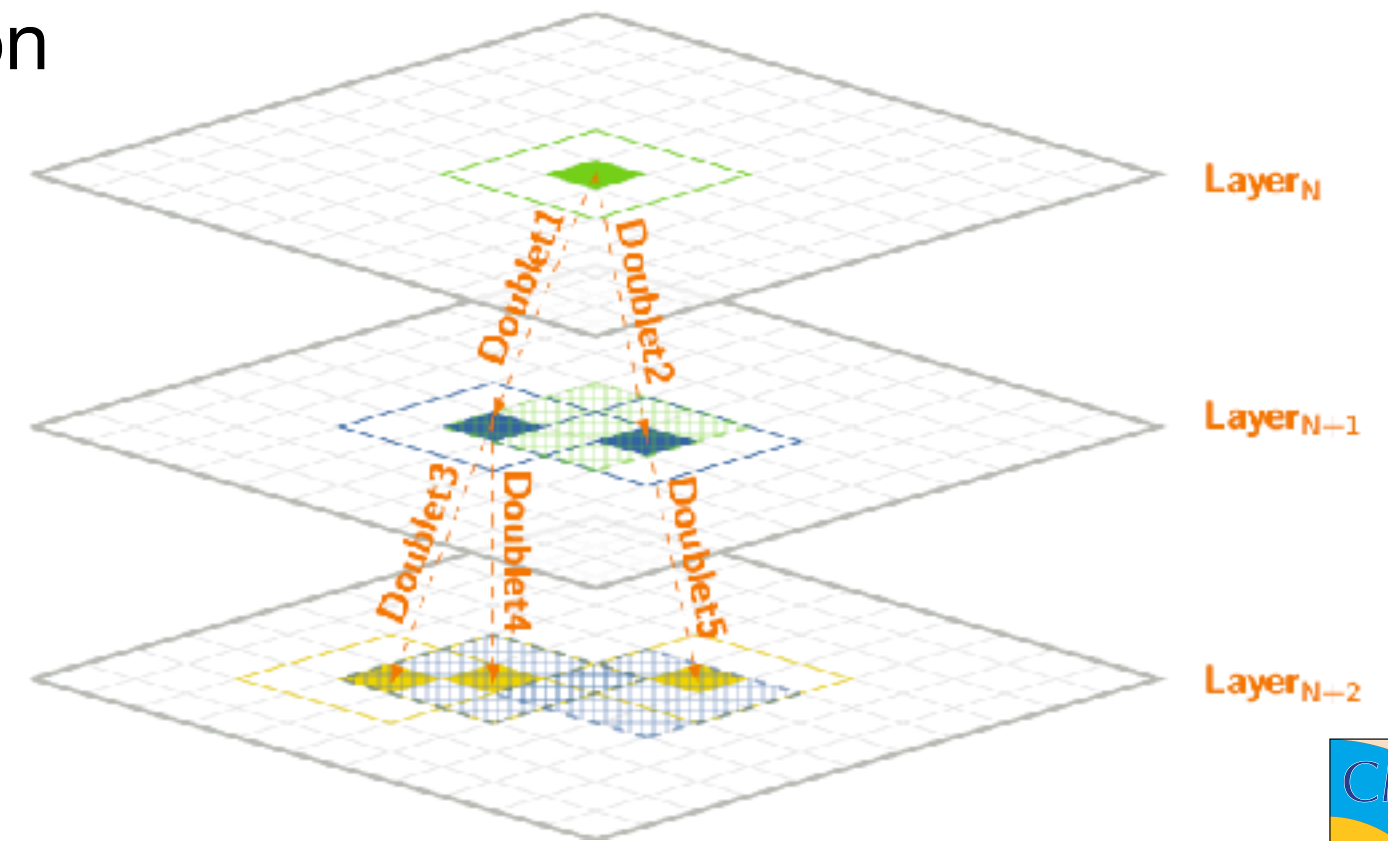


Current TICL highlights

- Modular framework, written in C++.
- Works well with single EM particles, validated with test beam.
- Pattern recognition for hadronic shower to be optimised.
- Competitive to end-to-end machine learning approaches.
- TICL reconstruction on tt+200PU = O(100ms) on CPU, only ~5% of CMS phase 2 reconstruction budget.

cf. vCHEP 2021

Pattern recognition based on cellular automaton, e.g. doublet-search.

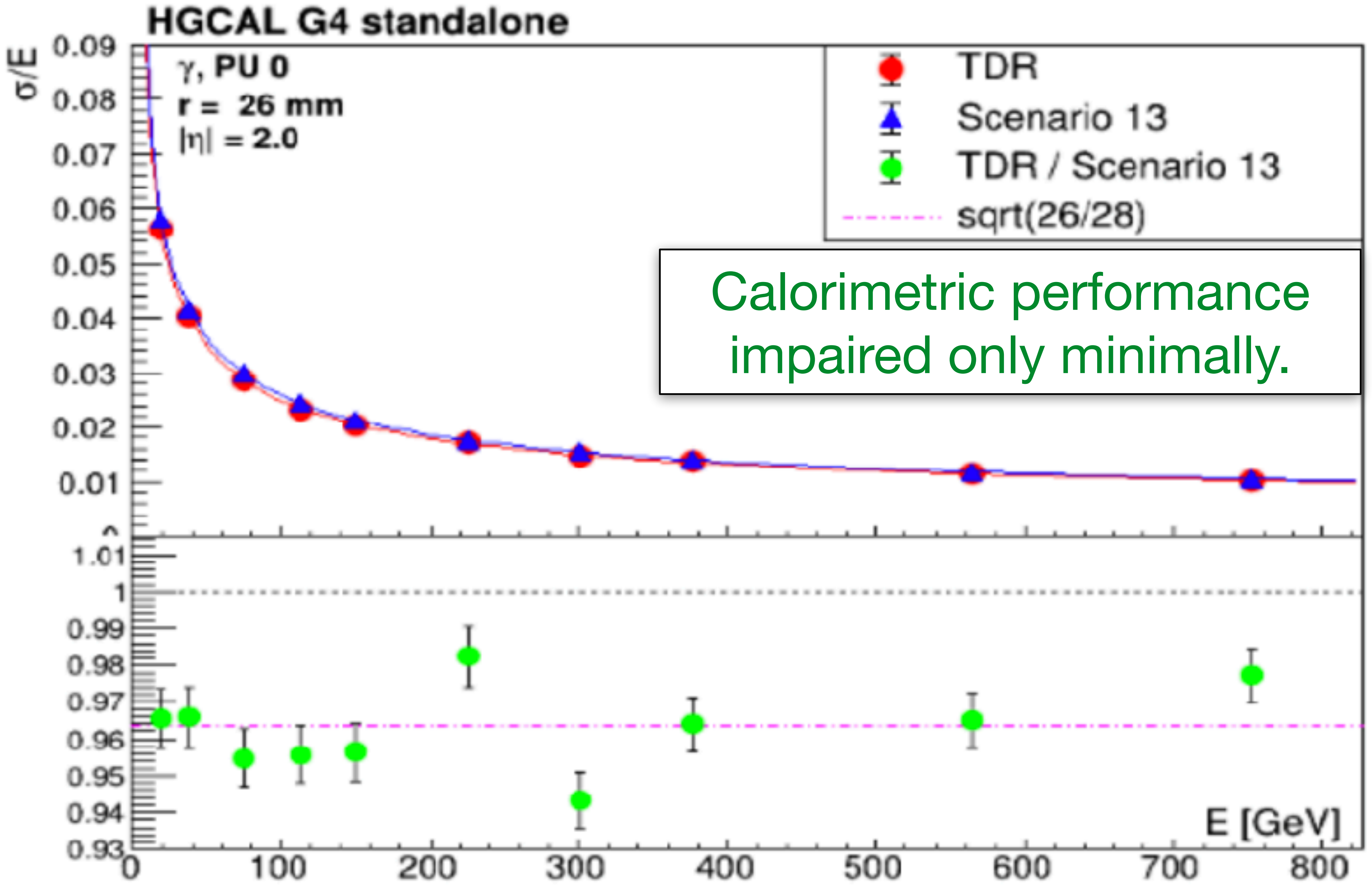


Recent re-optimisation of longitudinal sampling

- Mobile-phone-size front-end embedded in industrial-size absorbers.
  - **Absorber tolerances add up to ~height needed by front-end.**
- Absorber plates must be ordered soon.

➡ **Adapt to realistic absorber tolerances while preserving overall nuclear/radiation depths.**

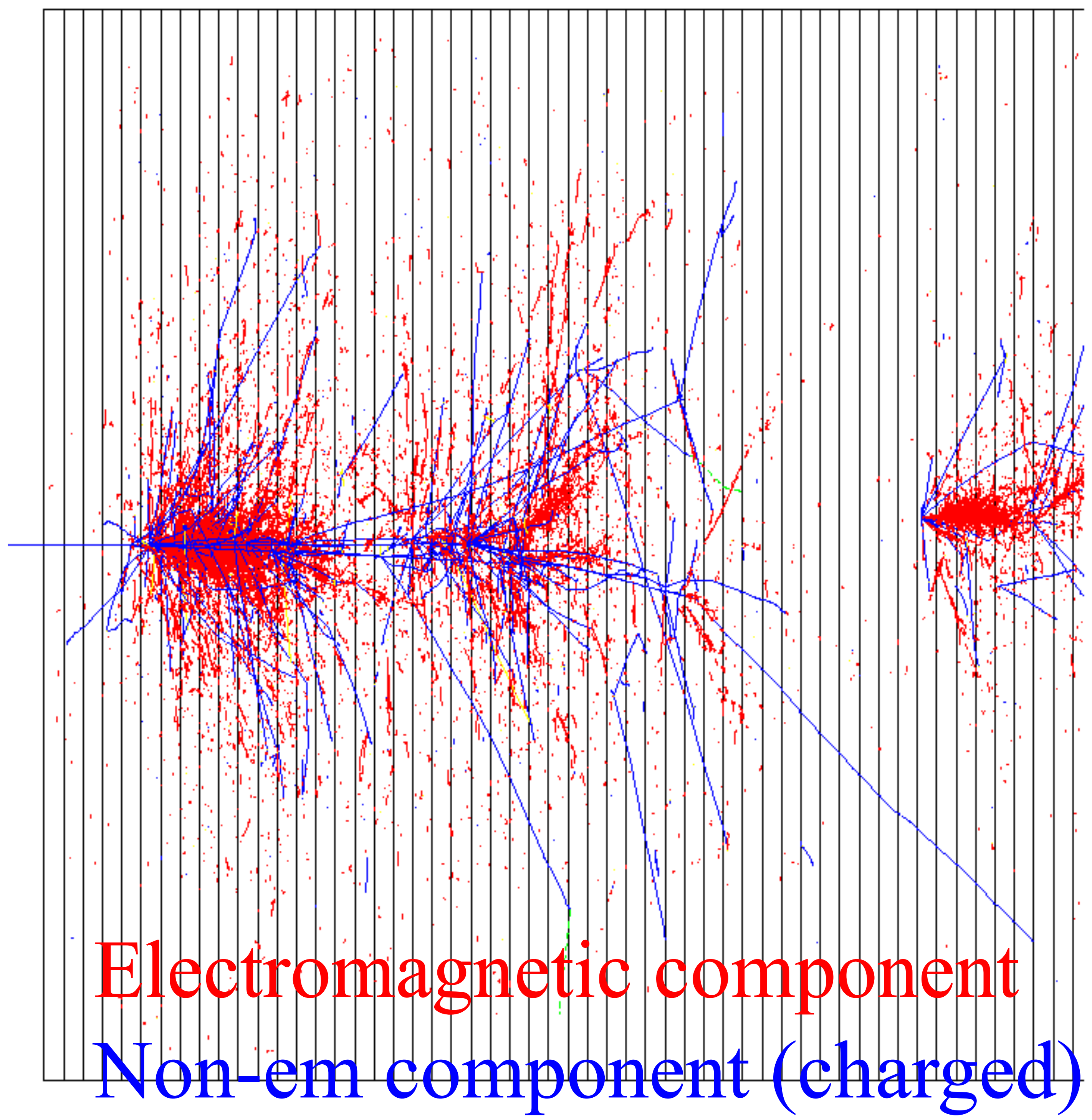
	Dec 2018	New: Scenario 13
# layers in CE-E, sampling layout	28, uniform	**26; last four thickened**
# layers in CE-H (all Si)	8	**7**
# layers in CE-H (mixed)	14	**14**
CE-H: thickness of thin/ thick absorbers	35.0mm / 66.0 mm	**41.5 mm / 60.7 mm**
Depth of CE-E	25.4 X_0	**27.7 X_0**
Total depth	9.85 λ	**9.97 λ**

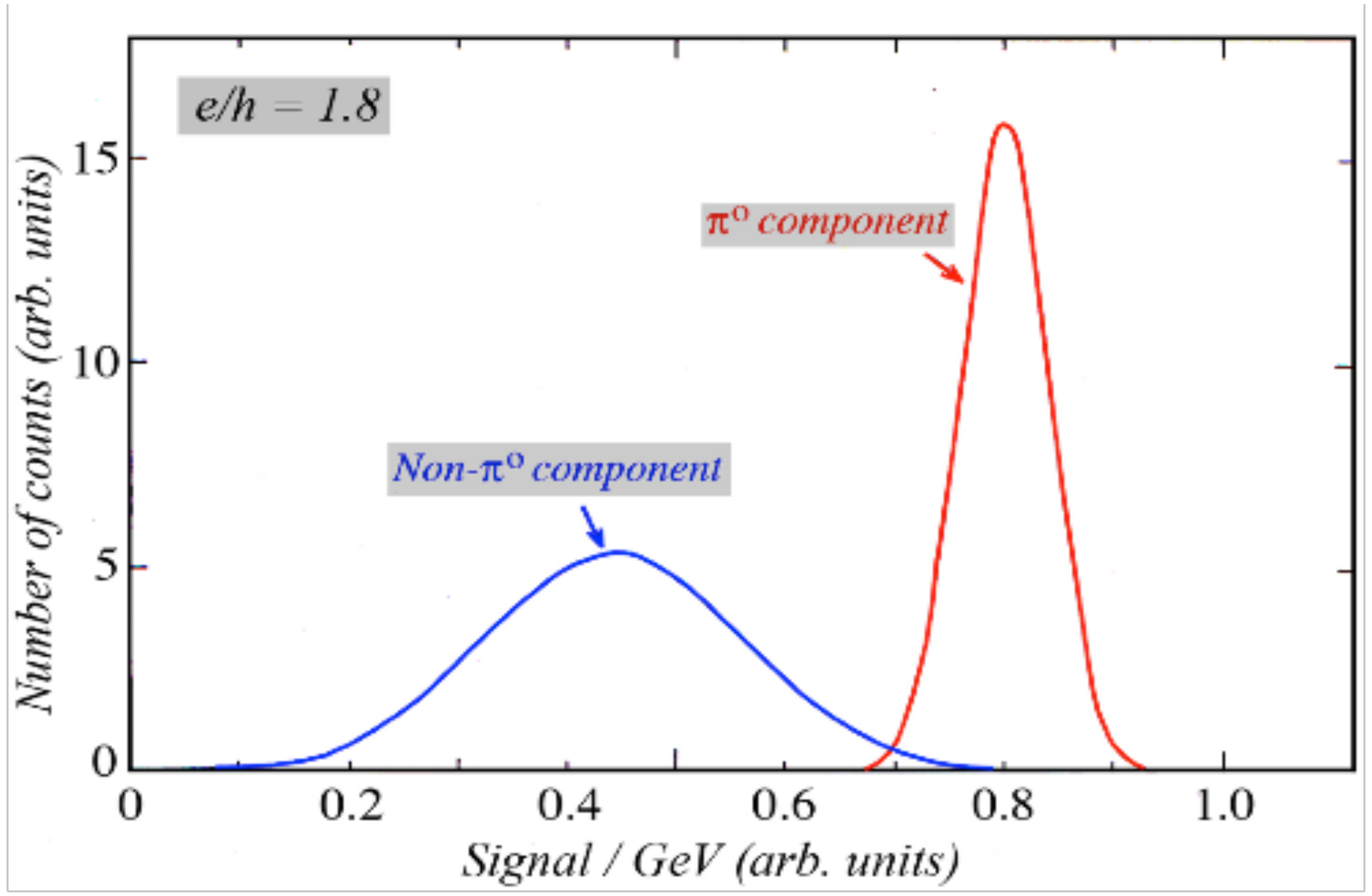


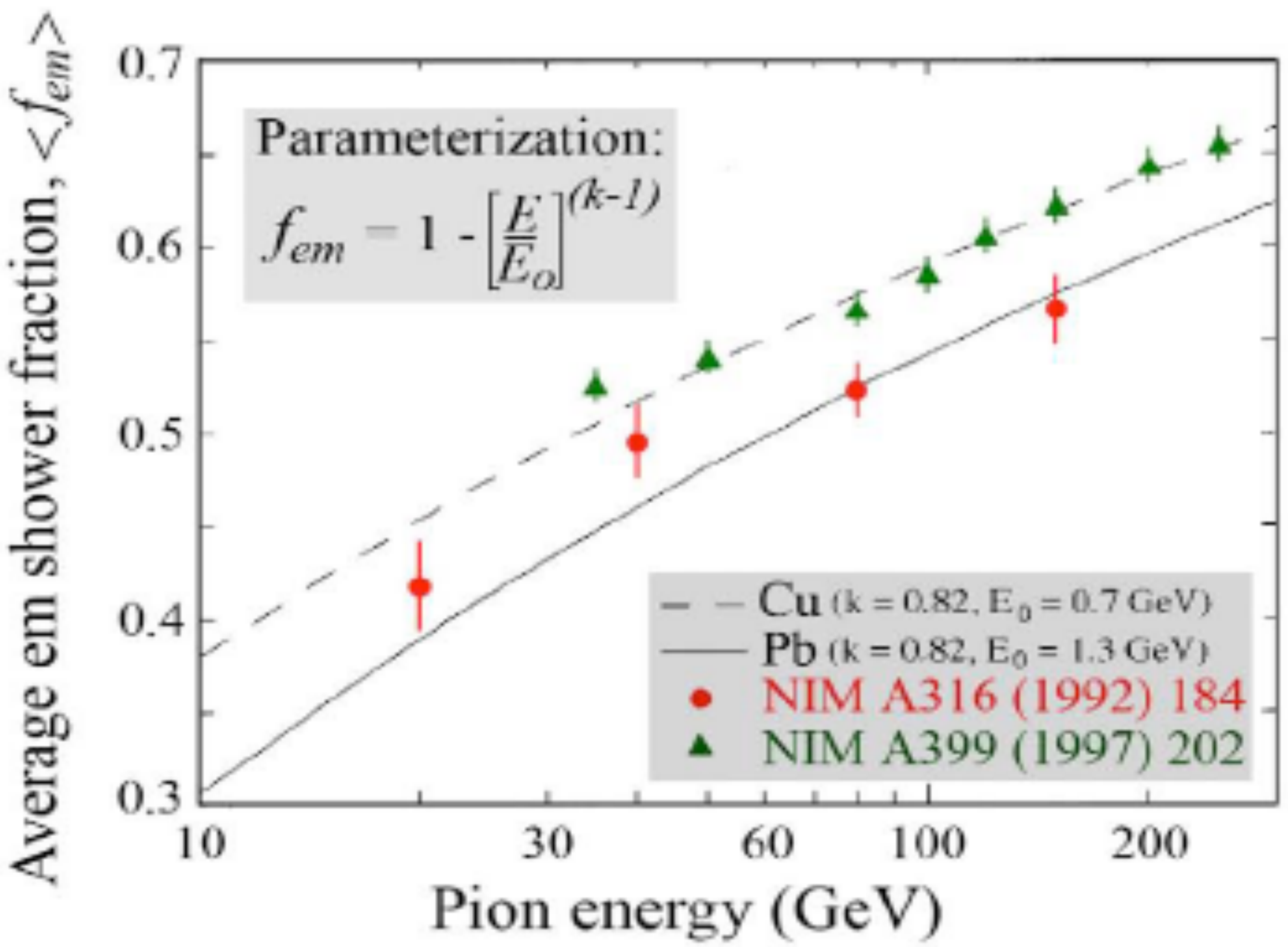
Calorimetric performance impaired only minimally.

➡ **Number of layers reduced to minimise overall risk with minimal impact of performance.**

Efficiency of detecting hadronic & em components differs from unity: non-compensation







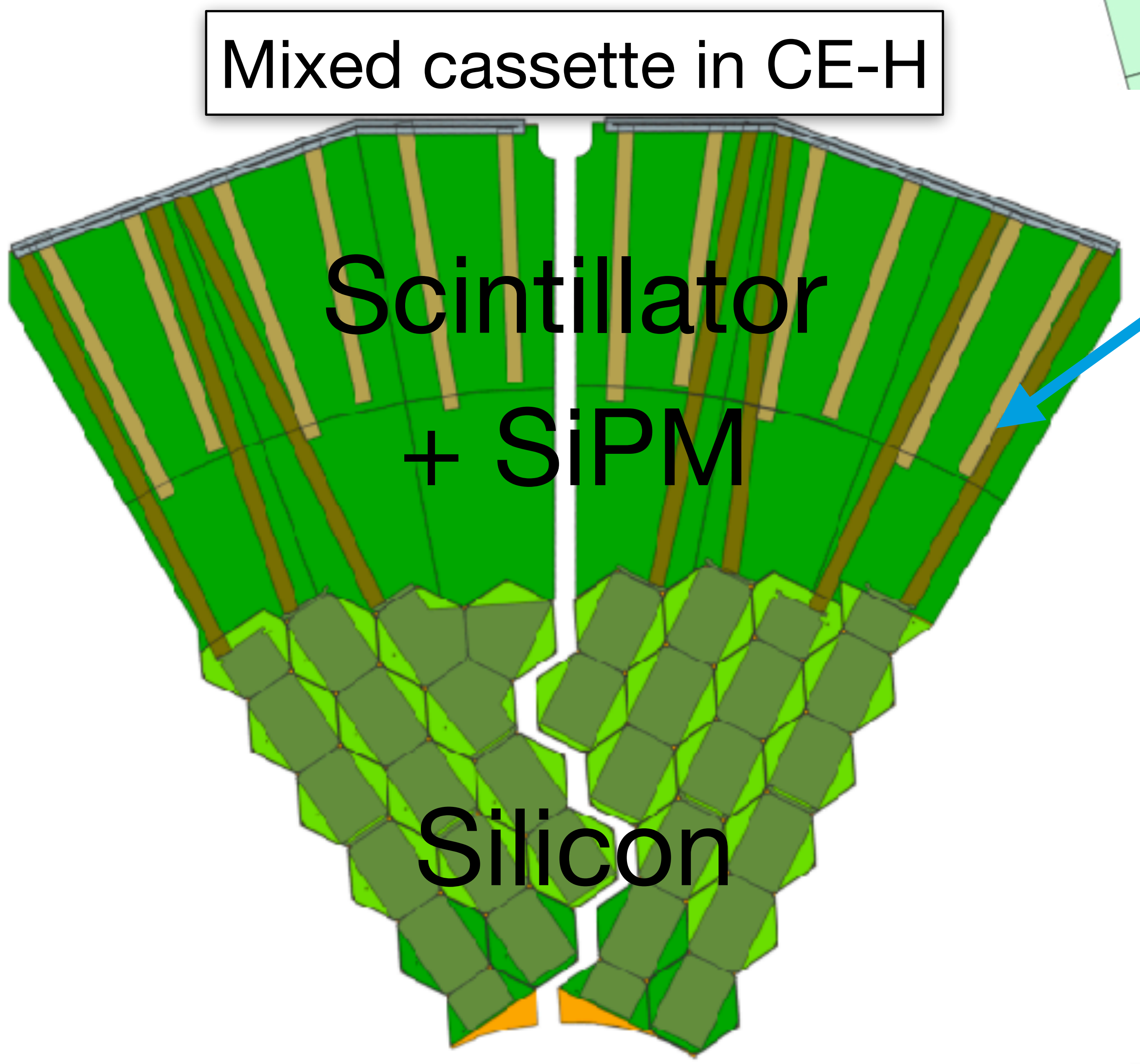
- Hadronic showers with EM and HAD constituents.
- Response typically not identical, i.e. e/h ≠ 1.
- Consequence: Non-linearities, worsened resolution for HAD showers.
- e/h—>1 = improved energy resolution via relative scaling of EM and HAD contributions.

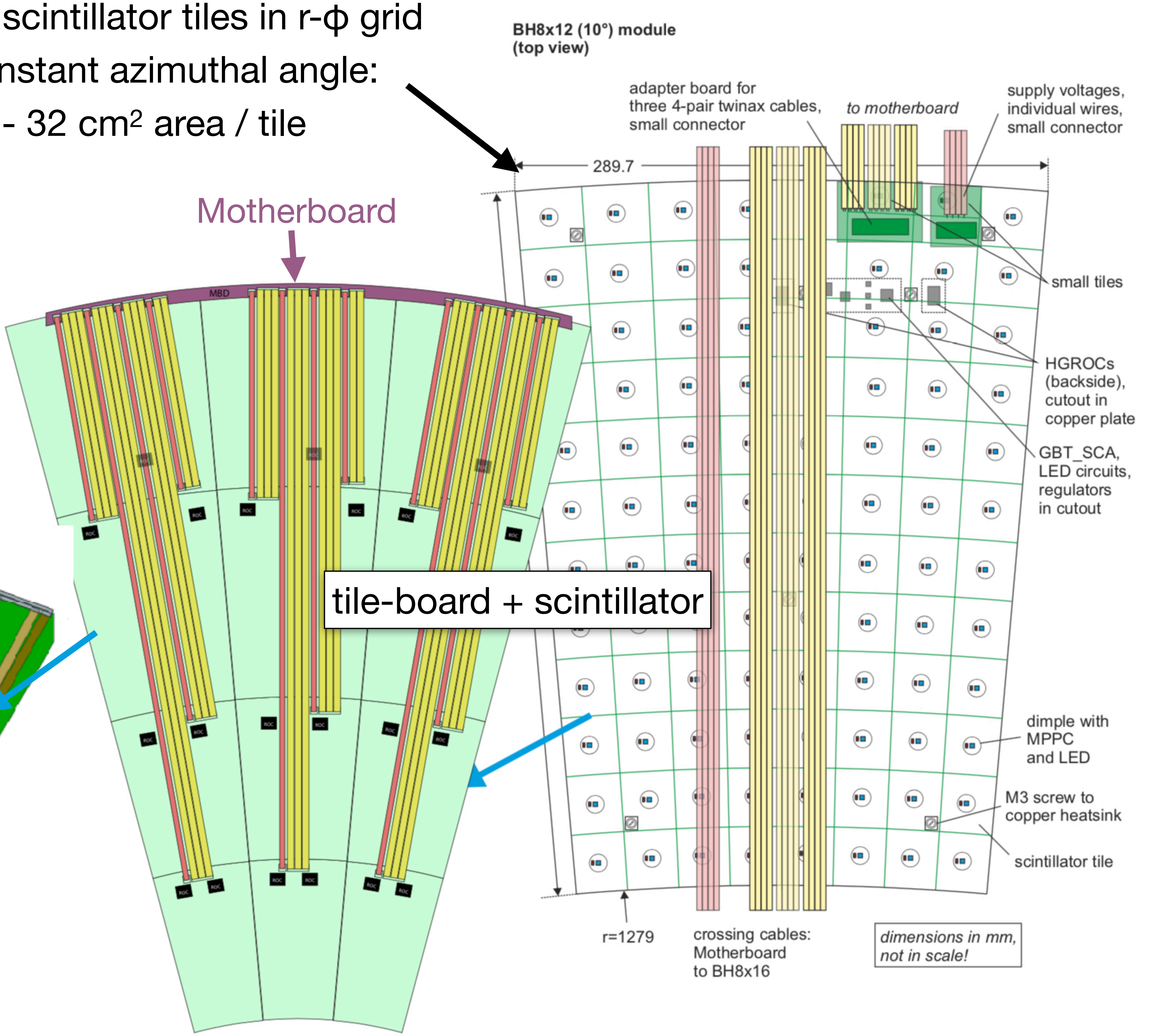
HGCAL tile-modules

Tileboards

- Holds SiPMs, HGROCs, LEDs, …
- Complex layout.
- *Good:* alive and sending data.
- Ongoing R&D: tile-board characterisation (electronically, thermo-mechanically).
-

Arranging scintillator tiles in r-ϕ grid
with constant azimuthal angle:
4 - 32 cm² area / tile



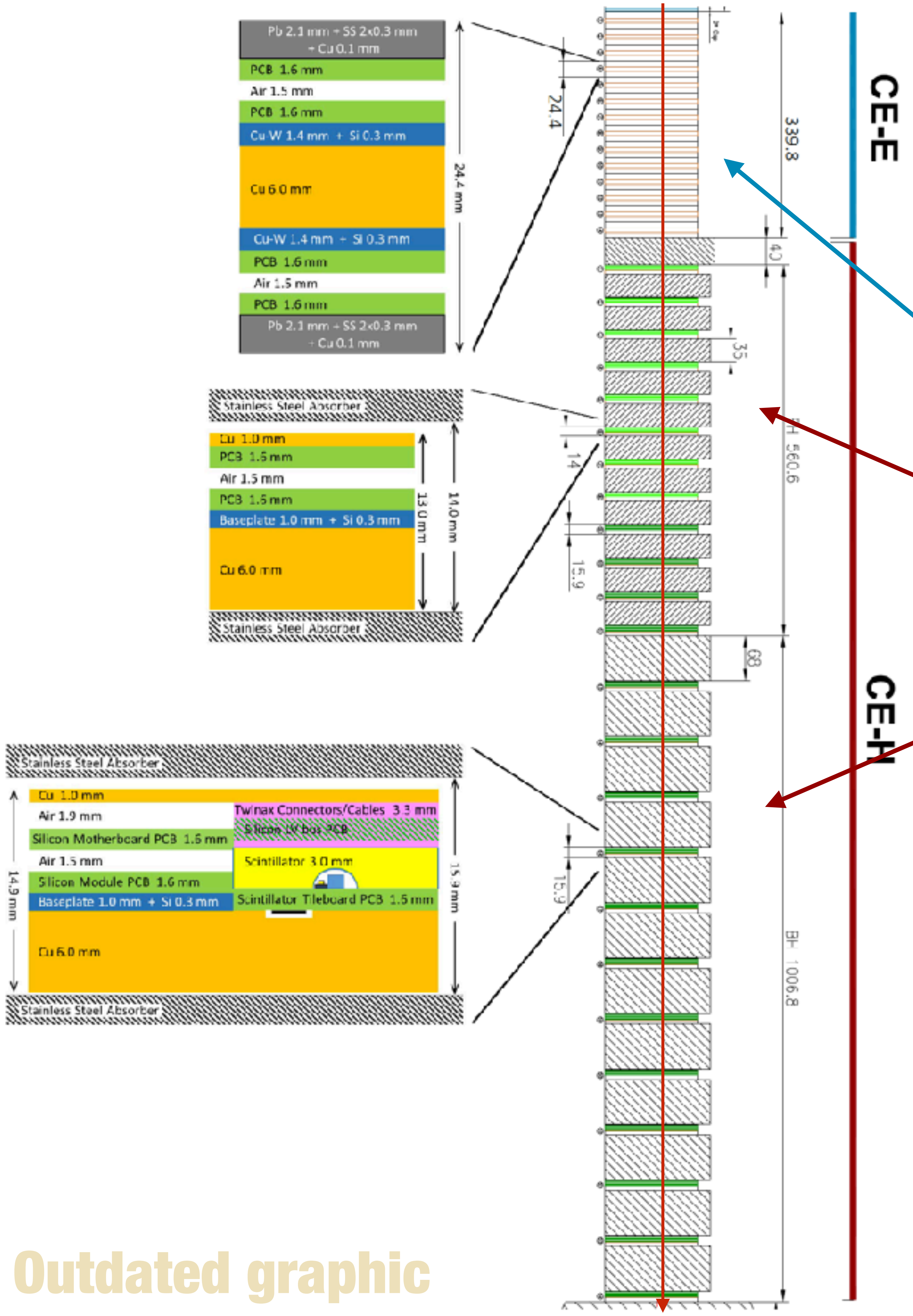


zoom out ⟷ zoom in

Technical challenges

- High-speed data transfer.
- Cooling of SiPMs through PCB.
- Thermo-mechanical rigidity +/- 40 °C.
- Radiation hardness.

Longitudinal structure and lateral coverage



Longitudinal sampling

50 layers for total depth of ~9.8 λ

CE-E: 28 fine samplings for 25 X_0 / 1.3 λ

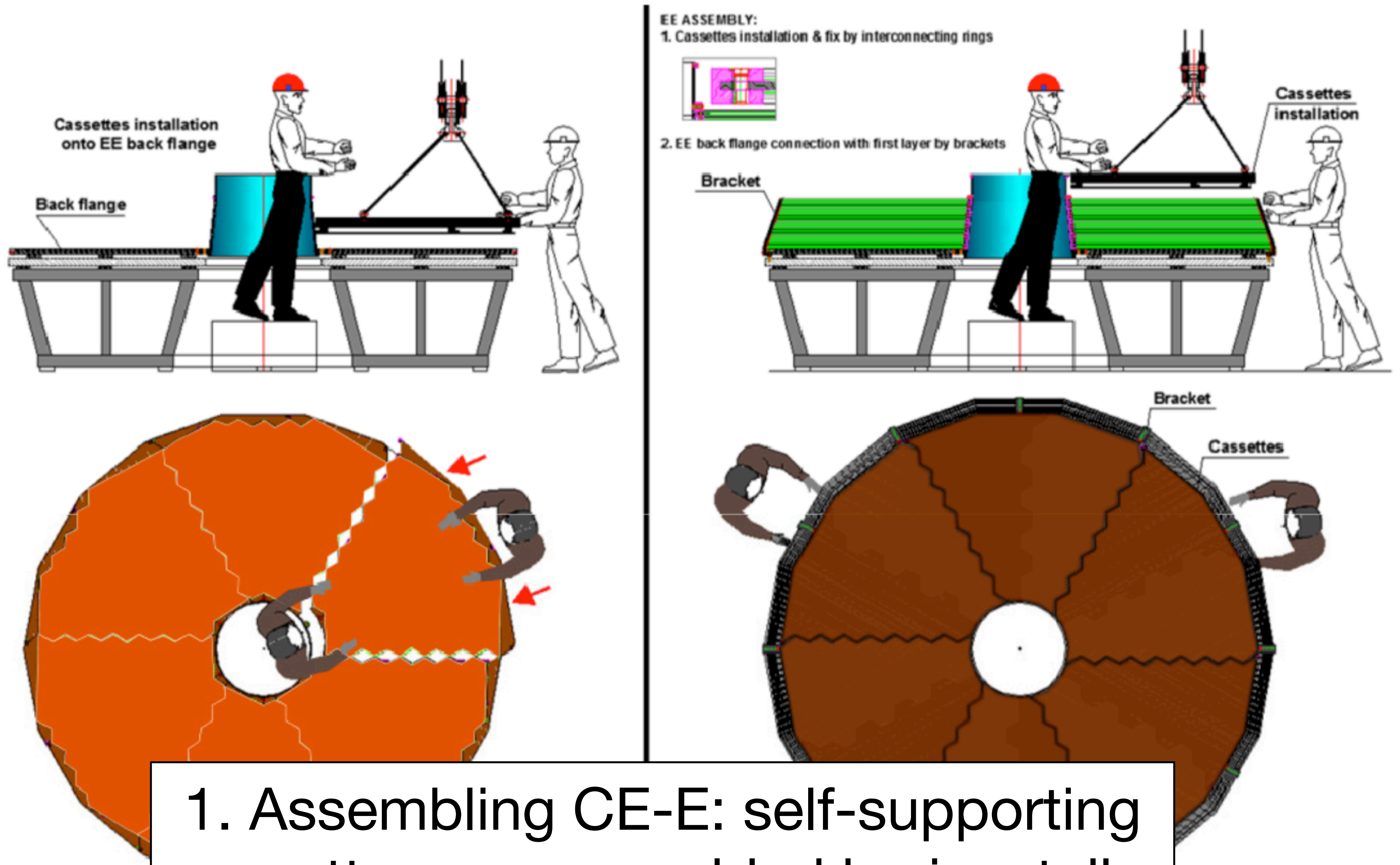
CE-H (1): 12 samplings in the first ~3.5 λ

CE-H (2): 10 samplings in the last ~5 λ

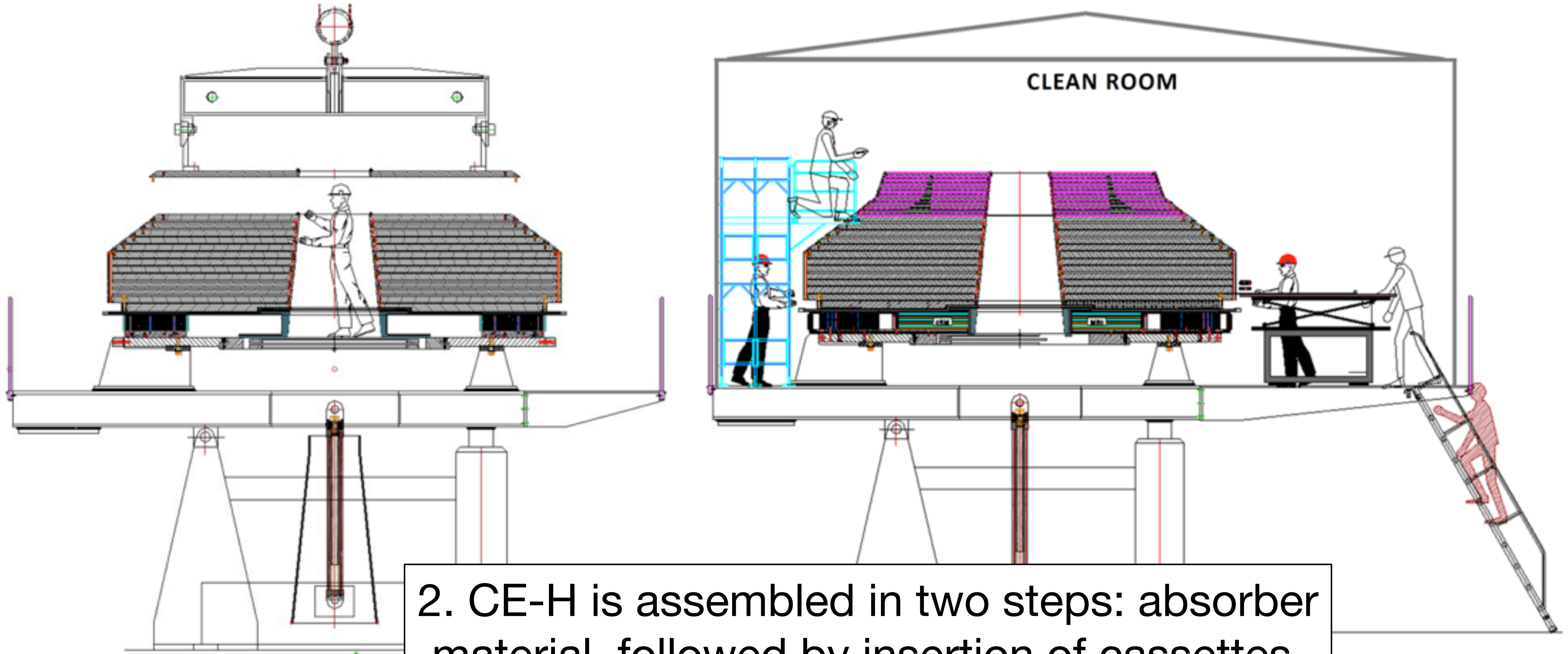
Main constraint: fit into existing detector endcap —> limited space.

- e.g. air gap in CE-E: limited space, very difficult for electrical components and connectors.

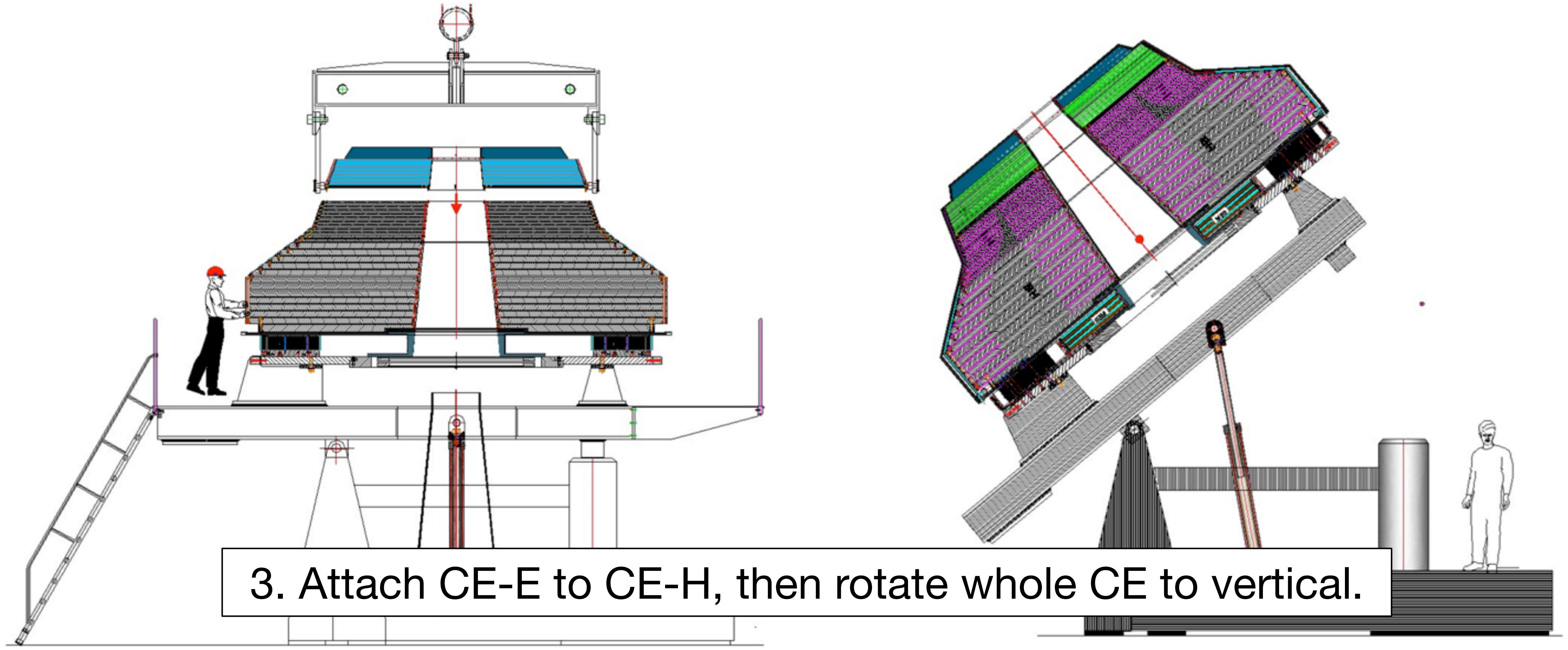
Planned calorimeter construction (x2)



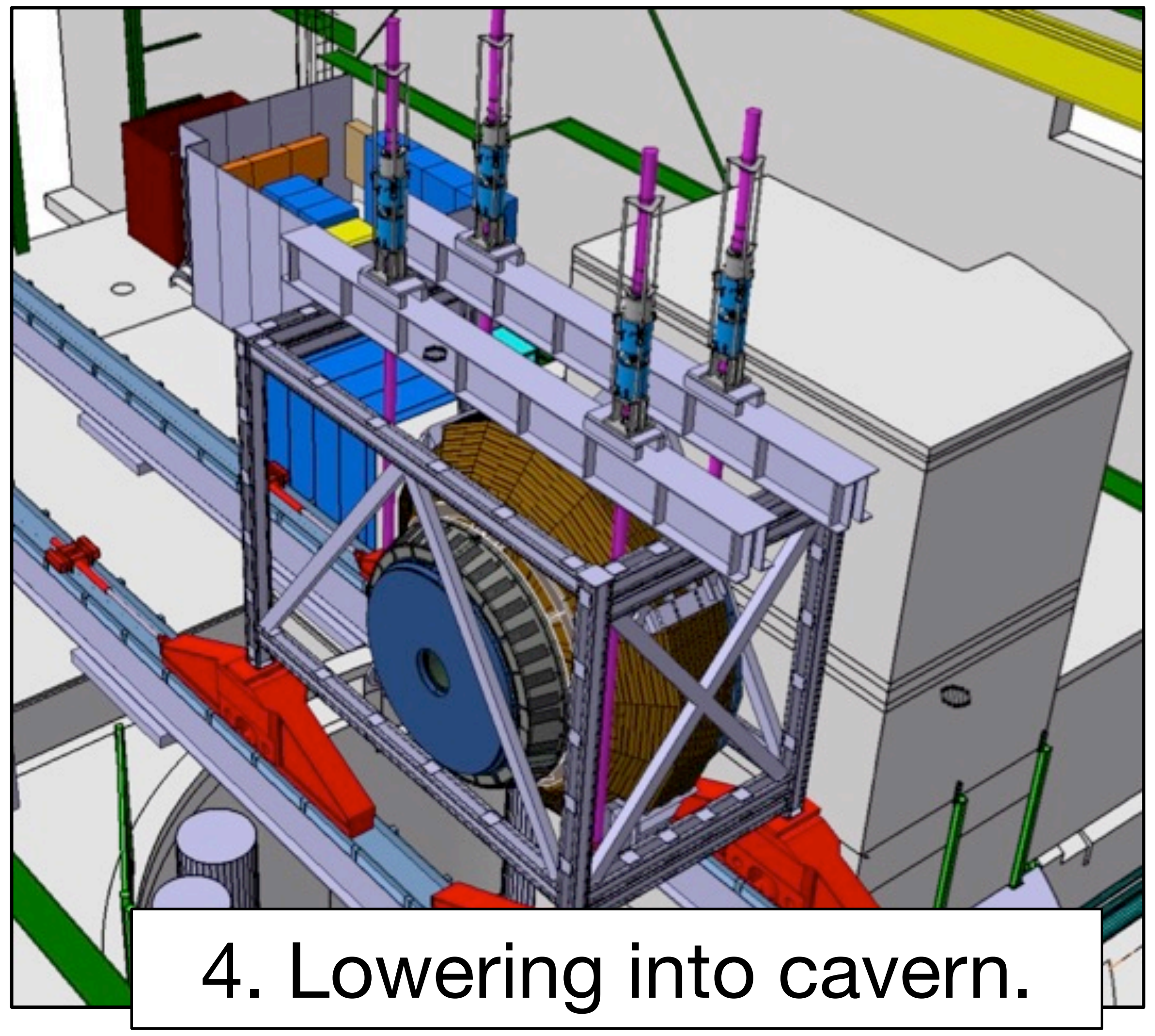
1. Assembling CE-E: self-supporting cassettes are assembled horizontally.



2. CE-H is assembled in two steps: absorber material, followed by insertion of cassettes.



3. Attach CE-E to CE-H, then rotate whole CE to vertical.



4. Lowering into cavern.

Shower development in a nutshell

<u>Charged particles</u>

- Ionisation (Bethe-Bloch) and multiple scattering.
- **Minimum ionising** for $\beta\gamma = 3$ and $E<E_{crit}$: $dE/dX = O(1\ \mathrm{MeV\ cm^2/g})$.

MIPs

<u>Particle showers</u>

<u>$e^{+/-}$</u>

- Bremsstrahlung dominant loss above O(50 MeV): $e^{+/-} \longrightarrow e^{+/-}\,\gamma$.
- Positron annihilation: $e^+ e^- \longrightarrow \gamma\,\gamma$.

<u>γ</u>

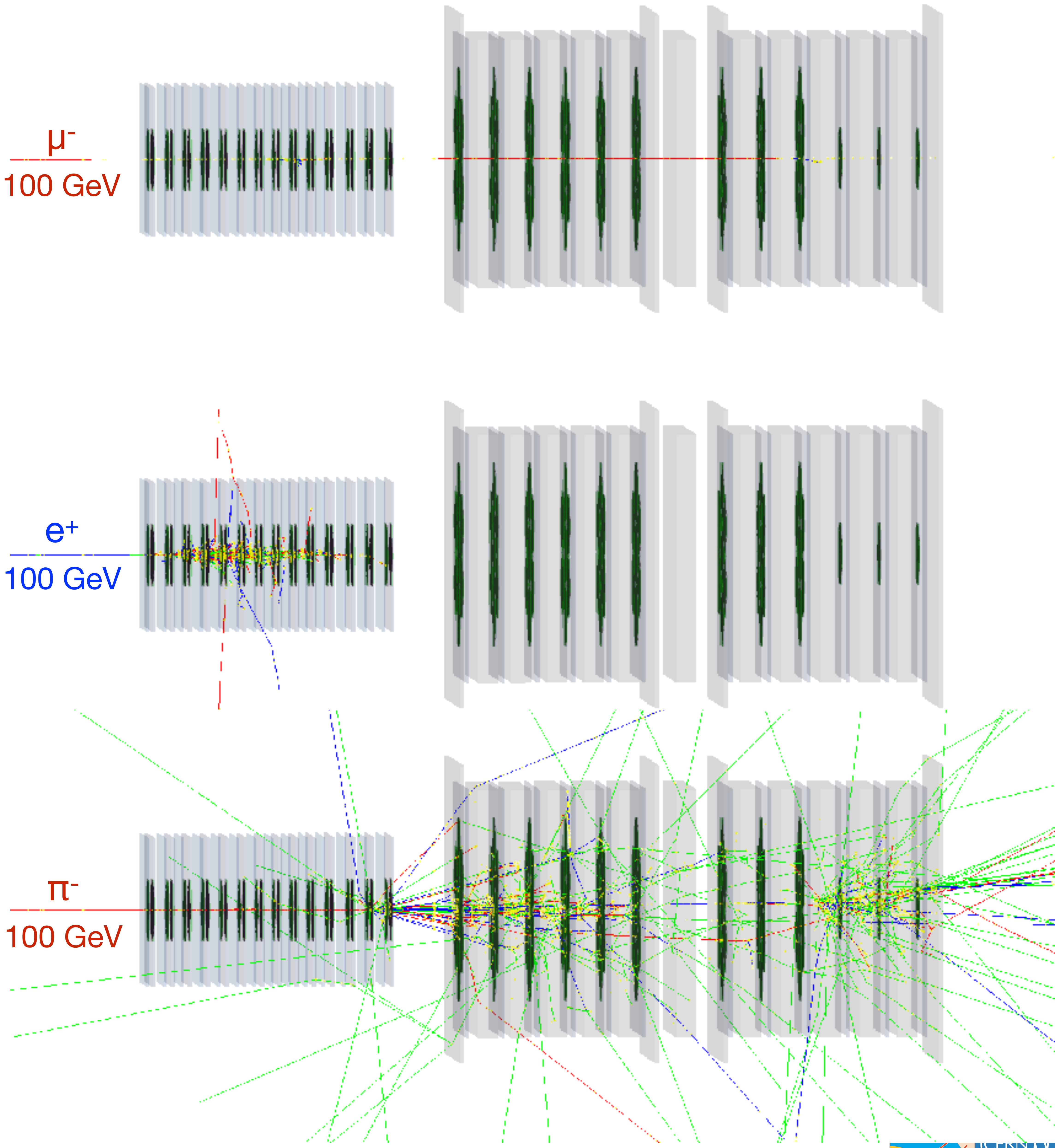
- Photo effect and Compton scattering for $E < O(1\ \mathrm{MeV})$.
- Pair production dominant for high energies.
- **EM showers**: Compact. Scale: X_0.

electromagnetic (EM)

<u>Hadrons</u>

- Nuclear reactions with target material and de-excitation processes.
- Only phenomenological descriptions available.
- **HAD showers**: Scale = $\lambda_n > X_0$. Sparser, wider, deeper than EM showers.
- $\pi_0 \longrightarrow \gamma\,\gamma$: EM component in hadronic showers.

hadronic (HAD)

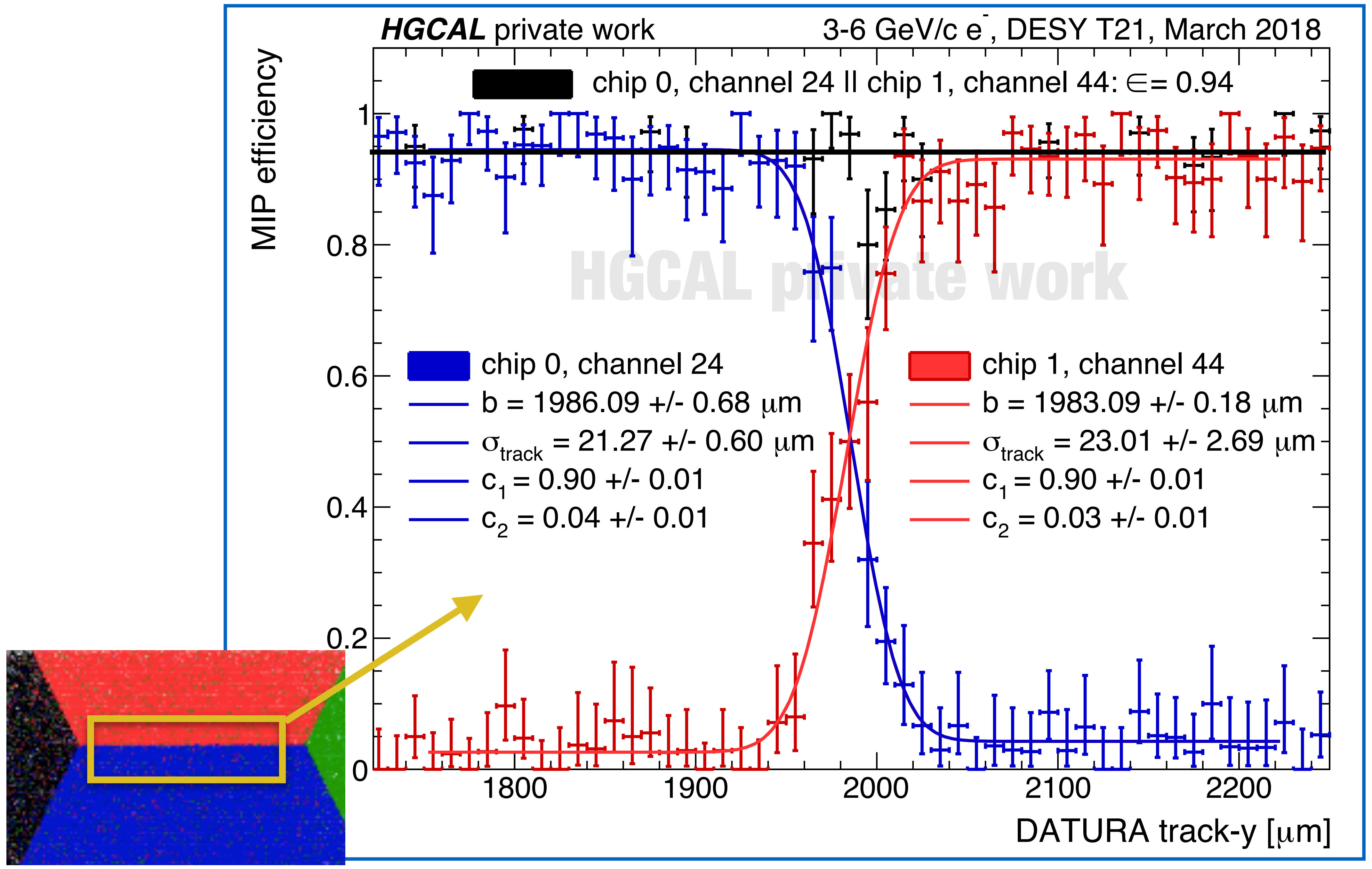


MIP detection efficiency of Si-based prototype modules

MIP efficiency at cell-cell boundary

Efficiency to detect electron-MIPs measured at DESY. Integral component: Precise tracking with DATURA beam telescope.

- Close to 100% for exposed cells.
- Per-cell MIP efficiency falling quickly at cell boundary.
- No efficiency gap between cells.

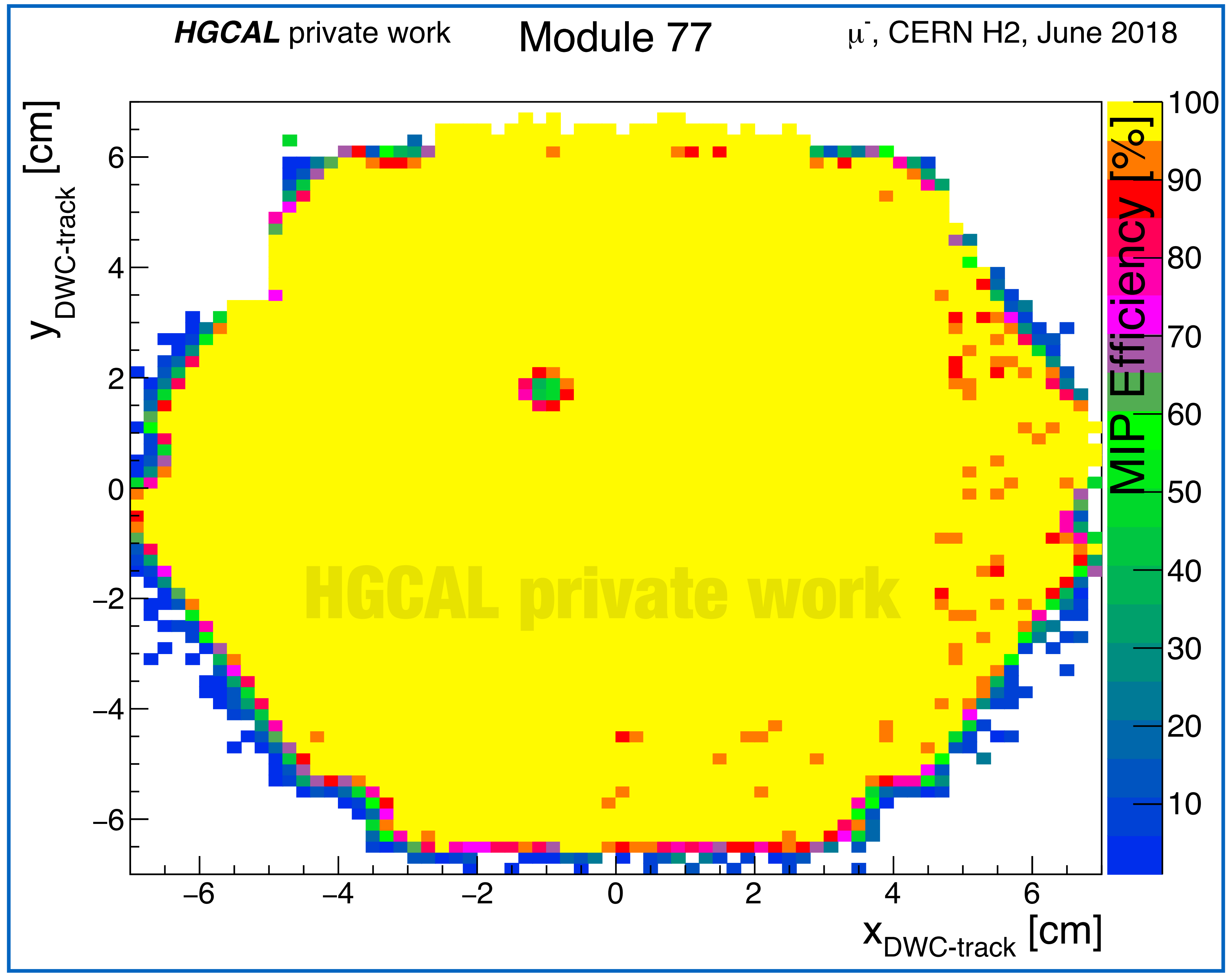


➡ **MIP signals confined to single cells: Good.**

Full module MIP efficiency maps

1. Denominator: Extrapolate μ-track from DWC.
2. Numerator: Check if active cell is in vicinity.

- Integrated efficiency close to 100% for most modules.
- 5 / 28 modules with areas of reduced efficiency.
  - 1x bad ASIC, 1x high leakage current, 3x insufficient pad-chip bonding.



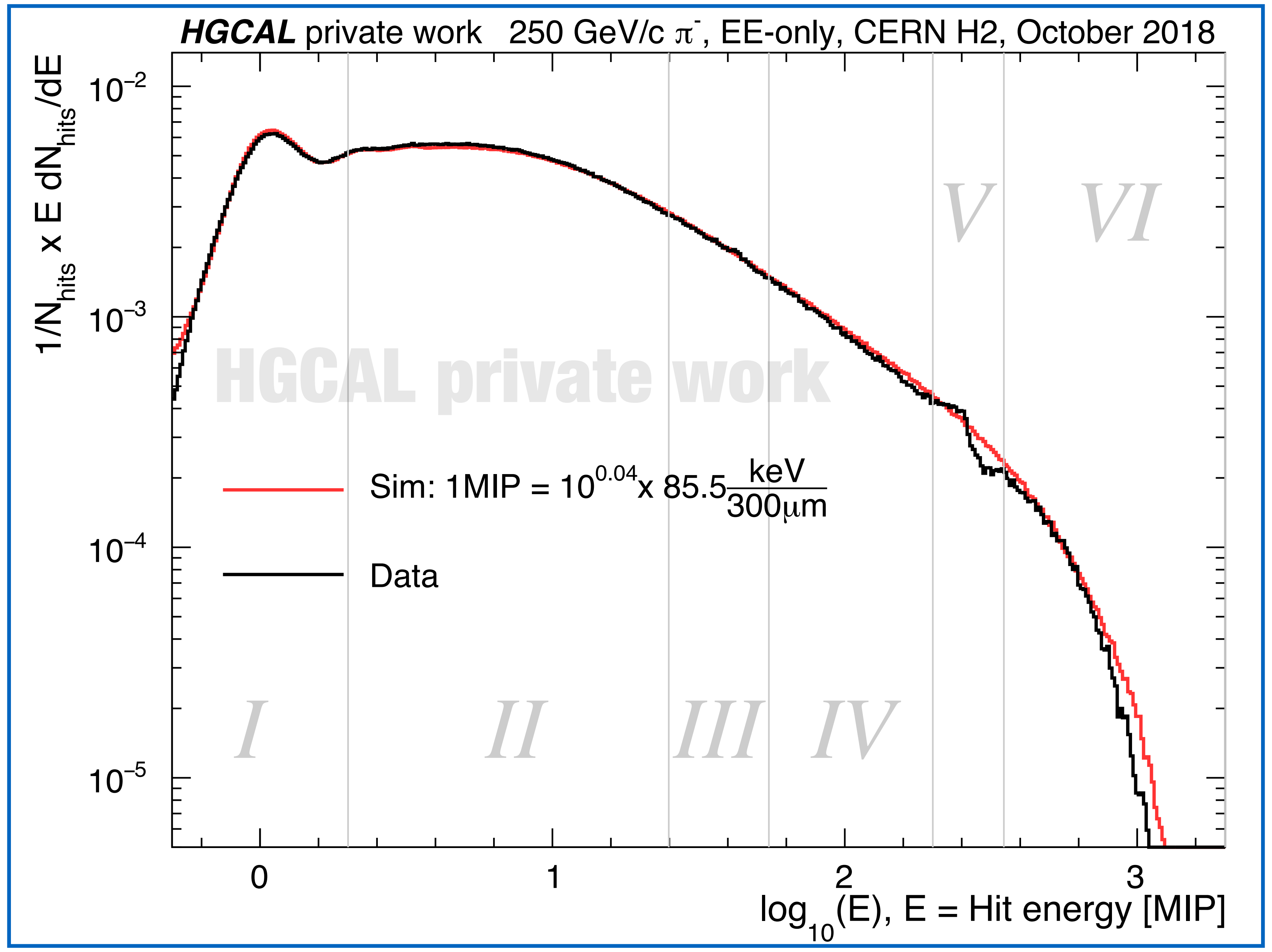
➡ **MIP efficiency: Good.**

Hit energy & timing calibration

✓ Scale calibration with MIPs.
✓ Gain linearisation.

Hit energy spectrum: Data vs. simulation

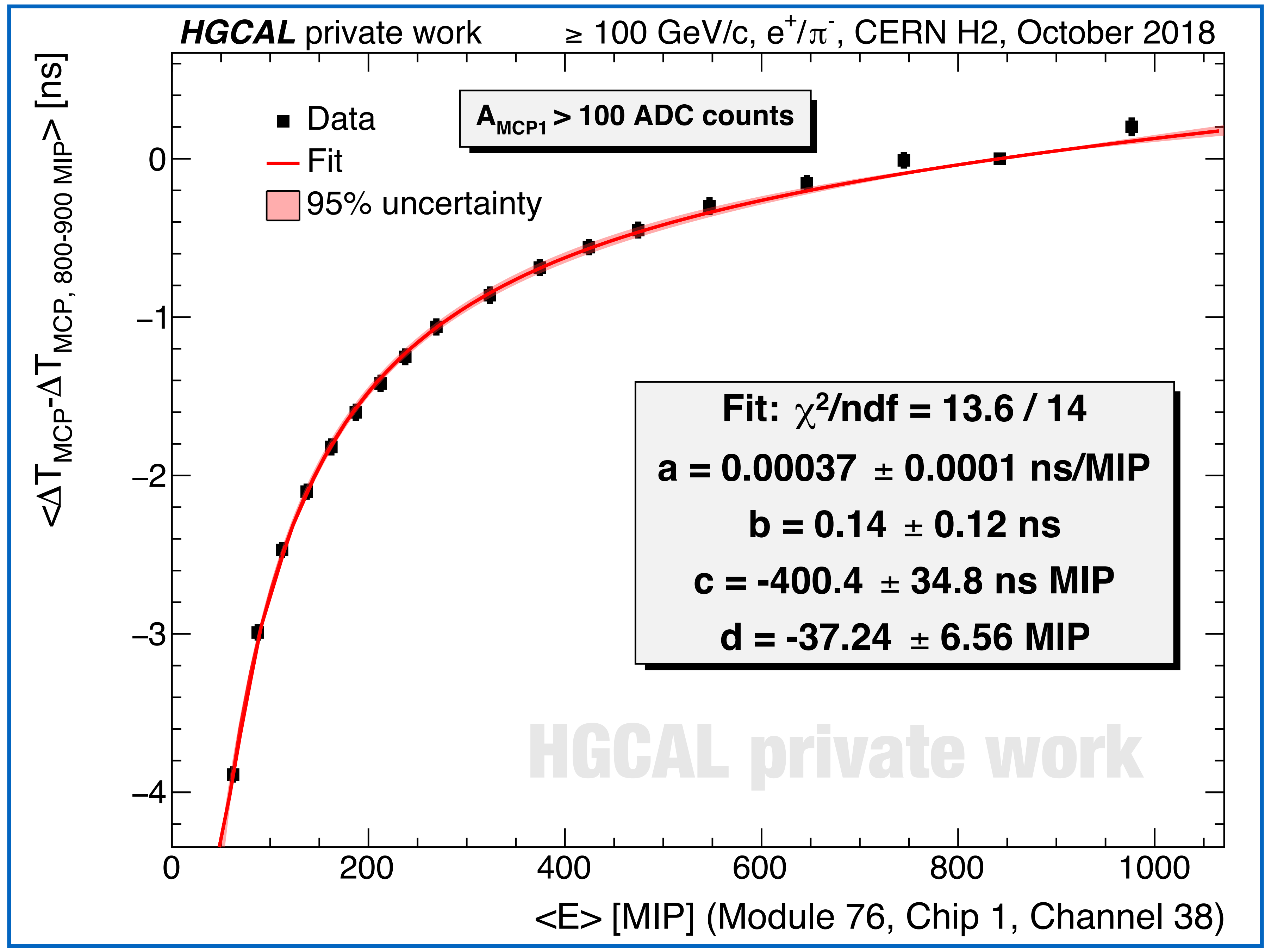
- 6 interesting ranges: MIPs —> TOT.
- Allows for tuning of keV/MIP in simulation.



➡ **Energy calibration: Reasonable.**

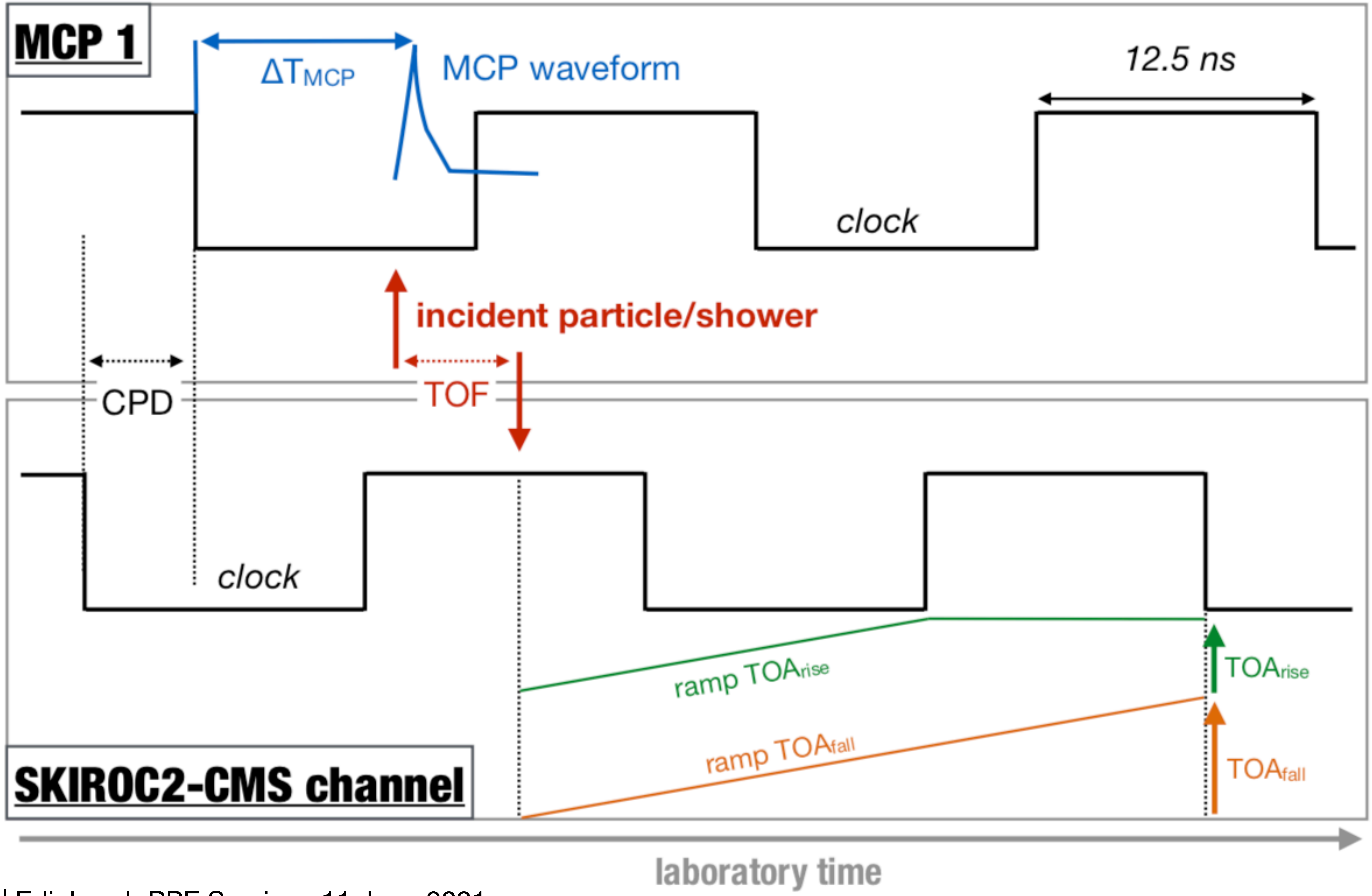
Timing calibration

(at least) 2 calibration ingredients:
- TOA-nonlinearity.
- Time walk due to fixed threshold discriminator.

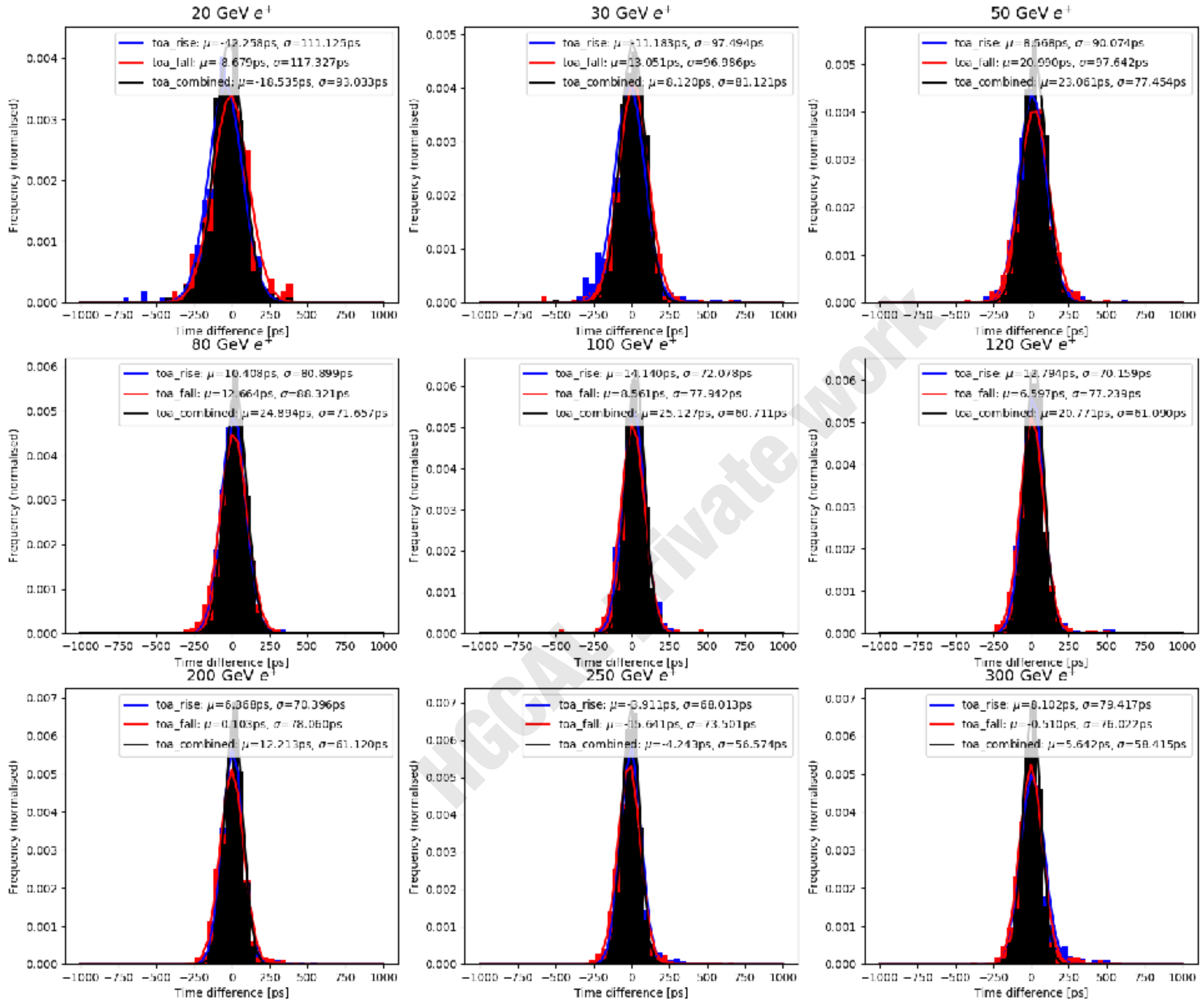


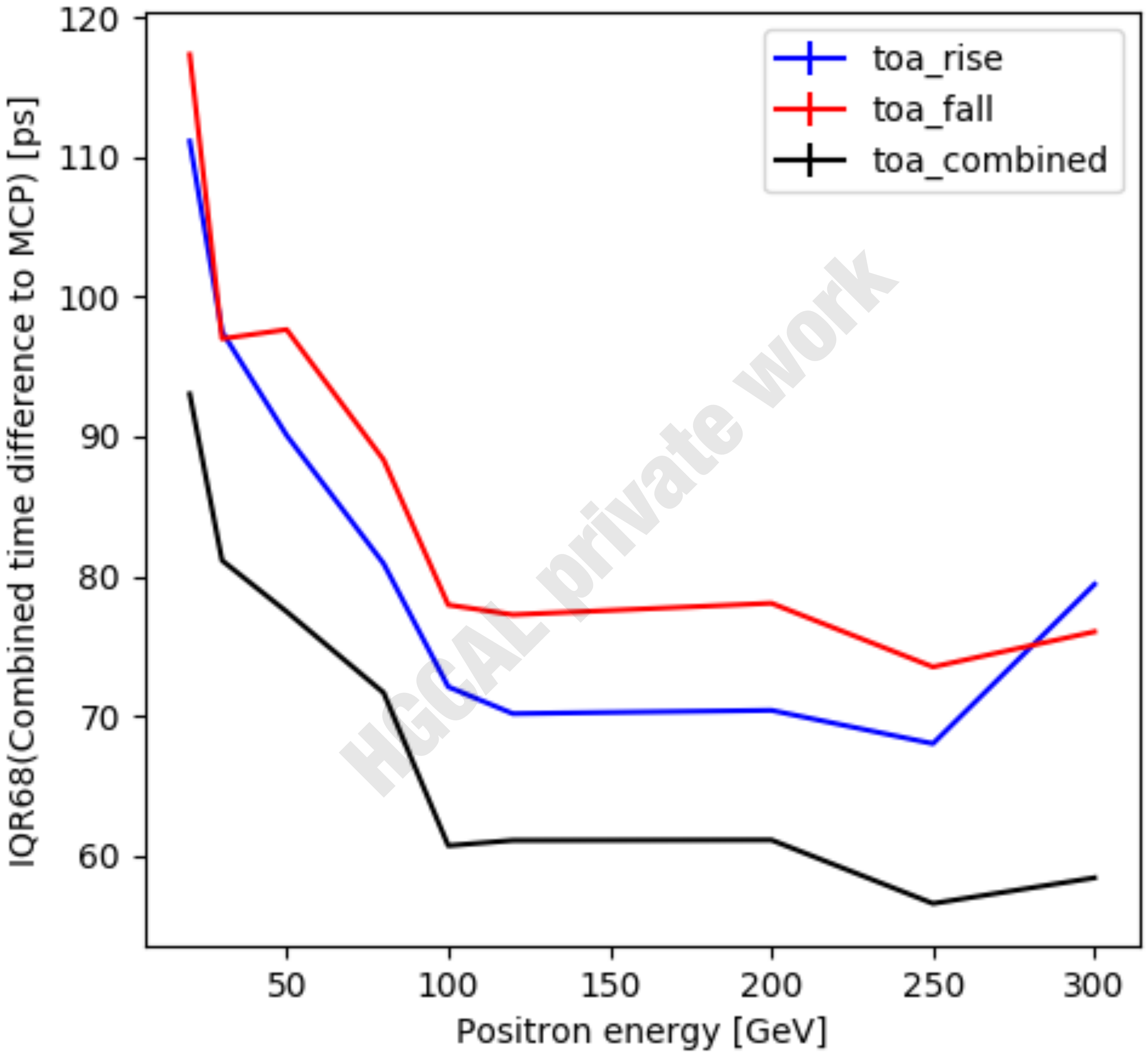
➡ **Timing calibration (with ext. time reference): Feasible.**

Principle of the timing measurements in test beam



EM shower timing resolution with >100 channels calibrated

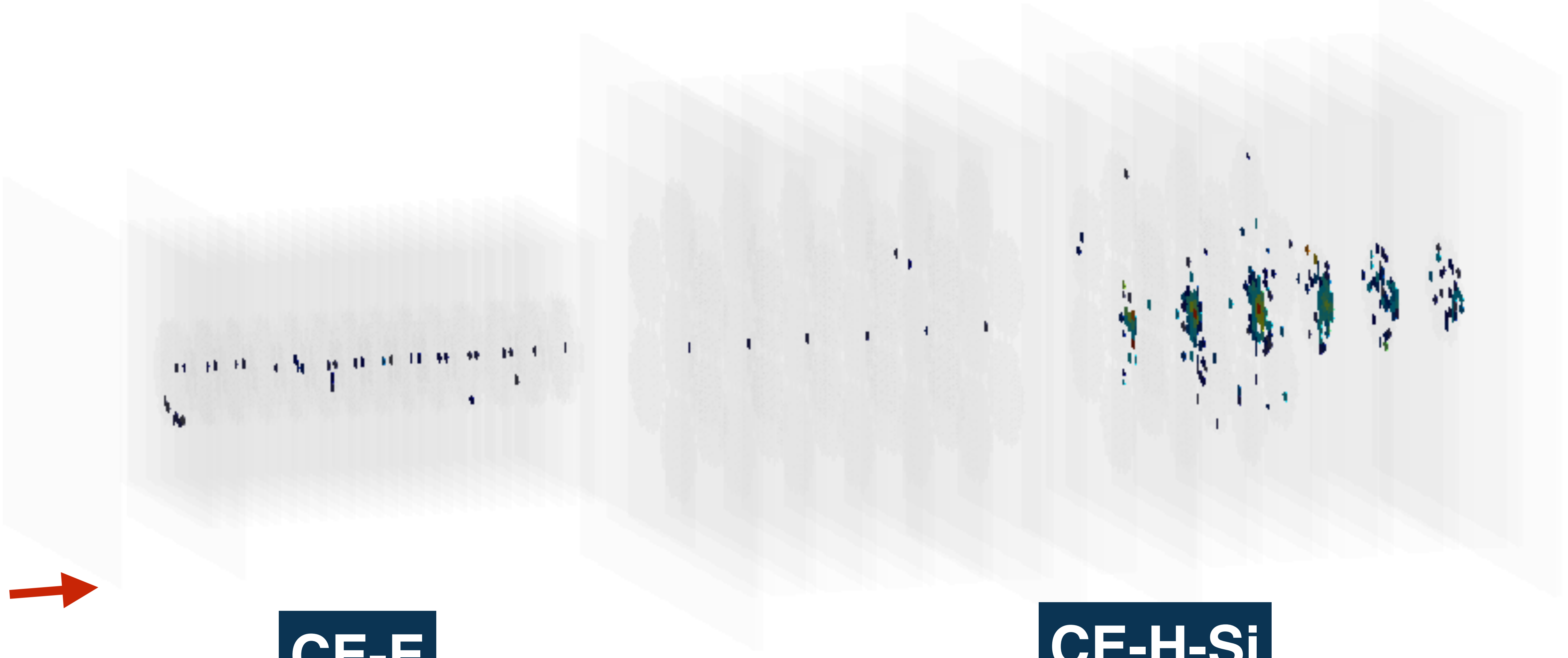




AHCAL + HGCAL prototype: Joint data taking October 2018

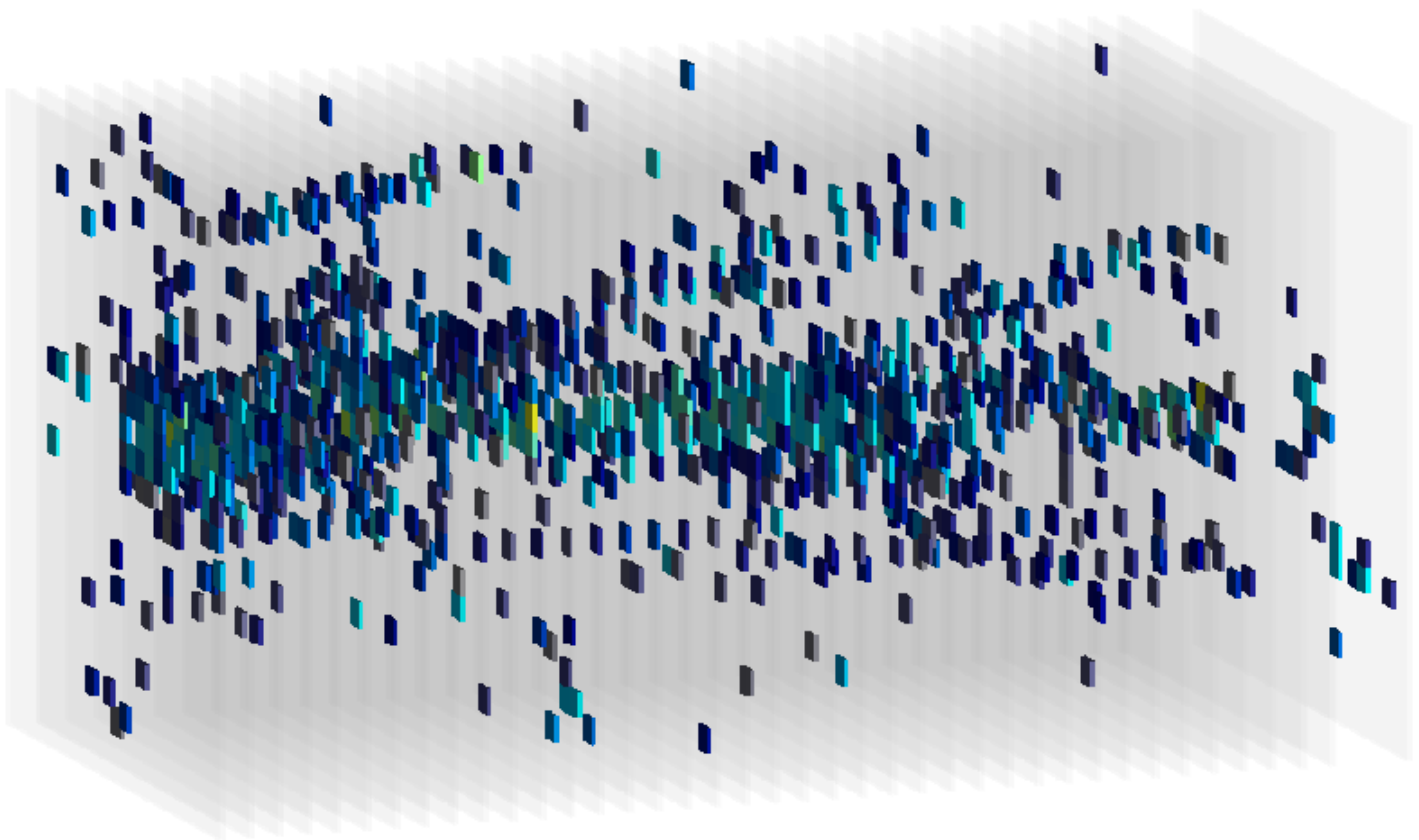
October 2018 run 517 - event 30:

250 GeV π^-



CE-E

CE-H-Si



CALICE AHCAL