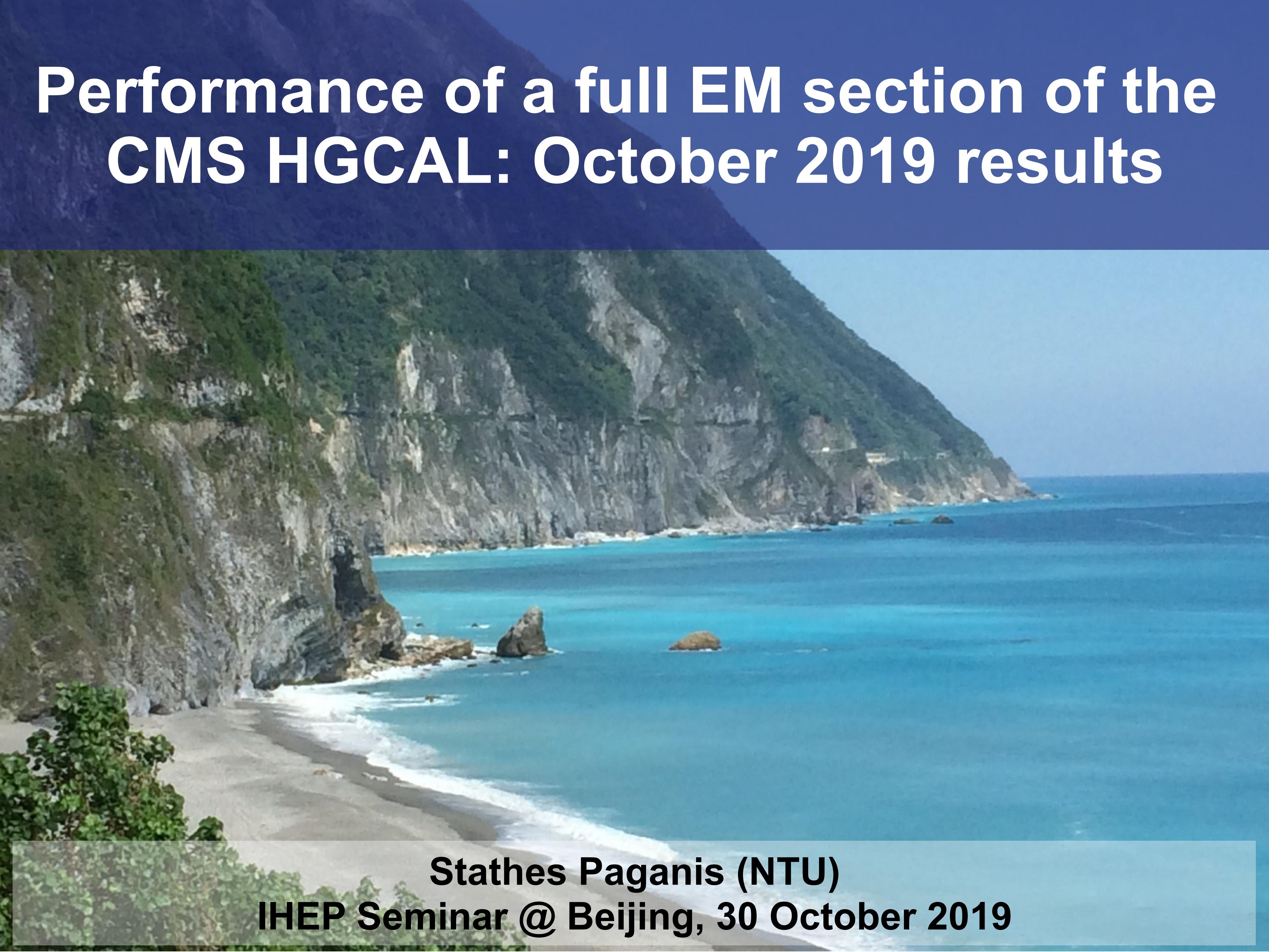


Performance of a full EM section of the CMS HGCAL: October 2019 results

Stathes Paganis (NTU)
IHEP Seminar @ Beijing, 30 October 2019

Phase II: High Luminosity LHC

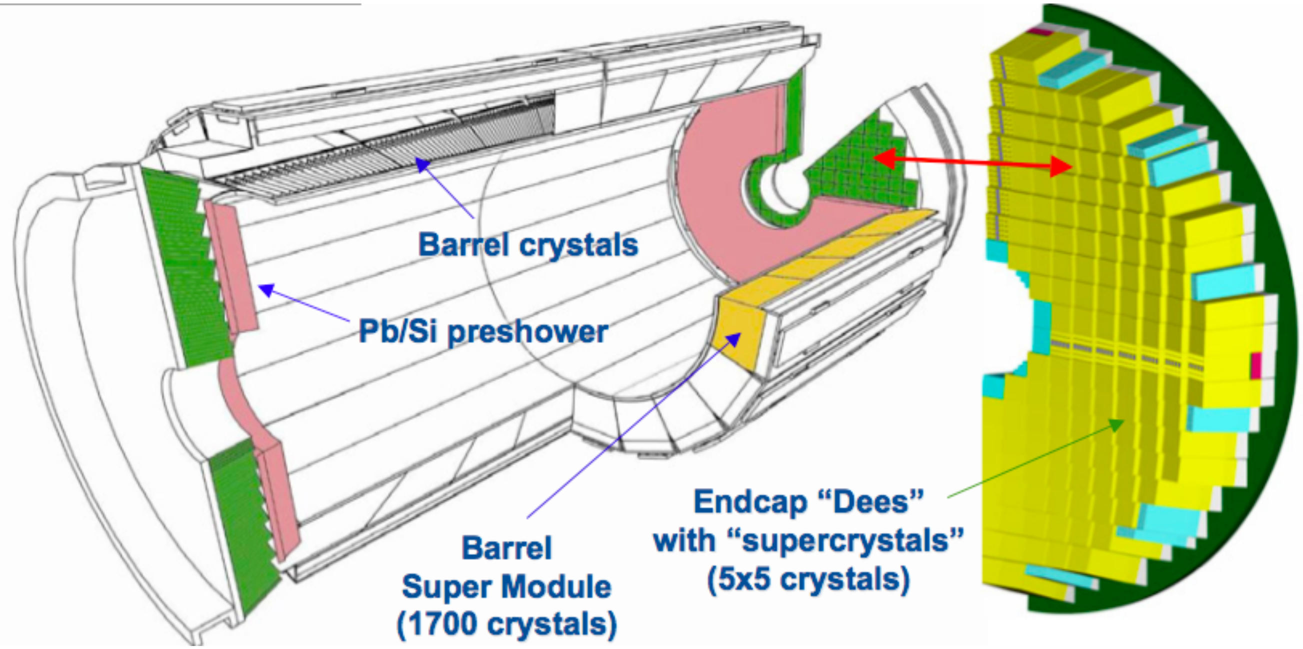
- ❑ HL-LHC: expected to deliver 10x the luminosity delivered in Phase I

	LHC	HL-LHC baseline	HL-LHC ultimate*
$\mathcal{L}_{inst}(\mathrm{cm}^{-2}\mathrm{s}^{-1})$	2×10^{34}	5×10^{34}	7.5×10^{34}
PU (n_{vtxs})	40-60	140	200

*unexpected at the time of original ECAL TDR.

- ❑ CMS upgrade
  - Increased acceptance: tracker (|η|=4) and muon spectrometer (|η|=2.8)
  - Higher first level trigger (L1) rate: 100kHz → 750kHz
    - ➢ to maintain comparable trigger performance at higher pileup
  - L1 trigger latency 3.4μs → 12.5μs
    - ➢ to provide time for the new track-based hardware trigger

ECAL: from Phase 1 to HL-LHC



Barrel (EB)
$|\eta| < 1.48$
61200 crystals
Avalanche Photo-Diode (APD) readout

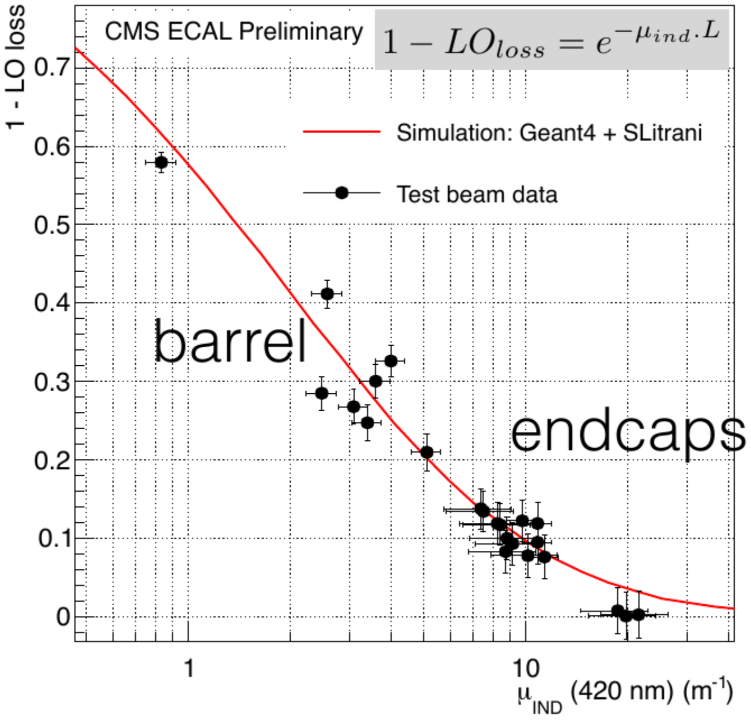
Endcaps (EE)
$1.48 < |\eta| < 3.0$
14648 crystals
Vacuum Photo-Triode (VPT) readout

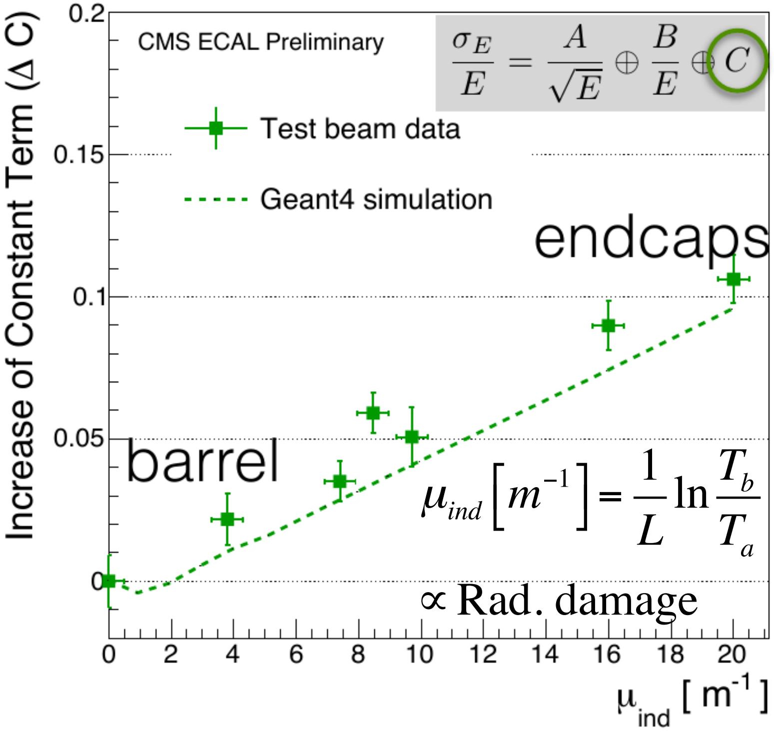
Pb/Si preshower
$1.65 < |\eta| < 2.6$
3X0 of Pb/Si Strips

- ☐ Endcaps: complete replacement of current calorimeters to cope with expected radiation flux
  - ✓ HGCAL: High Granularity (Silicon-based) Sampling Calorimeter

- ☐ Barrel:
  - ✓ ECAL: retain crystals+APD → upgraded readout electronics
  - ✓ HCAL: Brass/plastic scintillator + SiPM

ECAL resolution at HL-LHC

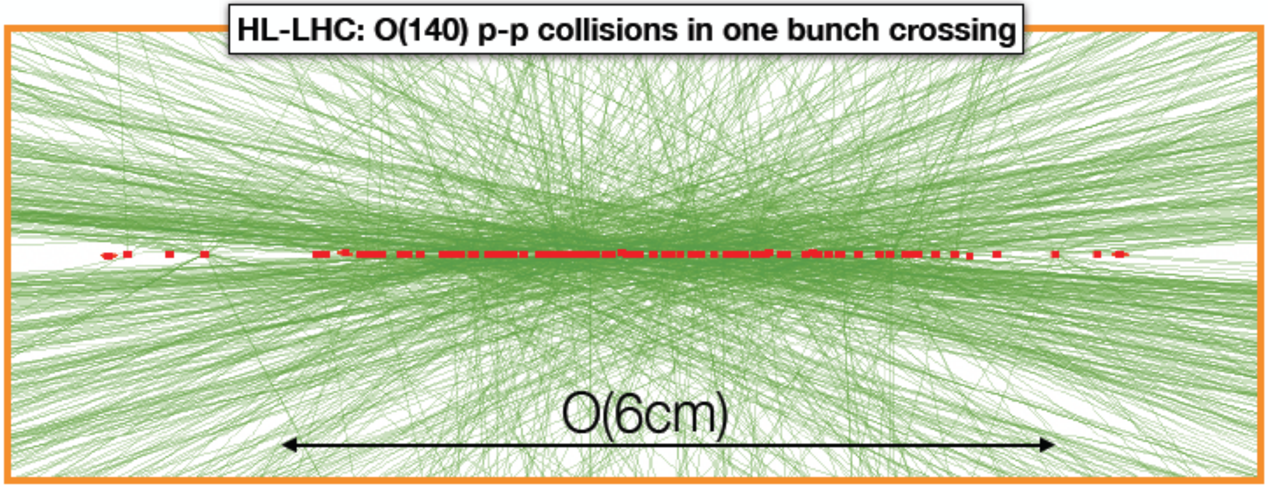


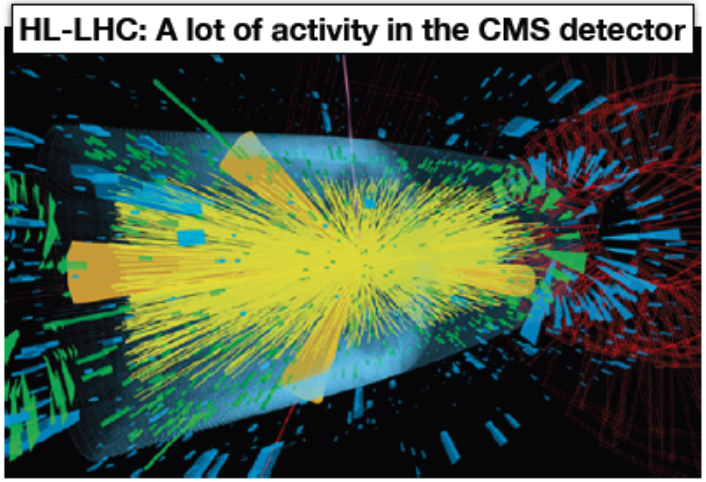


- Barrel: crystals will retain 30-50% of light output after 3000fb^{-1}
- Endcaps: crystals lose most of the light output.

- Constant term for Barrel acceptable.
- Constant term for Endcaps ~10%, leads to unacceptable energy resolution.

Physics pileup at HL-LHC


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


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

Nominal 5E34 luminosity "Ultimate" 7.5E34 luminosity

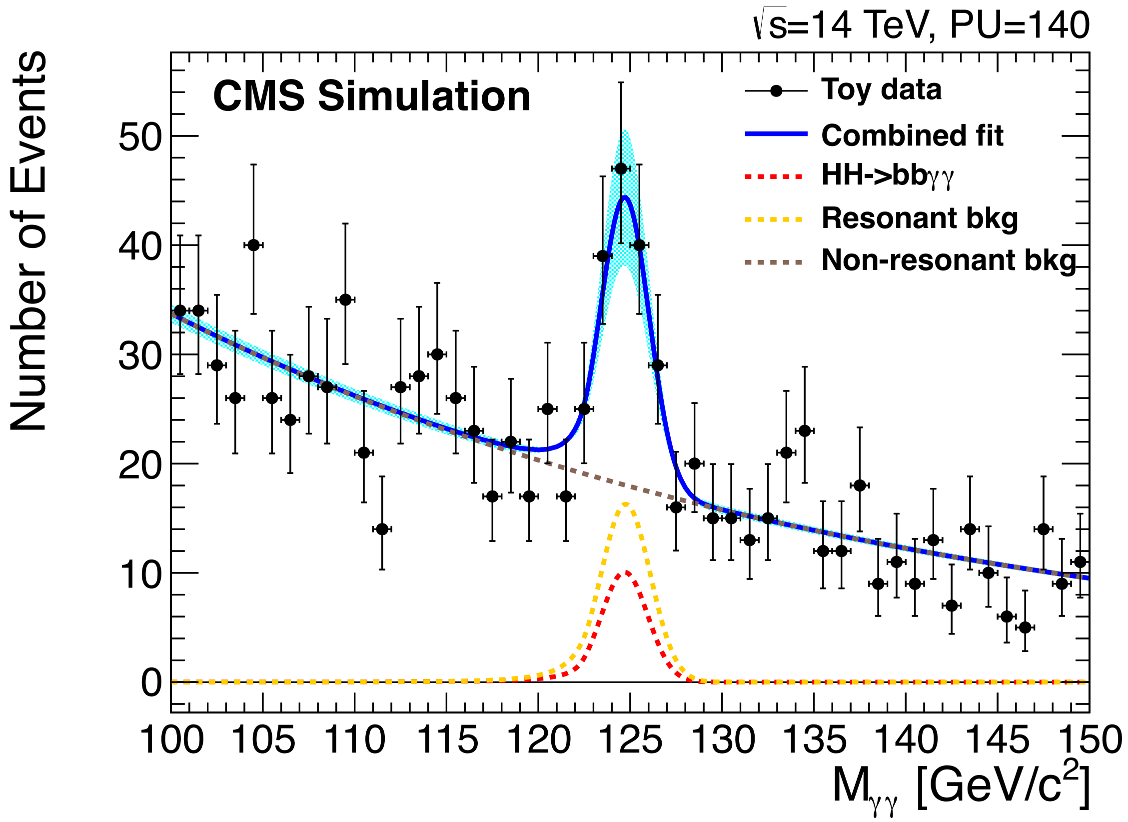
Pile-up

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

EM Calorimetry and Physics

Shopping list for the Endcap region

- ☐ Good resolution (~1%) at High Energies
  - Low constant term ~0.5%
- ☐ Not affected by radiation damage
- ☐ Improve VBF and VBS analyses
  - Tag forward jets
  - Discriminate quark from gluons
- ☐ Particle flow
  - PID
  - Excellent jet energy resolution.
  - Background rejection
- ☐ 50 ps timing resolution for PU mitigation



CMS-PAS-FTR-15-002

HL-LHC

- One of the main goals:
  Discovery of di-Higgs HH production
- Higgs Boson self coupling
- VBF and VBS

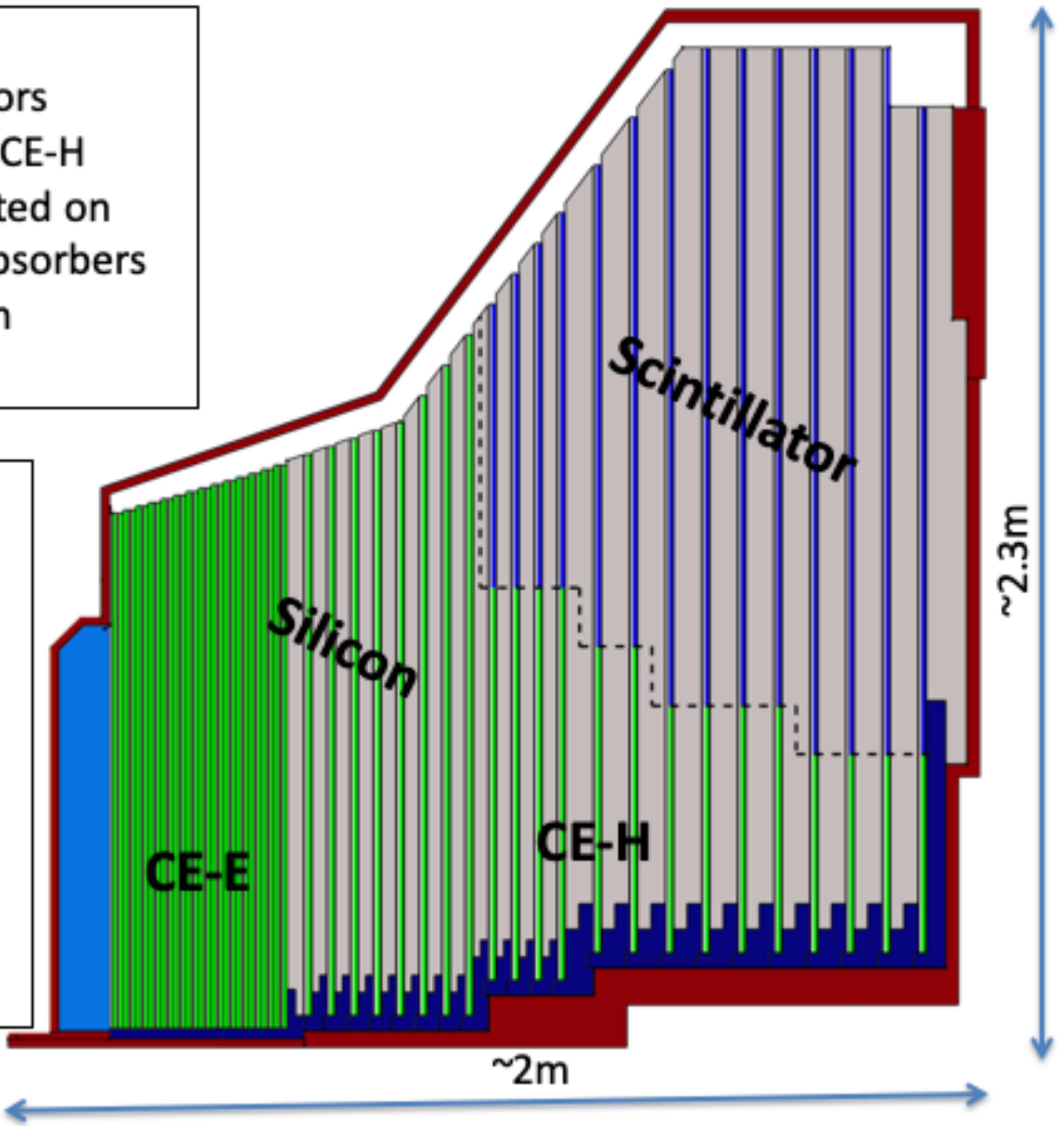
CMS High Granularity Calorimeter

Active Elements:

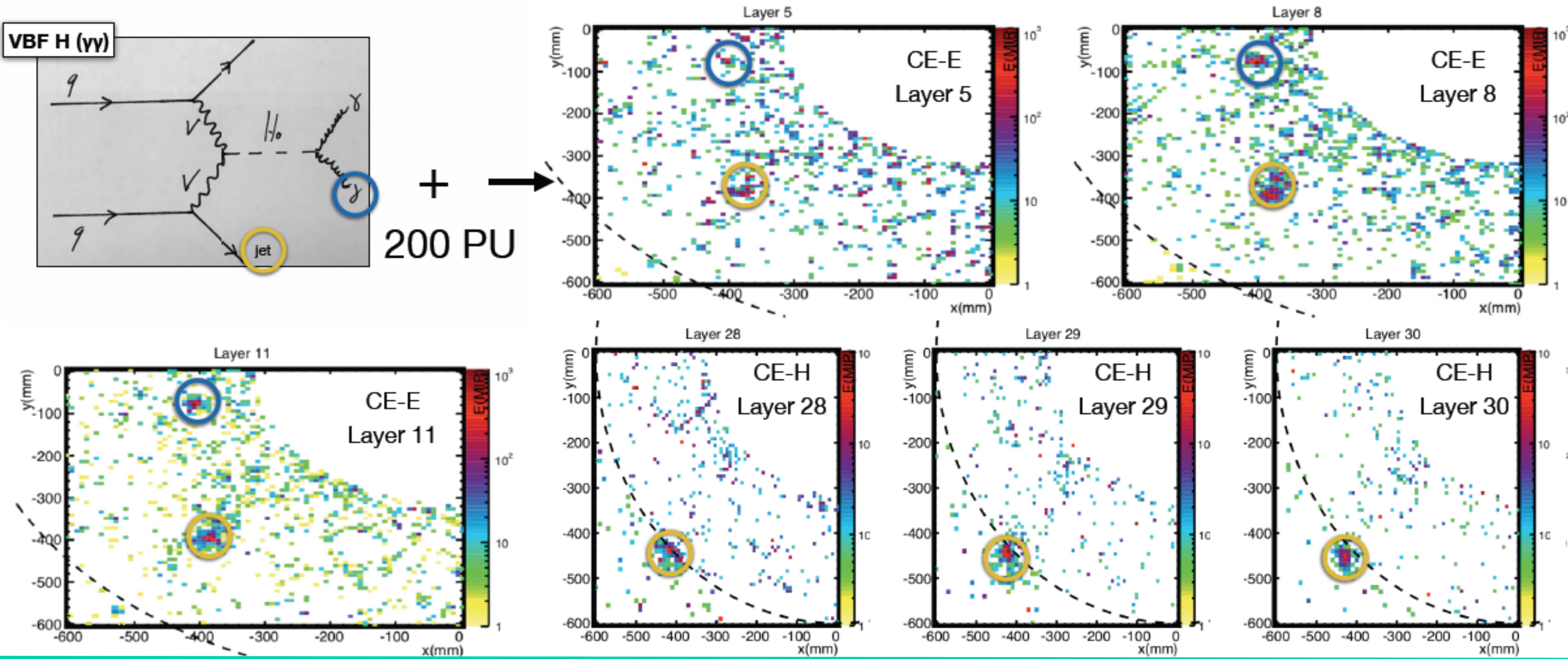
- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- "Cassettes": multiple modules mounted on cooling plates with electronics and absorbers
- Scintillating tiles with SiPM readout in low-radiation regions of CE-H

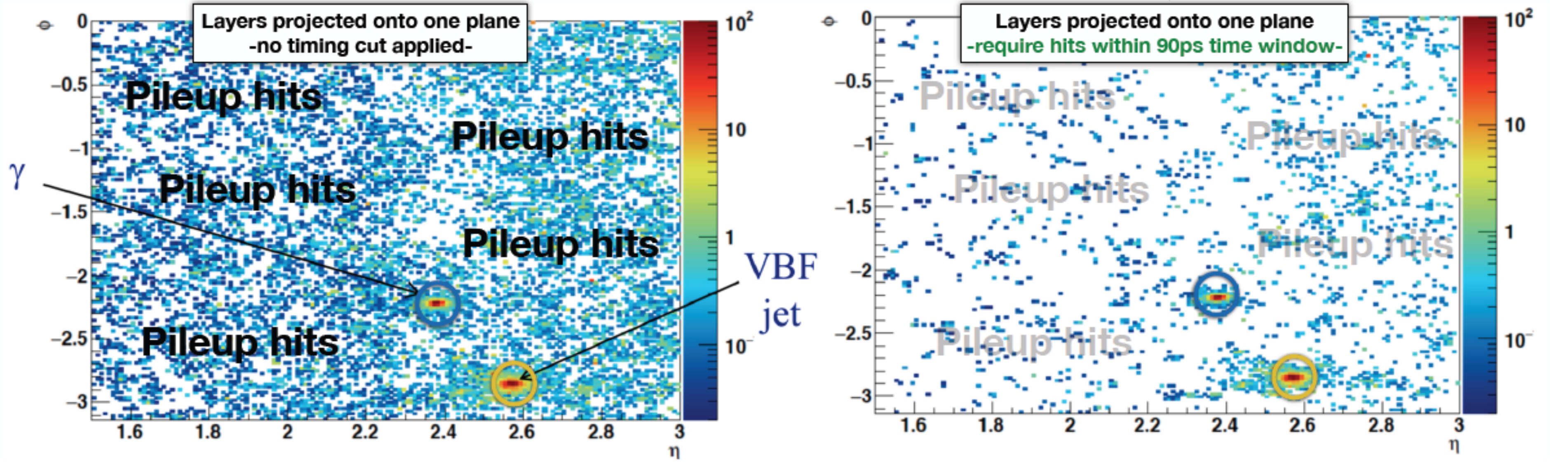
Key Parameters:

Coverage: $1.5 < |\eta| < 3.0$
~215 tonnes per endcap
Full system maintained at -30°C
~620m^2 Si sensors in ~30000 modules
~6M Si channels, 0.5 or 1cm^2 cell size
~400m^2 of scintillators in ~4000 boards
~400k scint. channels, 4-30cm^2 cell size
Power at end of HL-LHC:
~125 kW per endcap

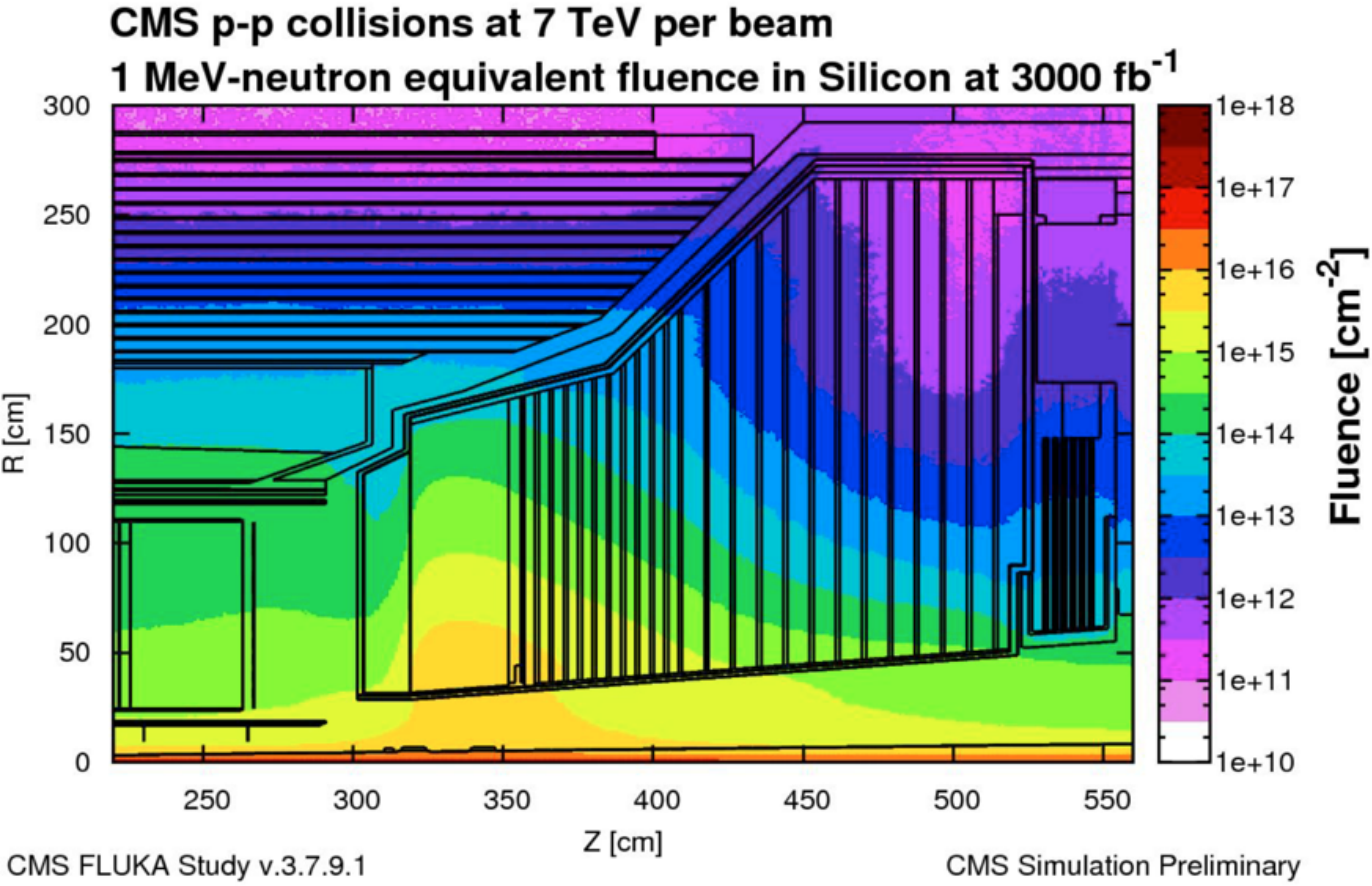


Electromagnetic calorimeter (**CE-E**): **Si**, Cu & CuW & Pb absorbers, 28 layers, 25 X_0 & ~1.3λ
Hadronic calorimeter (**CE-H**): **Si** & **scintillator**, steel absorbers, 22 layers, ~8.5λ

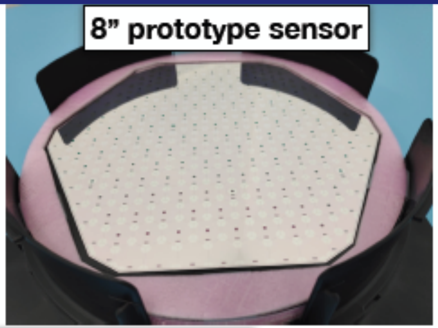

VBF H (γγ)
q
q
V
V
H₀
γ
γ
jet
+
200 PU
Layer 5
CE-E
Layer 5
Layer 8
CE-E
Layer 8
Layer 11
CE-E
Layer 11
Layer 28
CE-H
Layer 28
Layer 29
CE-H
Layer 29
Layer 30
CE-H
Layer 30
y(mm)
x(mm)
E(MIP)
0
-100
-200
-300
-400
-500
-600
10^3
10^2
10
1


Layers projected onto one plane
-no timing cut applied-
Pileup hits
Pileup hits
Pileup hits
Pileup hits
Pileup hits
γ
VBF jet
Layers projected onto one plane
-require hits within 90ps time window-
Pileup hits
Pileup hits
Pileup hits
Pileup hits
Pileup hits
φ
η
0
−0.5
−1
−1.5
−2
−2.5
−3
1.6
1.8
2
2.2
2.4
2.6
2.8
3
10^2
10
1
10^{-1}

Expected radiation dosage vs R,Z



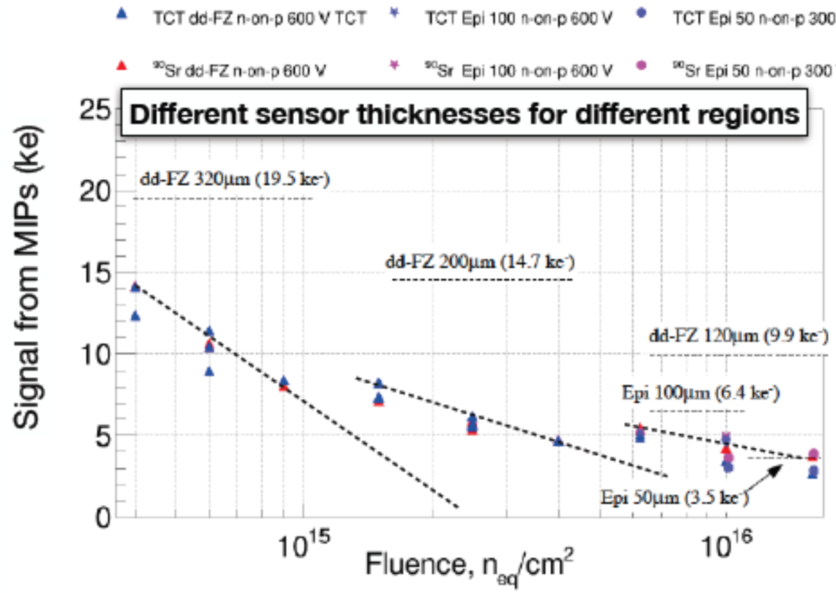
HGCAL Silicon sensors



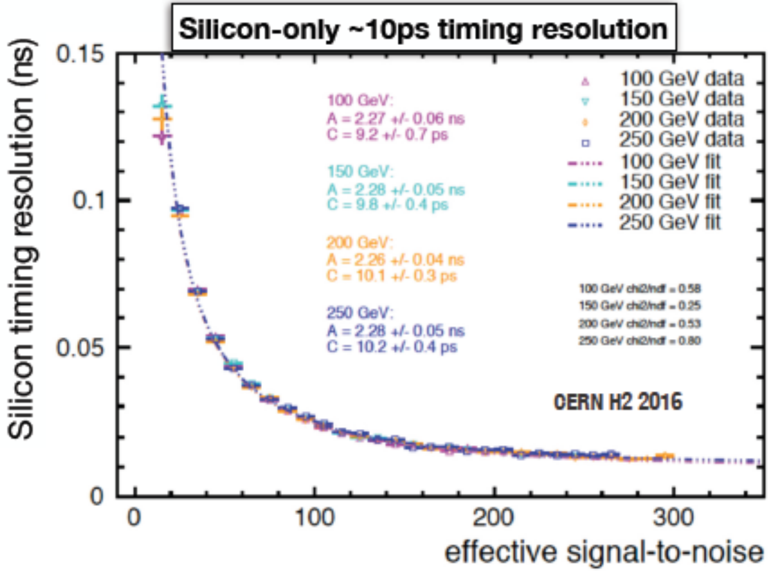
8” prototype sensor

Silicon sensors

- For regions with high fluences, HGCAL uses 600m^2 of silicon
- Hexagonal wafers to maximise used area (—> minimise costs)
- Followed HEP standard initially 6” wafers. New baseline: 8”



Different sensor thicknesses for different regions



Silicon-only ~10ps timing resolution

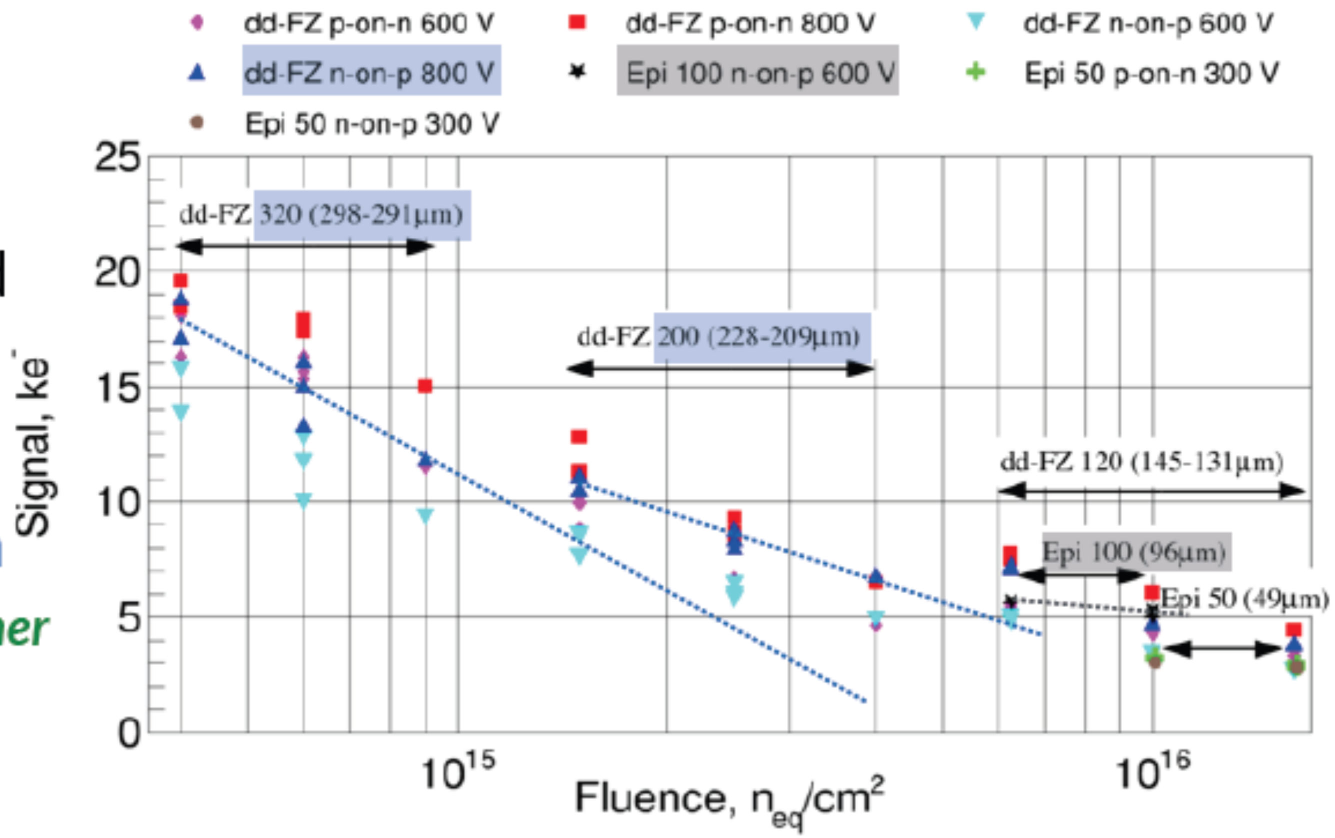
Minimising degradation

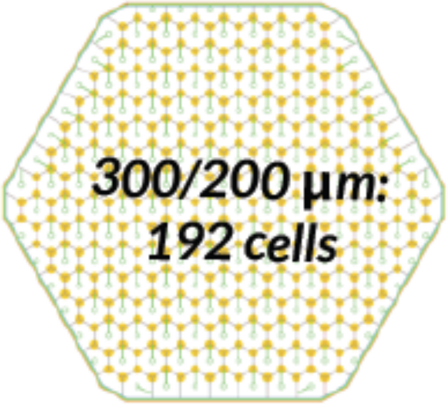
- Operation at -30° C: Reduce increasing bulk leakage current
- Increasing the bias voltage up to -800V to reduce signal loss

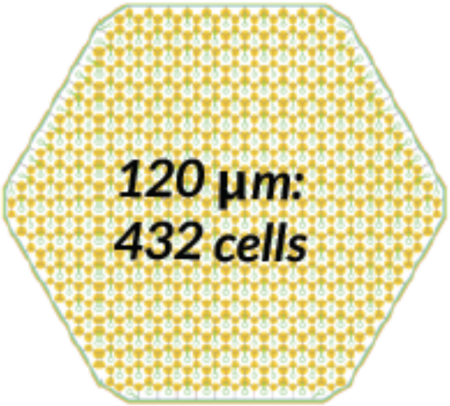
HGCAL Silicon sensors

- 8 inch wafers
- Hexagonal sensor geometry
- Planar p-type DC-coupled sensor pads
- Active thickness:

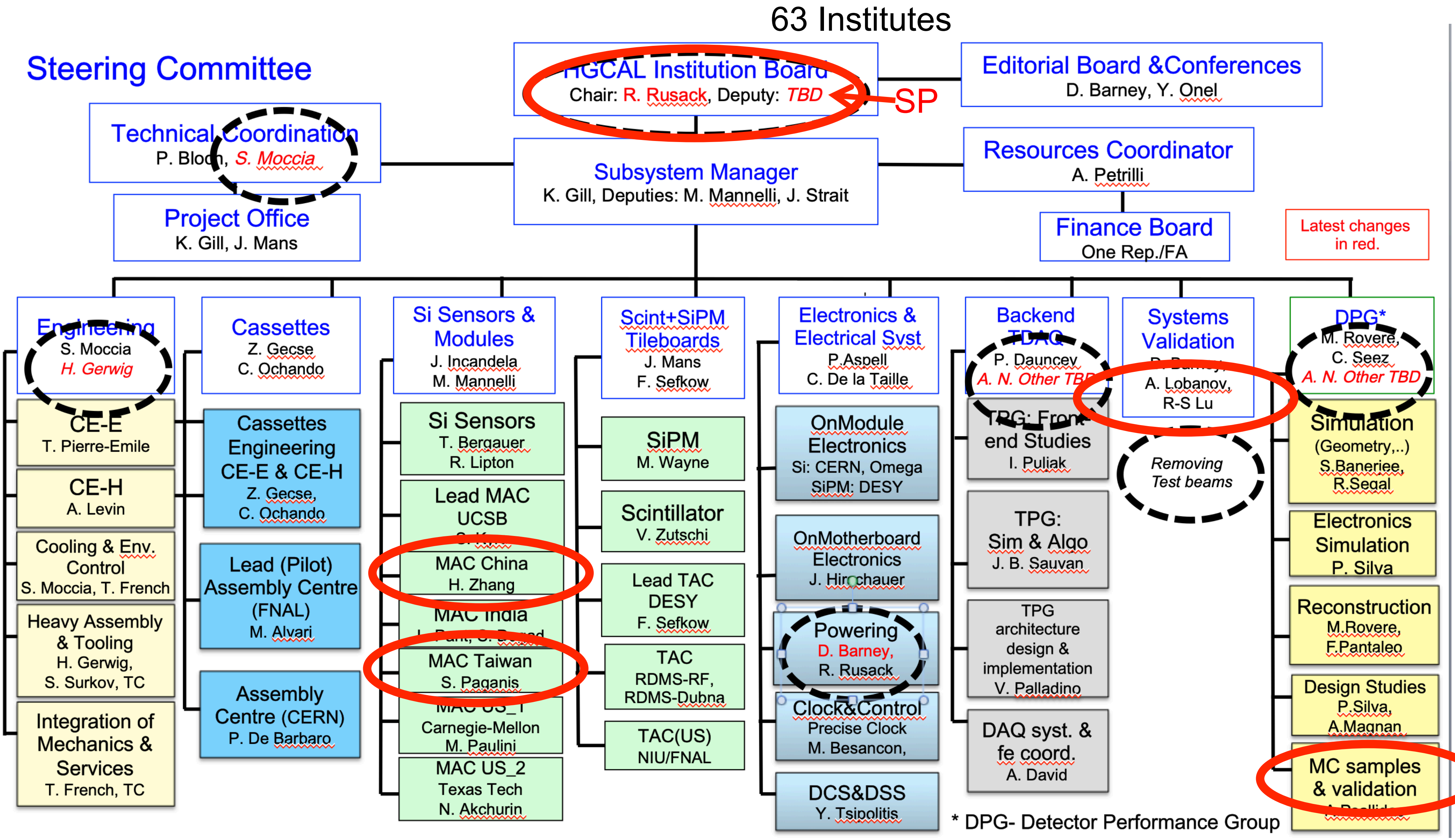
  300 µm, 200 µm, 120 µm
  - *Advantage of deploying thinner sensors in the higher fluence regions*
    - *More tolerant to large neutron fluences*
  - *Reduced cell size in thinner sensors*
    - *Keeping the capacitance reasonable*







HGCAL Project Organization



63 Institutes

Steering Committee

HGCAL Institution Board
Chair: R. Rusack, Deputy: TBD

SP

Editorial Board &Conferences
D. Barney, Y. Onel

Technical Coordination
P. Bloch, S. Moccia

Project Office
K. Gill, J. Mans

Subsystem Manager
K. Gill, Deputies: M. Mannelli, J. Strait

Resources Coordinator
A. Petrilli

Finance Board
One Rep./FA

Latest changes in red.

Engineering
S. Moccia
H. Gerwig

- CE-E
  T. Pierre-Emile
- CE-H
  A. Levin
- Cooling & Env. Control
  S. Moccia, T. French
- Heavy Assembly & Tooling
  H. Gerwig, S. Surkov, TC
- Integration of Mechanics & Services
  T. French, TC

Cassettes
Z. Gecse
C. Ochando

- Cassettes Engineering CE-E & CE-H
  Z. Gecse, C. Ochando
- Lead (Pilot) Assembly Centre (FNAL)
  M. Alvari
- Assembly Centre (CERN)
  P. De Barbaro

Si Sensors & Modules
J. Incandela
M. Mannelli

- Si Sensors
  T. Bergauer
  R. Lipton
- Lead MAC
  UCSB
  [illegible]
- MAC China
  H. Zhang
- MAC India
  [illegible]
- MAC Taiwan
  S. Paganis
- MAC US_1
  Carnegie-Mellon
  M. Paulini
- MAC US_2
  Texas Tech
  N. Akchurin

Scint+SiPM Tileboards
J. Mans
F. Sefkow

- SiPM
  M. Wayne
- Scintillator
  V. Zutschi
- Lead TAC
  DESY
  F. Sefkow
- TAC
  RDMS-RF, RDMS-Dubna
- TAC(US)
  NIU/FNAL

Electronics & Electrical Syst
P.Aspell
C. De la Taille

- OnModule Electronics
  Si: CERN, Omega
  SiPM: DESY
- OnMotherboard Electronics
  J. Hirschauer
- Powering
  D. Barney,
  R. Rusack
- Clock&Control
  Precise Clock
  M. Besancon,
- DCS&DSS
  Y. Tsipolitis

Backend TDAQ
P. Dauncey
A. N. Other TBD

- TPG: Front-end Studies
  I. Puliak
- TPG: Sim & Algo
  J. B. Sauvan
- TPG architecture design & implementation
  V. Palladino
- DAQ syst. & fe coord.
  A. David

Systems Validation
[illegible]
A. Lobanov,
R-S Lu

Removing Test beams

DPG*
M. Rovere,
C. Seez
A. N. Other TBD

- Simulation (Geometry,..)
  S.Banerjee,
  R.Segal
- Electronics Simulation
  P. Silva
- Reconstruction
  M.Rovere,
  F.Pantaleo
- Design Studies
  P.Silva,
  A.Magnan
- MC samples & validation
  [illegible]

* DPG- Detector Performance Group

HGCAL test-beam campaigns

Main objectives for beam tests:

- Technological **prototyping** of the detector modules
- **First experience** with a **FE ASIC** with components of the ultimate (HGC)ROC **in beam conditions**: ADC, ToT, ToA
- **Physics performance** of the CE-E and CE-H silicon / scintillator parts
- Check **agreement** with **simulation**

Time

2016 ➡ *N. Akchurin et al 2018 JINST 13 P10023*

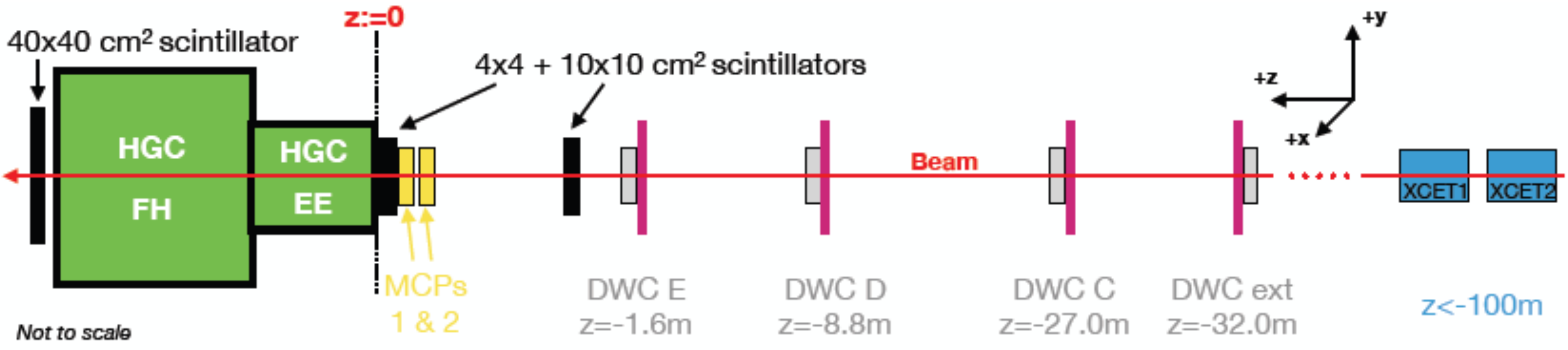
2017 First beam tests with **Skiroc2-CMS** ASIC

March 2018 @ **DESY**
3 modules

June 2018 @ CERN's **SPS**
full CE-E: 28 modules

October 2018 @ CERN's **SPS**
full prototype: 94 modules

H2 beam-line setup



After working close with the CERN SPS beamline experts, we have simulated in detail the full beamline in our Geant4 simulation of the test beam

Micro-channel plate (MCP) photomultiplier tubes were employed to provide t-reference.

Delay wire chambers (DWCs) monitoring the beam profile in X and Y.

Scintillators for triggering/vetoing.

2018 HGCAL Test-beam

- **28-layer CE-E setup**

+12-layer CE-H-Si setup (94 modules)

- 3 configurations tested

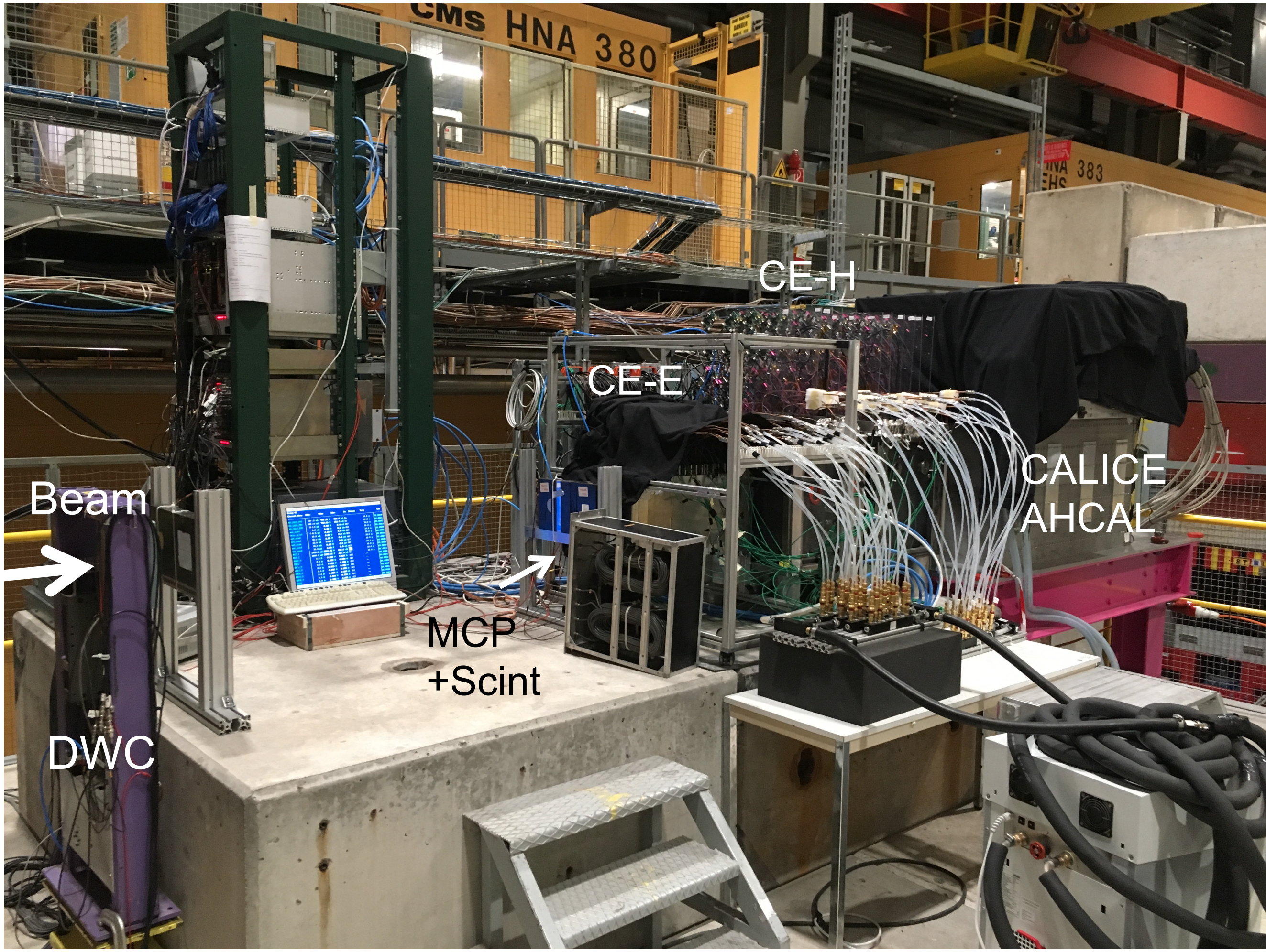
- Environmental control
- Delay Wire chambers
- Threshold Cherenkov counters
- MCPs for timing
- **CALICE - AHCAL**

- **e, μ, hadrons up to 300 GeV**
- Trigger: 2x scintillators in front of CE-E

+ 1x additional (veto) behind CE-H-Si

➡**First large-scale test of**

O(100) HGCal modules

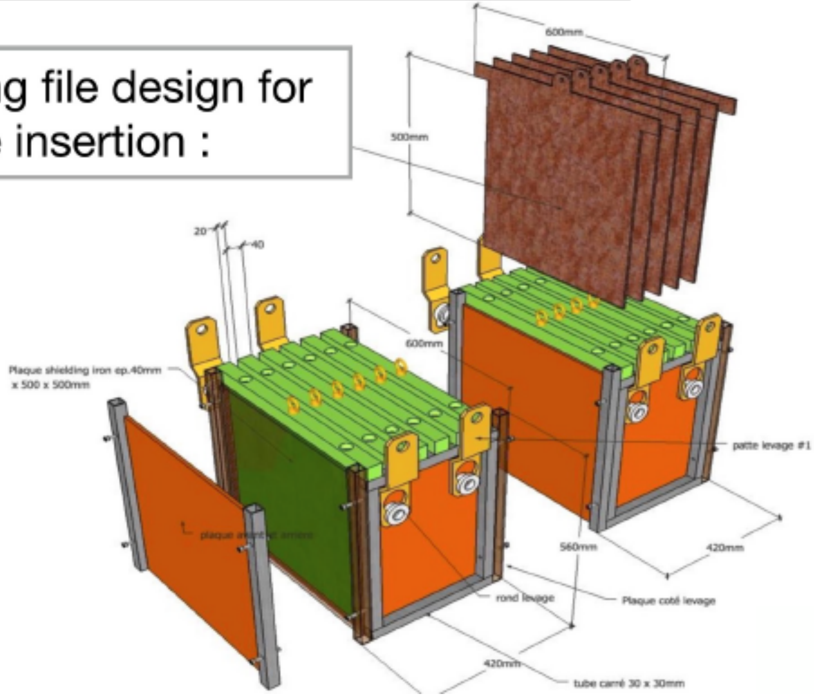


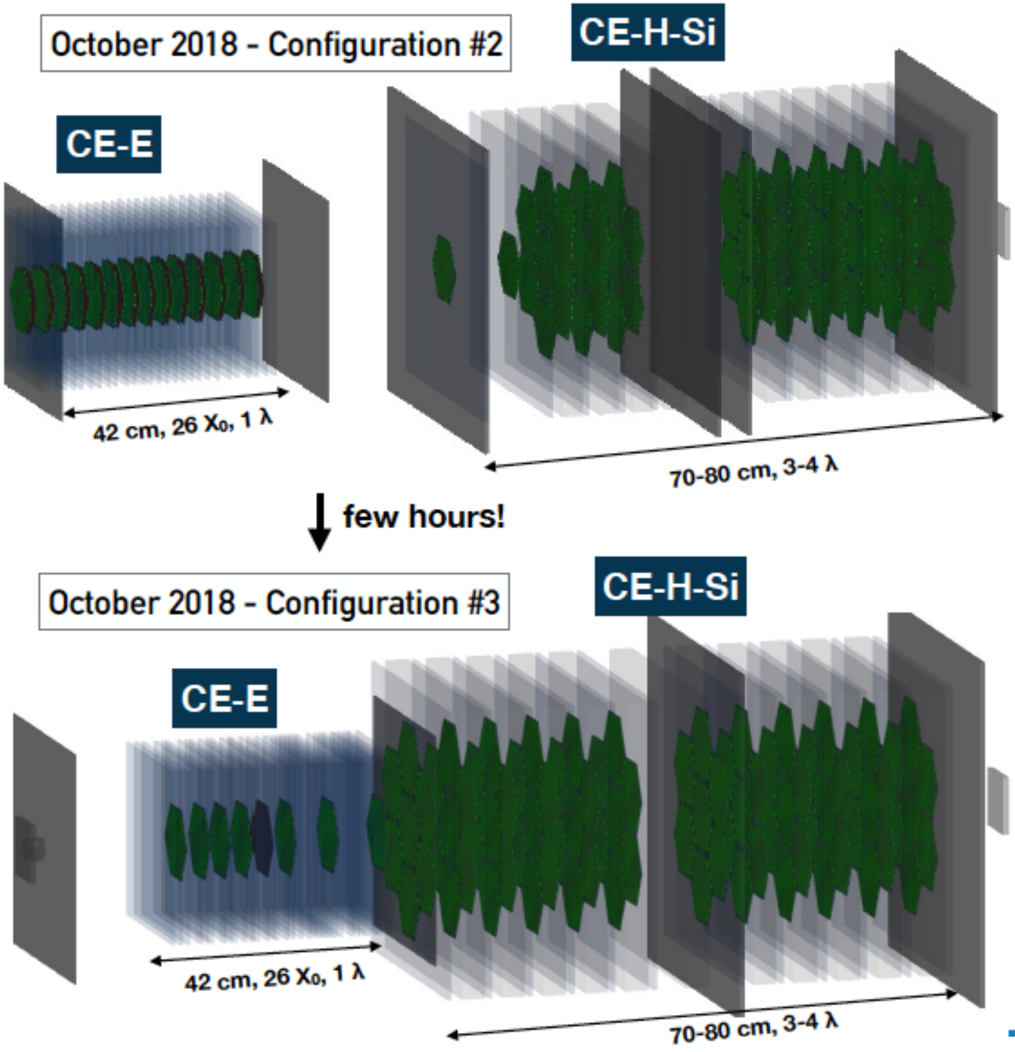
2018 Configurations

Passive material

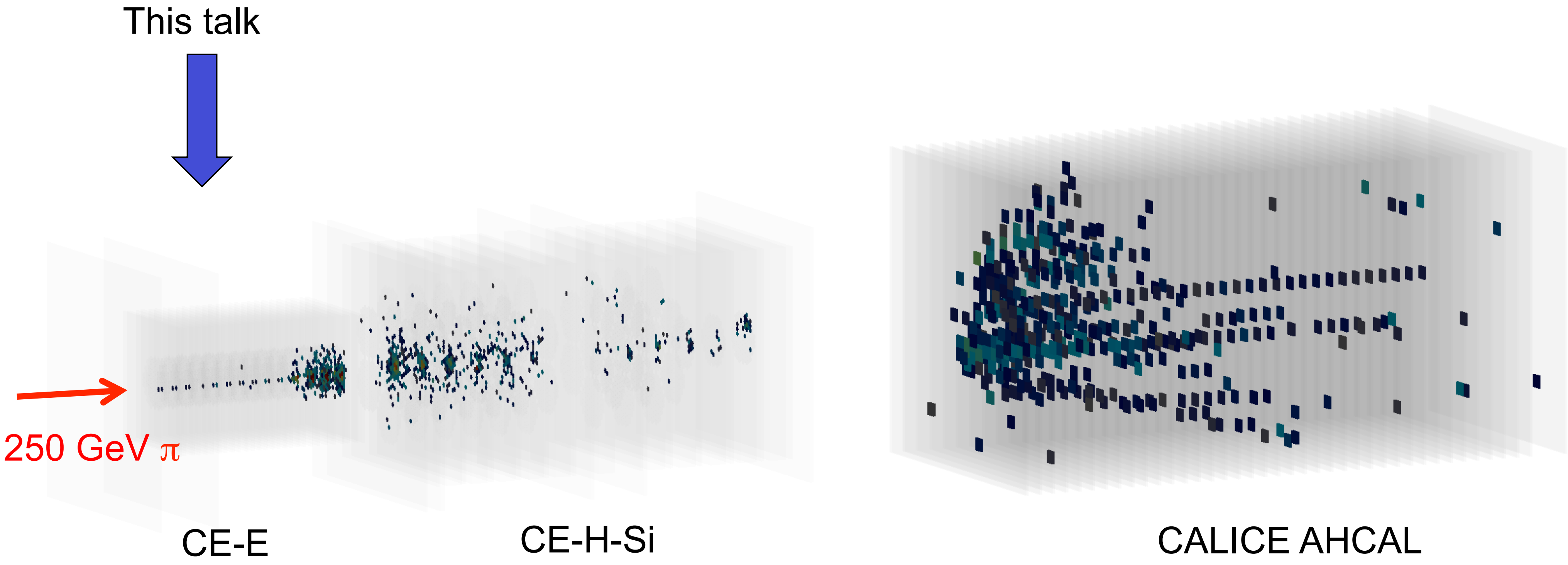
- **CE-E:**
  - **material: Pb, W, Cu**
  - **thickness: 5-6 mm**
- **CE-H-Si:**
  - **material: Fe**
  - **thickness: 4 cm**
  - **weight: O(1000kg)**

Hanging file design for flexible insertion :



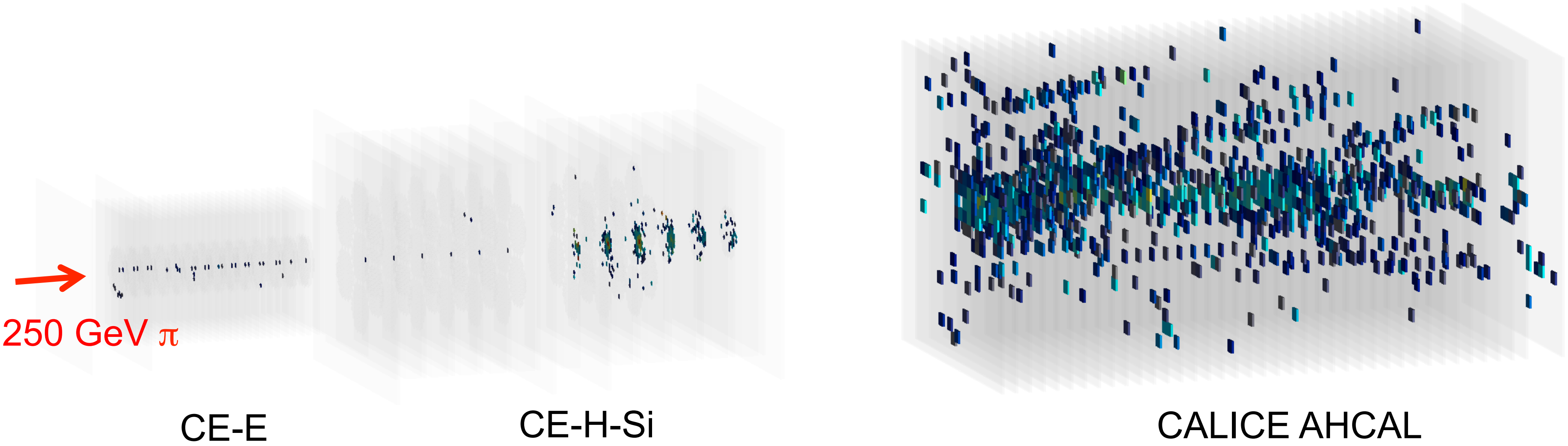


HGCAL is an imaging Calo



HGCAL is an imaging Calo

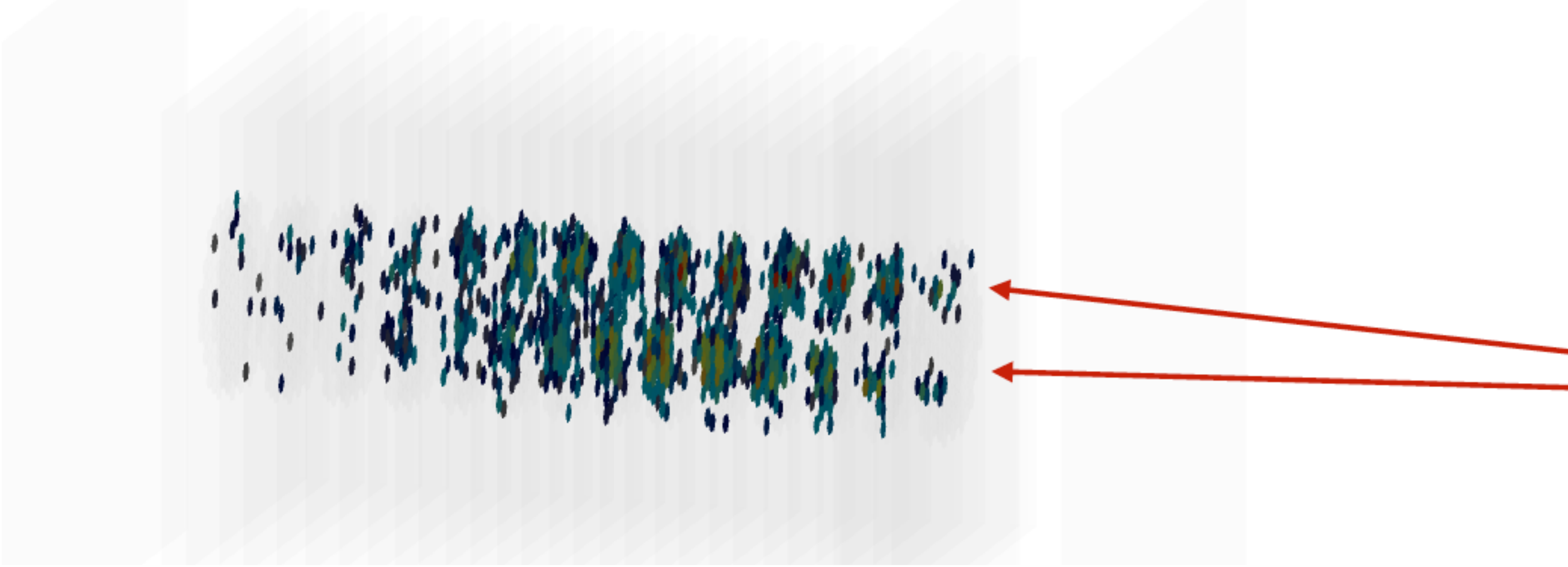
Run 517, event 30



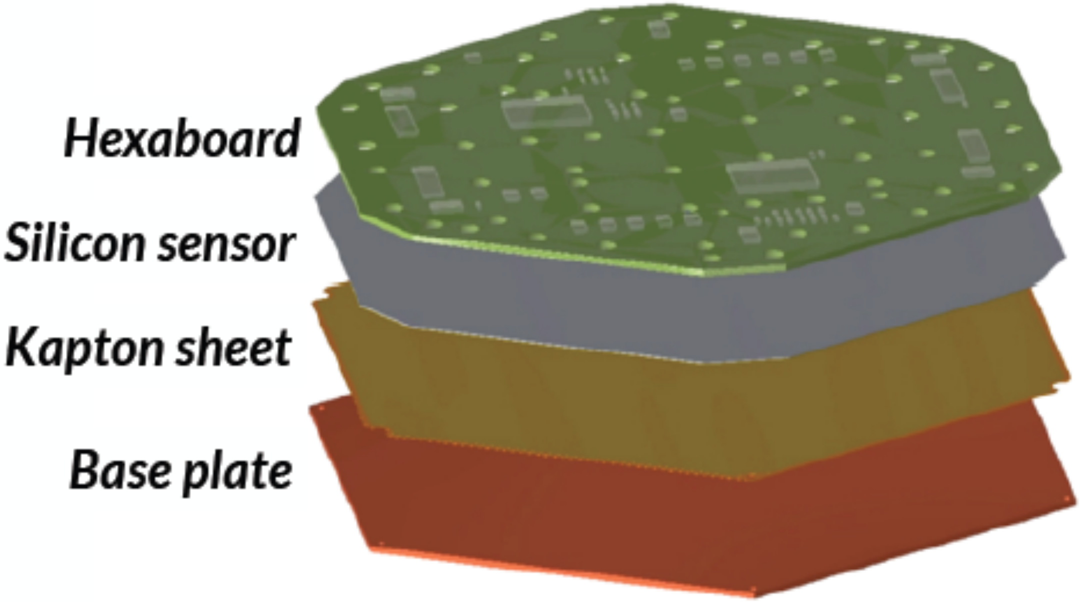
HGCAL is an imaging Calo

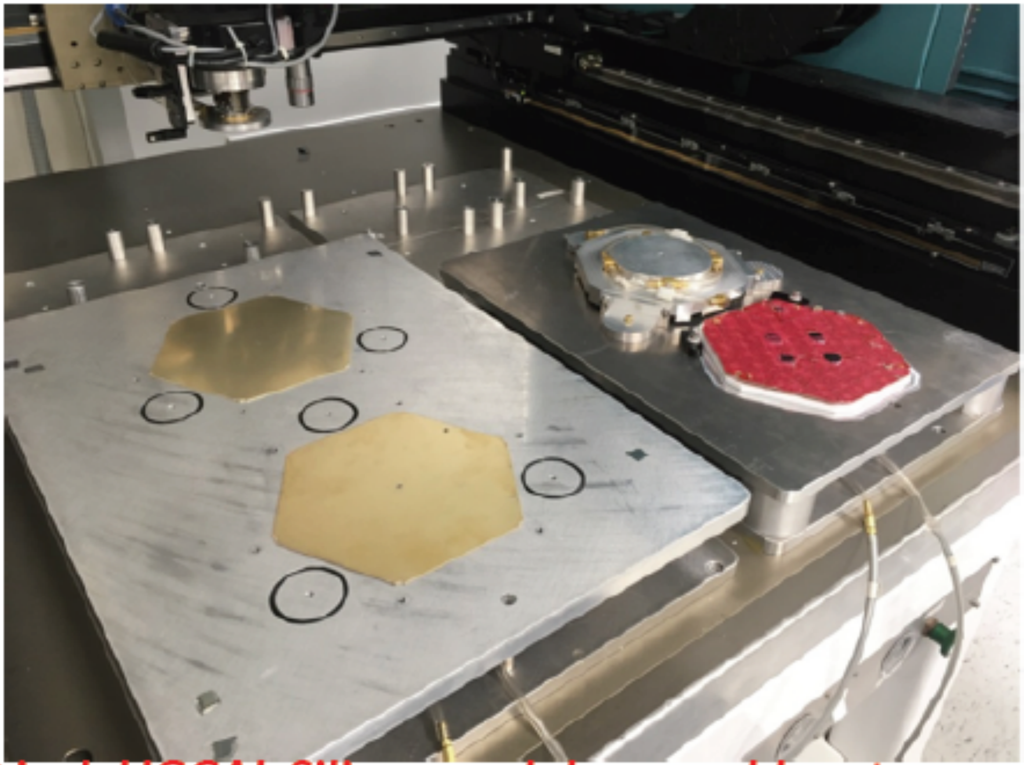
June 2018 run 407 - event 1:

“150 GeV e^-“

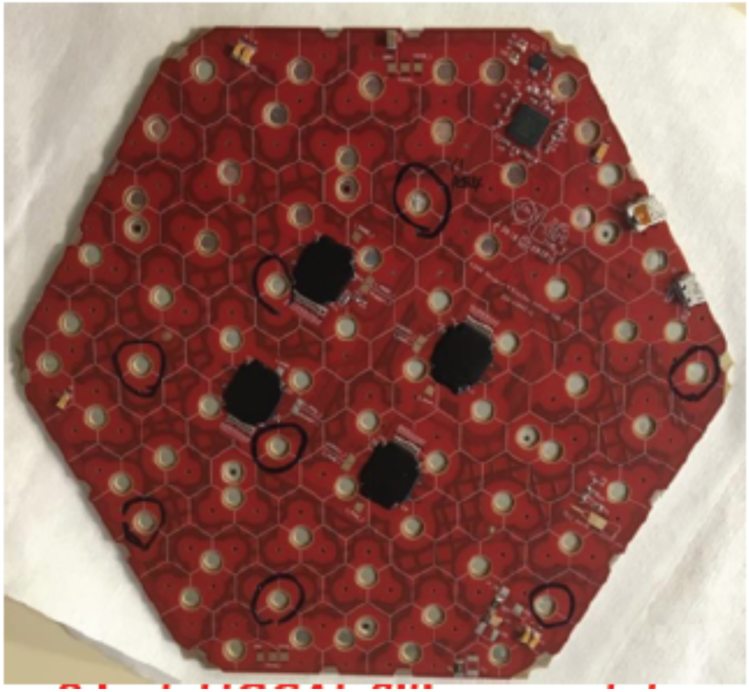


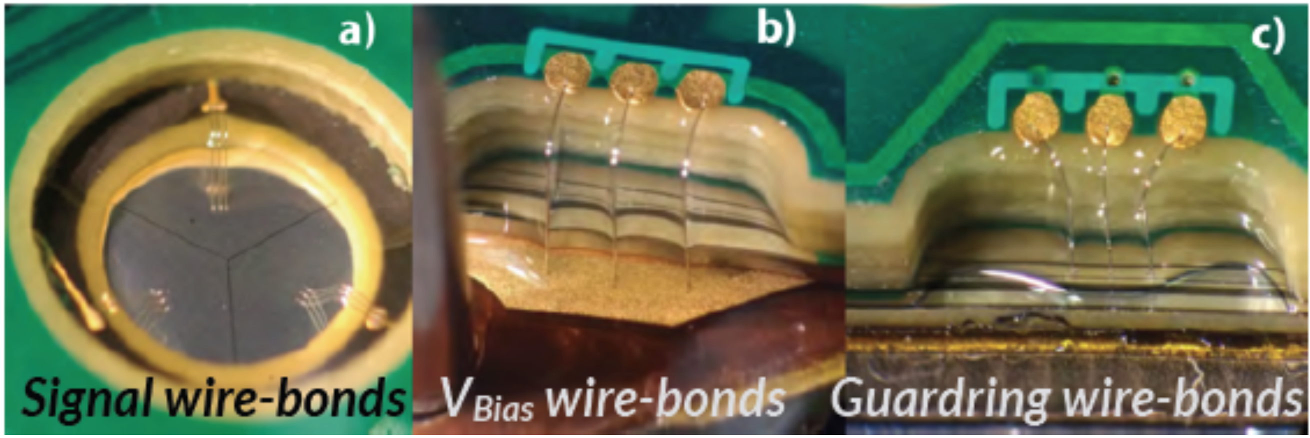
HGCAL Modules





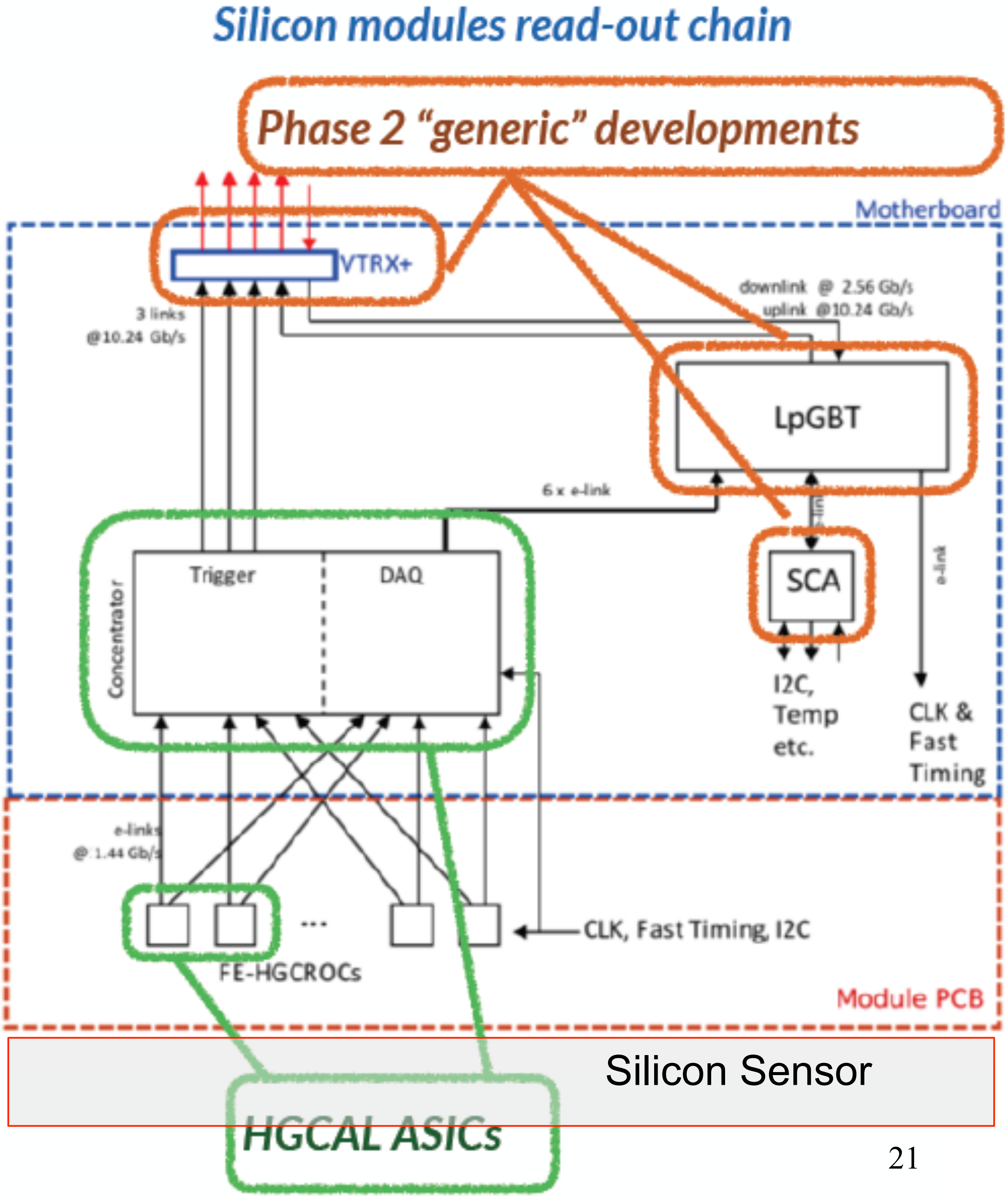
8 inch HGCAL Silicon module assembly set-up
(At one of the 6 module assembly centers worldwide)



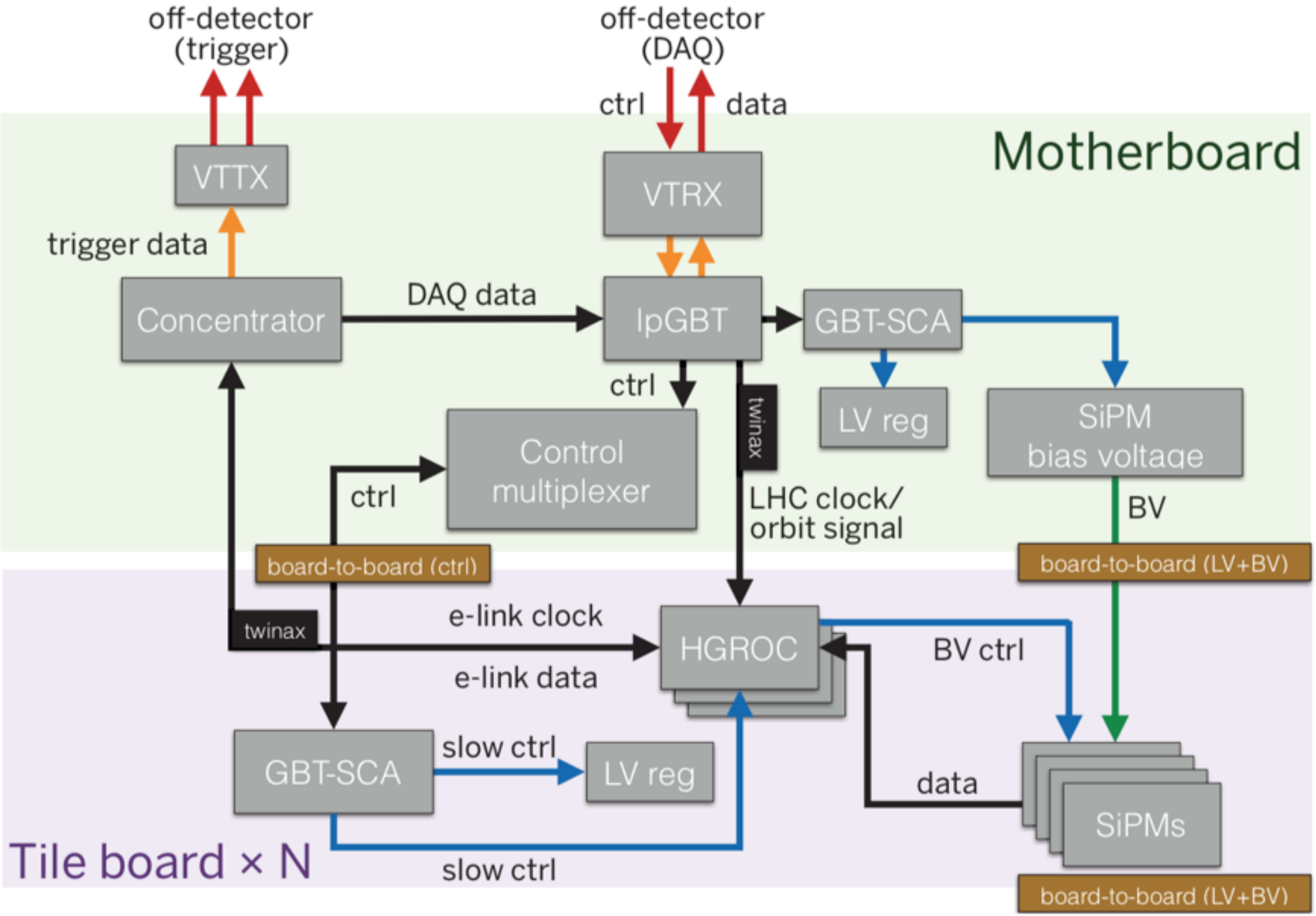


FEE Read-Out Chain

- The front-end electronics
  - Measures and digitizes the charge
    - 10bit ADC (0.2fC - 100fC)
    - 12bit TDC (50fC to 10pC)
  - Provides a high precision measurement of the time of arrival of the pulses
    - 10bit TDC with 25ps bins
  - Transmits the digitized data to the back-end electronics
- Similar front end electronics for the readout of the SiPMs



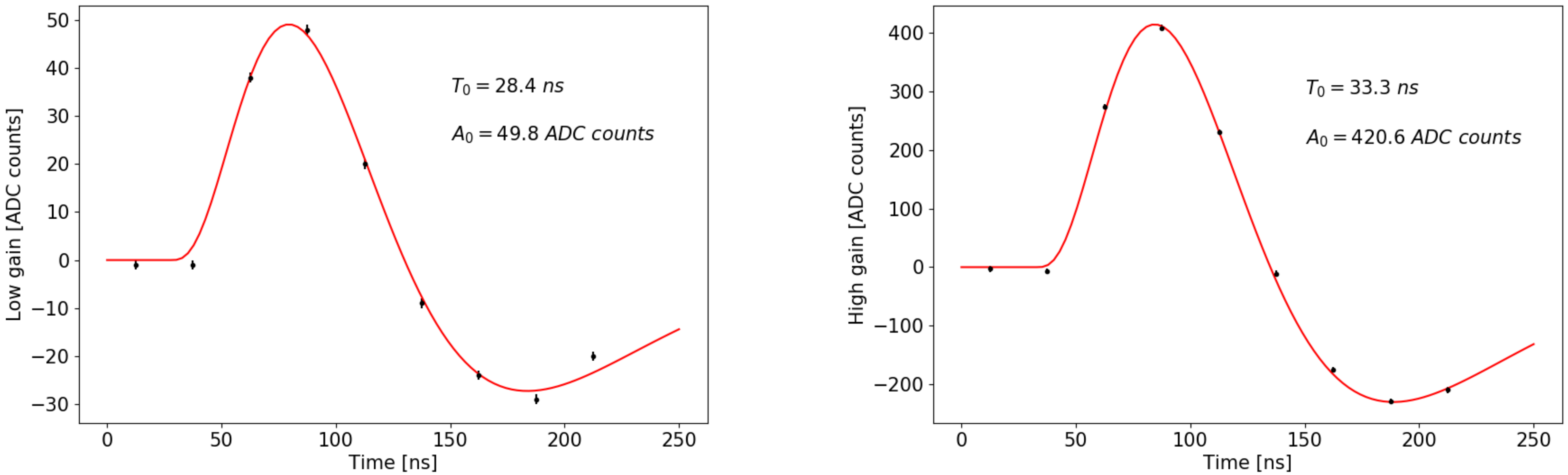
Scintillator Tile Read-Out Chain



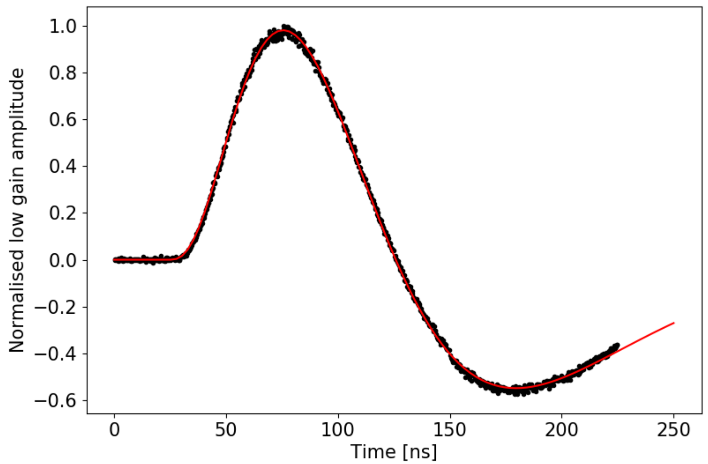
Step-by-step pad energy reco

1. Amplify, Shape and sample the signal pulse (25nsec rate)
   - Hold 13 HG + 13 LG samples in SCAs
2. Readout 13 samplings in per hit and digitize
   - Keep the (time-over-threshold) TOT and (time of arrival) TOA
   - Extract the pad (x,y) info from ROC ID
   - Store all the above in **Calorimeter Hits**
3. Subtract pedestals and common noise from every sampling.
4. **Fit the resulting pulse with a model to extract the amplitude A_0**
5. **Depending on A_0: Go from HG, LG, TOT ➔ pad Energy**
   - Energy ~ Amplitude
   - Use muons and/or pions to extract for each pad the Landau MIP MPV (the peak).
     - ☐ ADCperMIP: ~40 (High Gain), ~5 (Low Gain)
   - Store energy, position and time in **RecHits**

Step 4: fitting the pulse shape



Low gain shaper pulse (left) vs High Gain pulse (right) for 300GeV electrons.
The model pulse has been extracted by sampling pulses at 1nsec.



$$S(t) = \begin{cases} A_0\left[\left(\frac{t-t_0}{\tau}\right)^n - \frac{1}{n+1}\left(\frac{t-t_0}{\tau}\right)^{n+1}\right] e^{-\alpha(t-t_0)/\tau} & \text{if } t > t_0 \\ 0 & \text{otherwise} \end{cases}$$

Dedicated injection runs on test stands with waveforms sampled at 1nsec.

Step 5: use muons to get ADCperMIP

- The hit energy is estimated using a preliminary HG-MIP calibration.
- Hits with more than 0.5 MIP, corresponding to 20-25 HG ADC of the reconstructed waveform amplitude are visualised.
- (A hit-energy-colour bar could be added.)

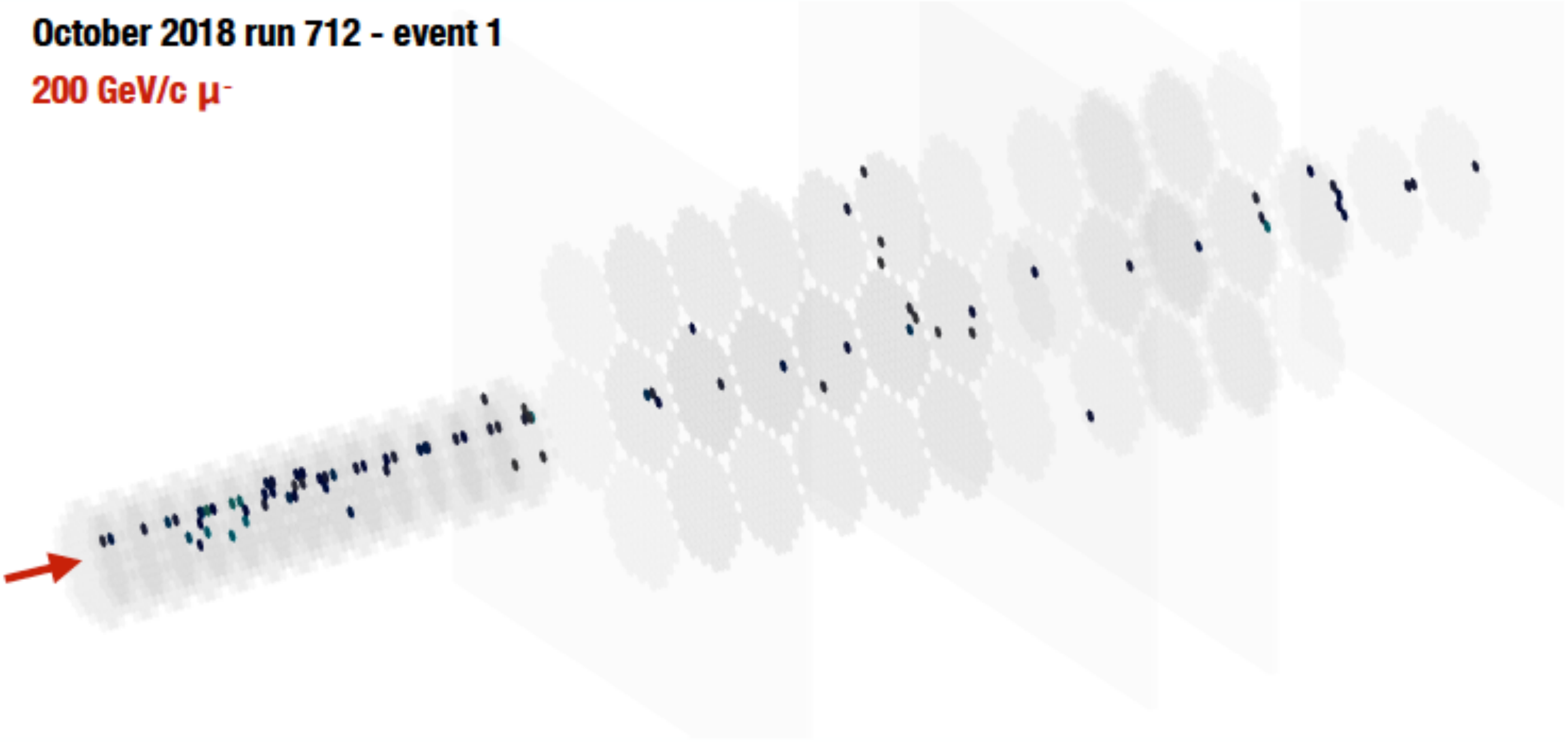


Figure: Event display of a 200 GeV/c muon traversing the CE-E (28 layers) and CE-H (12 layers) prototypes during the beam test of October 2018. The incoming muon enters the detector from the left-hand side.

Step 5: use muons to get ADCperMIP

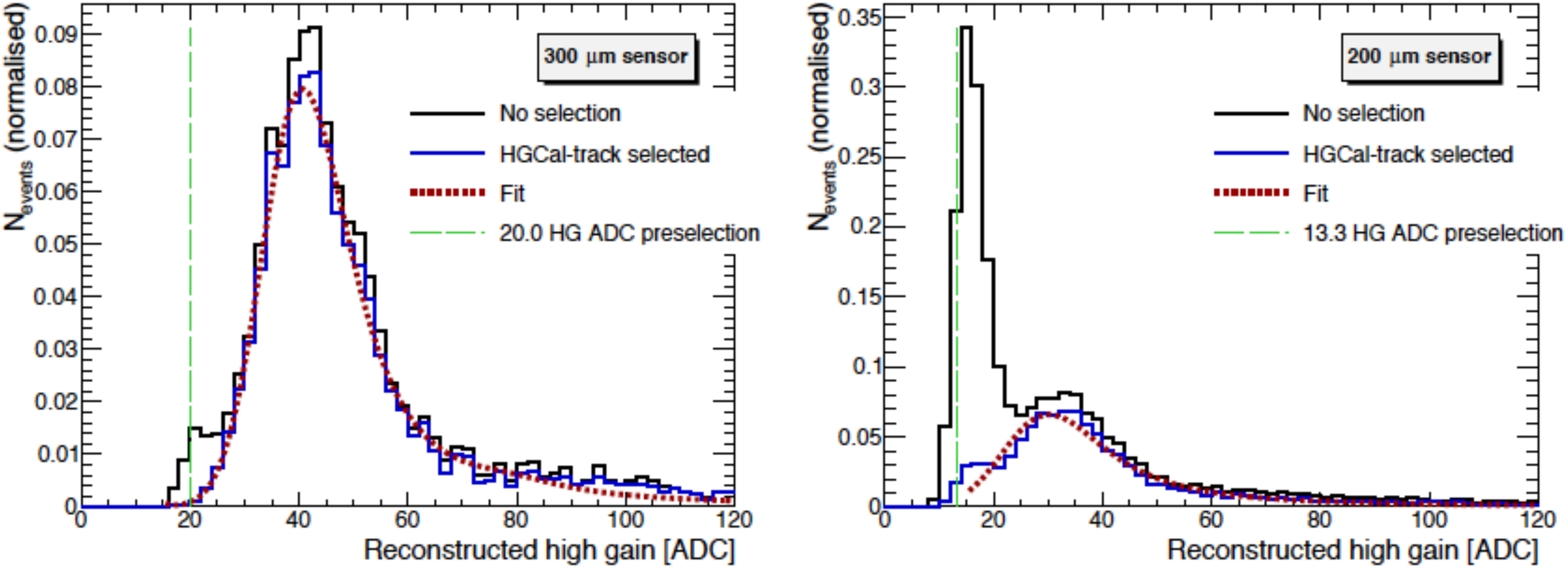


Figure: Energy spectrum of reconstructed ADC both in high (top left and right) [...] for two example readout channels due to incident 200 GeV/c muons. MIP- selected spectra are normalized to unity integral. The shown raw spectra are scaled accordingly.

Step 5: use muons to get ADCperMIP

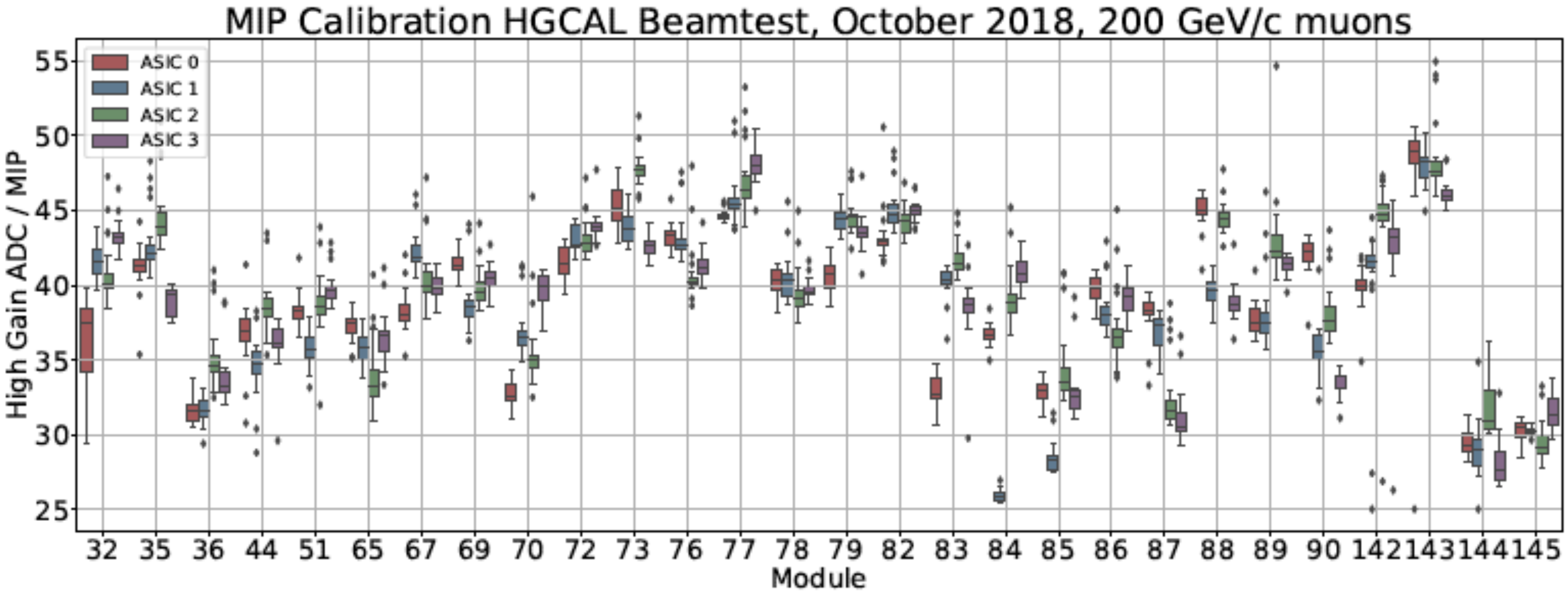
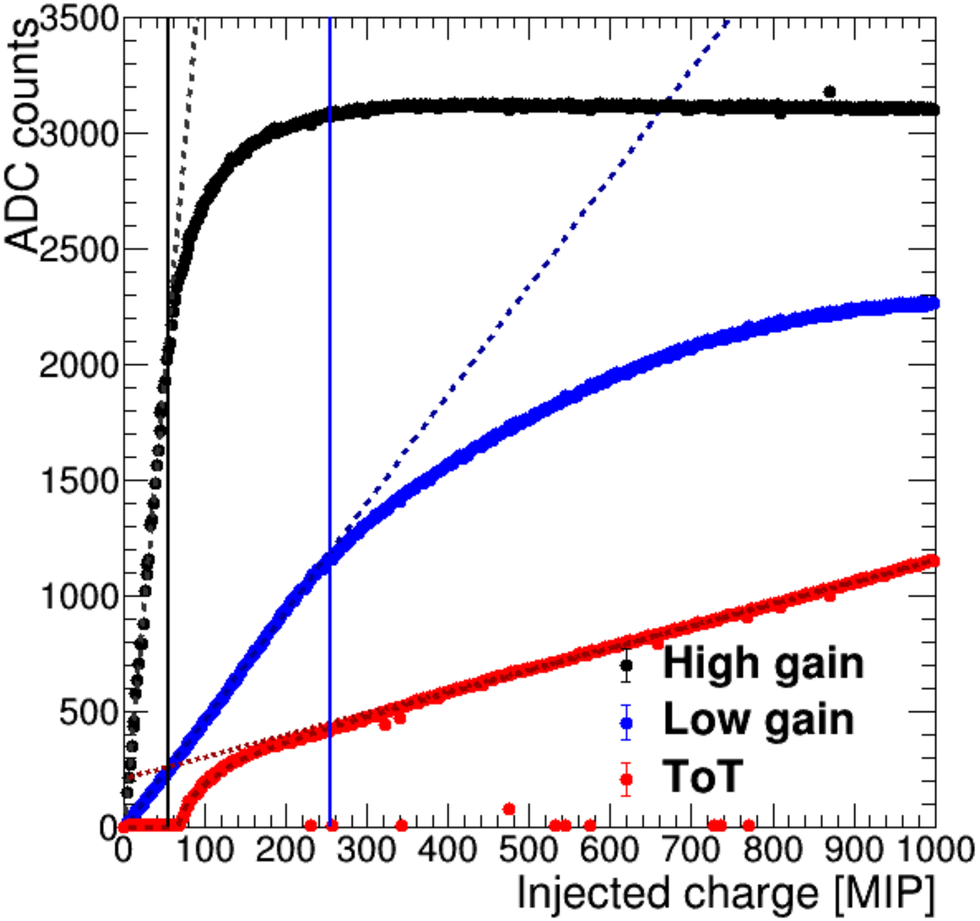


Figure: Per-module distribution of calibrated high gain ADC per MIP for the October 2018 beam tests of the silicon electromagnetic calorimeter prototype. Modules 144 and 145 consist of 200 μm thick silicon sensors.

Pad energy reconstruction: LG,HG,ToT



$$A'_{HG} = \begin{cases} A^{TOT} \cdot m_{LG/TOT} \cdot m_{HG/LG} & \text{, if } A^{LG} > TP_{LG} \\ A^{LG} \cdot m_{HG/LG} & \text{, else if } A^{HG} > TP_{HG} \\ A^{HG} & \text{, otherwise} \end{cases}$$

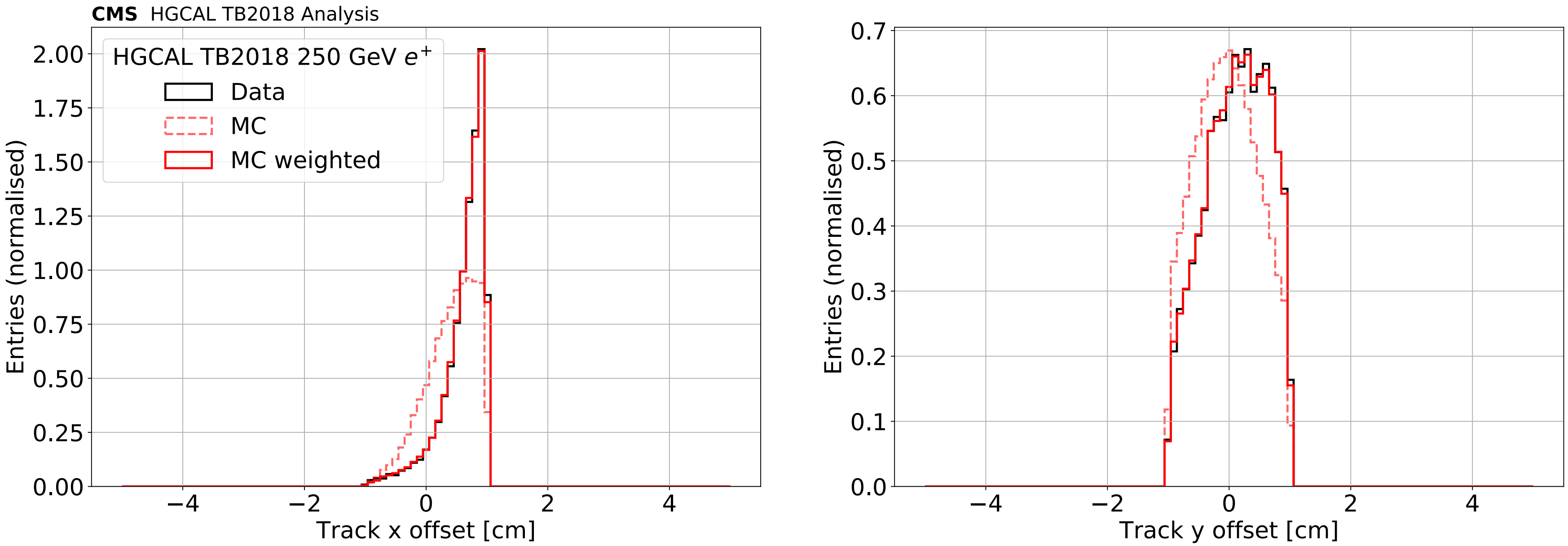
$$E^{Si}_{pad}[MIP] = A'_{HG} \cdot M_{MIP/HG},$$

Data/MC comparisons

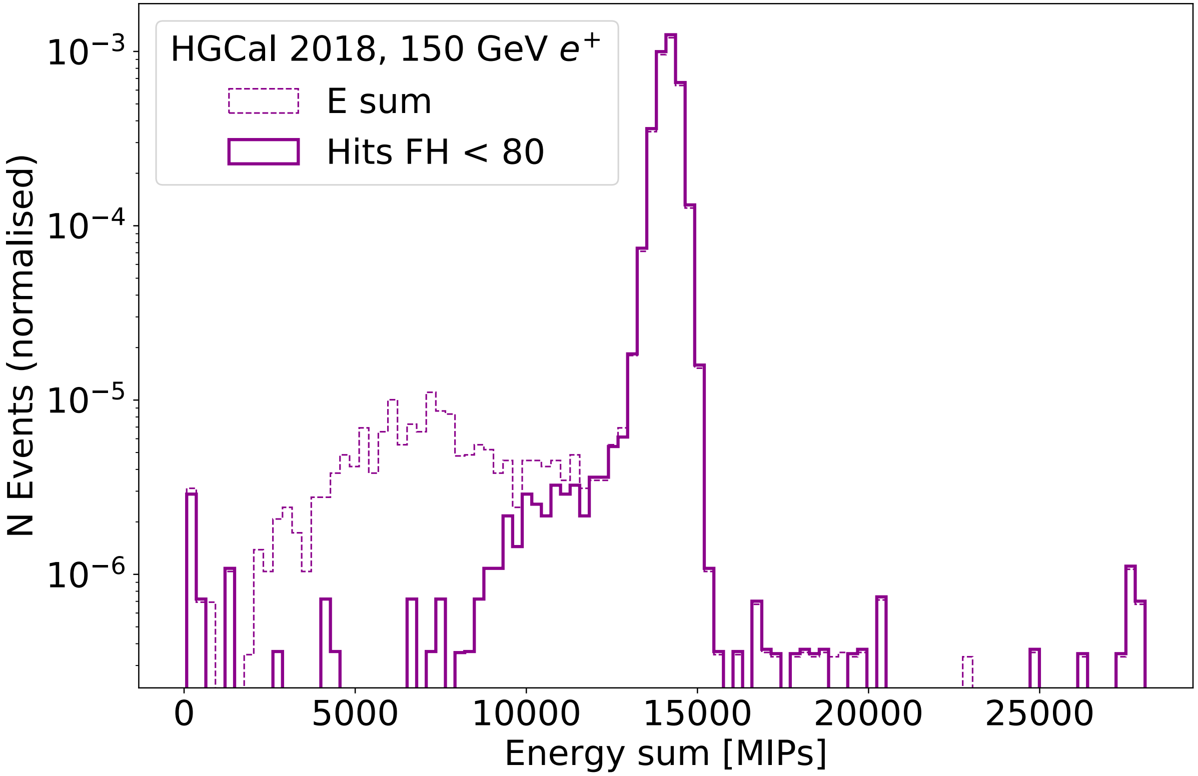
Earlier and Later attempts

Event Selection

- RecHits are required to have Erec > 0.5MIPs (~4 times the pad noise)
- Problematic channels masked off
- A single track was required in DWCs (electron).
- Events with more than 80 RecHits in the hadronic section are rejected.
- Fiducial cut on the impact track (+/- 1cm). This puts the seed within ~4 pads.



EM tails and pion rejection

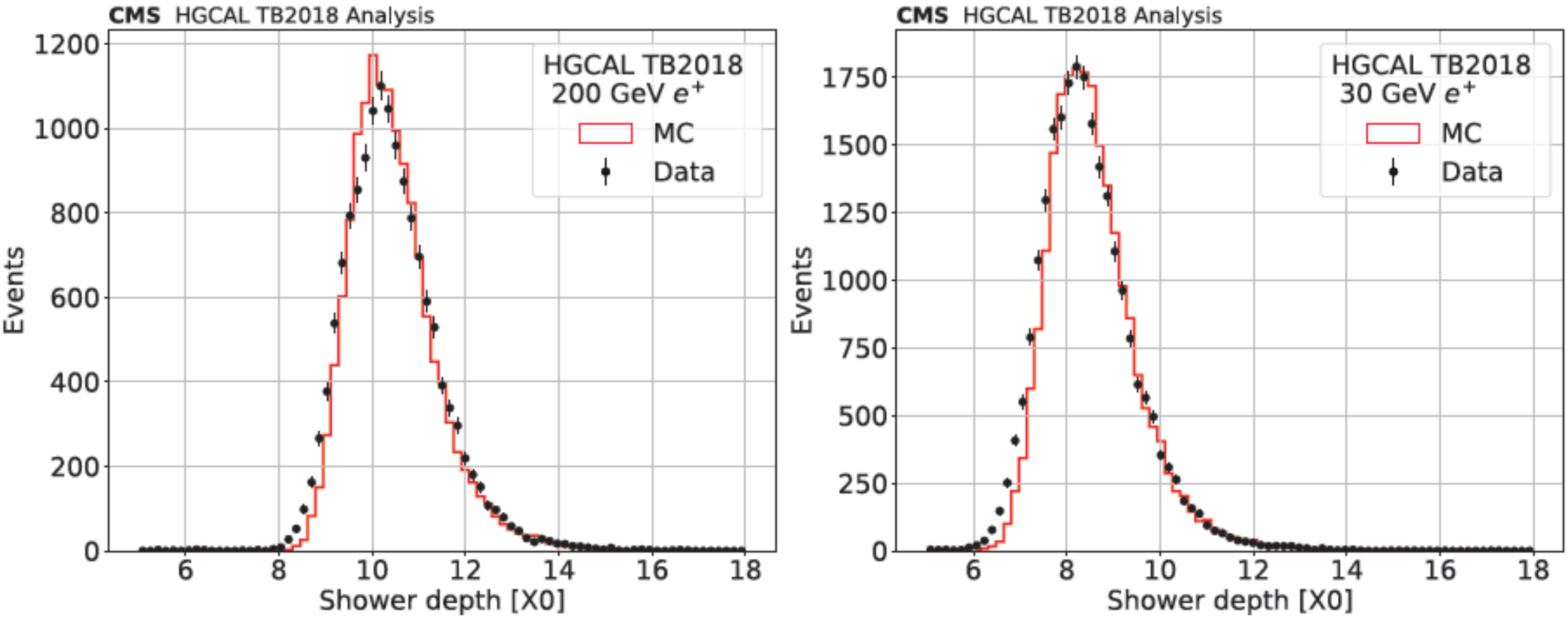


- Presence of pions in certain runs (like the 150GeV) is obvious.
- Pion removal without biasing the electron reconstruction is based on a cut in the FH

Longitudinal Shower Shapes

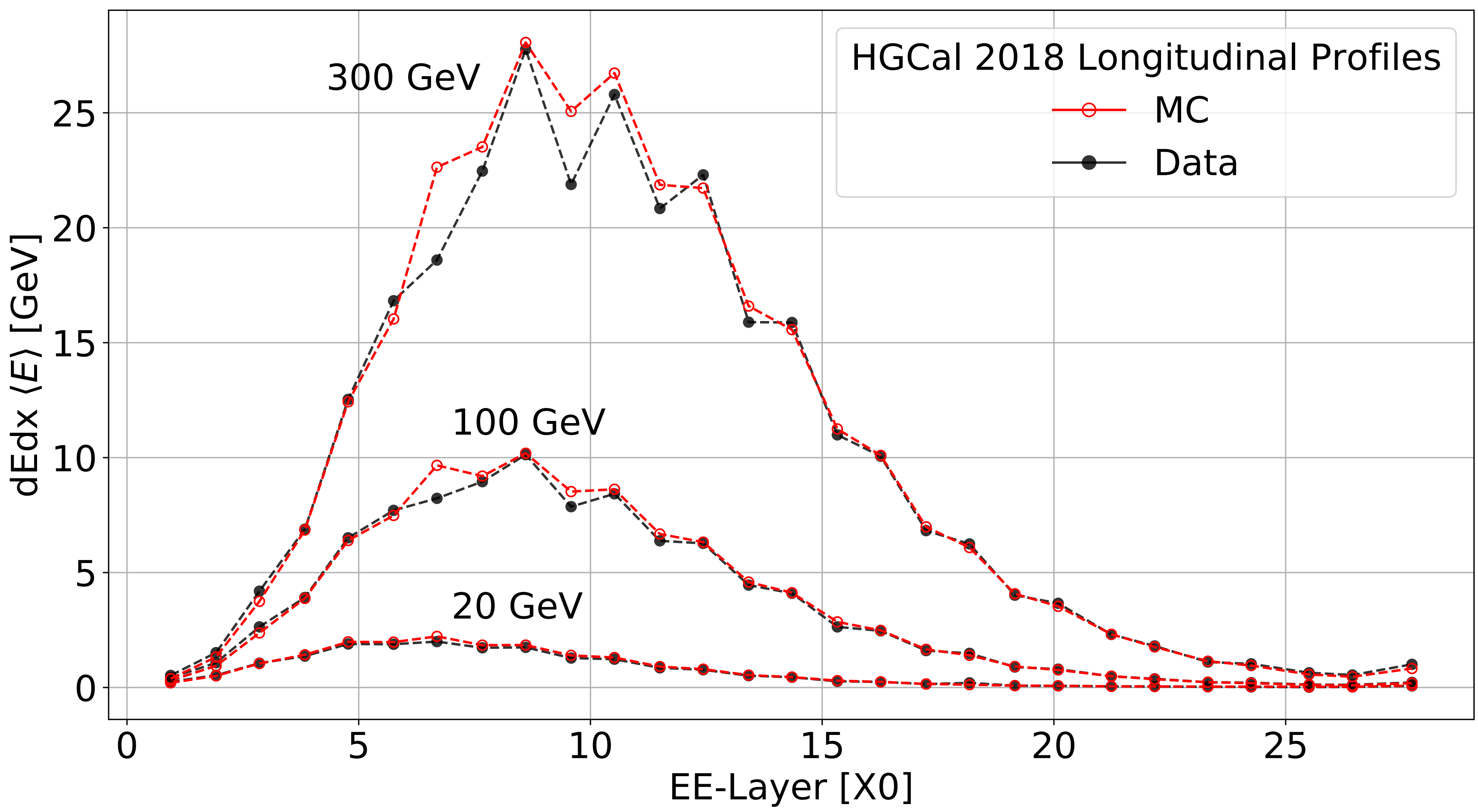
SHOWER DEPTH

“Center of Gravity” definition here



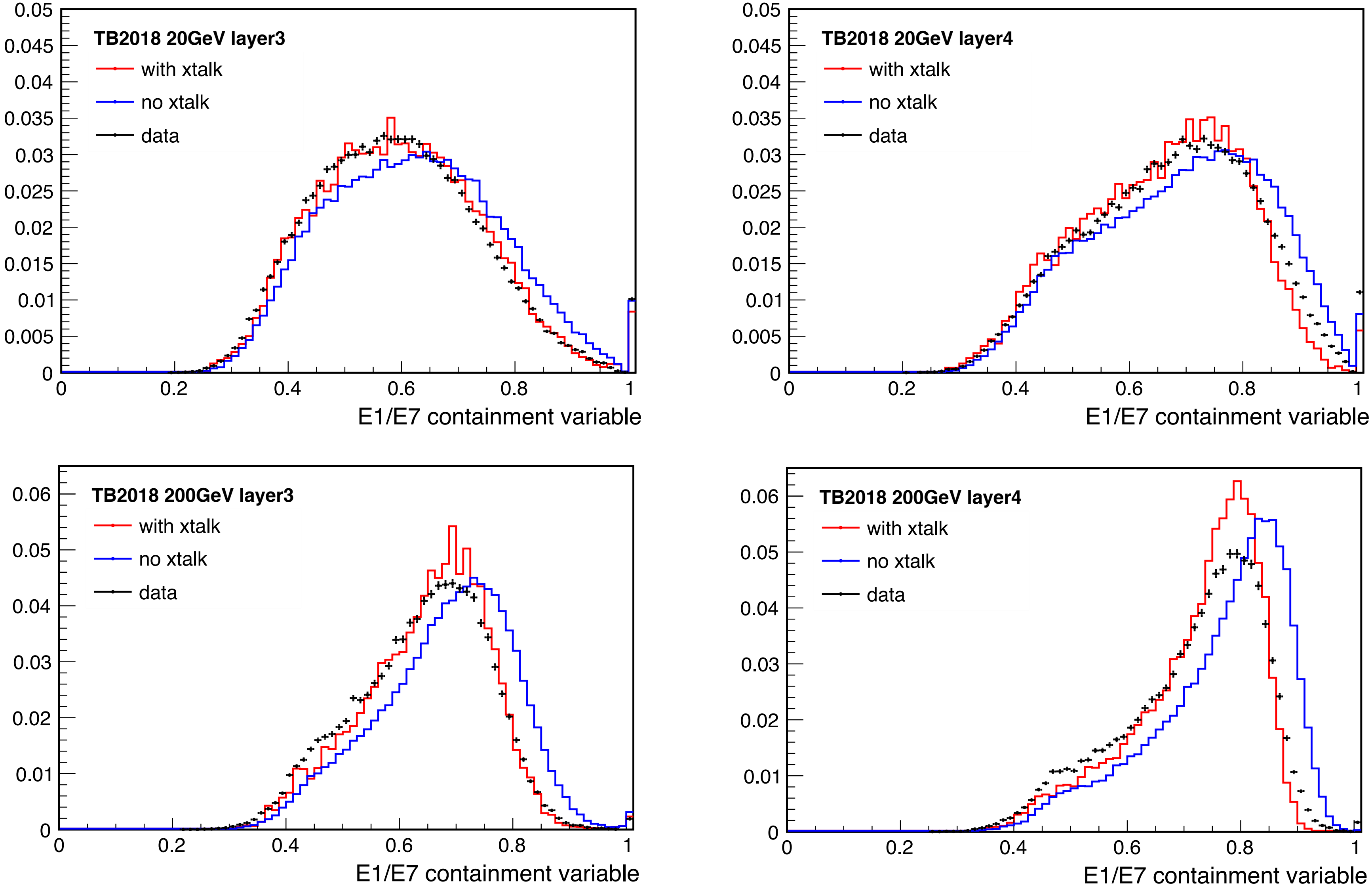
Shower depth distribution defined as: $SD[X_0] = \dfrac{\sum_i E_i z_i[X_0]}{\sum_i E_i}$

Longitudinal Shower Profile



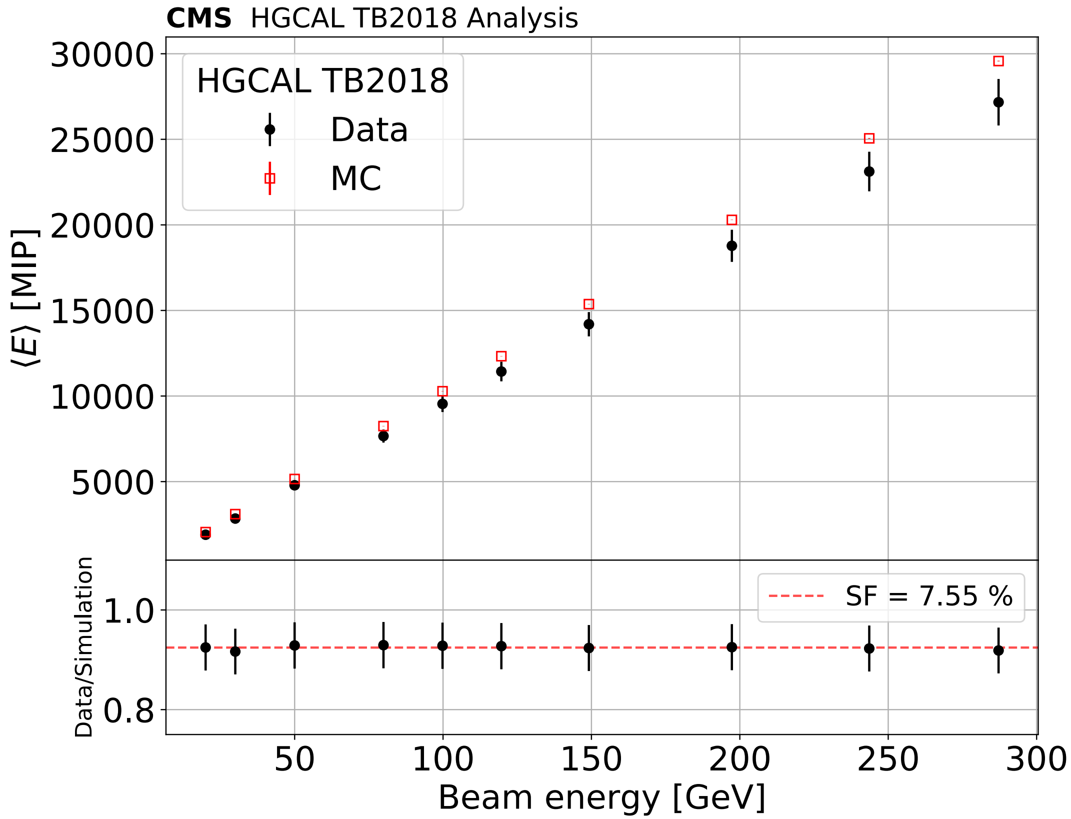
Note that in some layers (like Layer 7 and 10), the response in data is lower than MC

Lateral Shower Profile



Cross-talk noise (pad-to-pad) affects the later shower shapes
Correcting the MC with the measured xtalk from injection runs improves the agreement

Applied factor: data and MC

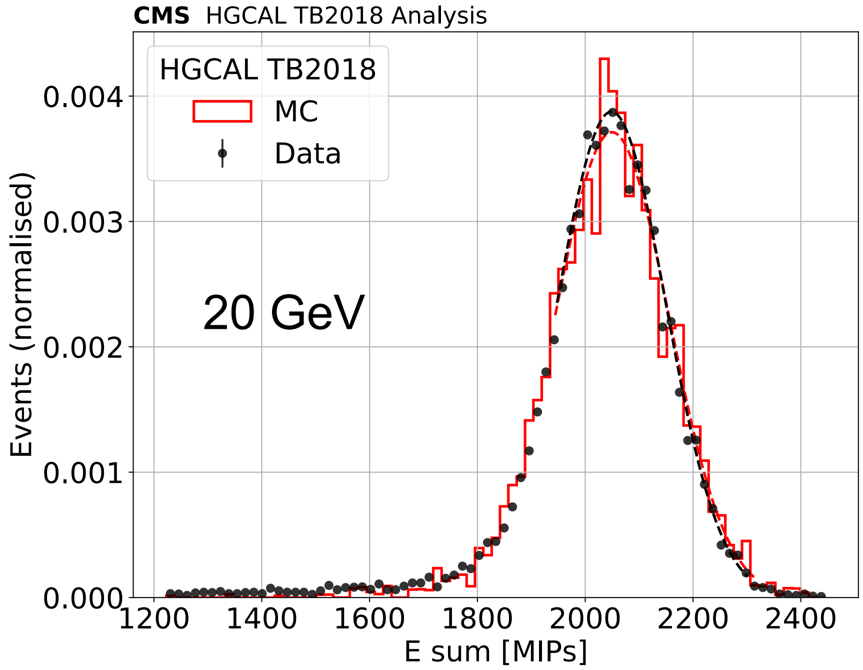


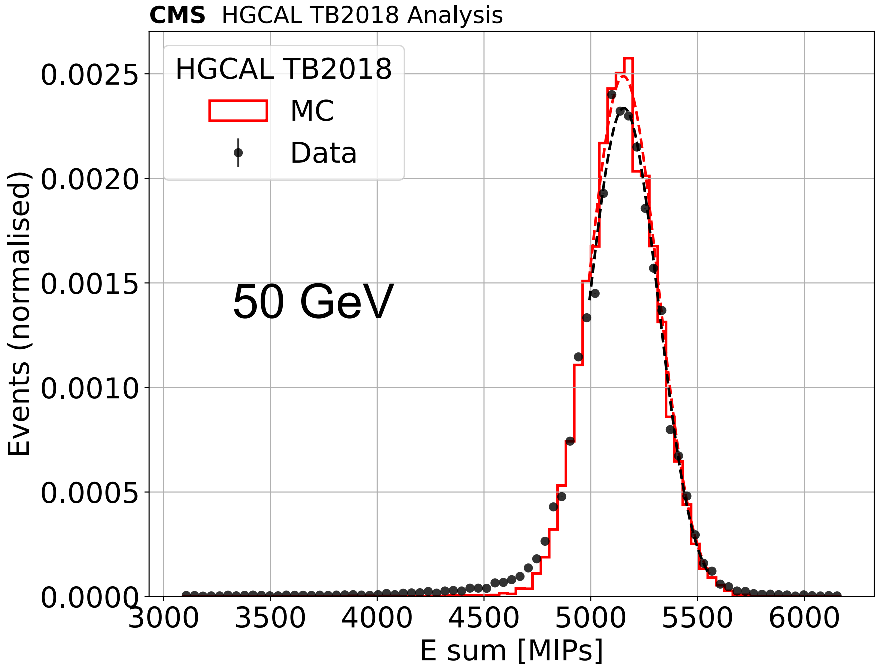
MC raw <Erec> overshoots data by about 8%, constant across the full E-range.

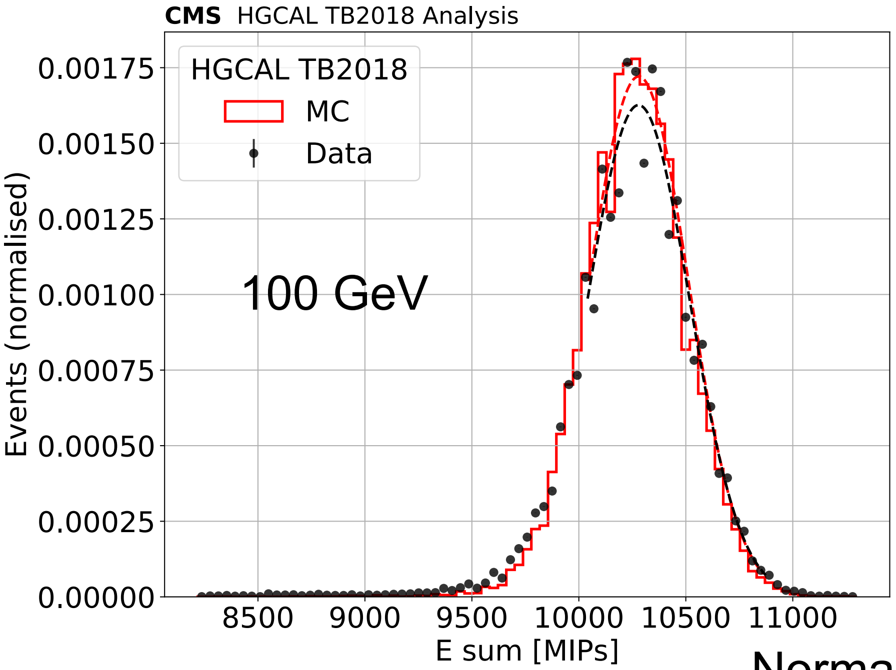
Unofficial:

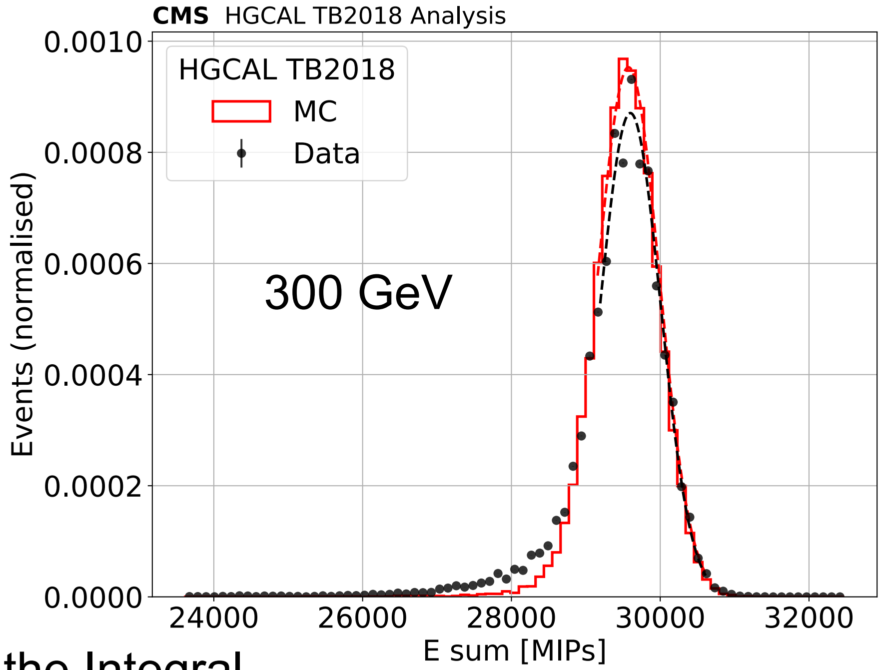
In MC, the depletion region (active area) equals the sensor thickness (300 or 200mic).
In Data, HPK manufacturing has a few micron (20 to 30mic) extra passivation layer on the back side.

Raw energies: data vs MC (MIP)



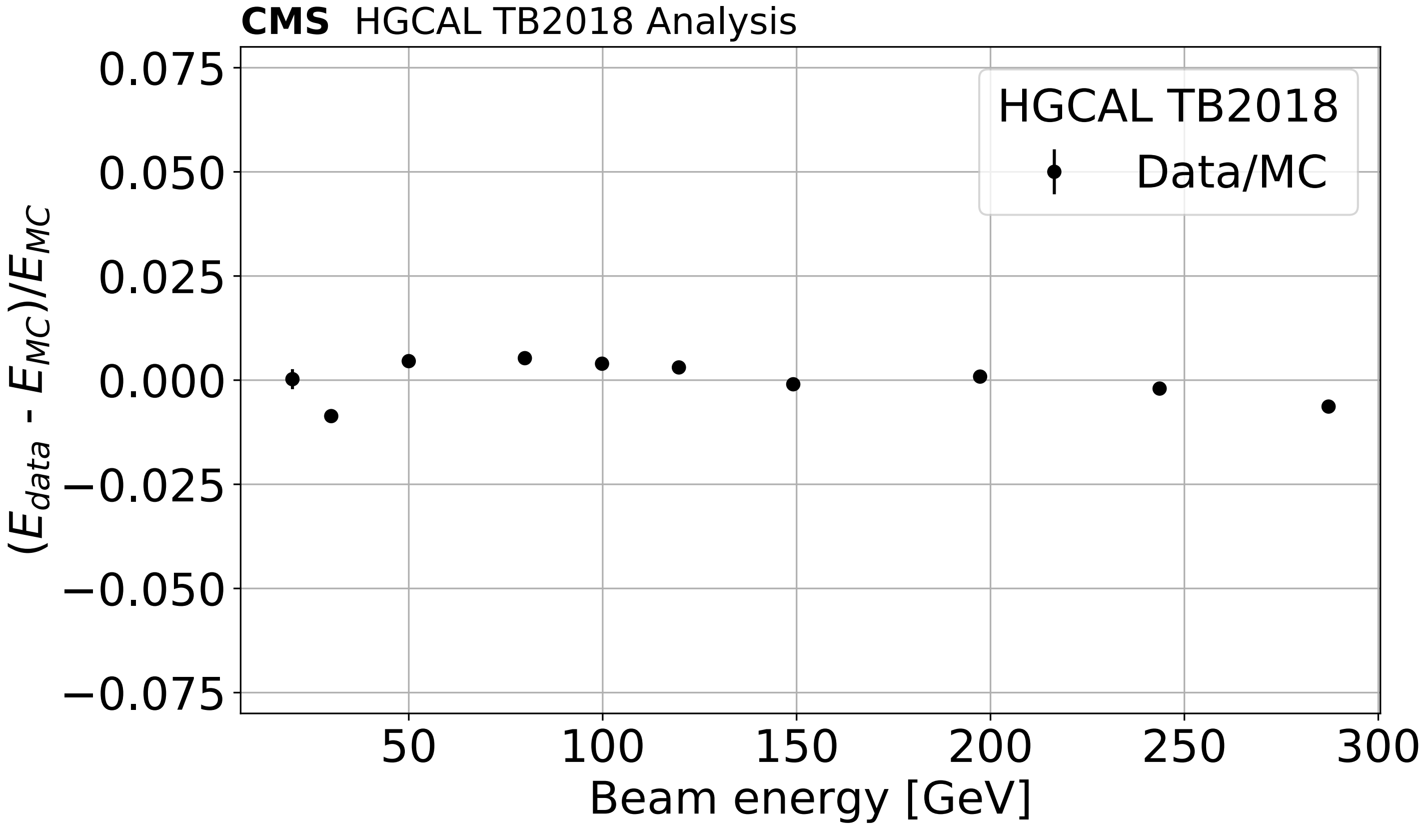






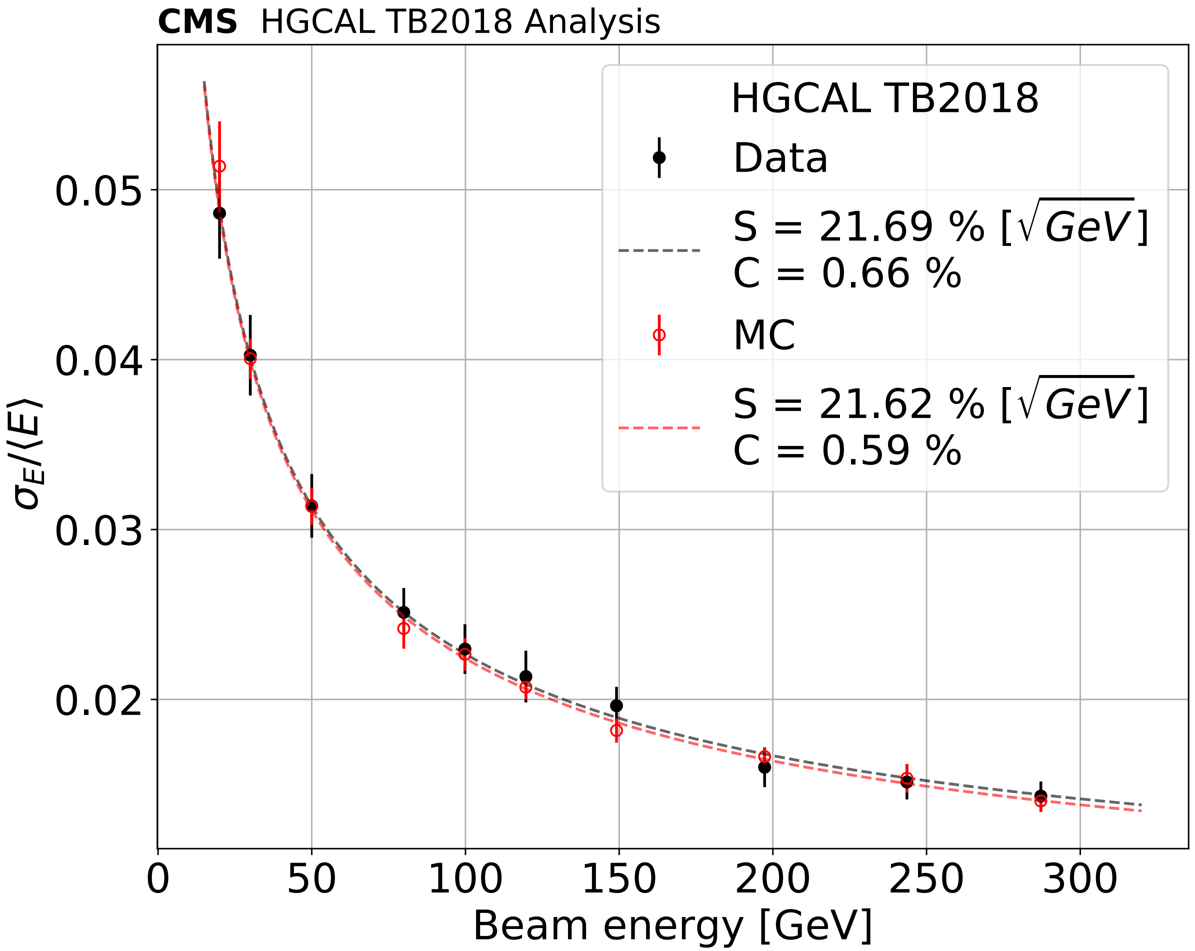
Normalized to the Integral

$\langle E_{rec} \rangle$: Data/MC fractional



- Data energies in agreement with MC within 1% from 20-300GeV (Gaussian means).
- How about the std deviation σ_E ?

$\sigma_E/\langle E_{rec}\rangle$: Data vs MC



- Measured Resolution at the level of Visible energies is nominal.
- Excellent agreement with MC in both stochastic and constant terms.

Calibration

Geant4: Expected Resolution

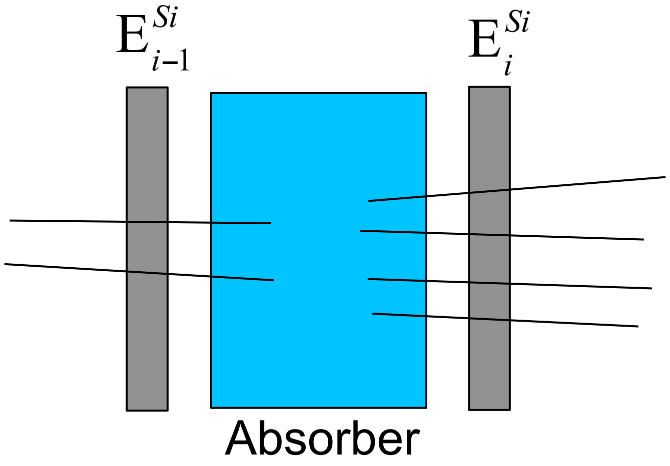
$$E_e = \sum_{i}^{N_{layer}} \underbrace{\left(\mathrm{W}_i \times \mathrm{E}_i^{Si}\right)}_{\substack{\text{Measured Energy in Silicon.} \\ \text{Weighted using a weighing scheme.} \\ \text{Simplest: a single factor SF} \\ \text{(loosely called Sampling Fraction)}}} + \underbrace{\mathrm{E}_{Upstream}}_{\substack{\text{Losses} \\ \text{before ECAL}}} + \underbrace{\mathrm{E}_{Lateral}}_{\substack{\text{Lateral} \\ \text{Losses}}} + \underbrace{\mathrm{E}_{Leak}}_{\substack{\text{Losses} \\ \text{from the} \\ \text{Back}}}$$

- Geant 4: provides all losses on an event-by-event basis.
- Save this information in the MC files, and check their impact on performance.
- Device different calibration schemes, regression schemes etc.

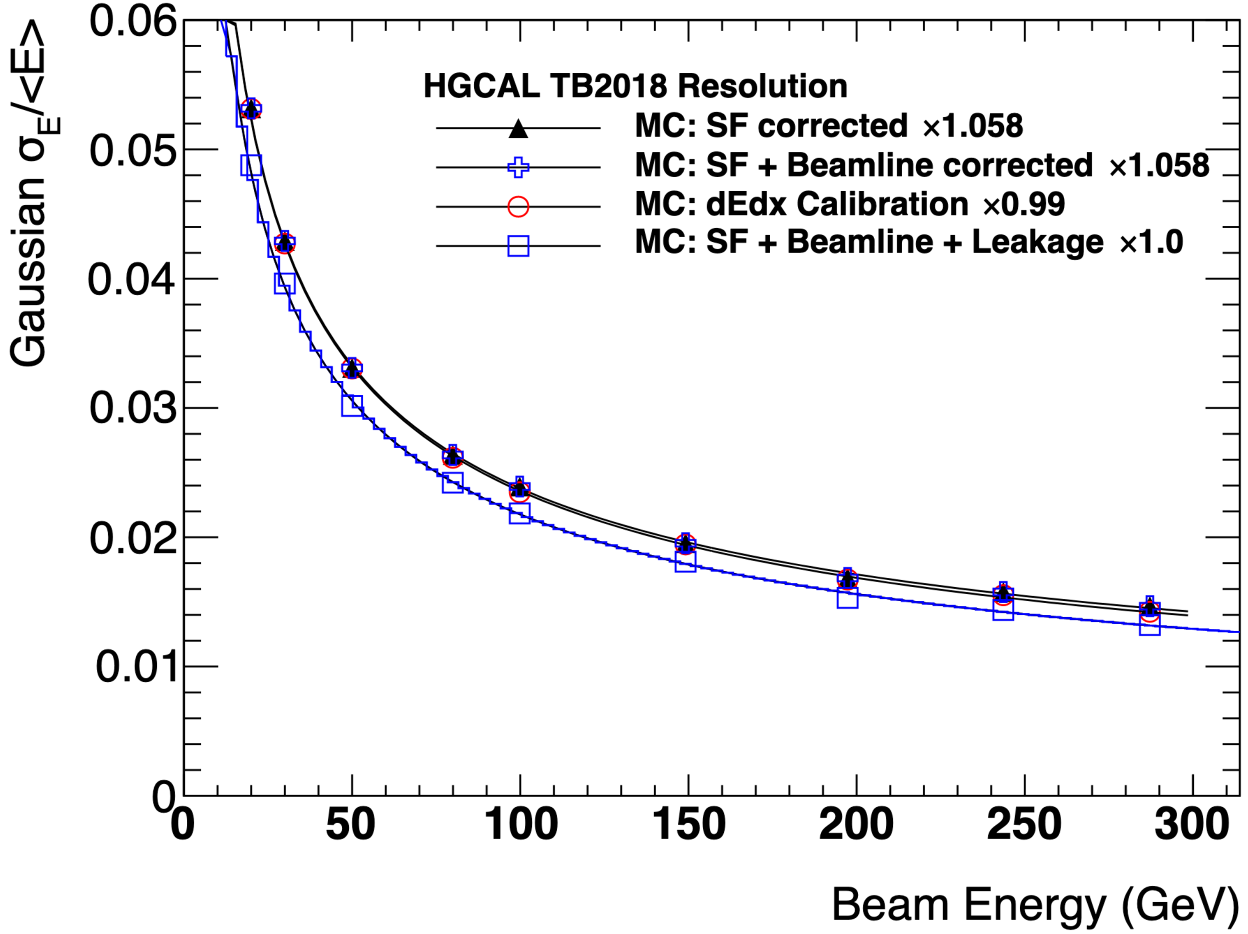
dEdx Calibration

$$E_e = \sum_i^{N_{layer}} \left(\underbrace{\frac{\Delta E_i^{Abs} + \Delta E_{i+1}^{Abs}}{2} + \Delta E_i^{Si}}_{W_i} \right) \times E_i^{Si}$$

This is the same as averaging the number of MIPs seen in the sensors before and after the passive layer



Geant4: Expected Resolution

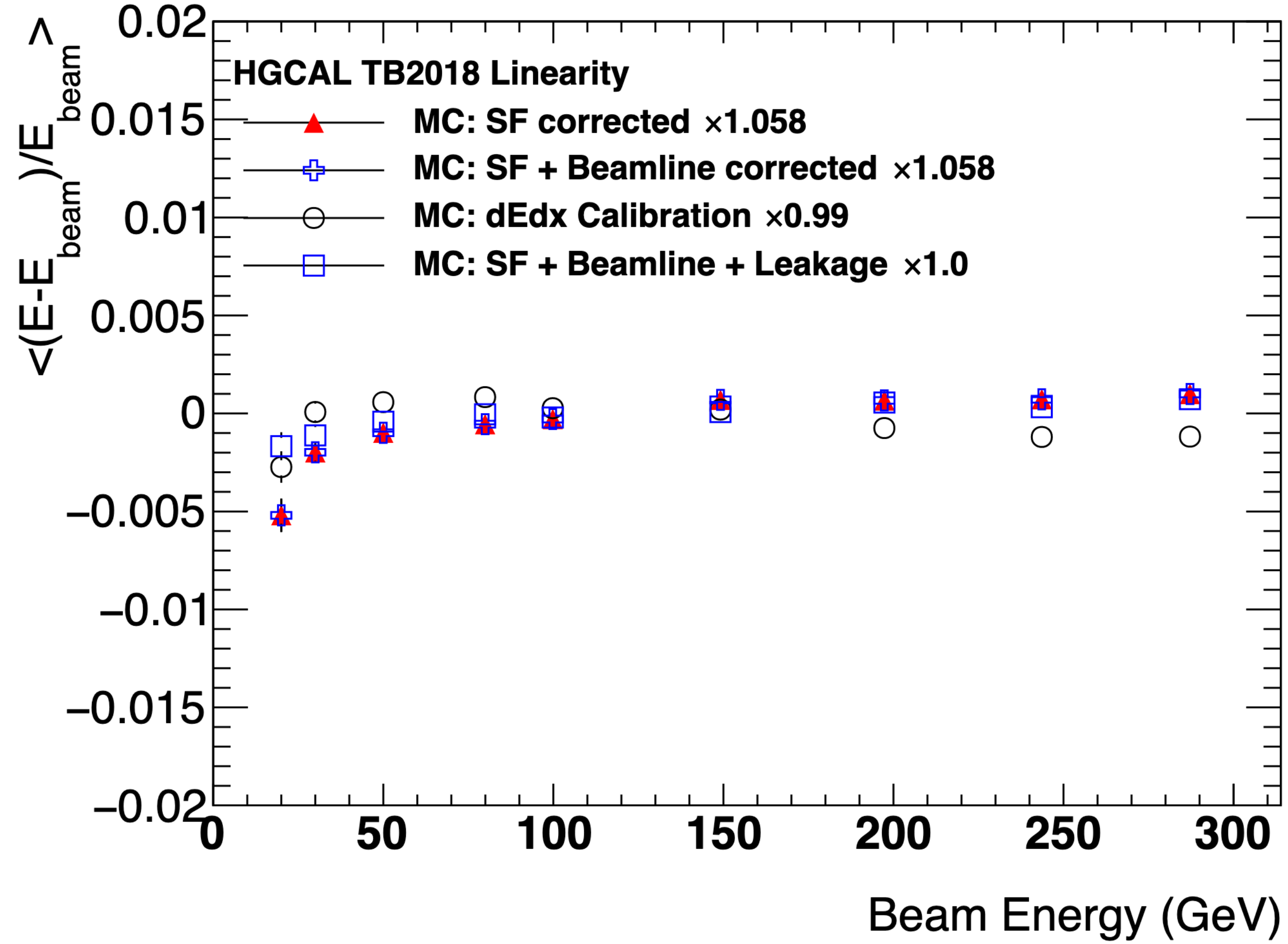


Stoch Term:
21.5% (after calibration)
21.5% (added losses)

Const Term:
0.55% (after calibration)
0.40% (added losses)

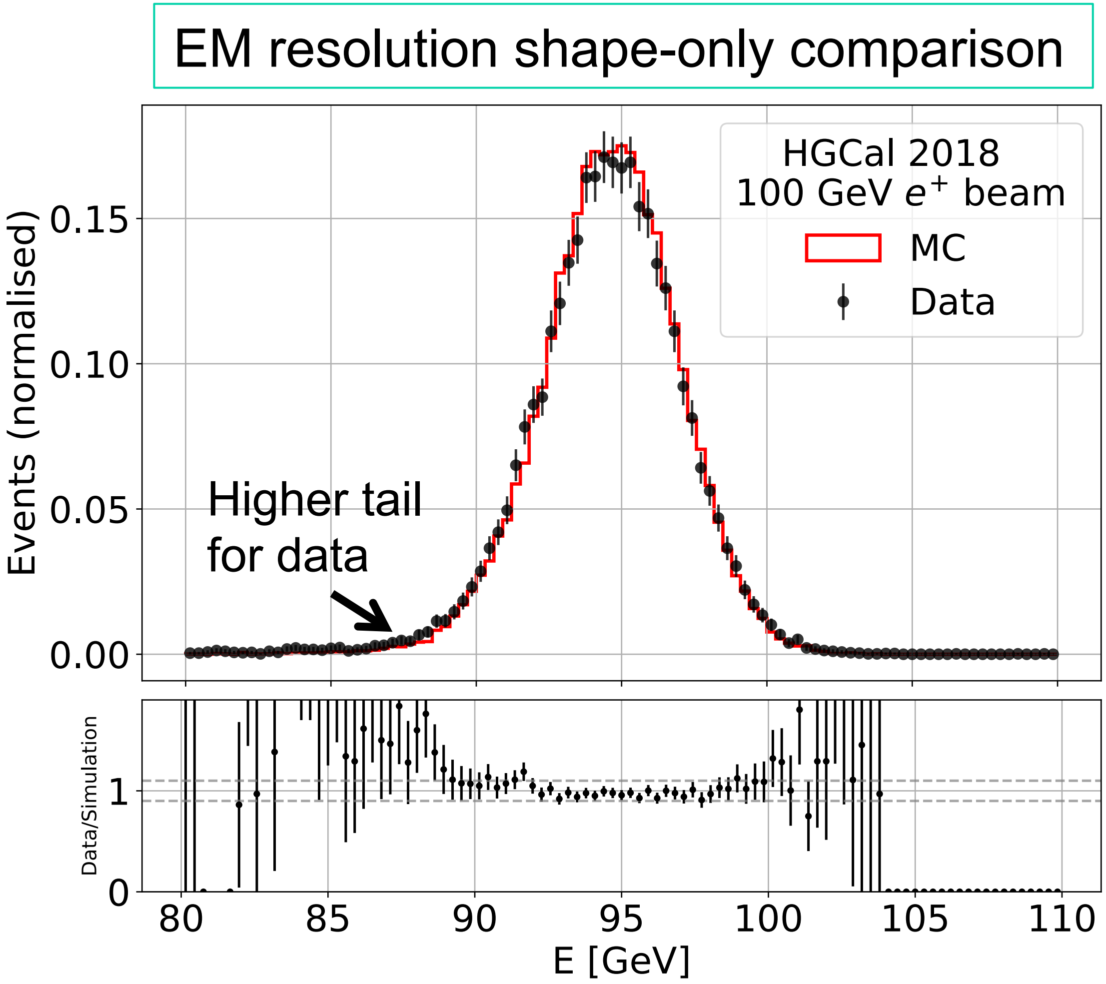
- Closure test, checking the performance of the dEdx method.
- Also checks the impact of removing/adding energy lost outside the HGCAL
- Adding outside losses from truth improves the c-term by 0.2%

Geant4: Expected Linearity



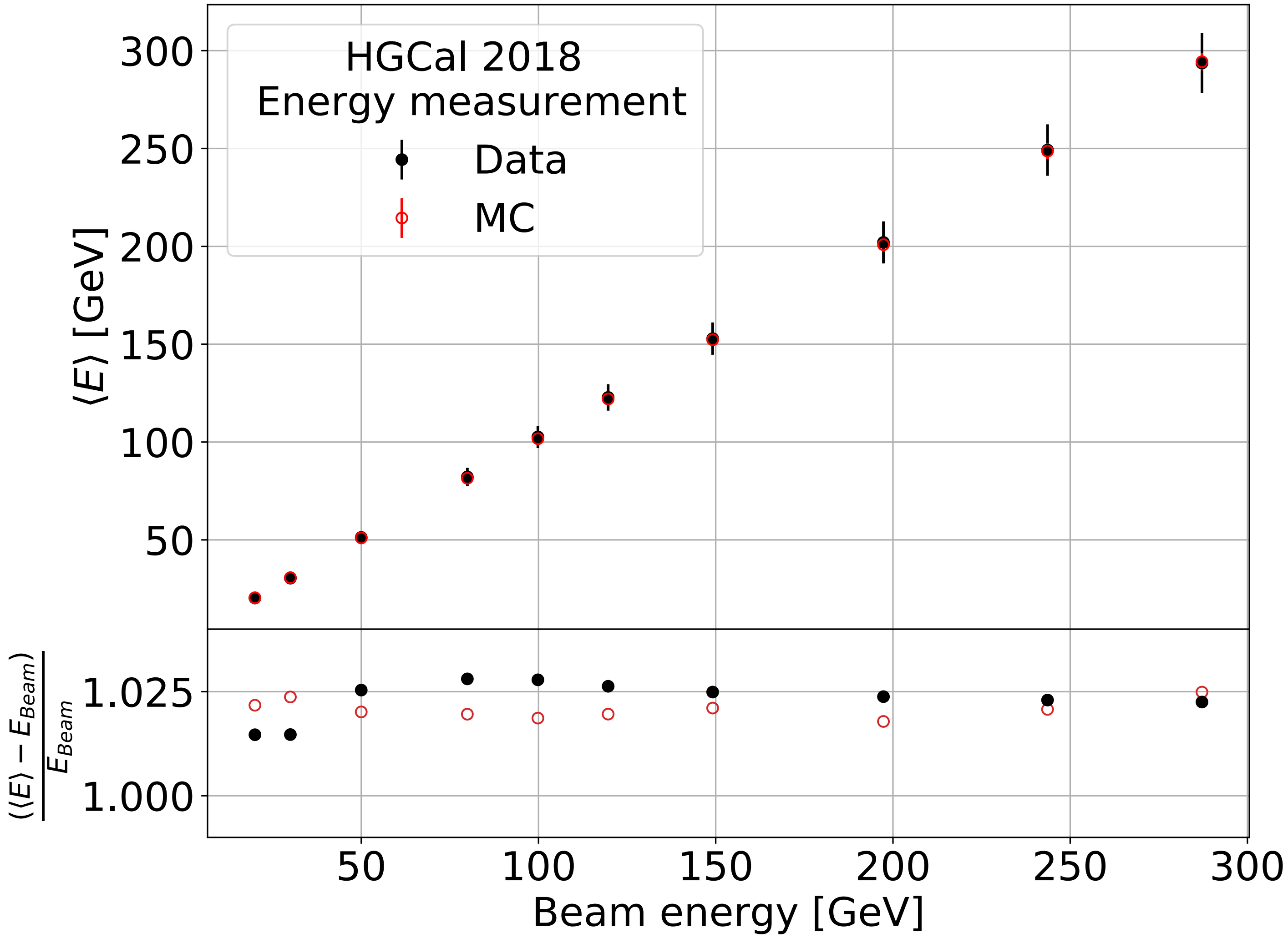
- Closure test, checking the performance of the dEdx method.
- Also checks the impact of removing/adding energy lost outside the HGCAL
- dEdx weights: overcorrect by 5% to 6%, but maintain linearity to <0.5%

dEdx calibrated, total Energy



- No factors applied here
- MC has been scaled (down) to match the data.
- Tails from incomplete beam-line simulation (work in progress)

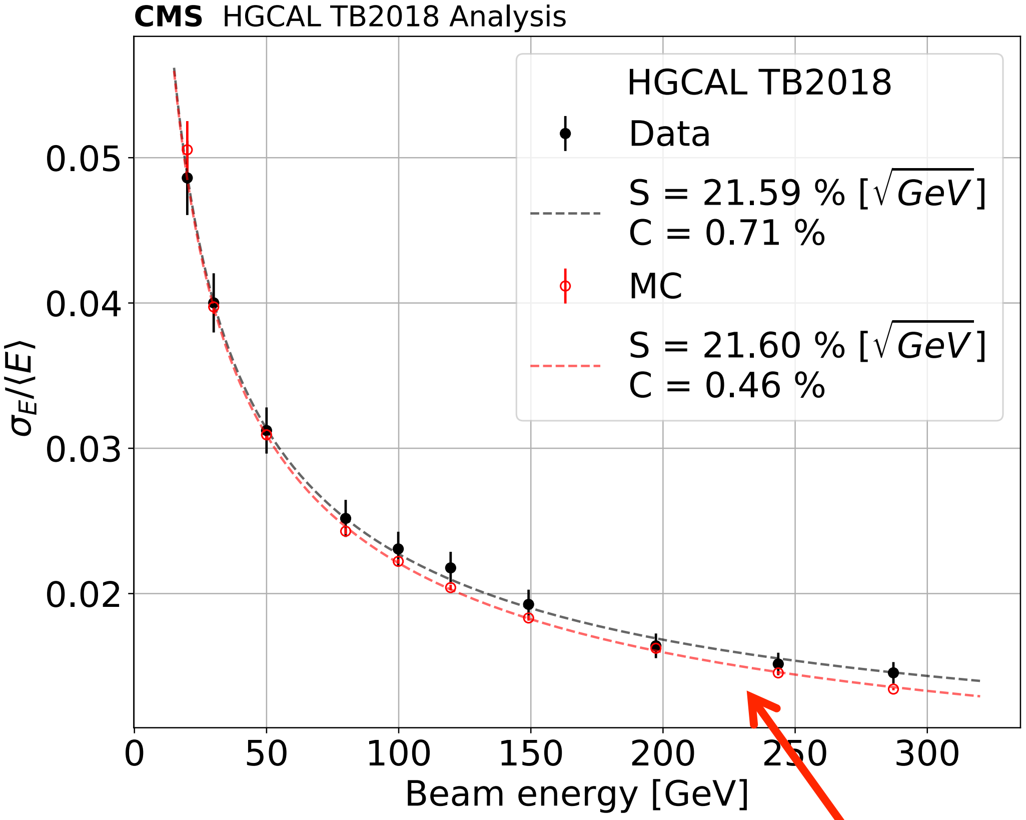
Absolute scale: data and MC



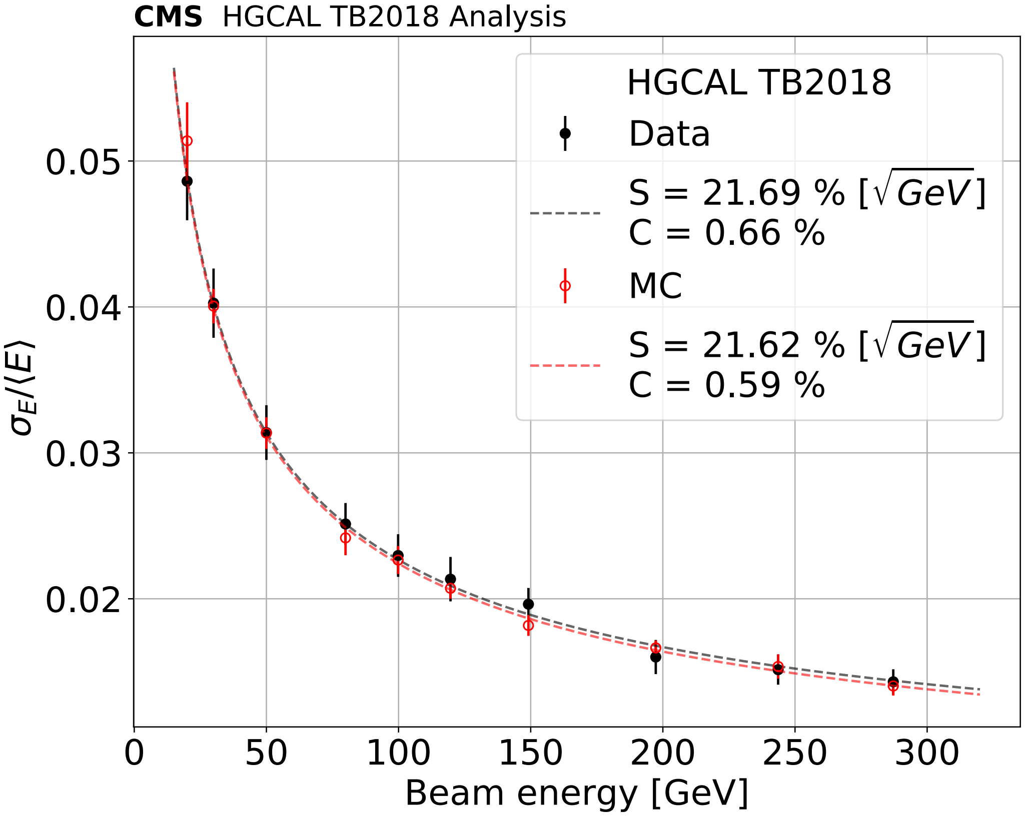
After dEdx weights: both Data and MC overshoot the absolute scale by 2% - 2.5%

Energy Resolution

Resolution after dEdx Calibration



Resolution prior to Calibration

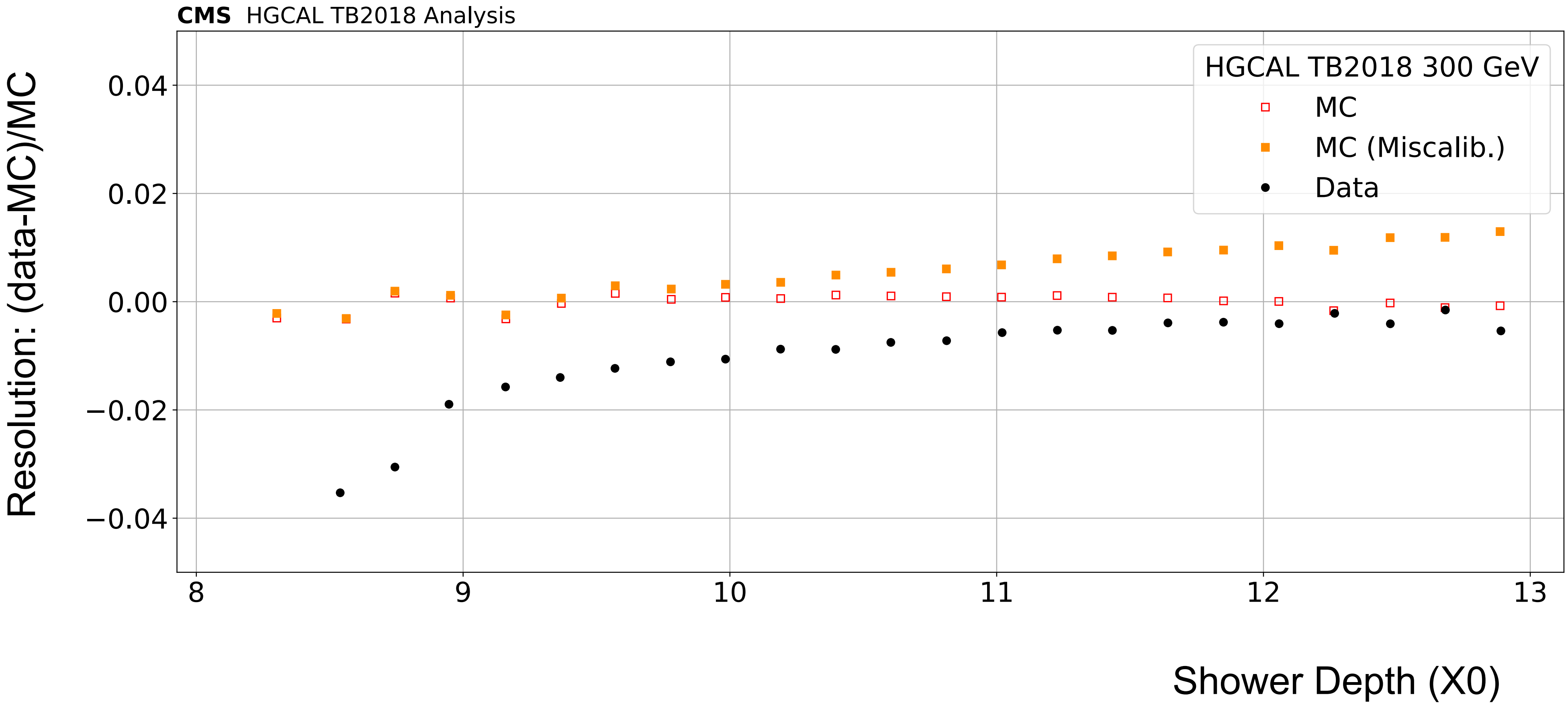


Electron Energy Resolution

	dEdx S [$\sqrt{\text{GeV}}$] %	dEdx C %	Vis S [$\sqrt{\text{GeV}}$] %	Vis C %
Data	21.59 ± 0.15	0.71 ± 0.05	21.69 ± 0.14	0.66 ± 0.07
Monte Carlo	21.63 ± 0.24	0.41 ± 0.03	21.62 ± 0.24	0.59 ± 0.09

TDR:
S: 23%
C: 0.5%

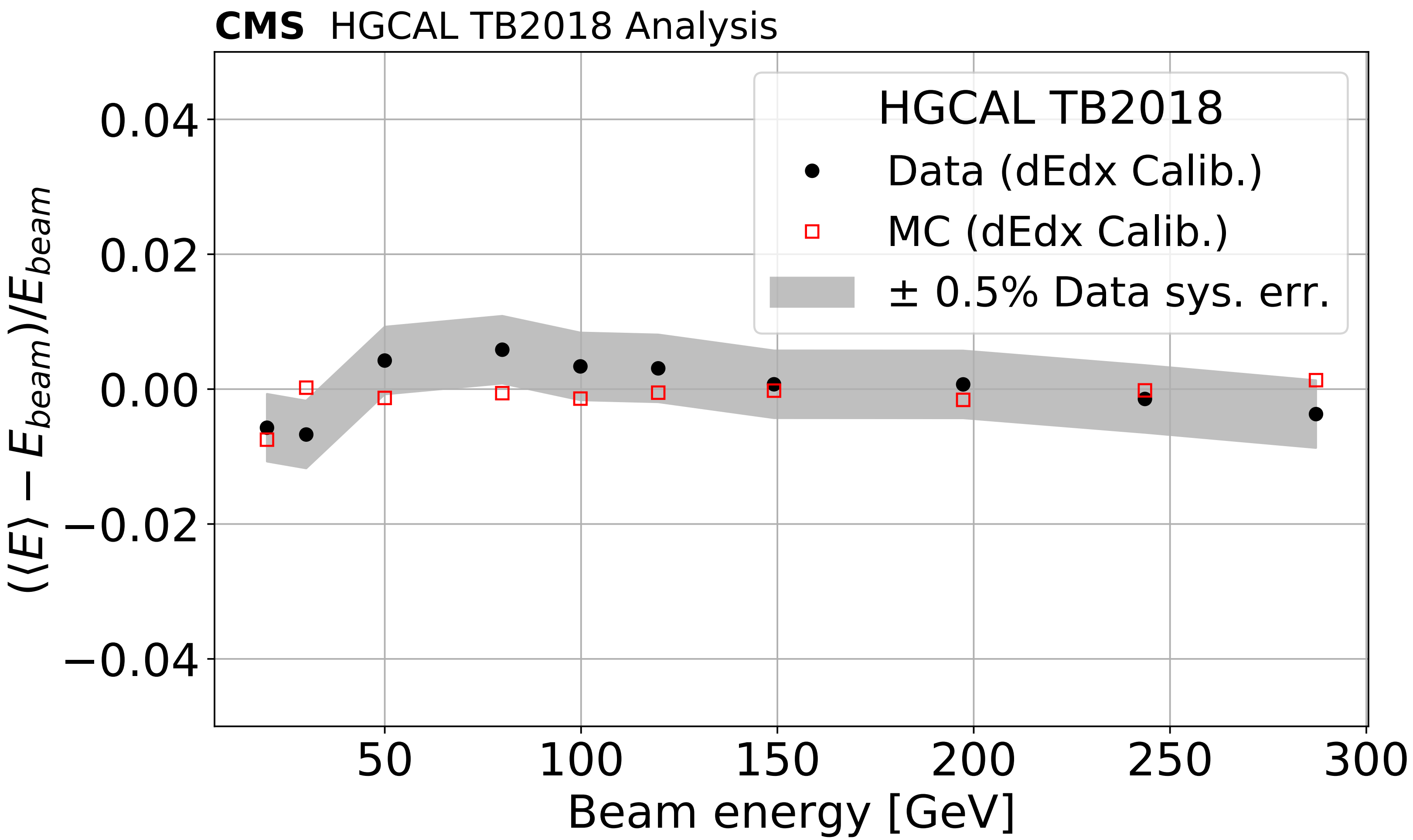
Layer weights can induce c-term



Default MC without any miscalibration shows a constant resolution vs depth.
Data show a slope, that leads to the worse resolution we observe.

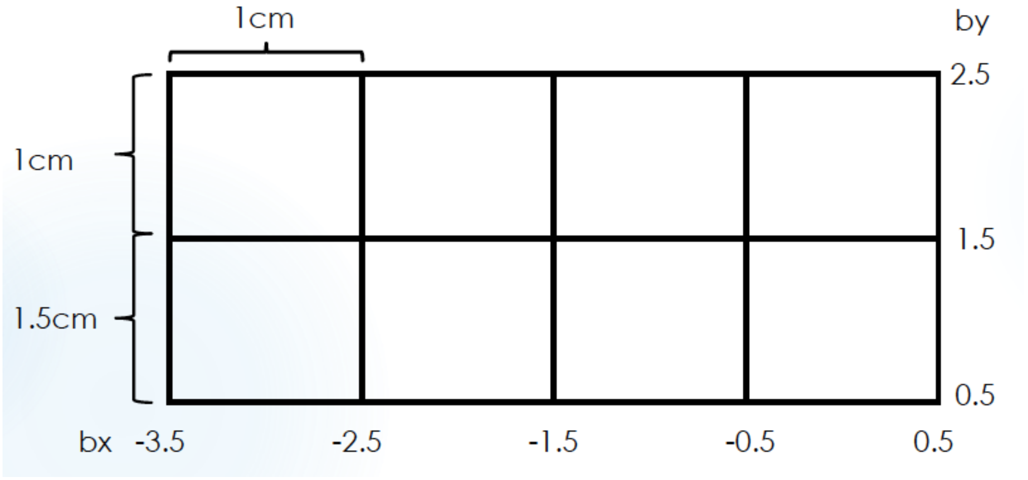
If we induce miscalibrations to MC, we manage to reproduce the data slope.

Energy Linearity



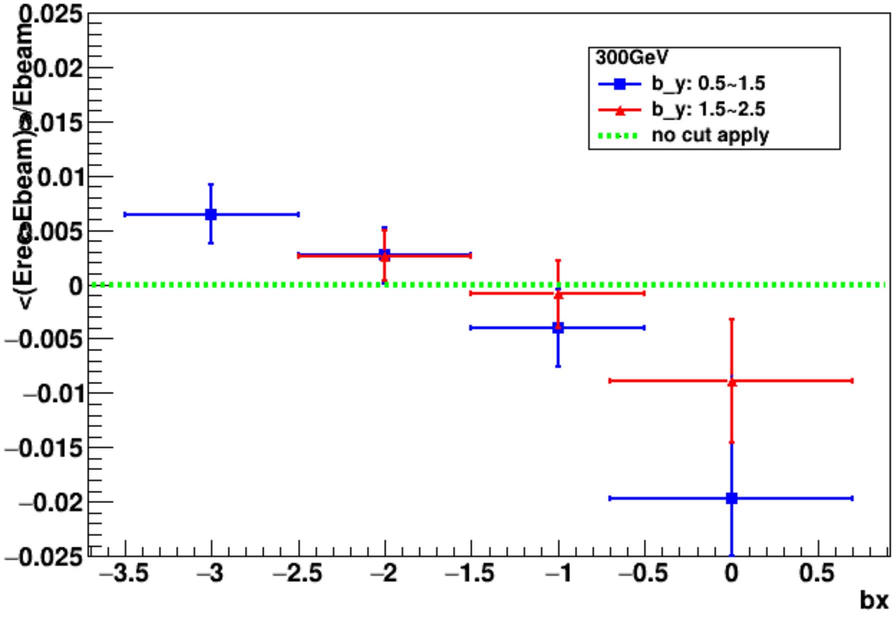
- dE/dx Energy Linearity within ~1% from 20 to 300 GeV
- Expected Linearity from MC is at the level of 0.5%

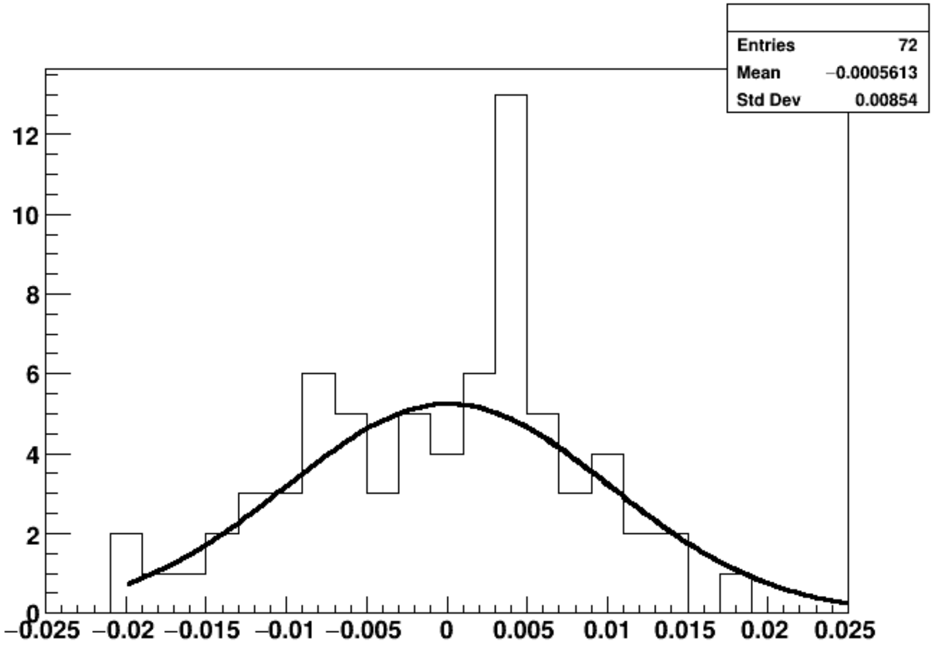
Energy Uniformity?



We extend our fiducial acceptance to study Energy uniformity.

The c-term receives non-local contributions.
(MC predicts 0.4% local c-term)





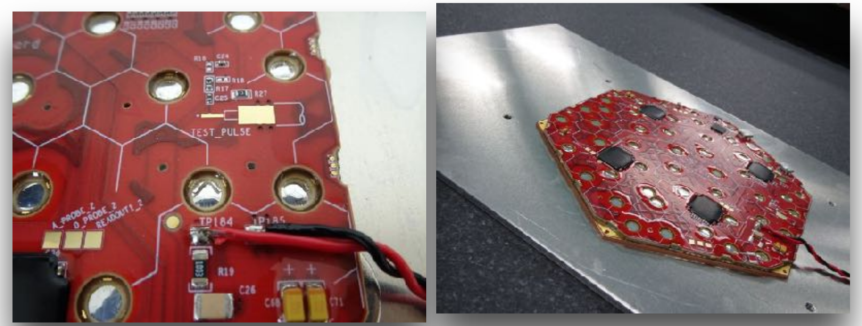
Taiwan MAC

- Facility commissioned in March 2019
- In April we assembled a full module.
- On-going R&D in tooling, bonding, encapsulating, biasing.

Milestone: completed a 3-year setup/commissioning phase

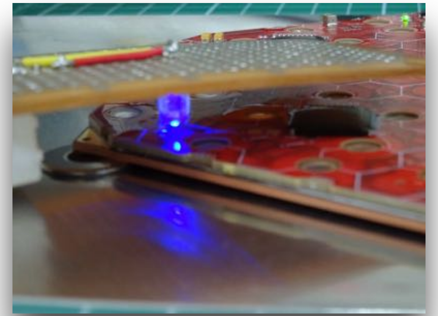
Module Assembly & Testing

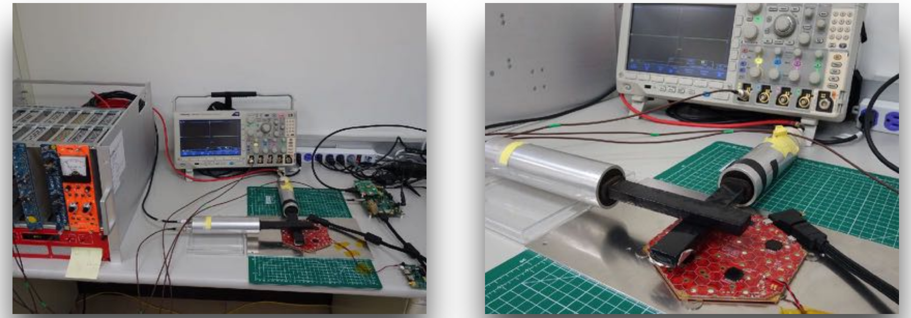
- First 6 inch module assembled & bonded in April



- Encapsulation tests/practice
  - Sylgard 184
  - Dispensing by glue dispenser and LabVIEW
  - Syringe handled manually.

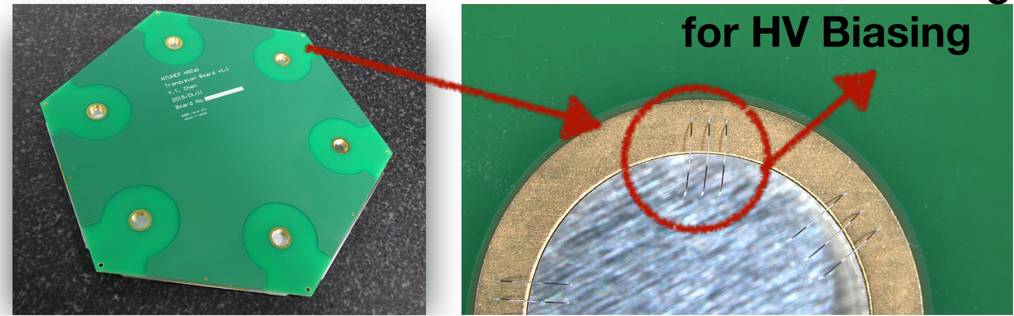
- Testing our Modules with LED and Cosmics





Cosmic trigger settings

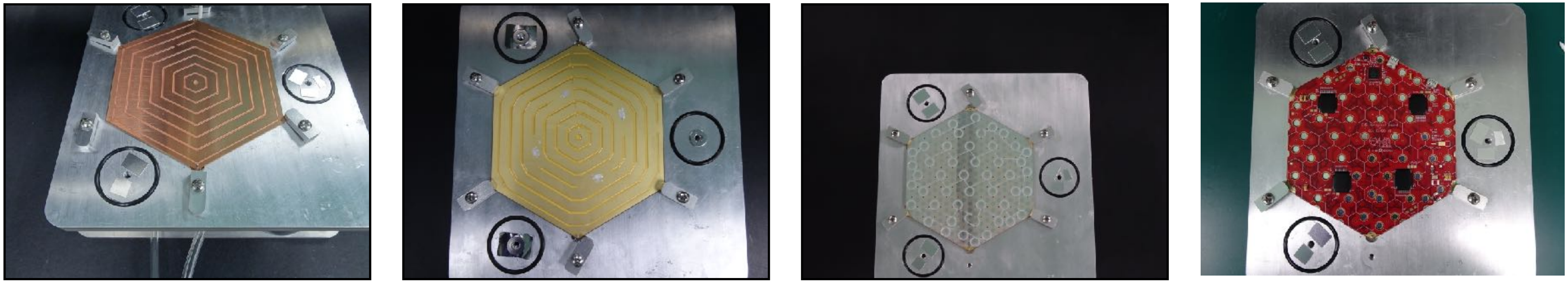
- We have made one PCB baseplate mock module
  - PCB baseplate + Aluminum Layer + Bare Hexaboard
  - Practice backside bonding
  - Plan to make a real module



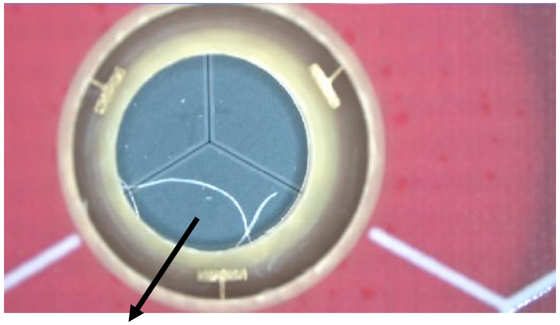
Backside Bonding for HV Biasing

Module Assembly: 6-inch

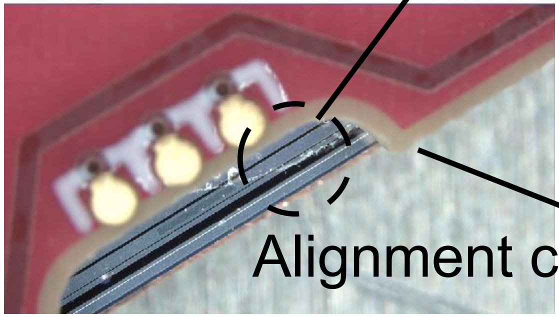
- 1.2 mm Cu BasePlate + 70μm gold-Kapton + 400μm Si Sensor + V3 PCB



- Some Problems encountered, but overall the assembly procedure has been smooth



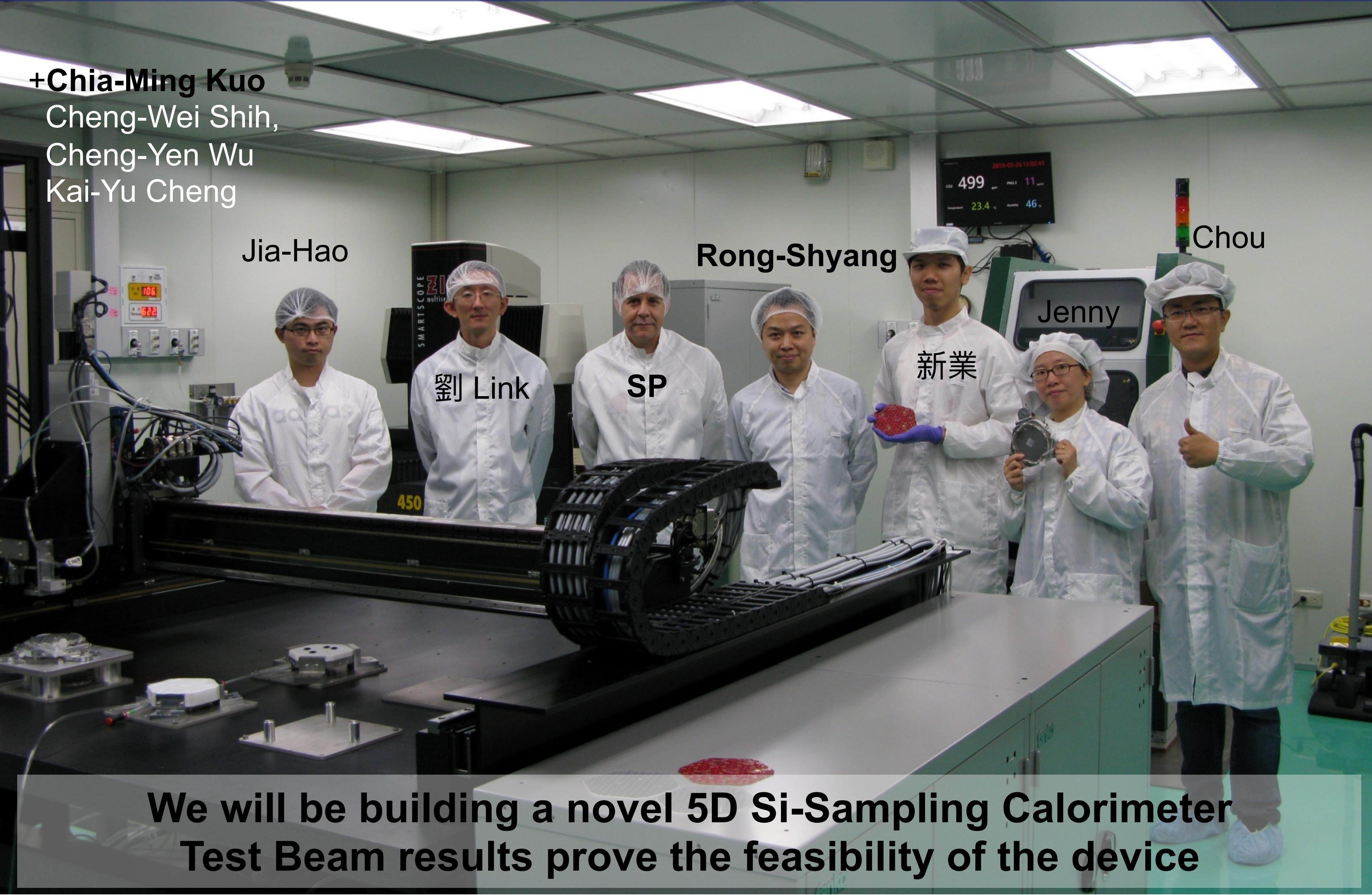
Fibers stuck between PCB and Sensor



Glue leakage at edge

Alignment can be improved

Summary



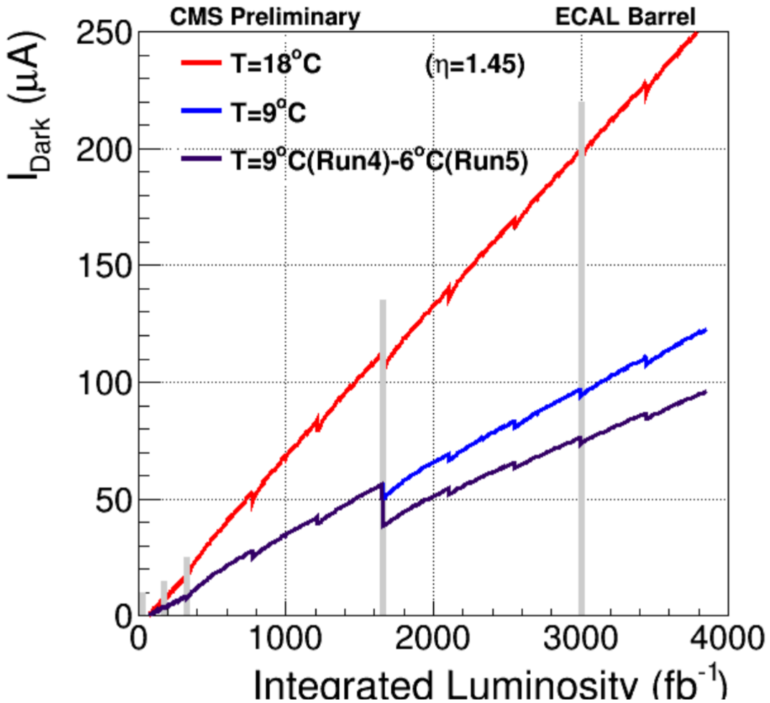
We will be building a novel 5D Si-Sampling Calorimeter
Test Beam results prove the feasibility of the device

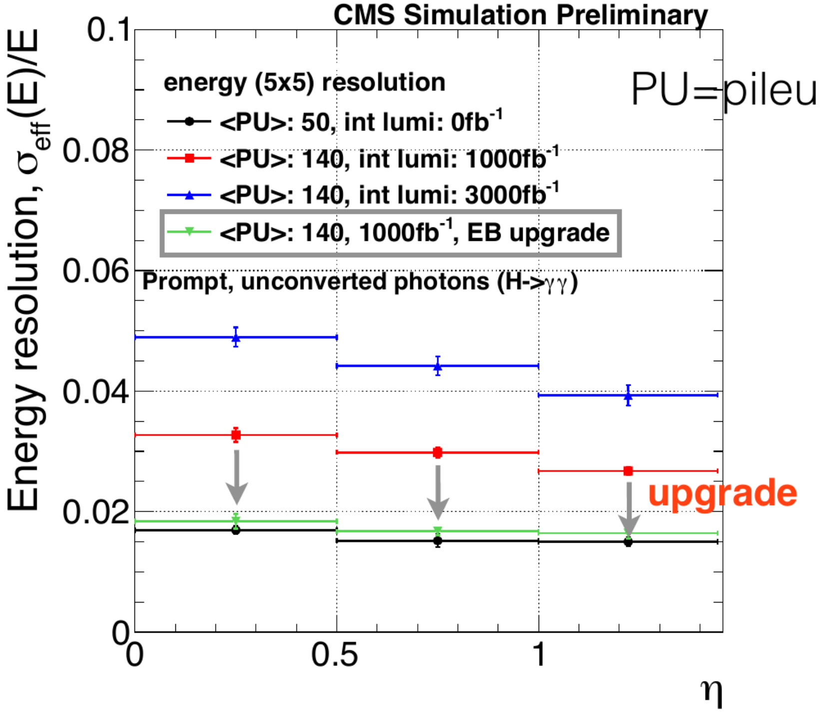
Extra Slides

ECAL APD performance

- ❑ ECAL APDs will continue to operate well during HL-LHC
  - Increase in leakage current due to radiation damage
    - APD noise will dominate energy resolution at HL-LHC

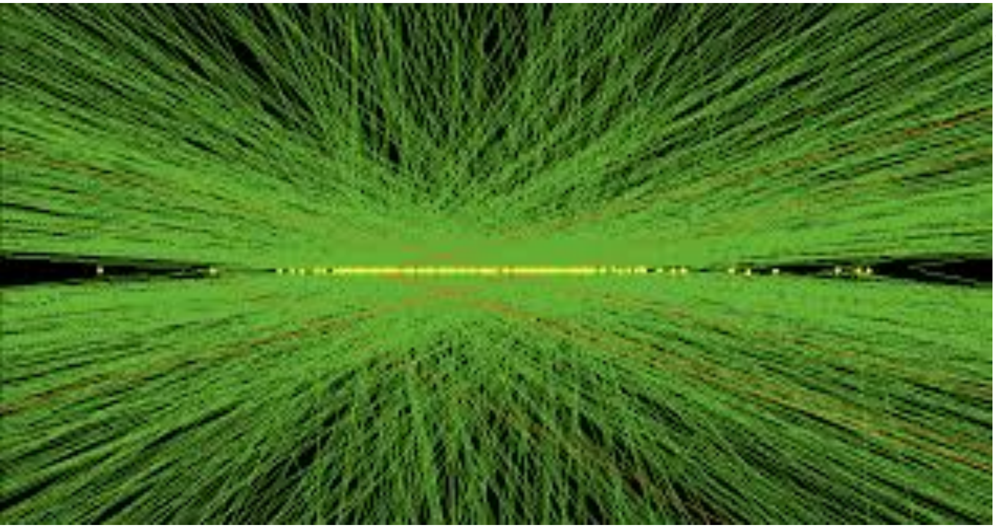
- ❑ Actions Taken:
  - ✓ Lower ECAL operation temperature from 18^{o}C to 6-9^{o}C
  - ✓ To reduce the PU impact and obtain better S/N, the pre-amplifier will have shorter signal pulse length.



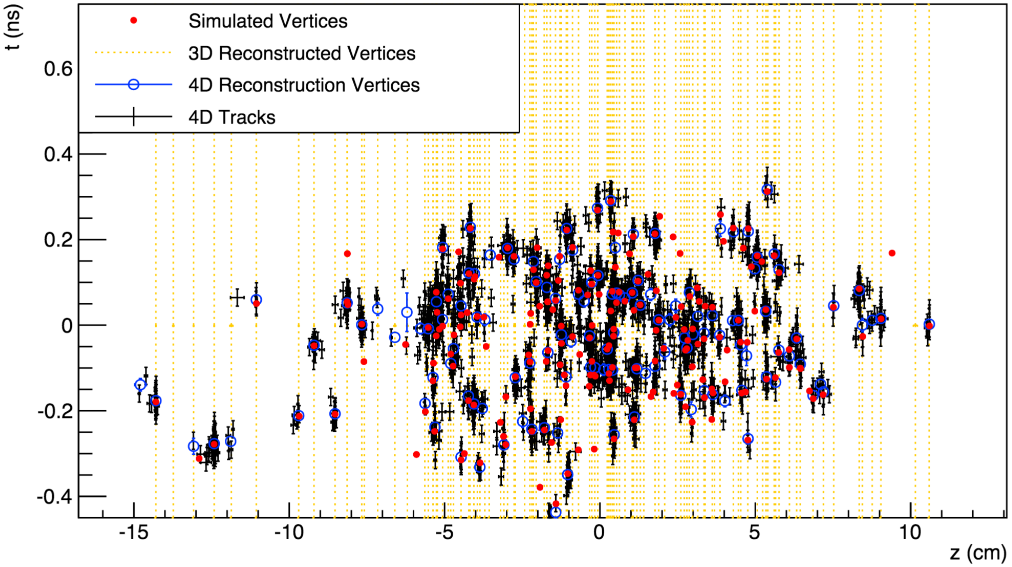


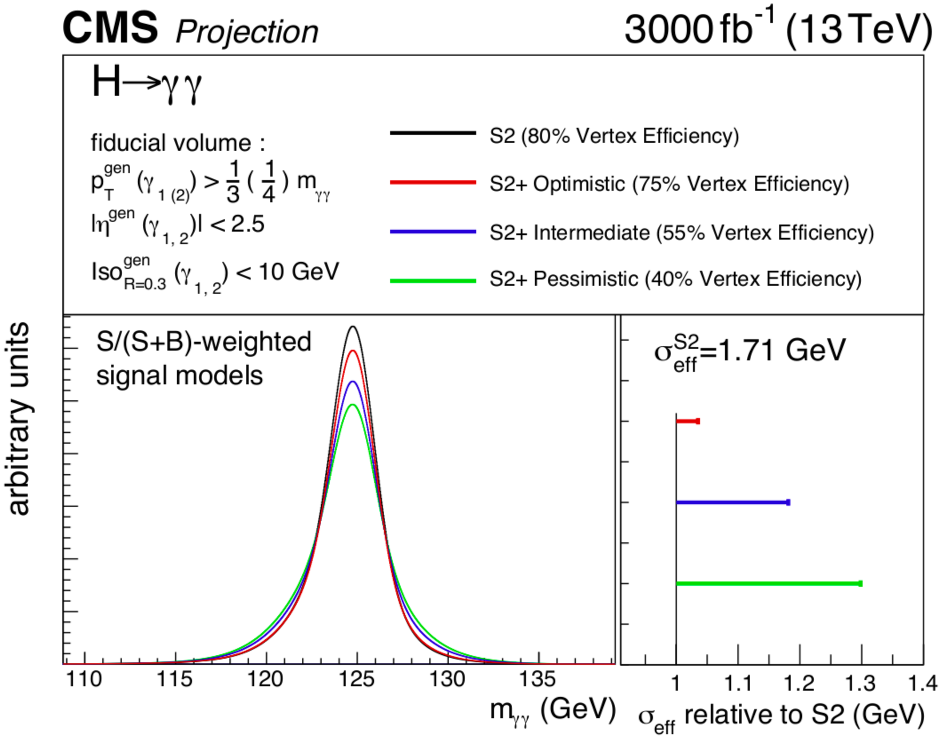
PU=pileup

PU: Timing Resolution



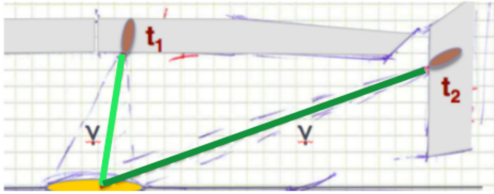
Phase II Pileup 5x higher than Phase I
Vertex ID efficiency drops from 80% to 40%





- Precise ~30ps TOF timing can improve vtx ID
- $PbWO_4$+APD intrinsic resolution <30ps
- Global CMS effort to provide high precision clock

H→γγ mass Resolution under different assumptions



No precise timing
+ upgraded ECAL timing
+ new CMS MIP timing layer

ECAL Challenges at Phase II

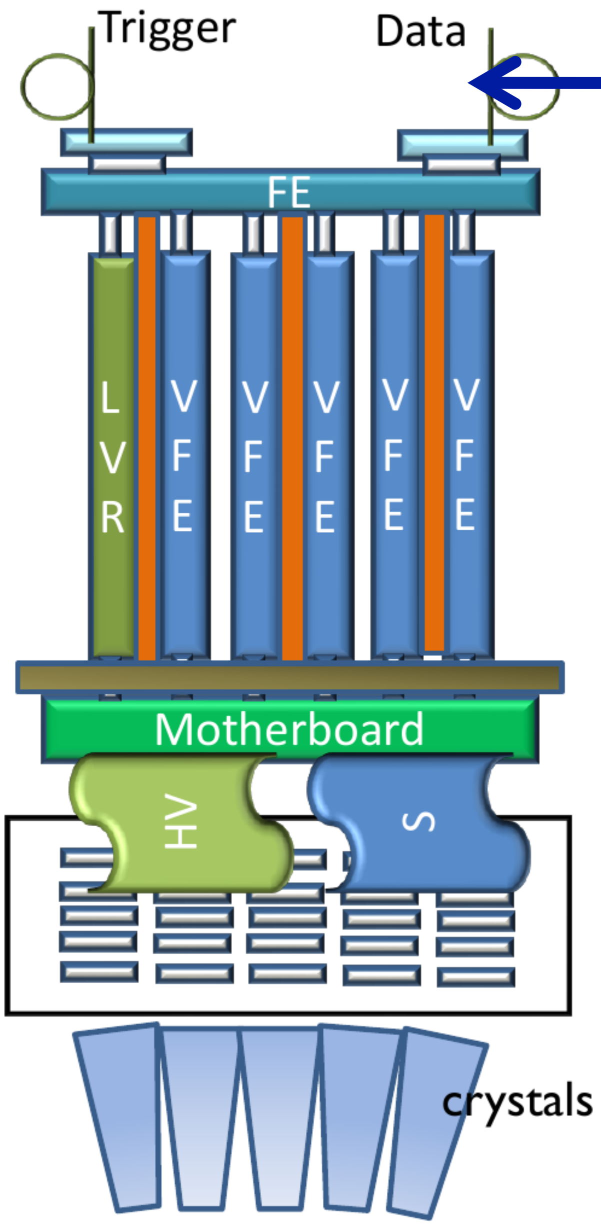
Phase II goal:

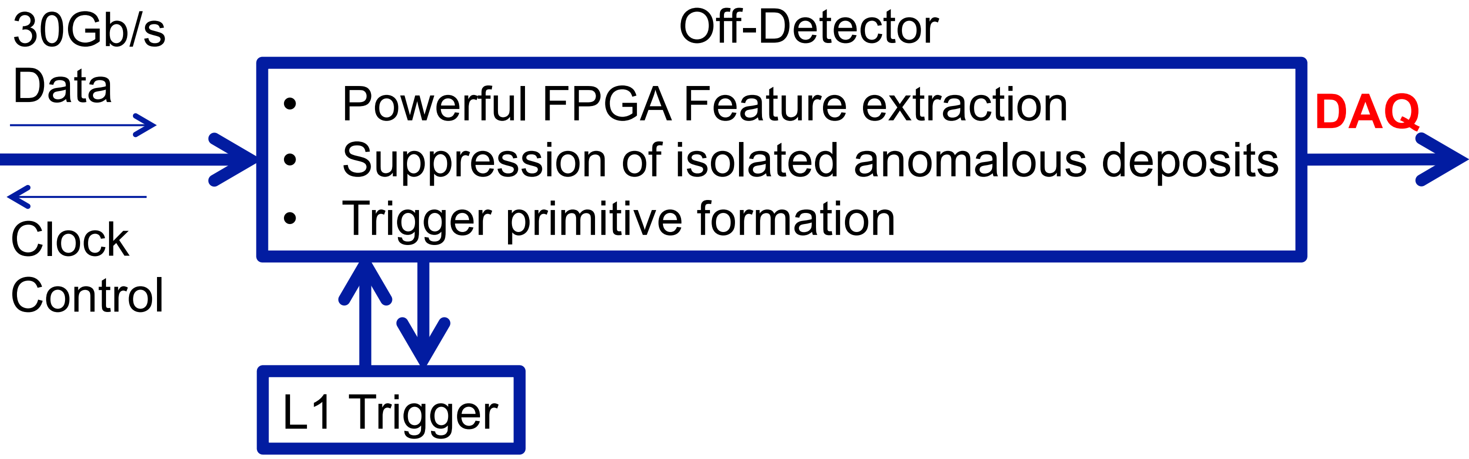
- ☐ Preserve current ECAL physics performance under HL-LHC and CMS Phase II conditions and demands

Challenges:

- ☐ Higher trigger rates and longer latency
- ☐ Crystal transparency loss due to higher radiation damage
  - ✓ Impacts ECAL energy resolution
- ☐ 10x noise increase from APD leakage currents due to higher radiation damage
  - ✓ Dominates ECAL energy resolution
- ☐ Reduced vertex ID efficiency due to much higher pileup
  - ✓ Impacts $H\rightarrow\gamma\gamma$ mass resolution
- ☐ Increased pileup contamination
  - ✓ Impacts ECAL energy resolution

ECAL Upgrade




30Gb/s Data

Clock Control

Off-Detector

- Powerful FPGA Feature extraction
- Suppression of isolated anomalous deposits
- Trigger primitive formation

DAQ

L1 Trigger

Main Reason: cope with higher L1 trigger rate and latency

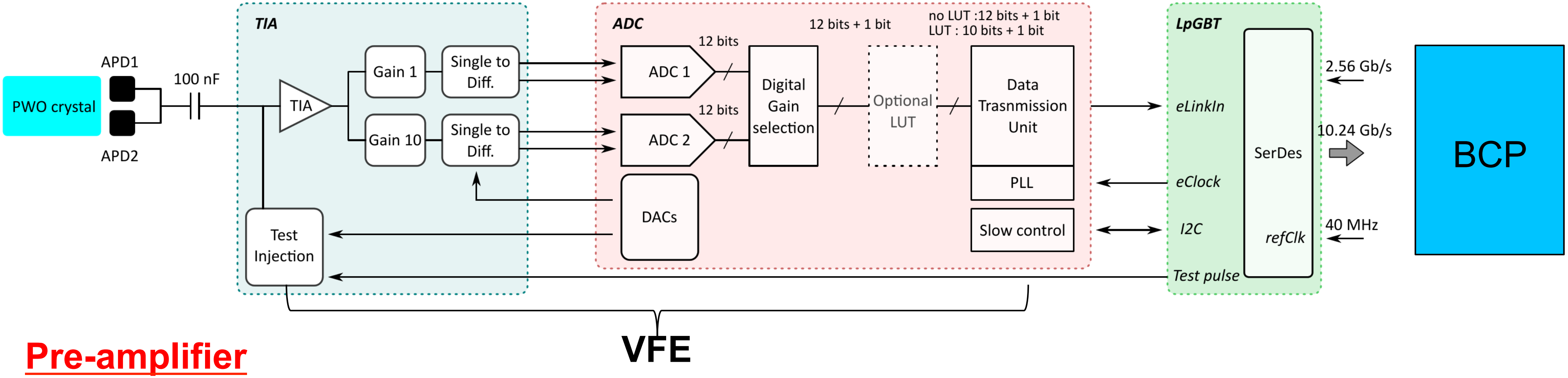
Replace VFE and FE:

- Stream detector data along one path.
- Move pipelines and trigger primitive generation to off-detector

Re-design VFE:

- Reduce shaping time
- Increase sampling frequency (160MHz)
- New ADC and data compression
  - ✓ Excellent energy resolution
  - ✓ Fast response for pileup mitigation and noise reduction
  - ✓ Timing resolution and spike discrimination

ECAL upgraded electronics



Pre-amplifier

- Trans Impedance Amp (TIA) architecture optimizes pulse length and sampling rate.
- Matches the requirements for noise, spike rejection, pileup mitigation, and precision timing.
- 2 TeV dynamic range, two gain ranges (G1, G10) with 50, 500 MeV LSB

ADC

- 12 bit, 160MHz sampling frequency
- IP block which will be put in custom chip with rad hard design + data compression in Data TU

FE

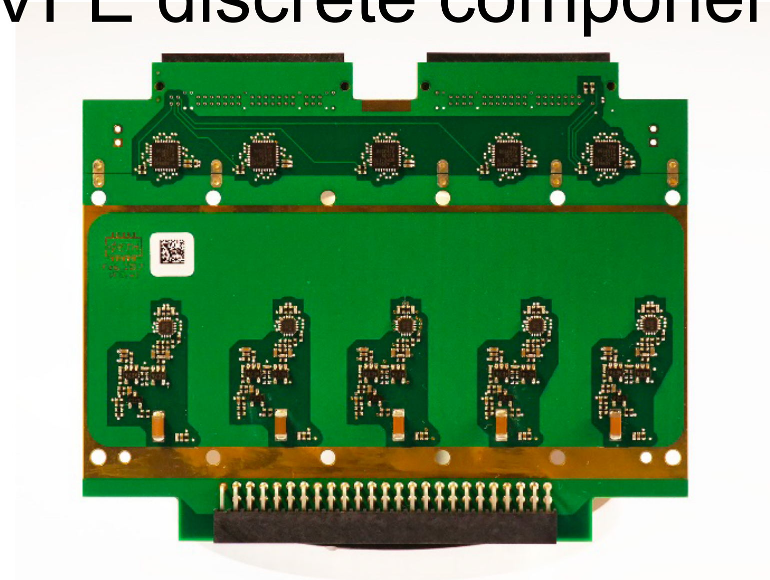
- Fast rad-hard optical links to stream crystal data off-detector (OD) through CERN lpGBT/VL

BCP

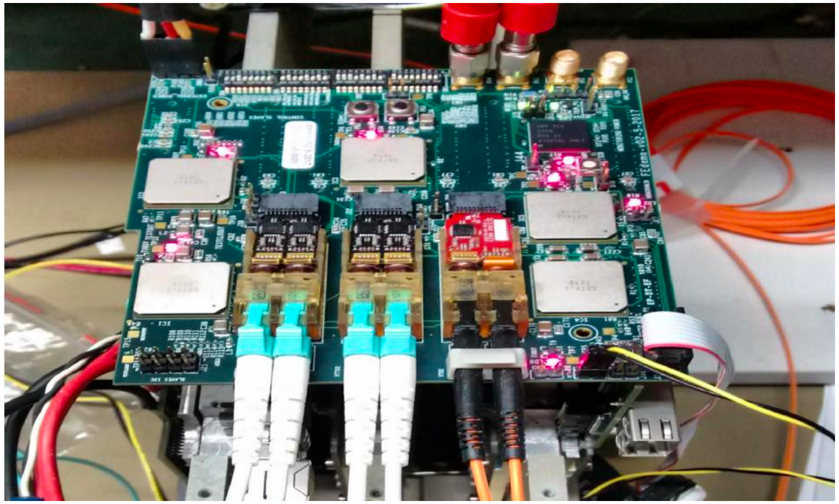
- Barrel calorimeter processor, FPGA based → Data pipeline, trigger primitives, signal analysis for spike reduction, channel calibration and more

Some Hardware

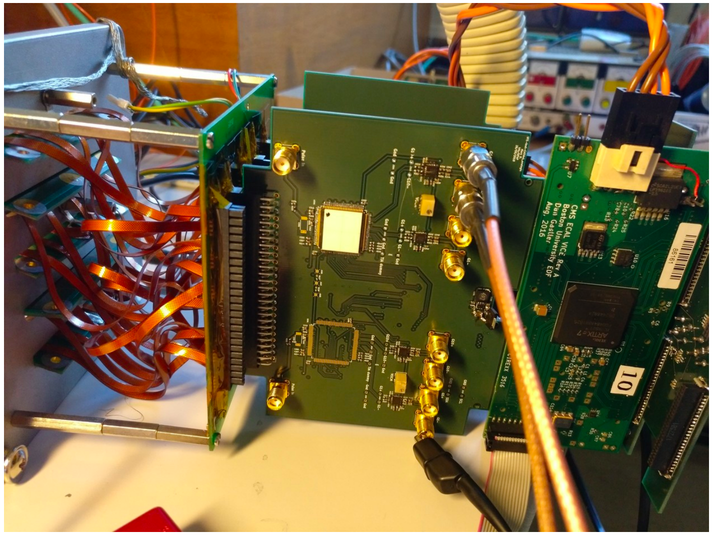
VFE discrete components



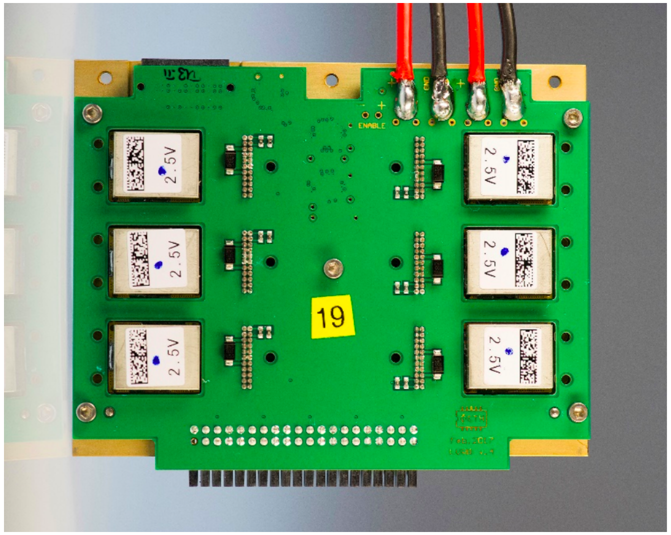
FE prototype



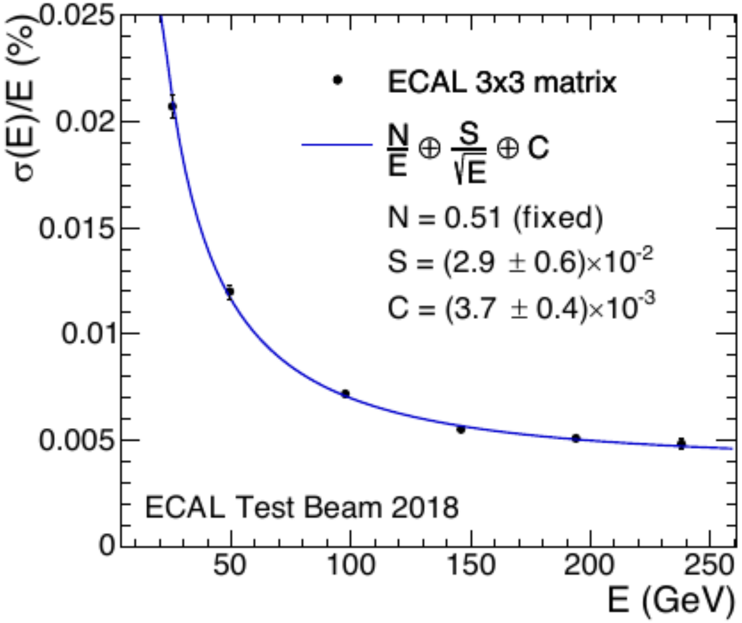
CATIA asic analog board



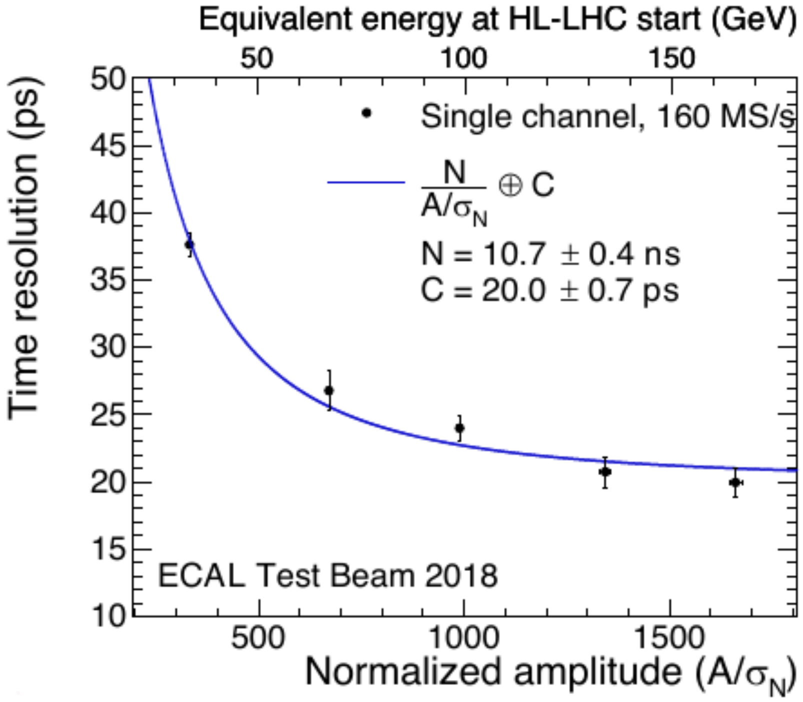
Low voltage regulator prototype



VFE prototypes in 2018 Test Beam



Energy Resolution:
matches CMS phase I



Time Resolution:
Matches target of <30ps for E>50GeV

- One ECAL tower (5x5=25 channels) equipped with the first prototype of Phase II ASIC amplification chip and 160 MHz commercial ADC

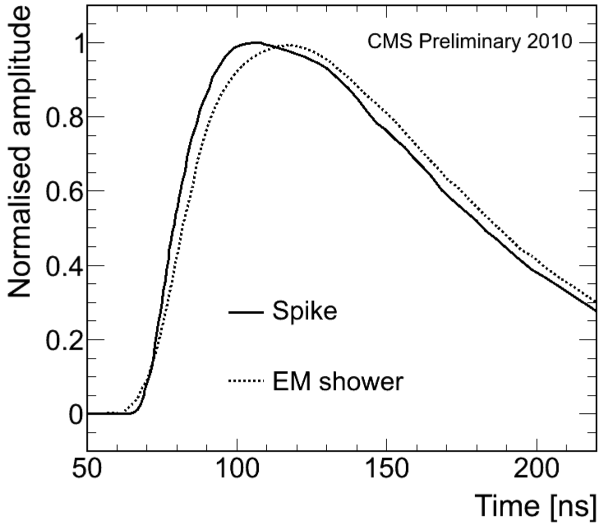
- Electron beam: 25-250 GeV energy range. Setup kept at 18^{o}C

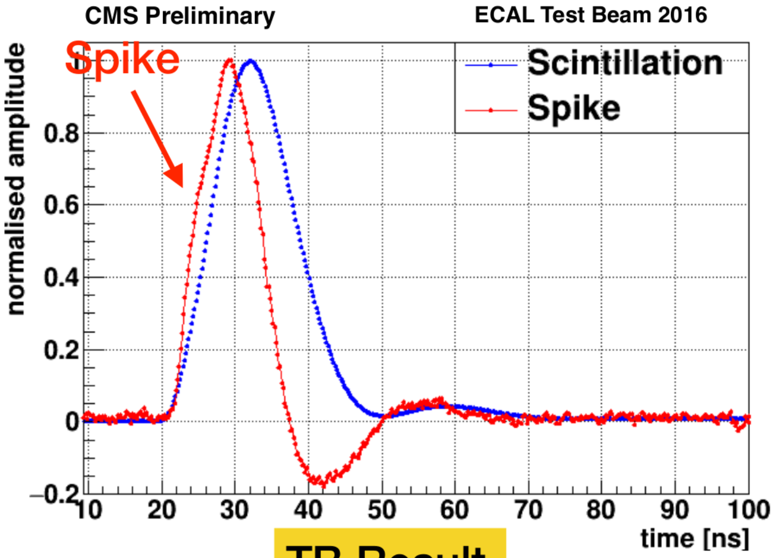
Trigger

- ☐ Granularity increase from tower level (5x5) to crystal level
- ☐ More sophisticated hardware-level trigger algorithms
- ☐ Pileup and background rejection
- ☐ Online signal shape analysis → online reduction of anomalous hadron signals.
  - ✓ Target: 1kHz for E > 5GeV

CMS-DP-2012/008

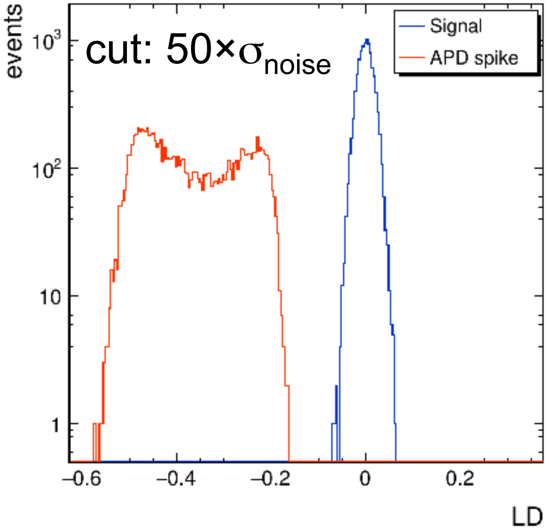
Phase-I (CMS in-situ)





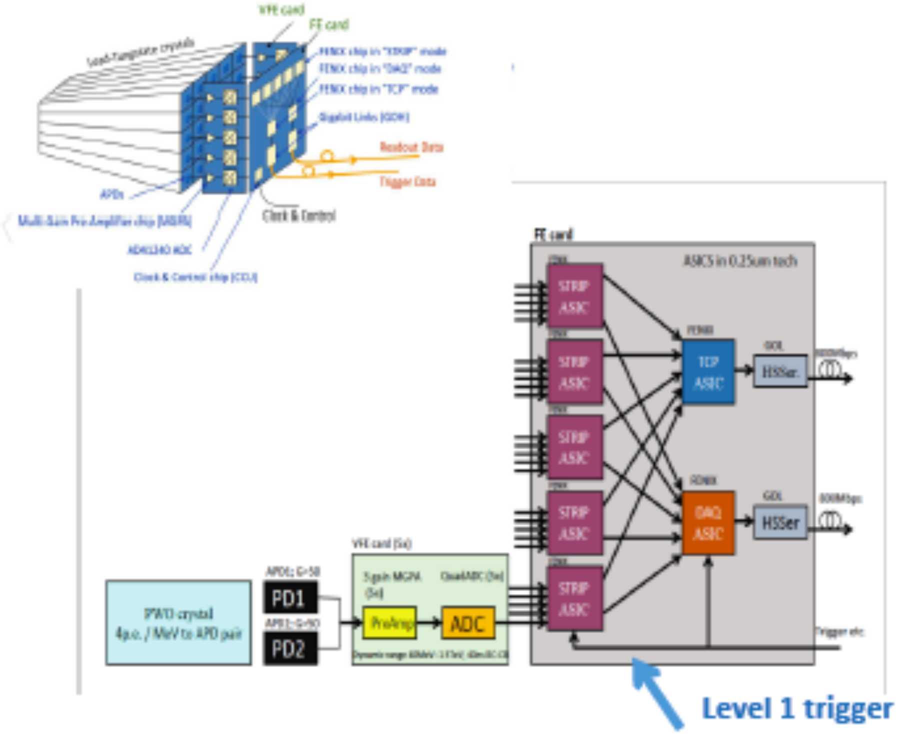
TB Result

Example discriminant (TDR Simulation)



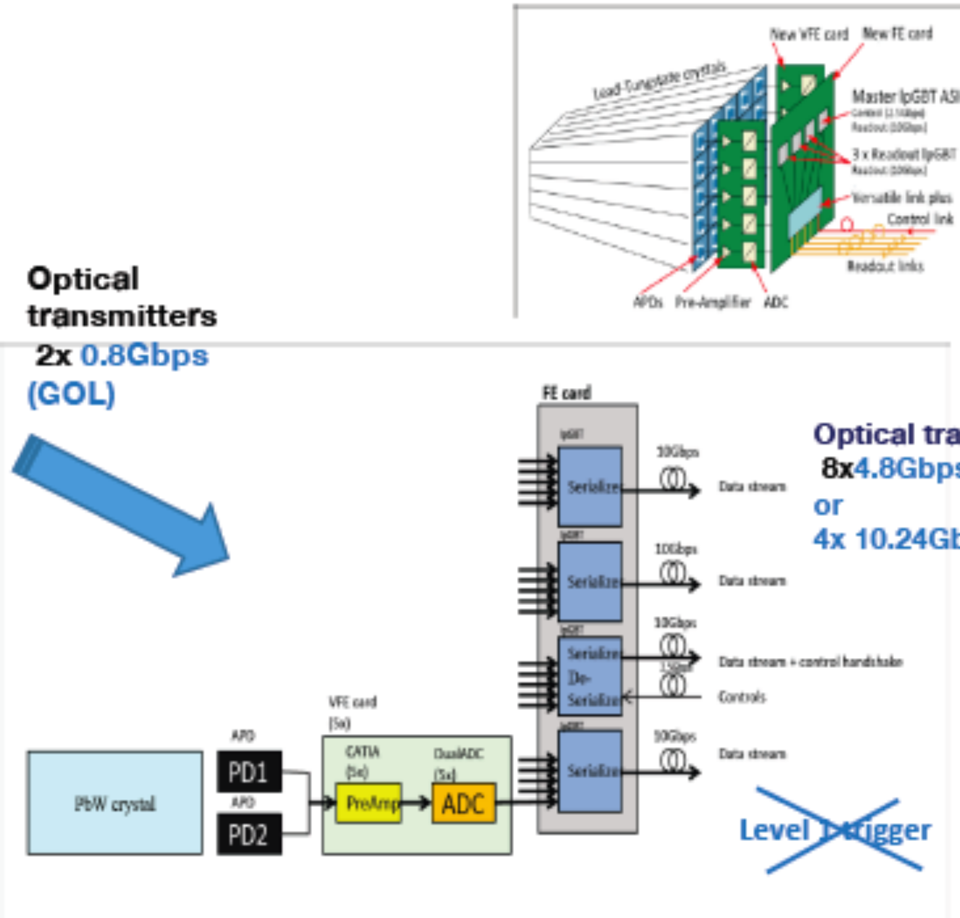
ECAL Electronics Upgrade

ECAL legacy on-detector electronics



Level 1 trigger

ECAL Upgrade on-detector electronics



Optical transmitters
2x 0.8Gbps (GOL)

Optical transmitters
8x4.8Gbps (GBTx)
or
4x 10.24Gbps (lpGBT)

Data rates:

Per crystal:
- Pre-amp 3 ranges
- 12 bit ADC
- 14 bit data @ 40 MHz
- 560 Mbps data flow

Per VFE card:
- 5 crystals
- 2.8Gbps @ 40 MHz sampling

Per Trigger Tower:
- 5 VFE cards
- 14Gbps @ 40 MHz
- → 0.8Gbps TRIGGER primitives
- L1 trigger → 0.8Gbps DATA

Per VFE card:
- 5 crystals
- 10.4Gbps @ 160 MHz
- 5.4Gbps @ 160Mhz @ compression

Per Trigger Tower:
- 5 VFE cards
- 52Gbps @ 160 MHz
- 27Gbps @ 160Mhz @ compression

Crystal→APDs→VFE→FE